# ATLAS Confidential: From Cosmic Rays to the Higgs Boson

Eric Feng

Argonne National Laboratory


PilcherFest Symposium
September 22, 2012

Argonne NATIONAL LABORATORY

# ATLAS Confidential: From Cosmic Rays to the Higgs Boson

~~*(The Unauthorized Biography of James E. Pilcher)*~~


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# Introduction

- Undergraduate student in CDF and ATLAS groups at Berkeley (circa 2005)
- When applying to graduate schools, a professor recommended the University of Chicago as an outstanding place for HEP
  - Suggested some professor named Jim Pilcher would be a good potential thesis advisor
- After being accepted to the Physics Department, received email from Jim about working on ATLAS and we chatted on the phone
  - Started graduate research with Jim at CERN in summer 2005
  - Defended thesis on a measurement of inclusive jet & dijet production early this year
- Show representative (not exhaustive) examples of the work we did together in those 6.5 years
  - Listed UC folks besides Jim and me who also worked on these projects, apologies to anyone I've forgotten

# TileCal Commissioning with Cosmic Rays

- During my first summer at CERN (2005), we observed cosmic rays using Tile Calorimeter [*with K. Anderson, A. Farbin, R. Teuscher*]
  - First ATLAS data taken with the detector underground
- Worked on offline reconstruction of the data

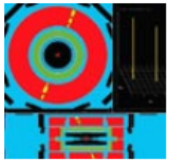
CERN COURIER

Aug 23, 2005

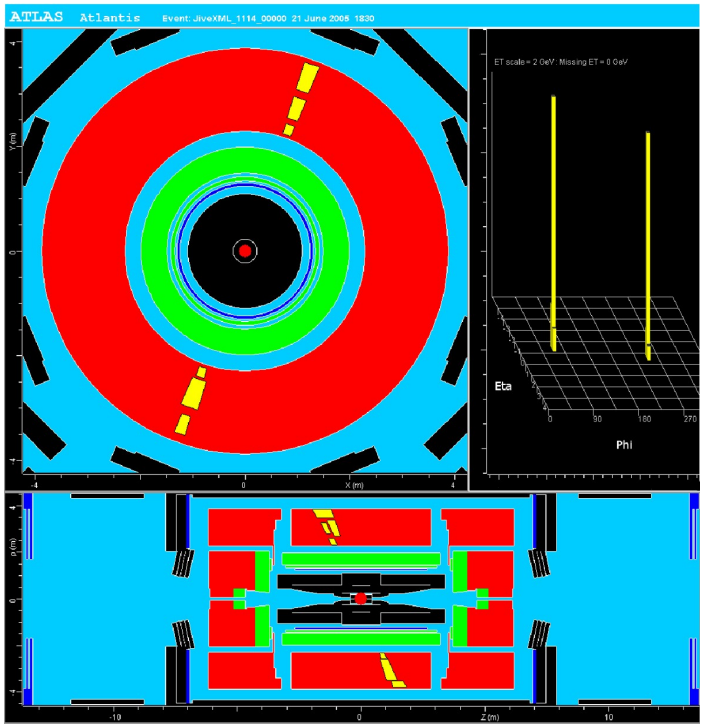
**ATLAS calorimeter records cosmic-ray events underground**

On the evening of 21 June, the ATLAS detector, now being installed in the underground experimental hall UX15 at CERN, reached an important psychological milestone: the first cosmic-ray events were recorded by the barrel hadronic tile calorimeter *in situ*. Although only four of the 64 calorimeter slices were included in the trigger, beautiful muon tracks were seen traversing the detector. The purpose-made trigger box selected cosmic rays passing close to the interaction region, thus giving the impression of "back-to-back" tracks.

An estimated 1 million cosmic muons enter the ATLAS cavern every 3 min, and the ATLAS team decided to use of some of them for the commissioning of the detector. For two weeks, experts of different disciplines from CERN and the experiment (cooling,



Cosmic-ray muon




- In summer 2006, wrote first software to reconstruct cosmic ray data from combined TileCal & Muon Spectrometer run
- Major milestone to time-in detector subsystems, interface to Central Trigger Processor, etc

# Cosmic ray coincidence trigger

- UC group built dedicated electronics to form the Tile Calorimeter coincidence trigger
- Major responsibility for TileCal front-end readout electronics, including “3-in-1” bi-gain card in PMT block that shapes and amplifies signals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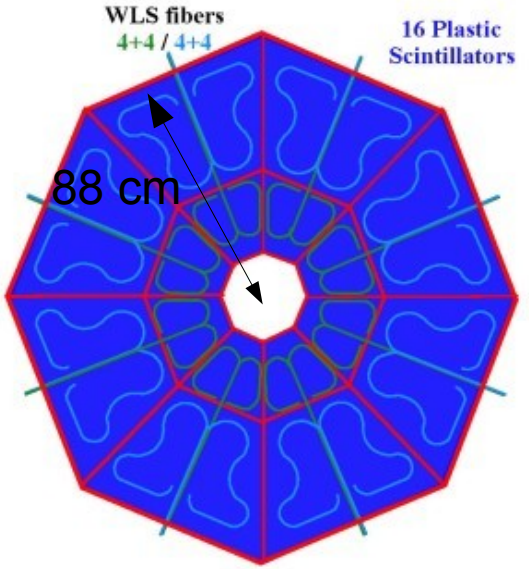
- Strength of UC ATLAS group in hardware is due in large part to Jim's expertise

# Minimum bias trigger scintillators

- Plastic scintillators ~1 cm thick and almost 1 m radius designed to trigger on minimum bias events
- From 2006-2007, we performed test bench studies at UC with cosmic ray muons
  - Modified TileCal 3-in-1 card to derive trigger output from high-gain branch for sufficient S/N to read out the MBTS

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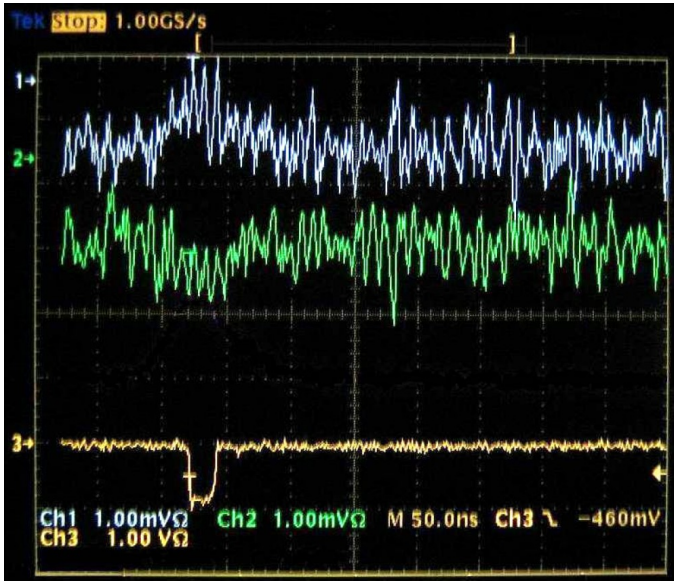


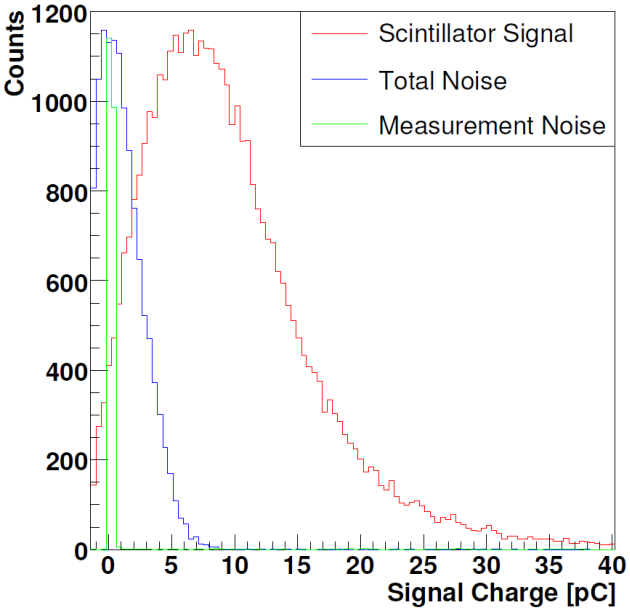


**Before**

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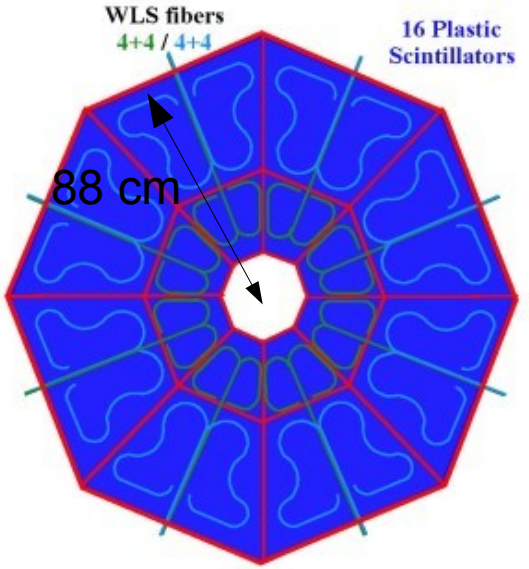


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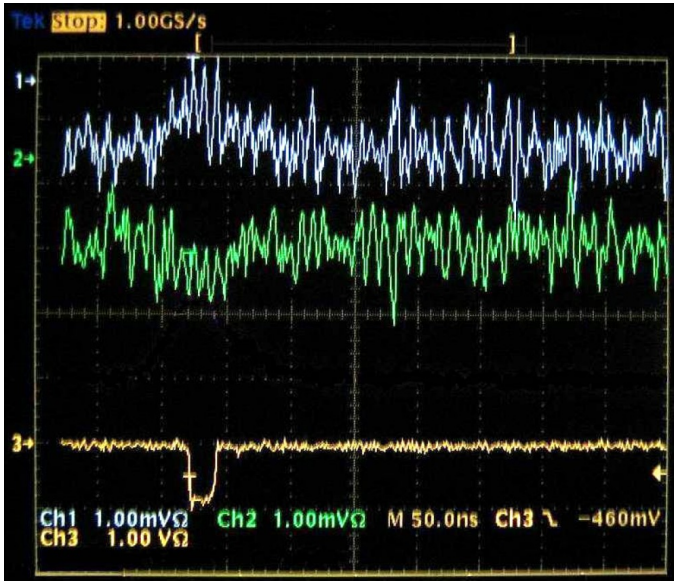
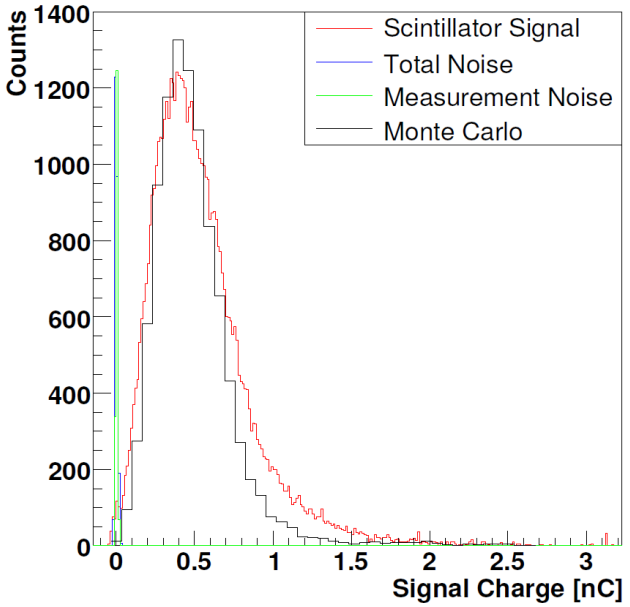
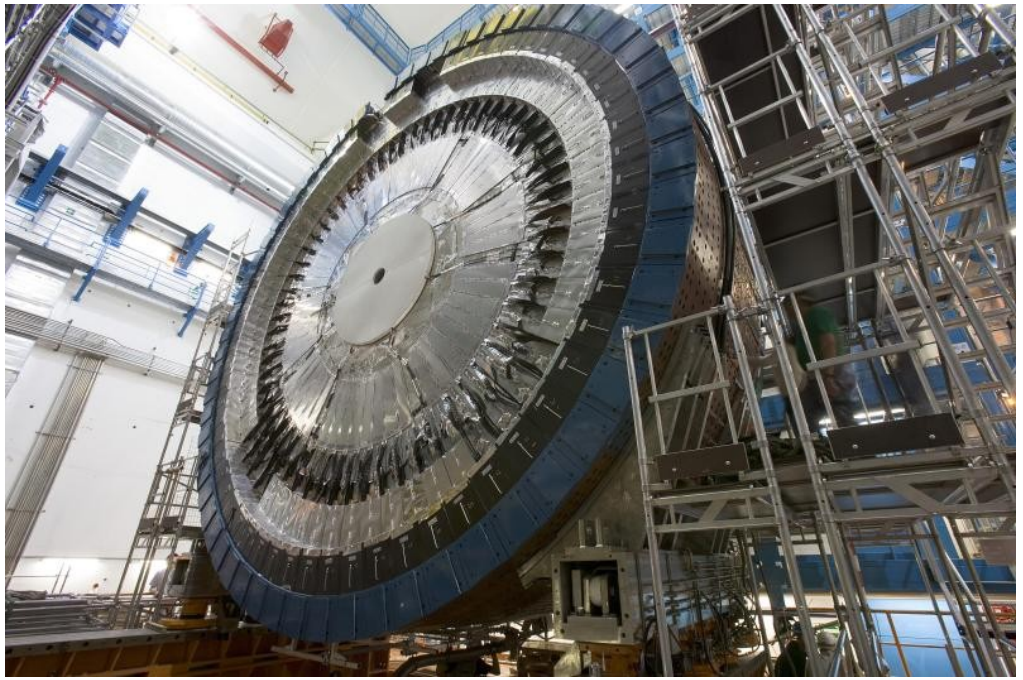


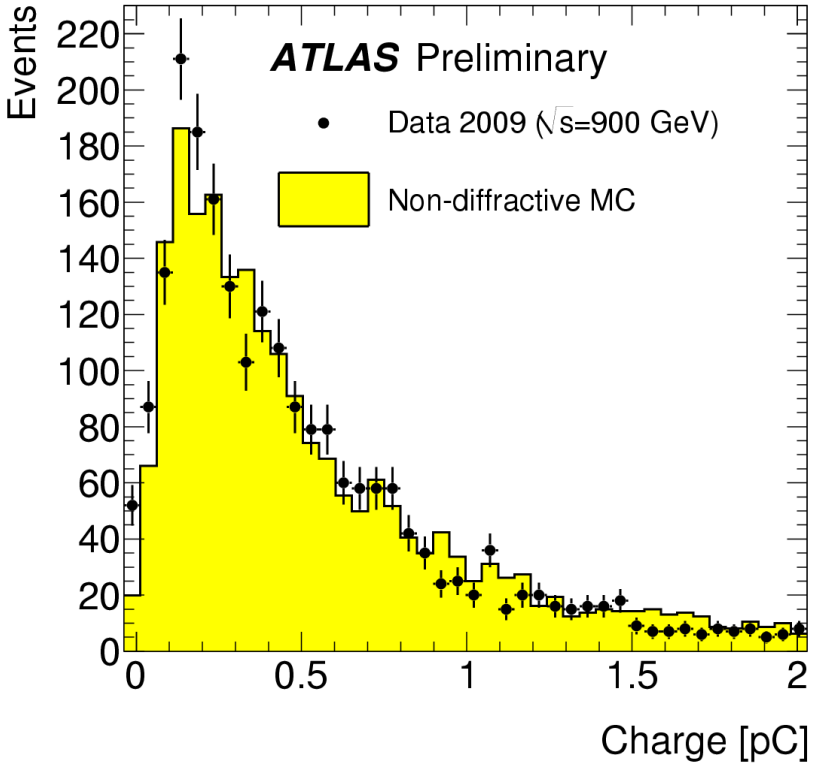




**After**

# Triggering first LHC data

- MBTS triggered most of first LHC collision data in 2009 – early 2010
  - First ATLAS conference notes and first analysis published on minimum bias data
  - Key feature was high trigger efficiency:
    **Eur. Phys. J. C 72, 1849 (2012)**
- We validated modeling of counter response to single particles using collision data at 900 GeV and 7 TeV [*with M. Dunford, L. Tompkins*]





# U. of Chicago – Remote Monitoring Station

- In 2008, we developed remote monitoring system for ATLAS
  - Built monitoring station for Tile Calorimeter remote shifts (first such system in ATLAS)
  - Control command console modeled after ATLAS and CERN Control rooms, as well as Fermilab Remote Operations Center
  - Worked with TDAQ to implement software & hardware at CERN P1
- SLC workstation for two operators, with rack-mounted monitors:
  - 2 x 30” displays
  - 8 x 19” displays

# Design of the Remote Monitoring Station

- Phone conversation with Jim about specs:

  *Jim: "I was thinking that we need more monitors for the remote monitoring station."*

  *Eric: "Um, are you sure? We already have a lot."*

  *Jim: "How many do we have now?"*

  *Eric: "We have one 30" monitor and four 19" now.*

  *Jim: "I think we need more."*

# Design of the Remote Monitoring Station

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=

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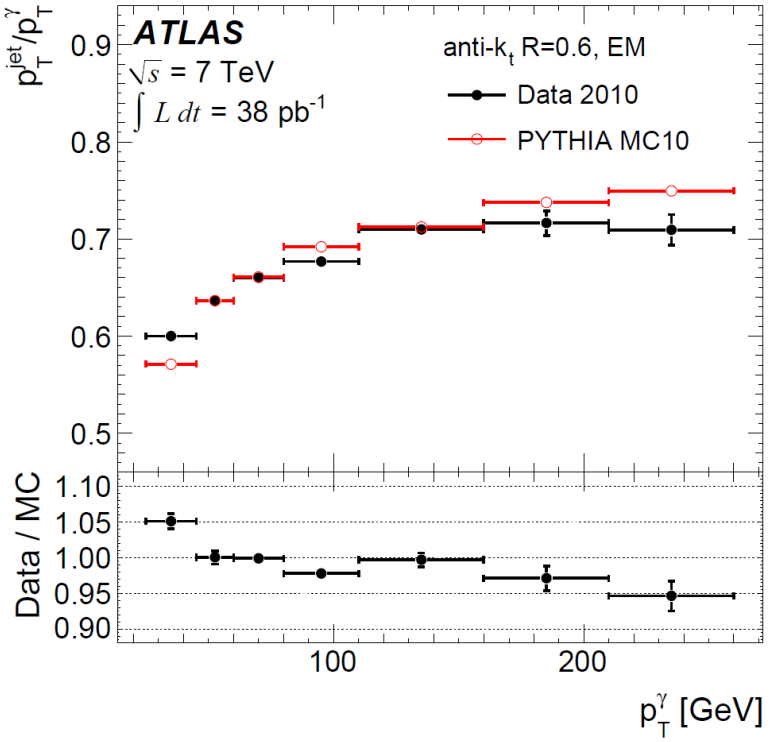
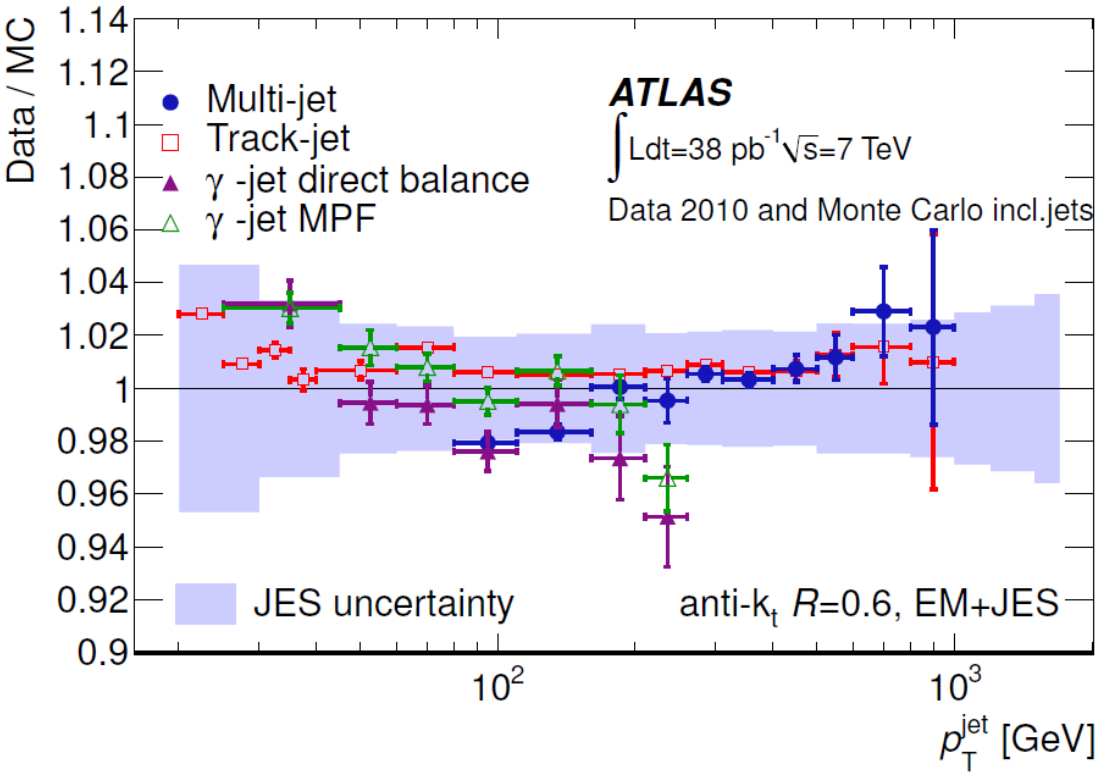
# Jet calibration

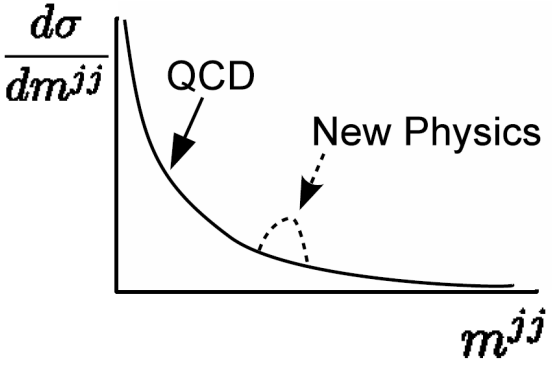
- In 2009-2010, we studied various aspects of jet calibration and properties in Monte Carlo and 7 TeV collision data
  - For example, we developed photon+jet pT balance as a method to calibrate absolute JES: **arXiv:1112.6426 [hep-ex] (EPJC).** [*with G. Choudalakis, M. Hurwitz*]
  - Key part of in-situ validation of JES to few percent uncertainty

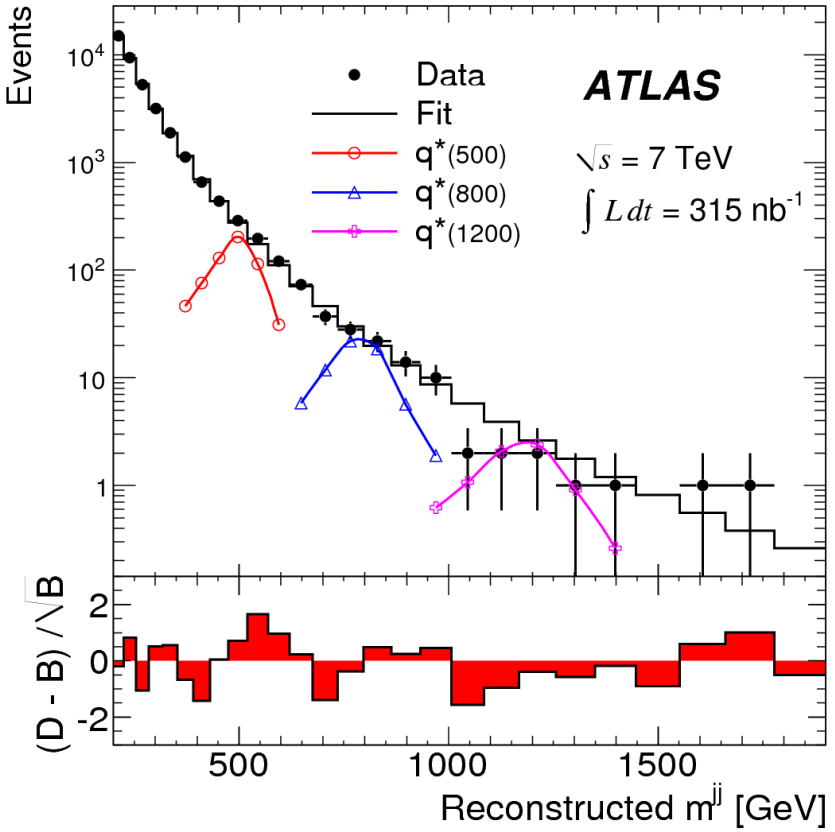


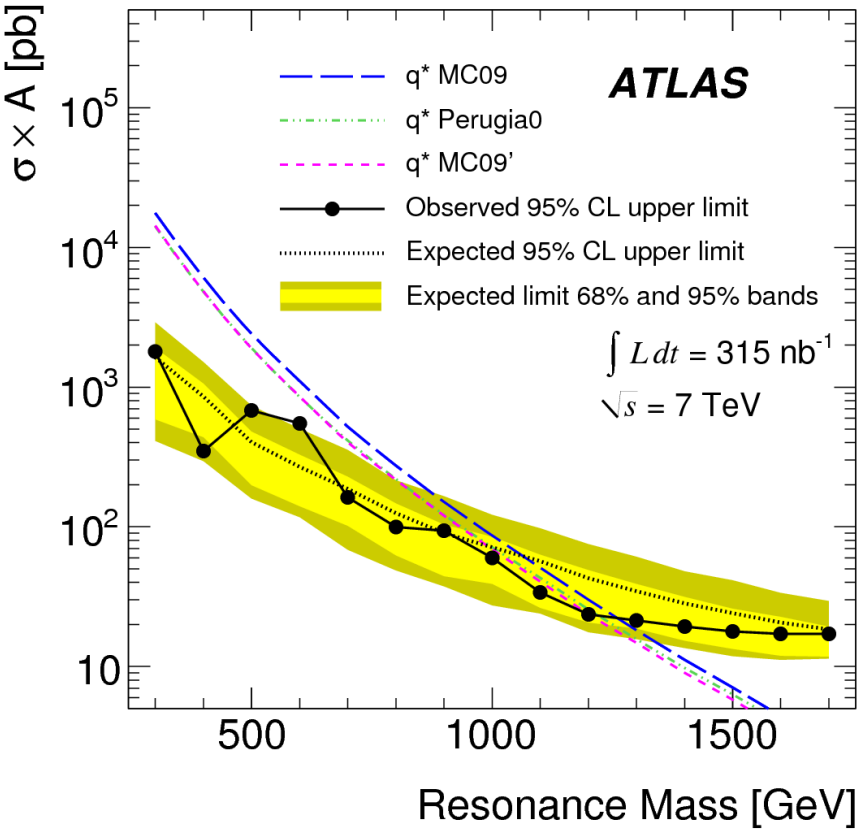



# Dijet resonance search (315 nb$^{-1}$)

- In 2010, we published first search at the LHC: **Phys. Rev. Lett. 105, 161801 (2010)** [*with G. Choudalakis*]
- With 315 nb$^{-1}$ @ sqrt(s) = 7 TeV, excited quarks with mass less than 1.25 TeV excluded at 95% CL
  - In 2012 with 5.8 fb$^{-1}$ @ sqrt(s)=8 TeV, limited extended to 3.6 TeV

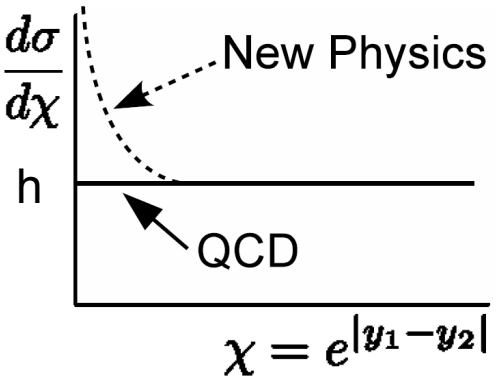


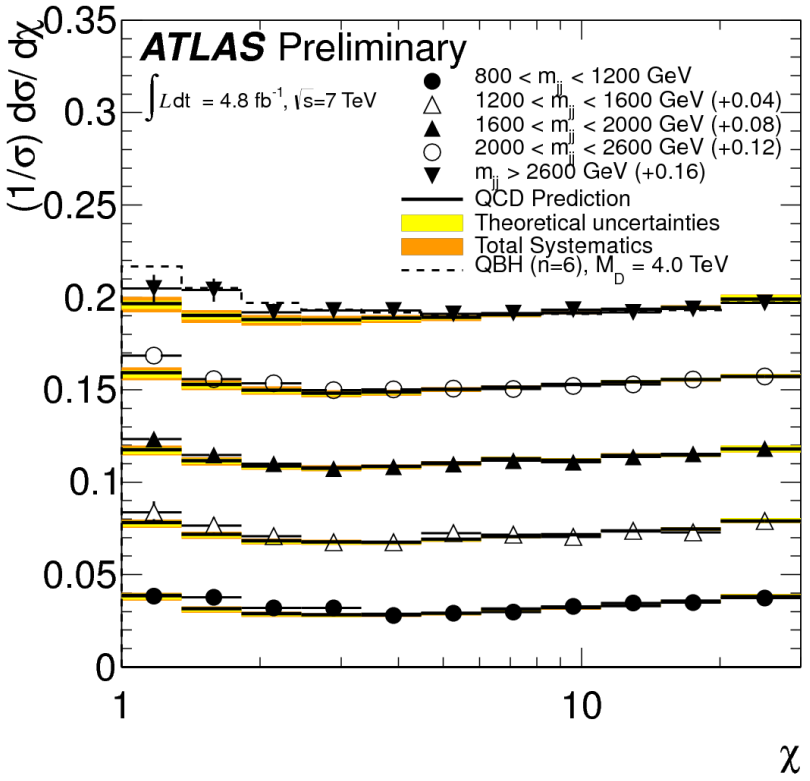



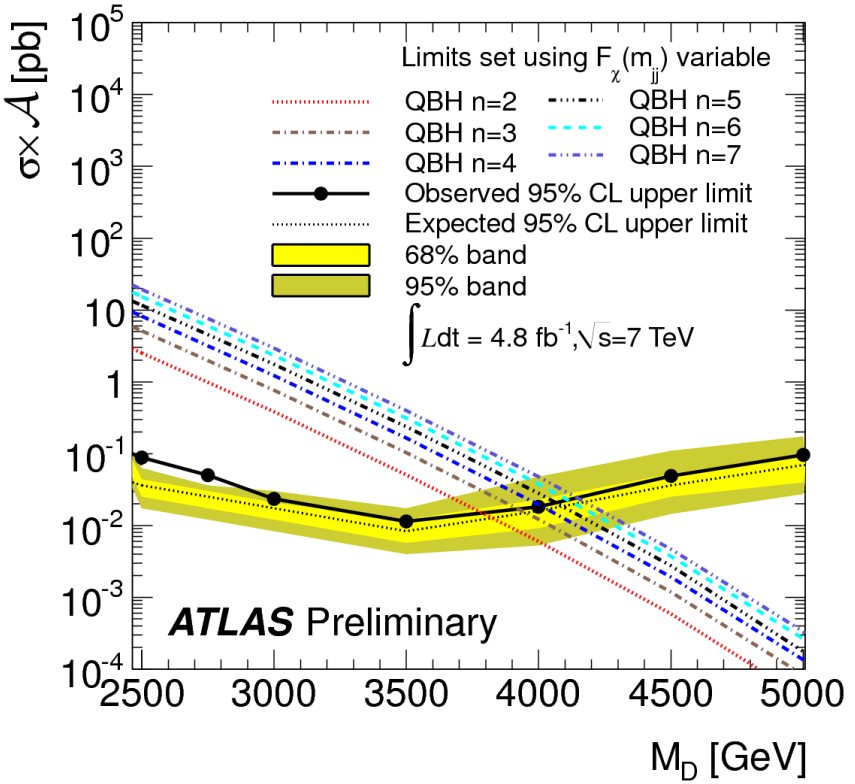
# Search for contact interactions

- We examined dijet χ angular data in 2010 for contact interactions: **New J. Phys. 13, 053044 (2011)**
  - Jim chaired Task Force to investigate feature in 7 TeV data in 2011 [*with G. Choudalakis, C. Meyer, M. Oreglia*]




- With 4.8 fb$^{-1}$ @ 7 TeV, quantum black holes with reduced Plank mass $M_D$ <~ 4 TeV (depending on n extra dimensions) excluded at 95% CL



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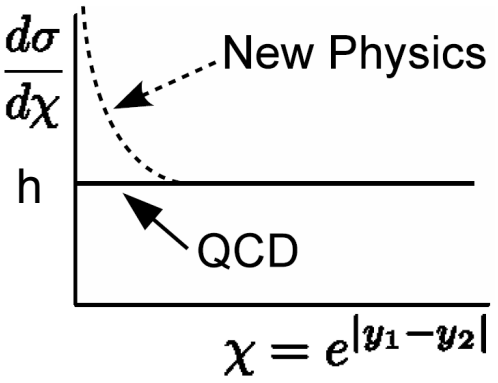


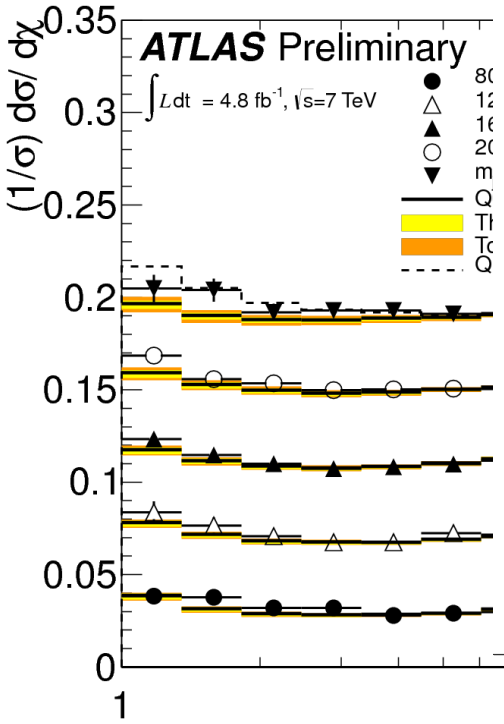


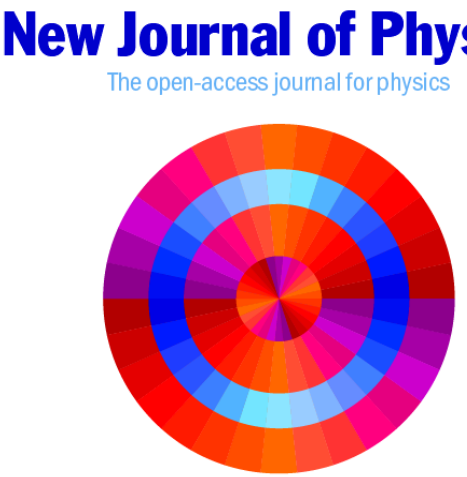

New Journal of Physics

The open-access journal for physics

This is to certify that the article

*A search for new physics in dijet mass and angular distributions in pp collisions at √s=7 TeV measured with the ATLAS detector*

by

The ATLAS Collaboration

**G Aad *et al*** 2011 *New J. Phys.* **13** 053044

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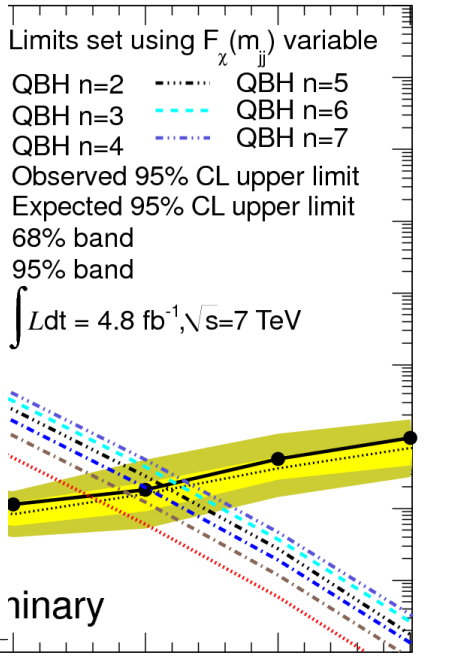
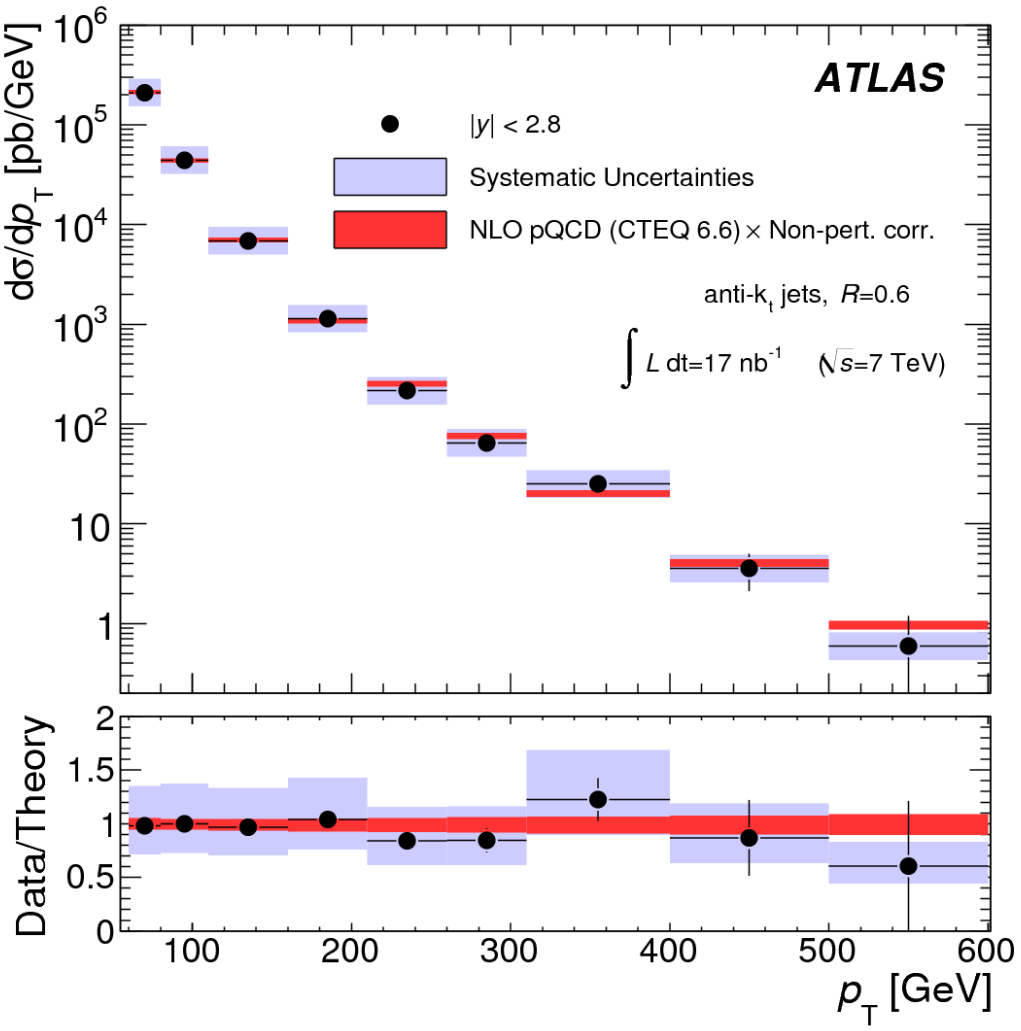


# Inclusive jet and dijet measurements

- In 2010, we measured the cross-sections for at least 1 or 2 jets using 17 $nb^{-1}$ of 7 TeV data
  - Inclusive jet pT spectrum
  - Dijet mass spectrum
- Sensitive to heavy resonances or contact interactions
- Probe of perturbative QCD and parton distribution functions
- We published the first cross-section measurements at 7 TeV:

  **Eur. Phys. J. C 71, 1512 (2011)**



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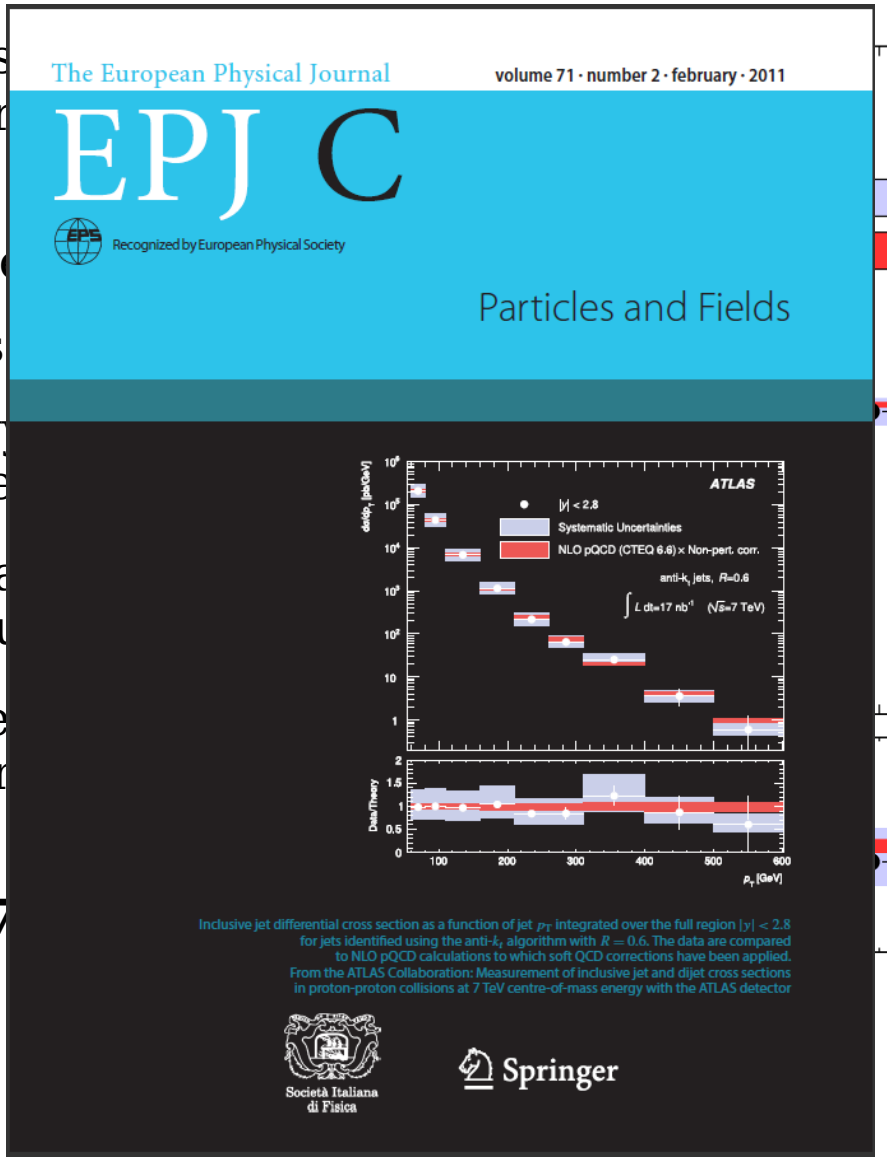
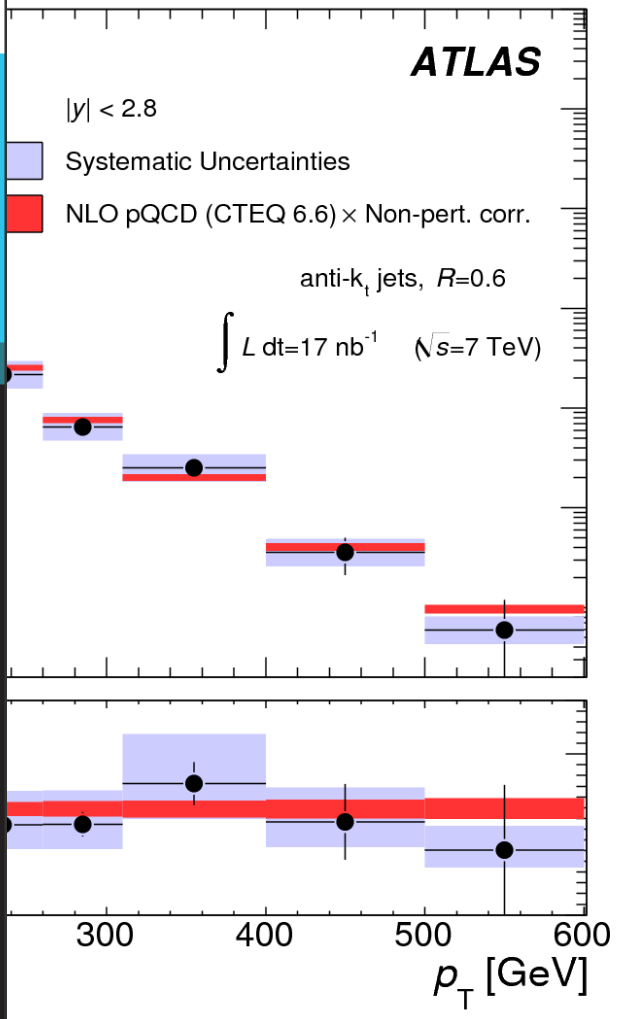
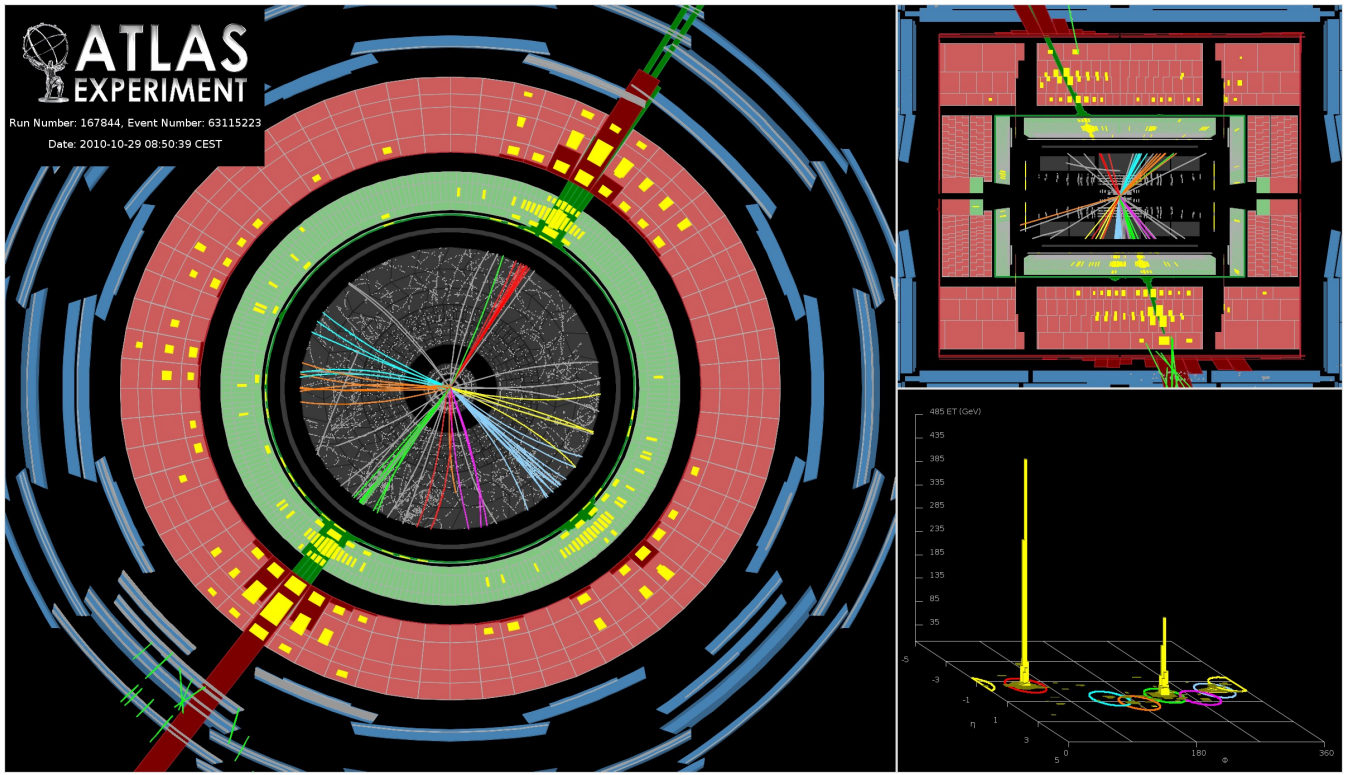


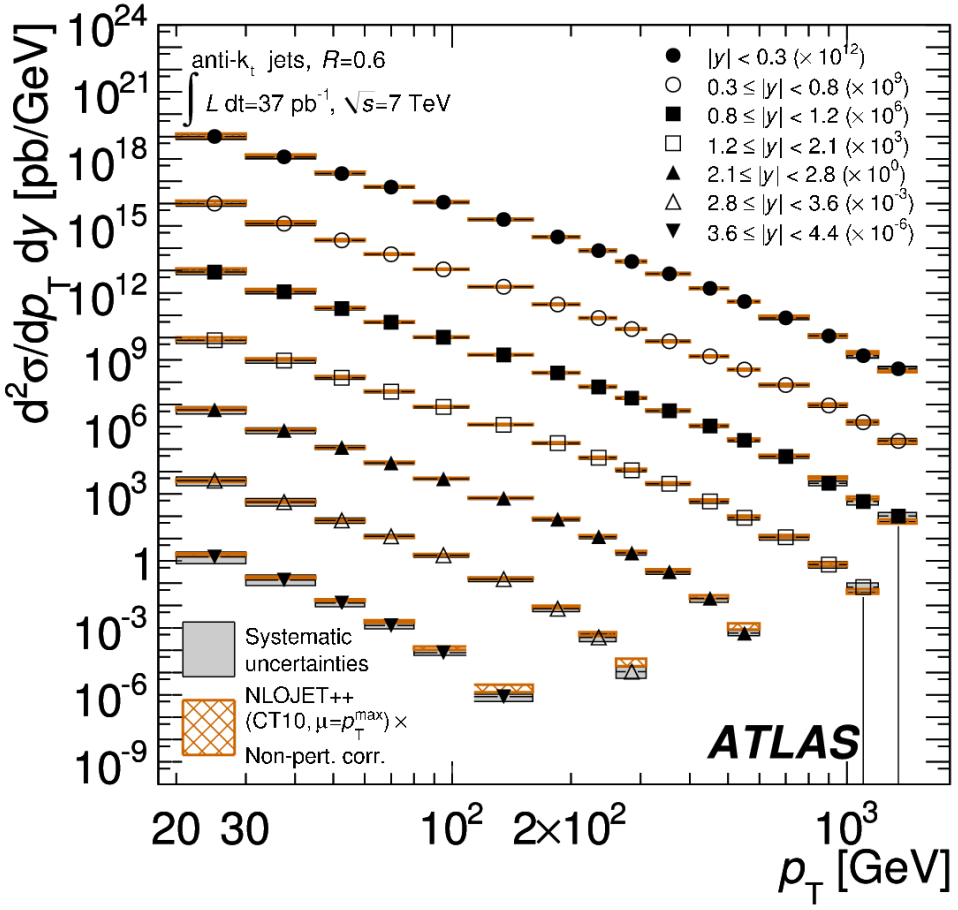
# Inclusive jet and dijet measurements

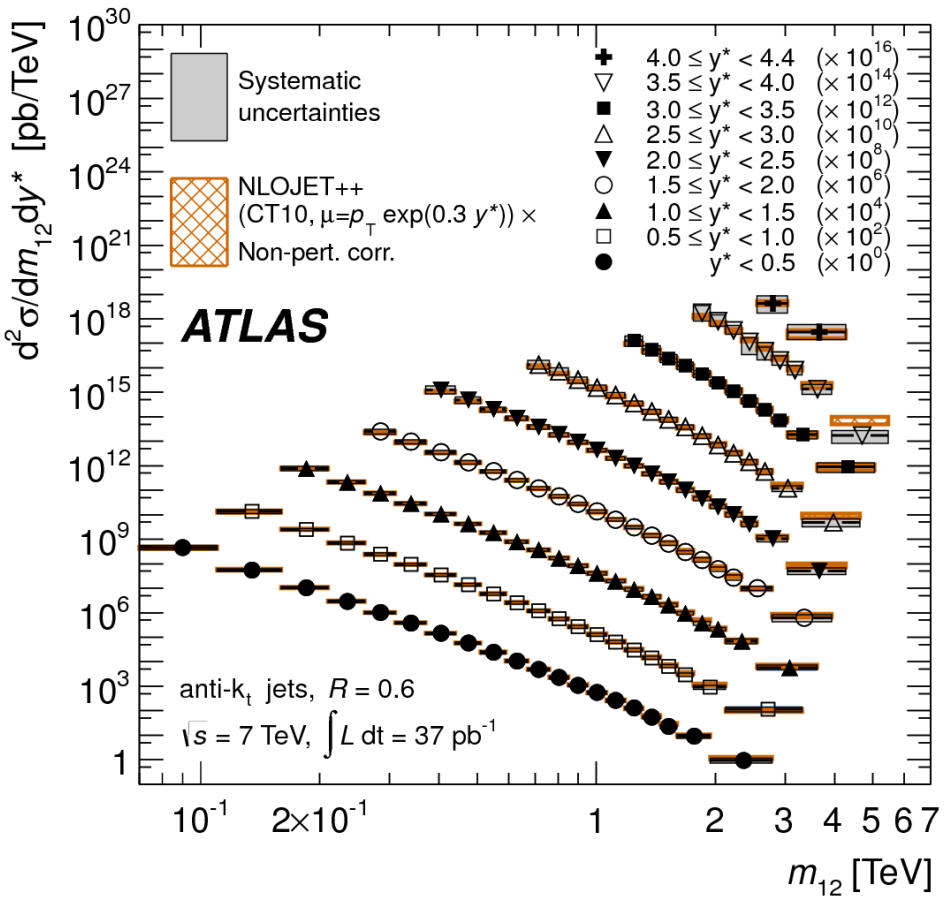
- In late 2011, we published updated measurements with full 2010 data sample of 37 $pb^{-1}$ [*my thesis; with C. Meyer, M. Oreglia*]:
  **Phys. Rev. D 86, 014022 (2012)**
- Numerous improvements (more data, lower and higher pT & mass, wider rapidity, lower systematic uncertainties, correlations in systematics, superior unfolding, NLO+PS MC, newer PDFs, etc)
- Highest-$p_T$ jet = 1.5 TeV (below) and largest dijet mass = 5 TeV



# Inclusive jet and dijet update

- Inclusive jet $p_T$ spectrum measured in 20 GeV < $p_T$ < 1.5 TeV
- Dijet mass spectrum measured in range 70 GeV < $m_{12}$ < 5 TeV
- Data described by NLO QCD over 10 orders of magnitude in cross-section
  - Still best such measurements at LHC



# Inclusive jet and dijet update

- Inclusive jet $p_T$ spe … TeV
- Dijet mass spectru… 5 TeV
- Data described by … e in cross-section
  - Still best s…

International Journal of High-Energy Physics



CERN COURIER

Jun 6, 2011

## ATLAS explores new frontiers with high-$p_T$ jet measurements

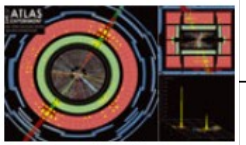


Fig. 1.

The ATLAS collaboration has announced its latest cross-section measurements of inclusive jet and dijet production, which involve final states containing at least one or two jets, respectively. Each jet is the result of a parton (quark or gluon) that emits radiation through the strong force, creating a collimated spray of hadrons.

These high-$p_T$ jet measurements confront QCD, the theory of the strong force, in a large and previously unexplored kinematic region in jet transverse-momentum and dijet invariant-mass. The measurements constitute one of the most stringent tests of QCD ever performed. They probe predictions of perturbative QCD, constrain the density of partons within the proton and are sensitive to new physics scenarios, such as quark compositeness, which may become apparent at very short distance scales.

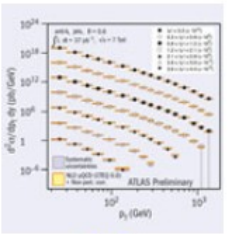
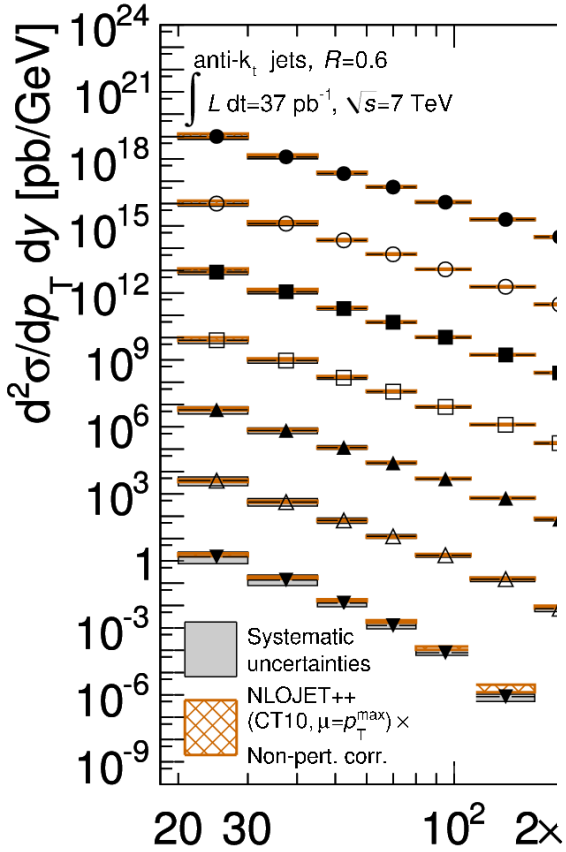
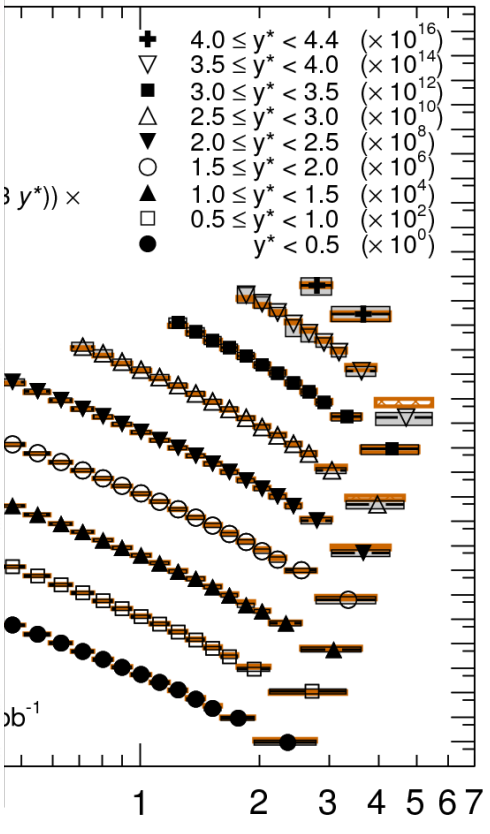


Fig. 2.

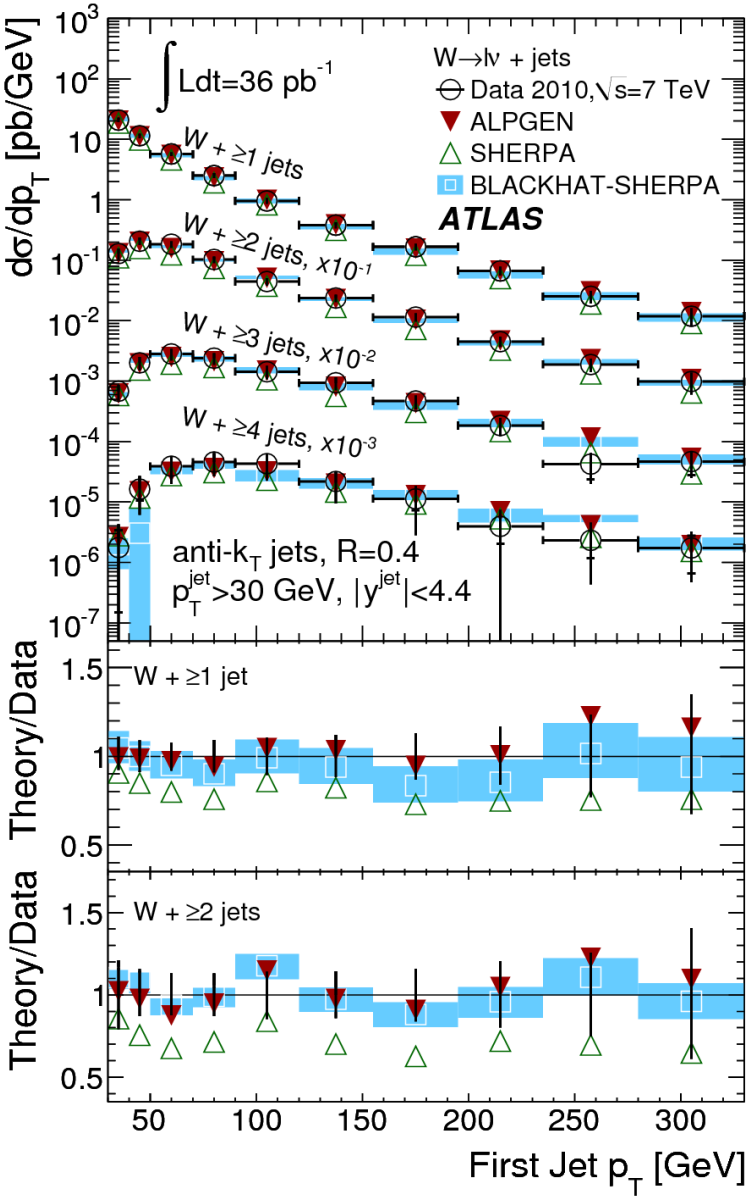
The analysis uses the full data sample collected in LHC proton-proton collisions at 7 TeV during 2010, corresponding to an integrated luminosity of 37 pb$^{-1}$. The results extend far beyond the kinematic reach achieved at the Tevatron, as do recent results from CMS (CMS collaboration 2011). The ATLAS results extend to 1.5 TeV in jet transverse-momentum (as in figure 1)



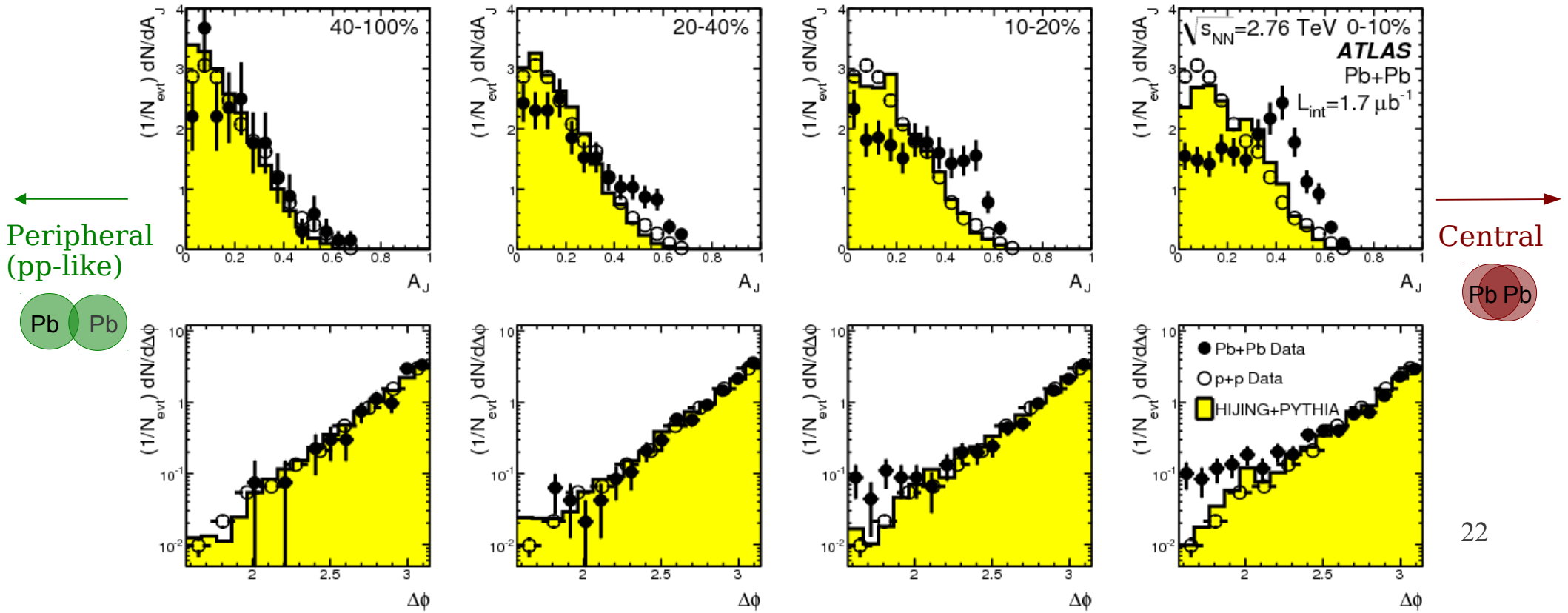
# W+jets measurements

- Measured cross-section for jets produced in association with W boson
  - Jet multiplicity, pT spectra, angular distributions, etc.
  - Tests of perturbative QCD
- ALPGEN generally describes data better than SHERPA (LO+PS)
  - SHERPA undershoots data
  - BLACKHAT+SHERPA (NLO+PS) also consistent as expected
- **Phys. Rev. D85, 092002 (2012)**
  **Phys. Lett. B698, 325-345 (2011)**
- [*I. Jen-La Plante's thesis (Jim's student); M. Dunford, M. Fiascaris, S. Paramonov (ANL)*]



# Jets in heavy ion collisions

- In late 2010, we observed jet quenching in 1.7 $\mu b^{-1}$ of data from lead ion collisions @ 2.76 TeV: **Phys. Rev. Lett. 105, 252303 (2010)**
- In "peripheral" lead ion collisions, dijet $p_T$ asymmetry $A_J=(p_{T,1}-p_{T,2})/(p_{T,1}+_{pT,2})$ similar to that in *pp* data
- Much larger $p_T$ asymmetry for "central" collisions, though $\Delta\varphi$ similar
  → Sub-leading jet is quenched



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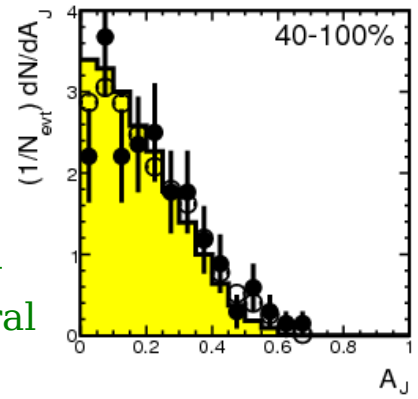
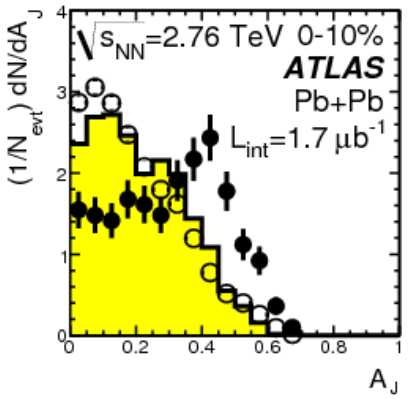
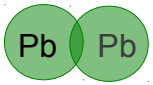
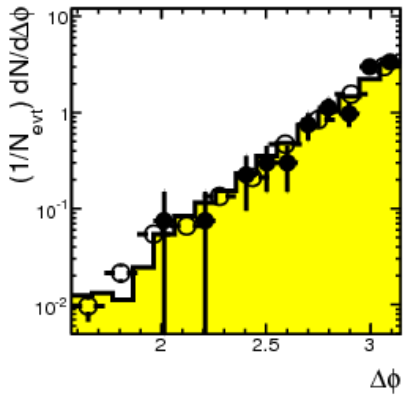


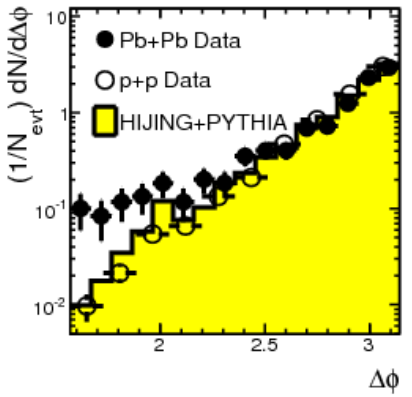




Peripheral (pp-like)




Central

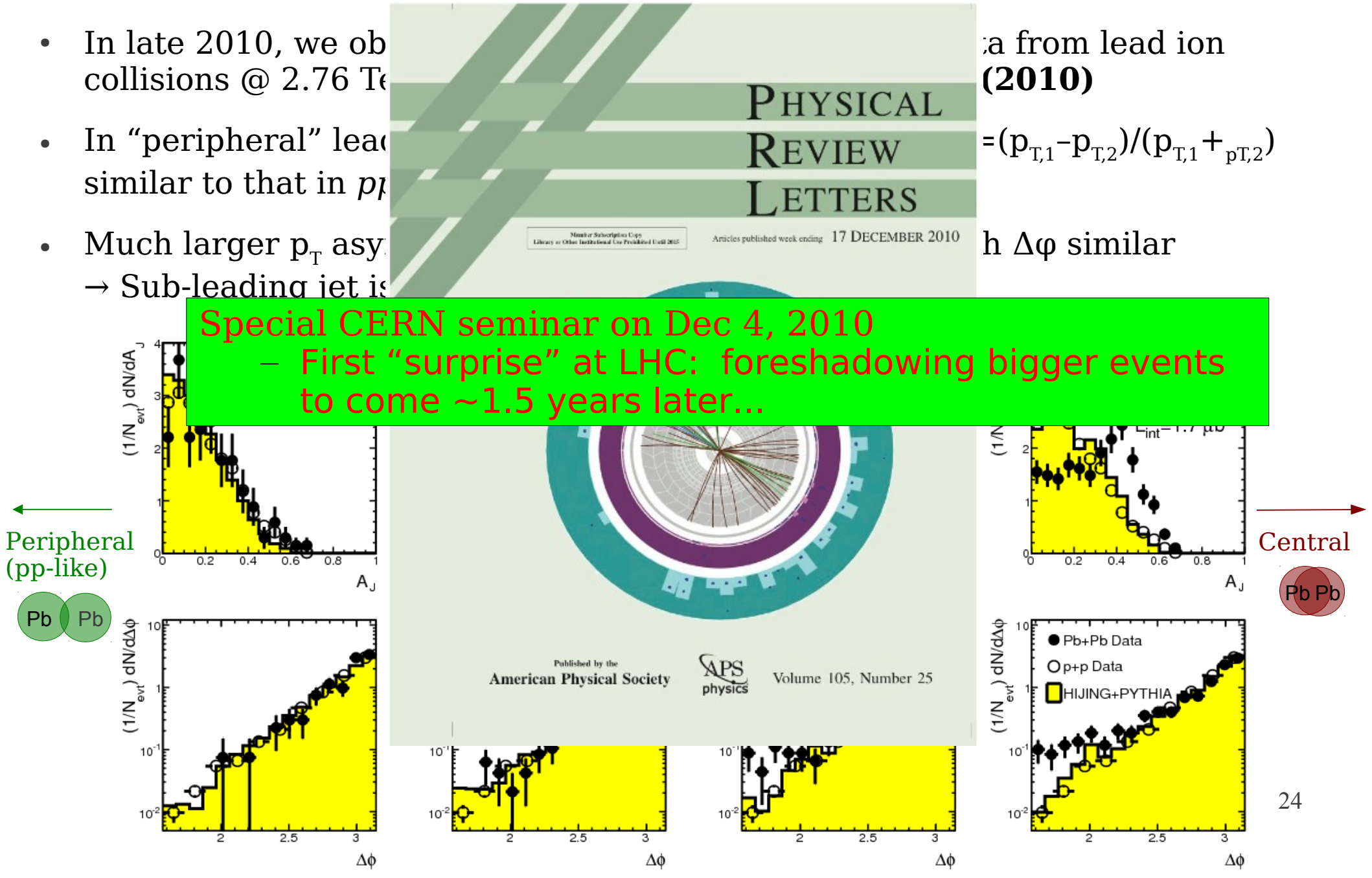



# Jets in heavy ion collisions

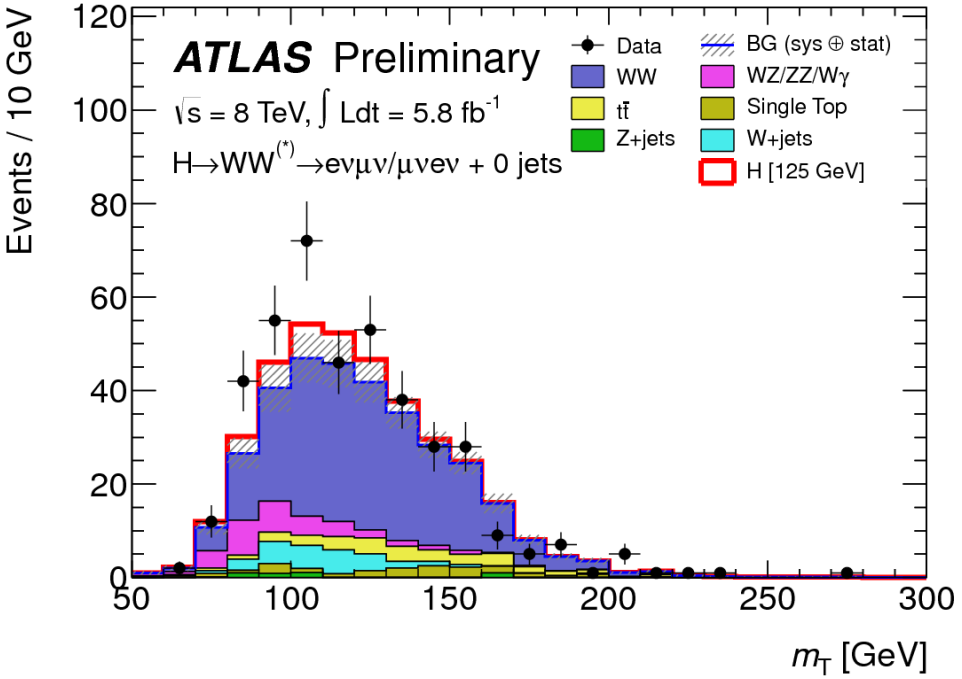
- In late 2010, we ob :a from lead ion collisions @ 2.76 Te **(2010)**
- In "peripheral" lea =$(p_{T,1}-p_{T,2})/(p_{T,1}+_{pT,2})$ similar to that in *p*
- Much larger $p_T$ asy h Δφ similar
  → Sub-leading jet is

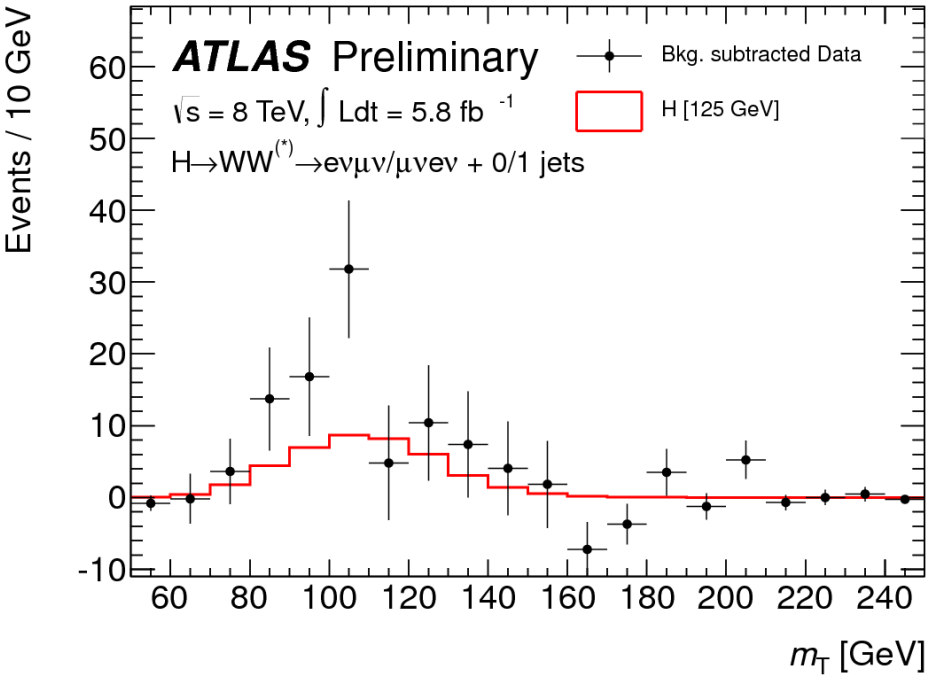
Special CERN seminar on Dec 4, 2010
– First "surprise" at LHC: foreshadowing bigger events to come ~1.5 years later...



# Search for H->WW

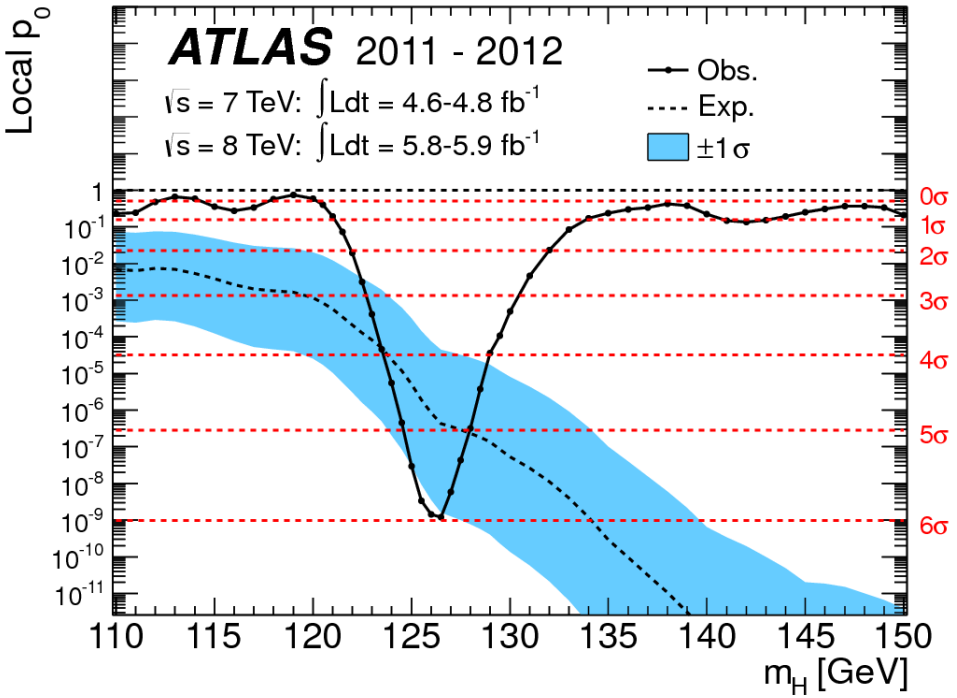
- In 2012, searched for Higgs boson in H->WW->lvlv final state [*with A. Boveia, P. Onyisi*]: **ATLAS-CONF-2012-098**
  - Fully blind analysis: only unblinded upon demonstrating good modeling of all backgrounds in respective control regions
    - Responsible for quantifying background modeling in CR's
  - Observed excess in WW transverse mass distribution corresponding to 2.8 sigma (“evidence”)

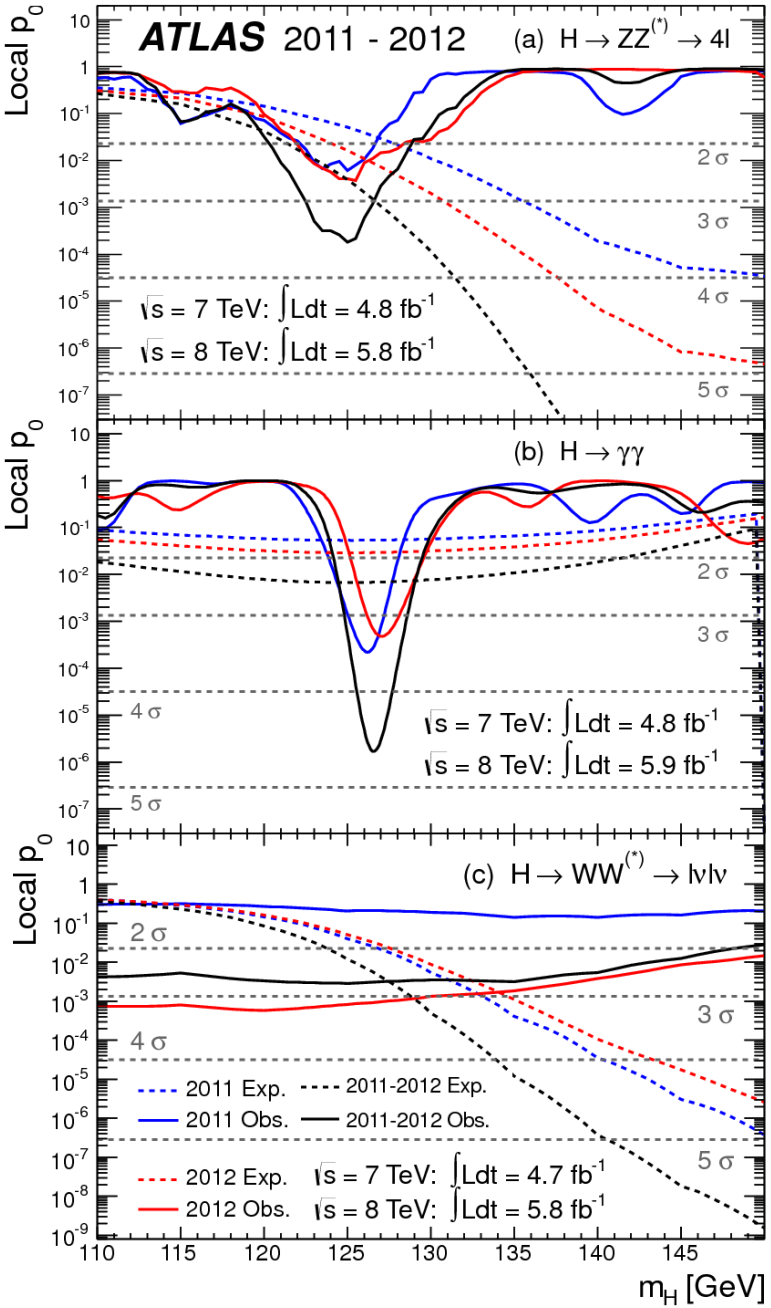


# Discovery of a Higgs-like boson

- Higgs(-like) discovery announced at CERN seminar on July 4, 2012
- 6.0 σ excess in discovery publication: **Phys. Lett. B 716, 1 (2012)**
  - ZZ: 3.6 σ
  - γγ: 4.5 σ
  - WW: 2.8 σ



# Discovery of a Higgs-like boson

- Higgs(-like) disco
  CERN seminar o
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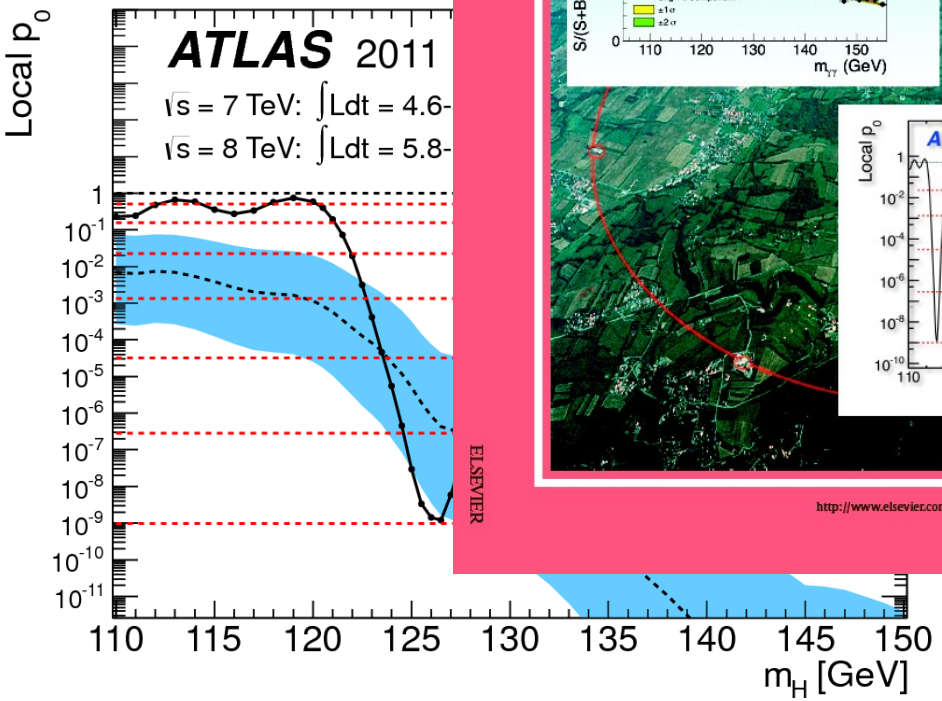
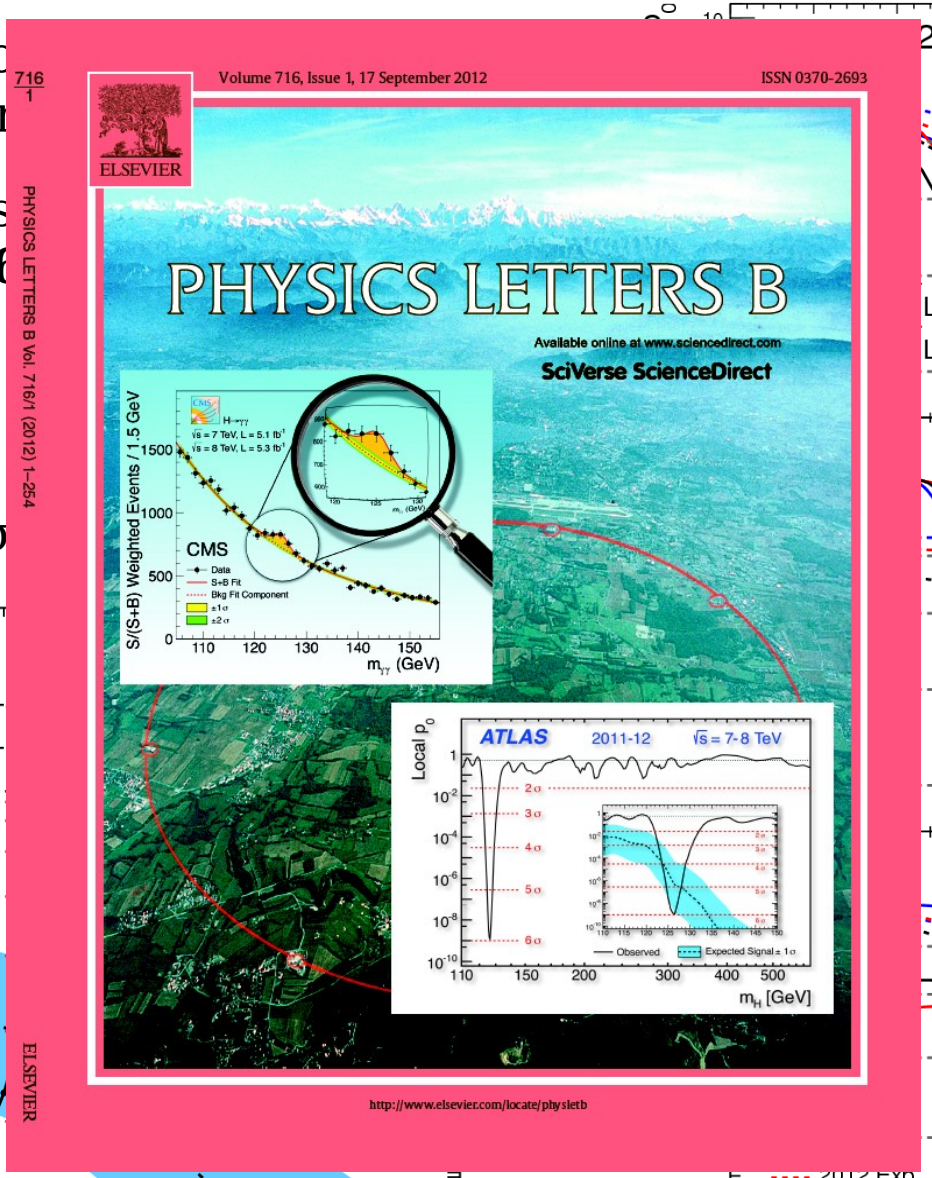
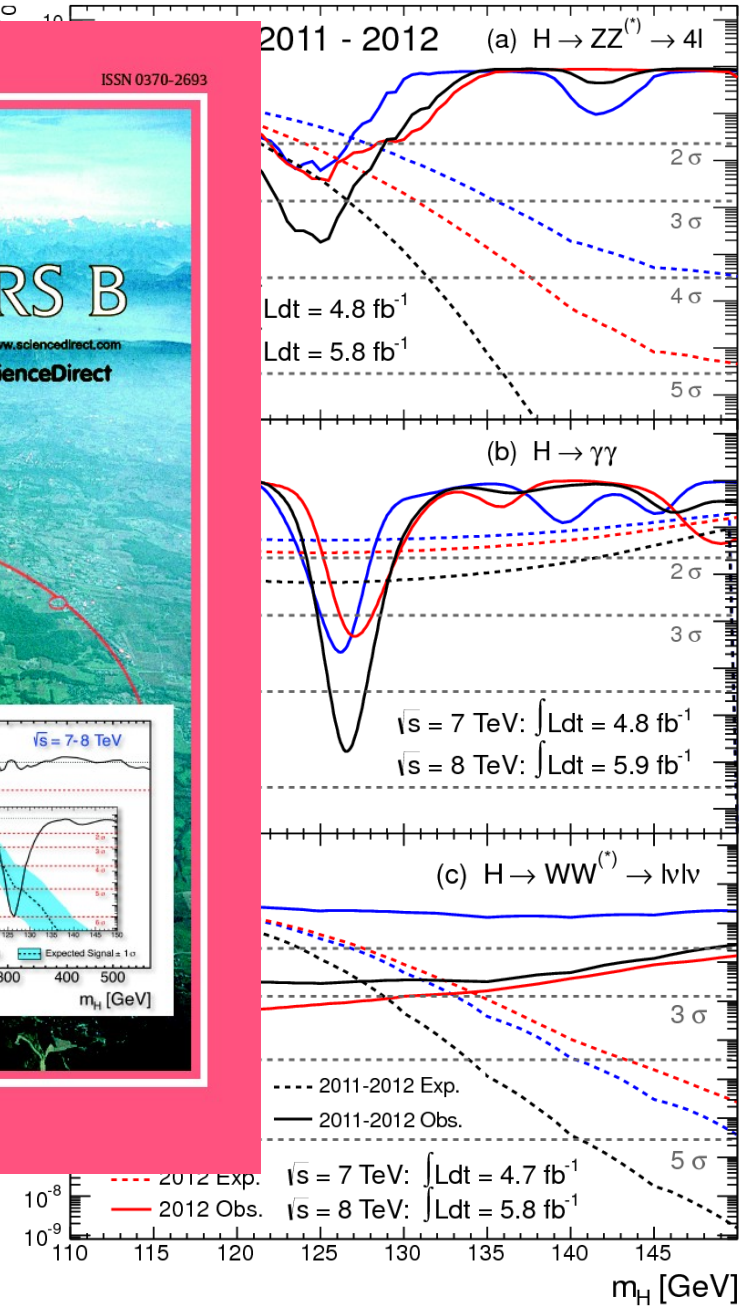
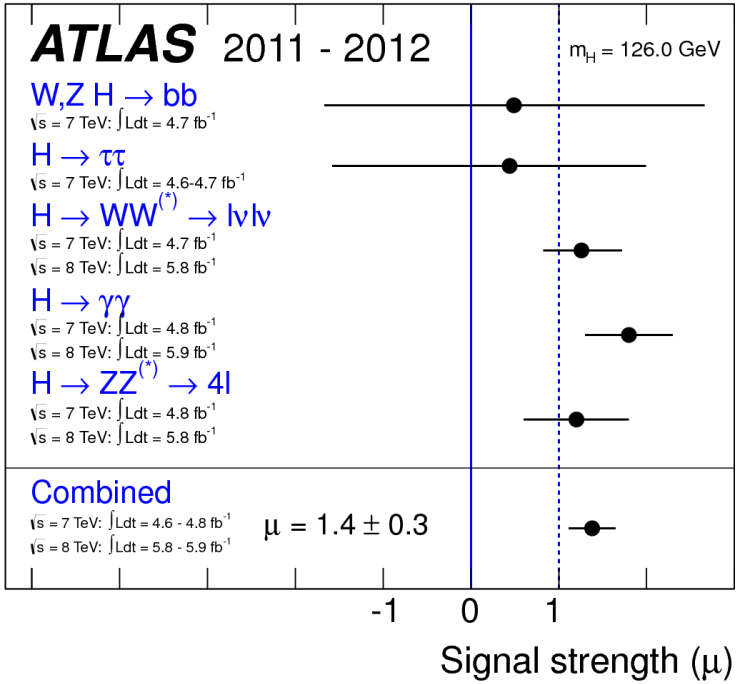


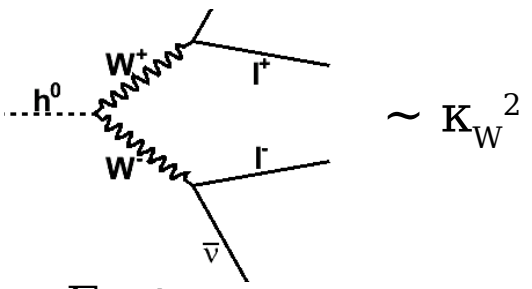



# Higgs coupling measurements

- One of most exciting and highest priority questions in HEP is whether the newly discovered particle is *the* SM Higgs boson, a Higgs boson in a BSM scenario, or a different particle altogether
  - Need to measure its spin, CP, and couplings
- Performed first Higgs coupling measurements (from LHC experiment): **ATLAS-CONF-2012-127**
- For each coupling $g_i$, introduce scaling from its SM value as: $\kappa_i = g_i/g_{i,SM}$
  - Defined in analogy to signal strength $\mu = \sigma/\sigma_{SM}$
- Make simple assumptions (universality) to reduce DOF's and probe particular symmetries
- Combined fit for coupling parameters $\kappa_i$

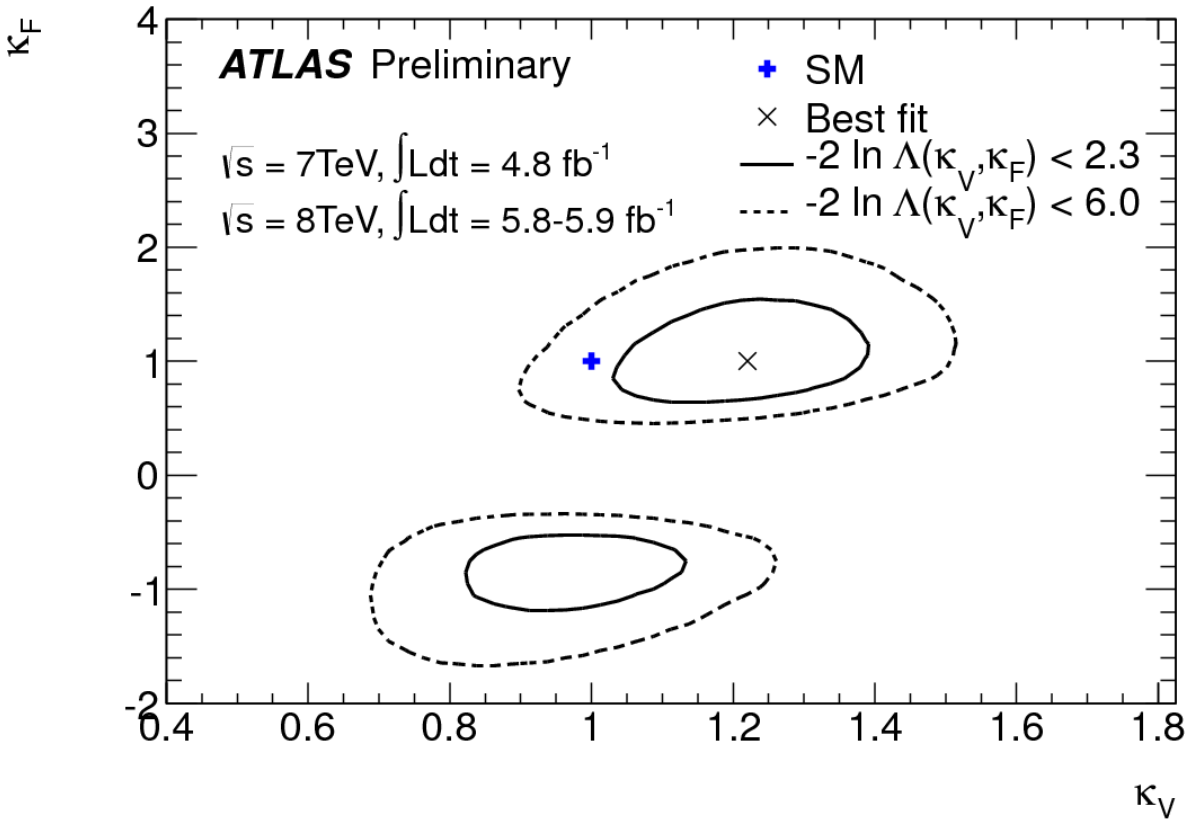


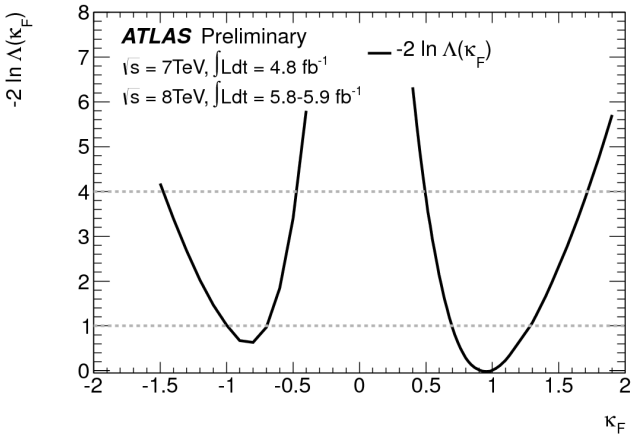



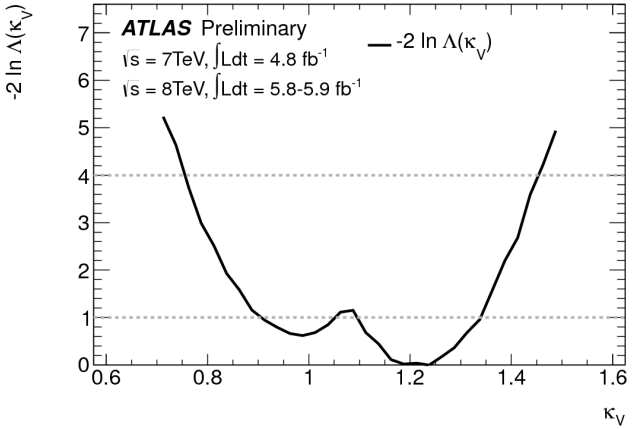

$\sim \kappa_W^2$

# Weak boson & fermion couplings

- For example, assume couplings to (weak) vector bosons are all scaled by some universal value: $\kappa_V = \kappa_W = \kappa_Z$
  - Similarly for fermions: $\kappa_f = \kappa_t = \kappa_b = \kappa_\tau = \ldots$
  - Assume no invisible decays of Higgs

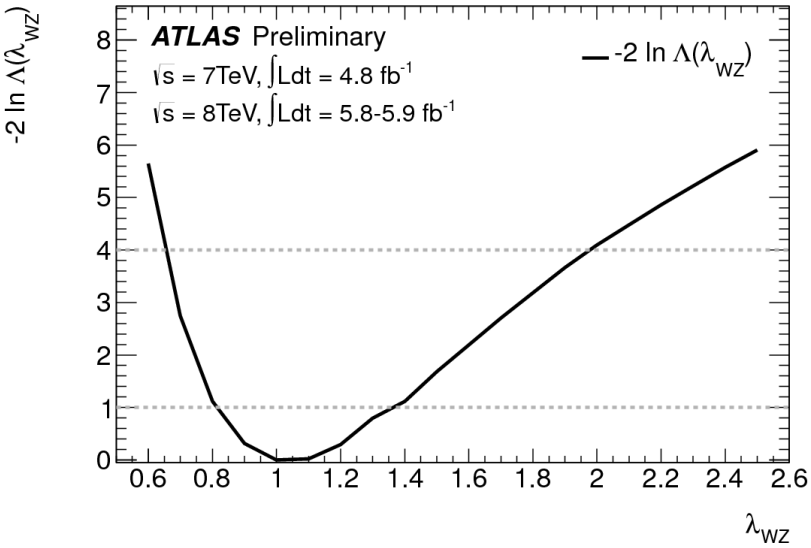


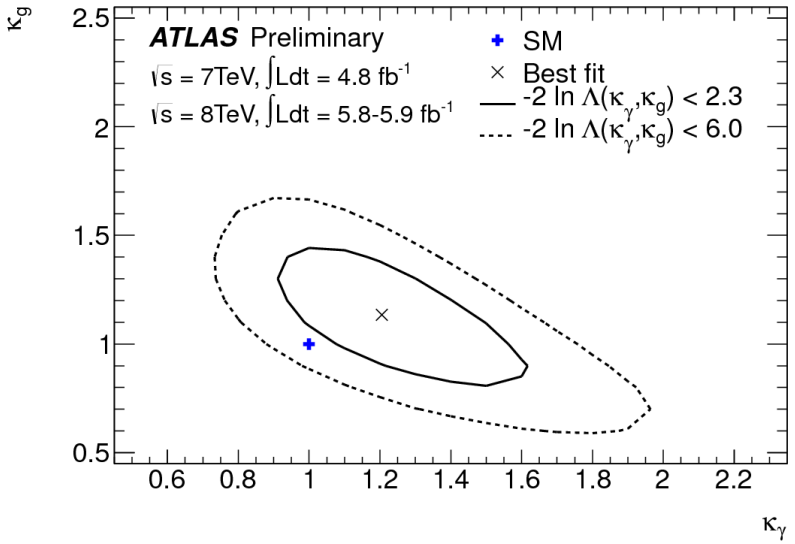



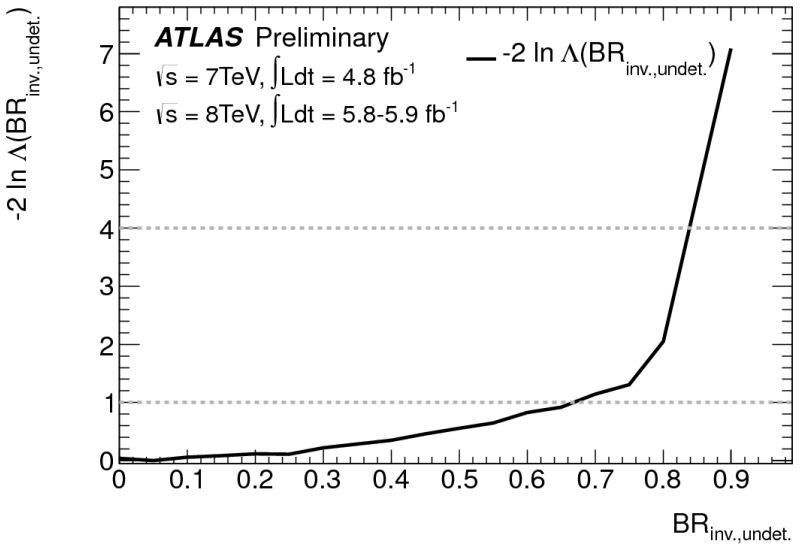



# Custodial symmetry & loop couplings

- With independent scalings of W, Z couplings: $\lambda_{WZ} = \kappa_W / \kappa_Z = 1.07$ (+0.35 -0.27)
  - Custodial symmetry (W vs. Z boson) respected
- With effective loop couplings to photons ($\kappa_\gamma$) and gluons ($\kappa_g$), best-fit values are close to 1
  - *If* one assumes SM tree-level couplings $\kappa_V = \kappa_f = 1$, one can extract the invisible branching ratio: $BR_{inv} < 0.65$ @ 68% CL

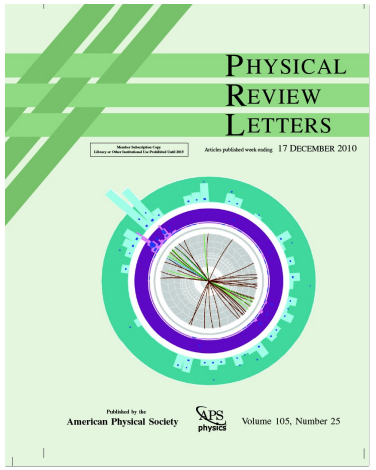


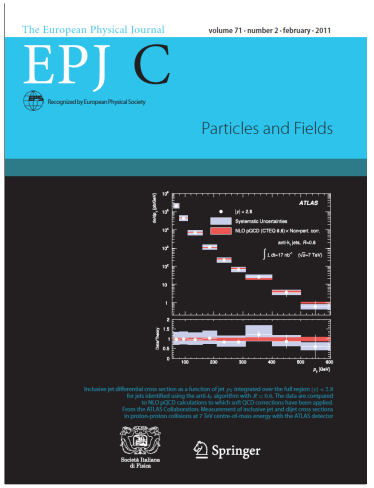



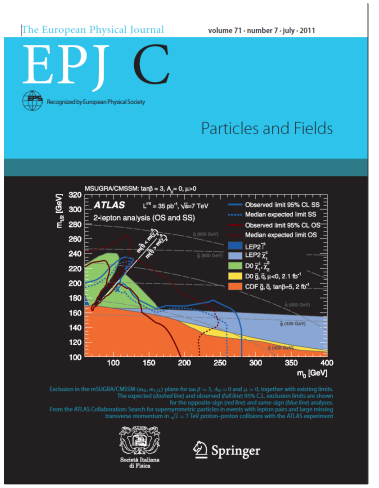
# ATLAS journal covers

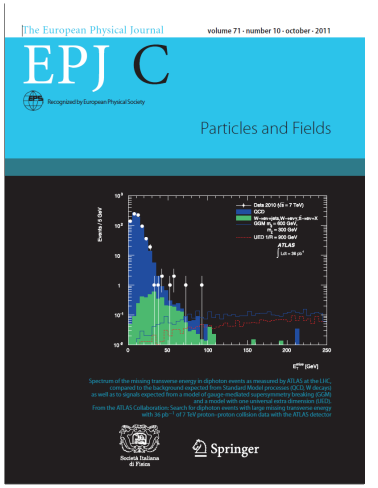
- 10 ATLAS publications have been highlighted with journal covers
  - 2 PRL, 6 EPJC, 1 NJP, and 1 PLB

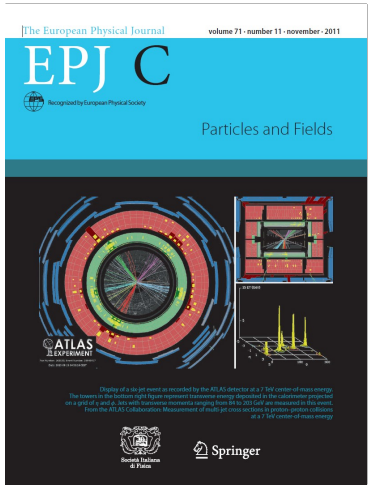




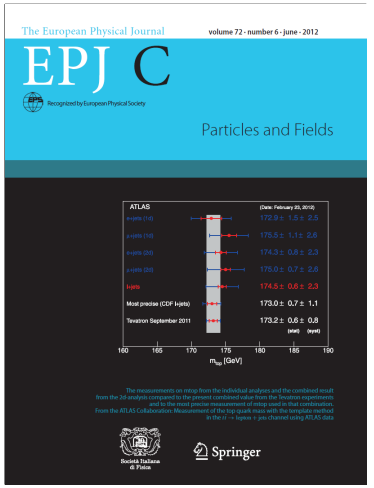


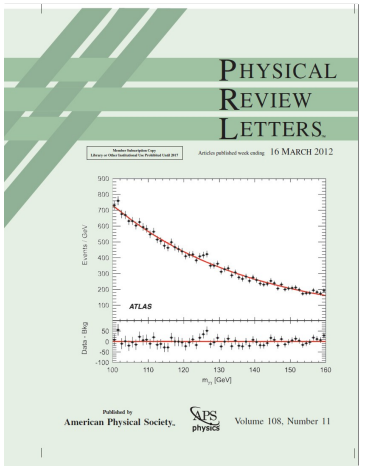



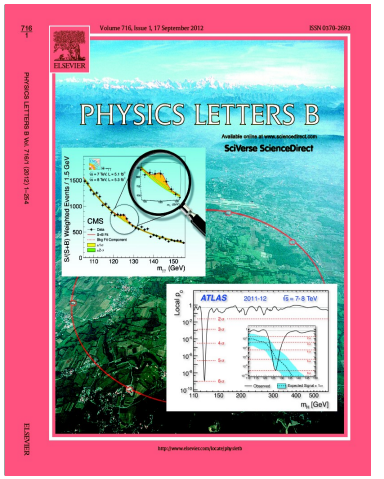





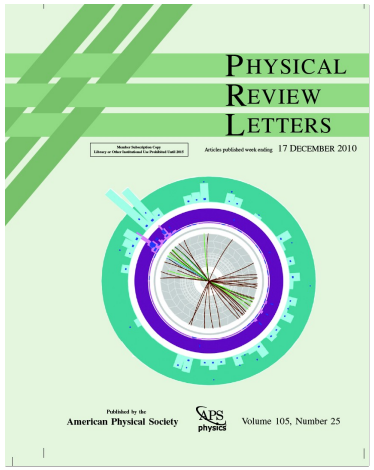


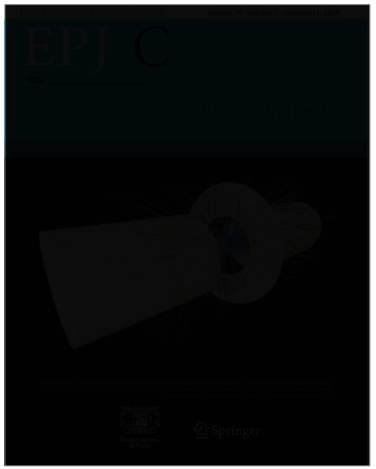



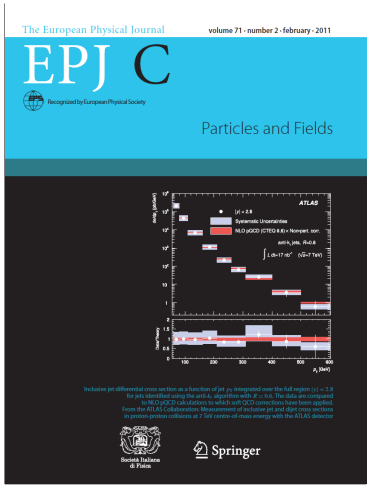



# ATLAS journal covers

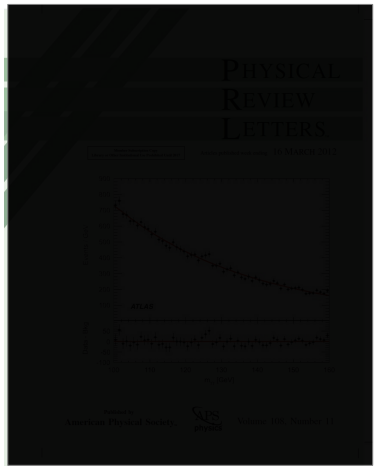
- 10 ATLAS publications have been highlighted with journal covers
  - 2 PRL, 6 EPJC, 1 NJP, and 1 PLB
- **I'm proud to say that 4 out of 10 were produced by Jim's students and postdocs as primary authors!**

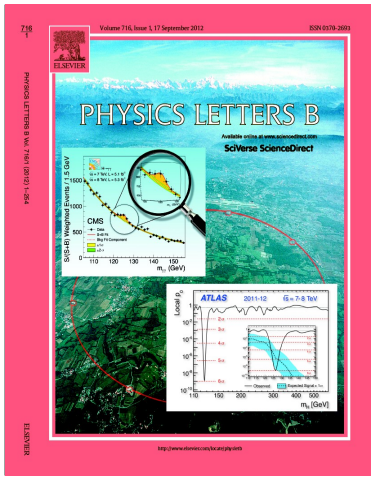


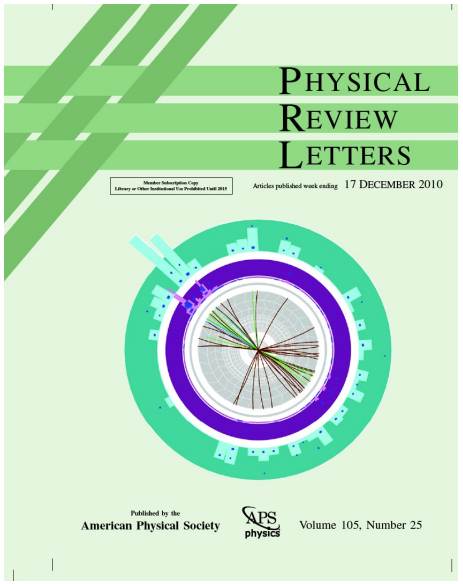


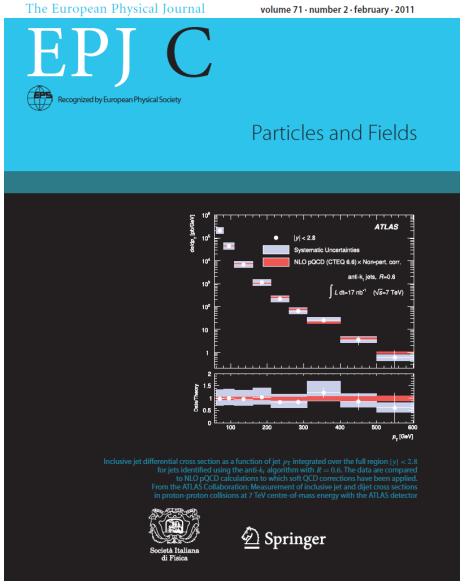




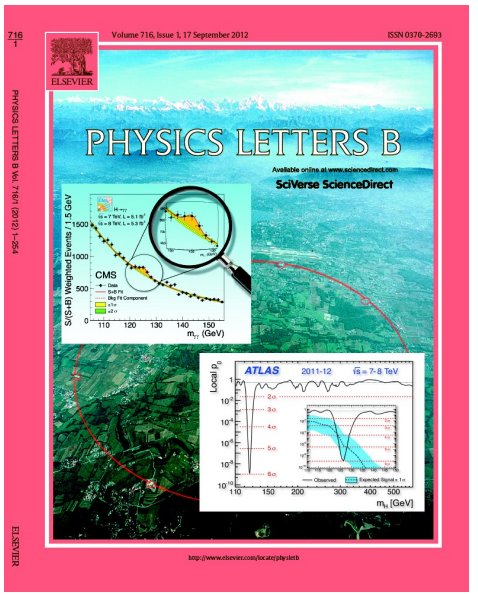



# Jim's journal covers



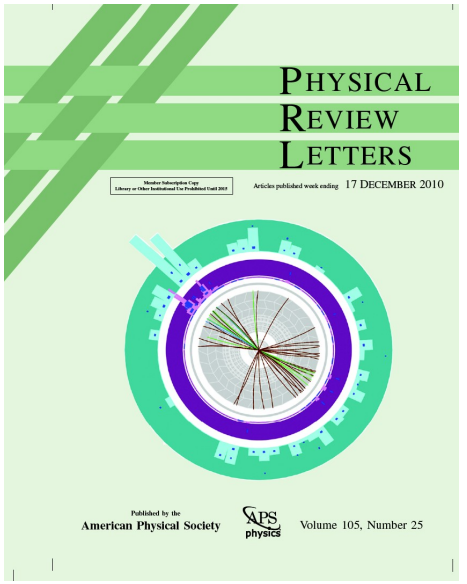


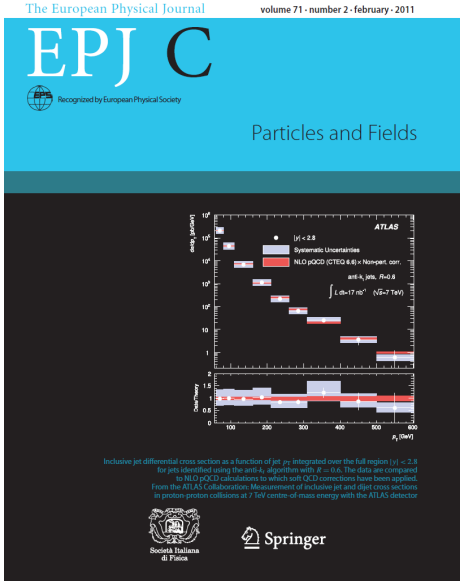


# Conclusions

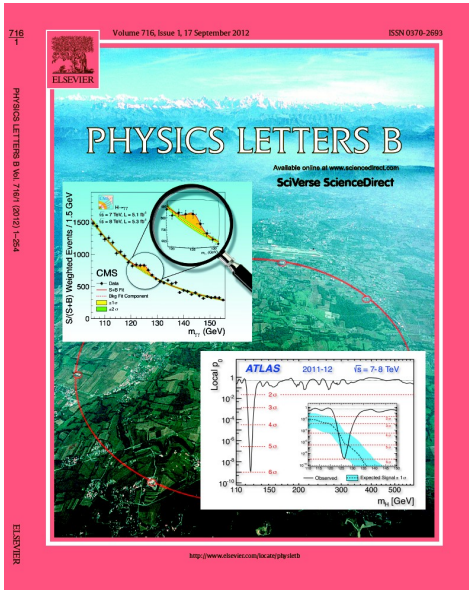
*Dear Jim:*

*Congratulations on a wonderful career, warmest thanks for all your guidance and friendship, and best wishes for continued success as emeritus!*

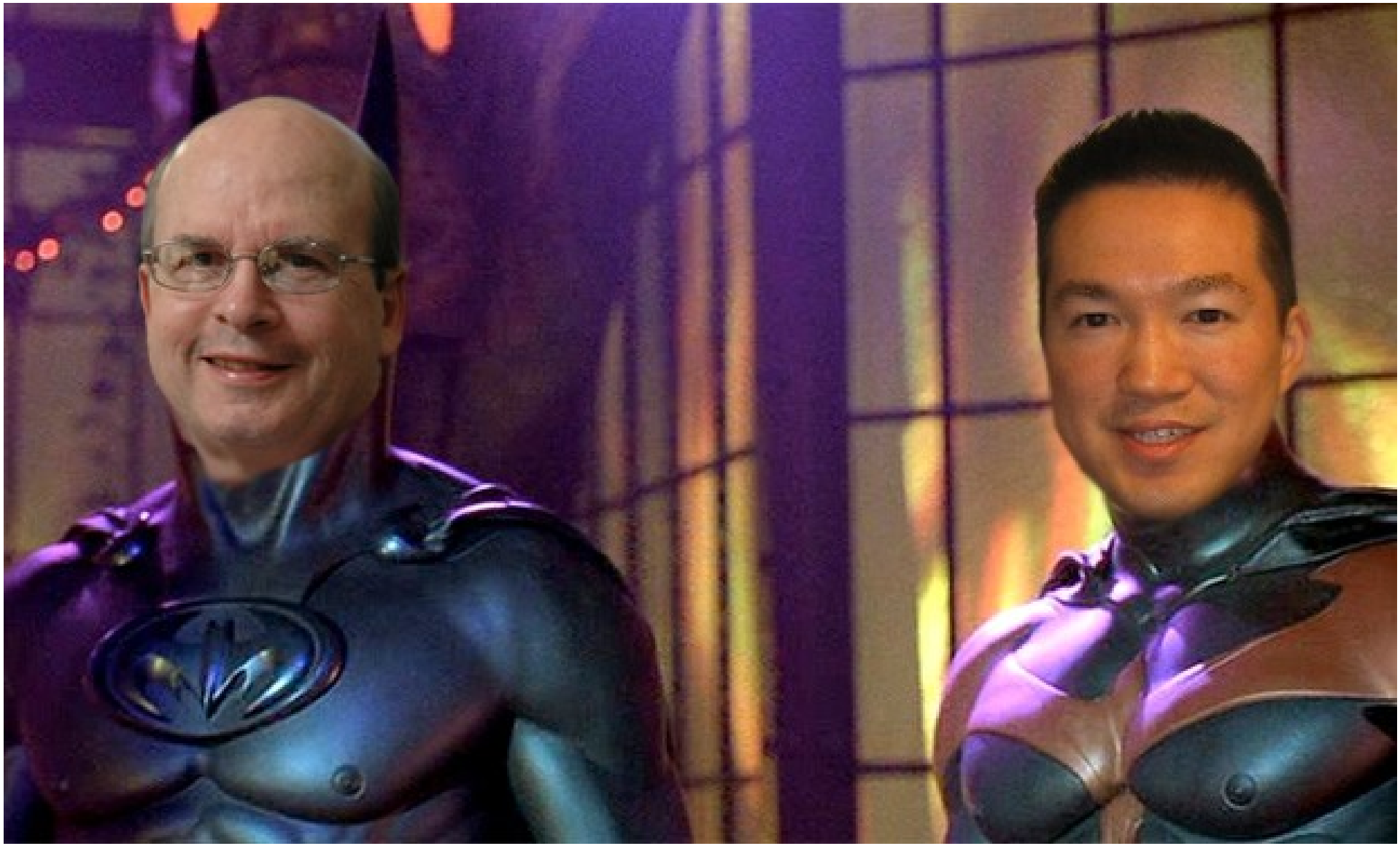




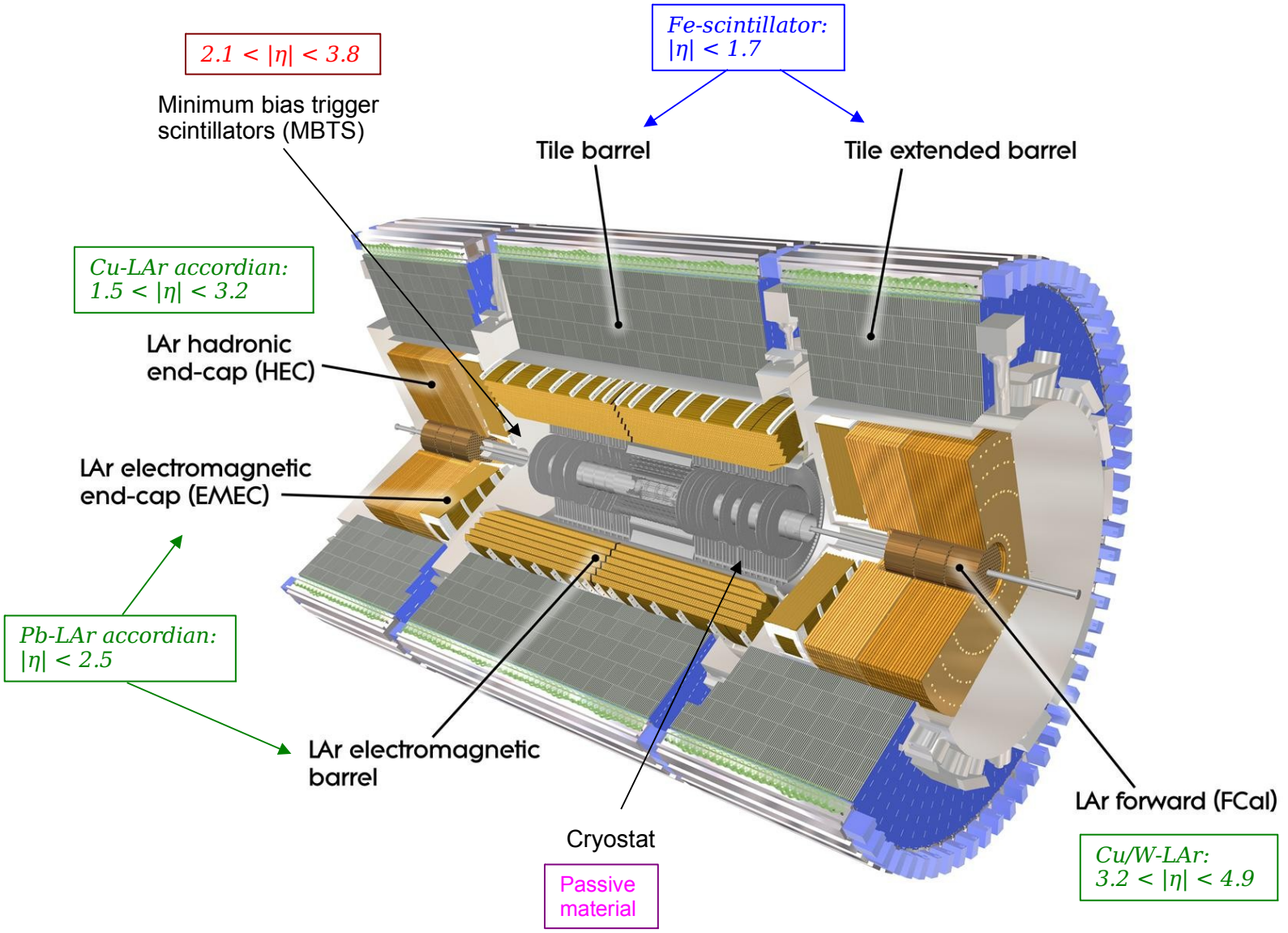


# Congratulations!



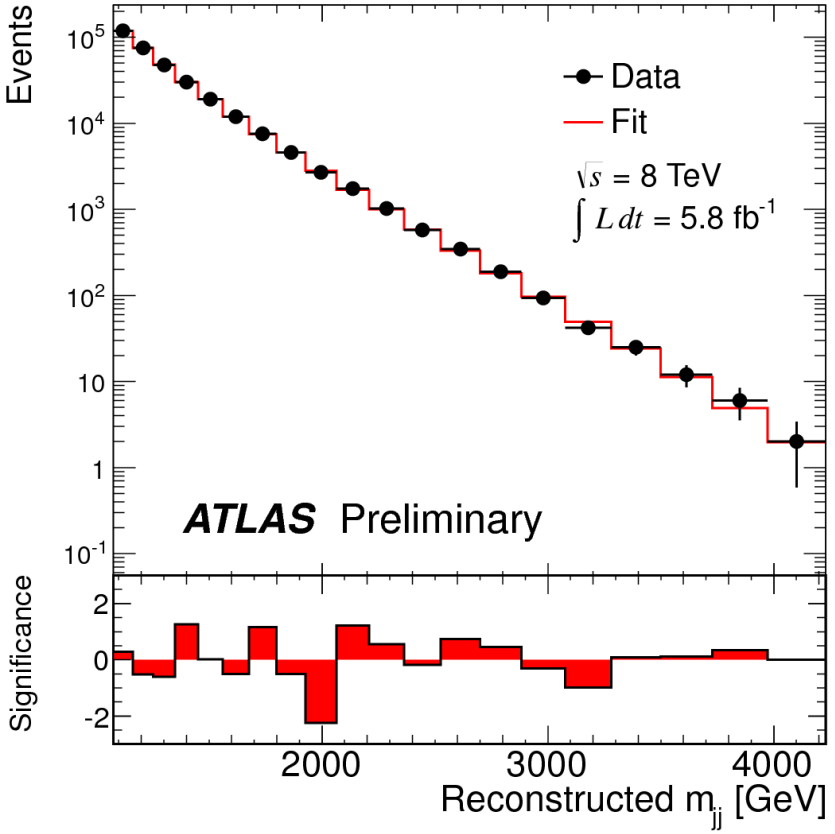
# ADDITIONAL INFORMATION

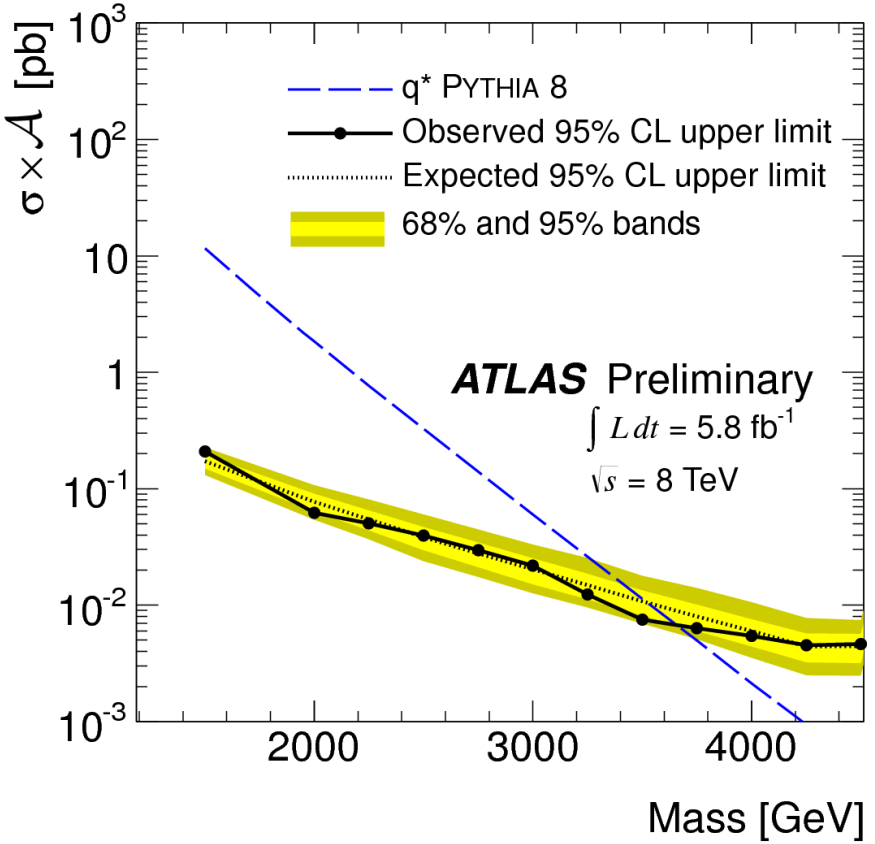
# ATLAS Tile Calorimeter



# Dijet resonance search (5.8 $fb^{-1}$)

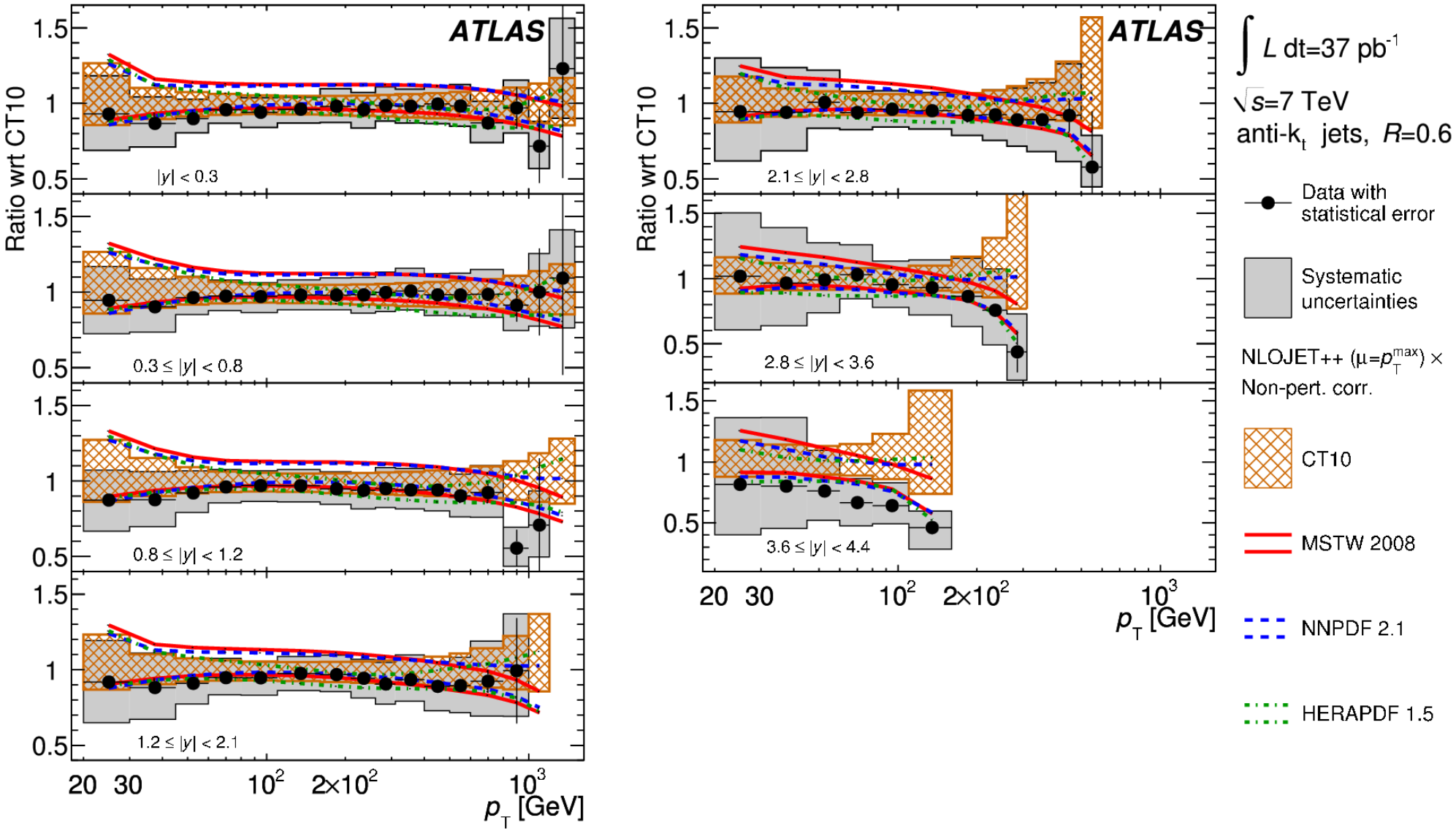
- In 2012 with 5.8 $fb^{-1}$ @ sqrt(s)=8 TeV, excited quarks with mass less than 3.6 TeV excluded at 95% CL:
  - Dijet mass spectrum extended to ~4.2 TeV
  - **ATLAS-CONF-2012-088**



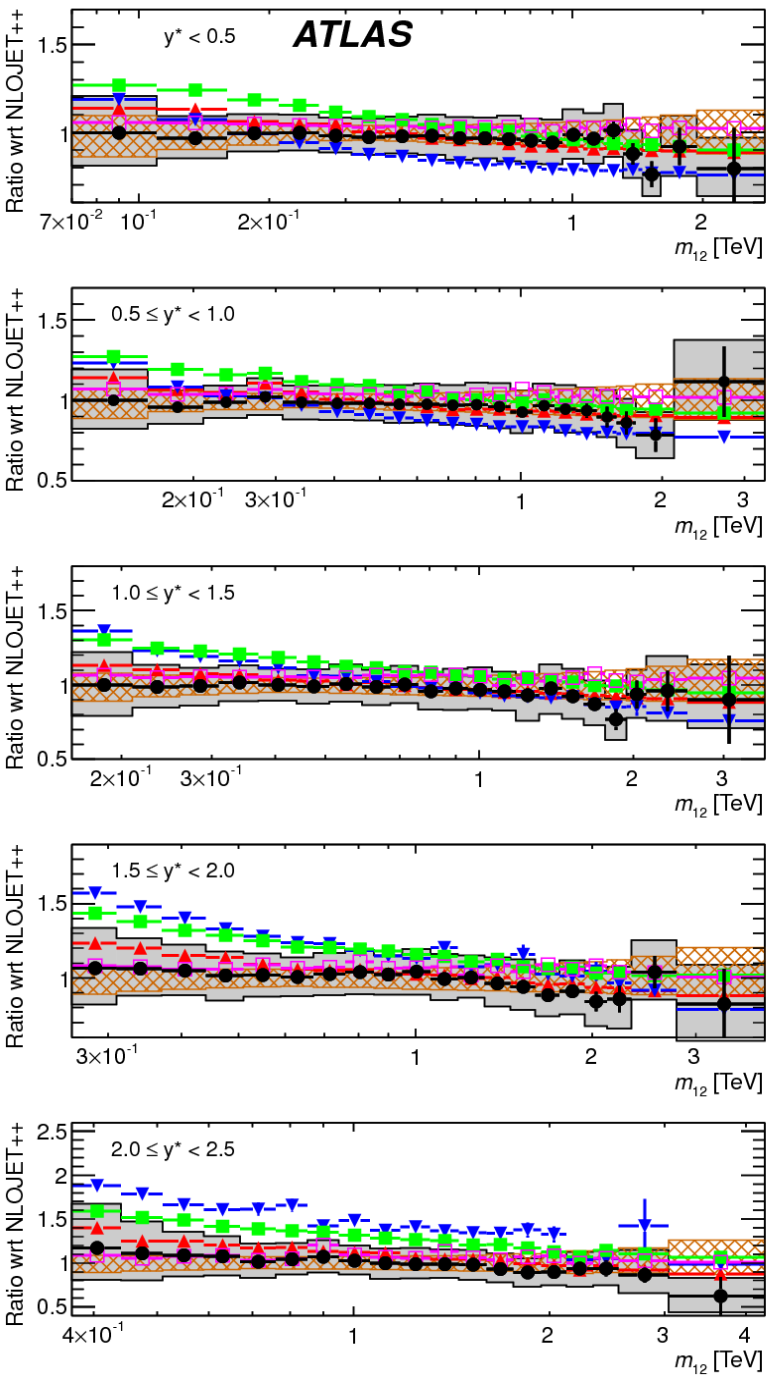



# Inclusive jet comparisons to PDFs

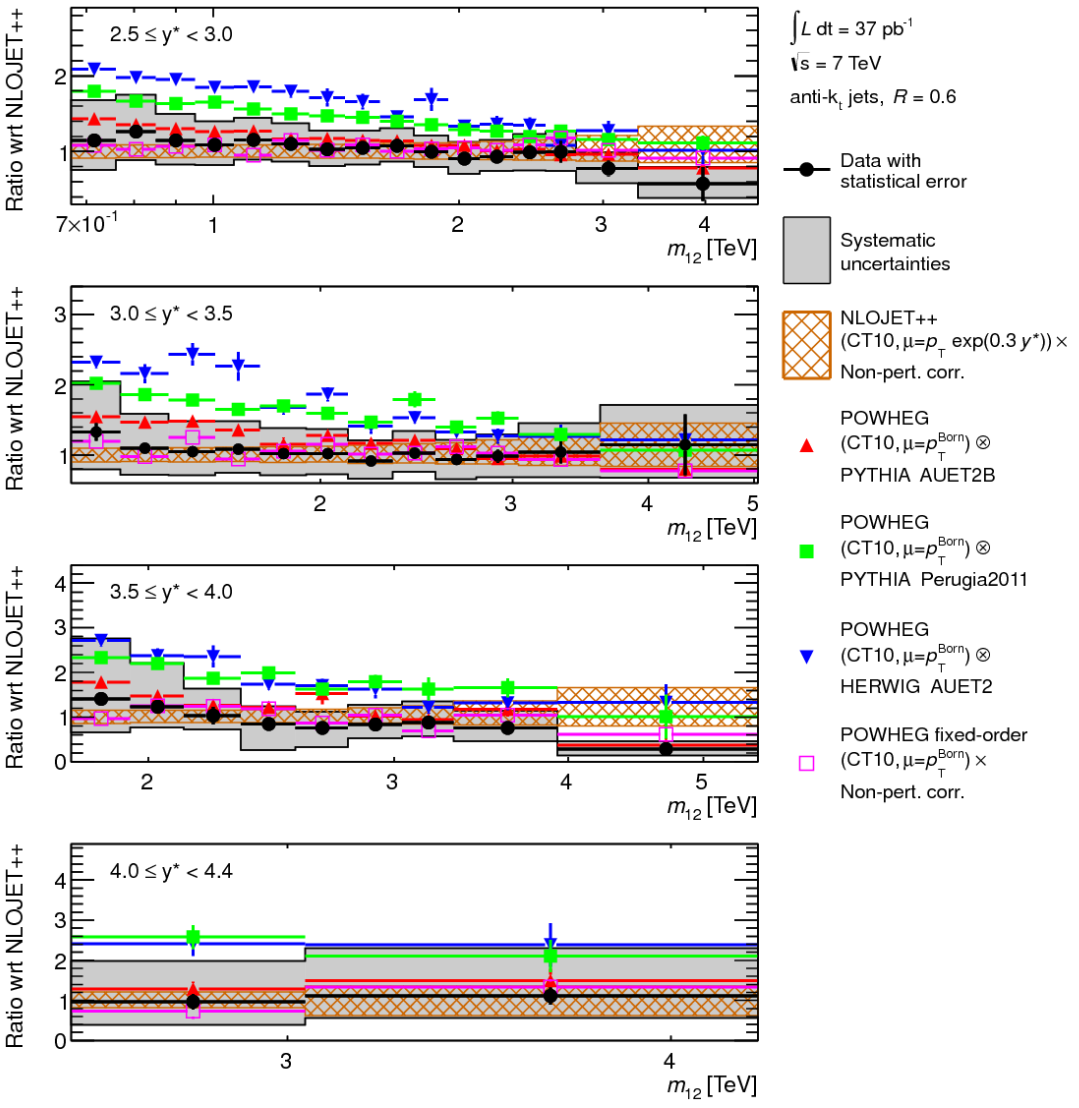
- NLO prediction with different PDF sets generally consistent with data
  - Less well described in most forward region



# Dijet comparisons to POWHEG




- POWHEG+PYTHIA (AUETB tune) describes data well with NLO+PS
- Perugia2011 tune and HERWIG poor



# 2011 dijet measurements

- Dijet mass measurements updated with 4.8 $fb^{-1}$ in 2011 data sample
  - Primary challenge wrt 2010 data sample is much larger pileup
    → limit to central, high-mass
  - Results consistent with 2010 measurements