Progress in Jet substructure at the LHC

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Selected results from ATLAS at the LHC

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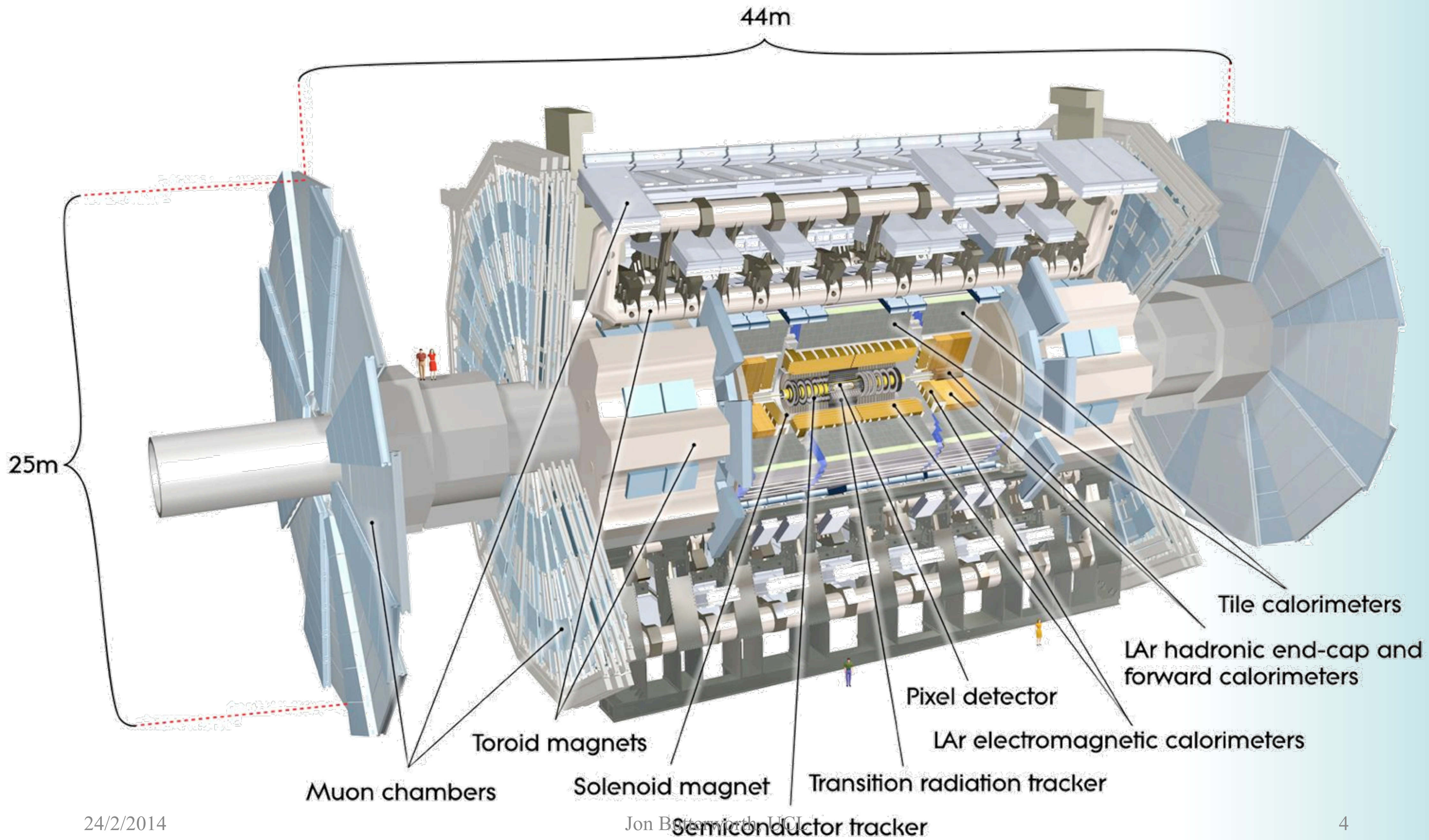
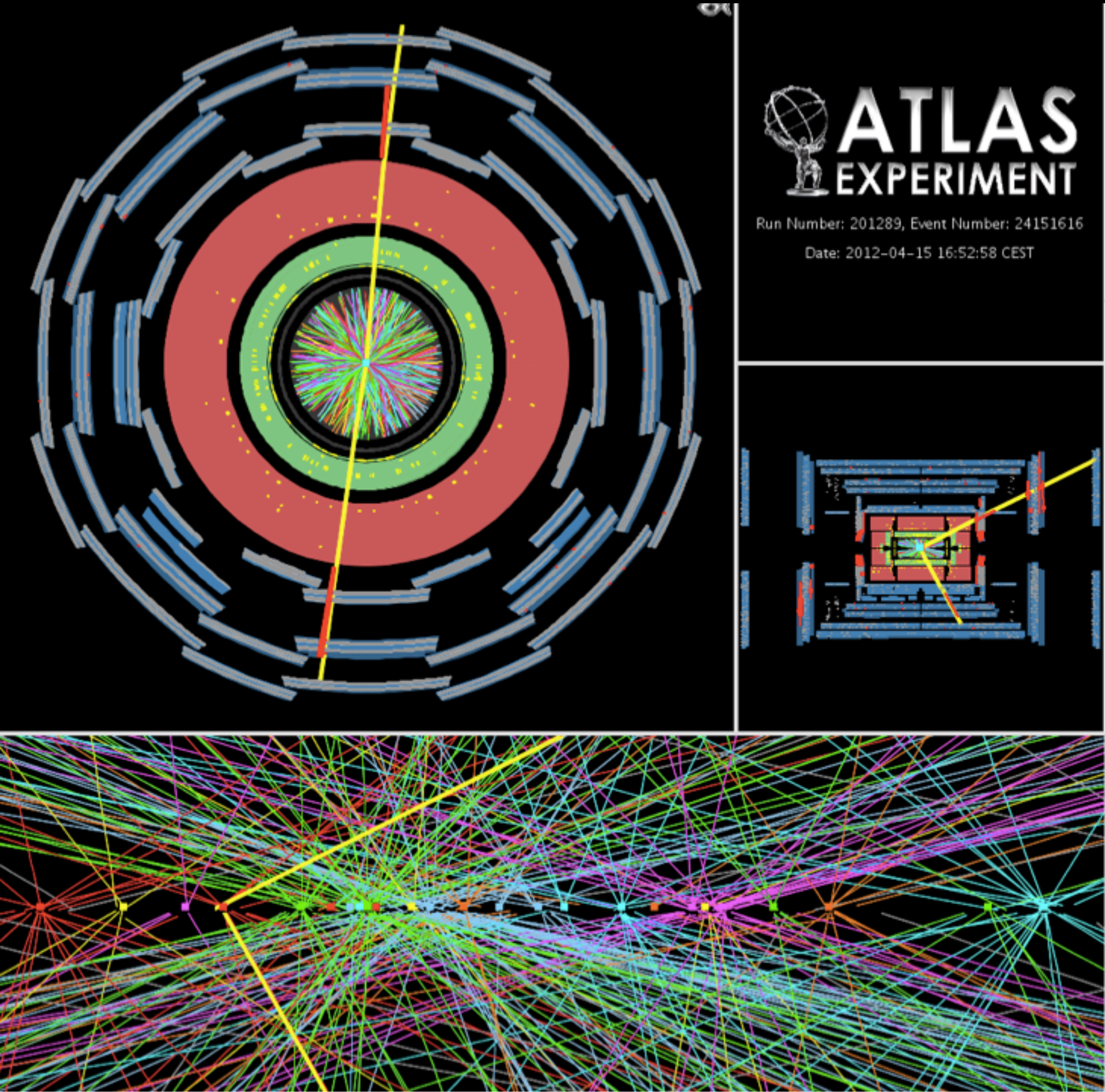
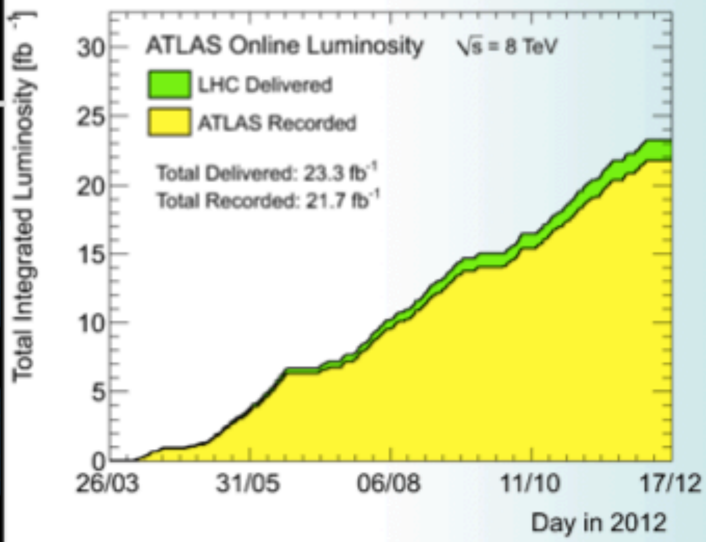
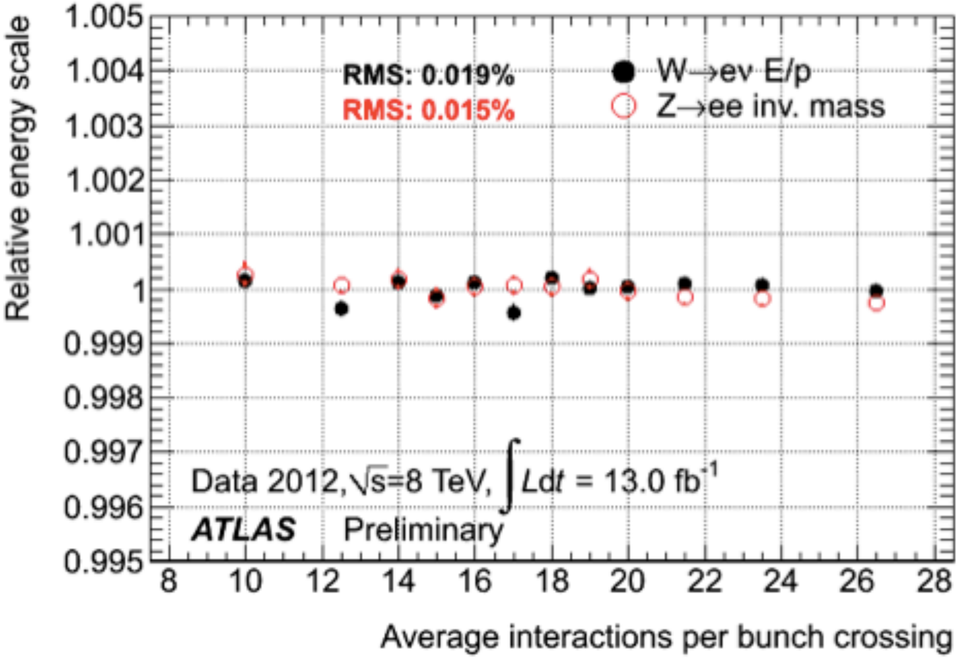
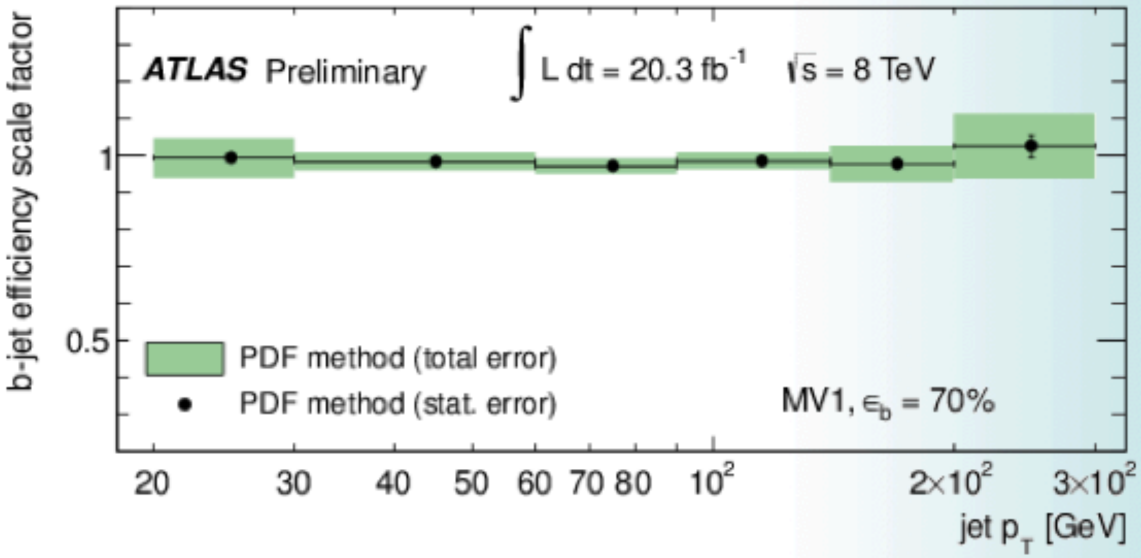
LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km

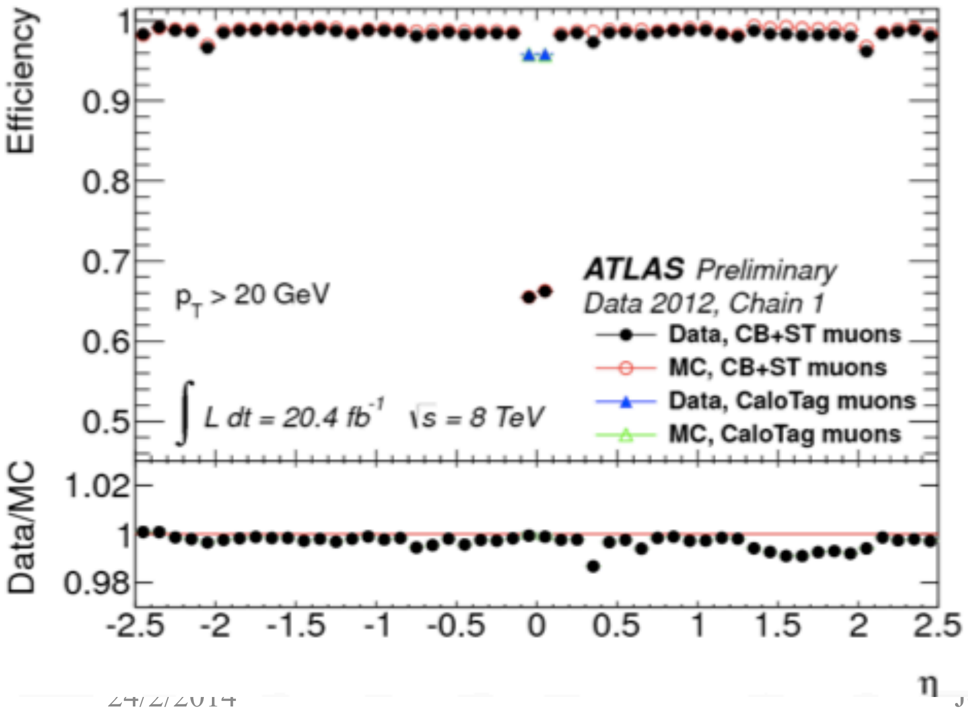

44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

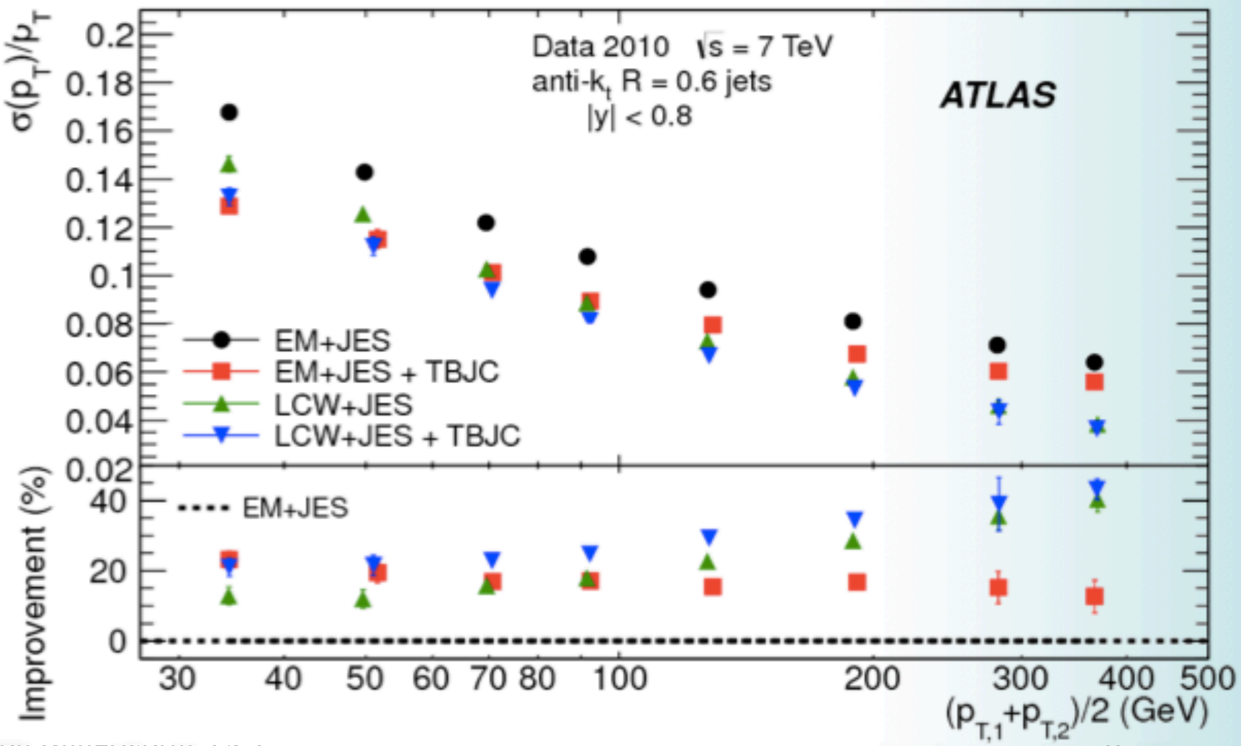

ATLAS
EXPERIMENT
Run Number: 201289, Event Number: 24151616
Date: 2012-04-15 16:52:58 CEST

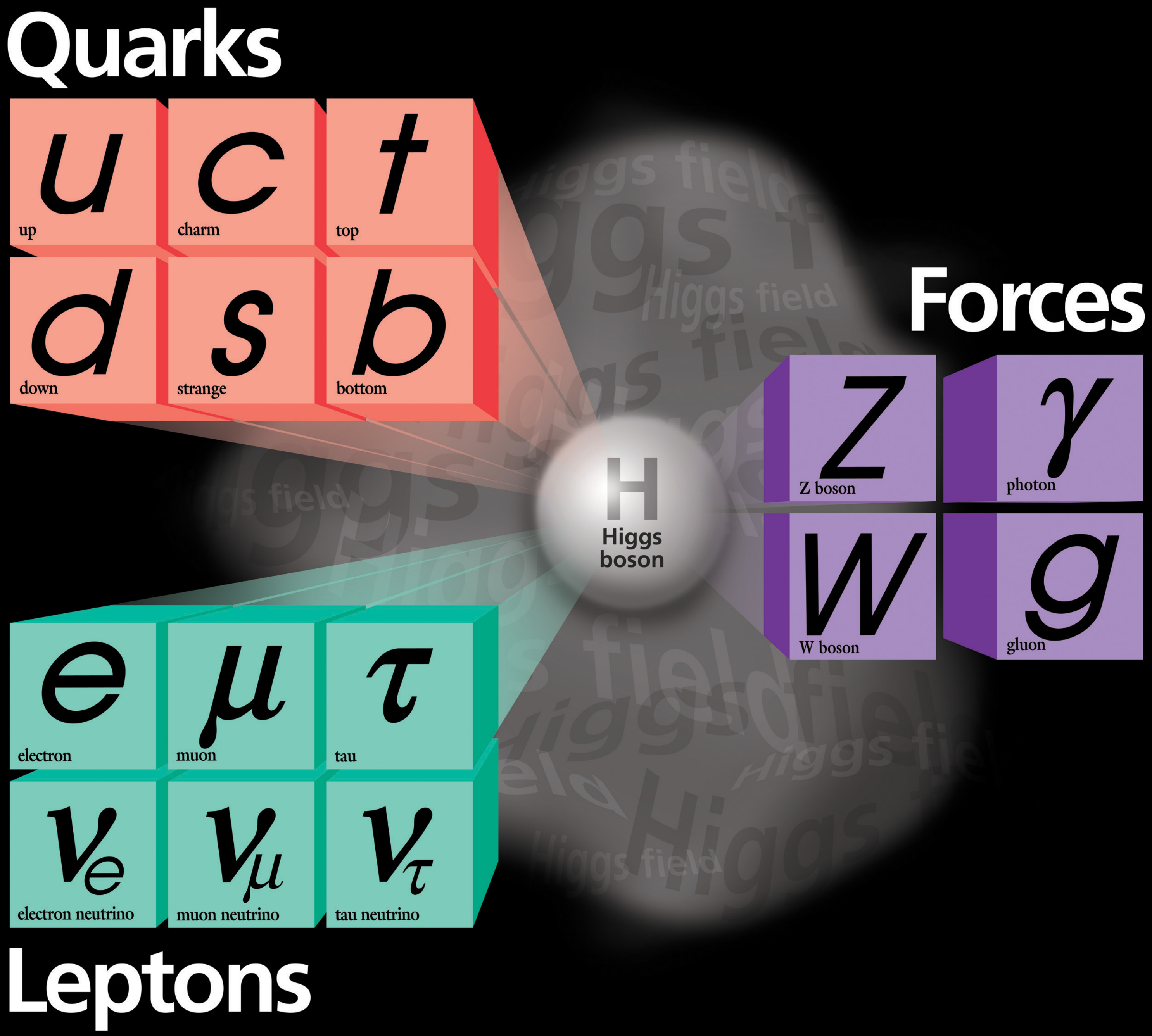

ATLAS Online Luminosity
$\sqrt{s}$ = 8 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 23.3 fb^{-1}
Total Recorded: 21.7 fb^{-1}
Total Integrated Luminosity [fb^{-1}]
0
5
10
15
20
25
30
26/03
31/05
06/08
11/10
17/12
Day in 2012

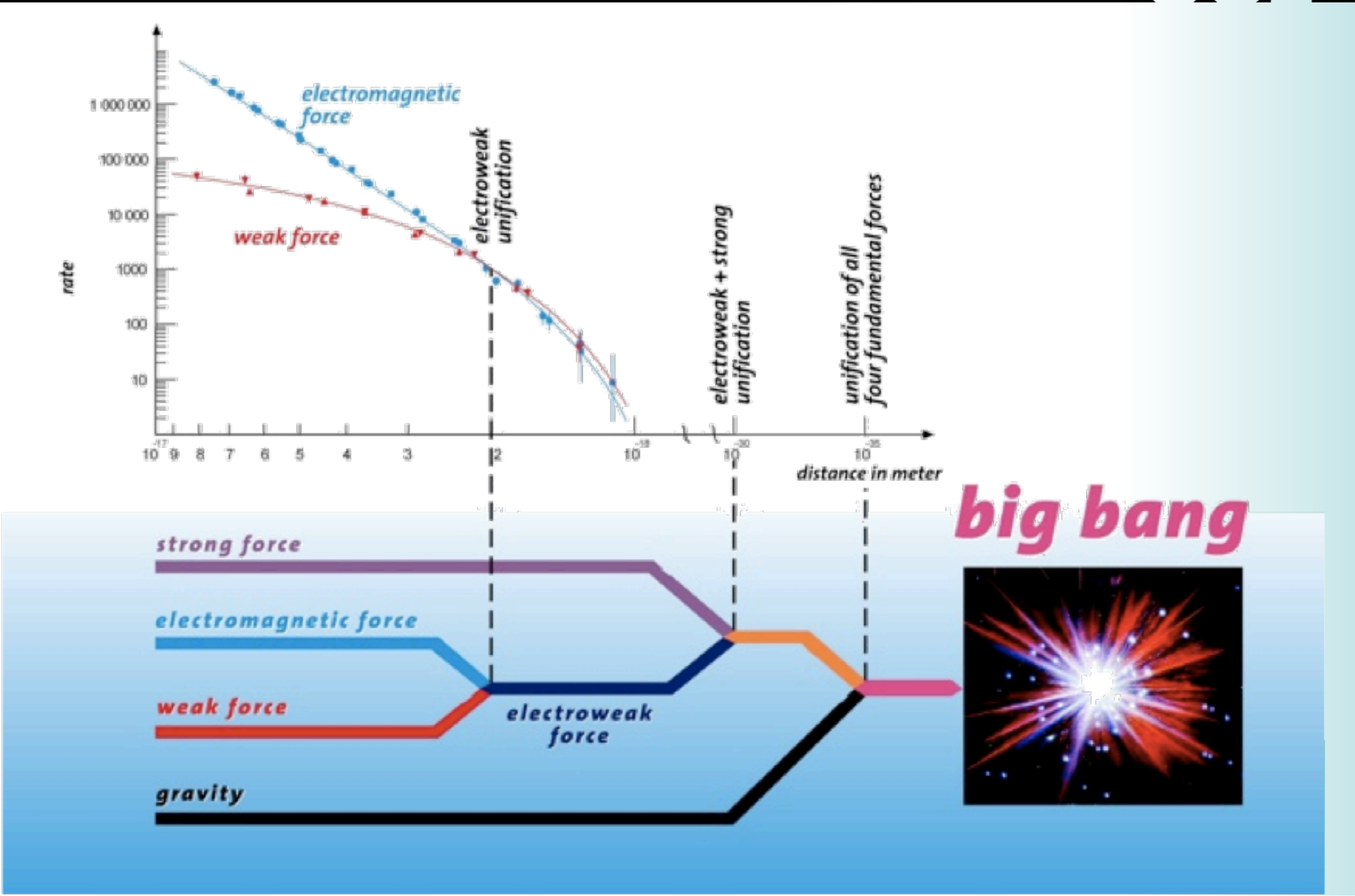

Relative energy scale
RMS: 0.019%
RMS: 0.015%
W→eν E/p
Z→ee inv. mass
Data 2012, √s=8 TeV, ∫Ldt = 13.0 fb-1
ATLAS Preliminary
Average interactions per bunch crossing


b-jet efficiency scale factor
ATLAS Preliminary
∫L dt = 20.3 fb-1 √s = 8 TeV
PDF method (total error)
PDF method (stat. error)
MV1, ϵb = 70%
jet pT [GeV]

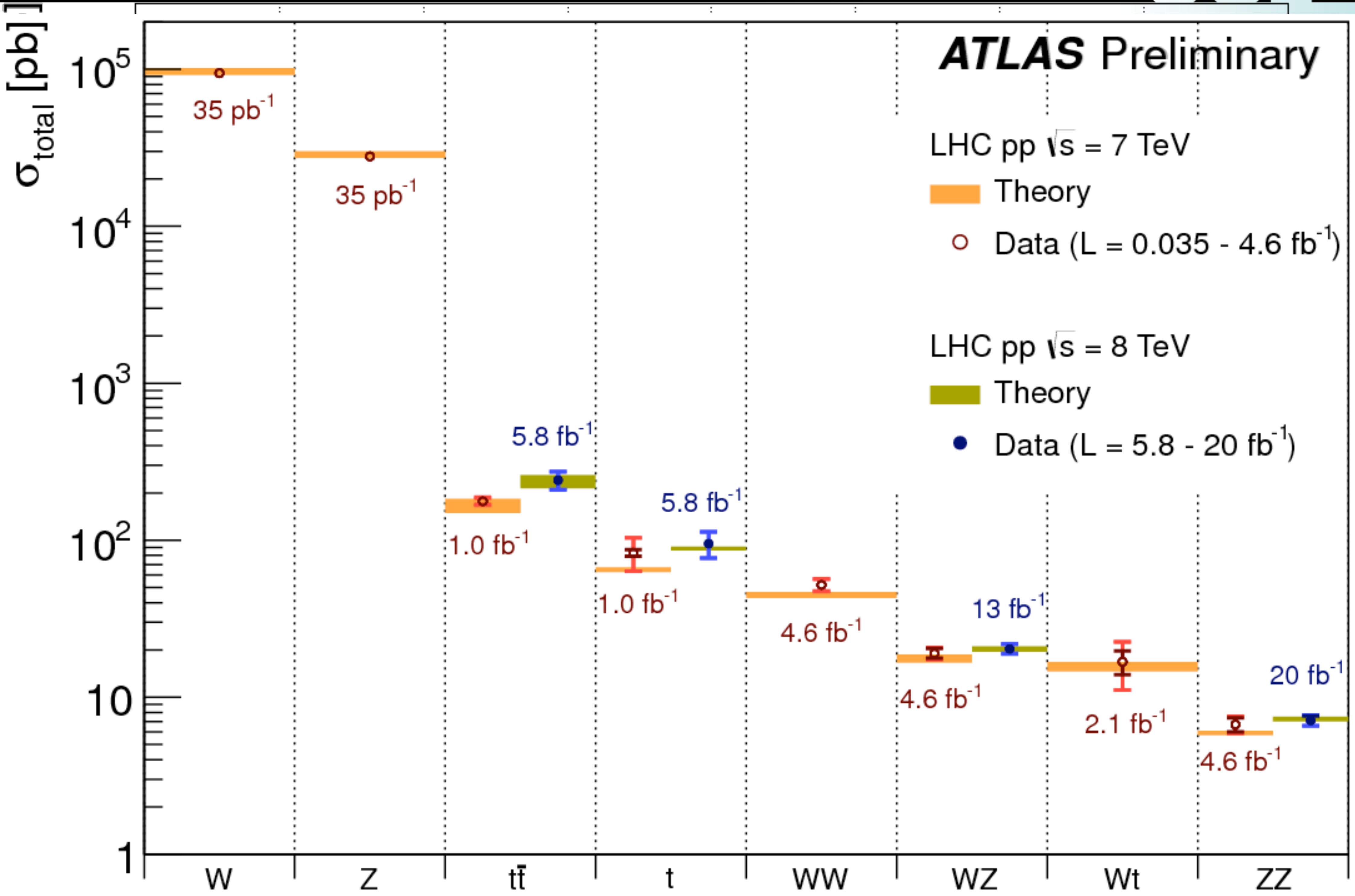

Efficiency
pT > 20 GeV
ATLAS Preliminary
Data 2012, Chain 1
Data, CB+ST muons
MC, CB+ST muons
Data, CaloTag muons
MC, CaloTag muons
∫L dt = 20.4 fb-1 √s = 8 TeV
Data/MC
η


σ(pT)/pT
Data 2010 √s = 7 TeV
anti-kt R = 0.6 jets
|y| < 0.8
ATLAS
EM+JES
EM+JES + TBJC
LCW+JES
LCW+JES + TBJC
Improvement (%)
EM+JES
(pT,1+pT,2)/2 (GeV)

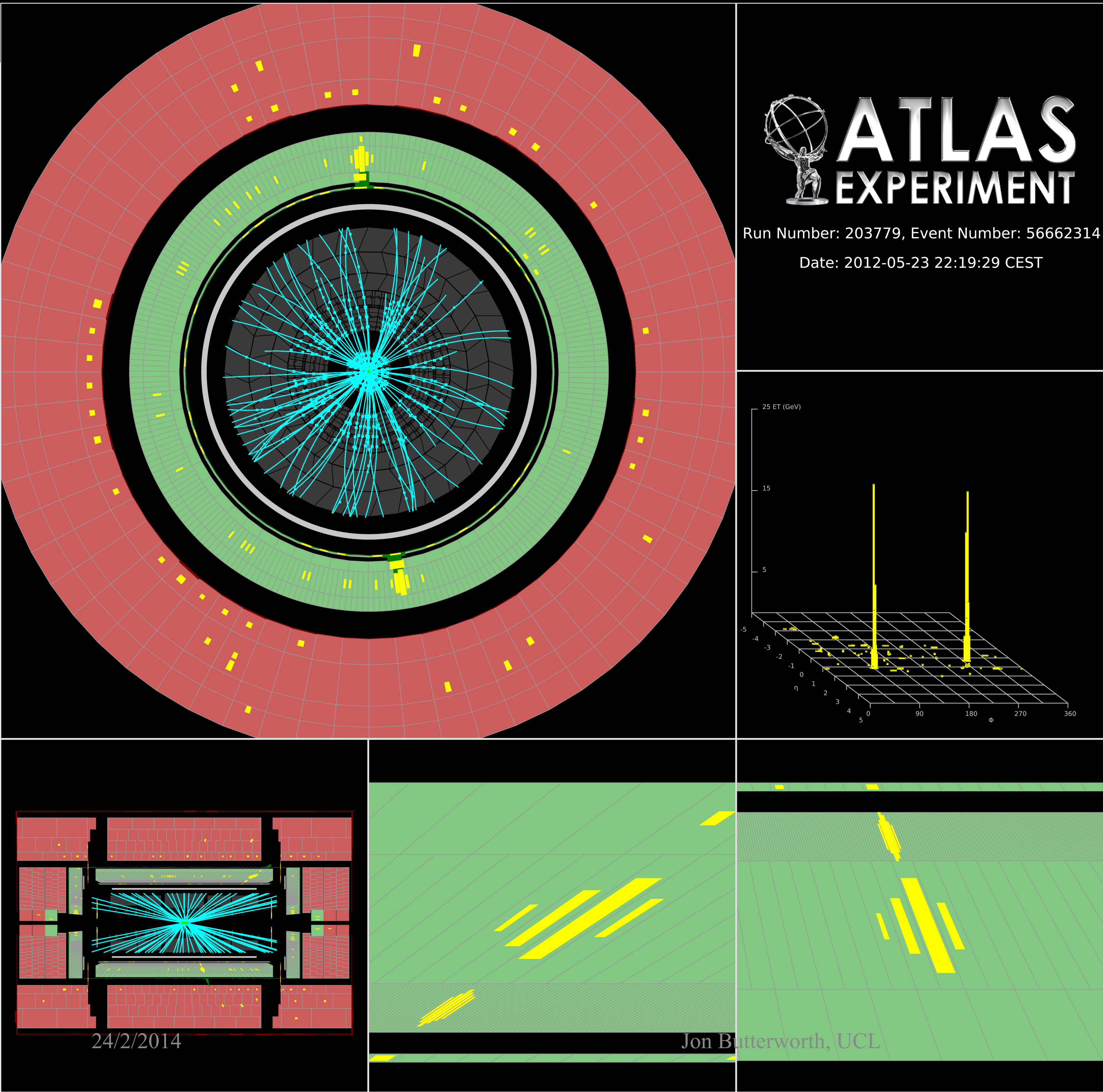

Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
H
Higgs boson
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons

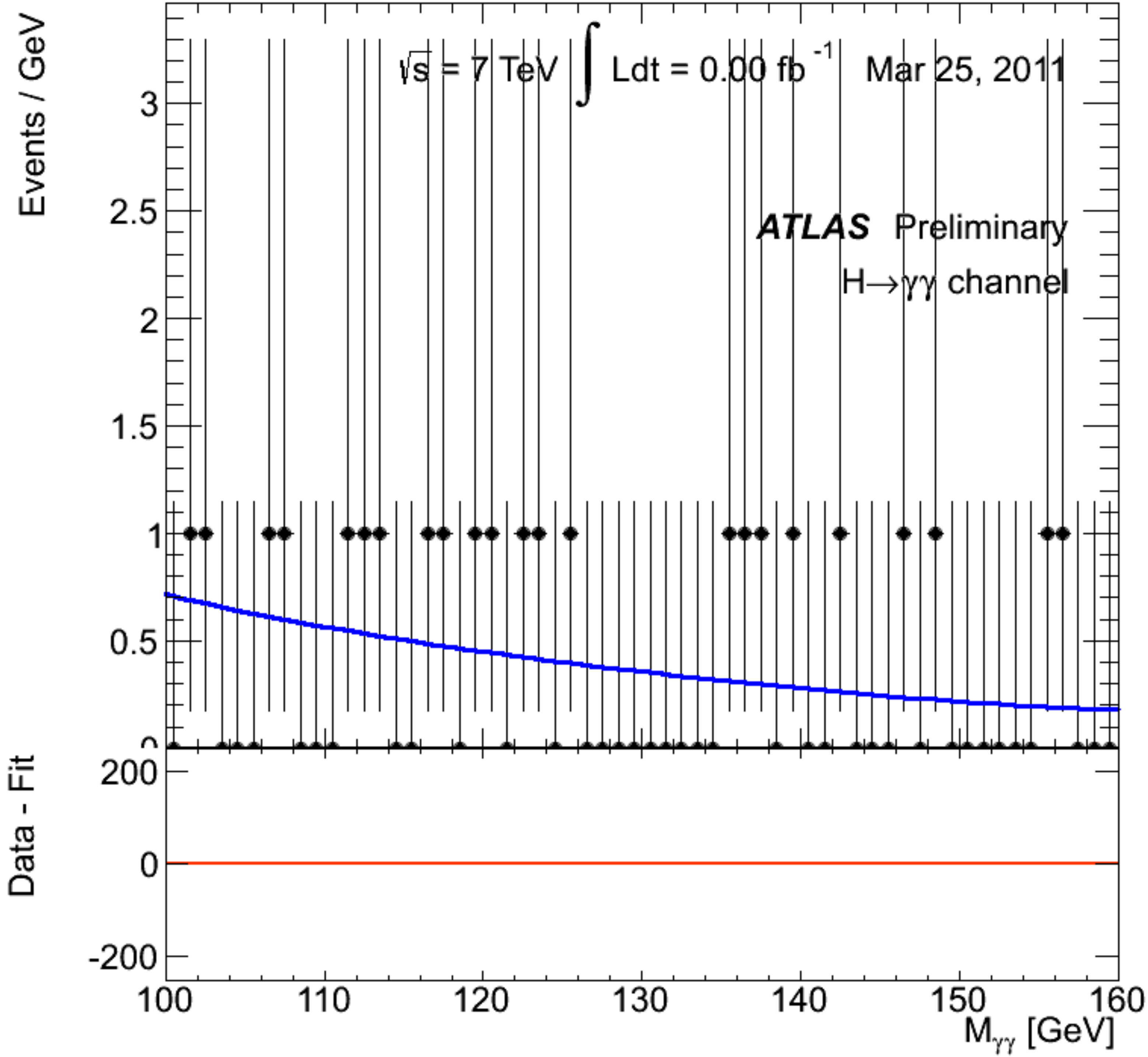


UCL
electromagnetic force
weak force
rate
1 000 000
100 000
10 000
1000
100
10
electroweak unification
electroweak + strong unification
unification of all four fundamental forces
distance in meter
big bang
strong force
electromagnetic force
weak force
electroweak force
gravity

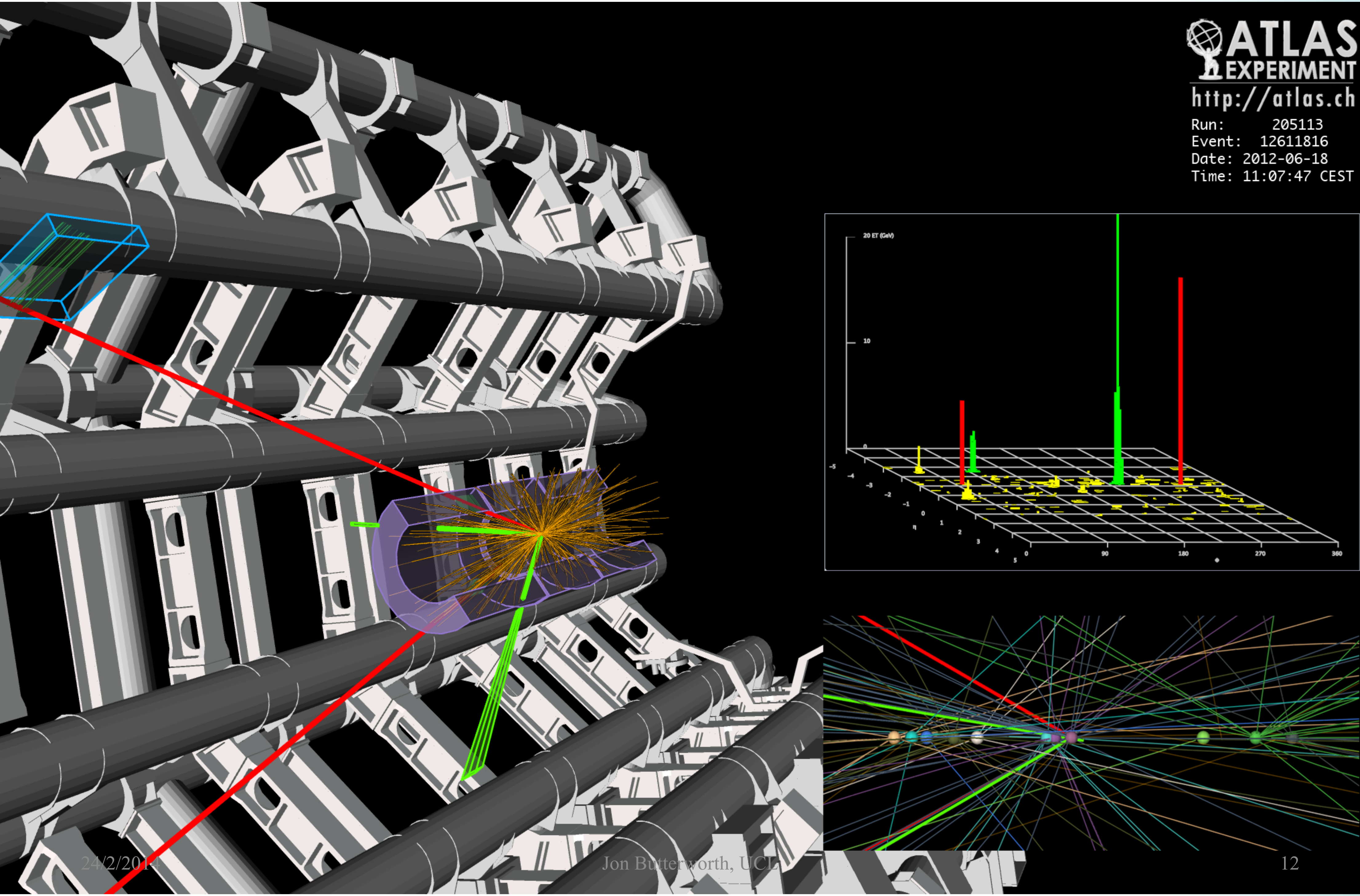


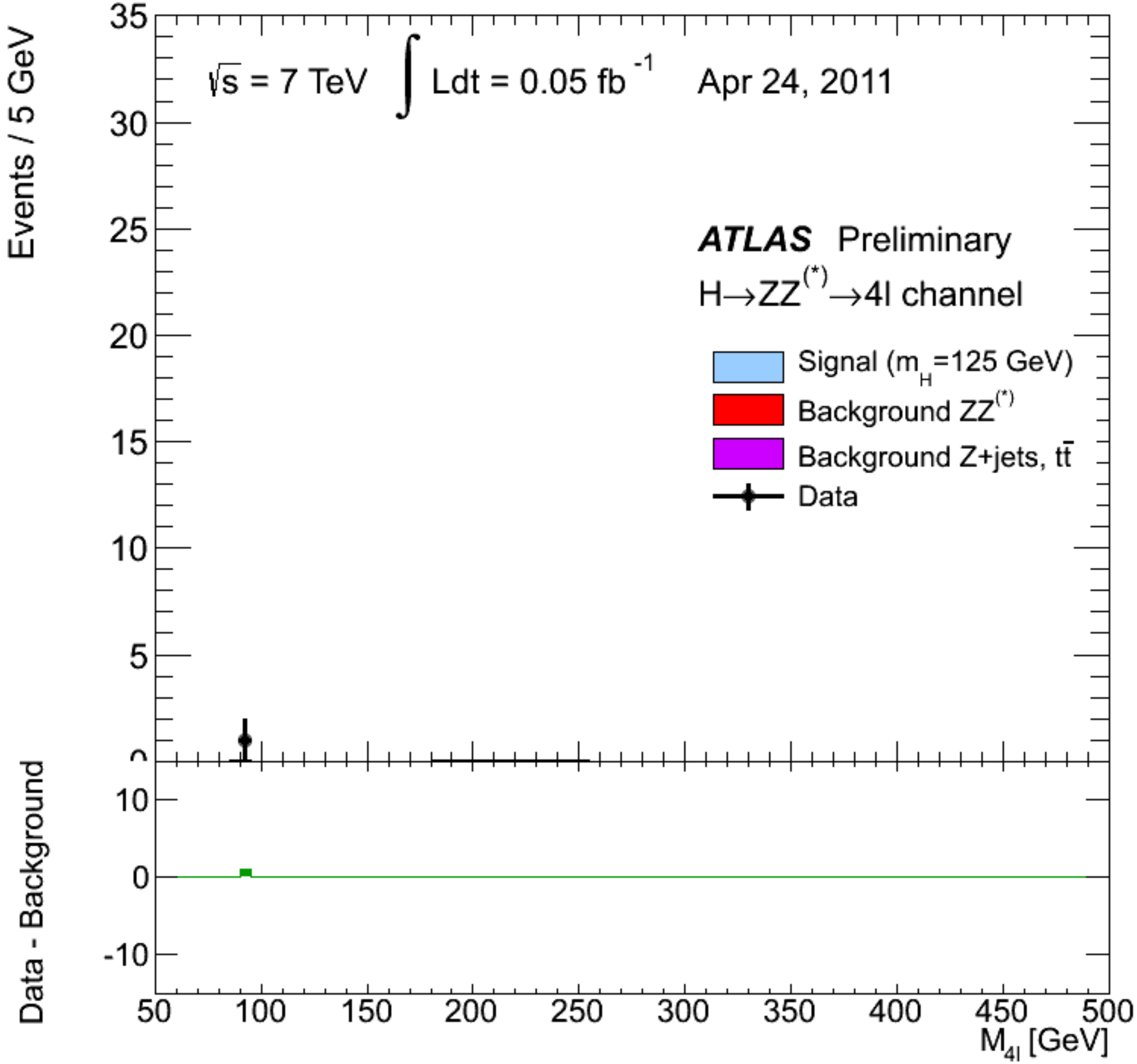
ATLAS Preliminary
σ_total [pb]
10^5
10^4
10^3
10^2
10
1
35 pb^-1
35 pb^-1
5.8 fb^-1
1.0 fb^-1
5.8 fb^-1
1.0 fb^-1
4.6 fb^-1
13 fb^-1
4.6 fb^-1
2.1 fb^-1
20 fb^-1
4.6 fb^-1
LHC pp √s = 7 TeV
Theory
Data (L = 0.035 - 4.6 fb^-1)
LHC pp √s = 8 TeV
Theory
Data (L = 5.8 - 20 fb^-1)
W
Z
tt̄
t
WW
WZ
Wt
ZZ


ATLAS
EXPERIMENT
Run Number: 203779, Event Number: 56662314
Date: 2012-05-23 22:19:29 CEST
25 ET (GeV)
15
5
η
Φ
0
90
180
270
360

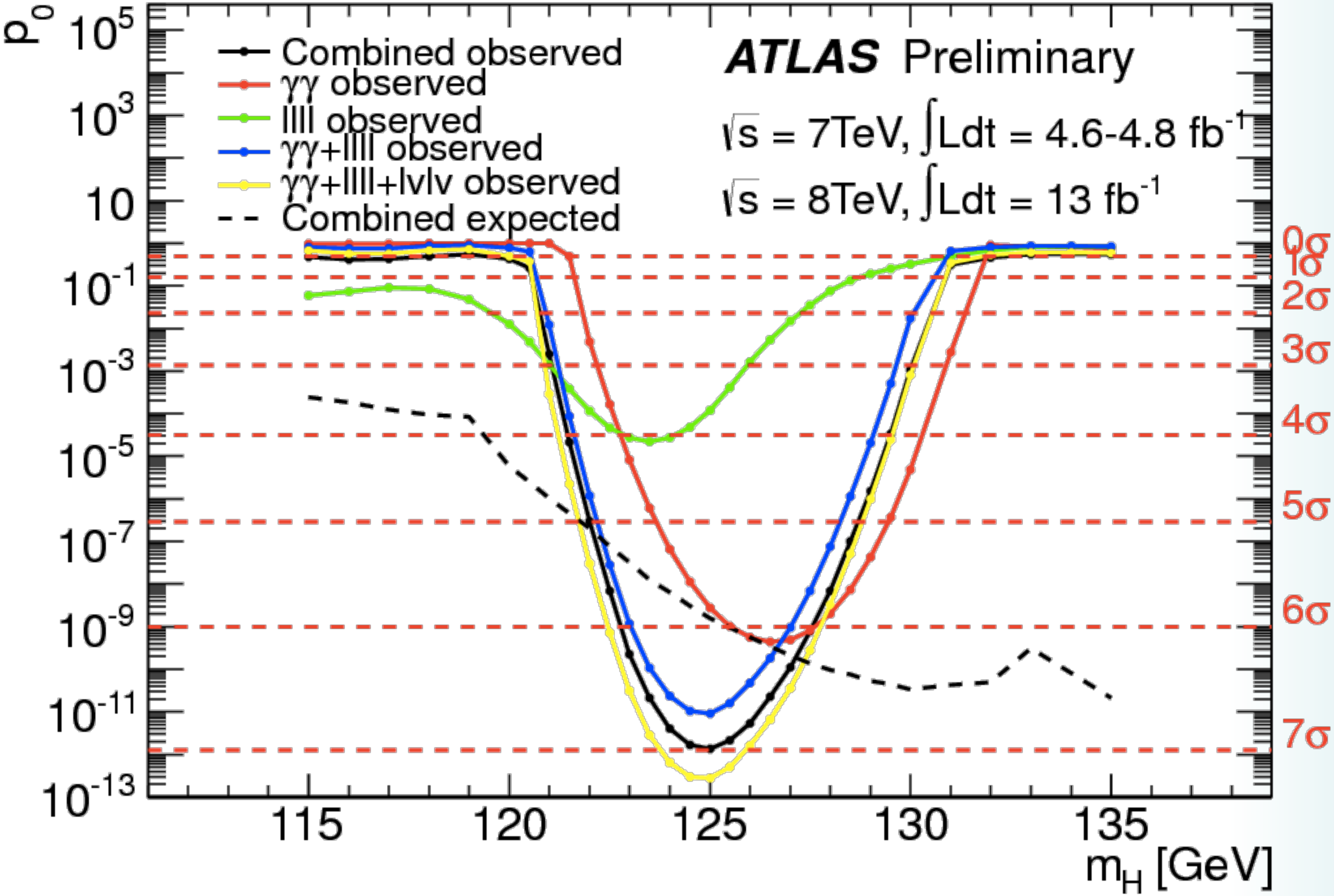


Events / GeV
$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.00 fb^{-1} Mar 25, 2011
ATLAS Preliminary
H→γγ channel
3
2.5
2
1.5
1
0.5
0
Data - Fit
200
0
-200
100
110
120
130
140
150
160
$M_{\gamma\gamma}$ [GeV]

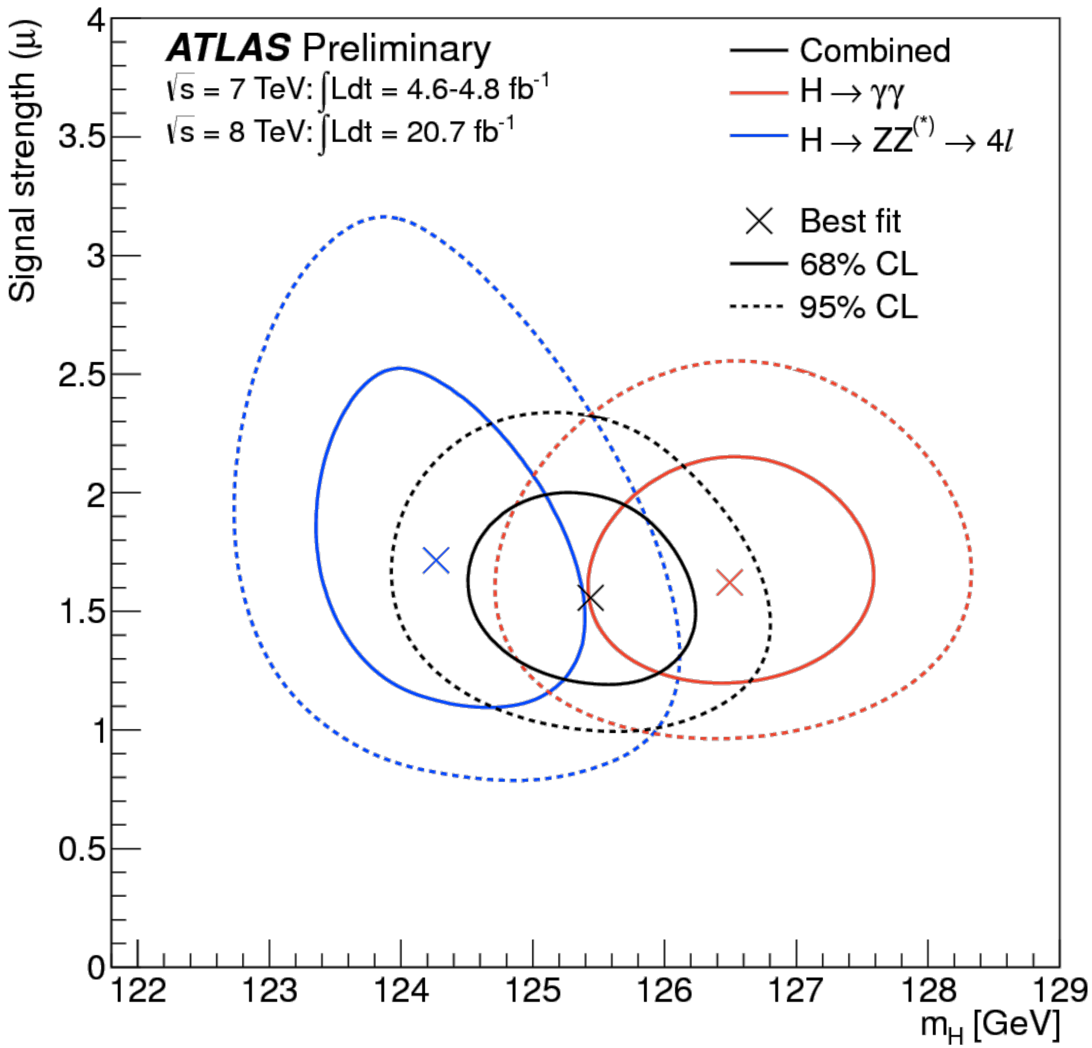

ATLAS EXPERIMENT
http://atlas.ch
Run: 205113
Event: 12611816
Date: 2012-06-18
Time: 11:07:47 CEST
20 ET (GeV)
10
η
φ
0
90
180
270
360

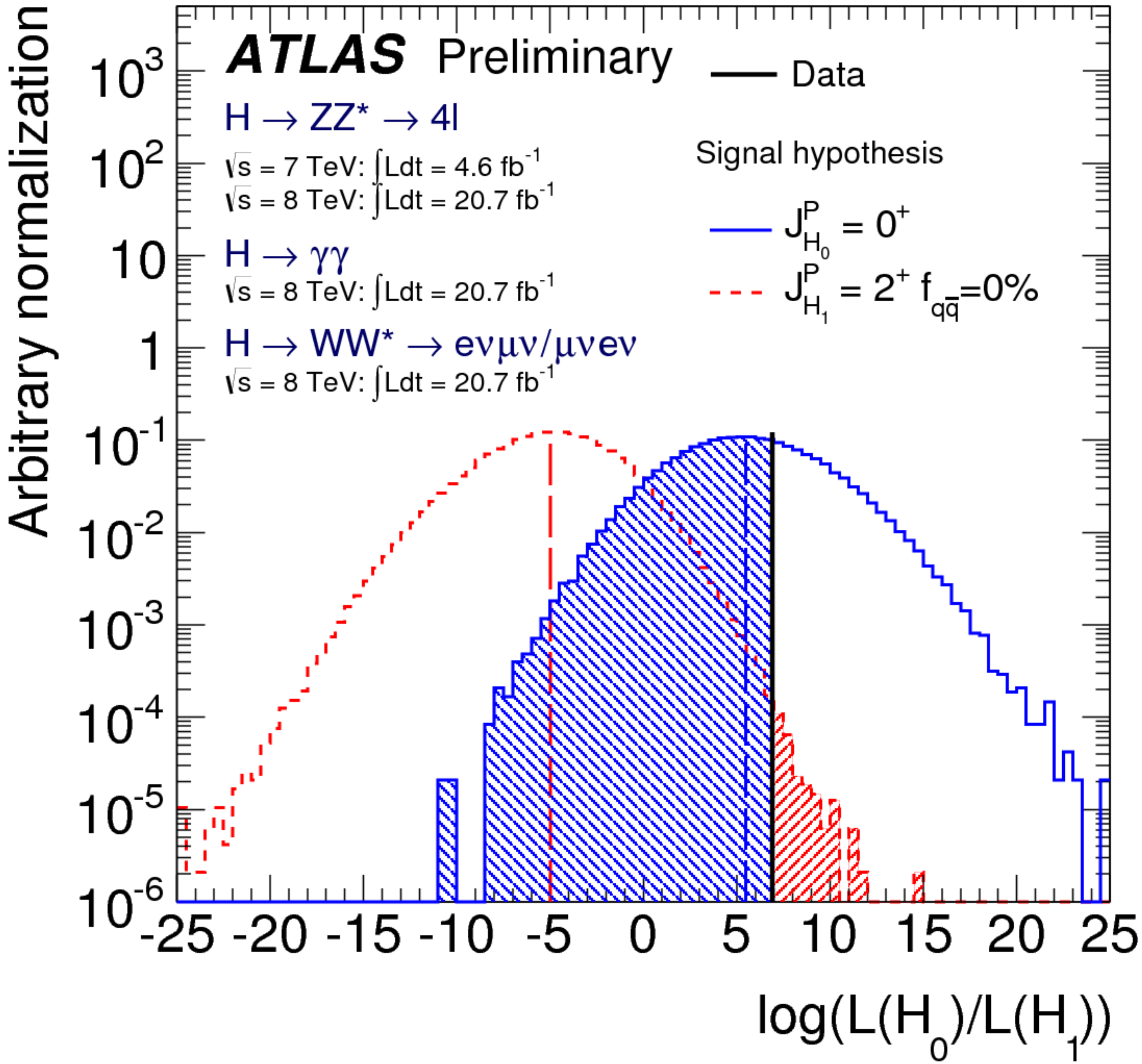


$\sqrt{s}$ = 7 TeV
$\int Ldt = 0.05\ fb^{-1}$
Apr 24, 2011
ATLAS Preliminary
$H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel
Signal (m_H=125 GeV)
Background $ZZ^{(*)}$
Background Z+jets, $t\bar{t}$
Data
Events / 5 GeV
Data - Background
M_{4l} [GeV]

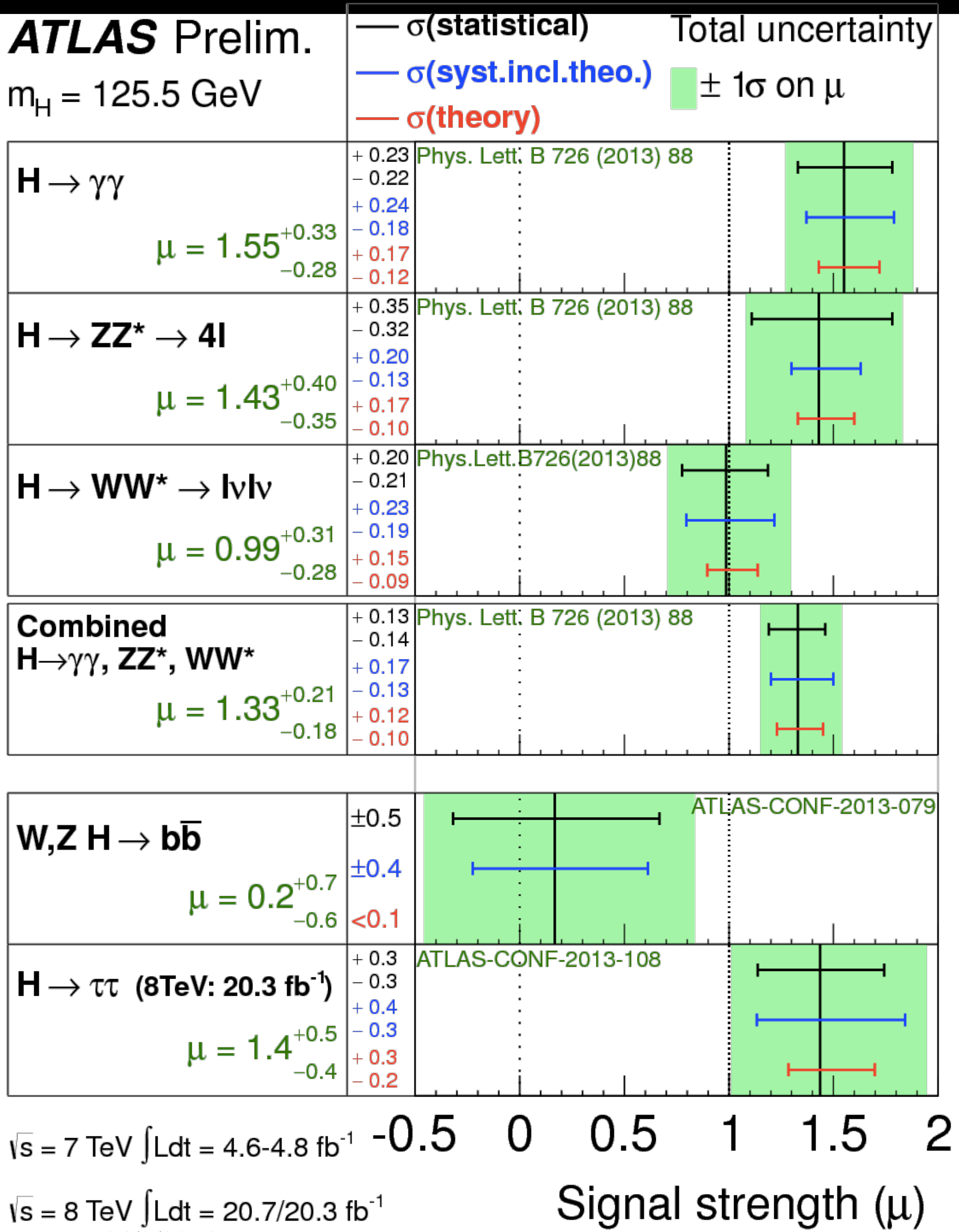


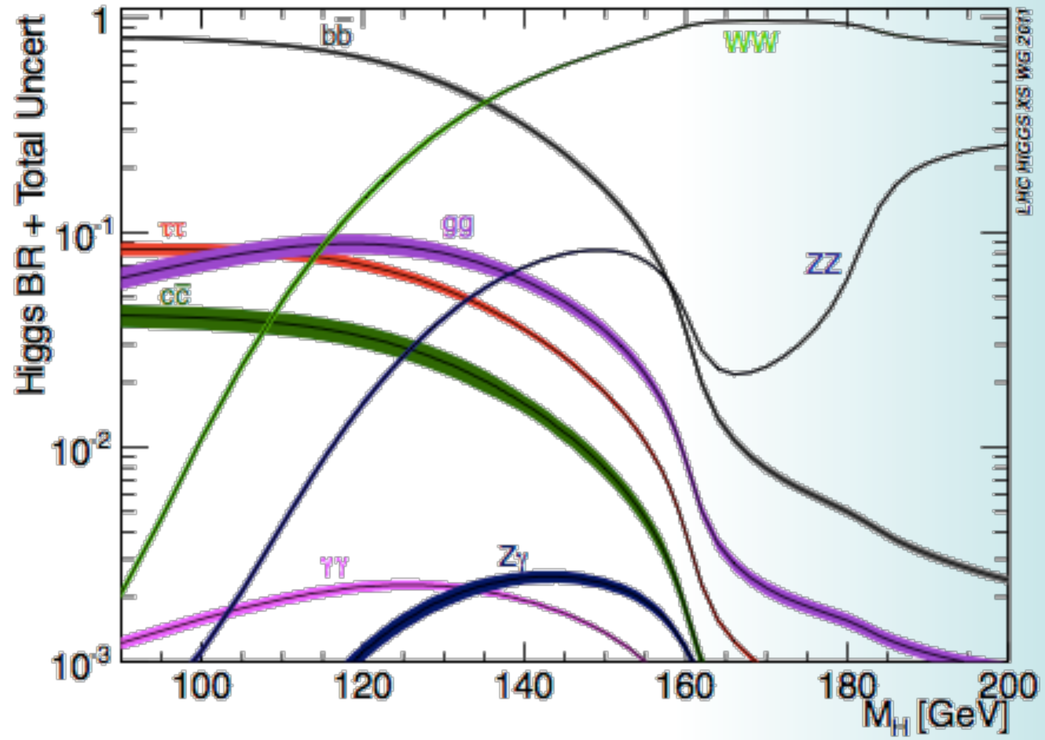
p_0
Combined observed
γγ observed
llll observed
γγ+llll observed
γγ+llll+lνlν observed
Combined expected
ATLAS Preliminary
$\sqrt{s}$ = 7TeV, $\int Ldt$ = 4.6-4.8 fb^{-1}
$\sqrt{s}$ = 8TeV, $\int Ldt$ = 13 fb^{-1}
0σ
1σ
2σ
3σ
4σ
5σ
6σ
7σ
10^5
10^3
10
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
115
120
125
130
135
m_H [GeV]


ATLAS Preliminary
√s = 7 TeV: ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 20.7 fb⁻¹
Combined
H → γγ
H → ZZ(*) → 4l
Best fit
68% CL
95% CL
Signal strength (μ)
m_H [GeV]
0
0.5
1
1.5
2
2.5
3
3.5
4
122
123
124
125
126
127
128
129



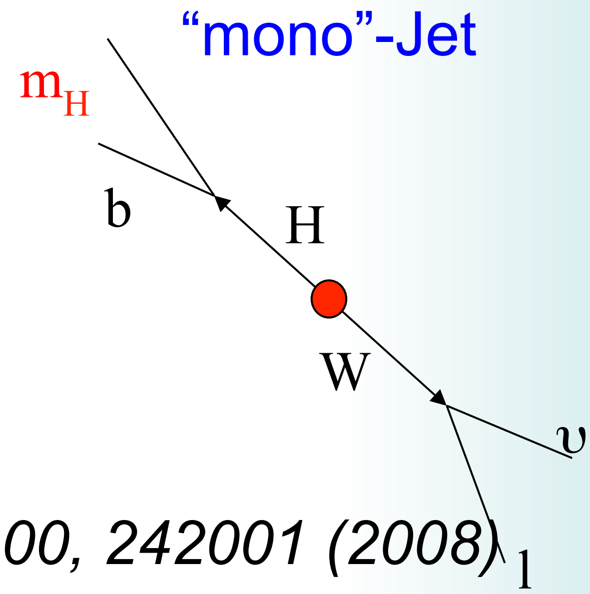
Pure spin 2 excluded at > 99.9%


ATLAS Prelim.
m_H = 125.5 GeV
σ(statistical)
σ(syst.incl.theo.)
σ(theory)
Total uncertainty
± 1σ on μ
H → γγ
μ = 1.55 +0.33 −0.28
+ 0.23 − 0.22 + 0.24 − 0.18 + 0.17 − 0.12
Phys. Lett. B 726 (2013) 88
H → ZZ* → 4l
μ = 1.43 +0.40 −0.35
+ 0.35 − 0.32 + 0.20 − 0.13 + 0.17 − 0.10
Phys. Lett. B 726 (2013) 88
H → WW* → lνlν
μ = 0.99 +0.31 −0.28
+ 0.20 − 0.21 + 0.23 − 0.19 + 0.15 − 0.09
Phys.Lett.B726(2013)88
Combined H→γγ, ZZ*, WW*
μ = 1.33 +0.21 −0.18
+ 0.13 − 0.14 + 0.17 − 0.13 + 0.12 − 0.10
Phys. Lett. B 726 (2013) 88
W,Z H → bb̄
μ = 0.2 +0.7 −0.6
±0.5 ±0.4 <0.1
ATLAS-CONF-2013-079
H → ττ (8TeV: 20.3 fb-1)
μ = 1.4 +0.5 −0.4
+ 0.3 − 0.3 + 0.4 − 0.3 + 0.3 − 0.2
ATLAS-CONF-2013-108
√s = 7 TeV ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV ∫Ldt = 20.7/20.3 fb-1
-0.5 0 0.5 1 1.5 2
Signal strength (μ)


Higgs BR + Total Uncert
bb̄
WW
ττ
gg
cc̄
ZZ
γγ
Zγ
1
10-1
10-2
10-3
100 120 140 160 180 200
MH [GeV]
LHC HIGGS XS WG 2011

High p_T Higgs and Vector Boson

- By requiring that the Higgs and Vector Boson have a high transverse momentum, we lose a factor of ~20 in cross section
  - However, much of this would have failed other analysis cuts anyway
  - Background cross sections fall by a bigger factor (typically t-channel not s-channel)
- W/Z and H are all central
  - Better b-tagging, better jet resolution
- W/Z and H decay products collimated
  - Simpler topology, fewer combinatorials
  - Difficult for tops to fake this
- Z ➔ neutrinos becomes visible
  - High missing E_T
- *JMB, Davison, Rubin, Salam, Phys. Rev. Lett. 100, 242001 (2008)*



Sub-jet analysis

1. Start with Higgs candidate jet (highest p_T jet in acceptance) with mass m)
2. Undo last stage of clustering (reduce radius to R_{12})

   $J \rightarrow J_1, J_2$
3. If $\max(m_1,m_2) < 2m/3$

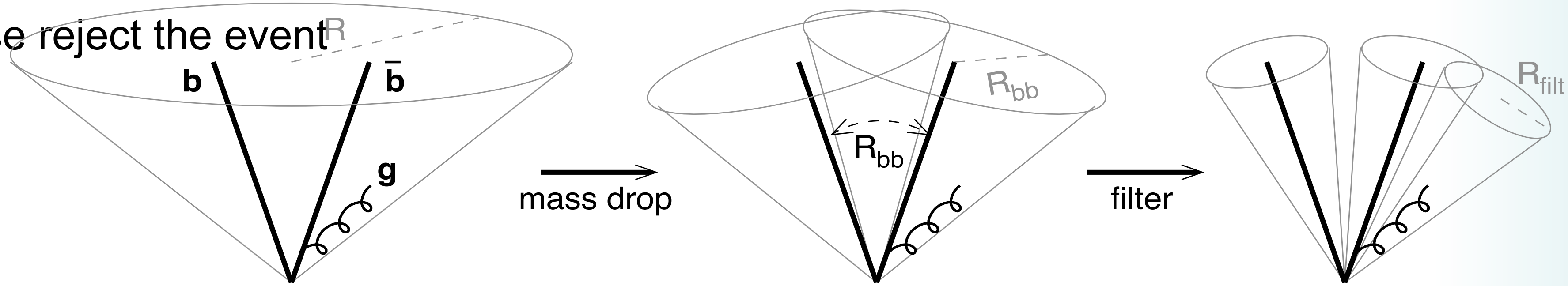
   Call this a "mass drop". This fixes the optimal radius for reconstructing the Higgs decay. Keep the jet J and call it the Higgs candidate.

   Else, go back to 2
4. Require $Y_{12} > 0.09$

   Dimensionless rejection of asymmetric QCD splitting

   Else reject the event
5. Require J_1, J_2 to each contain a b-tag

   Else reject the event



Sub-jet analysis

6. Define $R_{filt} = \min(0.3, R_{bb}/2)$

   Make use event-by-event of the known Higgs decay radius

   Angular ordering means this is the characteristic radius of QCD radiation from Higgs products

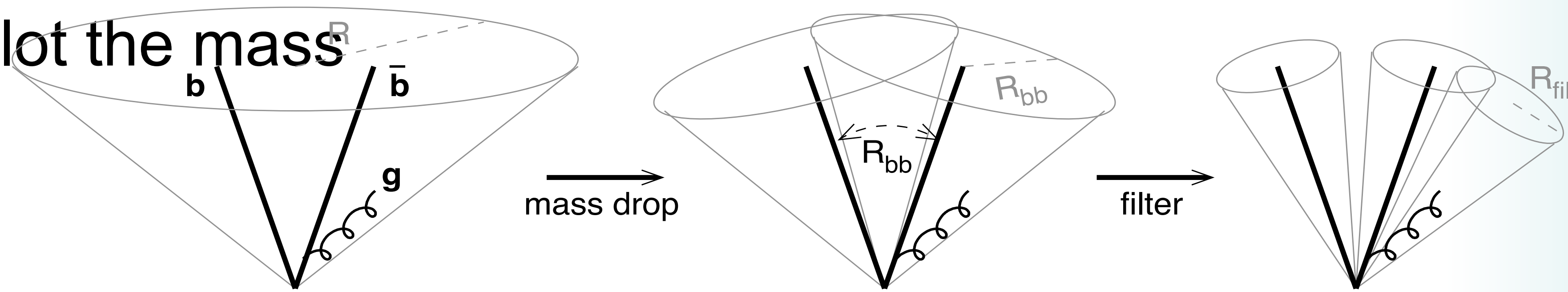
   Stuff outside of this is likely to be underlying event and pileup.

7. Recluster, with Cambridge/Aachen, $R = R_{filt}$

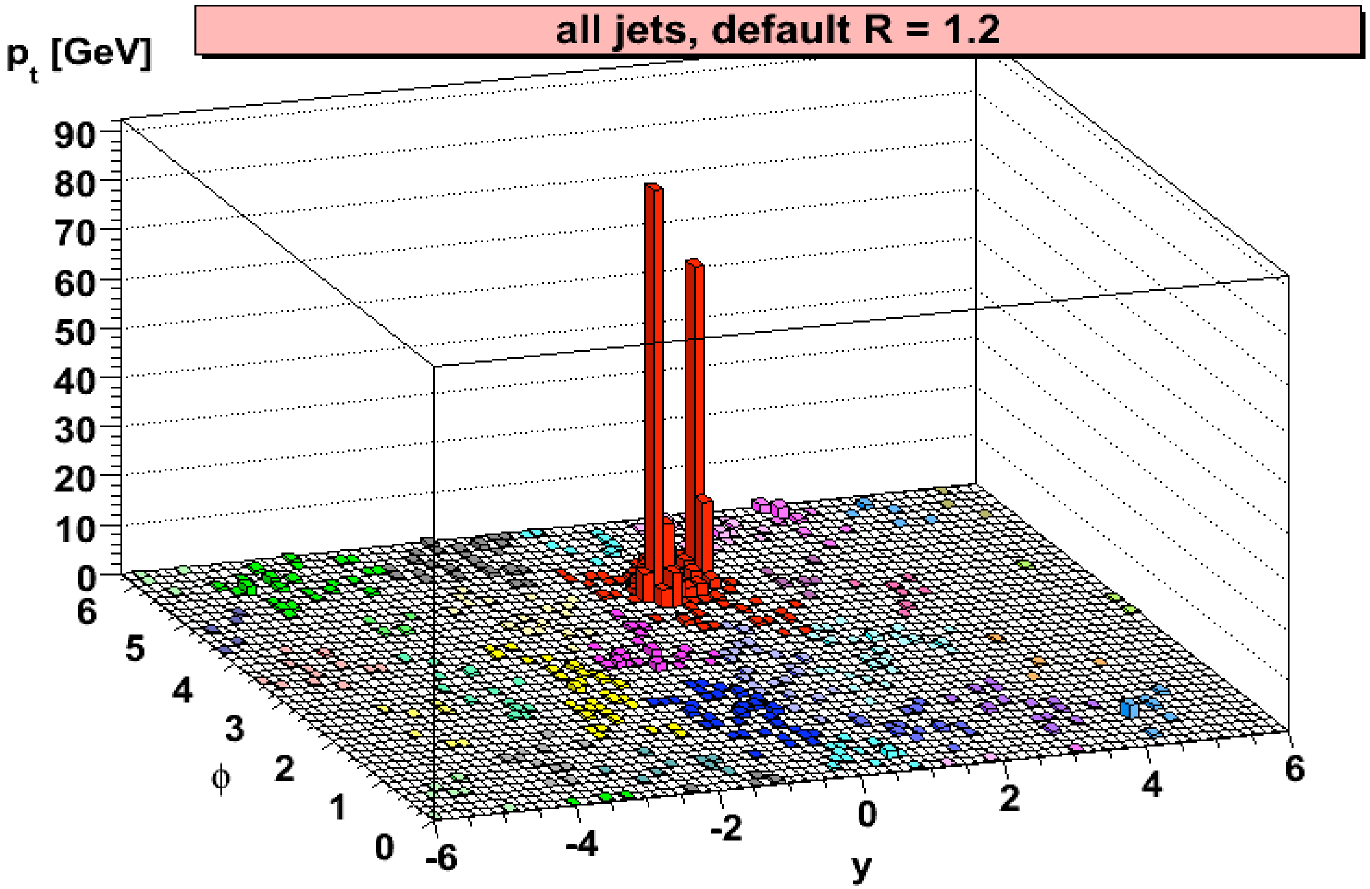
8. Take the 3 hardest subjets and combine to be the Higgs

   b, anti-b and leading order final state gluon radiation

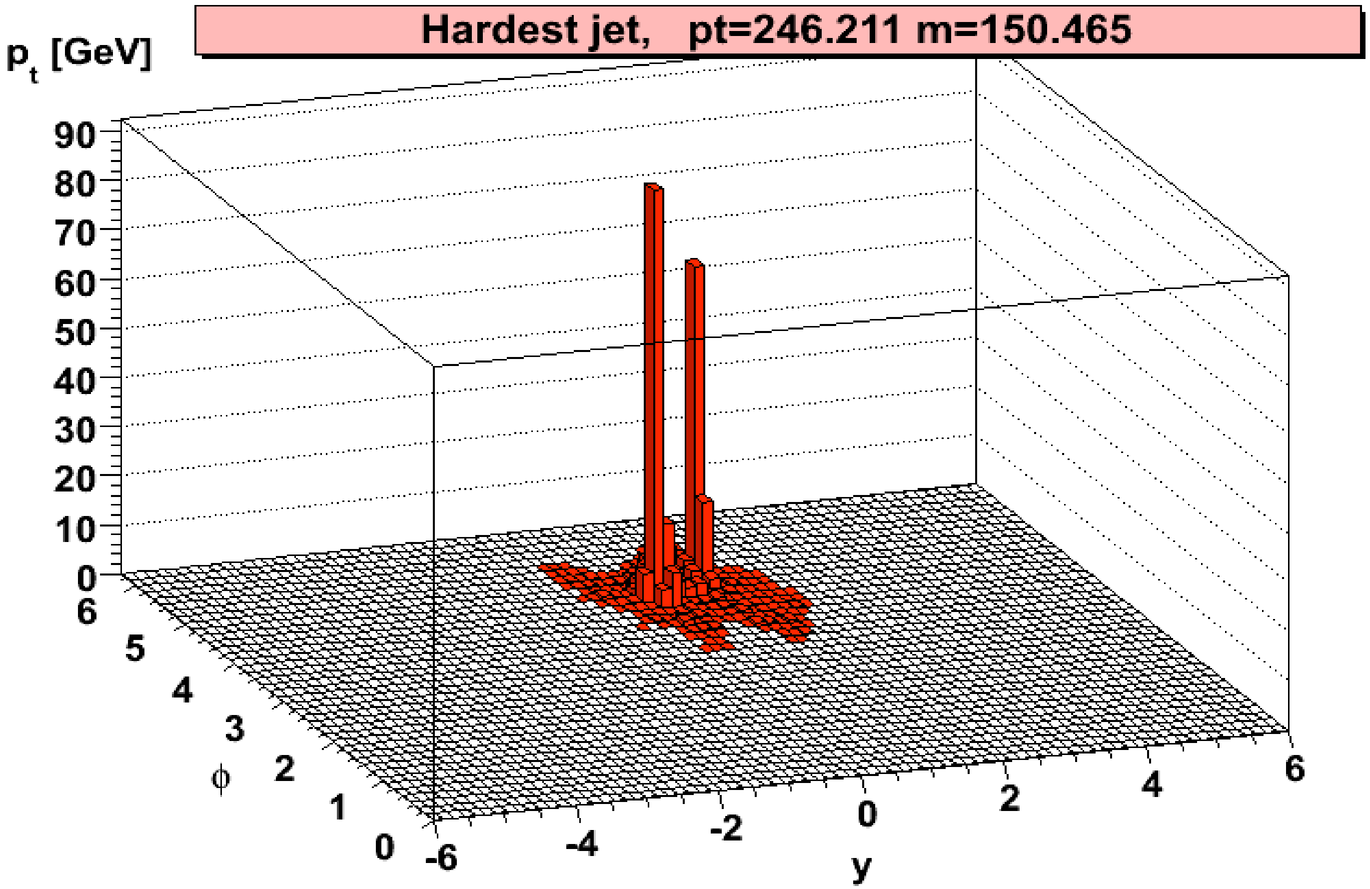
9. Plot the mass

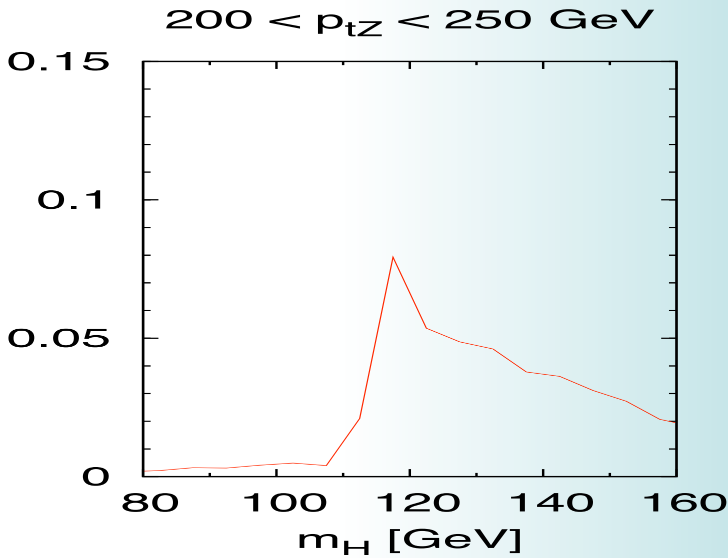


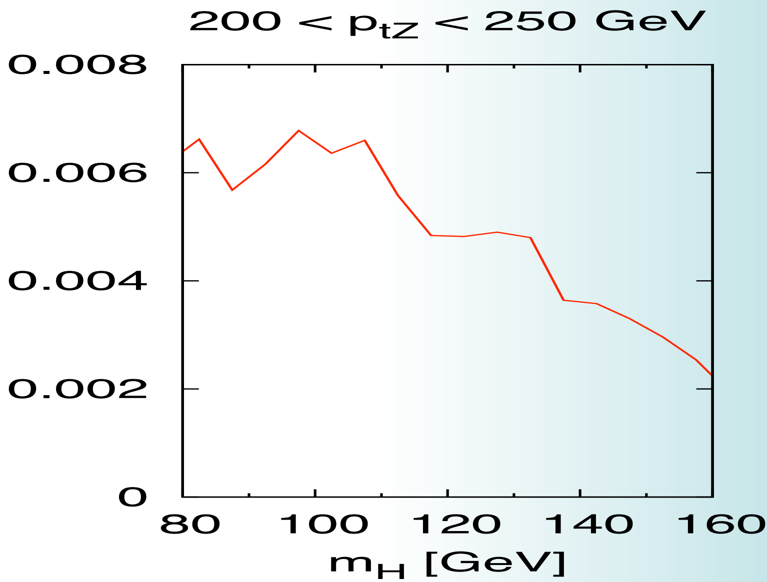
Improved subjet analysis



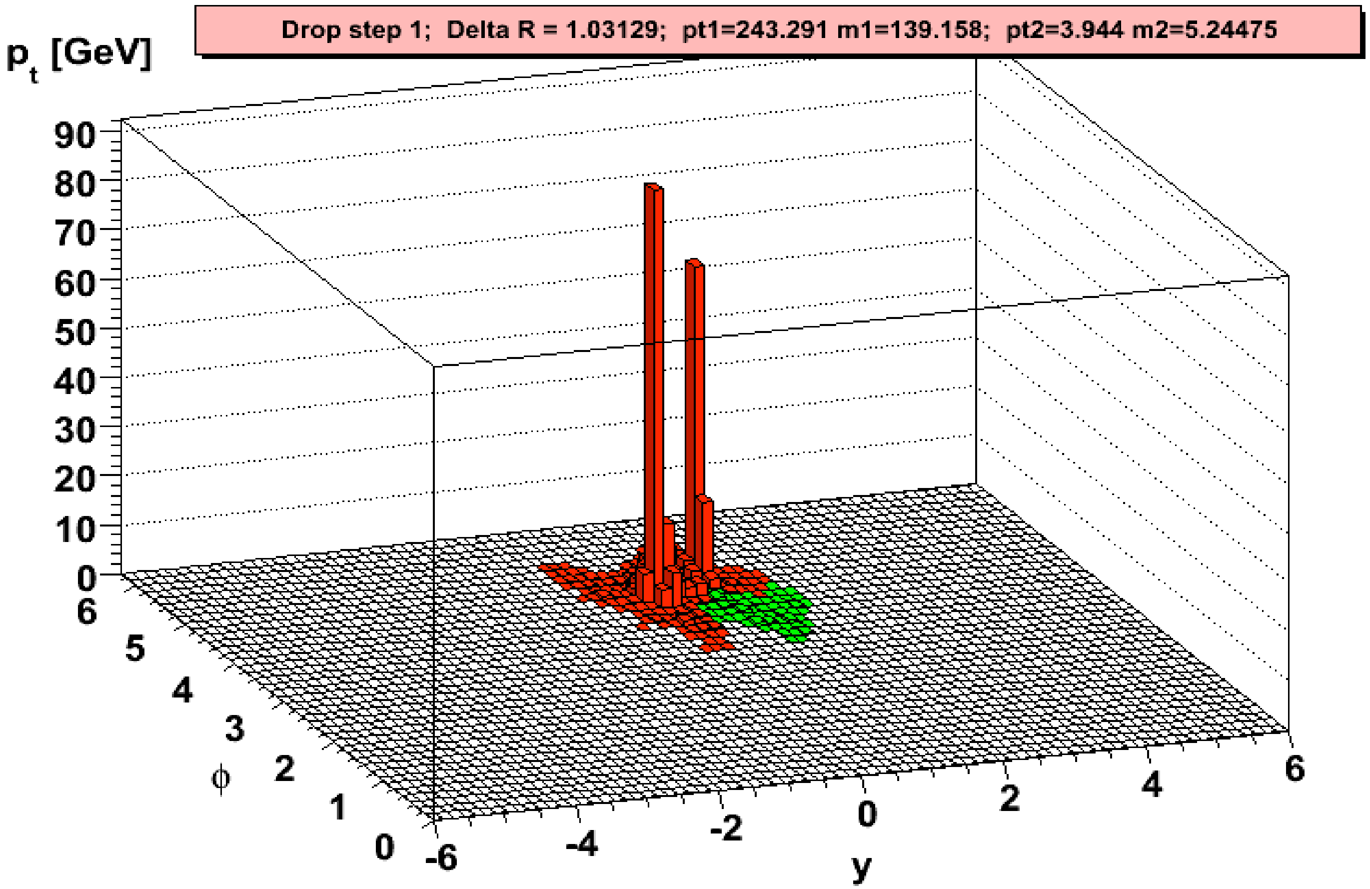
Improved subjet analysis

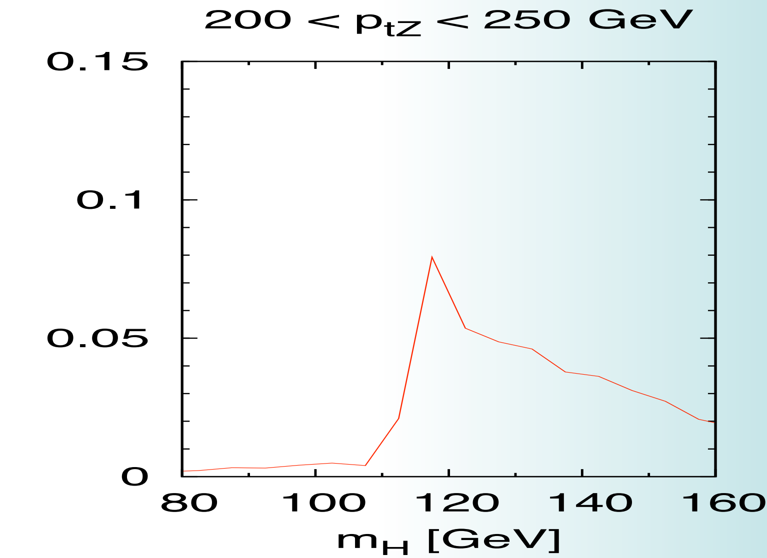


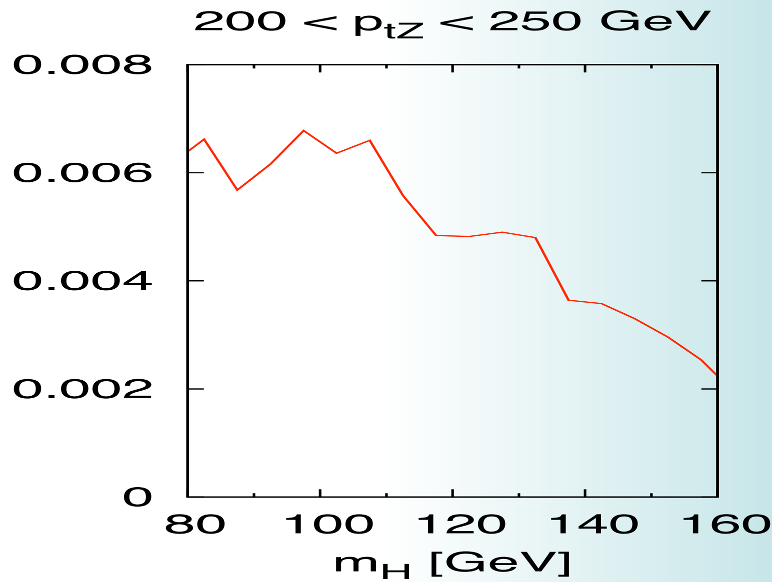




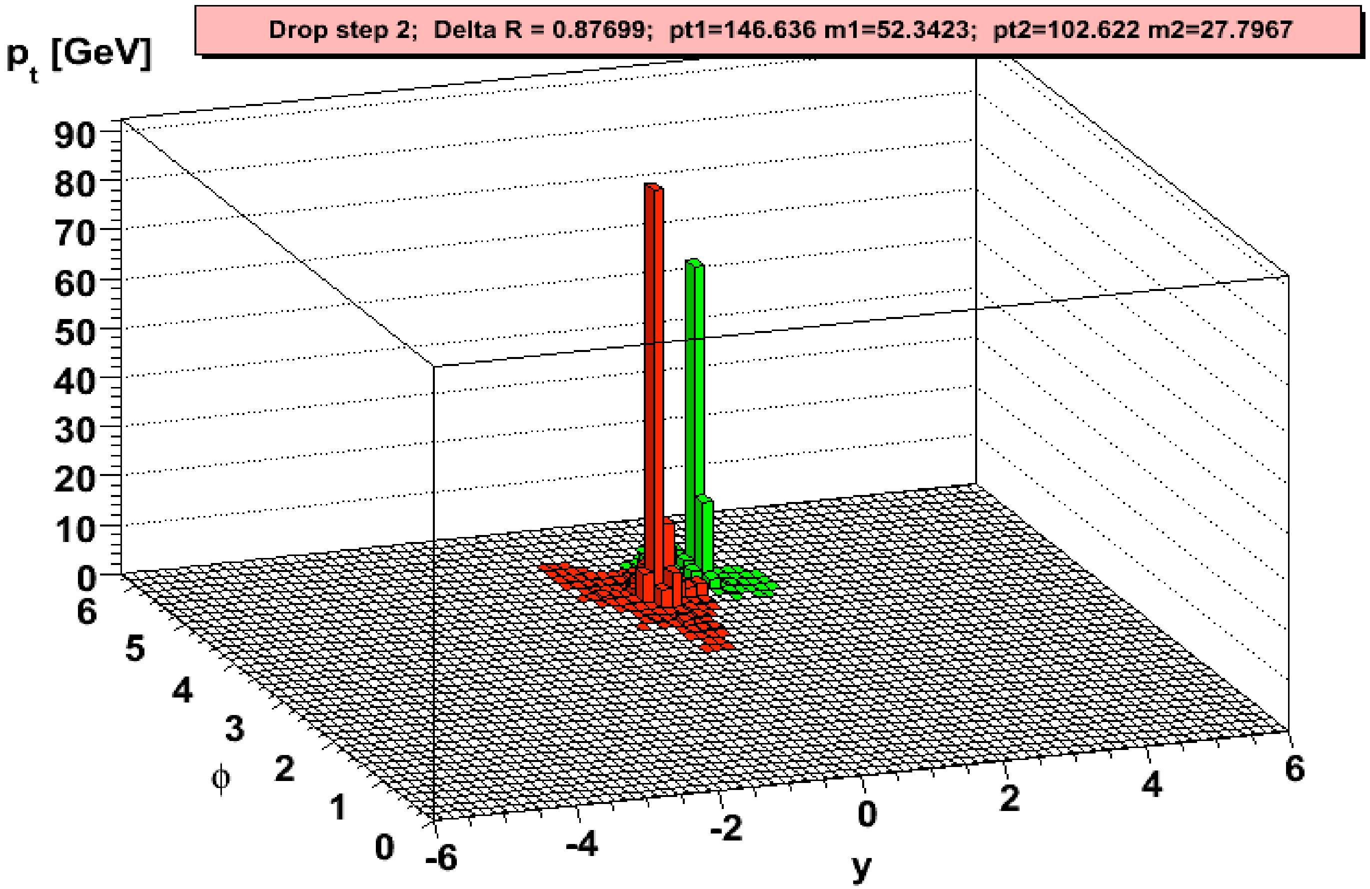
Improved subjet analysis

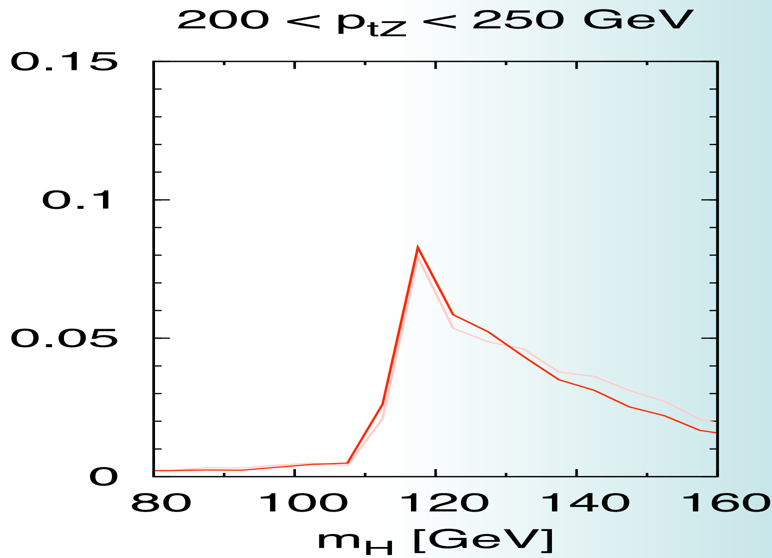


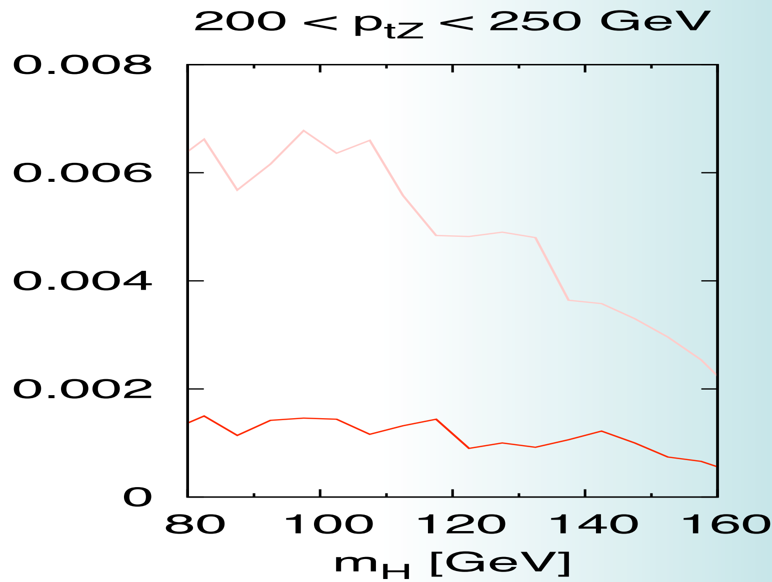




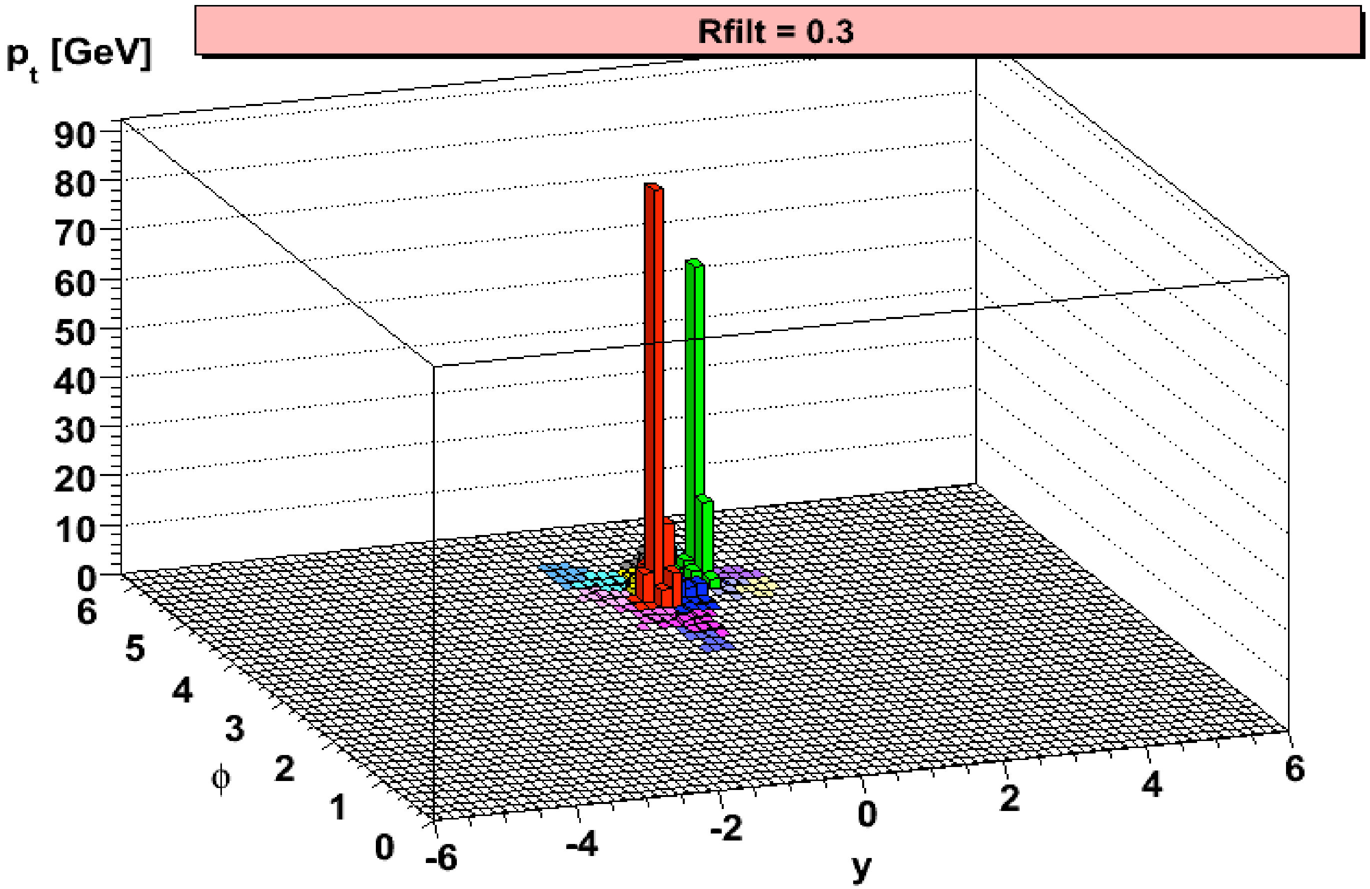
Improved subjet analysis

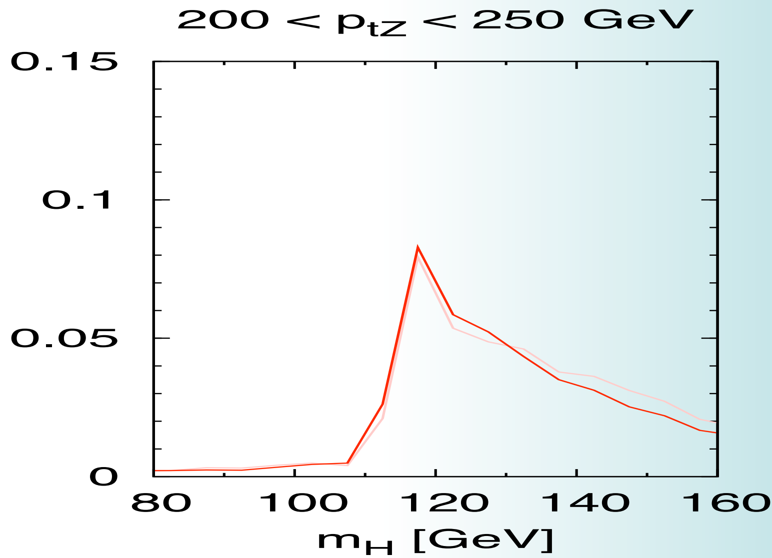


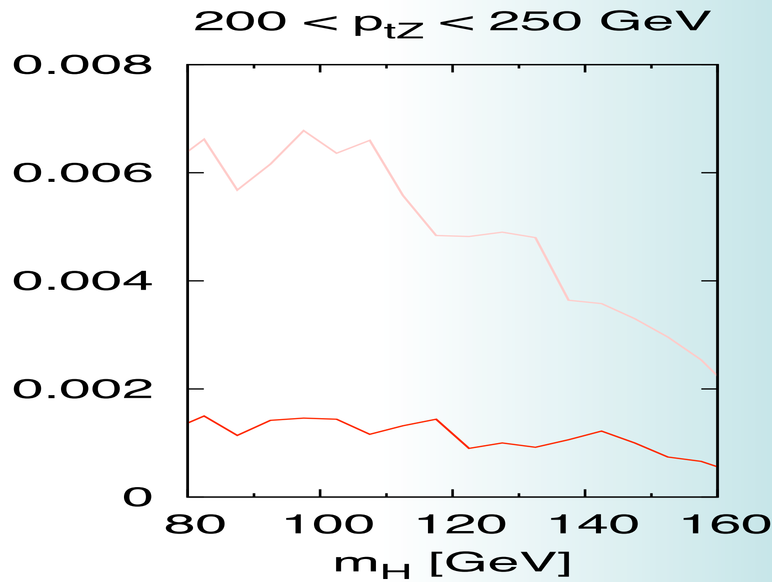




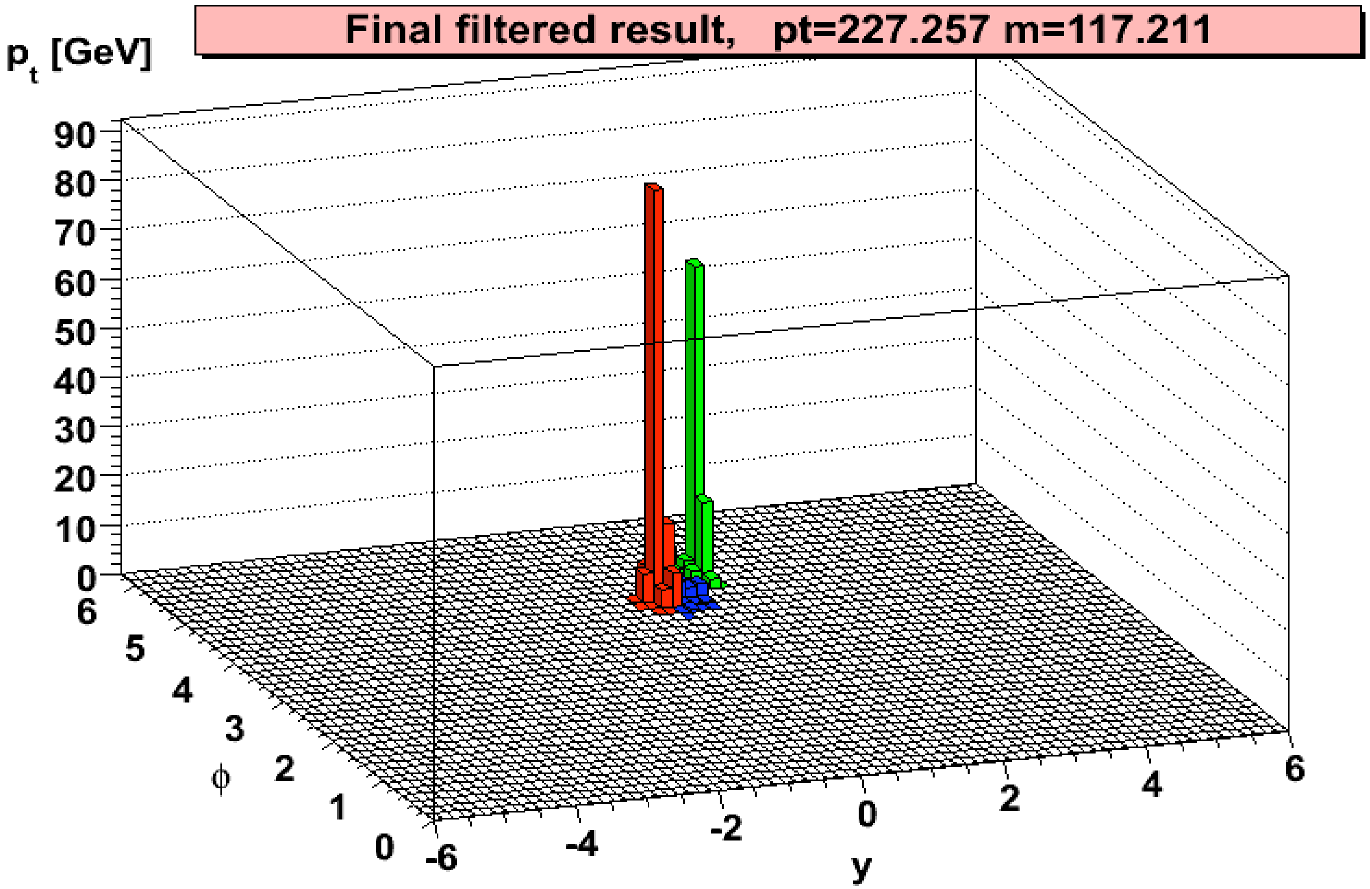
Improved subjet analysis

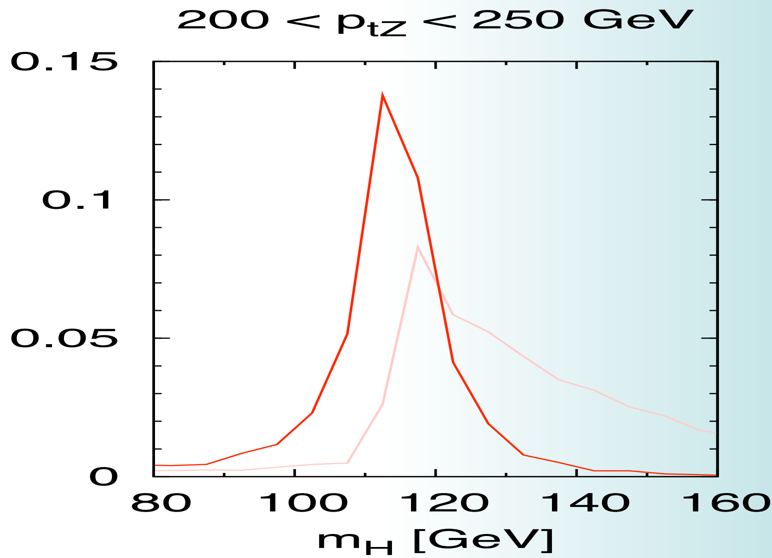


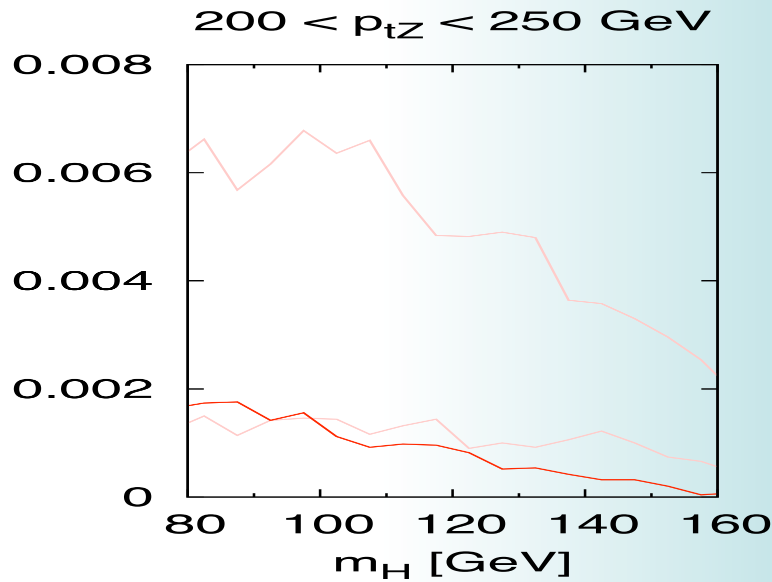




Improved subjet analysis



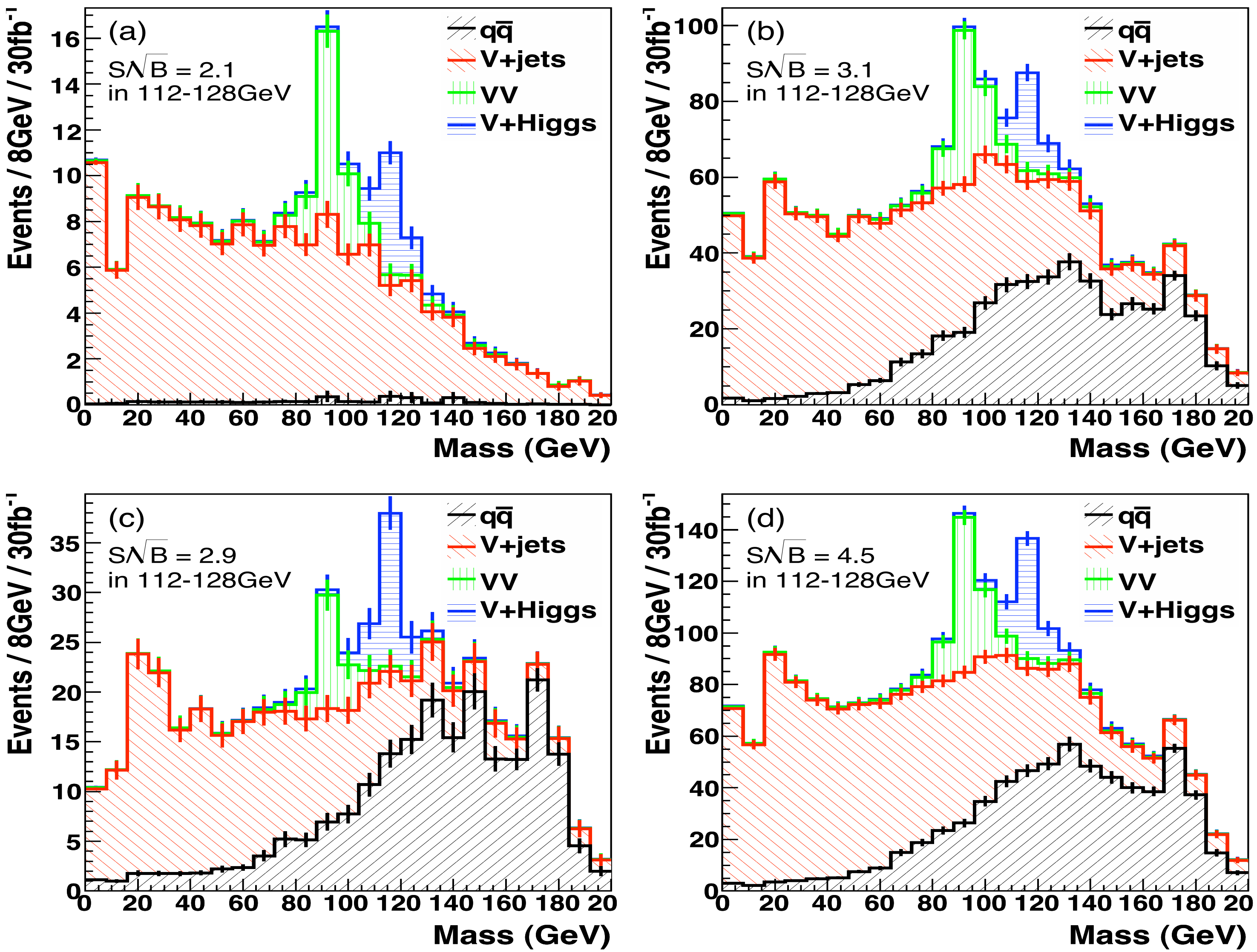




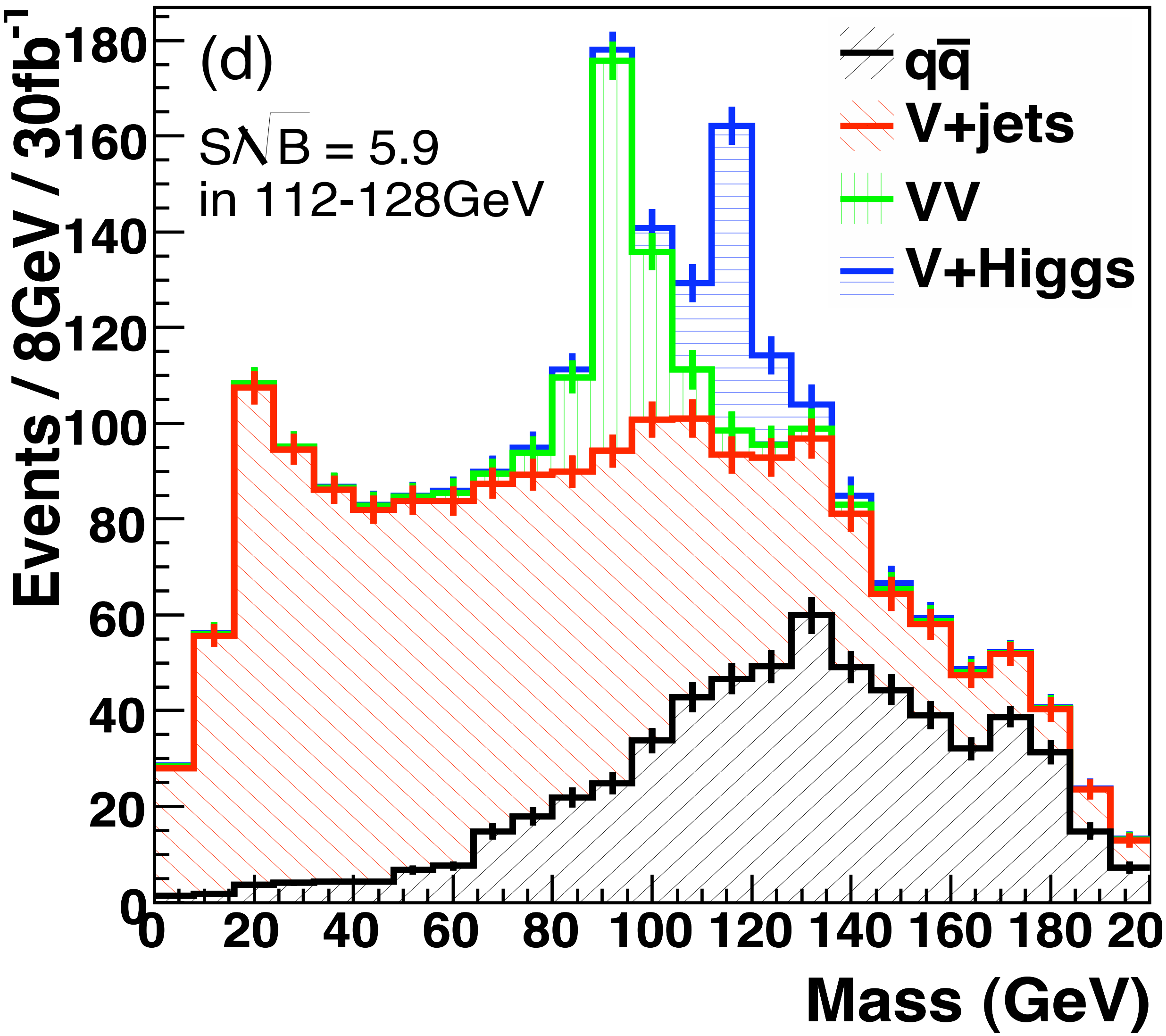
Analysis Overview

- Consider three cases
  - HZ, Z ➔ ee, $\mu\mu$
  - HZ, Z ➔ $\nu\nu$
  - HW, W➔ e/μ + ν
- Three non-overlapping selections
  - l + missing E_T + jet **("Leptonic W case")**
  - $l^+ l^-$ + jet **("Leptonic Z case")**
  - Missing E_T + jet **("Z ➔ neutrinos case")**
- Common cuts
  - p_T Higgs candidate > 200 GeV, p_T VB candidate > 200 GeV
  - $|\eta|$ < 2.5 (Higgs candidate and leptons)
  - p_T > 30 GeV, $|\eta|$ < 2.5 (leptons)
  - No extra b jet (p_T >30 GeV, $|\eta|$ < 2.5) or lepton passing these cuts.

Individual Channels



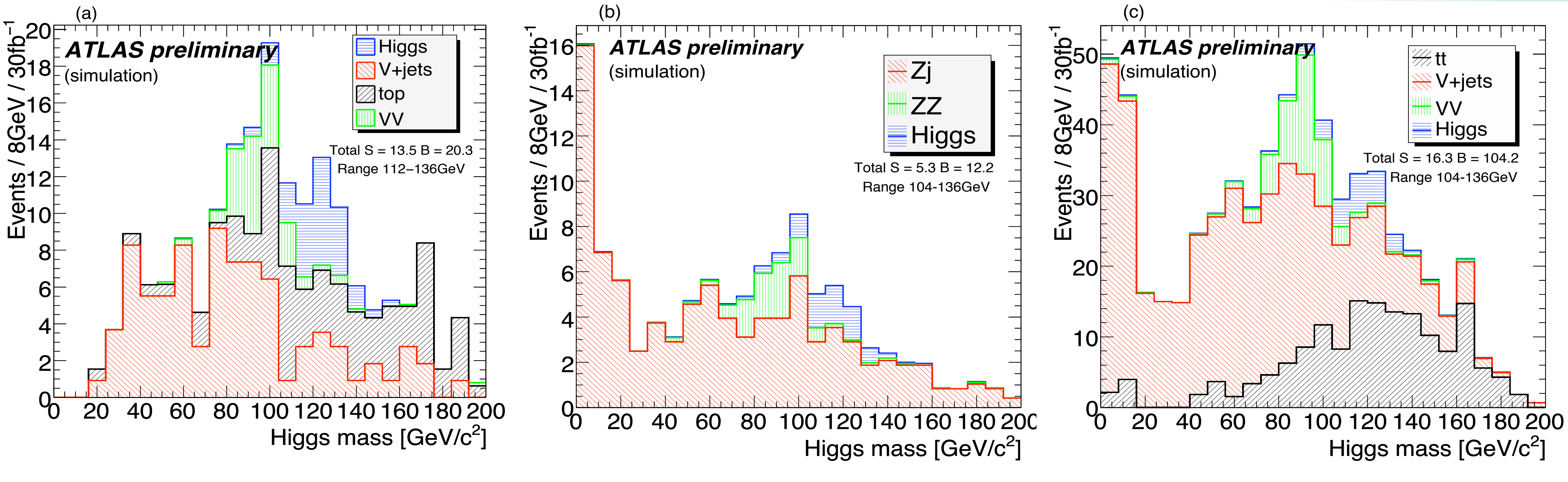
Combined particle-level result



- Note excellent Z peak for calibration
- 5.9 σ; potentially very competitive
- bb branching information critical for extracting Higgs properties
  - *"Measuring the Higgs sector" Lafaye, Plehn, Rauch, D.Zerwas, Duhrssen, arXiv: 0904.3866 [hep-ph]*
- Studies with full simulation supported this.

Fully simulated detector

- Included trigger, real ATLAS b-tagging algorithm, detailed tracking & calorimeter
- Also include Wt background omitted from initial study.
- Also included study of Wbb ME vs Wg->Wbb
- Slight degradation w.r.t particle level, but still very promising



Higgs and top together

- Combine techniques for top and Higgs tagging to improve sensitivity to Higgs in ttH channel
  - *Plehn, Salam, Spannowsky arXiv: 0910.5472 [hep-ph]*
- Also use Higgs techniques in new physics events
  - *Kribs, Martin, Roy, Spannowsky arXiv: 0912.4731 [hep-ph]*

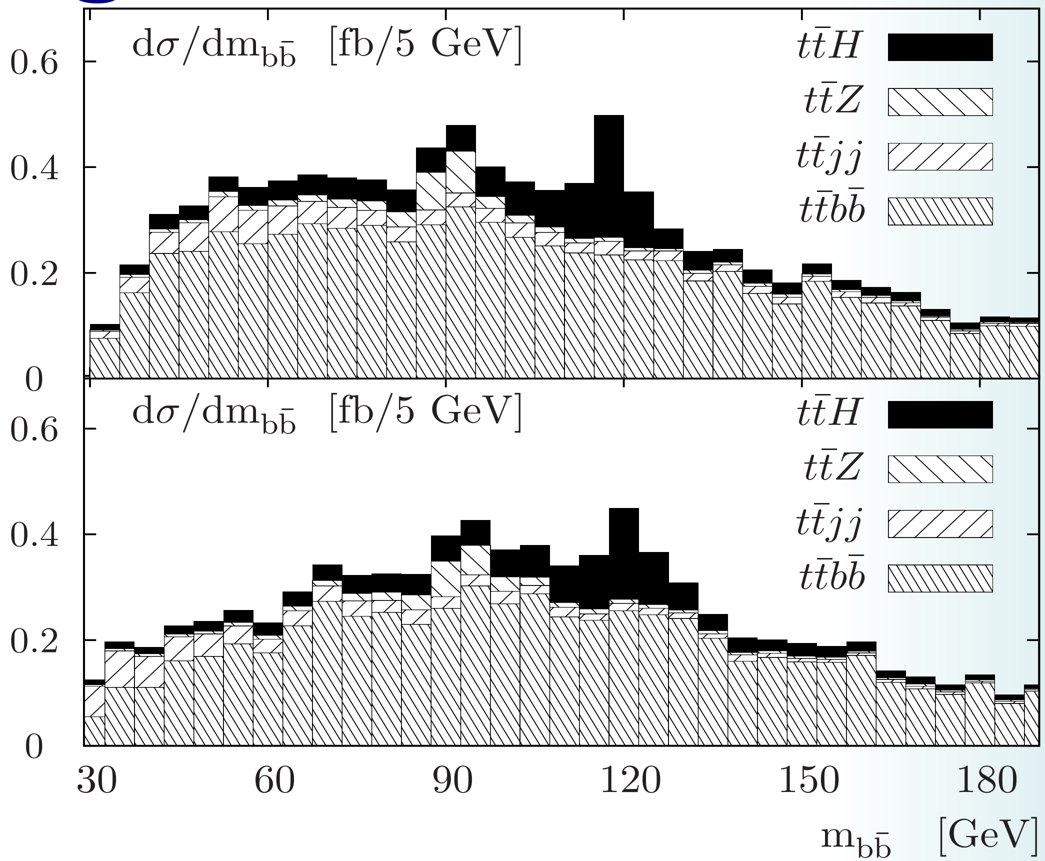
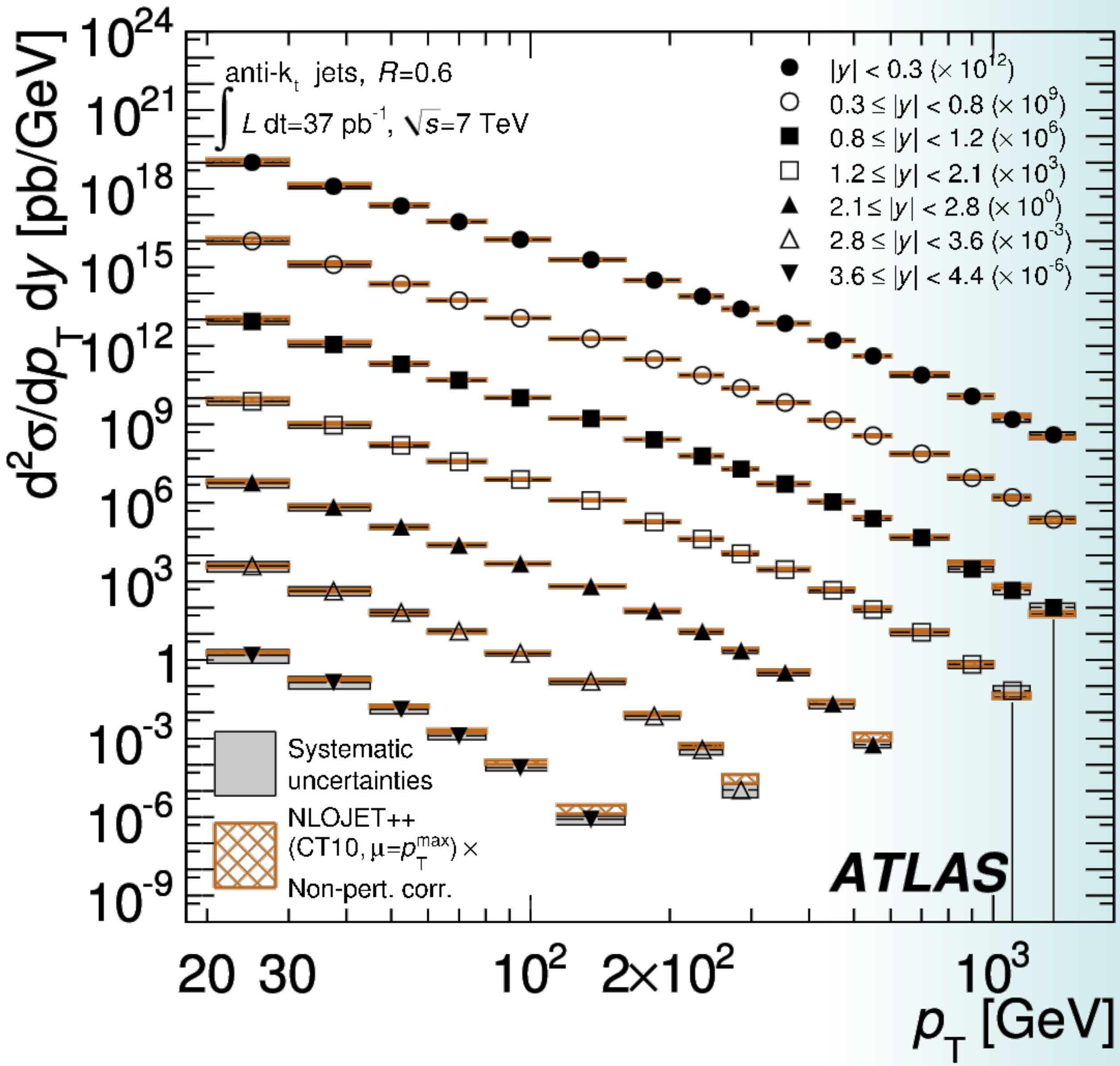


FIG. 3: Reconstructed bottom-pair mass $m_{bb}^{\rm rec}$ for signal ($m_H = 120$ GeV) and backgrounds without (upper) and including (lower) underlying event. The distributions shown include three b tags.

Jets at the highest scales

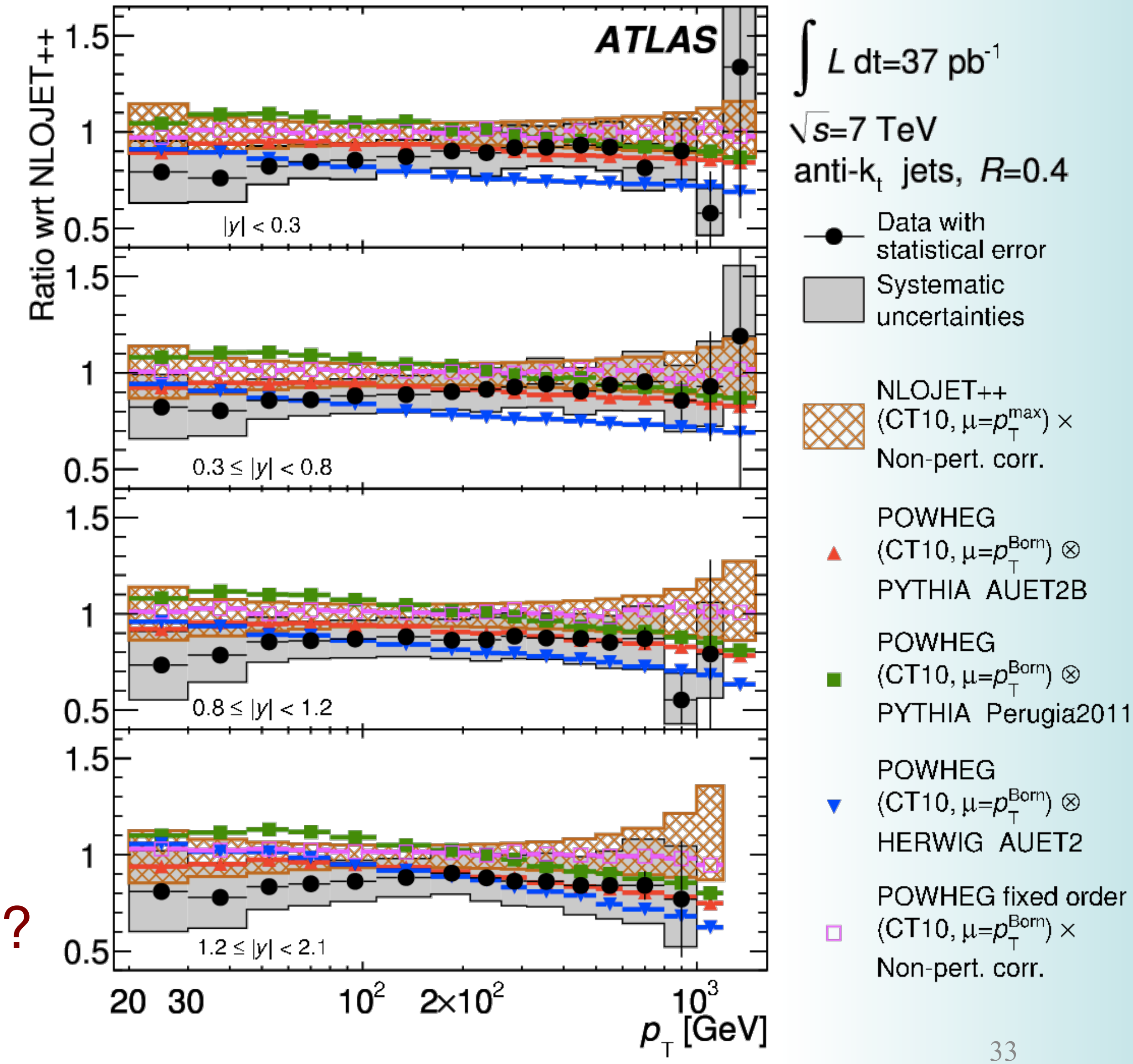
- Highest transverse momentum jets; at the TeV scale
  - *arXiv:1009.5908 (EPJC),arXiv: 1112.6297 (PRD)*
  - *arXiv:1106.0208 (PRL)*



Jets at the highest scales

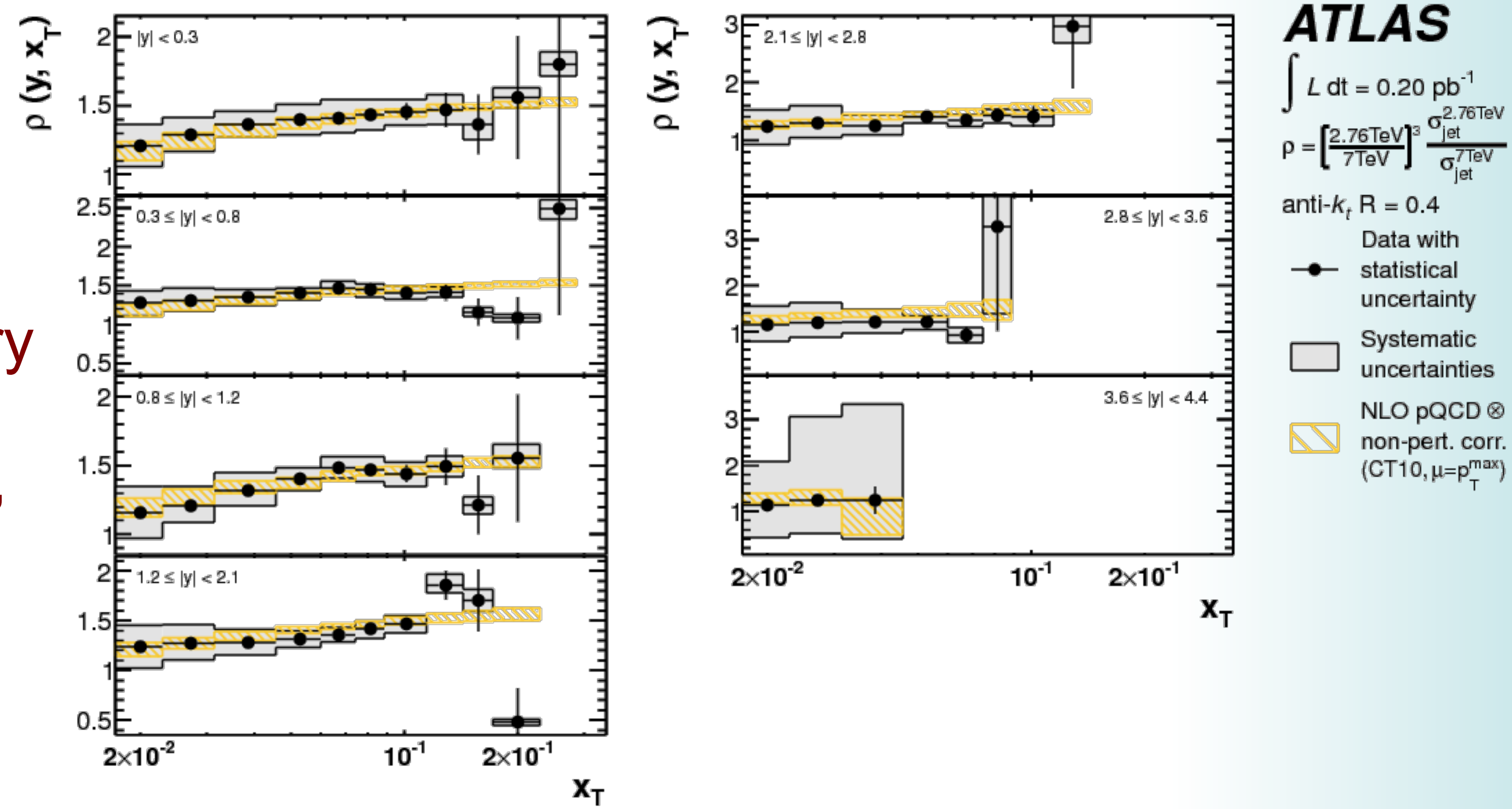
- Highest transverse momentum jets; at the TeV scale
  - *arXiv:1009.5908 (EPJC),arXiv: 1112.6297 (PRD)*
  - *arXiv:1106.0208 (PRL)*
- General agreement with NLO QCD calculations (after soft corrections)

  Significant spread in “NLO” predictions. ME/PS matching? MC tune (UE)? PDFs?



Jets as a probe of the proton

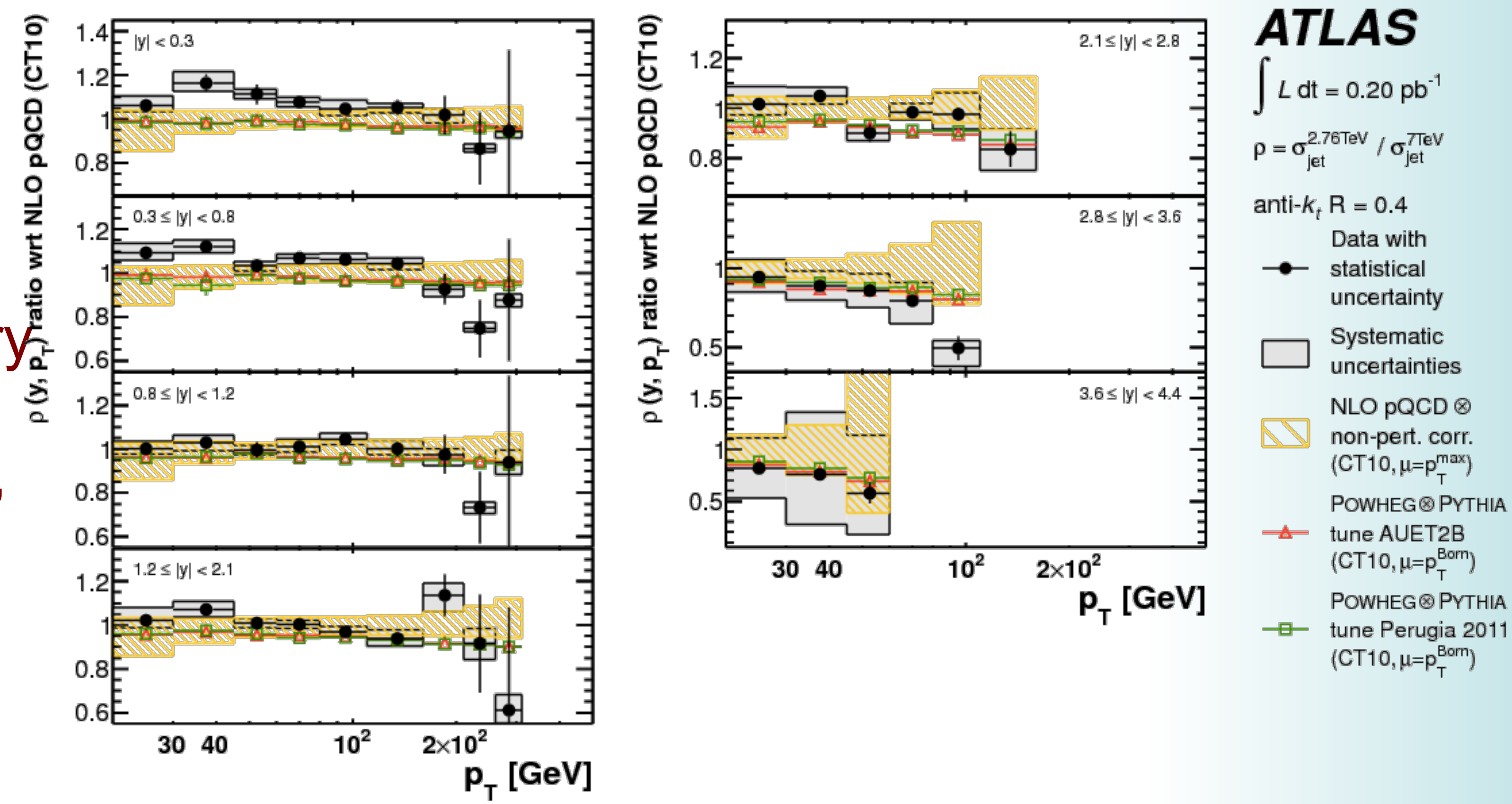
- Use 2.76 TeV CM data to measure cross sections.
- Ratios;
  - in x_T, many theory uncertainties ~cancel (same x, different Q^2)



arXiv:1304.4739

Jets as a probe of the proton

- Use 2.76 TeV CM data to measure cross sections.
- Ratios;
  - in x_T, many theory uncertainties ~cancel (same x, different Q^2)
  - In p_T, jet energy scale ~cancels (dominant experimental uncertainty)



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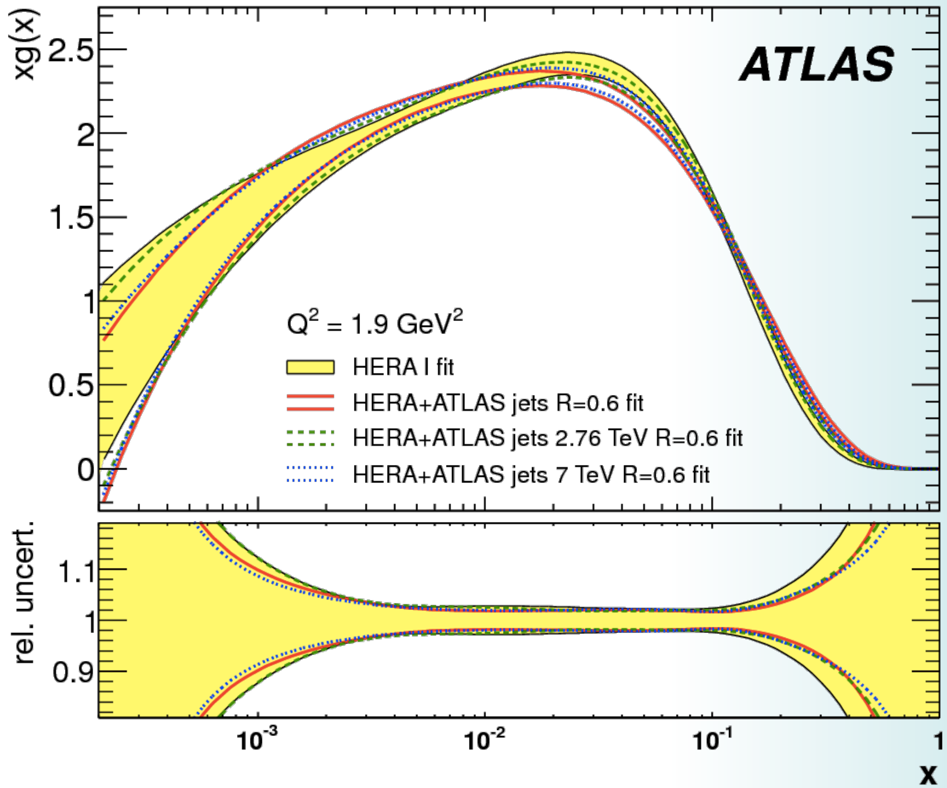
Jets as a probe of the proton

- Illustrative fit to HERA and ATLAS data
- Valence quarks heavily constrained by HERA
- High x gluon and sea quarks modified by addition of ATLAS data



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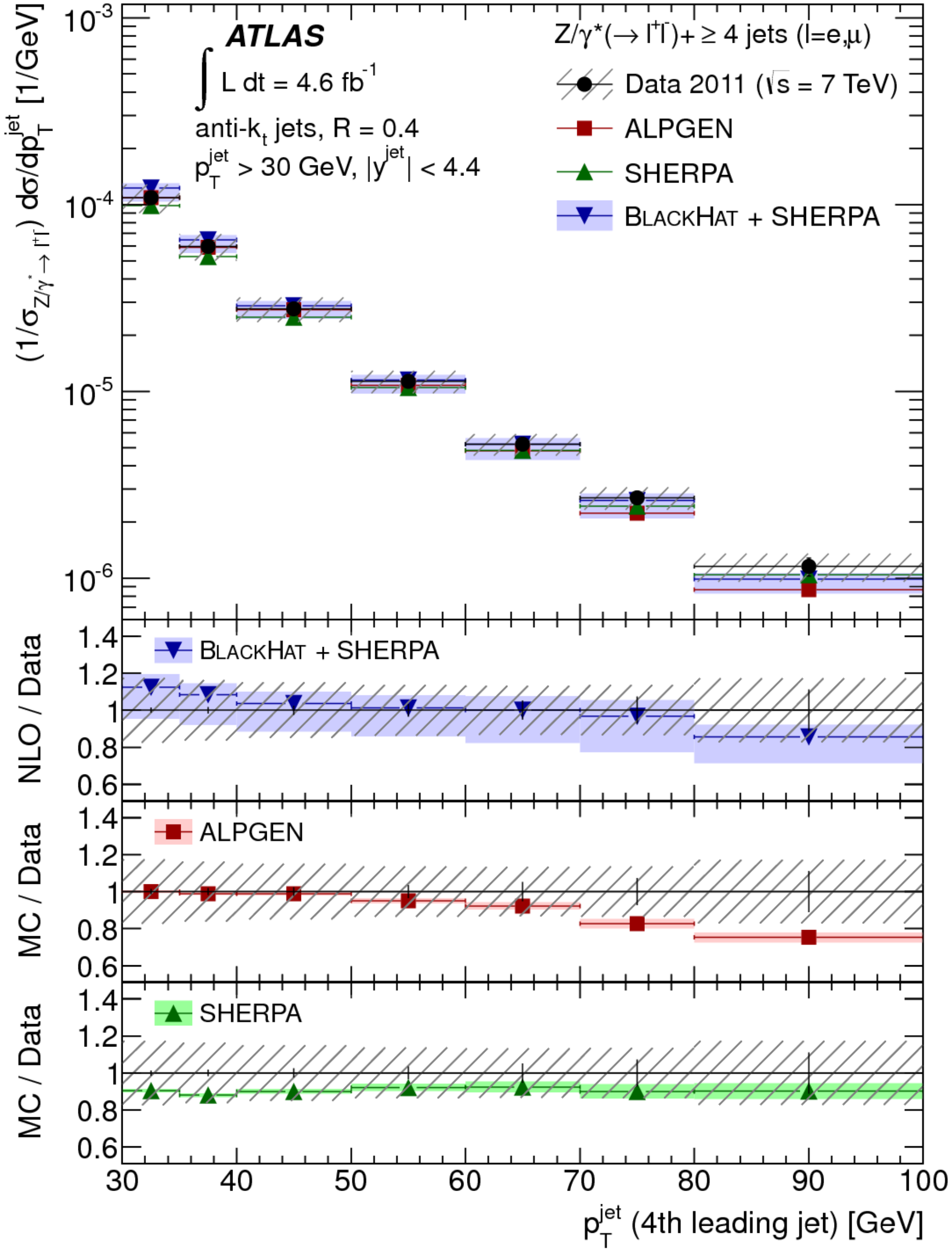
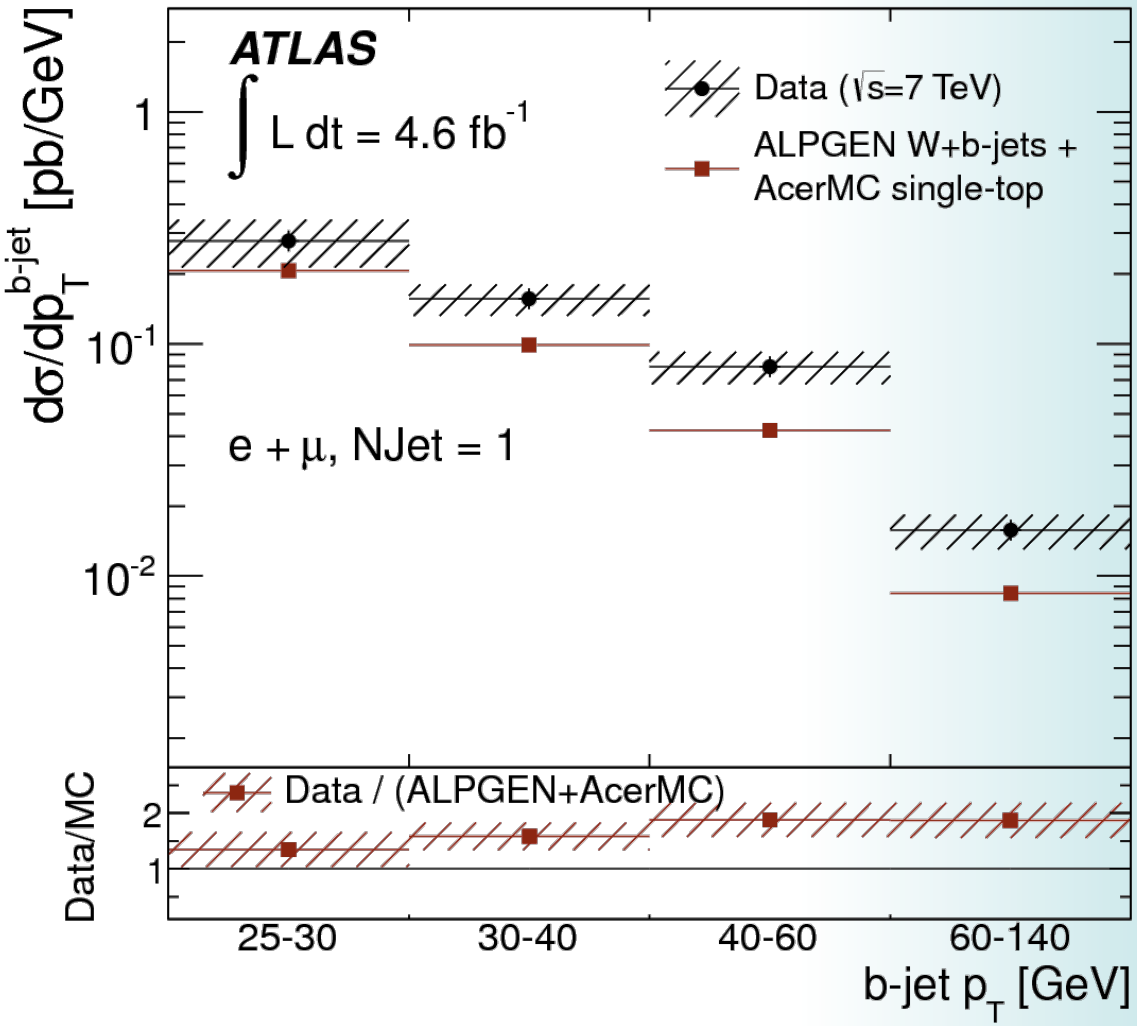
Vector bosons and (b) jets





arXiv:1304.7098
arxiv:1302:2929

Jet properties

- Final stage of jet structure is "soft" non-perturbative QCD.
  - Formation of hadrons from gluons, 100 MeV energy scales (Λ_{QCD})
- Vast phase space between quark-gluon scatter (100's GeV, few TeV) and Λ_{QCD}
- Most of jet substructure can be analysed perturbatively
- EWSB scale (~100 GeV) lies in this region
  - Jets may contain objects with EW-scale mass (W,Z,H,t,?)

Two goals in Jet Substructure

- Improve the single jet mass resolution
  - First unclustering stages in C/A, throw away softer or more distant partner
    - *Kaplan, Rehermann, Schwartz, Tweedie, PRL101:142001,2008.*
    - *JMB, Davison, Rubin, Salam, PRL 100, 242001 (2008)*
  - "Filtering": Rerun algorithm with tighter distance resolutions
    - *JMB, Davison, Rubin, Salam*
  - Variable R parameter
    - *Krohn Thaler, wang, JHEP 0906:059,2009.*
  - "Pruning": Remove soft splittings in clustering
    - *S. Ellis, Vermilion, Walsh, arXiv:0903.5081 [hep-ph]*
- Distinguish between QCD-generated high mass jets and those due to heavy object decays
  - None-strongly order k_T scale
    - *JMB, Cox, Forshaw, PRD 65; 096014 (2002).*
  - Symmetric splitting
    - *Kaplan et al, JMB et al*
  - Anomalously large mass drop
    - *JMB et al*
  - Analytic jet shapes (planar flow etc)
    - *Almieda et al PRD 79:074017,(2009).*

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MANY MORE SINCE

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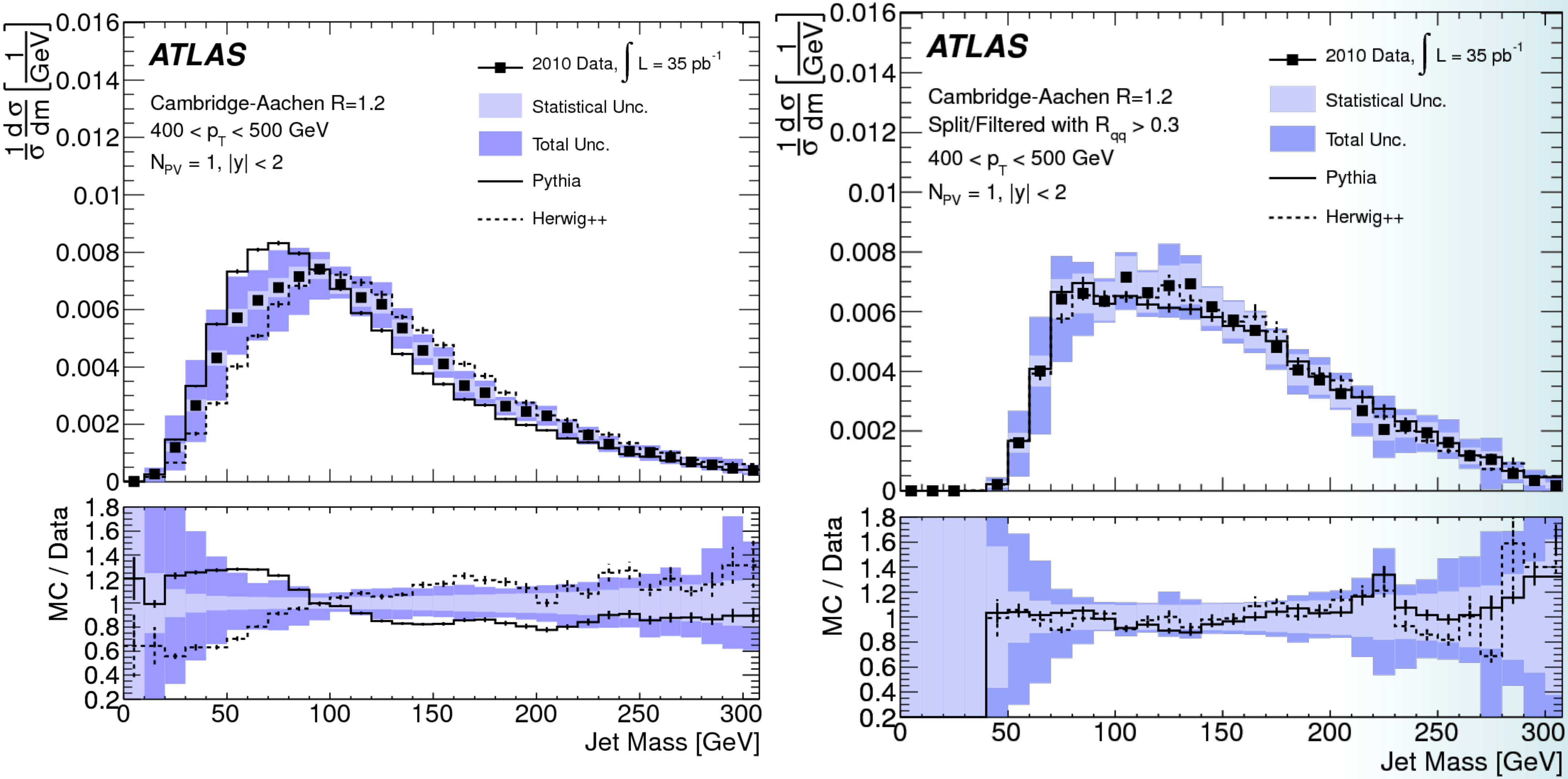
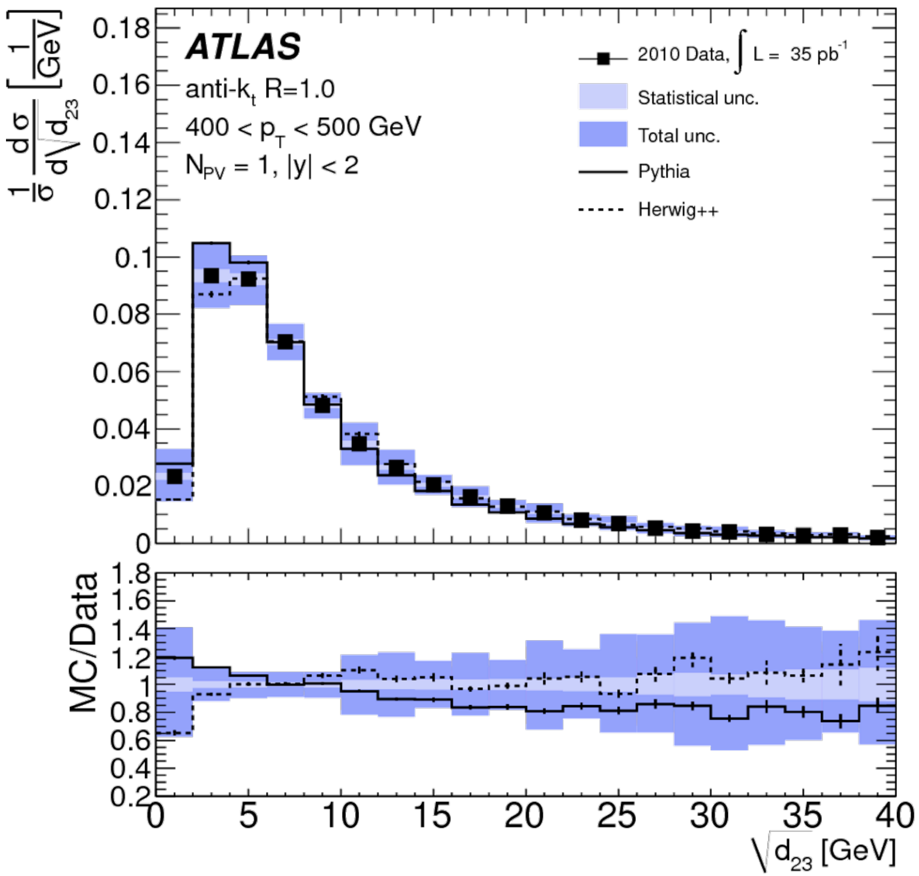
Jet "grooming" and subjets

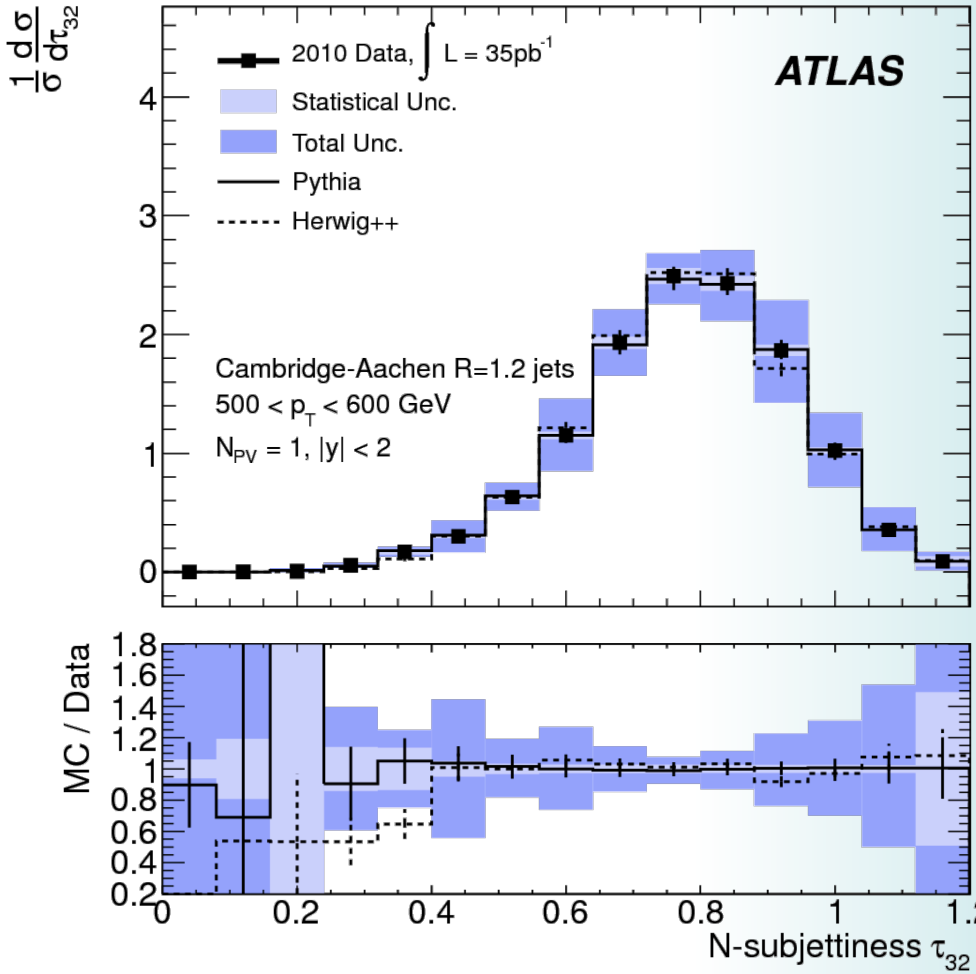


arXiv:1203.4606

Jet grooming and subjets

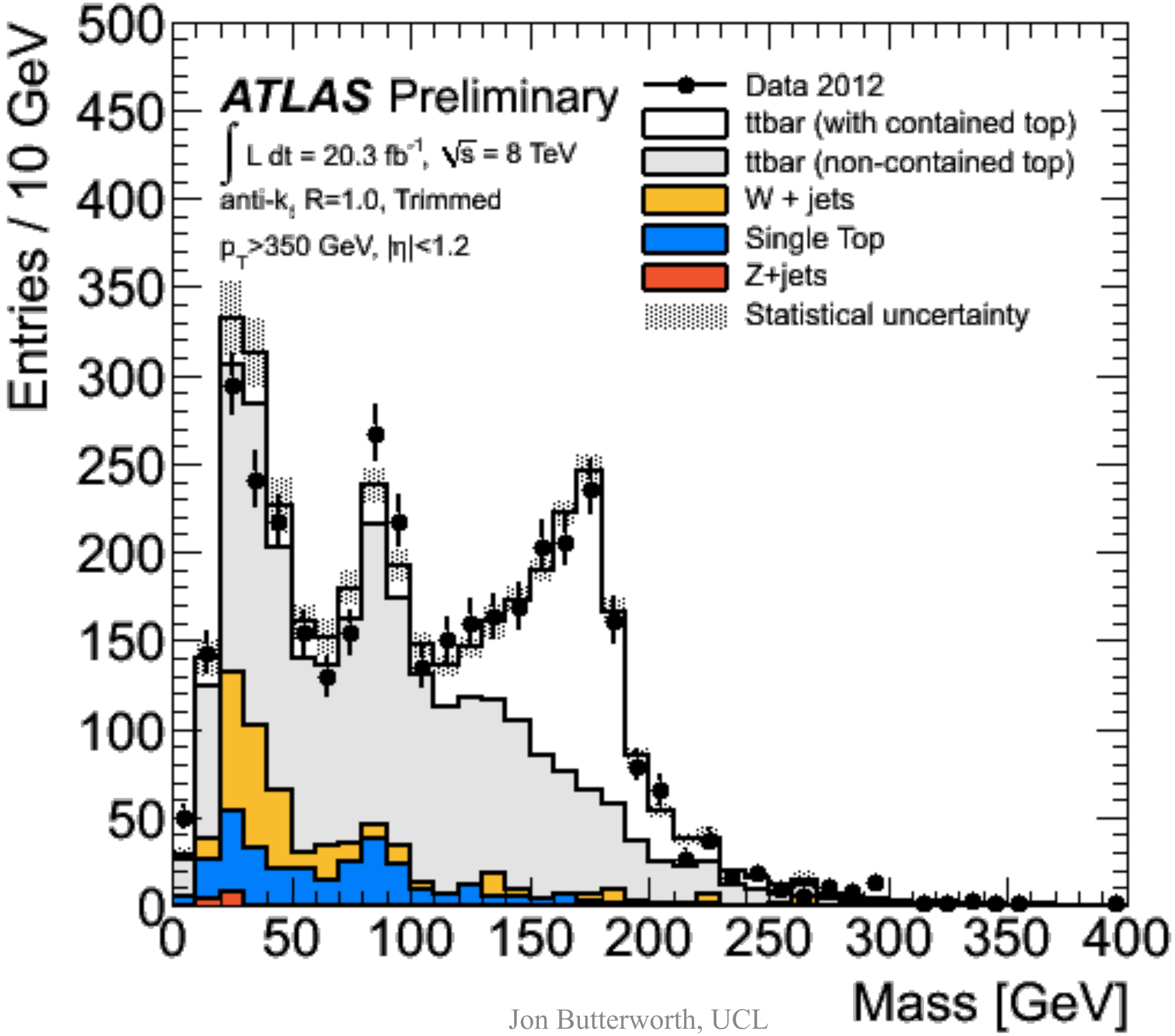
- k_T scale, N-subjettiness





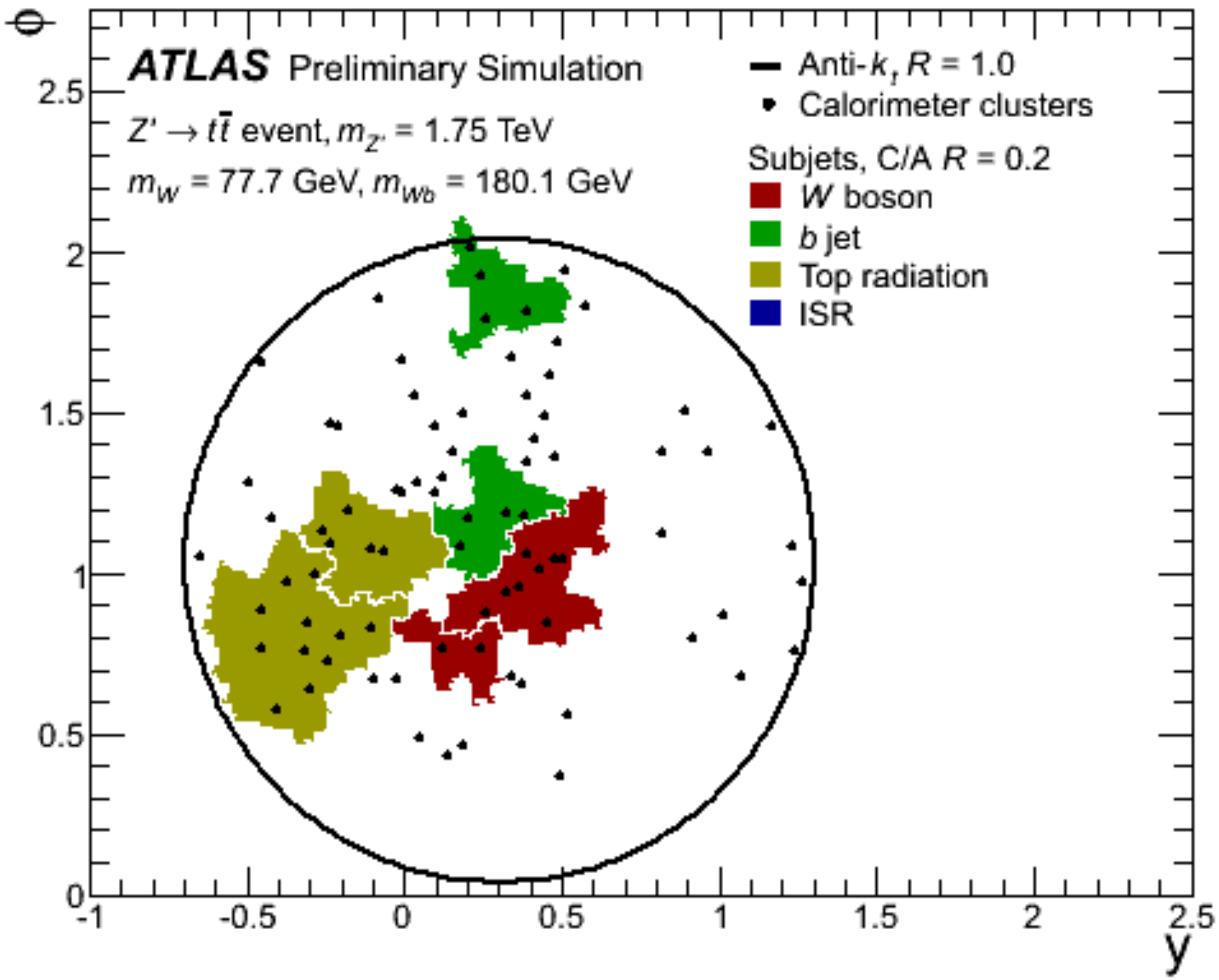
arXiv:1203.4606

Substructure in searches (boosted top, boosted W)



Shower deconstruction

(Soper & Spannowsky) and **ATLAS-CONF-2014-003**



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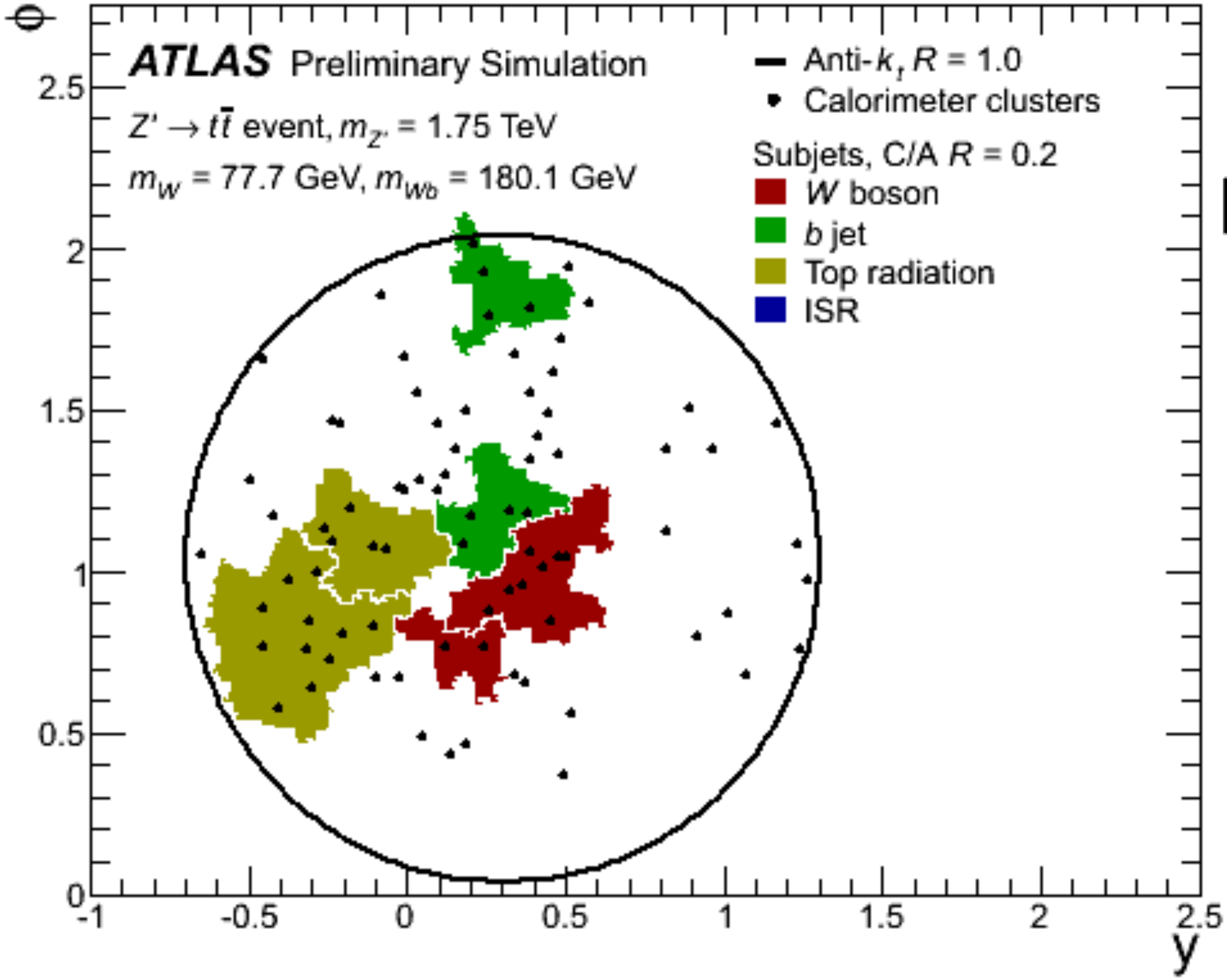

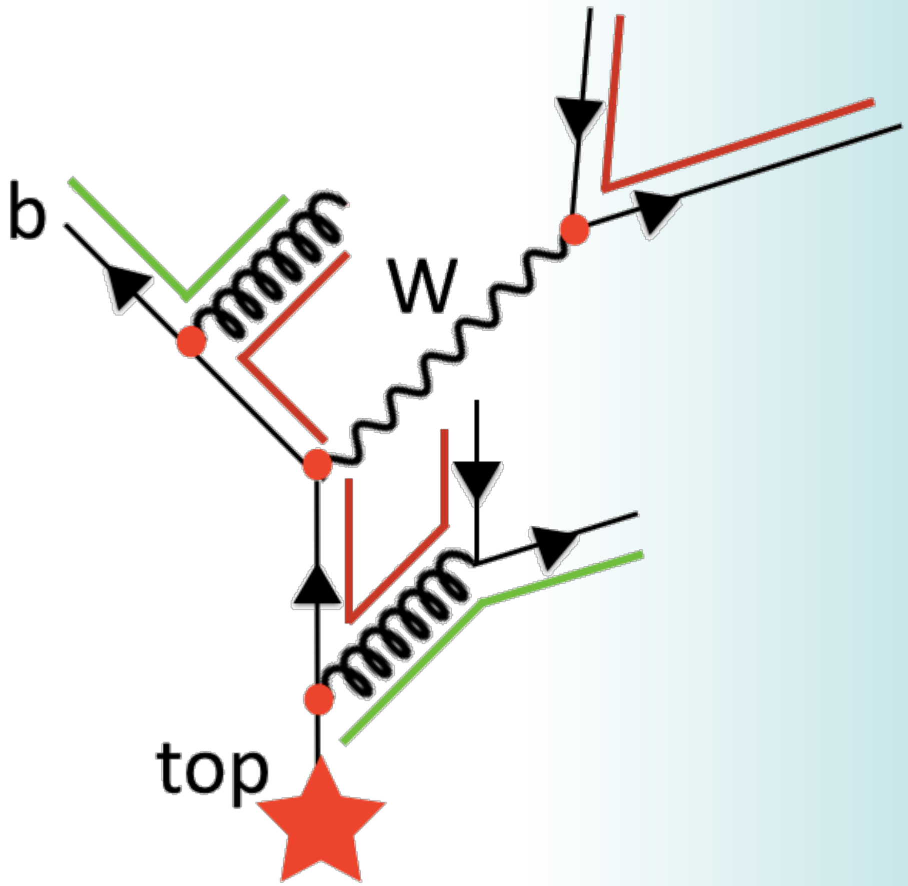

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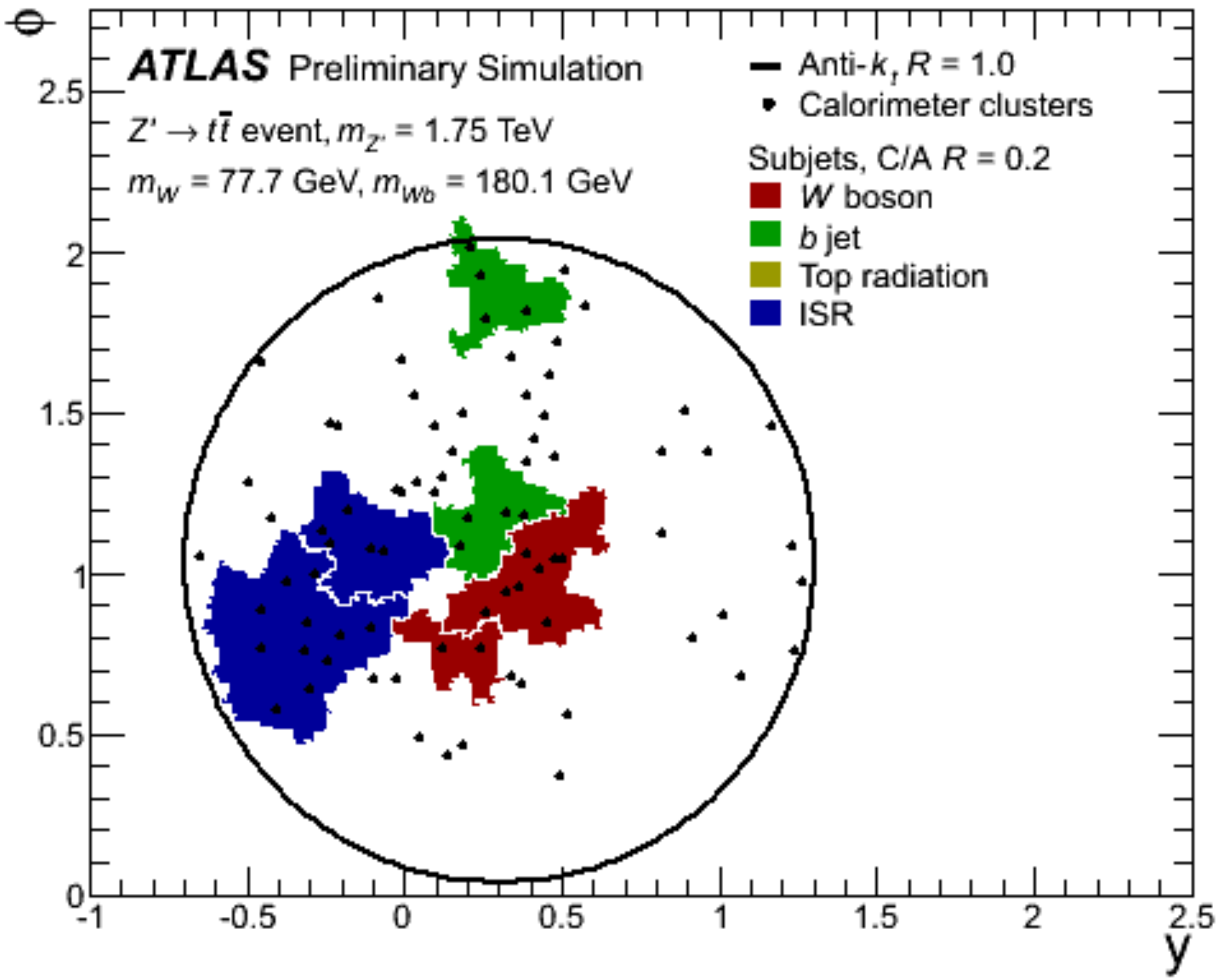

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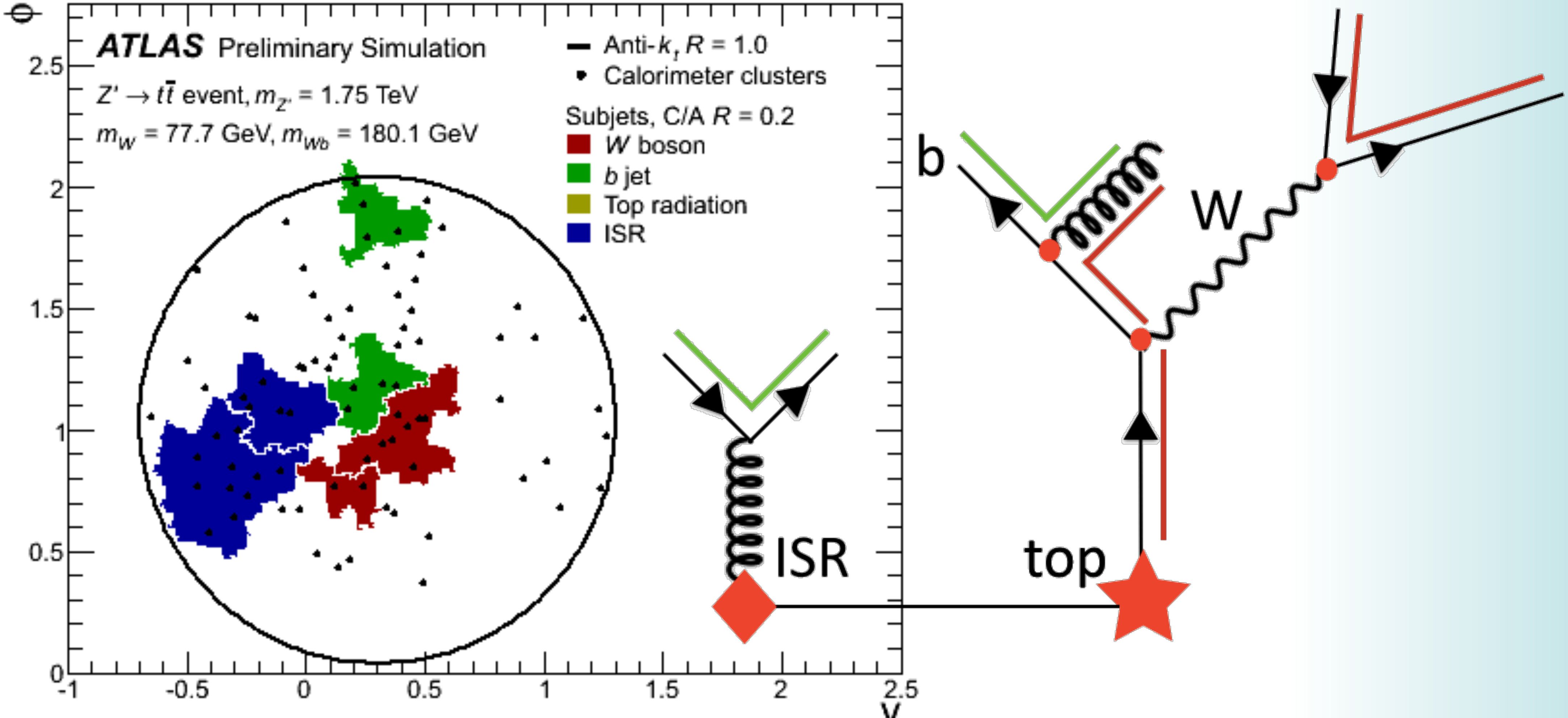

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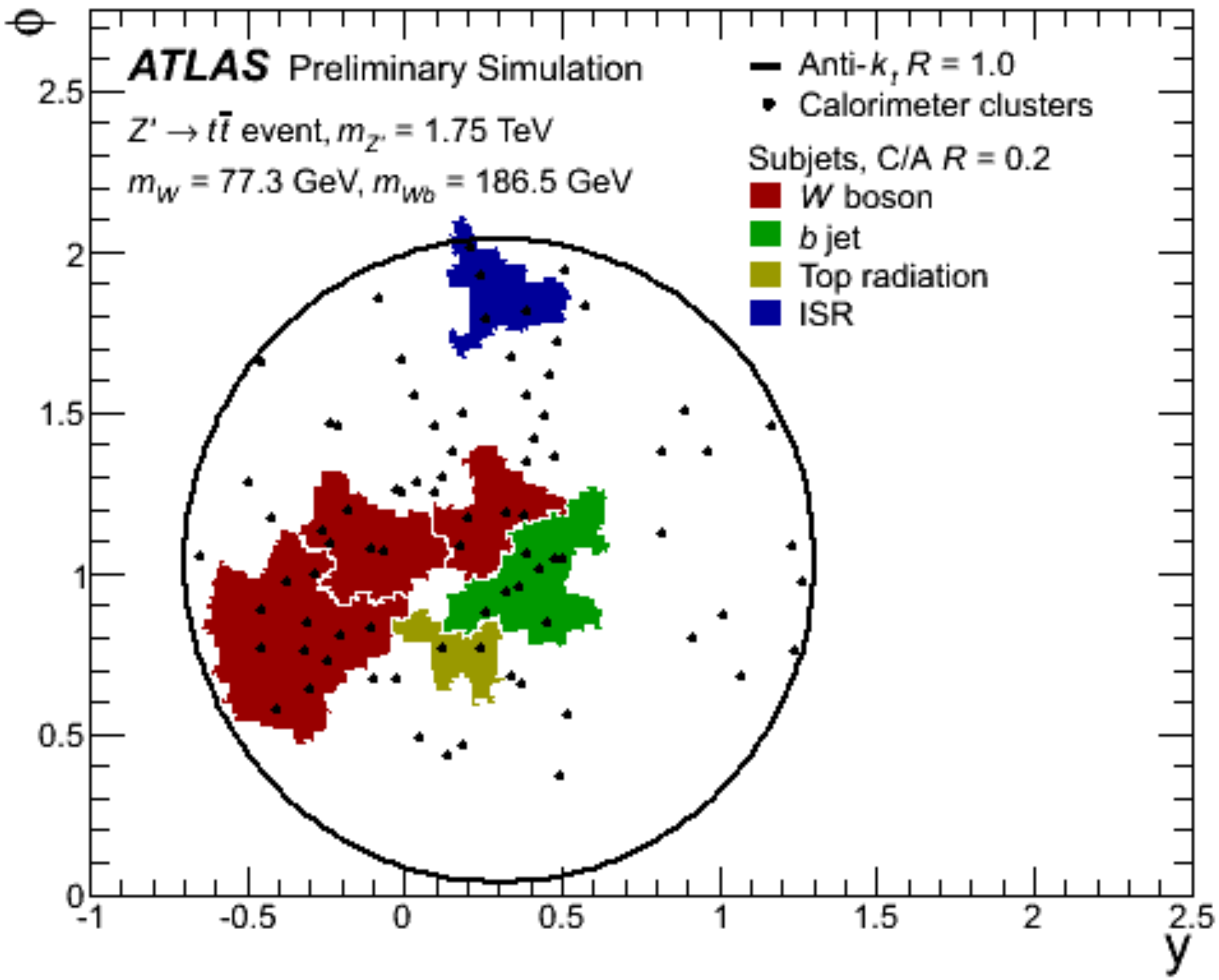

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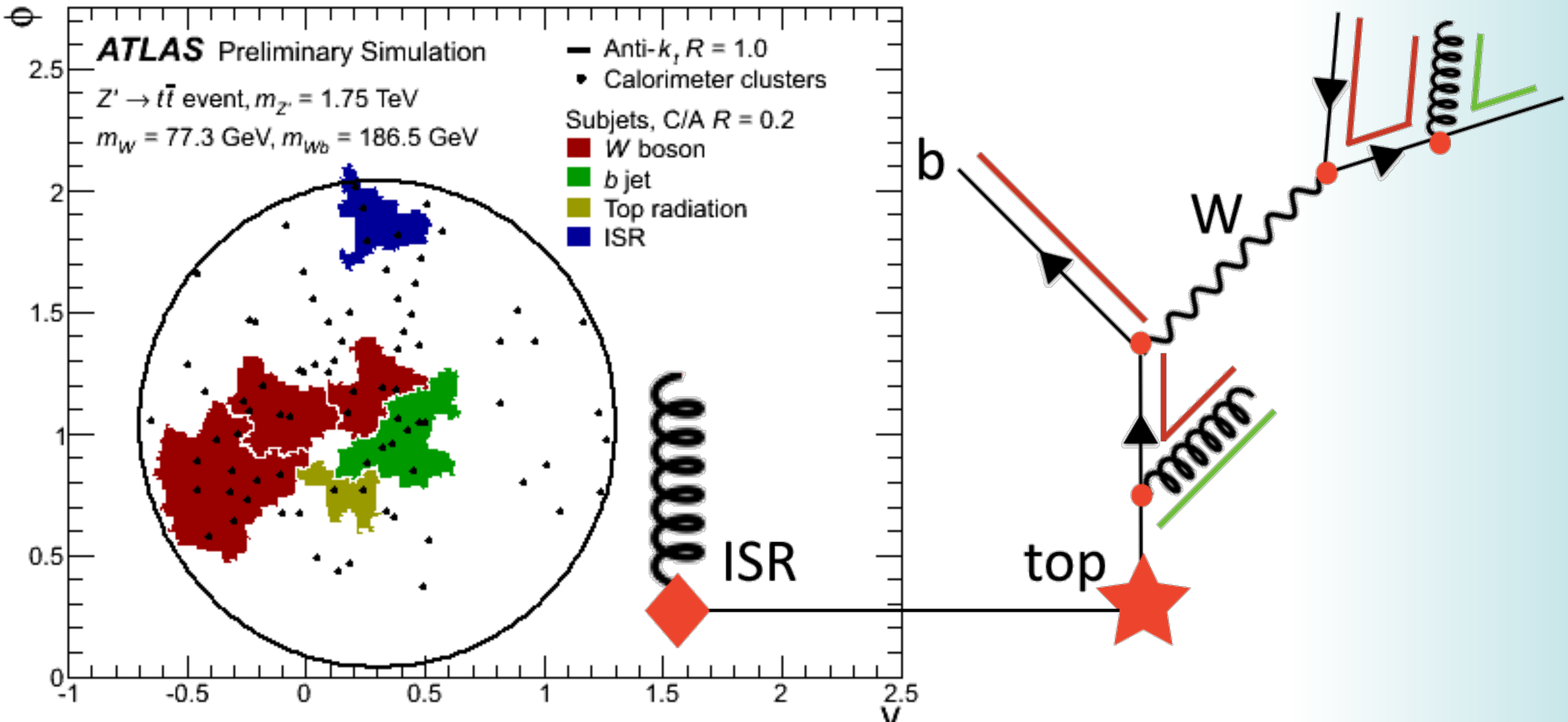

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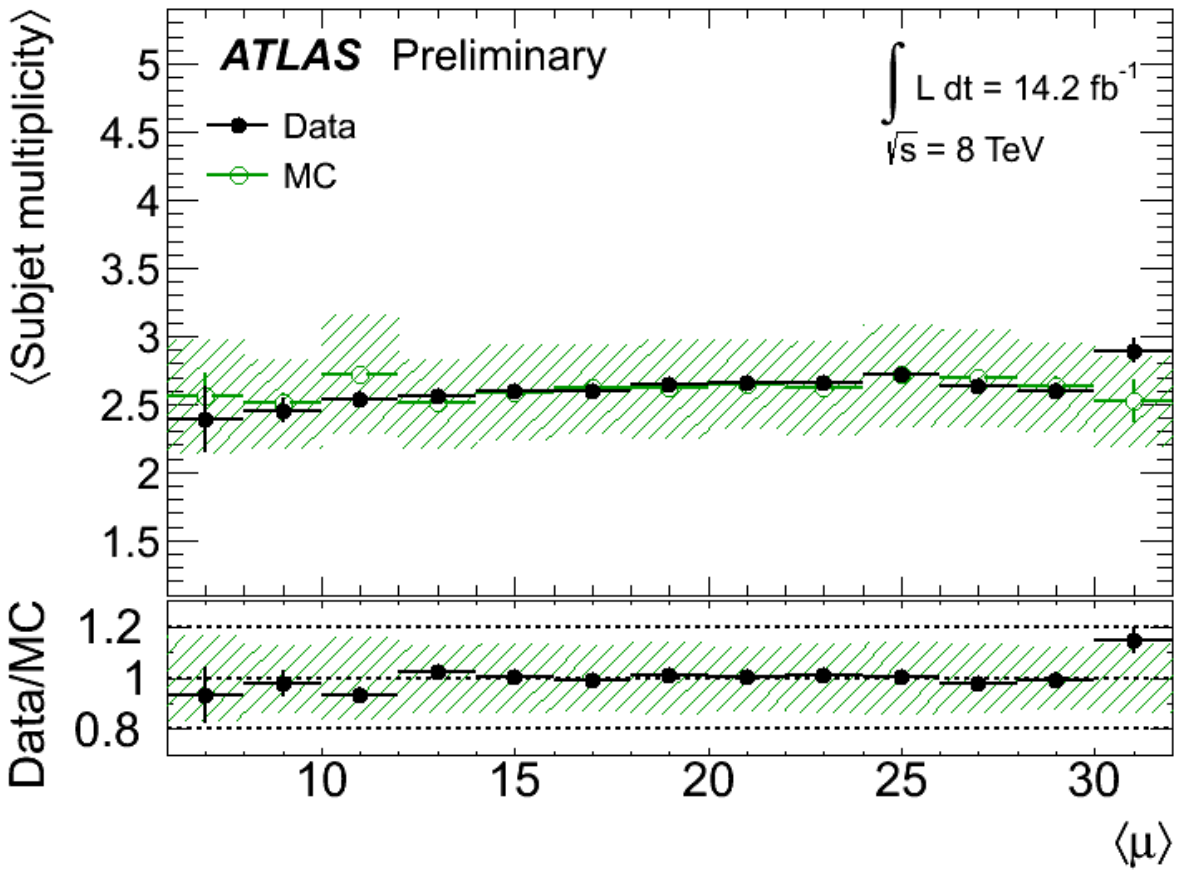

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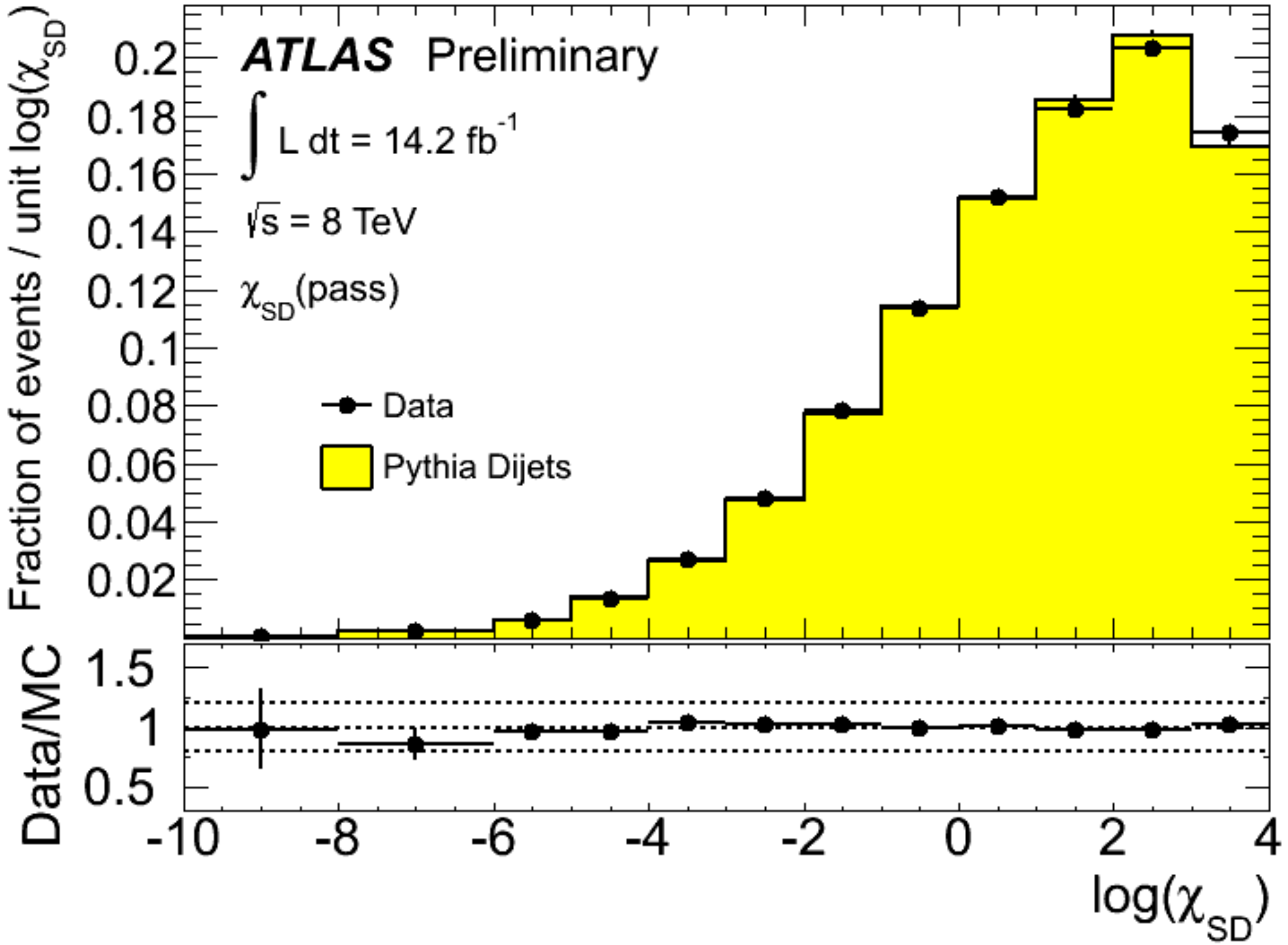

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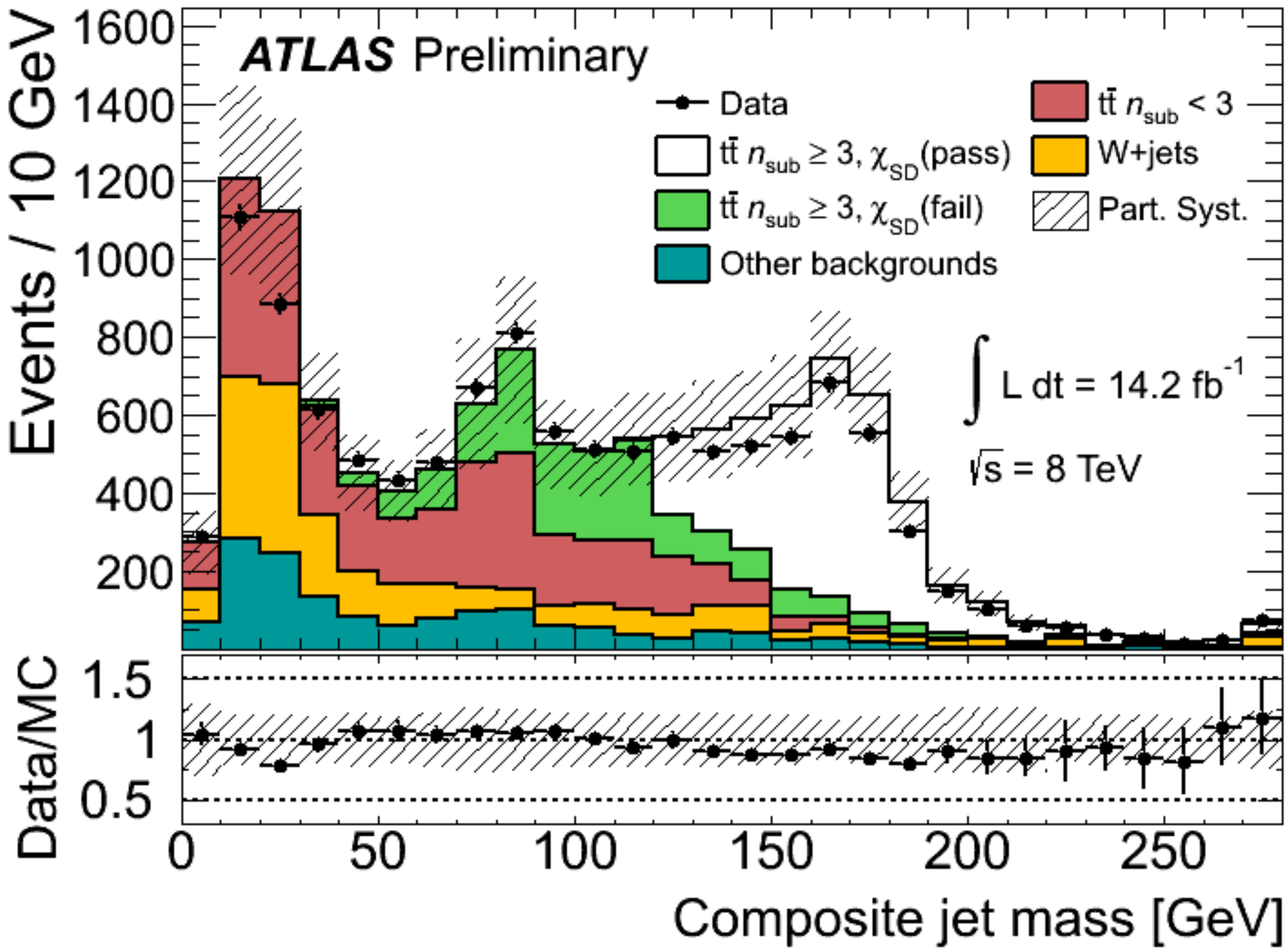
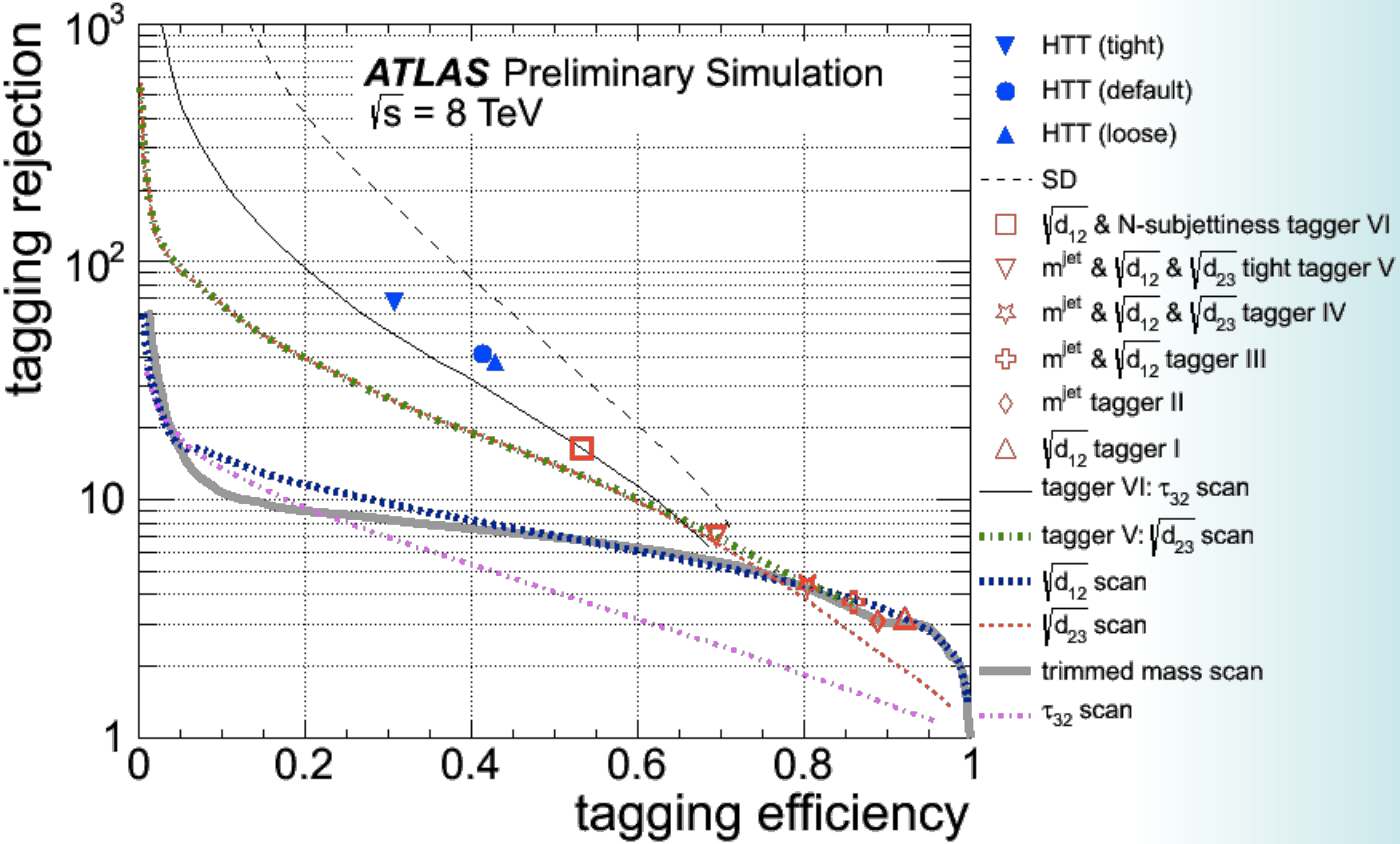


Substructure in searches



… also

- Jet shapes, Q-jets, jet charge, jet pull, jet superstructure…
- Moving on from the “two goals” (tagging & grooming) to finding still more information; identifying jet properties in context, learning more about the short-distance physics.

Subjets and measuring boosted objects

- Gone from wacky new idea to obviously essential item in the toolkit (~5 years)
- Studies with data show:
  - modelling is adequate but can be improved in some cases
  - Grooming is robust against pile up and important for controlling it in all jet measurements
- Not seen full potential yet in Higgs searches (cf 14 TeV)

Subjets and measuring boosted objects

- Already widely used in searches (mainly boosted tops, but results on H, W/Z coming)
- Calibration work on of novel observables is intense & interesting
- Theoretical work on developing (analytic?) understanding
  - Active ATLAS subgroup, open workshop @CERN 25th March (Lily Asquith, Emily Thomson,   )
  - Boost meetings 2009 Stanford 2010 Oxford 2011 Princeton 2012 Valencia 2013 Arizona **2014 UCL**

The beginning of physics above the Electroweak Symmetry Breaking scale