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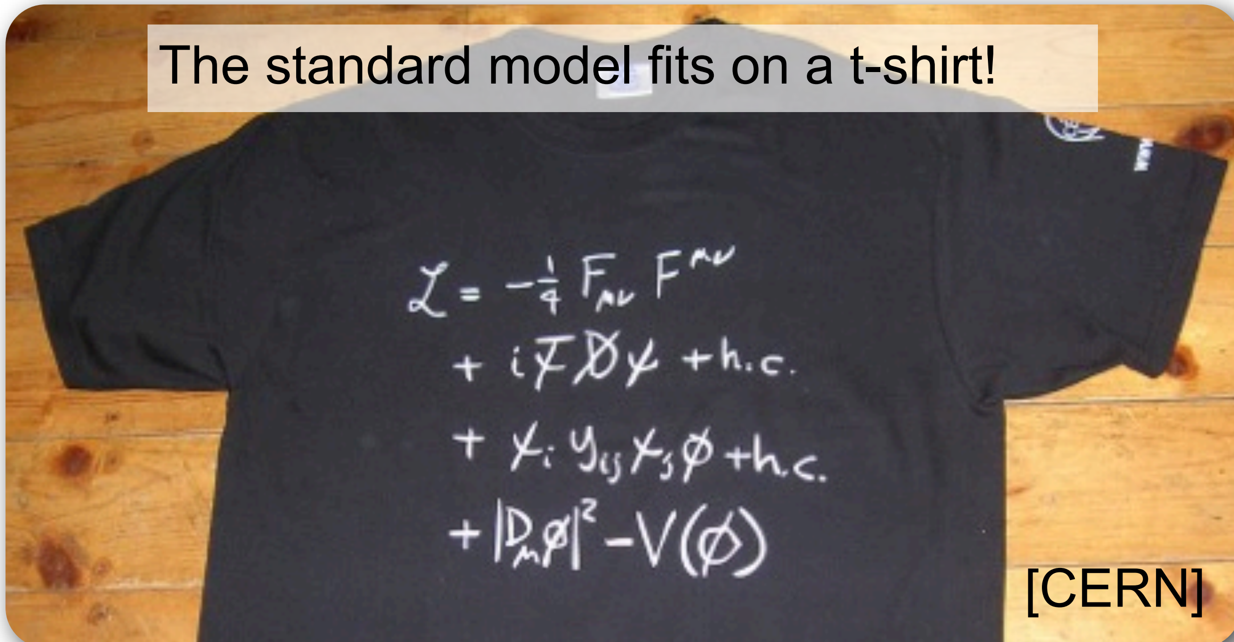
Top and Beyond
From the Tevatron to the LHC

Gemeinsames Teilchen- und Astroteilchenphysikalisches Seminar der Universitäten Heidelberg, Tübingen und des KIT

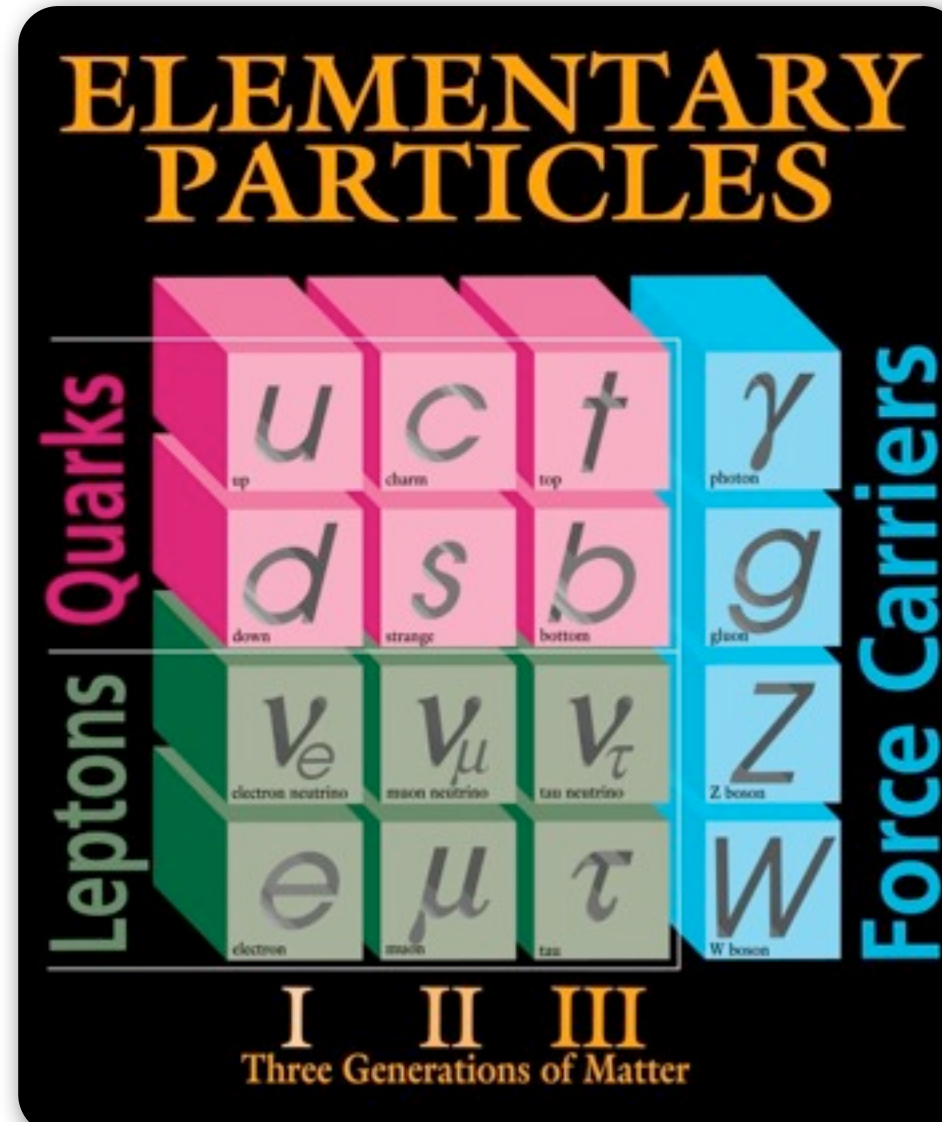
Karlsruhe, December 20, 2011

ULRICH HUSEMANN
INSTITUT FÜR EXPERIMENTELLE KERNPHYSIK, KARLSRUHE INSTITUTE OF TECHNOLOGY

The Standard Model of Particle Physics



- Very economic model of nature at the fundamental level
  - 12 matter + 12 antimatter particles (fermions)
  - 3 forces (carriers: bosons)
- Experimental confirmation to incredible precision in the last 30+ years, very little (persistent) tension up to now
- Last missing ingredient: the Higgs boson



[Fermilab Media Service]

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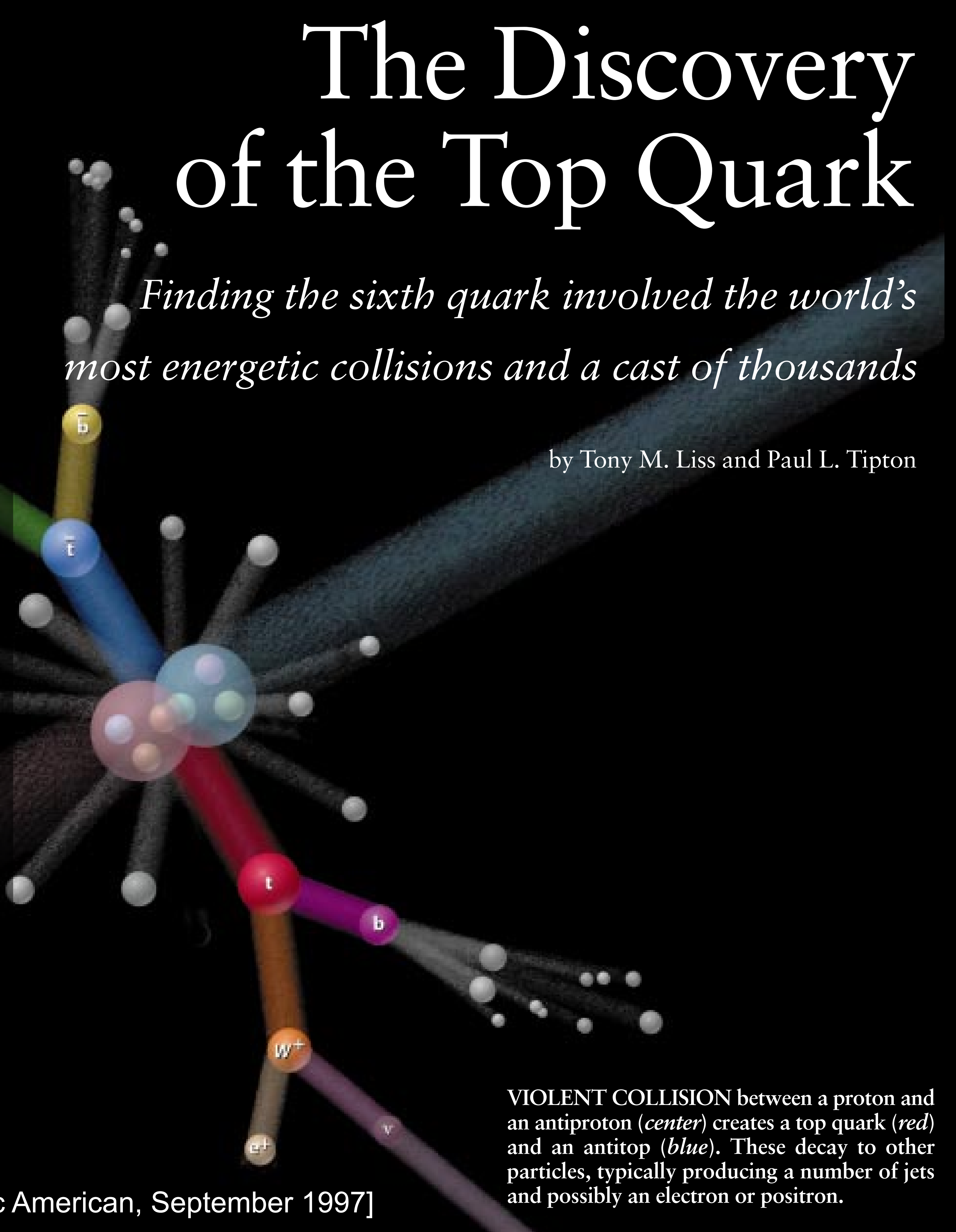
A Brief History of the Top Quark

- 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

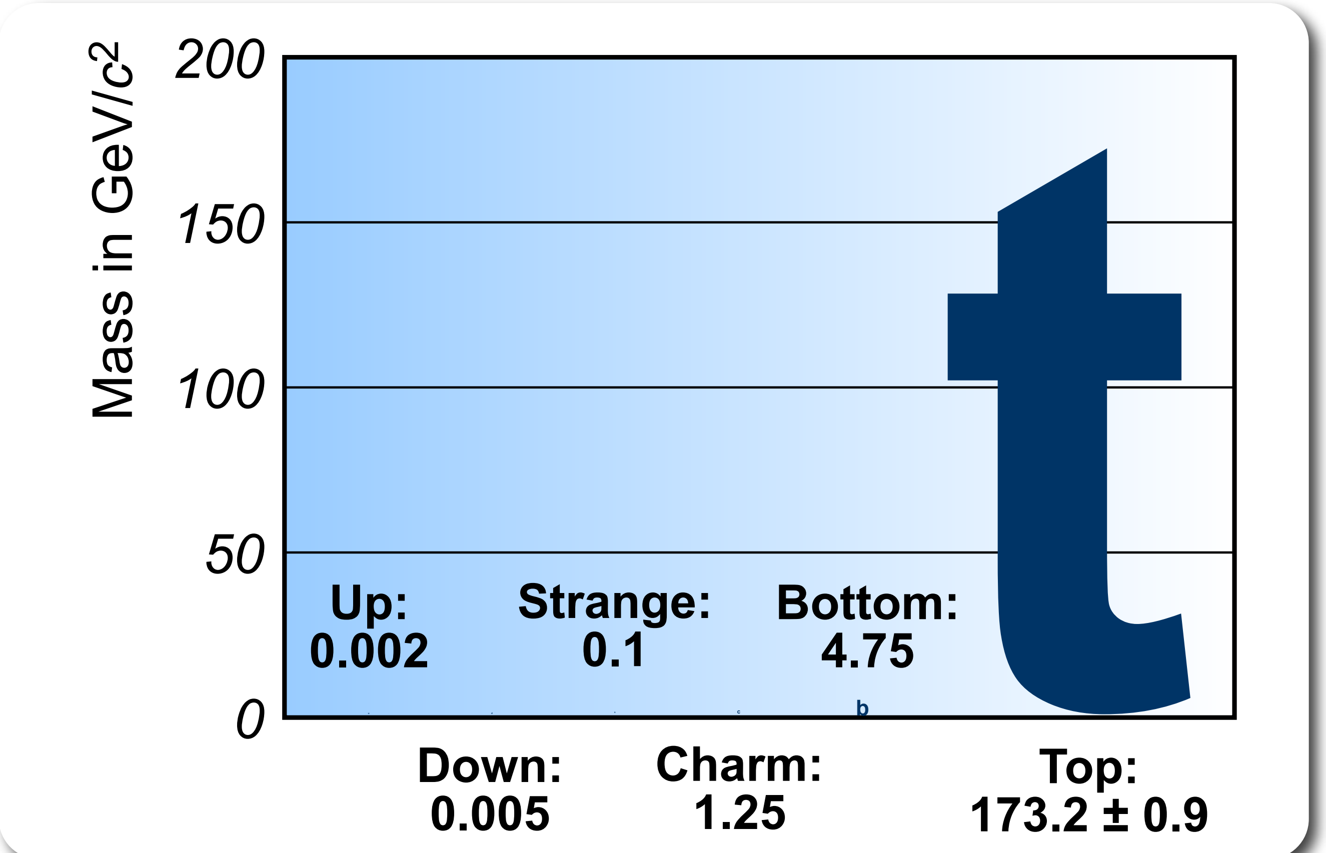
Finding the sixth quark involved the world’s most energetic collisions and a cast of thousands

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



event display: candidate for a top pair decay at CDF (09/24/92)

[CDF]

- Large mass: $m_t \approx 173$ GeV ($40 \times m_b$, approx. mass of a gold atom)
- Mass close to scale of electroweak symmetry breaking (EWSB)
  → Yukawa coupling $f \approx 1$:
  $$\mathcal{L}_{Y,t} = f \frac{v}{\sqrt{2}} \bar{t}_L t_R \equiv m_t \bar{t}_L t_R$$
  → important role in models that explain EWSB
- Top is the only „free" quark: life time much smaller than hadronization time
  $$\tau = \frac{1}{\Gamma} \approx (1.5\,\mathrm{GeV})^{-1} < \frac{1}{\Lambda_{\mathrm{QCD}}} \approx (0.2\,\mathrm{GeV})^{-1}$$
  → No bound states
  → Spin transfered to decay products

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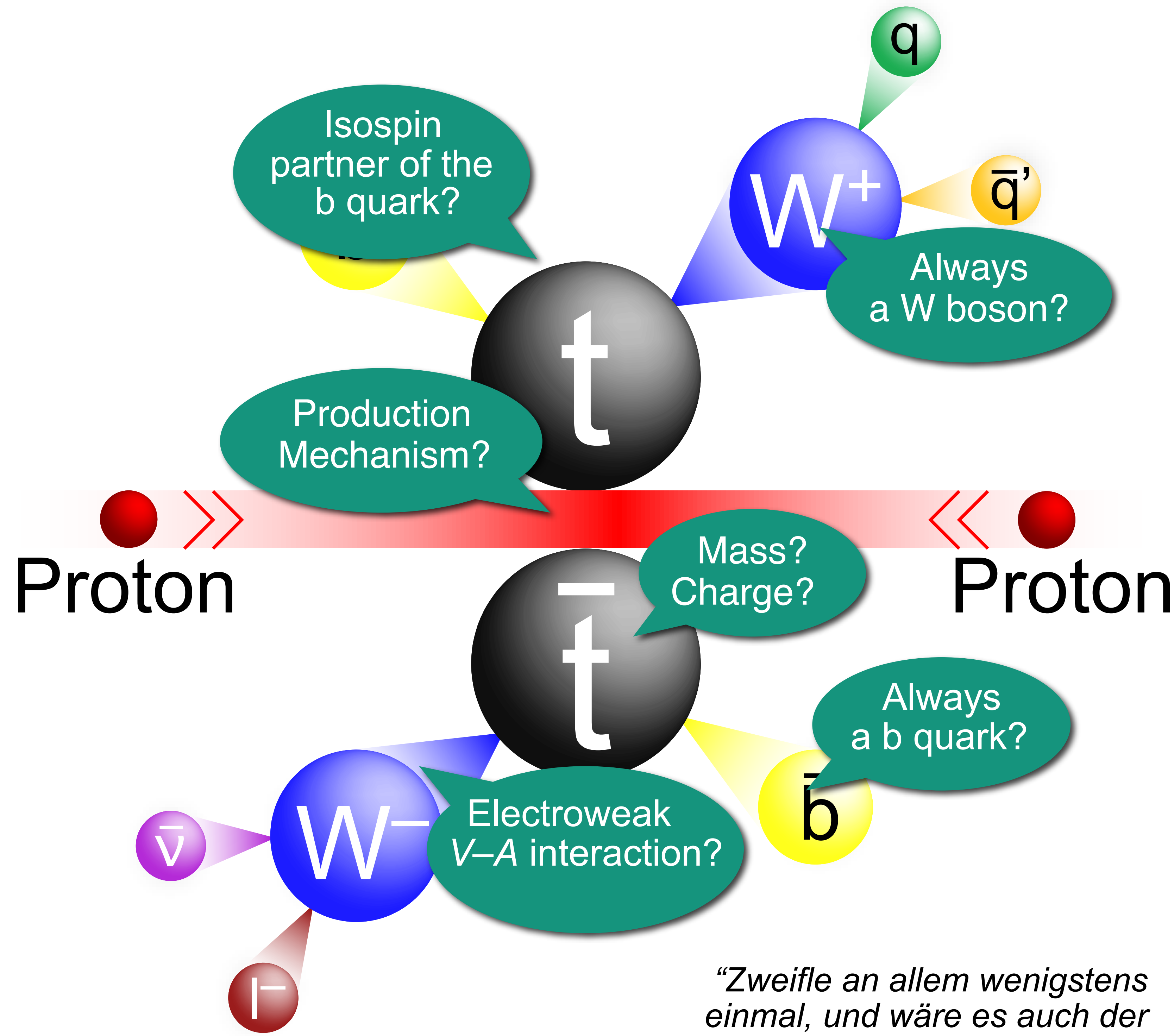
Questions in Top Quarks Physics



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

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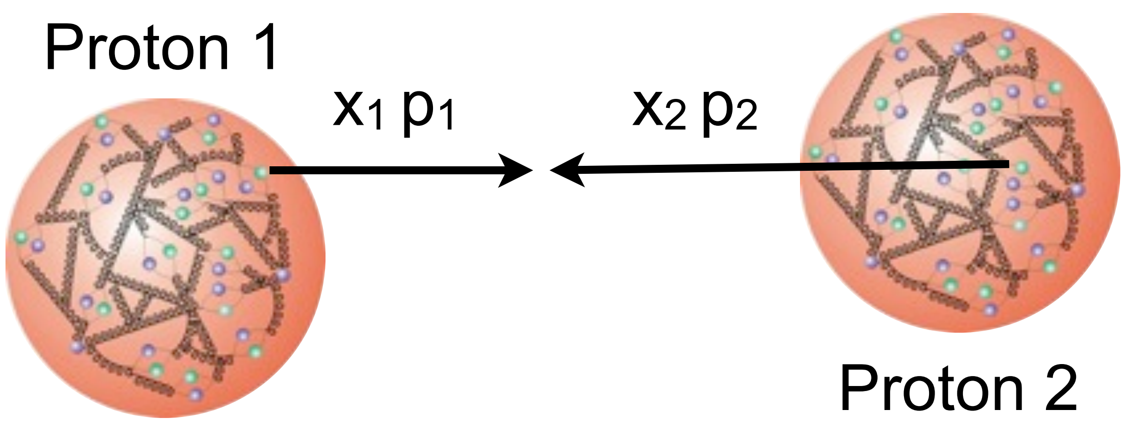
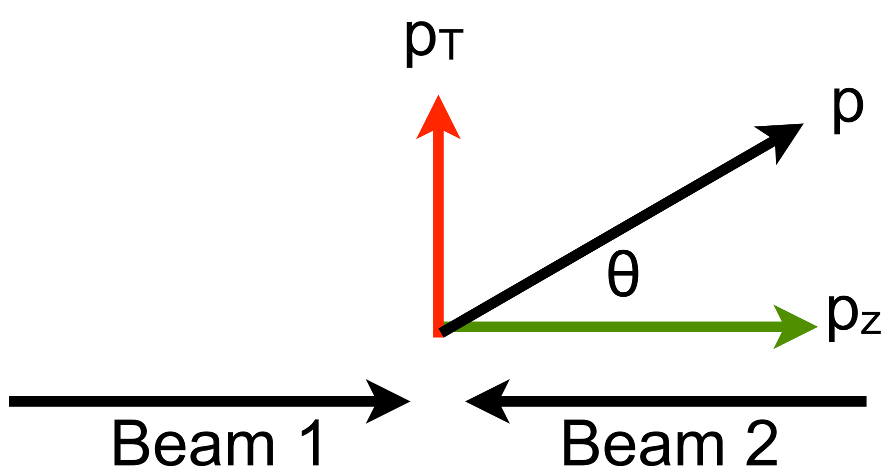
Reminder: Hadron Collider Kinematics



$$\hat{E}^2_{CMS} = x_1\, x_2\, E^2_{CMS}$$



- Hadron collider: collisions of "broadband" parton beams
  - Longitudinal momentum fractions x_i unknown → partonic center of mass frame unknown
  - Consequence: use only Lorentz invariant transverse quantities, e.g. transverse momentum

$$p_T = \sqrt{p_x^2 + p_y^2} = p \sin\theta$$

- Indirect reconstruction of "invisible particles" (e. g. neutrinos): missing transverse energy (MET) from transverse momentum balance
- Instead of polar angle: use pseudorapidity

$$\eta = -\ln\tan(\theta/2)$$

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Analyzing Top Quark Events

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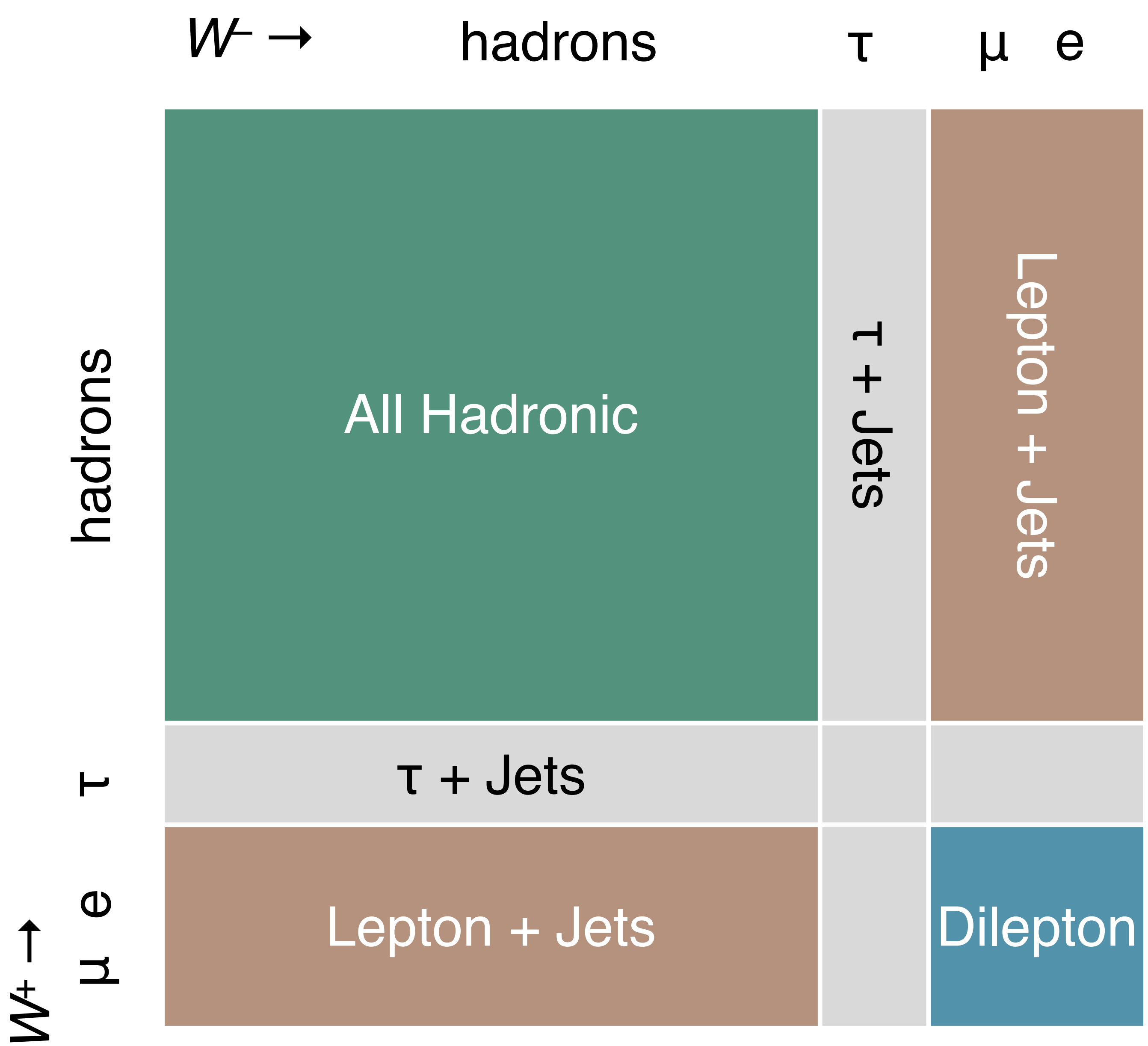

- Top decay in the standard model: $B(t \to Wb) \approx 100\%$
- Challenging signature: multiple leptons & jets, MET
- $t\bar{t}$ decay signatures characterized by W decays:
  - All-Hadronic: 45% of all decays, large QCD background
  - Lepton+Jets: 30% of all decays, moderate backgrounds
  - Dilepton: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

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Your Program for Tonight

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From the Tevatron to the LHC

↓

Top Quark Pair Production

↓

What's Next in Top Physics?

↓

The Advent of the Higgs?

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From the Tevatron to the LHC

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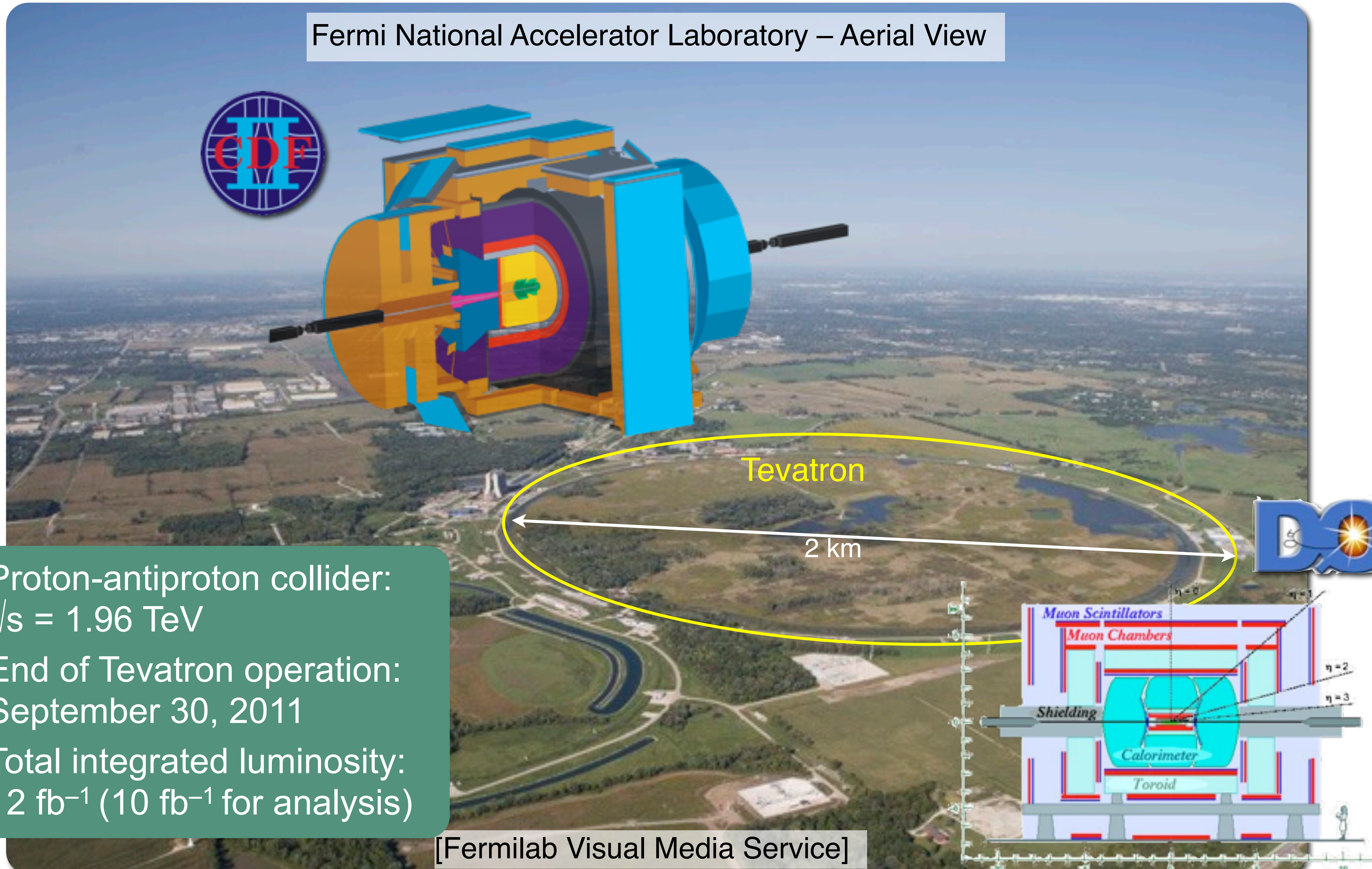
Tevatron Run II: 2001–2011



- 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)

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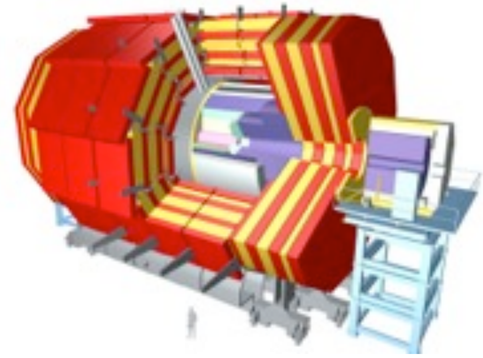
LHC – the Large Hadr

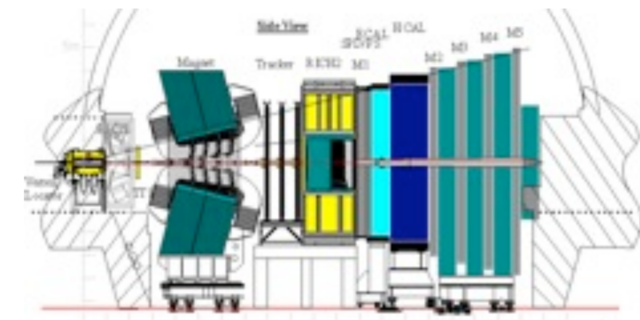
Lake Geneva

LHC Accelerator:
proton-proton and
lead-lead collisions

CMS Experiment:
multi-purpose experiment



LHCb Experiment:
CP violation and B physics



CERN accelerator complex,
about 100 m under ground
LHC circumference: ~27 km

ALICE Experiment:
heavy ion physics

ATLAS Experiment:
multi-purpose experiment

CMS – Compact Muon Solenoid

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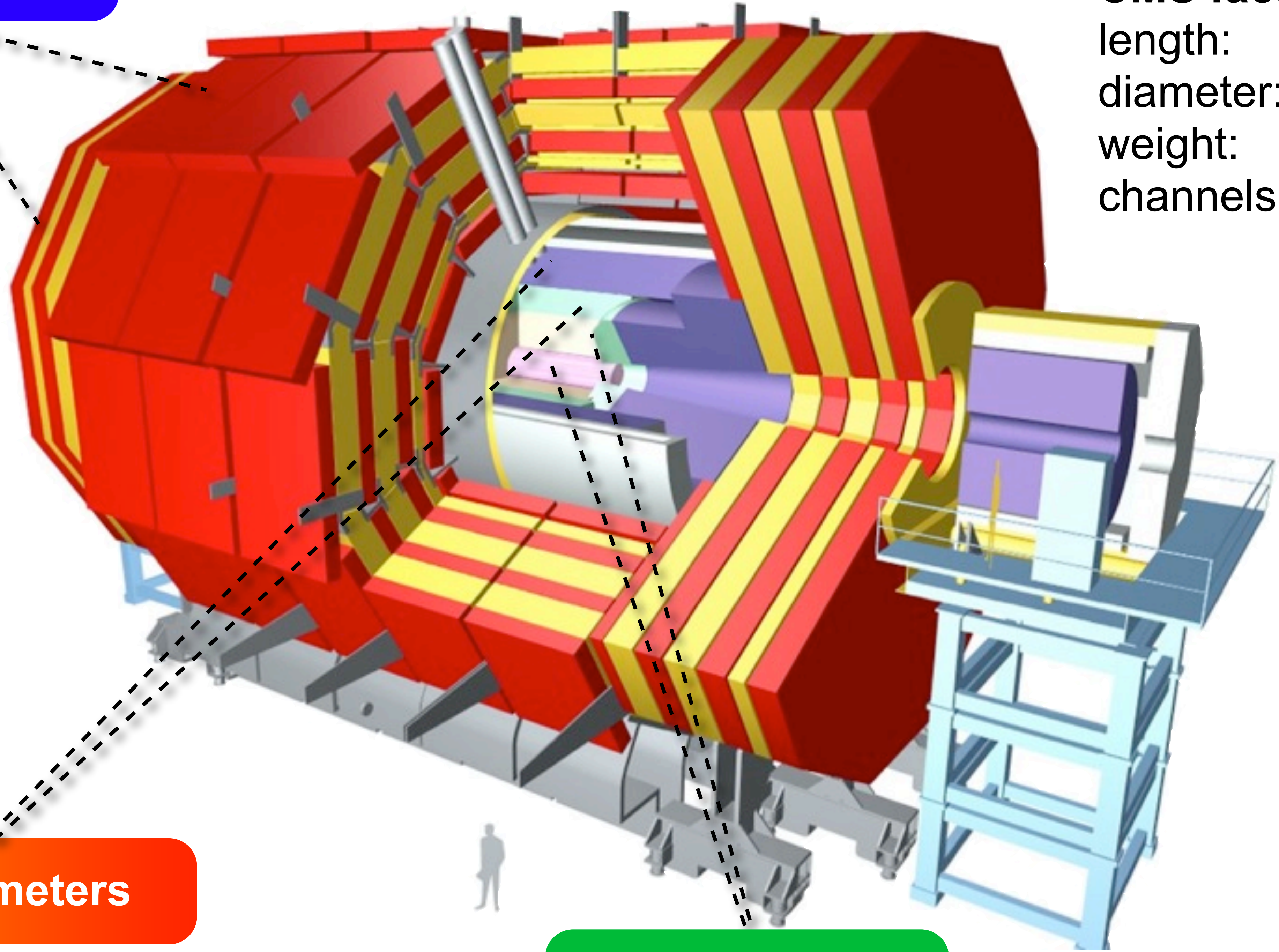

CMS fact sheet

length: 21 m
diameter: 15 m
weight: 14 ktons
channels: 80 M

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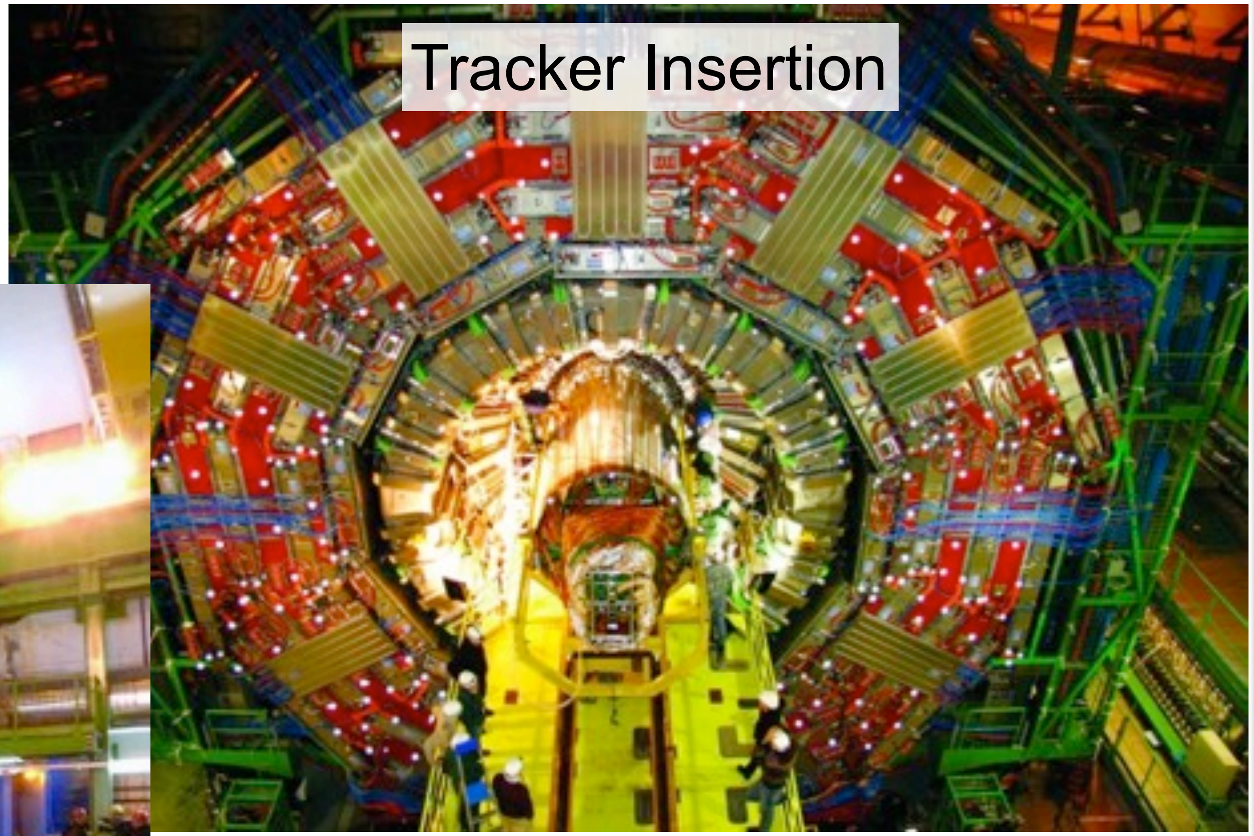
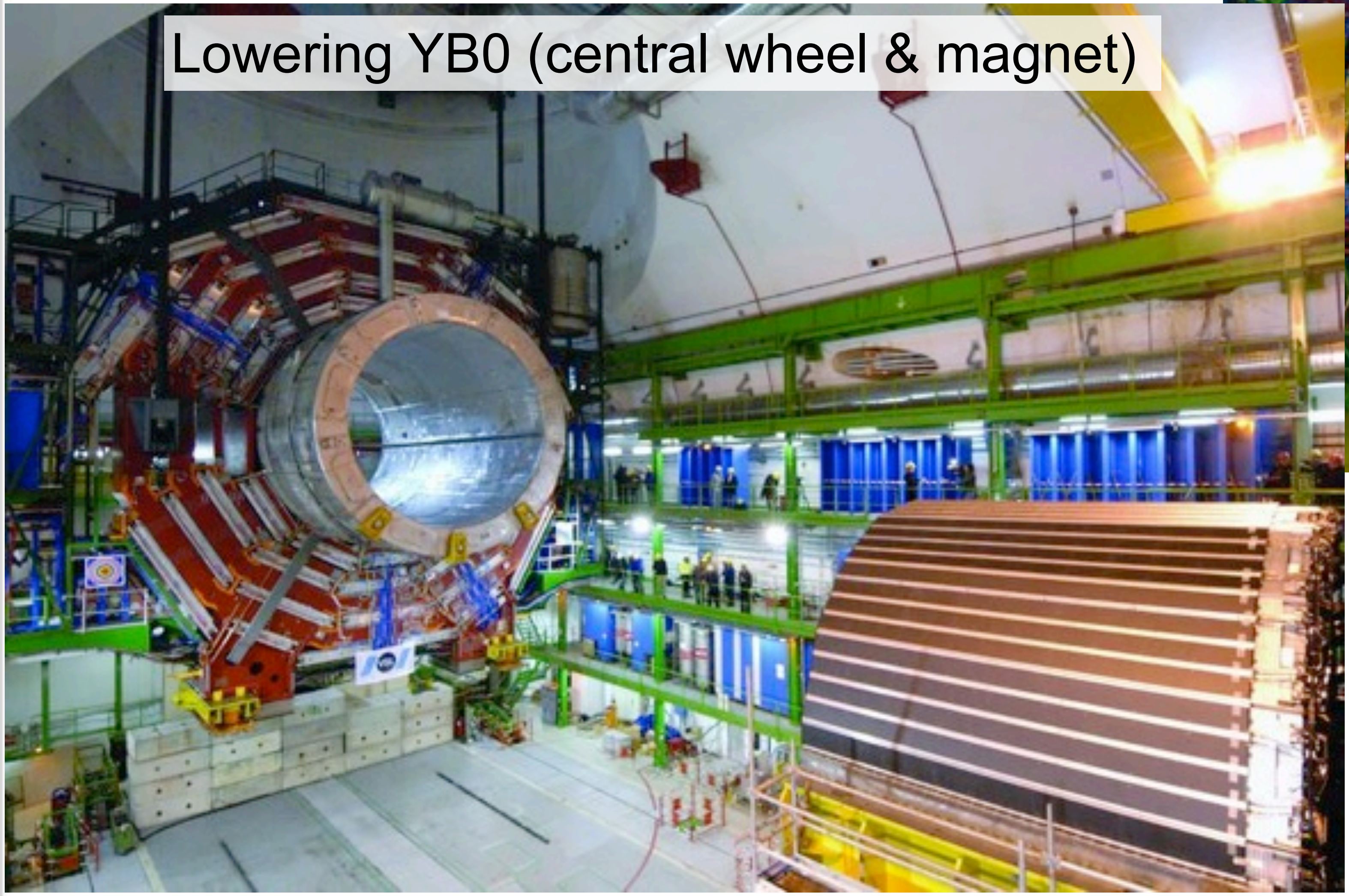
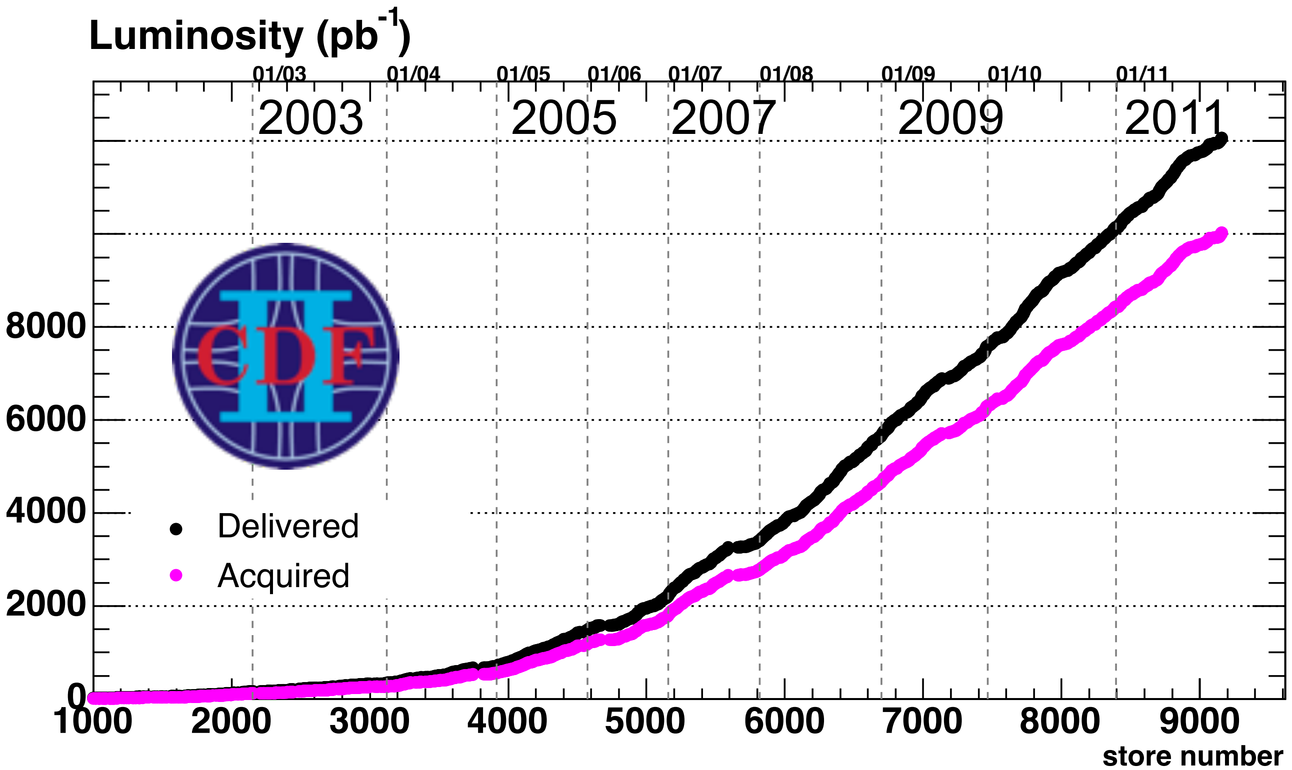
CMS Photo Gallery


Tracker Insertion


Lowering YB0 (central wheel & magnet)

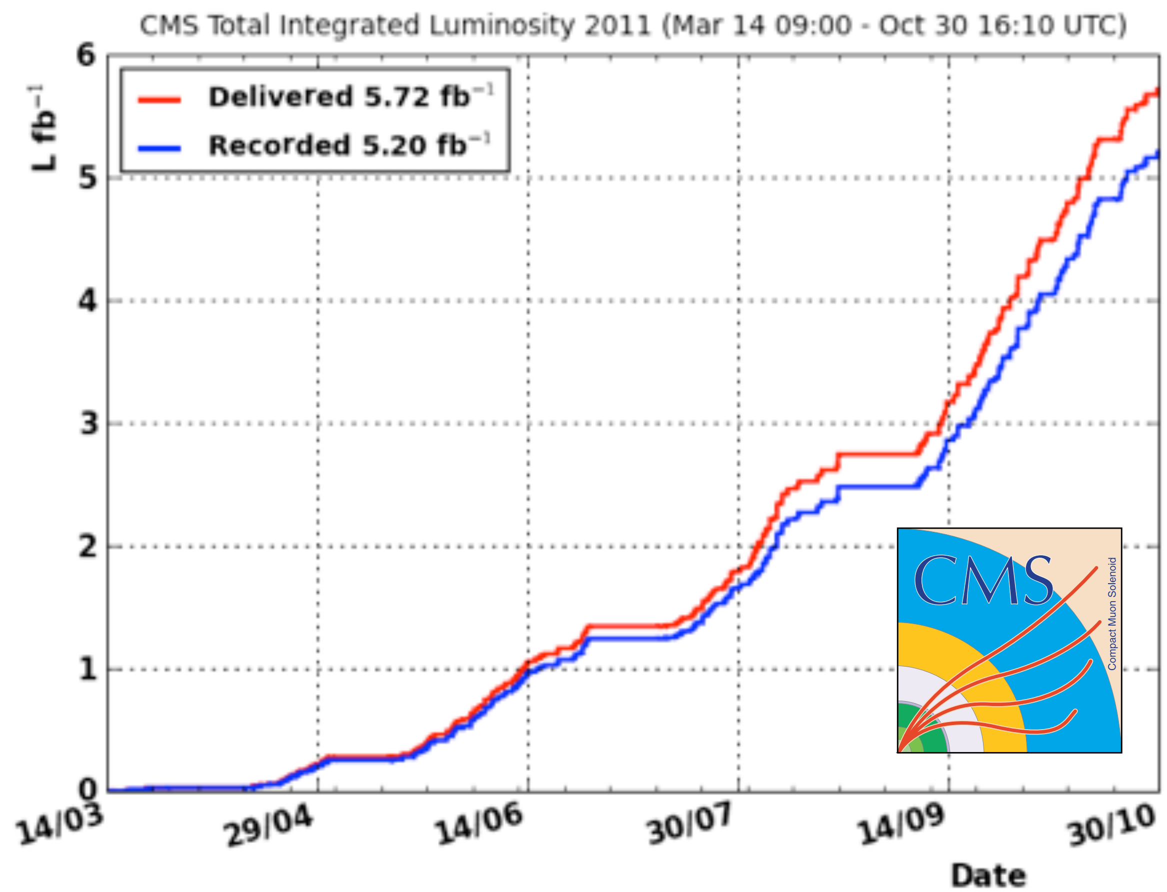

Off-detector Electronics

Luminosities: Tevatron vs. LHC



LHC 2010/2011: 7 TeV

- Record instantaneous lumi: 3.5×10^{33} cm^{-2} s^{-1}
- About 5 fb^{-1} (= 800,000 top pairs) per experiment
- Exceeding expectations



Tevatron Run II 2001–2011

- Record instantaneous lumi: 4.4×10^{32} cm^{-2} s^{-1}
- About 10 fb^{-1} (= 70,000 top pairs) per experiment
- Long commissioning phase, then smooth sailing

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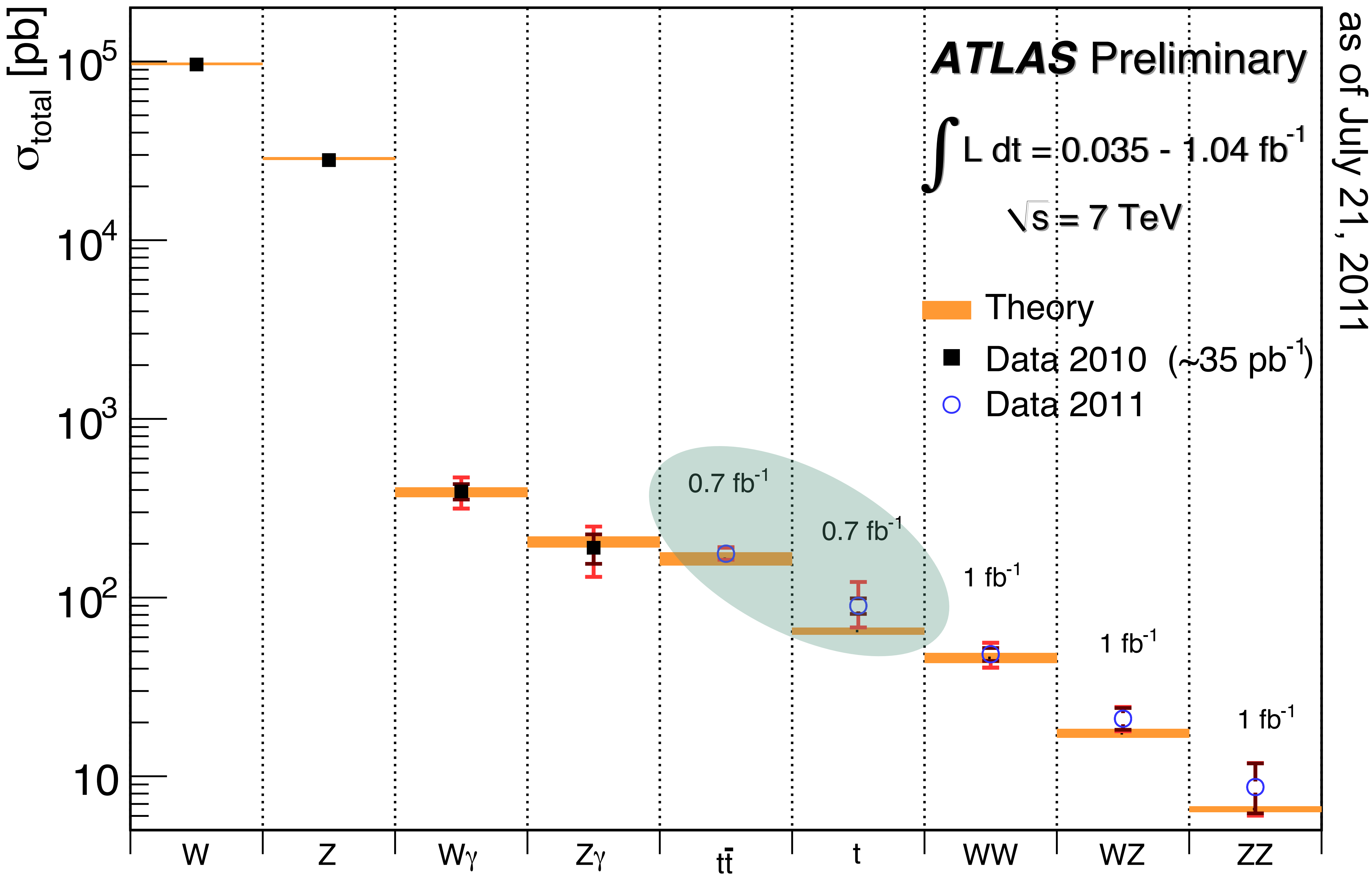
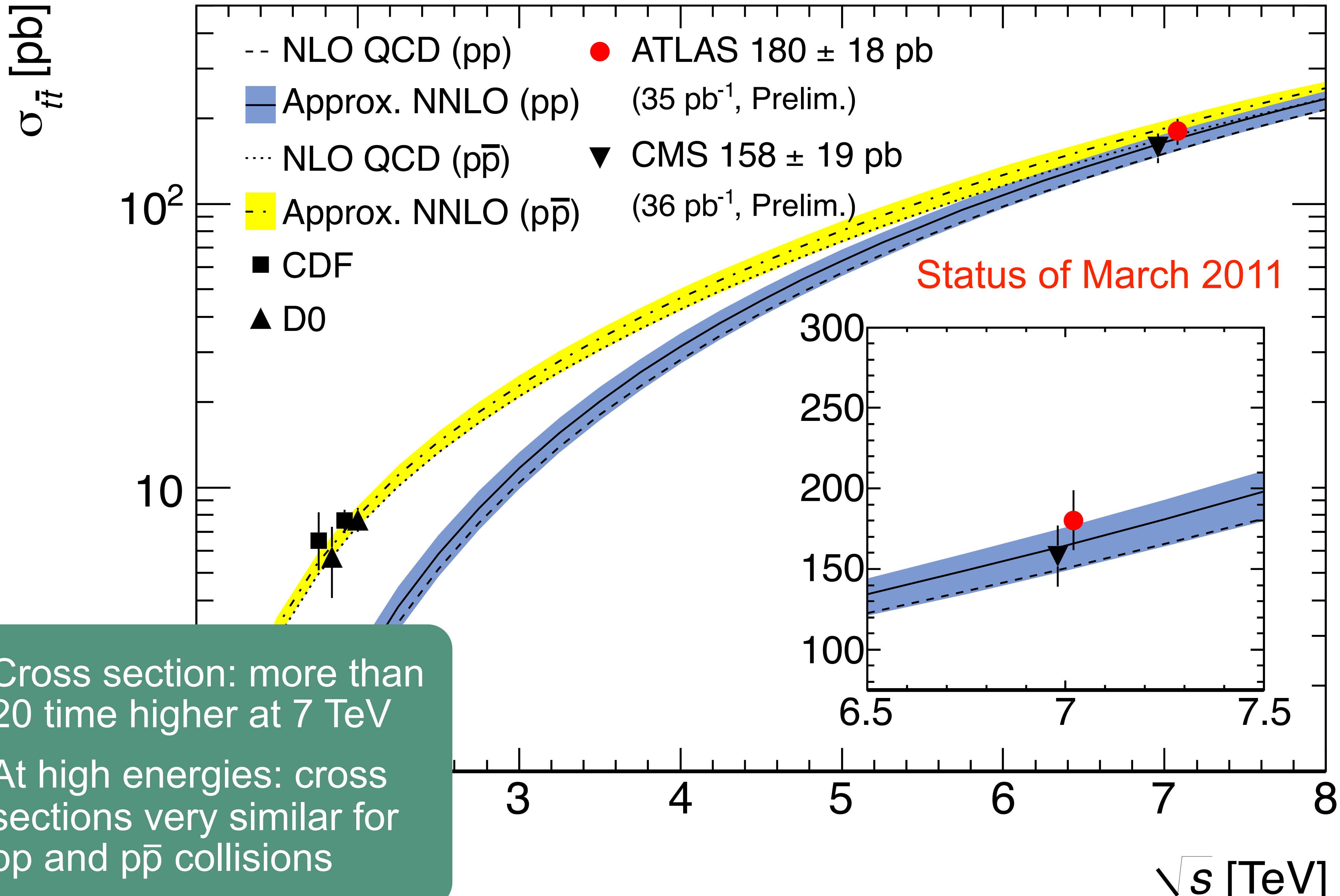
W, Z and Top at the LHC



[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots]

Top Quark Pair Production

Top Pair Production: From Tevatron to the LHC



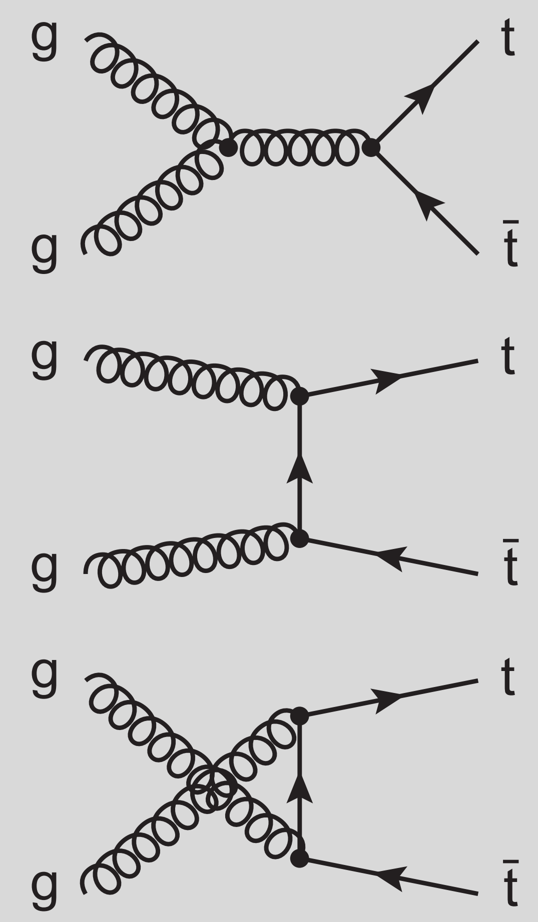
- Cross section: more than 20 time higher at 7 TeV
- At high energies: cross sections very similar for pp and $p\bar{p}$ collisions

[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-040/]

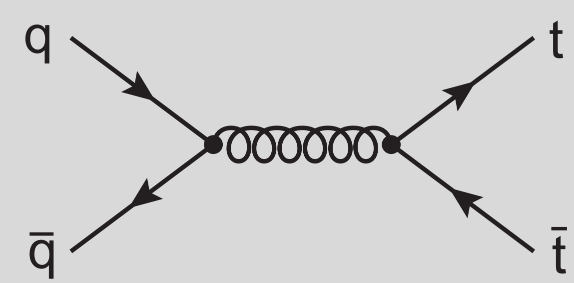
Precision Top Cross Section Measurement

- Top pair production cross section at current LHC energies:
  - At the LHC: top is becoming the new “standard candle” of particle physics – abundant and precisely known
  - Theory: “approximate” NNLO calculations → uncertainties below 10%
- Example: ATLAS measurement 2011
  - Decay channel: muon/electron + jets
  - Extract cross section from event kinematics
  - Multivariate discriminant: projective likelihood estimator build from few well-modeled kinematic variables
  - Profile likelihood template fit: constrain major systematic uncertainties in situ

Gluon-Gluon Fusion (LHC: 80%)



Quark-Antiquark Annihilation (LHC: 20%)



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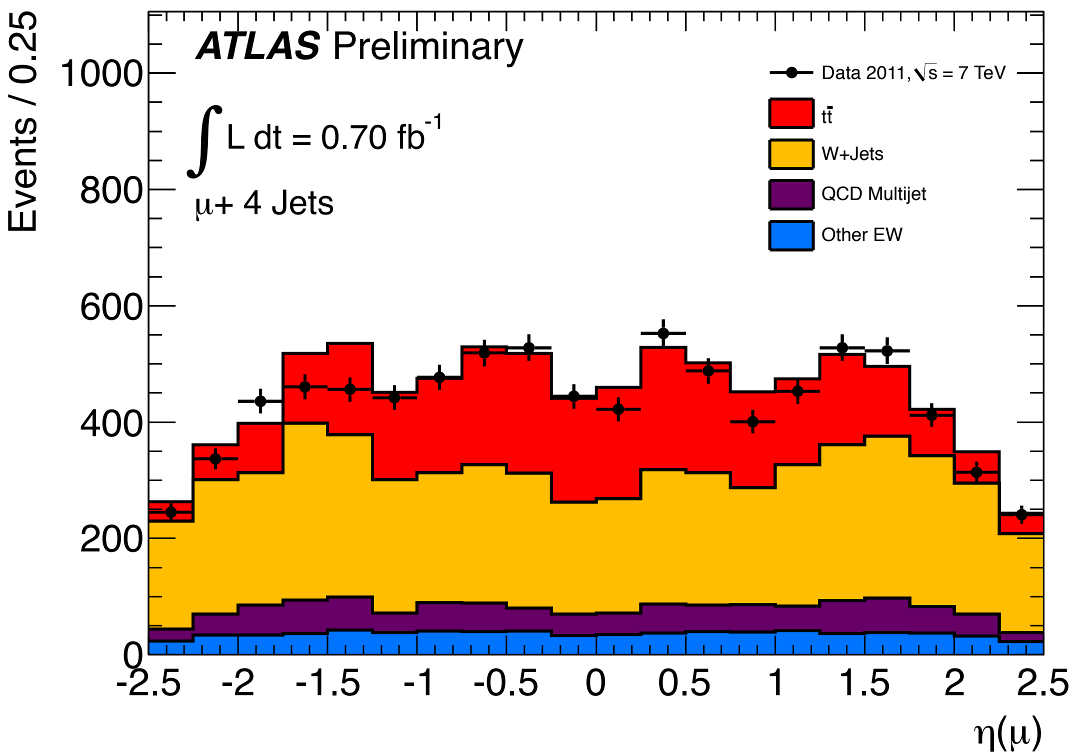
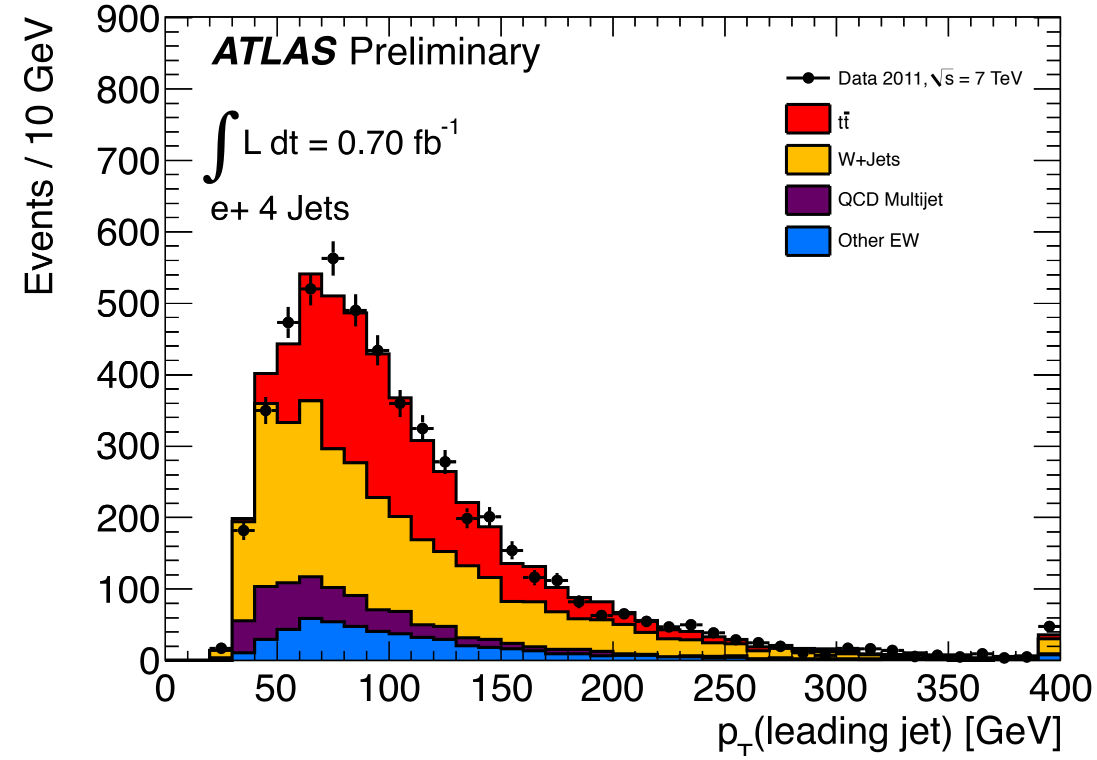
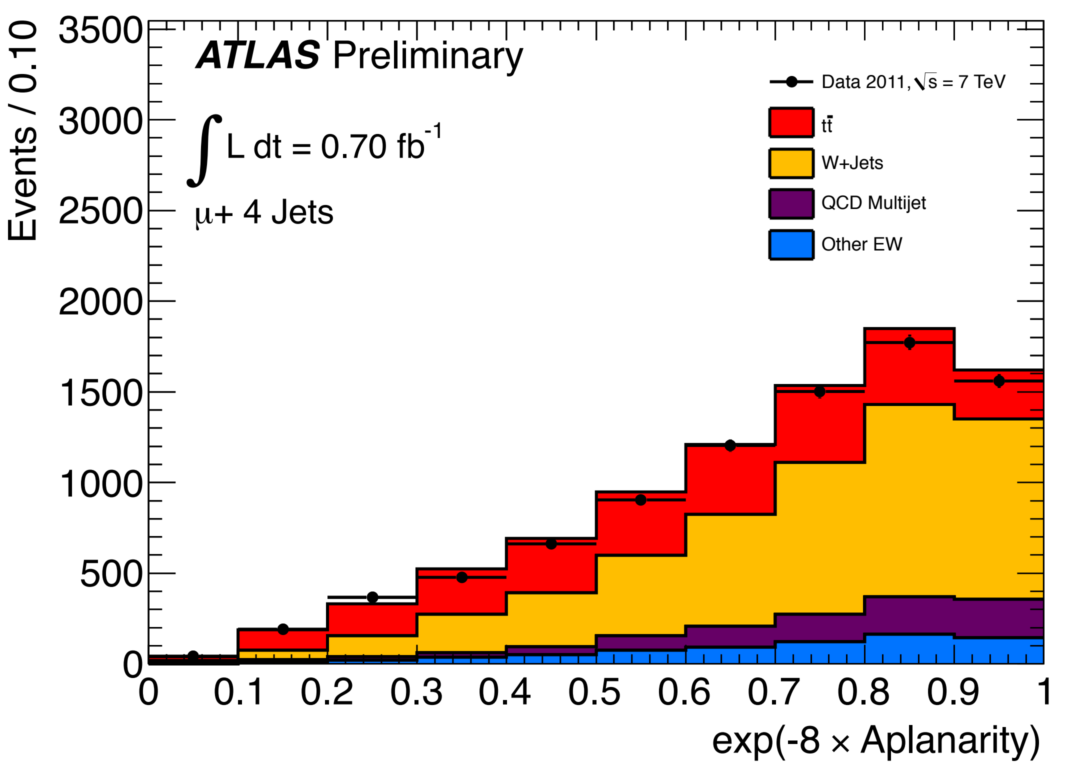
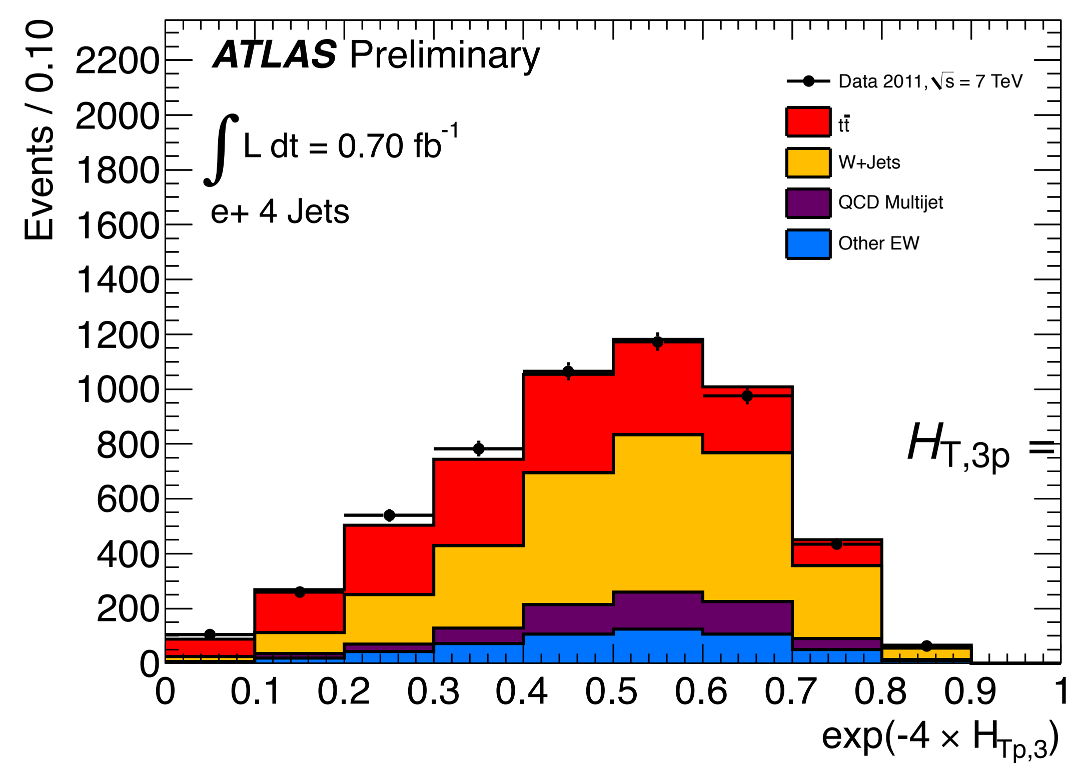
Top Cross Section: Input Variables









$$H_{T,3p} = \frac{\sum_{i=3}^{max(N_{jets},4)} |p_{T,i}^2|}{\sum_{j=1}^{N_{objects}} |p_{z,j}|}$$

[ATLAS-CONF-2011-121]

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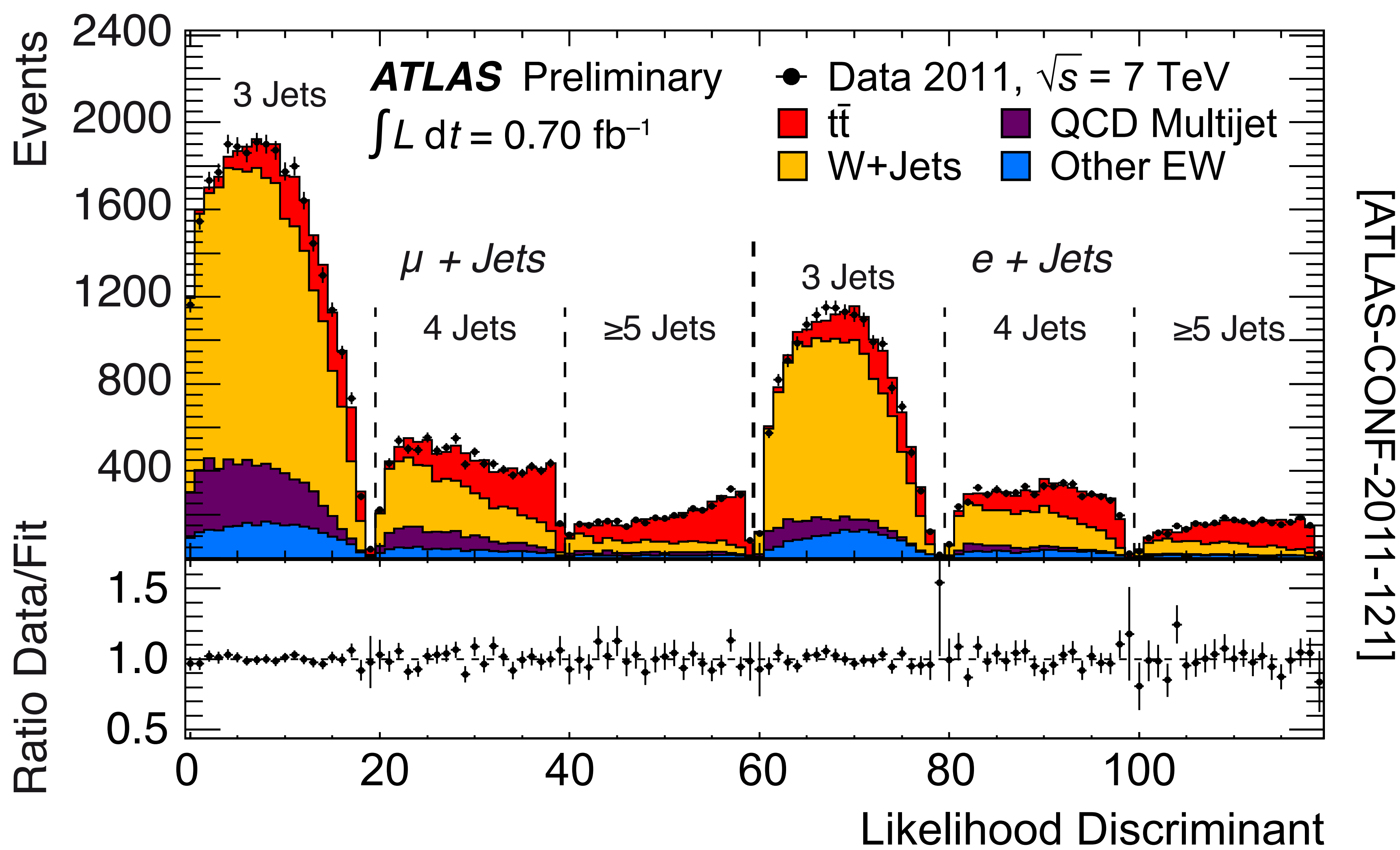
Top Cross Section: Result

- Final fit to discriminant in six regions (muon/electron+ 3,4,≥5 jets)



- Result: $\sigma_{t\bar{t}} = 179.0^{+9.8}_{-9.7}$ (stat.+syst.) $\pm$ 6.6 (lumi) pb
  - Most precise top cross section at the LHC → 6.6% relative uncertainty
  - Good agreement with theory (QCD at approx. NNLO): $\sigma_{t\bar{t}} = 165^{+11}_{-16}$ pb

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What's Next in Top Physics?

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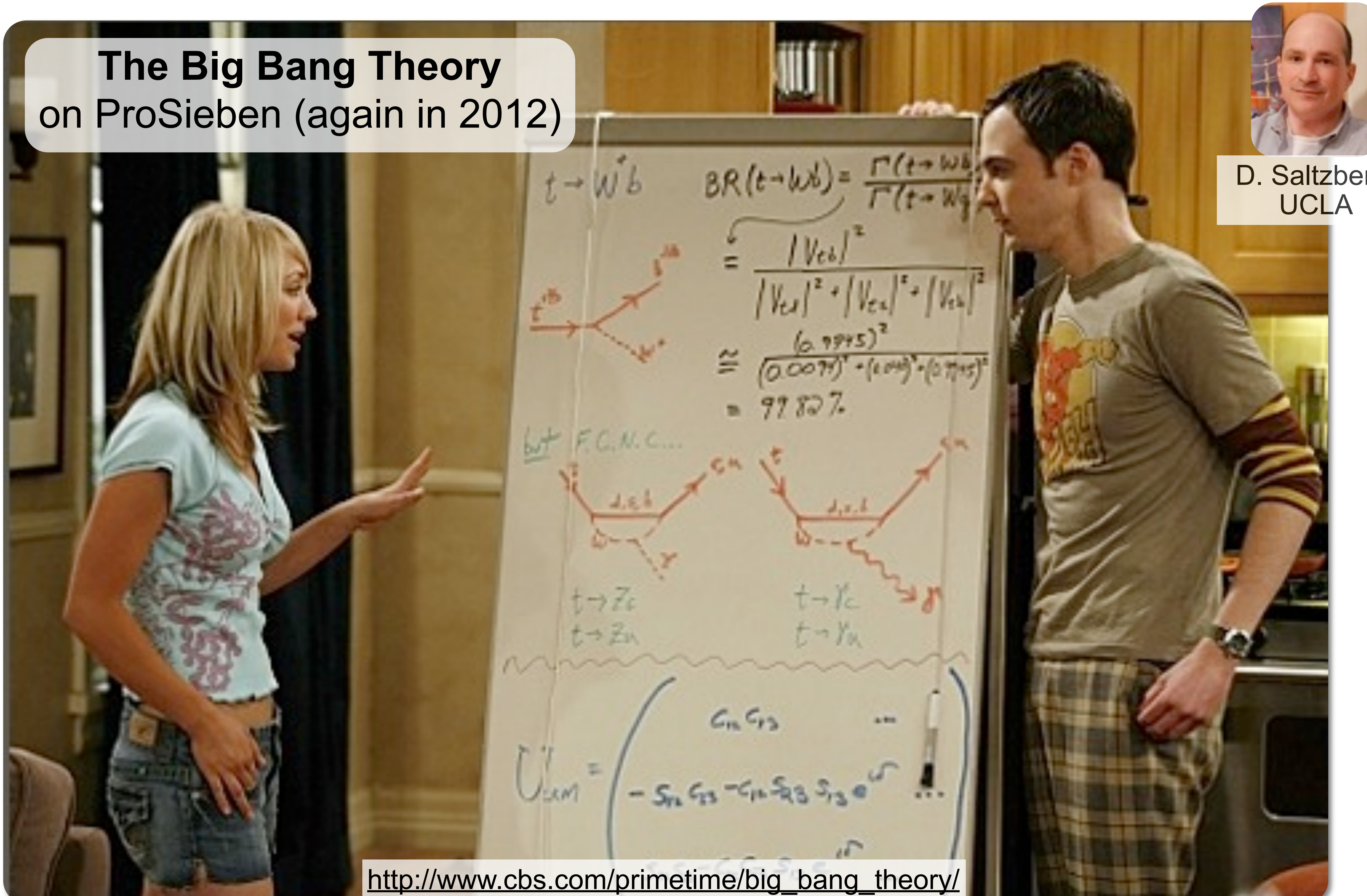
Top Physics Makes Prime Time!



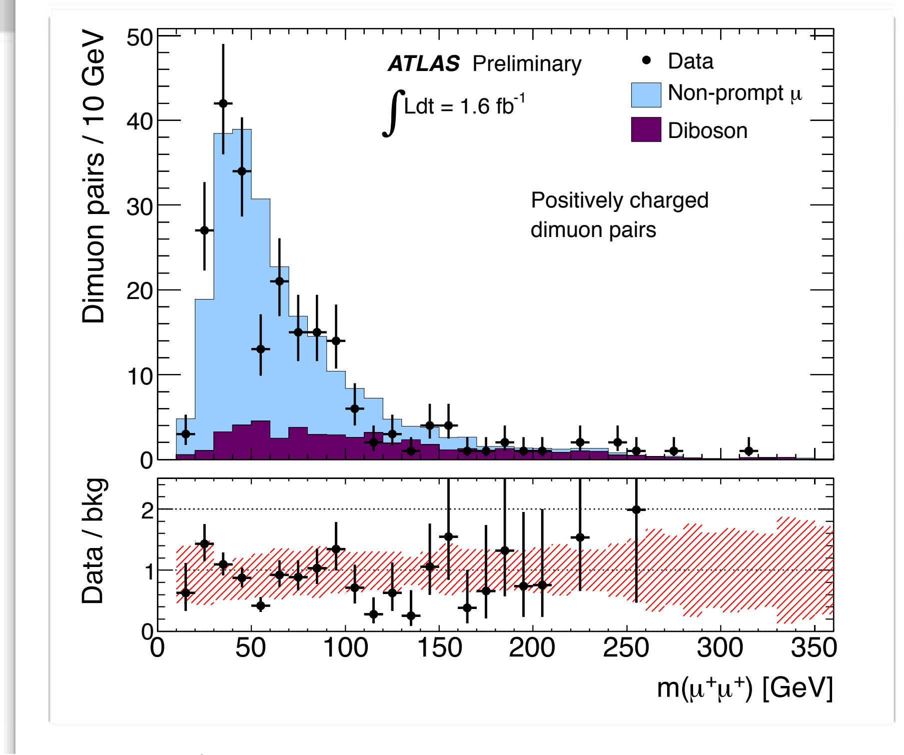
The Big Bang Theory
on ProSieben (again in 2012)

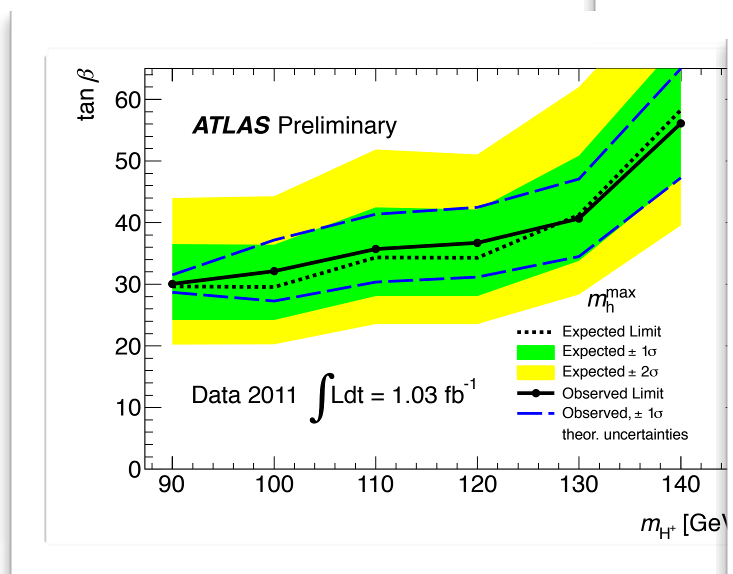
http://www.cbs.com/primetime/big_bang_theory/

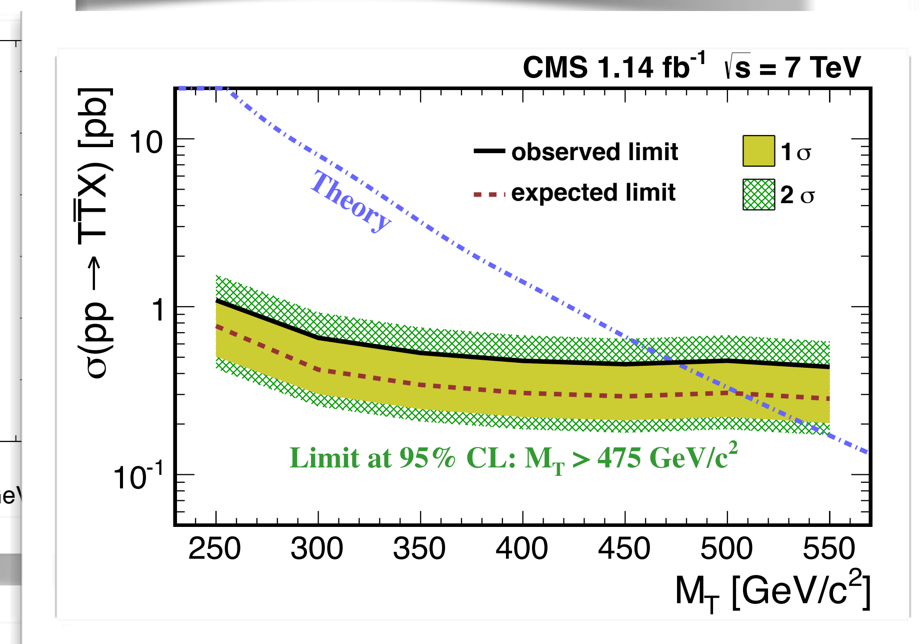
D. Saltzberg, UCLA

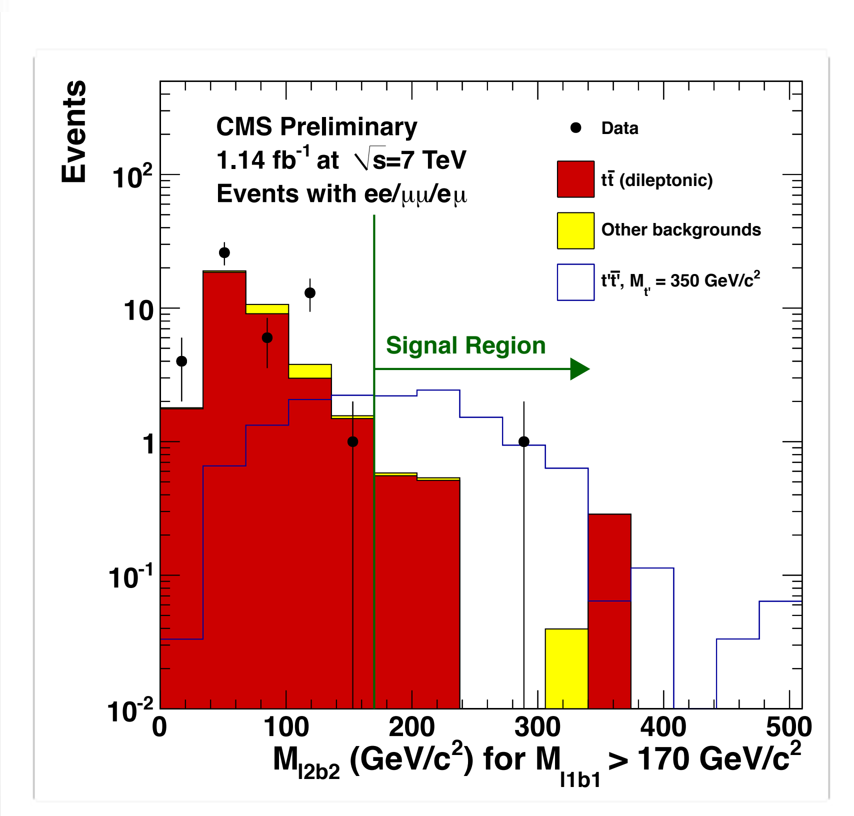
Many Ways to go Beyond Top

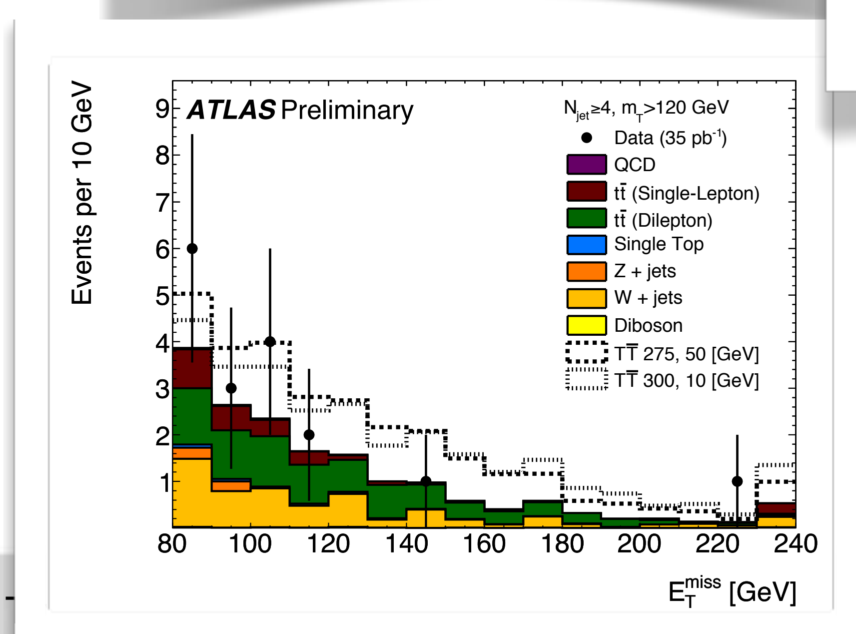
- Searches at Tevatron & LHC include:
  - Heavy Z' or KK gluon decaying to $t\bar{t}$
  - Heavy tops T decaying to $t\bar{t}$+X
  - Anomalous missing transverse momentum in top events
  - Like-sign tops
  - Charged Higgs in $t \rightarrow H^+b$
  - Fourth generation $t' \rightarrow bW$

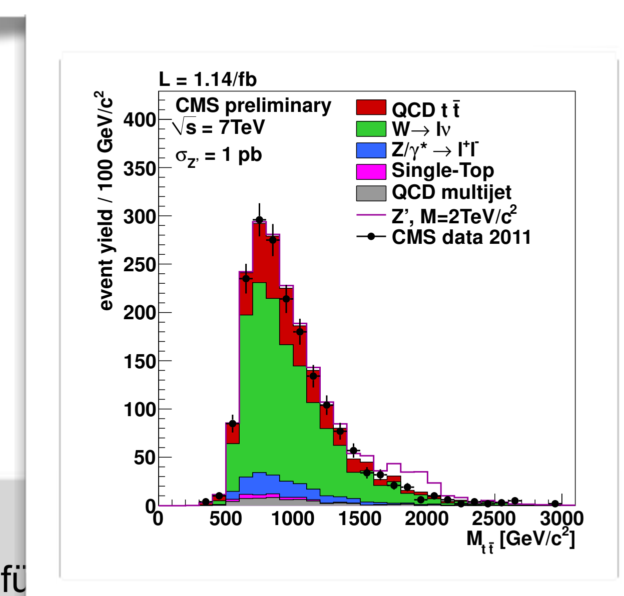












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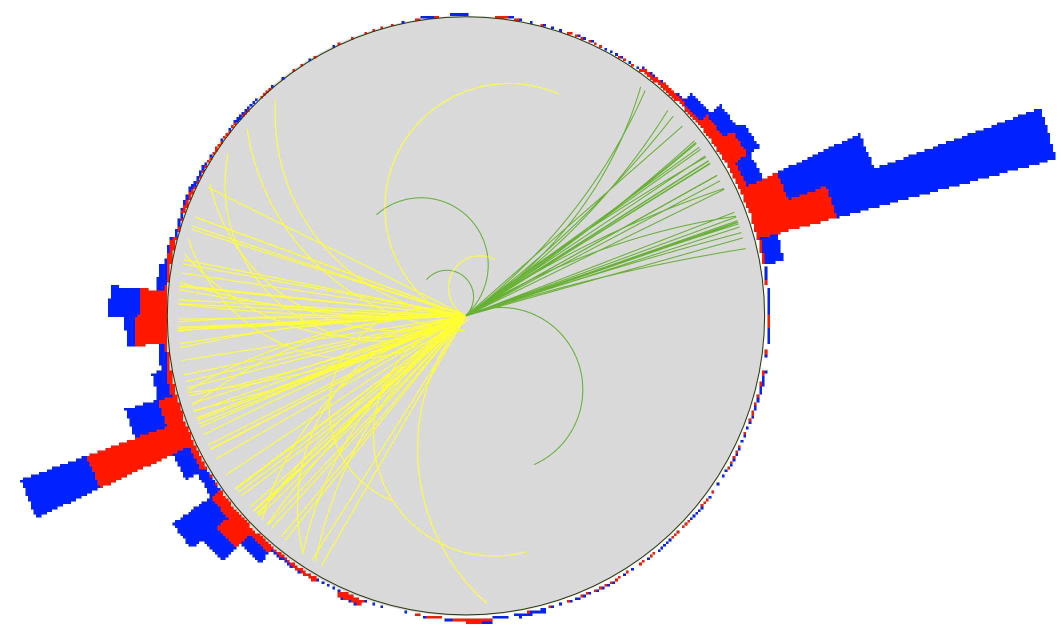
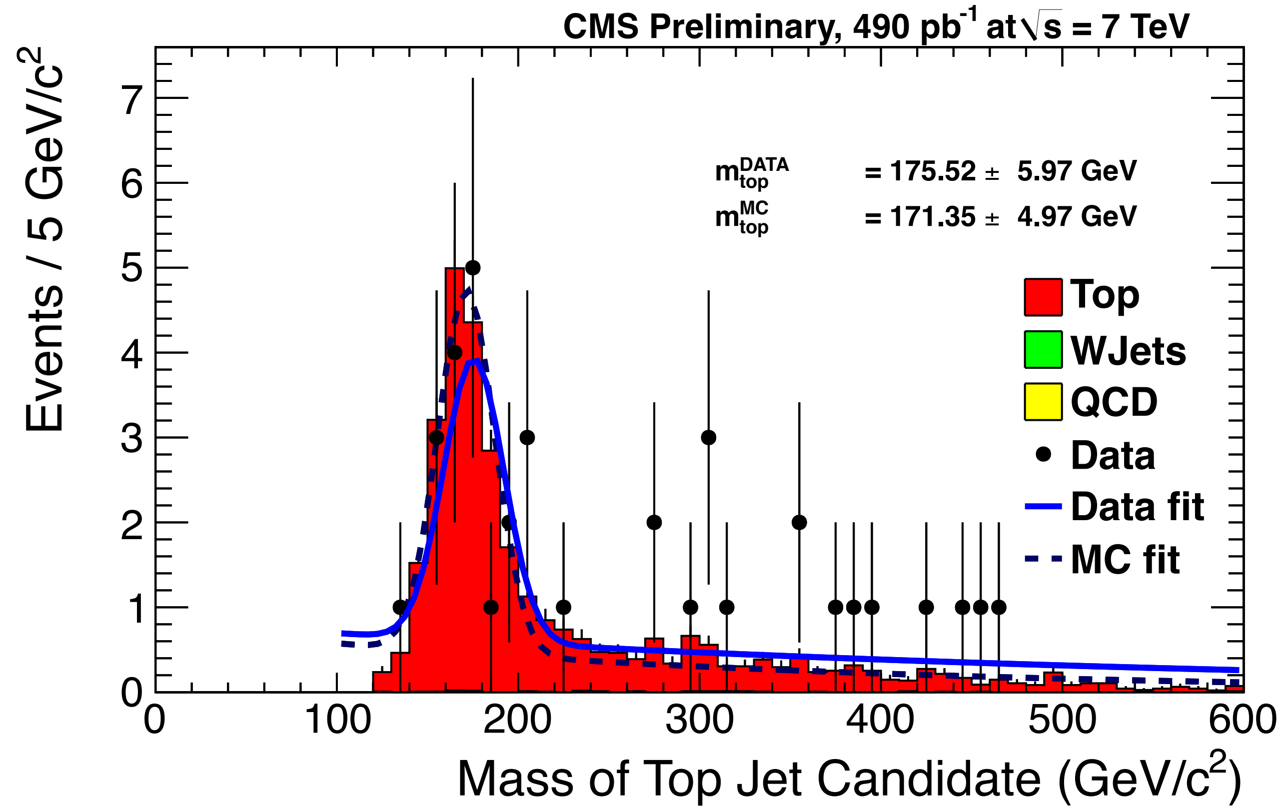
Boosted Tops

- At LHC energies: top may have significant Lorentz boost
  - Decay products are collimated
  - Hadronic top decays
    $t \rightarrow Wb \rightarrow qq'b$
    can have three overlapping jets
- New algorithms available to deal with such “fat jets”
  - Reconstruct jets with sequential recombination algorithms (e.g. k_T)
  - Resolve jet-substructure
    → efficient top reconstruction and tagging at large boost
- Successfully applied to e.g.
  - Search for $t\bar{t}$ resonances
  - Higgs search: $H \rightarrow b\bar{b}$

Event Display: All-Hadronic Top Decay





[https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11006]

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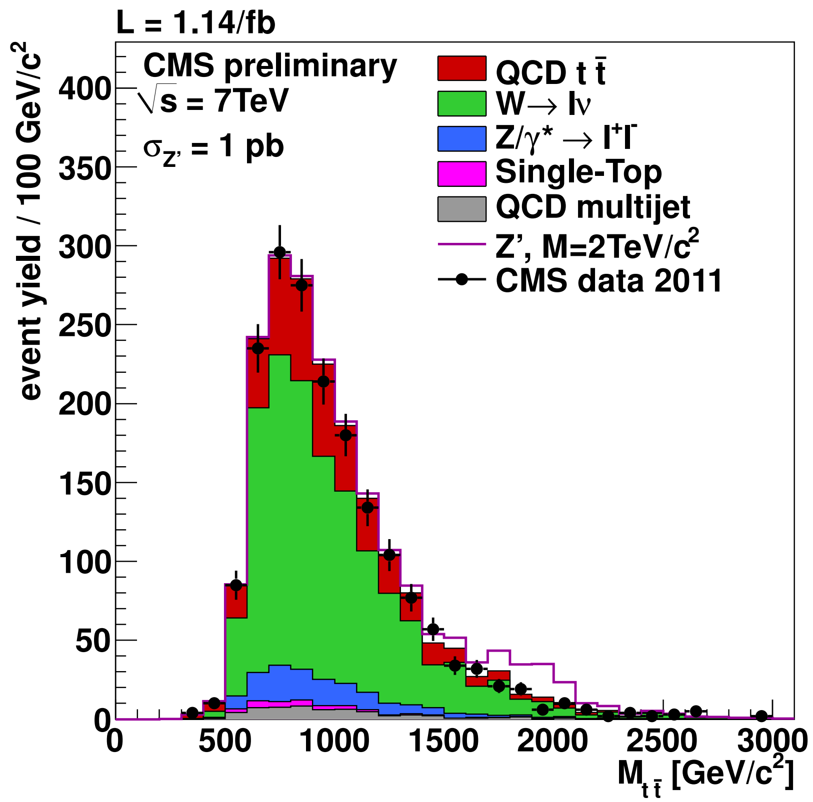
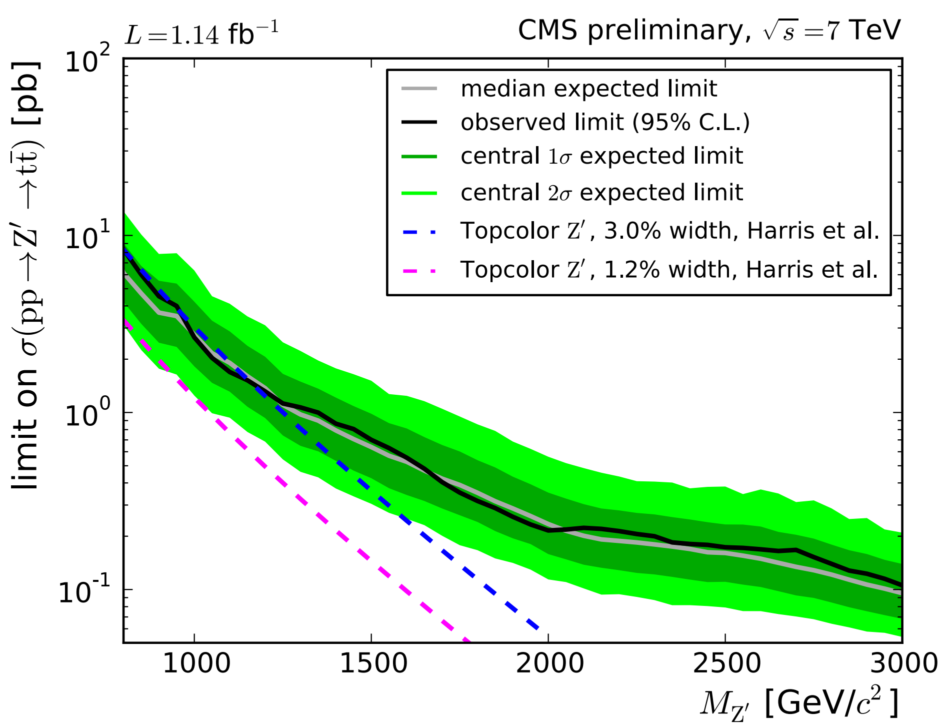
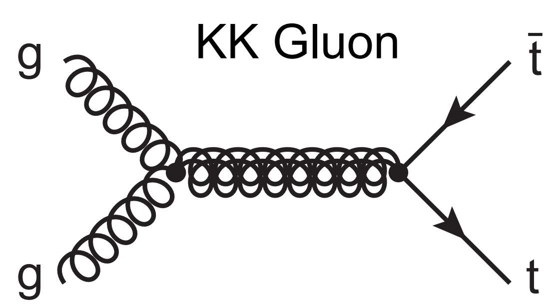
Heavy Narrow Resonances Decaying to Top

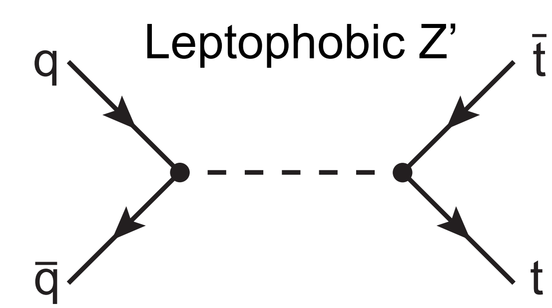
[https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11055]





- Heavy resonance models
  - Generic model at Tevatron and LHC: leptophobic Z' → narrow resonance in $t\bar{t}$ invariant mass spectrum
  - Randall-Sundrum model: Kaluza-Klein gluons decaying to $t\bar{t}$ → broad resonance





- CMS search (Summer 2011)
  - Reconstruction of boosted tops in μ+jets: 8–12% resolution in $M_{t\bar{t}}$ above 1 TeV
  - Narrow Z' with masses above 1.35 TeV: sub-picobarn limits on production cross section for pp → Z' → $t\bar{t}$

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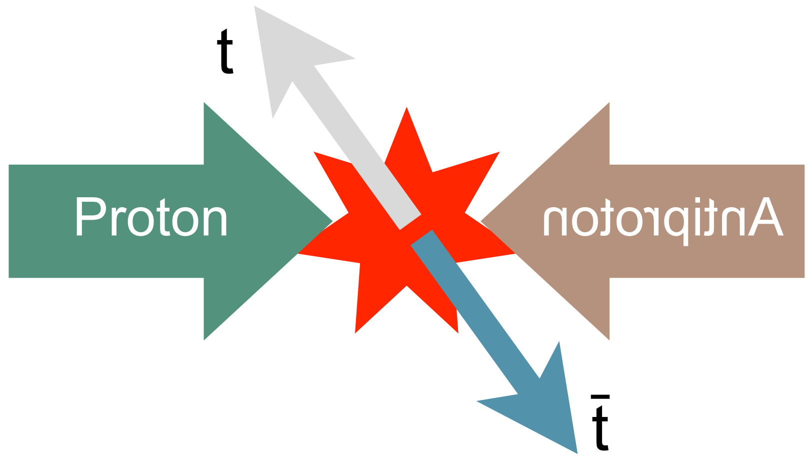
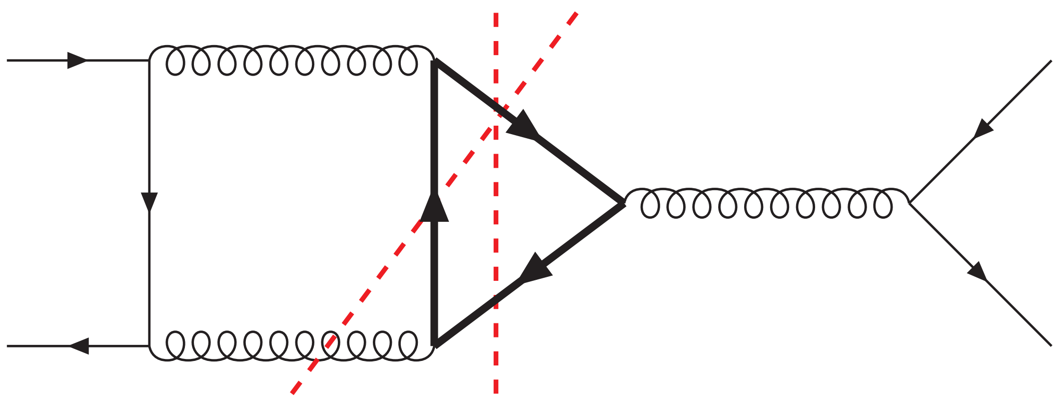
Asymmetries in Top Production

- Tevatron: top preferably produced in direction of the incoming p or p̄?
- Physics: interference between amplitudes even/odd in $t \leftrightarrow \bar{t}$
  → NLO effect [Kühn, Rodrigo, PRL 81 (1998) 49]





N.B.: this has nothing to do with C violation, everything is CP conserving QCD

- Tevatron:
  - pp̄ is a CP eigenstate $N_t(y) = N_{\bar{t}}(-y)$
  - Charge asymmetry → forward-backward asymmetry, e.g. expressed as "pair asymmetry": rapidity difference $q\Delta y = y_t - y_{\bar{t}}$

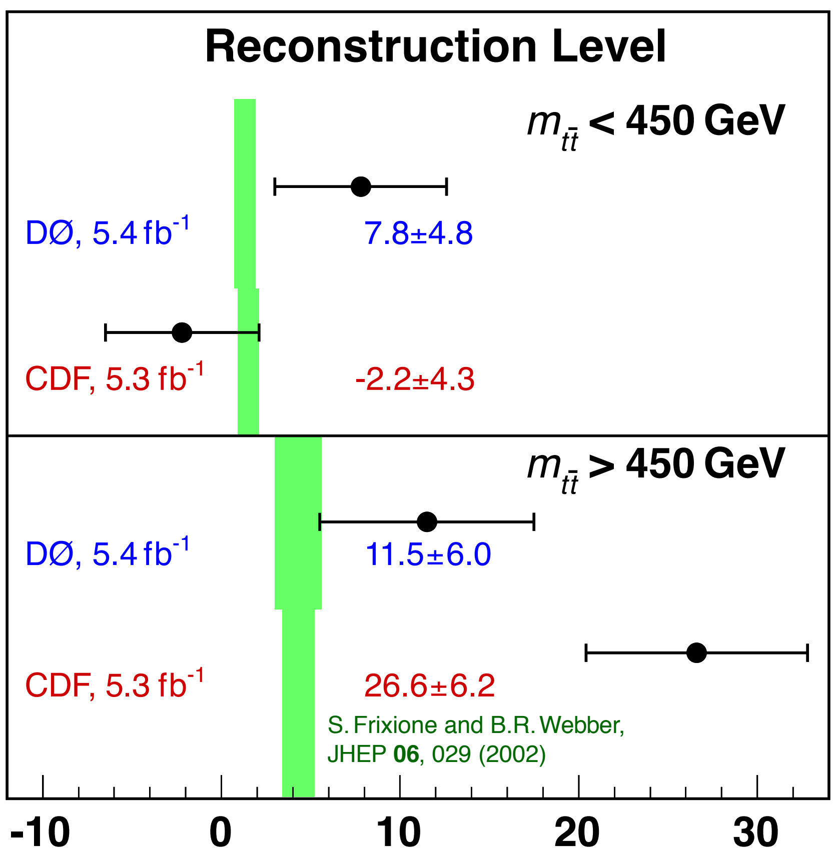
$$A^{t\bar{t}} = \frac{N((y_t - y_{\bar{t}}) > 0) - N((y_t - y_{\bar{t}}) < 0)}{N((y_t - y_{\bar{t}}) > 0) + N((y_t - y_{\bar{t}}) < 0)}$$

  - Theory expectations at NLO: 7.3% (with about 15% relative uncertainty)

Asymmetries in Top Production

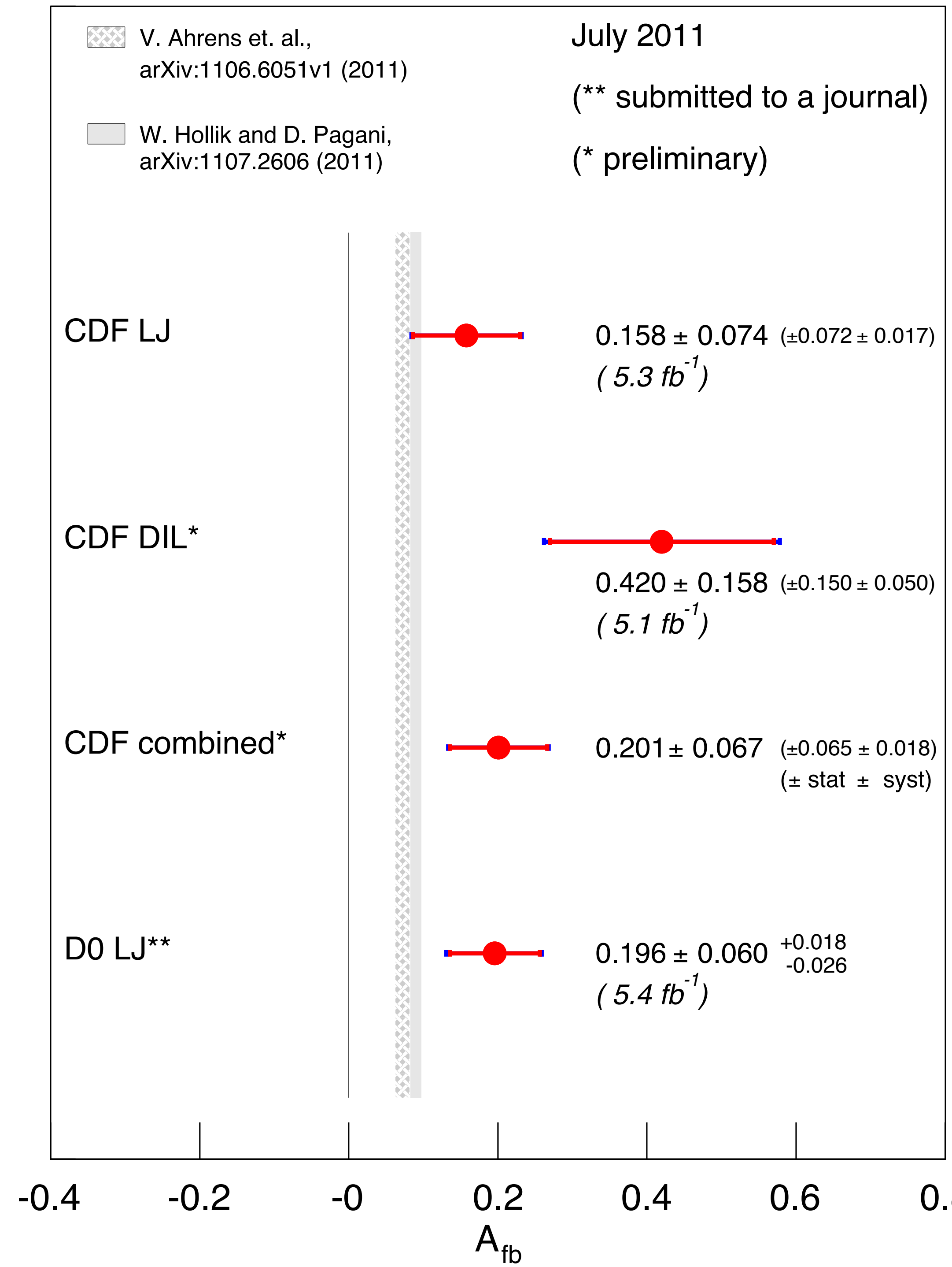
- Surprising Tevatron results:
  - Asymmetry is much larger than expected (observed both in CDF and DØ)
  - Asymmetry seems to increase with invariant mass of $t\bar{t}$ pairs (only CDF)

Forward-Backward Top Asymmetry, %



[http://www-d0.fnal.gov/Run2Physics/WWW/results/final/TOP/T11O/]

A_{fb} of the Top Quark



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

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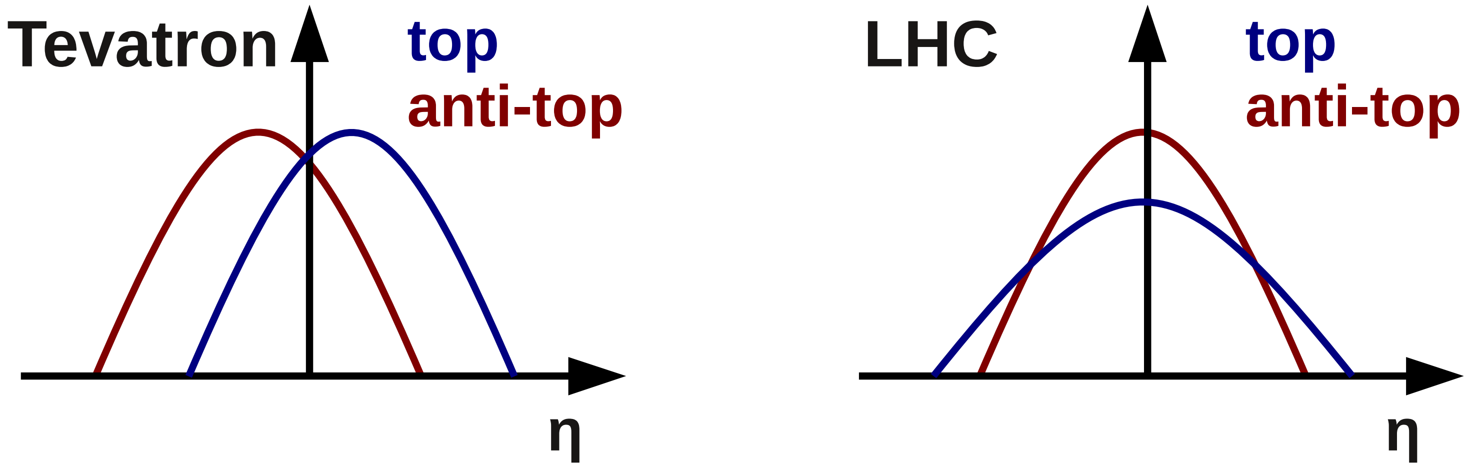
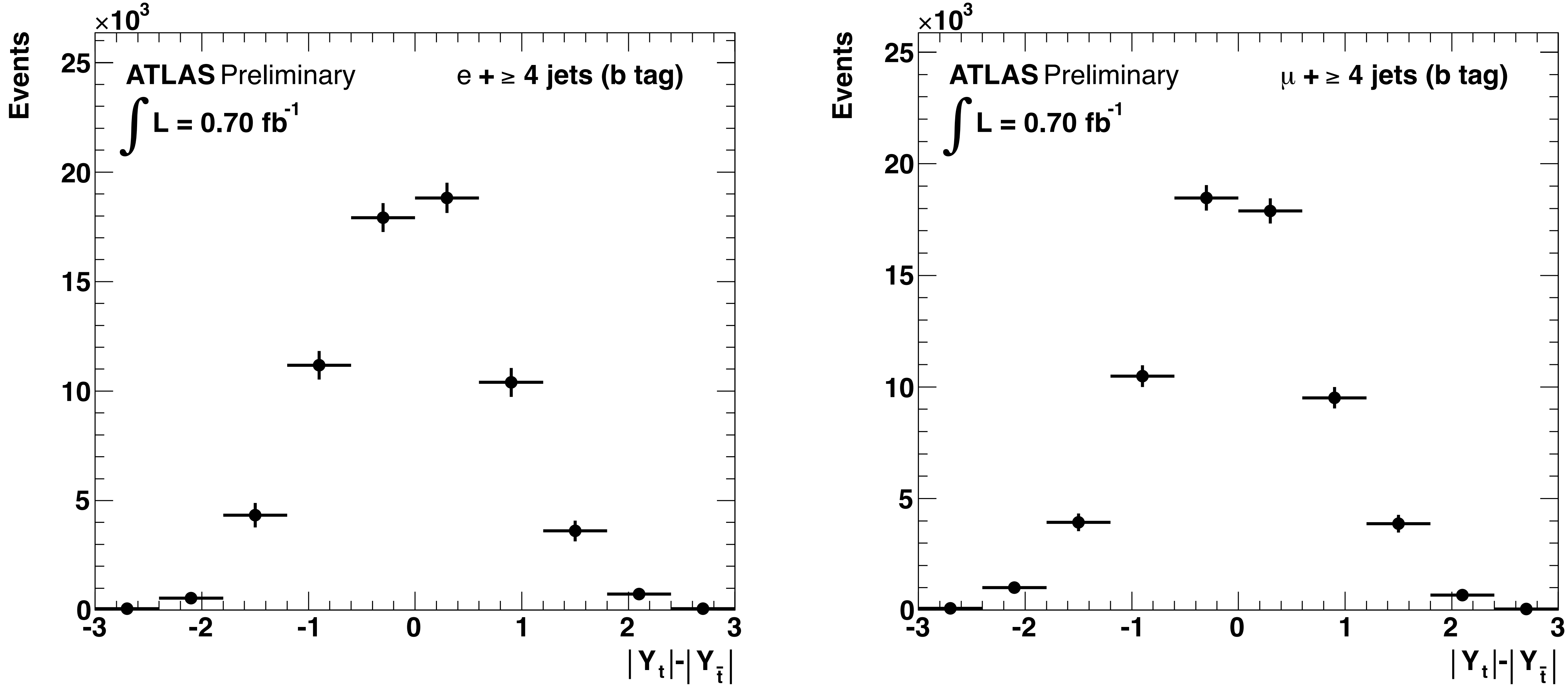
Enter the LHC

- Top charge asymmetry at the LHC
  - pp is parity eigenstate → no forward-backward asymmetry
  - Bose symmetry: dominant process gg → $t\bar{t}$ is symmetric
  - But: there is still a small (differential) charge asymmetry at NLO



- LHC analyses in a nutshell
  - CMS observables: $\Delta|\eta| = |\eta_t| - |\eta_{\bar{t}}|$ and $\Delta y^2 = y_t^2 - y_{\bar{t}}^2$
  - ATLAS observables: $\Delta|y| = |y_t| - |y_{\bar{t}}|$
  - Analysis strategy: reconstruct "raw" observables
    → unfold detector effects (ATLAS: iterative Bayesian, CMS: regularization)

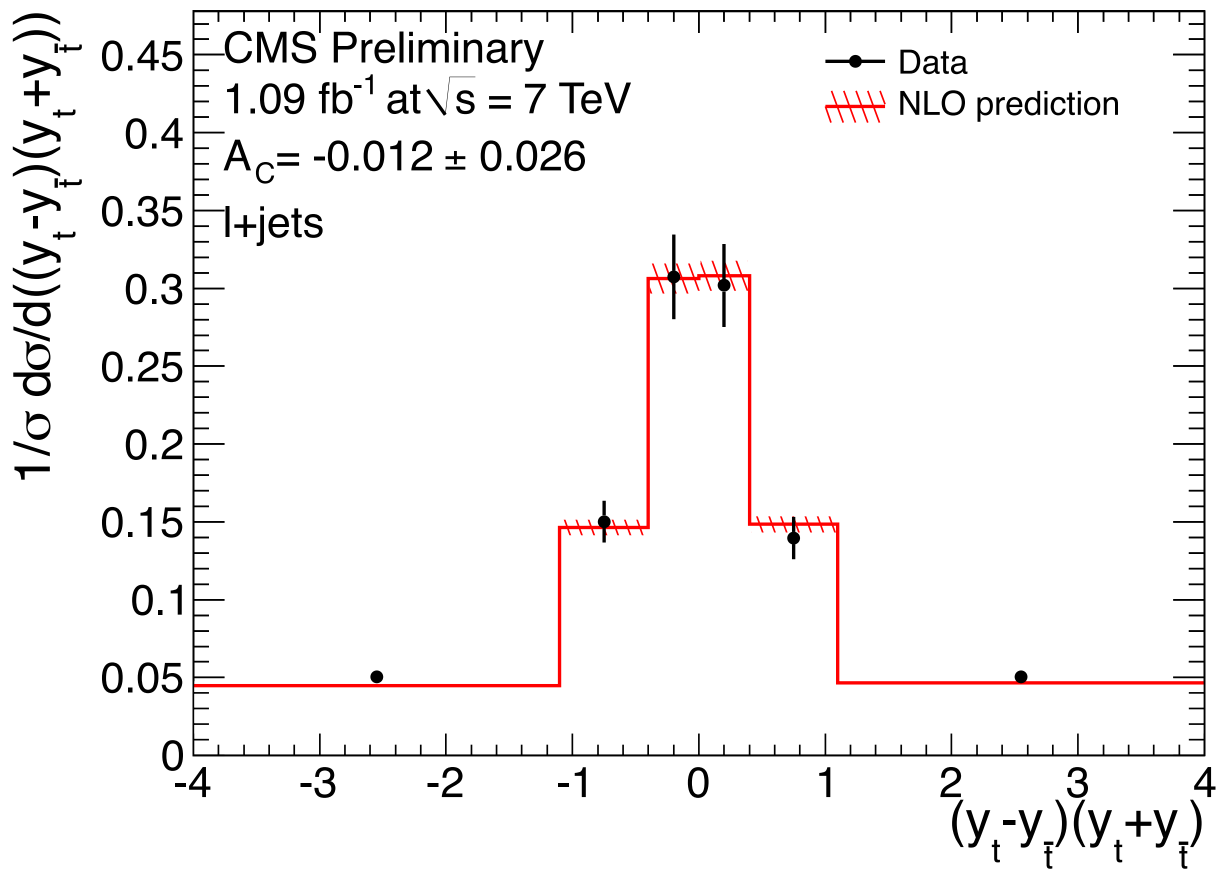
ATLAS

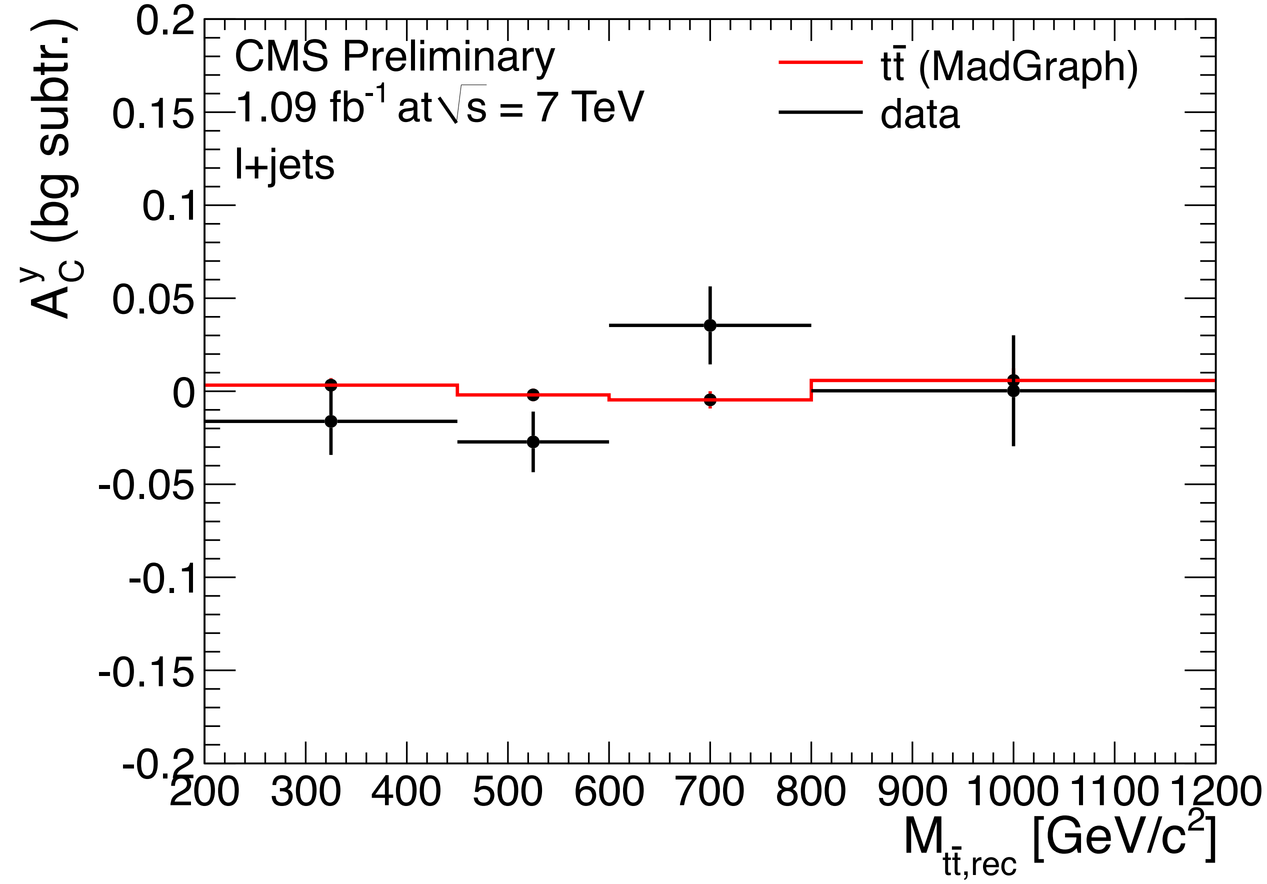


ATLAS Combined Result:
$A_C = -2.4 \pm 1.6(\text{stat}) \pm 2.3(\text{syst})\ \%$

[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-106/]

CMS





CMS Results:

$A_C^\eta = -1.6 \pm 3.0(\text{stat})\ ^{+1.0}_{-1.9}(\text{syst})$ %

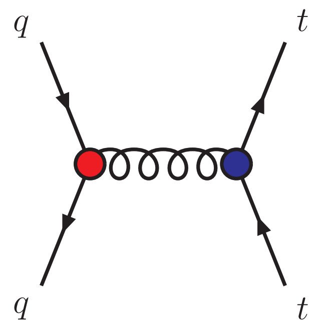
$A_C^y = -1.3 \pm 2.6(\text{stat})\ ^{+2.6}_{-2.1}(\text{syst})$ %

no significant $t\bar{t}$ mass dependence

[CMS-PAS-TOP-11-014]

… which leaves our theory colleagues puzzled

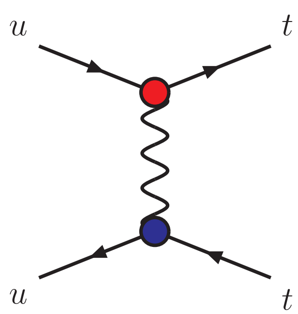
Most popular models . . . after 2011 LHC data



s channel: $t\bar{t}$ tail $\sim$ SM

$\mathcal{G}_\mu \sim (8,1)_0$ 0809.3354 , 0906.0604 , 0911.2955 , 1007.0243 , 1011.6380 , 1011.6557 , 1101.2902 , 1101.5203 , 1103.0956 1104.1917 , 1105.3158 , 1105.3333 , 1106.0529 , 1106.4054 , 1107.0978 , 1107.1473 , 1107.2120 , 1107.5769 , 1109.0648

t channel: $A_C = -0.016$ (CMS), -0.024 (ATLAS)



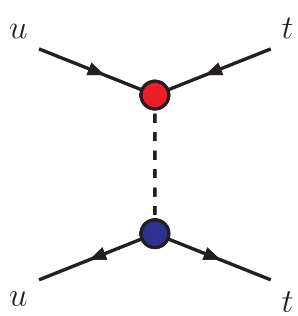
$Z' \sim (1,1)_0$ 09(11(110 11(1101 , 1106 102.(108.(03.1266 1103.4835 ,

$W' \sim (1,1)_1$ 0908.258 1104.008 .1048 . 1003.346 .460 .1445 , 1 , 1102.0279

$\phi \sim (1,2)_{-\frac{1}{2}}$ 1104.4782 , 1107.084 4350 , 1108.4005

single top?
top FCNC?

u channel: $t\bar{t}$ tail $\sim$ SM



$\omega^4 \sim (3,1)_{-\frac{4}{3}}$ 09 11 4875 , (2757 , 1 1007 2.3374 ,

$\Omega^4 \sim (\bar{6},1)_{-\frac{4}{3}}$



J. A. Aguilar Saavedra (Univ. Granada) Overview of models for the $t\bar{t}$ asymmetry TOP 2011 29 / 56

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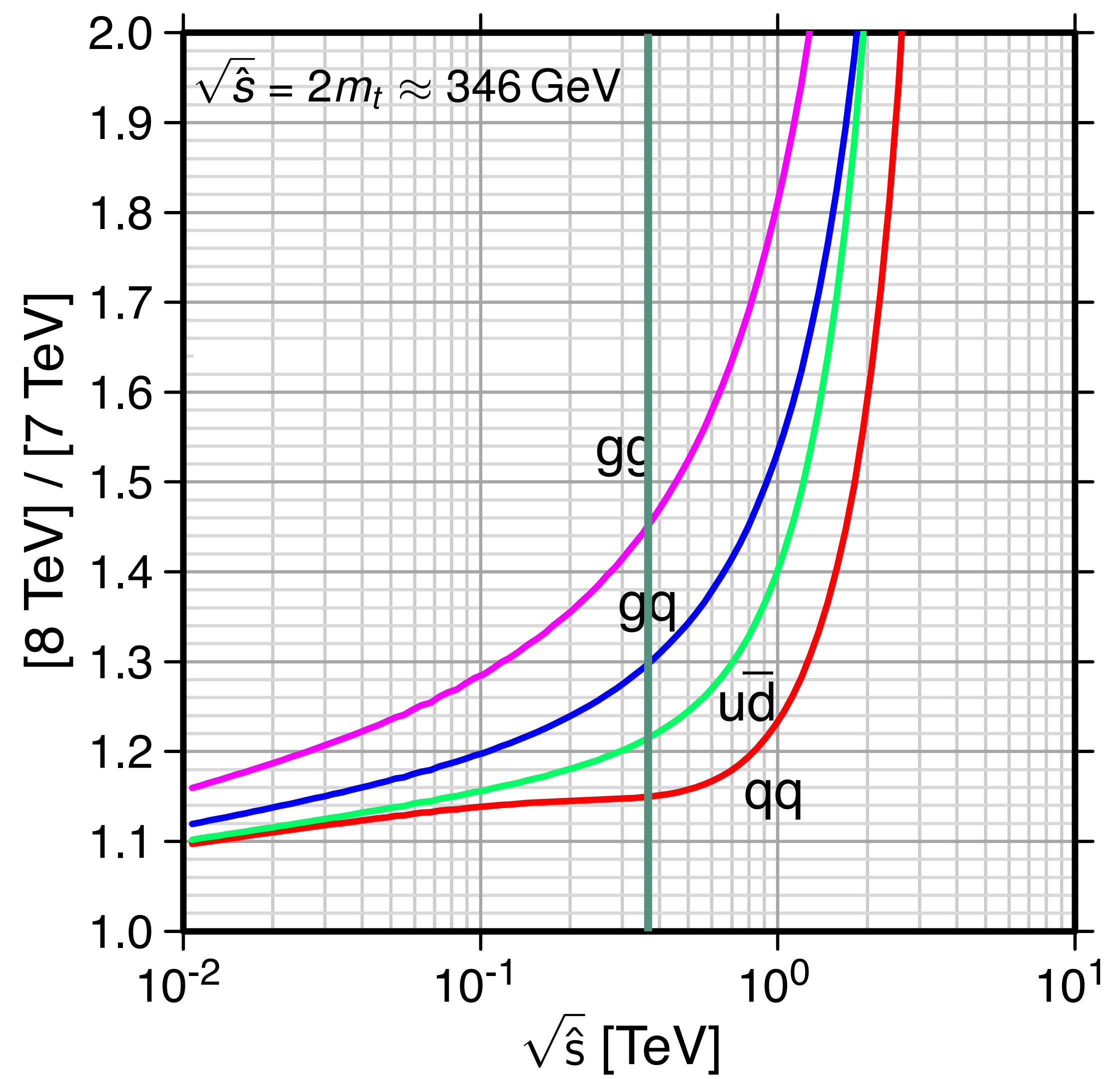
The Upcoming Run: 2012 Energy

- Running conditions for 2012 currently under discussion
  - Center of mass energy: 7 or 8 TeV (or starting with 7 TeV and then moving up to 8 TeV)
  - Decision during Chamonix retreat, early 2012
- Running at 8 TeV
  - Machine physicists: magnet quenching risk manageable (remember the 2008 incident!)
  - Gains in almost all channels, e.g. top cross section about 1.4 times larger
  - Higher reach for searches for new physics

Factorization
production cross section =
parton lumi ⊗ partonic cross section

CTEQ6L1: Parton Luminosity Ratios



[C. Quigg, arXiv:1101.3201]

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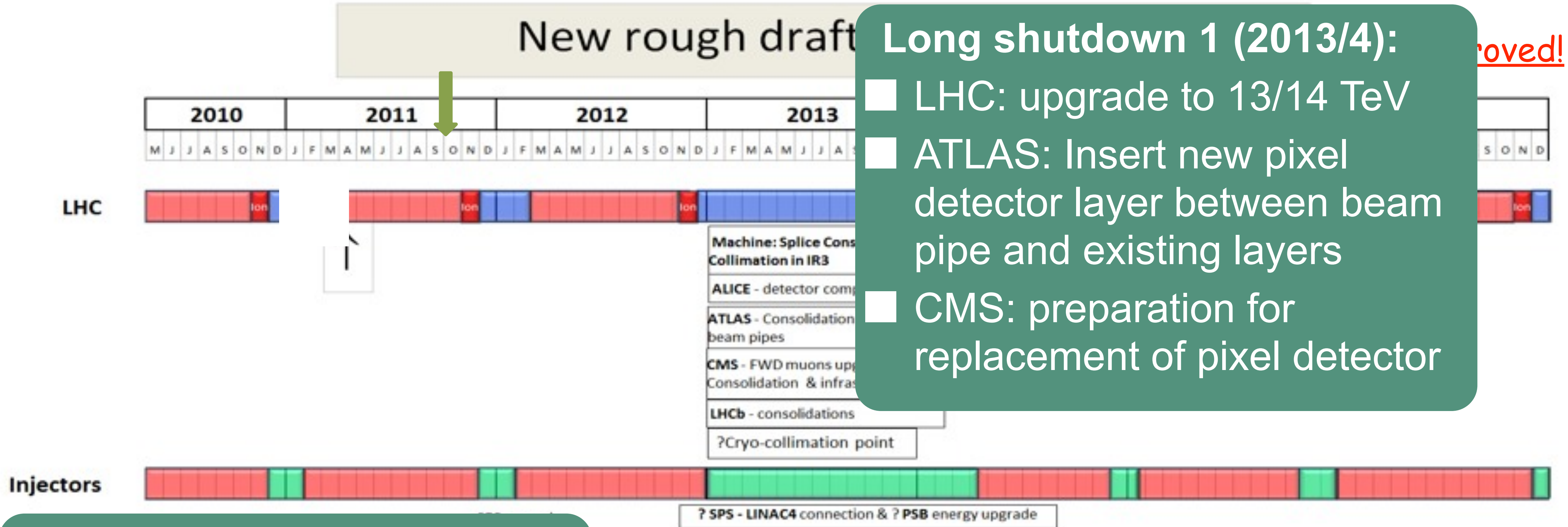
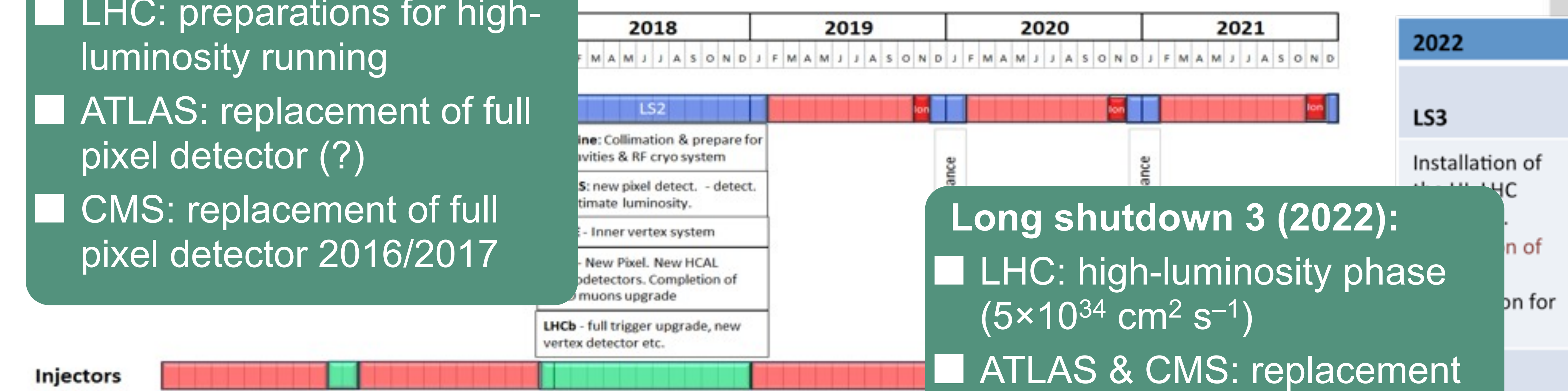
Longer Term Planning



Long shutdown 1 (2013/4):

- LHC: upgrade to 13/14 TeV
- ATLAS: Insert new pixel detector layer between beam pipe and existing layers
- CMS: preparation for replacement of pixel detector



Long shutdown 2 (2018):

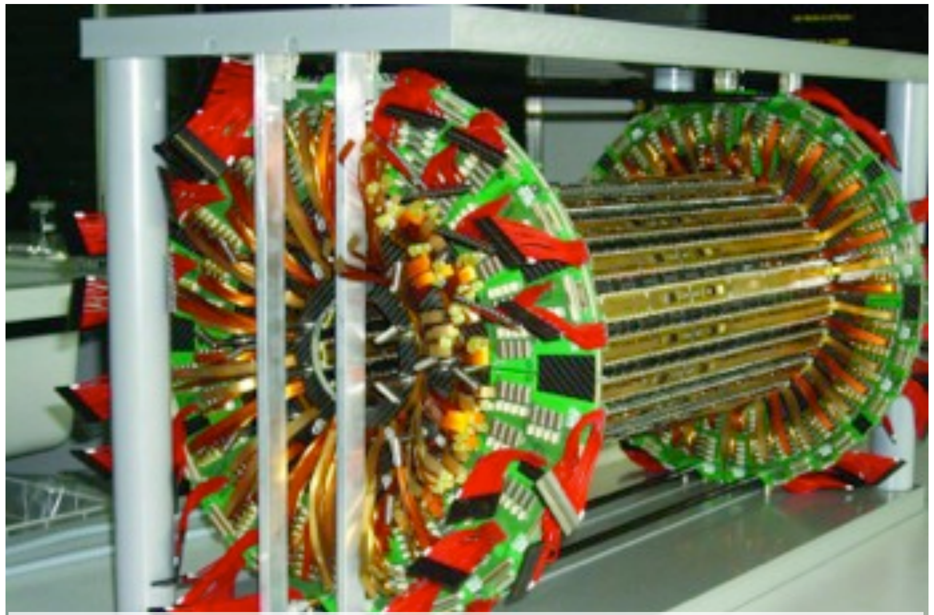
- LHC: preparations for high-luminosity running
- ATLAS: replacement of full pixel detector (?)
- CMS: replacement of full pixel detector 2016/2017

Long shutdown 3 (2022):

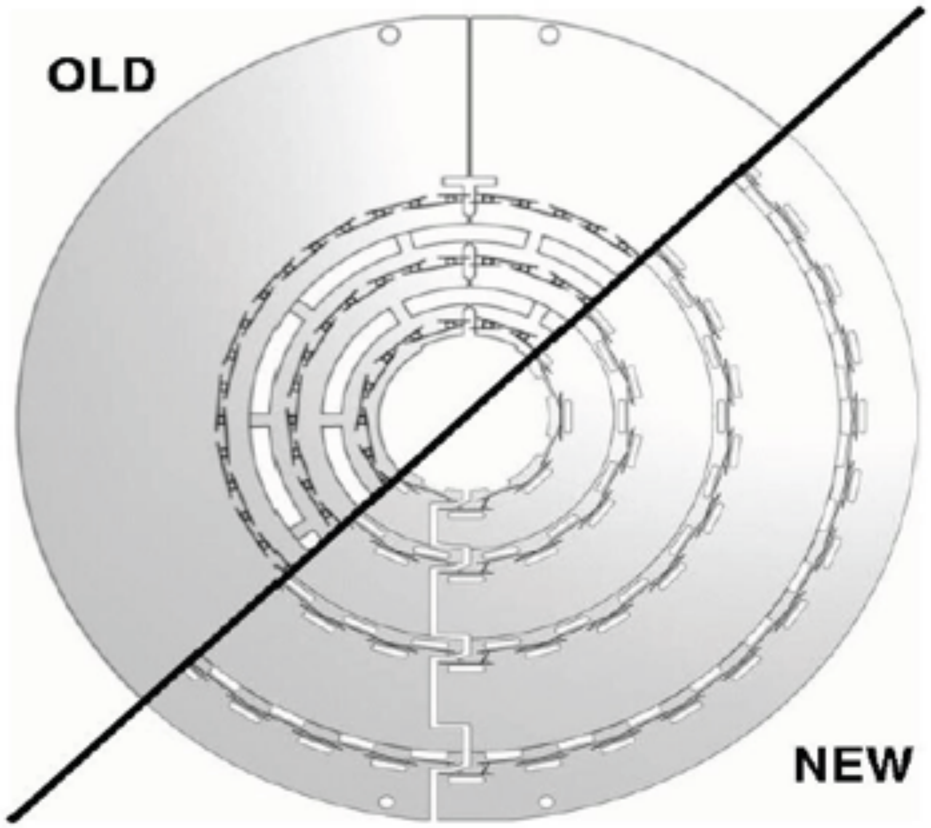
- LHC: high-luminosity phase (5×10^{34} cm^2 s^{-1})
- ATLAS & CMS: replacement of all tracking detectors

[Paul Collier, LHCC, Septembe

CMS Pixel Detector Replacement



Current CMS Barrel Pixel Detector



- Motivation: keep equal or better performance at very high luminosities
  - Much larger number of particles per bunch crossing
    → more readout channels
  - Current detector: aging and radiation damage → replace, add redundancy

- New CMS pixel detector:
  - 3 layers → 4 layers,
  - To be installed in winter shutdown 2016/2017 → (almost) plug & play
  - Better resolution for impact parameters of charged particle tracks
    → improved B-tagging

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The Advent of the Higgs?

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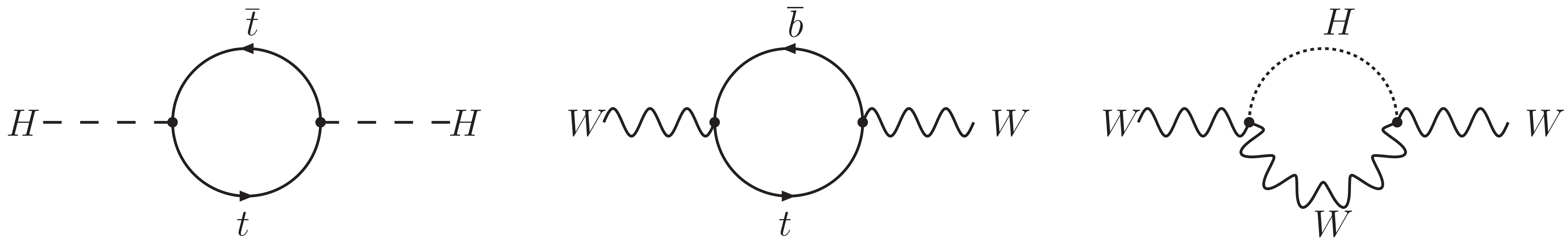
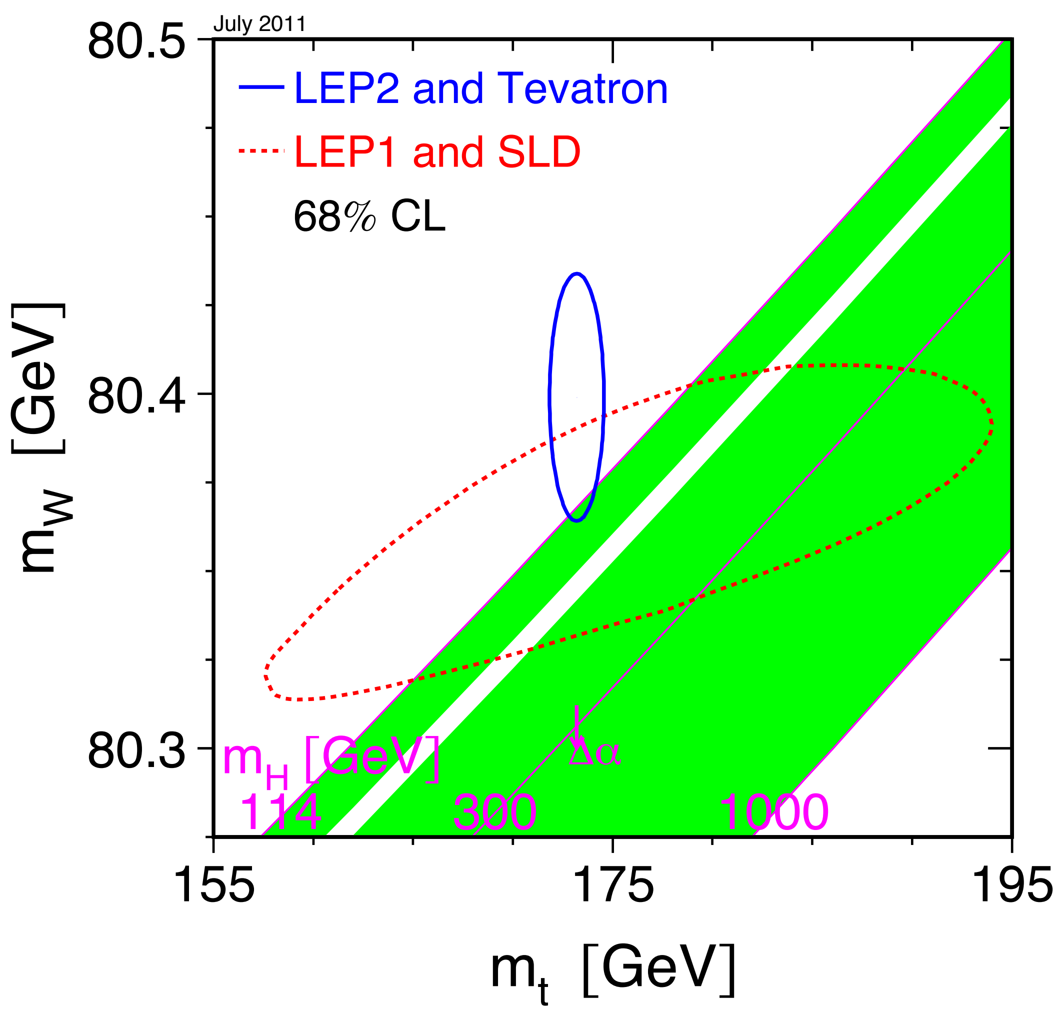
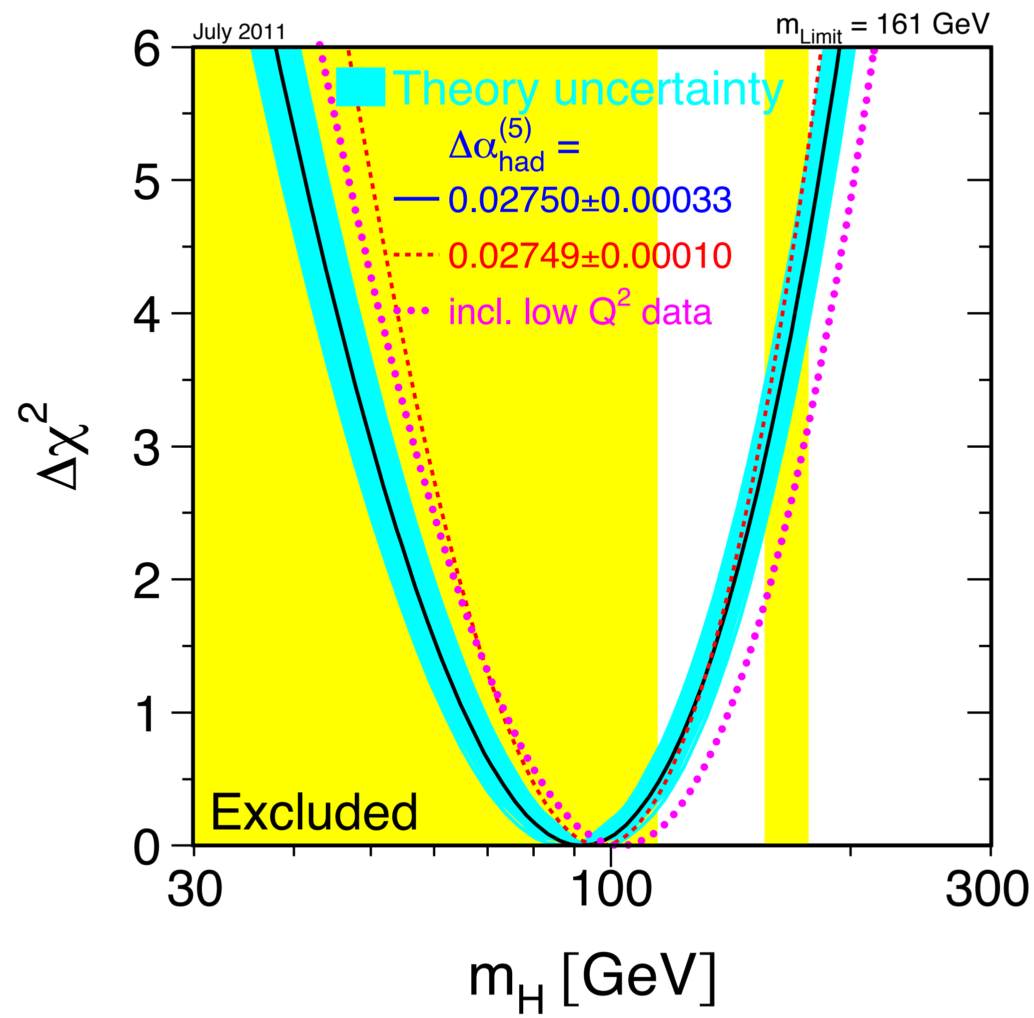
The Top, the W, and the Higgs

Top, W, and Higgs masses: closely related by loop corrections







[LEP EWWG]

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Precision Top Mass Measurements

- One of the most important Tevatron legacies
- Two key ideas for ultimate precision
  - Squeeze the most out of each event: matrix element method → likelihood built from matrix element for $t\bar{t}$ production and decay
  - Dominant uncertainty: jet energy scale → constrain by measuring the W boson mass in situ ($t \to Wb$, $W \to 2$ jets)
- Summer 2011 combination (CDF+DØ, arXiv:1107.5255)

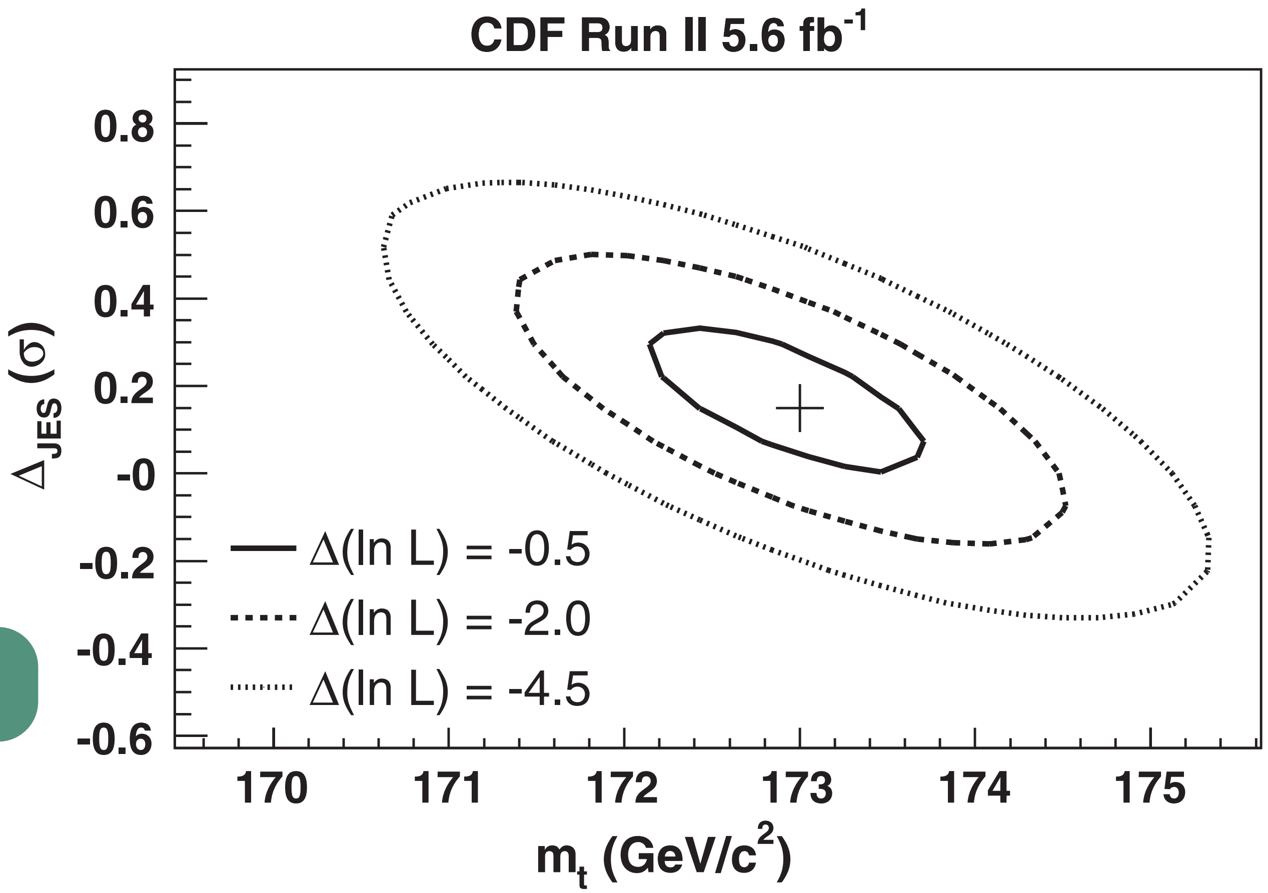
$m_t = 173.2 \pm 0.6(\text{stat}) \pm 0.8(\text{syst})$ GeV

→ 0.9 GeV (=0.5%) uncertainty!

Matrix Element Likelihood

$$L_i(\vec{y} \mid m_t, \Delta_{JES}) = \int \frac{f(z_1)f(z_2)}{FF} \; TF(\vec{y} \mid \vec{x}, \Delta_{JES}) \; |M(m_t, \vec{x})|^2 \; d\Phi(\vec{x})$$

PDFs | Transfer Functions | Matrix Element & Phase Space



[PRL **105** (2010) 252001]

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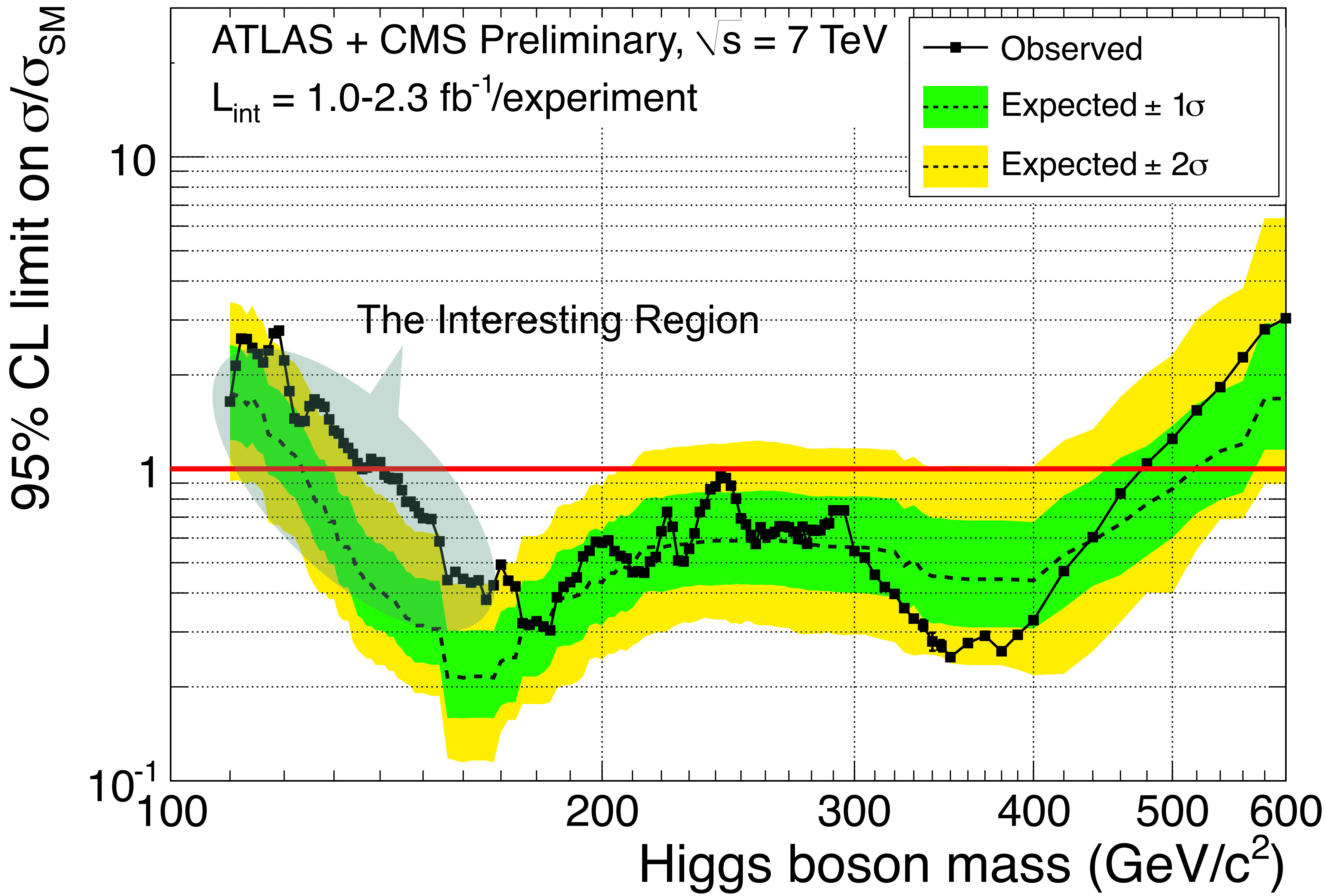
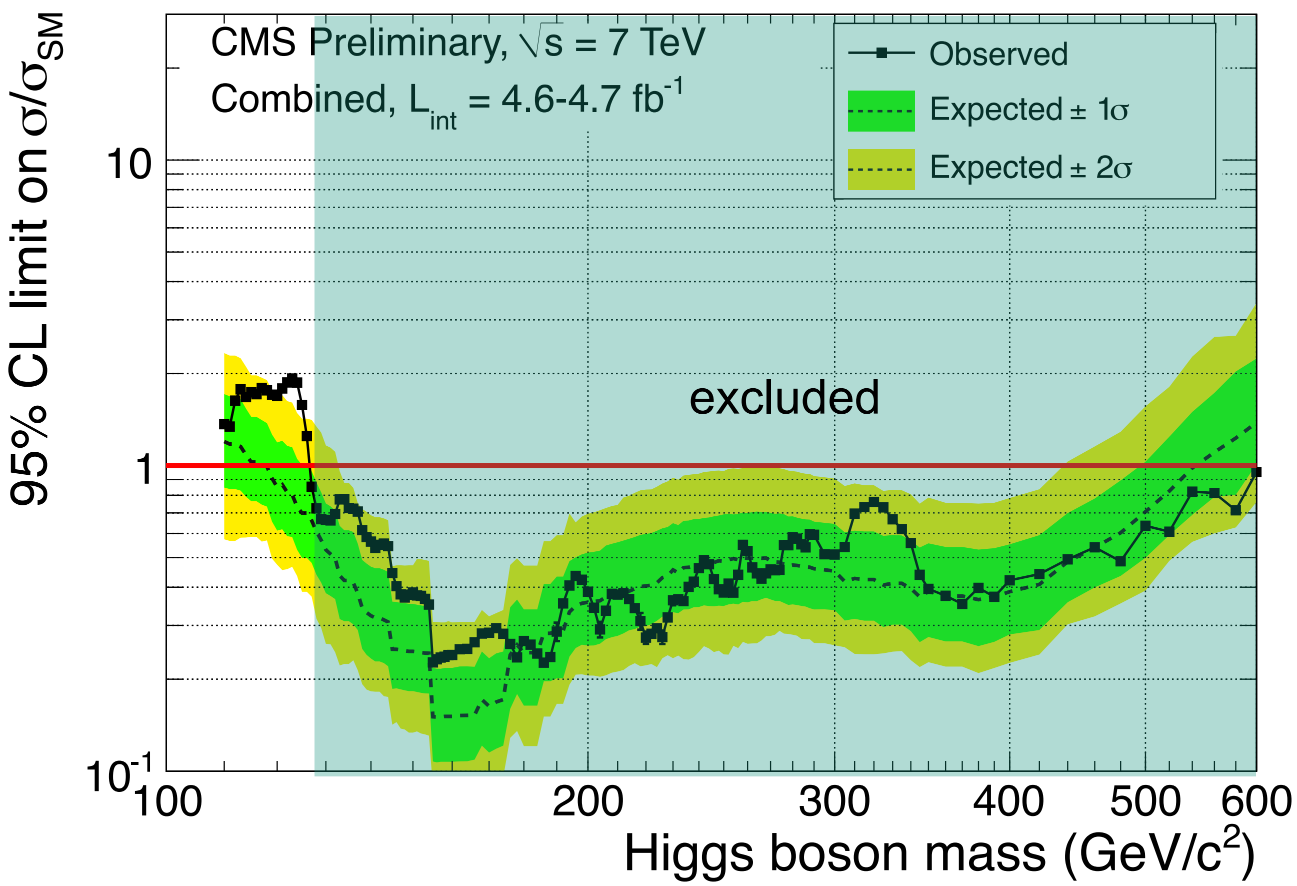
Summer 2011 LHC Higgs Combination

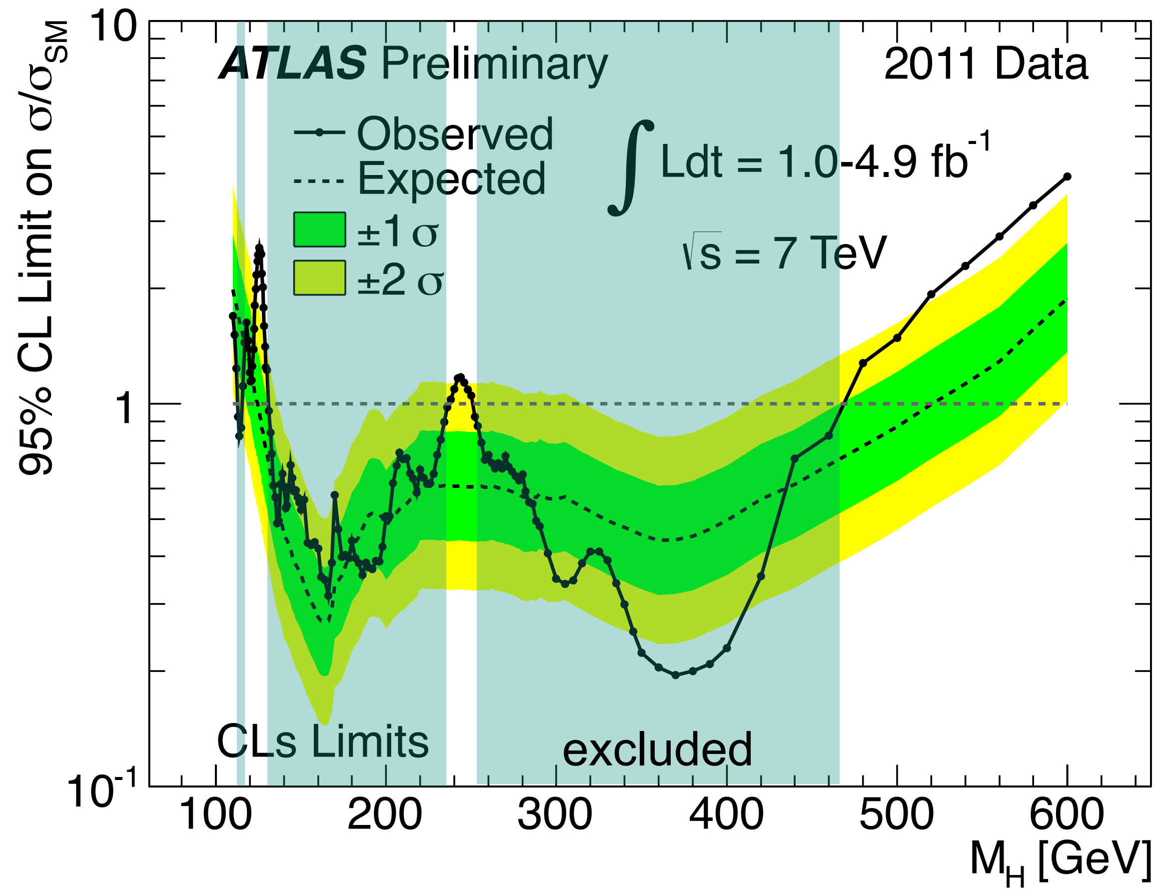


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-157/

Latest News from the Higgs

- Results of Higgs searches using the full 2011 dataset (12/13/2011)





http://cdsweb.cern.ch/record/1406347

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-163/

- Sensitivity to exclude Higgs boson almost in full mass range 115–600 GeV
- Observed limits somewhat weaker, e.g. CMS: 127–600 GeV

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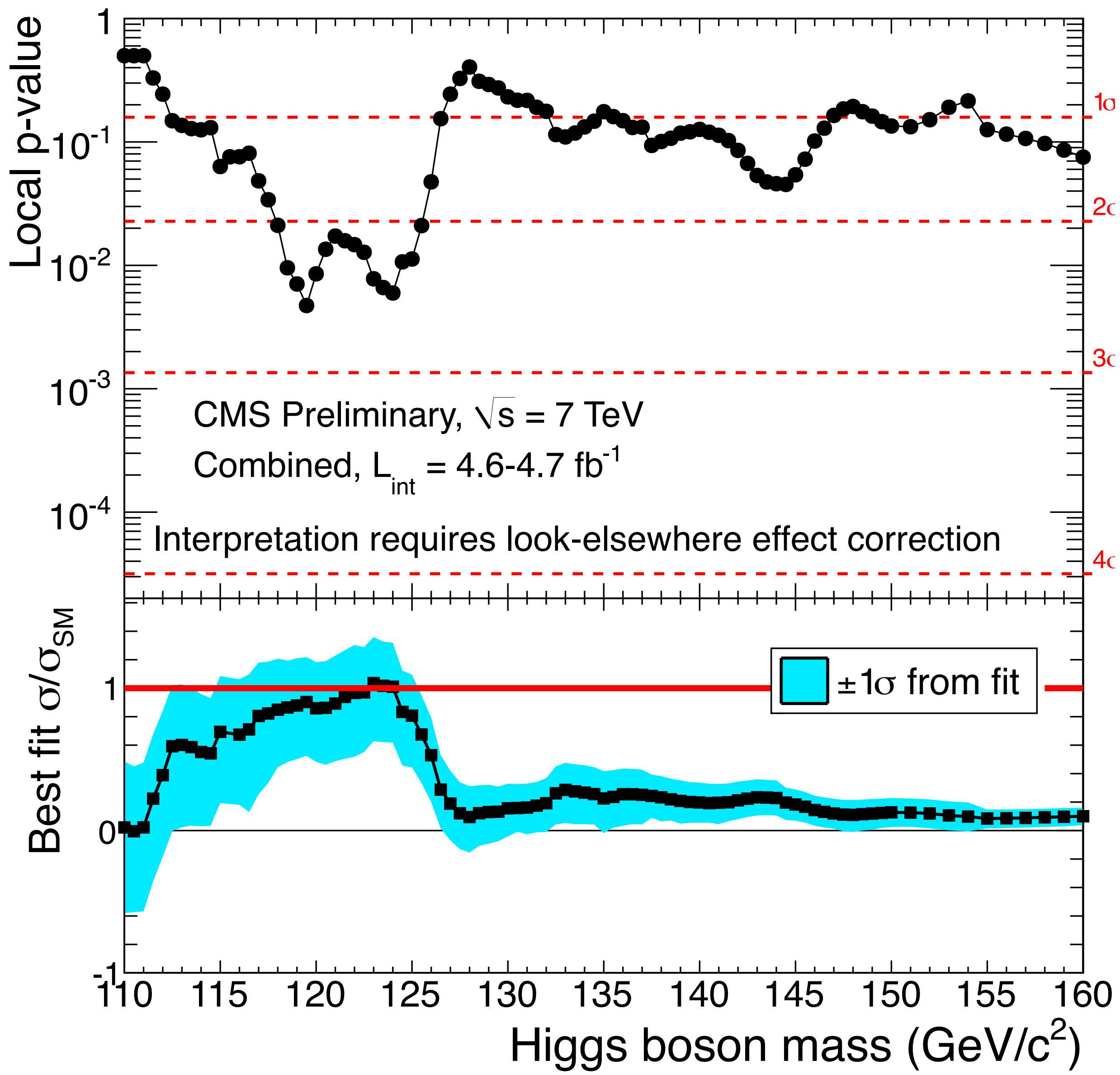
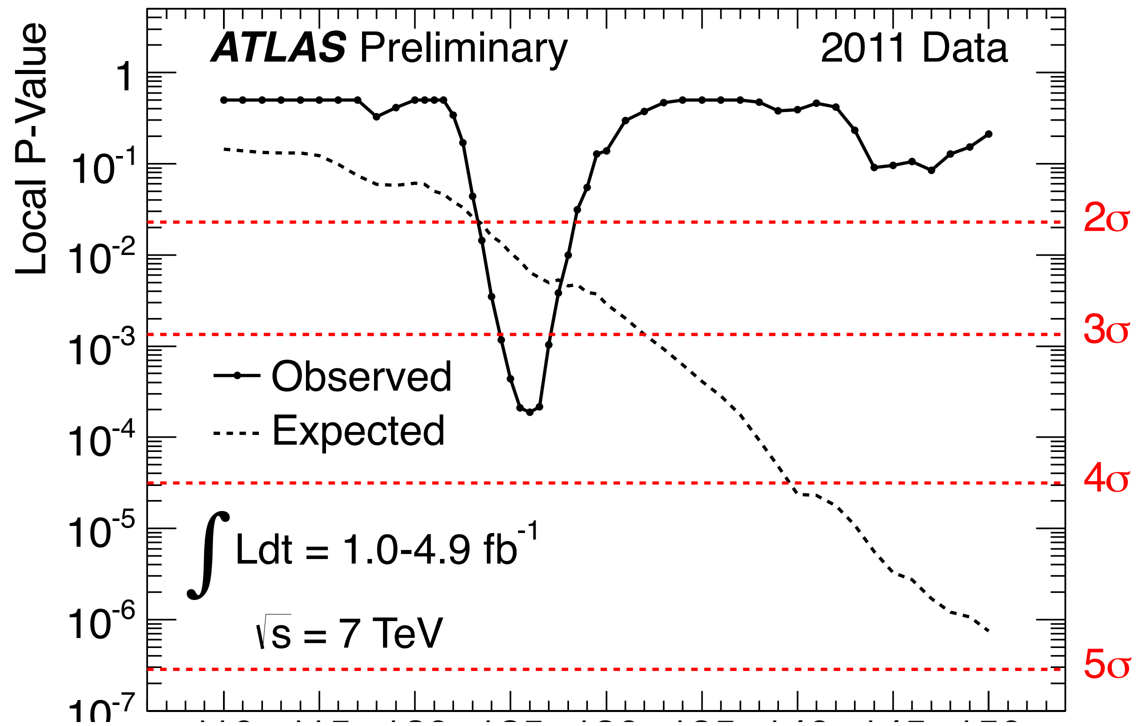
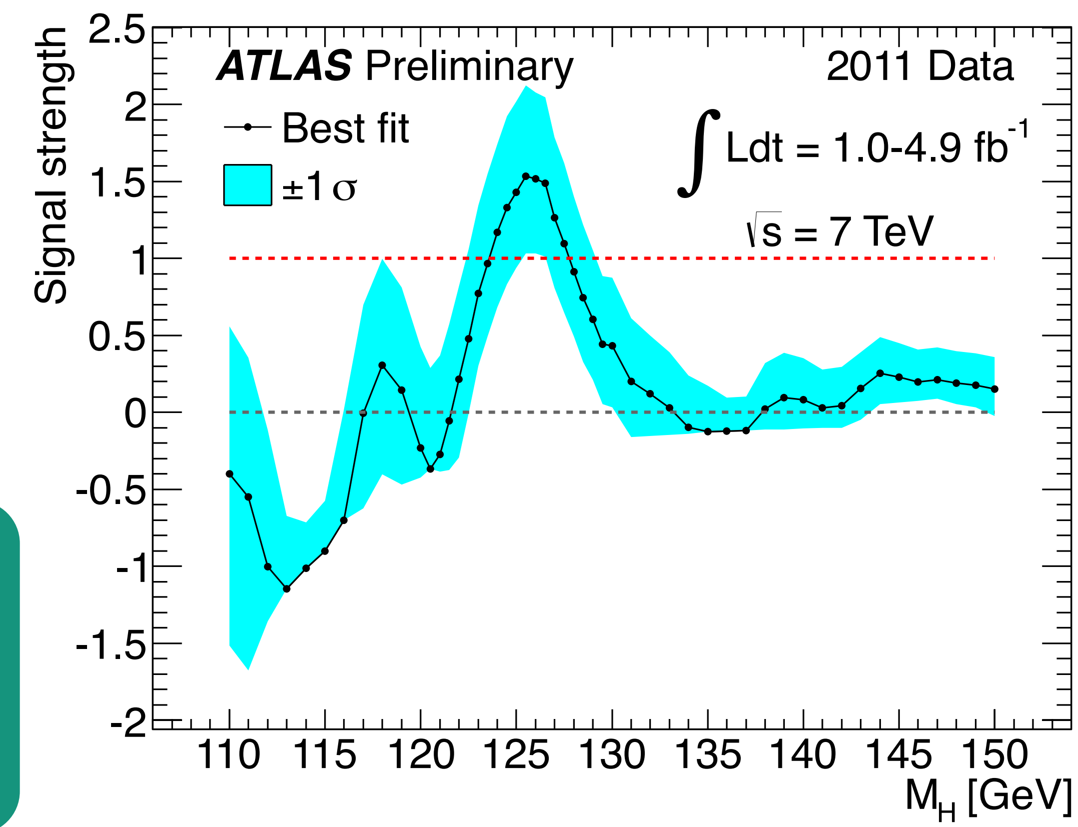
Latest News from the Higgs



[http://cdsweb.cern.ch/record/1406347]





[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-163/]

Modest excess, mainly around 124-126 GeV
→ compatible with SM Higgs, but statistical significance not large enough to say anything conclusive

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Summary and Conclusions

- Tevatron: 20 very successful years for top physics coming to an end
  - Established the field: ideas, measurement techniques, …
  - Important legacy measurements, e.g. top mass, FB asymmetry
- LHC physics program in full swing and top is a key ingredient
  - Precision measurements, searches for new physics beyond top, calibrations with tops
  - Many new ideas to be exploited
- LHC long term perspective
  - 13–14 TeV CM energy from 2014
  - Two-phase upgrade for high luminosity

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