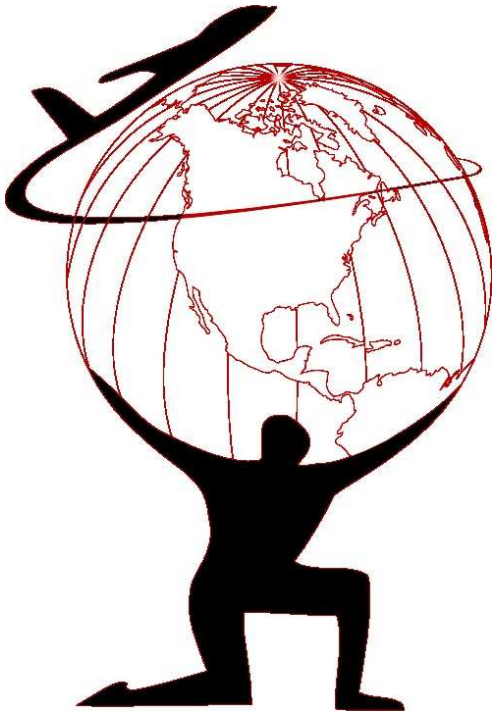
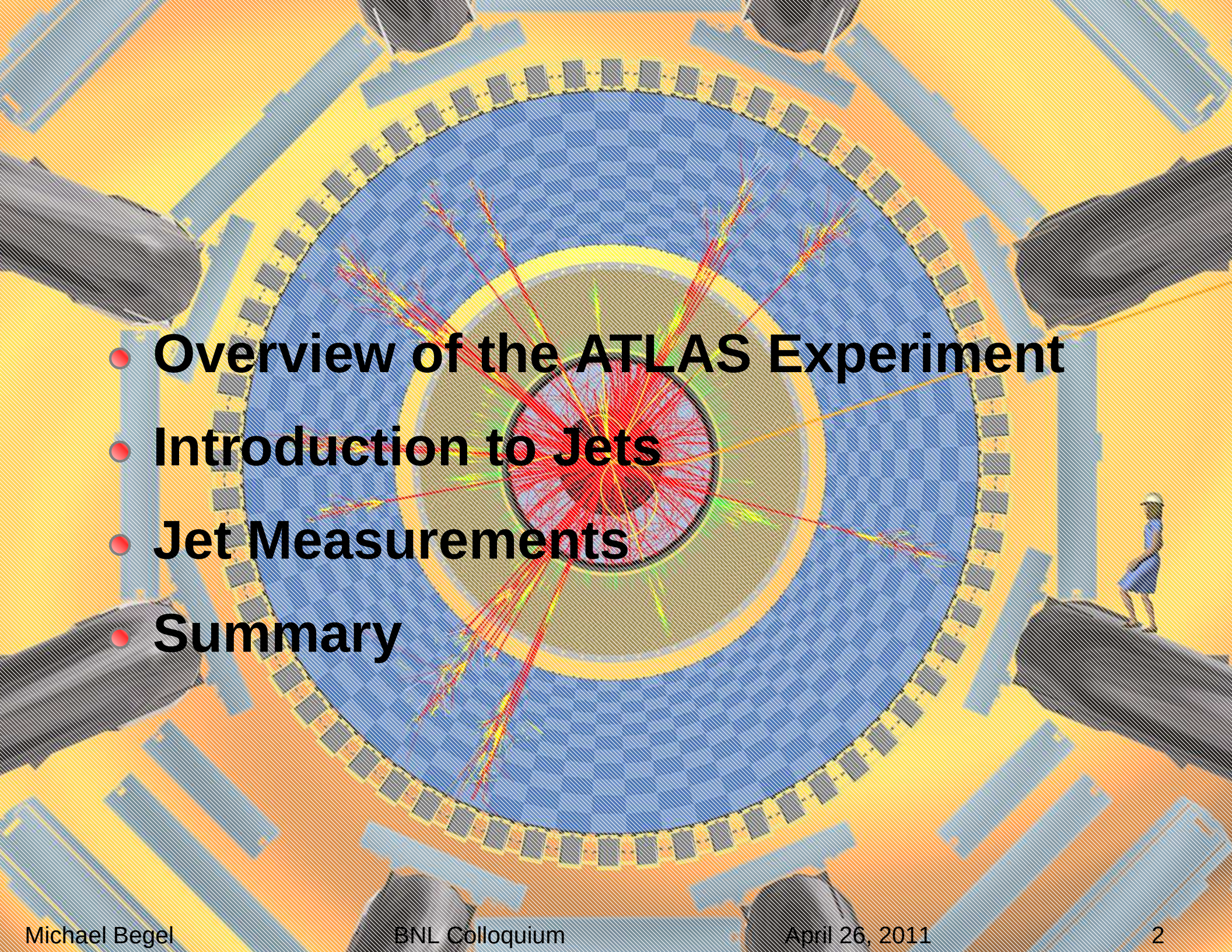
Recent Jet Results From ATLAS



Michael Begel

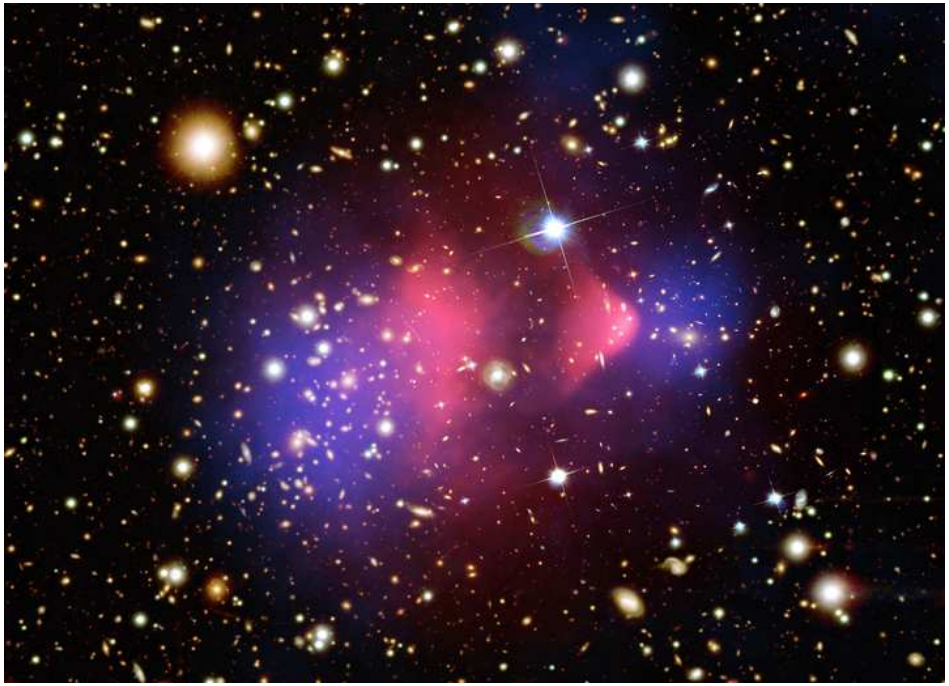
BROOKHAVEN NATIONAL LABORATORY

April 26, 2011



- **Overview of the ATLAS Experiment**
- **Introduction to Jets**
- **Jet Measurements**
- **Summary**

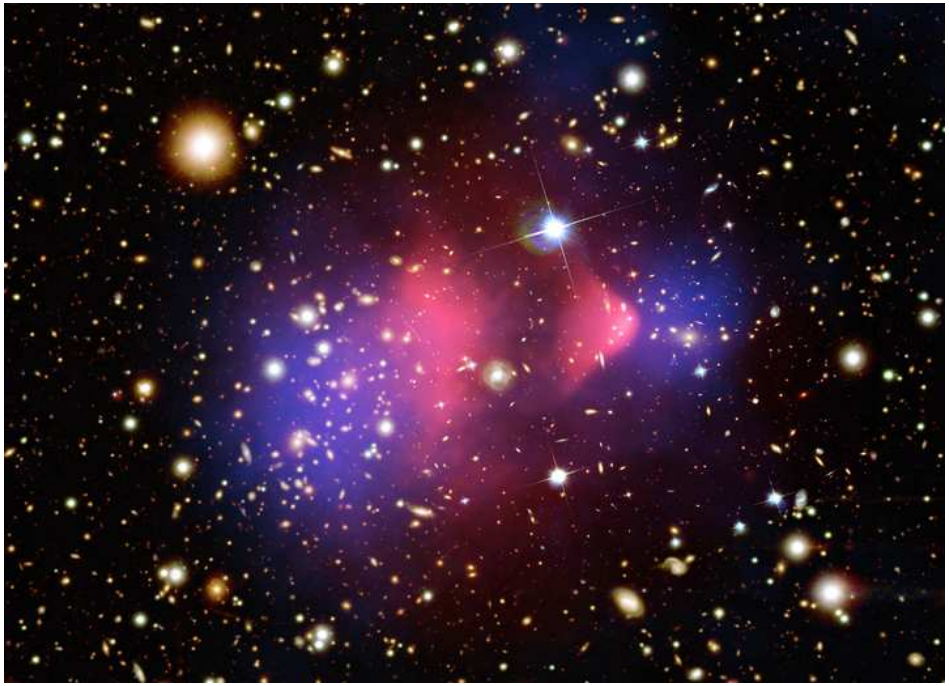
Questions



ATLAS was designed to answer several key questions:

- What is the mechanism behind electroweak symmetry breaking?
- What lies beyond the Standard Model?
- What is dark matter?

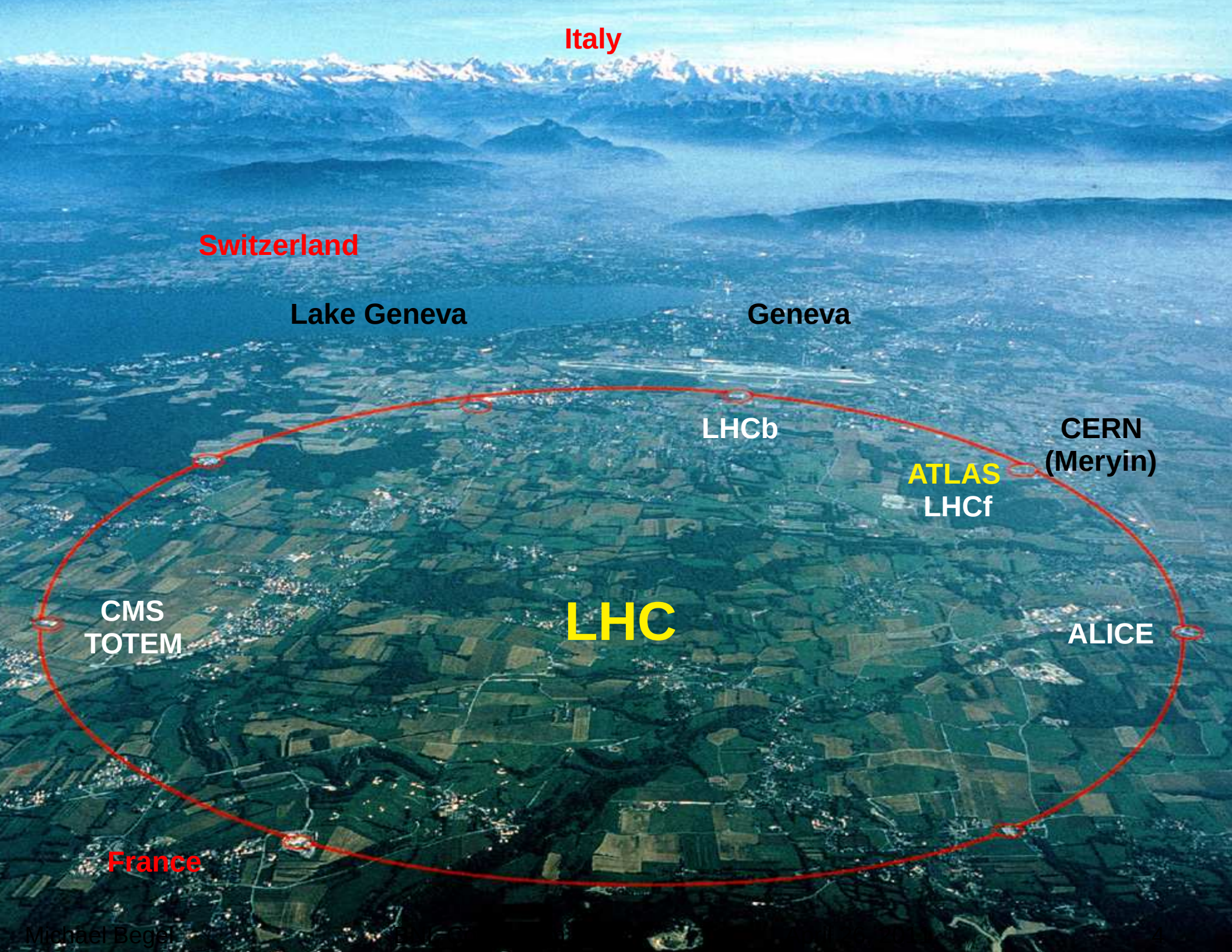
Questions



ATLAS was designed to answer several key questions:

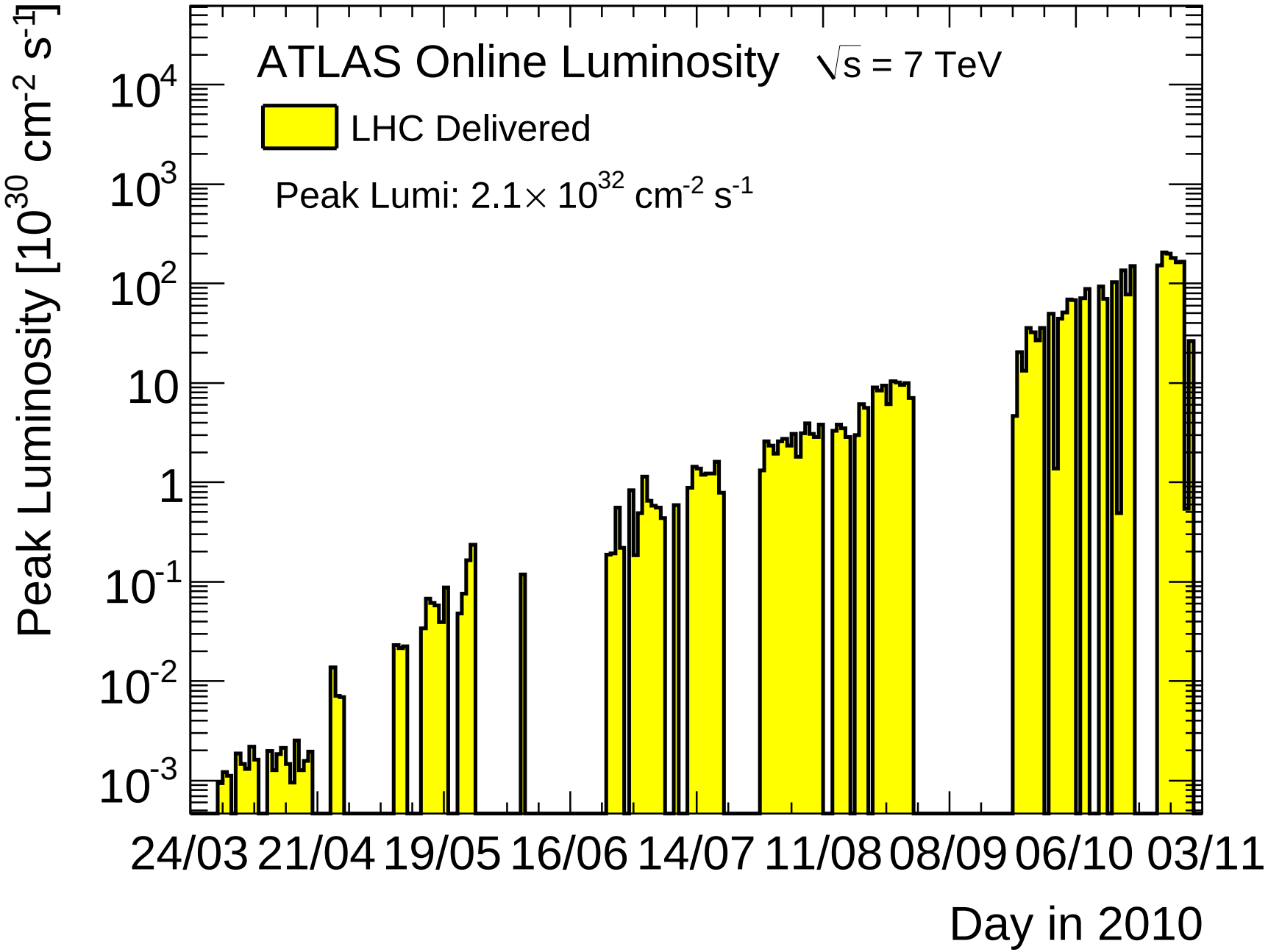
- What is the mechanism behind electroweak symmetry breaking?
- What lies beyond the Standard Model?
- What is dark matter?

- How can 3000 physicists collaborate together effectively to find answers to questions no one has asked?

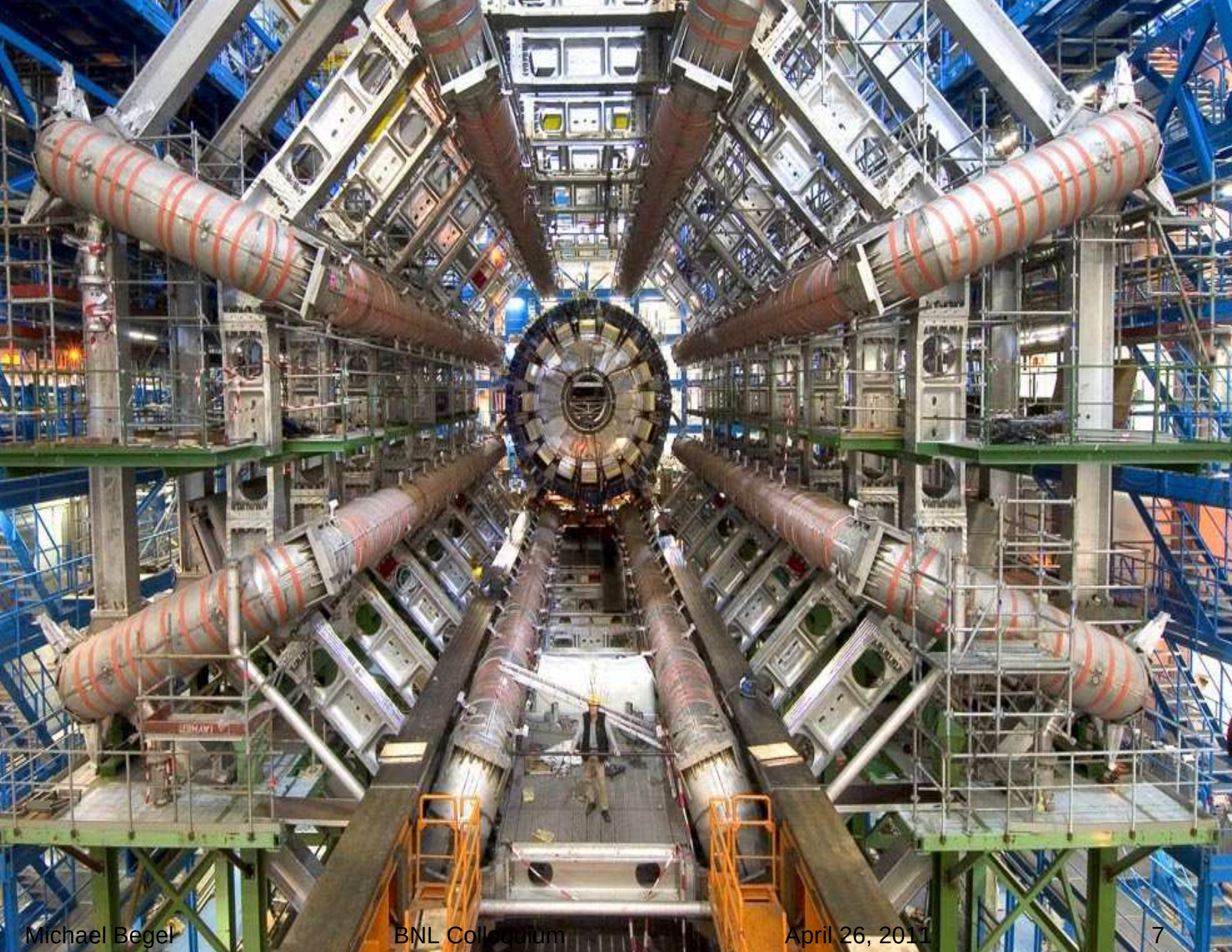


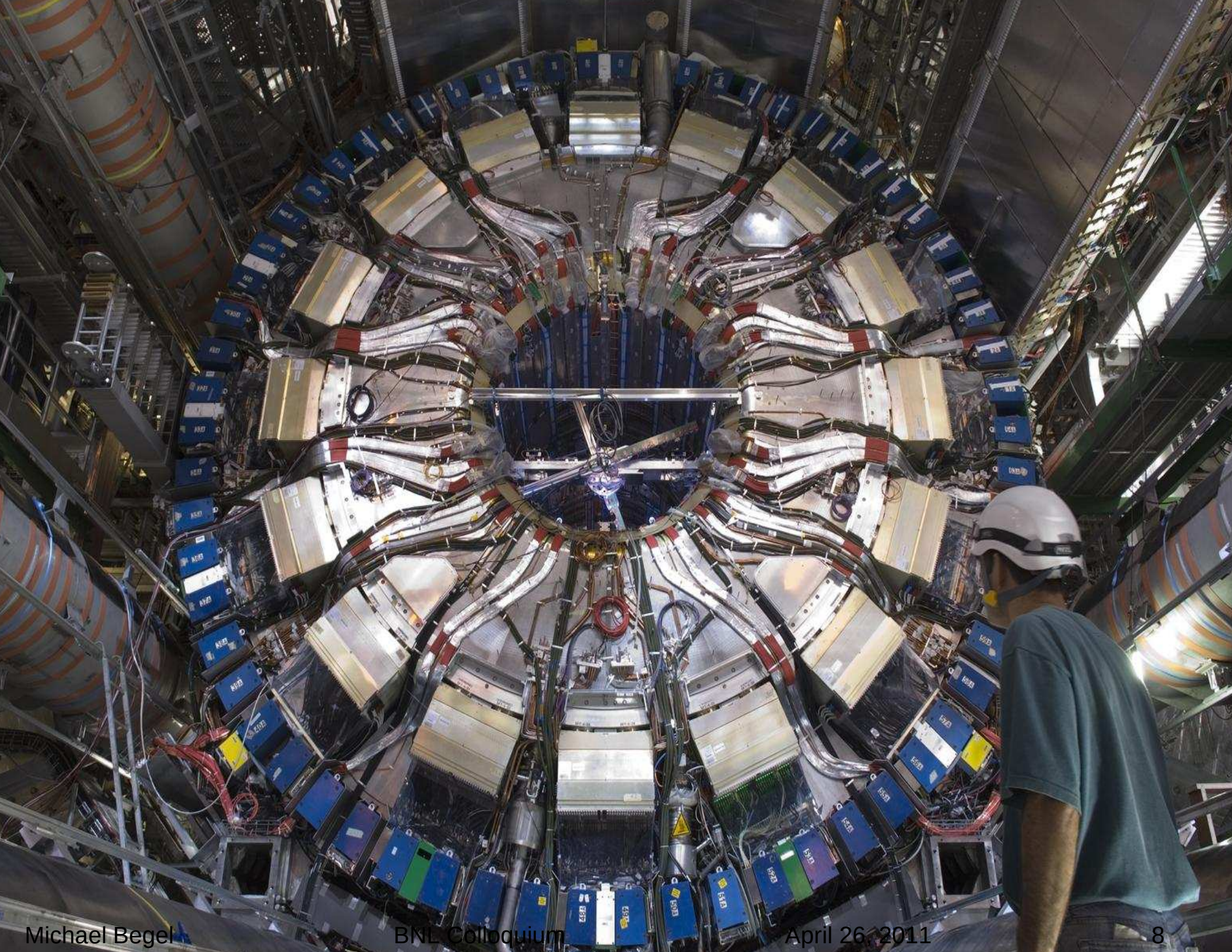
Michael Begel

LHC: 2010

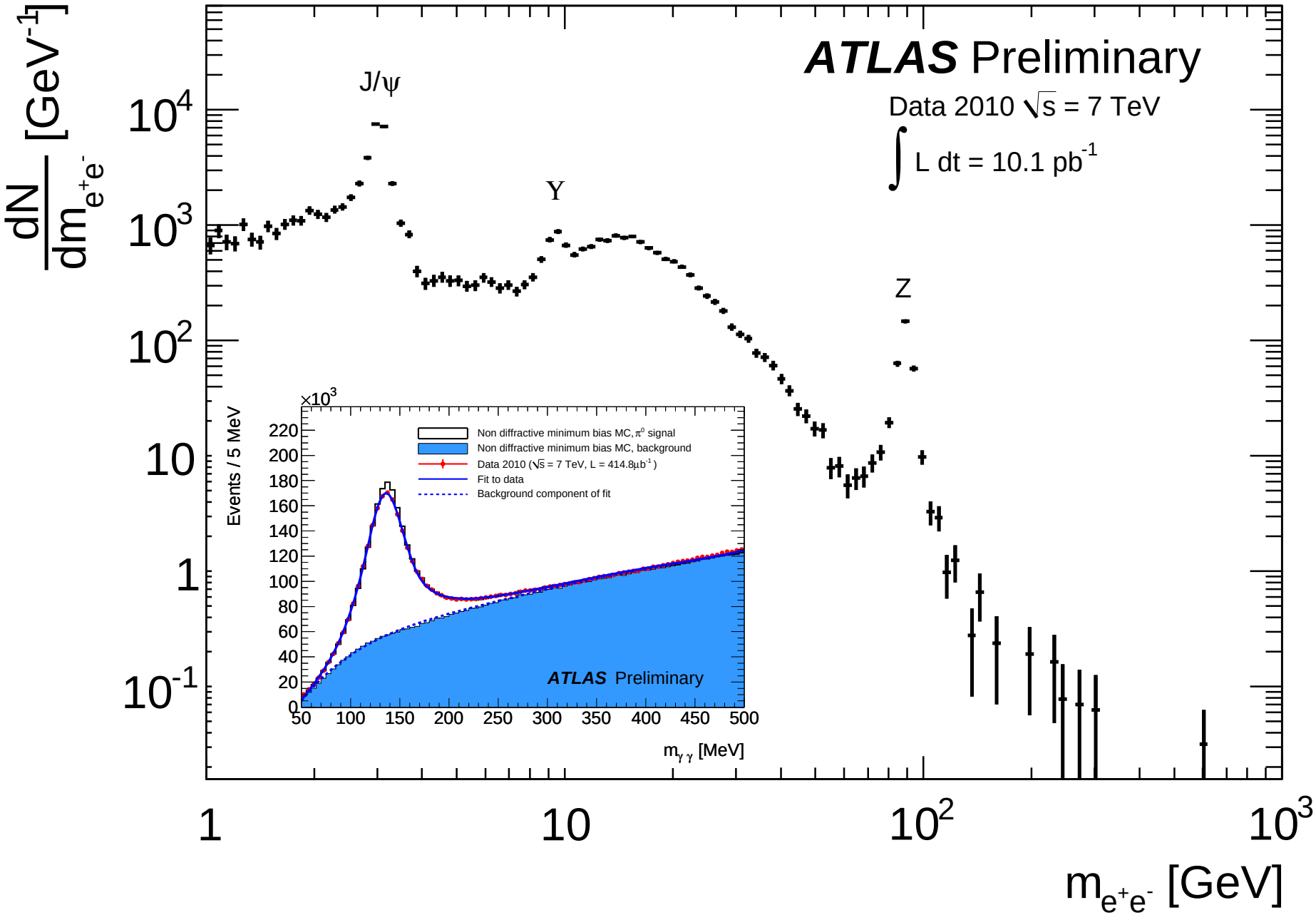

ATLAS Online Luminosity
√s = 7 TeV
LHC Delivered
Peak Lumi: 2.1× 10^32 cm^-2 s^-1
Peak Luminosity [10^30 cm^-2 s^-1]
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
24/03
21/04
19/05
16/06
14/07
11/08
08/09
06/10
03/11
Day in 2010

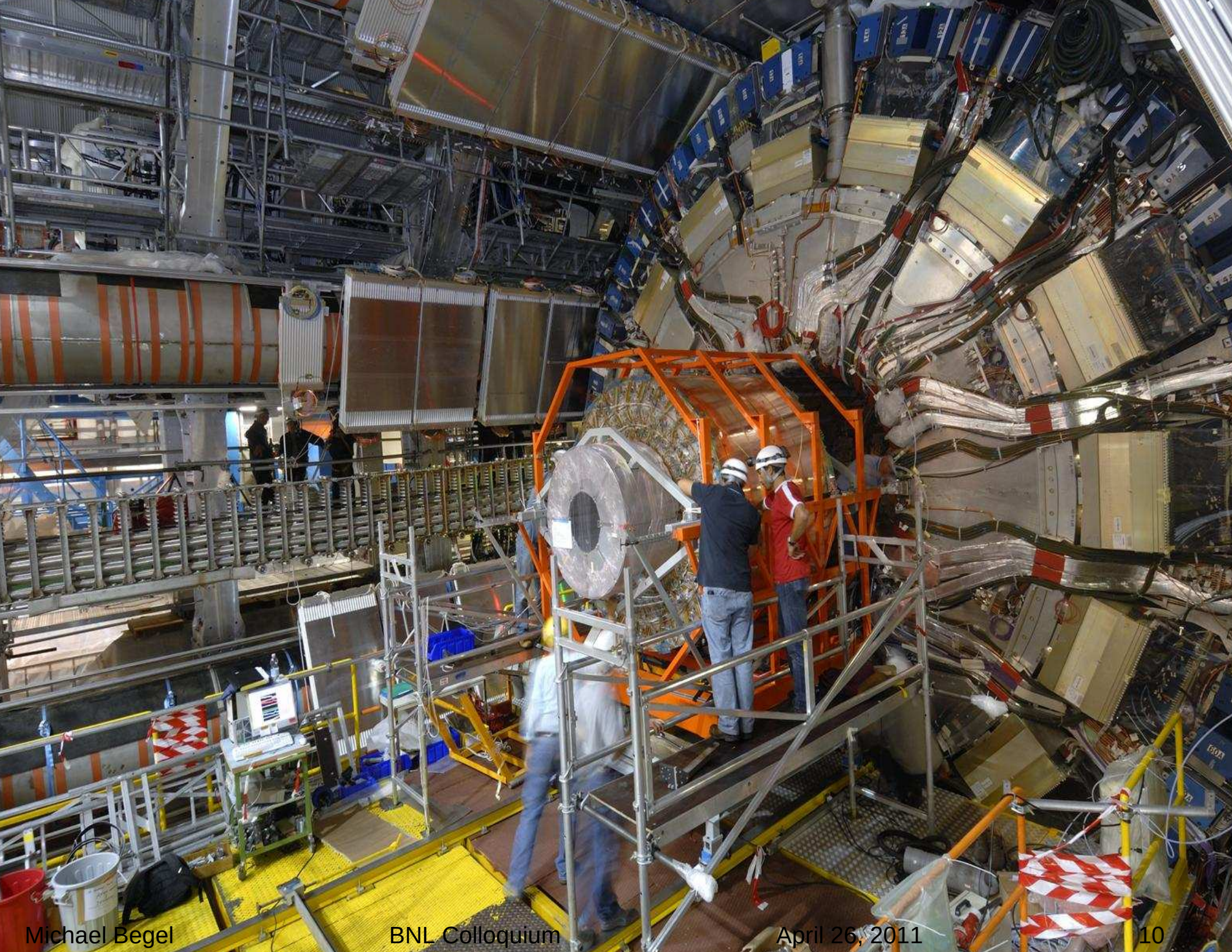
Mural by Josef Kristofoletti
(painted 2009–10; 1/3 scale)
ATLAS
EXPERIMENT
http://atlas.ch



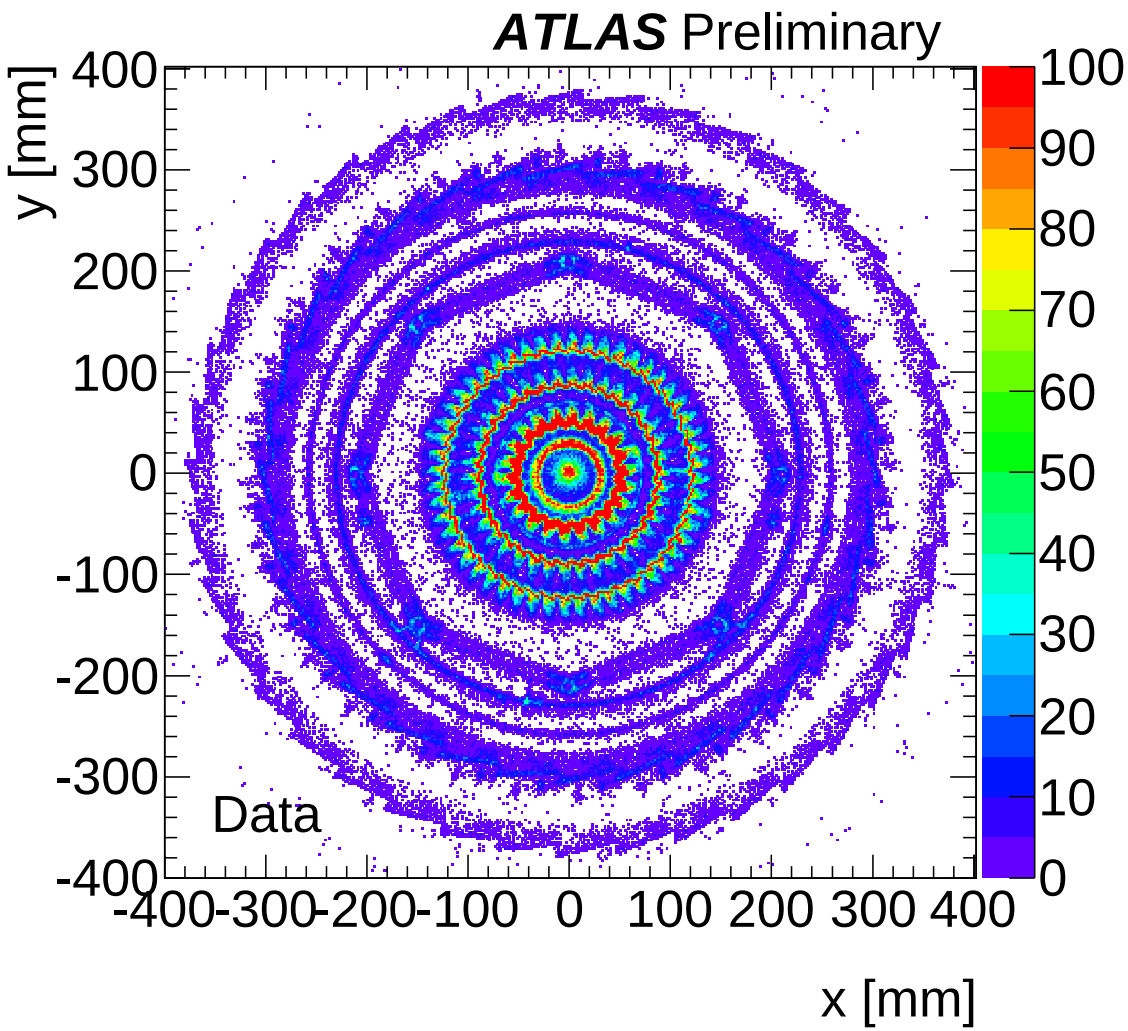


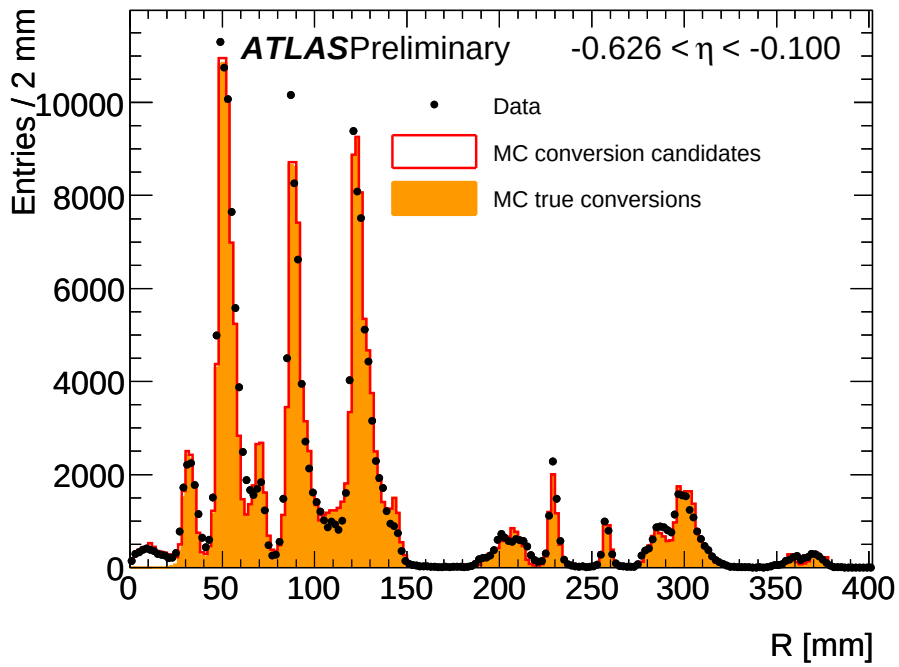
Electrons & Photons

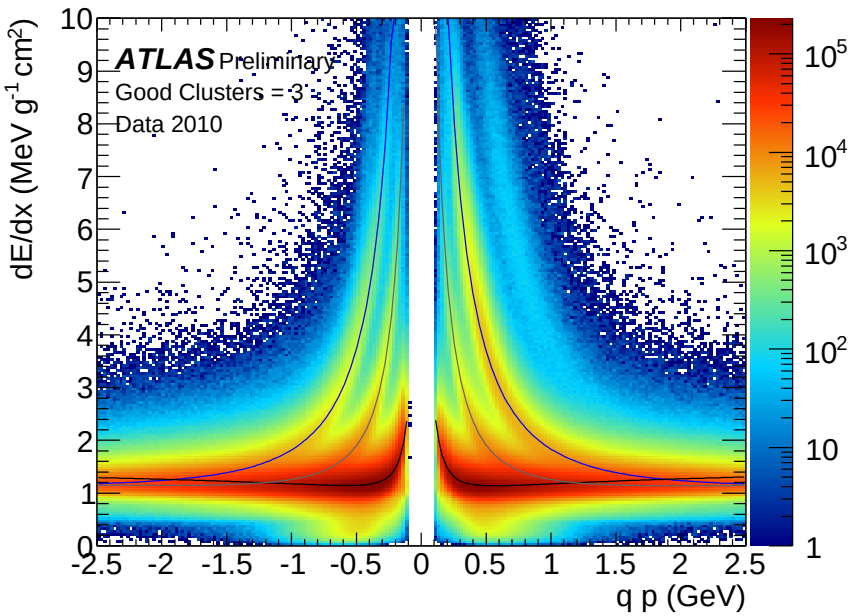




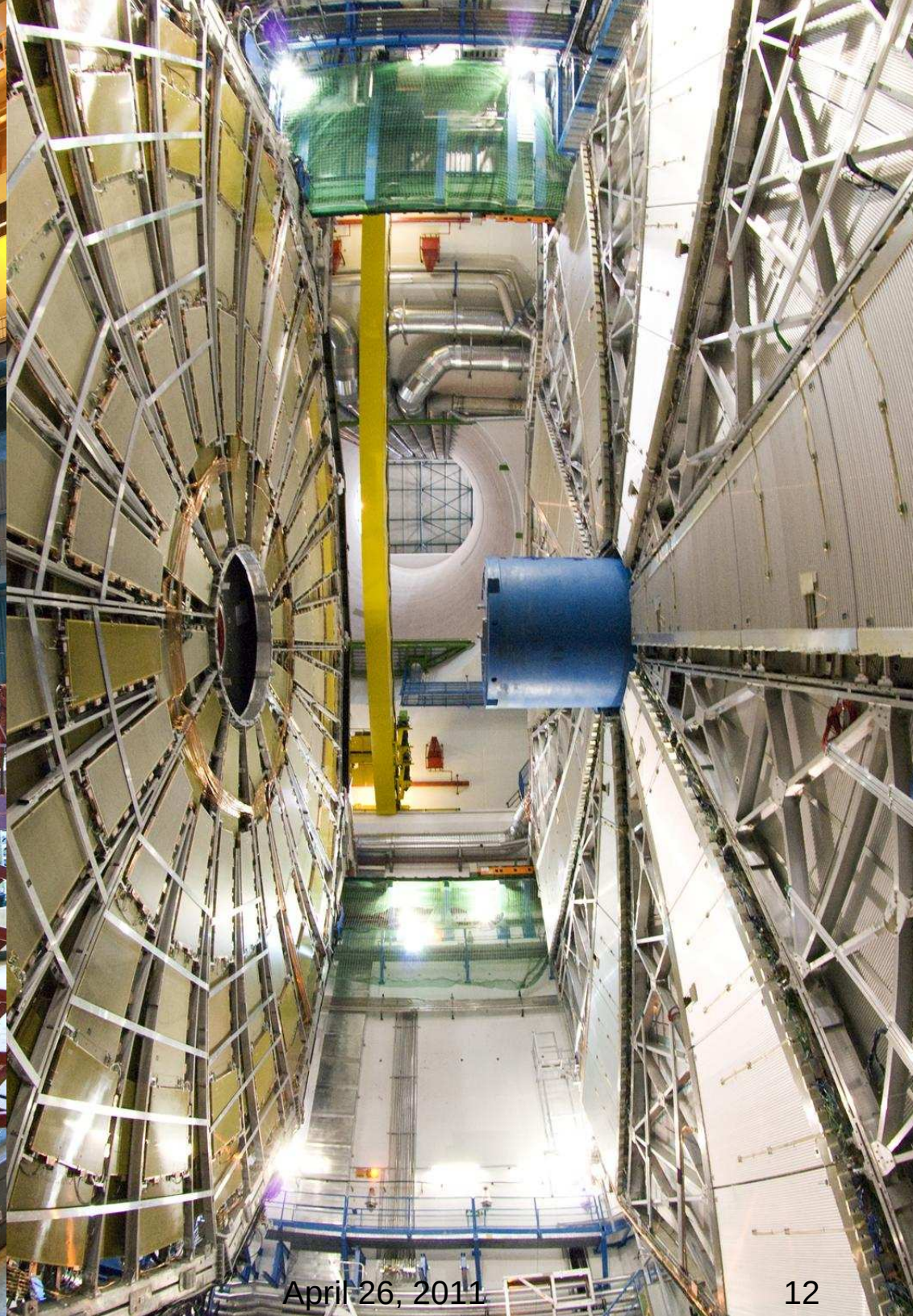
Tracks


ATLAS Preliminary
y [mm]
x [mm]
Data

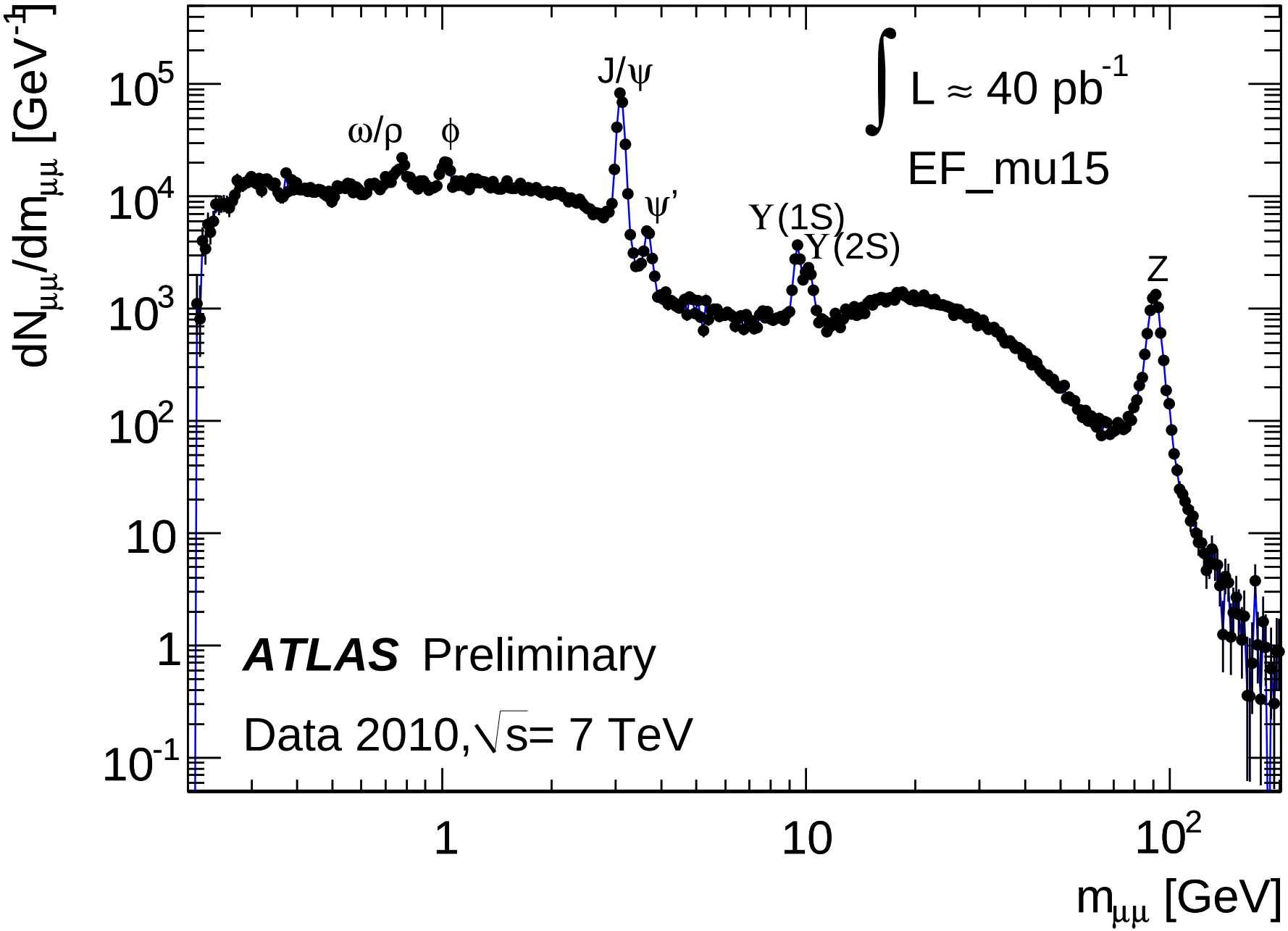

ATLAS Preliminary
-0.626 < η < -0.100
Data
MC conversion candidates
MC true conversions
Entries / 2 mm
R [mm]


ATLAS Preliminary
Good Clusters = 3
Data 2010
dE/dx (MeV g-1 cm2)
q p (GeV)

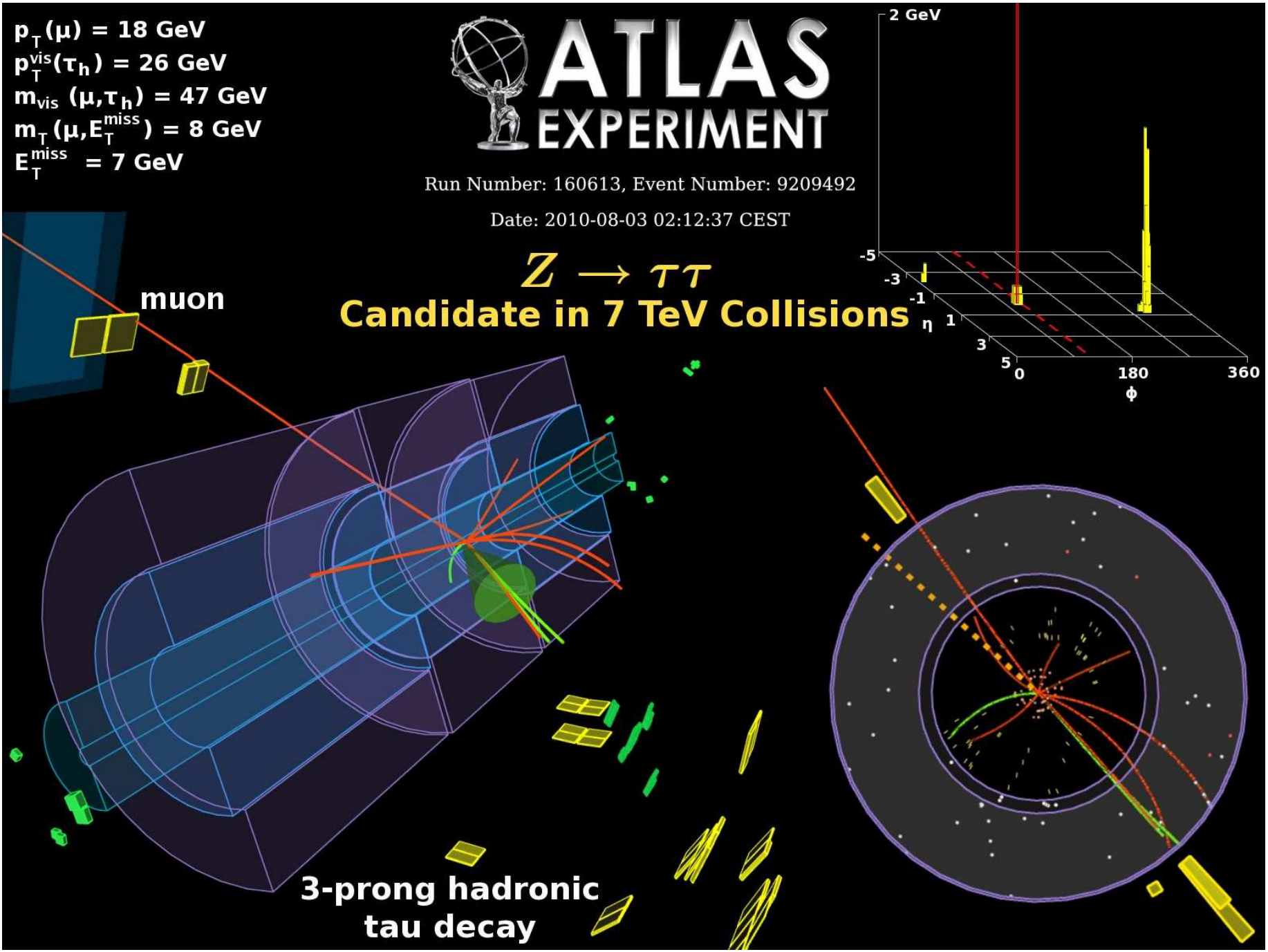
MOLOXA
GLOXAM



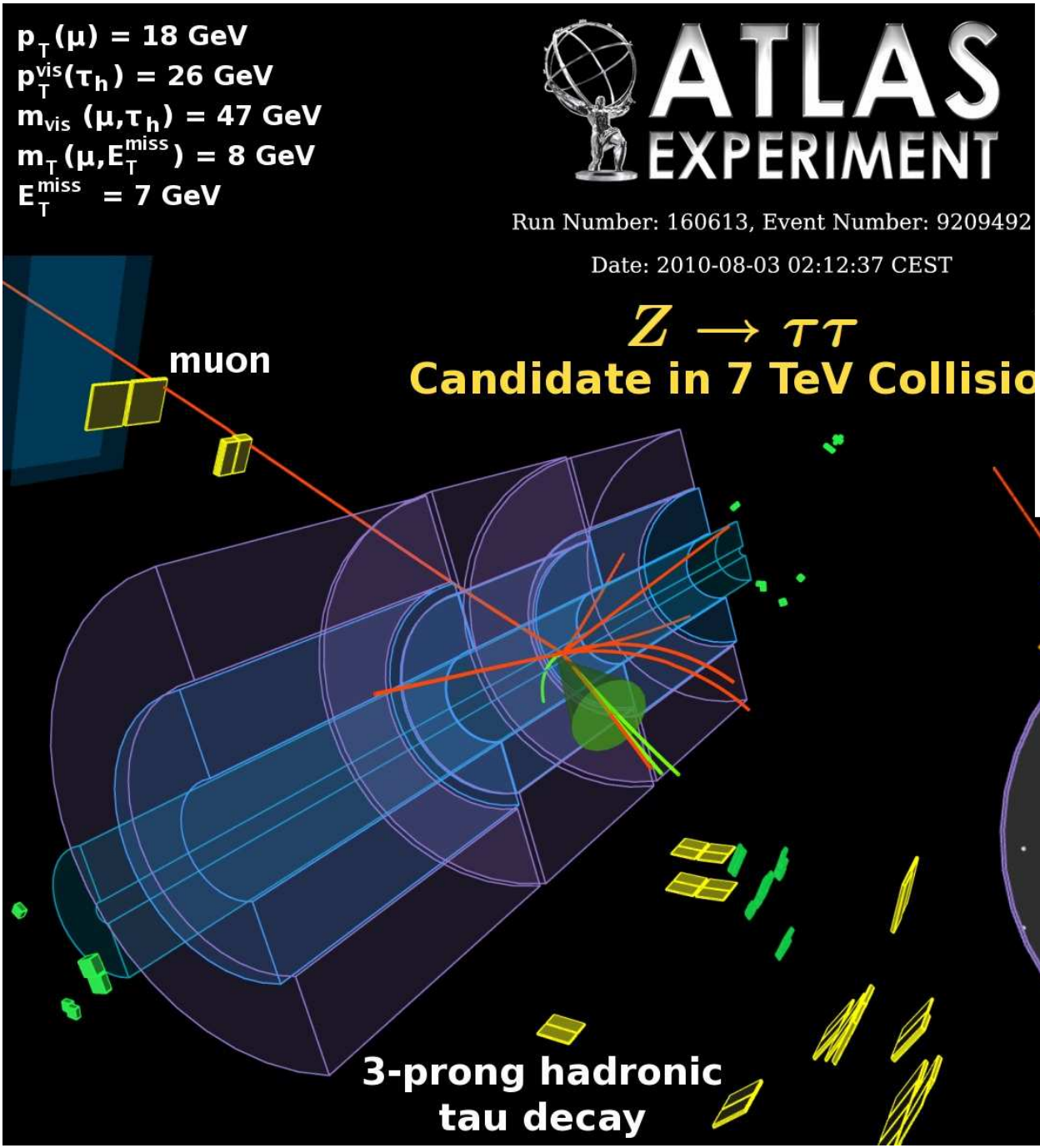
Muons


$dN_{\mu\mu}/dm_{\mu\mu}$ [GeV^{-1}]
10^5
10^4
10^3
10^2
10
1
10^{-1}
ω/ρ
φ
J/ψ
ψ'
Υ(1S)
Υ(2S)
Z
$\int L \approx 40$ pb^{-1}
EF_mu15
ATLAS Preliminary
Data 2010, $\sqrt{s}$= 7 TeV
1
10
10^2
$m_{\mu\mu}$ [GeV]

Taus


$p_T(\mu)$ = 18 GeV
$p_T^{vis}(\tau_h)$ = 26 GeV
$m_{vis}(\mu,\tau_h)$ = 47 GeV
$m_T(\mu,E_T^{miss})$ = 8 GeV
E_T^{miss} = 7 GeV
ATLAS EXPERIMENT
Run Number: 160613, Event Number: 9209492
Date: 2010-08-03 02:12:37 CEST
$Z \rightarrow \tau\tau$
Candidate in 7 TeV Collisions
muon
2 GeV
-5
-3
-1
η
1
3
5
0
180
360
φ
3-prong hadronic tau decay

Taus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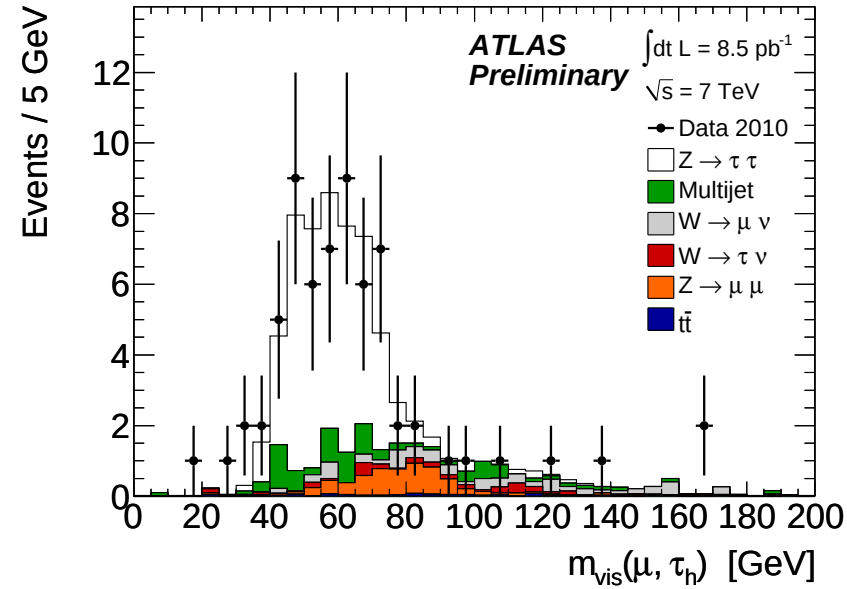
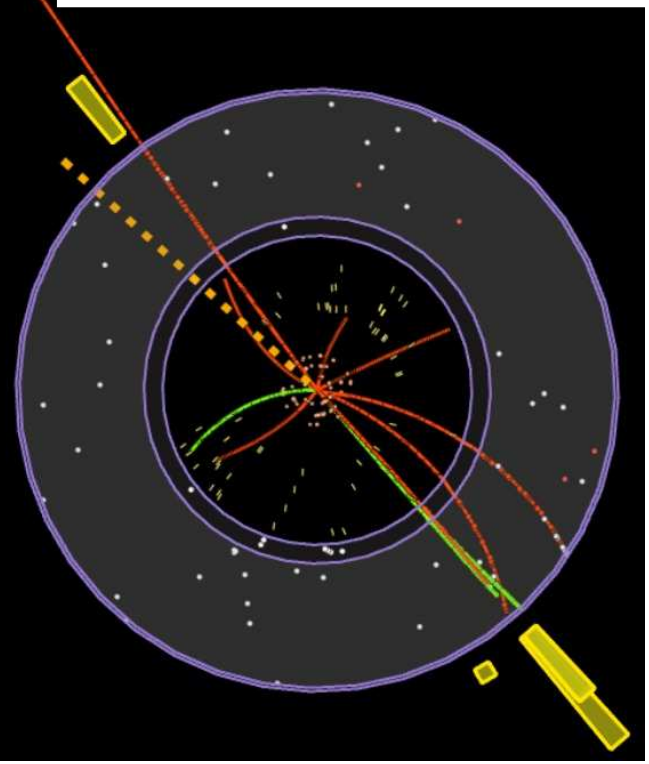
$Z \rightarrow \tau\tau$
Candidate in 7 TeV Collisio
muon
3-prong hadronic tau decay

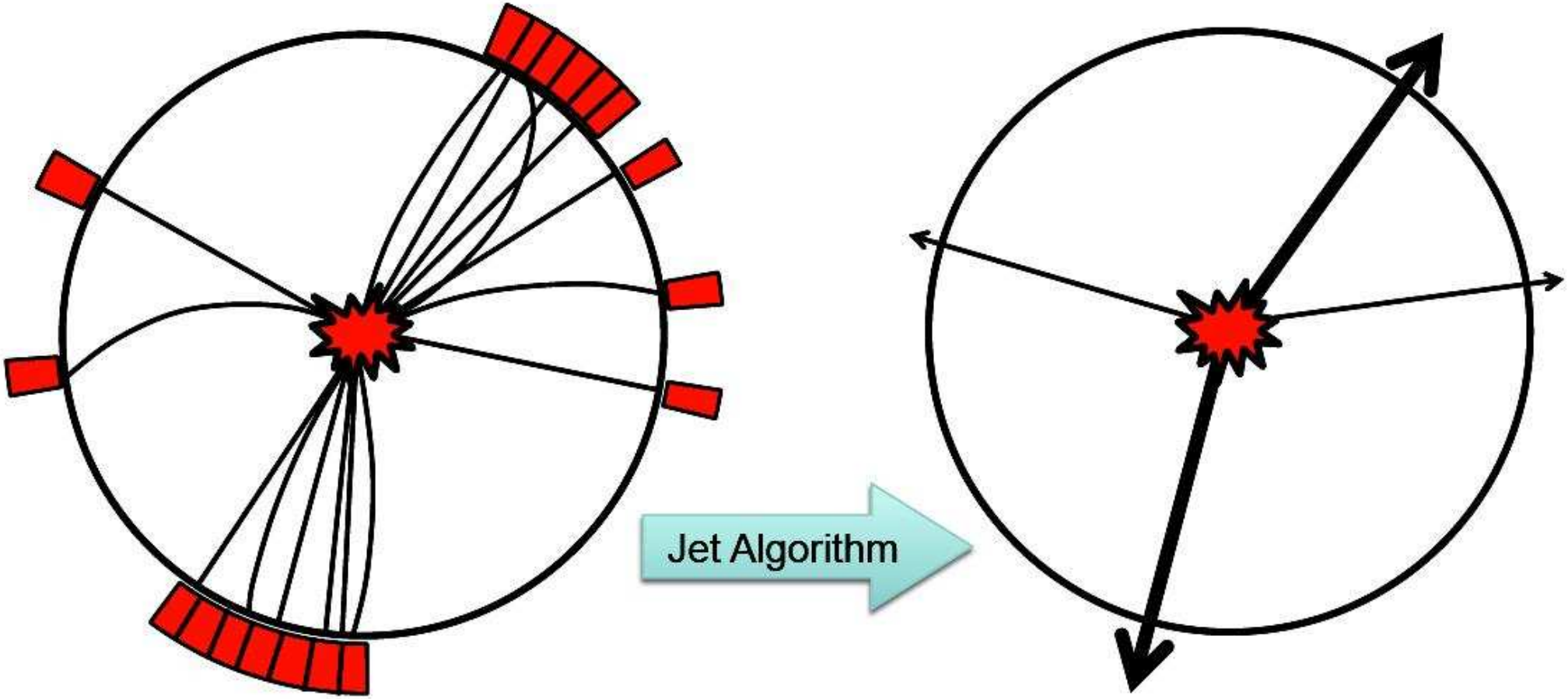

ATLAS Preliminary
$\int dt\, L = 8.5\ pb^{-1}$
$\sqrt{s}$ = 7 TeV
Data 2010
$Z \rightarrow \tau\tau$
Multijet
$W \rightarrow \mu\nu$
$W \rightarrow \tau\nu$
$Z \rightarrow \mu\mu$
$t\bar{t}$
Events / 5 GeV
0 2 4 6 8 10 12
0 20 40 60 80 100 120 140 160 180 200
$m_{vis}(\mu, \tau_h)$ [GeV]



Jets

What is a Jet?

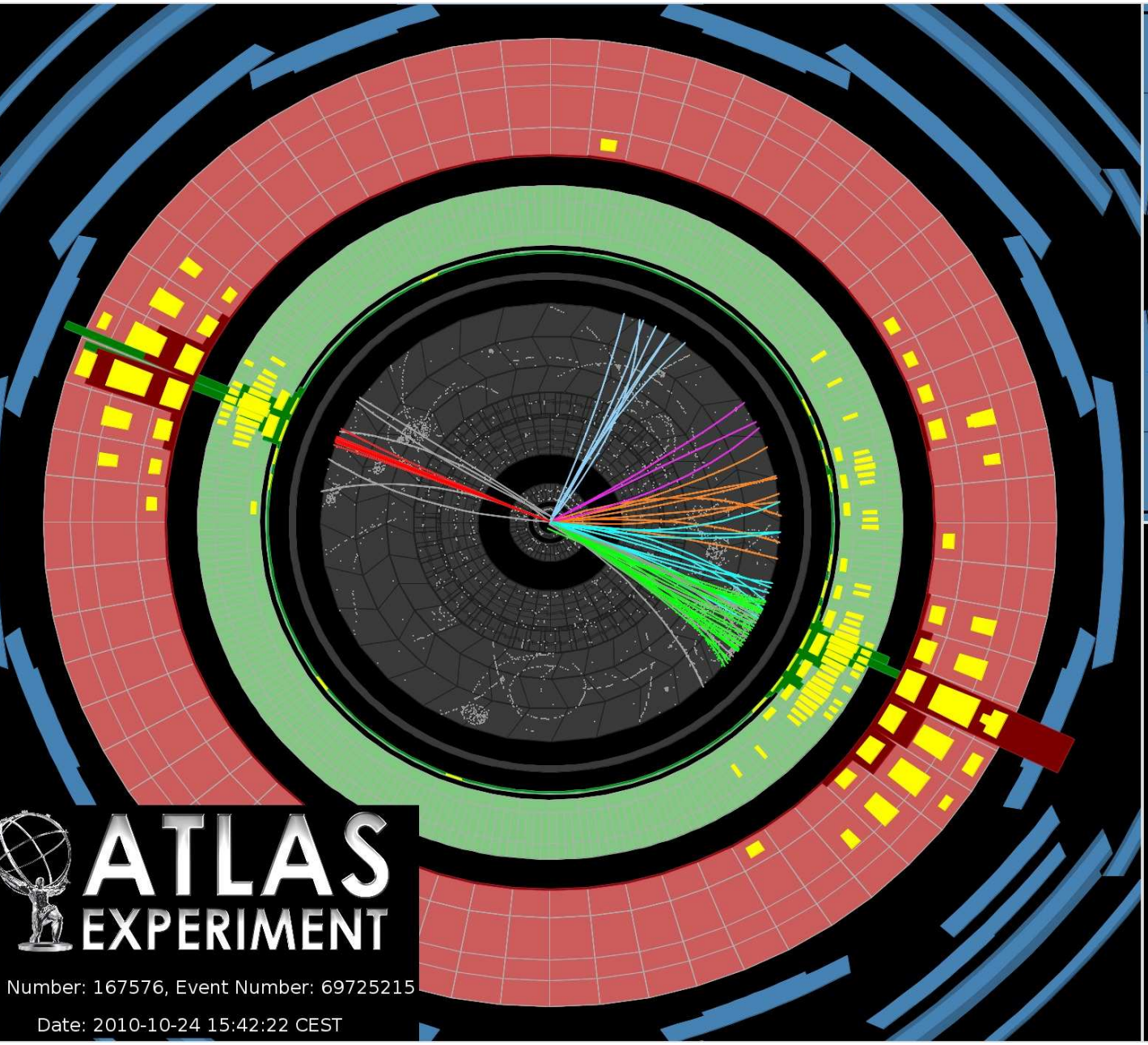
The output of an algorithm that clusters together objects.

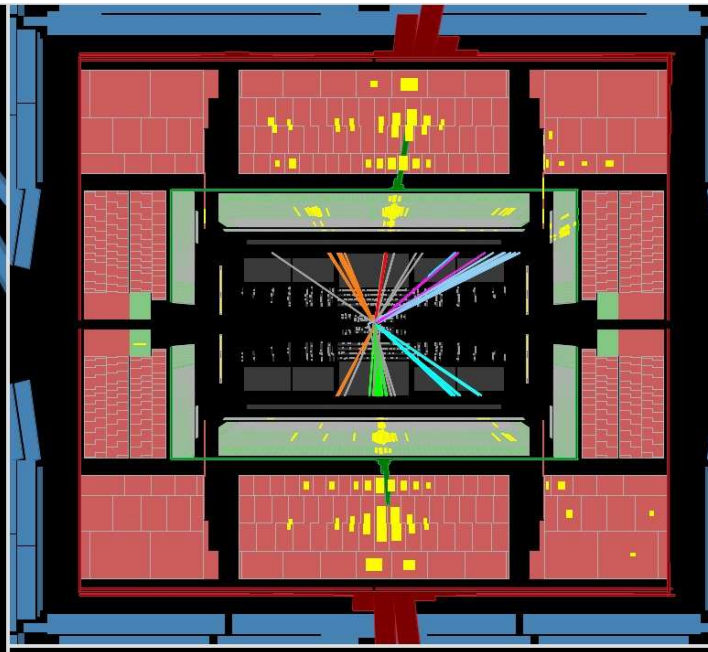


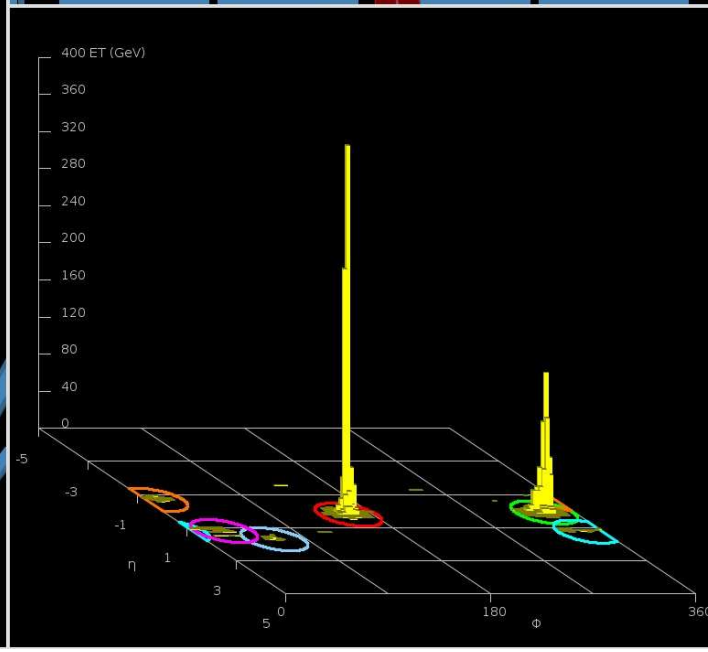
Before
many particles
complicated event

After
few jets
simpler structure

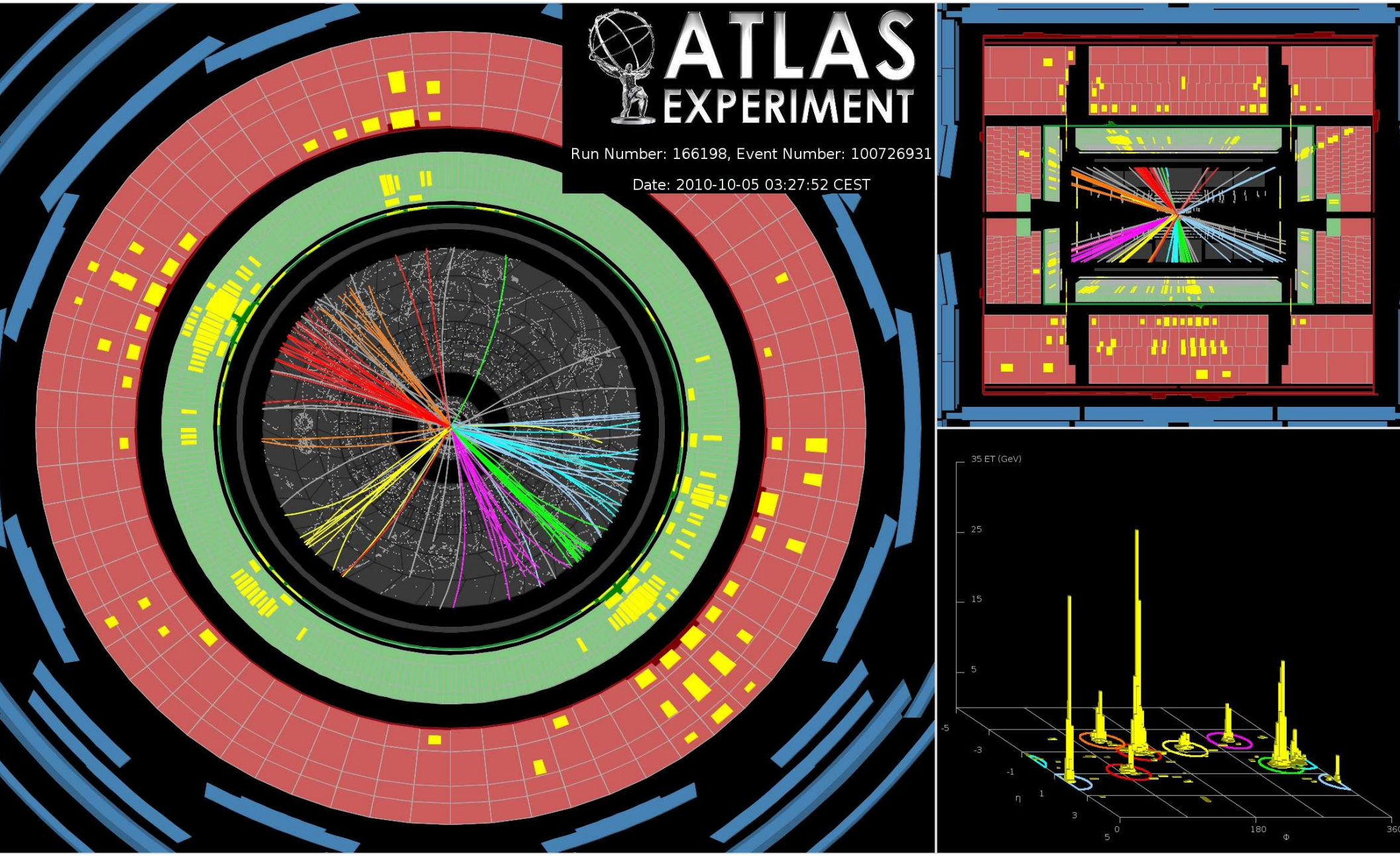
Event Display







Event Display



Jet Algorithms

There is no unique or correct way to group particles.
Choose the appropriate jet algorithm according to:

- analysis requirements
- resource limitations
- physics goals

Practical

- fast
- independent of environment
- easy to calibrate

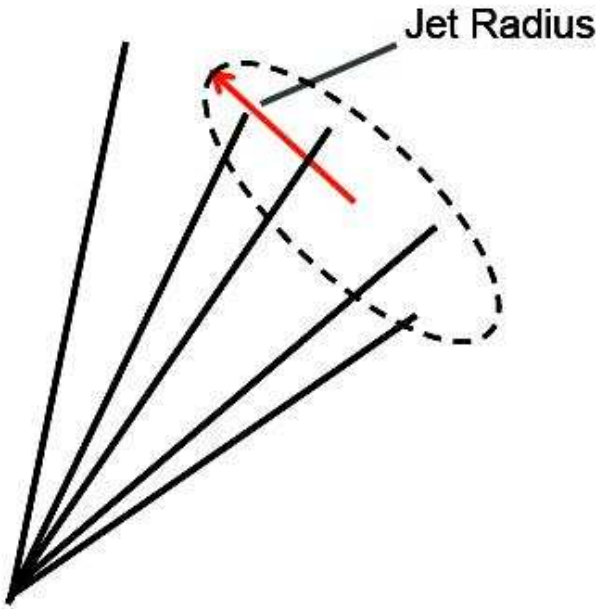
Theoretical (avoid)

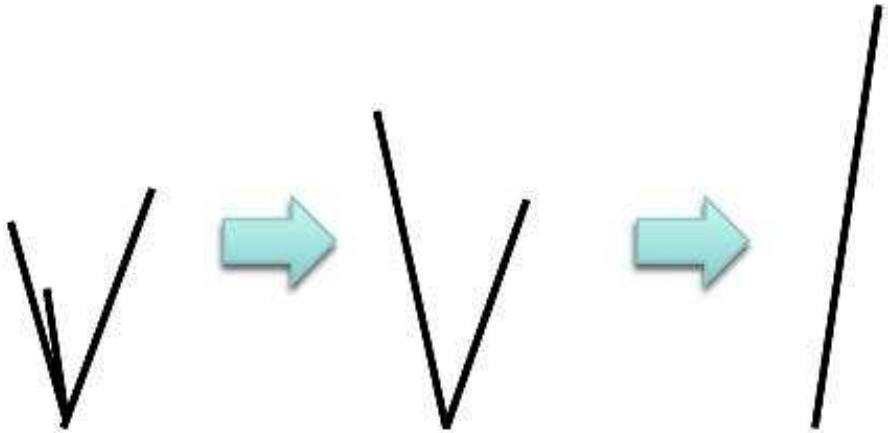
- infrared divergences
  (prob. to emit soft radiation $\rightarrow \infty$)
- collinear divergences
  (prob. to emit collinear radiation $\rightarrow \infty$)

Important

- boost invariant
- universal application
  (partons, particles, tracks, calorimeter cells)

Jet Algorithms





Cone

Energy flow in a fixed-sized cone (geometrical)
top-down approach

Examples:

- JetClu (CDF)
- Mid-Point Cone (DZero, CDF)
- SISCone

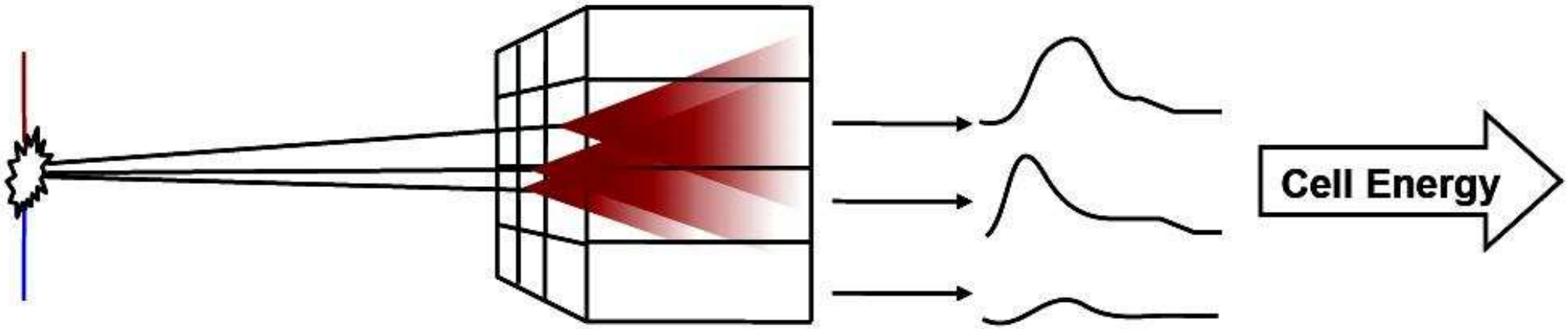
Clustering

Successive merging of pairs of (proto)-jets
bottom-up approach

Examples:

- k_T
- anti-k_T
- Cambridge–Aachen

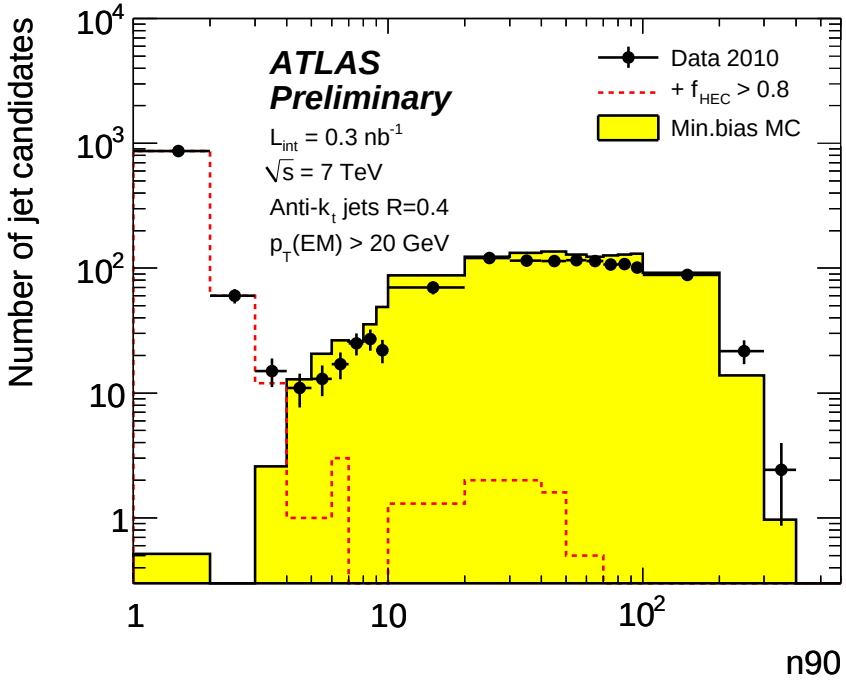
Calorimeters

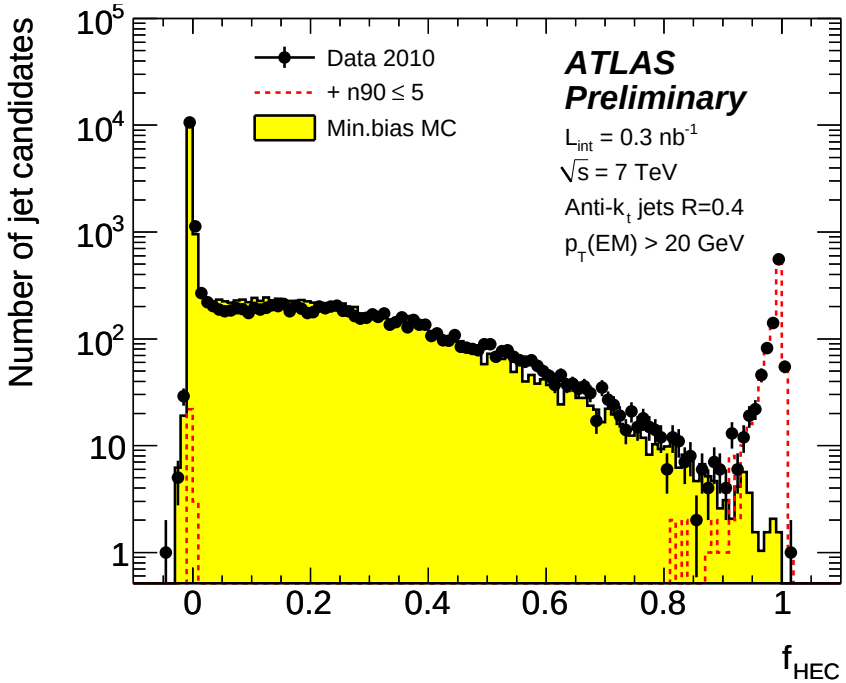


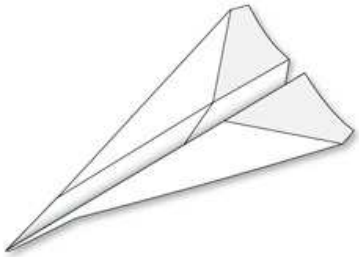
- Calorimeters do not identify individual particles
  - finite energy and position resolution
  - respond differently to different incident particles
- Dead material scatters & absorbs particles
- Electronic noise
- Gaps between detector elements and for services and supports
- Extra energy from other *pp* interactions

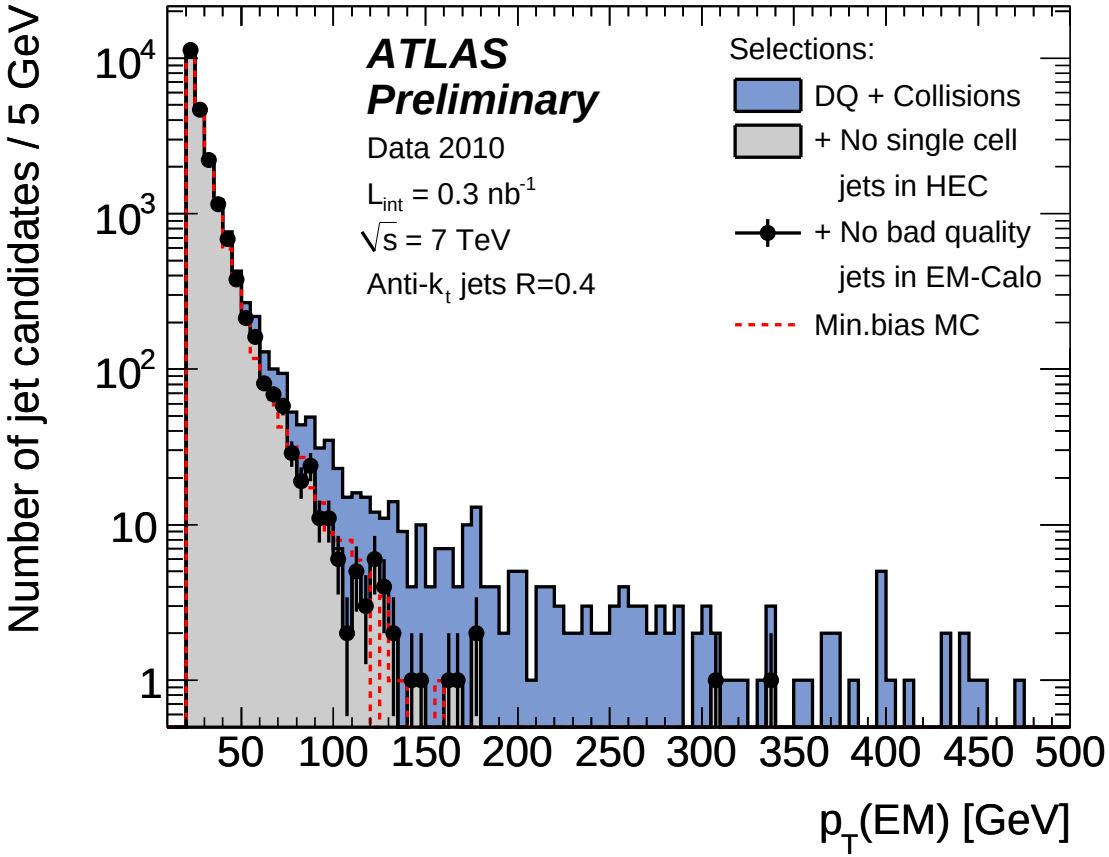
Calibration

Separating Real From Fake Jets

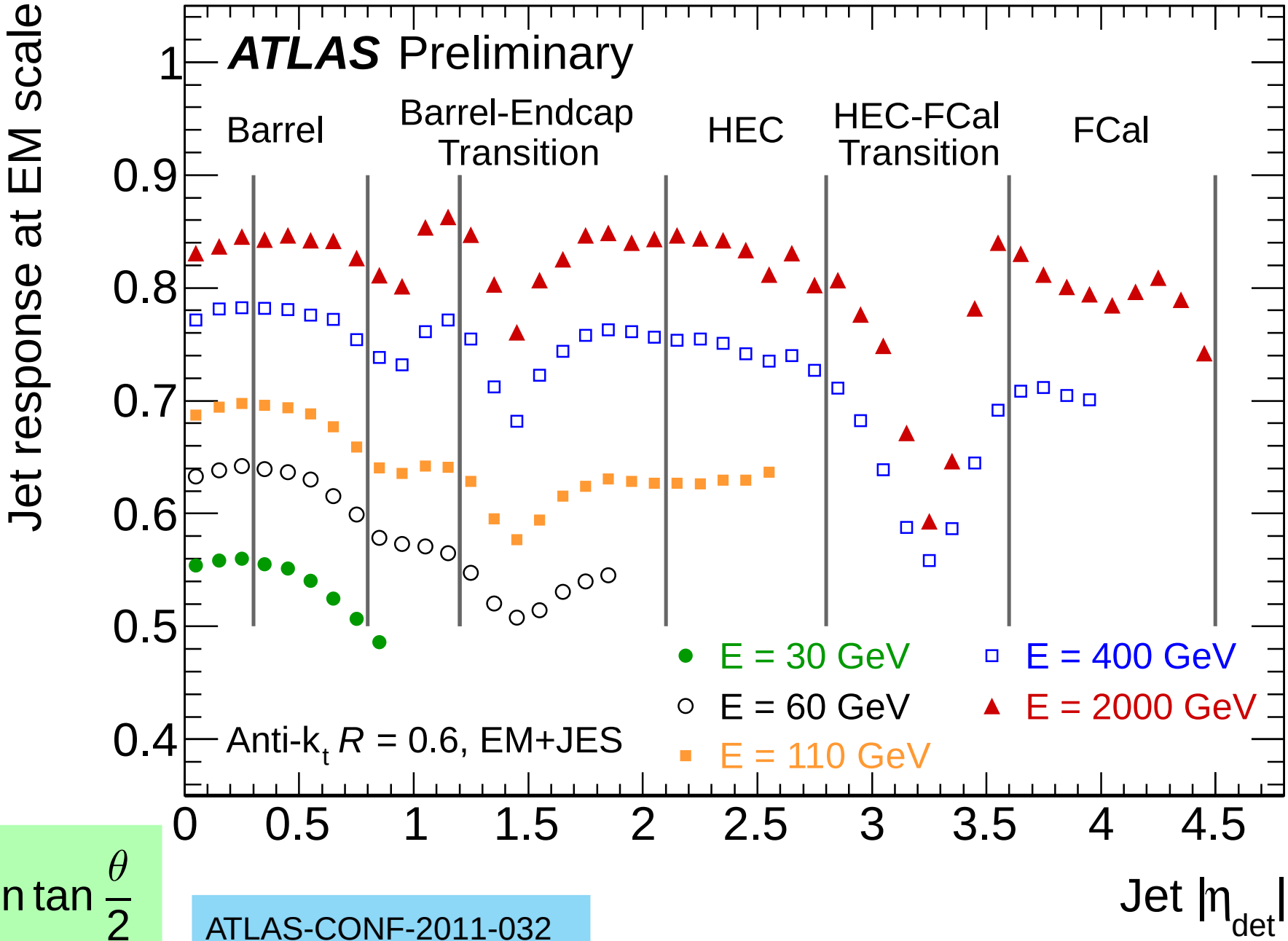








Calorimeter Response



$$\eta = -\ln\tan\frac{\theta}{2}$$

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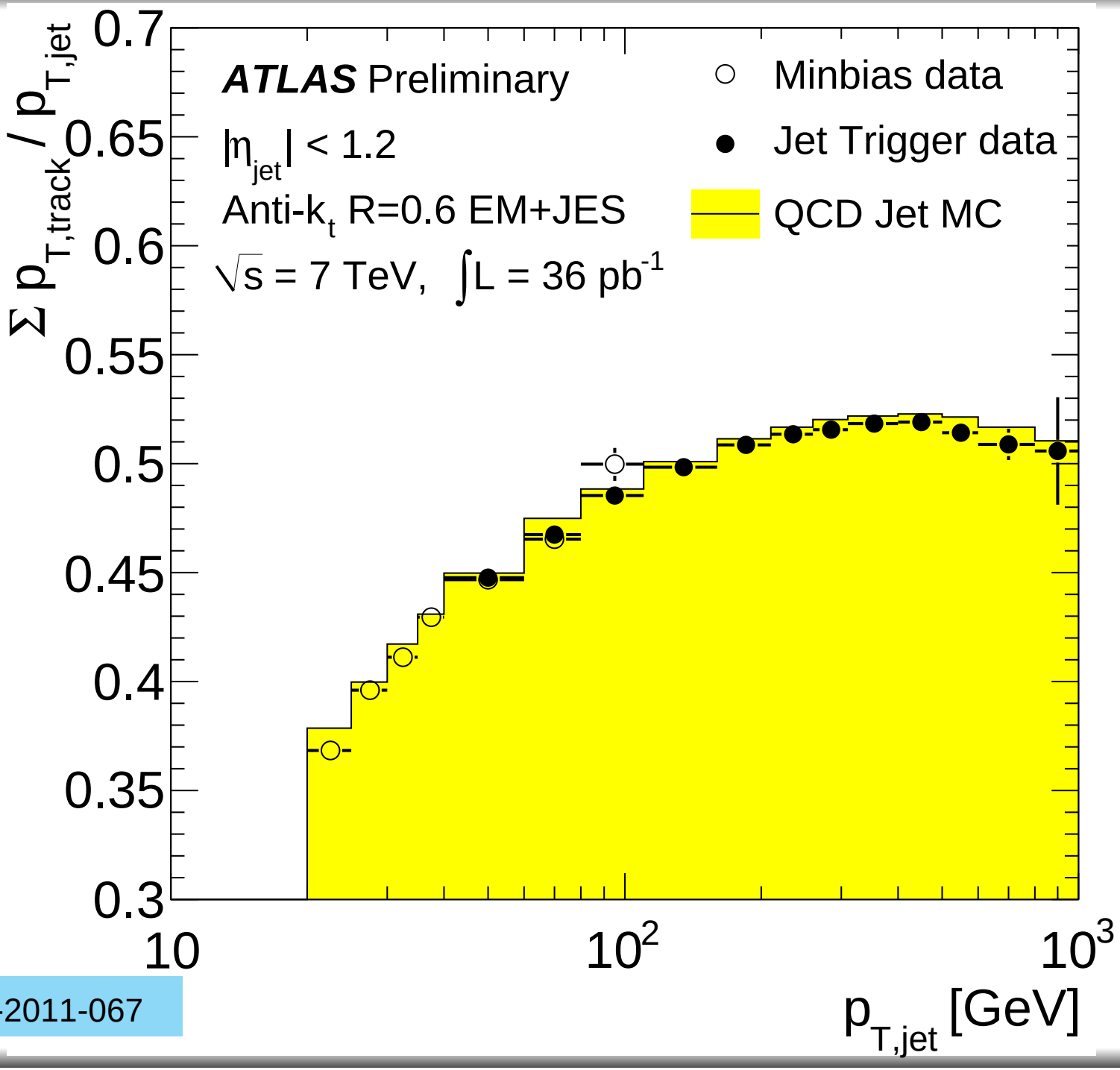
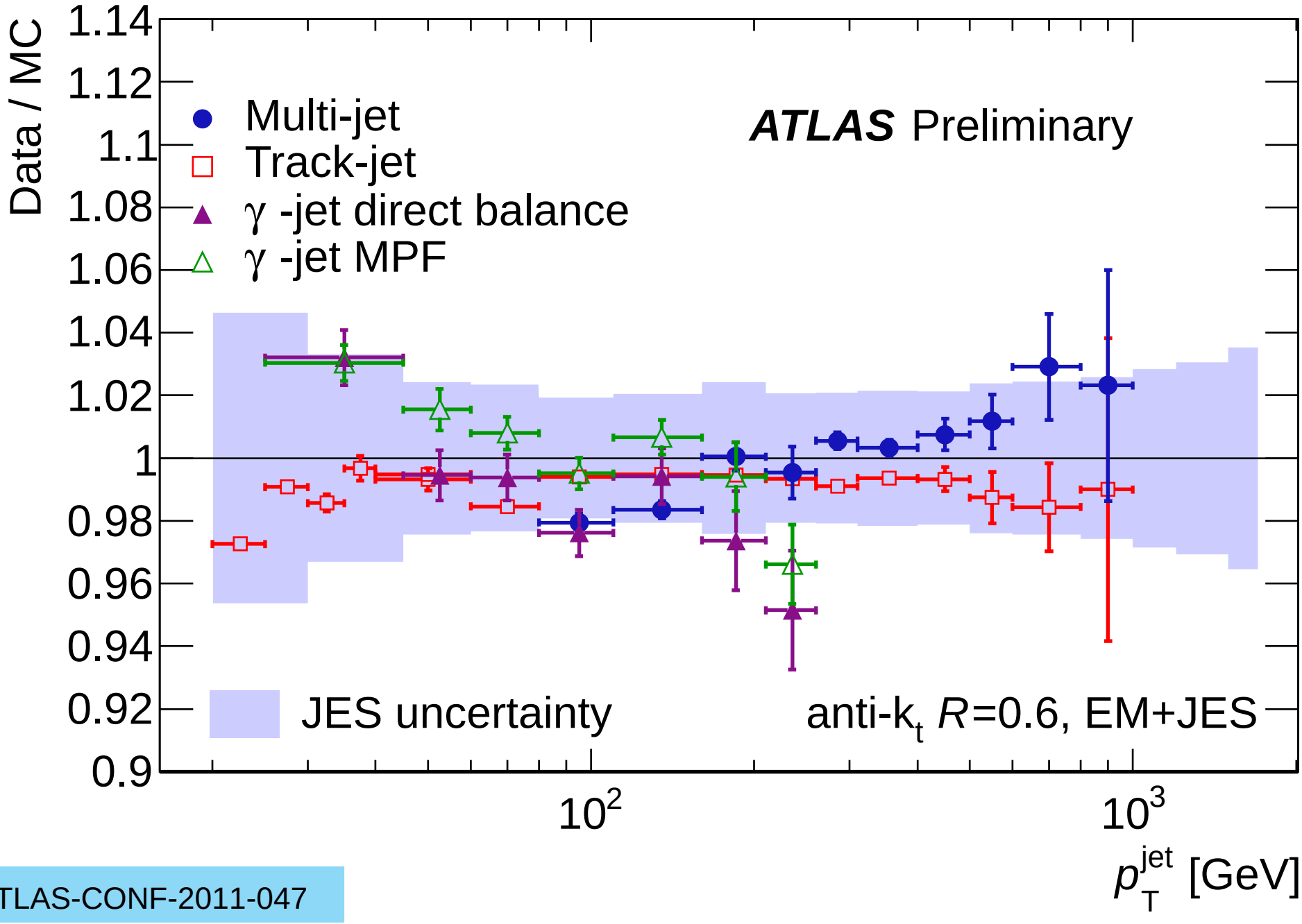
Calorimeter Response



ATLAS-CONF-2011-067

Jet Energy Scale Uncertainty



ATLAS-CONF-2011-047

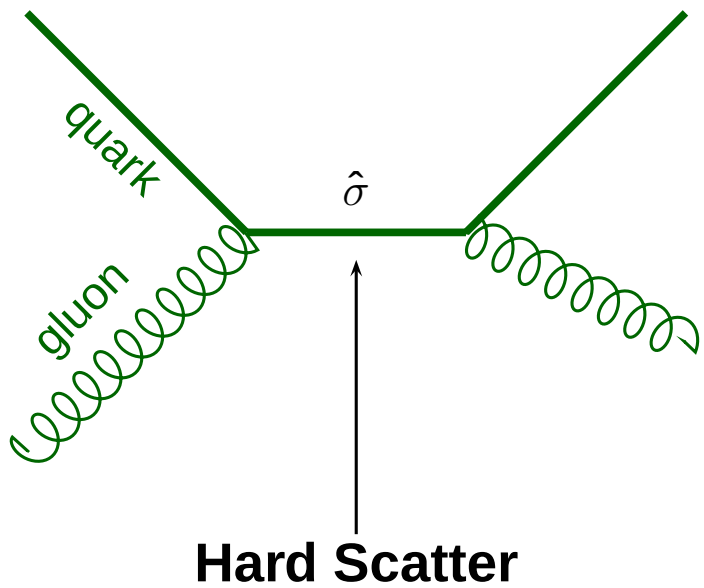
Measurements & Searches

QCD Hard Scatter

High-p_T processes originate in hard scatters between partons

- allow precision tests of perturbative QCD
- sensitive to presence of new physical phenomena

α_s	strength of strong force coupling
Q^2	momentum transferred in hard scatter



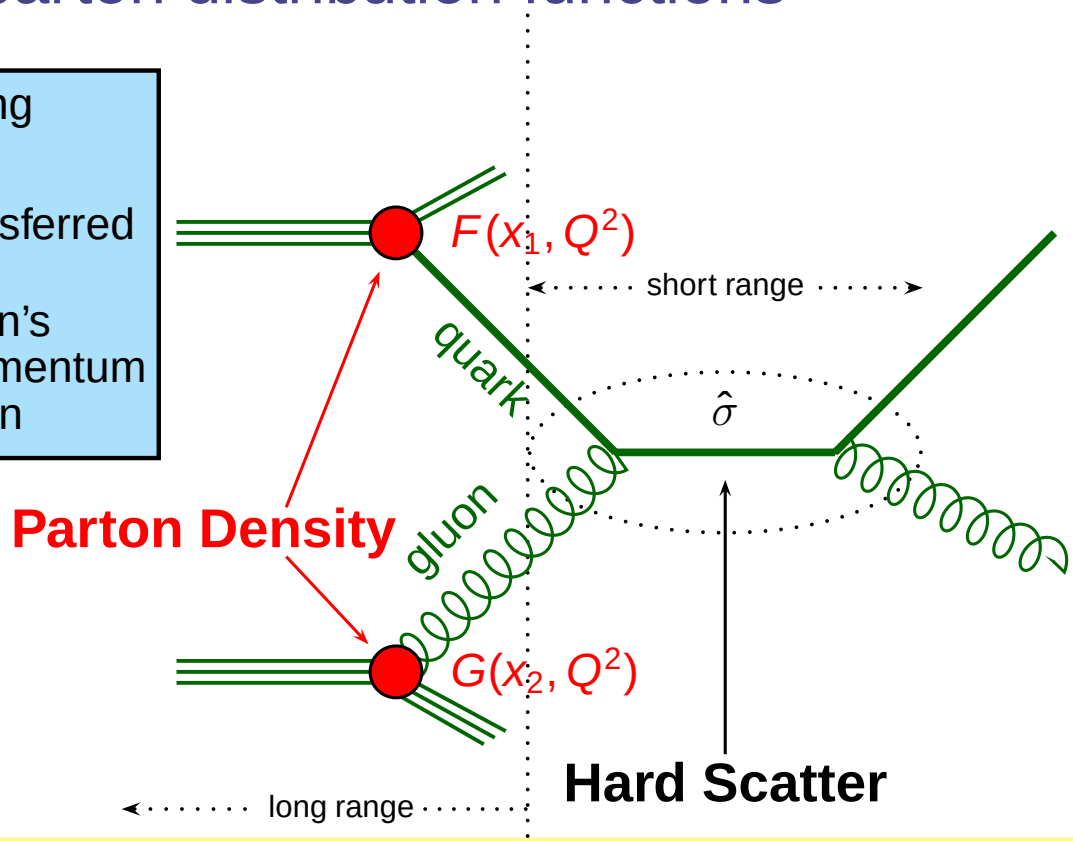
$$\sigma = \sum_{i,j} \hat{\sigma}_{ij}\left(\alpha_s(Q^2)\right)$$

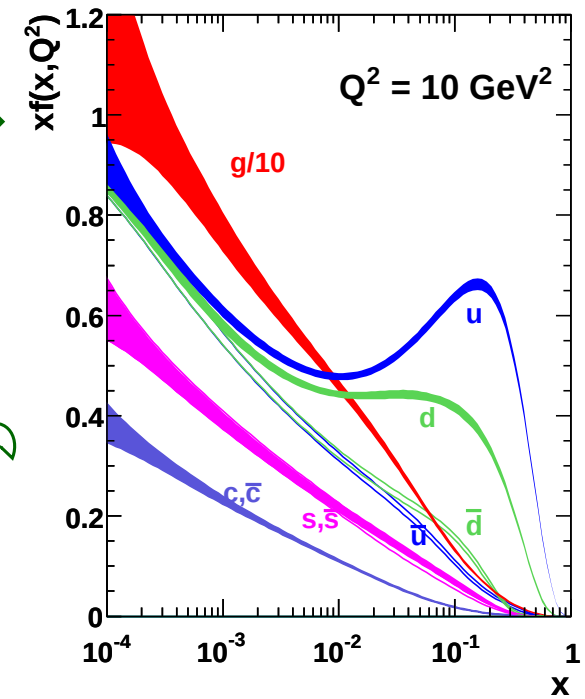
QCD Hard Scatter

High-p_T processes originate in hard scatters between partons

- allow precision tests of perturbative QCD
- sensitive to presence of new physical phenomena
- constrain parton distribution functions

α_S	strength of strong force coupling
Q^2	momentum transferred in hard scatter
x	fraction of proton's longitudinal momentum carried by parton





$$\sigma = \sum_{i,j} \int_0^1 dx_1 dx_2 \, F_i(x_1, Q^2) \, G_j(x_2, Q^2) \, \hat{\sigma}_{ij}\left(x_1, x_2, \alpha_S(Q^2)\right)$$

QCD Hard Scatter

High-p_T processes originate in hard scatters between partons

- allow precision tests of perturbative QCD
- sensitive to presence of new physical phenomena
- constrain parton distribution functions

α_S	strength of strong force coupling
Q^2	momentum transferred in hard scatter
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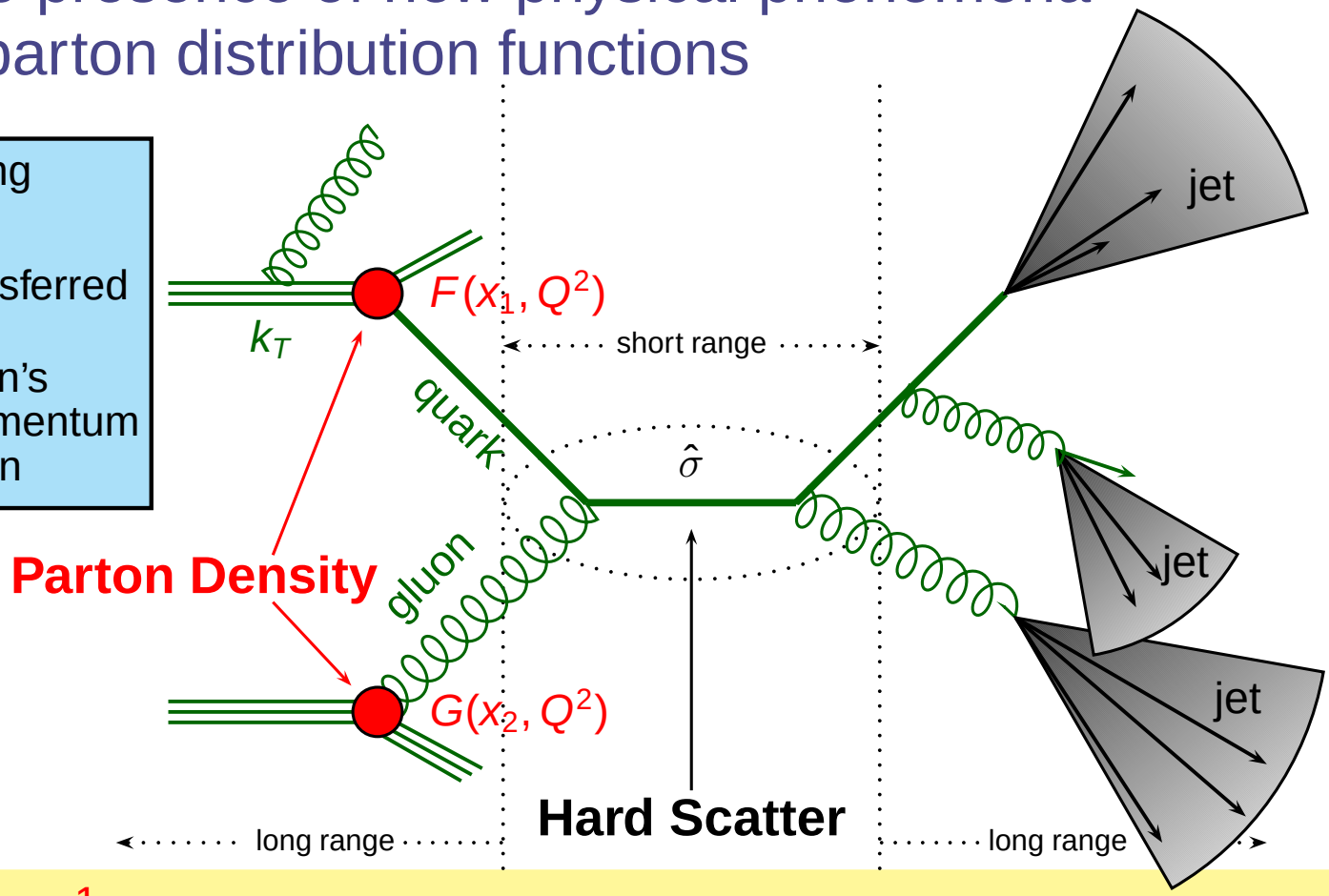

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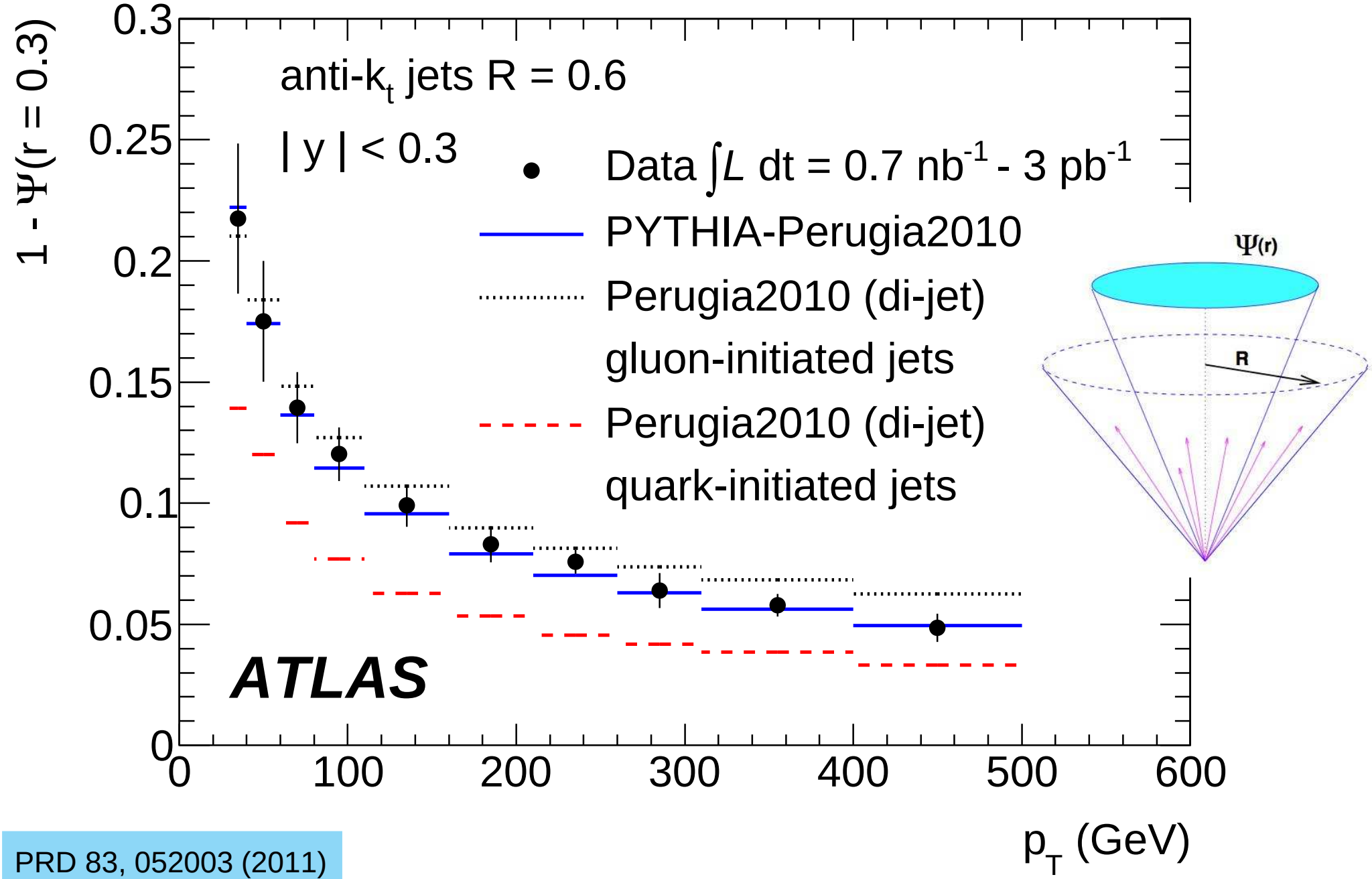
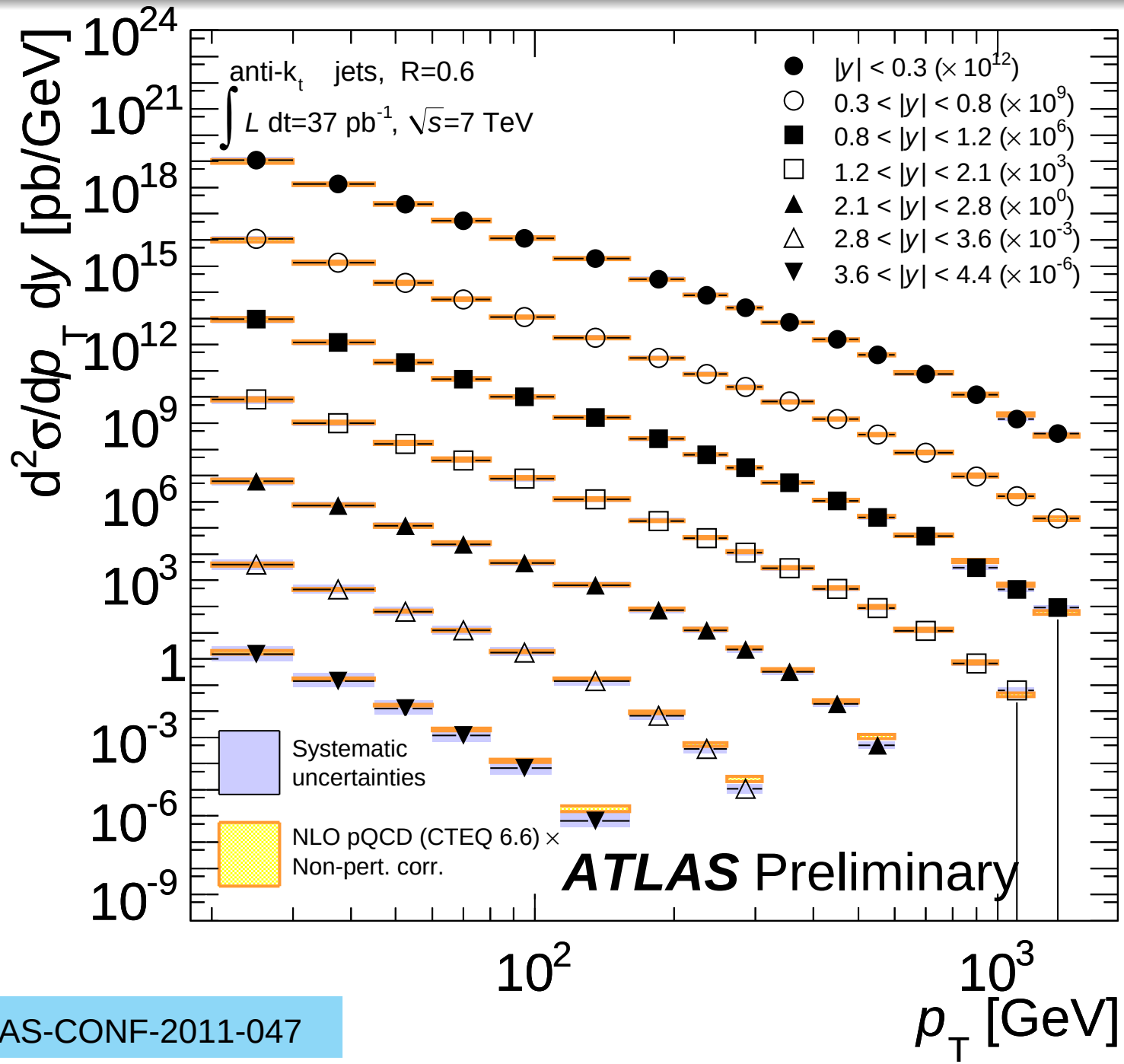
Jet Shapes



PRD 83, 052003 (2011)

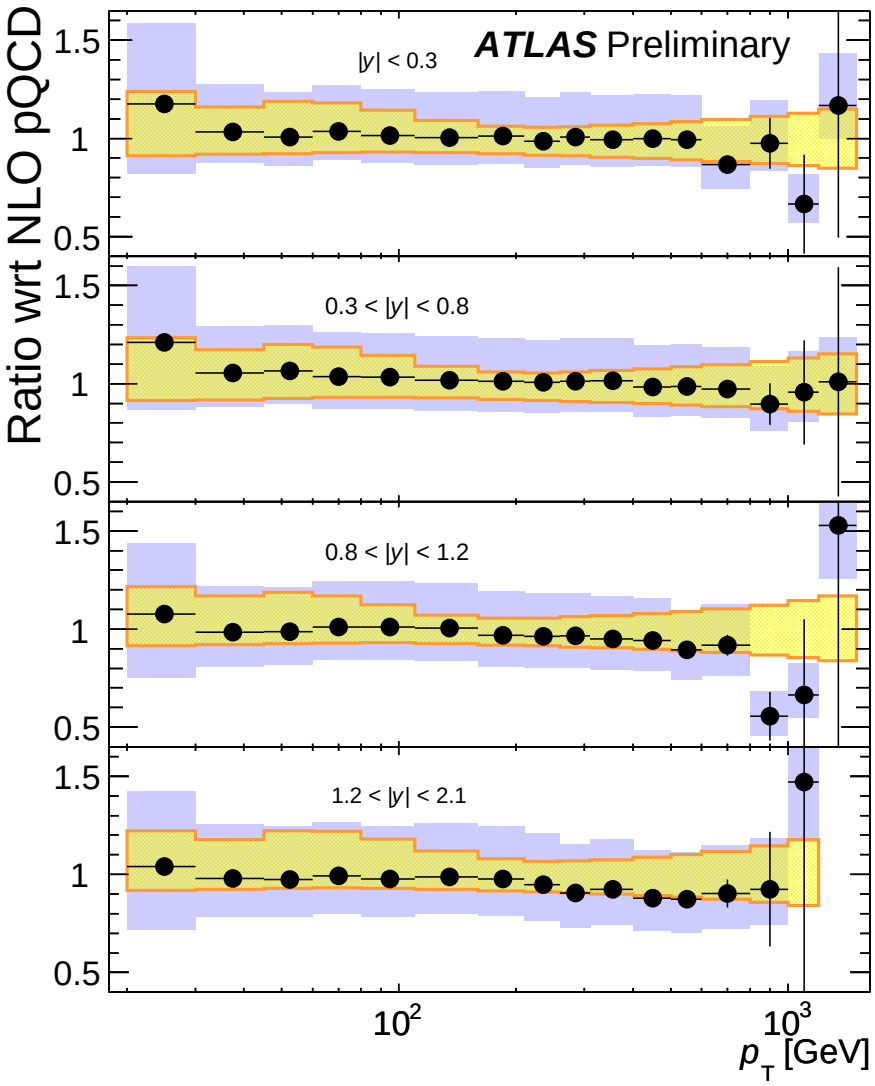
Inclusive Jet Cross Section

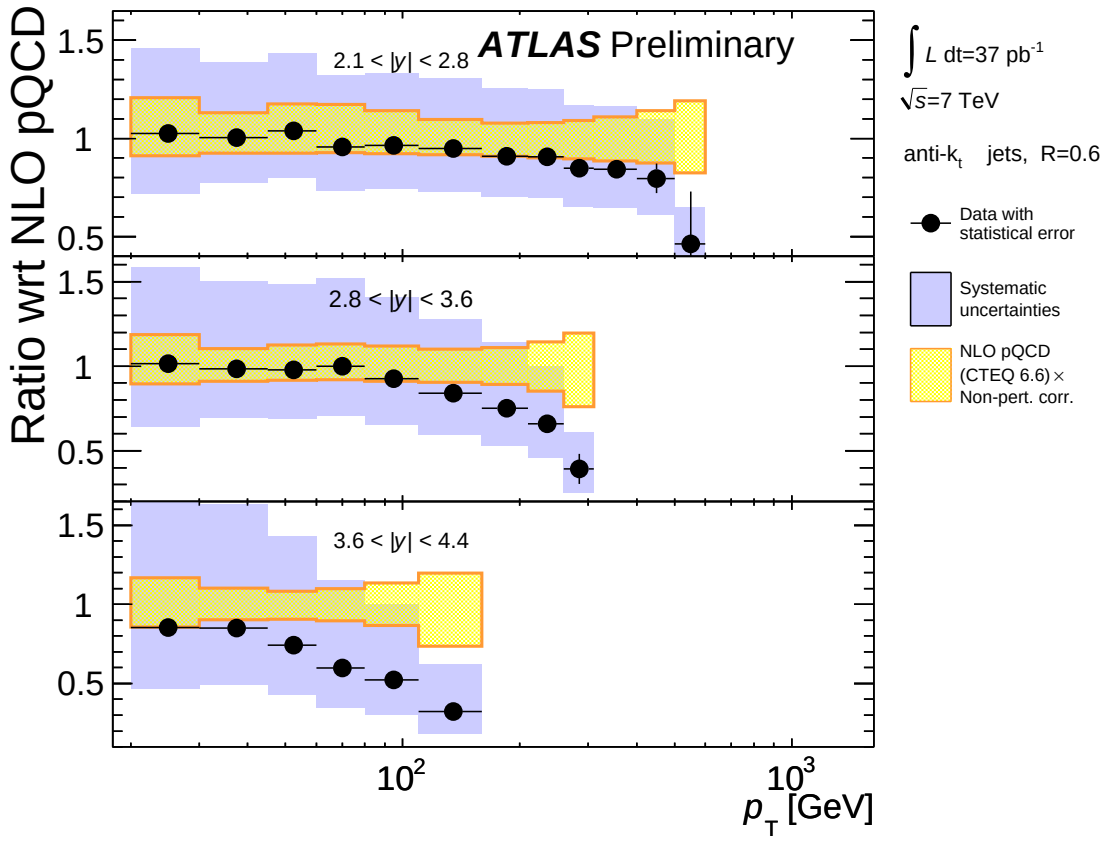


$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

ATLAS-CONF-2011-047

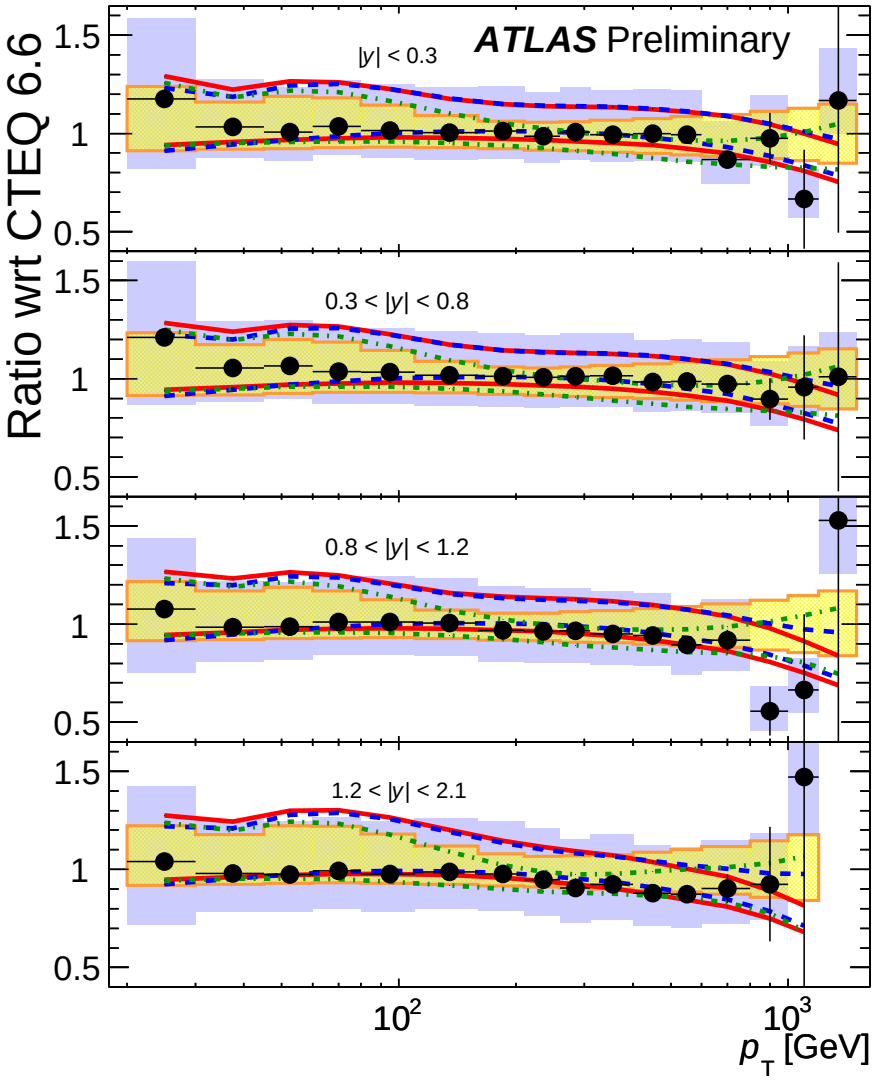
Inclusive Jet Cross Section

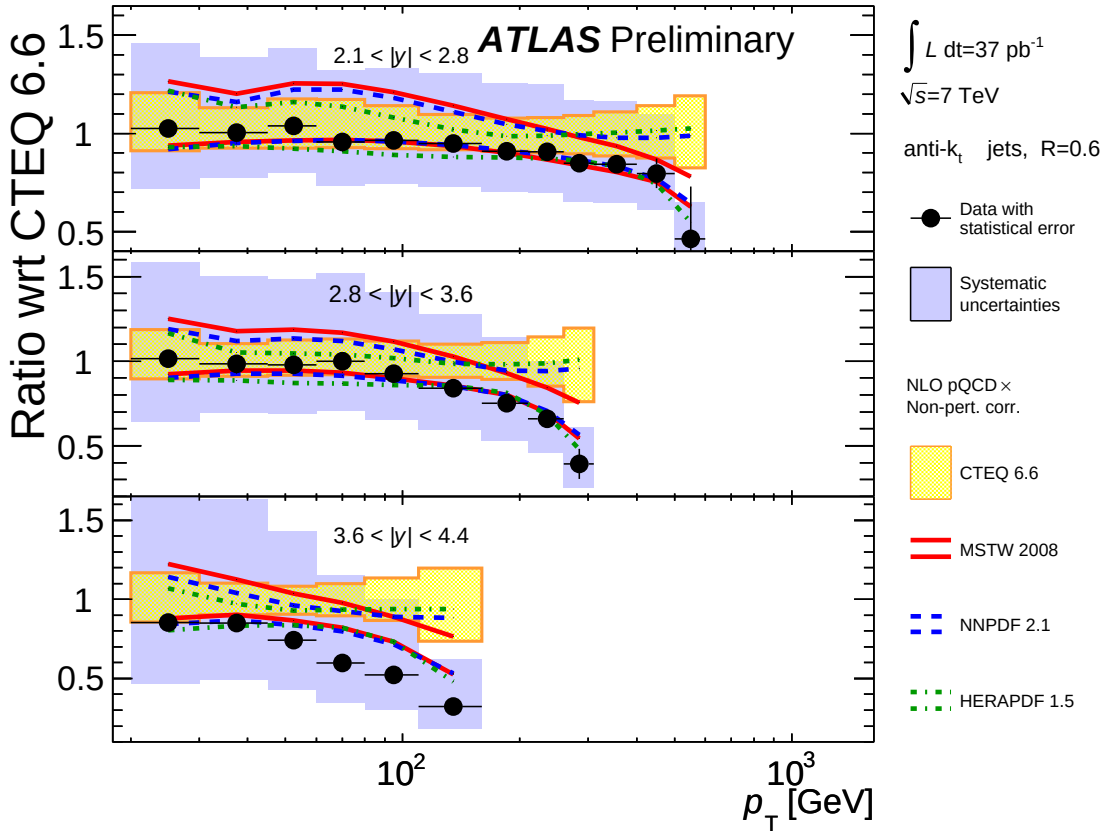




ATLAS-CONF-2011-047

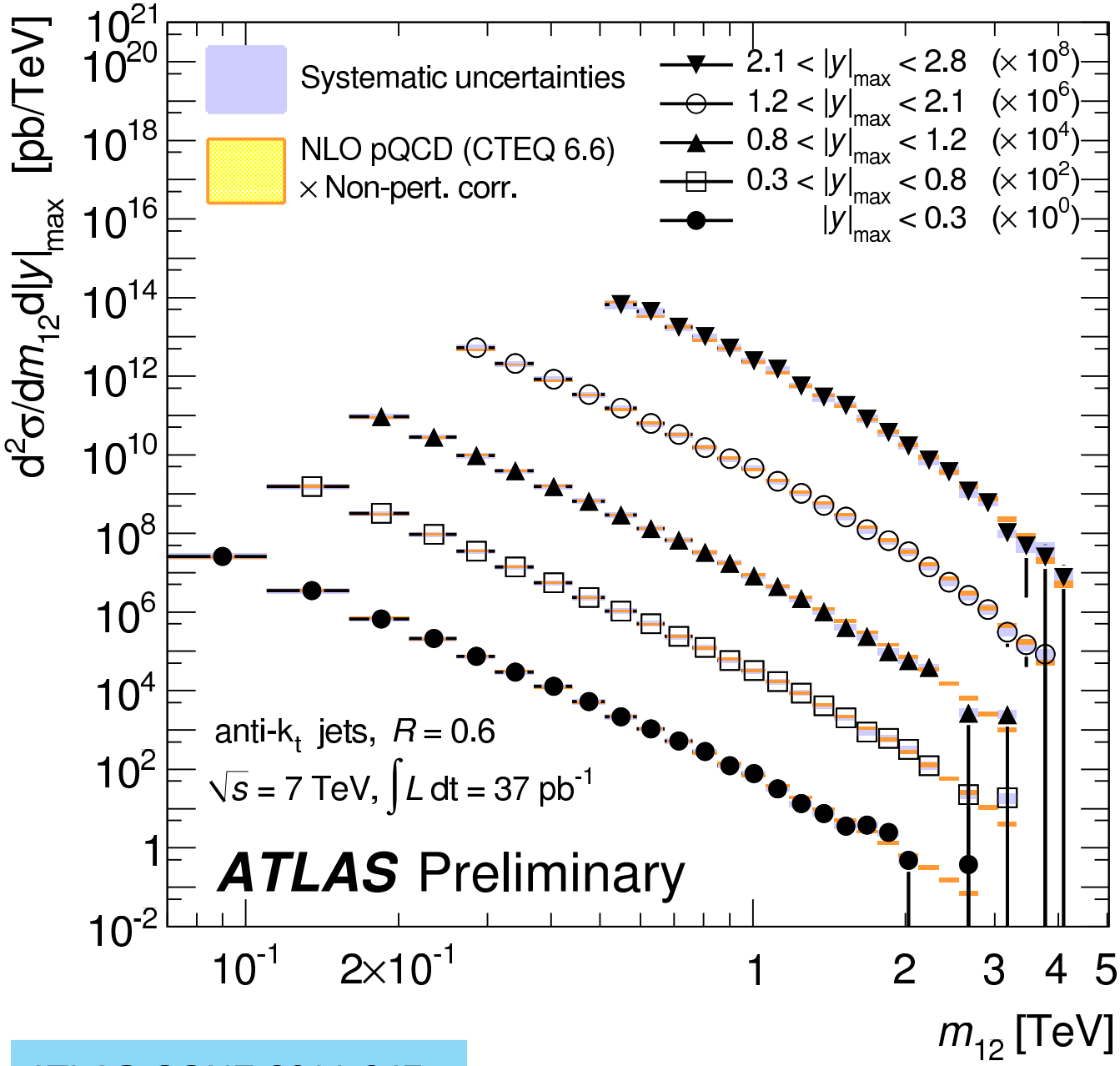
Inclusive Jet Cross Section

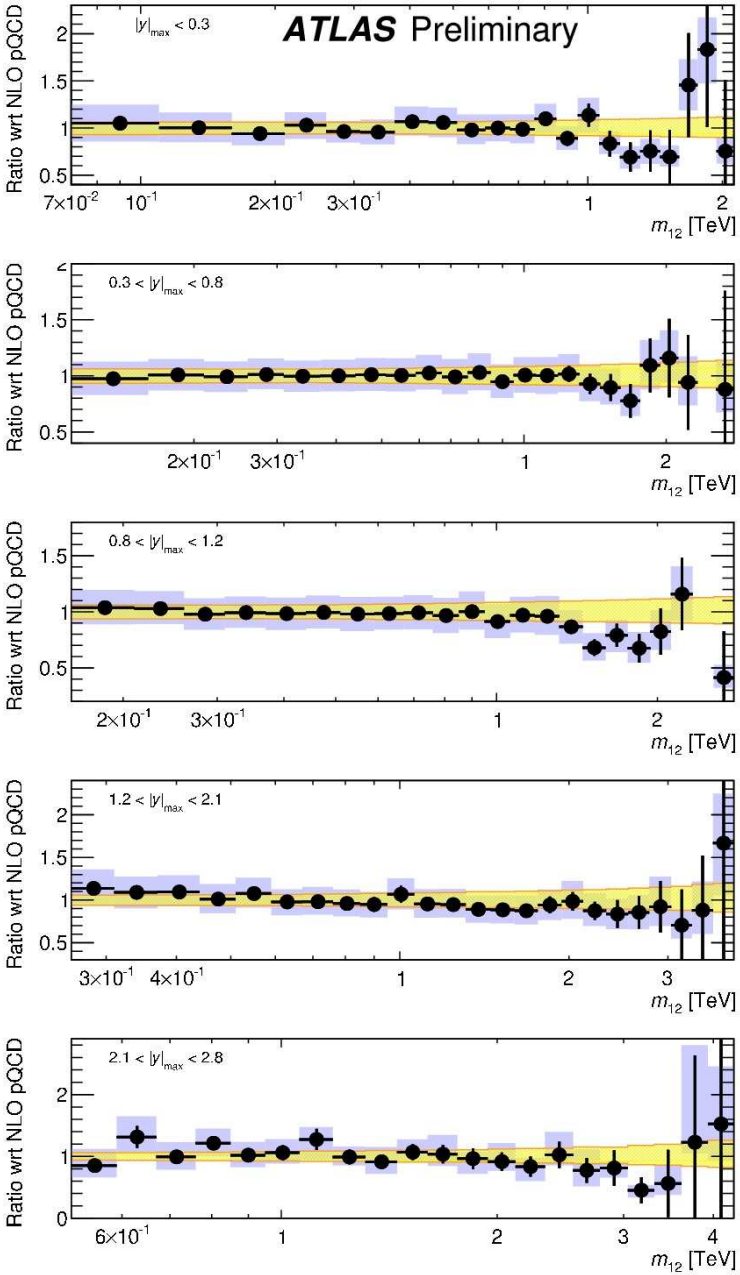




ATLAS-CONF-2011-047

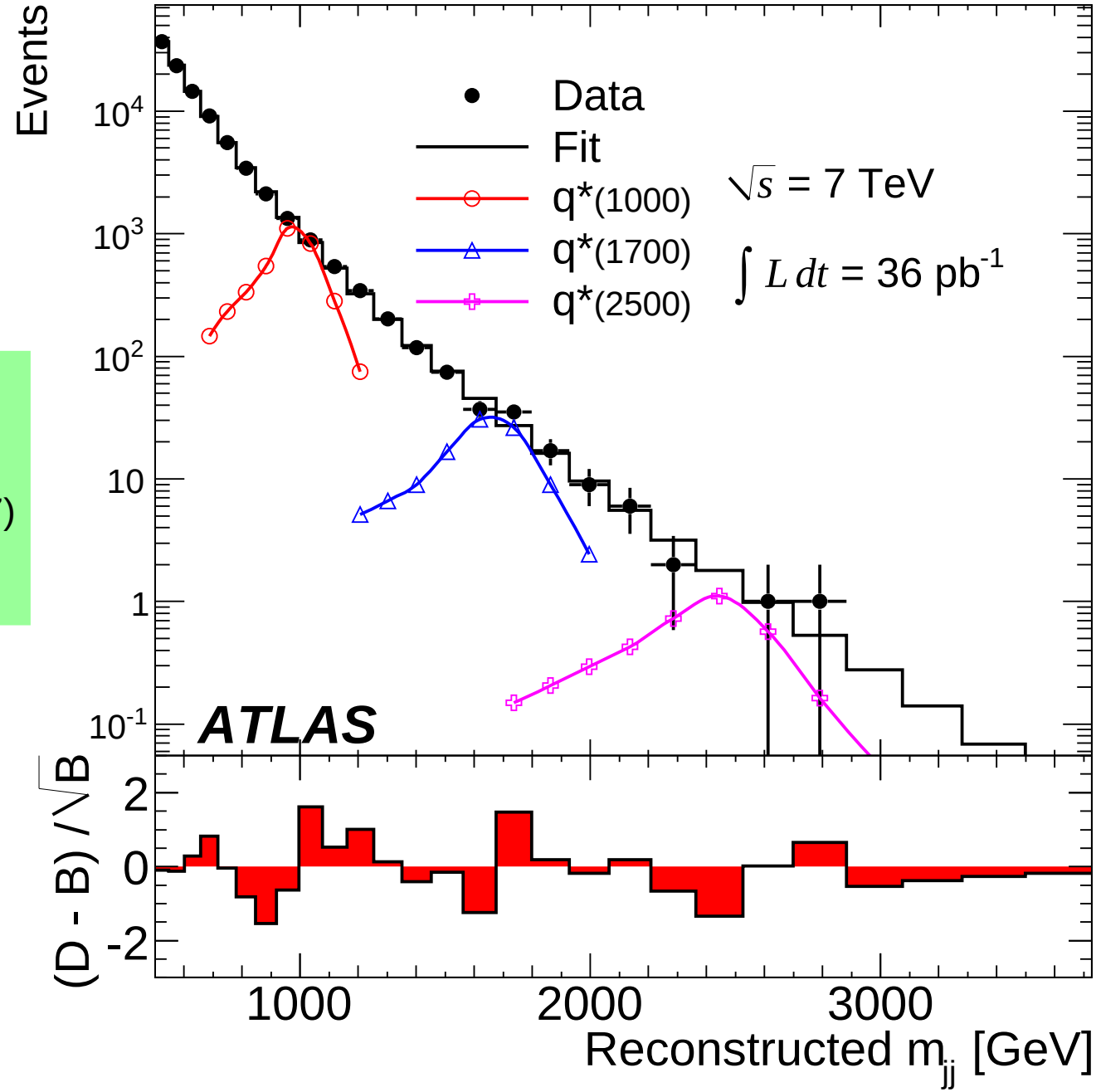
Dijet Cross Section





ATLAS-CONF-2011-047

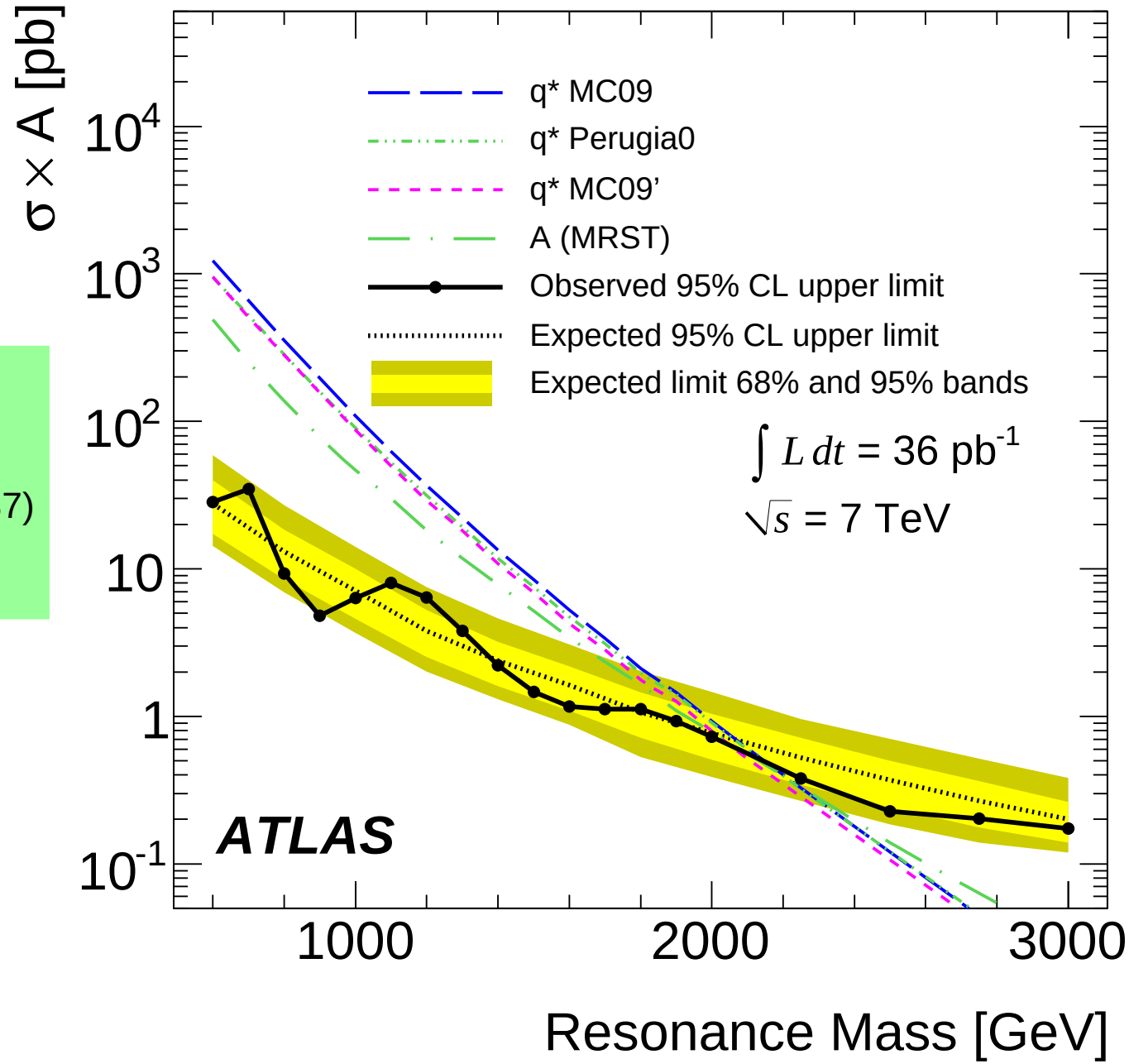
Dijet Resonances



Excited Quark Model
$qg \rightarrow q^{\star}$; $\Lambda = m_{q^{\star}}$
Baur, Hinchliffe, Zeppenfeld
Int. J. Mod. Phys. **A2**, 1285 (1987)
Baur, Spira, Zerwas
Phys. Rev. **D42**, 815 (1990)

arXiv:1103.3864 [hep-ex]
(accepted by NJP)

Dijet Resonances



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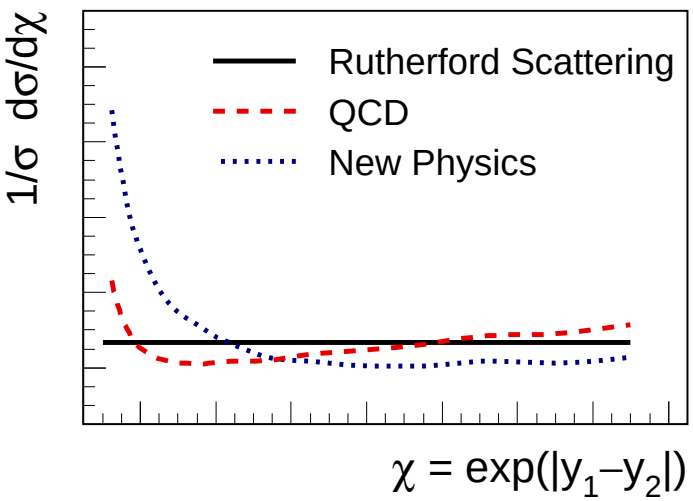
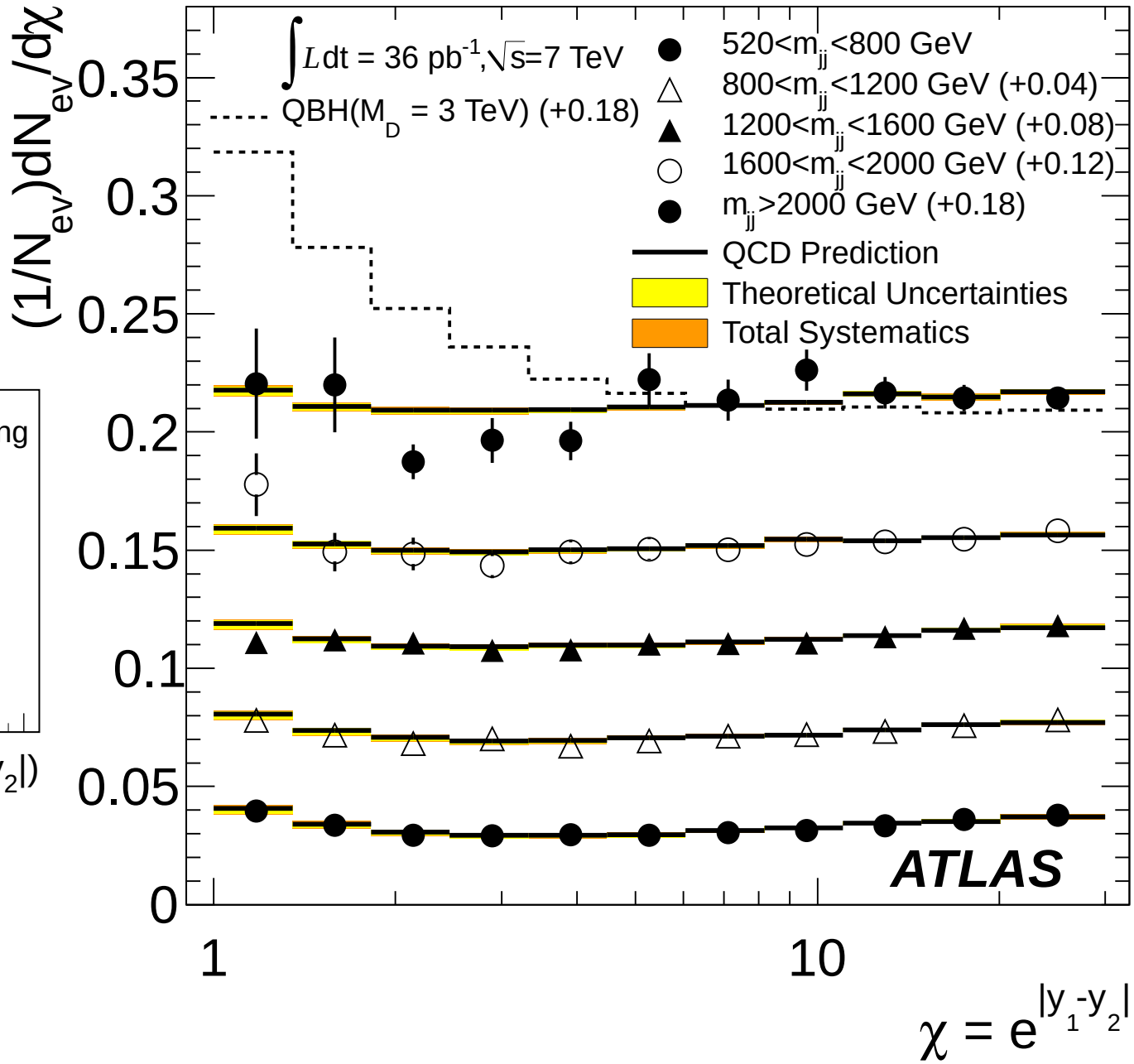
arXiv:1103.3864 [hep-ex]
(accepted by NJP)

Dijet Angular Correlations

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

$$\chi = e^{|y_1 - y_2|}$$





arXiv:1103.3864 [hep-ex]
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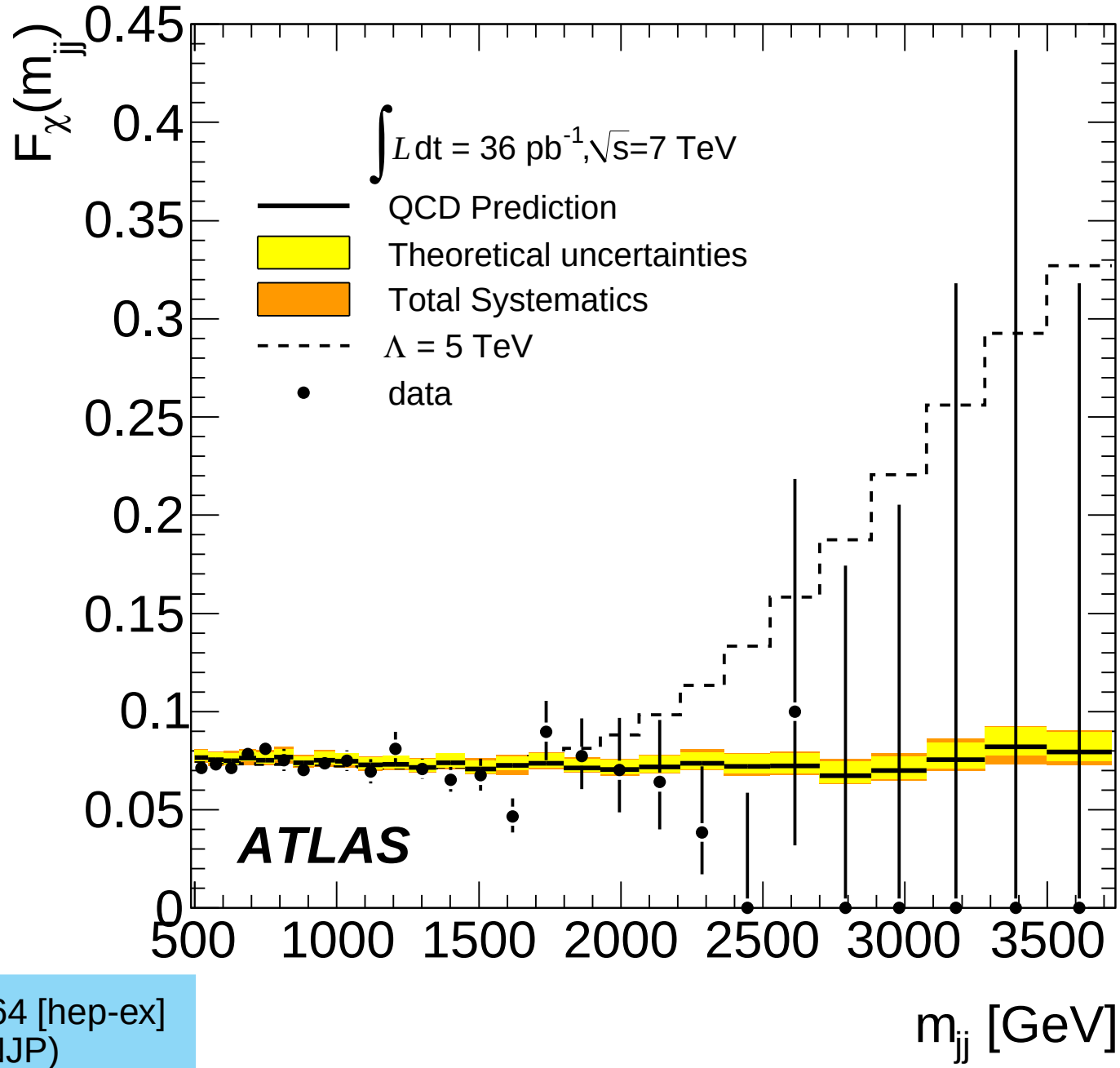
Dijet Angular Correlations



arXiv:1103.3864 [hep-ex]
(accepted by NJP)

Dijet Angular Correlations

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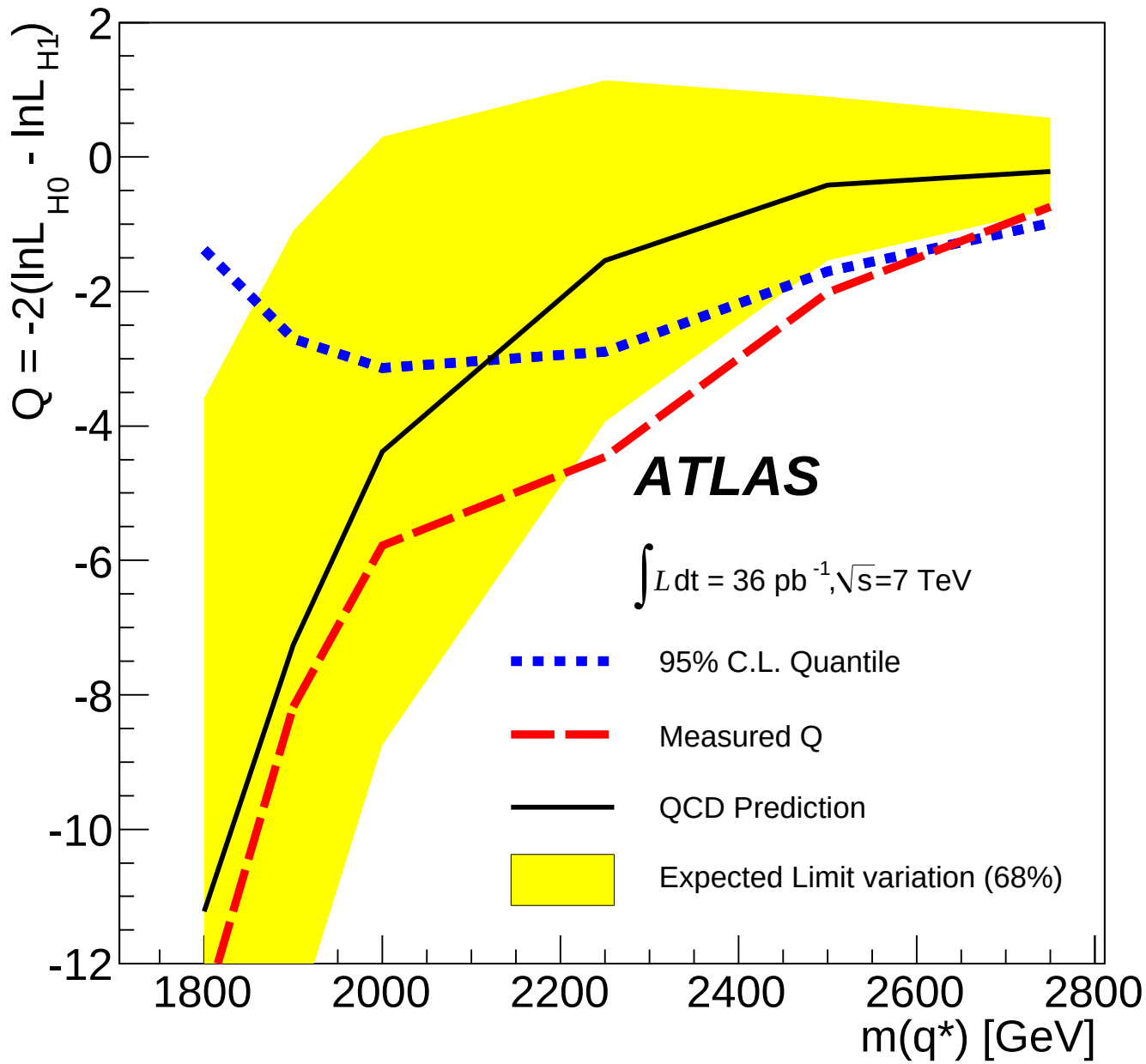


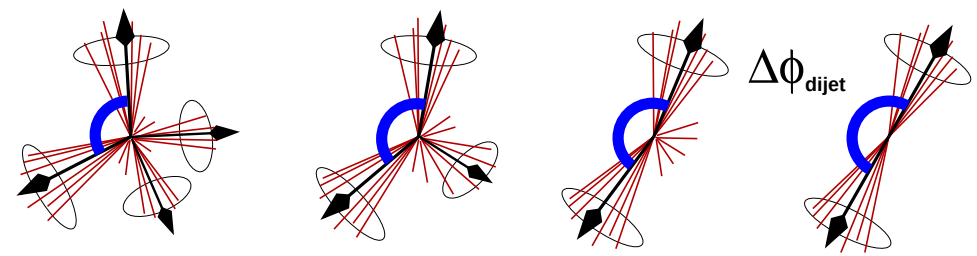
arXiv:1103.3864 [hep-ex]
(accepted by NJP)

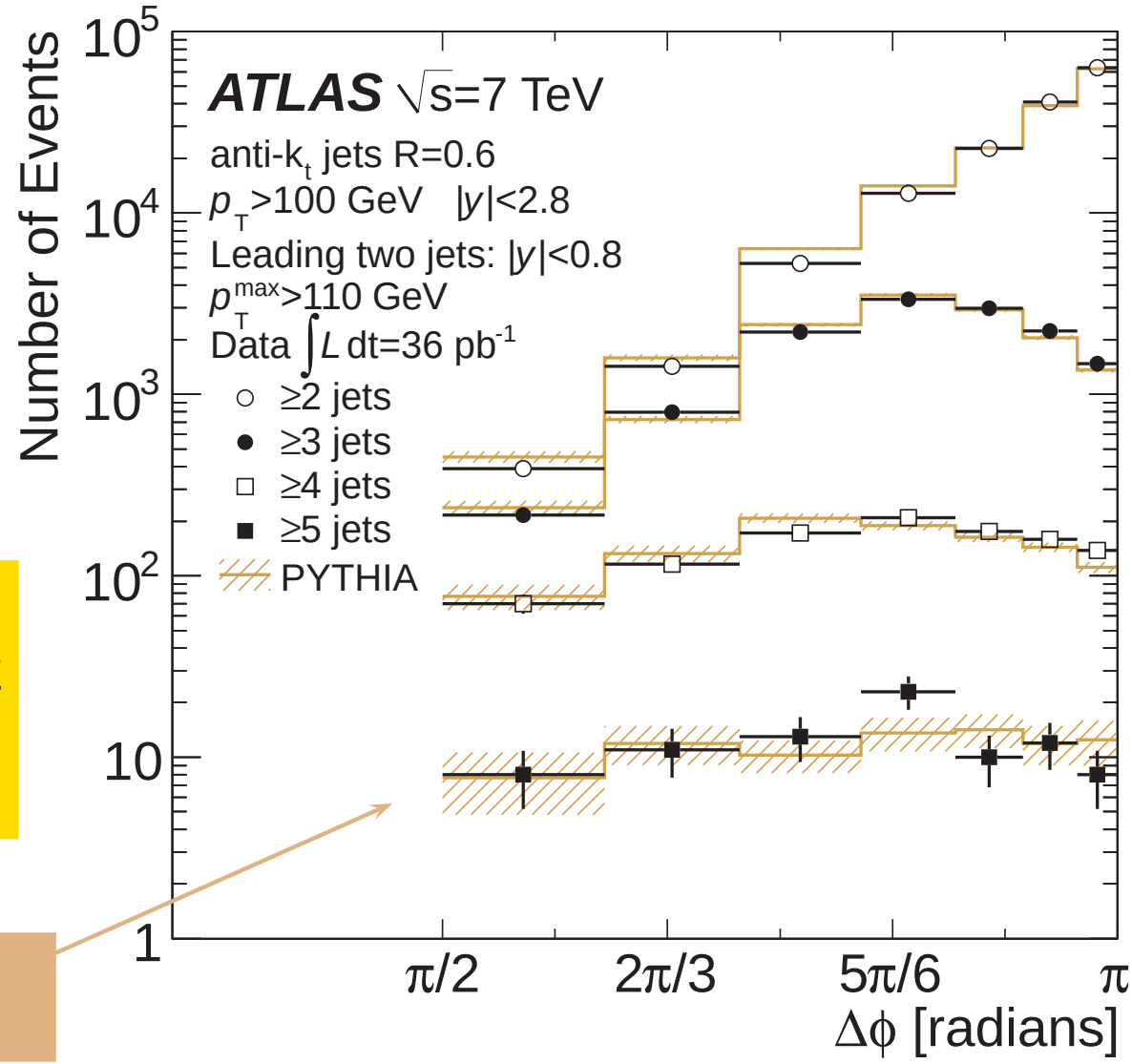
Dijet Azimuthal Decorrelations

BROOKHAVEN NATIONAL LABORATORY

$\Delta\phi$ between the leading two jets in an event reflects the activity in the rest of the event

- *soft* radiation causes *small* decorrelations
- *hard* radiation, such as from the presence of additional jets, can cause *large* decorrelations

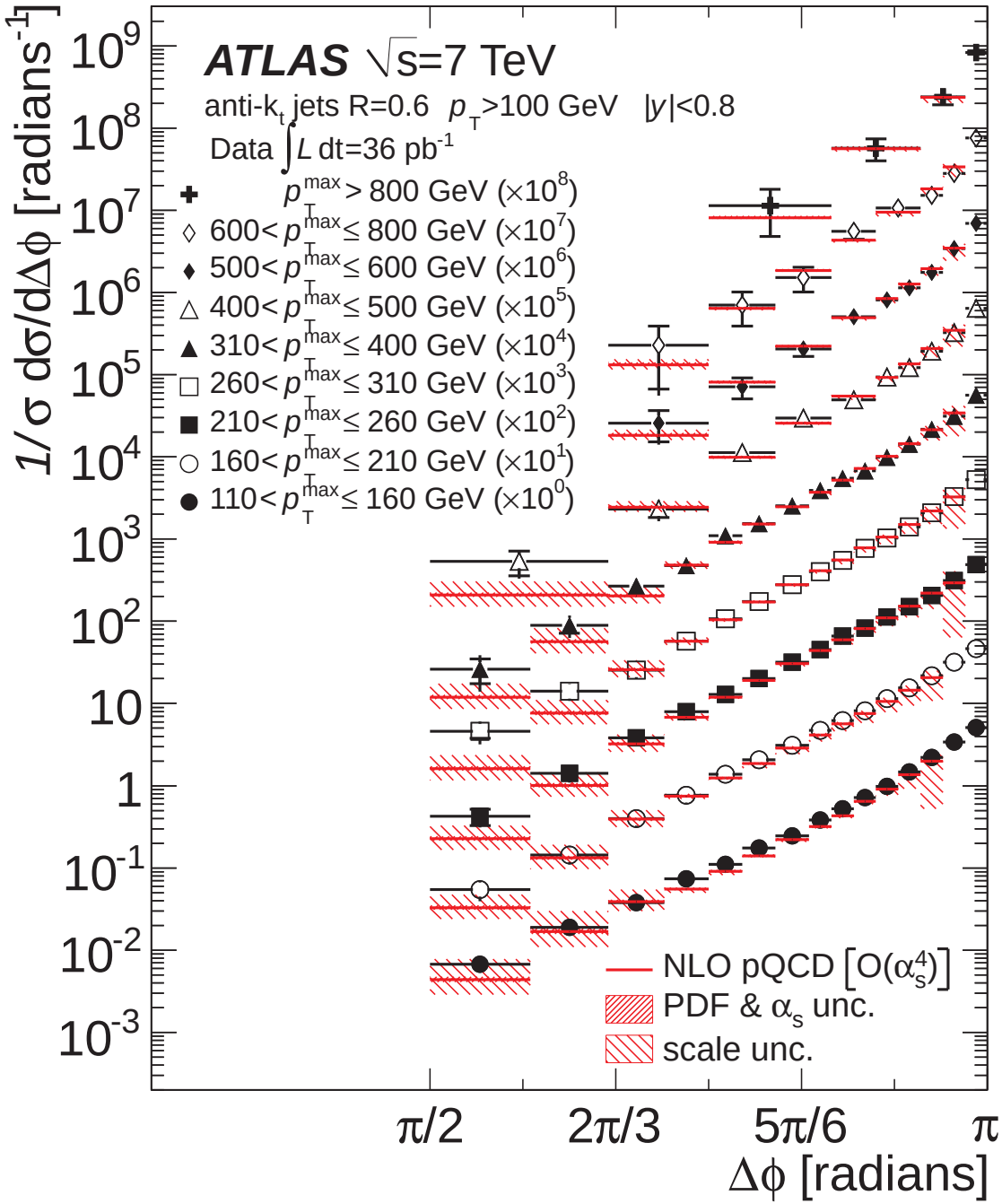




$\Delta\phi$ tests pQCD calculations for multijet final states without requiring the measurement of additional jets

85 events have 5 jets with $p_T > 100$ GeV

Dijet Azimuthal Decorrelations

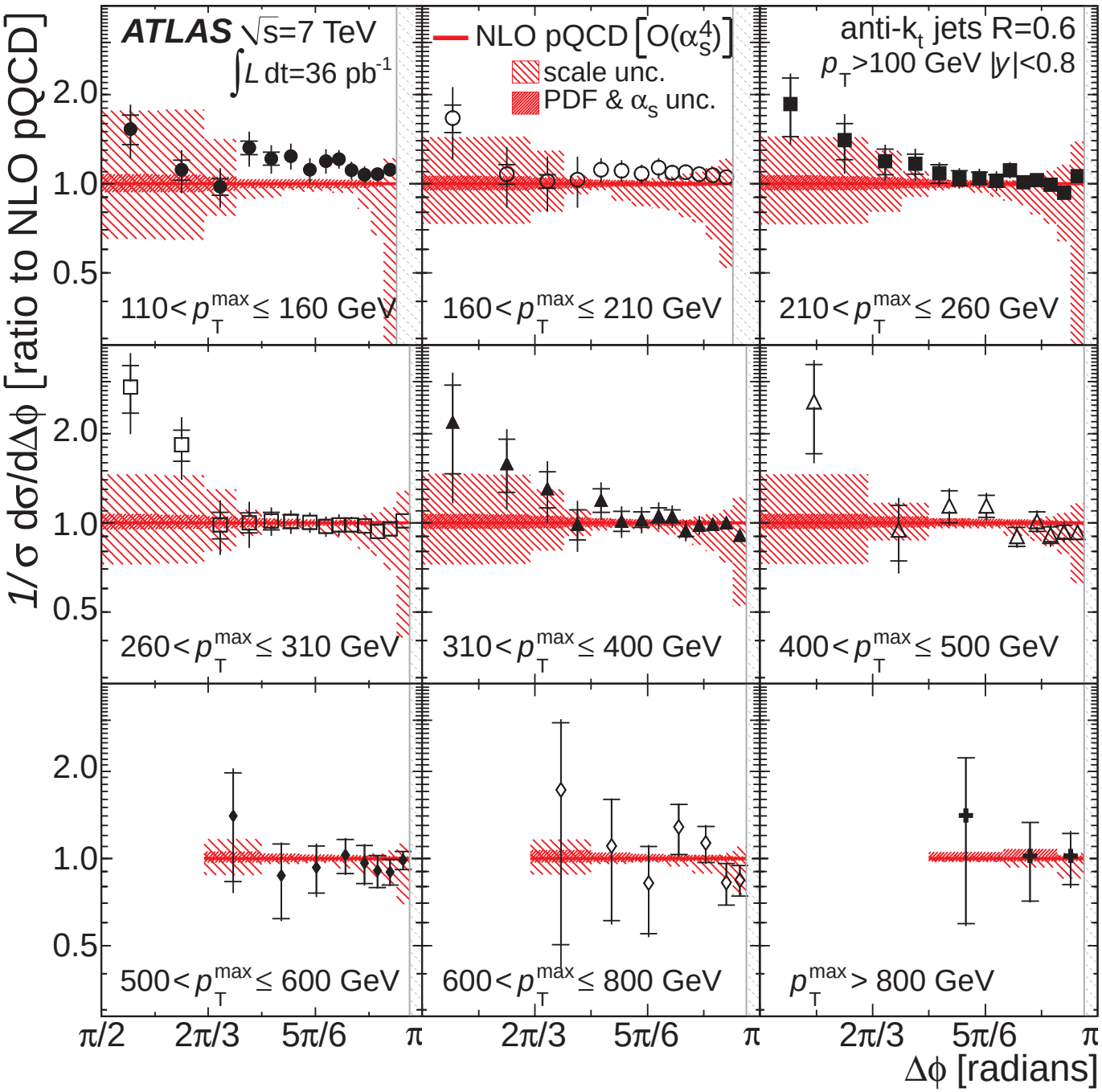


scale uncertainty large where NLO pQCD dominated by real $\mathcal{O}(\alpha_s^4)$ diagrams

comparison excluded where NLO pQCD diverges ($\Delta\phi \to \pi$)

arXiv:1102.2696 [hep-ex] (accepted by PRL)

Dijet Azimuthal Decorrelations



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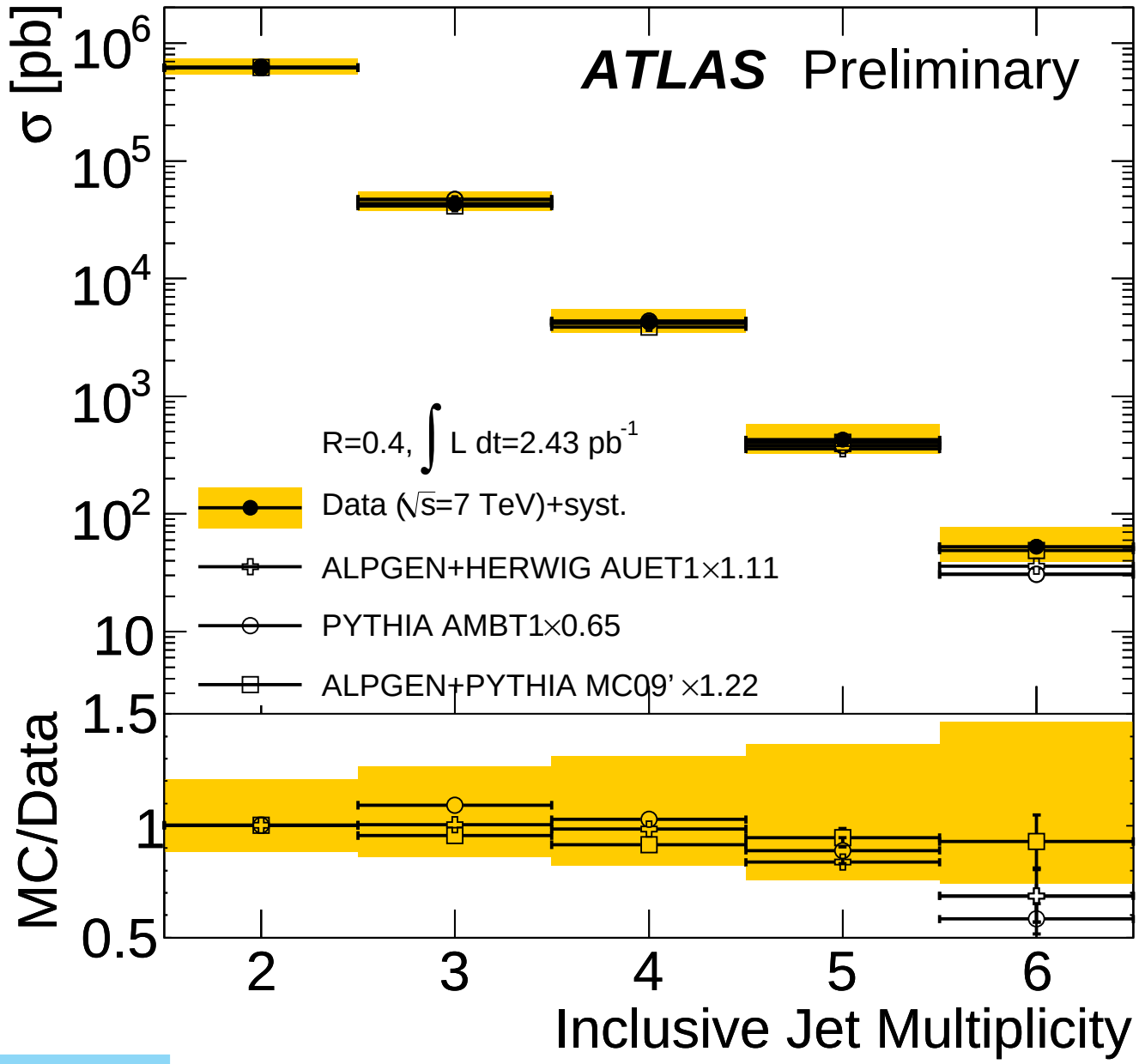
comparison excluded where NLO pQCD diverges ($\Delta\phi \to \pi$)

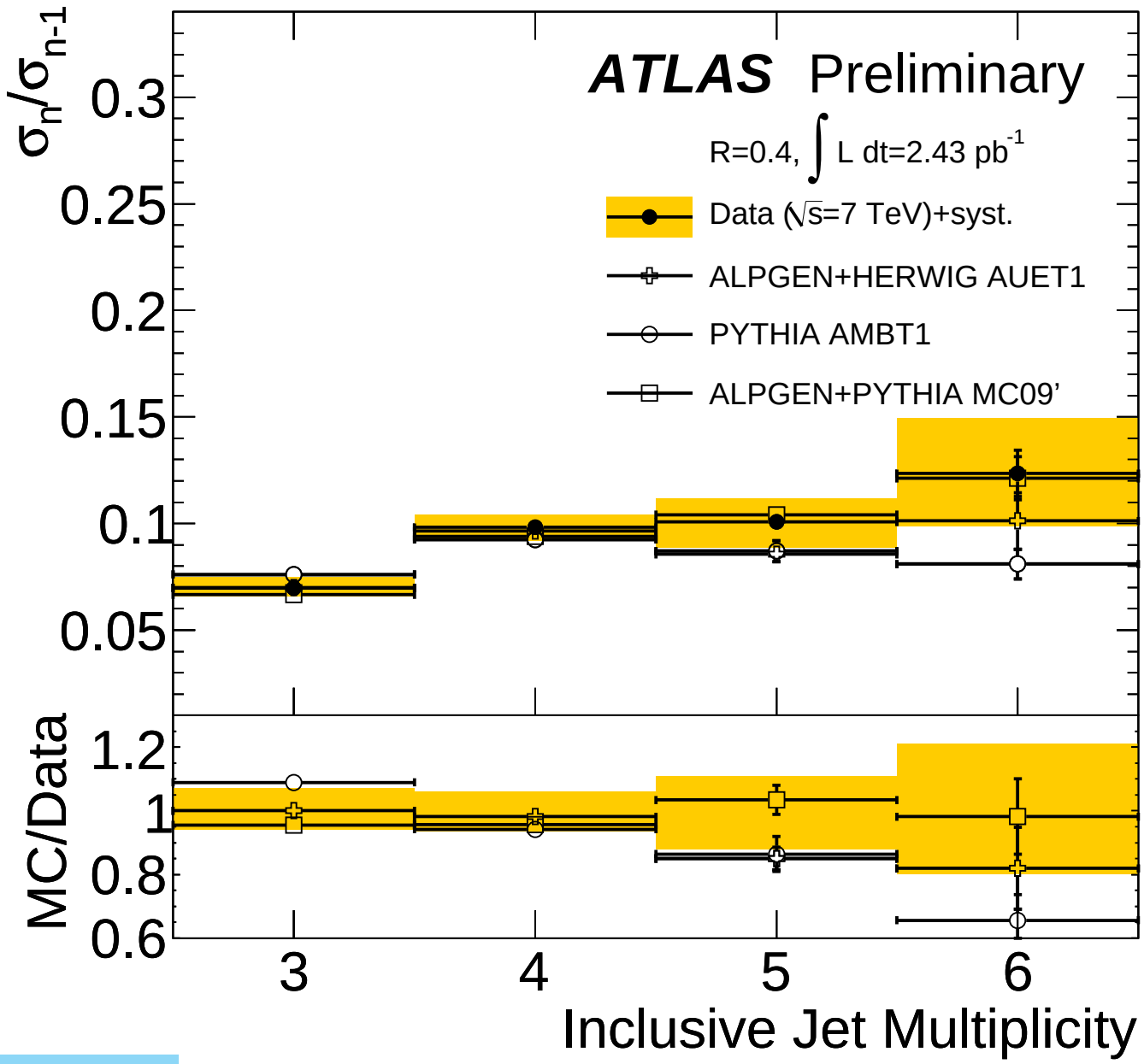
arXiv:1102.2696 [hep-ex] (accepted by PRL)

Multijet Cross Section



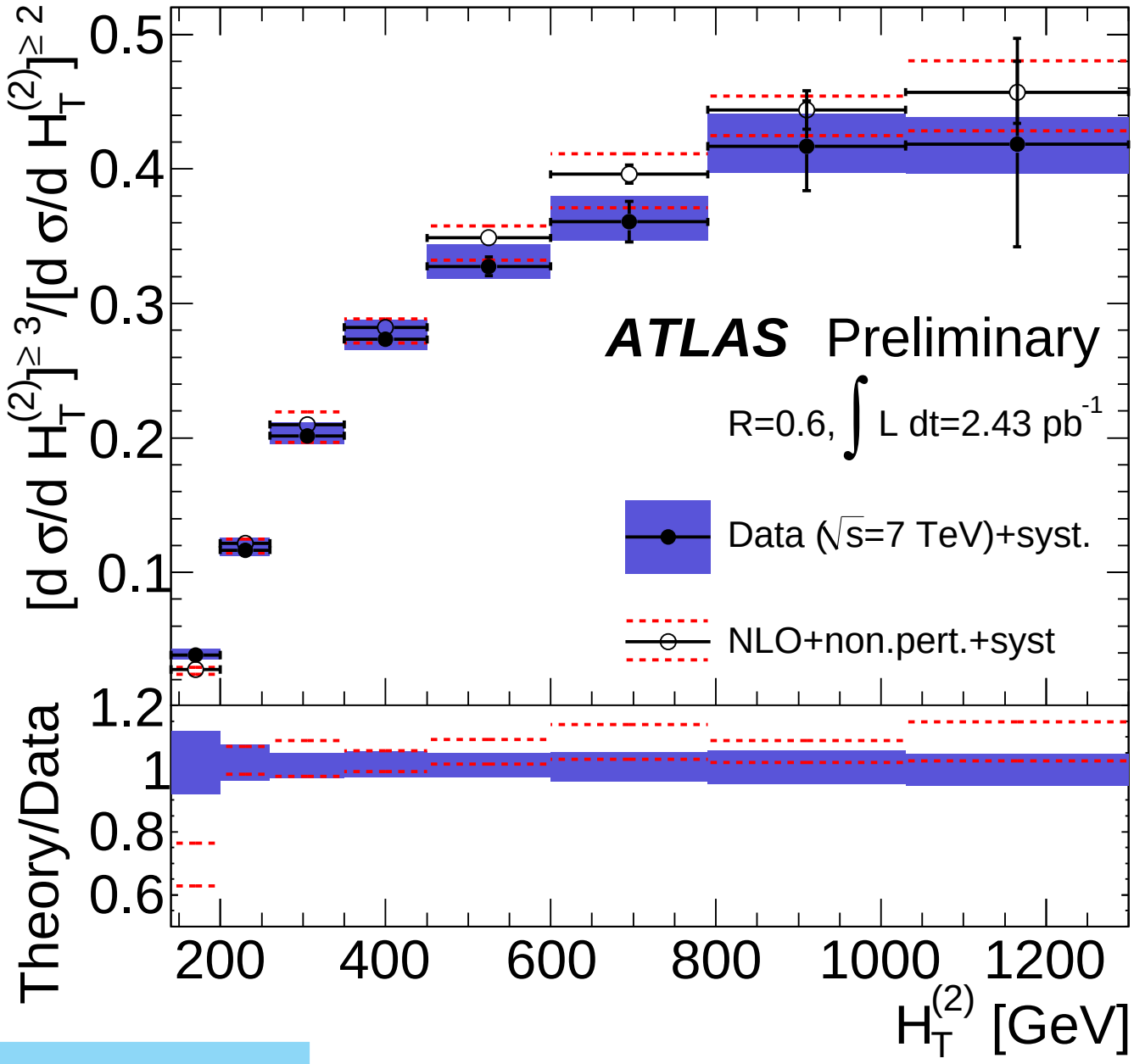
ATLAS-CONF-2011-043

Multijet Cross Section



ATLAS-CONF-2011-043

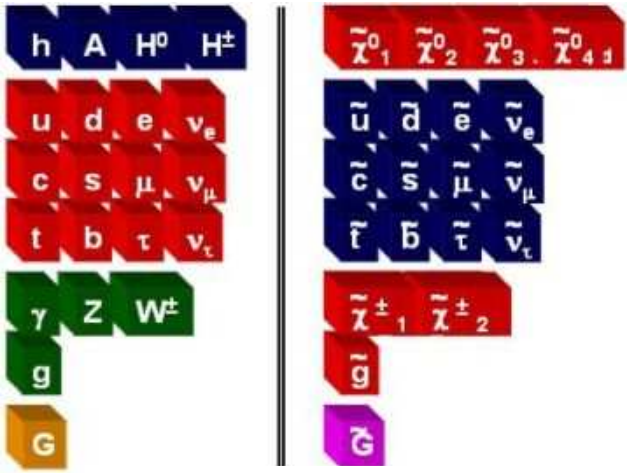
Multijet Cross Section

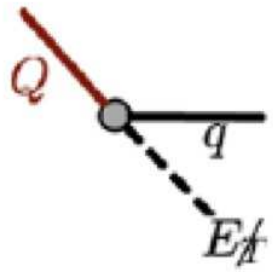


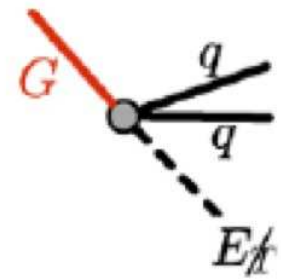
$$H_T^{(n)} = \sum_{i=1}^{n} p_T^{\text{jet } i}$$

ATLAS-CONF-2011-043

Supersymmetry



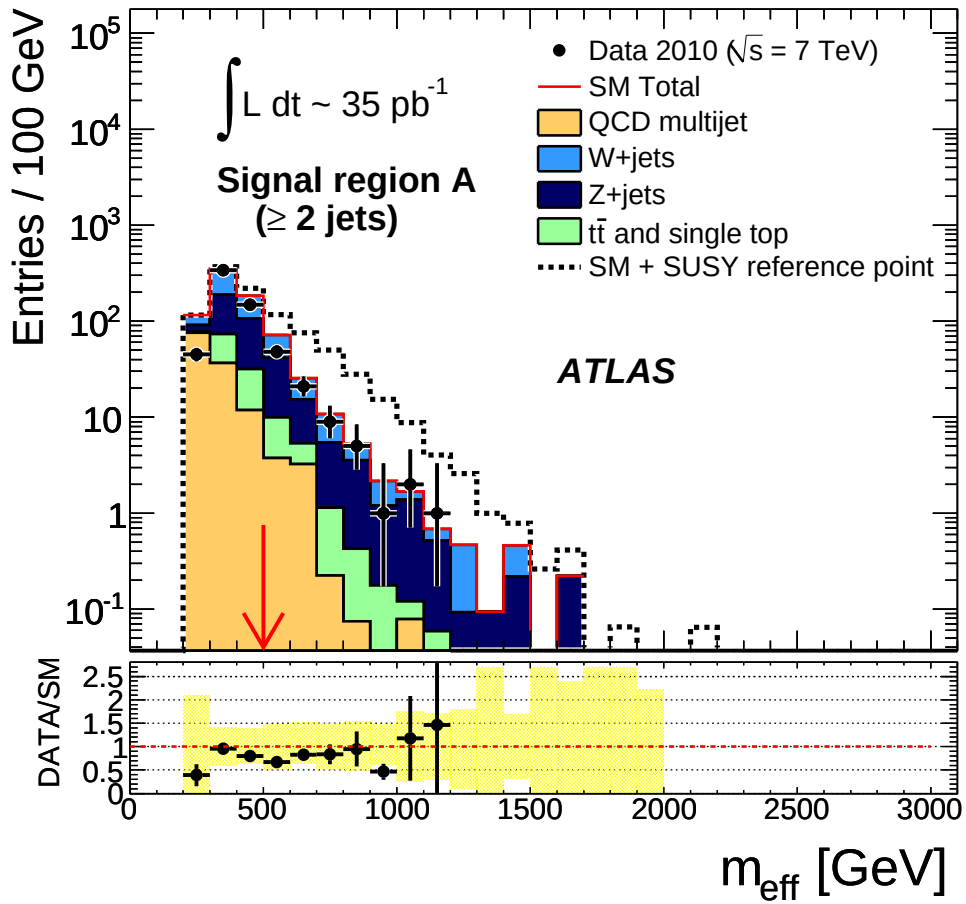


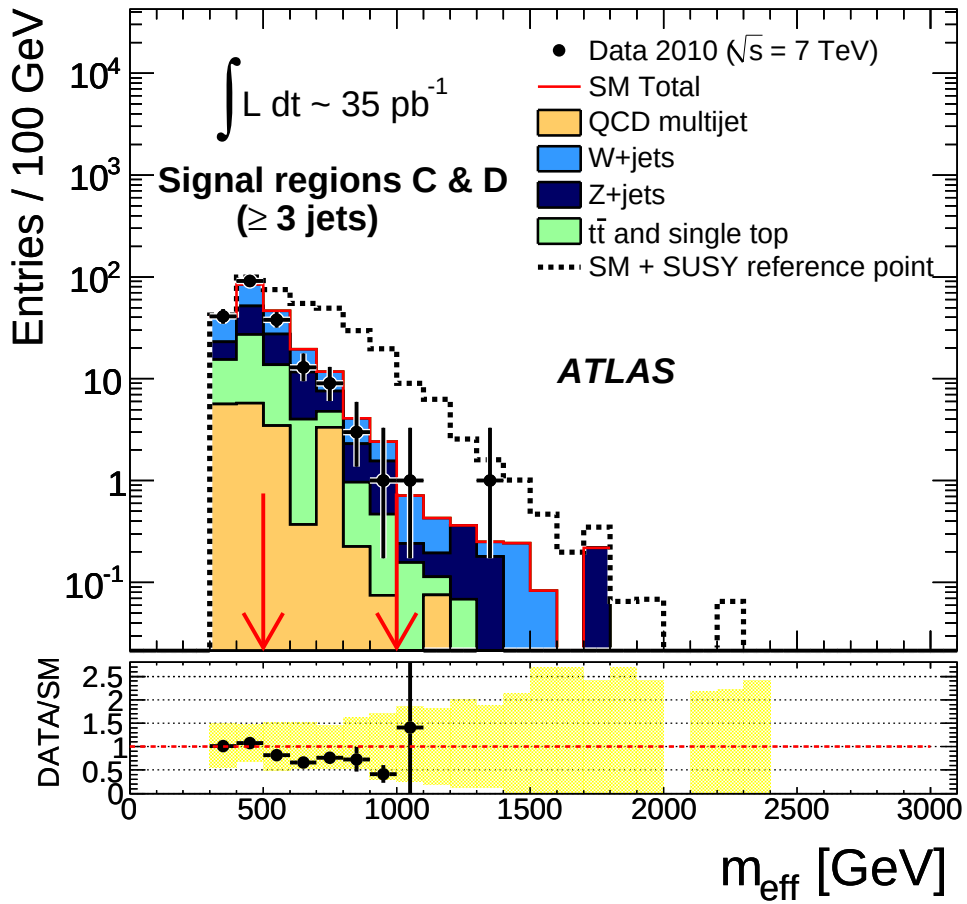


arXiv:1102.5290 [hep-ex]
(submitted to PLB)

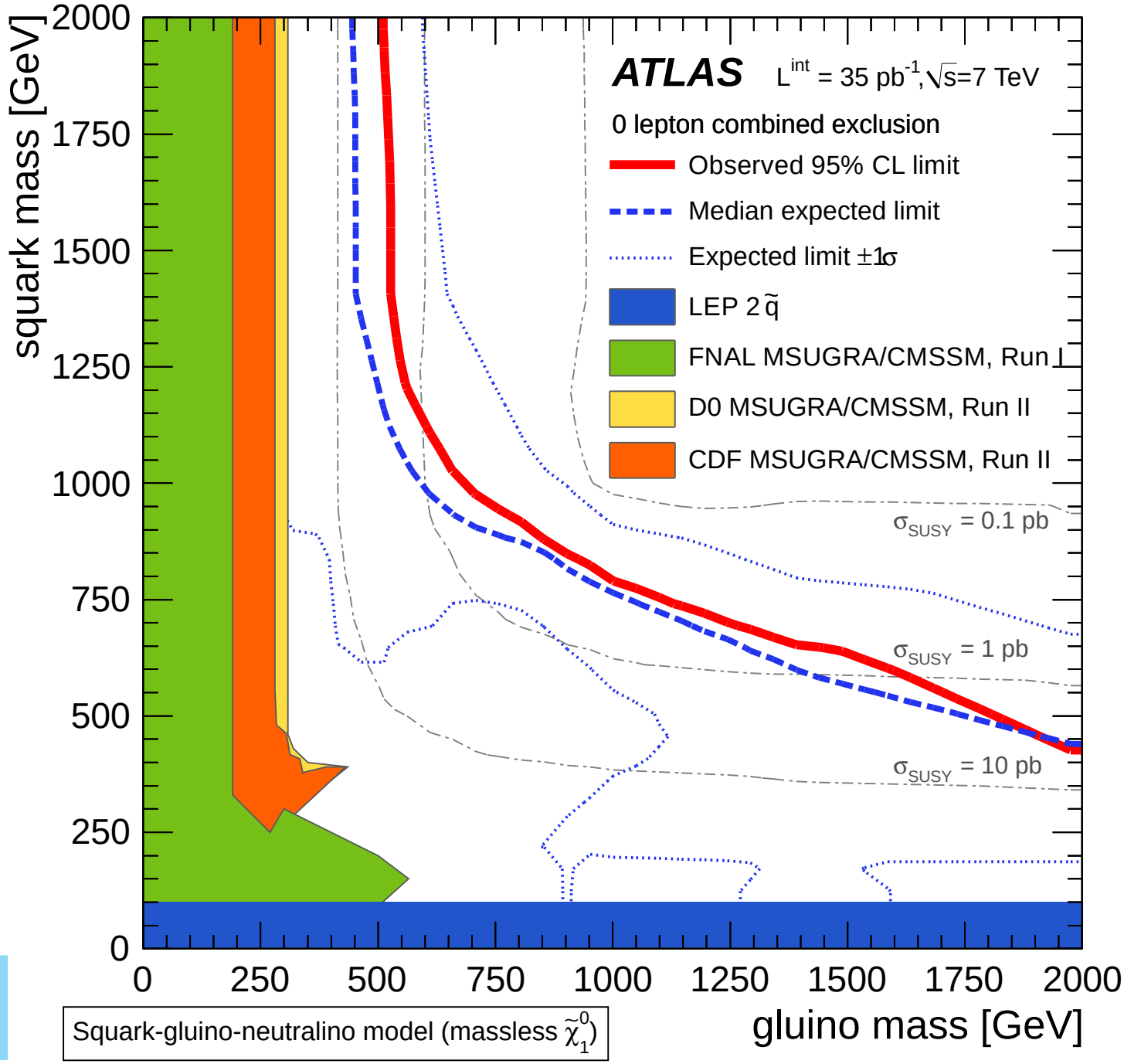
$$\tilde{q} \rightarrow q\tilde{\chi}_1^0 \qquad \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$$

$$m_{\text{eff}} = H_T^{(n)} + \not{E}_T$$



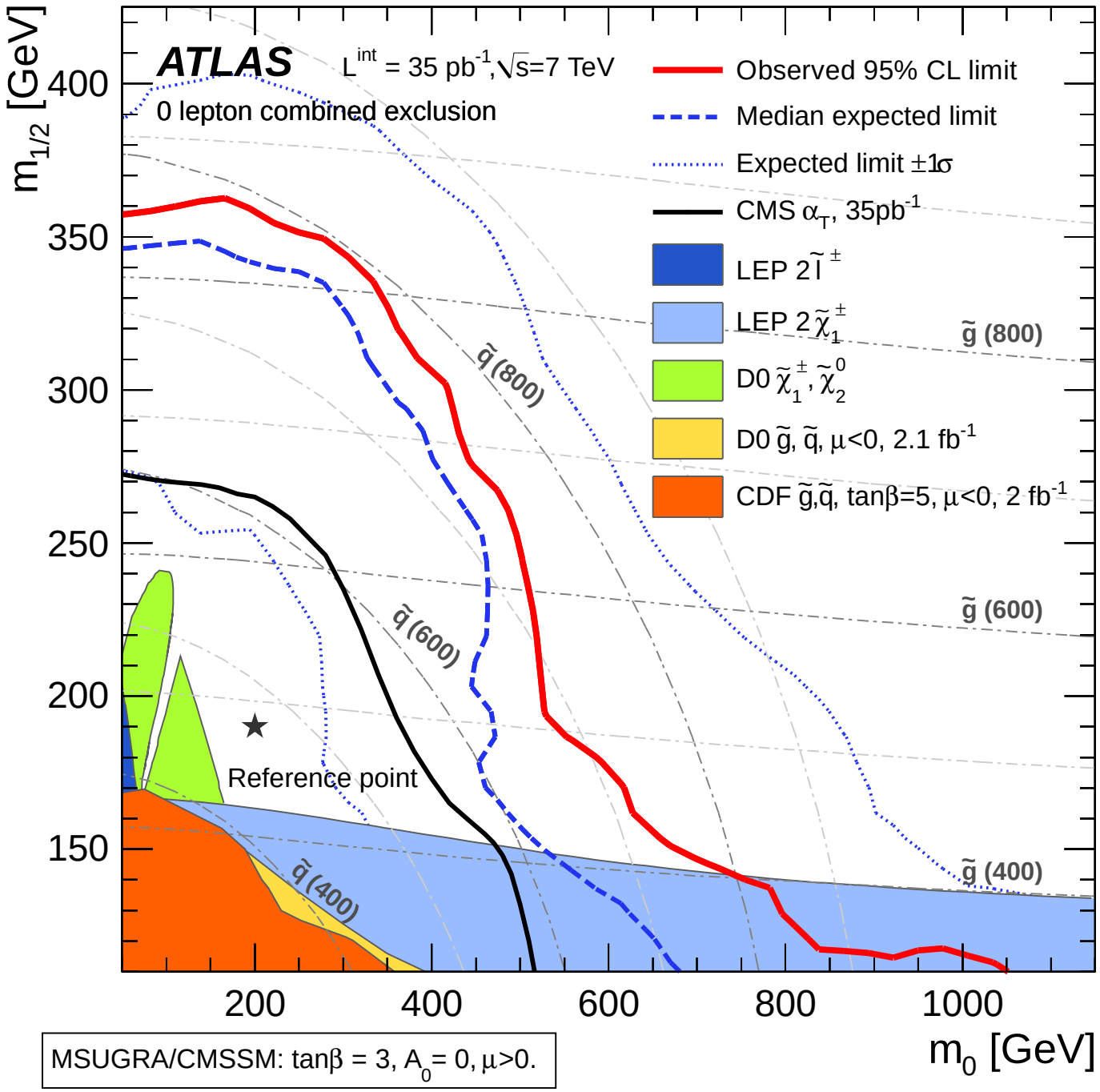


Supersymmetry



arXiv:1102.5290 [hep-ex]
(submitted to PLB)

Supersymmetry



arXiv:1102.5290 [hep-ex]
(submitted to PLB)

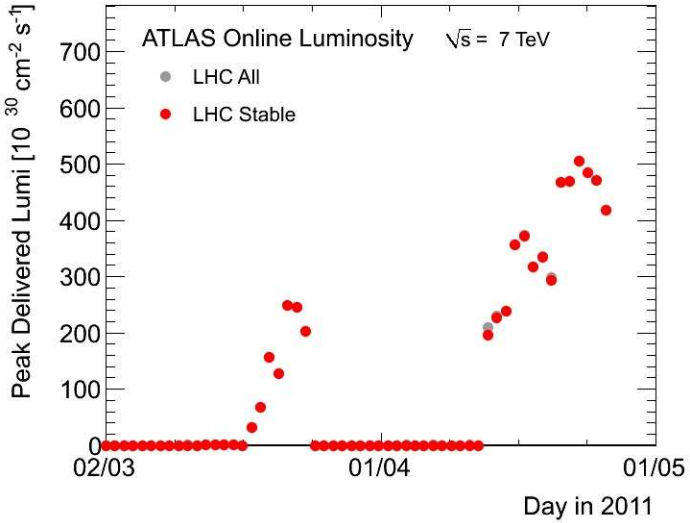
Summary

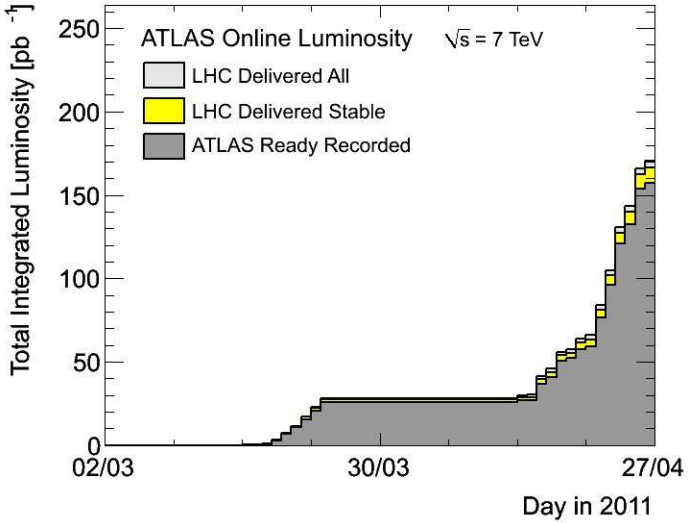
Summary

- The LHC performed very well in 2010...
- ...and ATLAS has profited
  - $\mathcal{O}$(30) papers
  - $\mathcal{O}$(175) public results

- Jets are an invaluable tool:
  - precision measurements of QCD
  - probe for new physical phenomena

- The ongoing 2011–2013 run will bring further exciting opportunities in jet physics

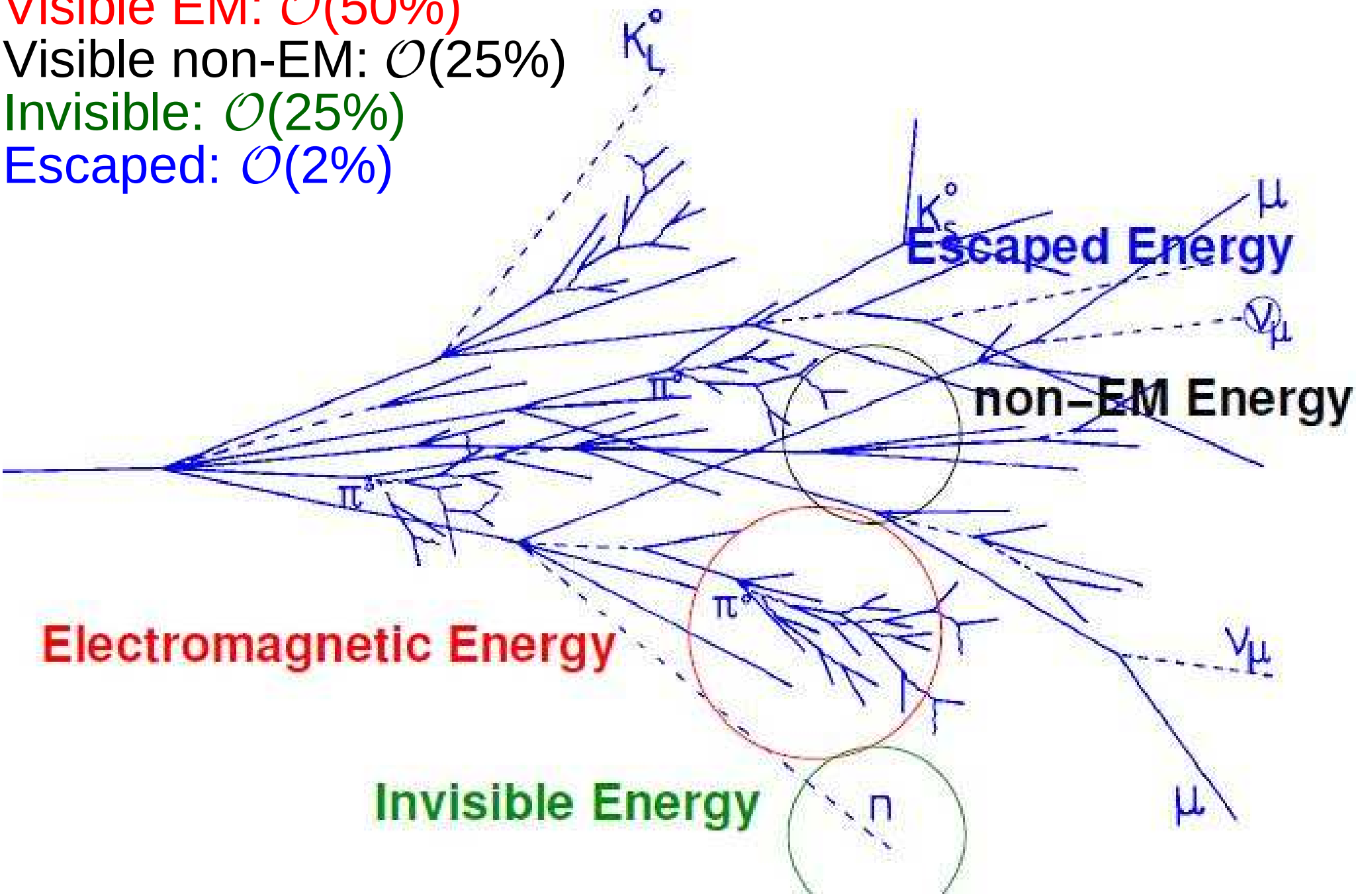




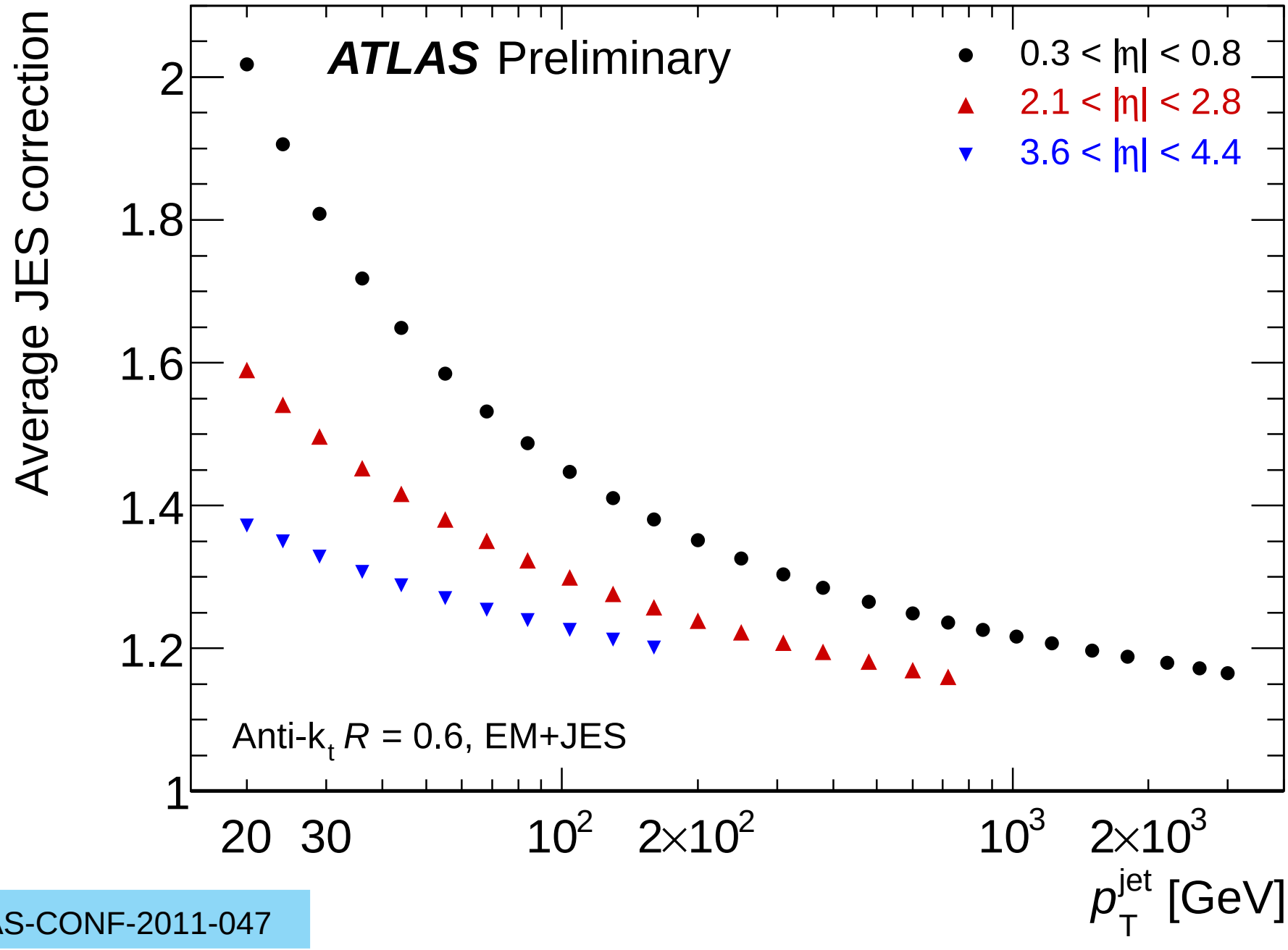
Backup

Hadronic Showers

Visible EM: $\mathcal{O}(50\%)$
Visible non-EM: $\mathcal{O}(25\%)$
Invisible: $\mathcal{O}(25\%)$
Escaped: $\mathcal{O}(2\%)$



Jet Energy Calibration



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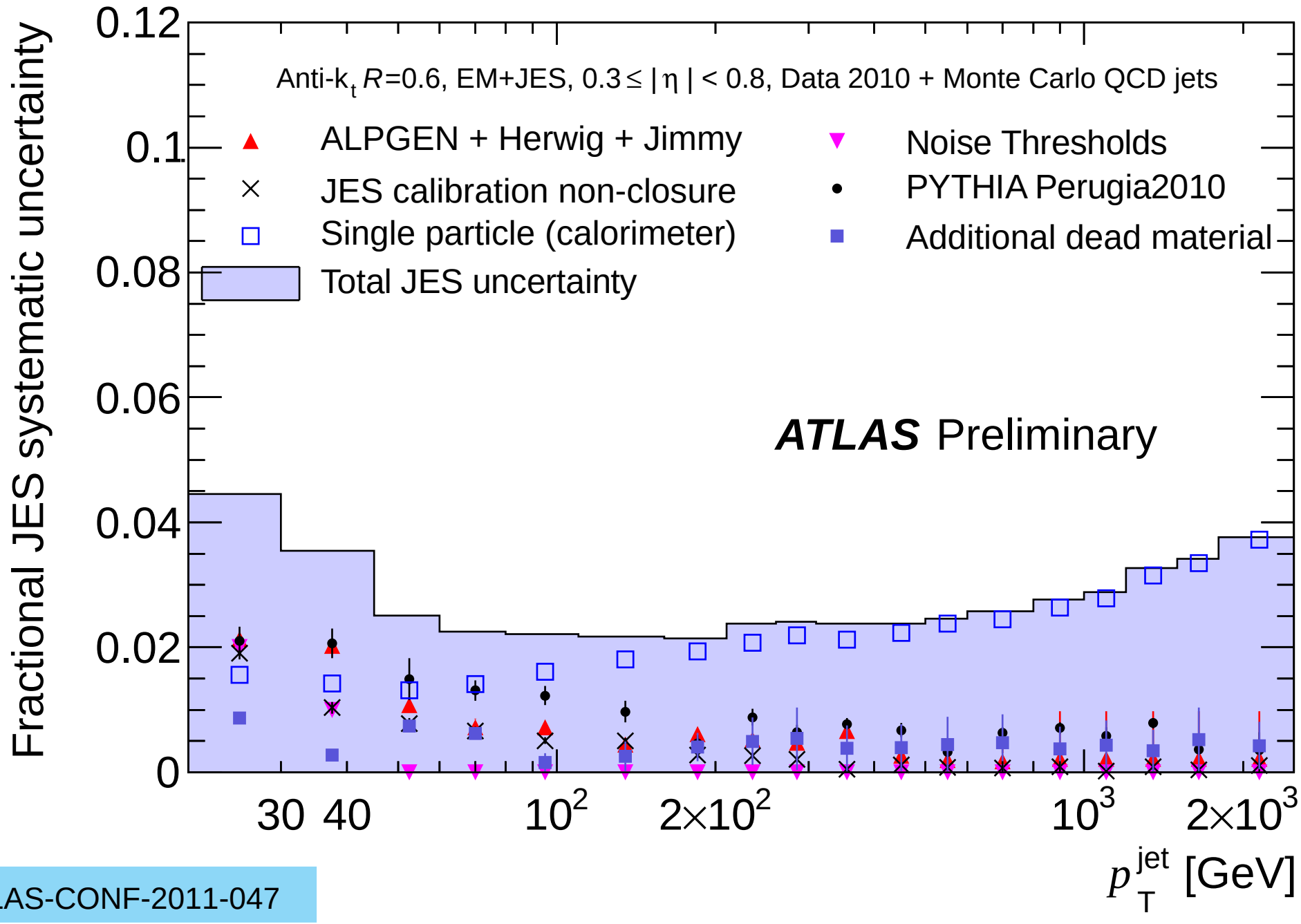
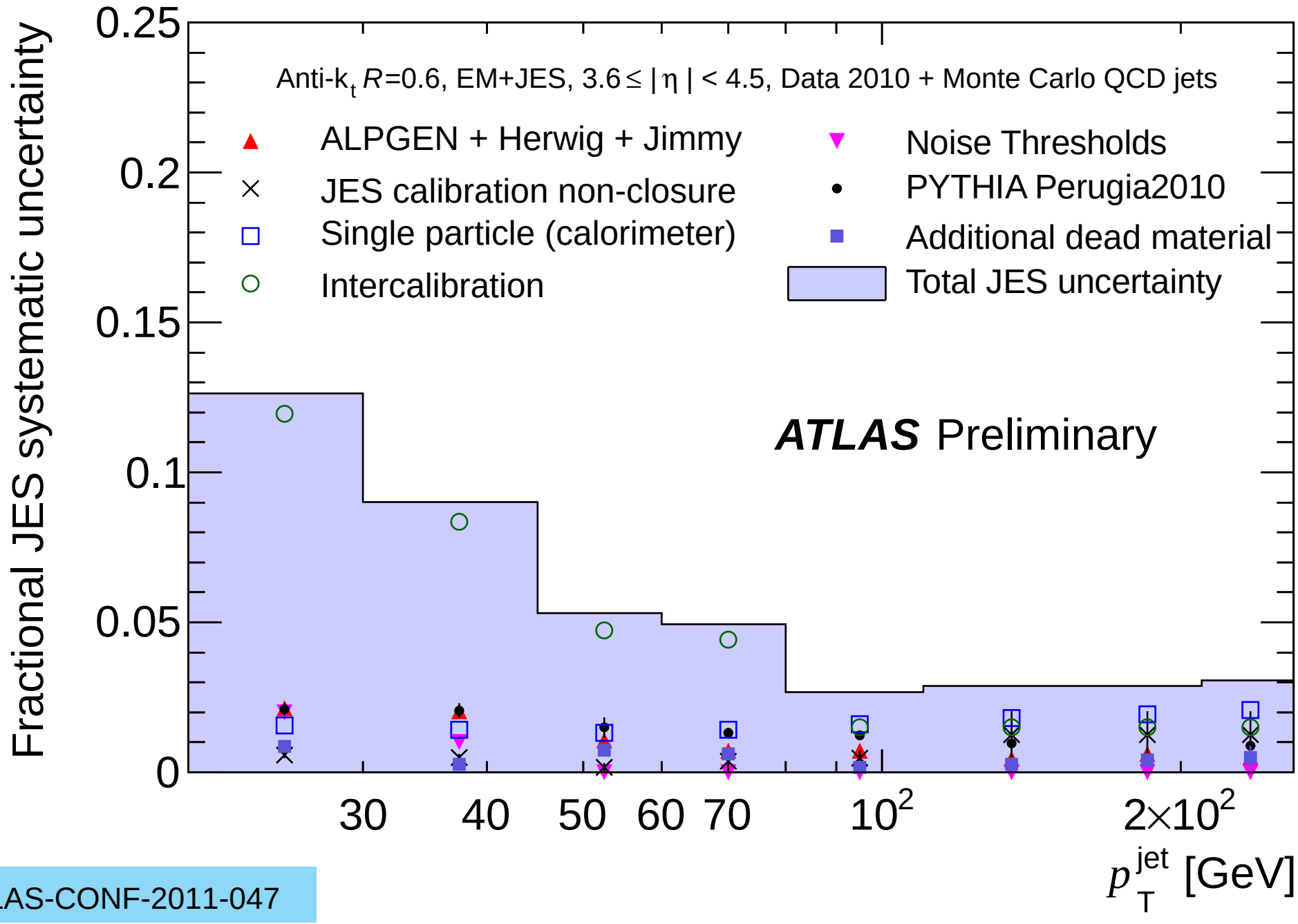
Jet Energy Calibration



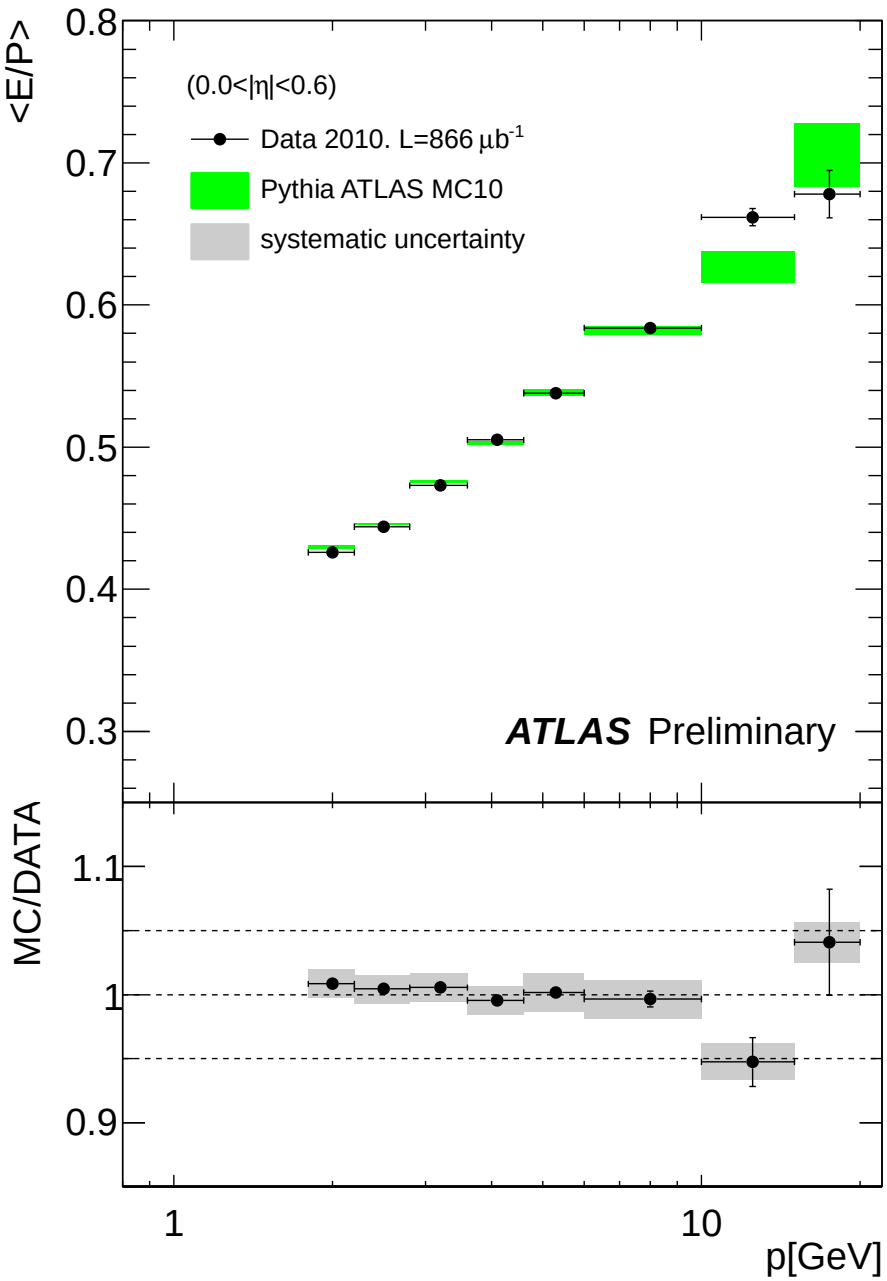
ATLAS-CONF-2011-047

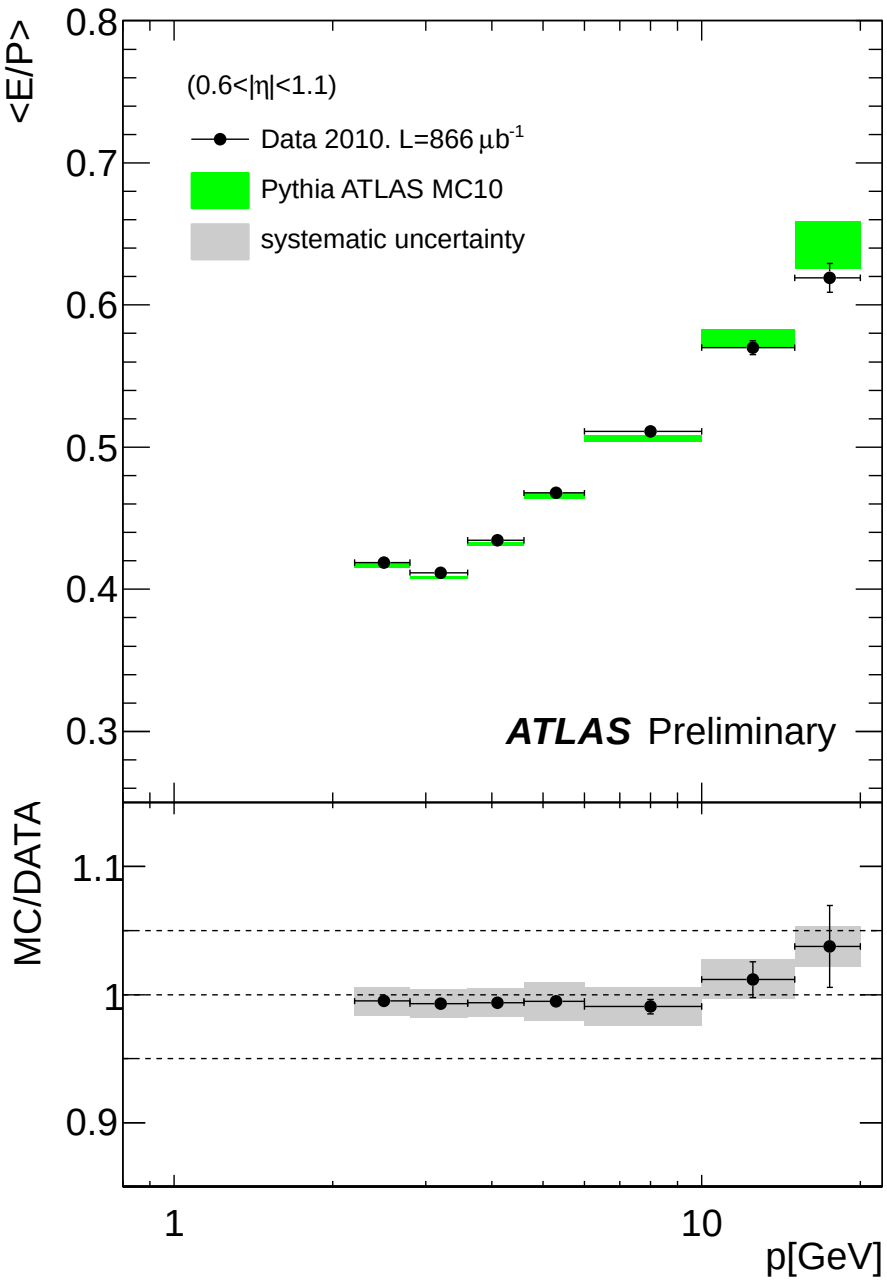
Jet Energy Calibration



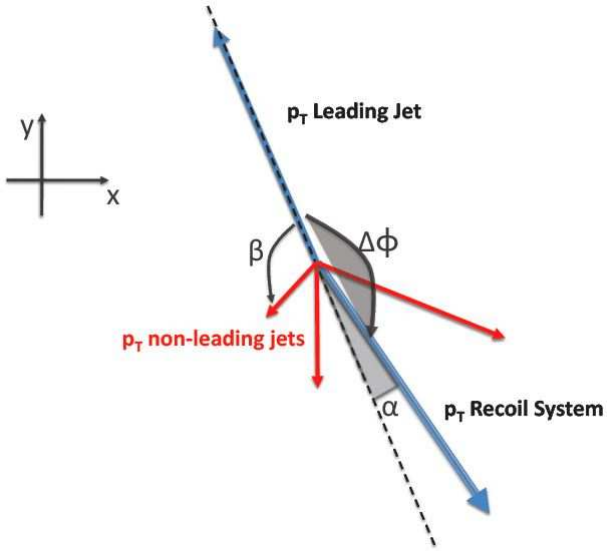
ATLAS-CONF-2011-047

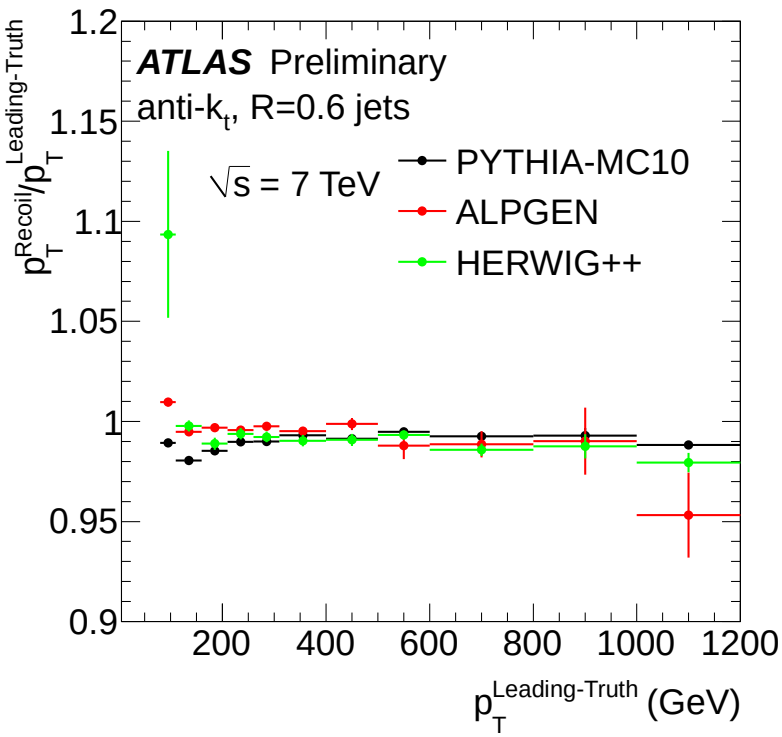
Jet Energy Calibration

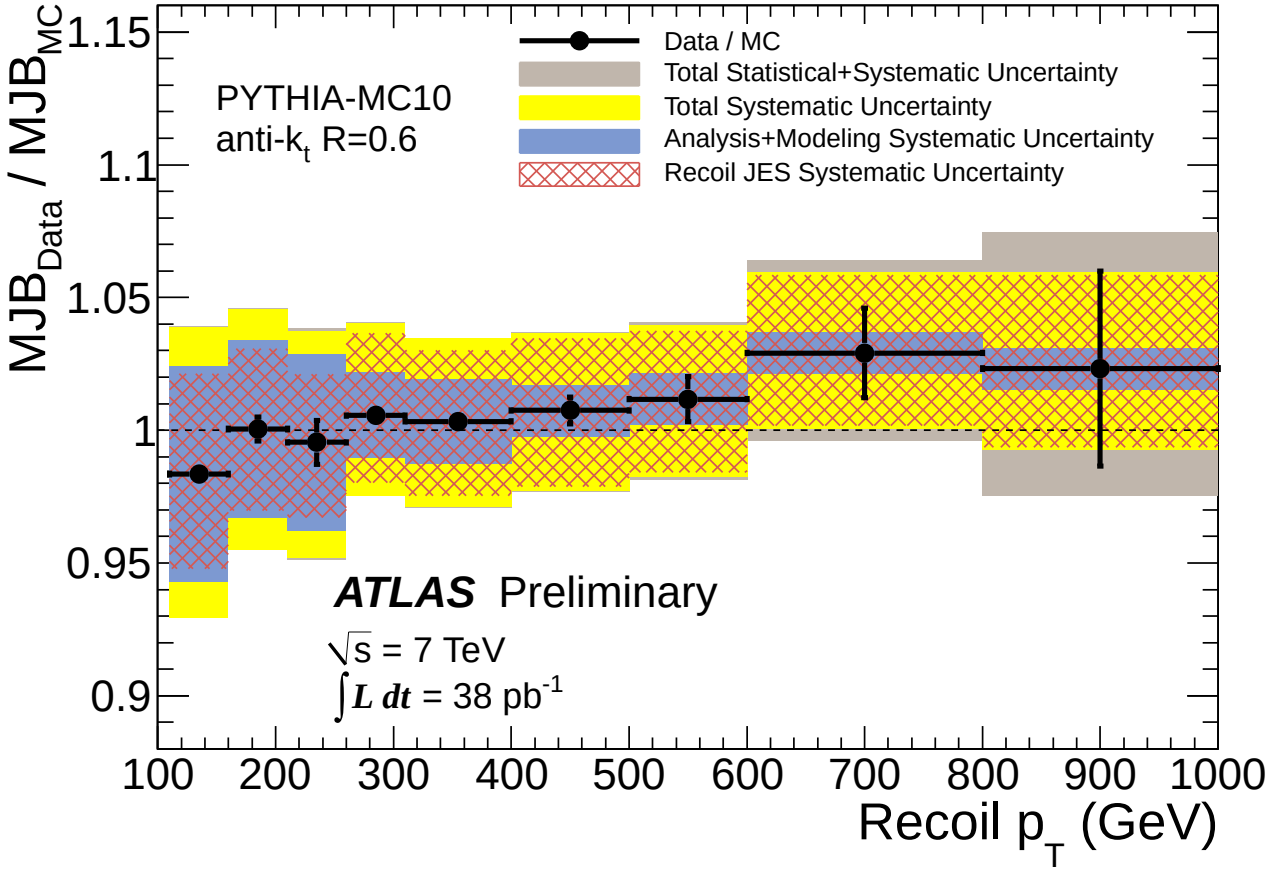




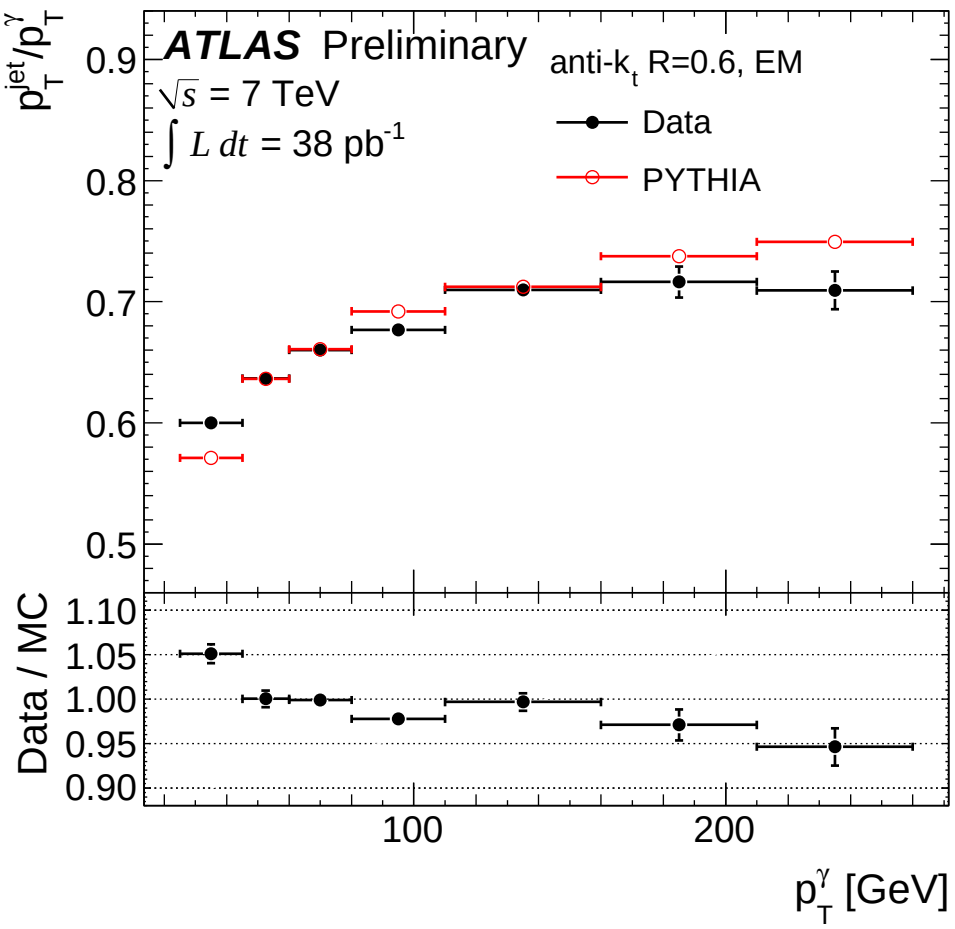
Jet Energy Calibration

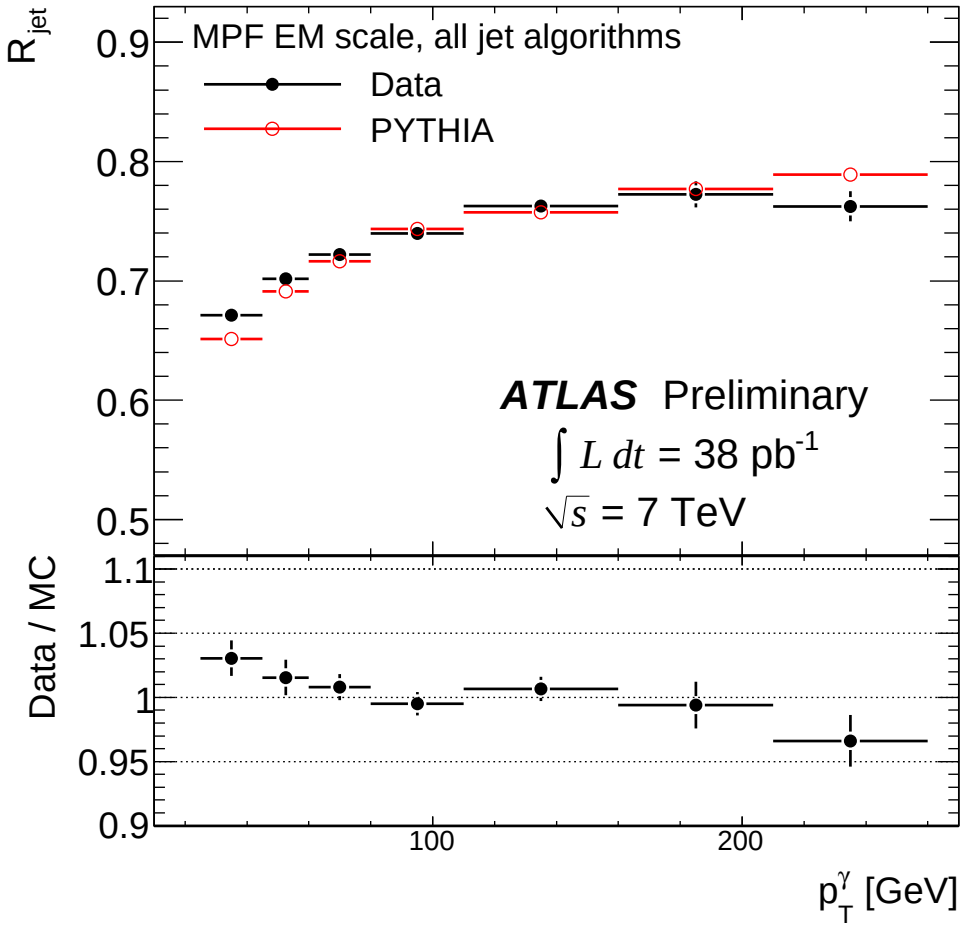


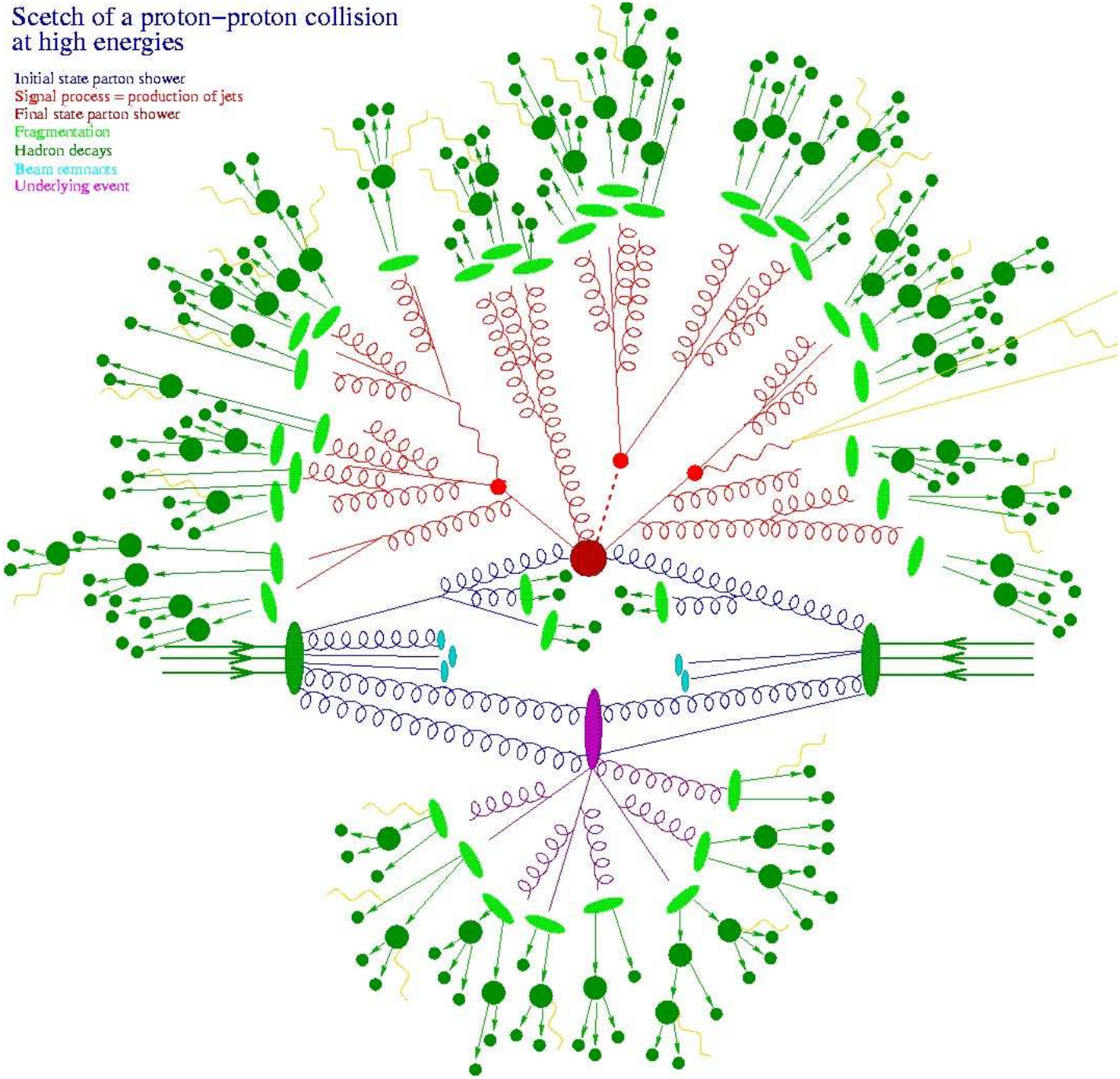


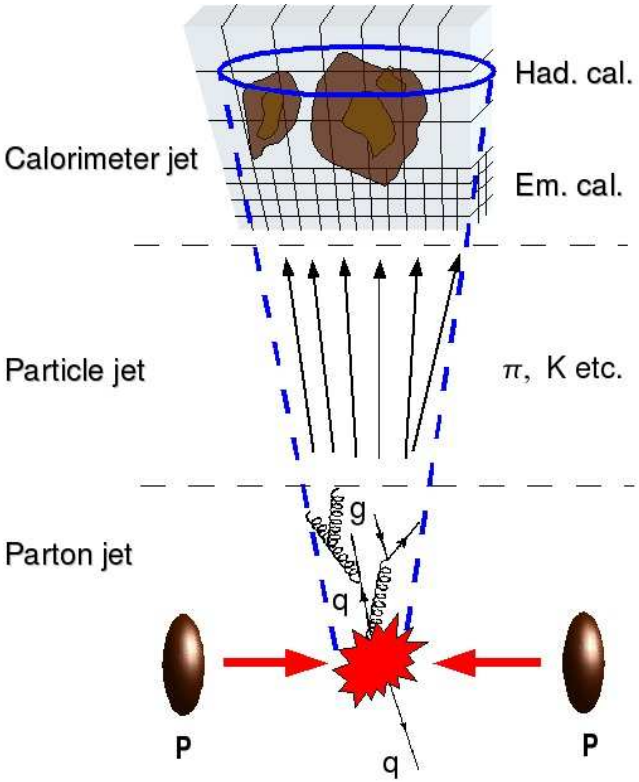


Jet Energy Calibration

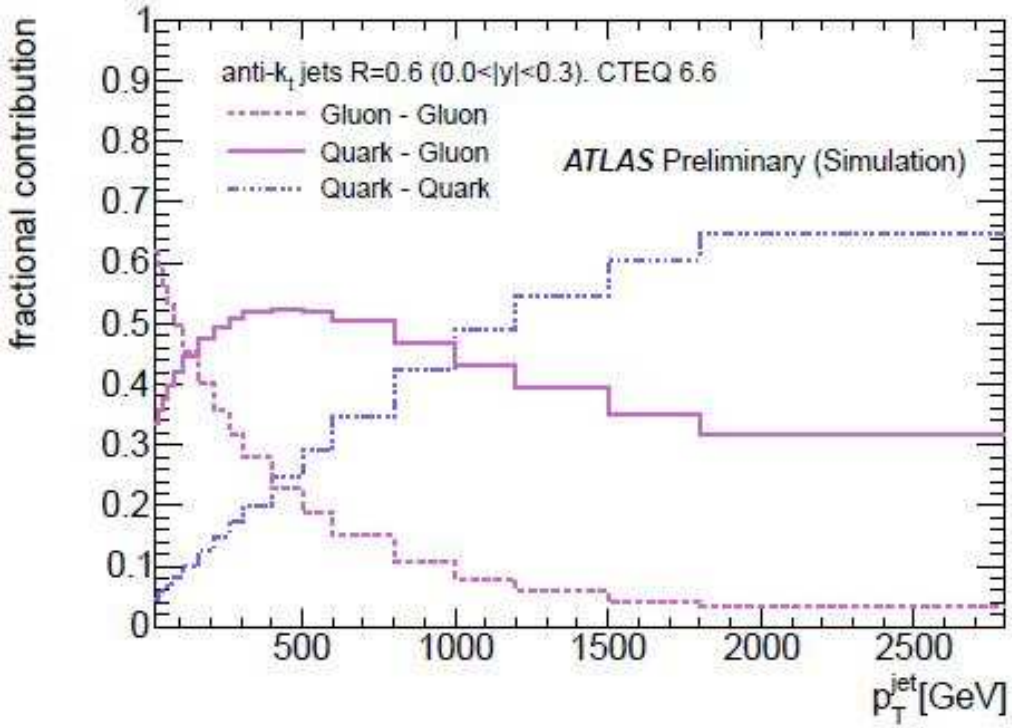


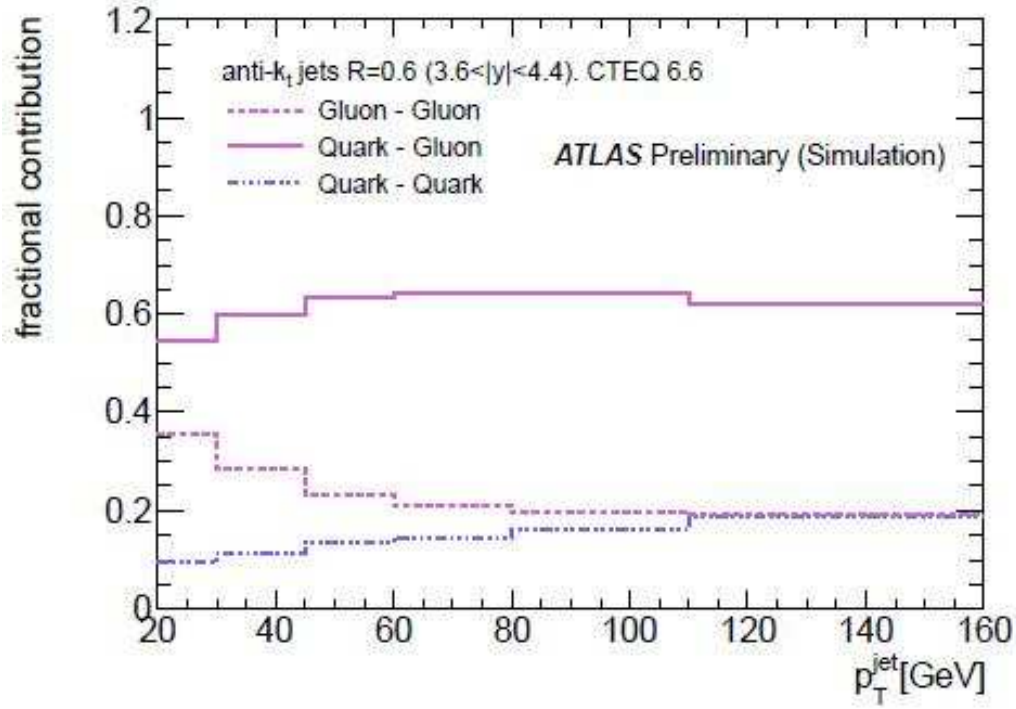



Scetch of a proton−proton collision
at high energies
Initial state parton shower
Signal process = production of jets
Final state parton shower
Fragmentation
Hadron decays
Beam remnants
Underlying event

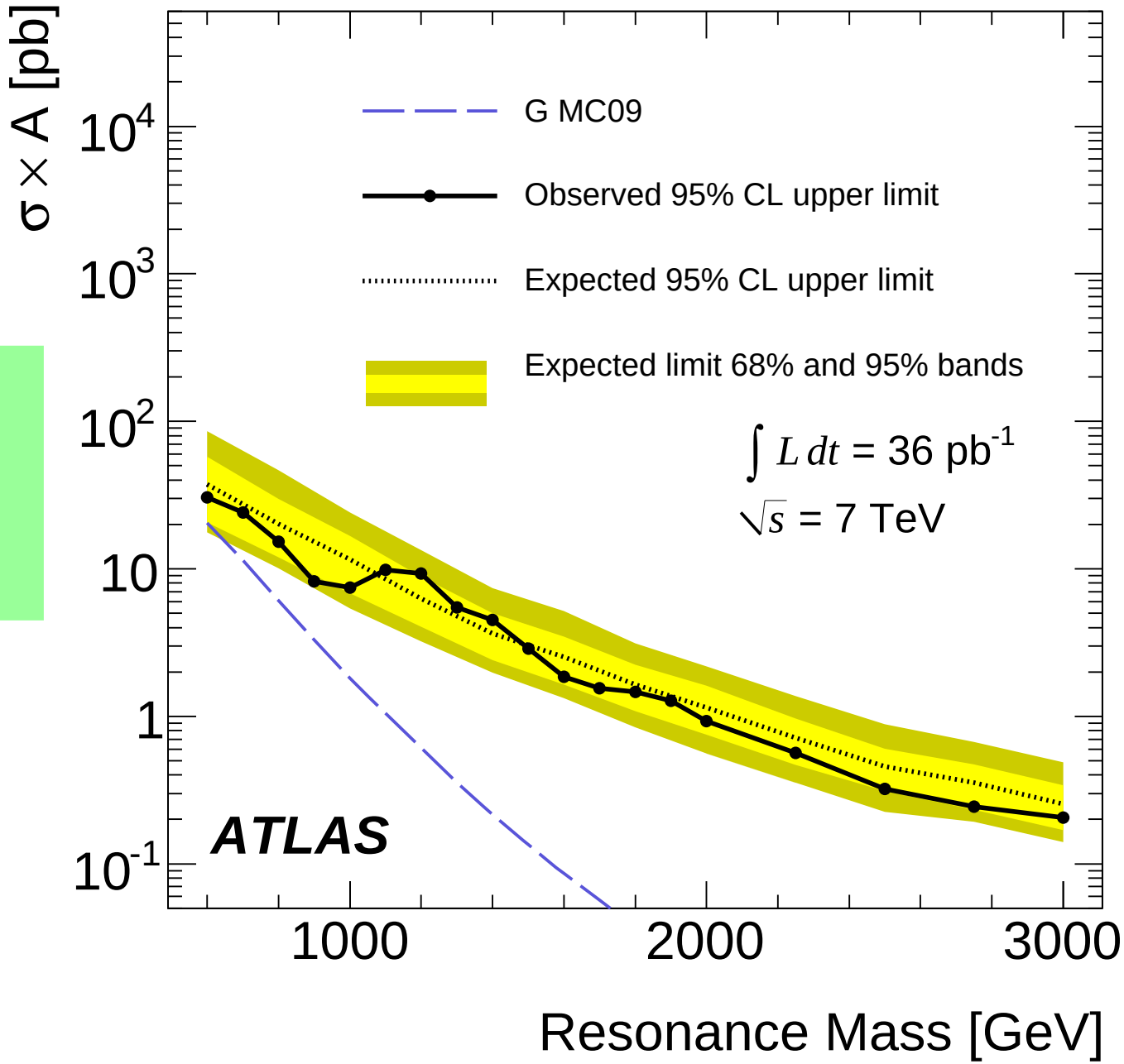

Had. cal.
Calorimeter jet
Em. cal.
Particle jet
π, K etc.
Parton jet
g
q
P
q
P

Inclusive Jet Cross Section





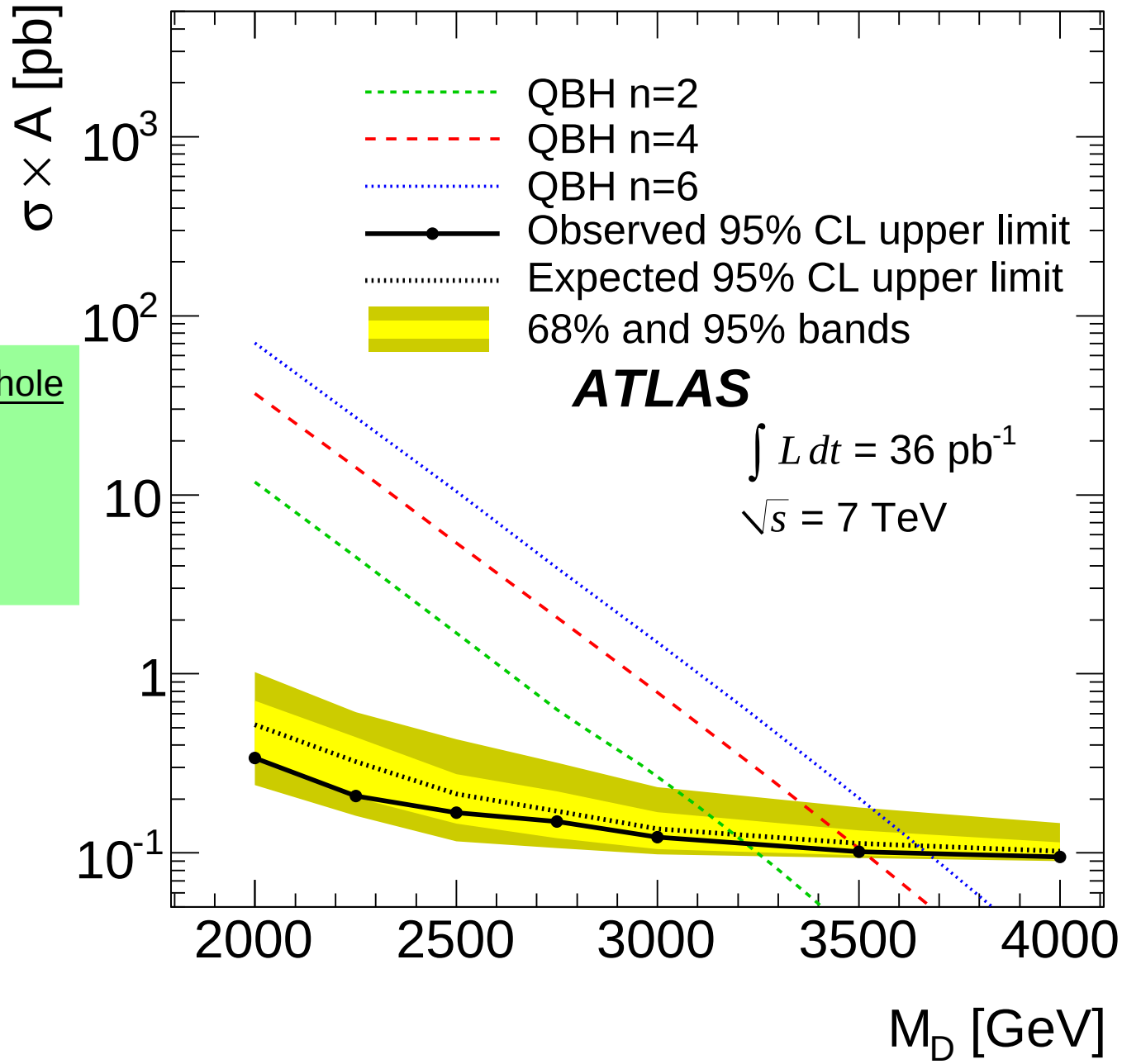
Dijet Resonances



Randall–Sundrum Gravitons
$\kappa/\tilde{M}_{\mathrm{Pl}}$ = 0.1
Randall, Sundrum
Phys. Rev. Lett. **83**, 3370 (1999)
Bijnens *et al.*
Phys. Lett. B**503**, 341 (2001)

arXiv:1103.3864 [hep-ex]
(accepted by NJP)

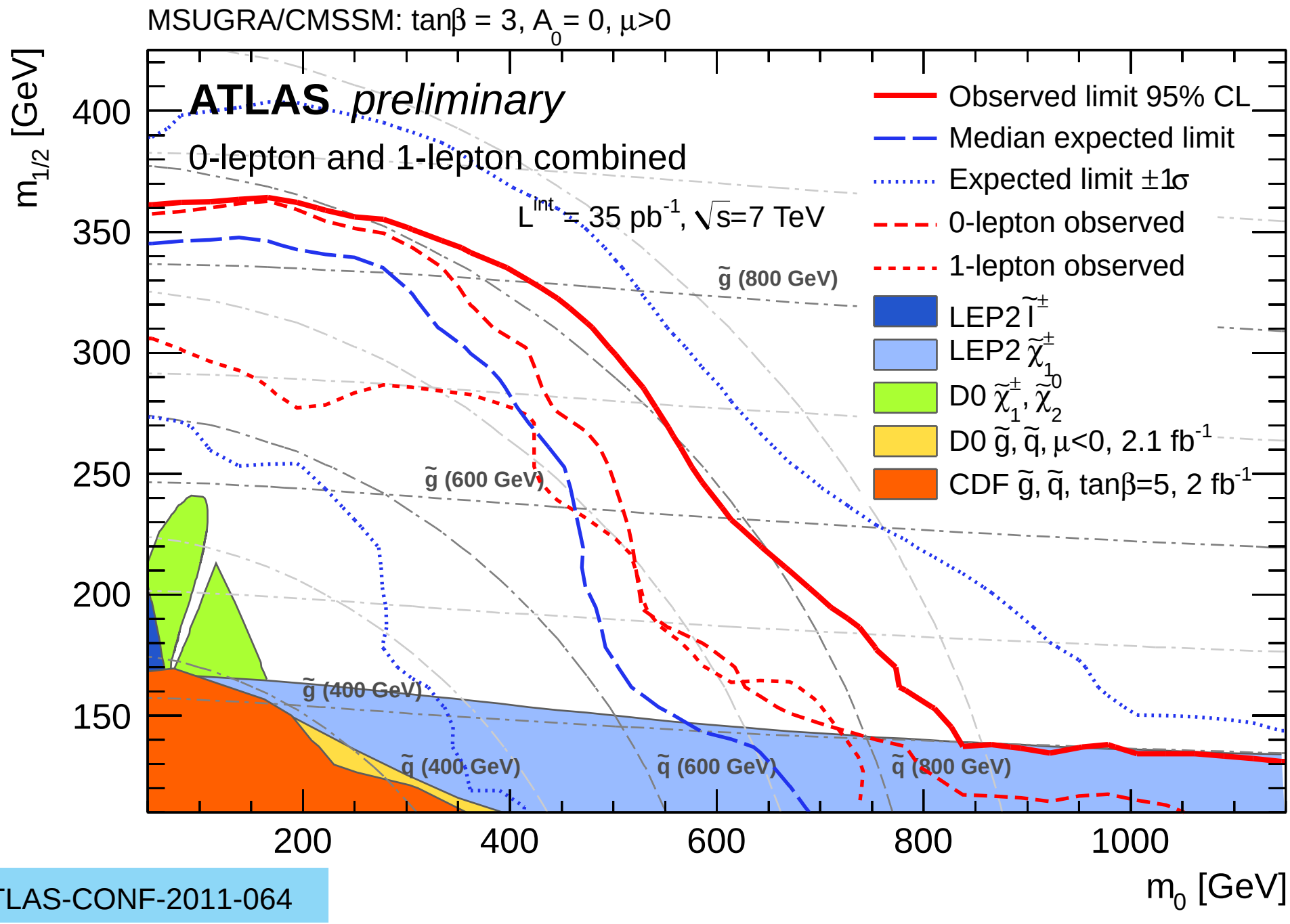
Dijet Resonances



Randall–Meade Quantum Blackhole
(BlackMax)
Meade, Randall
JHEP **05**, 2008:03 (2008)
D. Dai *et al.*
Phys. Rev. D**77**:076007 (2008)

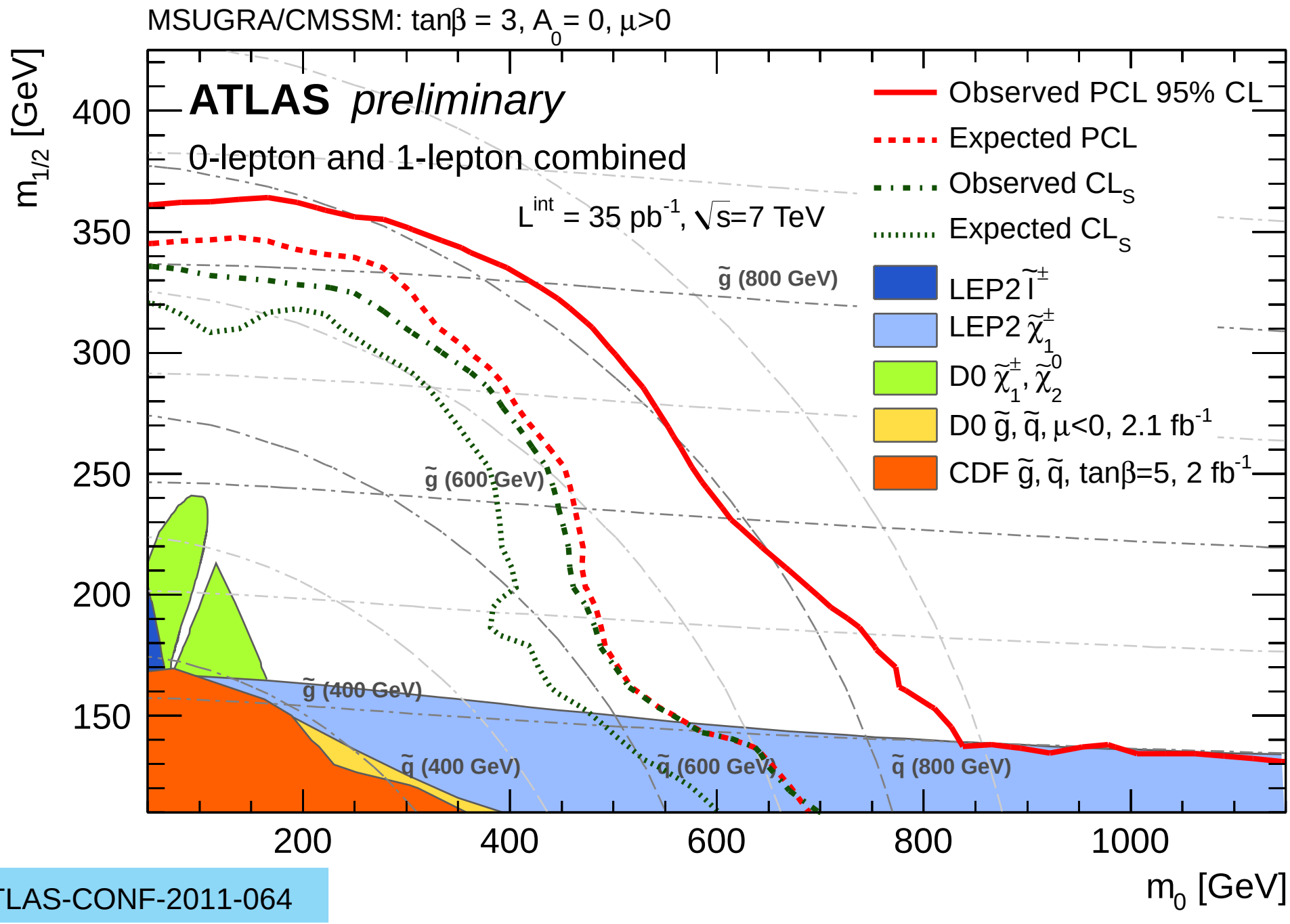
arXiv:1103.3864 [hep-ex]
(accepted by NJP)

Supersymmetry



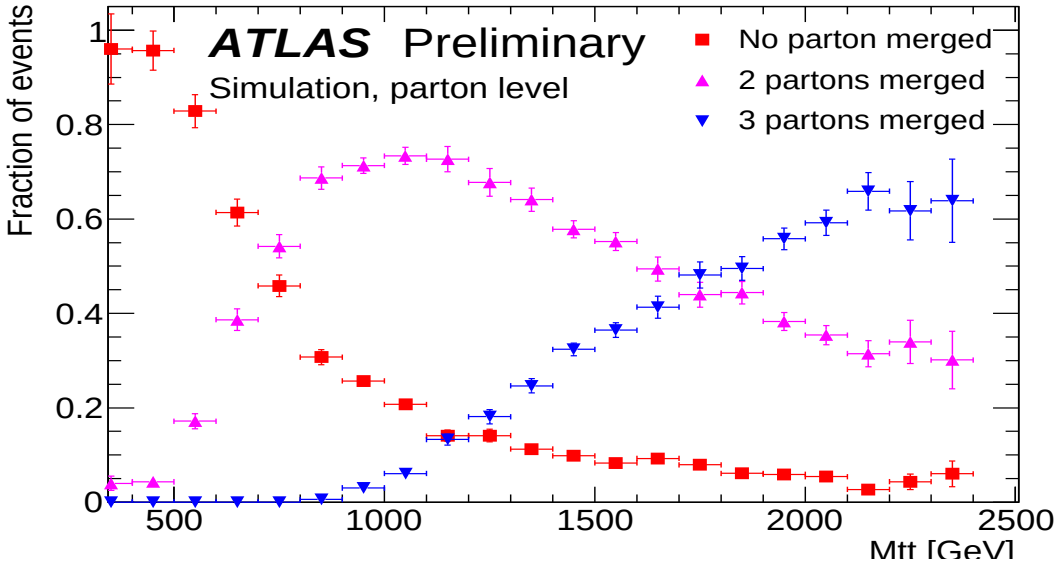
ATLAS-CONF-2011-064

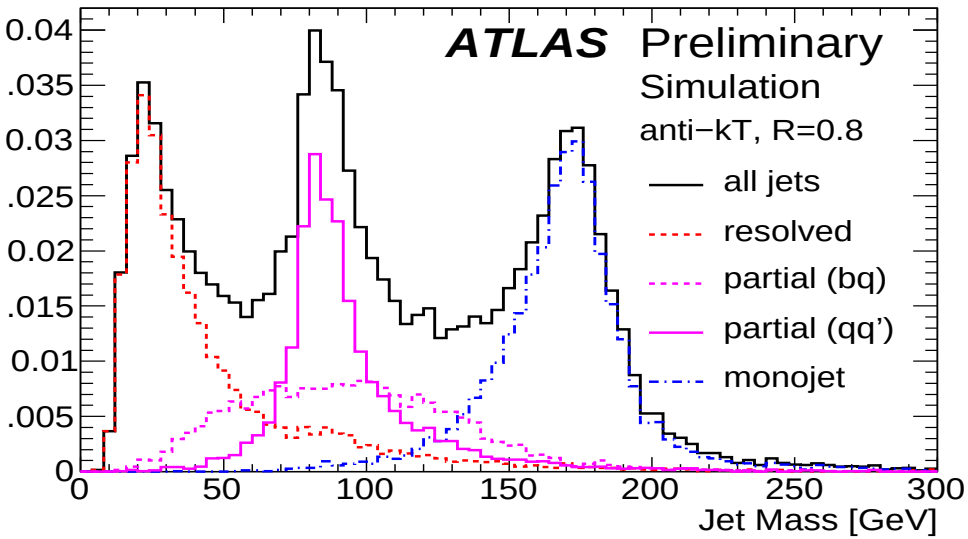
Supersymmetry

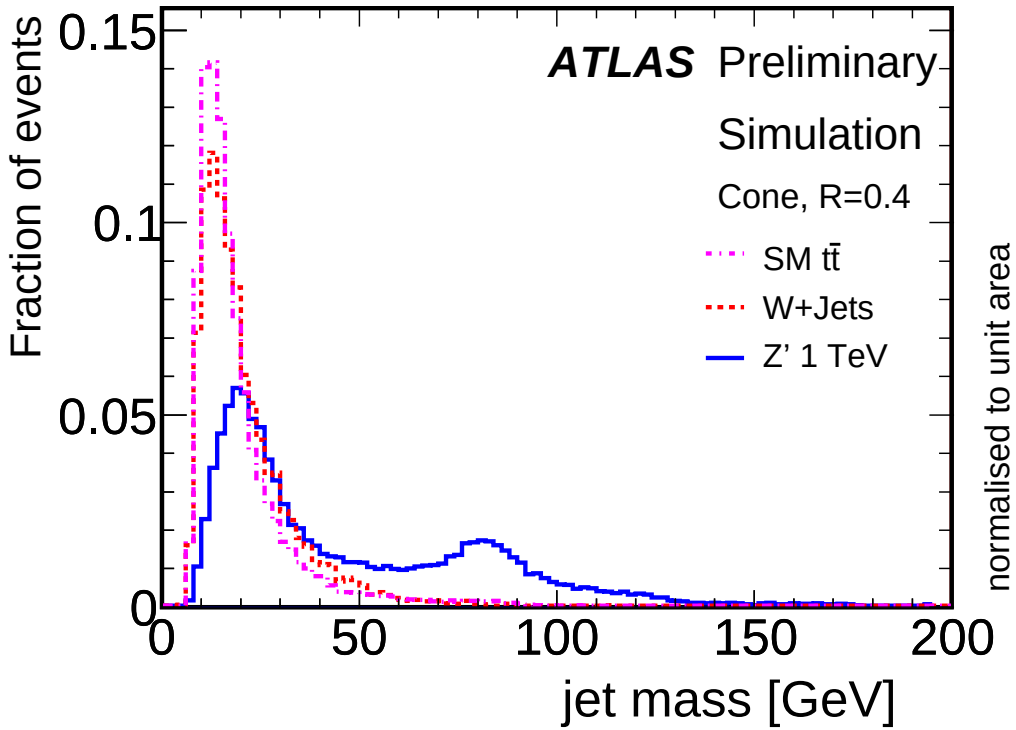


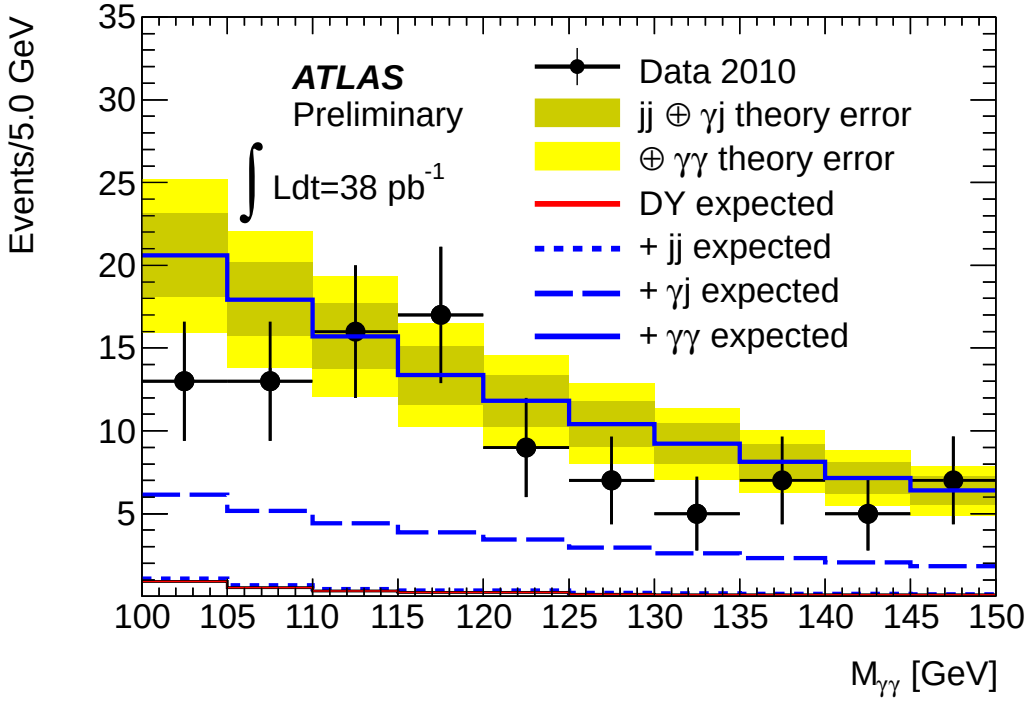
ATLAS-CONF-2011-064

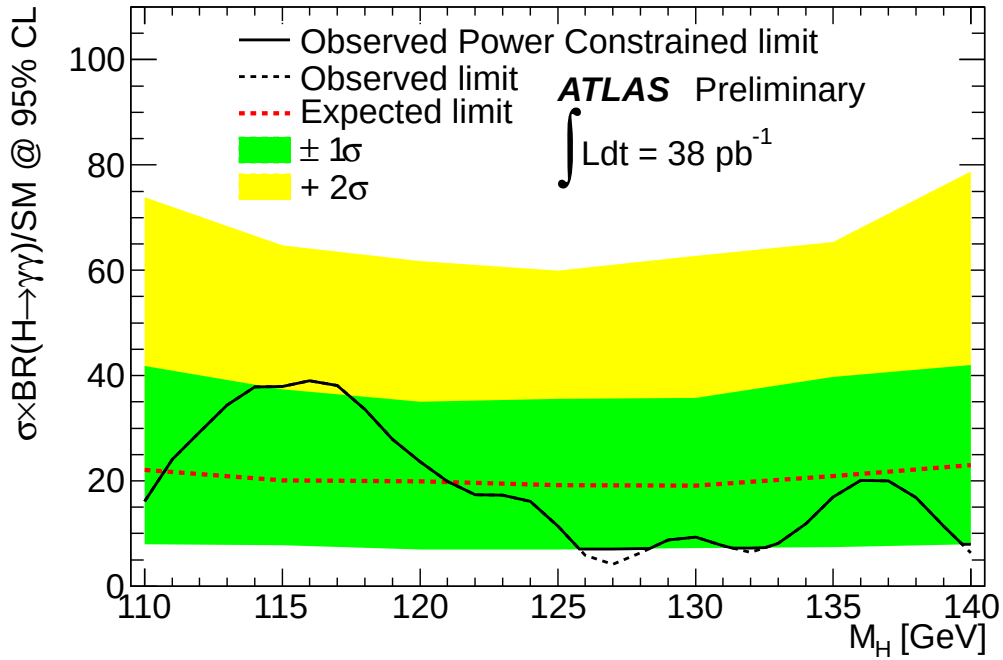
Jet Mass

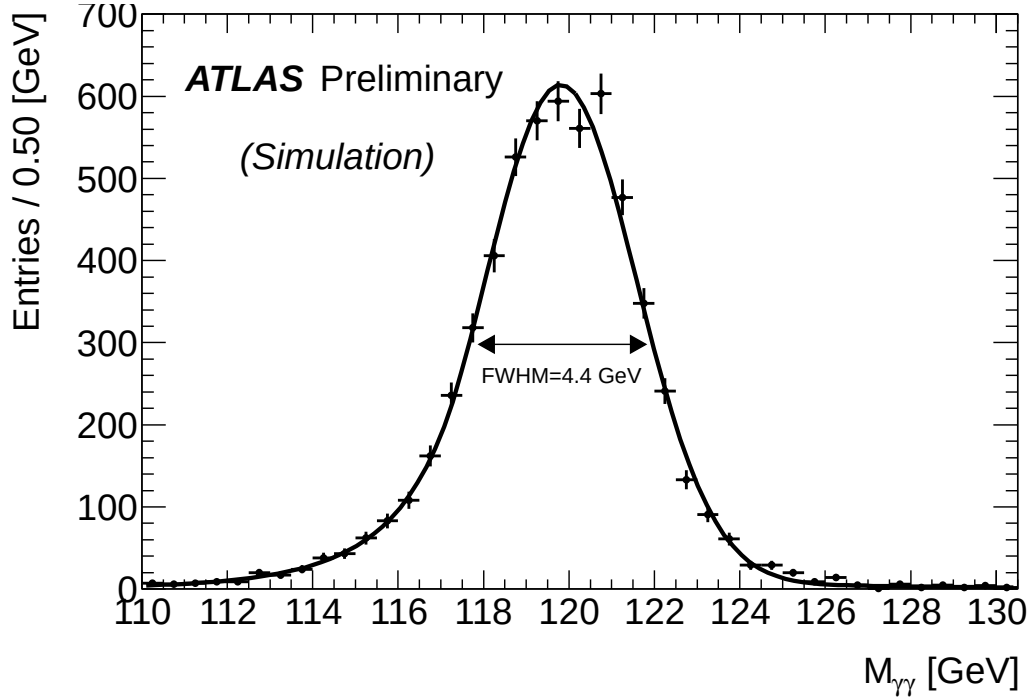

ATLAS Preliminary
Simulation, parton level
No parton merged
2 partons merged
3 partons merged
Fraction of events
Mtt [GeV]

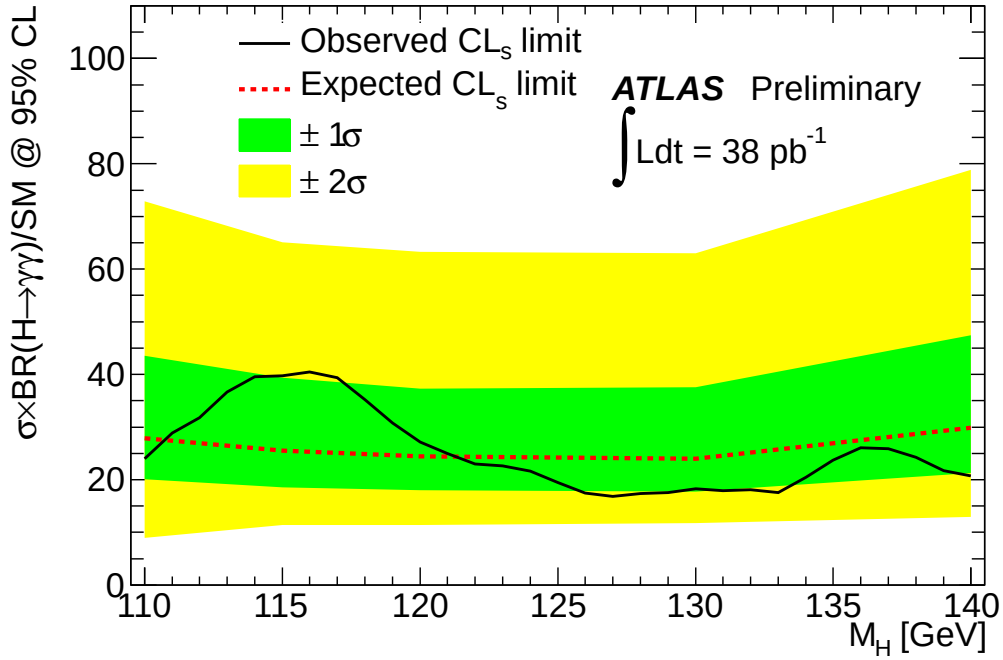

ATLAS Preliminary
Simulation
anti−kT, R=0.8
all jets
resolved
partial (bq)
partial (qq')
monojet
Jet Mass [GeV]


ATLAS Preliminary
Simulation
Cone, R=0.4
SM tt̄
W+Jets
Z' 1 TeV
Fraction of events
normalised to unit area
jet mass [GeV]


ATLAS
Preliminary
∫ Ldt=38 pb-1
Data 2010
jj ⊕ γj theory error
⊕ γγ theory error
DY expected
+ jj expected
+ γj expected
+ γγ expected
Events/5.0 GeV
Mγγ [GeV]


Observed Power Constrained limit
Observed limit
Expected limit
± 1σ
+ 2σ
ATLAS Preliminary
∫ Ldt = 38 pb-1
σ×BR(H→γγ)/SM @ 95% CL
MH [GeV]


ATLAS Preliminary
(Simulation)
FWHM=4.4 GeV
Entries / 0.50 [GeV]
Mγγ [GeV]


Observed CLs limit
Expected CLs limit
± 1σ
± 2σ
ATLAS Preliminary
∫ Ldt = 38 pb-1
σ×BR(H→γγ)/SM @ 95% CL
MH [GeV]