News from the Top

Status and Perspectives of Top-Quark Physics in Fall 2013

Meeting of the DFG Collaborative Research Center “Computational Particle Physics”
Karlsruhe, October 9, 2013

Ulrich Husemann
Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology

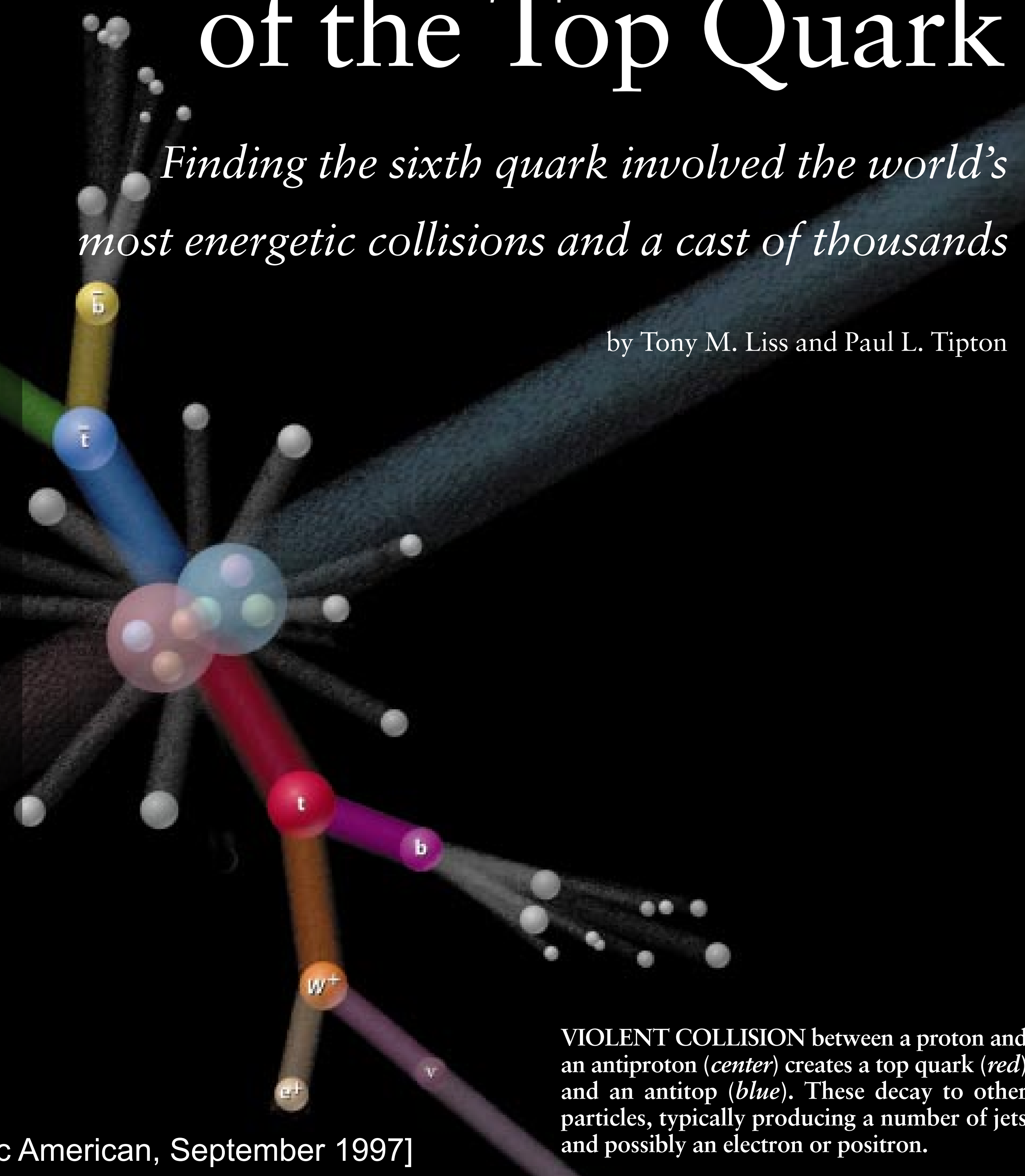
A Brief History of the Top Quark

- 1973: CP violation in the standard model requires three quark generations
- 1977: discovery of the bottom quark → first quark of the 3rd generation
- 1980ies: search for "light" top quarks in the decay $W^+ \rightarrow t\bar{b}$, electroweak precision data indicate "heavy" top
- 1992: first indication for "heavy" top quarks at the Tevatron
- 1995: Tevatron experiments CDF and DØ publish discovery of the top quark with a mass of about 175 GeV

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.

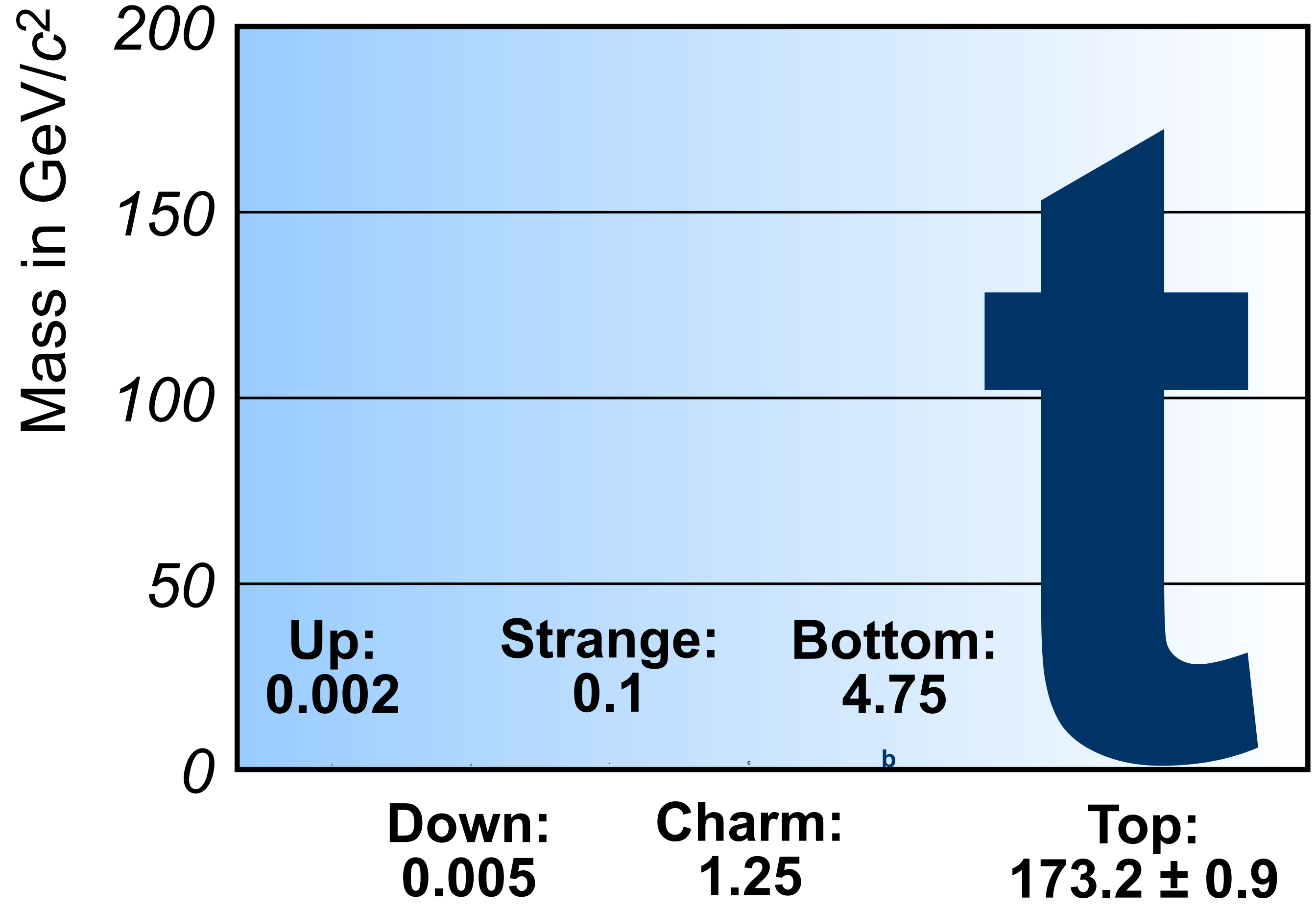
[Scientific American, September 1997]

Top – The Special One

- Large mass: $m_t \approx 173$ GeV
  - Close to scale of electroweak symmetry breaking
  - Yukawa coupling f ≈1

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

→ the only "normal quark"?

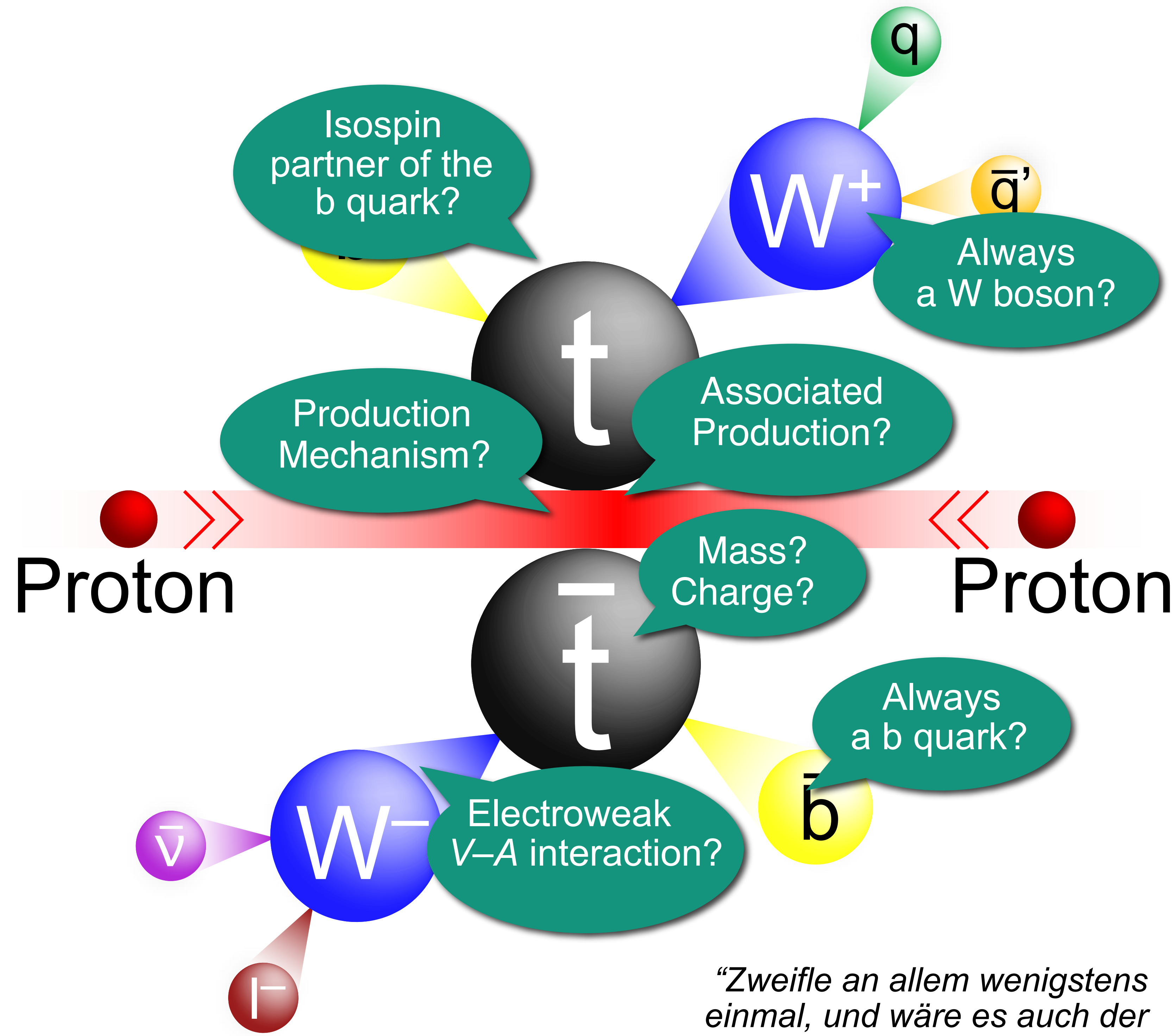


- Top is the only „free" quark: life time much smaller than hadronization time

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

→ No bound states, spin transferred to decay products

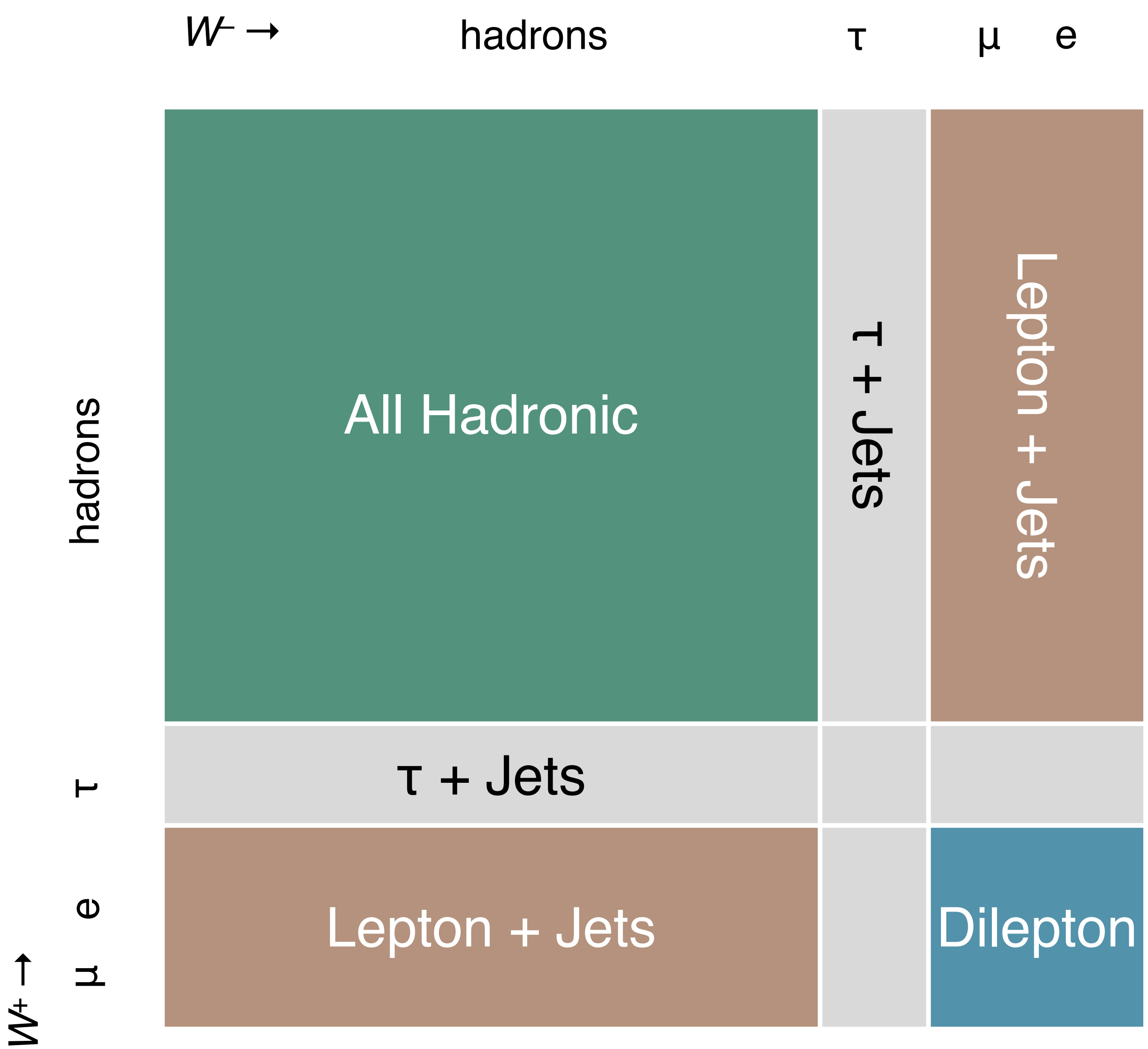
Questions in Top Quarks Physics



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

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

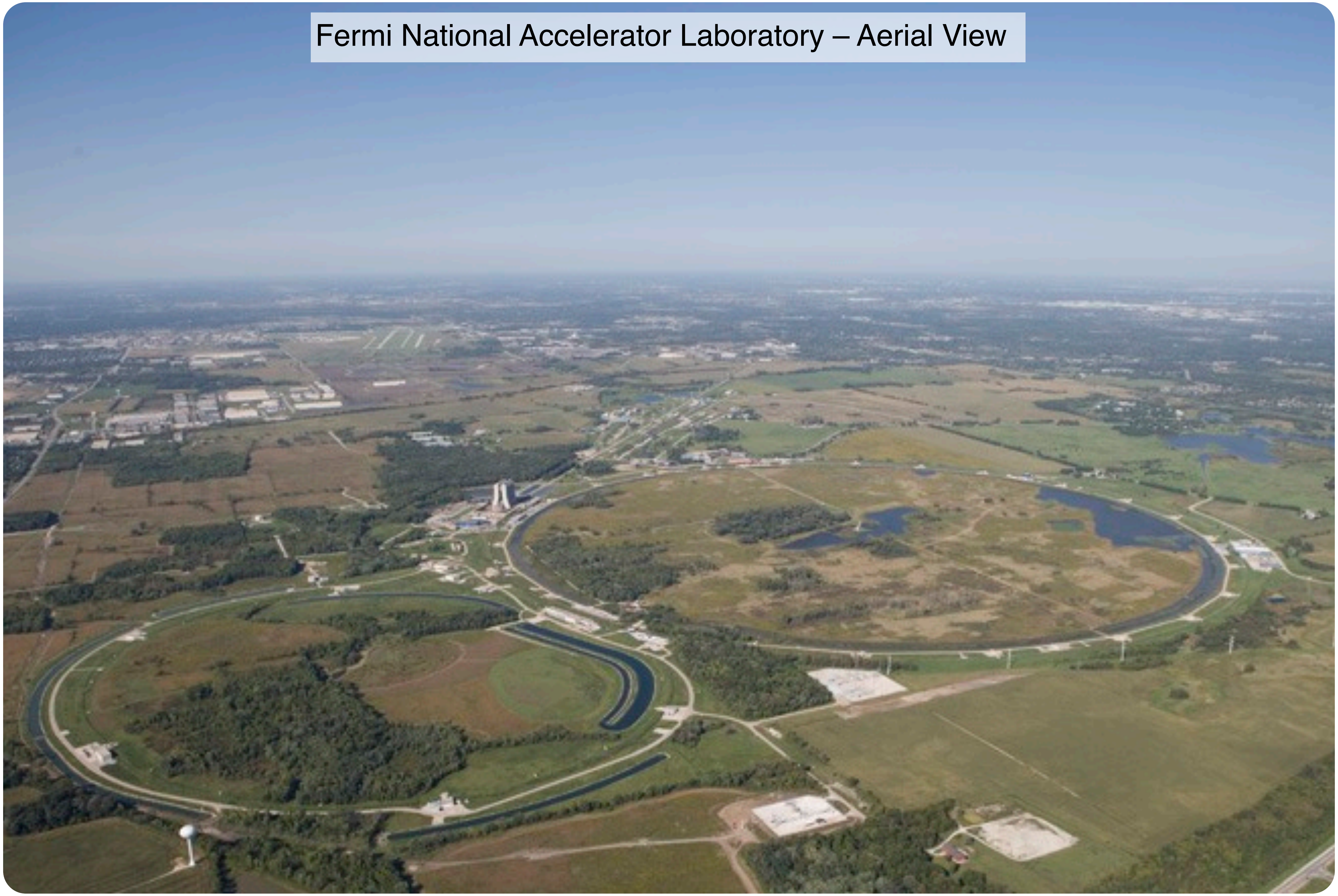
Analyzing Top Quark Events



- Top decay in the standard model: $B(t \rightarrow Wb) \approx 100\%$
- Challenging signature: multiple leptons & (b-)jets, missing transverse energy
- $t\bar{t}$ 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

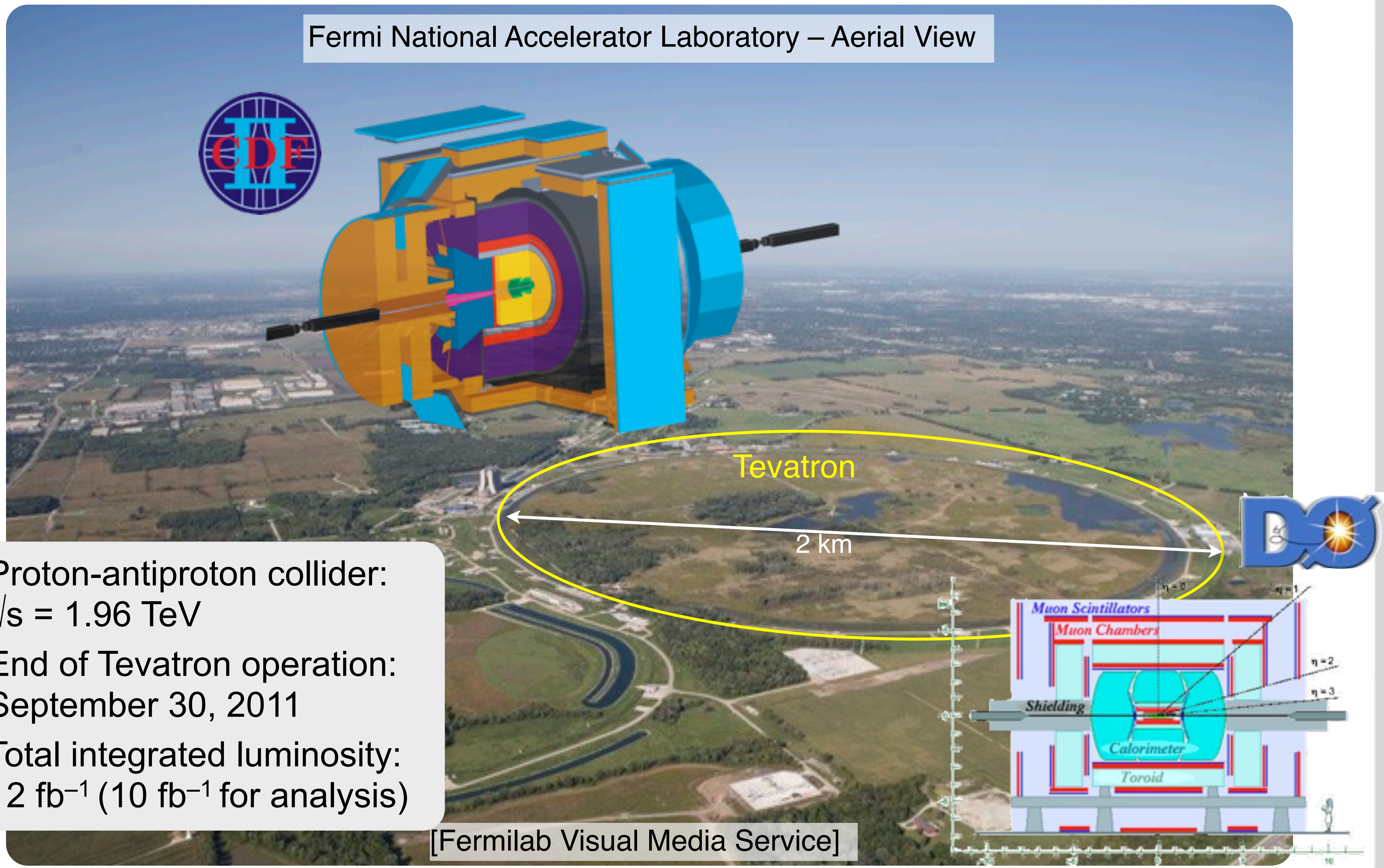
Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Tevatron Run II: 2001–2011



Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Tevatron Run II: 2001–2011



[Fermilab Visual Media Service]

- Proton-antiproton collider: $\sqrt{s}$ = 1.96 TeV
- End of Tevatron operation: September 30, 2011
- Total integrated luminosity: 12 fb^{-1} (10 fb^{-1} for analysis)

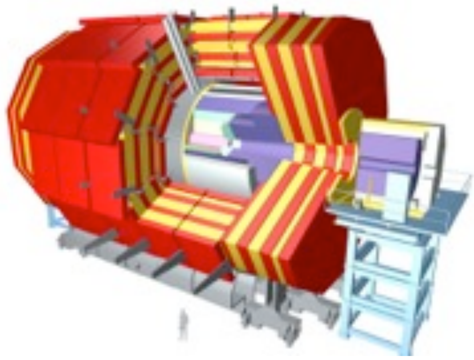
Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

LHC – the Large Hadron Collider

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

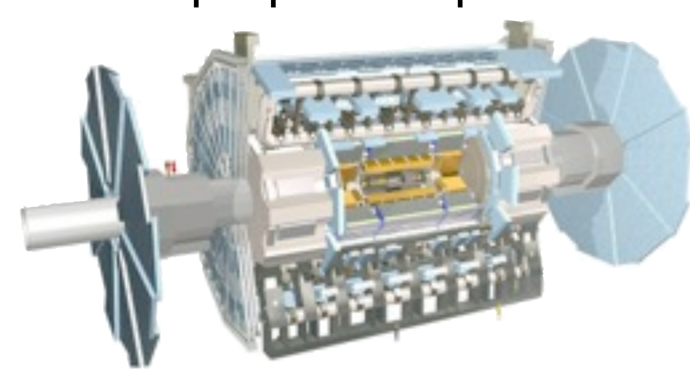
LHC – the Large Hadron Collider

CMS Experiment:
multi-purpose 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

ATLAS Experiment:
multi-purpose experiment



Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

From the Tevatron to the LHC

	Authors	Tops Produced per Experiment	Tops Reconstructed (Lepton+Jets, 1 b-Tag)
Tevatron Run II	600	70,000	2000

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

From the Tevatron to the LHC

	Authors	Tops Produced per Experiment	Tops Reconstructed (Lepton+Jets, 1 b-Tag)
Tevatron Run II	600	70,000	2000
LHC Run I	2500	6 million	150,000

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

From the Tevatron to the LHC

	Authors	Tops Produced per Experiment	Tops Reconstructed (Lepton+Jets, 1 b-Tag)
Tevatron Run II	600	70,000	2000
LHC Run I	2500	6 million	150,000
LHC Run II		50–100 million/year	

LHC: Top Factory
Excellent Detectors – Unprecedented Statistics

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Recent workshop of the top physics community in Durbach:

- Several new results
- Lots of fruitful discussions

Outline

Top Pair Production

Single Top Production

Top + “Something Else”

Top Properties & New Physics

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Karlsruhe Institute of Technology

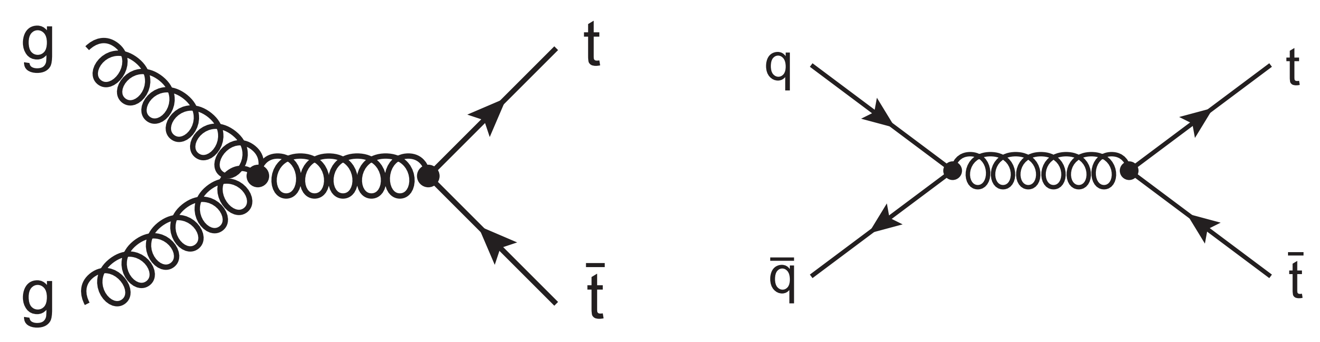
Top Pair Production: The Race for Ultimate Precision

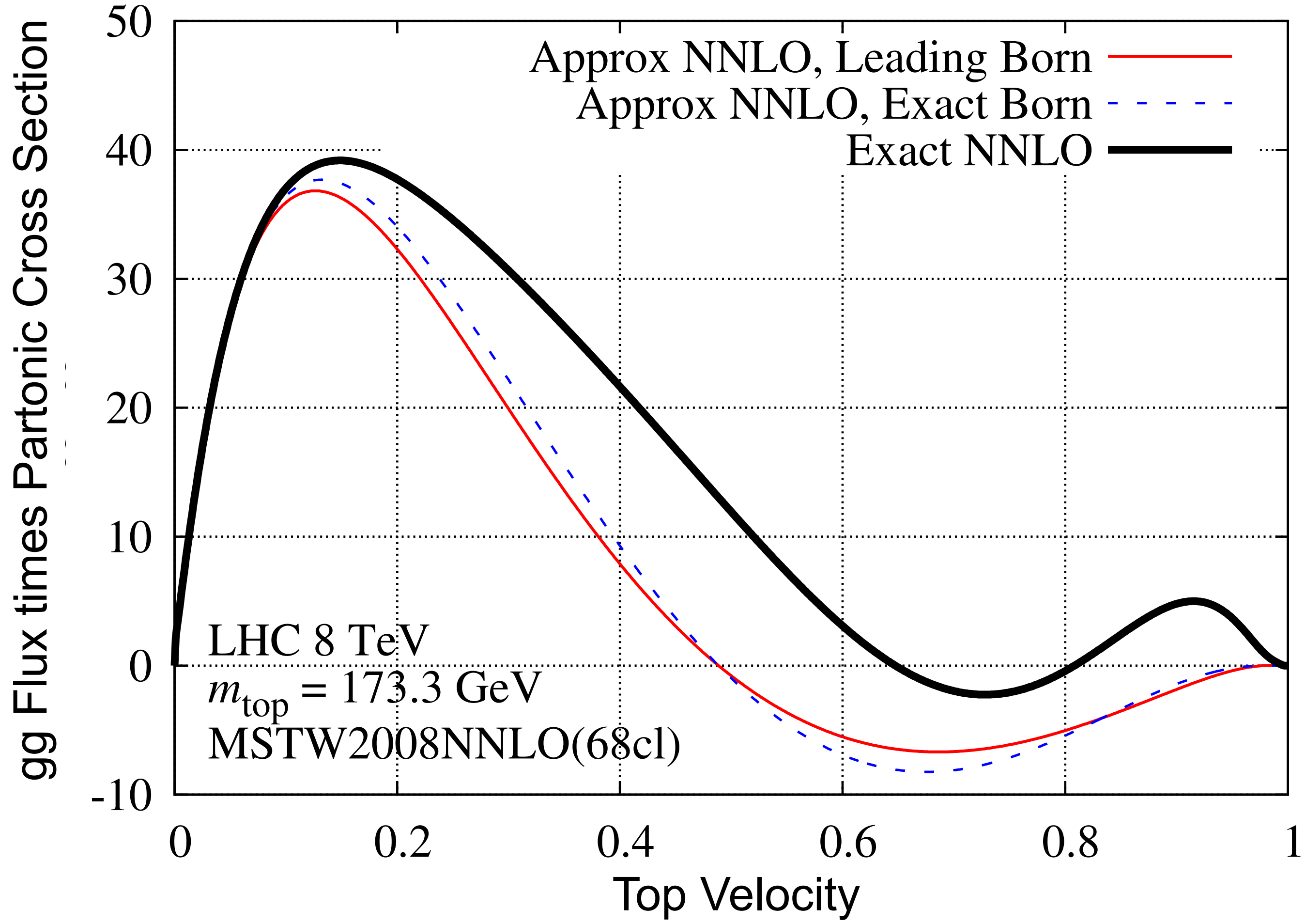
Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Top Production Cross Section

- Challenge for theory
  - Major breakthrough in early 2013: full NNLO+NNLL (Czakon, Fiedler, Mitov)
  - Typical uncertainty on total $t\bar{t}$ cross section: approx. 4%
  - Upcoming: differential cross sections, production asymmetries, …
- Challenge for experiment
  - Measurement of absolute production rates
  - Requirements: best possible detector calibration, background estimation, and MC modeling

Examples of LO Feynman diagrams: gg, $q\bar{q}$



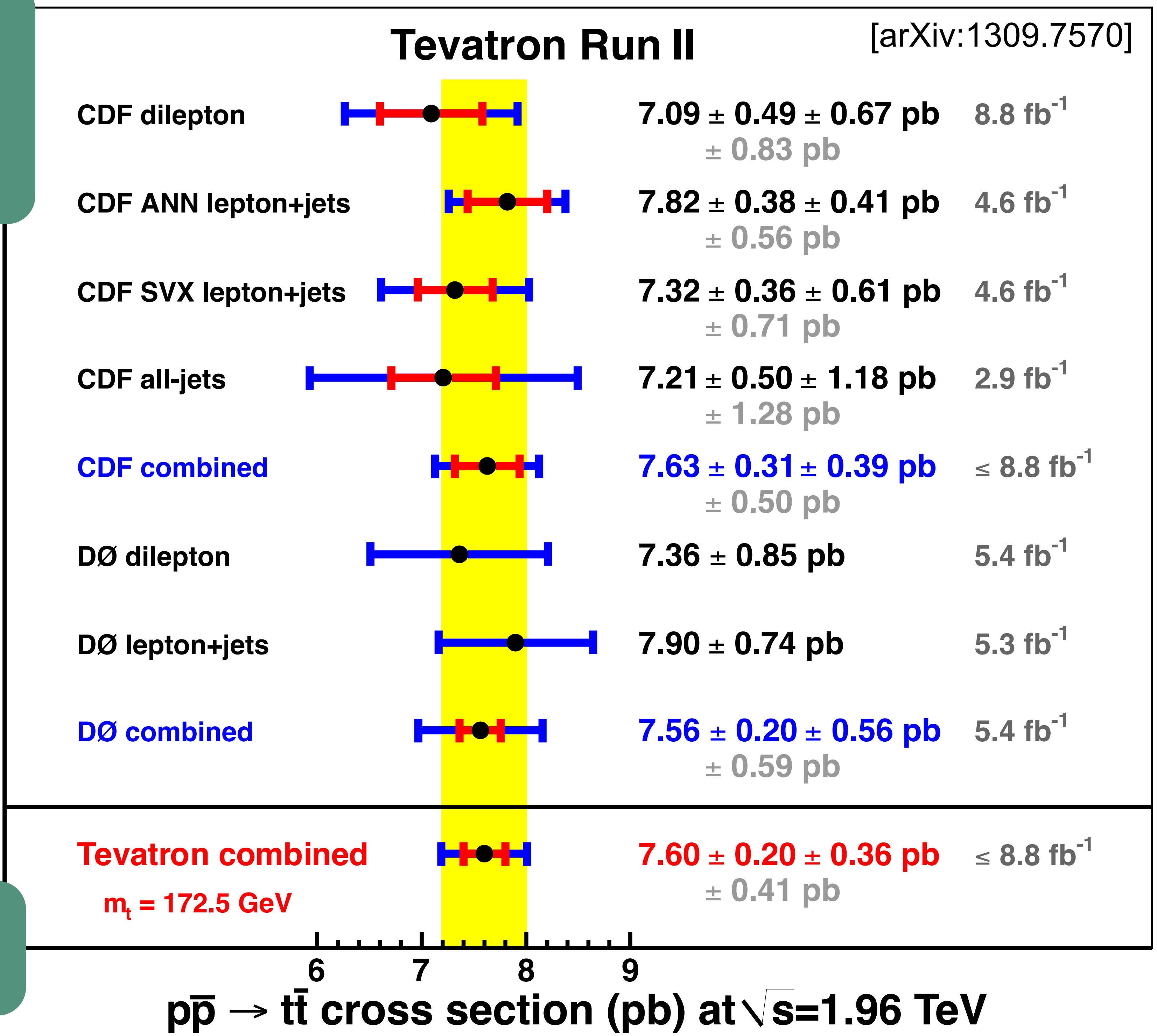


[PRL 110 (2013) 252004]

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Recent Results: Tevatron Combination

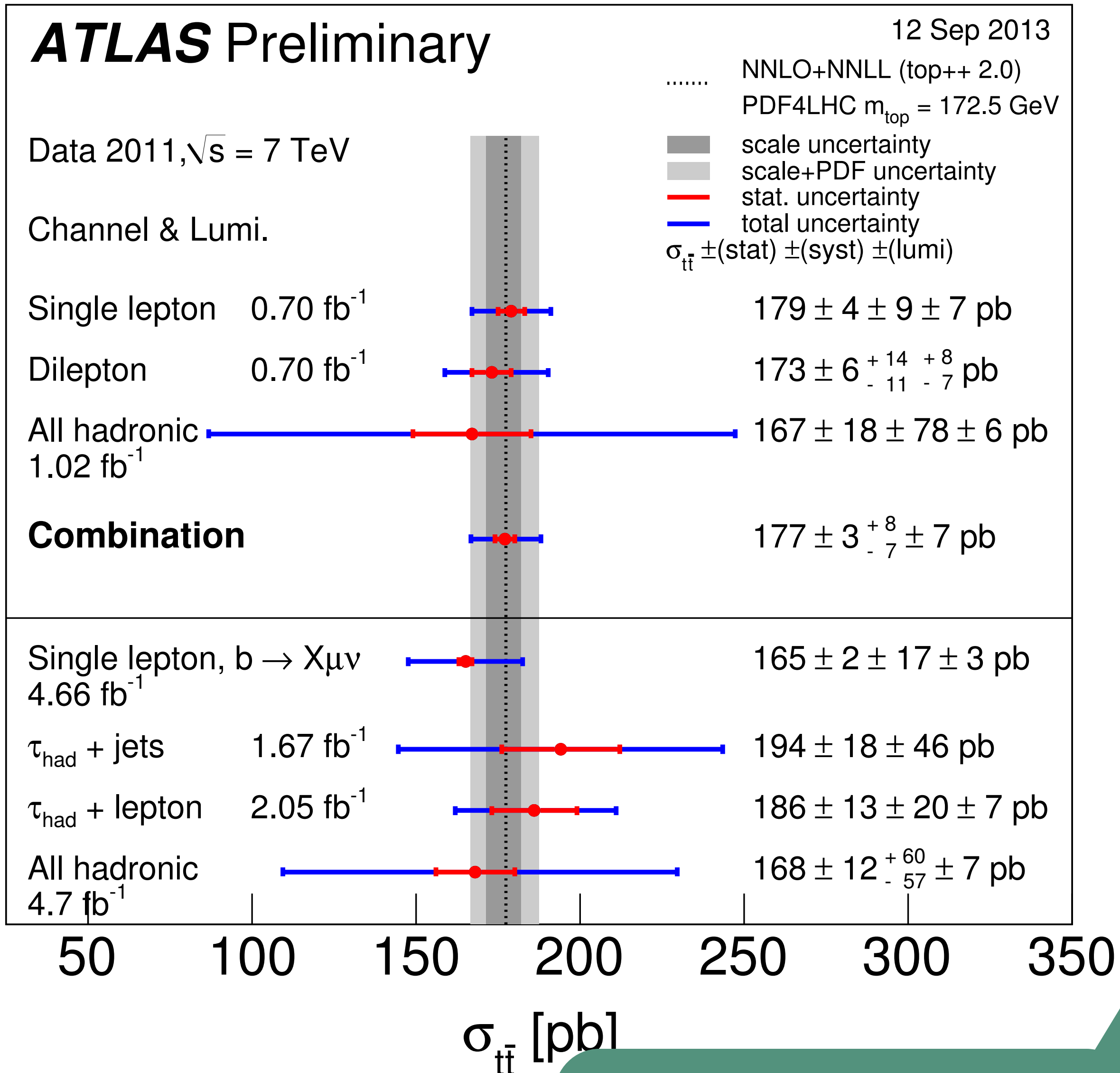
Theory @ NNLO+NNLL:
$(7.24\ ^{+0.23}_{-0.27})$ pb
(uncertainty: 3.4%)

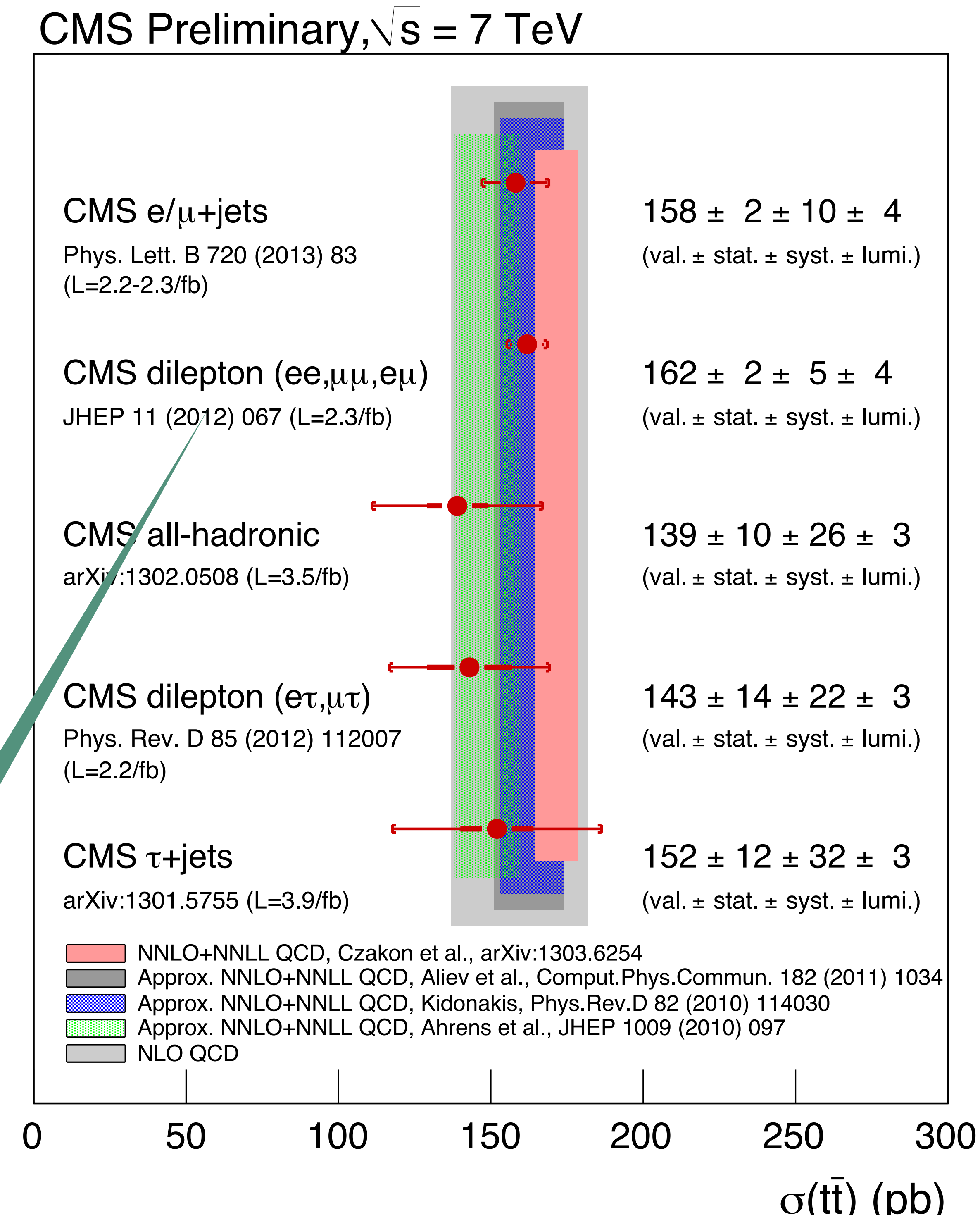


Combined uncertainty: 5.4%

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Recent Results: LHC @ 7 TeV





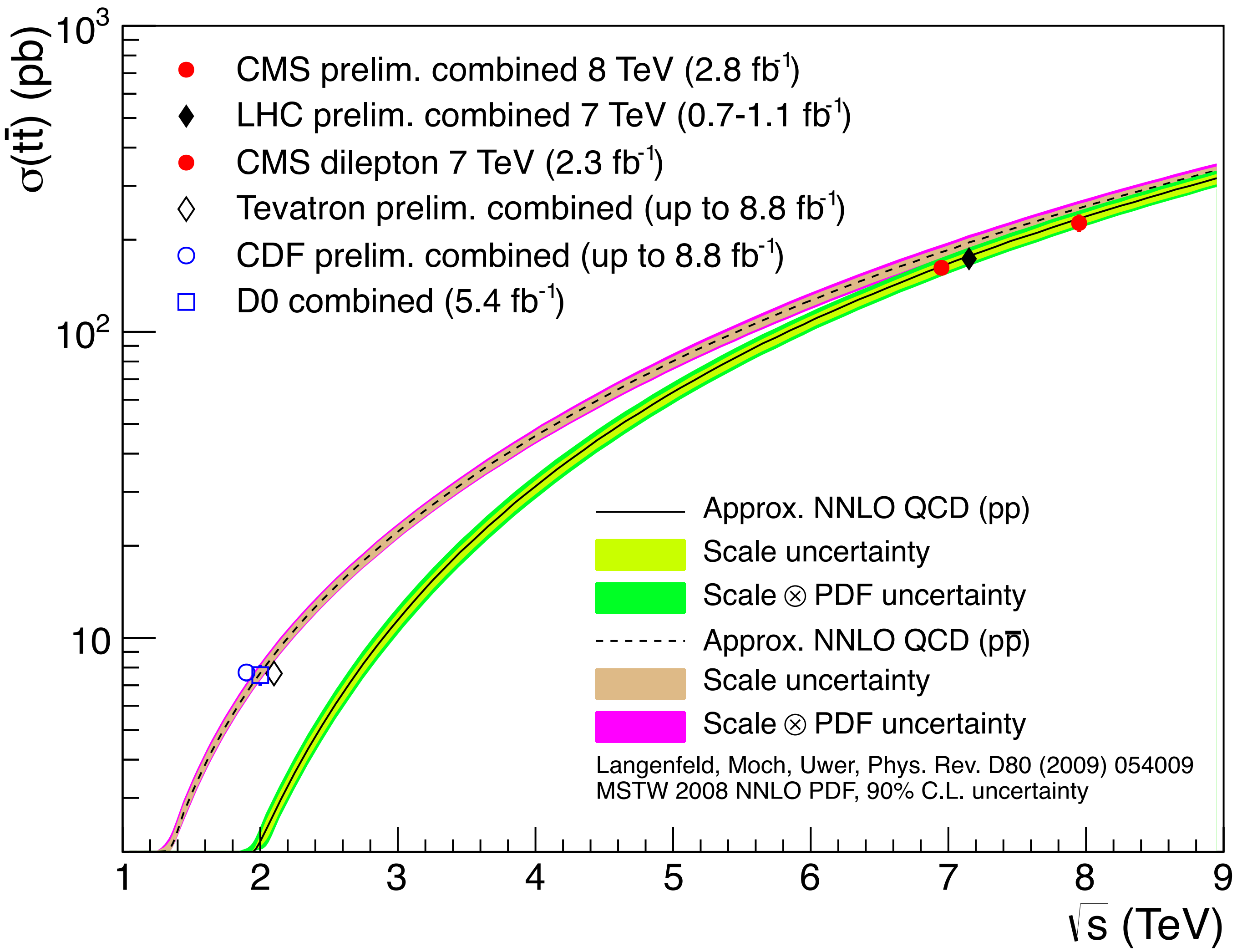
Most precise:
dilepton channel
(4.1% uncertainty)

[https://twiki.cern.ch/twiki/pub/AtlasPublic/CombinedSummaryPlots]

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

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

The Path Towards Ultimate Precision



[https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsTOPSummaryPlots]

- 8 TeV: consistent cross section results, uncertainties still slightly larger (e.g. luminosity, pileup)
- Major progress in the last years
  - Lepton+jets: in-situ constraints of systematics
  - Dilepton – the new gold-plated channel in LHC era: large data samples, almost background-free
  - Conceptual progress – better separation of uncertainties: detector vs. signal vs. background modeling
- Current limitation: extrapolation to full phase space with MC tools
  - Fiducial cross sections
  - Differential cross sections

Fiducial Cross Section

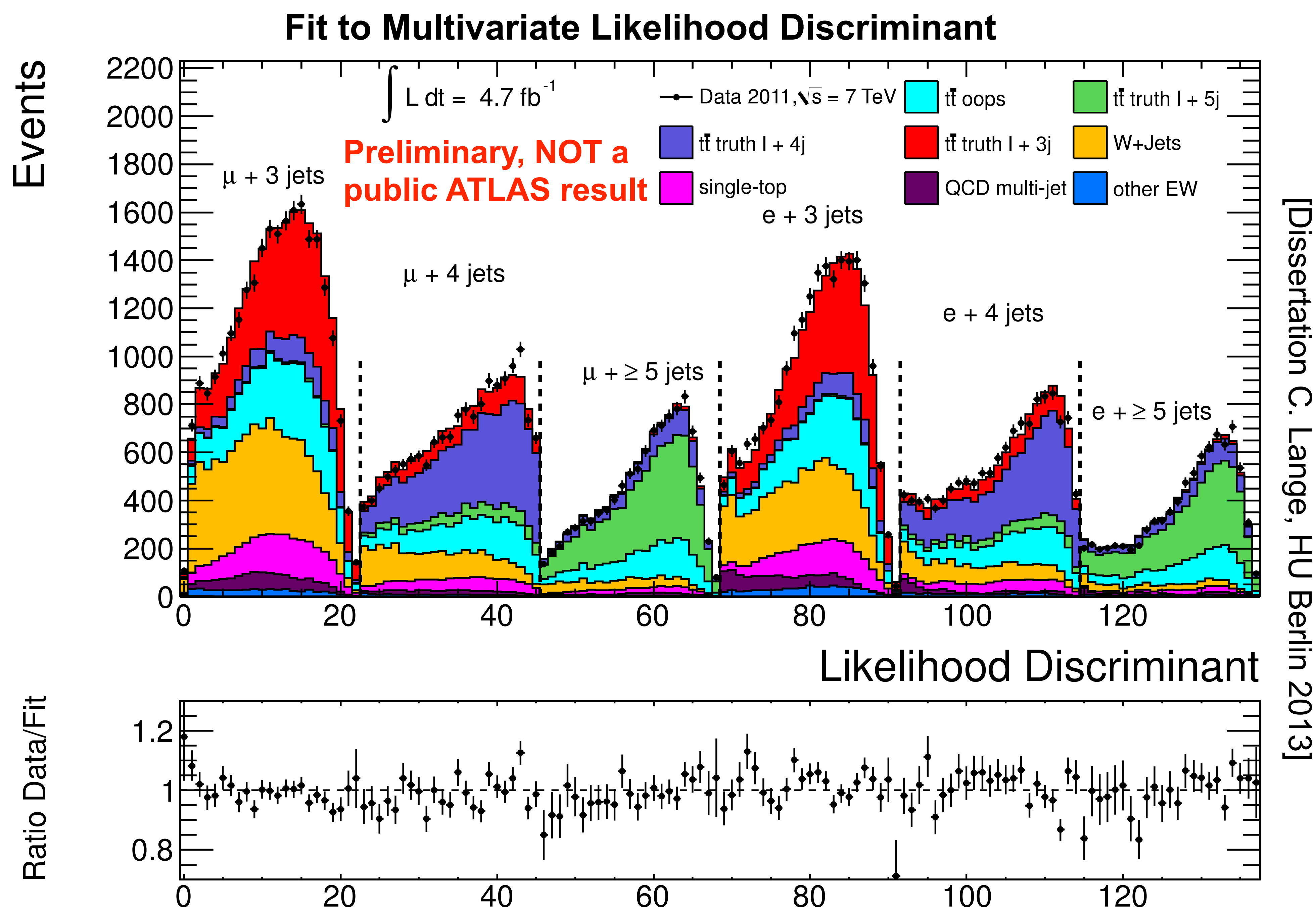
- Idea: measure cross section only in part of phase space accessible to experiment → reduced model dependence, comparison with models
- Implementation: particle-level selection close reconstruction cuts

particle level	**reconstruction level**
exactly one lepton (dressed e or μ), $p_T > 25$ GeV and $\eta < 2.5$	exactly one isolated lepton (e or μ), $p_T > 25$ GeV and $\eta < 2.5$
veto second lepton (dressed e or μ), $p_T > 15$ GeV and $\eta < 2.5$	veto second isolated lepton (e or μ), $p_T > 25$ GeV and $\eta < 2.5$
at least three jets, anti-k_T ($R = 0.4$), $p_T > 25$ GeV and $\eta < 2.5$	at least three jets, anti-k_T ($R = 0.4$), $p_T > 25$ GeV and $\eta < 2.5$
at least one b-tagged jet, B hadron with $p_T > 5$ GeV within $\Delta R = 0.3$ of the jet	at least one b-tagged jet, MV1 algorithm at 70% efficiency
$E_T^{\text{miss}} > 25$ GeV, all neutrinos in the event	$E_T^{\text{miss}} > 30$ GeV
$m_T^W > 30$ GeV	$m_T^W > 30$ GeV

[Dissertation C. Lange, HU Berlin 2013]

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Fiducial Cross Section: Result



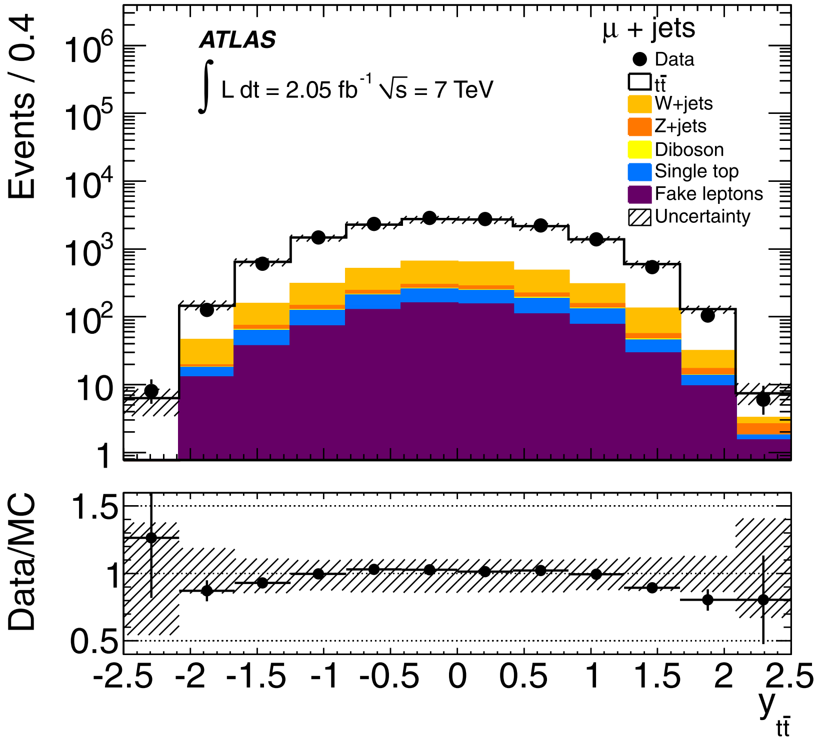
Fiducial cross section: $(24.4\ ^{+2.0}_{-1.9})$ pb

(Acceptance for PowHeg+Pythia: 13.9%)

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Differential Cross Sections

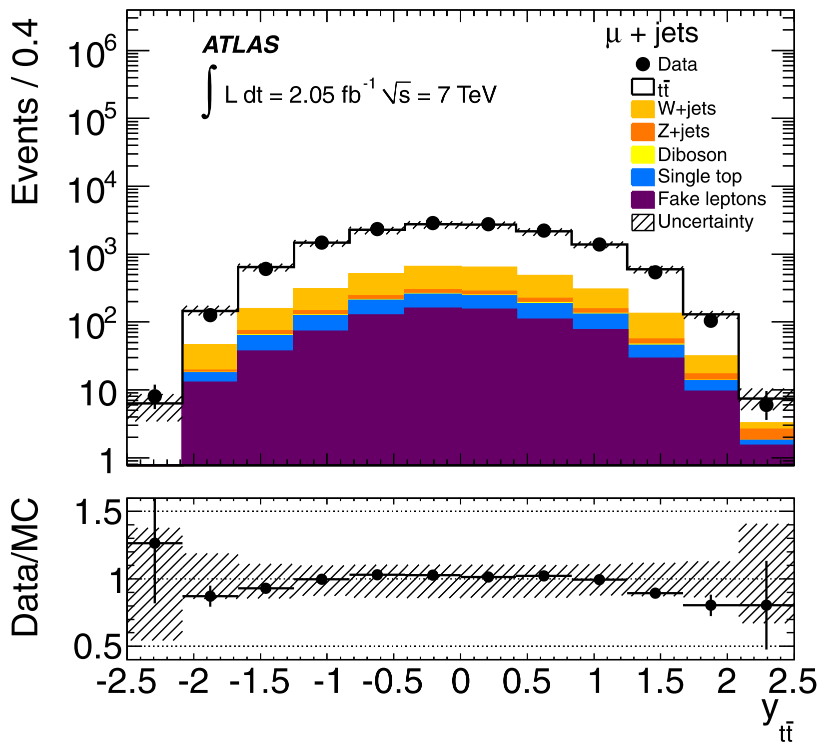
Reconstruction



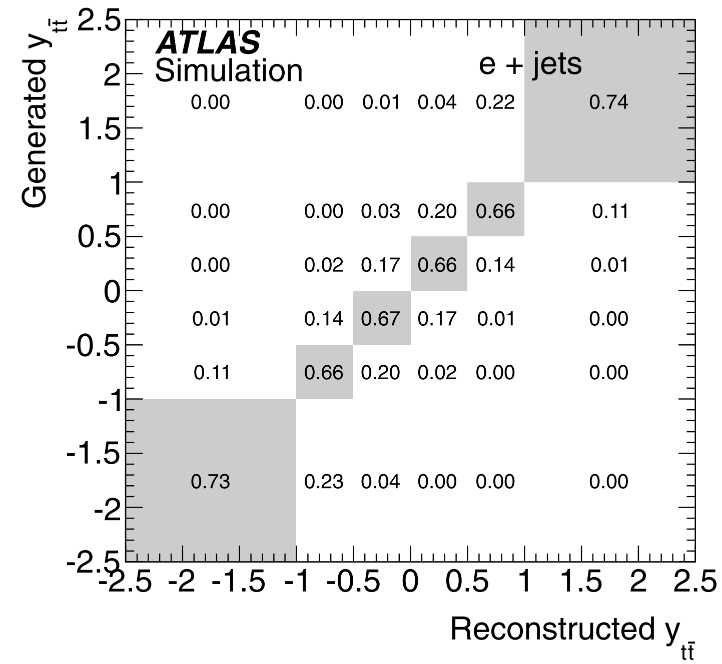
[Eur. J. Phys. C73 (2013) 2261]

Differential Cross Sections

Reconstruction



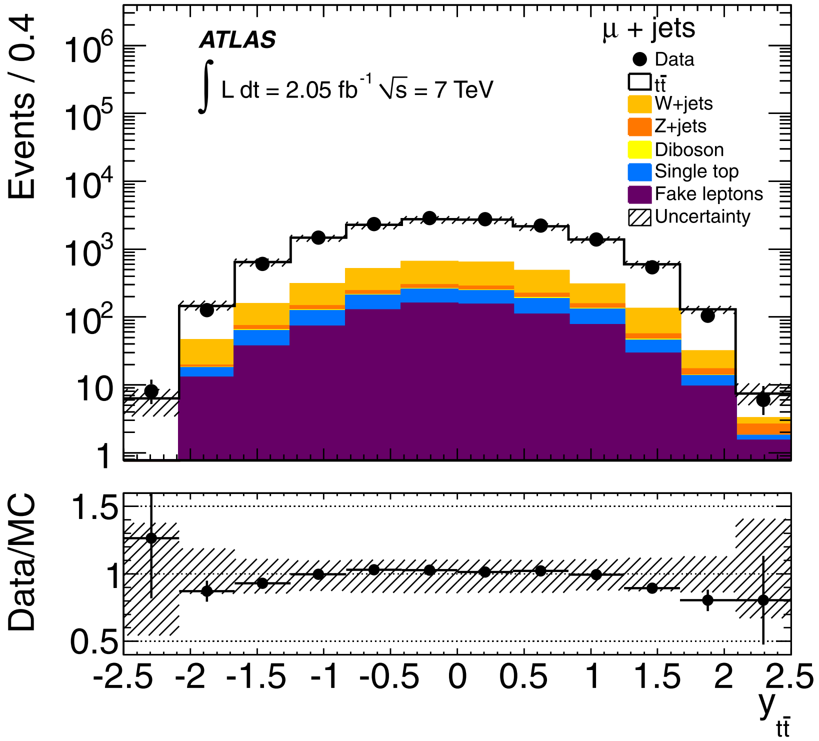
Migration Matrix



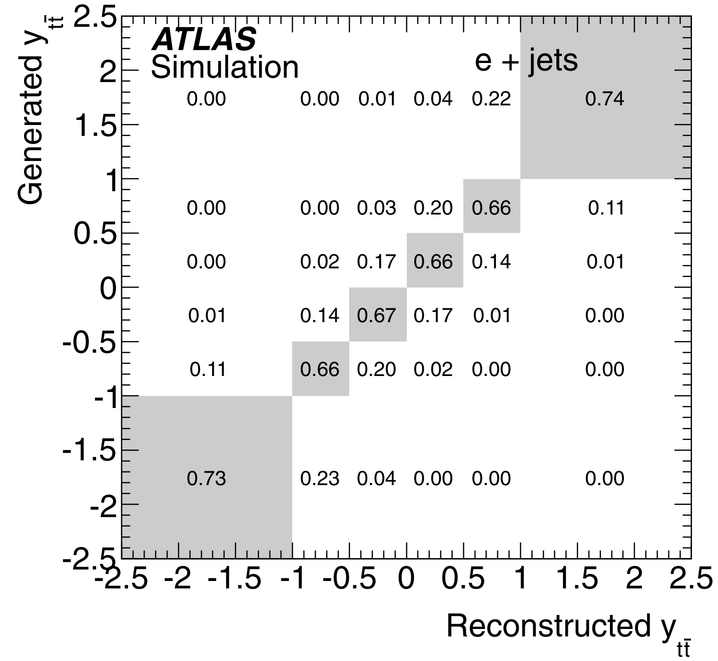
[Eur. J. Phys. C73 (2013) 2261]

Differential Cross Sections

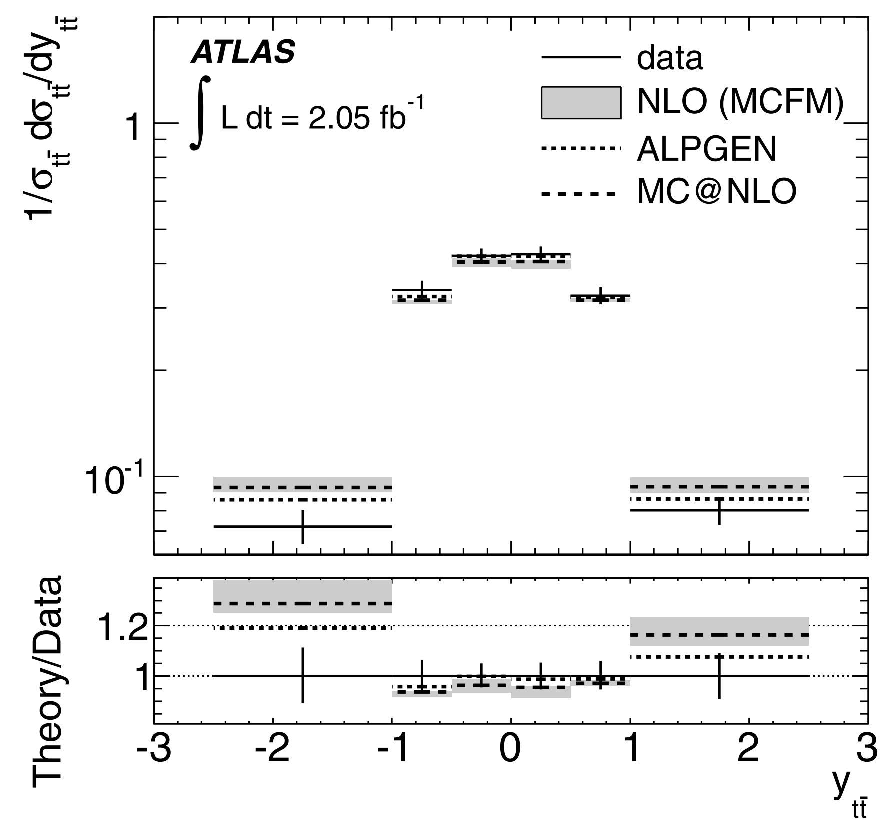
Reconstruction



Migration Matrix



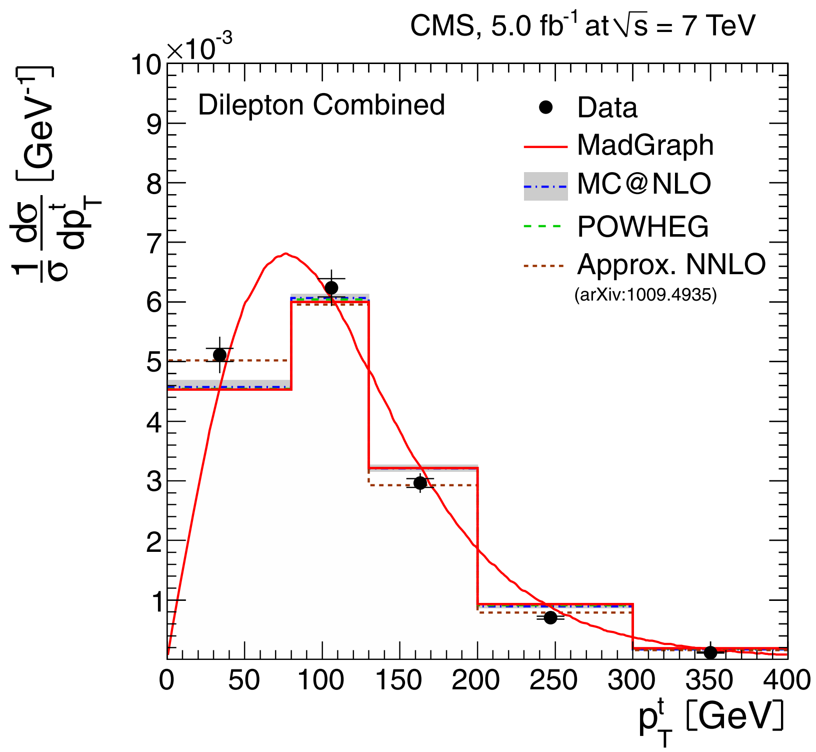
Unfolded Distribution

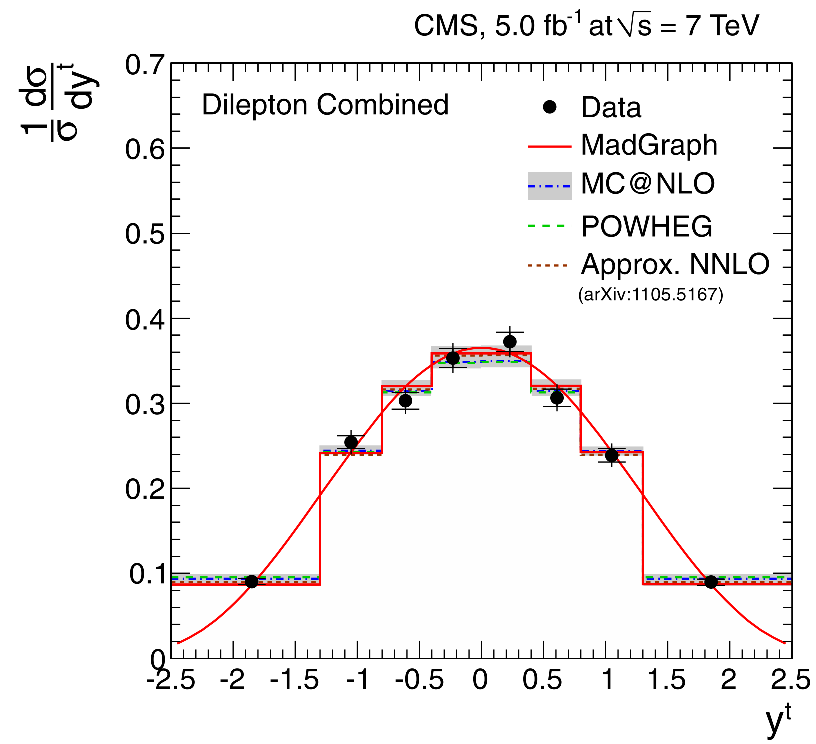


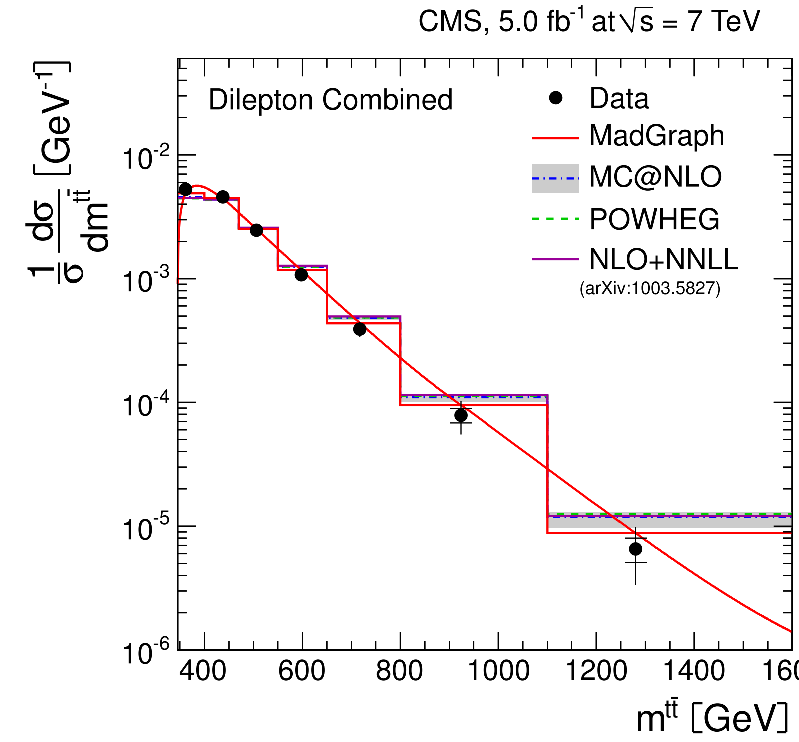
[Eur. J. Phys. C73 (2013) 2261]

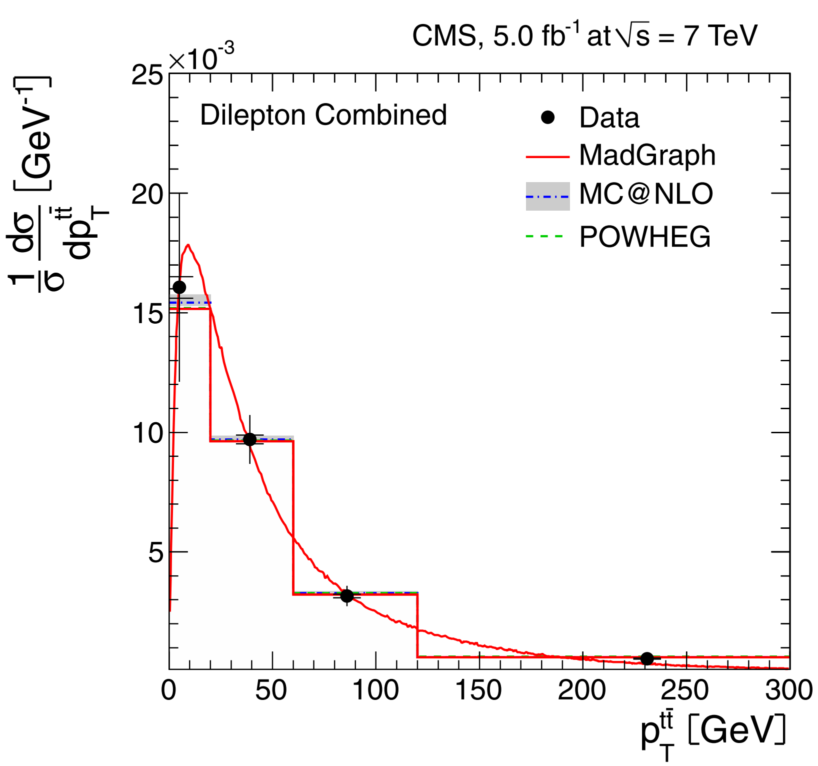
- Unfolding of reconstructed quantities to particle level (often in fiducial volume)
- Normalized differential cross section → access to shapes of distributions

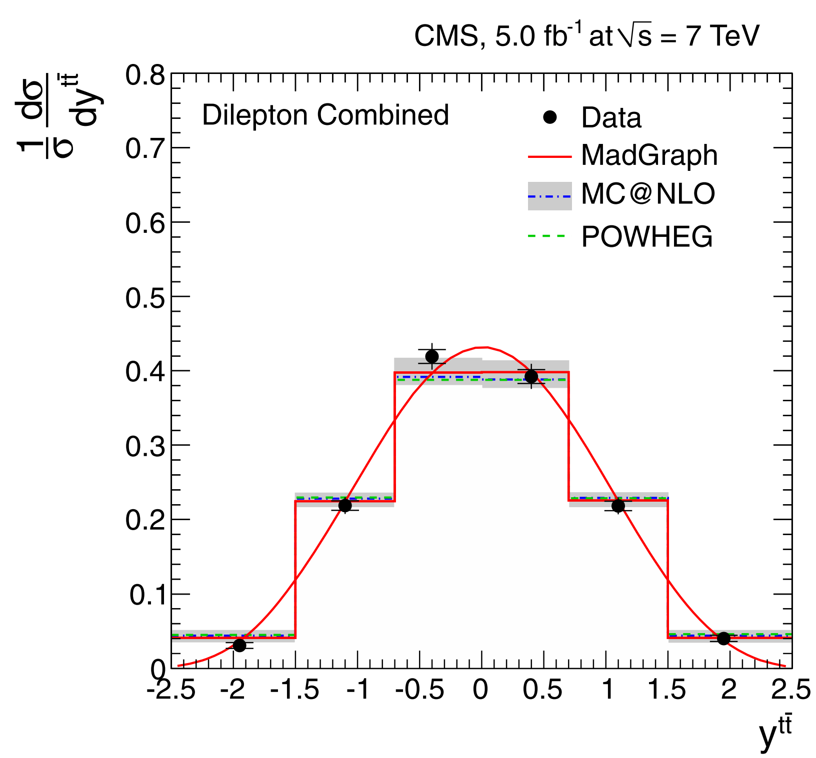
Examples of Differential Distributions











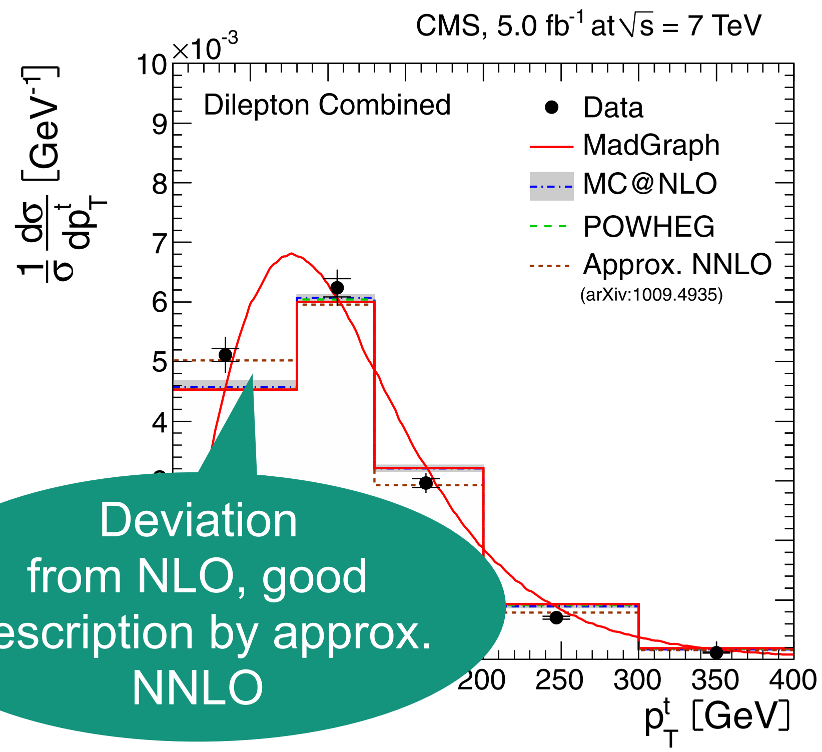
Observables:

- Top p_T and rapidity
- Mass, p_T, and rapidity of $t\bar{t}$ system

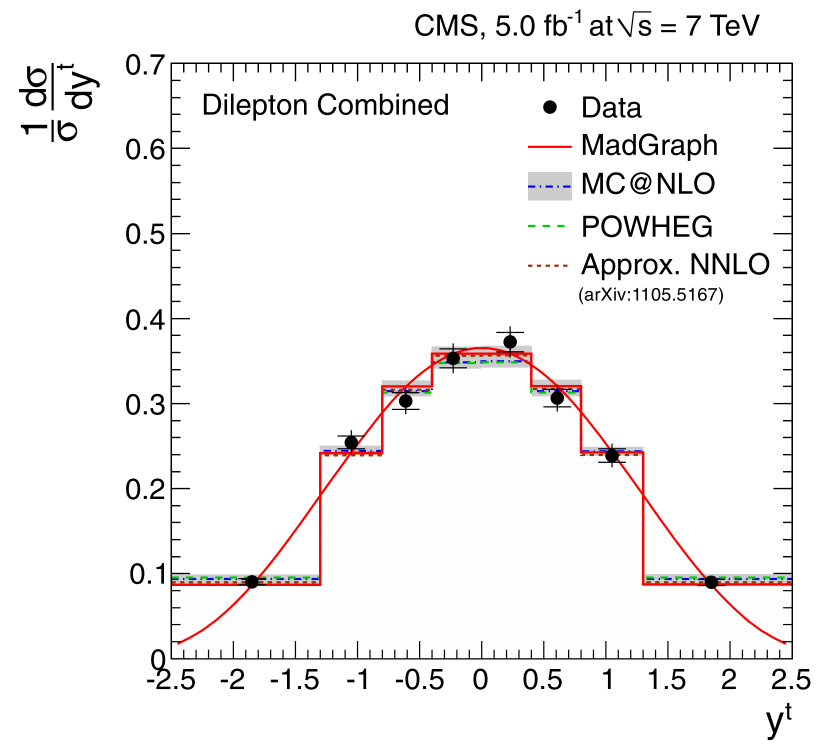
[Eur. J. Phys. C73 (2013) 2339]

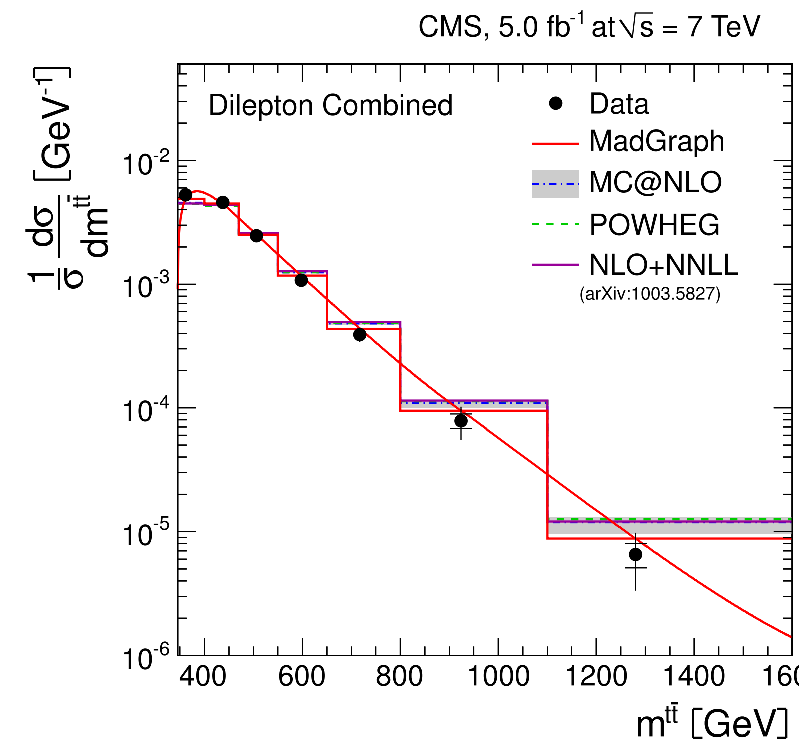
Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

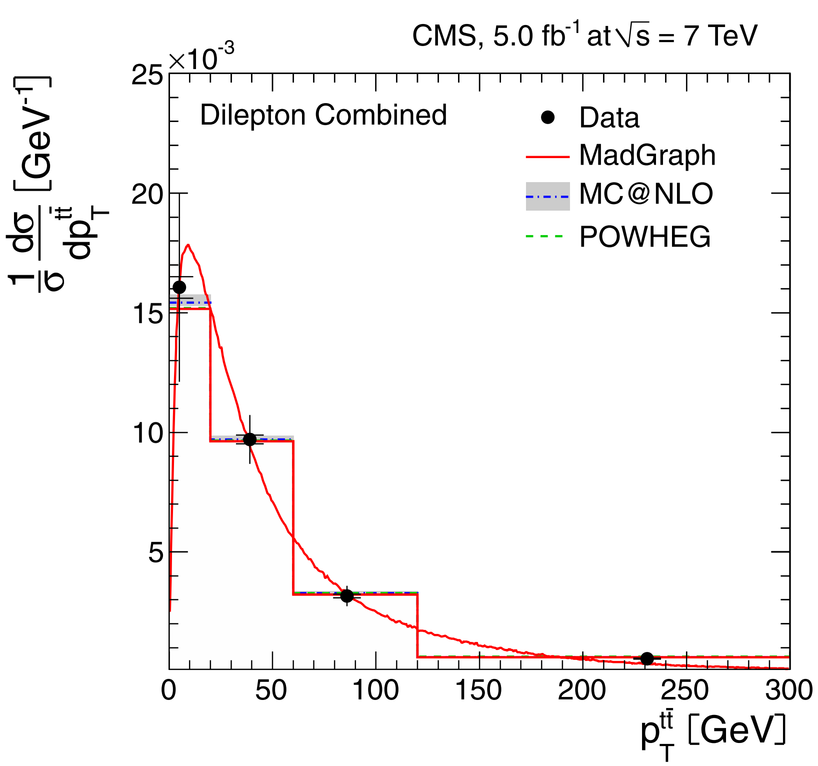
Examples of Differential Distributions

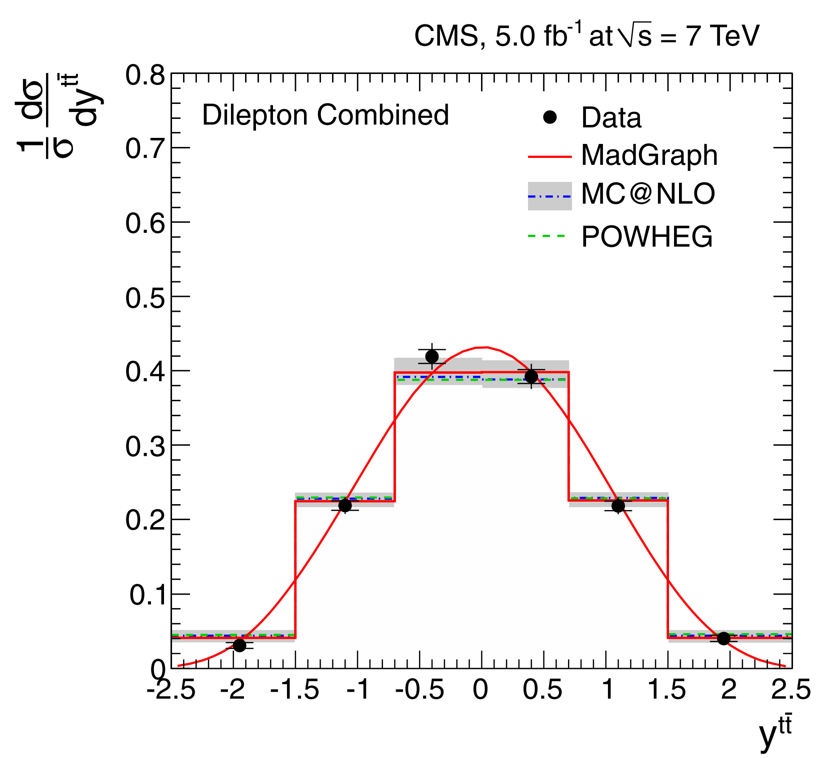


Deviation from NLO, good description by approx. NNLO









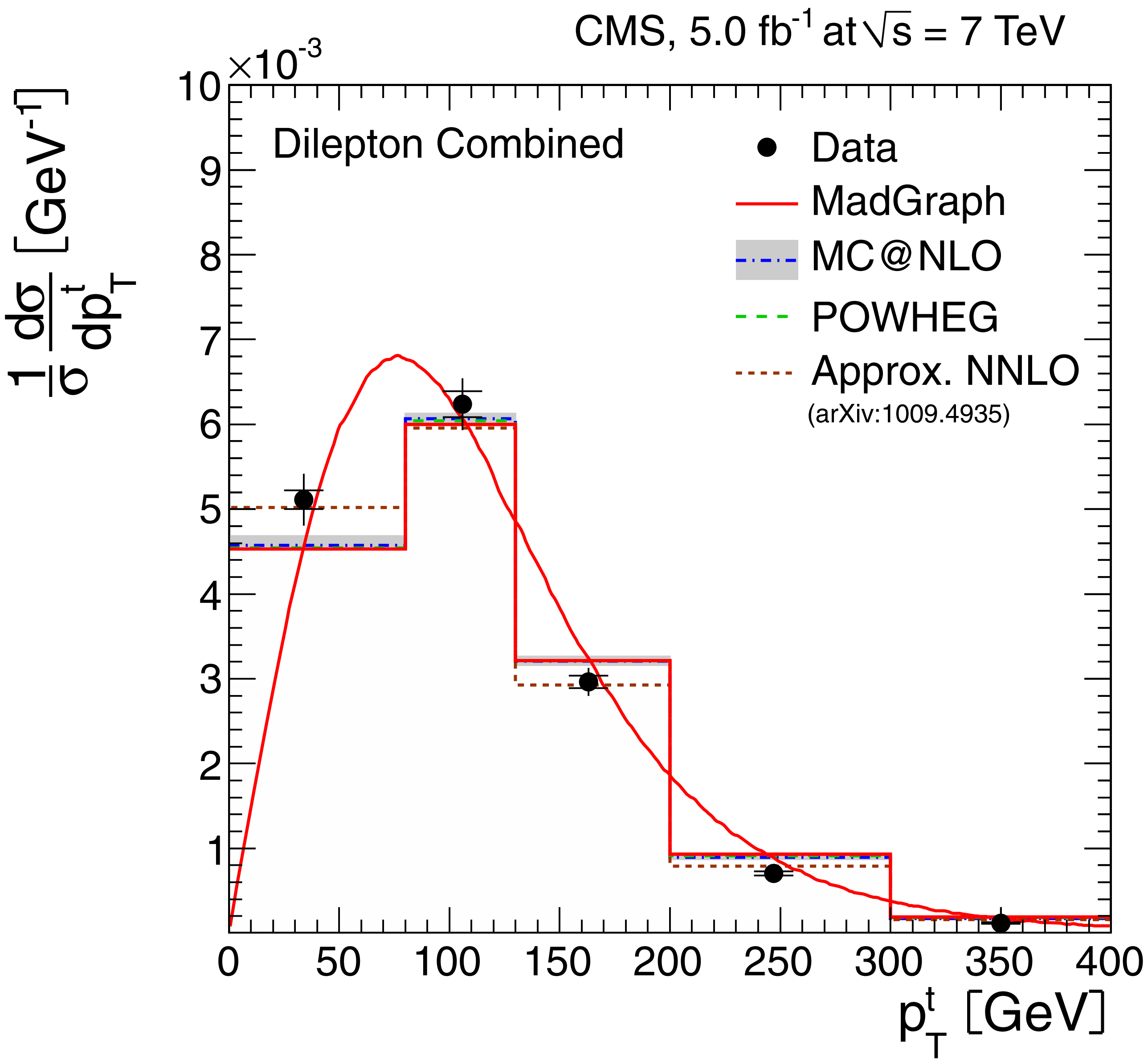
Observables:

- Top p_T and rapidity
- Mass, p_T, and rapidity of $t\bar{t}$ system

[Eur. J. Phys. C73 (2013) 2339]

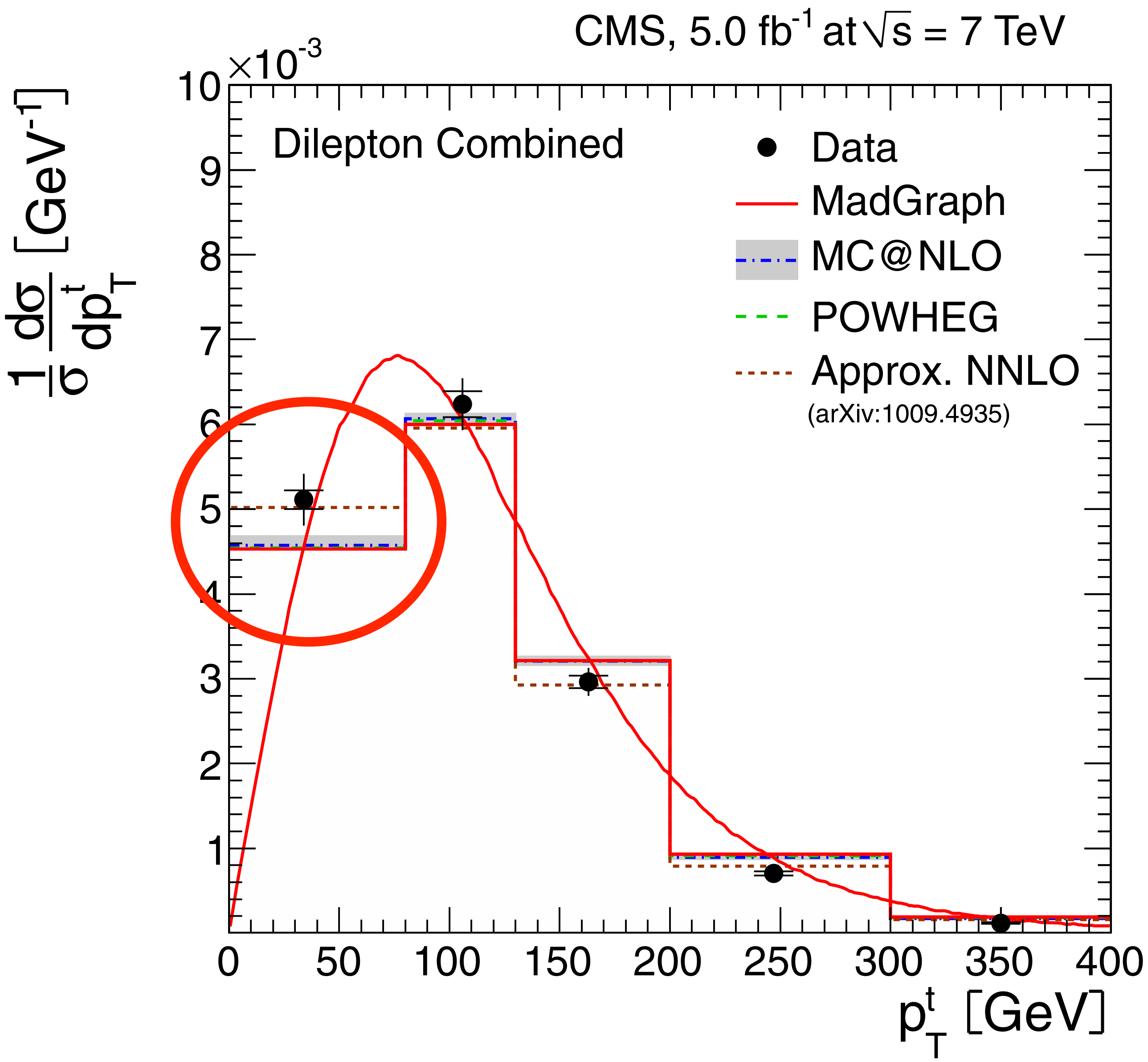
Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Top Transverse Momentum

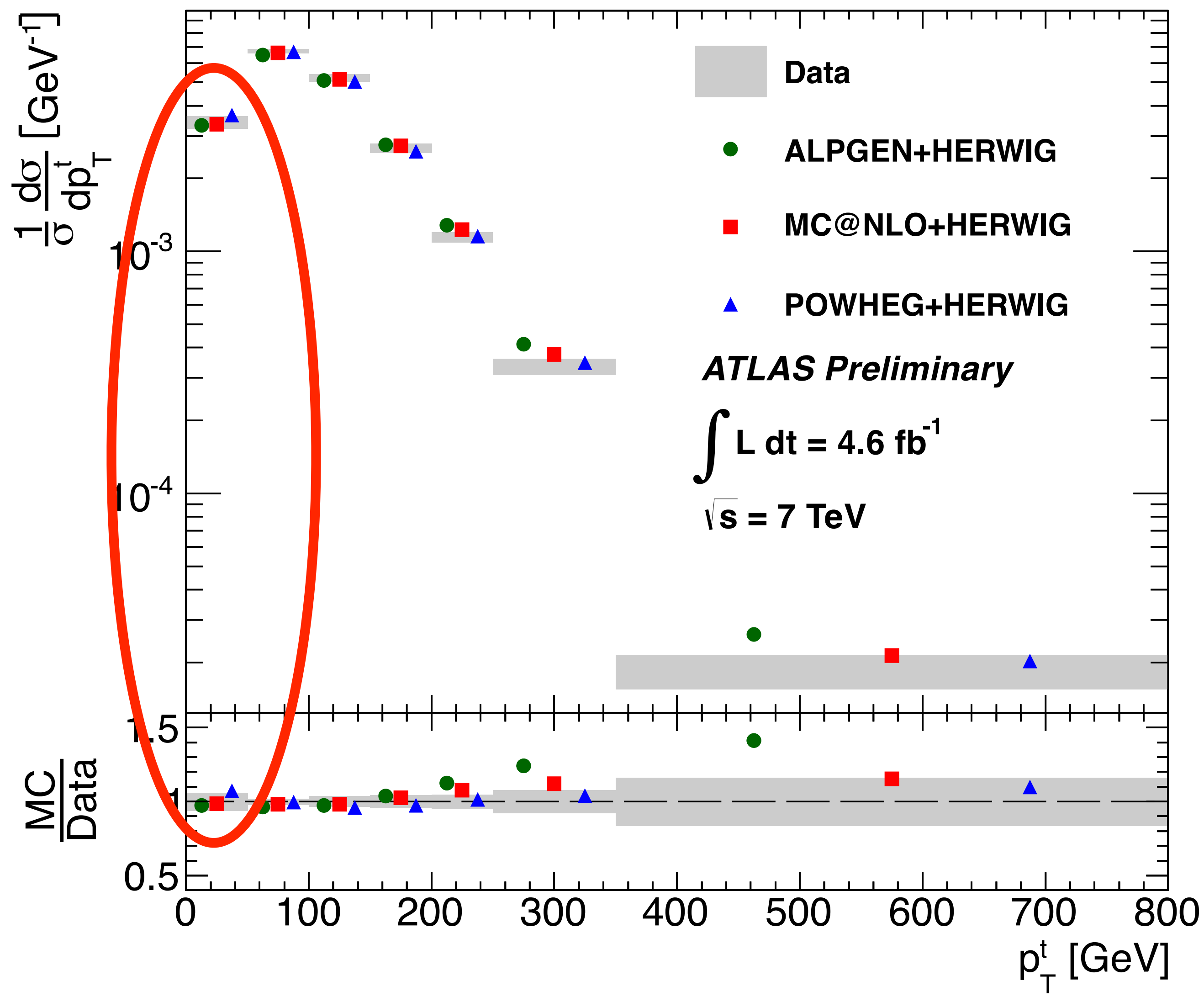


[Eur. J. Phys. C73 (2013) 2339]

Top Transverse Momentum



[Eur. J. Phys. C73 (2013) 2339]



[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-099]

Small tension between CMS and ATLAS results → under study

Karlsruhe Institute of Technology

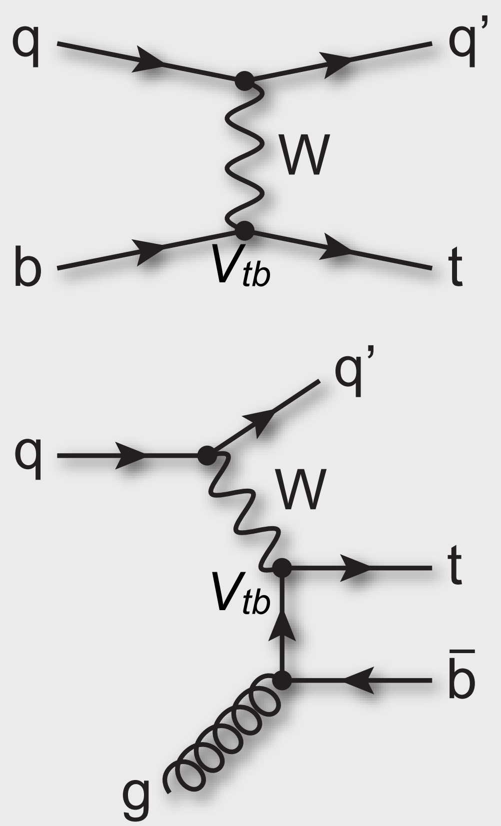
Single Top Production: The Importance of Being Single

[F. Maltoni]

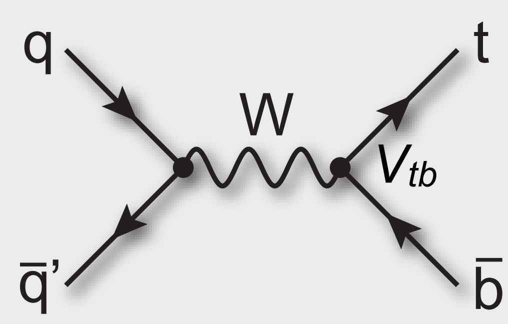
Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Electroweak Single Top Production

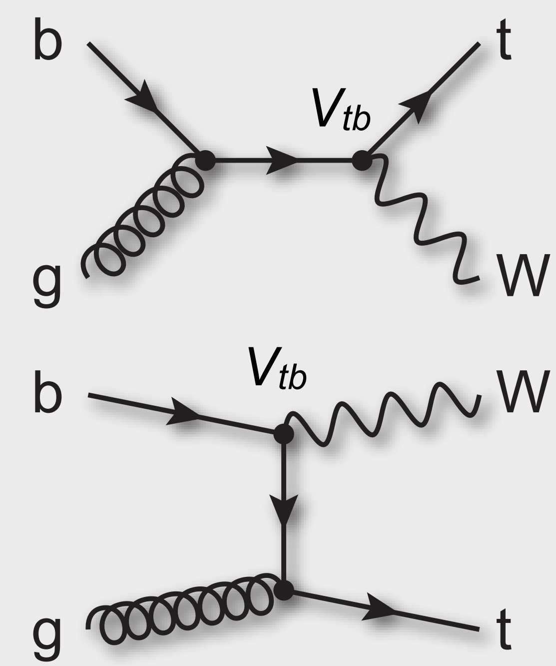
t channel



s channel



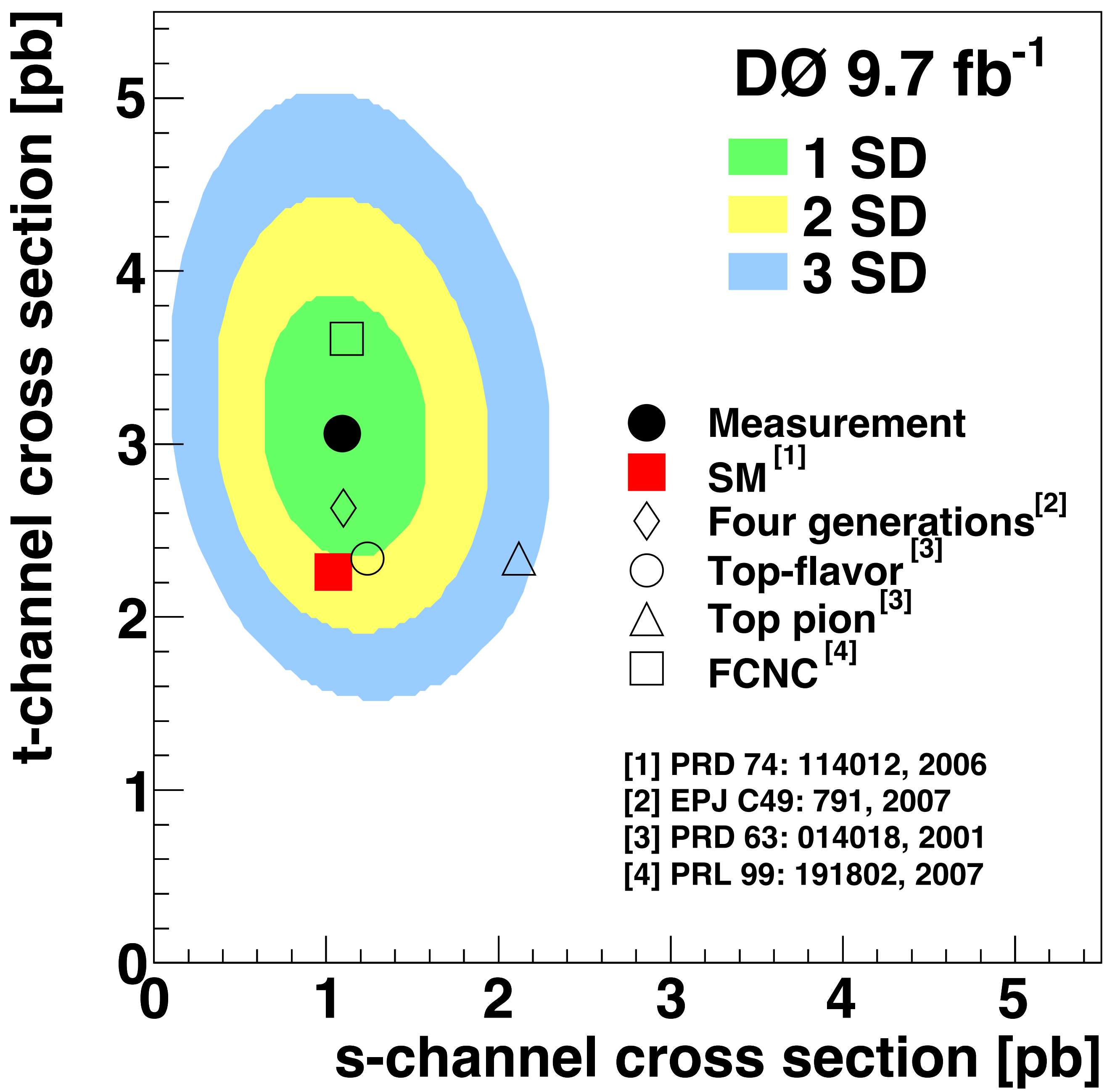
associated Wt production



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

Single Top at the Tevatron

- Full Run II data analyzed, still statistics limited
- Consistent s+t channel cross section results, e.g.
  - DØ lepton+jets: $(4.11^{+0.60}_{-0.55})$ pb
  - CDF lepton+jets: $(3.04^{+0.57}_{-0.53})$ pb
- s-channel only cross section:
  - So far only accessible at the Tevatron → "legacy measurement"
  - CDF and DØ independently: 3.7σ evidence

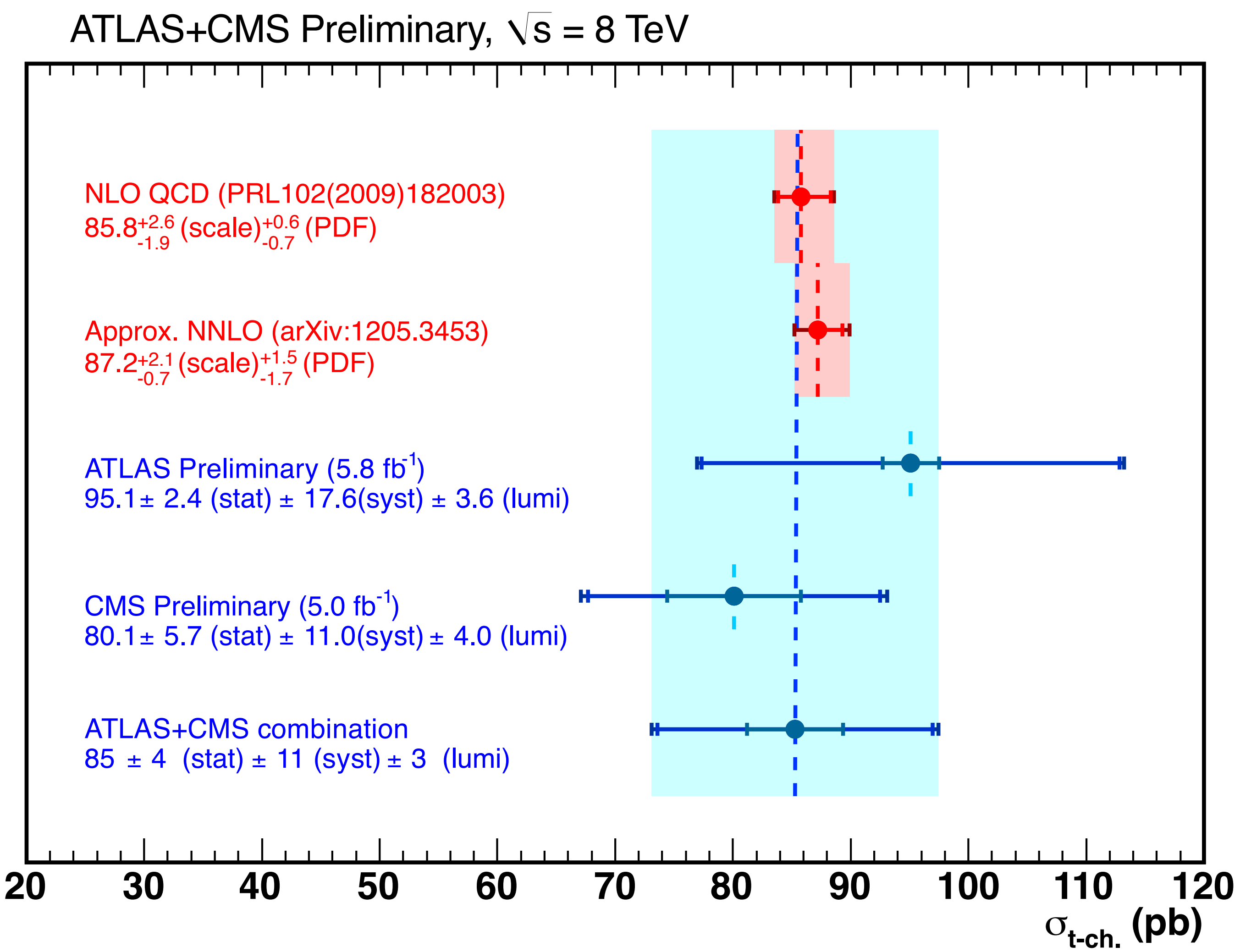


[arXiv:1307.0731, to appear in PLB]

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Single Top Production at the LHC

t-Channel Single Top Cross Section



[http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-098]

- t-channel cross section:
  - Large datasets at the LHC → now systematically limited
  - New: first LHC combination
- Associated Wt production:
  - Established at the LHC (4-6 σ)
  - ATLAS: (27.2 ± 5.8) pb
  - CMS: $(23.4\ ^{+5.5}_{-5.4})$ pb
  - Theory: (22.2 ± 1.5) pb
- Polarization and anomalous couplings → later

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Karlsruhe Institute of Technology

Production of Top + “Something Else”

Ulrich Husemann
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

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Top + “Something Else”: Overview

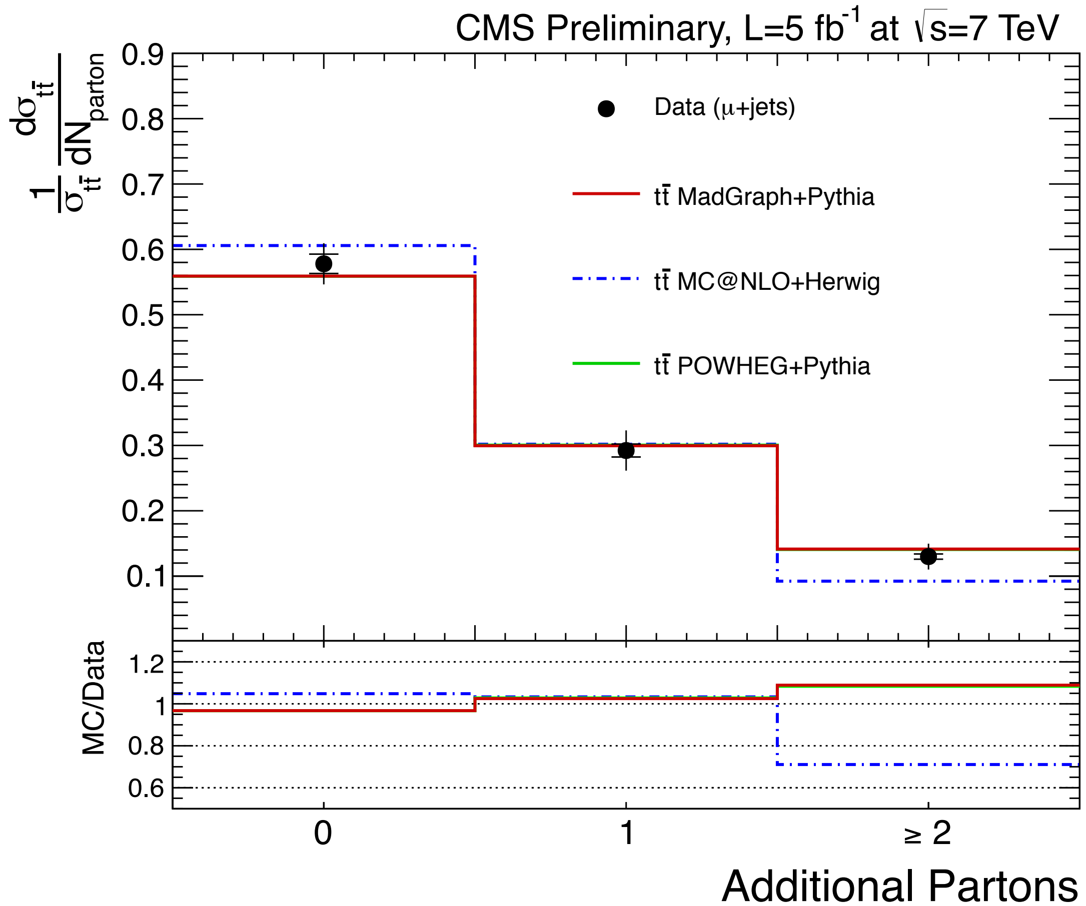
Signature	Impact
$t\bar{t}$ + (heavy flavor) jets	QCD test Background to Higgs and BSM searches
$t\bar{t}$ + missing transverse energy	Heavy BSM particles decaying into top
$t\bar{t}$ + vector bosons (γ, W, Z)	Electroweak top couplings Background to Higgs and BSM searches
$t\bar{t}$ + Higgs	Direct measurement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

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

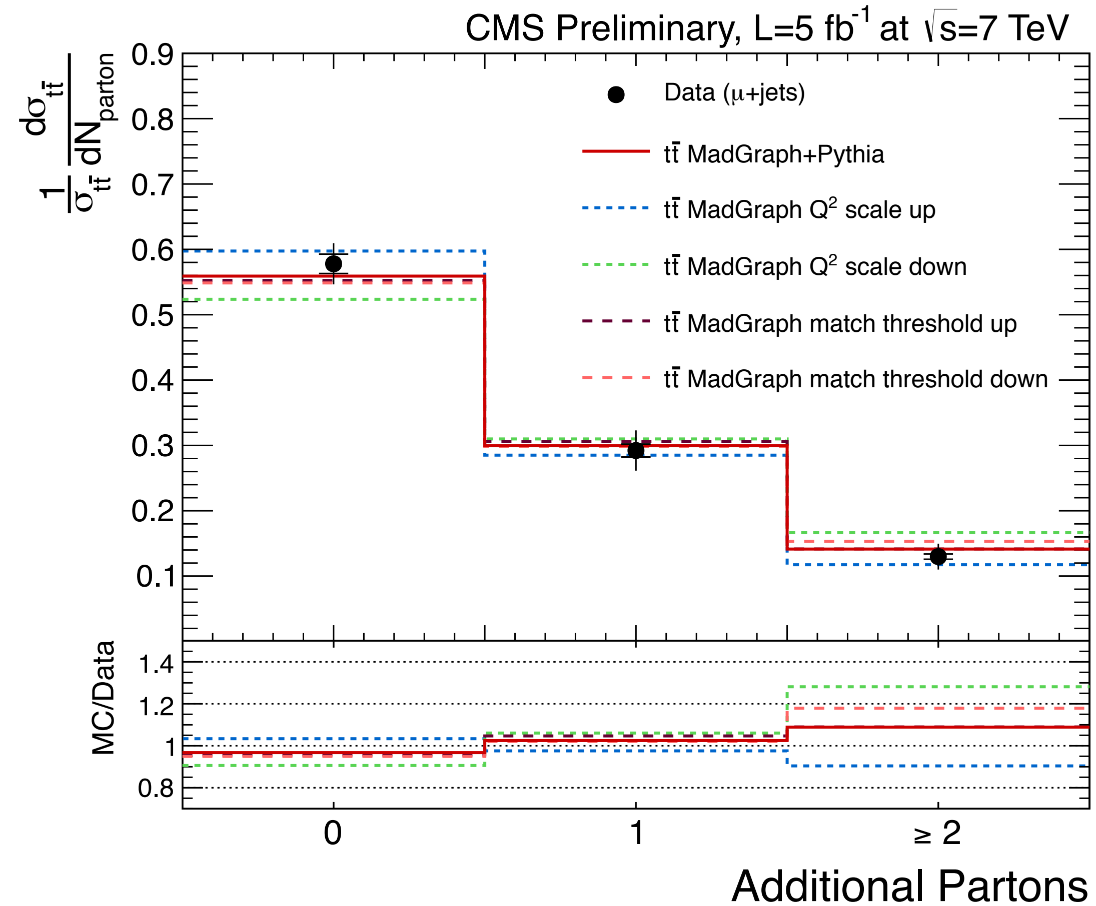
Top Pairs + Jets

- “Additional jets” = particle jets not pointing back to partons from top decay
- Comparison with MC generators
  - Generally good agreement with MC programs
  - Renormalization/factorization scale uncertainties seem too conservative

Comparison of Generators



Comparison of MC Scale Choices



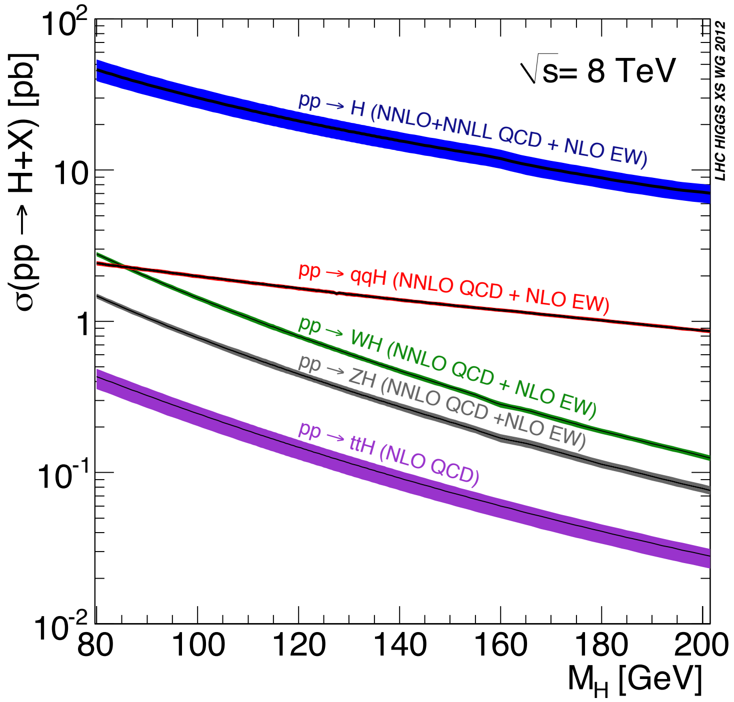
[CMS-PAS-TOP-12-018]

Update for publication and 8 TeV result upcoming

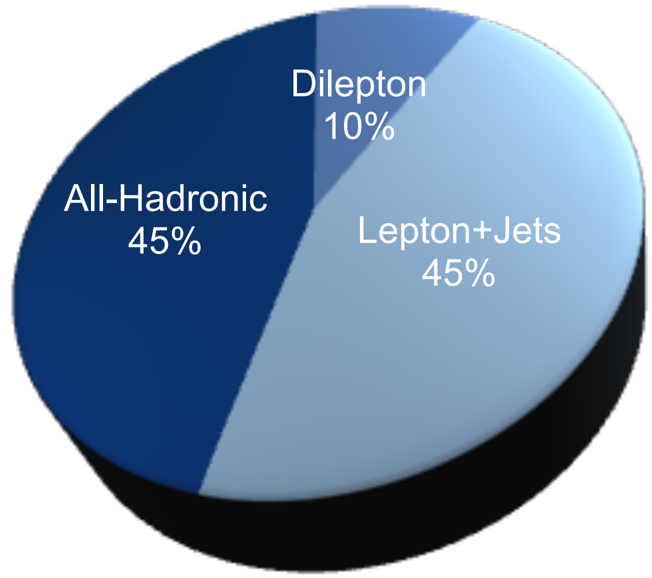
Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Associated Top-Higgs Production

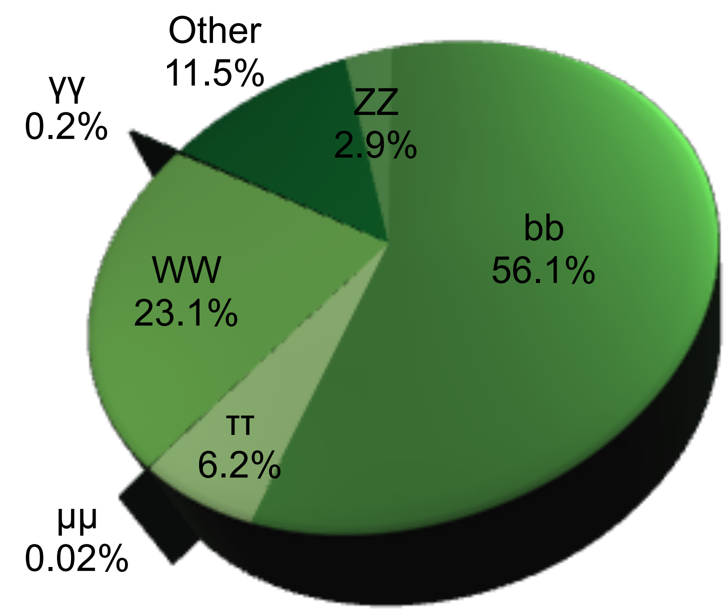
Production Cross Section



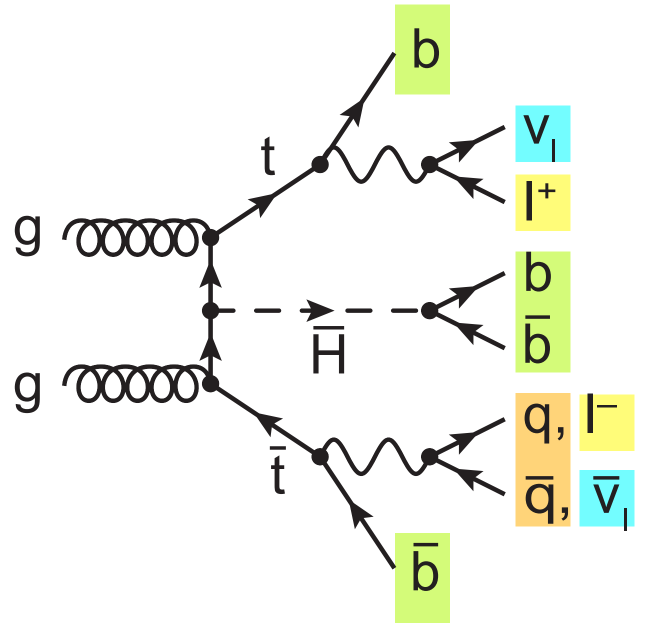
$t\bar{t}$ Branching Fractions



Higgs Branching Fractions



Largest contribution: $H \rightarrow b\bar{b}$

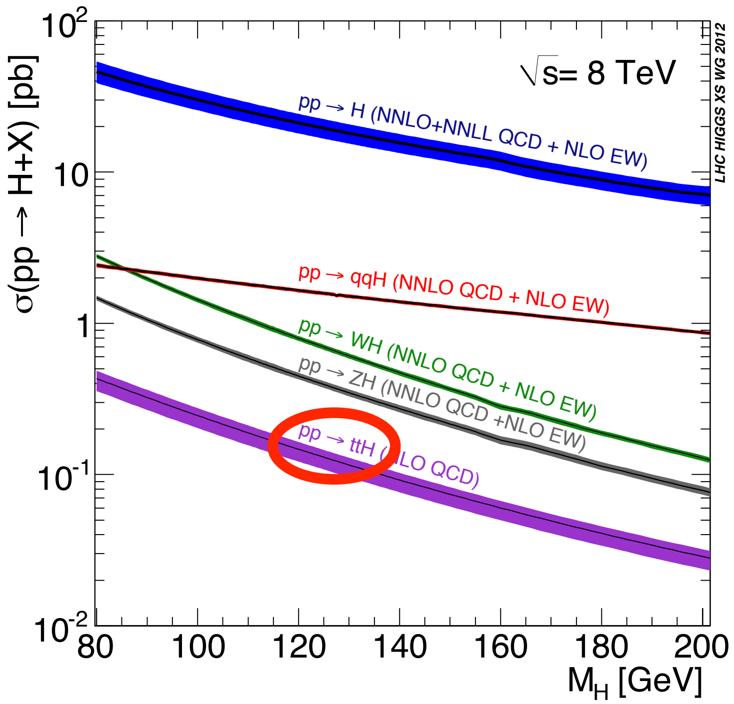


- Small SM production cross section (0.13 pb at 126 GeV), many possible final states with different signal/background
- Best sensitivity: include as many final states as possible → statistical combination

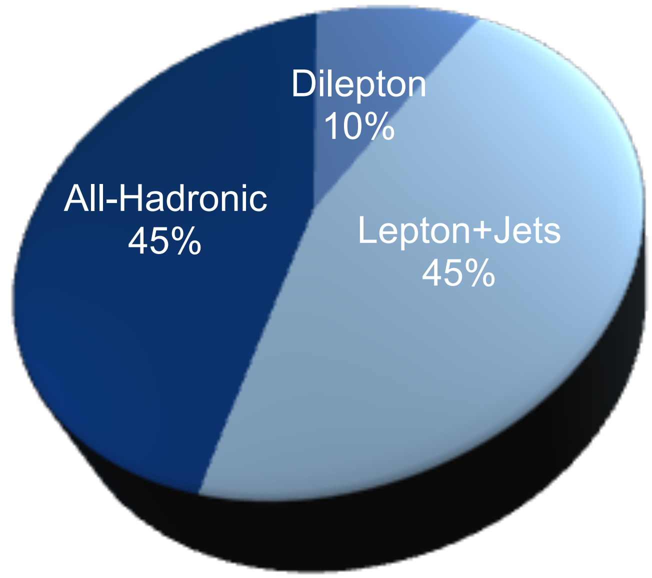
Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Associated Top-Higgs Production

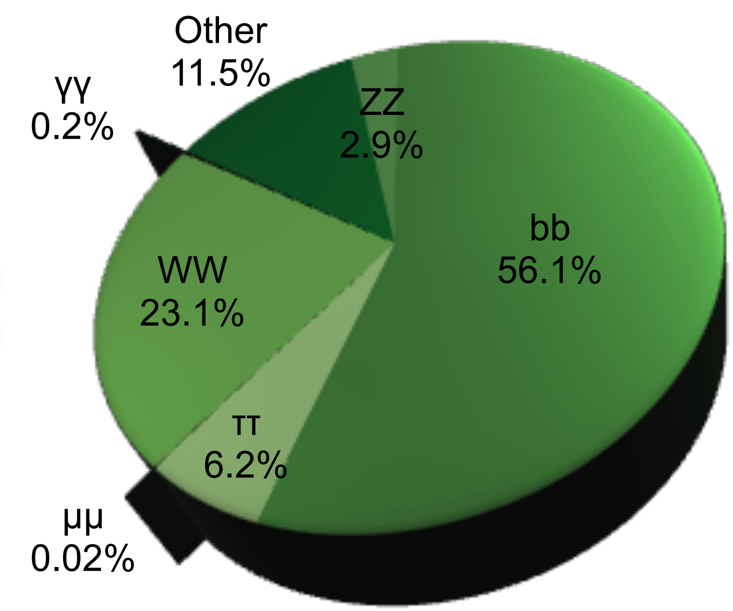
Production Cross Section



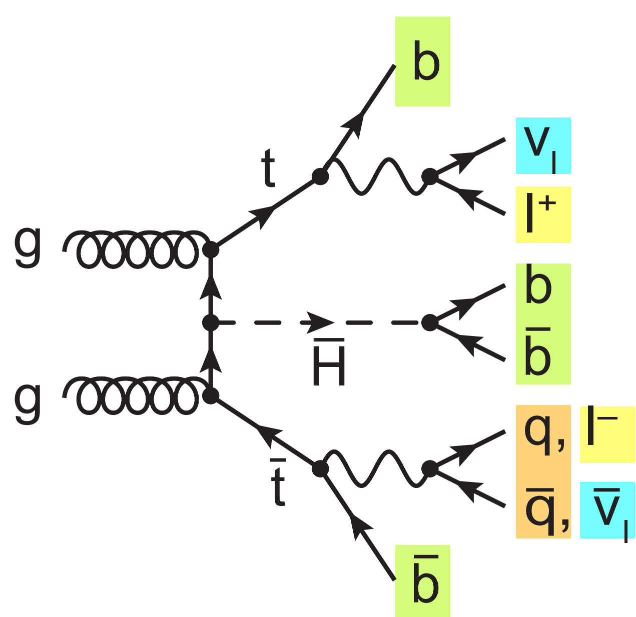
$t\bar{t}$ Branching Fractions



Higgs Branching Fractions



Largest contribution: H → $b\bar{b}$



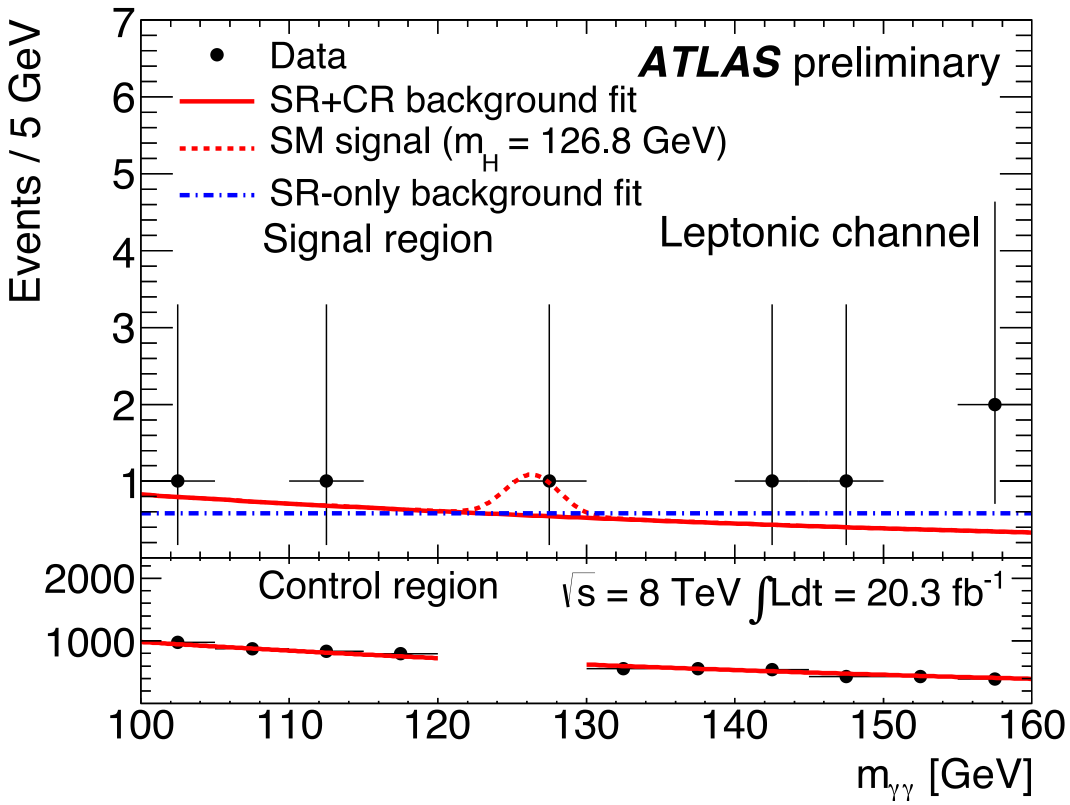
- Small SM production cross section (0.13 pb at 126 GeV), many possible final states with different signal/background
- Best sensitivity: include as many final states as possible → statistical combination

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Examples of ttH Final States

H → γγ:
small branching fraction, but small backgrounds and good $m_{\gamma\gamma}$ resolution

ttH → Lepton(s) γγ X



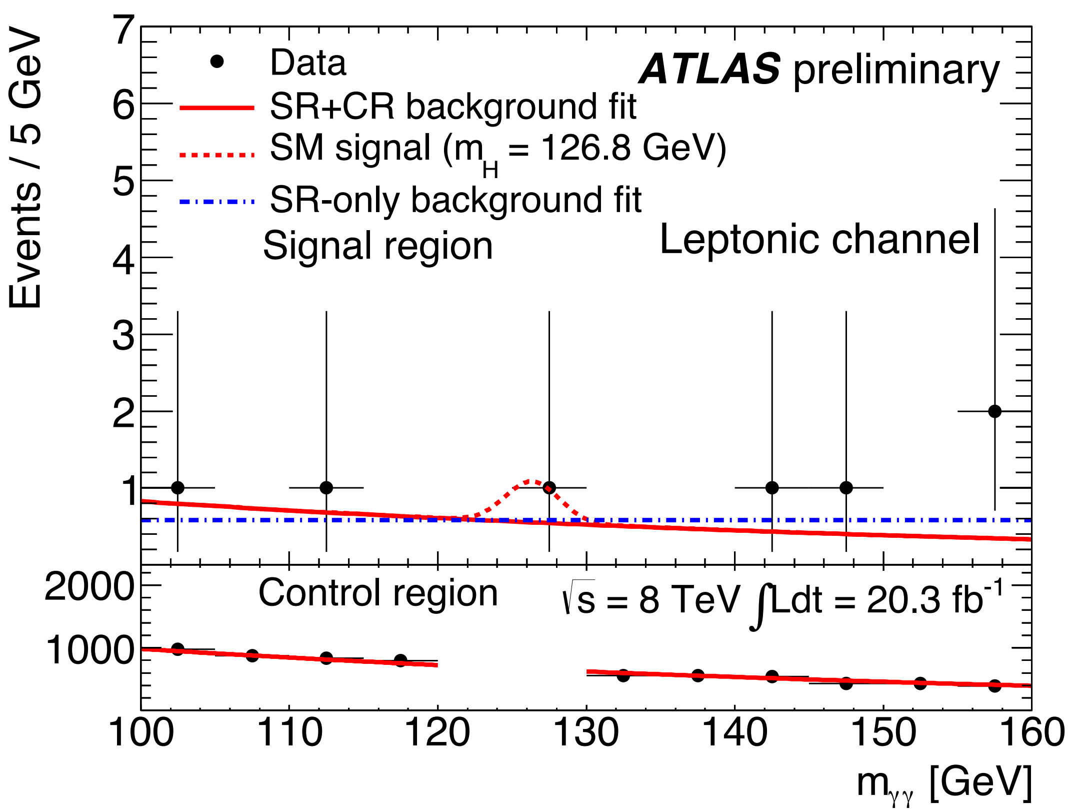
[ATLAS-CONF-2013-080]

Examples of ttH Final States

$H \to \gamma\gamma$:
small branching fraction,
but small backgrounds
and good $m_{\gamma\gamma}$ resolution

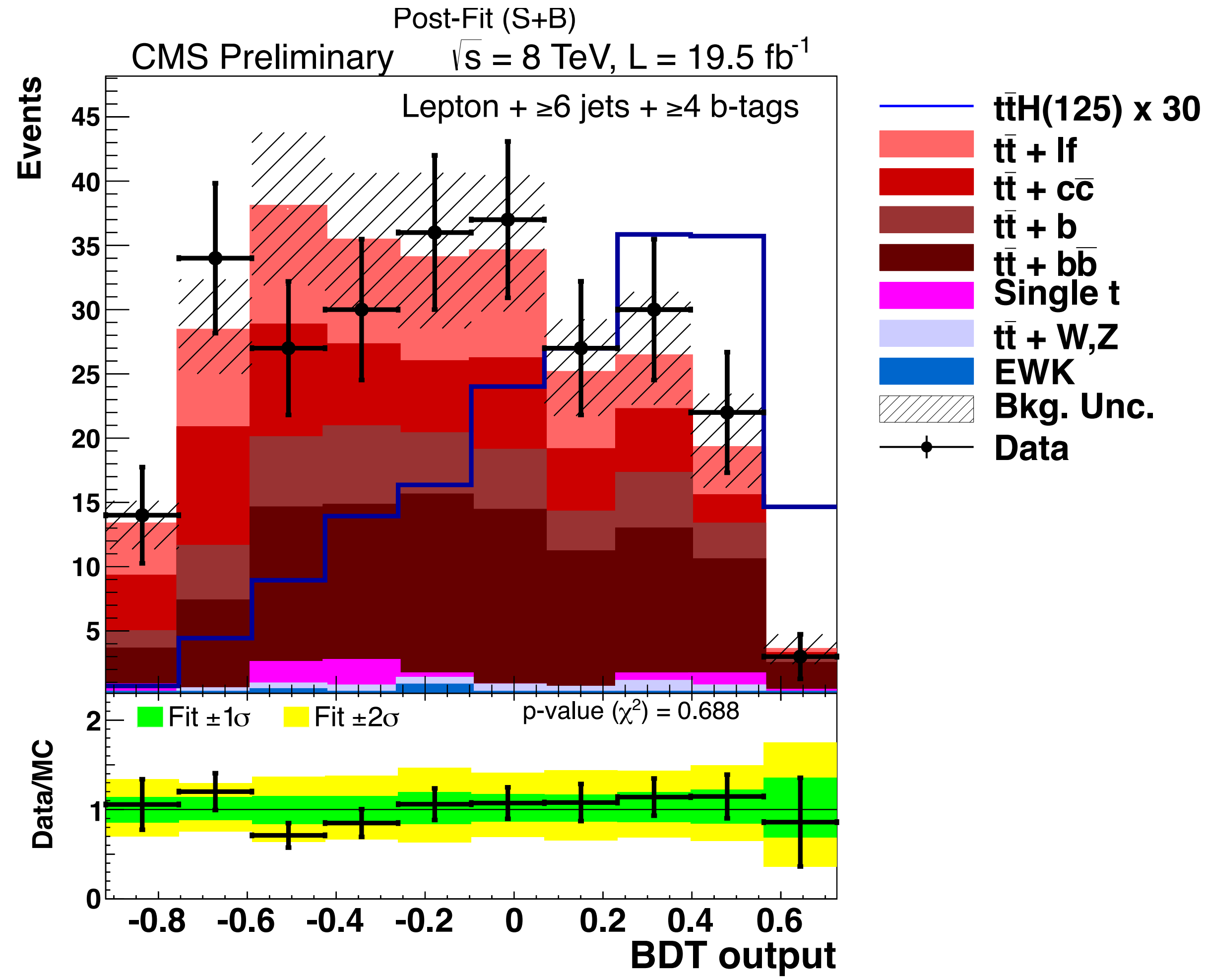
$H \to b\bar{b}/\tau^+\tau^-$:
large branching fraction,
but large $t\bar{t}$ + (heavy flavor) jets
background, large jet combinatorics

ttH → Lepton(s) γγ X



[ATLAS-CONF-2013-080]

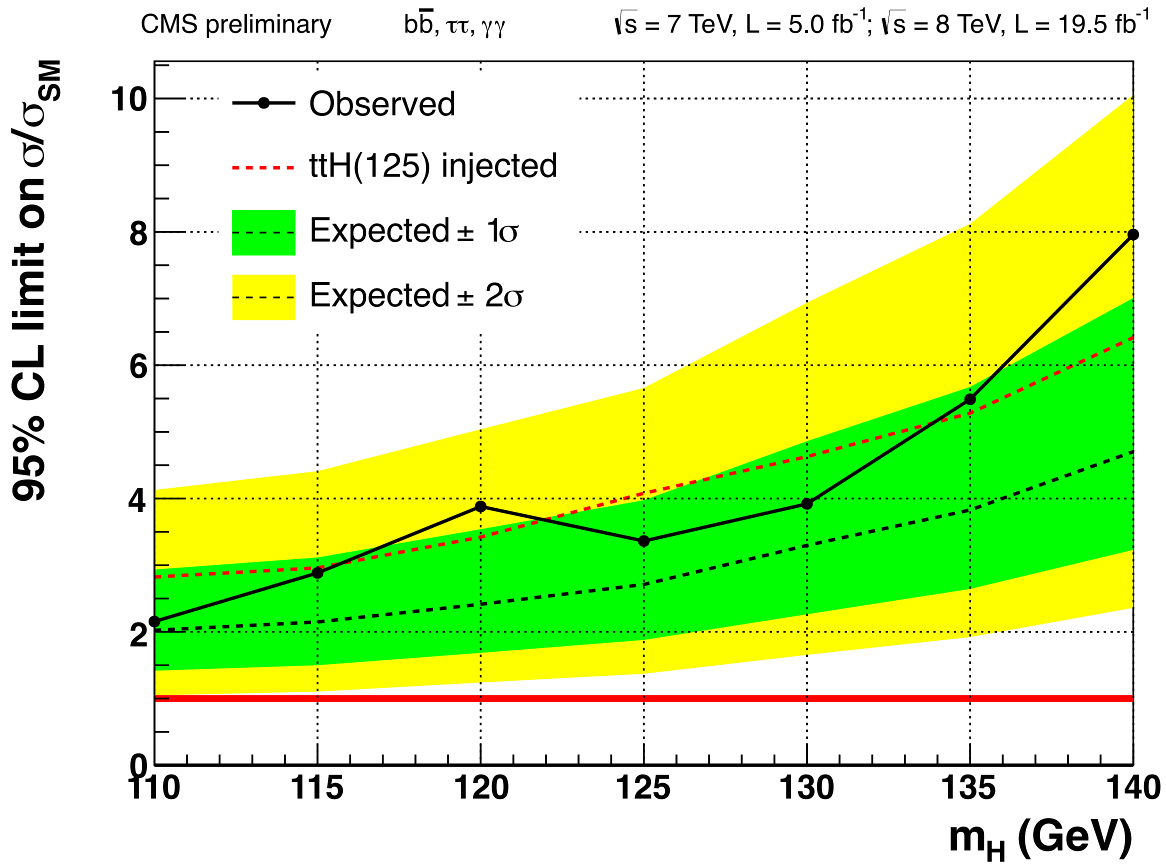
ttH → Lepton + ≥6 Jets

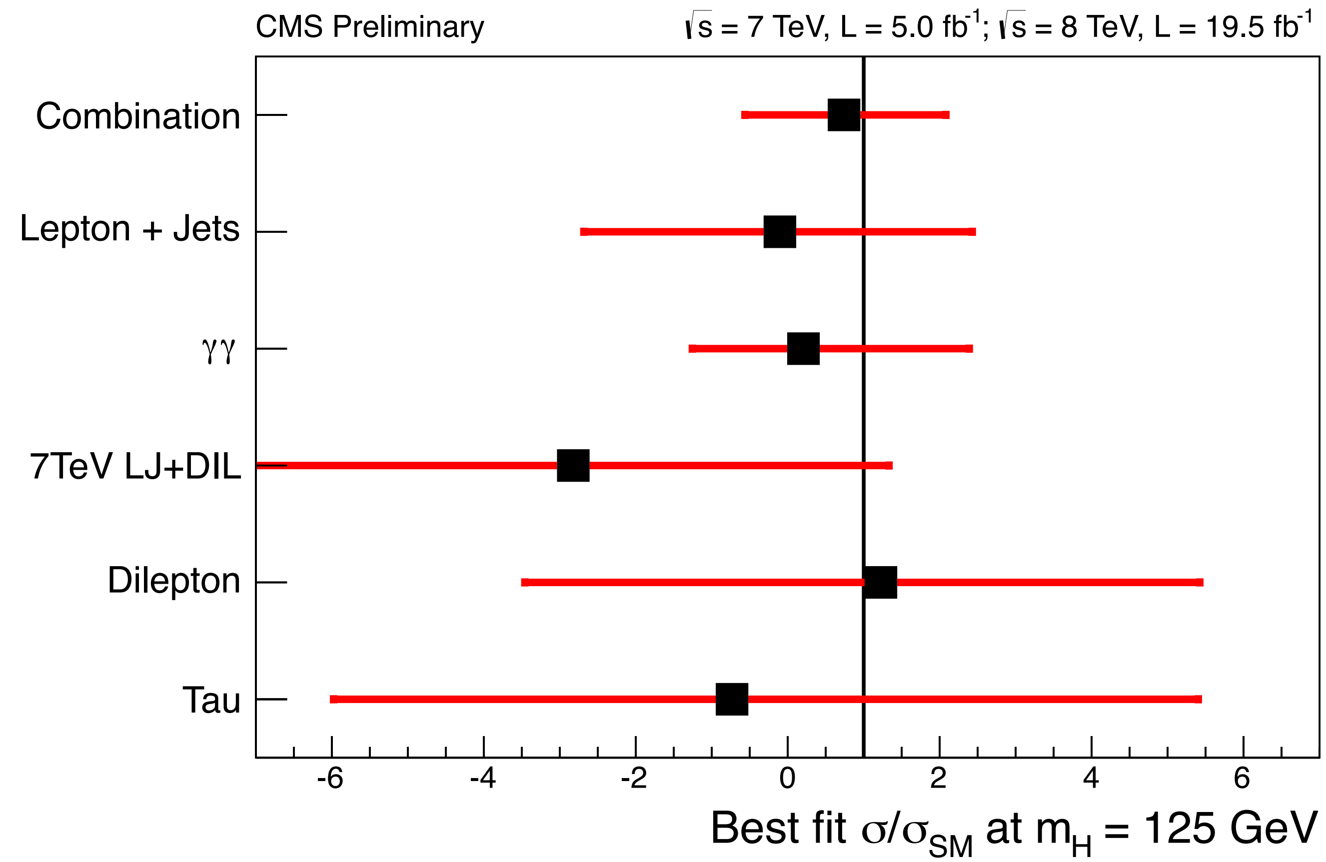


[CMS-PAS-HIG-13-019]

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

ttH Statistical Combination





[CMS-PAS-HIG-13-019]

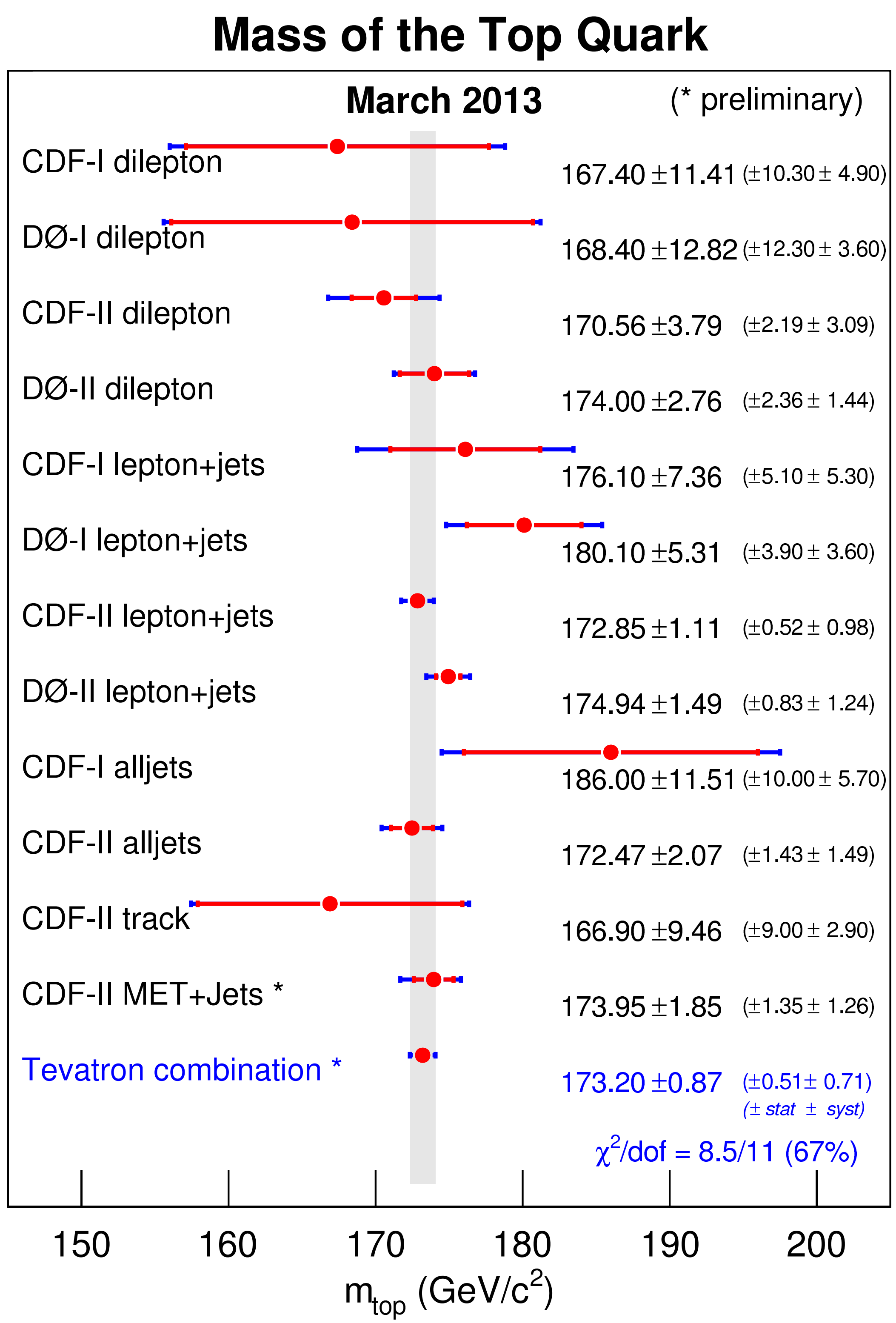
- Combination of 7 and 8 TeV data (CMS) → limit at m_H = 125 GeV:
  - Observed: 3.4 × SM cross section
  - Expected (without SM Higgs): 2.7 × SM
- Best fit cross section: $\frac{\sigma}{\sigma_{SM}} = 0.74^{+1.34}_{-1.30}$ (→ still compatible with both 0 and 1)
- Channel not yet established, huge potential for Run II

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Karlsruhe Institute of Technology

Top Properties
&
New Physics

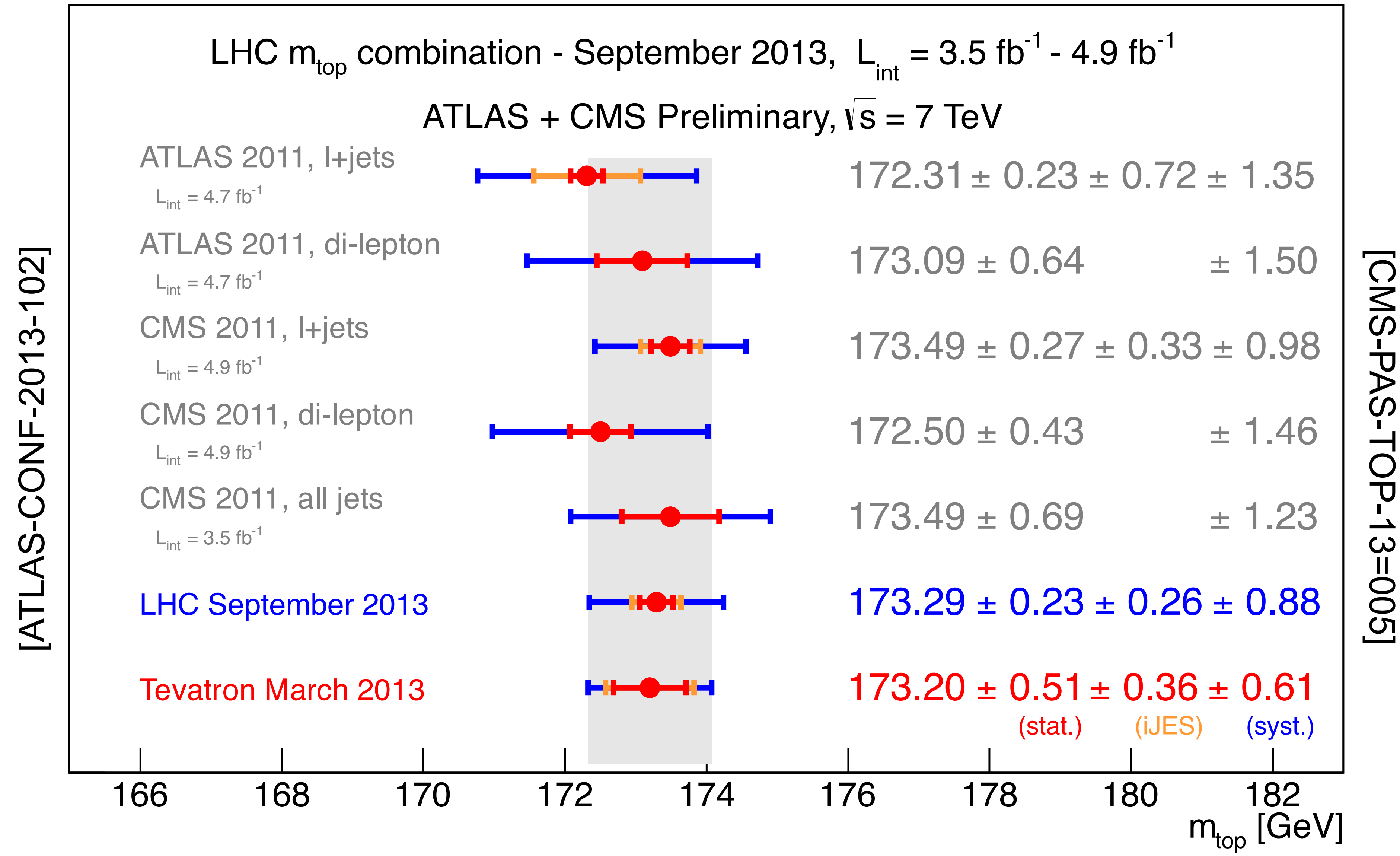
Top Mass at the Tevatron



- Many of today's analysis methods spear-headed at the Tevatron
  - Examples: in-situ jet energy scale, matrix element method
- Tevatron combination
  → still world's most precise top mass
  - Detailed understanding of all uncertainties and their correlations
  - All results consistent within uncertainties
  - Combined uncertainty: 0.5%
- Final word from the Tevatron expected in Winter 2014

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Top Mass at the LHC



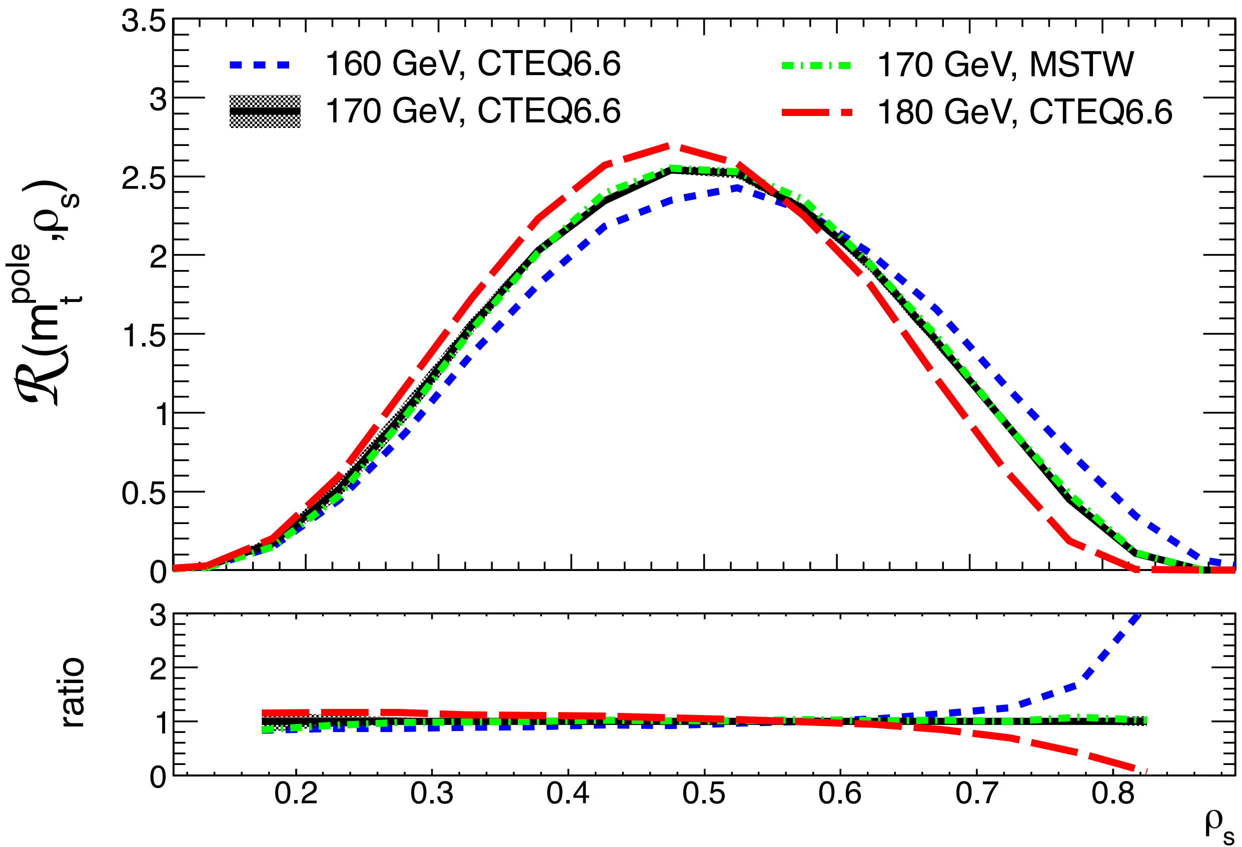
- LHC has caught up quickly: central top mass value and uncertainty comparable to Tevatron → below 1 GeV uncertainty
- Plenty of statistics, modeling systematics dominate uncertainty
- “World combination” effort started

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Top Mass: Alternative Approaches

- Old discussion: which top mass?
  - MC mass in kinematic mass measurement = pole mass?
  - TOP 2013: cease-fire → assumption should be ok up to precisions around 0.5 GeV
- Alternative methods being explored
  - Mass from pair production cross section: limited precision
  - Differential cross section in $t\bar{t}$ + 1 jet: 1 GeV precision seems feasible
  - B meson p_T: very sensitive to $t\bar{t}$ modeling
  - Average J/ψ + Lepton mass in $t \rightarrow Wb \rightarrow$ Lepton J/ψ X: 1 GeV precision only at HL-LHC
  - Kinematic endpoint of m_{lb} distribution

Top Mass from tt + 1 Jet Cross Section



[Eur. Phys. J. C73 (2013) 2438]

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\,\text{jet}}} \frac{d\sigma_{t\bar{t}+1\,\text{jet}}}{d\rho_s}$$

with $\rho_s = \dfrac{2m_0}{\sqrt{s_{t\bar{t}j}}}$

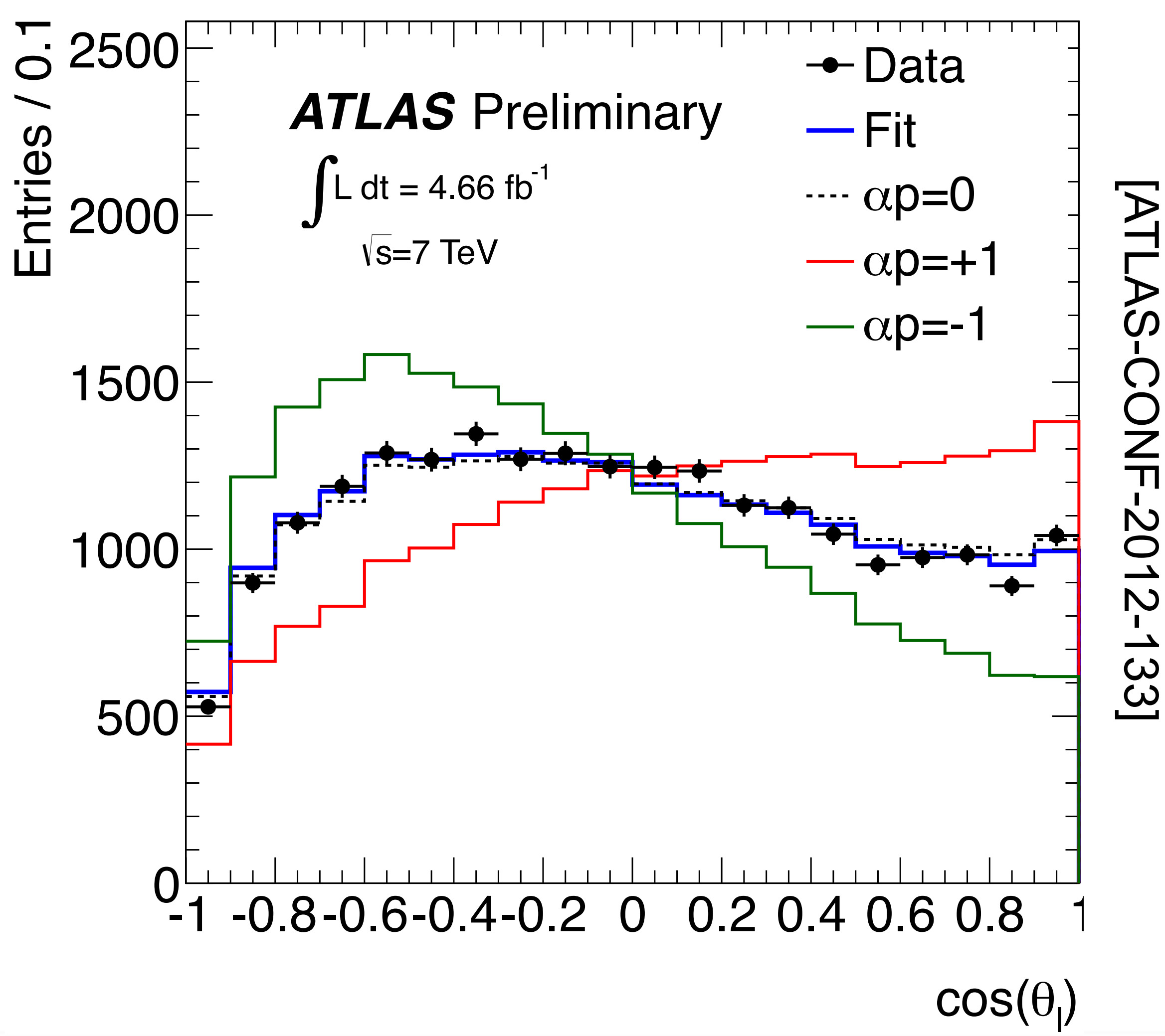
m_0: reference mass scale
$s_{t\bar{t}j}$: squared $t\bar{t}j$ invariant mass

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

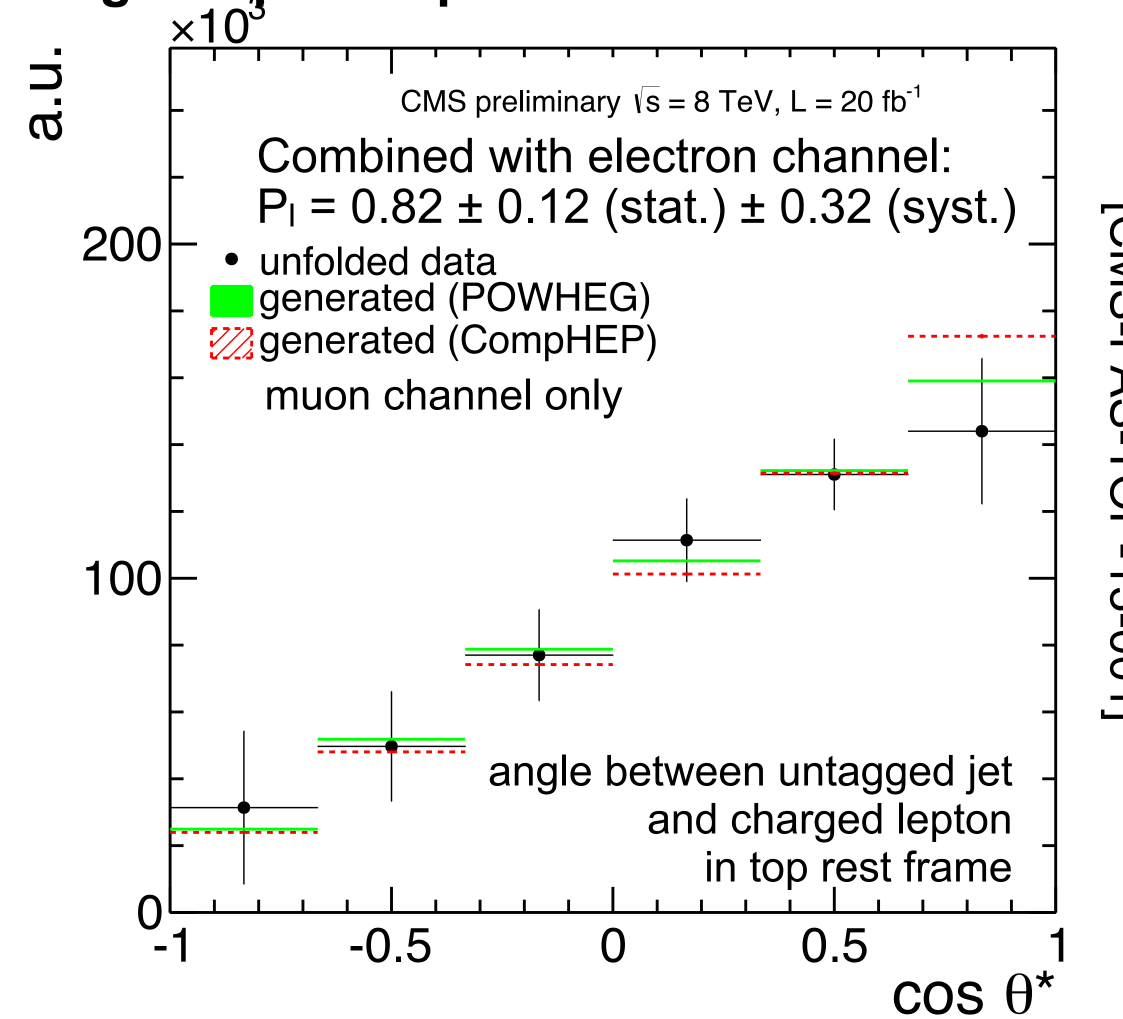
Polarization Observables

- Top spin “easily” accessible: no hadronization → spin transferred
- Standard model top production: $t\bar{t}$ unpolarized, single top 100% polarized
- Expect imprint of BSM physics, e.g. stop or heavy spin-1/2 (T) partner

$t\bar{t}$: Compatible with No Polarization



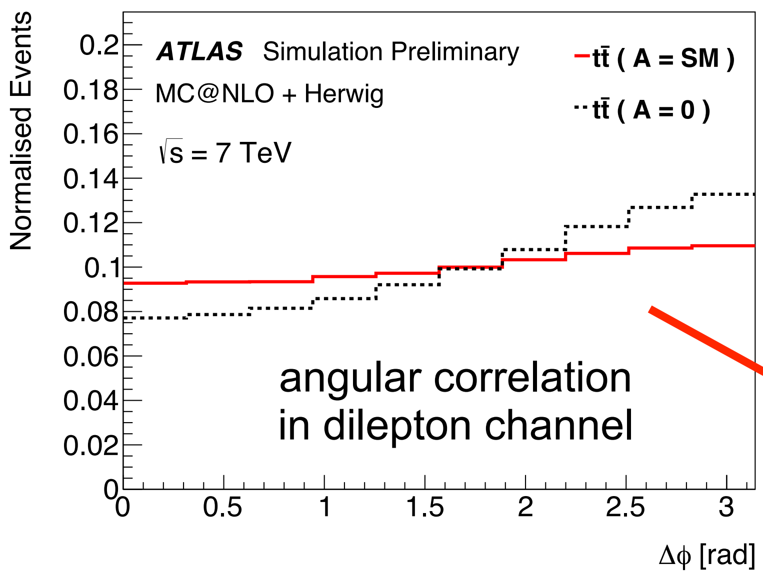
Single Top: Compatible with 100% Polarization

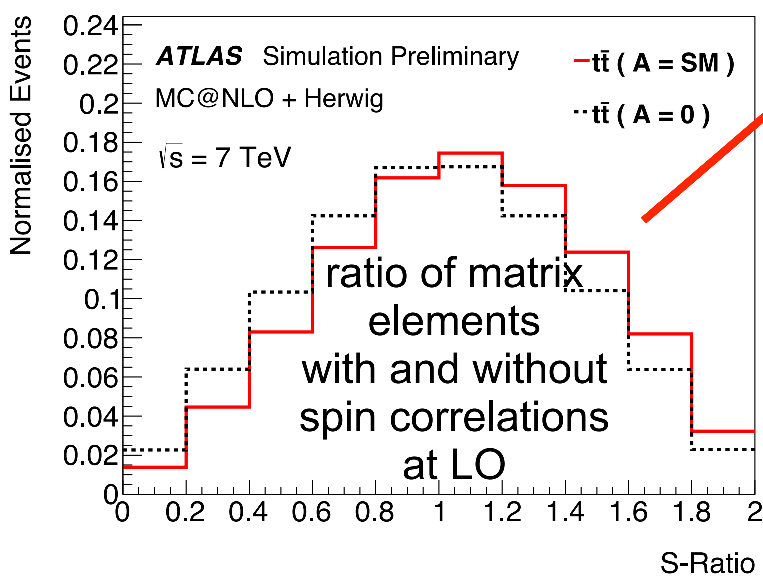


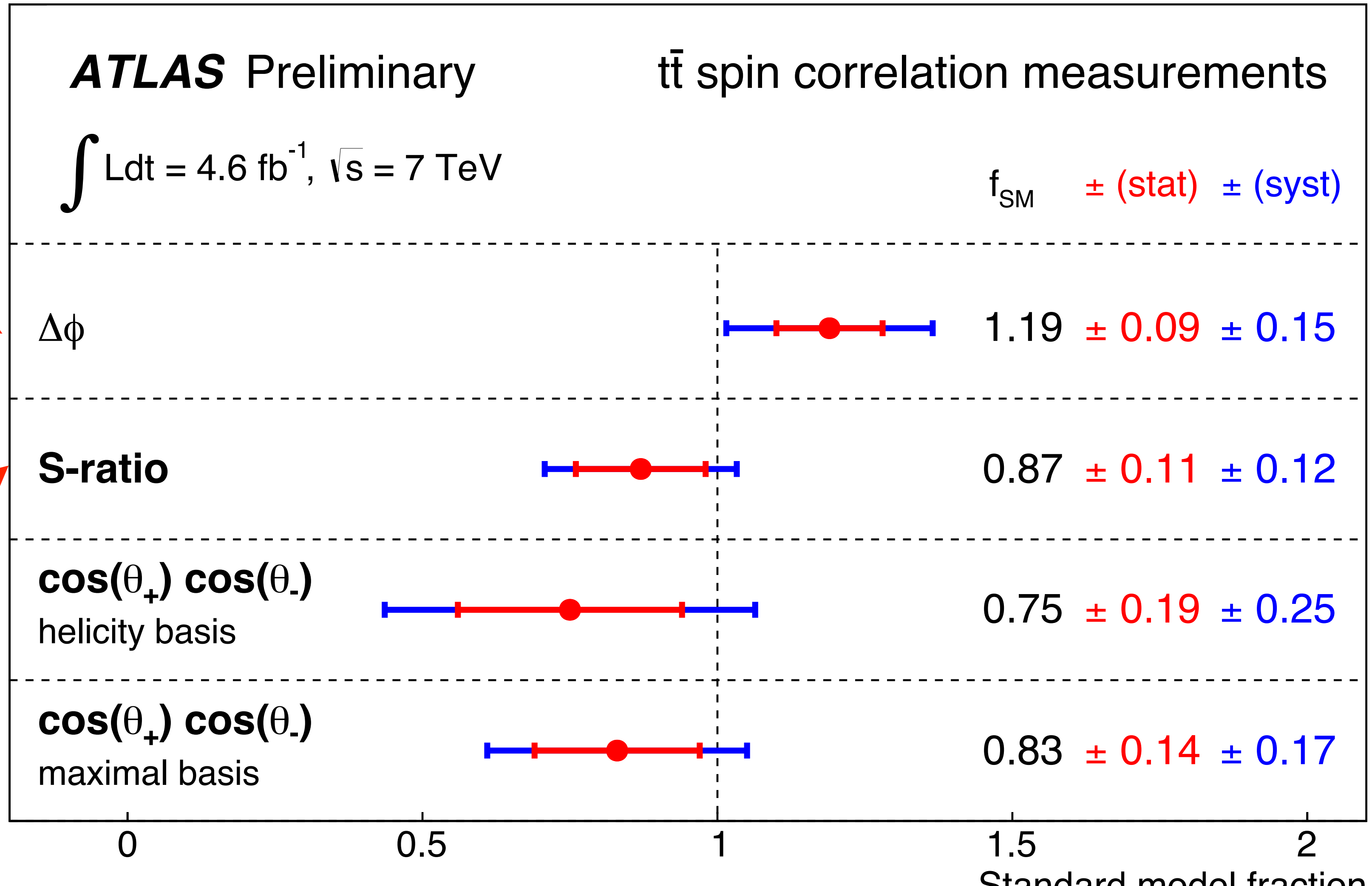
Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Spin Correlations

- Polarization in $t\bar{t}$ production:
  - Tops unpolarized but spins correlated
  - Strength depends on production mechanism (gg vs. $q\bar{q}$) and choice of spin basis



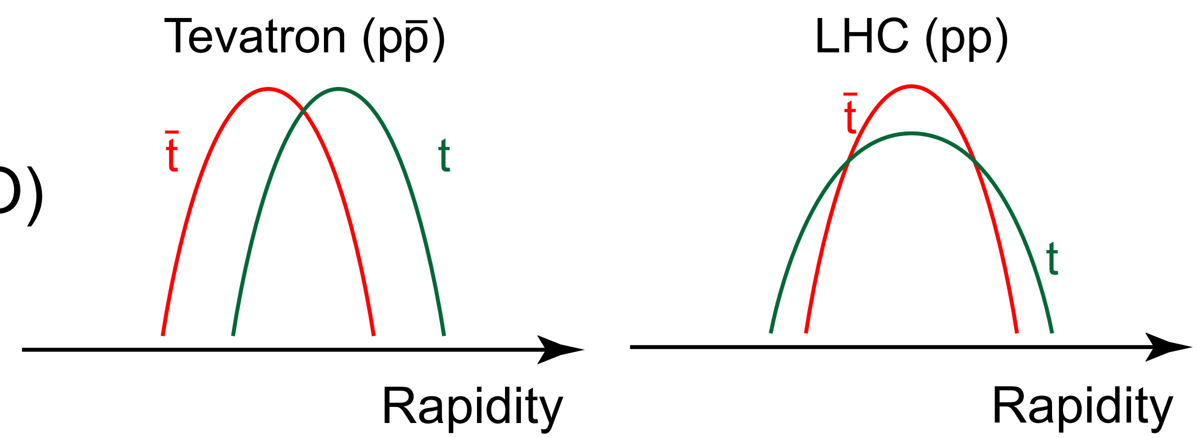


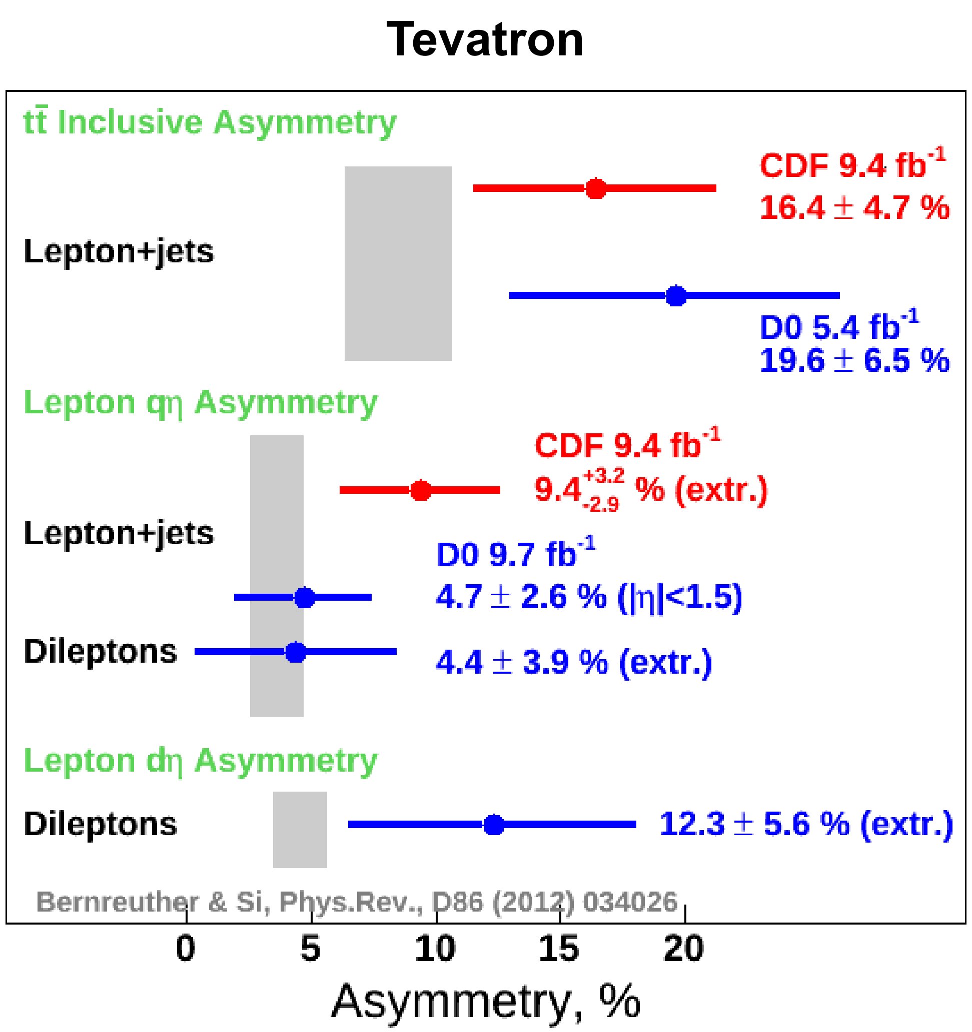


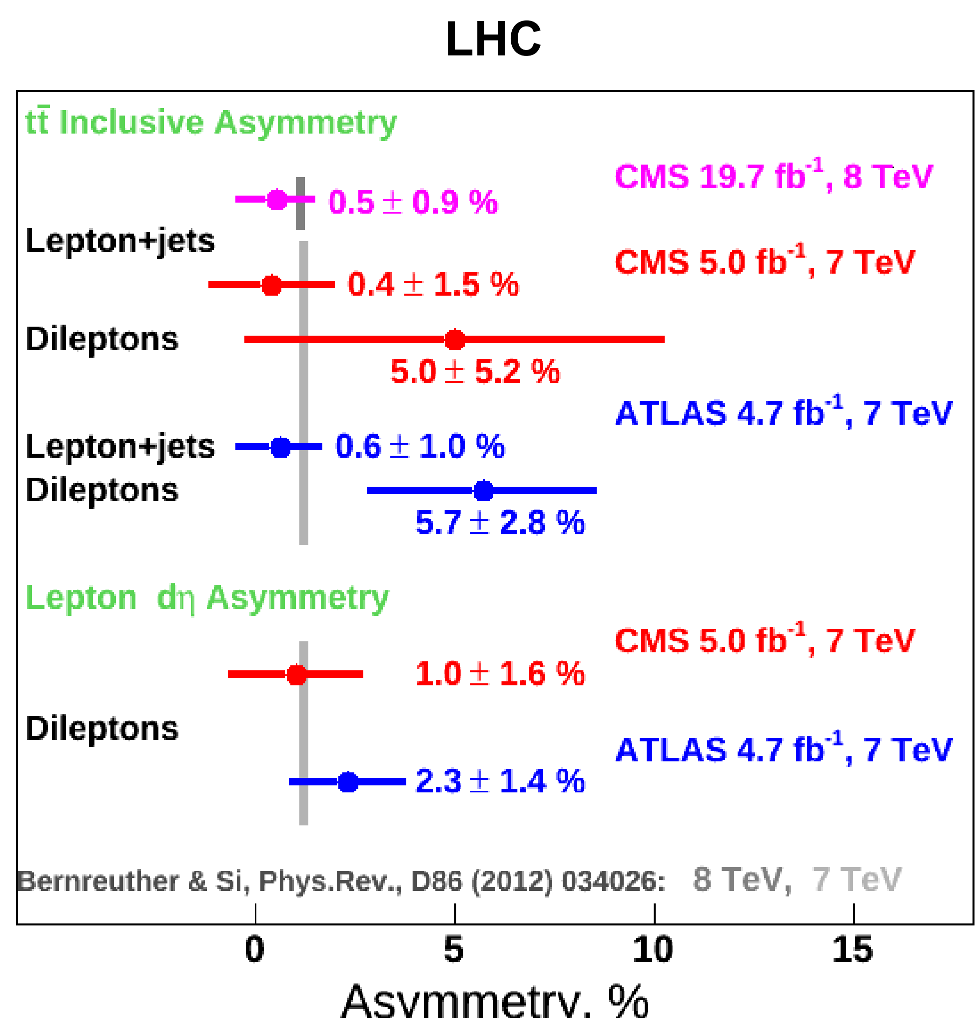
[ATLAS-CONF-2013-101]

Charge Asymmetry

- Top production asymmetries:
  - SM: small effect (contributes first in NLO)
  - Tevatron: tops like to move forward
  - LHC: t rapidity distribution wider than $\bar{t}$



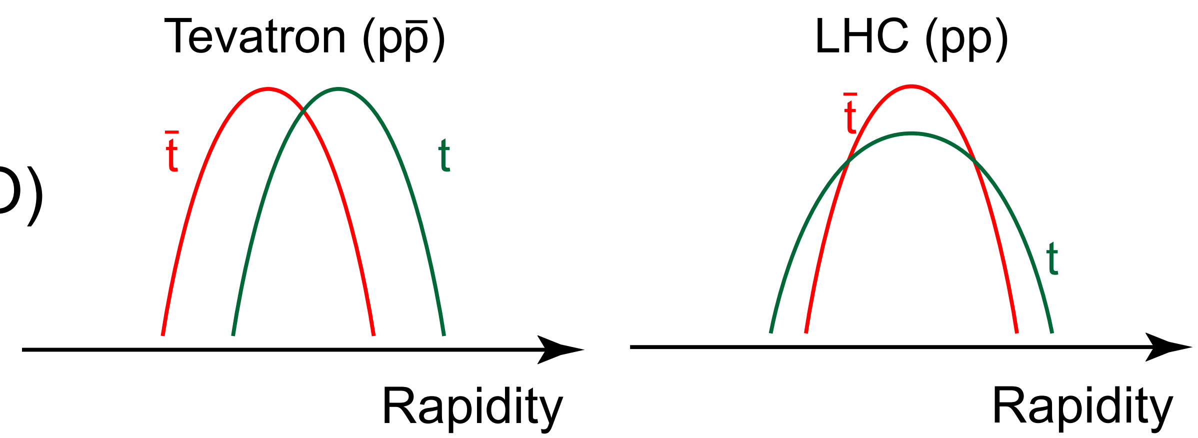


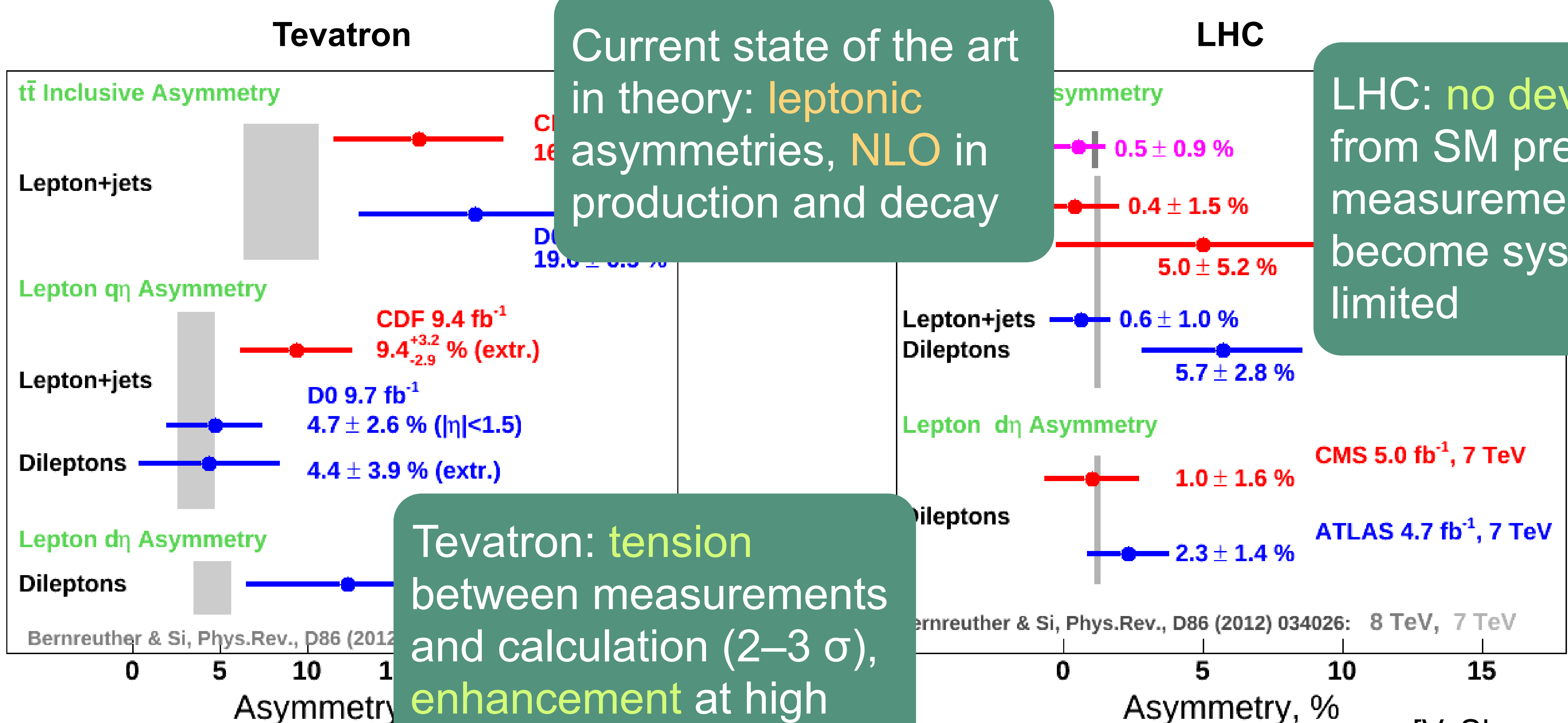


[V. Sharyy, TOP 2013]

Charge Asymmetry

- Top production asymmetries:
  - SM: small effect (contributes first in NLO)
  - Tevatron: tops like to move forward
  - LHC: t rapidity distribution wider than $\bar{t}$





Current state of the art in theory: leptonic asymmetries, NLO in production and decay

LHC: no deviations from SM predictions, measurements become systematics limited

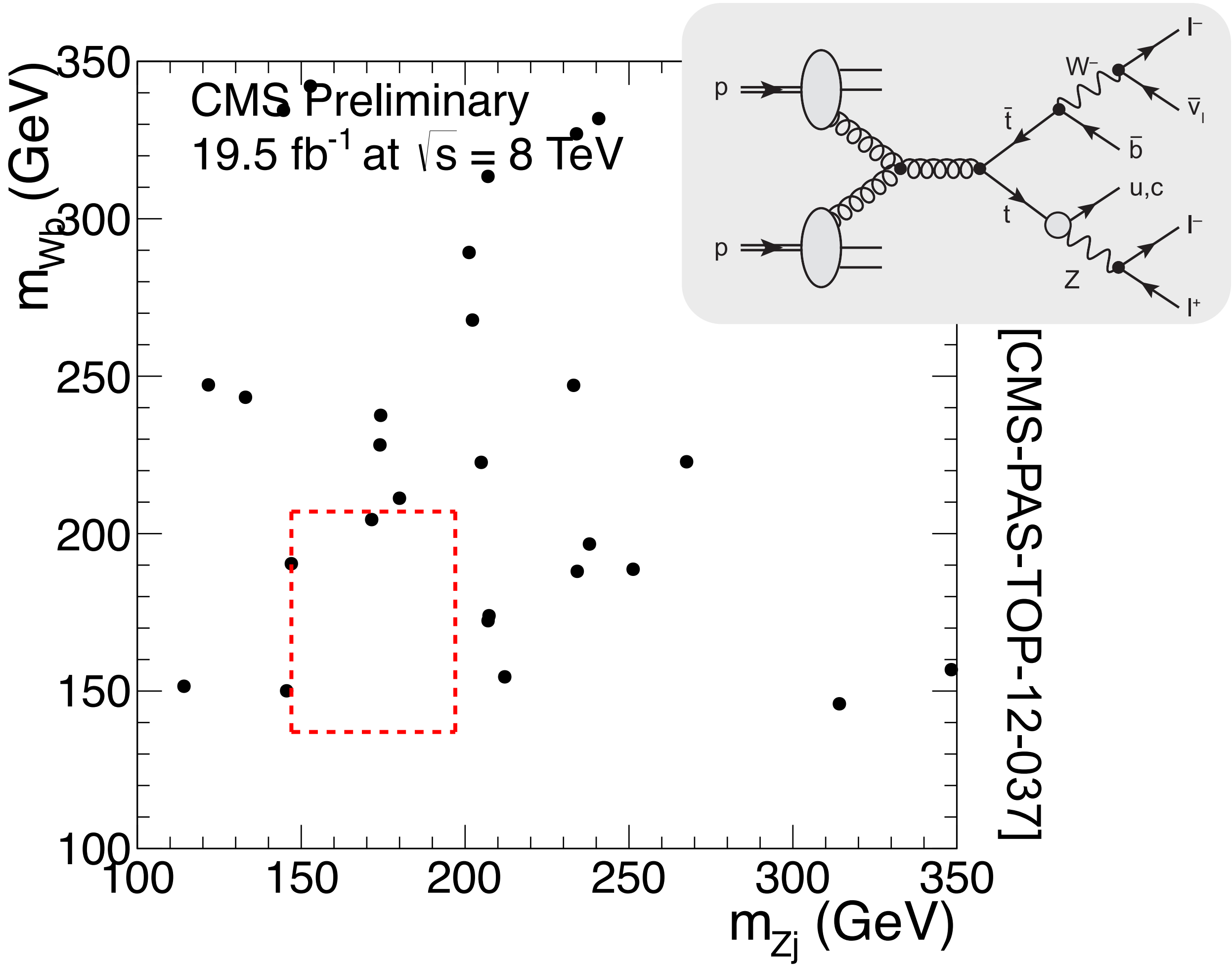
Tevatron: tension between measurements and calculation (2–3 σ), enhancement at high invariant $t\bar{t}$ masses → combination?

[V. Sharyy, TOP 2013]

Flavor-Changing Neutral Currents

- Top flavor-changing neutral currents (FCNC) very small in the SM: forbidden at tree level, effective GIM suppression in quantum corrections

- FCNCs in $t\bar{t}$ decays:
  - Probes tZq, tγq or tHq couplings
  - E.g. $B(t \rightarrow Zq) < 7\times10^{-4}$ @ 95% CL



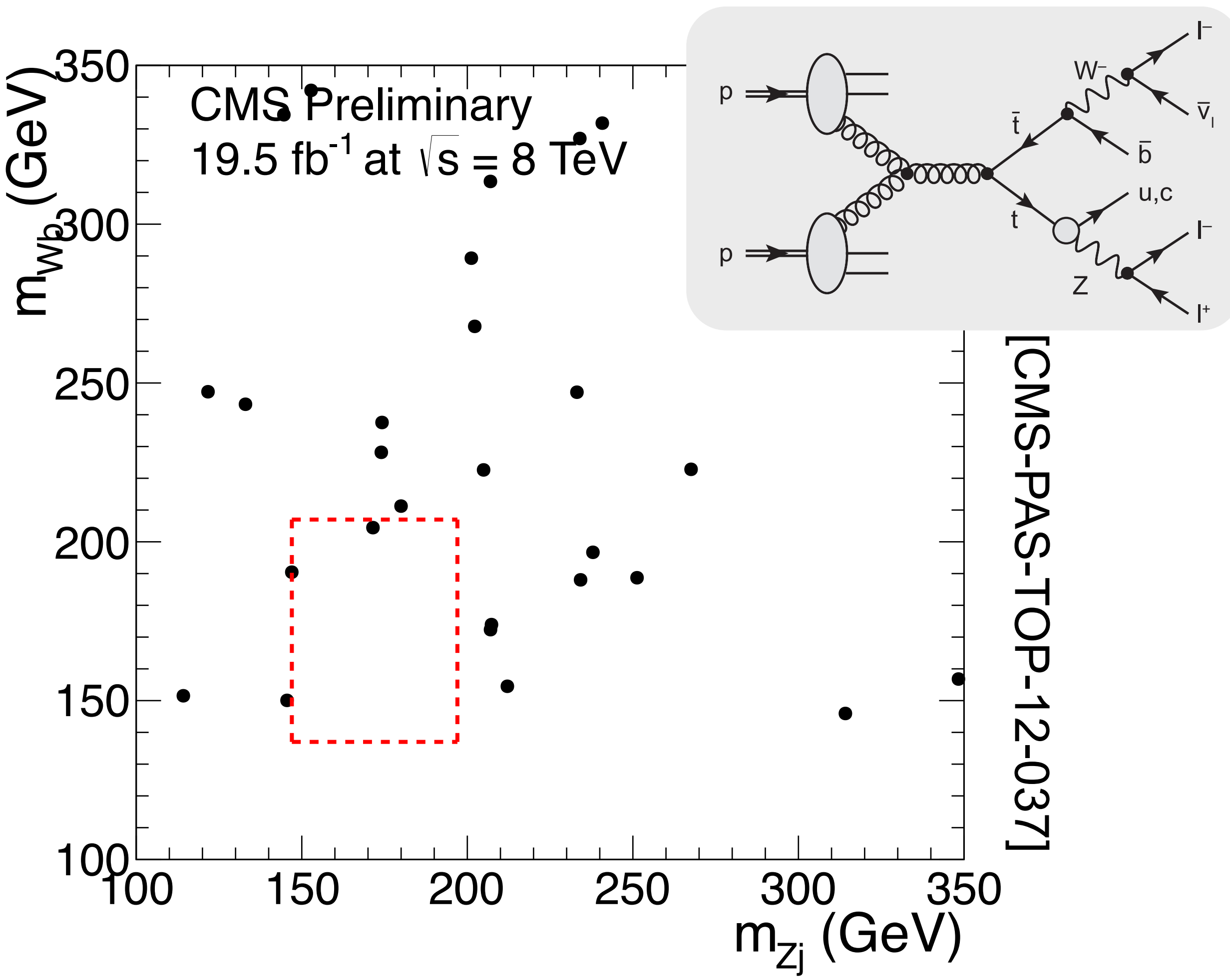
[CMS-PAS-TOP-12-037]

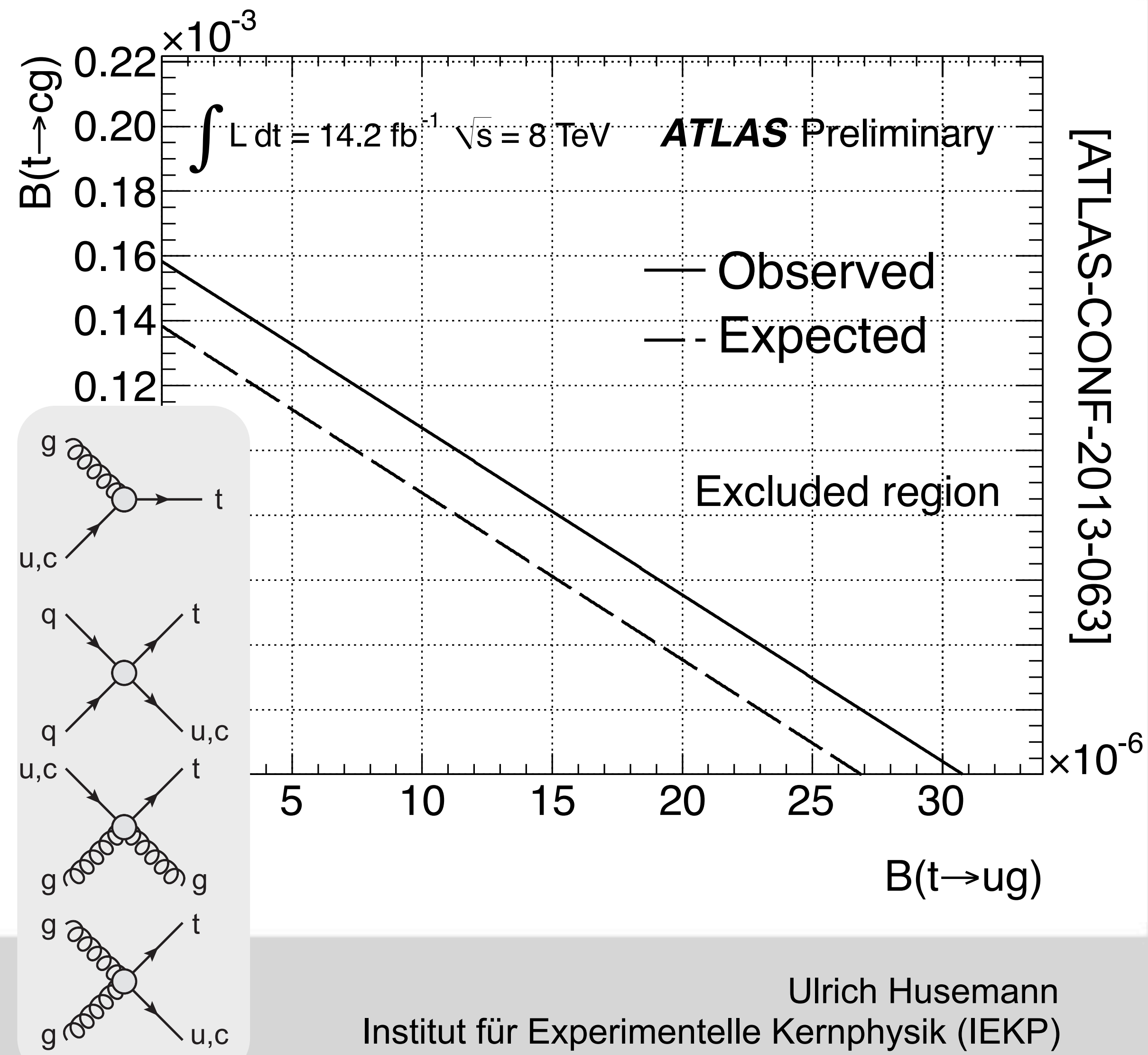
Flavor-Changing Neutral Currents

- Top flavor-changing neutral currents (FCNC) very small in the SM: forbidden at tree level, effective GIM suppression in quantum corrections

- FCNCs in $t\bar{t}$ decays:
  - Probes tZq, tγq or tHq couplings
  - E.g. $B(t \to Zq) < 7\times10^{-4}$ @ 95% CL

- FCNCs in single top production:
  - Probes tqg or tZq couplings
  - E.g. $B(t \to cg) < 1.6\times10^{-4}$ @ 95% CL

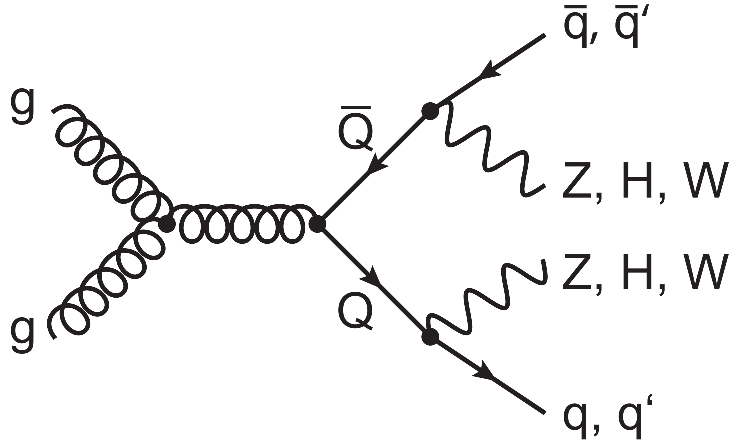




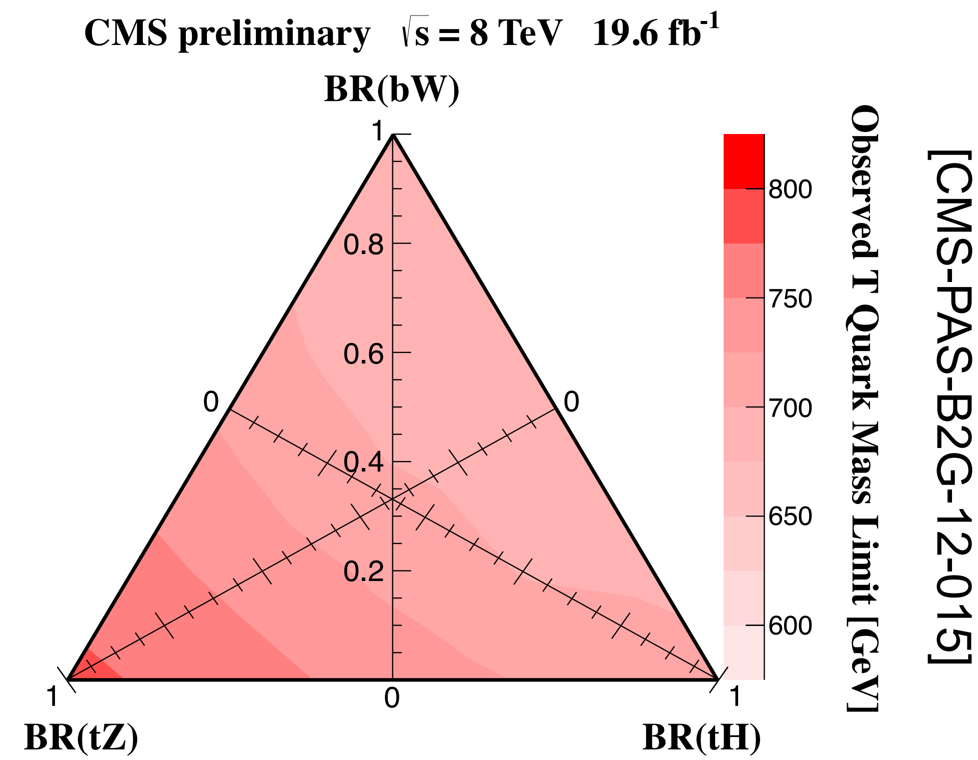
Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

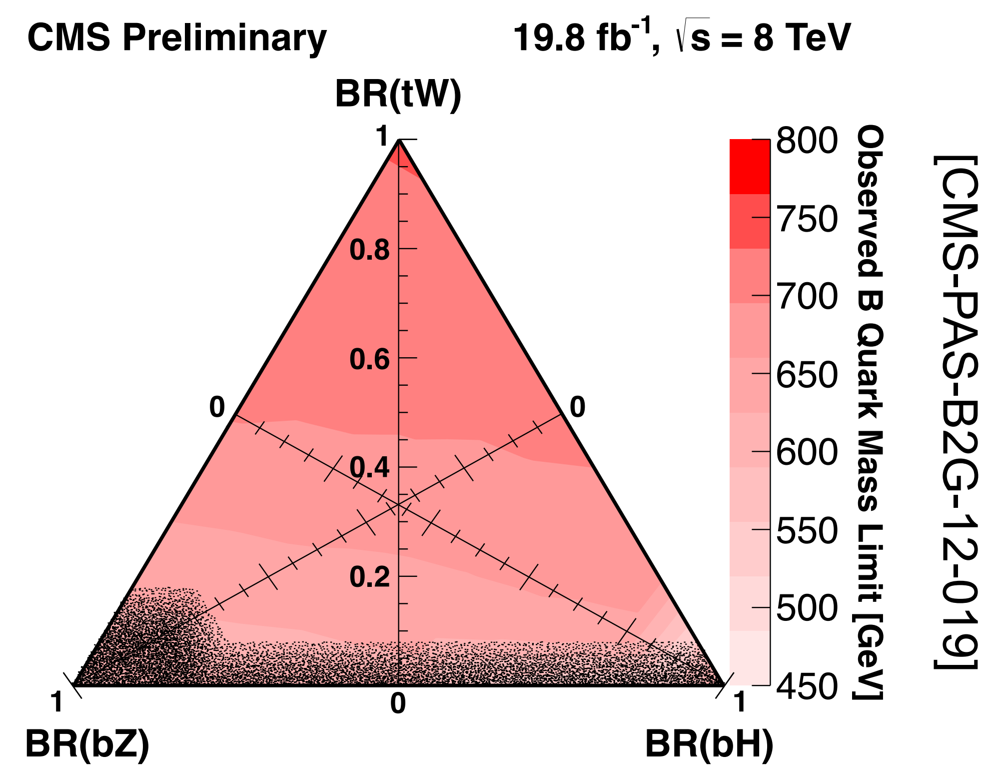
Search for Vector-Like Quarks

- Heavy vector-like quarks:
  - Vector-like: left-/right-handed with symmetric couplings, SU(2)×U(1) singlet or doublet
  - Generic signature, e.g. composite Higgs, Little Higgs, extra dimensions, …
  - Rich phenomenology: $T \rightarrow tH, tZ, bW$; $B \rightarrow tW, bZ, bH$



- Typical limits with full Run I dataset
  - Heavy T mass > 600–850 GeV
  - Heavy B mass > 400–750 GeV





Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

There is Much More…

- … than I could present in a one-hour talk:
  - More measurements: QCD parameters from cross section, W polarization
  - More associated production: $t\bar{t}$ + $b\bar{b}$, W, Z, γ
  - More searches: charged Higgs, same sign tops, four tops, …
  - Boosted topologies & searches for heavy $t\bar{t}$ and $t\bar{b}$ resonances
  - Top as a background to Higgs, SUSY, and exotics searches
  - …
- Check out the LHC and Tevatron experiments' public material
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic//TopPublicResults
  - http://www-cdf.fnal.gov/physics/new/top/top.html
  - http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

Summary & Conclusions

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