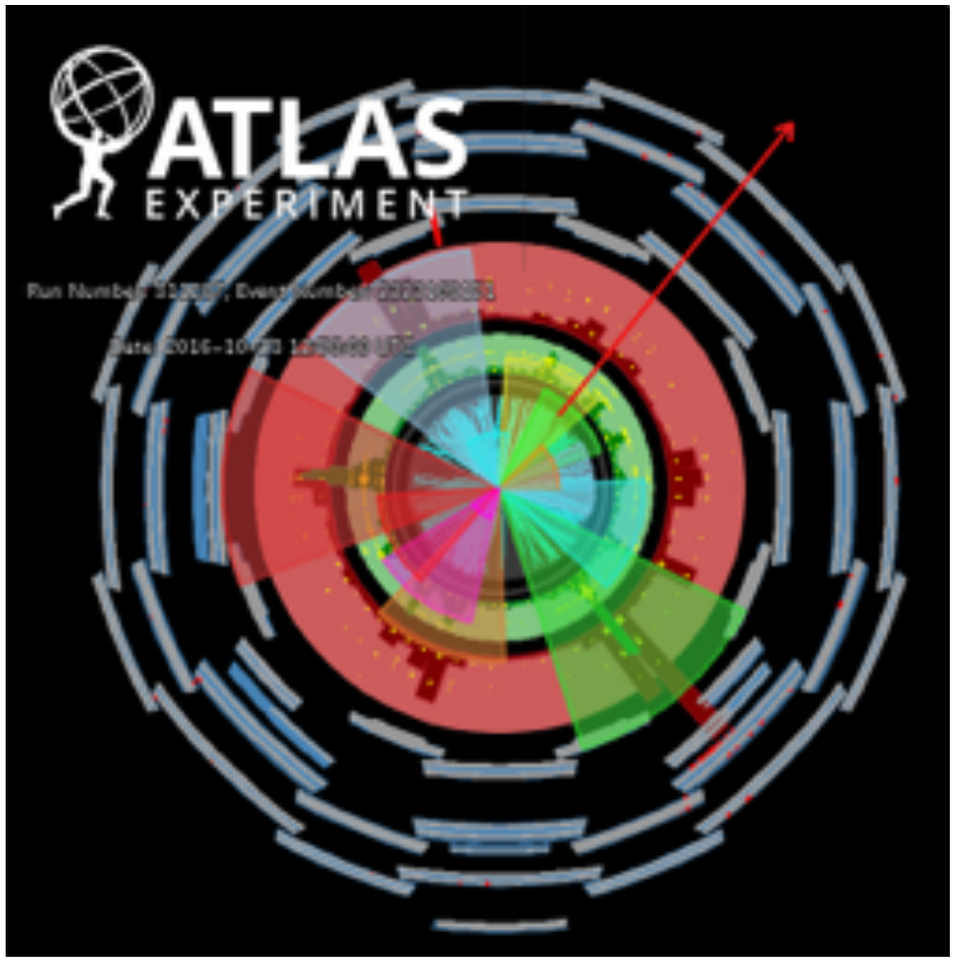
Status of Jet Substructure and W/Z/H tagging in the ATLAS



Shih-Chieh Hsu
University of Washington Seattle

May 18 2017
EPE Seminar in UW

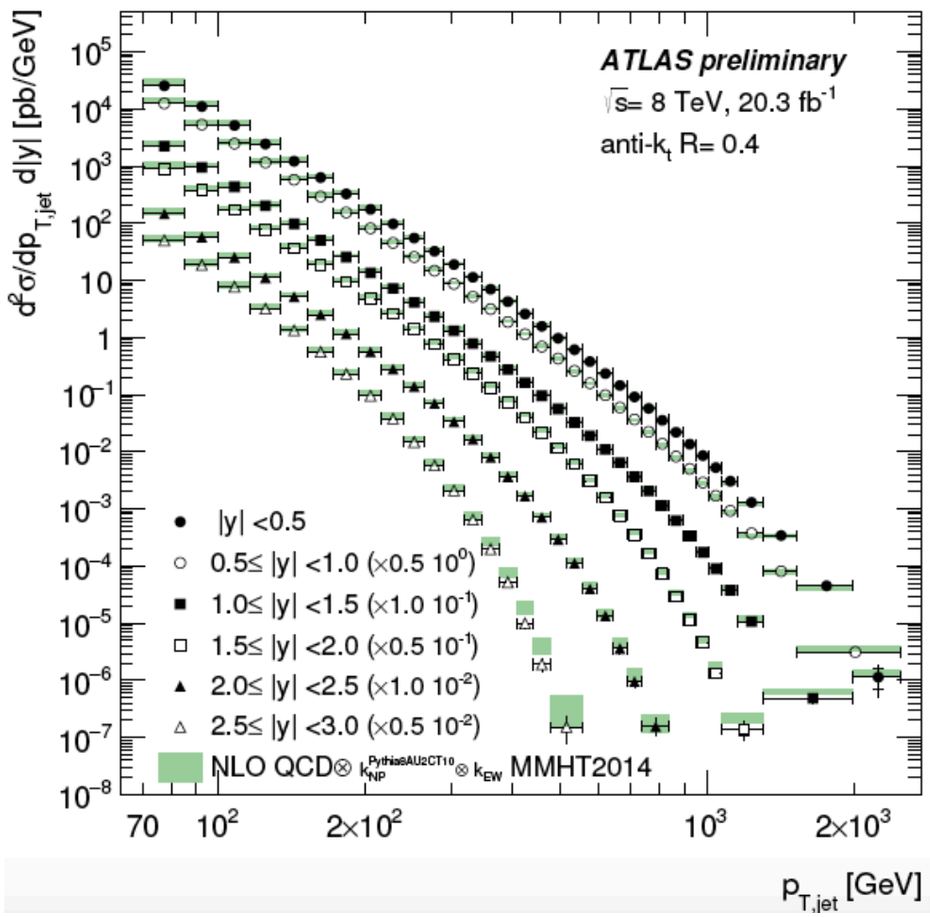
Outline

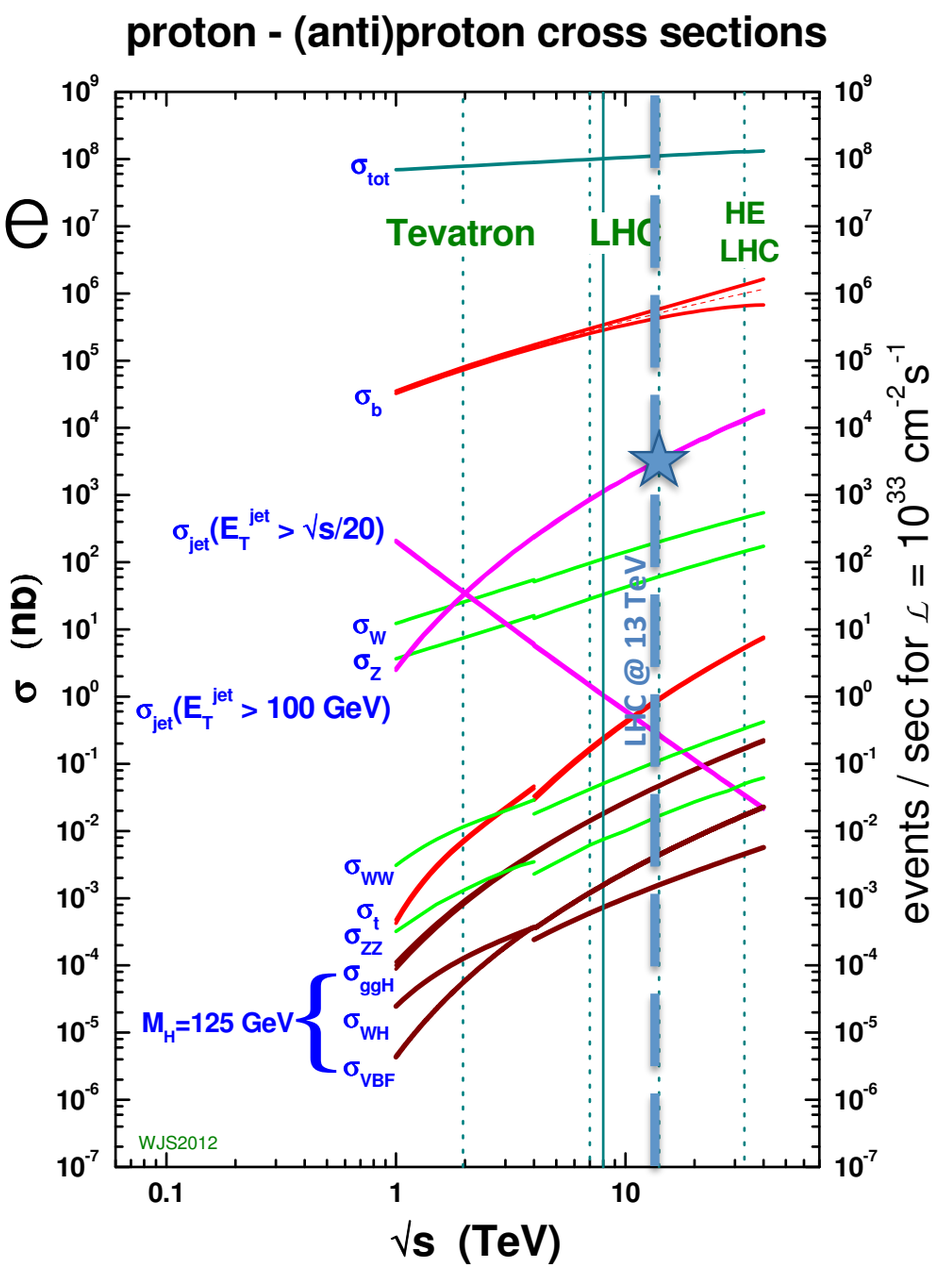
- Introduction
- Jet Reconstruction
- Jet substructure
- Advanced W/Z/H tagging

Jets at the LHC

The QCD understanding of jets production is a key component to extend our understanding of the SM background to BSM search

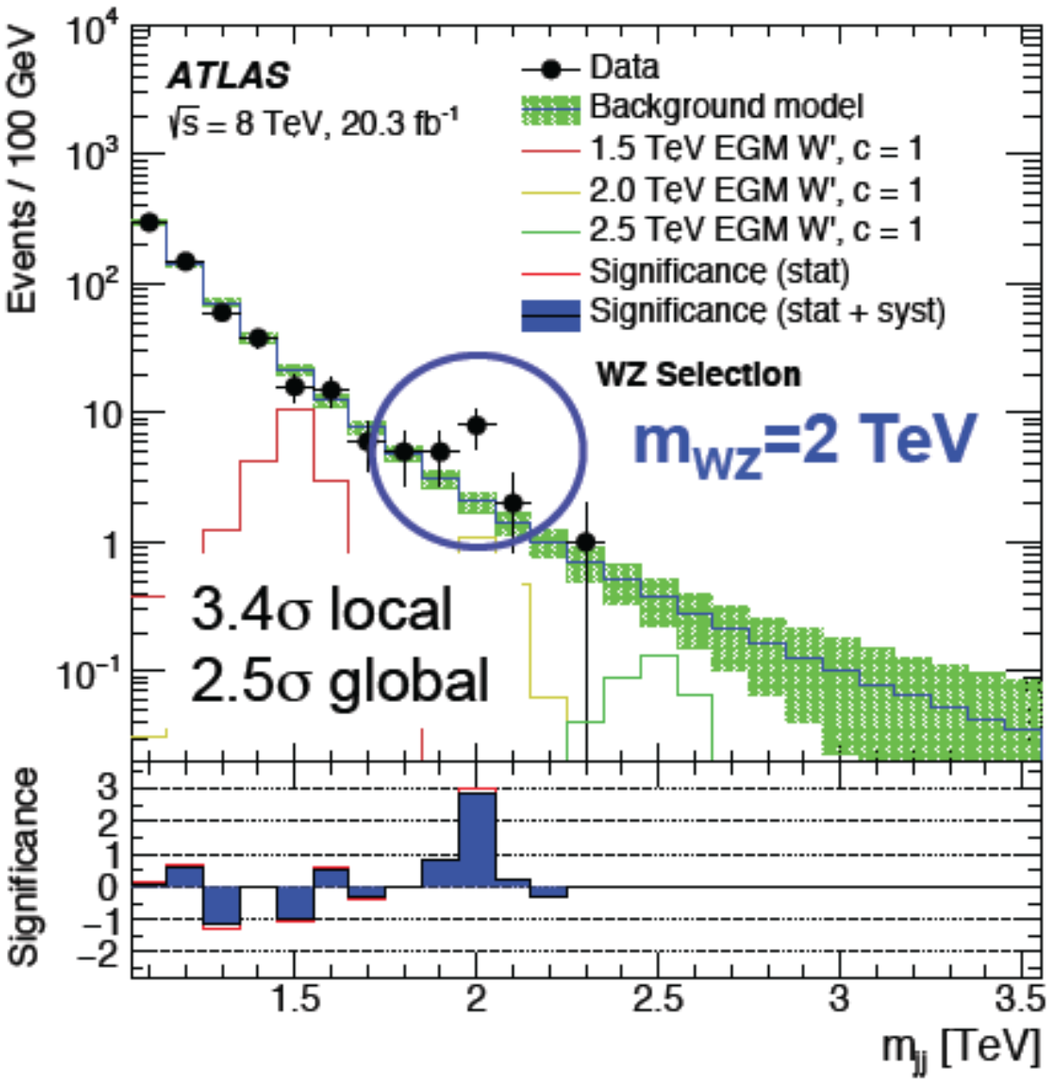
- proton structure: PDF uncertainty
- strong coupling α_s :up to TeV scale





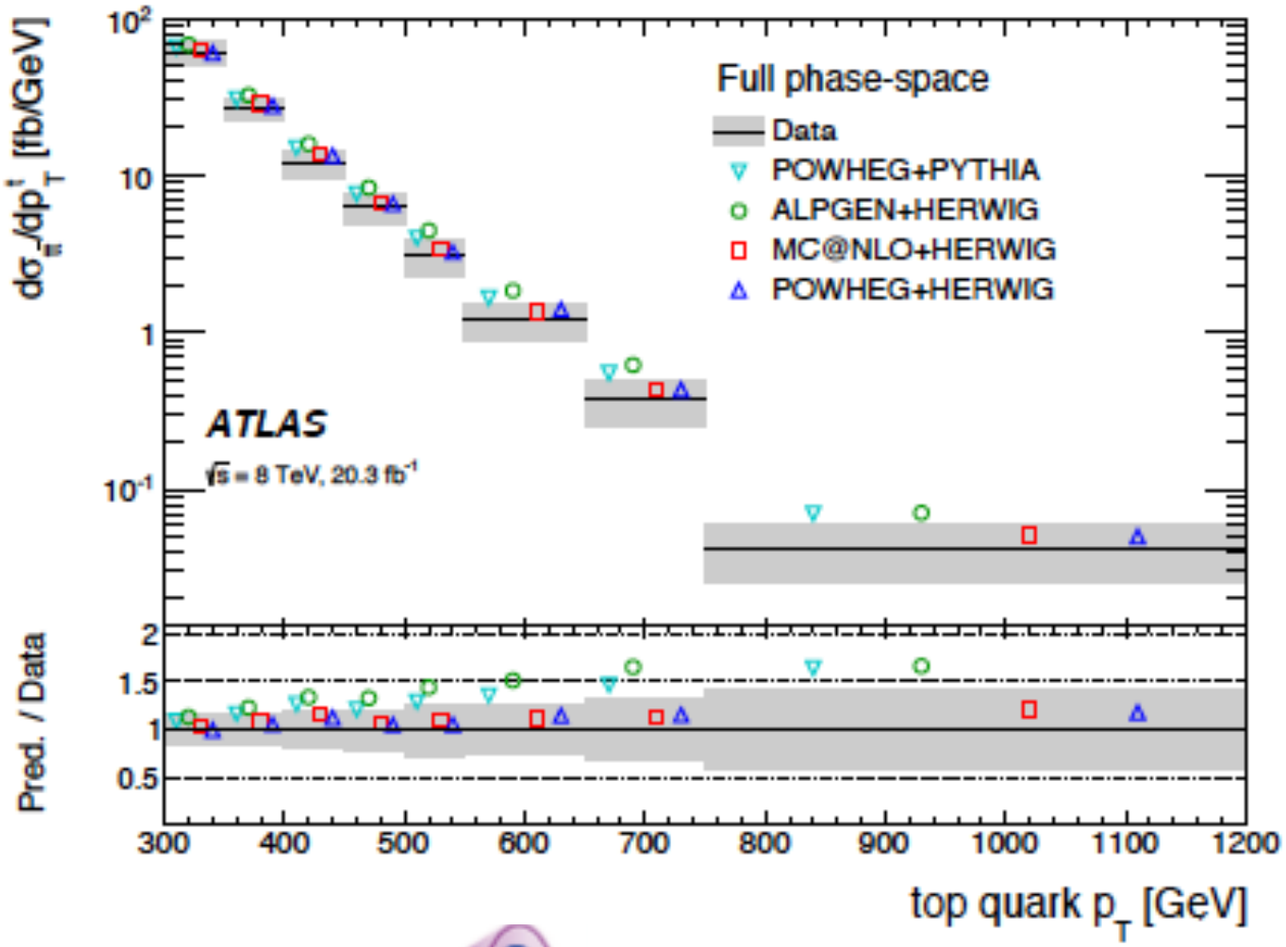
Physics with Jets

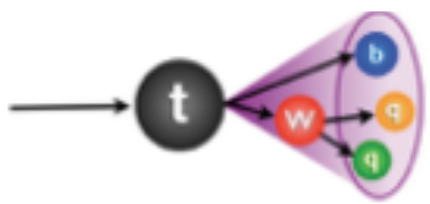
Search



Run1 (2012)

Measurement





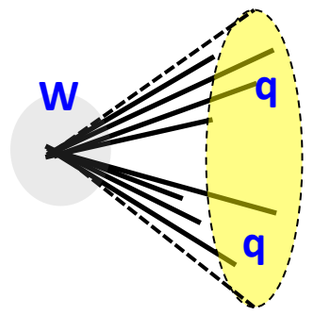
Phys. Rev. D 93, 032009 (2016)

JES uncertainty 13-29%

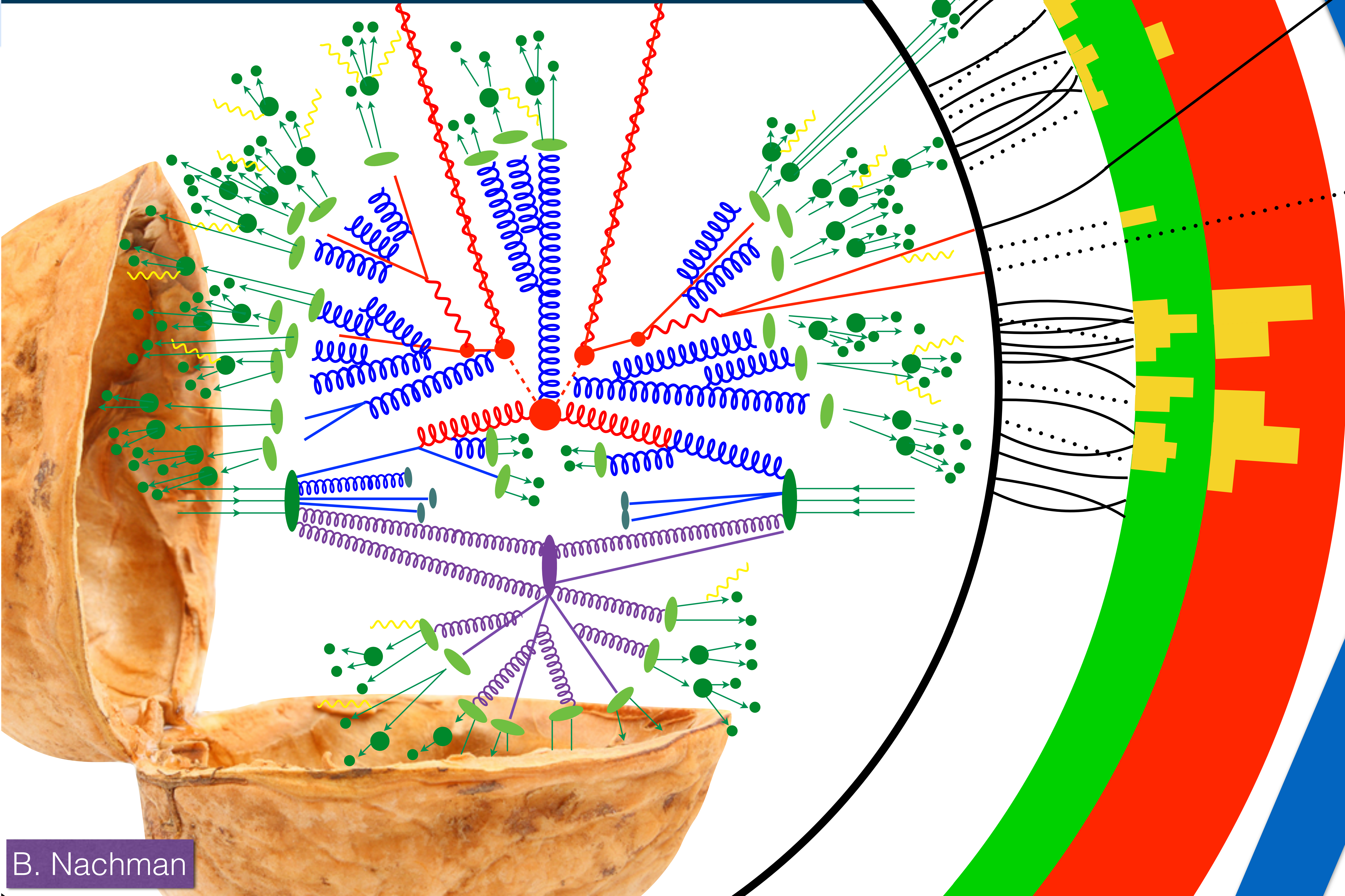
Jets

- Jets are key objects for discovery in ATLAS
  - A protocol of quarks and gluons
  - Cluster together energy depositions in the calorimeter
  - Combination of jets are used to identify unstable massive particles, e.g. W, Z and Higgs

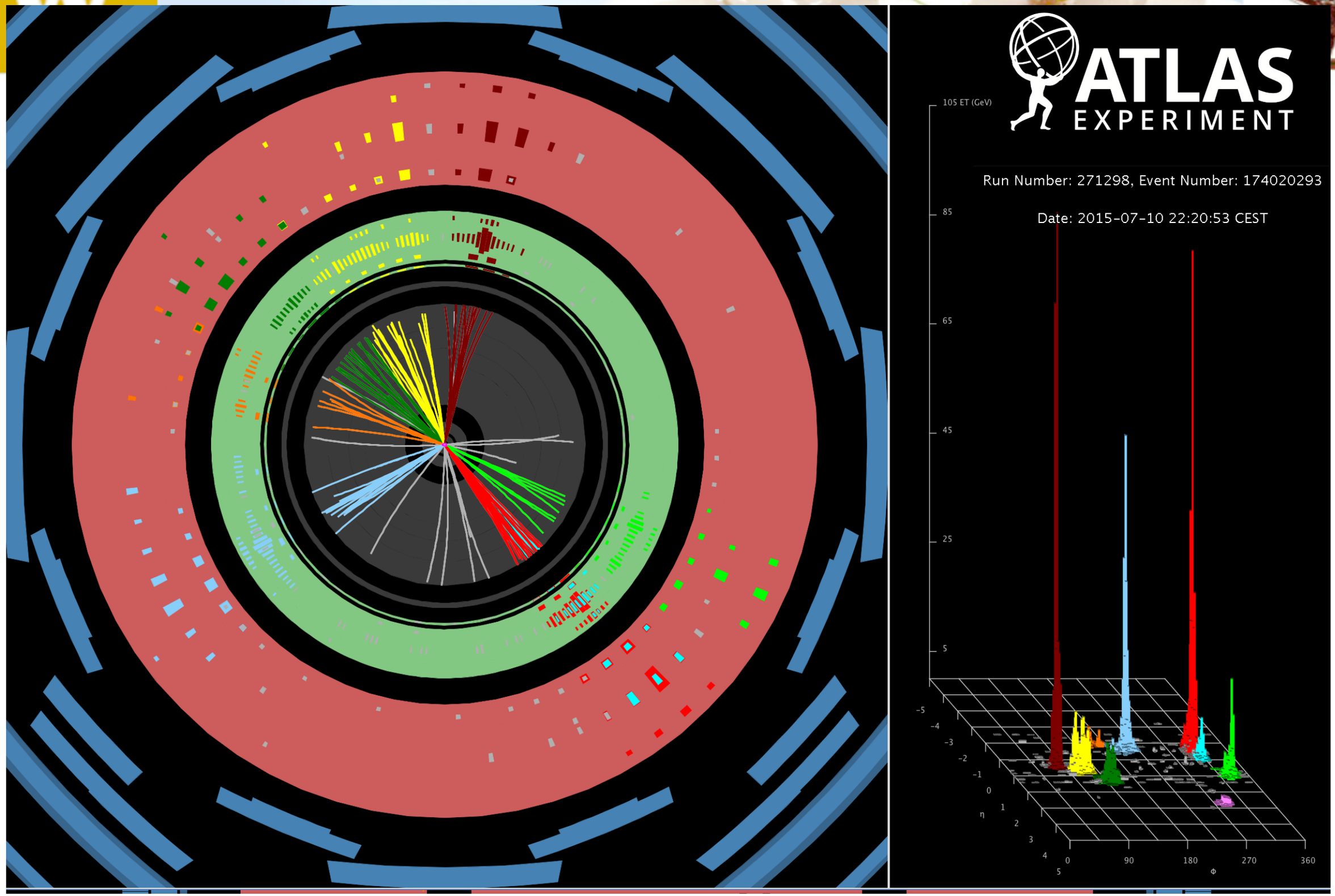
- Highly boosted (large momentum) states (W,Z,Higgs) can be reconstructed as single jets



Jets in a nutshell



B. Nachman


ATLAS
EXPERIMENT
Run Number: 271298, Event Number: 174020293
Date: 2015-07-10 22:20:53 CEST
105 ET (GeV)
85
65
45
25
5
-5
-4
-3
-2
-1
0
1
2
3
4
5
η
0
90
180
270
360
Φ

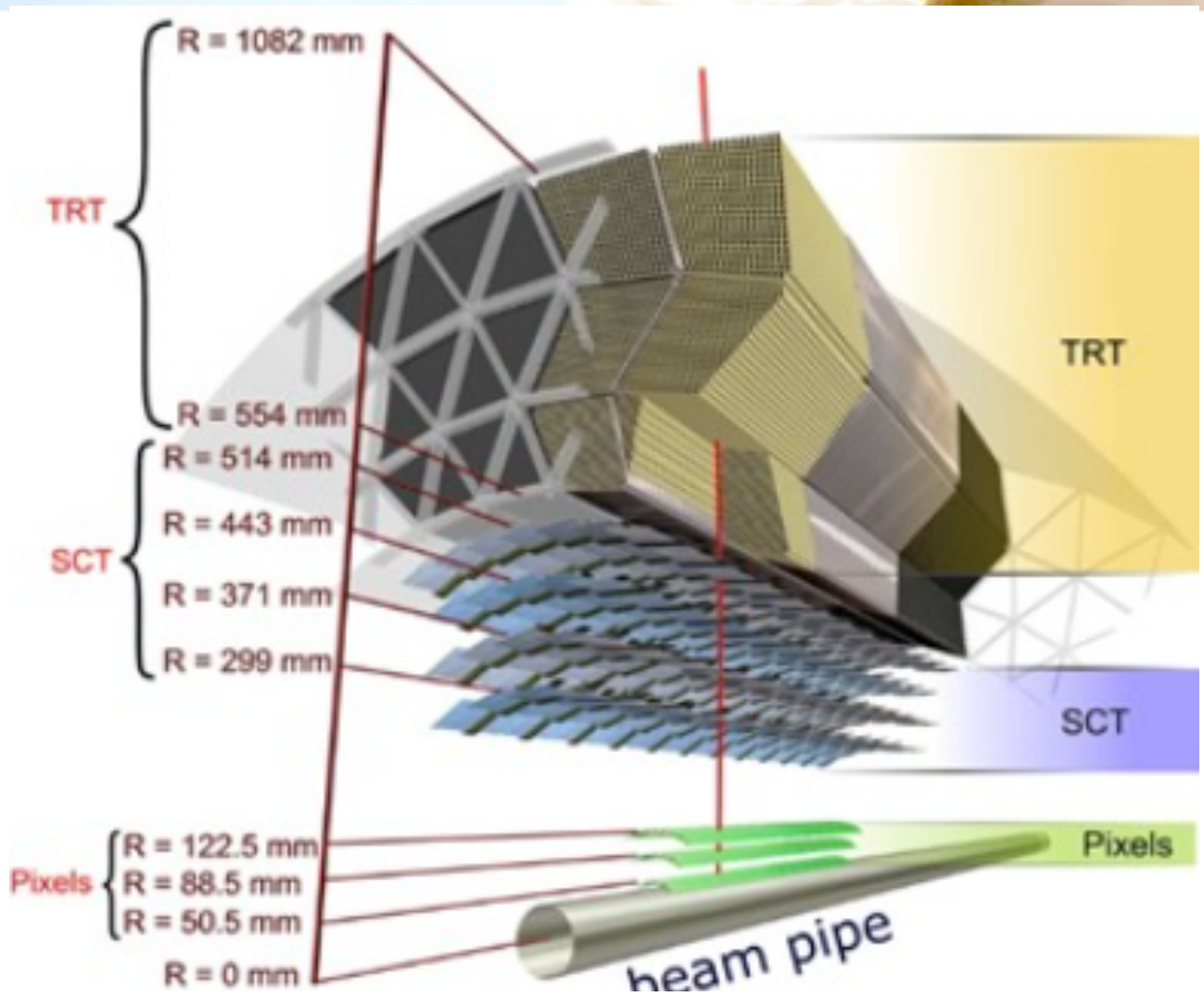
Challenge

2016

O(30-50) Pile-up events

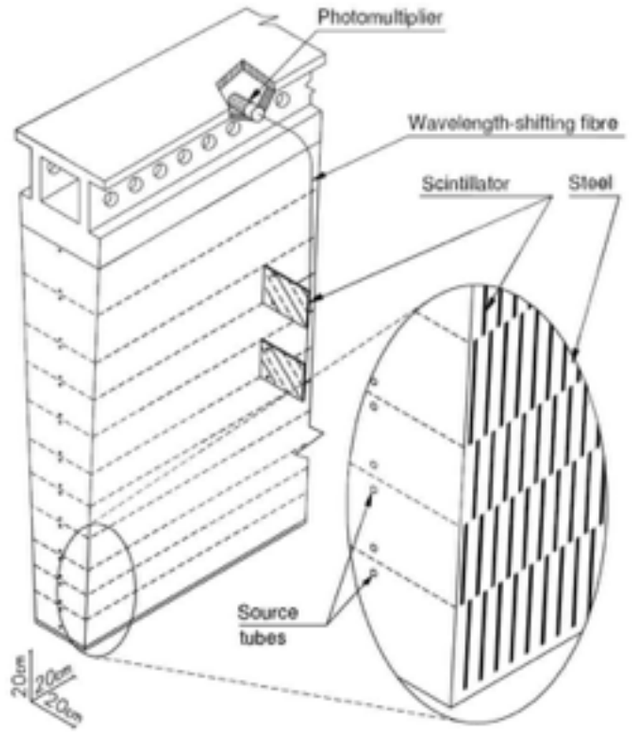
25 ns inter-bunch spacing

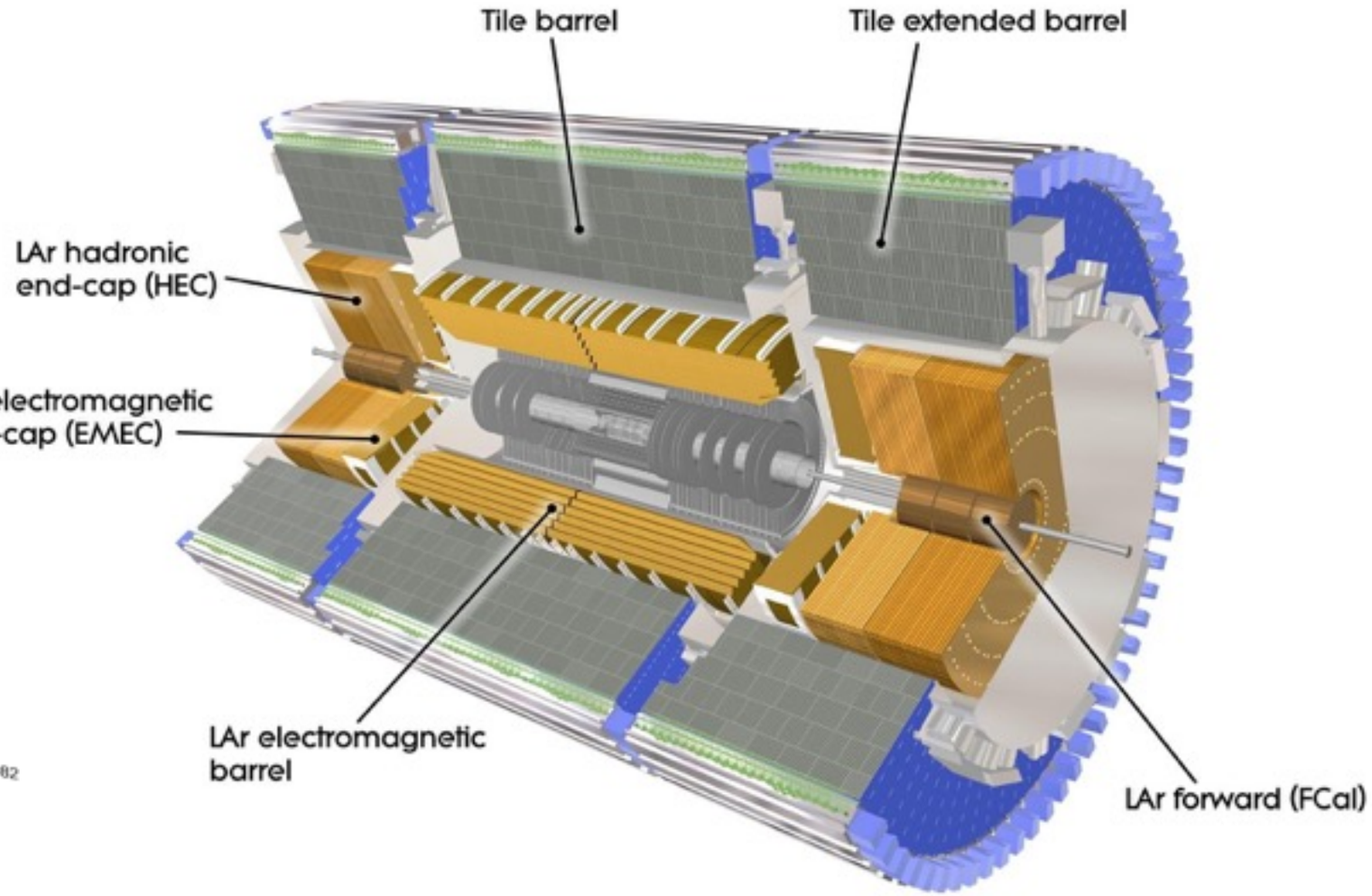
Inner Detector

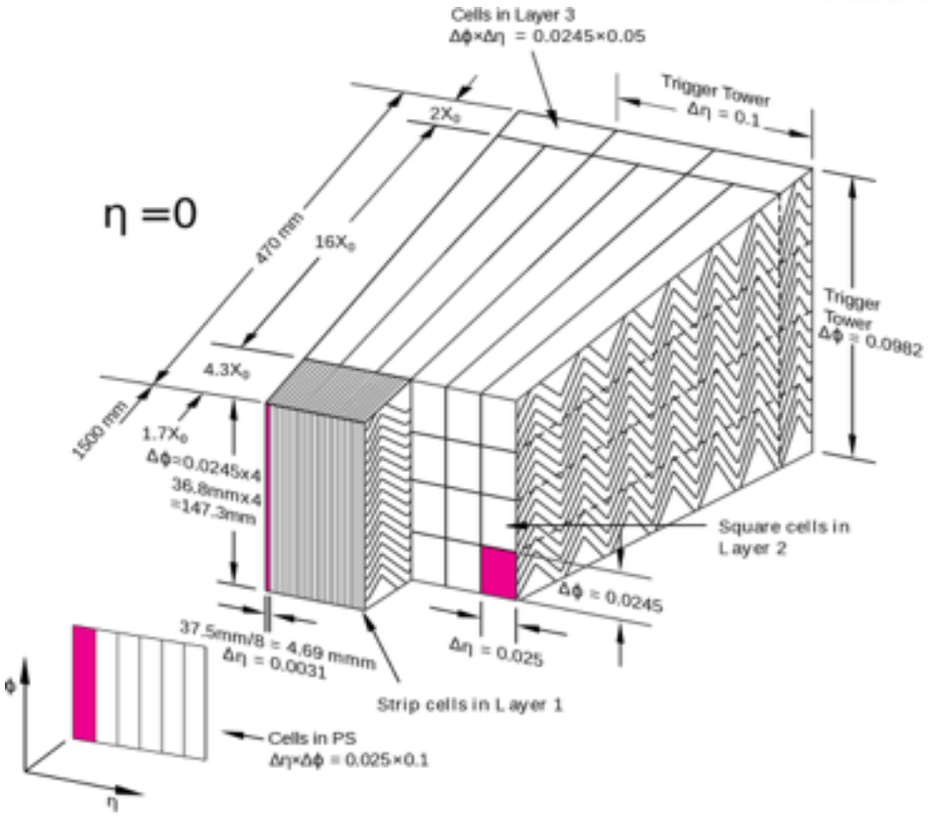


	R inner	R outer	|η| range	B field	X_0 at |η|=0	p_T resolution at 1 (100) GeV, |η|=0	d_0 resolution at 1 (100) GeV, |η|=0 [μm]
ATLAS	3.3 cm	1.1 m	2.5	2 T	0.3	1.3 (3.8)%	70 (5)

Calorimeter







Outline

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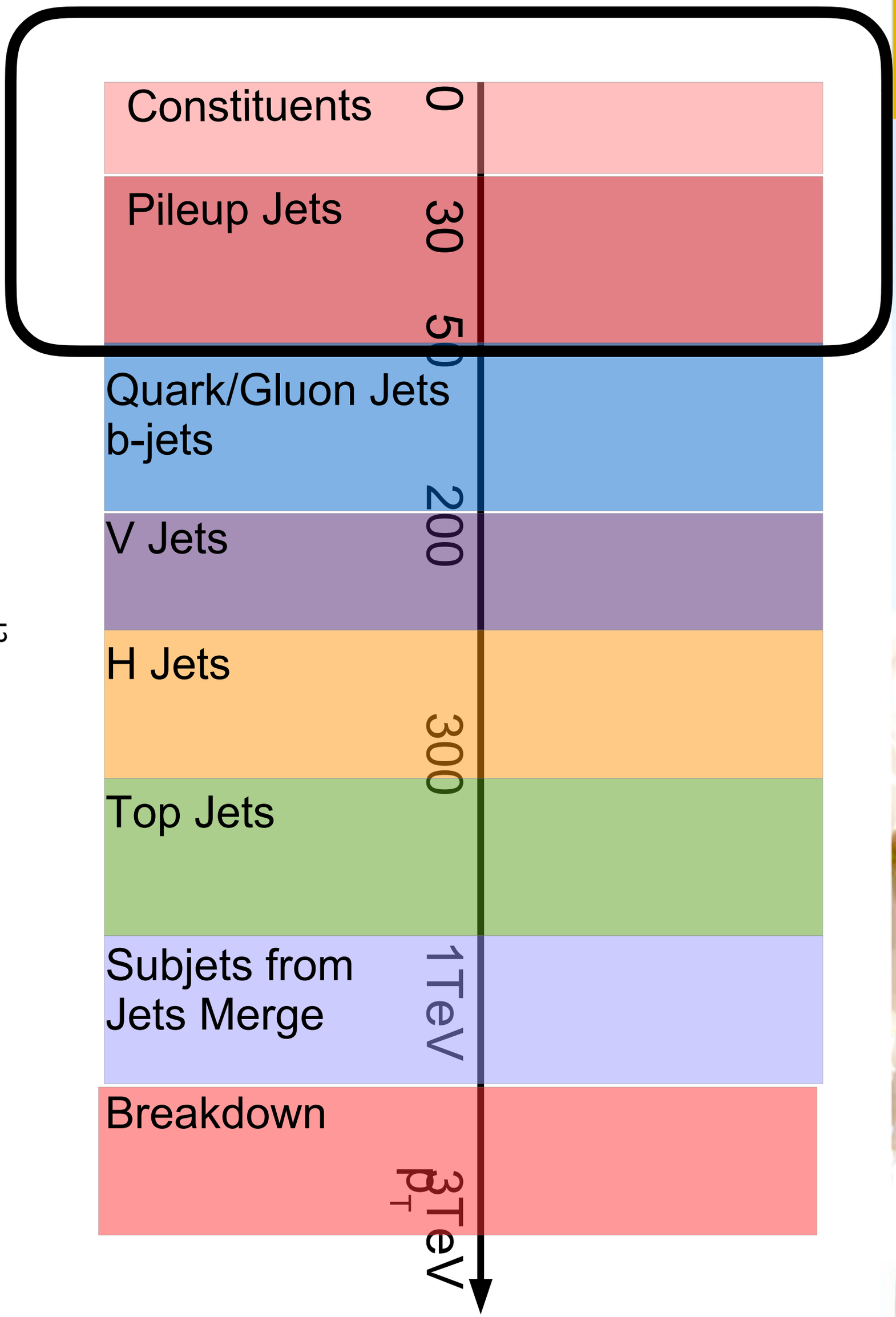
- Jet Reconstruction
- Jet substructure
- Advanced W/Z/H tagging


Constituents
Pileup Jets
Quark/Gluon Jets
b-jets
V Jets
H Jets
Top Jets
Subjets from
Jets Merge
Breakdown
0
30
50
200
300
1TeV
3TeV
p_T

Jet Reconstruction

Inputs → Constituent Corrections → Algorithms → Subjet corrections

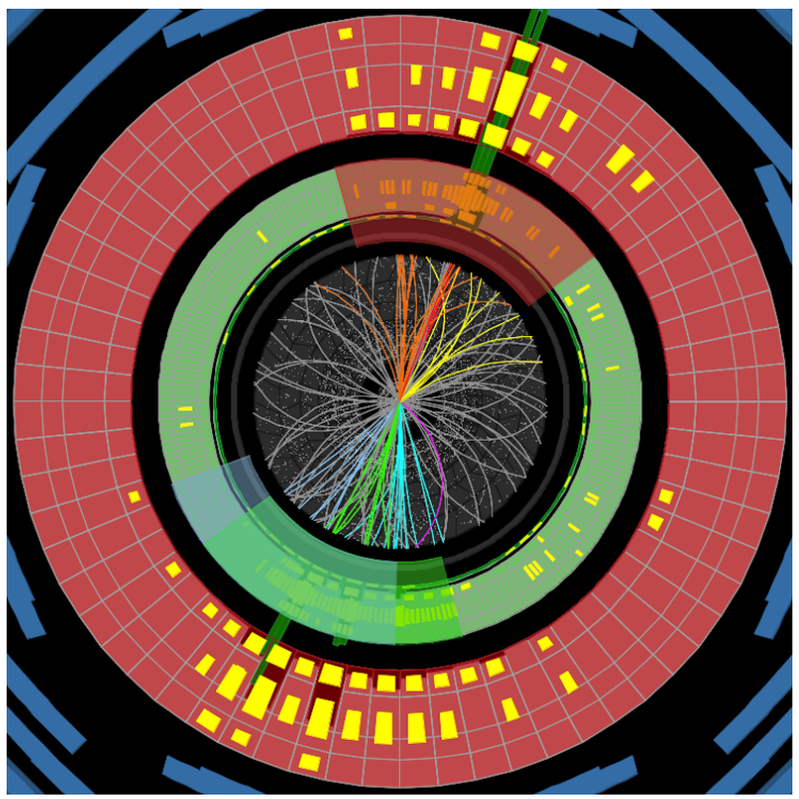
Topo clusters
Tracks
Particle flow

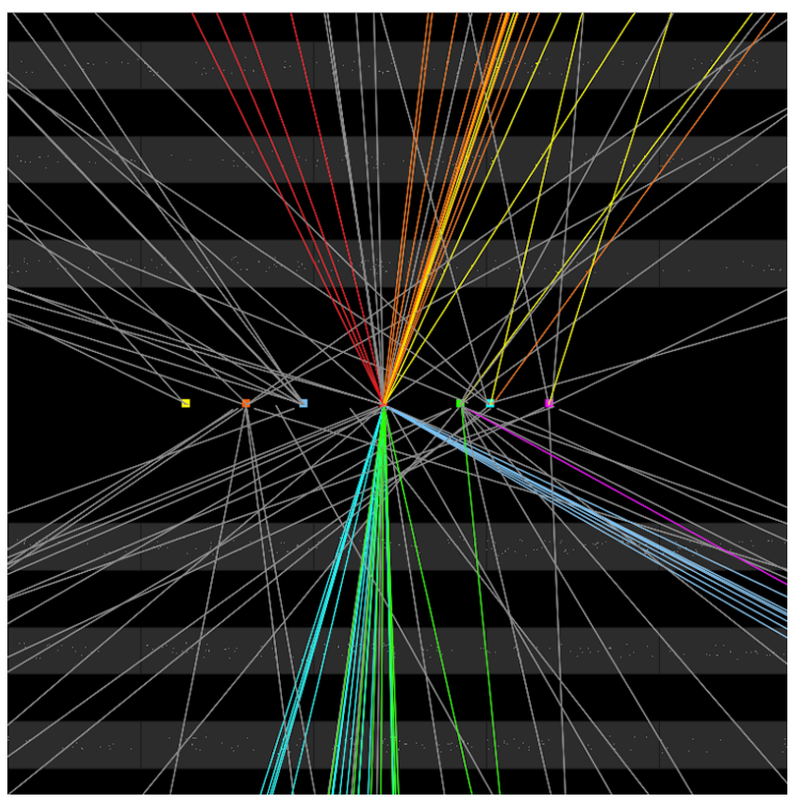
Charged Hadron Subtraction

General purpose:
Anti-kT R=0.4

W/Z/H/Top-tagging:
Anti-kT R=1.0
R=variable

Jet trimming
Rsub=0.2 fcut=0.05

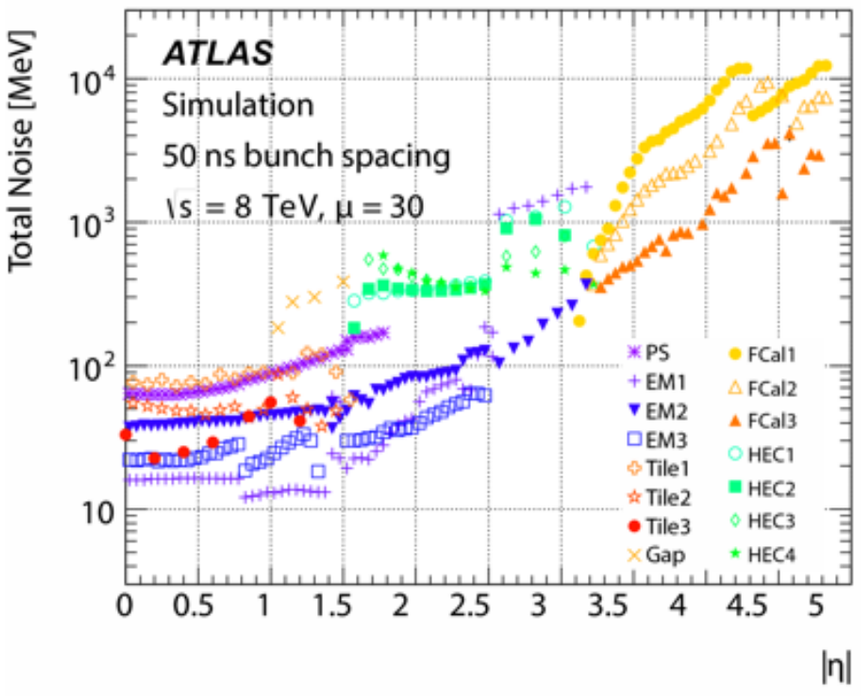


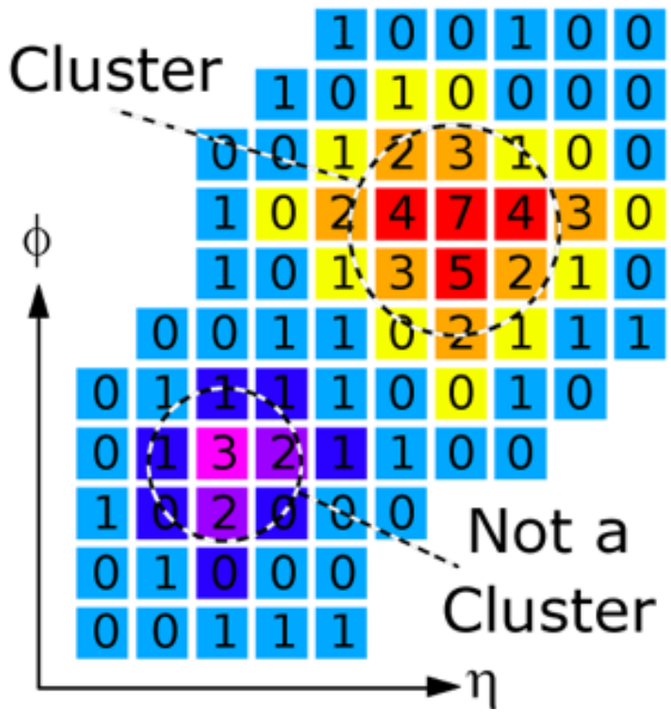


Topological Clustering

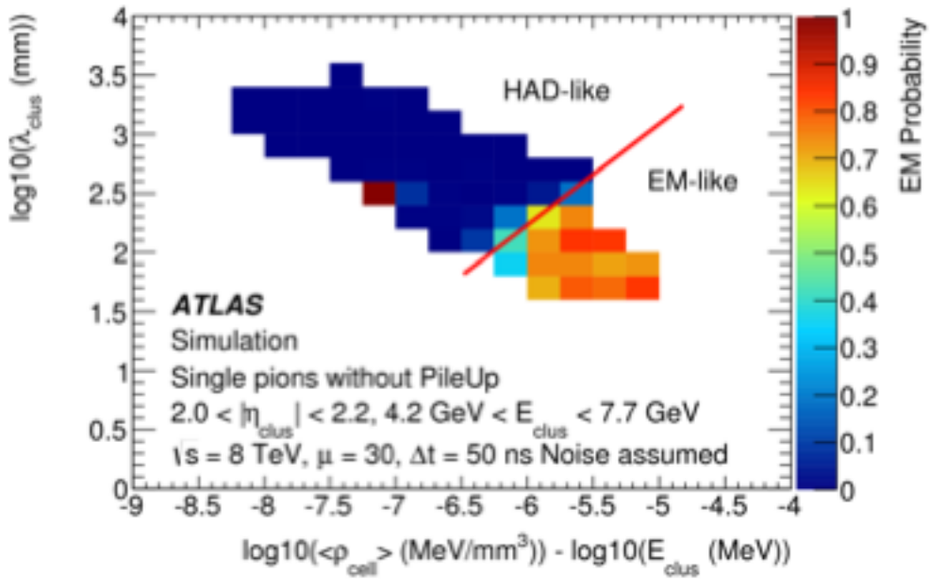
arXiv:1603.02934

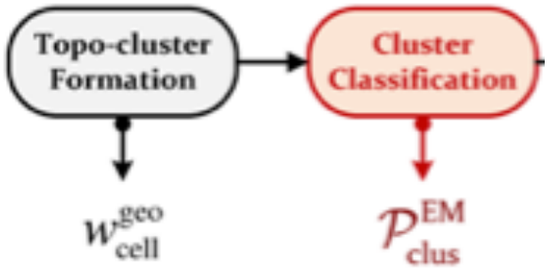
3D topological clusters constructed from calorimeter cells





cluster seeding
& expansion in 3D
(4/2/0 | σ_{noise}|)



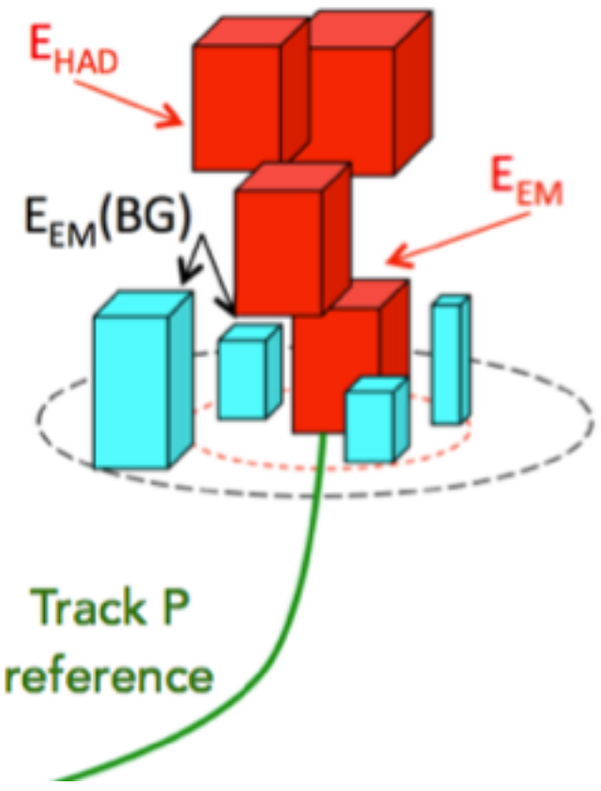


credit Jet Goodson

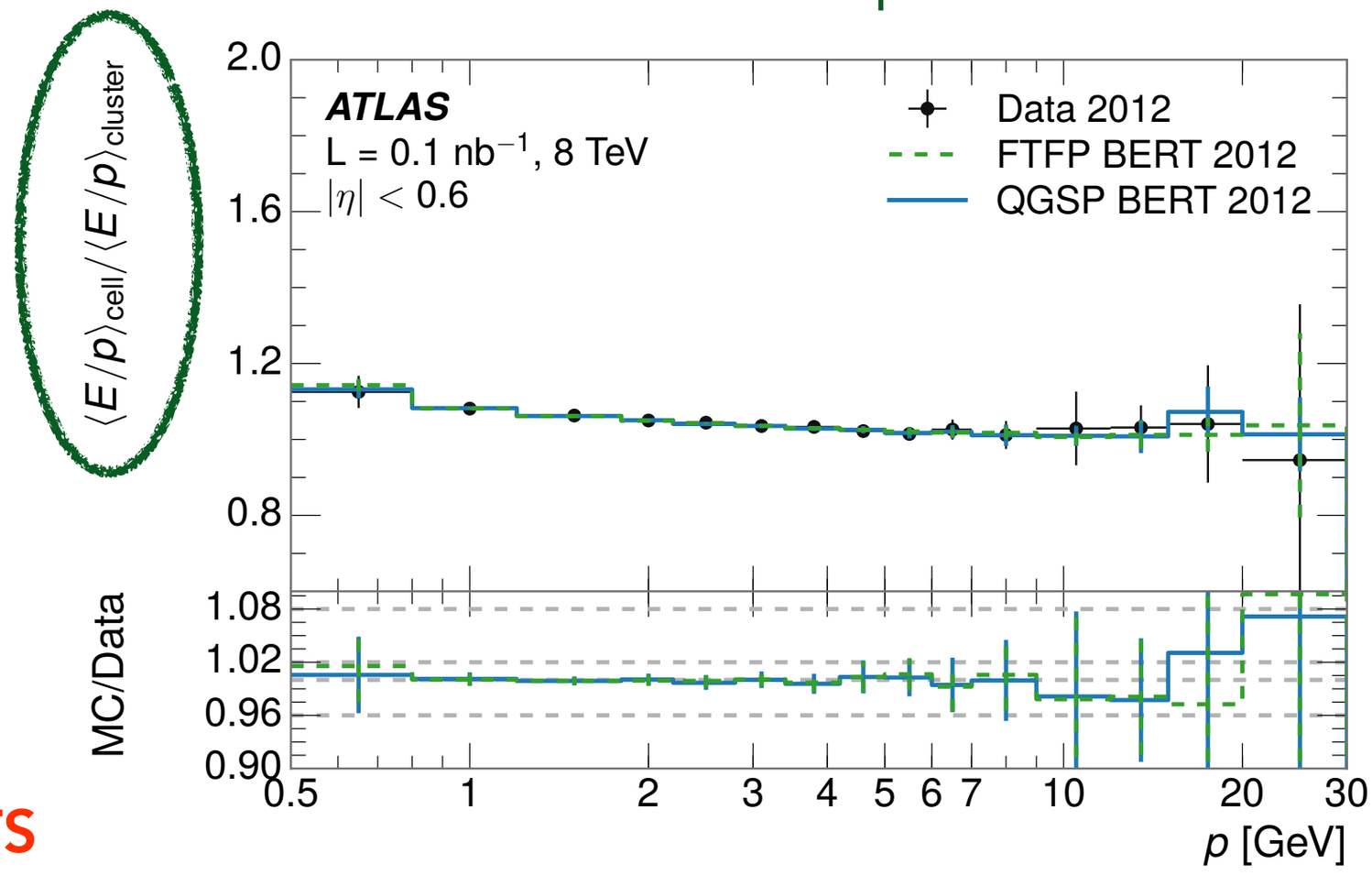
Single-Hadron Response

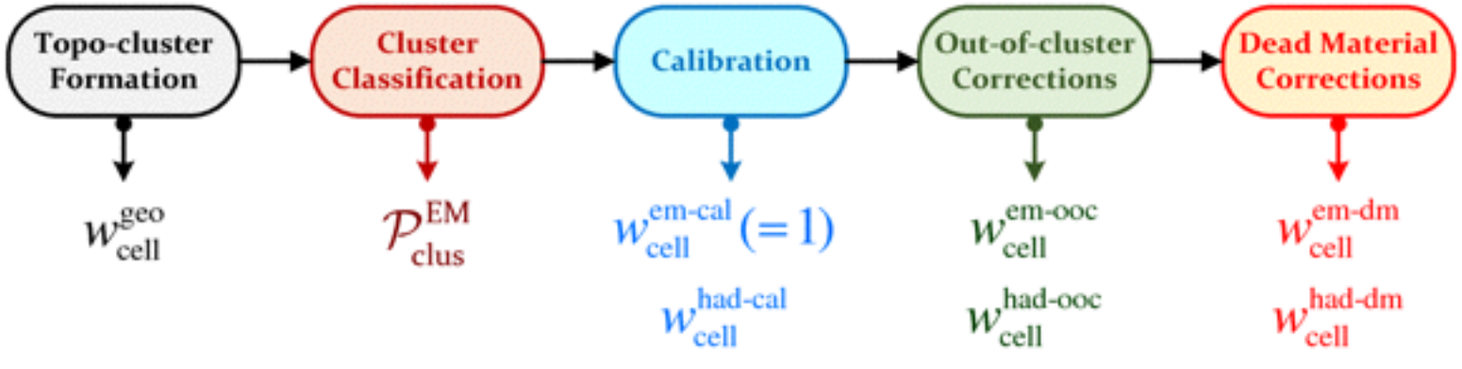
EPJC (2017) 77:26

Isolated charged hadron response measured in data

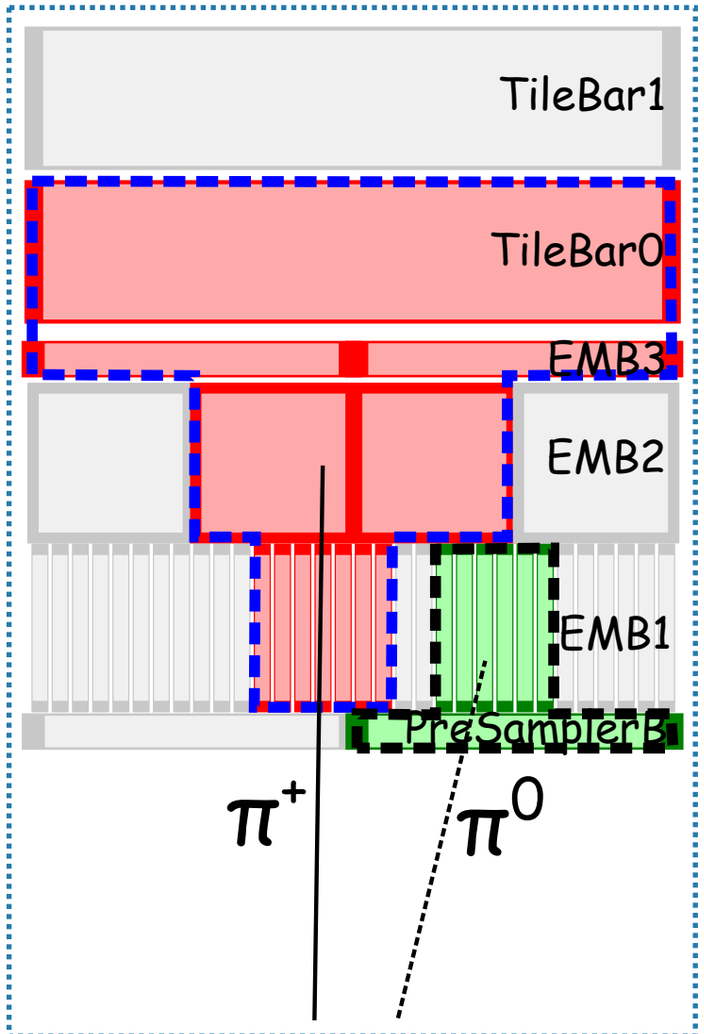


Full calorimeter R / topo-cluster R

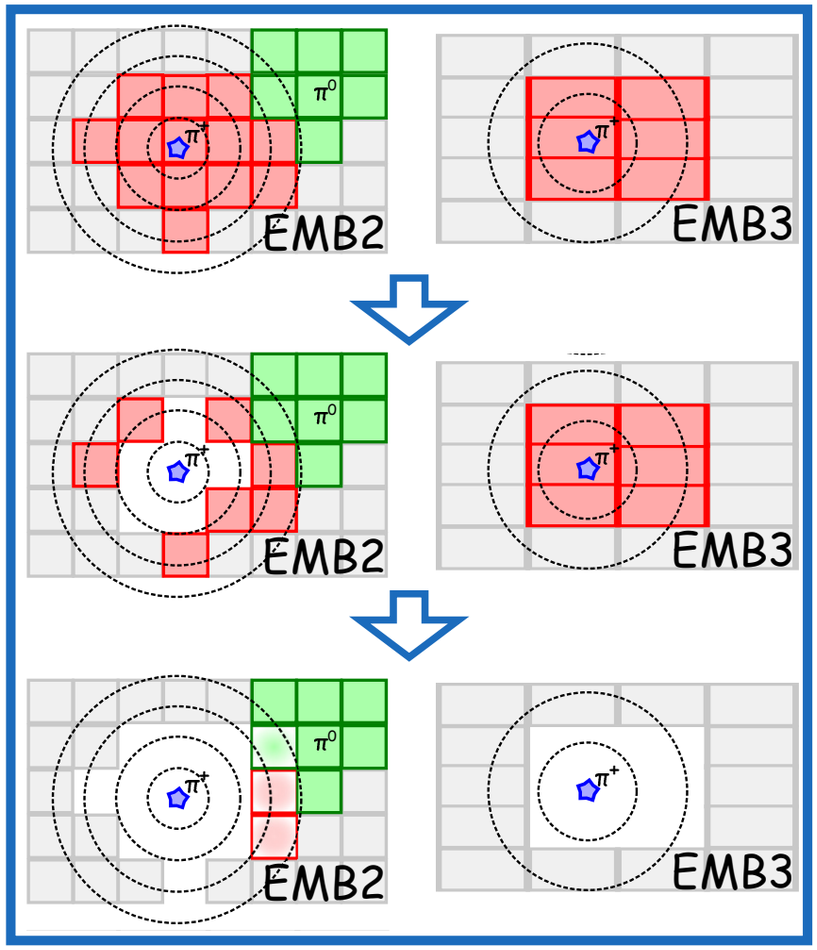




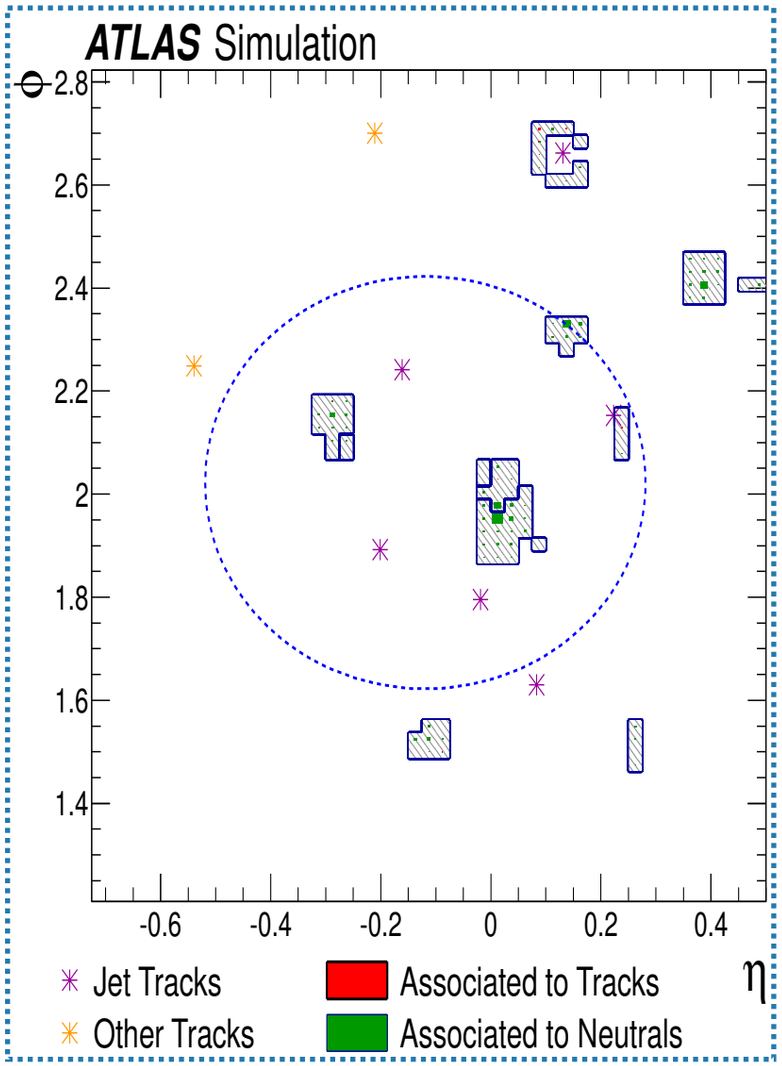
Particle Flow in ATLAS



Track-cluster matching
1:1 or 1:many



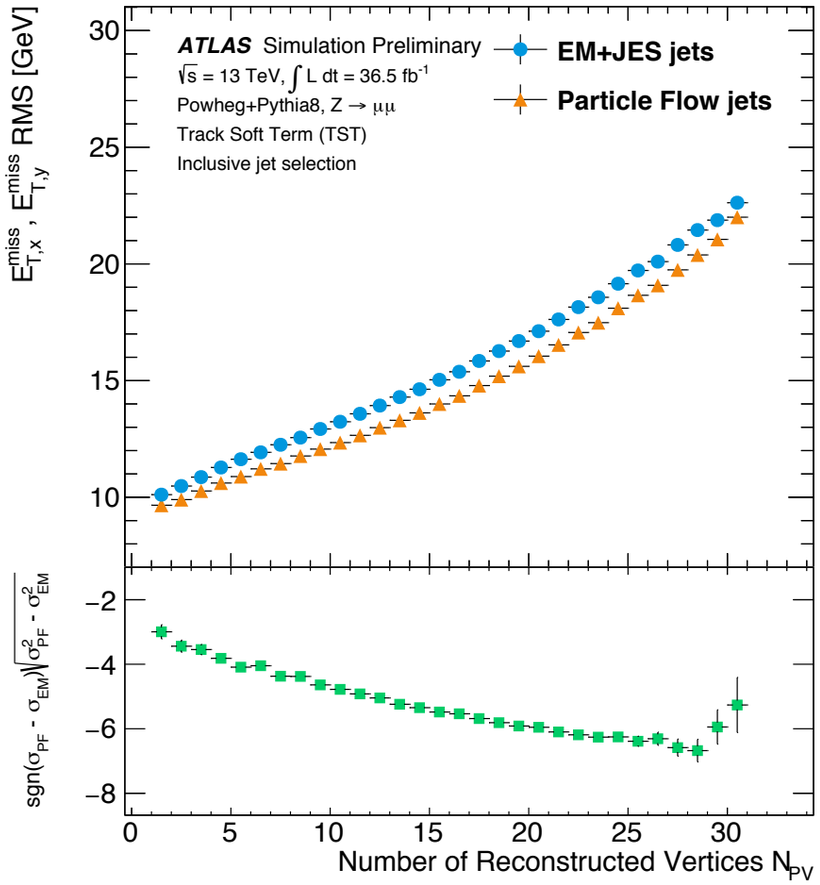
Cell-level subtraction
by ring & layer

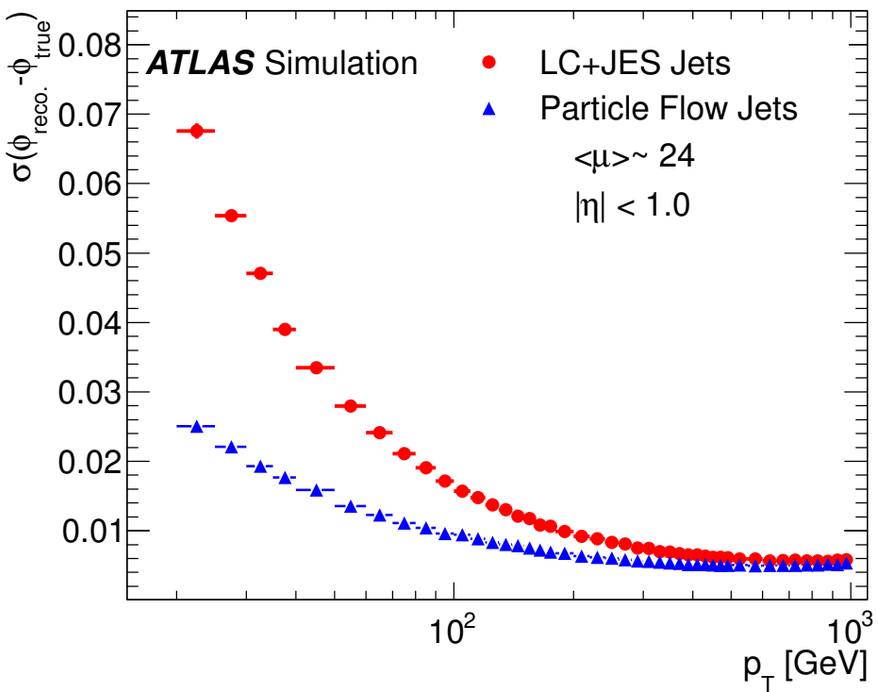


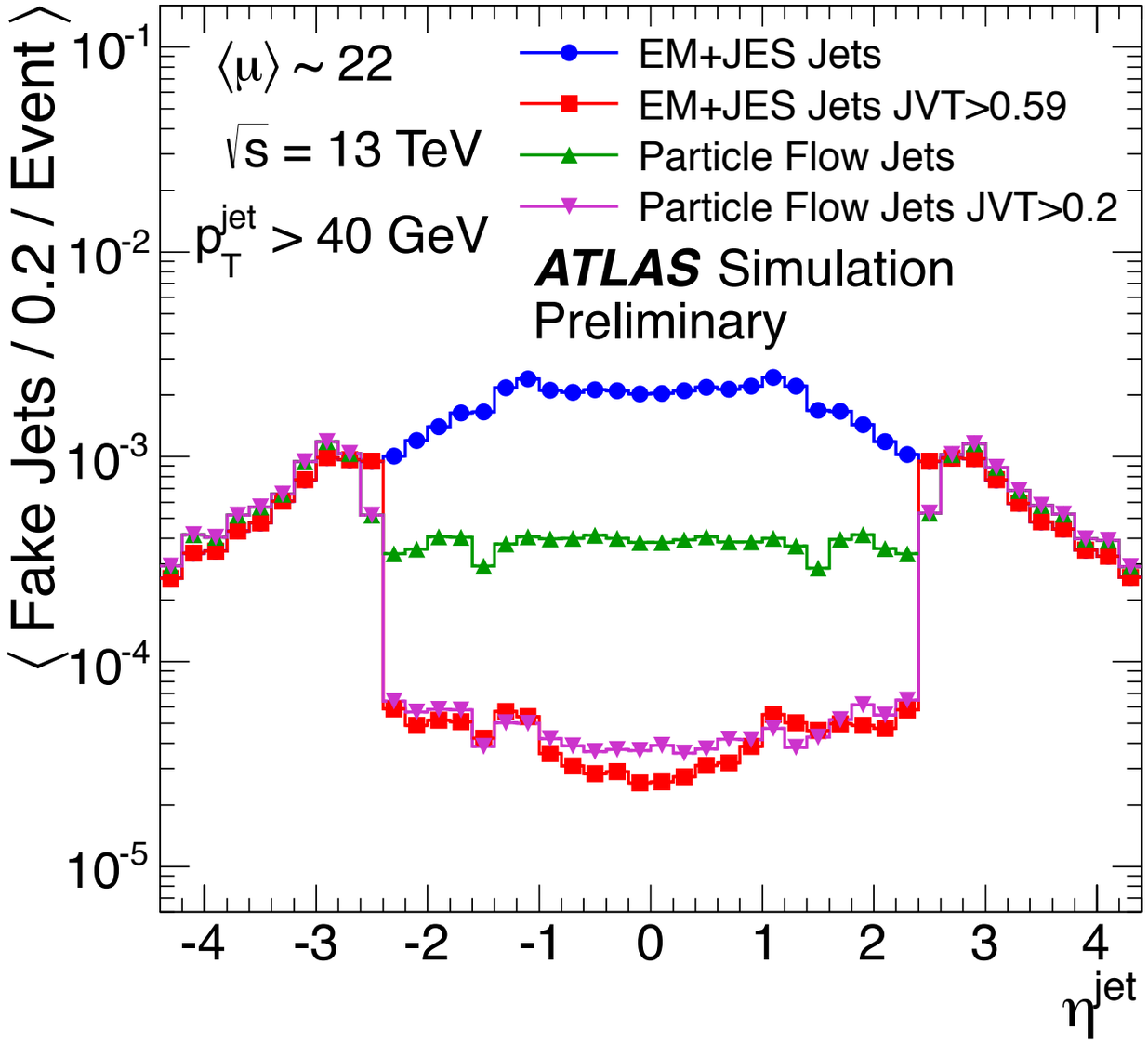
No-pileup illustration
(charged energy selectively removed)

arXiv:1703.10485

Why PFlow?







Better MET/angular resolution
better pileup suppression

Jet Calibration

EM-scale jets → Origin correction → Jet area-based pile-up correction → Residual pile-up correction

Jet finding applied to topological clusters at the EM scale.

Changes the jet direction to point to the hard-scatter vertex. Does not affect E.

Applied as a function of event pile-up p_T density and jet area.

Removes residual pile-up dependence, as a function of μ and N_{PV}.

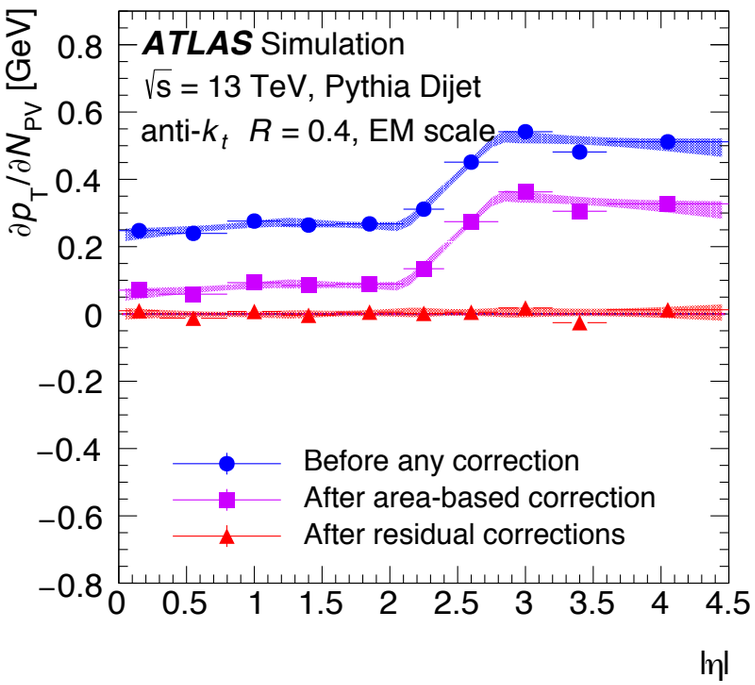
→ Absolute MC-based calibration → Global sequential calibration → Residual *in situ* calibration

Corrects jet 4-momentum to the particle-level energy scale. Both the energy and direction are calibrated.

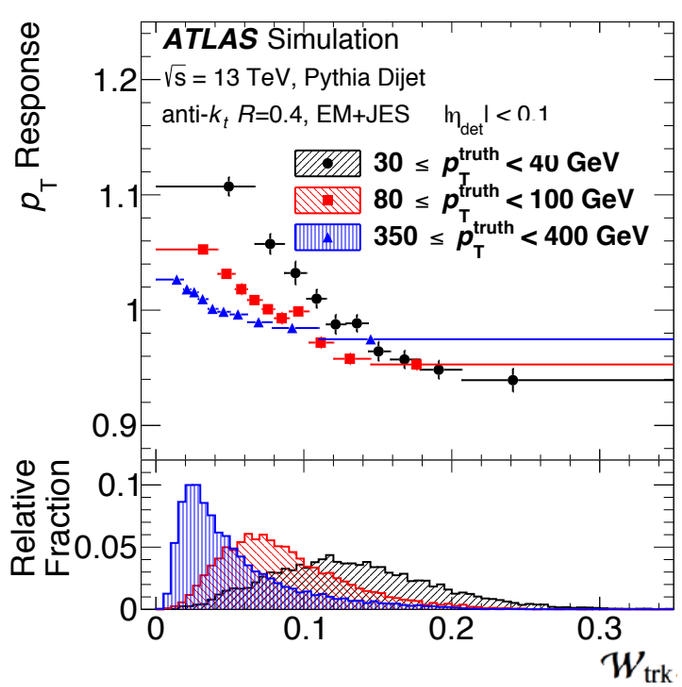
Reduces flavor dependence and energy leakage effects using calorimeter, track, and muon-segment variables.

*A residual calibration is derived using in situ measurements and is applied **only to data**.*

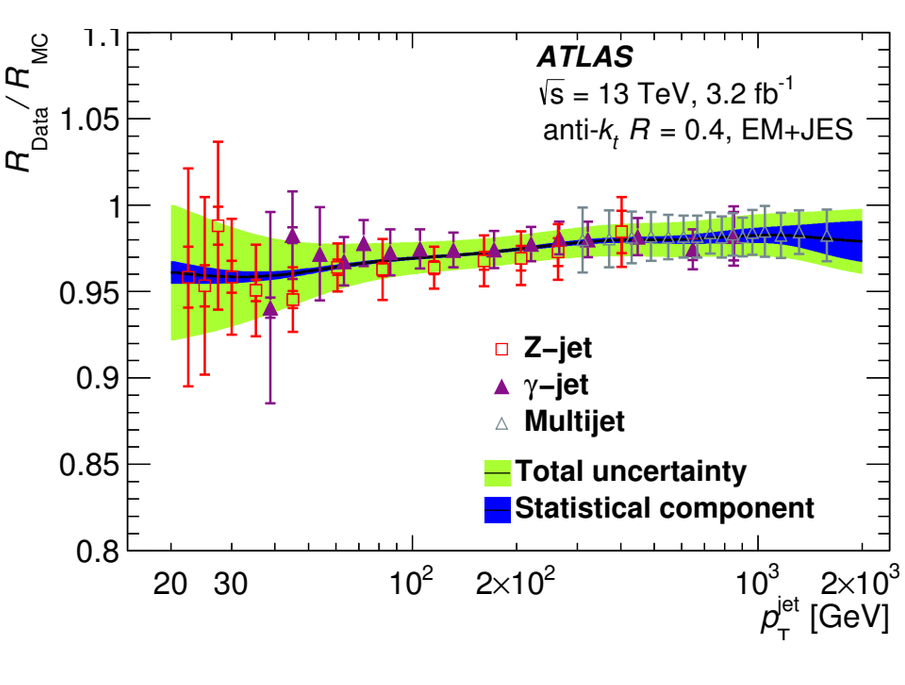
Pile-up corrections



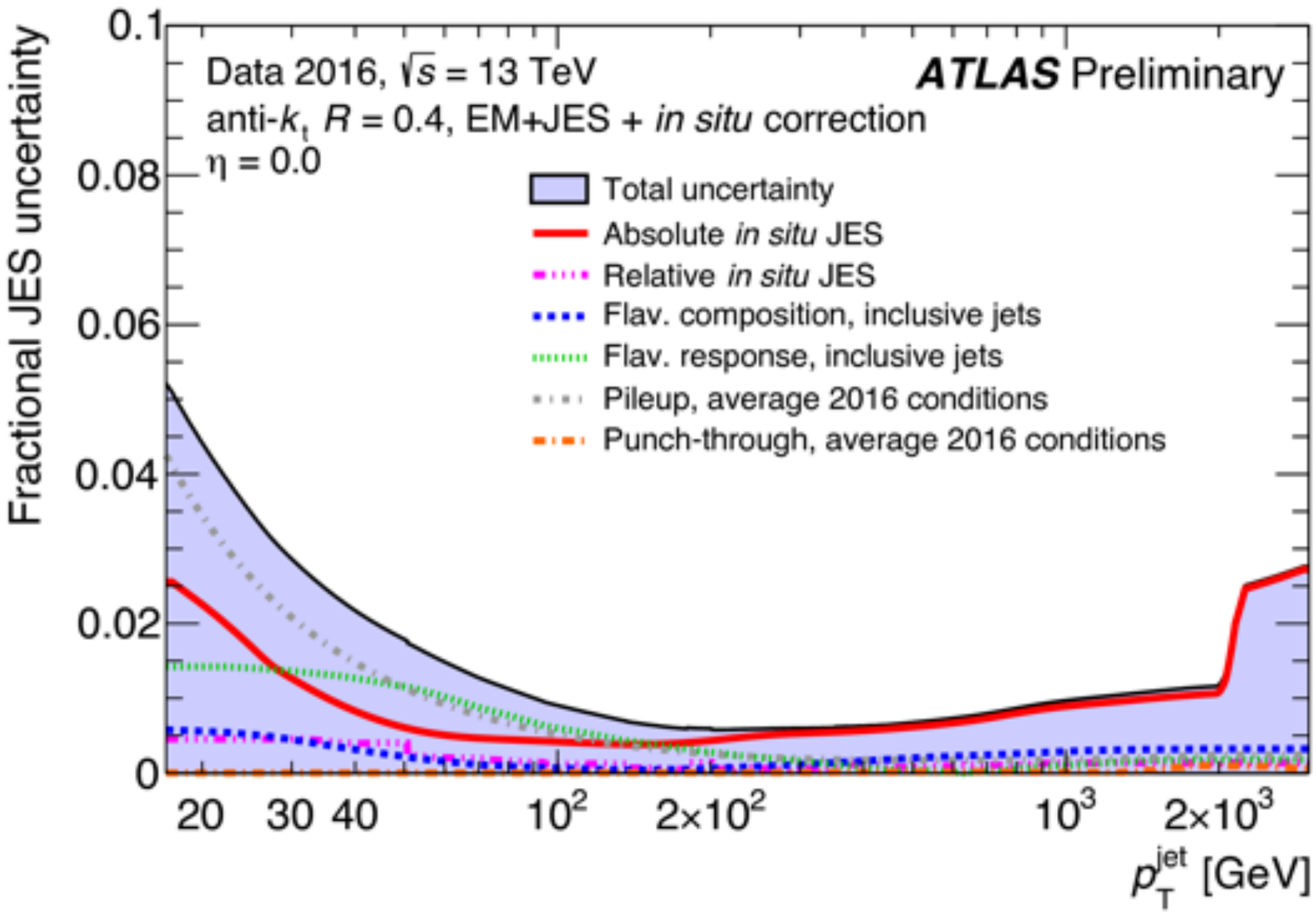
Additional corrections
(Flavour/fragmentation/shower depth)



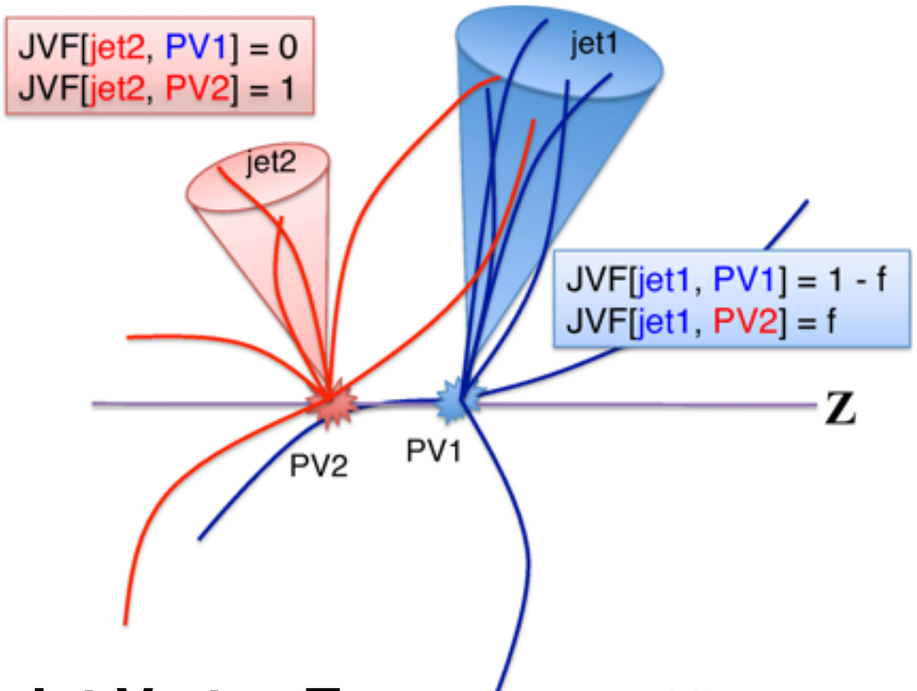
In situ calibration



Jet Uncertainty

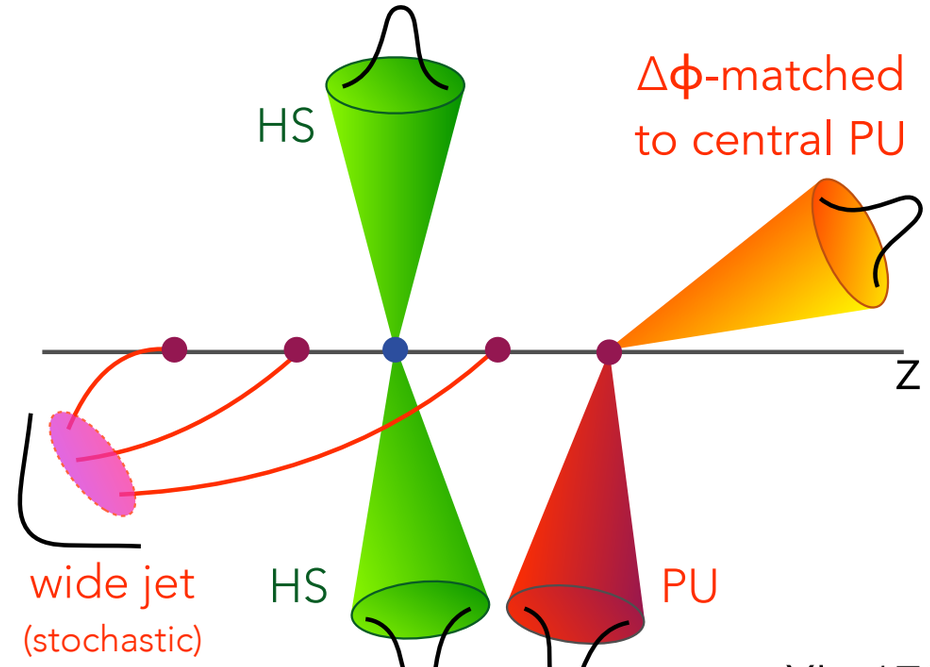


Jet-Level Pileup Suppression



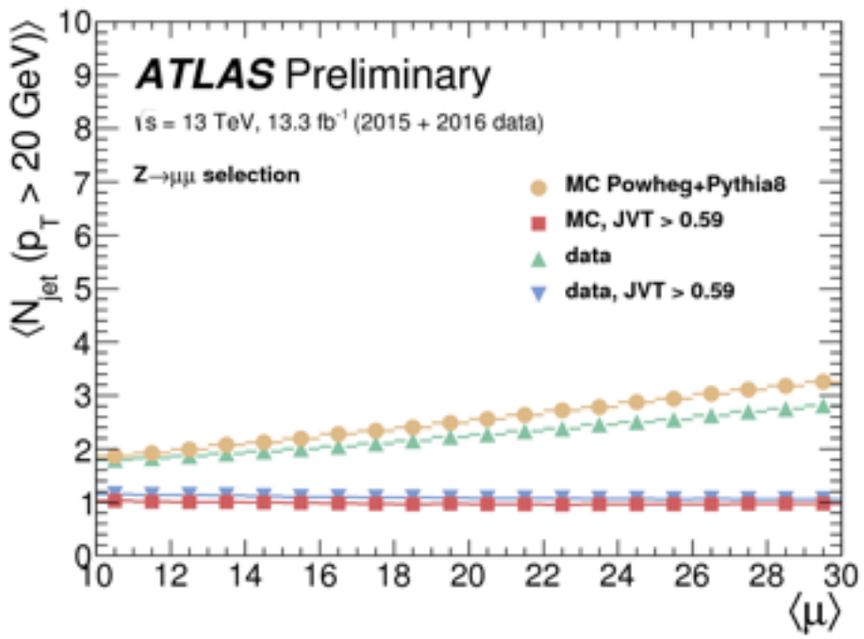
Jet Vertex Tagger arXiv:1510.03823

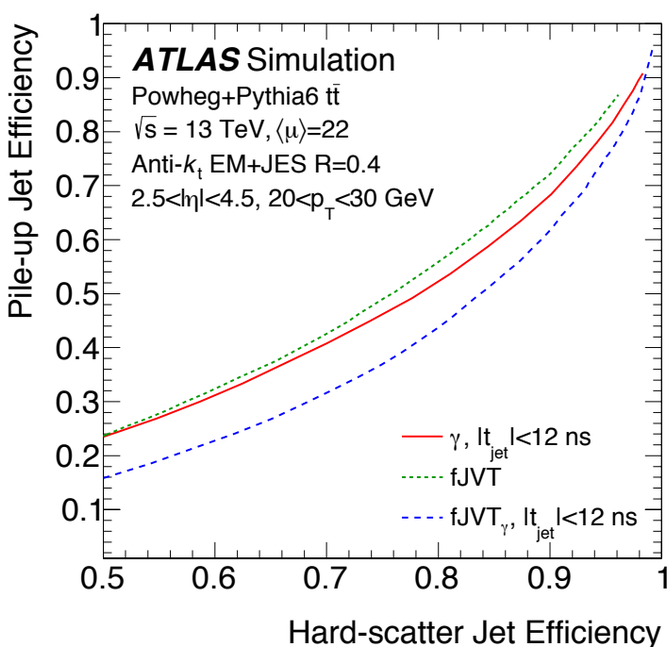
identify jets with large fraction of track pT from PU



Forward JVT arXiv:1705.02211

- Jet width & angular variables (wider spread in PU jets)
- Central-Coward matching





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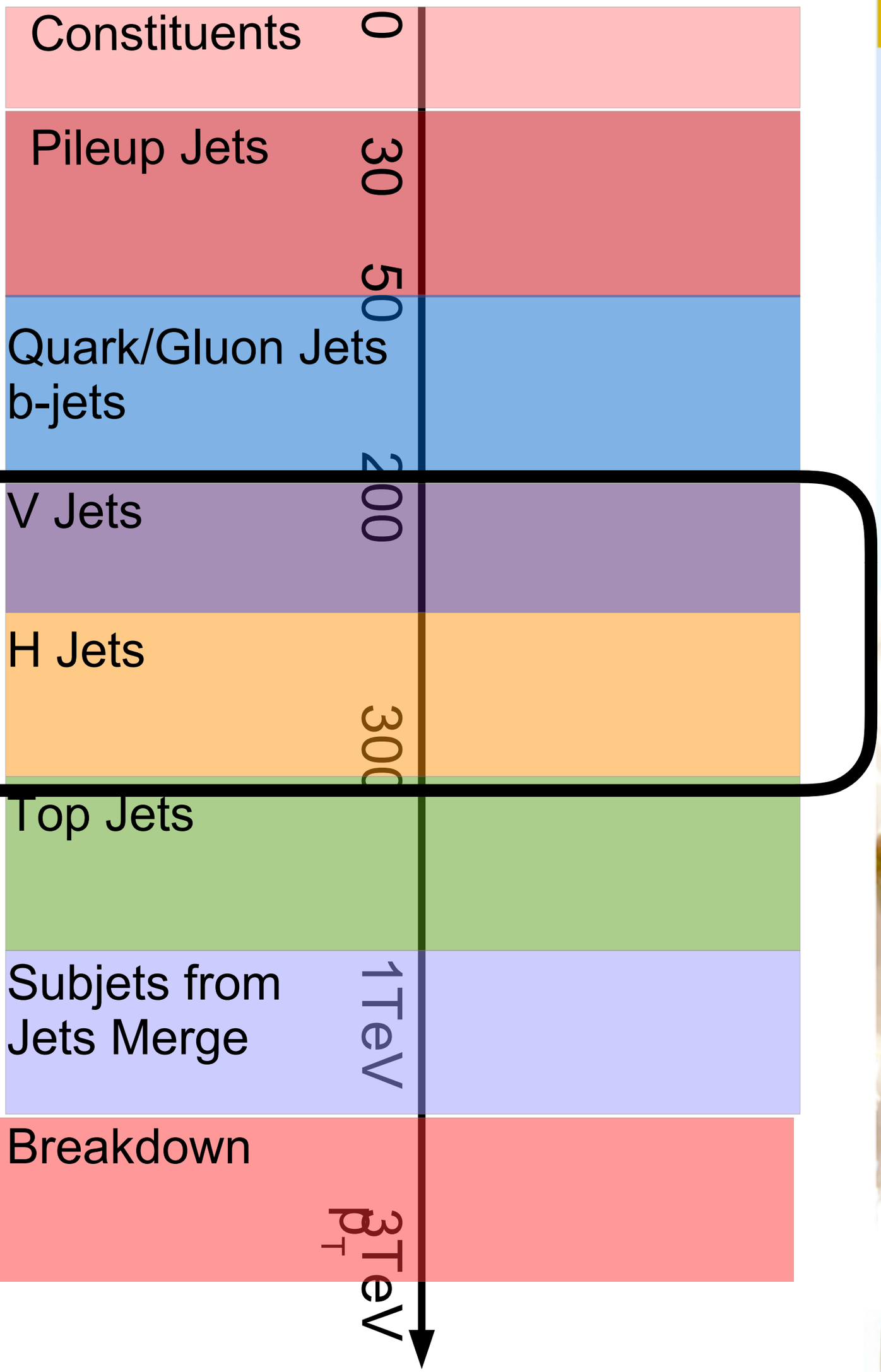

Constituents
Pileup Jets
Quark/Gluon Jets
b-jets
V Jets
H Jets
Top Jets
Subjets from
Jets Merge
Breakdown
0
30
50
200
300
1TeV
3TeV
p_T

Object Tagging

Color

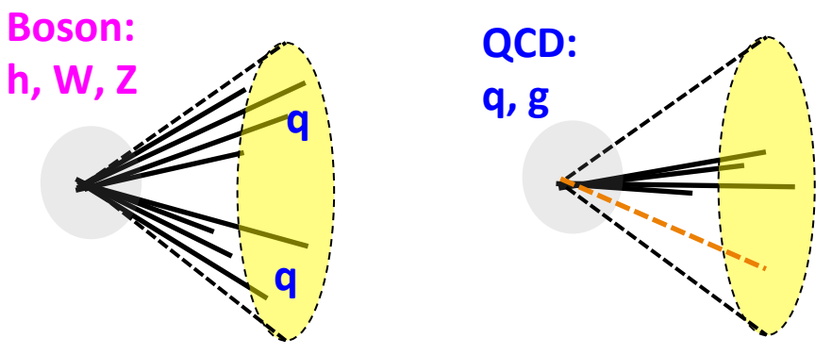
Quark
vs
Gluon

Constituent multiplicity
Jet angular opening
Jet fragmentation distribution

N-body decay

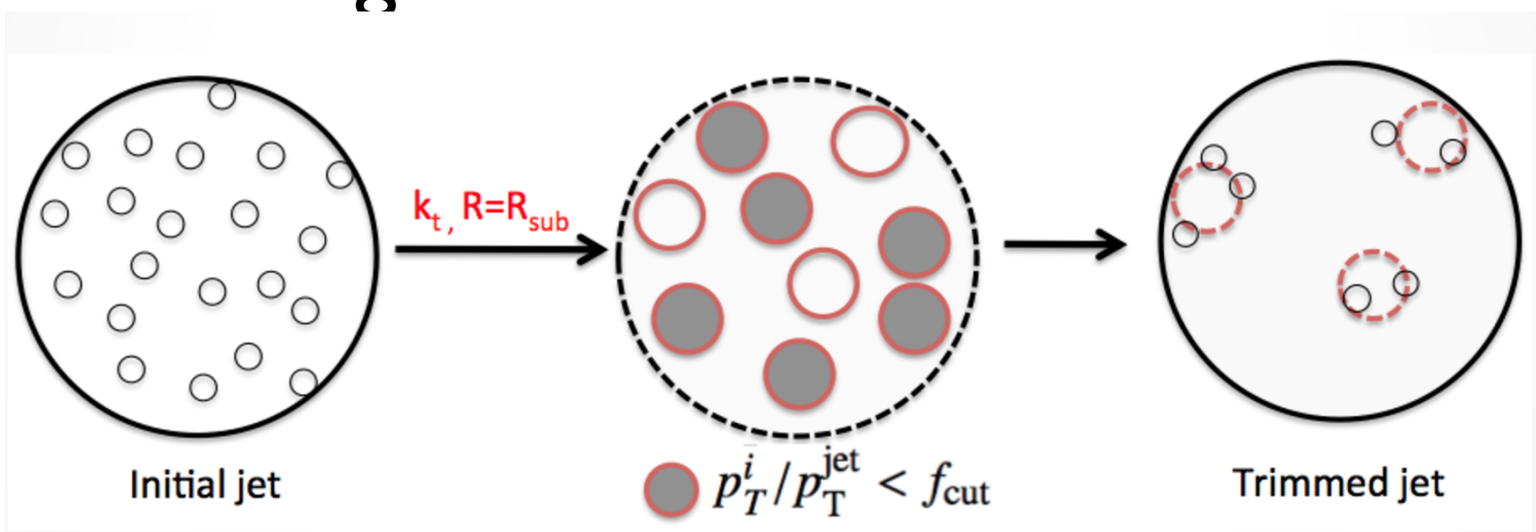
W/Z/H/Top
vs
Quark/Gluon

Jet mass
N-subjetiness
Energy correlation functions
…

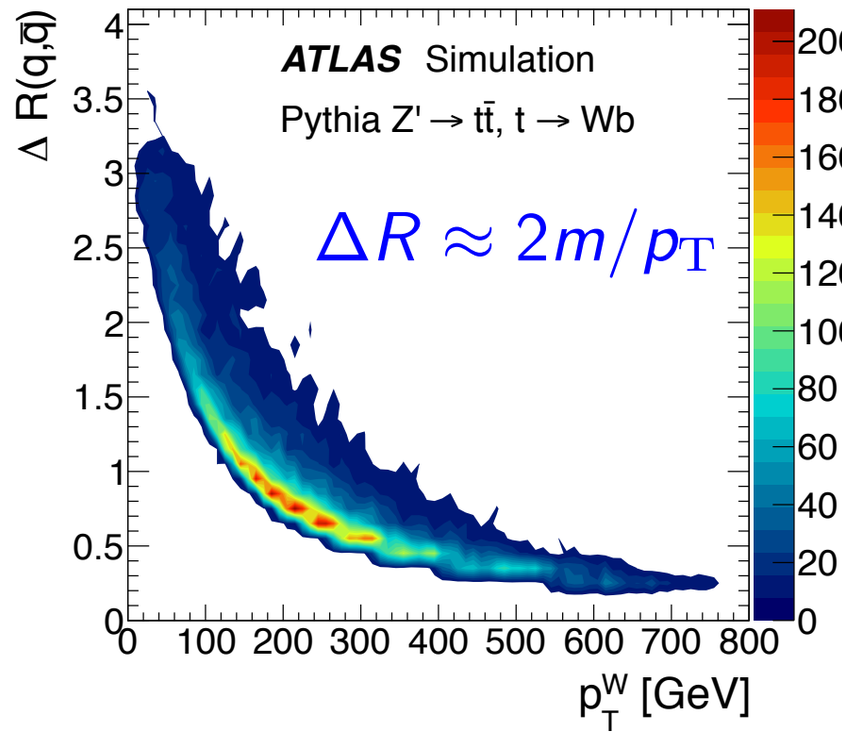


Large-R Jet Optimization

- R=1.0 calorimeter jets trimmed with kT R=0.2 subjects and fcut=0.05 to measure kinematics and substructure
- Trimming in a nutshell



arXiv:1510.05821



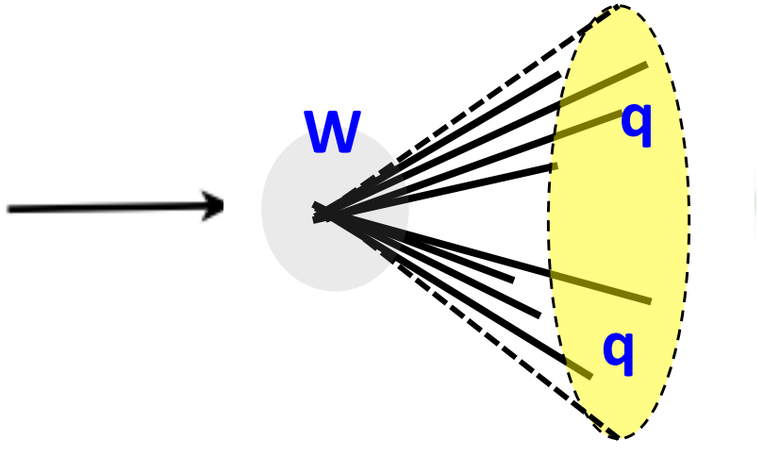
JHEP09 (2013) 076

- A dedicated scan for optimization

Trimming configurations

Input jet algorithms	R	R_{sub}	f_{cut} (%)
C/A, anti-k_t	0.6, 0.8, 1.0, 1.2	0.1, 0.2, 0.3	1, 2, 3, 4 , 5, 7, 9, 11, 13, 15

→ 2 x 4 x 3 x 10 = 240

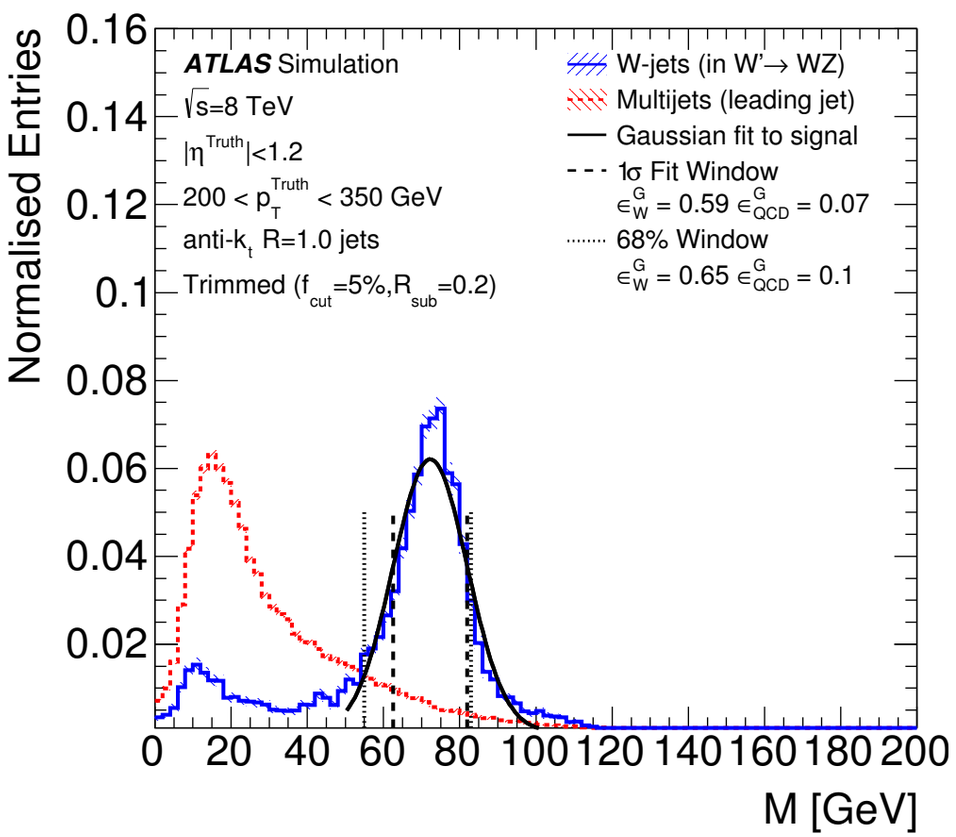


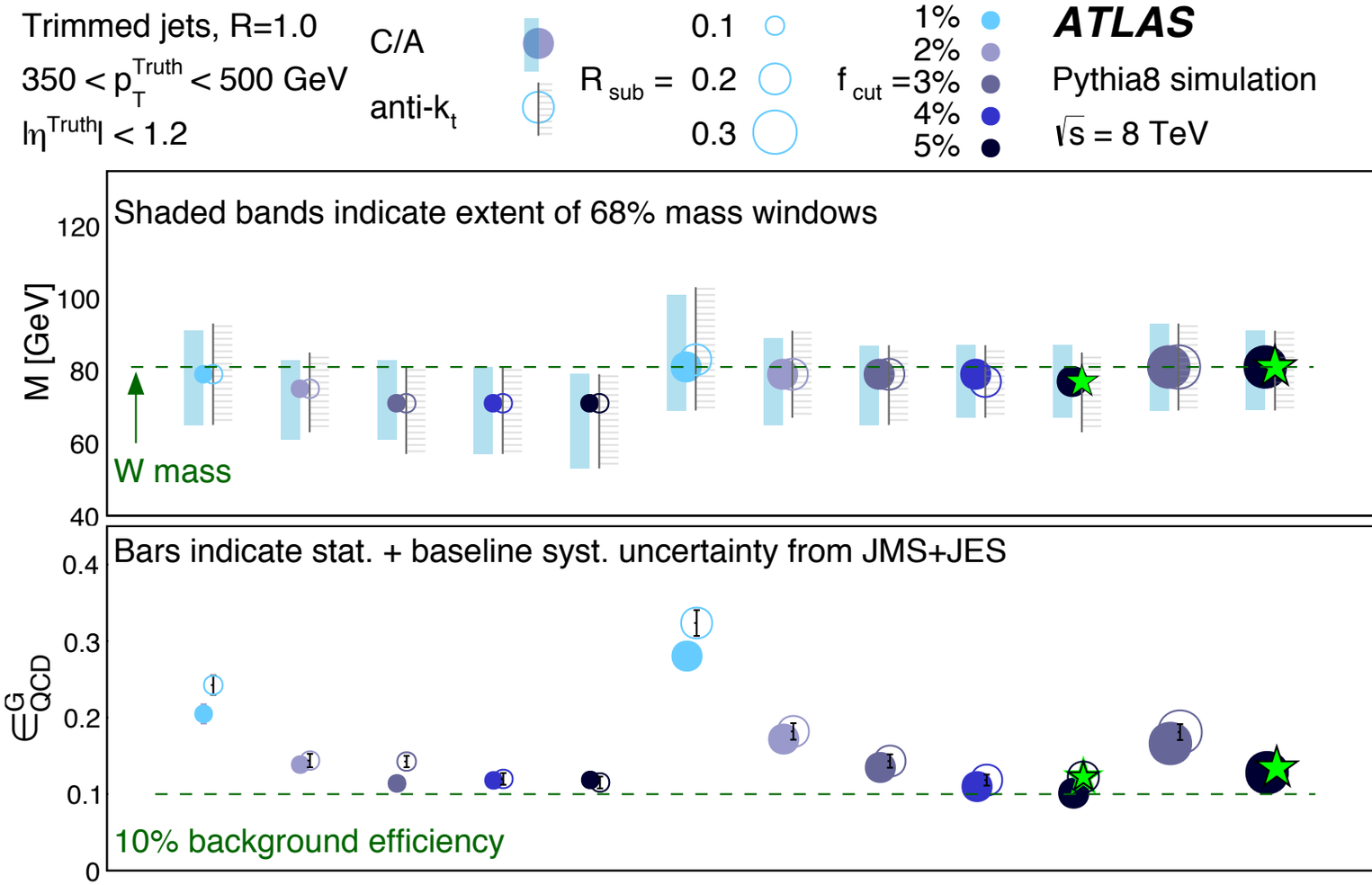
Mass optimization

Identify 68% mass window for 3 truth-jet pT (200, 350, 500 ~1000GeV)

Optimization figure of merit:

- mass peak is relative symmetric
- minimal QCD jet efficiency



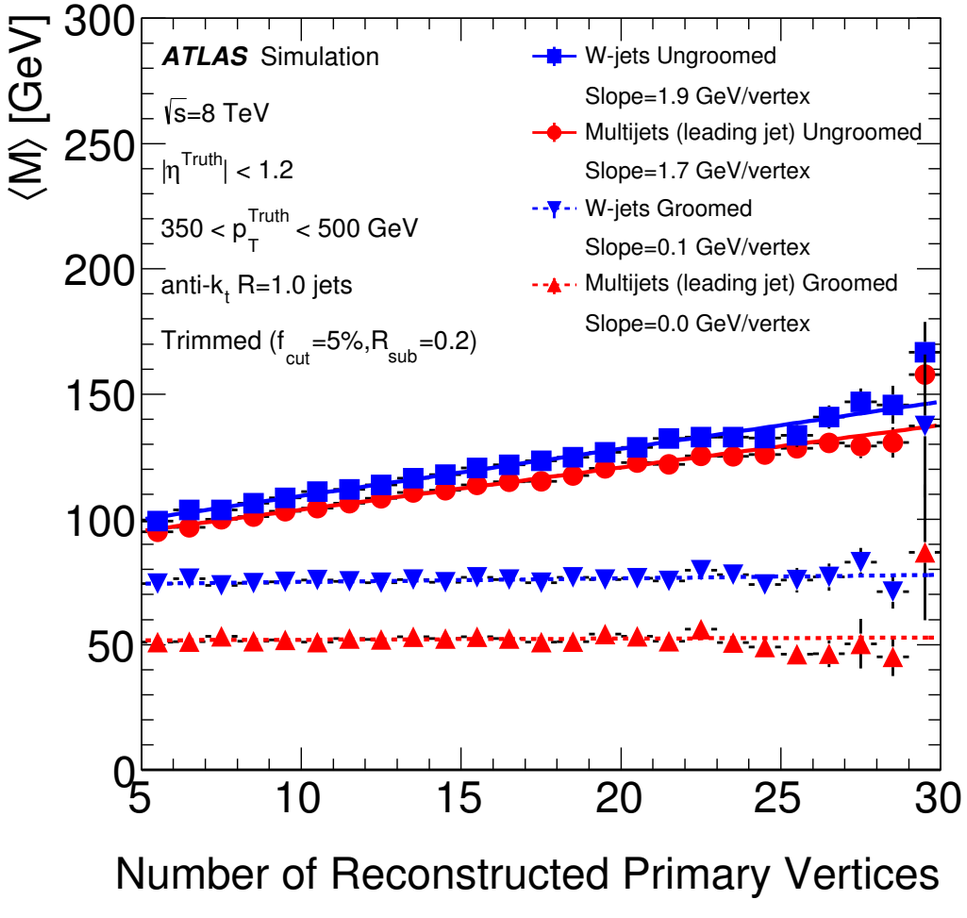


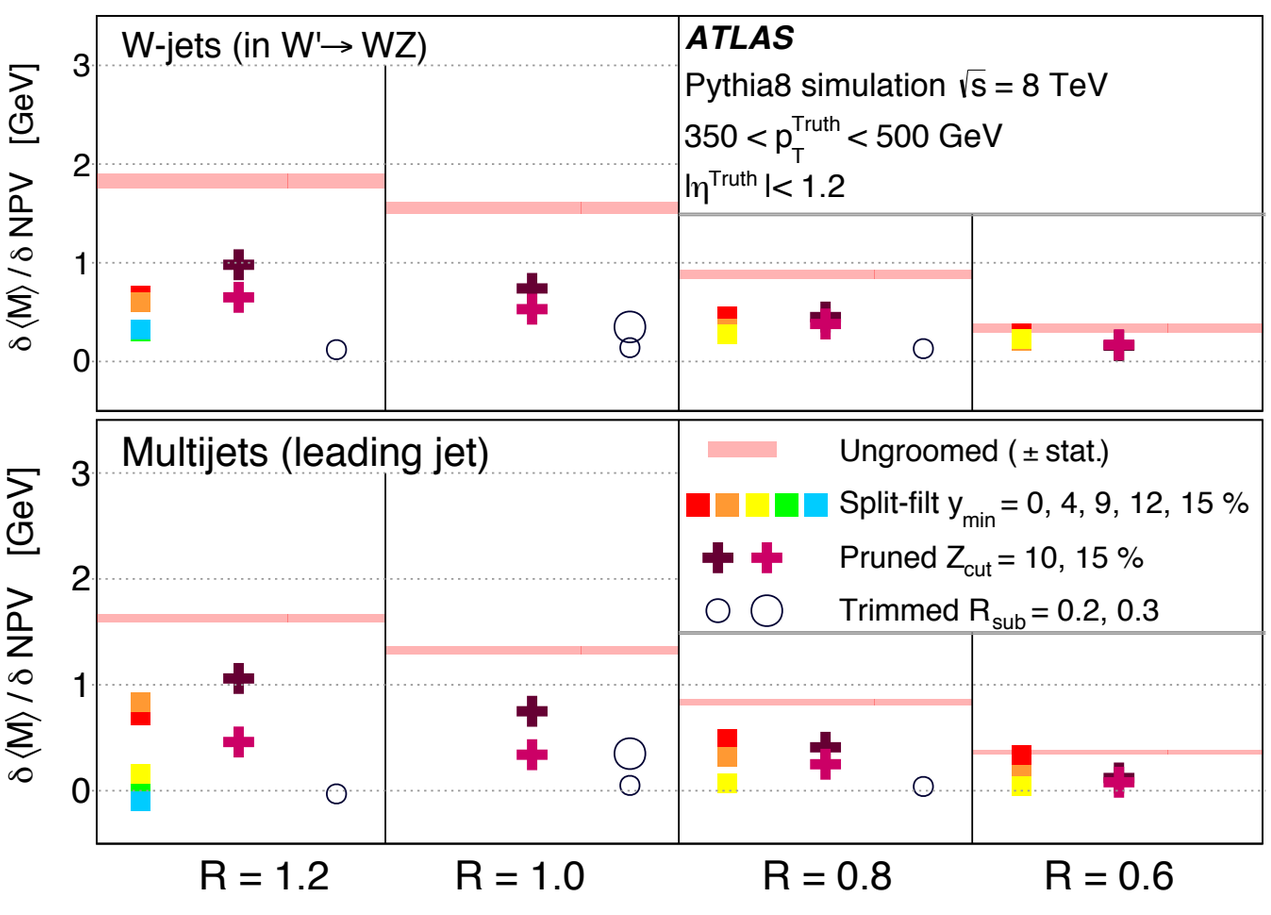
Comparison to other groomers

Optimal groomer in each algorithm can achieve equivalent bkg rejection.

best grooming: low bkgd eff. + good pileup stability

→ **anti-kt R=1.0 trimmed f_{cut}=5%, R_{sub}=0.2**





Jet substructure

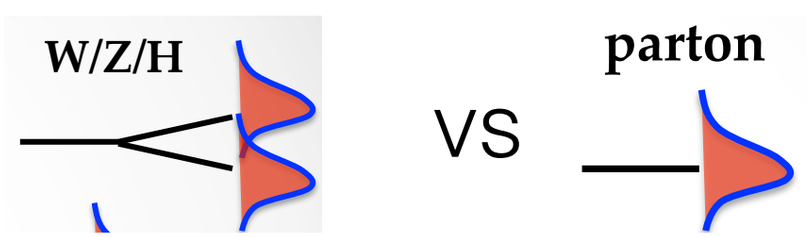
Prong Based
- N-subjettiness
- Split(1,2)
- $Z_{cut}(1,2)$
- μ (1,2)
- $\sqrt{y}_{filter}$

Soft Substructure
- Dipolarity(1,2) Excl.
- Planar Flow
- Angularity
- Width
- Energy Correlation Fncs.

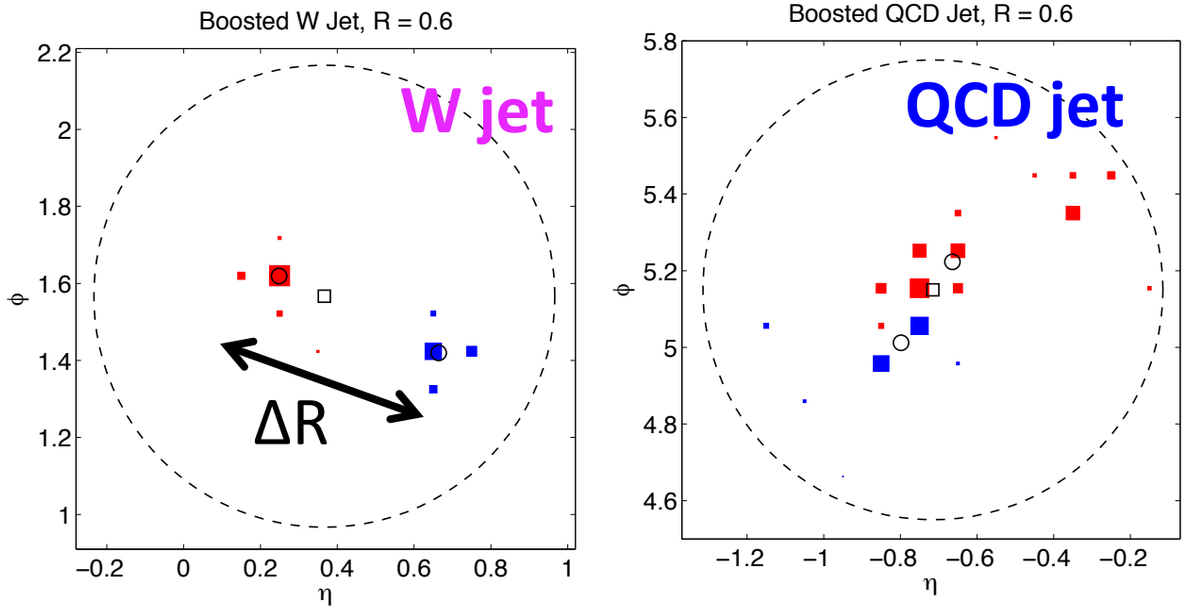
Center of Mass
- Aplanarity
- Sphericity
- Thrust Minor
- Thrust Major
- FoxWolfram20

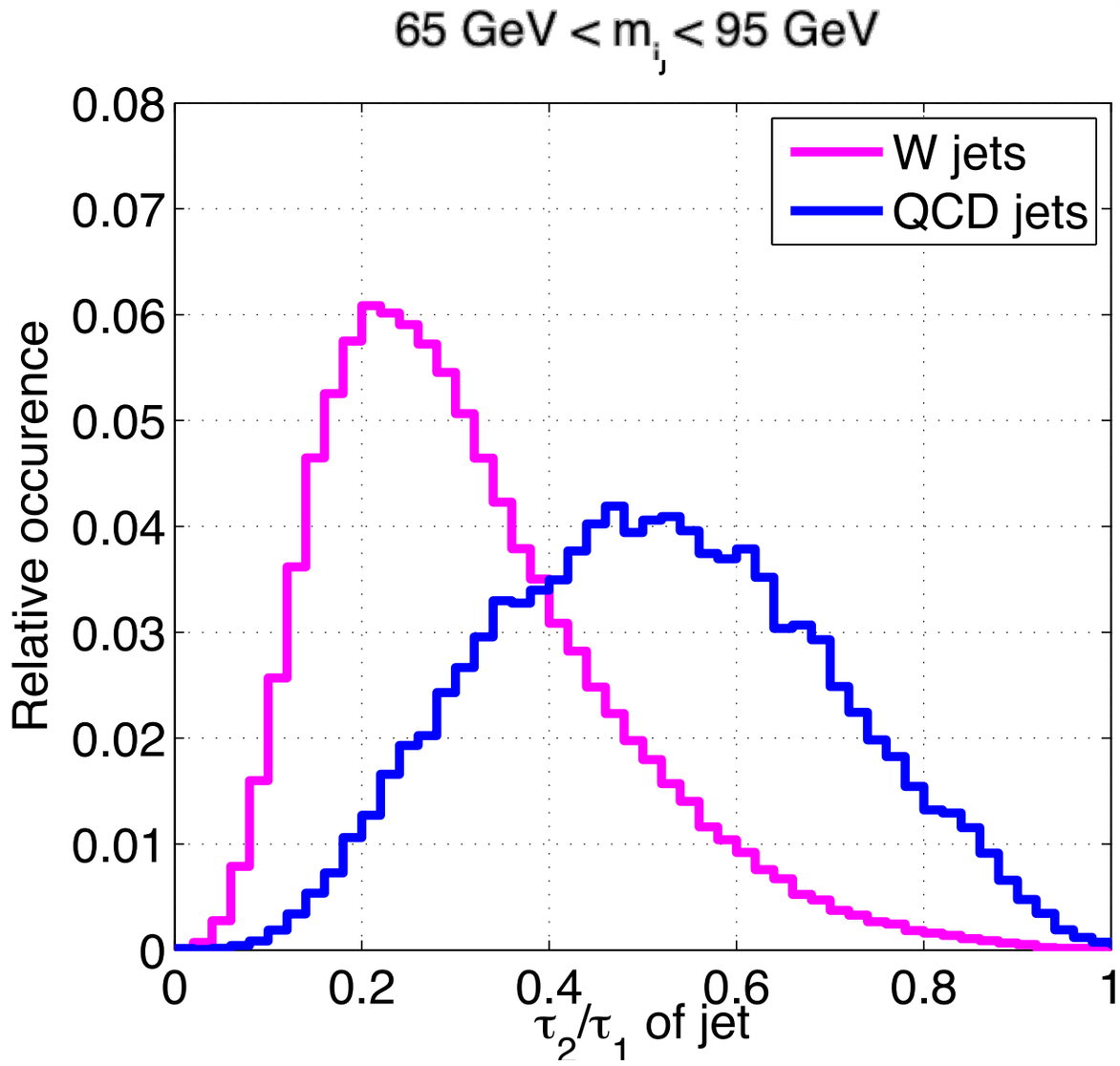
Jet Ensembles
- Q-Jets volatility
- T-Jets volatility

Pull Variables
- Subjet Pull Angle
- Pull Magnitude
- Pull C_{00} , C_{10} , C_{11}



W jet substructure: N-subjetiness





Counting prongs

$$\tau_N = \frac{1}{d_0} \sum p_{T,k} \min\{\Delta R_{k,axis-1}, \ldots, \Delta R_{k,axis-n}\}$$

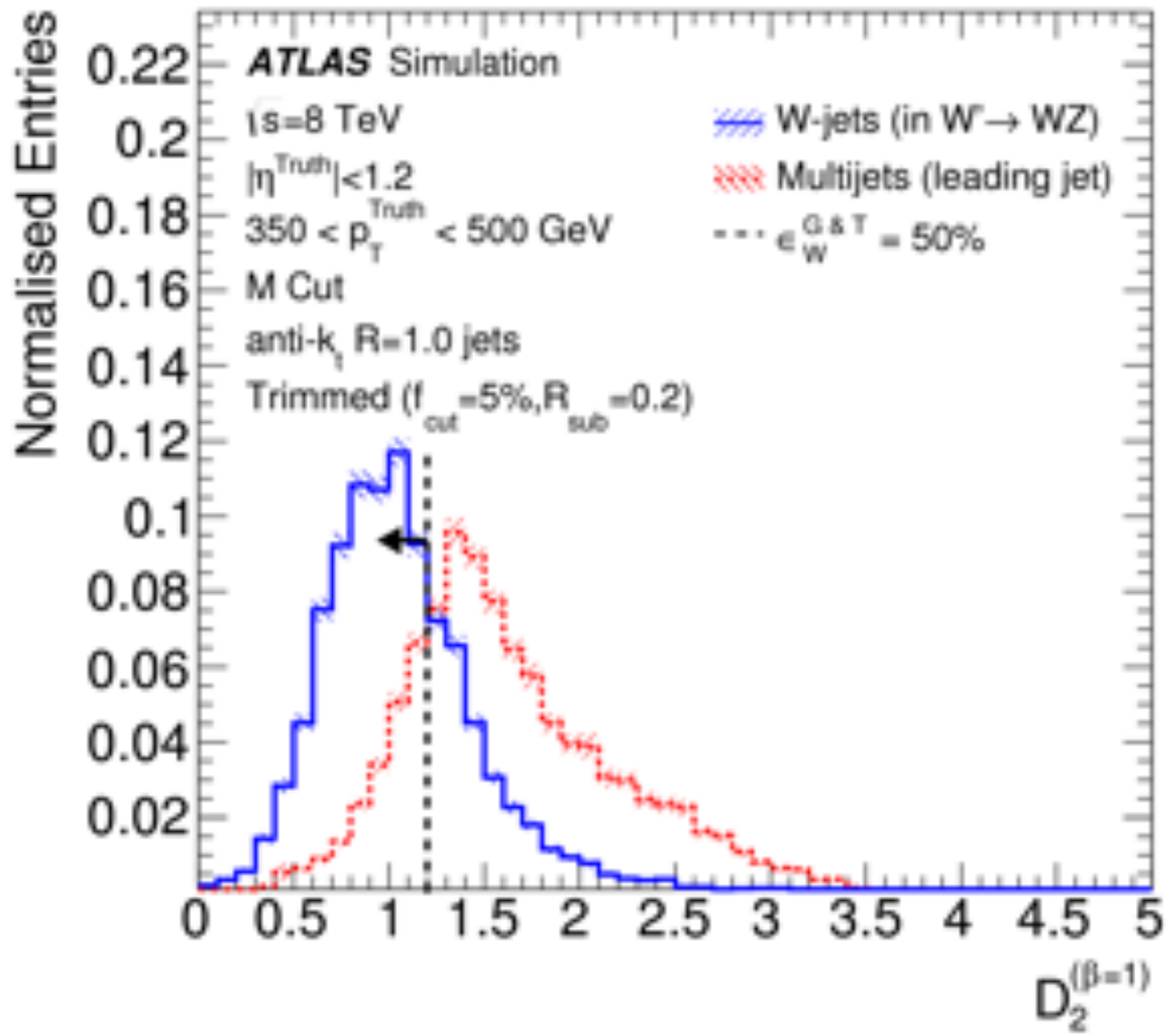
Energy Correlation Functions

ECFs: a complete representation of the jet by combining the pT and angular separation of

ECF1: all jet constituents

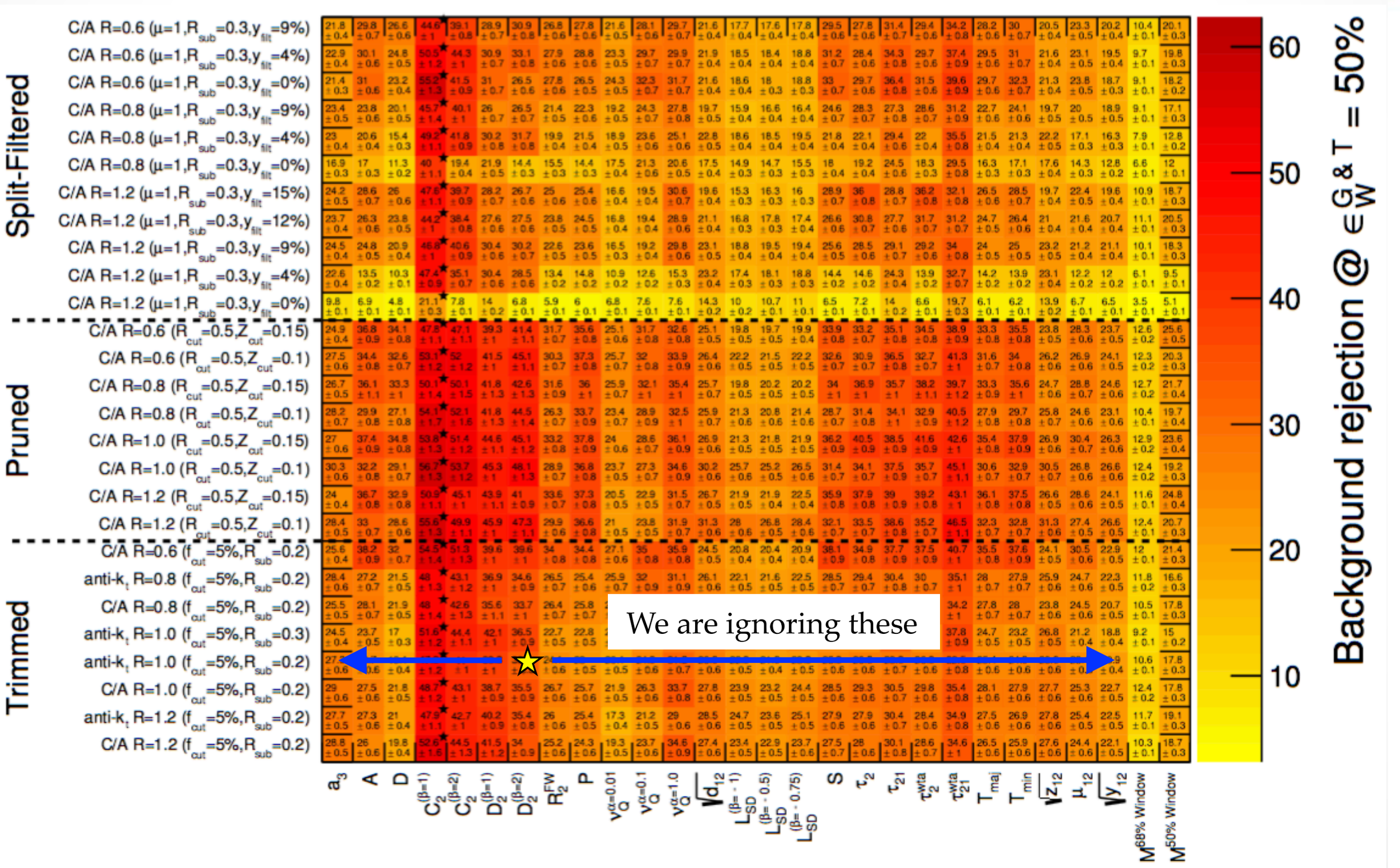
ECF2: pairs

ECF3: triplets

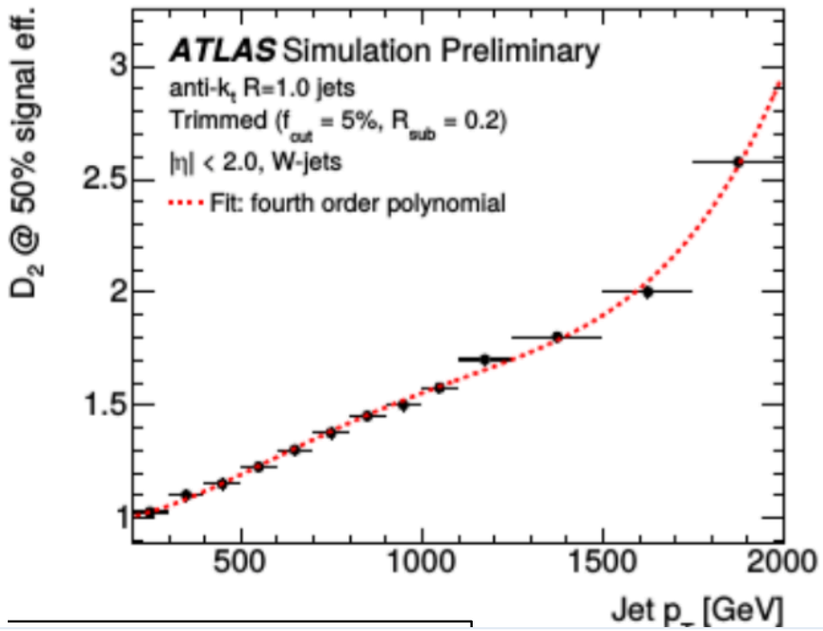


$$D_2^{\beta=1} = E_{\mathrm{CF3}} \left(\frac{E_{\mathrm{CF1}}}{E_{\mathrm{CF2}}} \right)^3$$

Brute force optimization

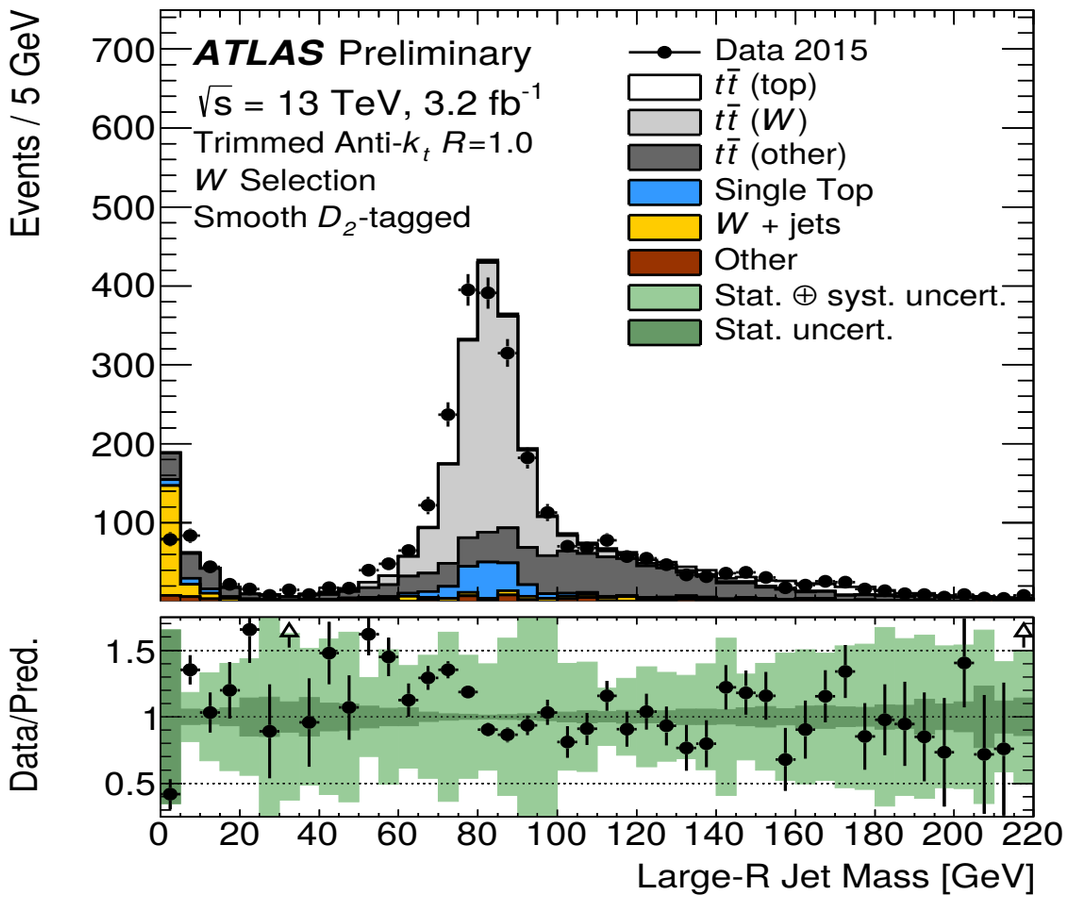


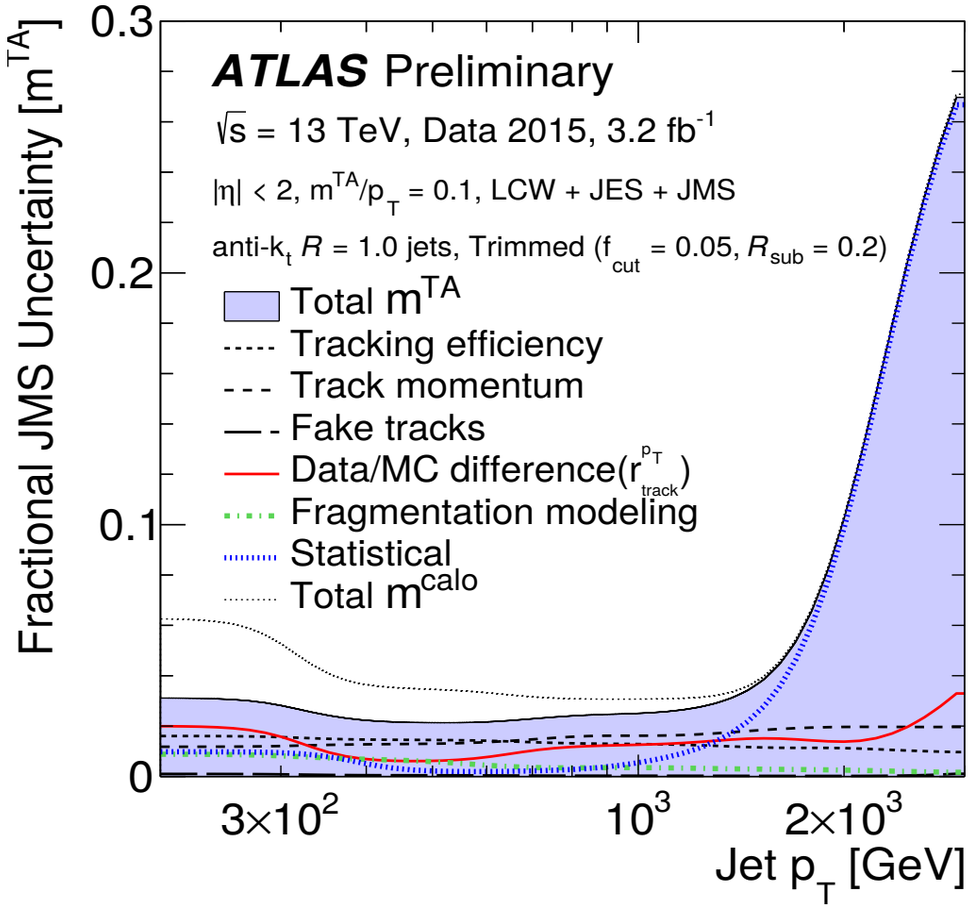
Large-R Jet Calibration



$$R_{\mathrm{trk}} = \frac{r_{\mathrm{track}}^{\mathrm{data}}}{r_{\mathrm{track}}^{\mathrm{MC}}} = \frac{X_{\mathrm{calo}}^{\mathrm{data}} / X_{\mathrm{track}}^{\mathrm{data}}}{X_{\mathrm{calo}}^{\mathrm{MC}} / X_{\mathrm{track}}^{\mathrm{MC}}}$$

X = {p_T, m_{jet}, ...}





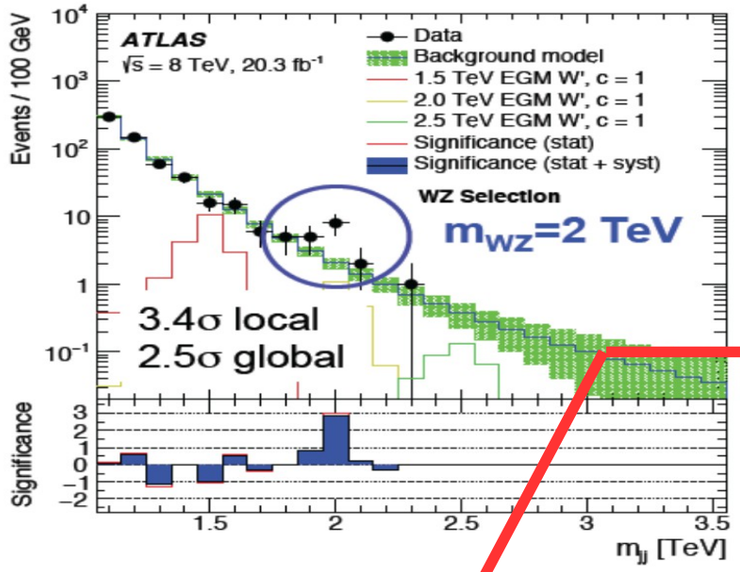
ATLAS
EXPERIMENT

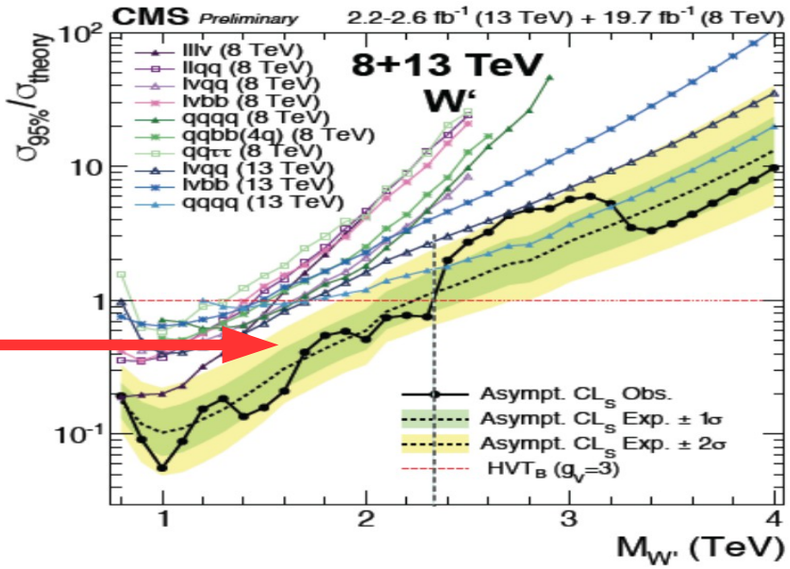
>1 TeV boson
candidate jets!

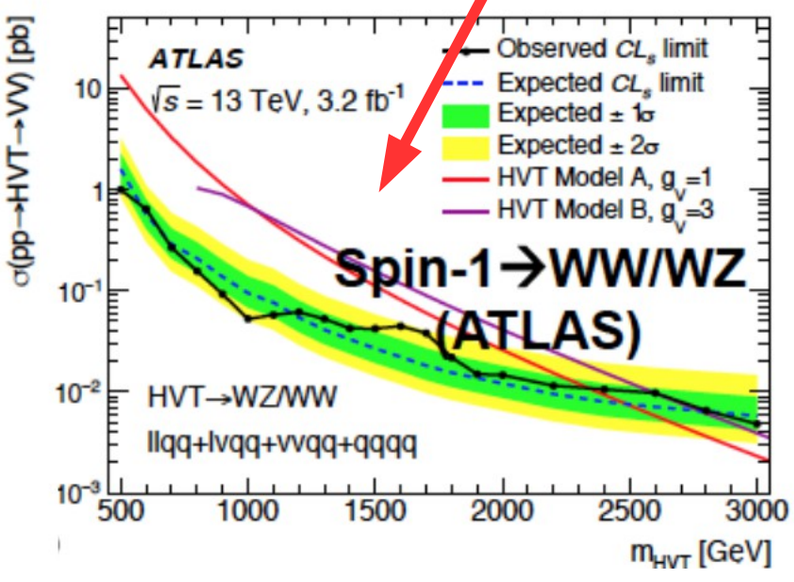
99584
563621388
5-20 08:26:49 CEST
2.40 TeV

2015 Review

- 2 TeV excess is dead



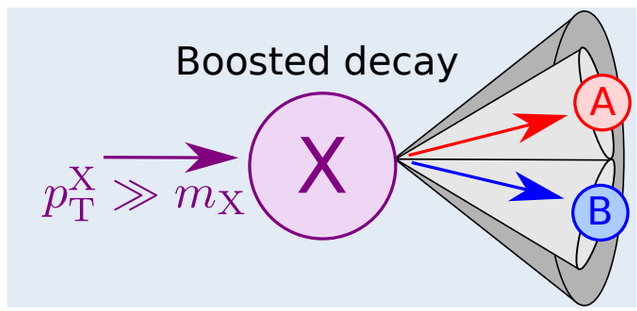




2015 Excitement was at 2 TeV
2016 Excitement is at …..

Outline

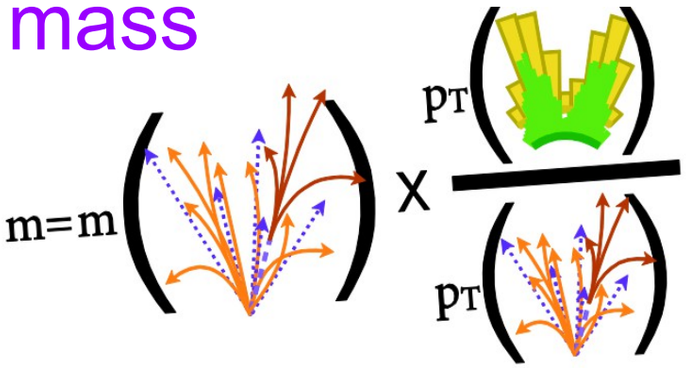
- Introduction
- Jet reconstruction
- Jet substructure
- Advanced W/Z/H tagging



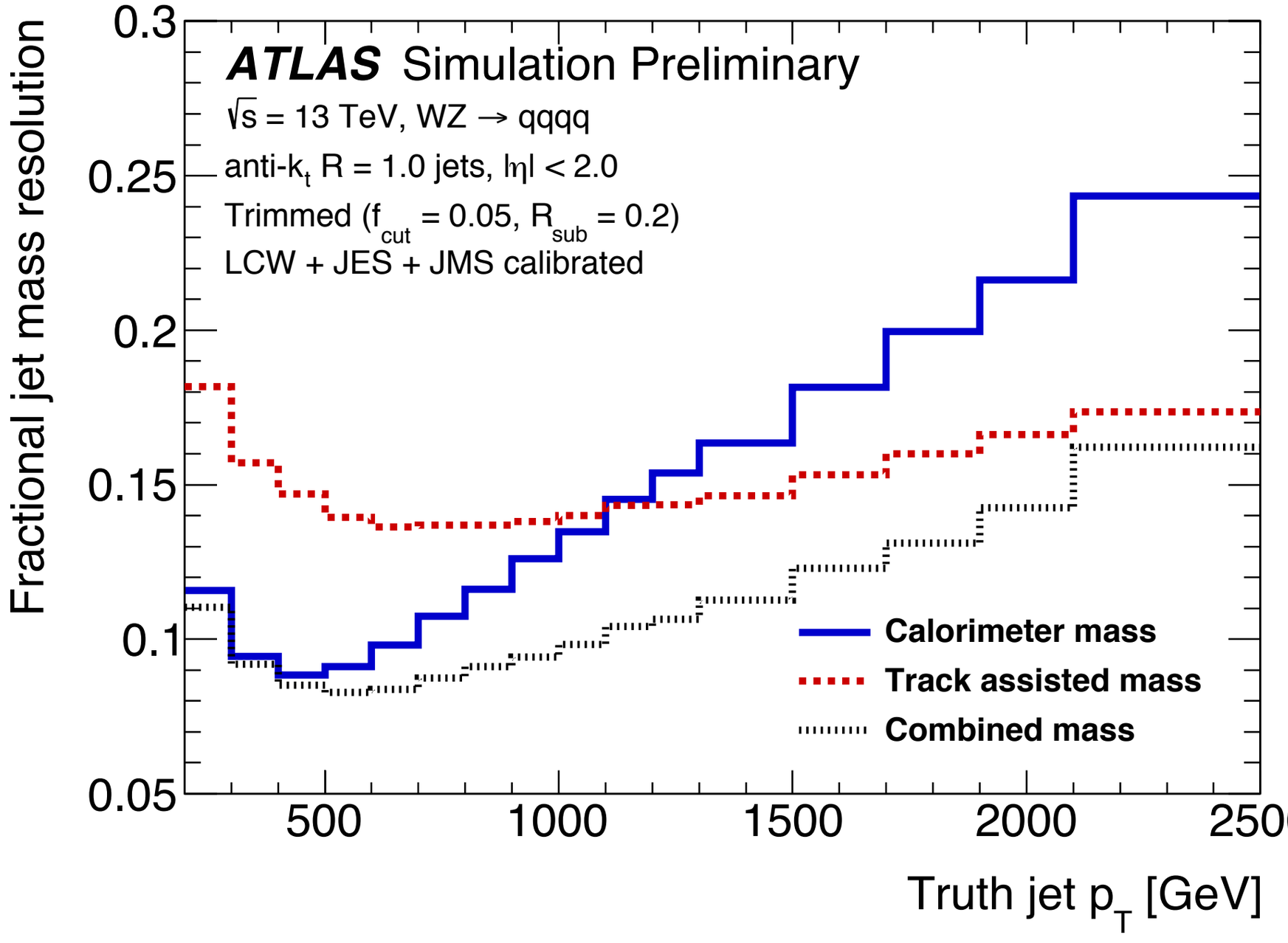
Jet Mass Calibration

ATLAS-CONF-2016-035

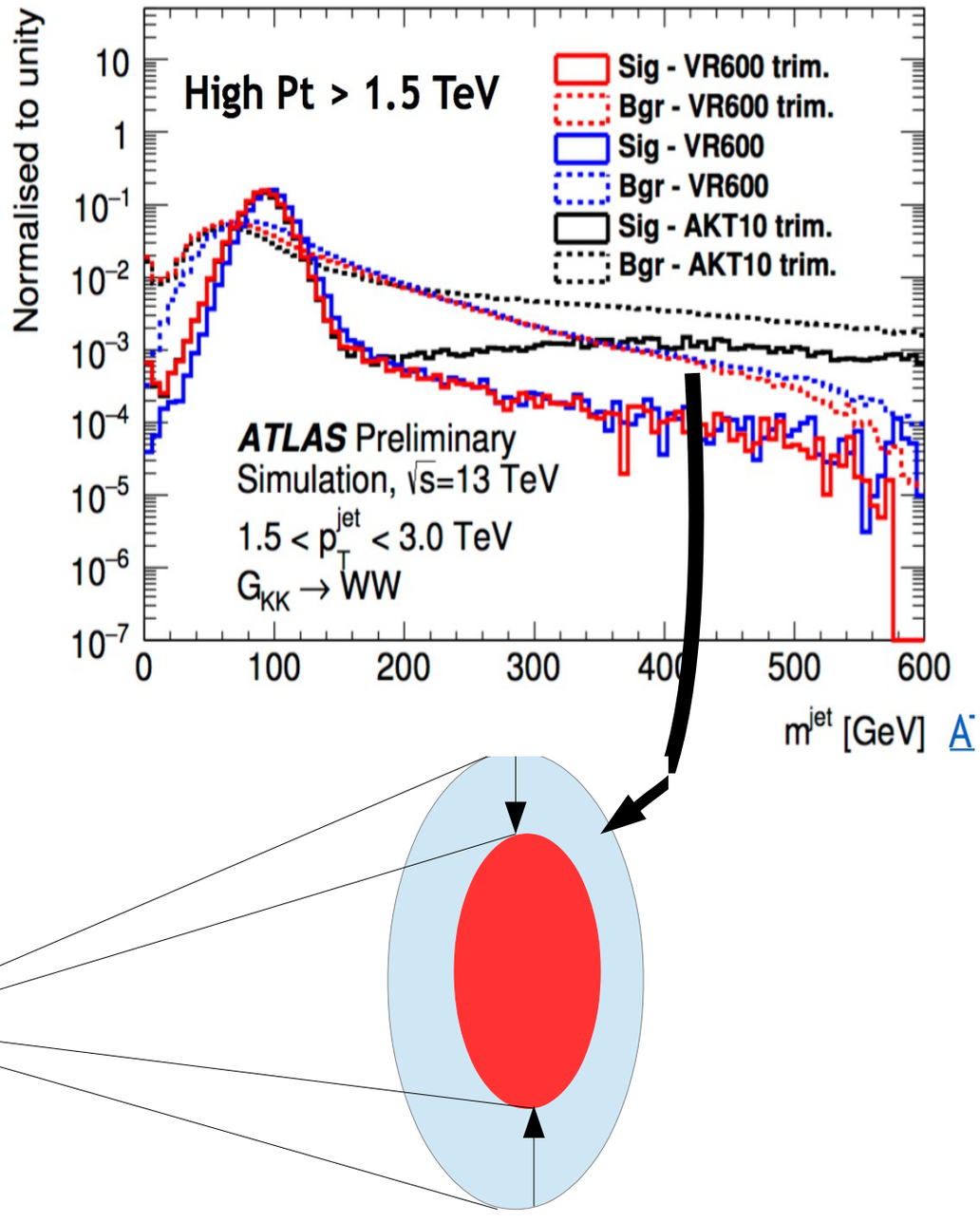
Bringing the tracks into mass

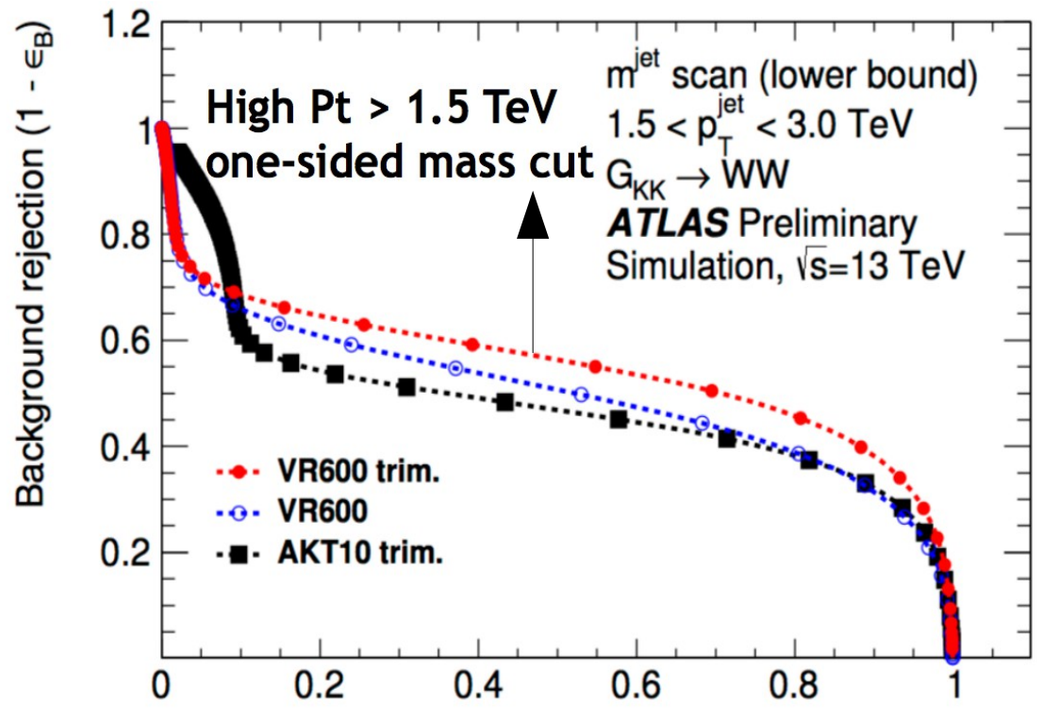


$$m^{\mathrm{TA}} = \frac{m^{\mathrm{track}}}{p_{\mathrm{T}}^{\mathrm{track}}} \times p_{\mathrm{T}}^{\mathrm{calo}}$$

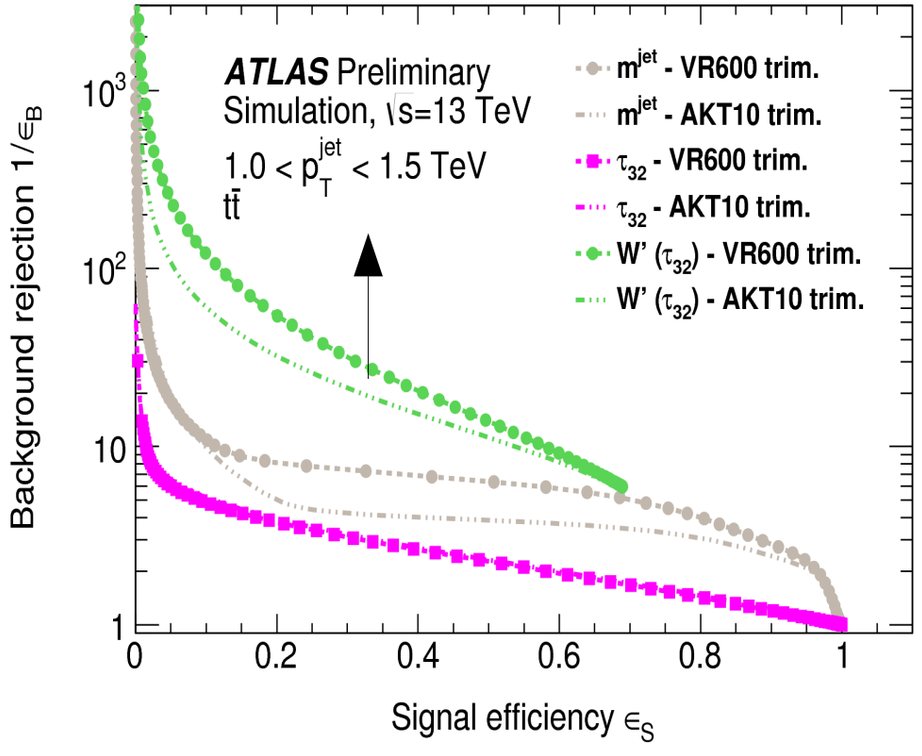


Variable-R

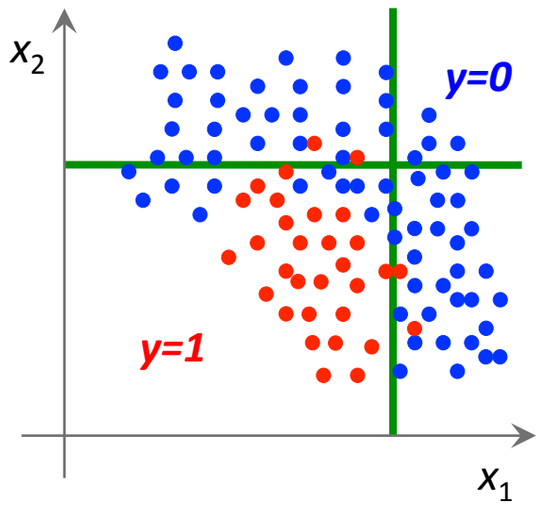




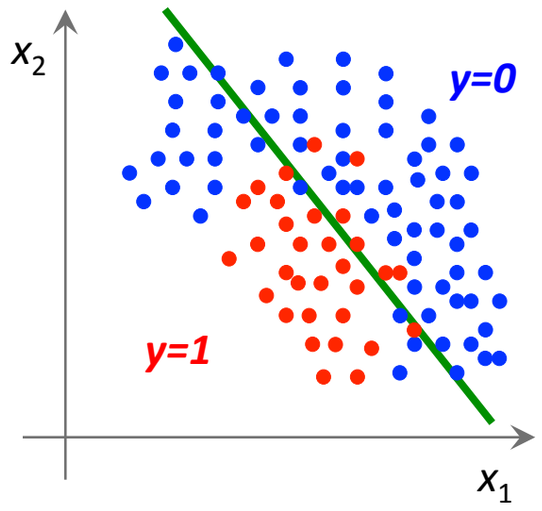
ATL-PHYS-PUB-2016-013



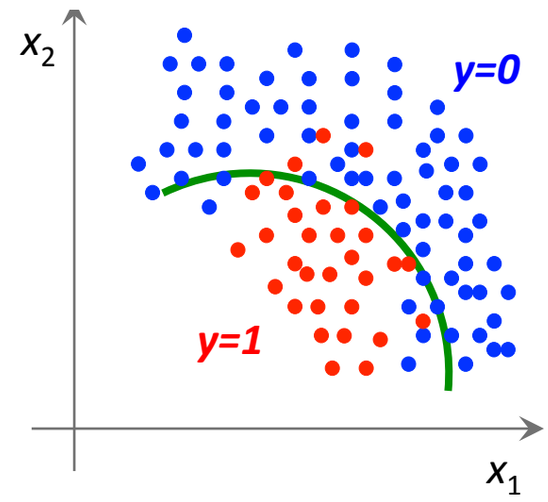
Machine Learning Tagger



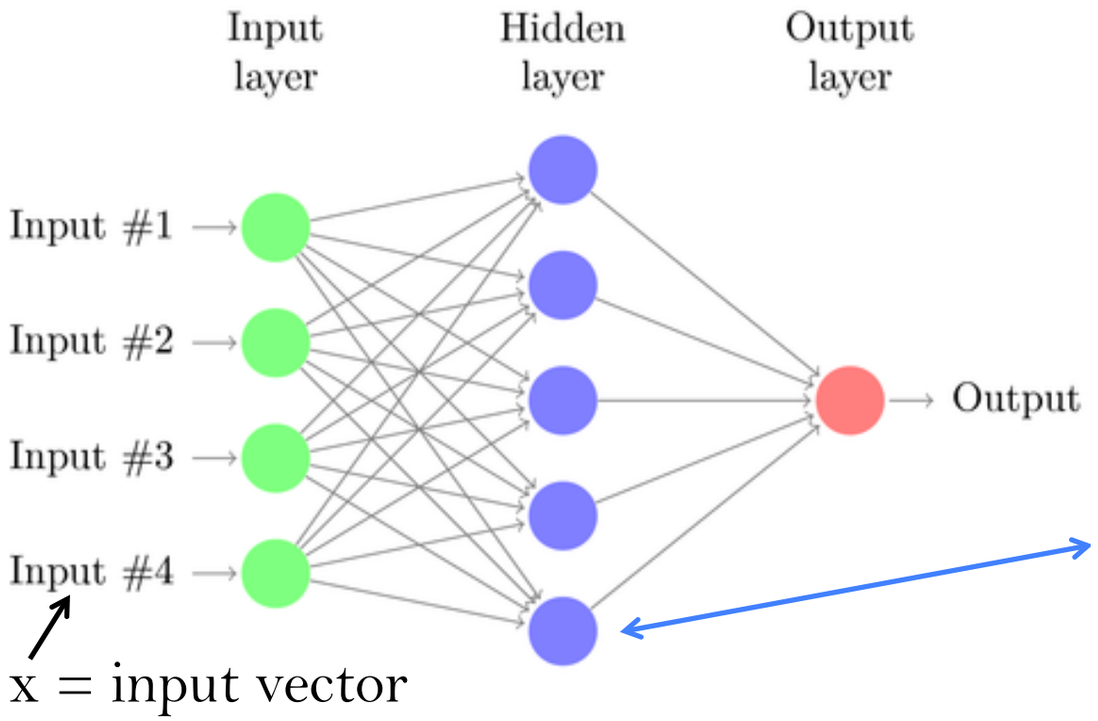
Rectangular cuts

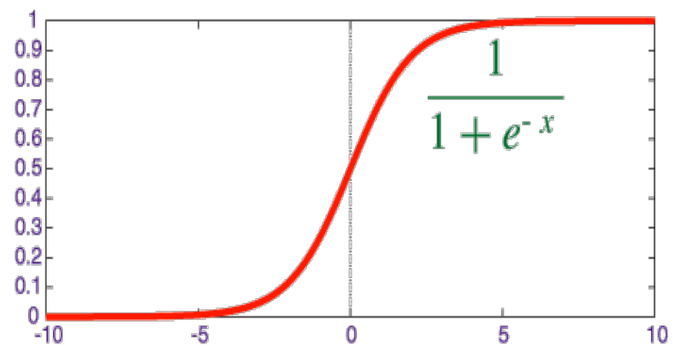


Linear discriminant



Nonlinear discriminant



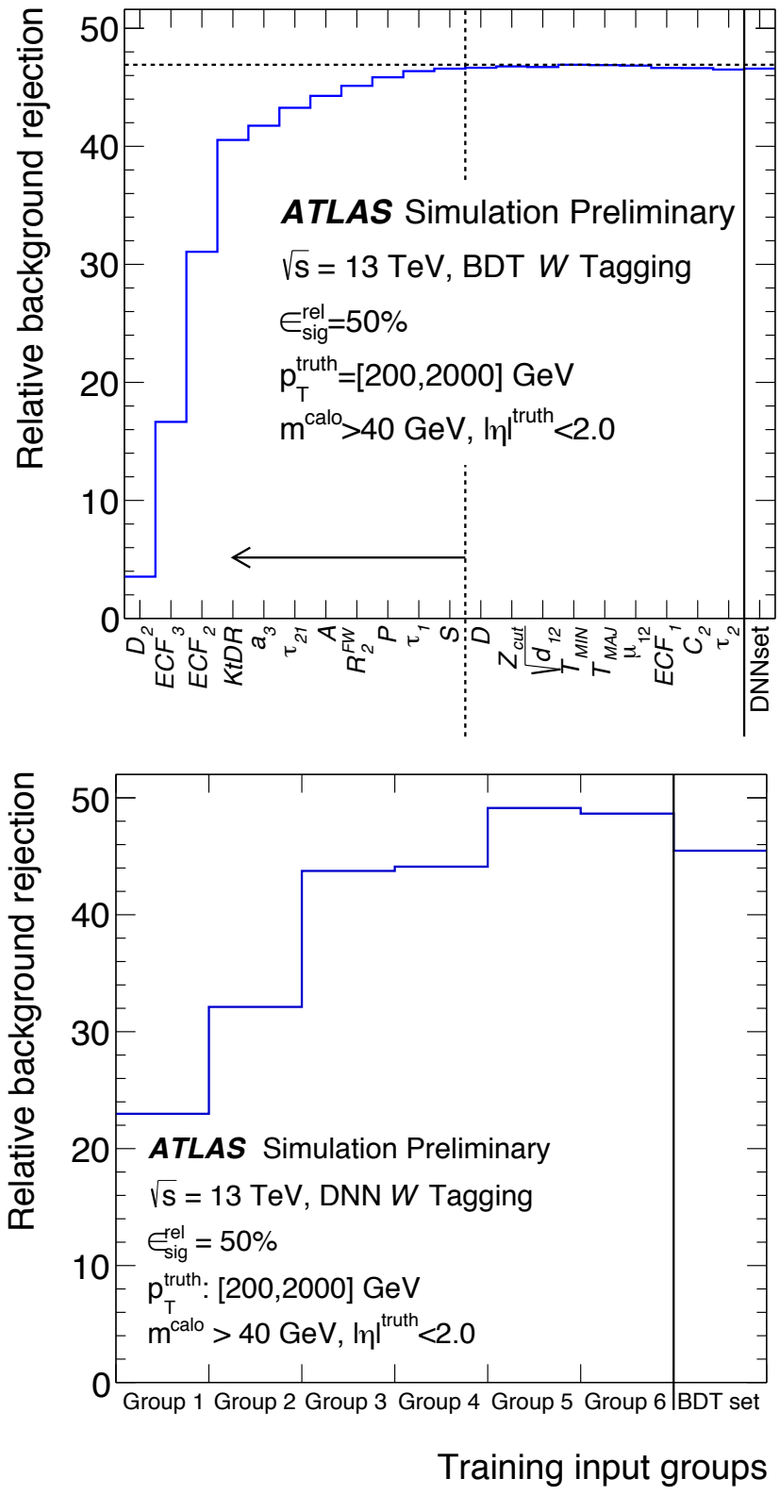


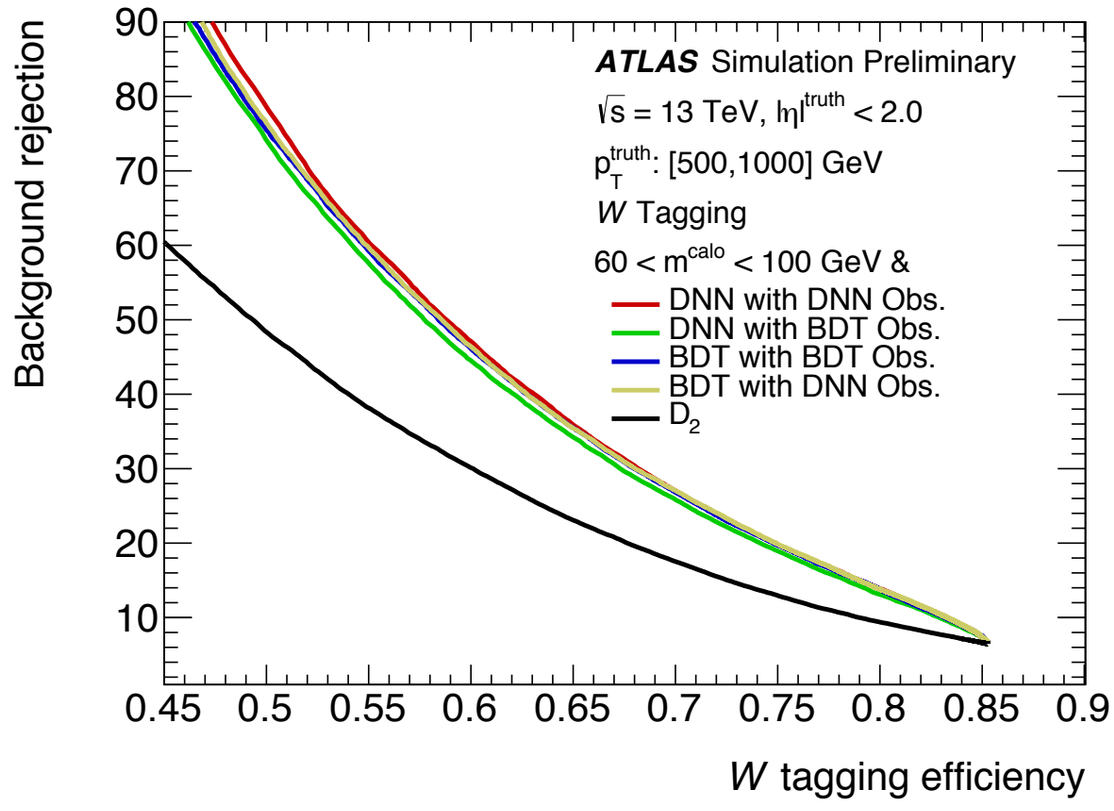
σ(x) = sigmoid function
is the *Activation Function*

Machine Learning Tagger

ATL-PHYS-PUB-2017-004

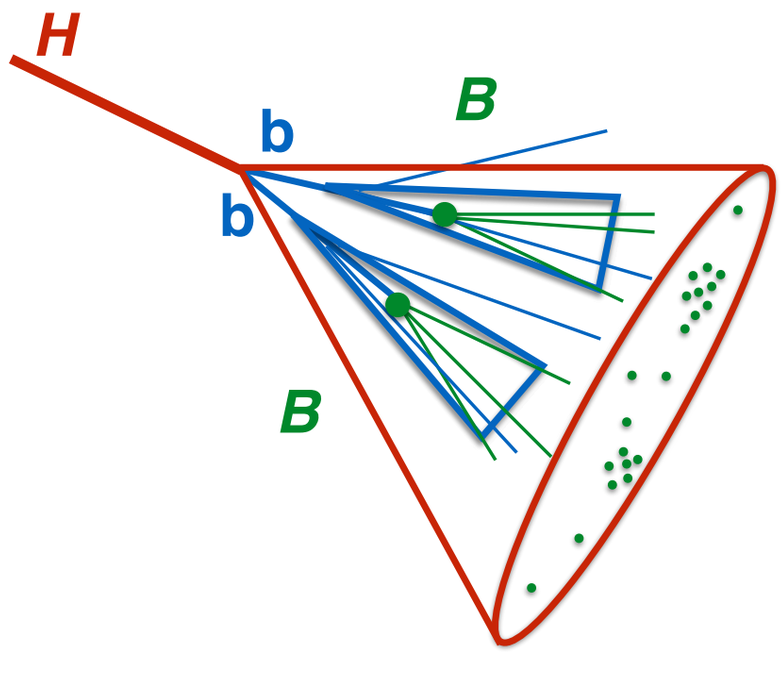
Observable	*W*-Boson Tagging BDT	DNN
ECF_1		○
ECF_2	○	○
ECF_3	○	○
C_2		○
D_2	○	○
τ_1	○	○
τ_2		○
τ_3		
τ_{21}	○	○
τ_{32}		
R_2^{FW}	○	○
S	○	○
$\mathcal{P}$	○	○
$\mathcal{D}$		○
a_3	○	○
A	○	○
T_{MIN}		
T_{MAJ}		
Z_{CUT}		○
μ_{12}		○
$\sqrt{d_{12}}$		○
$\sqrt{d_{23}}$		
$KtDR$	○	○
Q_w		



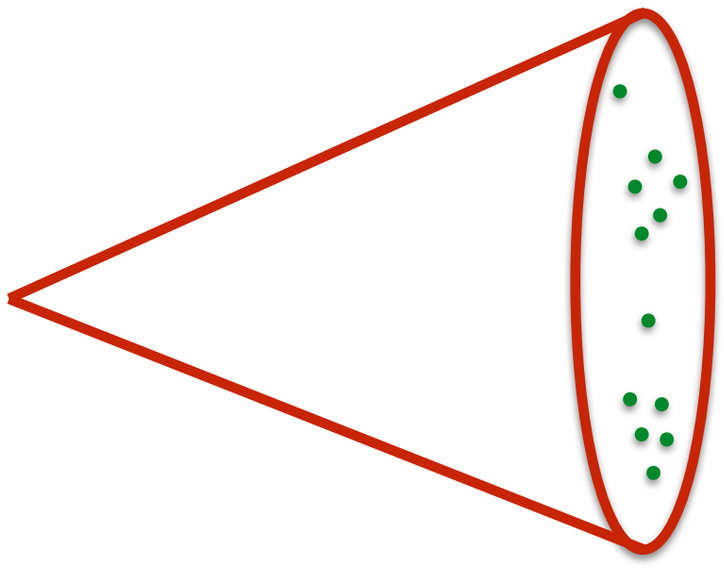


Bkg rejection increased by 50% w.r.t. D2

Higgs tagging

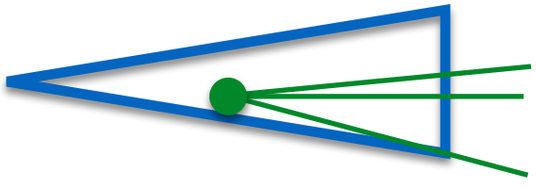


anti-k_t R = 1.0 calorimeter jet



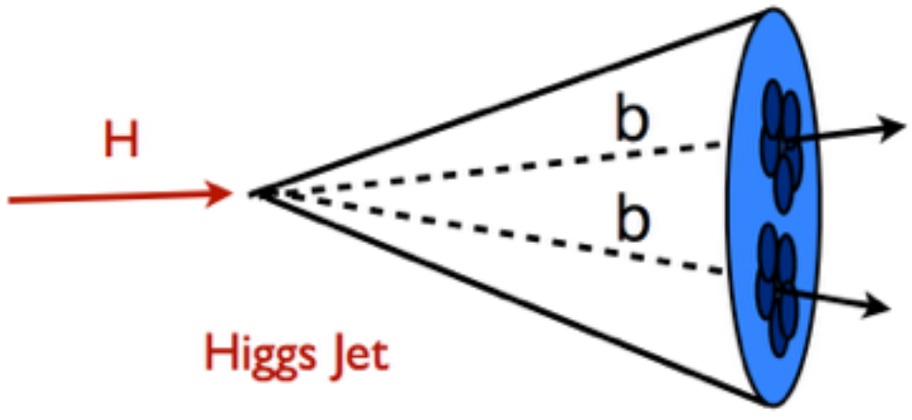
substructure

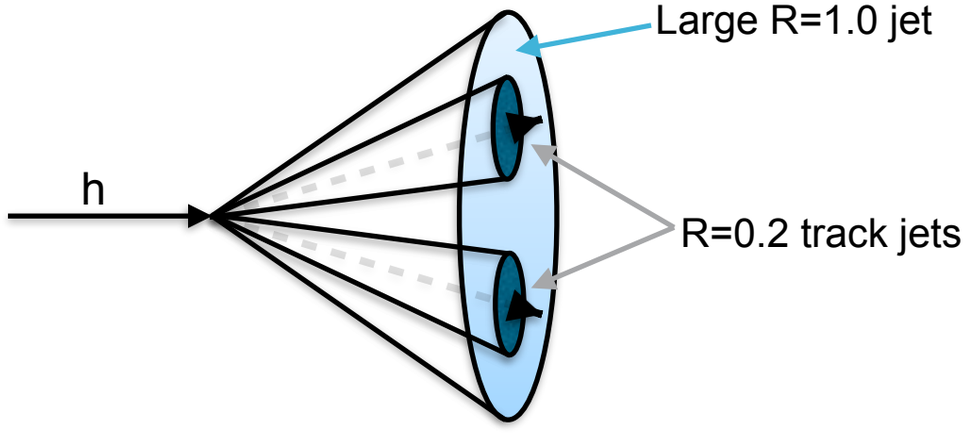
ghost-associated
anti-k_t R = 0.2 track jet

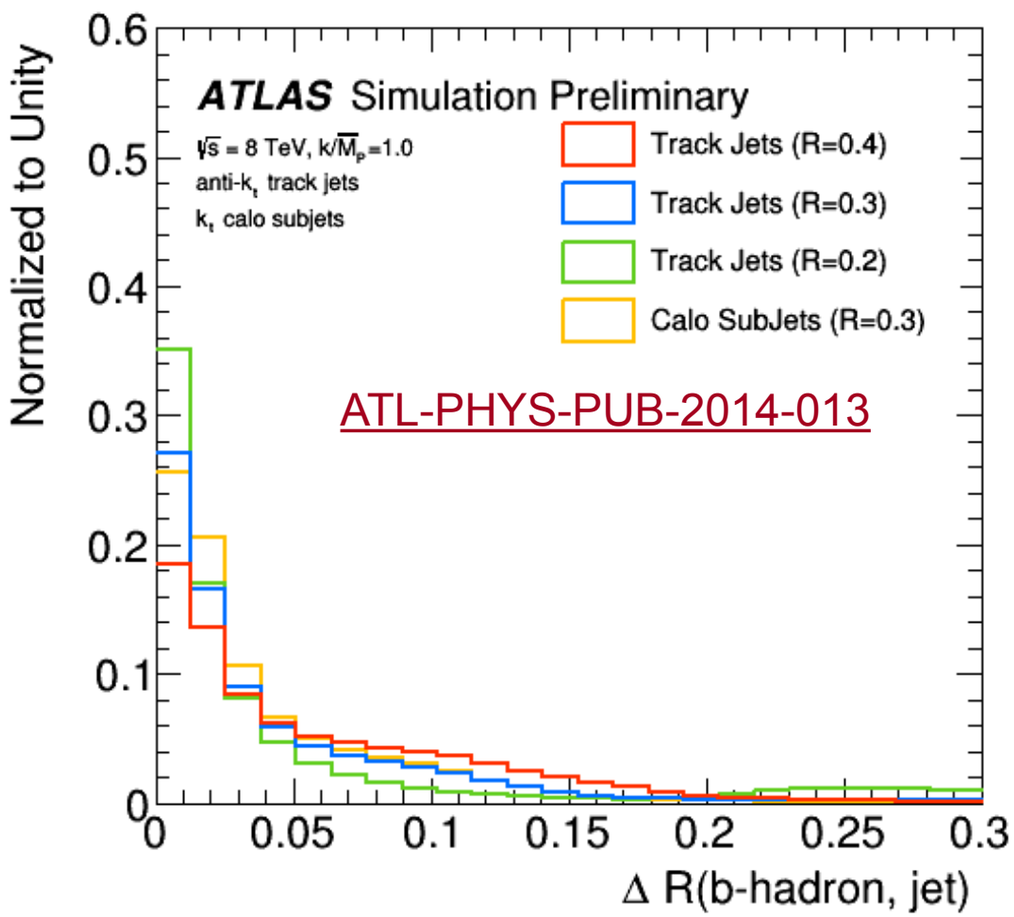


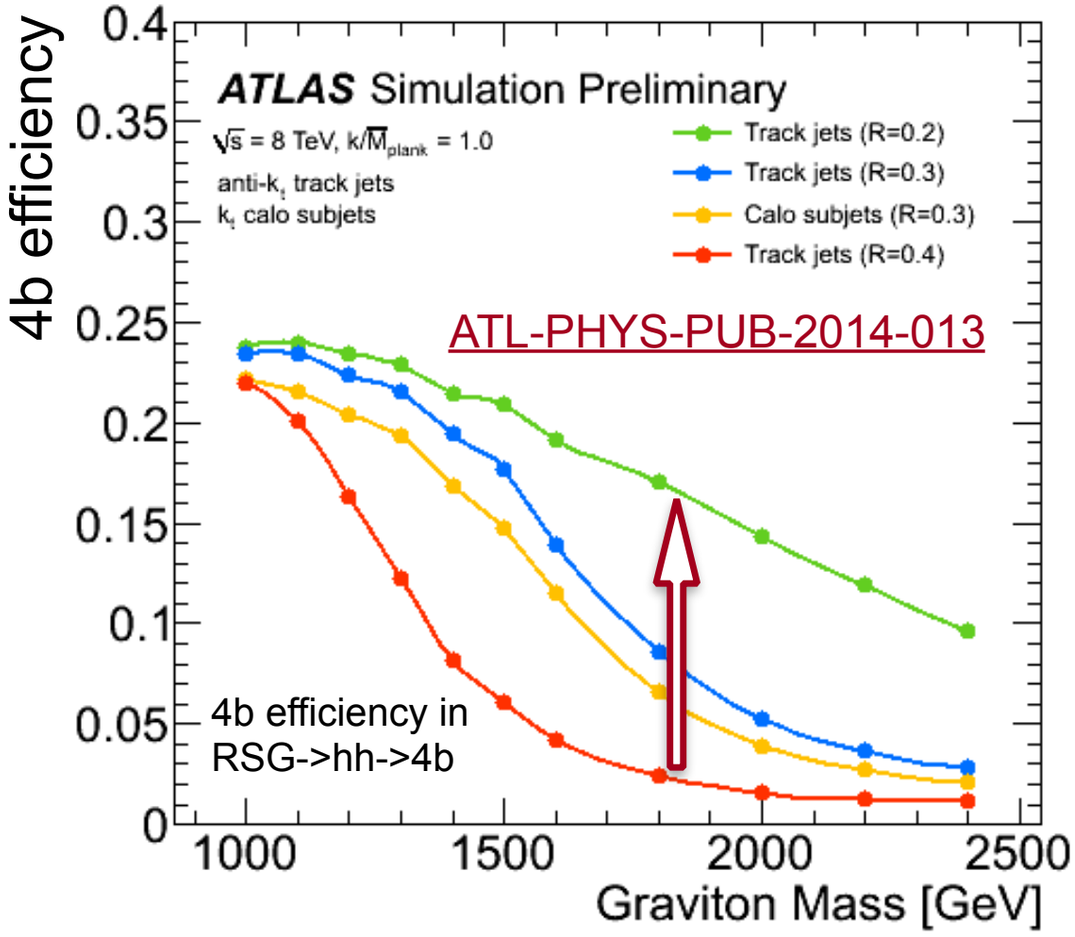
b-tagging

Higgs tagging

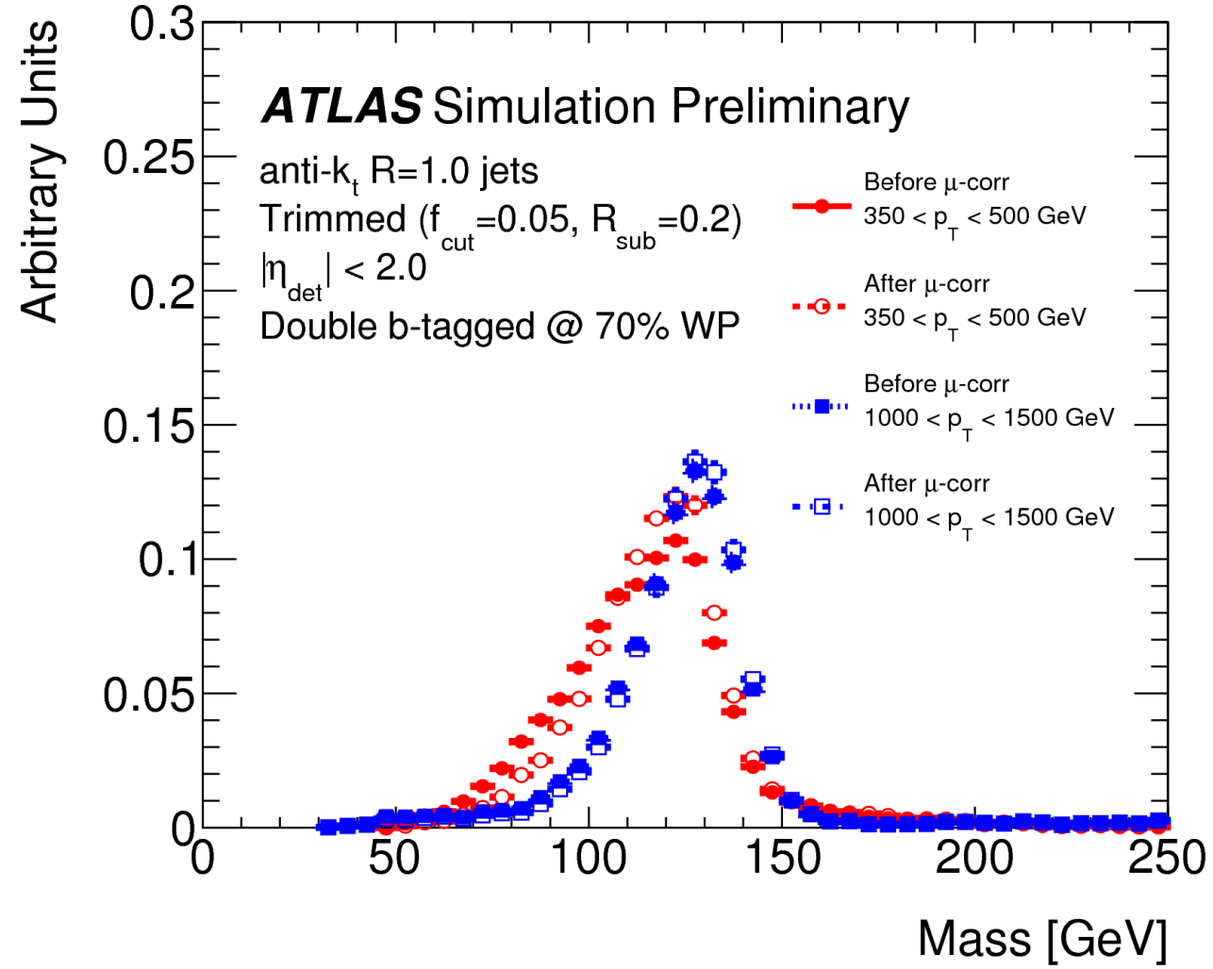


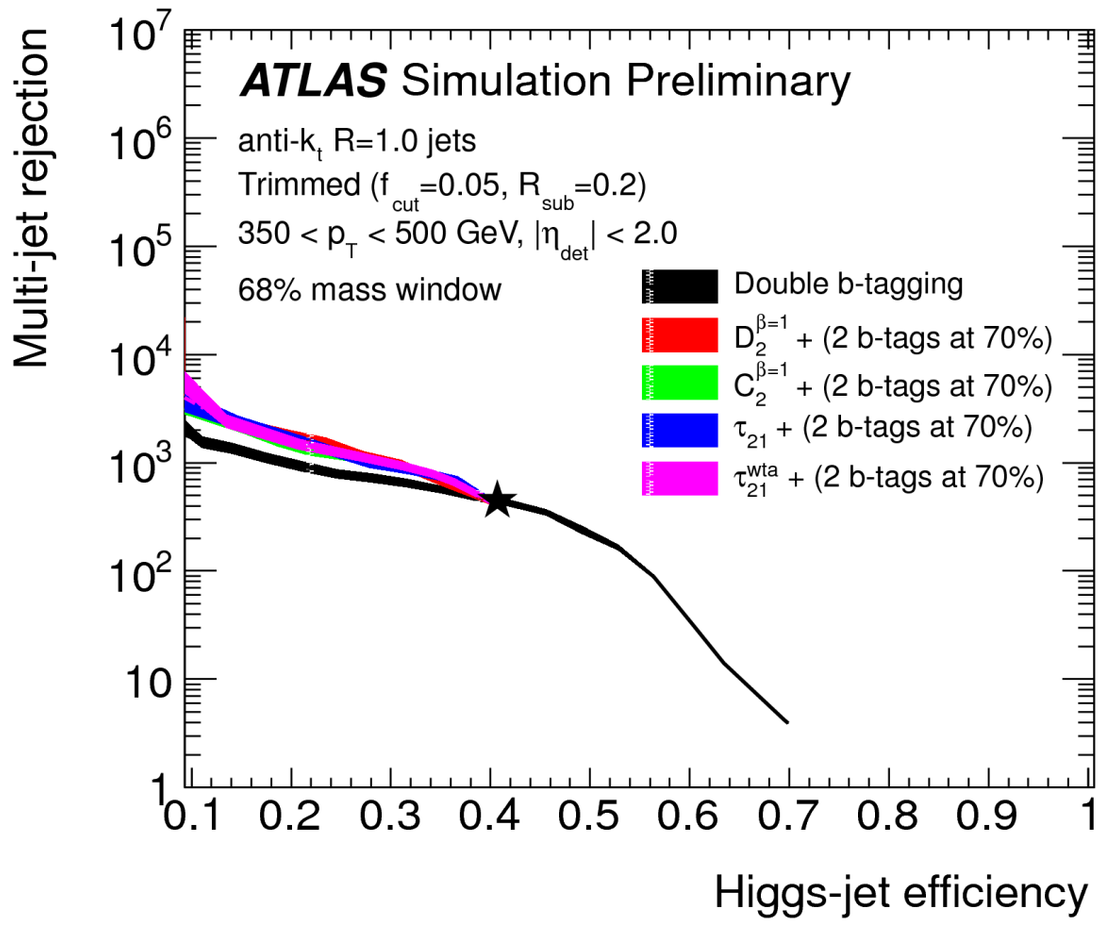






Higgs tagging + JSS





Summary

- Jets a powerful tool to reorganize events for physics
  - LHC Physics is Jet Frontier Physics
- Jet substructure and advanced calibrations are developed in ATLAS to improve analysis
- Advanced reconstruction and identification techniques for hadronic W/Z/Higgs are developed