Jet Physics

Selected results from ATLAS and CMS

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Outline

- Introduction
- Inclusive and multi jet measurements
  - Impact of Jet data on PDF fits
  - Determination of strong coupling constant
- Heavy Flavor production
- Jet shapes, substructure and mass
- Summary

Part I: Introduction

Jets are abundantly produced at the LHC

Good probes for QCD dynamics

strong interactions to the shortest distance

perturbative calculation and modeling of non-perturbative effects

Proton structure

Very important for new physics searches

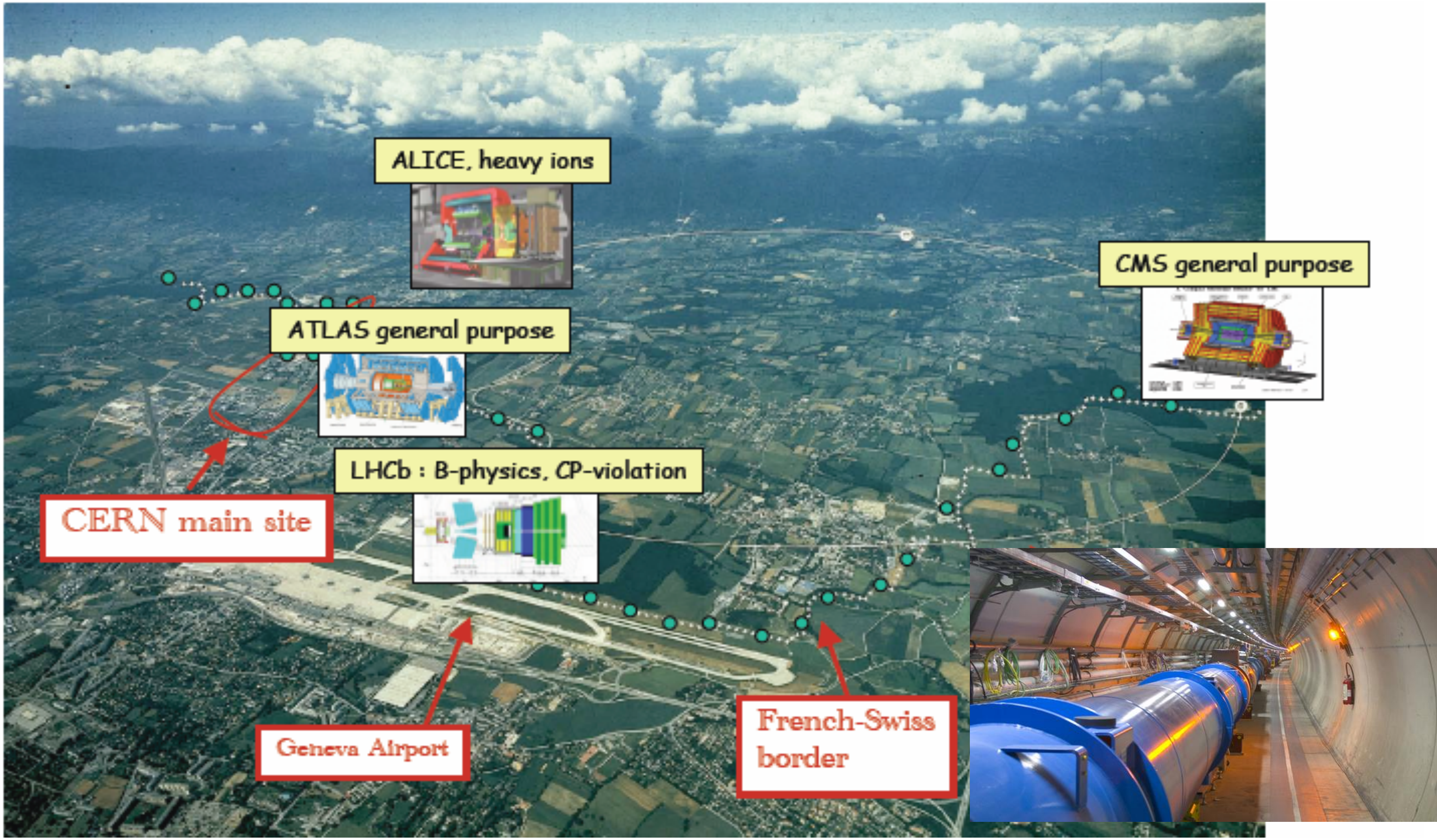
New Phenomena processes also affected by QCD effects

Jets may be important background and need accurate description

Effective techniques can be developed/tested with jet data

Challenge at LHC : pile up.

Experiments at LHC

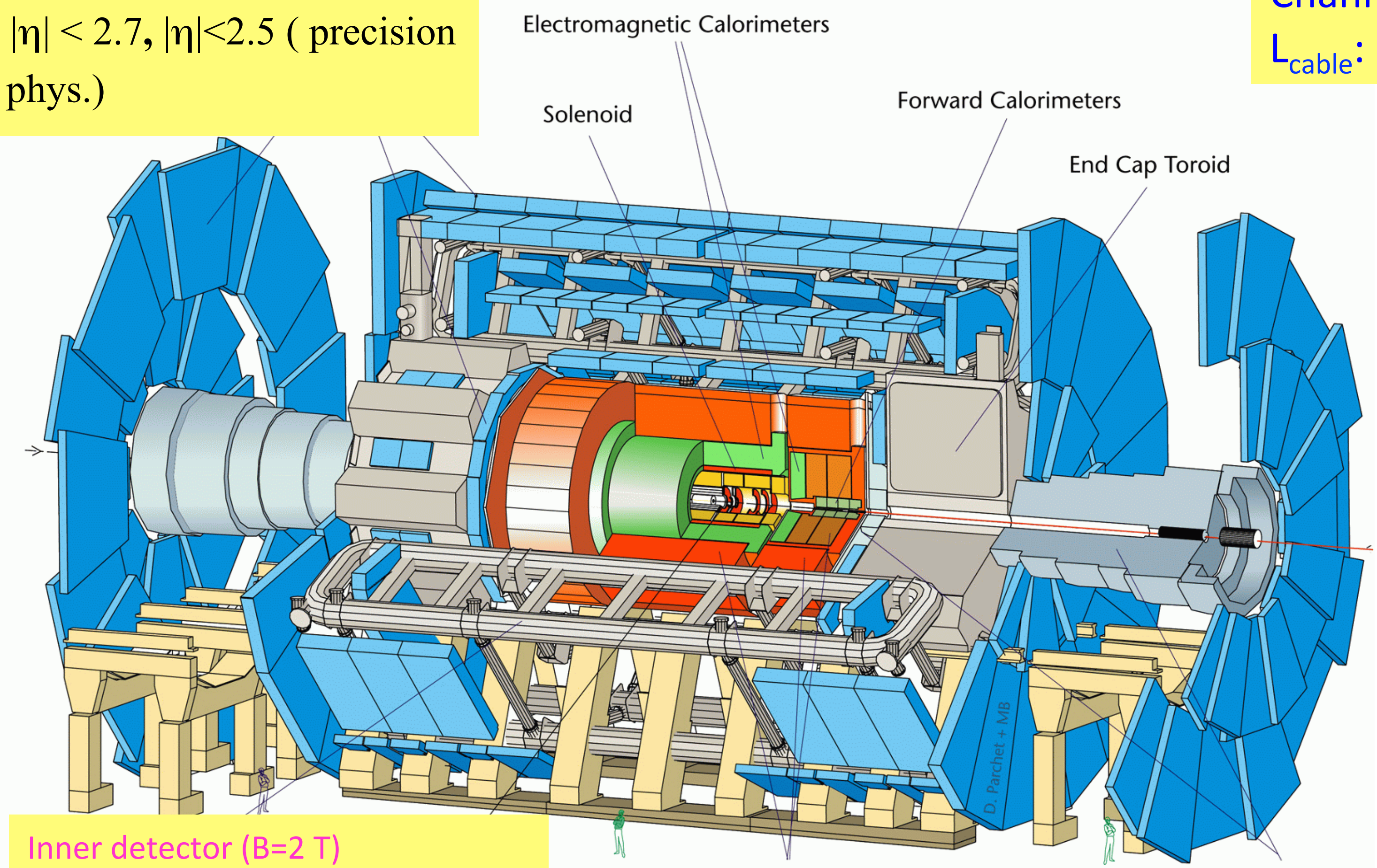


+LHCf, TOTEM

Muon spectrometer
- air-core toroids, MDT+RPC+TGC+CSC
- $\sigma/p_T \sim$ 2-7 %
- $|\eta| < 2.7$, $|\eta|<2.5$ (precision phys.)

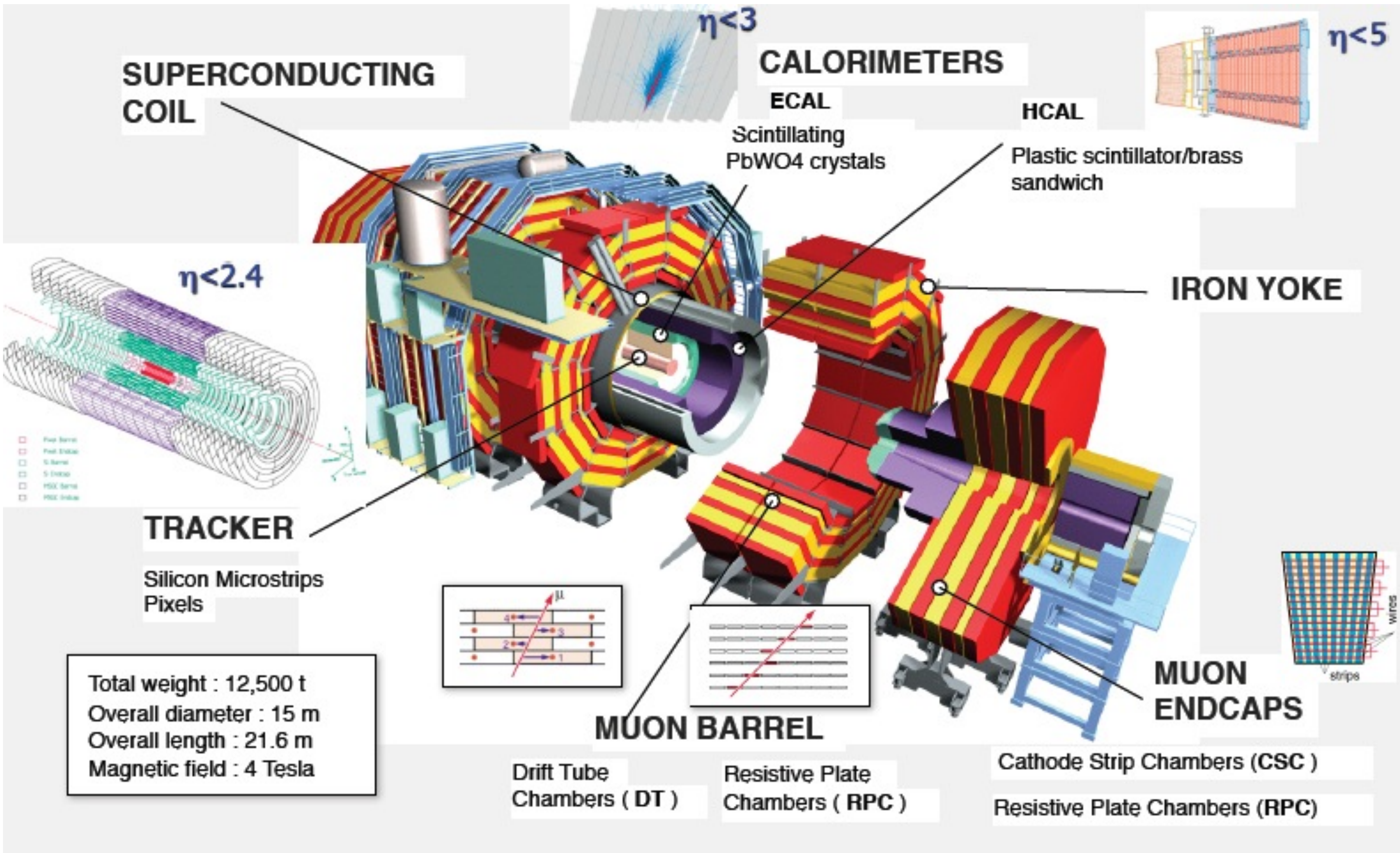
EM Calorimetry
- Pb-LAr
- $\sigma/E \sim 10\%/\sqrt{E(\mathrm{GeV})} \oplus 1\%$
- $|\eta|<3.2$, $|\eta| < 2.5$ (fine granularity)

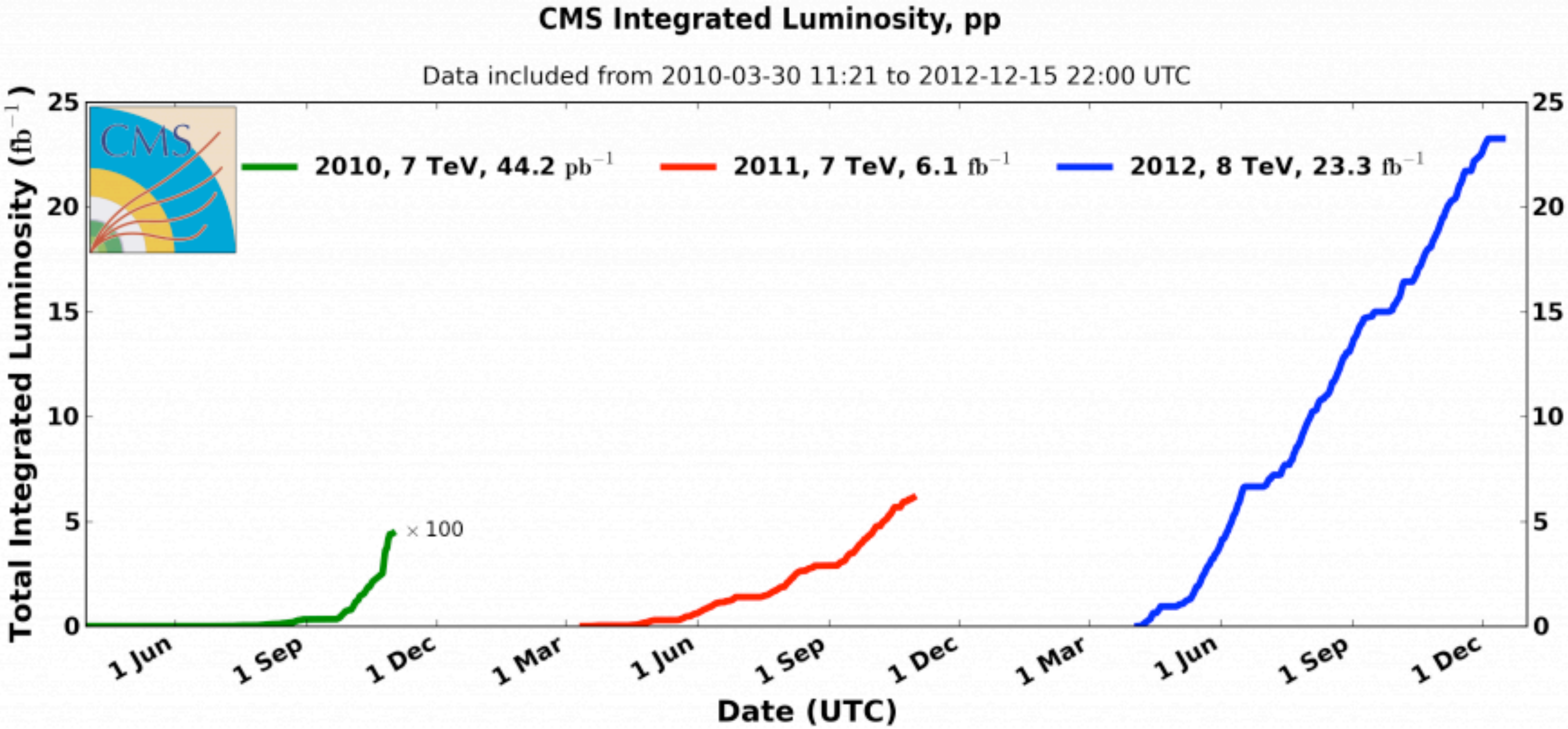
Length: ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
Channels: ~ 10^8
L_{cable}: ~ 3000 km

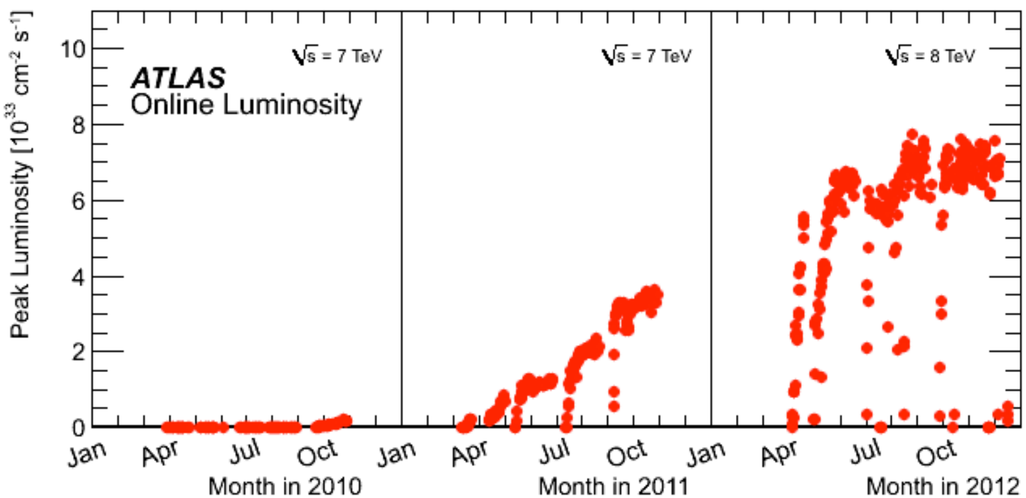


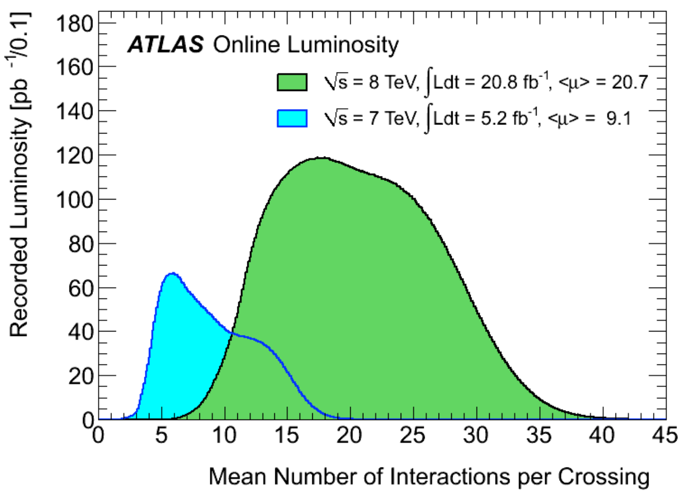
Inner detector (B=2 T)
- Si pixels and strips
- Transition Radiation Detector (e/π separation)
- $\sigma/p_T \sim 0.05\%\ p_T(\mathrm{GeV}) \oplus 0.1\%$;
- $|\eta| < 2.5$, B=2 T(central solenoid)

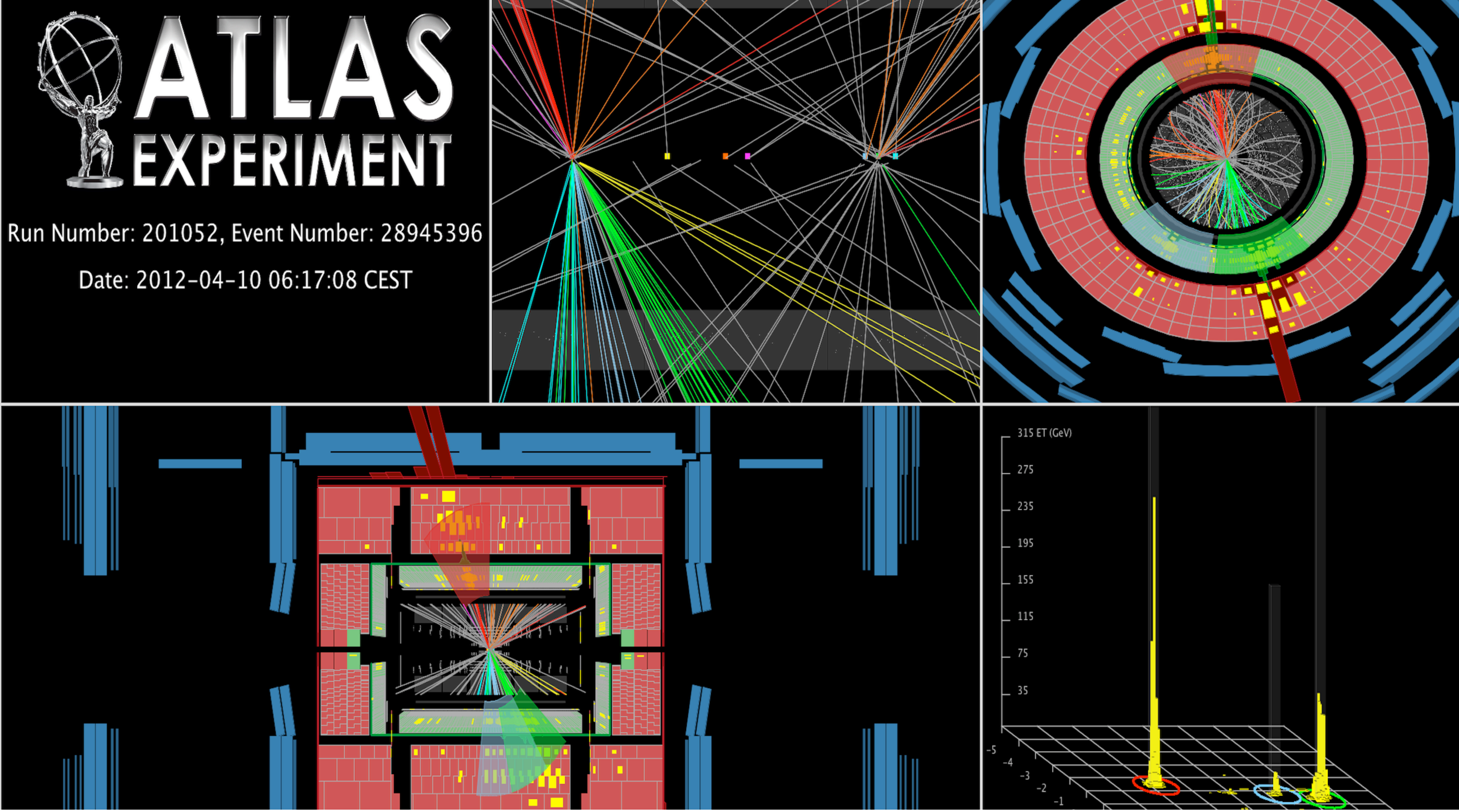
Hadron Calorimeter
- Fe/scintillator (central), Cu/W-LAr (fwd)
- $\sigma/E \sim 50\%/\sqrt{E(\mathrm{GeV})} \oplus 3\%$
- $|\eta|<3$


η<3
η<5
SUPERCONDUCTING COIL
CALORIMETERS
ECAL
Scintillating PbWO4 crystals
HCAL
Plastic scintillator/brass sandwich
η<2.4
IRON YOKE
TRACKER
Silicon Microstrips
Pixels
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla
MUON BARREL
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)
MUON ENDCAPS
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)
wires
strips


CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:21 to 2012-12-15 22:00 UTC
2010, 7 TeV, 44.2 pb⁻¹
2011, 7 TeV, 6.1 fb⁻¹
2012, 8 TeV, 23.3 fb⁻¹
× 100
Total Integrated Luminosity (fb⁻¹)
Date (UTC)
1 Jun
1 Sep
1 Dec
1 Mar
0
5
10
15
20
25


ATLAS
Online Luminosity
√s = 7 TeV
√s = 7 TeV
√s = 8 TeV
Peak Luminosity [10³³ cm⁻² s⁻¹]
Jan
Apr
Jul
Oct
Month in 2010
Month in 2011
Month in 2012
0
2
4
6
8
10

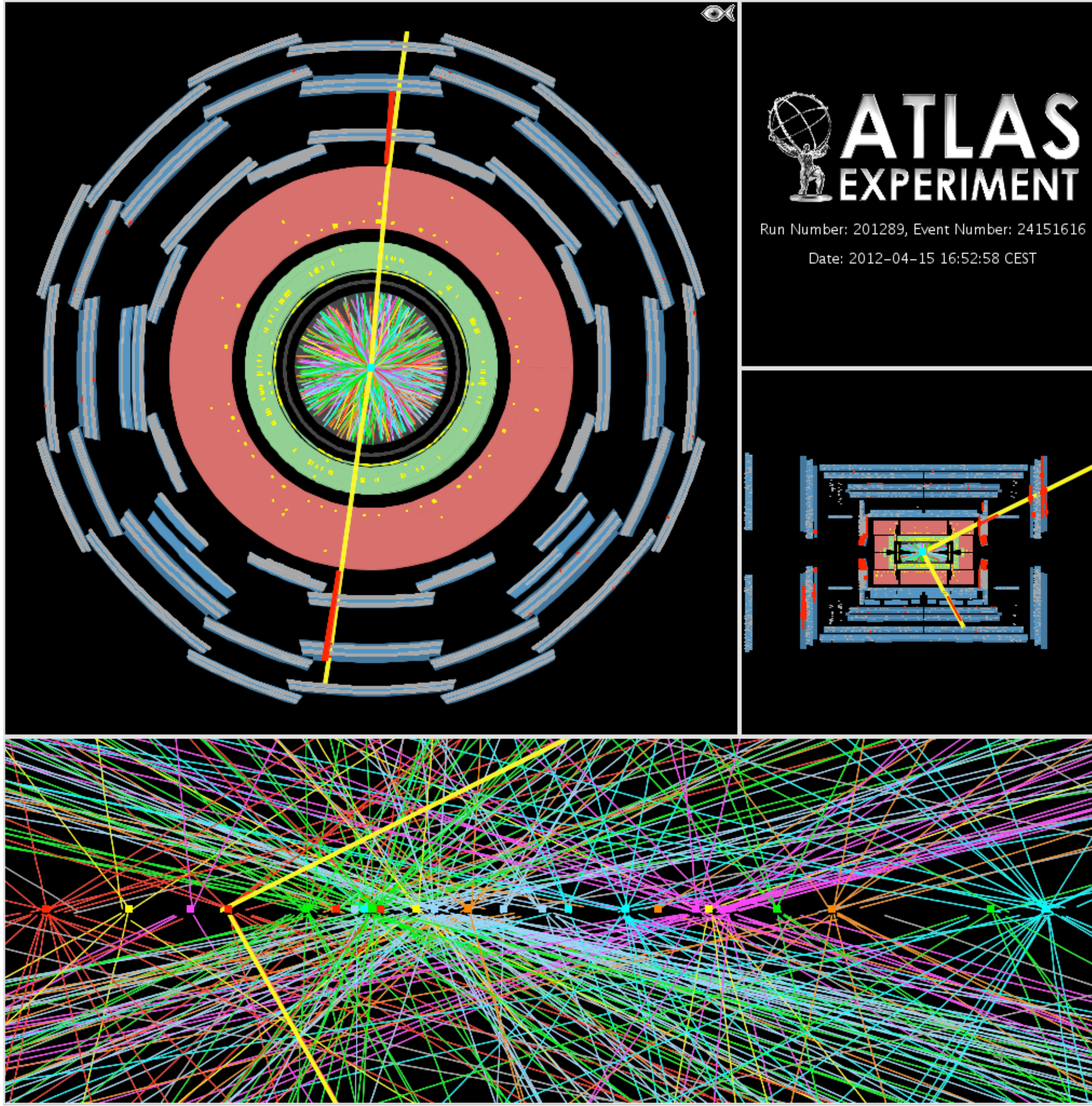

ATLAS Online Luminosity
√s = 8 TeV, ∫Ldt = 20.8 fb⁻¹, <μ> = 20.7
√s = 7 TeV, ∫Ldt = 5.2 fb⁻¹, <μ> = 9.1
Recorded Luminosity [pb⁻¹/0.1]
Mean Number of Interactions per Crossing
0
5
10
15
20
25
30
35
40
45
20
40
60
80
100
120
140
160
180



- 1st jet (ordered by p_T): p_T = 1.72 TeV, η = -0.04, φ = -2.68
- 2nd jet: p_T = 1.50 TeV, η = 0.64, φ = 1.70
- 3rd jet: p_T = 0.22 TeV, η = 0.28, φ = -2.13
- Missing E_T = 29 GeV, φ = 0.50
- Sum E_T = 3.91 TeV

Mjj = 3.65 TeV

di-muon event
with 25 reconstructed
vertices!



Pileup impact on resolutions

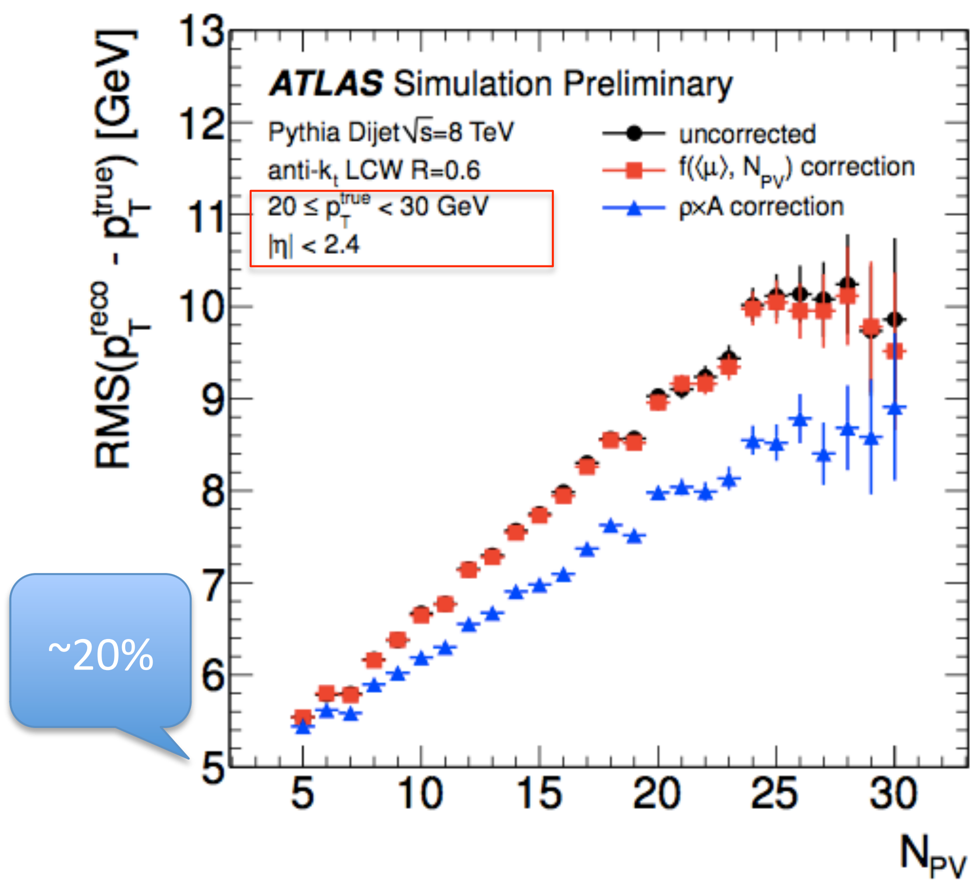
ATLAS

- subtract (pile-up density)*(jet area) from jets
- residual correction parameterized as a function of measured number of pile-up events.

CMS

- Particle flow to associate energy deposits with tracks
- (pileup density)*(jet area) correction for neutral particles and tracks not matched to vertex

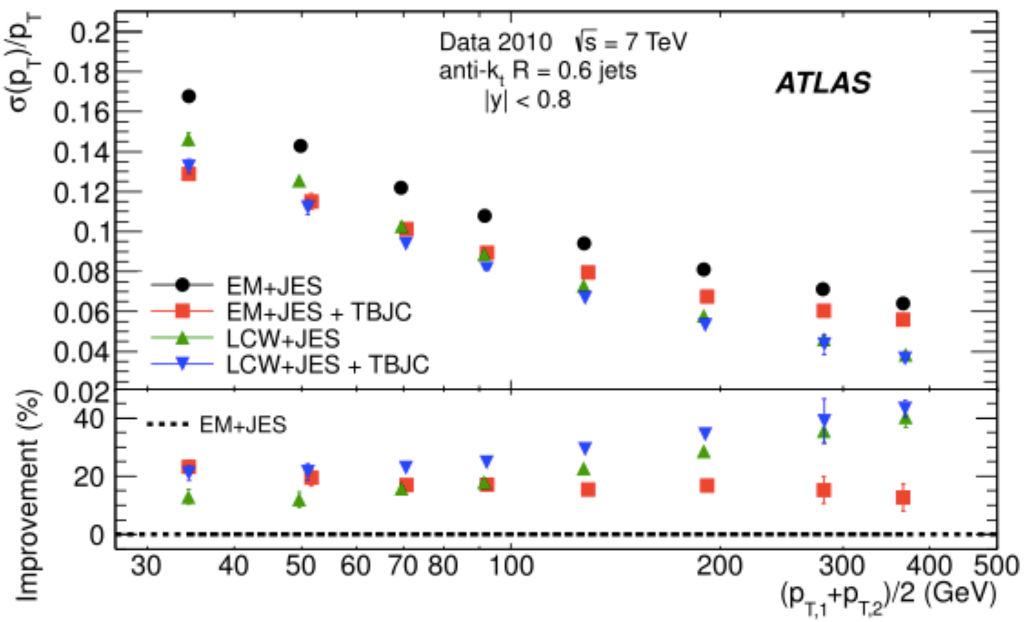
ATLAS-CONF-2013-083

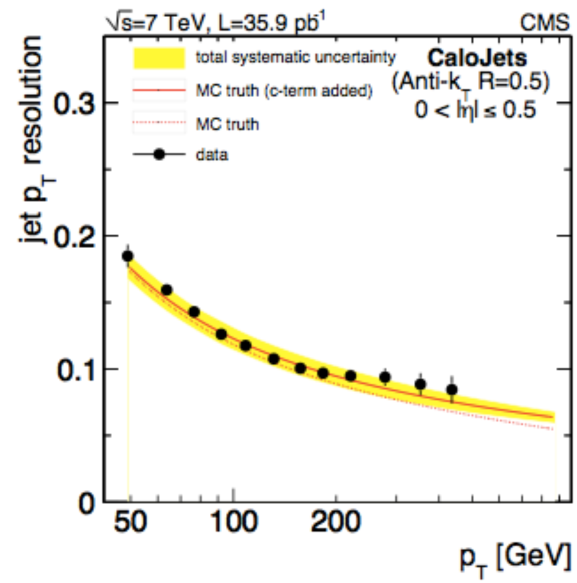


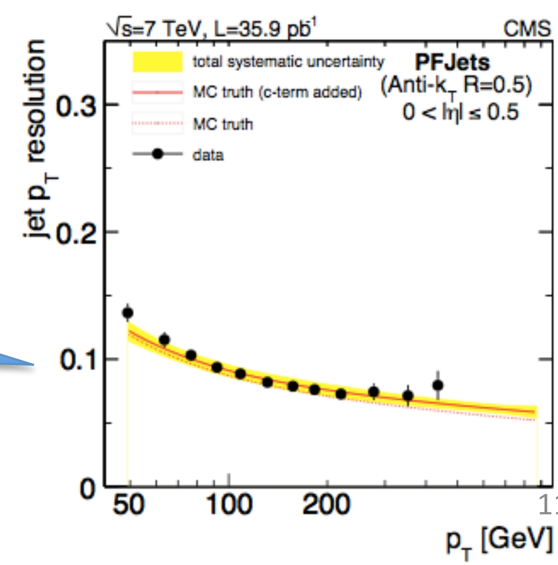
Jet momentum resolution

ATLAS Eur. Phys. J C(2013) 73:2306

CMS JINST 6(2011) P11002







particle flow

2010 7 TeV pp collisions
low pile-up

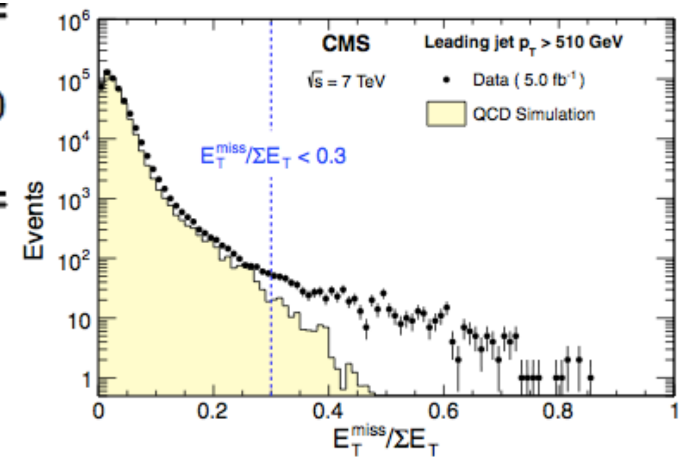
Part II:
Inclusive and di-jet measurements

Parton density functions
pQCD calculations
Modeling of Non-perturbative effects
Strong coupling constant

PRD87(2013)112002 CMS full 2011 data

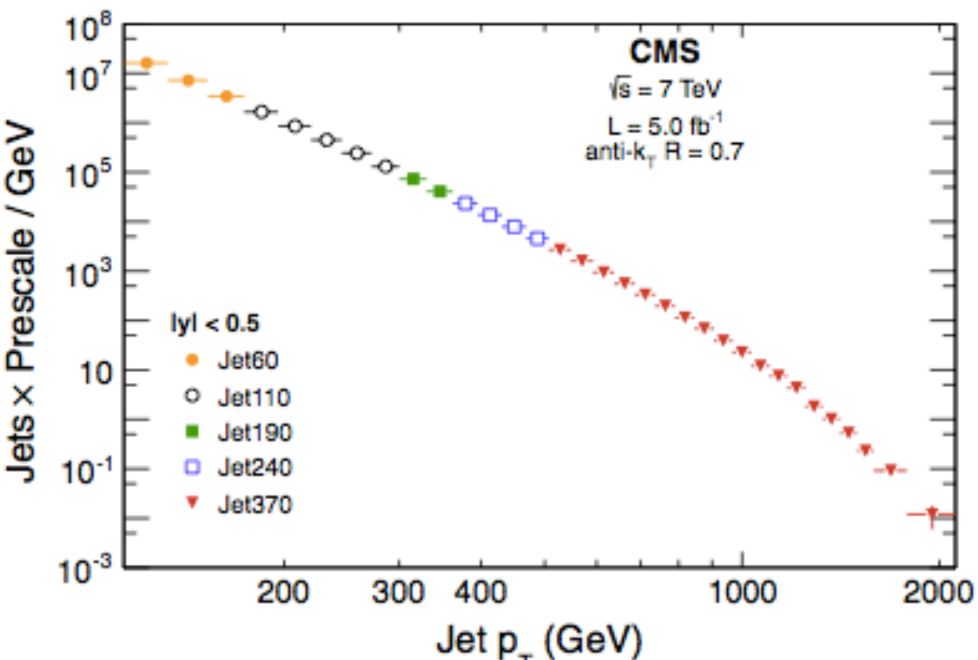
inclusive jet and di-jet cross section

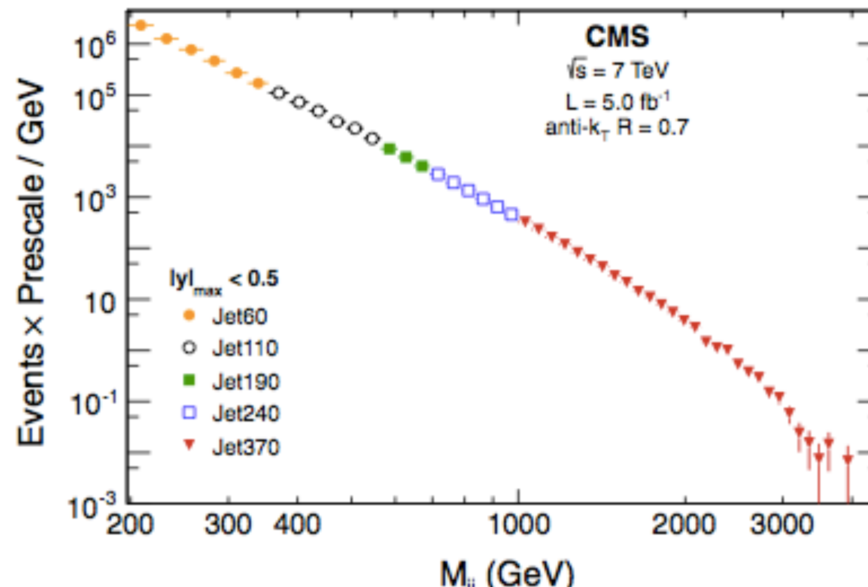
Min. jet trigger p_T (GeV)	60	110	190	240	370
Jet trigger name	Jet60	Jet110	Jet190	Jet240	Jet370
$\mathcal{L}_{\rm eff}$ (pb^{-1})	0.41	7.3	152	512	4980



anti-k_T R = 0.7
veto on MET

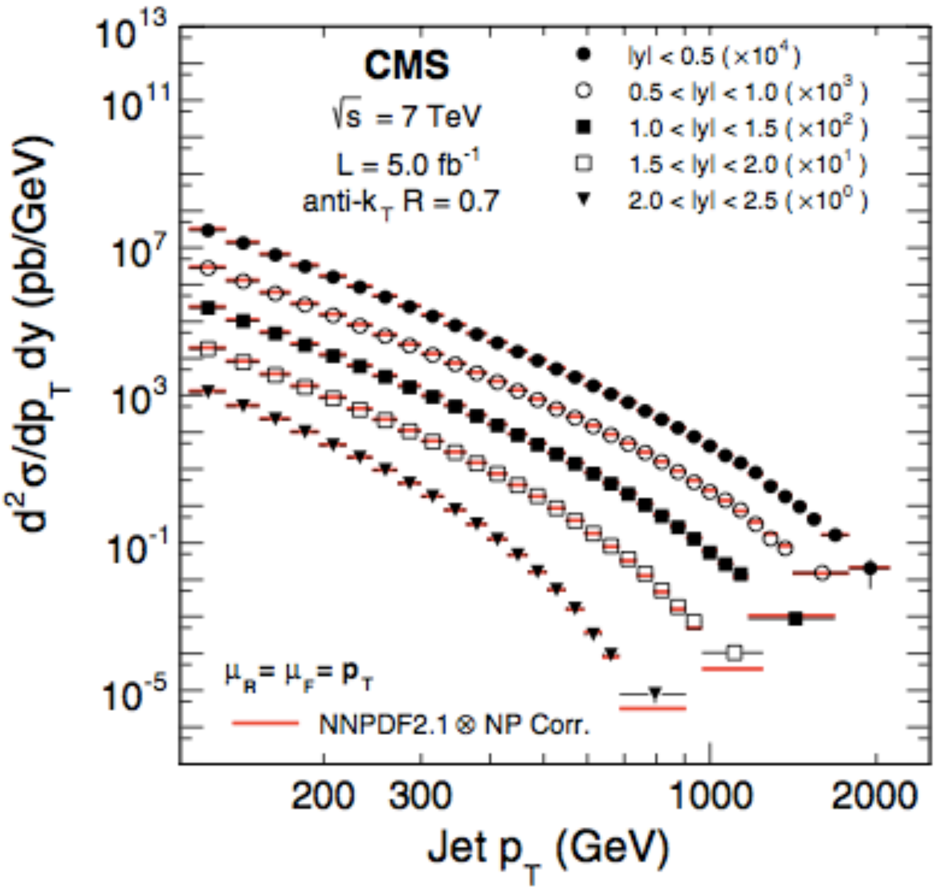
9 orders of magnitude!

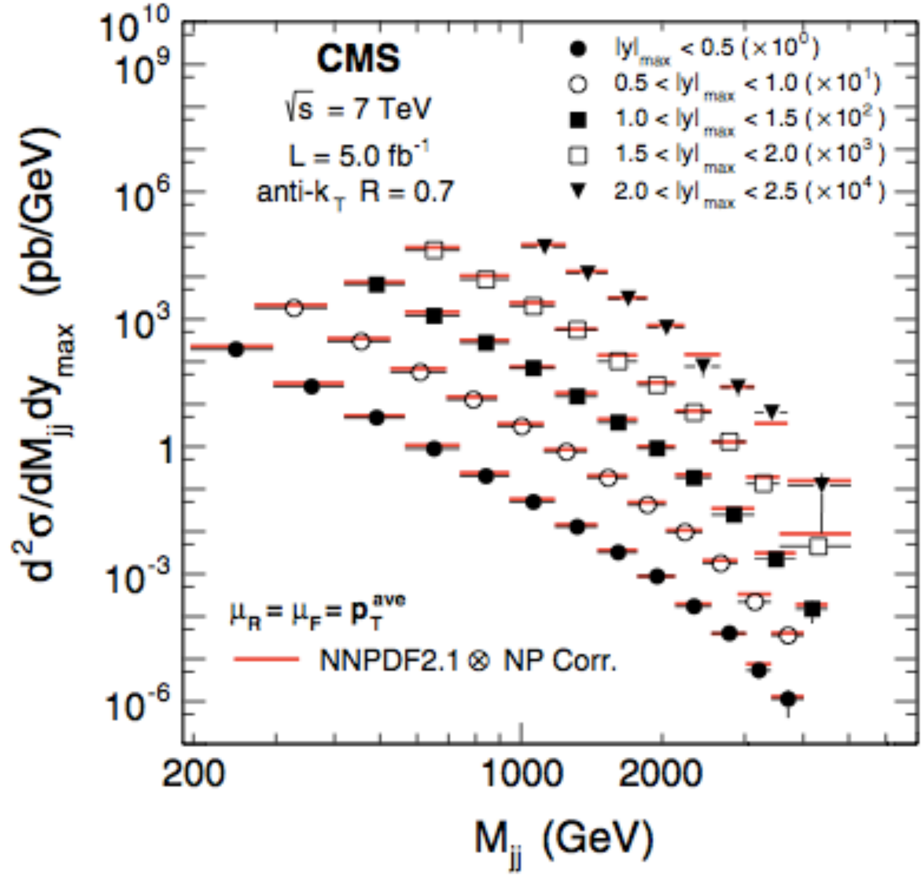




Comparison with NLOJet++

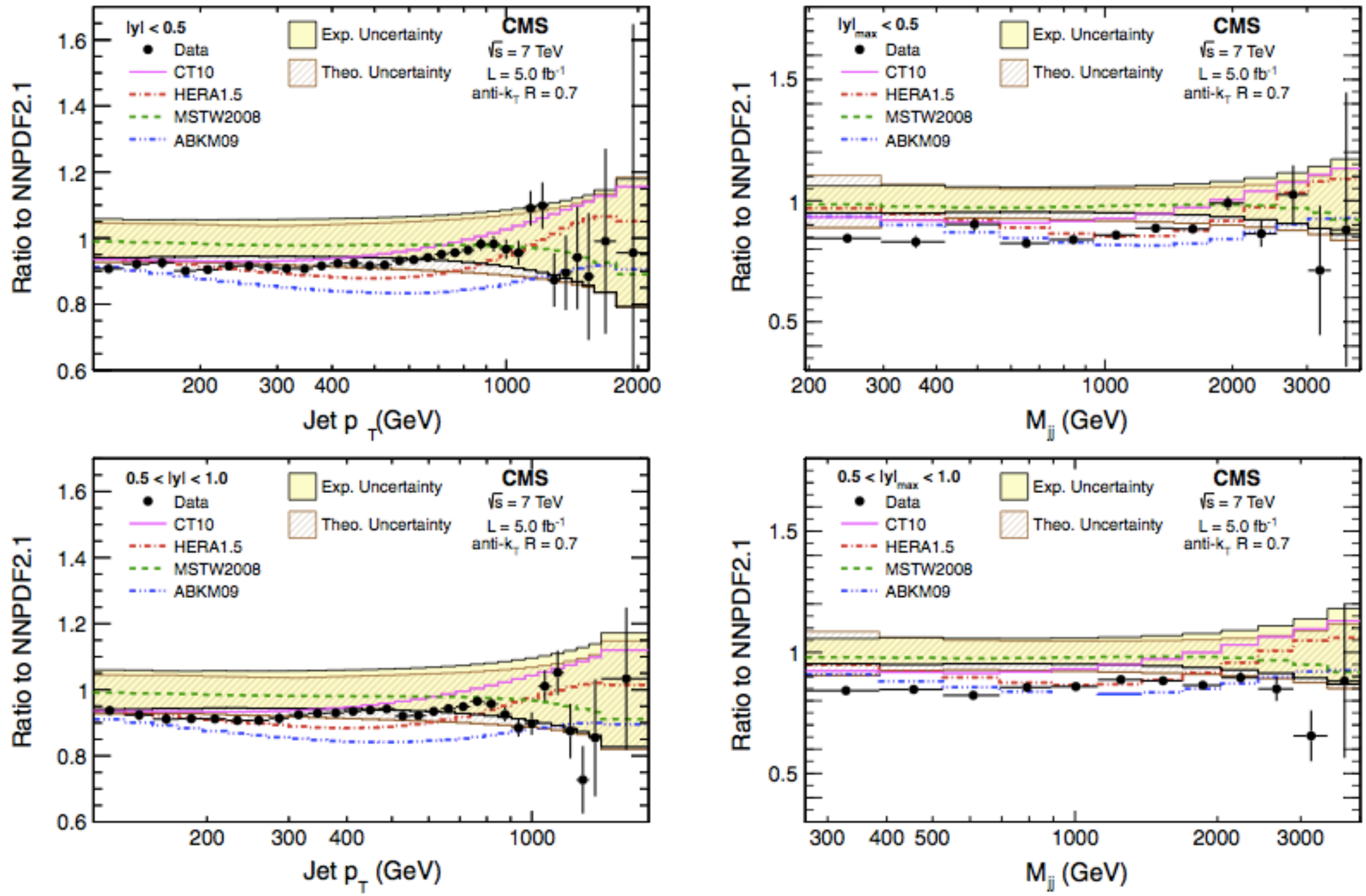
$y_{max} = max(y_1, y_2)$





testing different PDF sets

NNPDF as reference, i.e. y-axis corresponds to ratio w.r.t predictions with NNPDF.



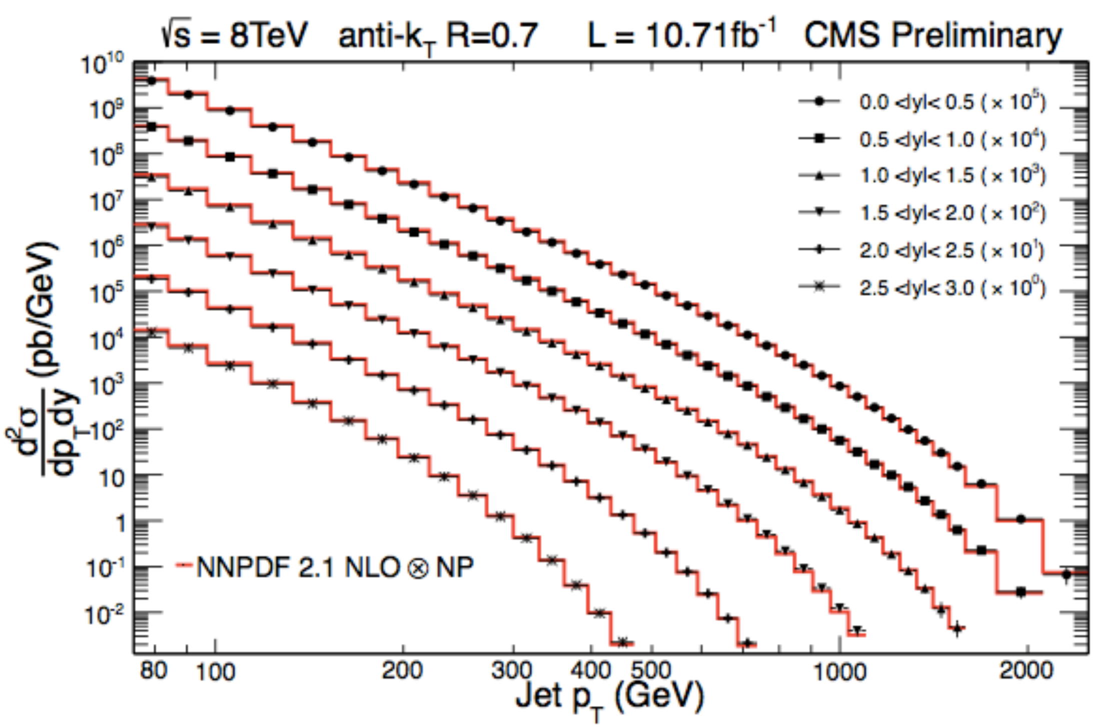
Experimental uncertainties and theoretical uncertainties comparable.

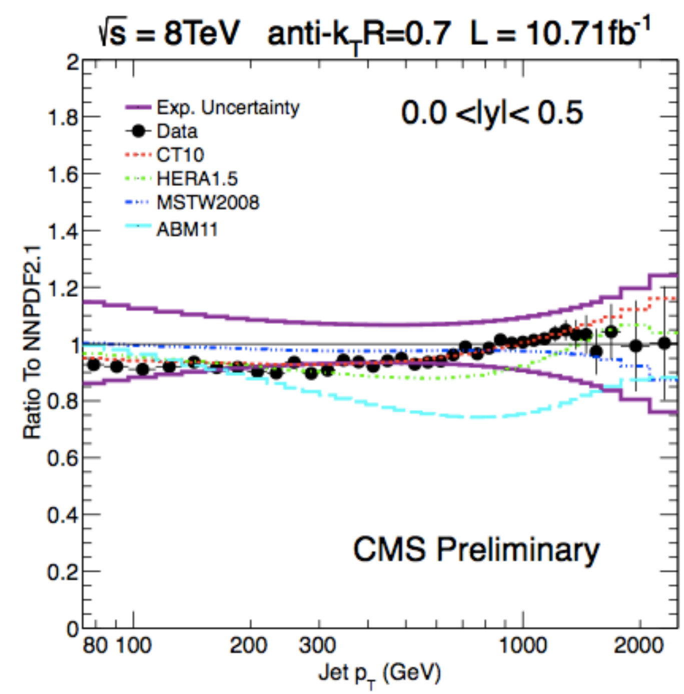
CMS PAS SMP-12-012

CMS 8 TeV results

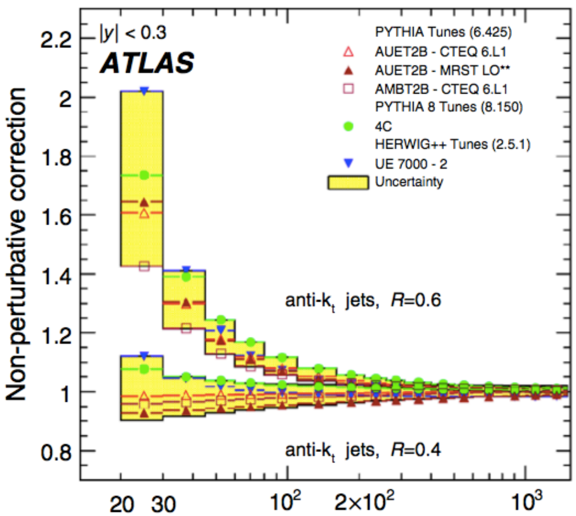
HLT Path		PFJet40	PFJet80	PFJet140	PFJet200	PFJet260	PFJet320
p_T range (GeV)		74 - 133	133 - 220	220 - 300	300 - 395	395 - 507	507 - 2500
Running period	Prescale	60000	3000	230	80	10	1
2012A	$\mathcal{L}_{int,eff}$ (pb^{-1})	0.010	0.195	2.782	14.08	60.57	611.02
Running period	Prescale	250000	7000	270	70	15	1
2012B	$\mathcal{L}_{int,eff}$ (pb^{-1})	0.017	0.630	16.30	64.08	266.286	4140
Running period	Prescale	220500	10000	400	80	20	1
2012C	$\mathcal{L}_{int,eff}$ (pb^{-1})	0.020	0.533	15.767	79.292	317.158	5966
Total	$\mathcal{L}_{int,eff}$ (pb^{-1})	0.047	1.358	34.85	157.45	644.014	10717.02

reduced stat.
uncertainty at high pT

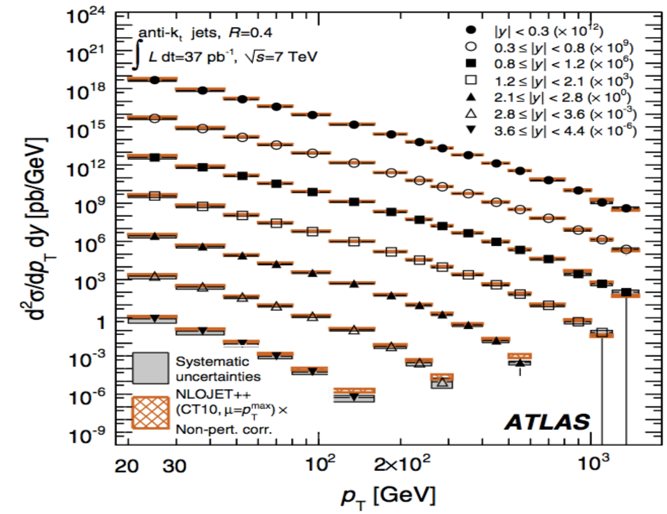


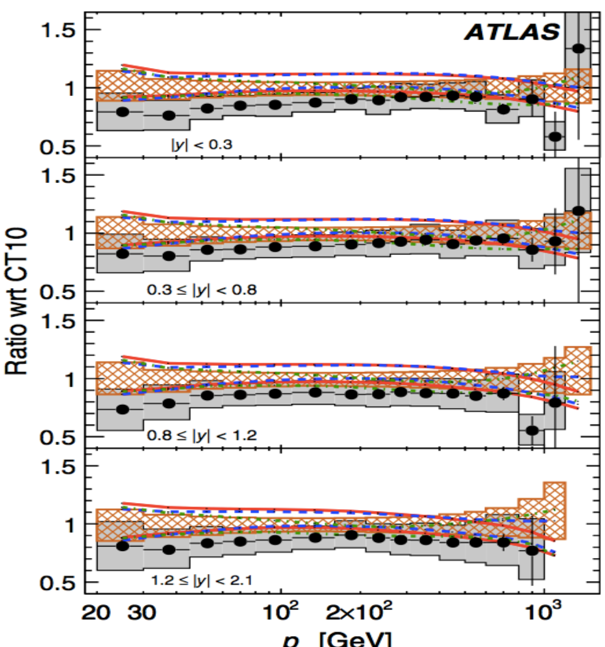


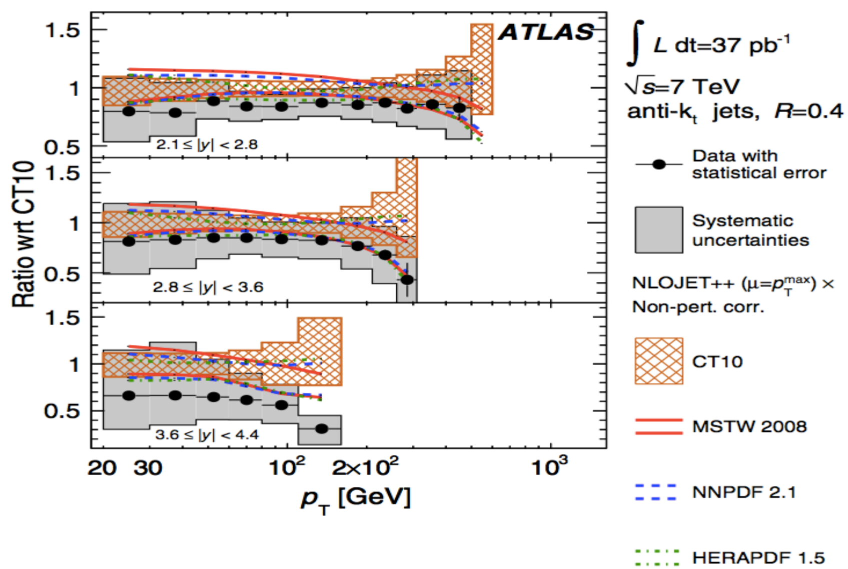
inclusive jet (ATLAS) testing PDF



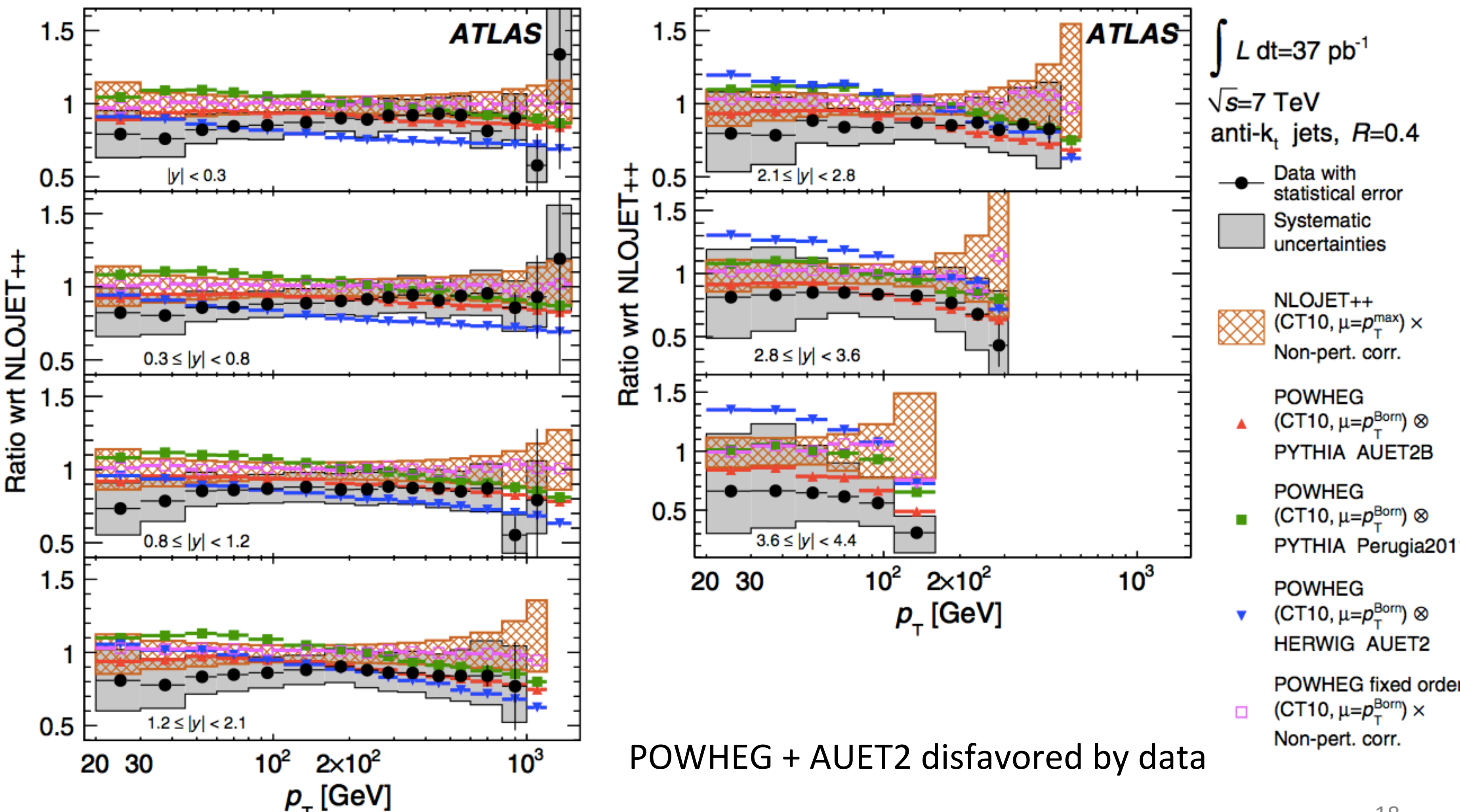
To be applied to fixed order predictions at parton level.







testing various PS tuning



POWHEG + AUET2 disfavored by data

EPJC (2013) 73 2509

Expect correlated systematics cancel in the ratio

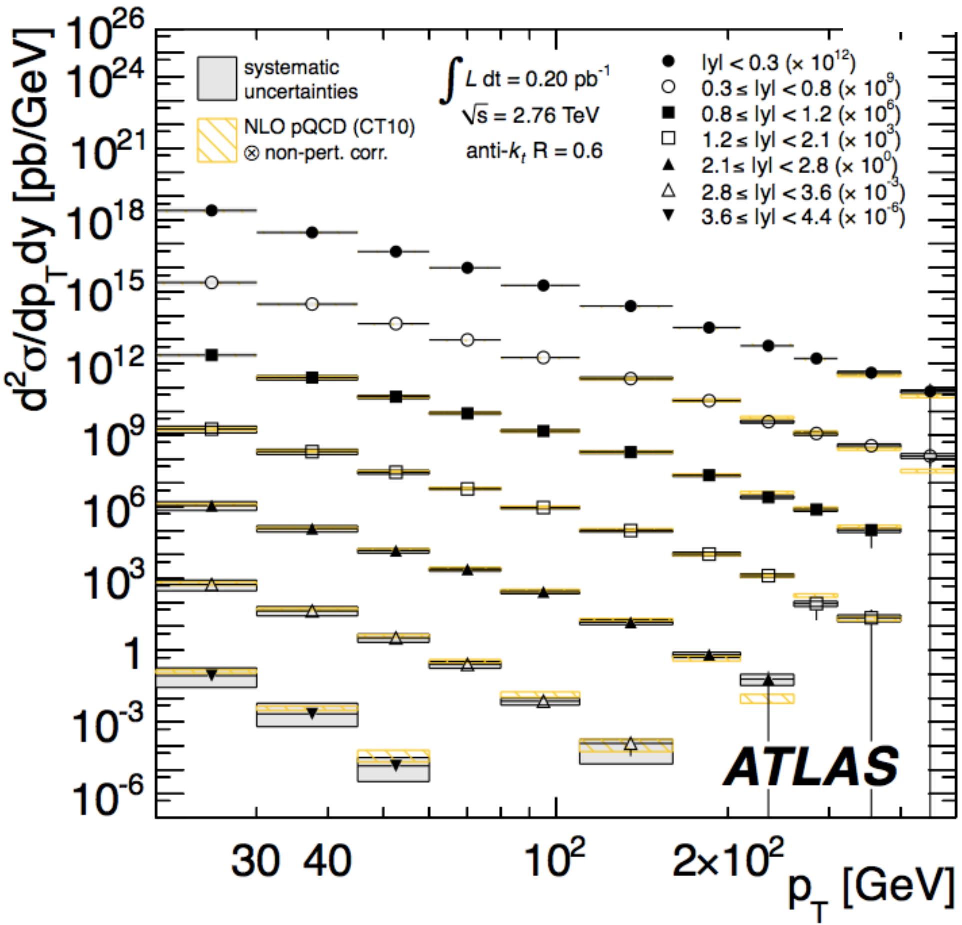
cross section ratio

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{2\pi p_T}\frac{d^2\sigma}{dp_T dy}$$

Dimensionless scale invariant cross section:

$$F(y, x_T, \sqrt{s}) = p_T^4 E\frac{d^3\sigma}{dp^3} = \frac{p_T^3}{2\pi}\frac{d^2\sigma}{dp_T dy} = \frac{s}{8\pi}x_T^3\frac{d^2\sigma}{dx_T dy}$$

Limitation: only 0.2 pb of 2.76 data

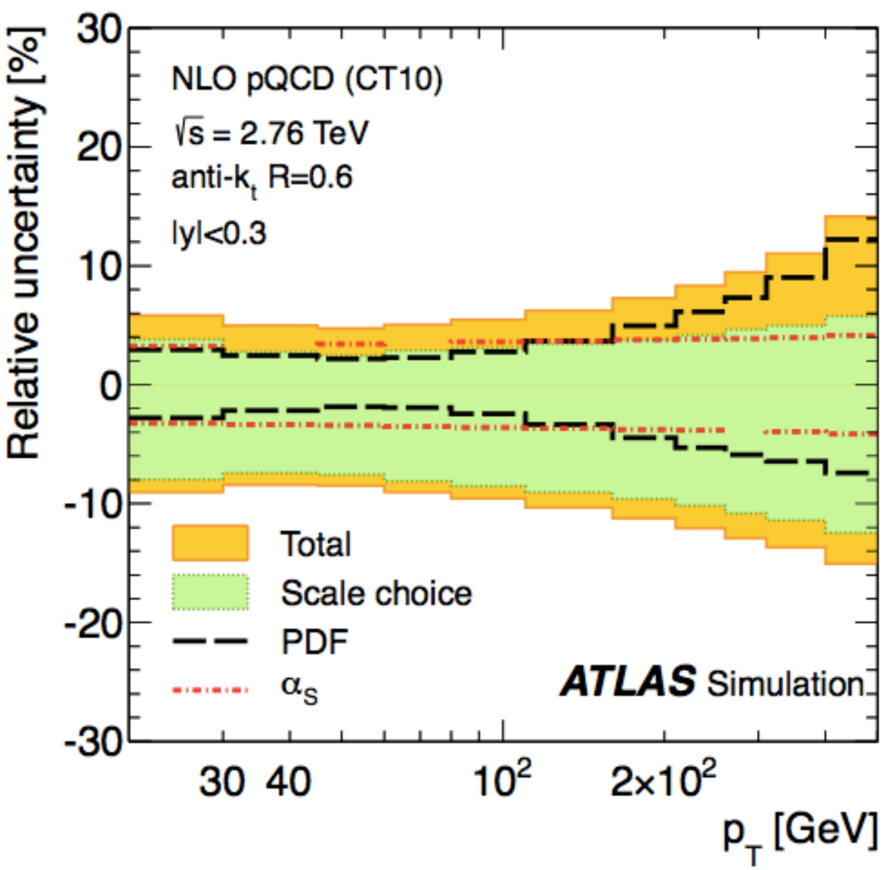


$$\rho(y, x_T) = \frac{F(y, x_T, 2.76\ \text{TeV})}{F(y, x_T, 7\ \text{TeV})}$$

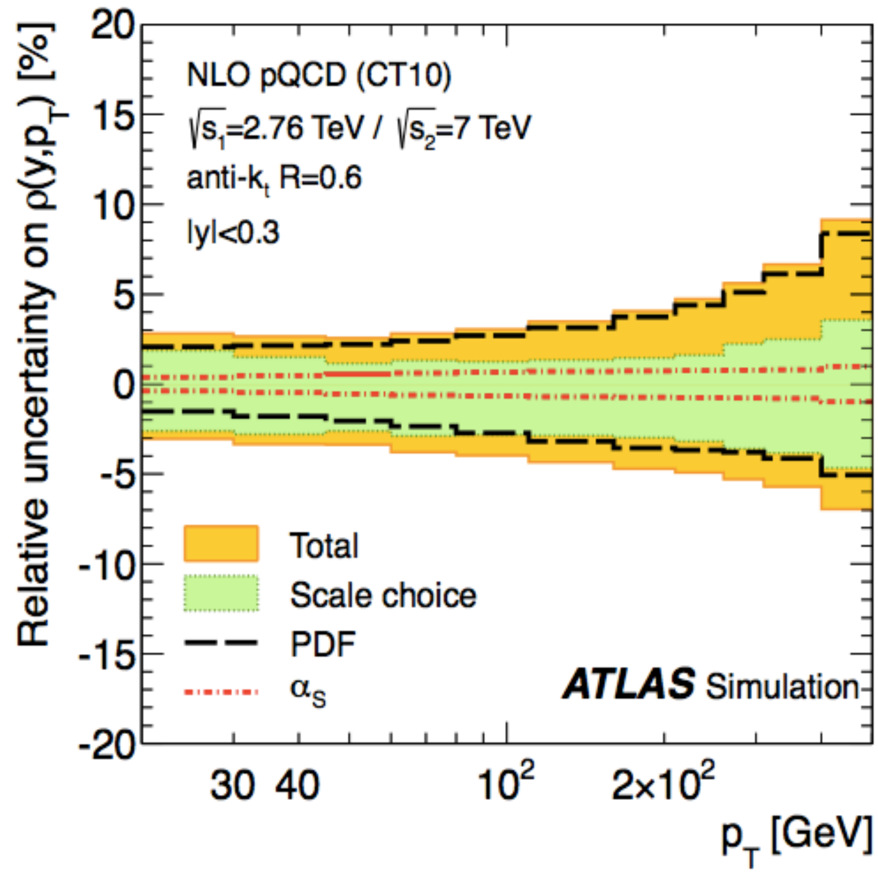
$x_T = 2\ p_T/\sqrt{s}$
to faciliate comparison of measurements at different √s
Ratio as a function of x_T cancels theor. uncertainties

Ratio as a function of pT cancels exp. uncertainties

pQCD uncertainties

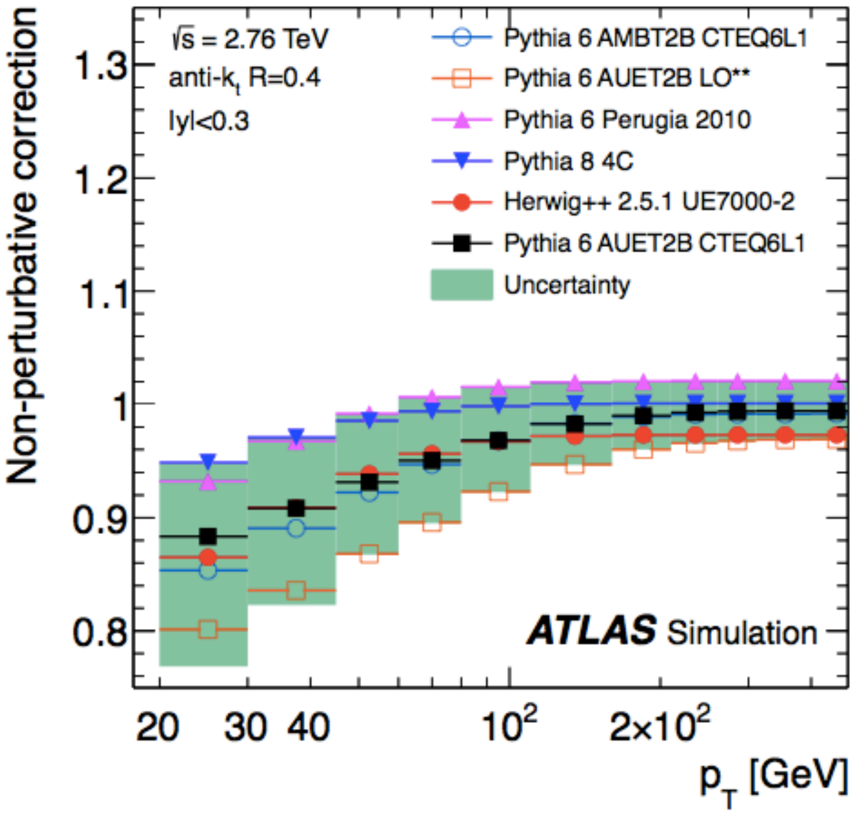


on inclusive cross sections

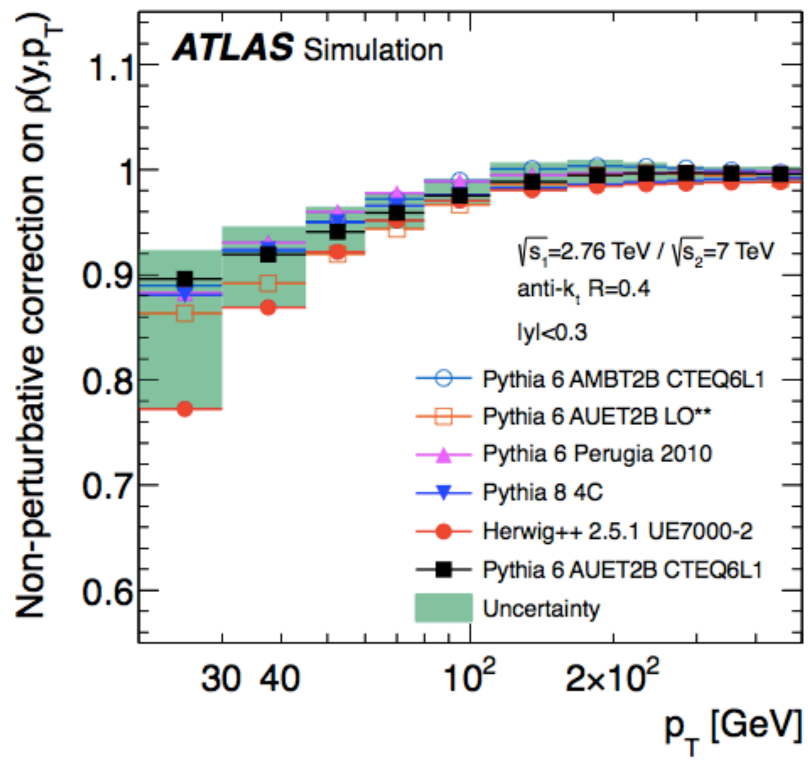


On the ratio of cross sections

Non-perturbative correction uncertainty



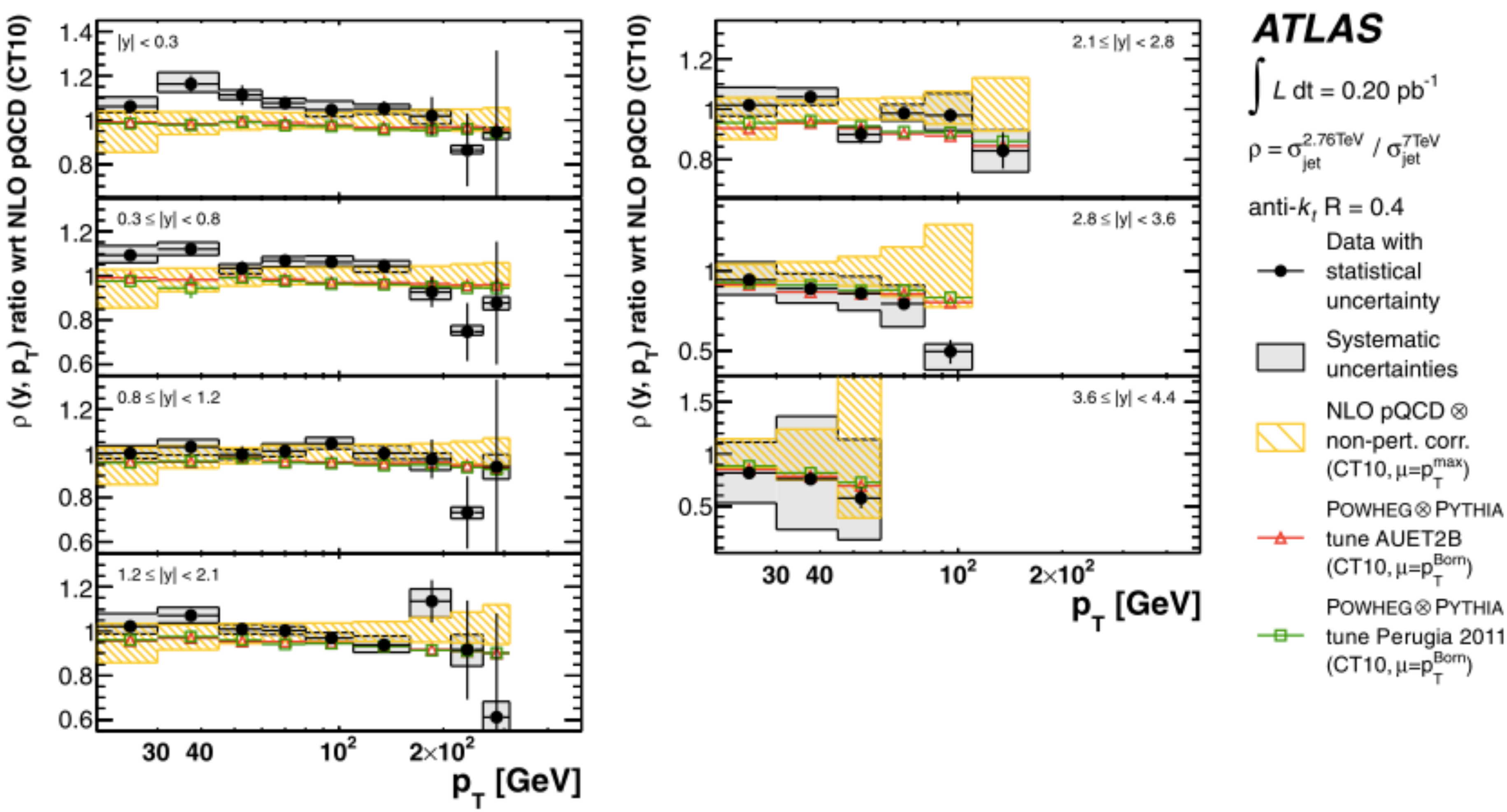
on inclusive cross section



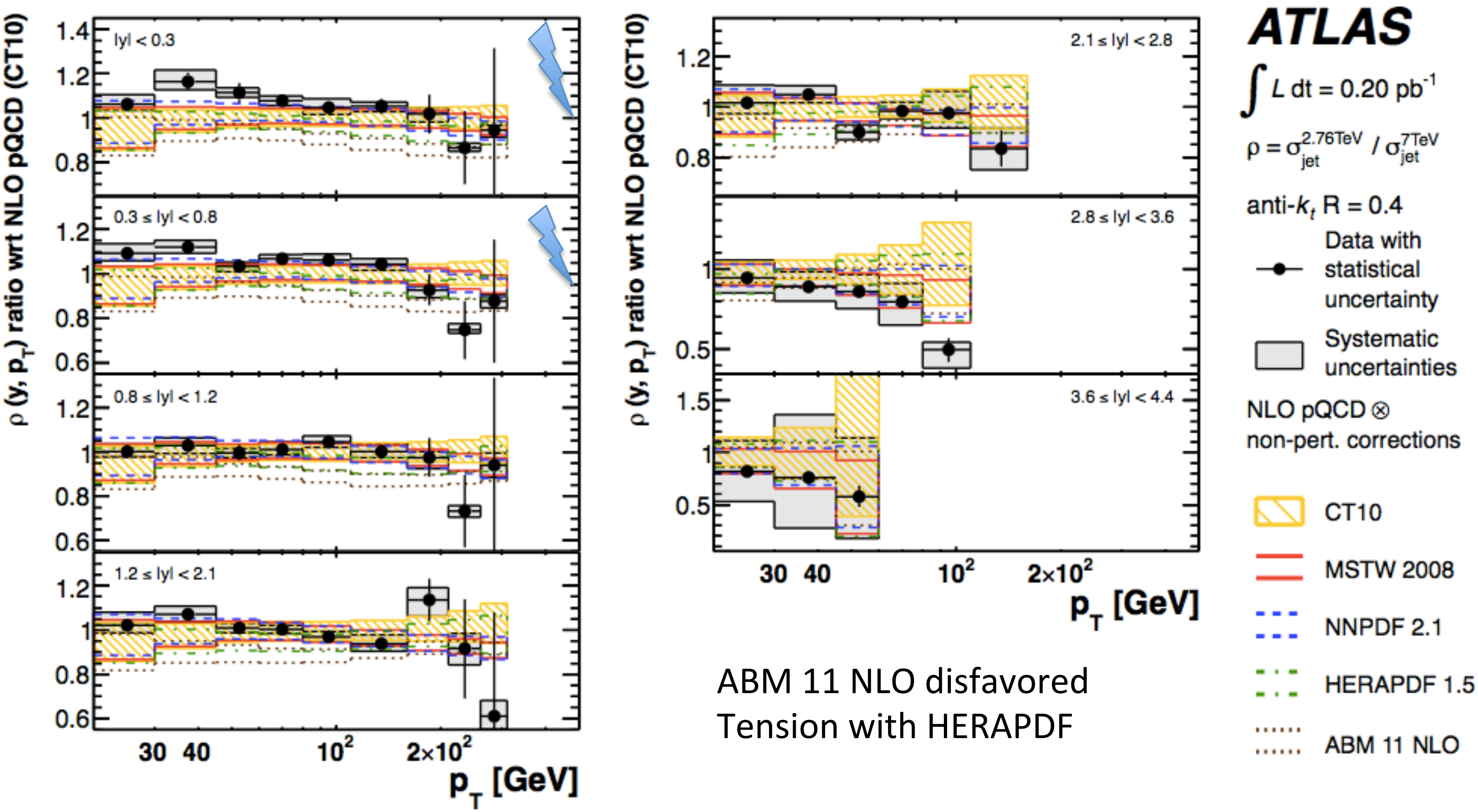
on ratios of cross sections

Comparison to NLO + PS Monte Carlo

significantly reduced theoretical uncertainties.



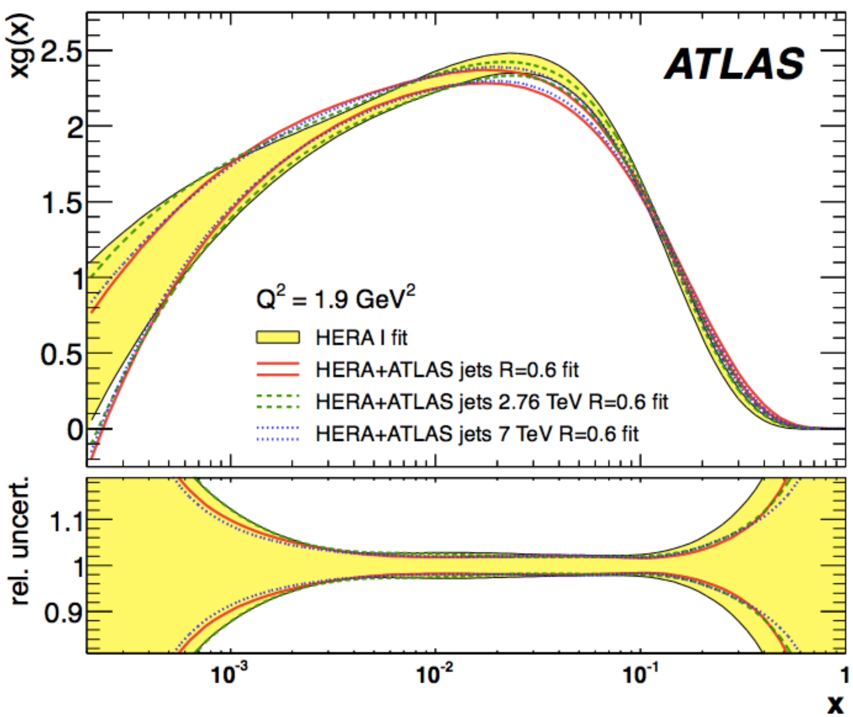
testing PDFS

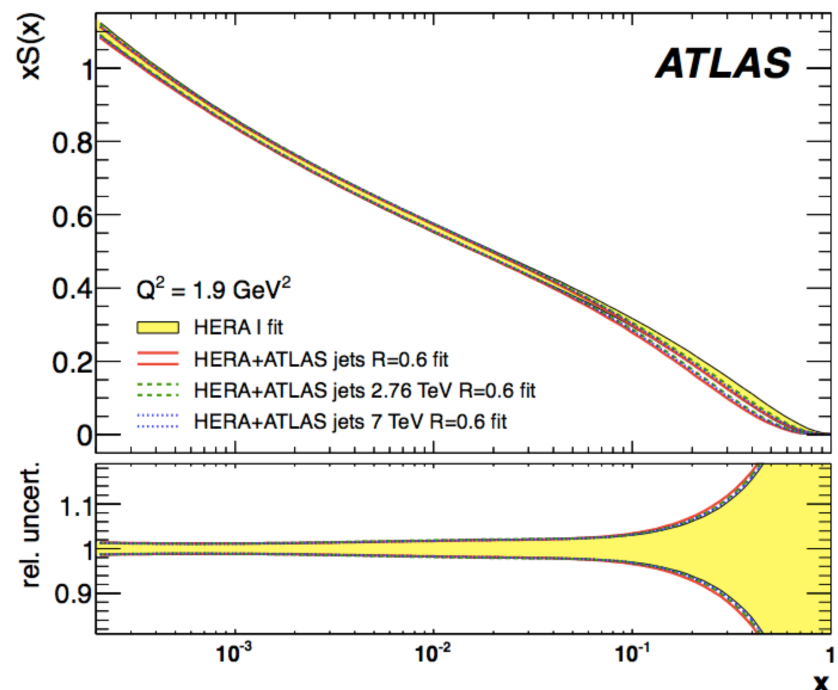


ABM 11 NLO disfavored
Tension with HERAPDF

influence on g and *sea* quark densities

ATLAS jet data (2.76 TeV and 7 TeV) favor higher (lower) density of gluons (sea quarks) at high x.





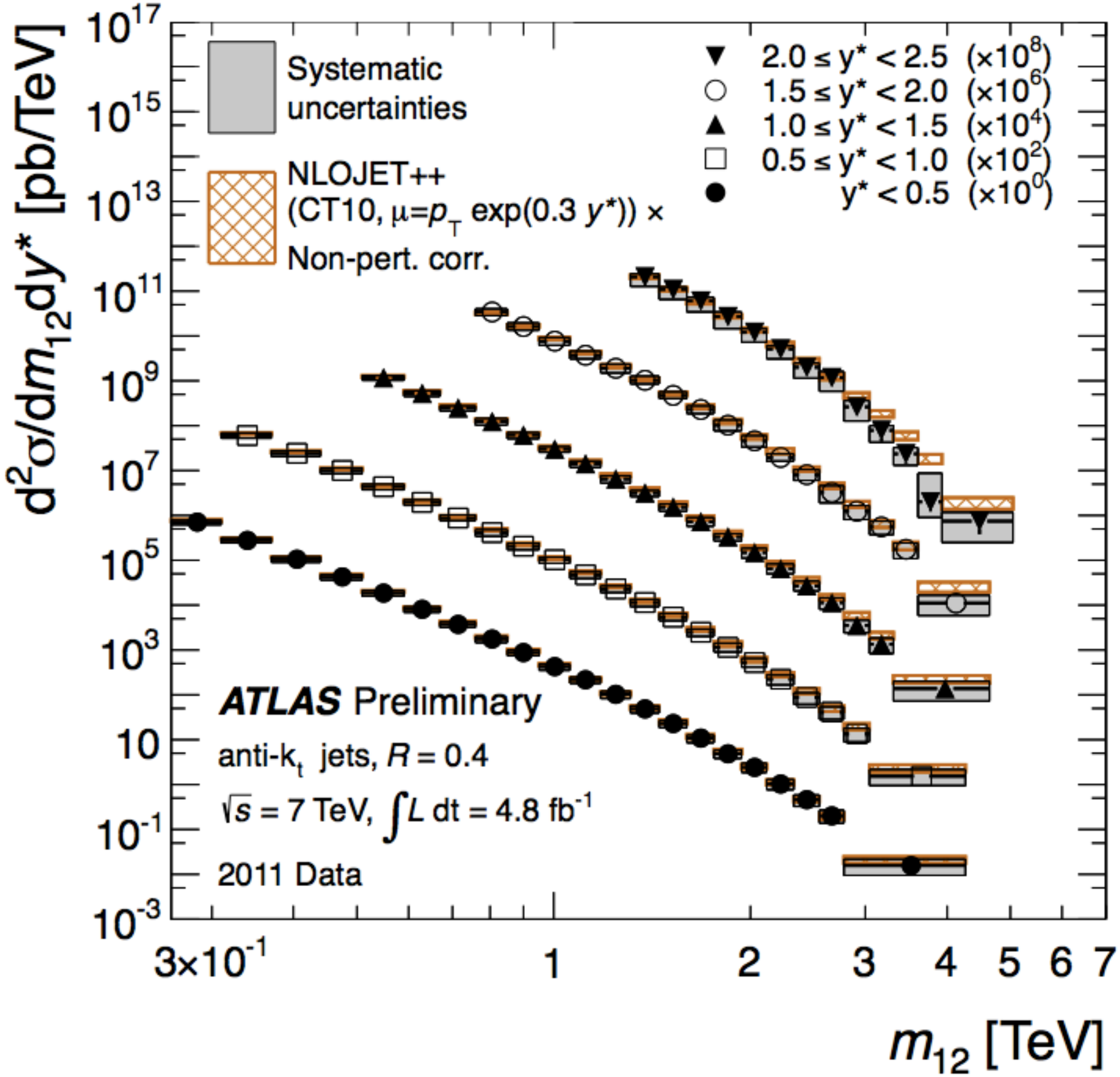
Anticipating ratio measurements of 14/7 14/8 8/7 8/2.76 14/2.76?

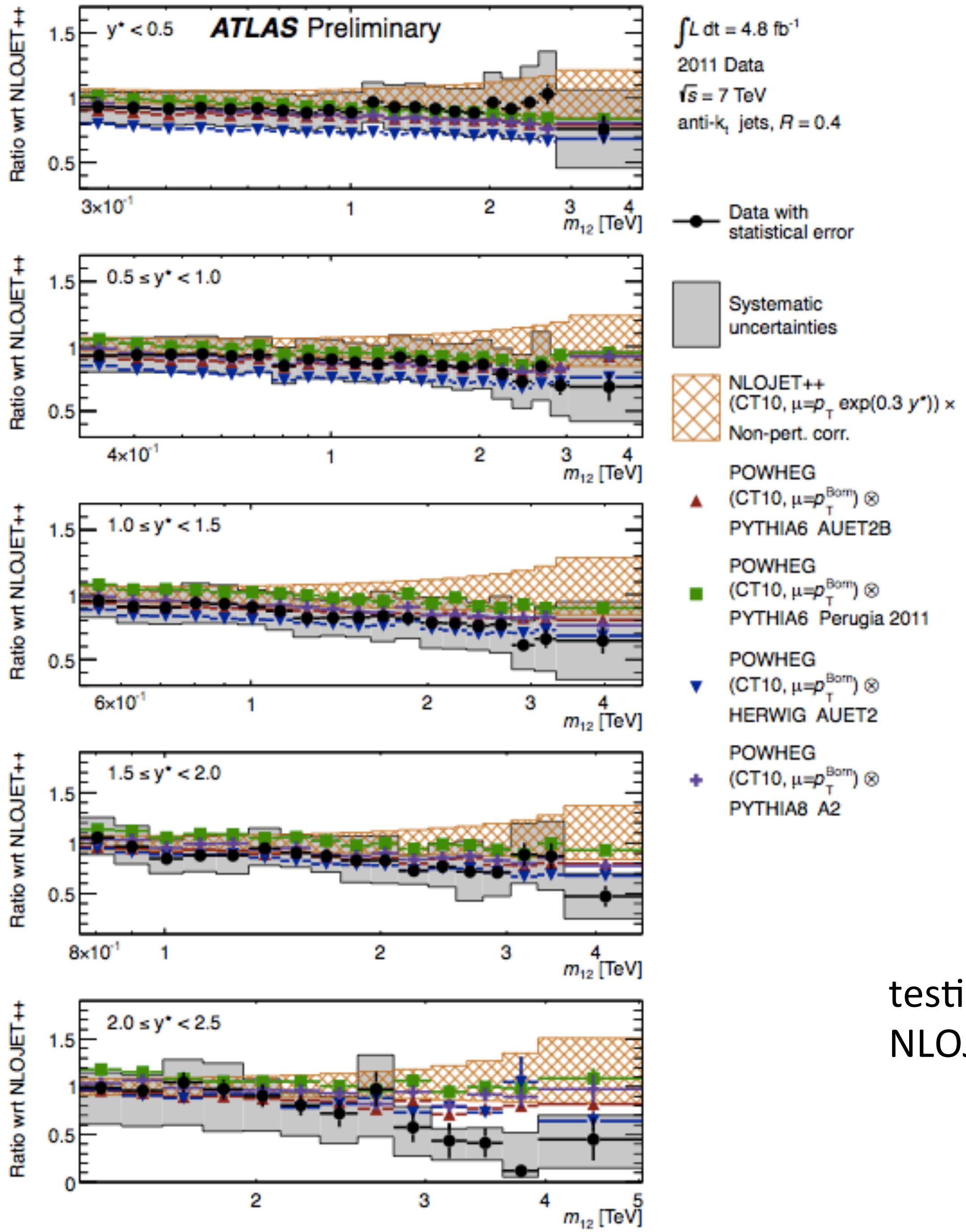
ATLAS-CONF-2012-021

full 2011 data

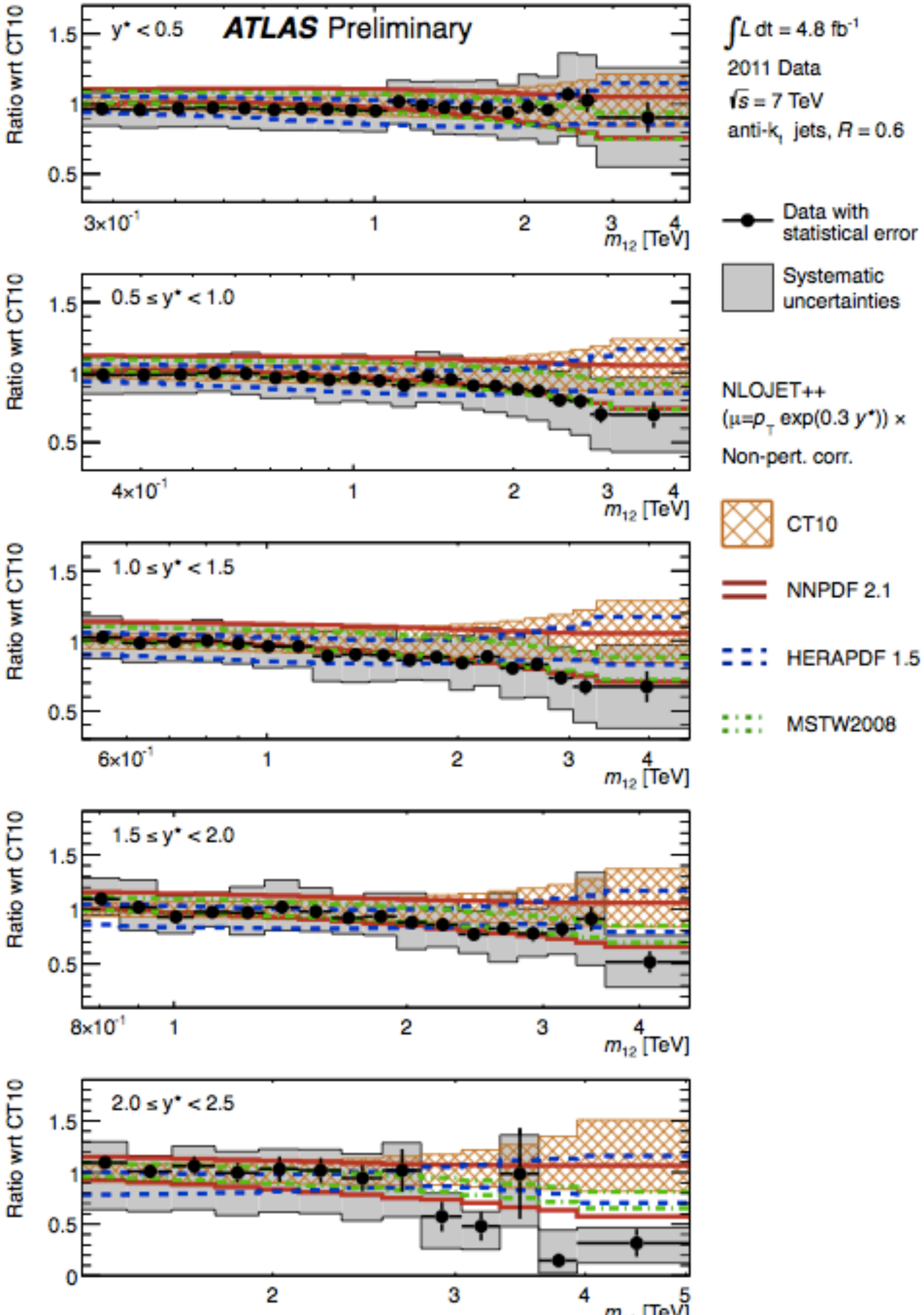
ATLAS di-jet data

$y^* = |y_1 - y_2|/2$





testing NLO + PS
NLOJET++ as reference



in some kinematic regions, experimental uncertainties comparable with theoretical uncertainties.
Starting to have sensitivity for PDFs.

arXiv:1304.7498v1

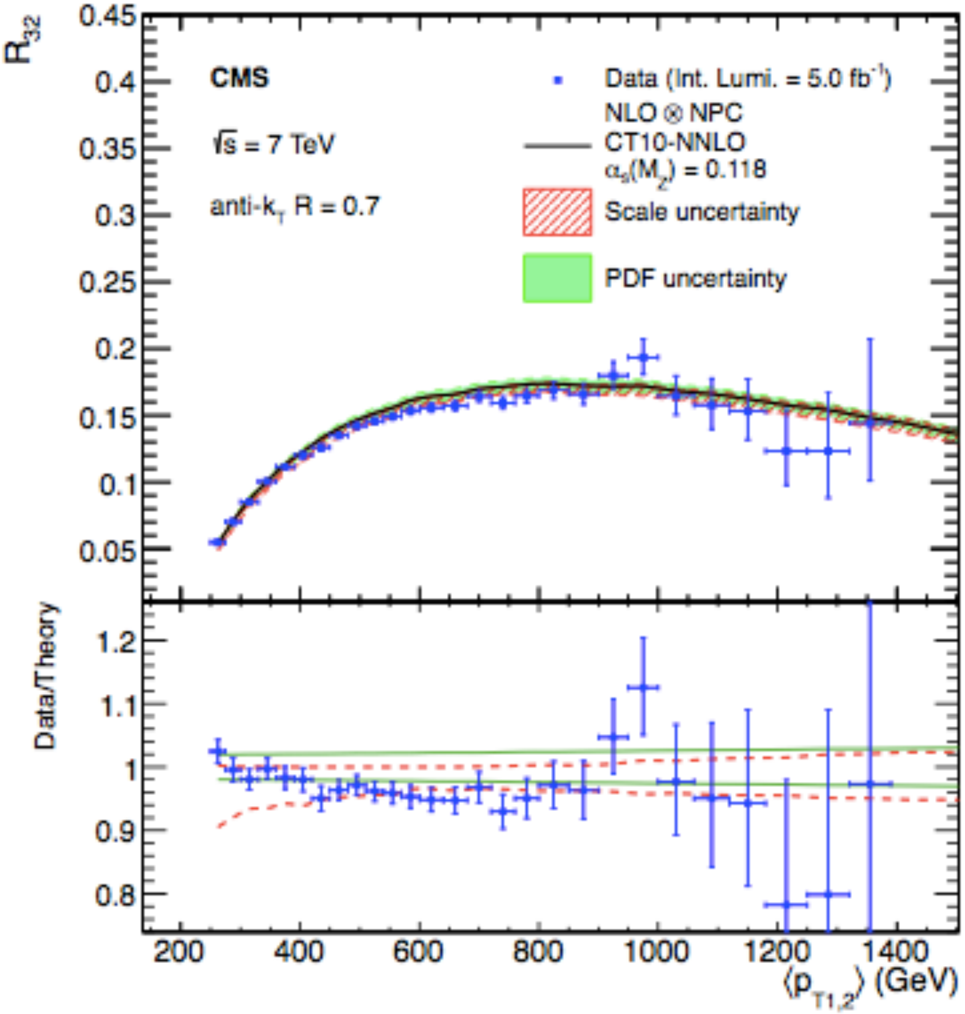
full 2011 data

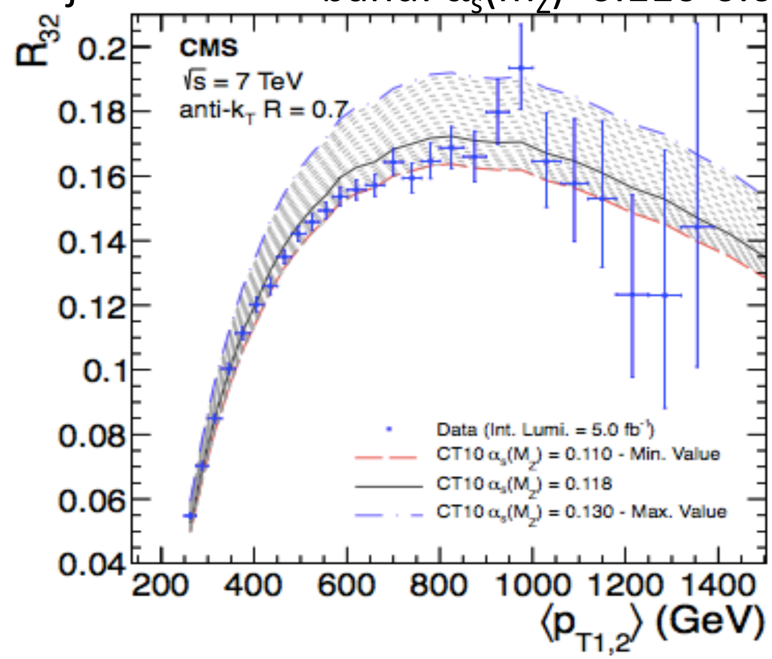
CMS 3-jet/2-jet ratio for α_s

$<p_{T1,2}> = (p_{T1} + p_{T2})/2$: mean of the two leading pT, representing Q

R32: event yield ratio of inclusive 3-jet / inclusive 2-jet

band: $\alpha_s(m_Z)$=0.110-0.0130





Vary the $\alpha_s(m_Z)$ in prediction and minimize the chi2 for the best fit.

$$\text{MSTW2008: } \alpha_S(M_Z) = 0.1141 \pm 0.0022\,(\text{exp.})$$

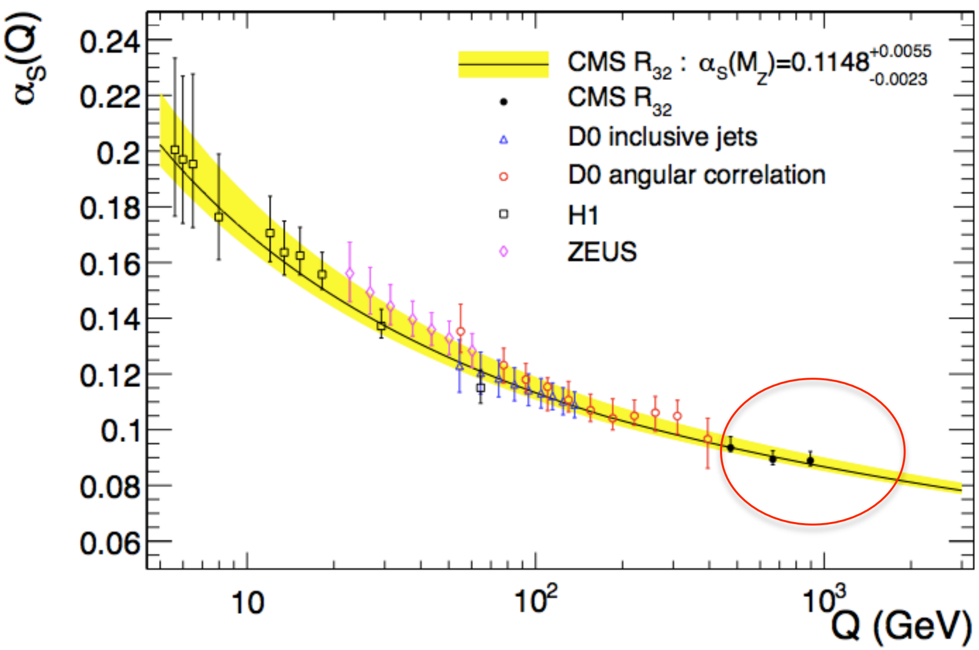
$$\text{CT10: } \alpha_S(M_Z) = 0.1135 \pm 0.0019\,(\text{exp.})$$

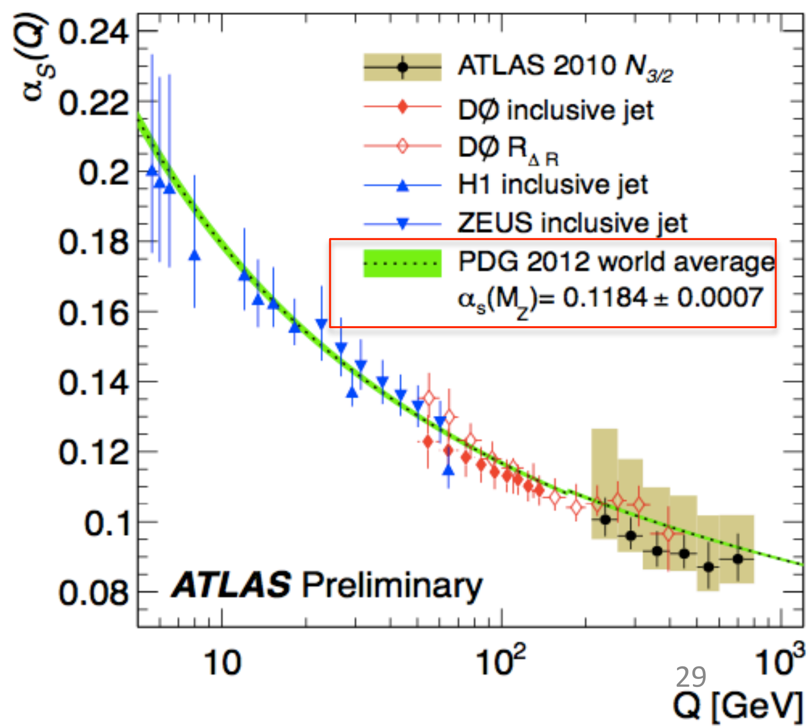
Running of α_s

$\langle p_{T1,2} \rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	$\alpha_S(Q)$	No. of data points	χ^2/N_{dof}
420–600	474	$0.1147^{+0.0061}_{-0.0021}$	$0.0936^{+0.0040}_{-0.0014}$	6	4.4/5
600–800	664	$0.1132^{+0.0050}_{-0.0031}$	$0.0894^{+0.0031}_{-0.0019}$	5	5.9/4
800–1390	896	$0.1170^{+0.0058}_{-0.0032}$	$0.0889^{+0.0033}_{-0.0018}$	10	5.7/9

Fit for α_s (m_Z) using events in each of the 3 <$p_{T1,2}$> bins
Determine the average Q for each bin with NLOJet++
3-Loop RGE for m_Z -> Q

ATLAS-CONF-2014-041





Summary for part II

Inclusive and dijet measurements consistent with MC predictions
Experimental uncertainties ~ theoretical uncertainties
=> starting to have constraining power on PDF, parton shower modeling
Ratios of different CME: good point!
Strong coupling constants measured up to ~ 1 TeV : compatible with PDG and RGE evolving.

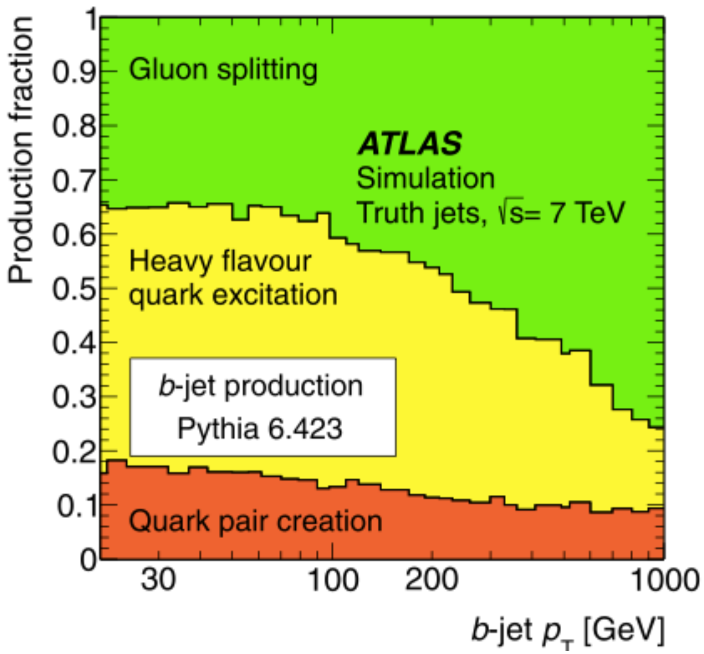
part III :
Heavy flavor production

Masses of c, b quarks significantly above QCD scale
Less influence of low energy hadronisation effects on the production cross sections of HF

Eur. Phys. J. C(2013)73:2301

PYTHIA

flavor composition in di-jet events



labels:

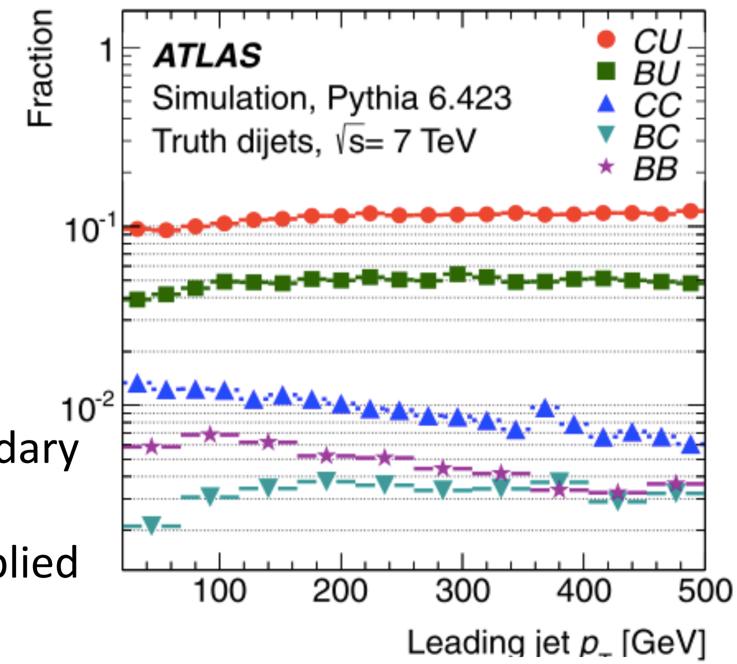
B – b quark

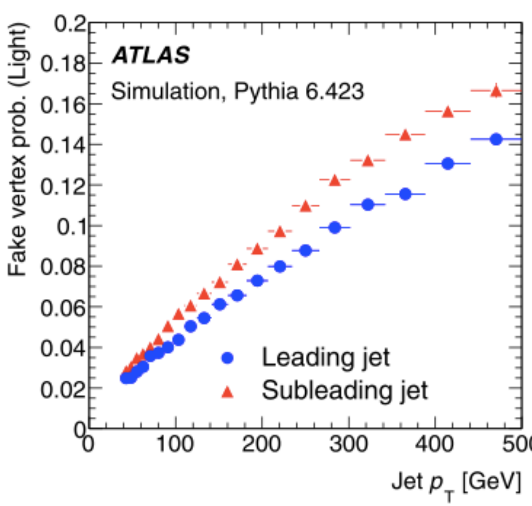
C – c quark

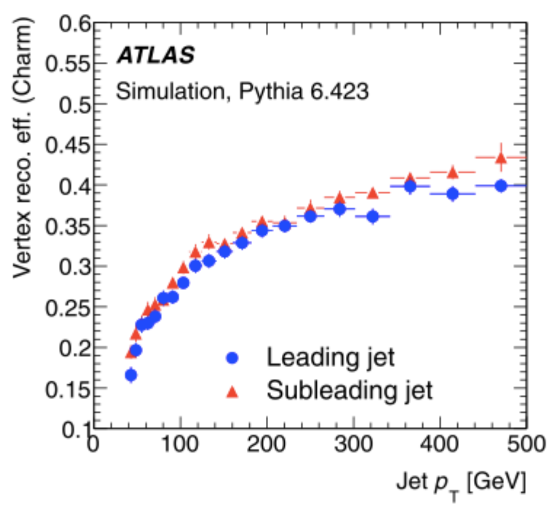
U – u,d,s

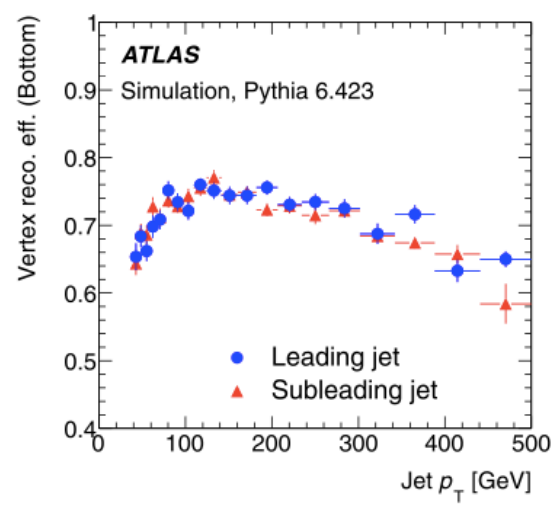
Use kinematic feature of secondary vertices

No b-tagging applied









flavor templates

~ energy fraction of the "B" system meson

$$\Pi = \frac{m_{\text{vertex}} - 0.4\ \text{GeV}}{m_B} \cdot \frac{\sum_{\text{vertex}} E_i}{\sum_{\text{jet}} E_i},$$

$$B = \frac{\sqrt{m_B} \cdot \sum_{\text{vertex}} |\vec{p}_{\text{T}i}|}{m_{\text{vertex}} \cdot \sqrt{p_{\text{Tjet}}}},$$

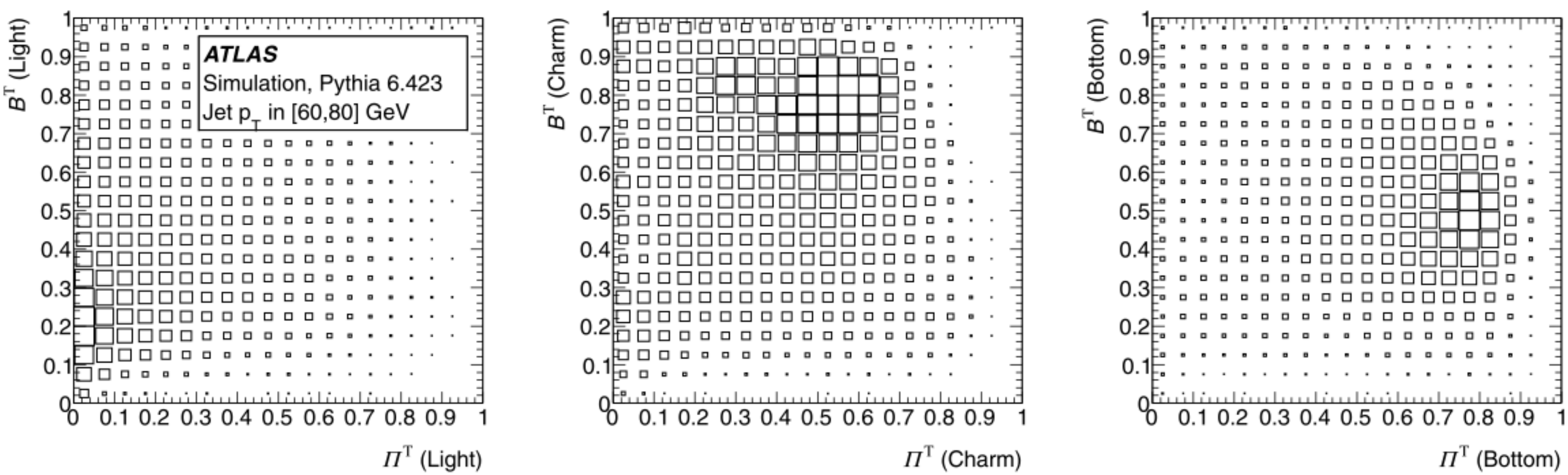
approx.γ factor for the "B" system

m_B = 5.2794 GeV

transform to (0,1) for conveniences

$$\Pi^{\text{T}} = \frac{\Pi}{\Pi + 0.04},$$

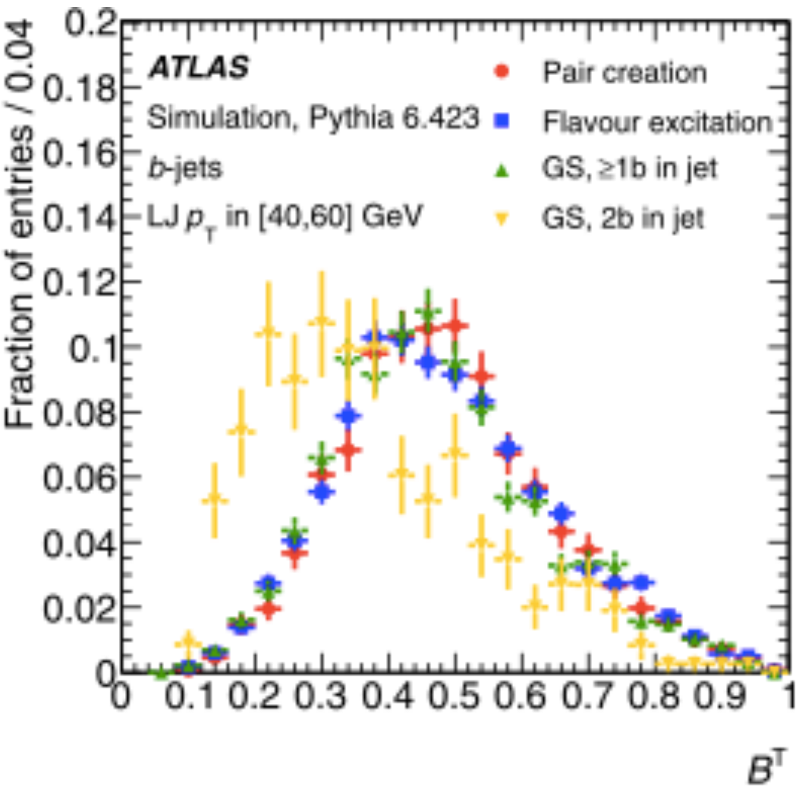
$$B^{\text{T}} = \frac{B \cdot B}{B \cdot B + 10.}$$



Next : pair templates for 2 jets in each event and fit to data

But there are complications that require modifications to the templates

jets containing two b- or c- hadrons



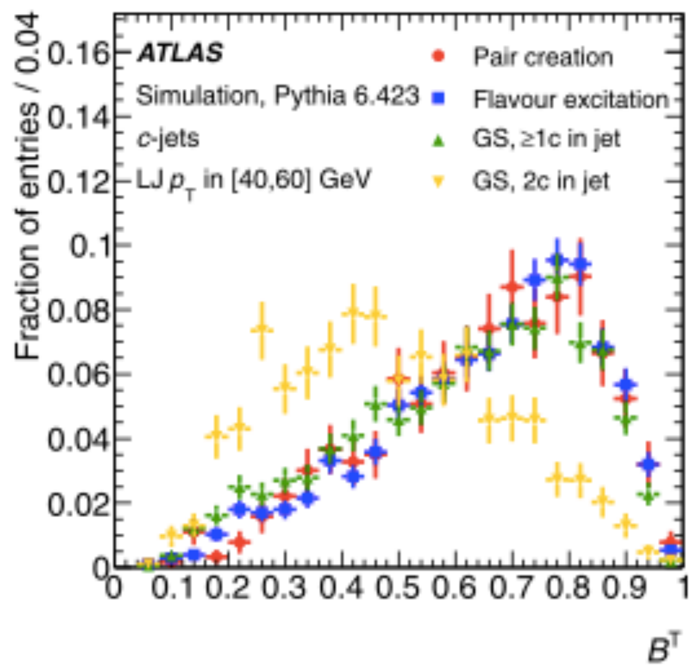
GS = Gluon Spliting

B^T distribution different for jets containing 1 or 2 b hadrons

Modifying the templates to including a free parameter, b2 : fraction of jets with 2 hadrons

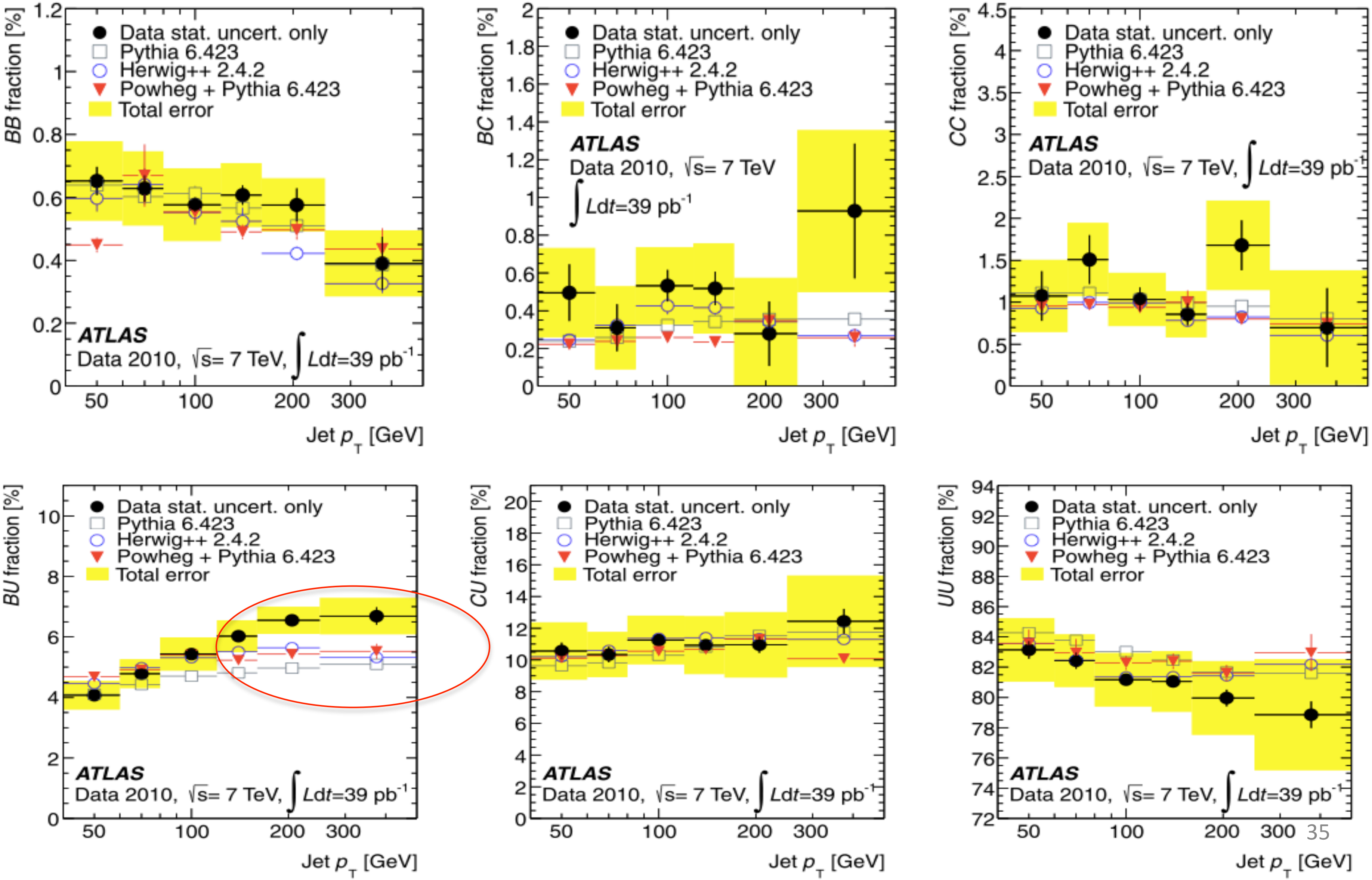
$$B(\Pi^\top, B^\top) \rightarrow (1-b_2)\cdot B(\Pi^\top, B^\top) + b_2 \cdot B_2(\Pi^\top, B^\top)$$

same treatment for c-hadrons.



Fitting the “flavor” templates to data
to extracting fractions of each component

simultaneous fitting results



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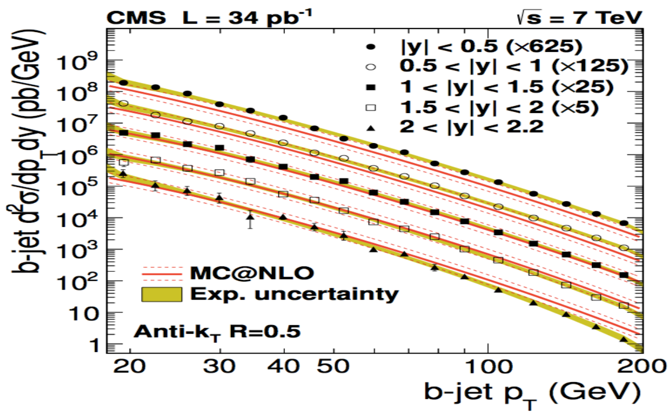
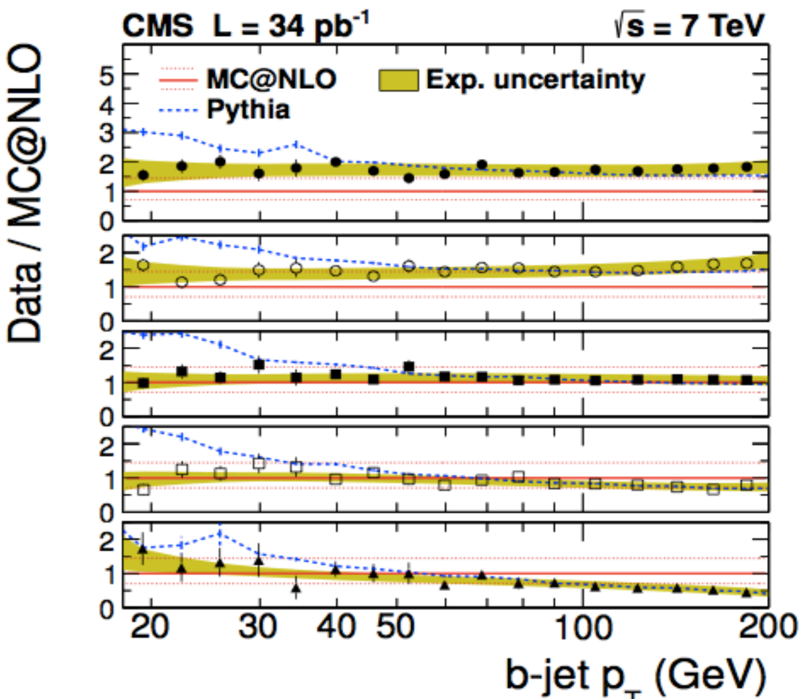
Similar ATLAS measurement Eur. Phys. J. C(2011) 71:1846

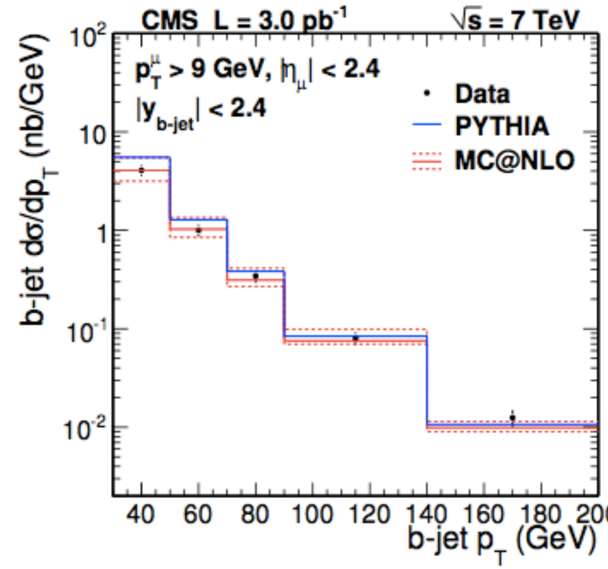
inclusive b jet production (CMS)

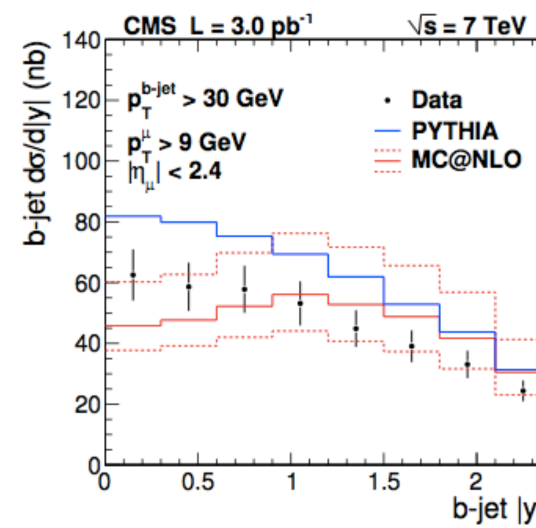
jet analysis: secondary vertex for tagging





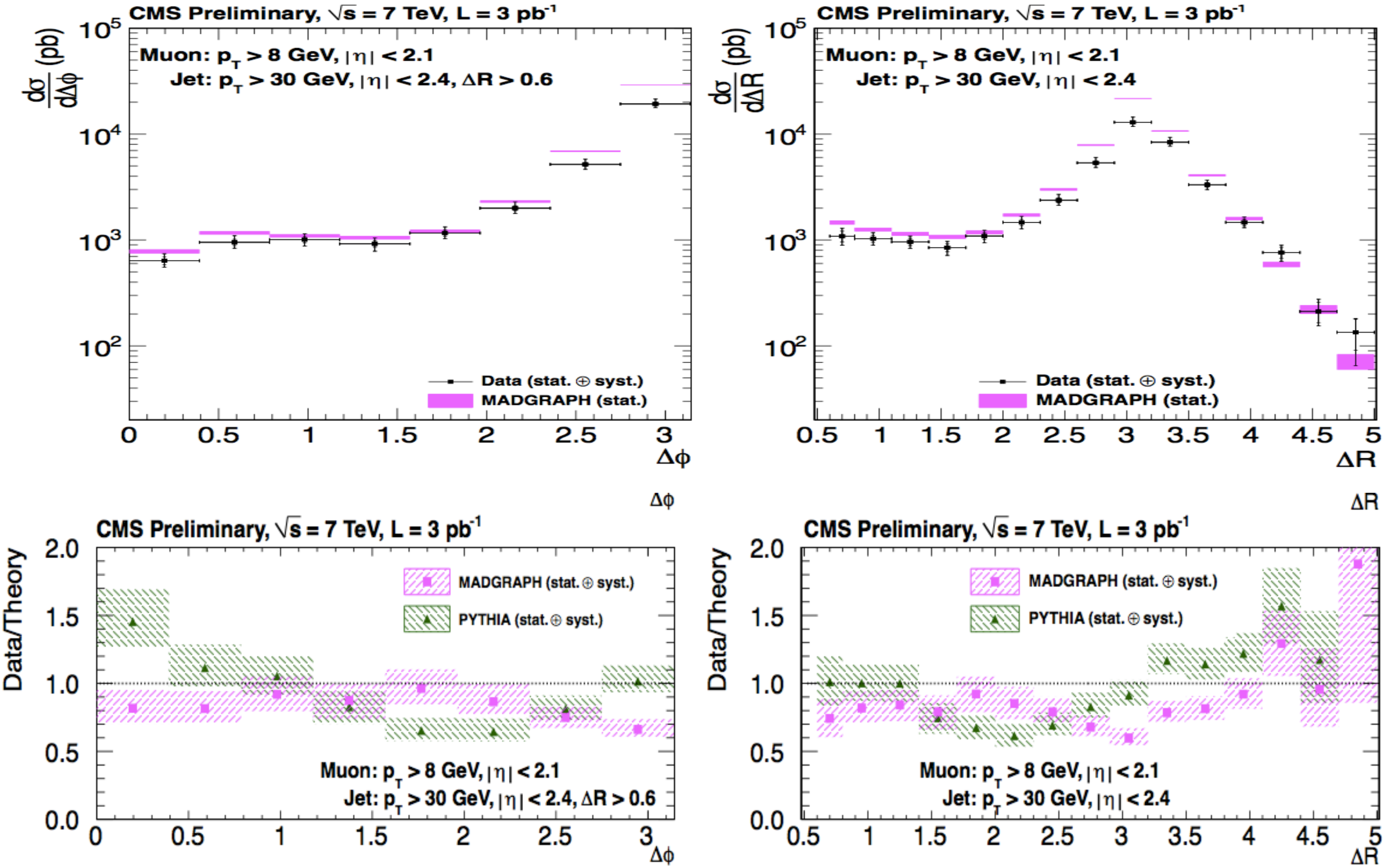
muon analysis: muon tagging





CMS PAS BPH-10-019

b-jet angular correlations



PYHTIA better at predicting the total rate, MadGraph better at predicting the shape.

Summary for part III

Heavy flavor production consistent with predictions.
LO MC not good enough in describing the data.

part IV:
Jet shape, substructure and mass

Looking inside the jets now!

Important technique for NP search

Jets from decays of a highly boosted heavy particle
merged as one “fat” jet.
Using the substructure to reconstruct the mass of the heavy particle.

arXiv:1307.5749

Jet shapes in ttbar events

pT distributions of b-tagged jets (NN tagger)

MC :

baseline generators : MC@NLO and POWHEG

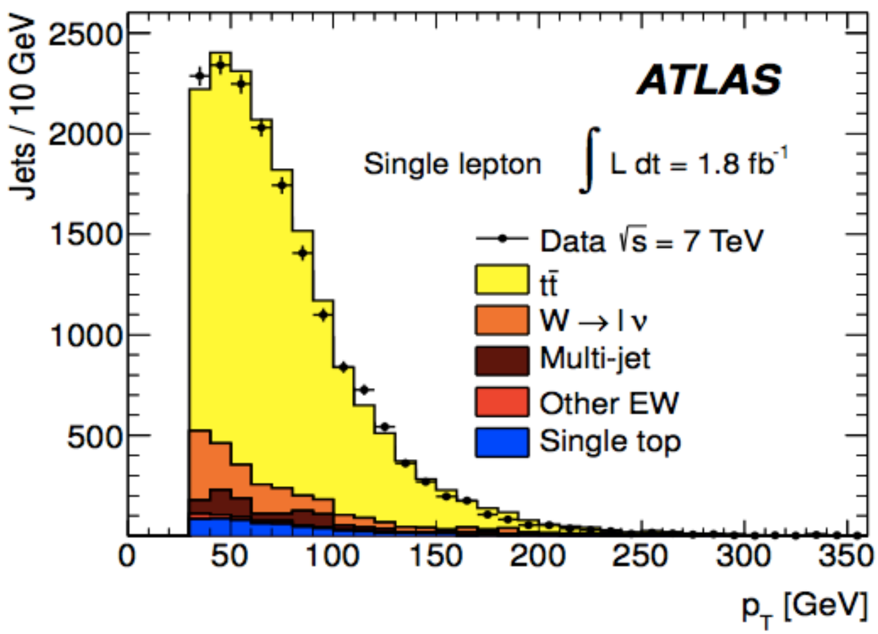
normalized to best cross sections available

Event selection:

two lepton

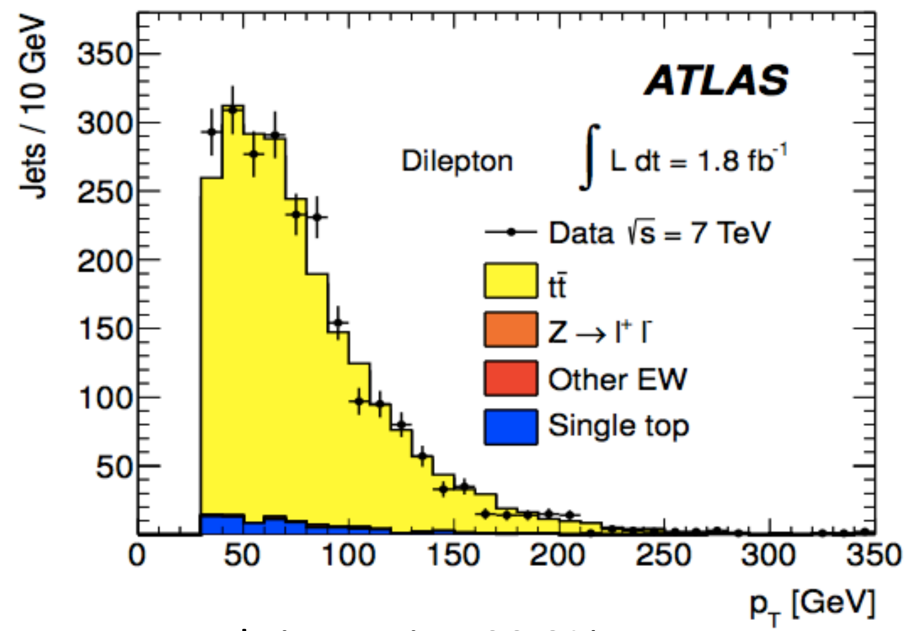
MET

2 jets (at least 1 b-tag)



require 1 lepton, 4 jets, MET

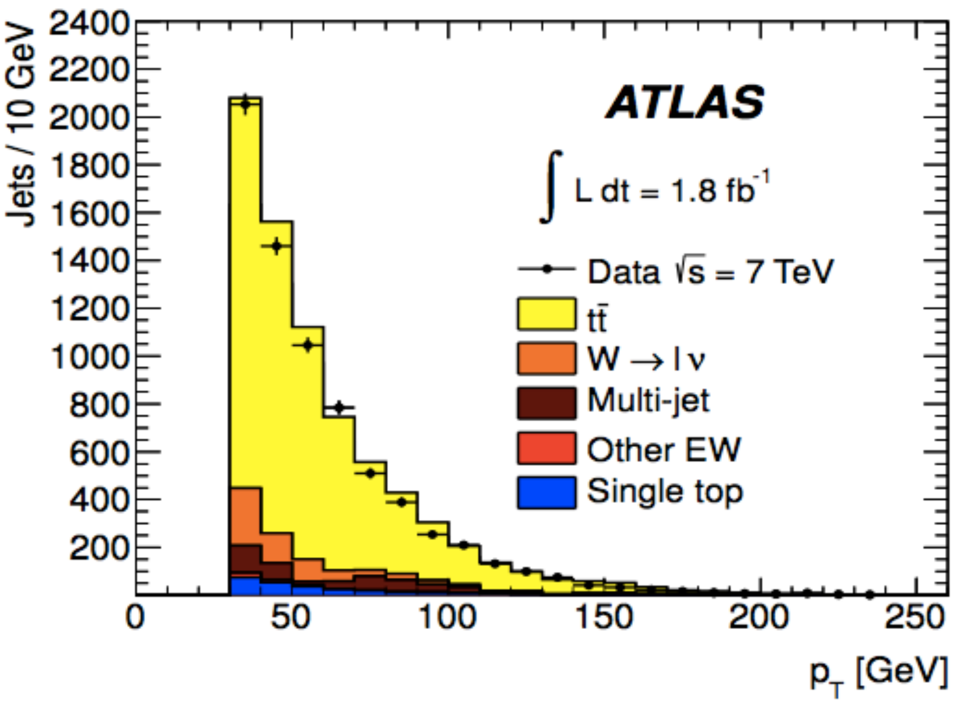
b-jet purity: 88.5%

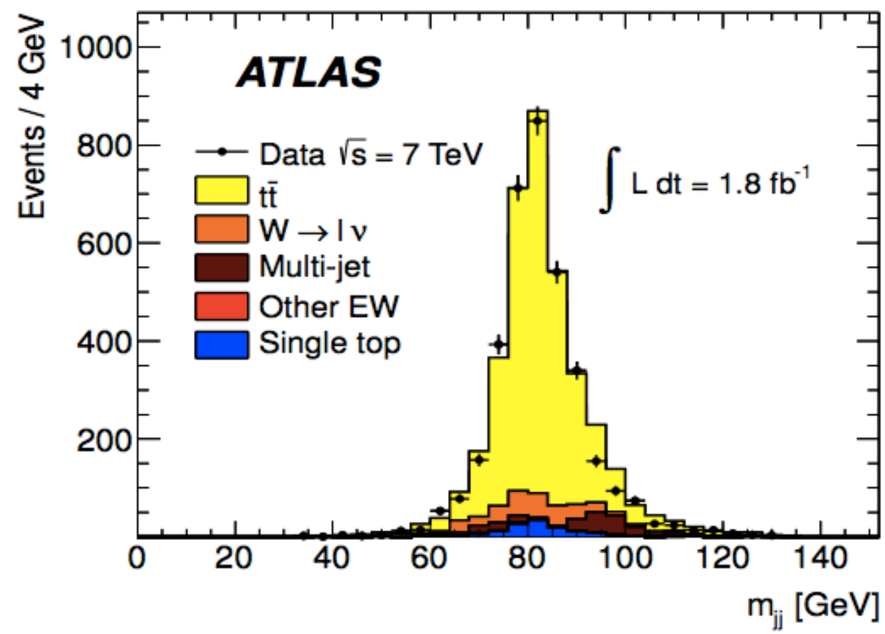


b-jet purity: 99.3%

ttbar events at LHC : pure b-jet sources

light jets in ttbar events



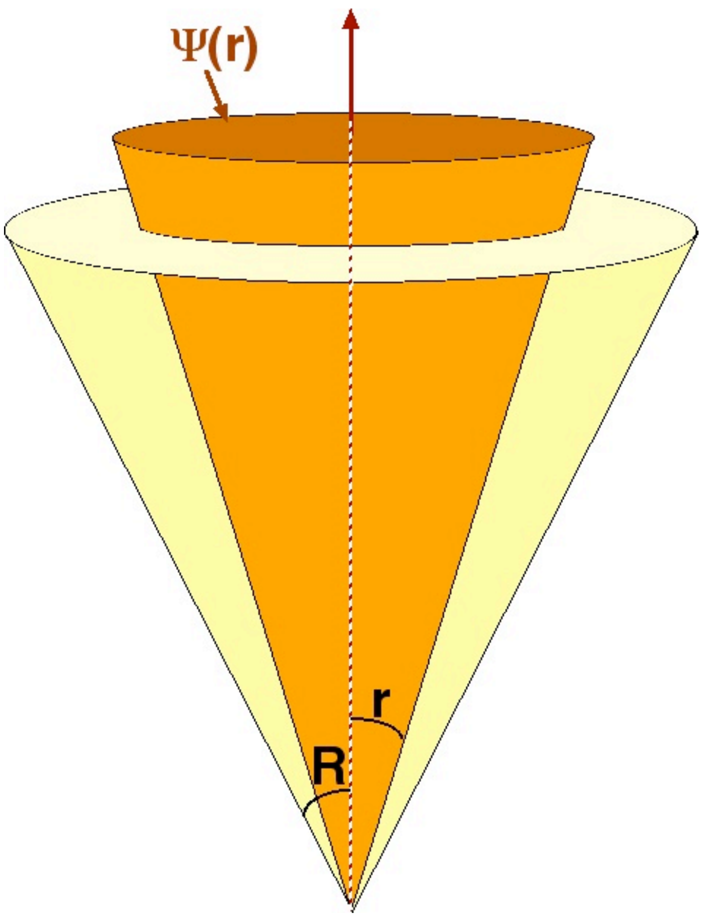


light jet from single-lepton channel.
purity: 66.2%

differential and integral jet shape

$$\Psi(r) = \frac{p_T(0,r)}{p_T(0,R)};\; r \leq R$$

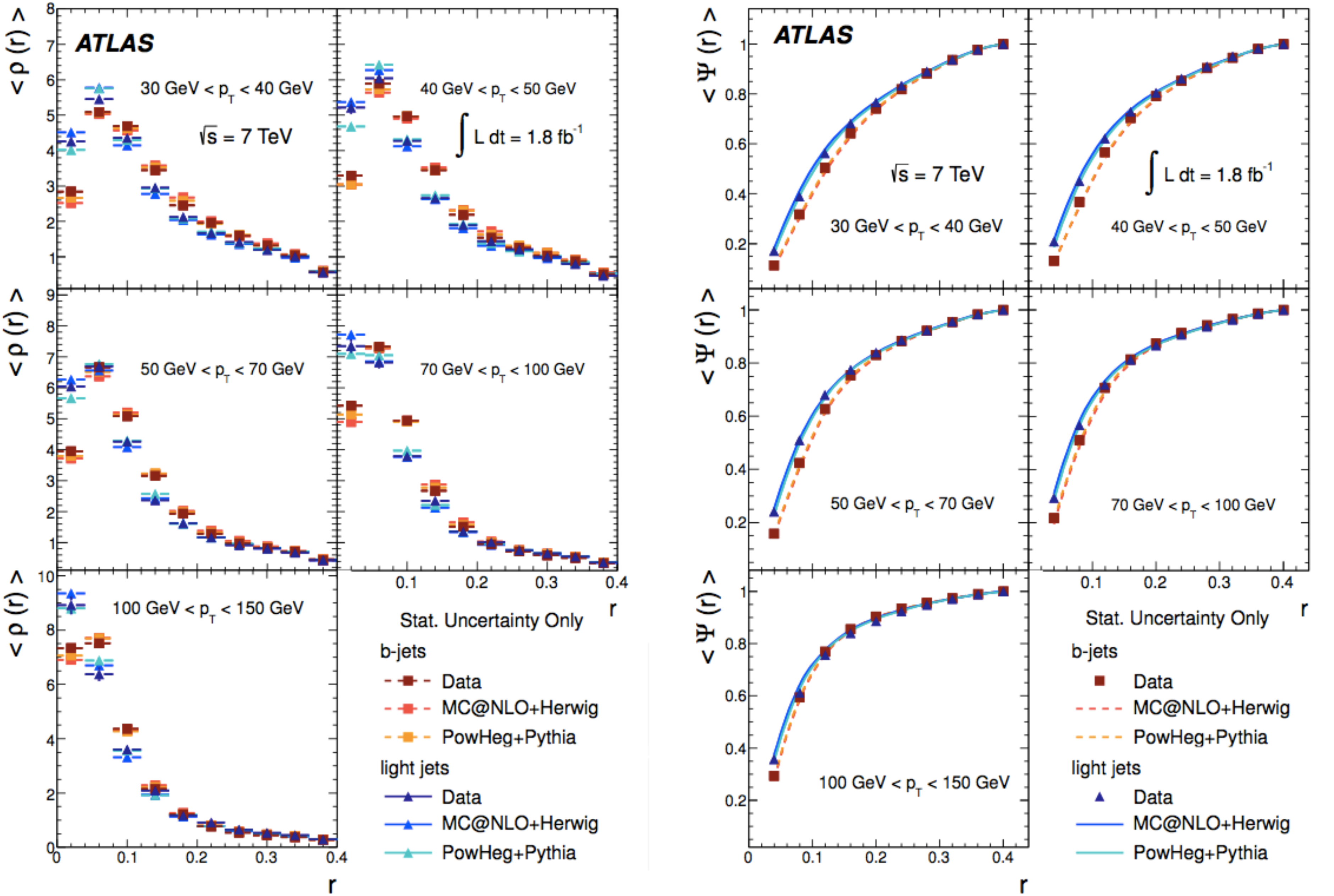
$$\rho(r) = \frac{1}{\Delta r}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)}$$



$$\langle\Psi(r)\rangle = \frac{1}{N_{\text{jets}}}\sum_{\text{jets}}\frac{p_T(0,r)}{p_T(0,R)}$$

$$\langle\rho(r)\rangle = \frac{1}{\Delta r}\frac{1}{N_{\text{jets}}}\sum_{\text{jets}}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)}$$

For current analysis , set $\Delta r = 0.04$

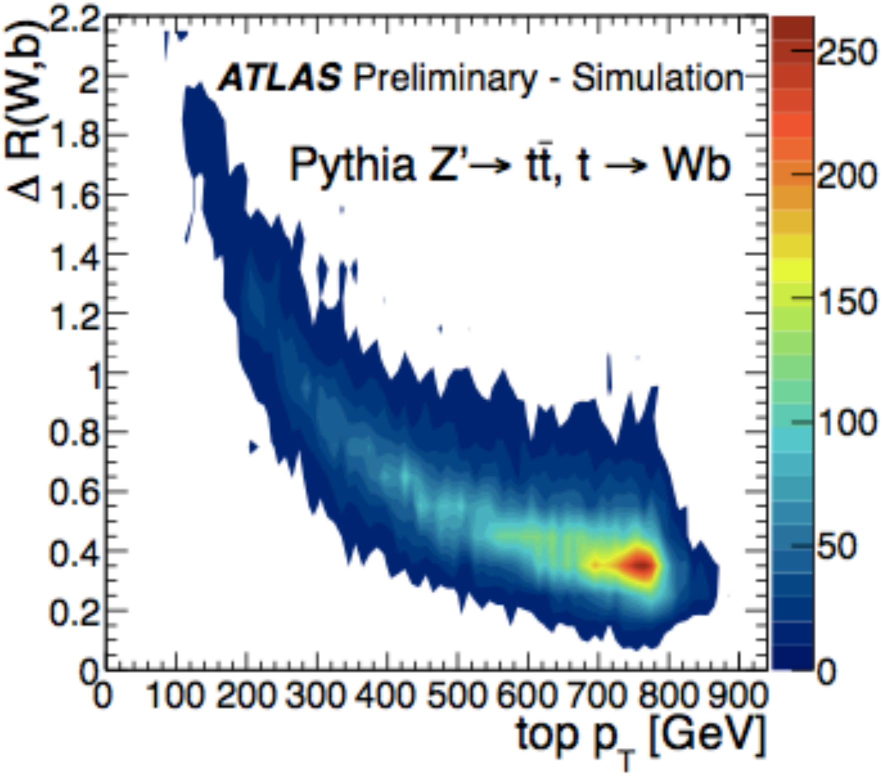


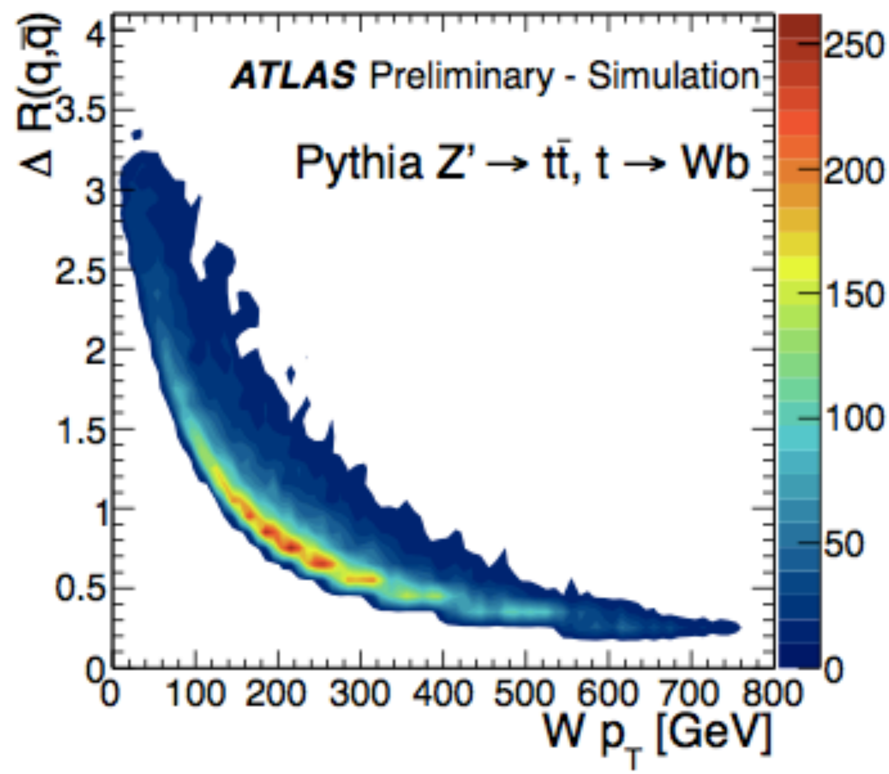
shapes well described by MC

On average, b jets broader than light jets as expected due to higher mass of b quarks

ATLAS-CONF-2012-065

Jet mass and substructure



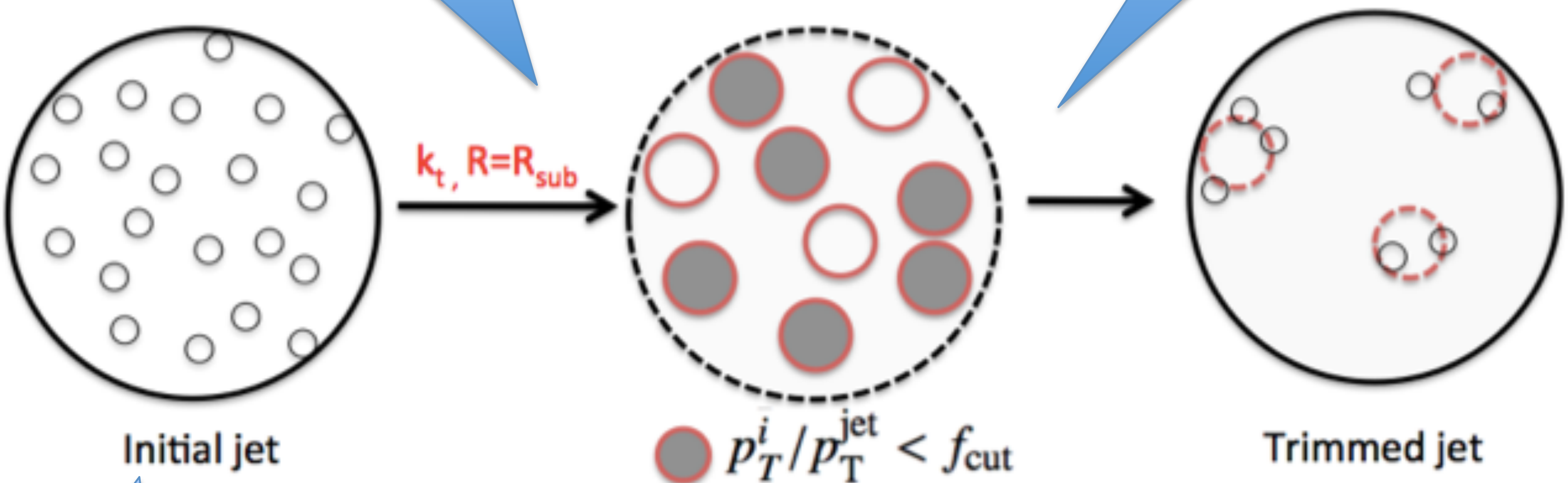


Particles from top decay form a "fat" jet.
The large jet area contaminated with energies from pile-up
To be removed by "grooming".

trimming

re-cluster the constituents with smaller cone

keep only the sub jets above certain fraction of jet pT

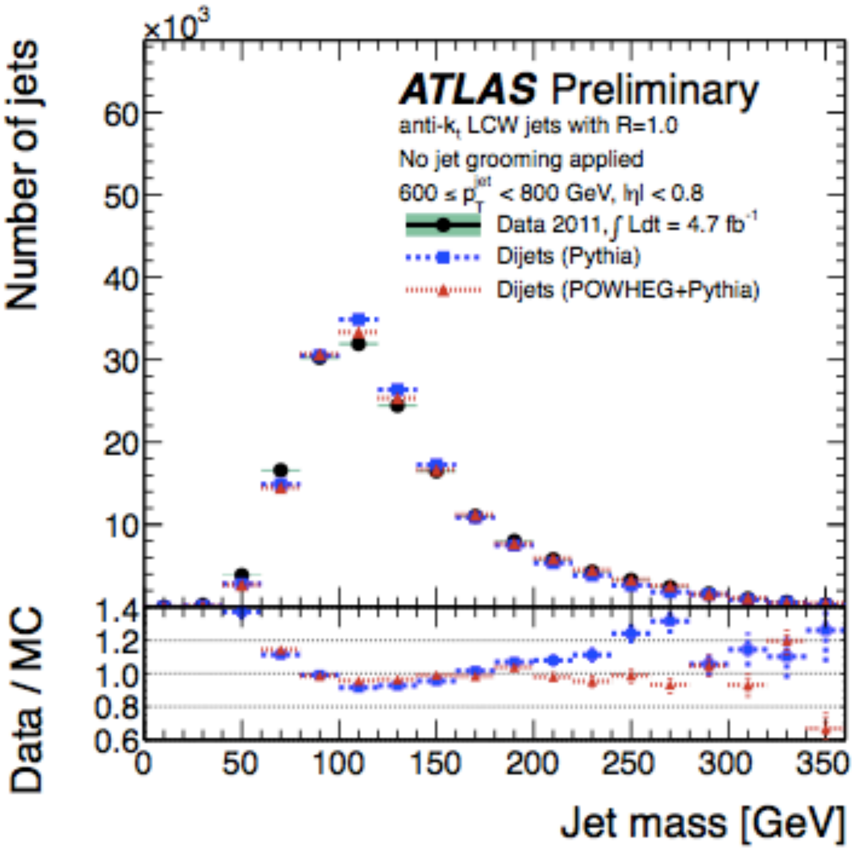


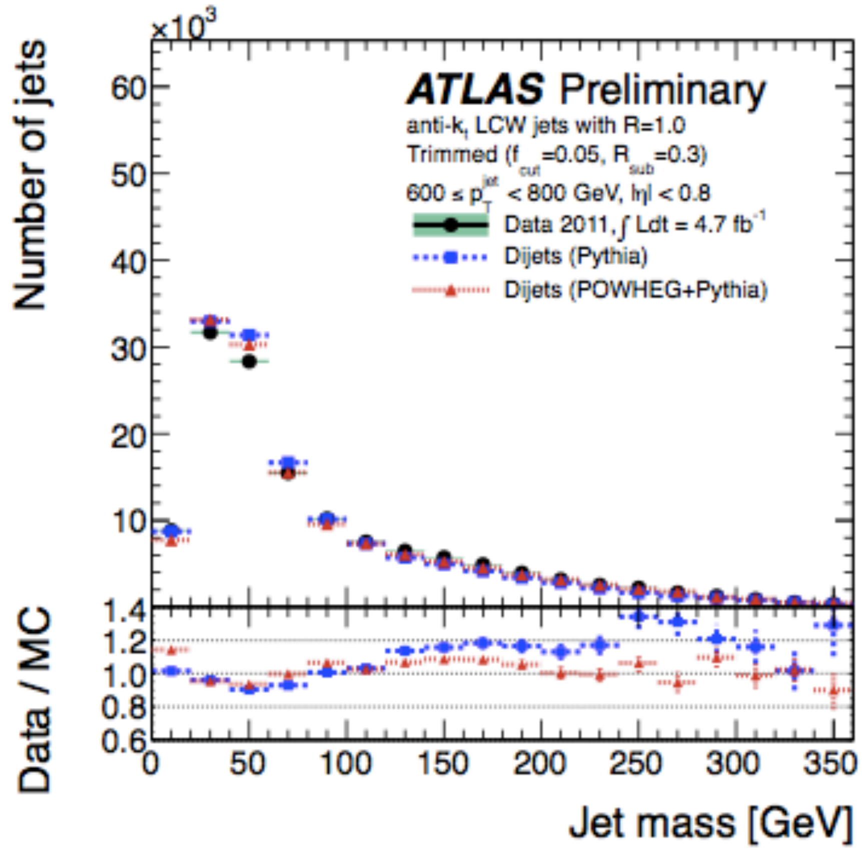
jet algorithm with large distance parameter

remove soft sub-jets.

impact on jet mass

inclusive di-jet sample



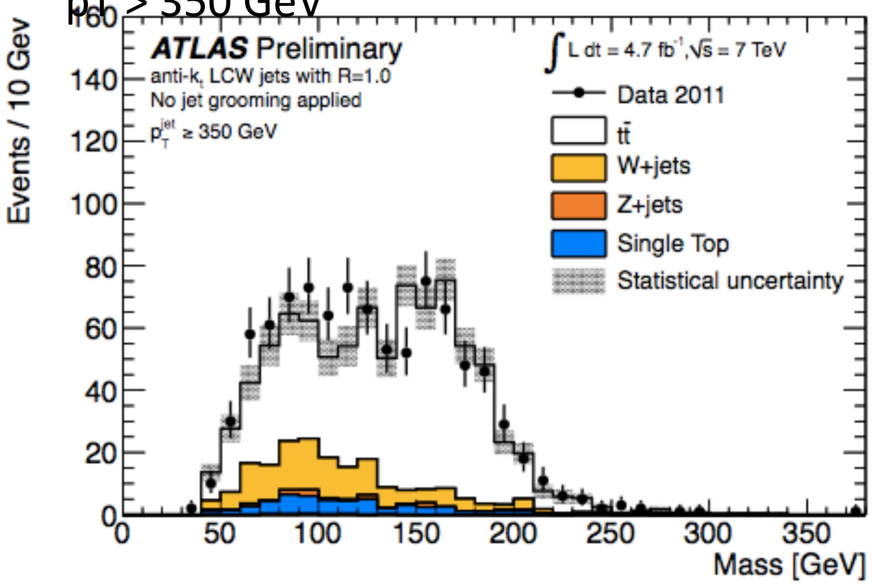


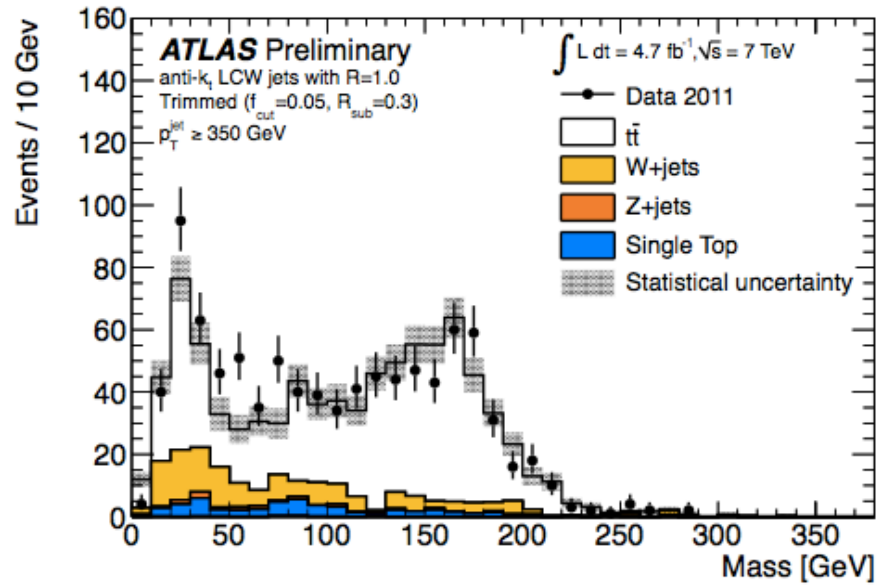
full 2011 data

jet mass in ttbar events

ttbar single-lepton channel
require a b-tagging
anti k_T R = 1.0

pT > 350 GeV





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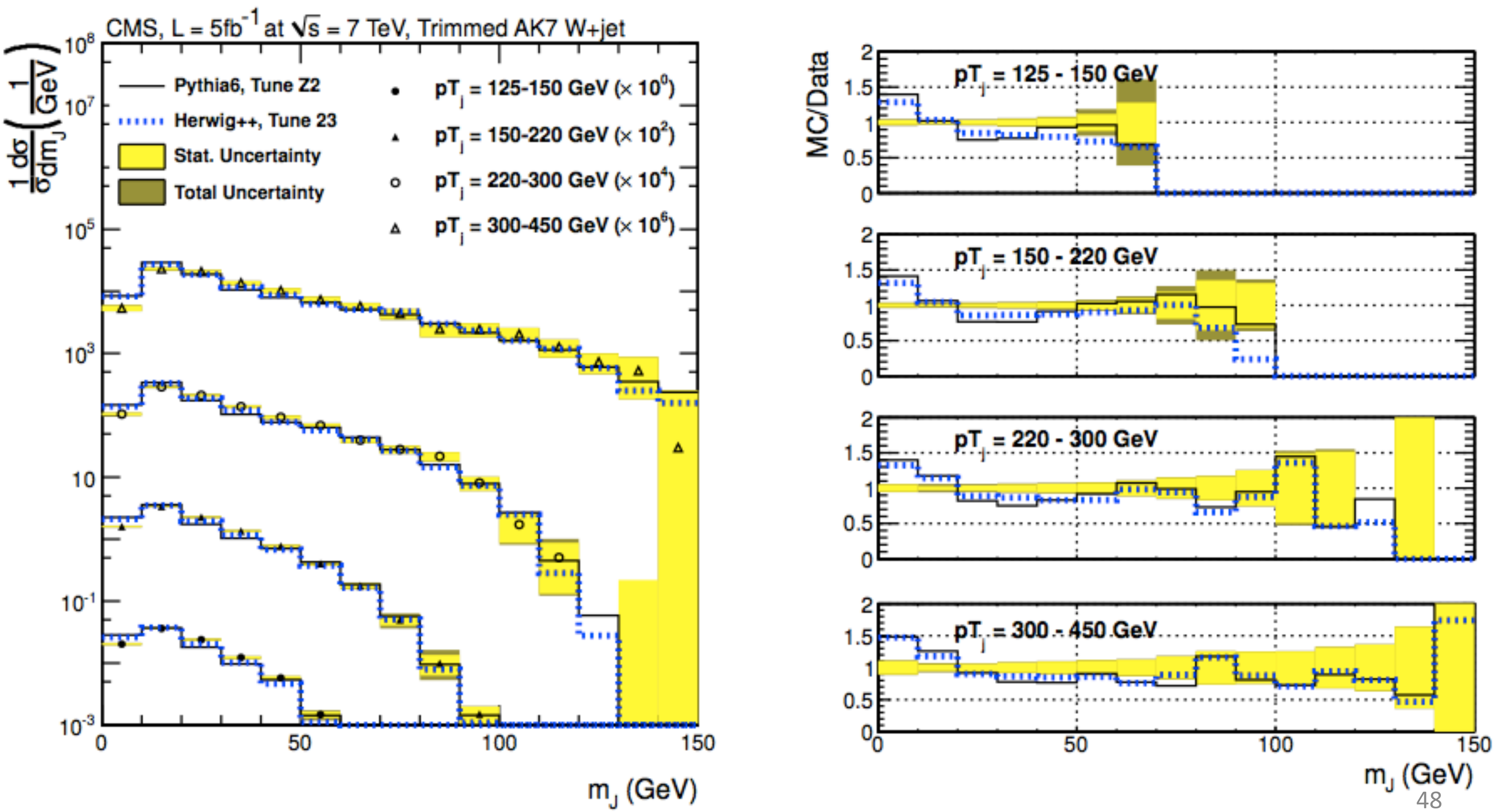
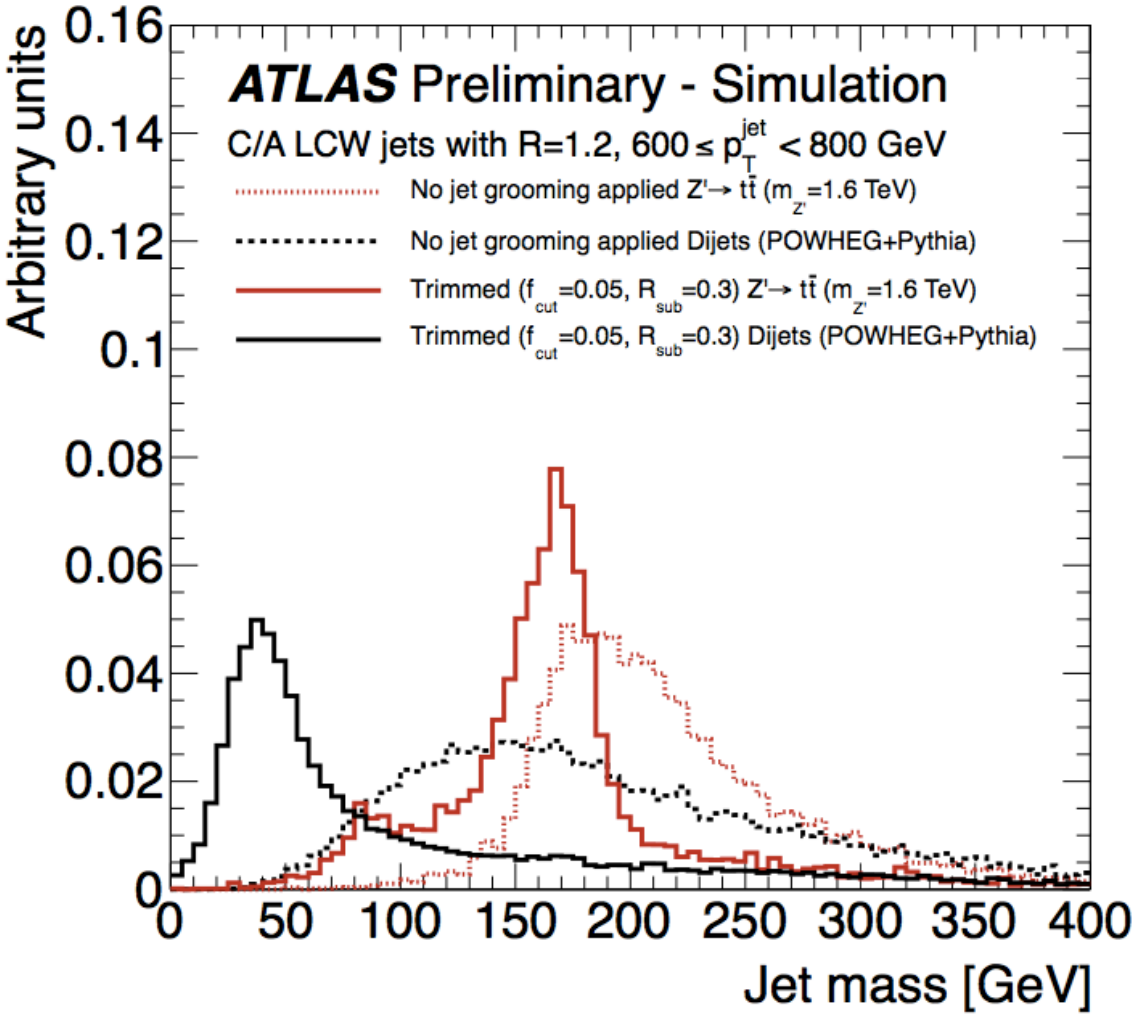
CMS trimmed jet mass



future : Z’ -> ttbar



Summary for part IV

Shapes of light jets and b well described by MC

Jet substructure technique tested on di-jet and ttbar events:

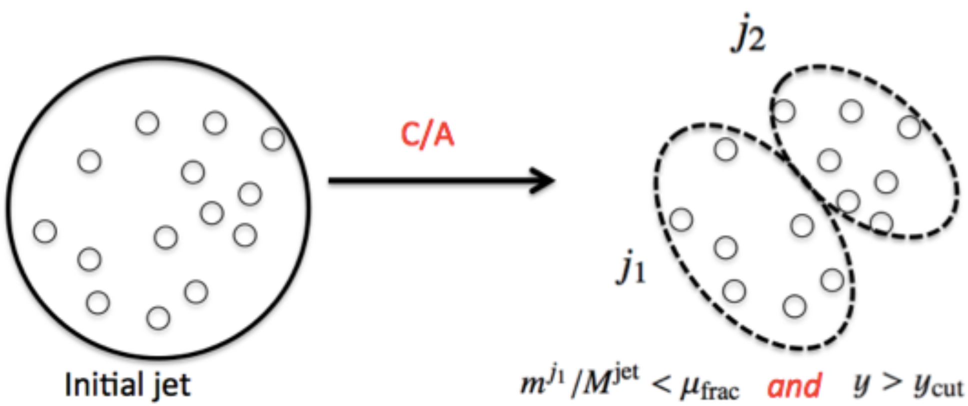
Working!

Summary

- QCD works!
  - Good theory/data agreement in jet measurements (pQCD)
  - Starting to constraint PDF, no perturbative effects modeling
  - Strong coupling constant consistent with previous results
- jet shape and substructure technique tested with jet and ttbar data. Promising for new physics searches.

back up slides

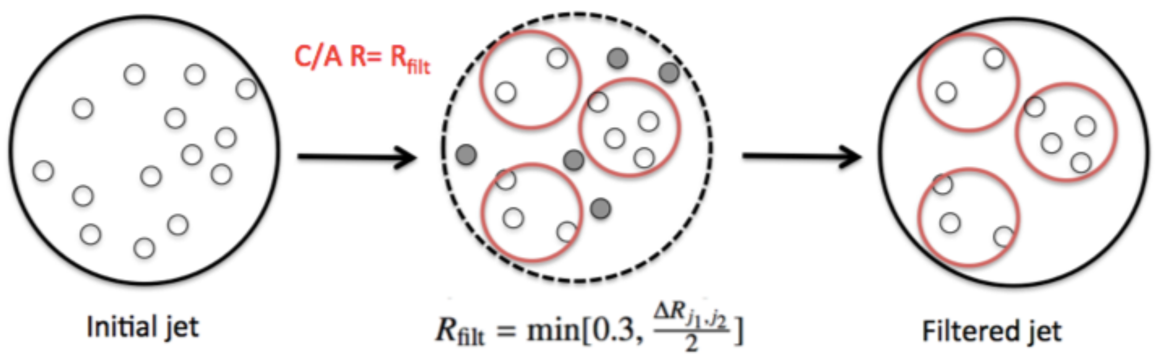
filtering algorithms



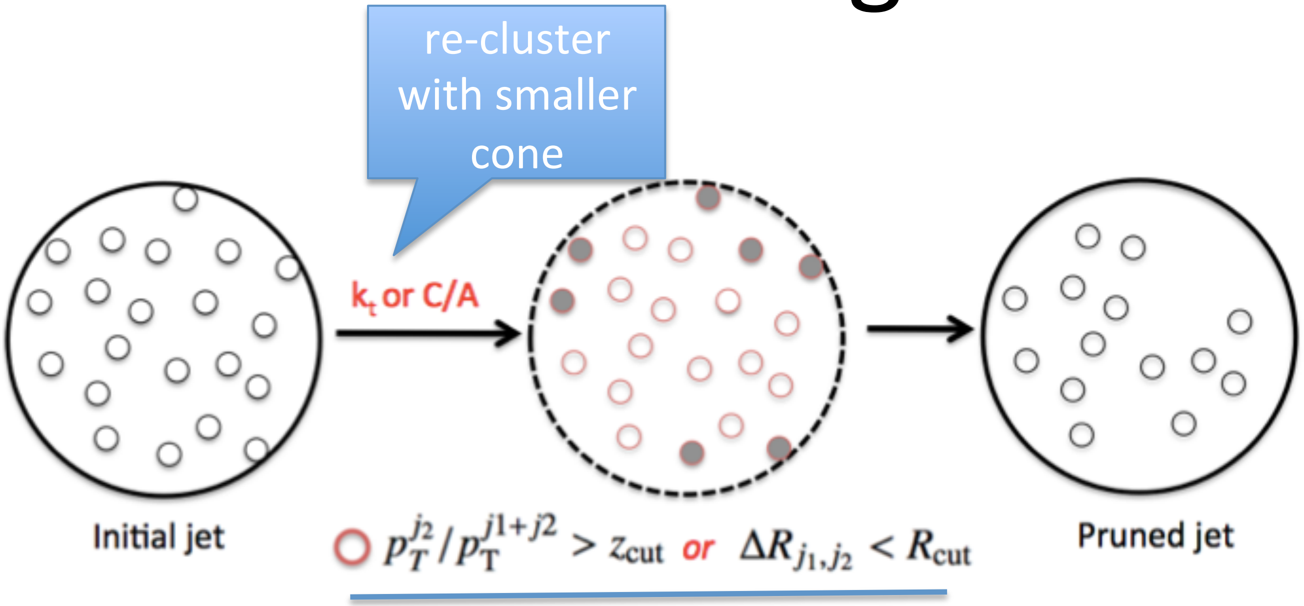
$$\frac{\min[(p_T^{j_1})^2, (p_T^{j_2})^2]}{(m^{\mathrm{jet}})^2} \times \Delta R^2_{j_1,j_2} > y_{\mathrm{cut}}$$

Mass drop and symmetric splitting

for each sub jet:



Pruning



If yes, merge j1 and j2.
Otherwise, drop j2.

Jet algorithms

$$\rho_{ij} = \min\left(p_{Ti}^{2p}, p_{Tj}^{2p}\right) \frac{(\Delta R_{ij})^2}{R^2}$$

"Distance between proto-jets"

$$\rho_{iB} = p_{Ti}^{2p}$$

"Beam distance"

if $\rho_{ij} < \rho_{iB}$, i, j combined as one proto-jet

k_t : p = +1

Cambridge-Aachen : p = 0

anti-k_t: p = -1