Jet tagging with ATLAS for discoveries in Run II

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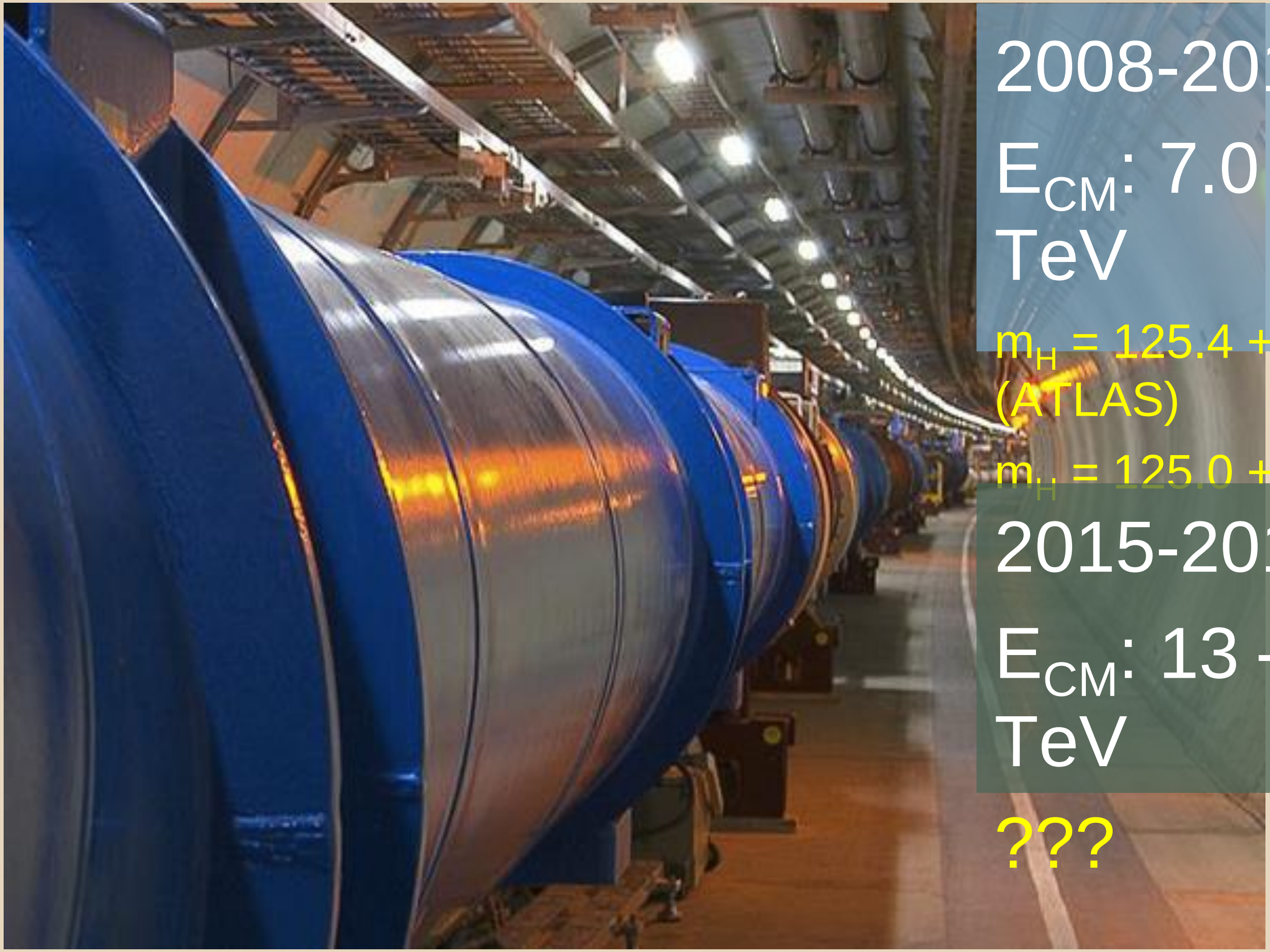
November 5th 2014

The Large Hadron Collider



2008-2013:

E_{CM}: 7.0 – 8.0 TeV

m_H = 125.4 +/- 0.4 (ATLAS)

m_H = 125.0 +/- 0.3 (CMS)

2015-2018:

E_{CM}: 13 – 14 TeV

???

Discoveries at the LHC

dark matter/**low EWSB scale** → new physics

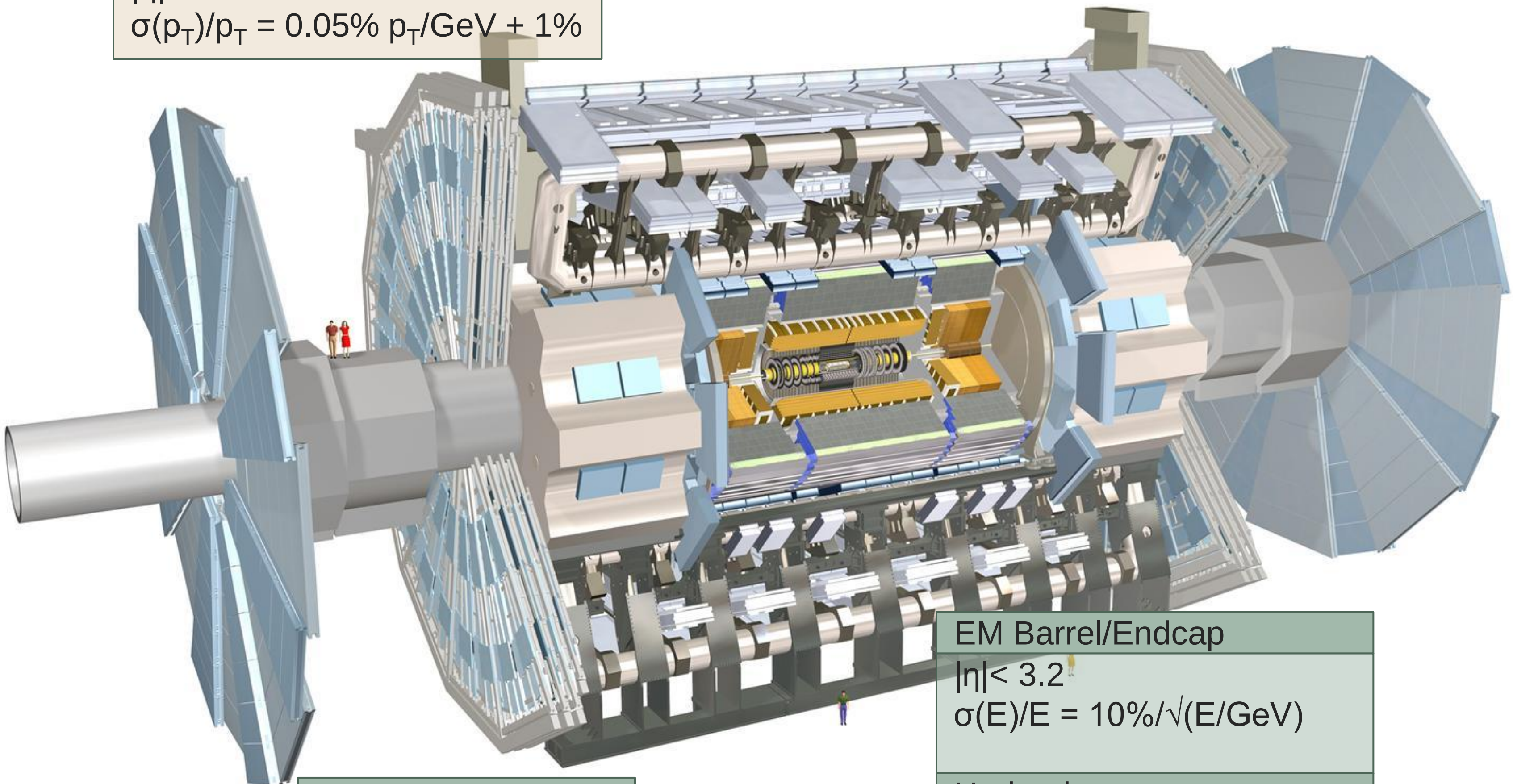
The LHC is prepared to find:

✦**top partners**

✦superpartners (***squark/gluino***)

✦new gauge couplings

✦***extra dimensions***



Inner tracker

$|\eta| < 2.5$

$\sigma(p_T)/p_T = 0.05\%\ p_T/\mathrm{GeV} + 1\%$

EM Barrel/Endcap

$|\eta| < 3.2$

$\sigma(E)/E = 10\%/\sqrt{(E/\mathrm{GeV})}$

Forward Calorimeter

$3.0 < |\eta| < 4.9$

$\sigma(E)/E = 100\%/\sqrt{E}$

Hadronic

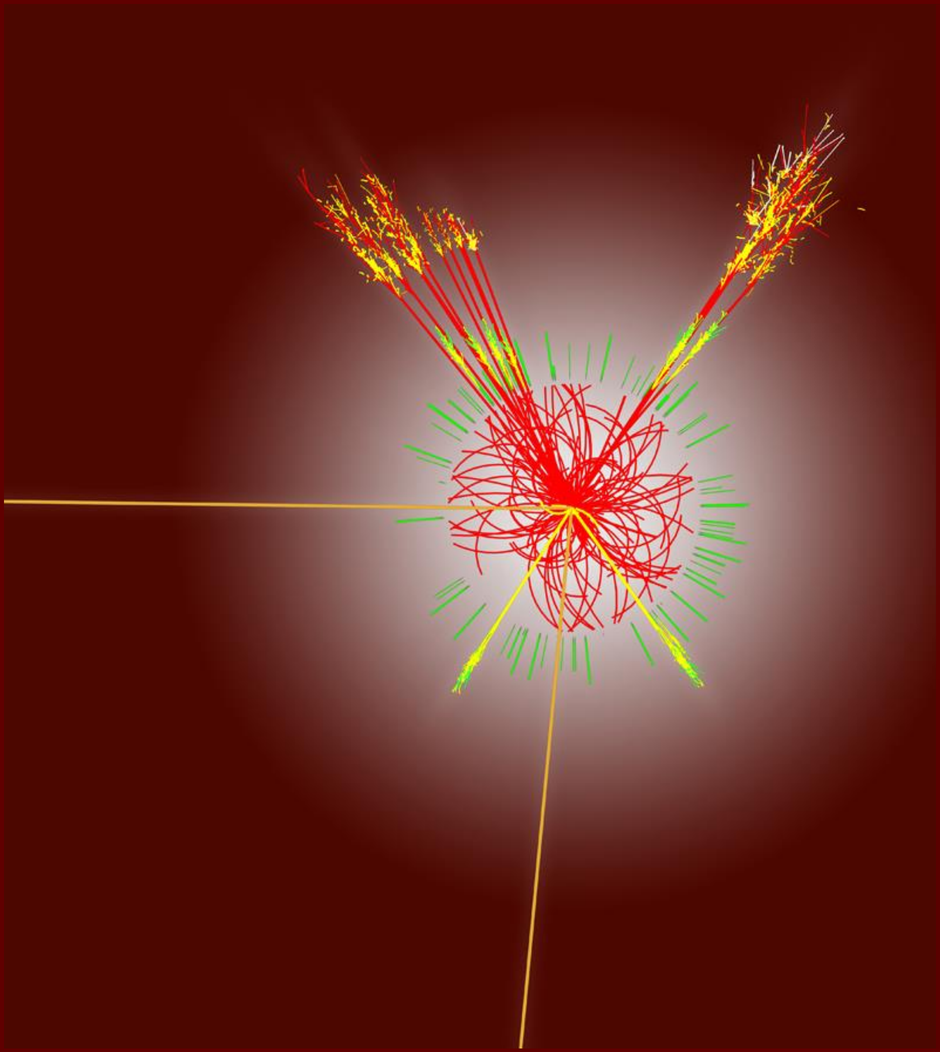
$0 < |\eta| < 1.7$

$1.7 < |\eta| < 3.2$

$\sigma(E)/E = 50\%/\sqrt{E}$

the ATLAS detector

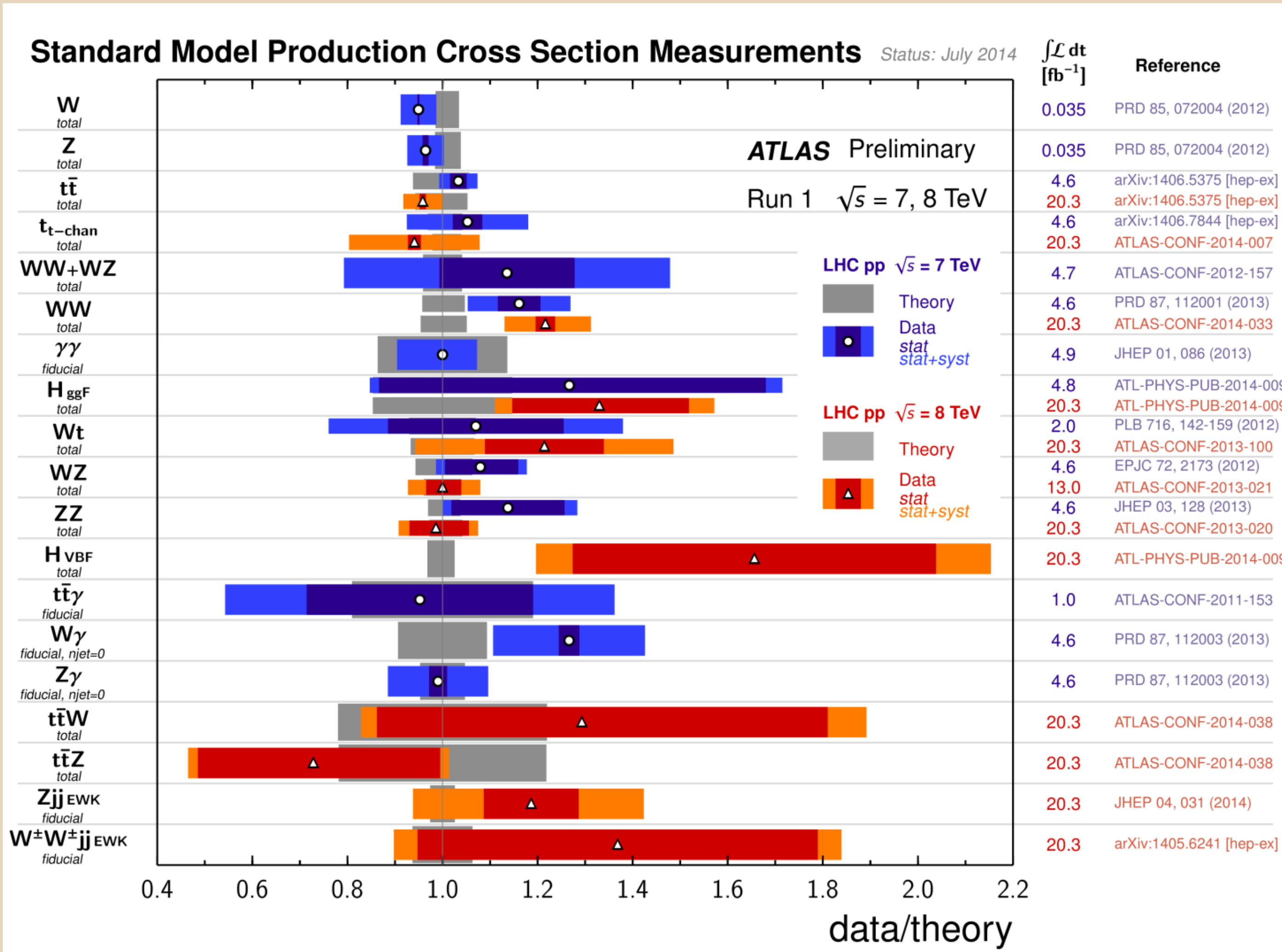
Overview



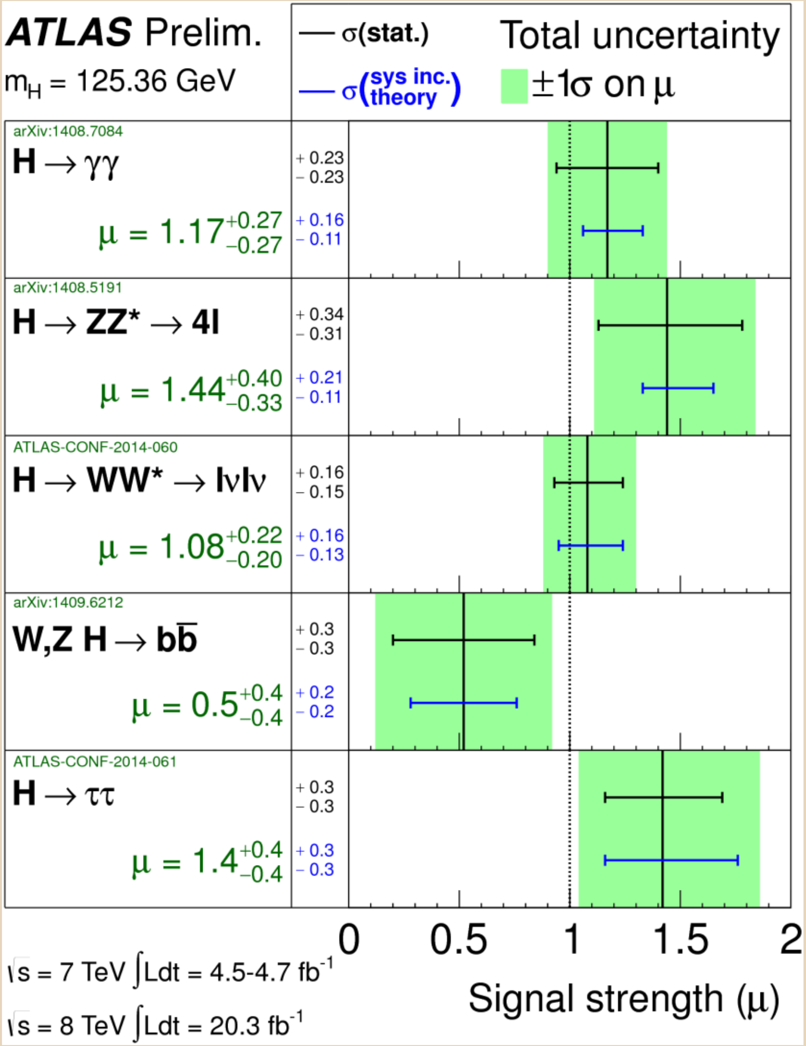
- What's left to discover in Run II?
- *Why jets? Why now?*
- Jet substructure tagging
- *experimental challenges + solutions*
- Run I constraints on models of new physics using substructure tags
- Outlook

Prospects for discoveries in Run II

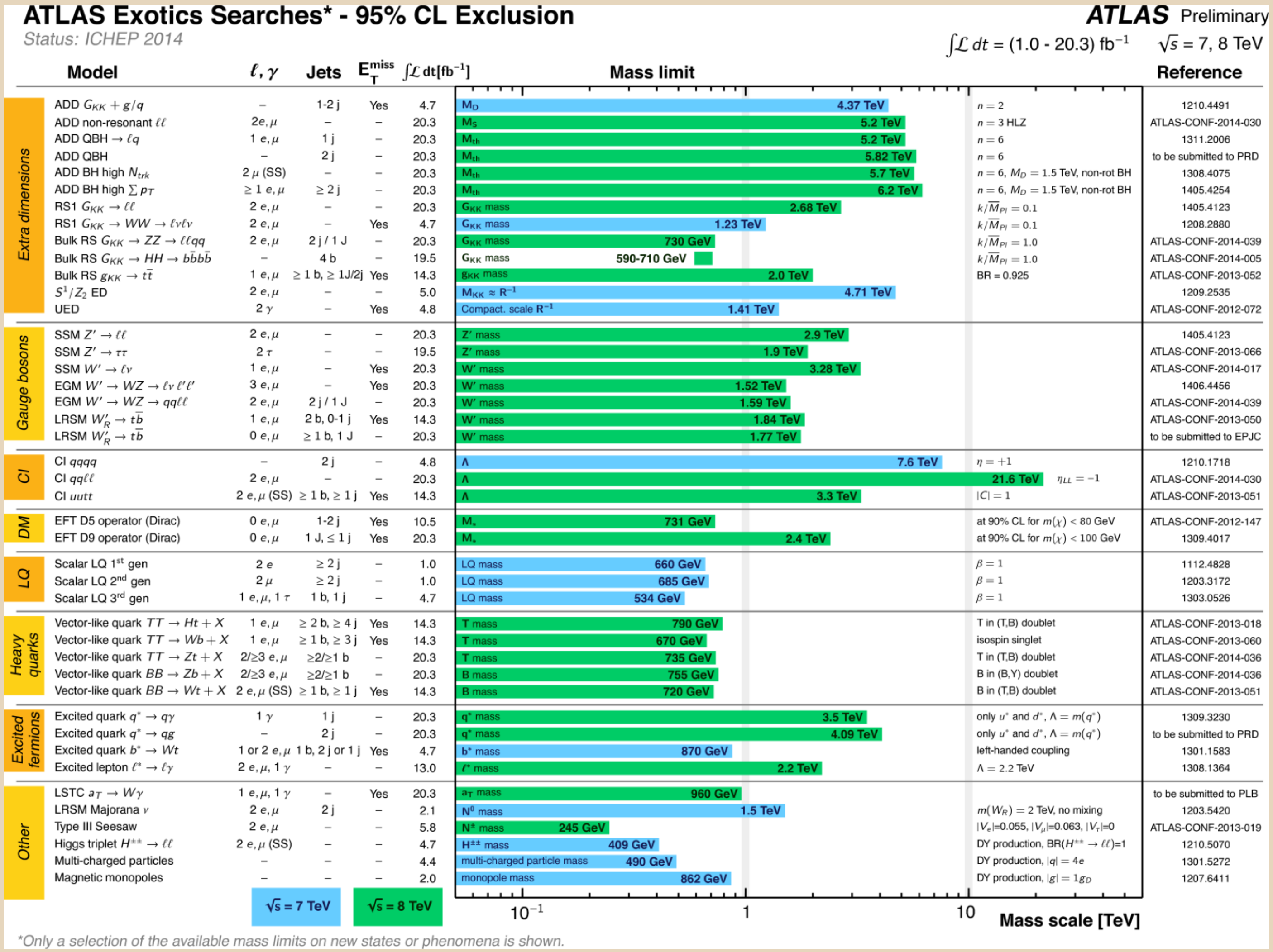
Probing the electroweak scale in Run I

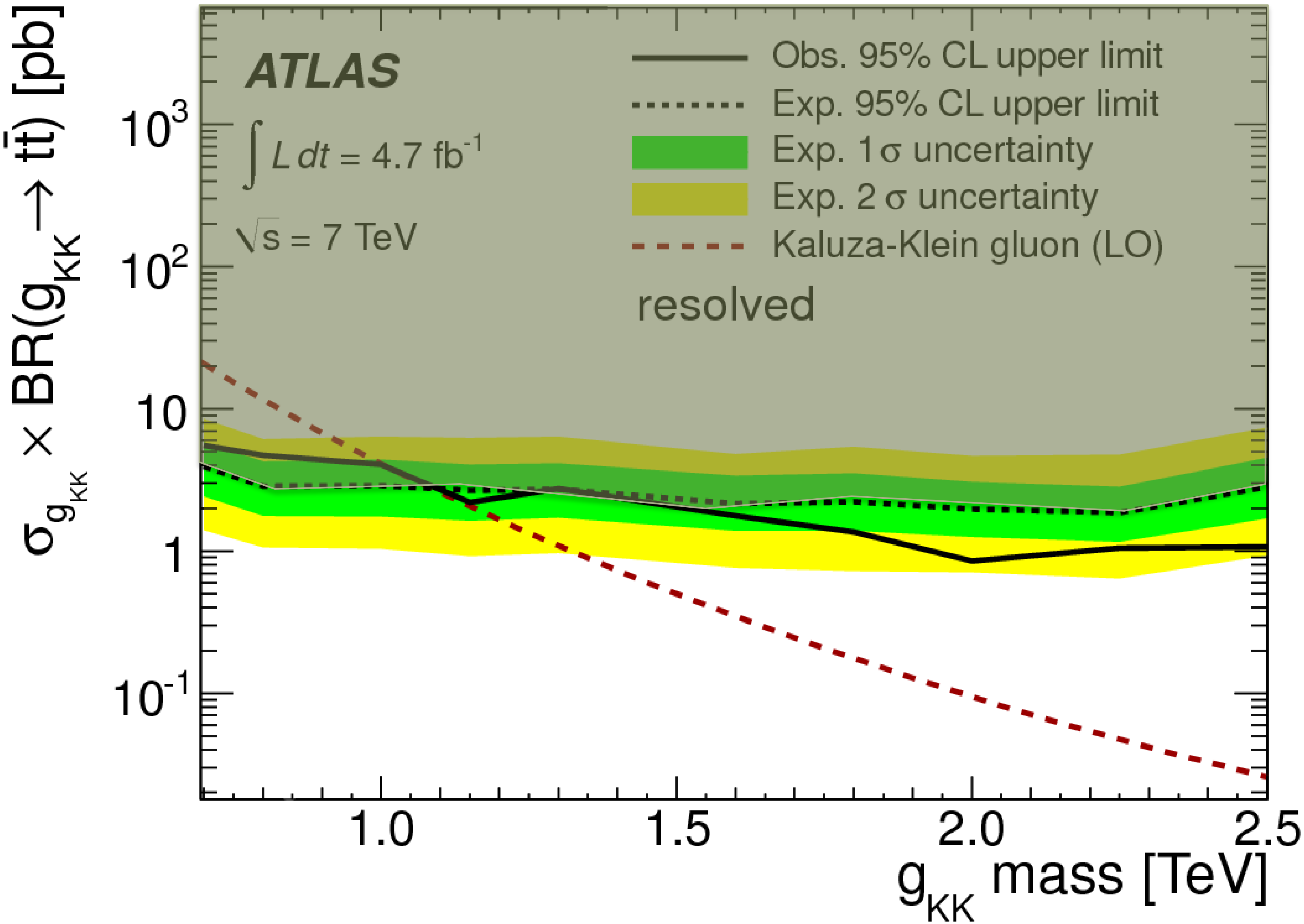


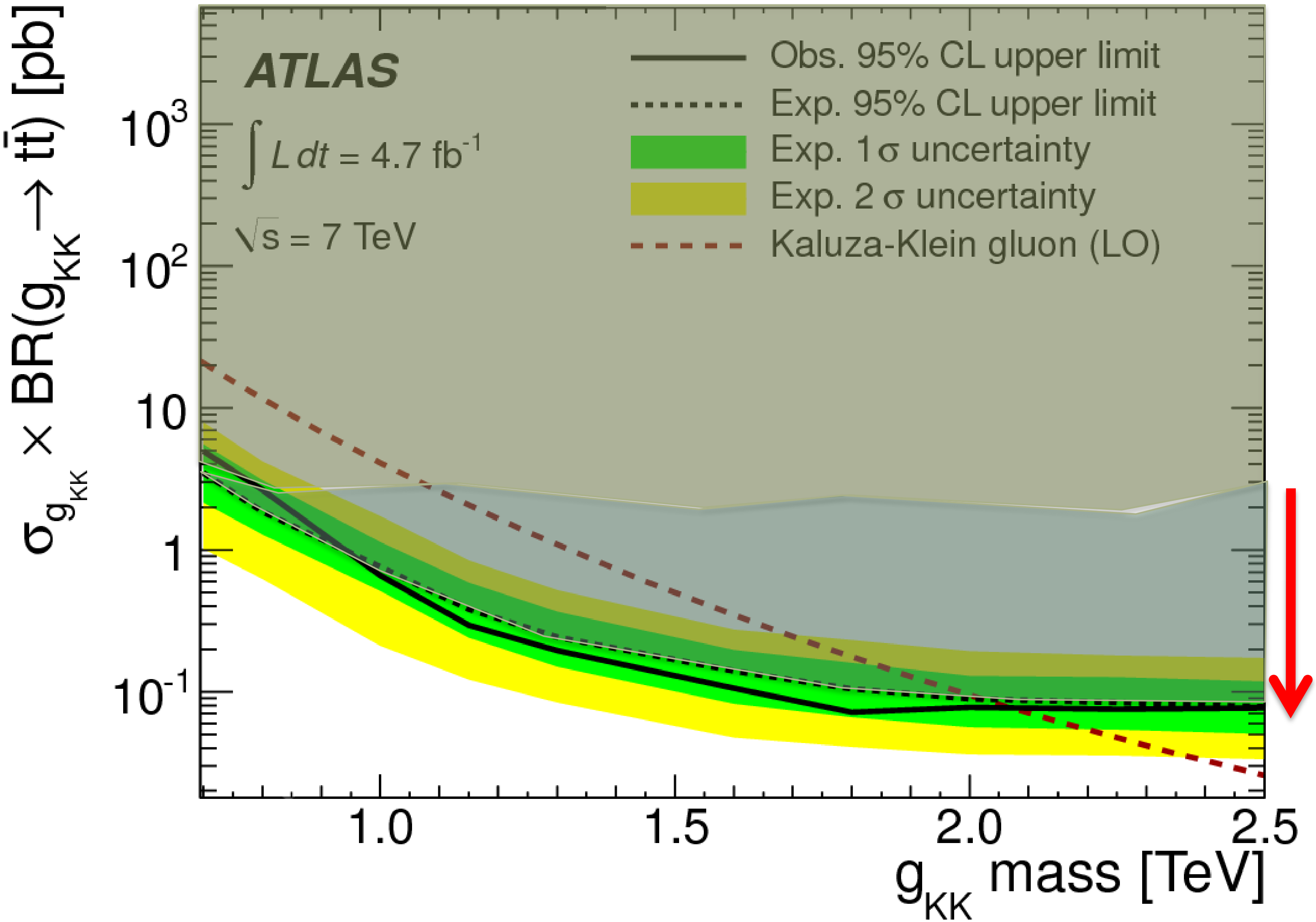
Probing electroweak symmetry breaking in Run I



Beyond the electroweak scale




ATLAS
∫ L dt = 4.7 fb⁻¹
√s = 7 TeV
Obs. 95% CL upper limit
Exp. 95% CL upper limit
Exp. 1σ uncertainty
Exp. 2σ uncertainty
Kaluza-Klein gluon (LO)
resolved
σ_gKK × BR(gKK → tt̄) [pb]
gKK mass [TeV]
10³
10²
10
1
10⁻¹
1.0
1.5
2.0
2.5



ATLAS
$\int L\,dt = 4.7\ fb^{-1}$
$\sqrt{s} = 7$ TeV
Obs. 95% CL upper limit
Exp. 95% CL upper limit
Exp. 1σ uncertainty
Exp. 2 σ uncertainty
Kaluza-Klein gluon (LO)
$\sigma_{g_{KK}} \times BR(g_{KK} \rightarrow t\bar{t})$ [pb]
10^3
10^2
10
1
10^{-1}
1.0
1.5
2.0
2.5
g_{KK} mass [TeV]

Lessons from Run I

Higgs mass requires us to study a variety of decays:

- large branching fraction to bb
- Searches for exotic di-higgs, etc. require fermionic decay channels

Next searches must probe multi-TeV mass scales

- large pT for final-state particles in decay
- parton luminosity requires large acceptance in searches

Hadronic decays and boosted object

Looking towards Run II

We **will** probe higher masses/boosts at the same luminosity…

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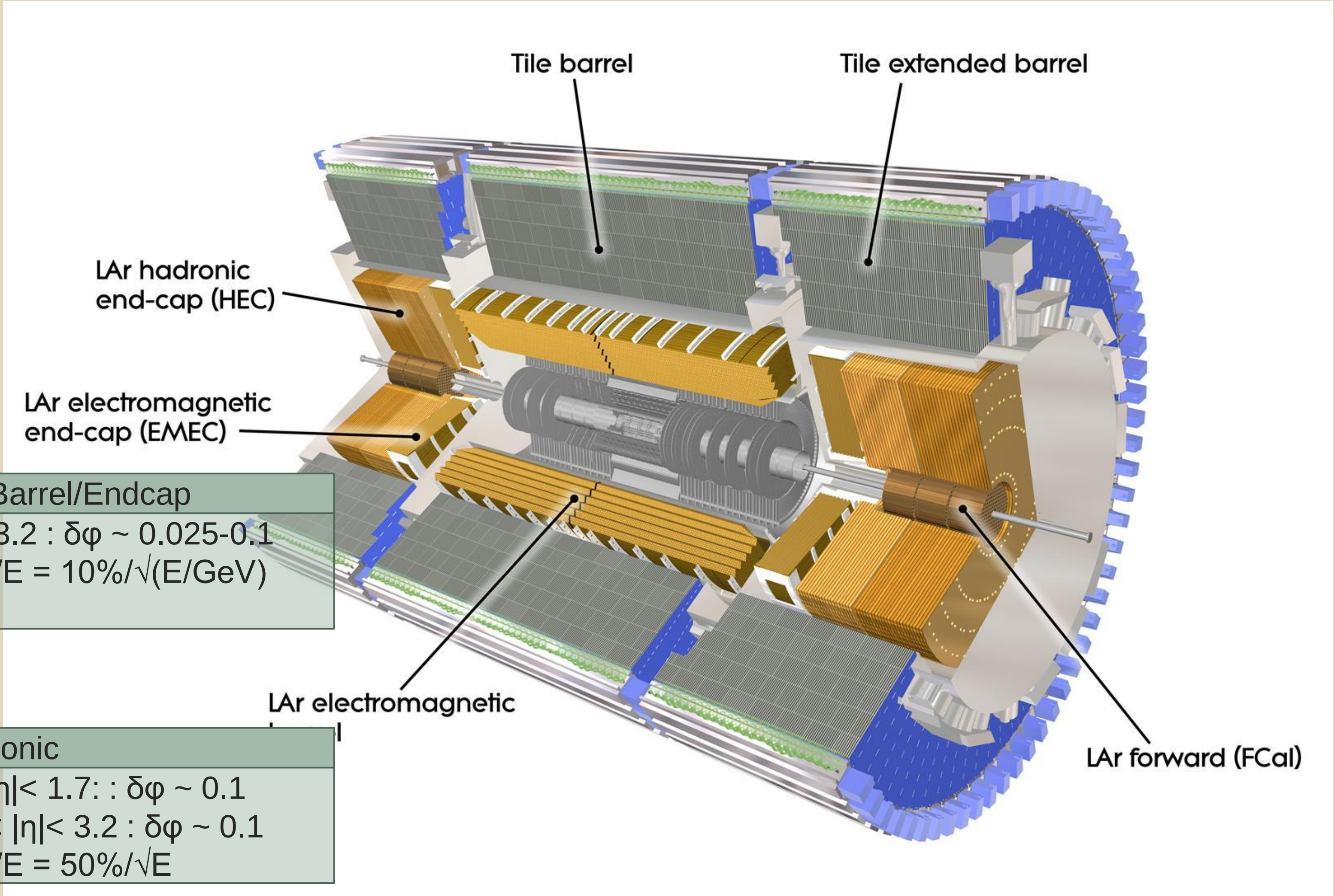
Quigg: http://lutece.fnal.gov/PartonLum

Jet substructure at ATLAS

Hadronic measurements at ATLAS



EM Barrel/Endcap

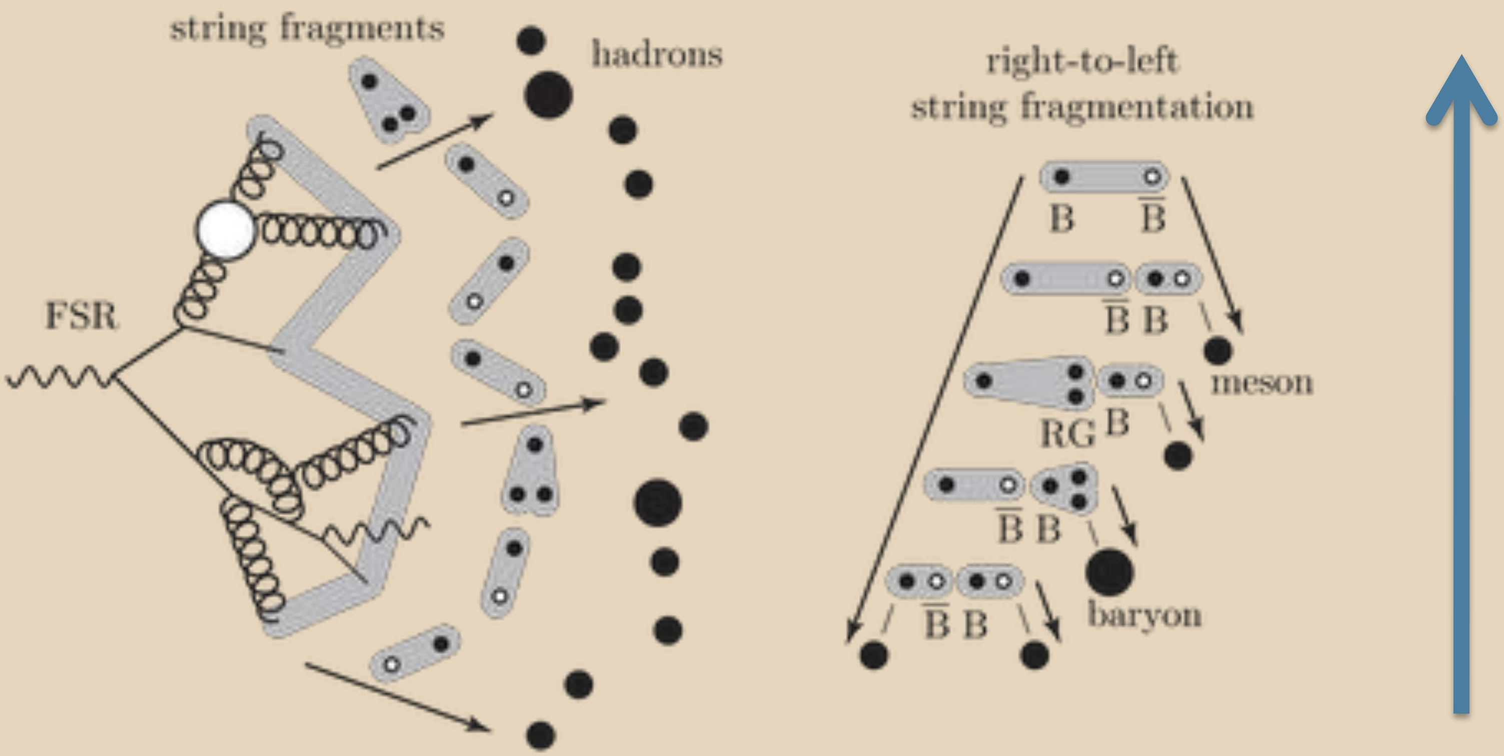
$|\eta| < 3.2$: $\delta\phi \sim 0.025\text{-}0.1$
$\sigma(E)/E = 10\%/\sqrt{(E/\mathrm{GeV})}$

Hadronic

$0 < |\eta| < 1.7$: : $\delta\phi \sim 0.1$
$1.7 < |\eta| < 3.2$: $\delta\phi \sim 0.1$
$\sigma(E)/E = 50\%/\sqrt{E}$

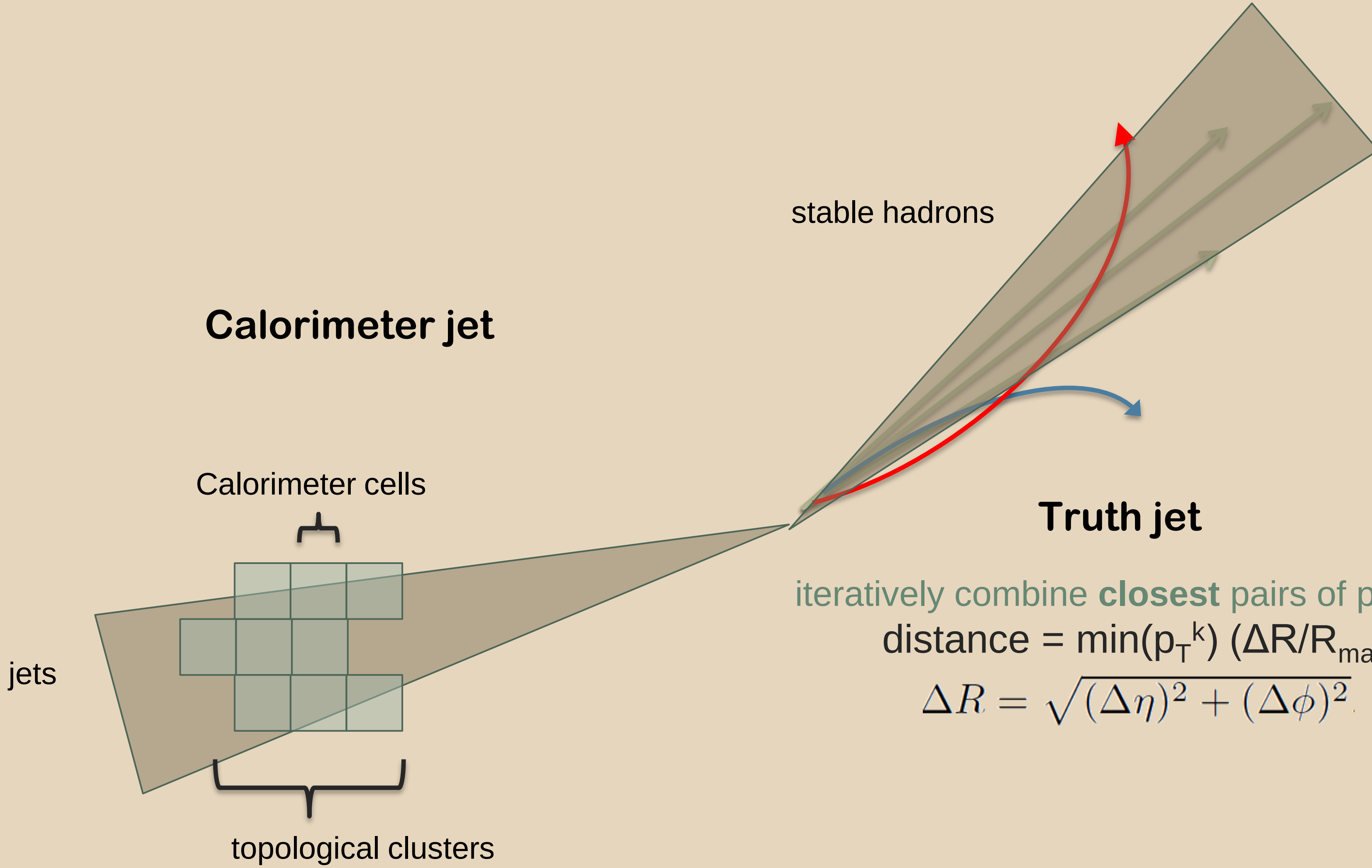
Hadronic reconstruction

perturbative shower suggests iterative, pairwise merging algorithms:



jet reconstruction

Jet reconstruction



iteratively combine **closest** pairs of particles

distance = $\min(p_T^{k})\ (\Delta R/R_{max})$

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

Jet constituent observable moments: calculations

jet mass

$m^2 = (\Sigma E_i)^2 - (\Sigma p_i)^2$

$$\langle M^2 \rangle \simeq C \cdot \frac{\alpha_s}{\pi} p_t^2 R^2$$

average jet charge

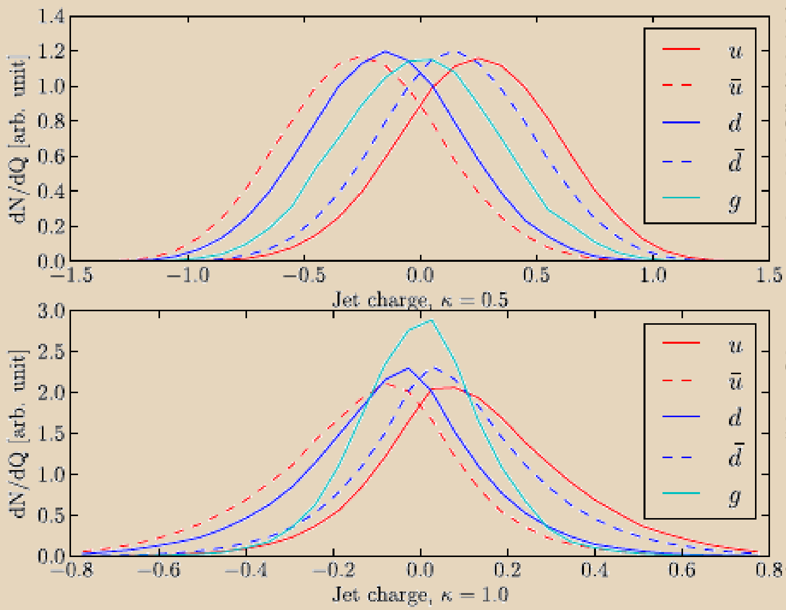
$$\langle Q_\kappa^q \rangle = \frac{1}{16\pi^3} \frac{\widetilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu)}{\mathcal{J}_q(E,R,\mu)} \sum_h Q_h \widetilde{D}_q^h(\kappa,\mu)$$

jet functions

from fragmentation functions

Jet constituent observables: parton shower

jet charge



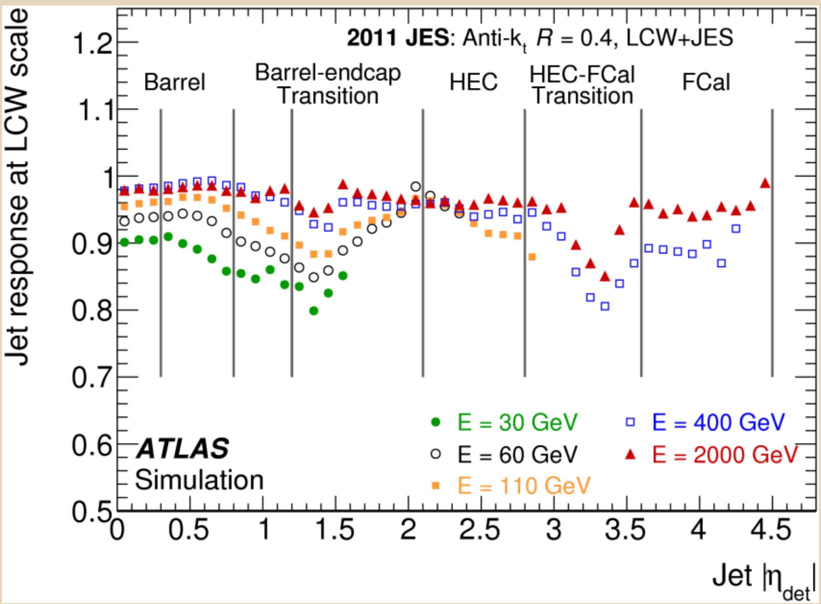
Krohn et. al. “Jet Charge at the LHC” (2012)

top jet mass

Boost2012 Report, EPJC 74 (2014)

Jet constituent calibration

Cluster constituents calibrated to local hadron scale



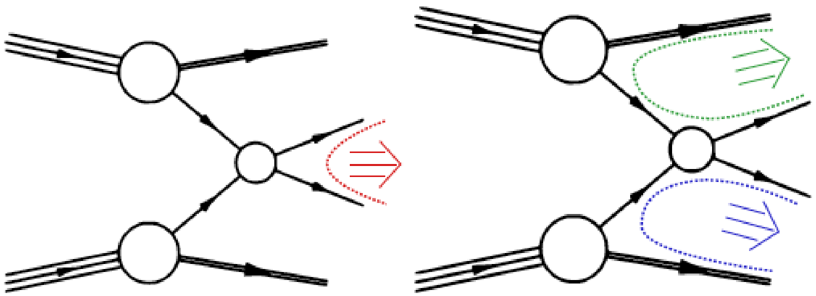
Substructure moments re-calibrated at jet level

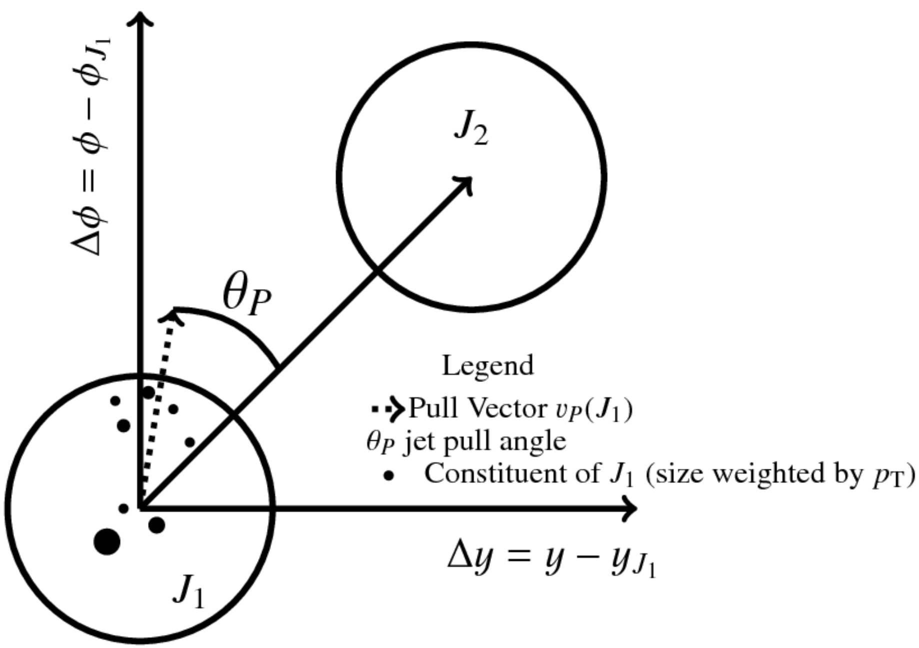
Substructure-based tagging

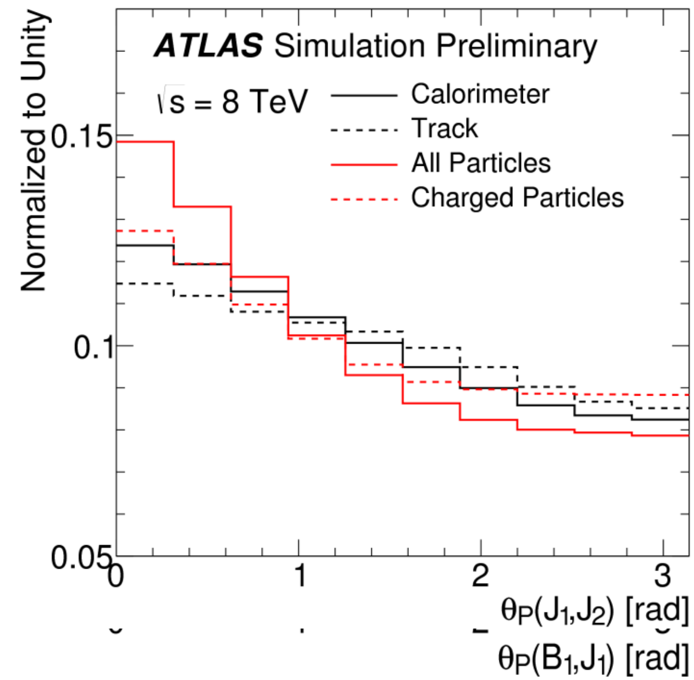
Interesting particles are color singlet

Color singlet

Color octet







Charge conservation is powerful

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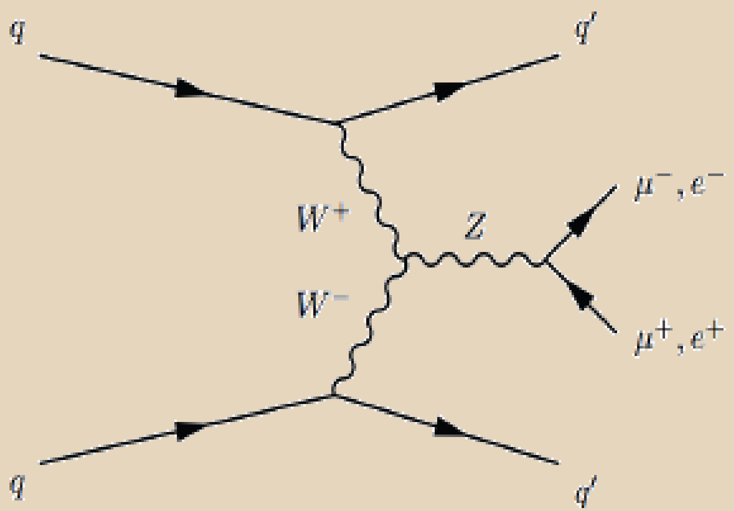
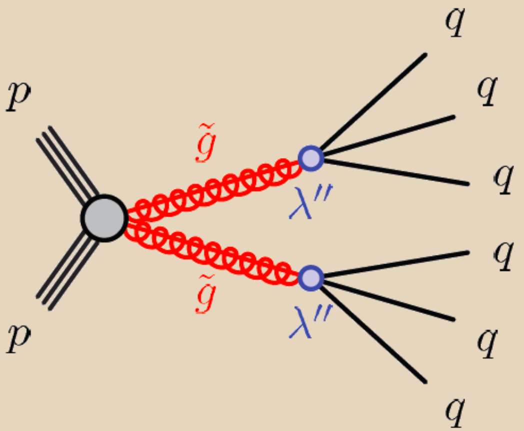
LHC backgrounds are … gluey

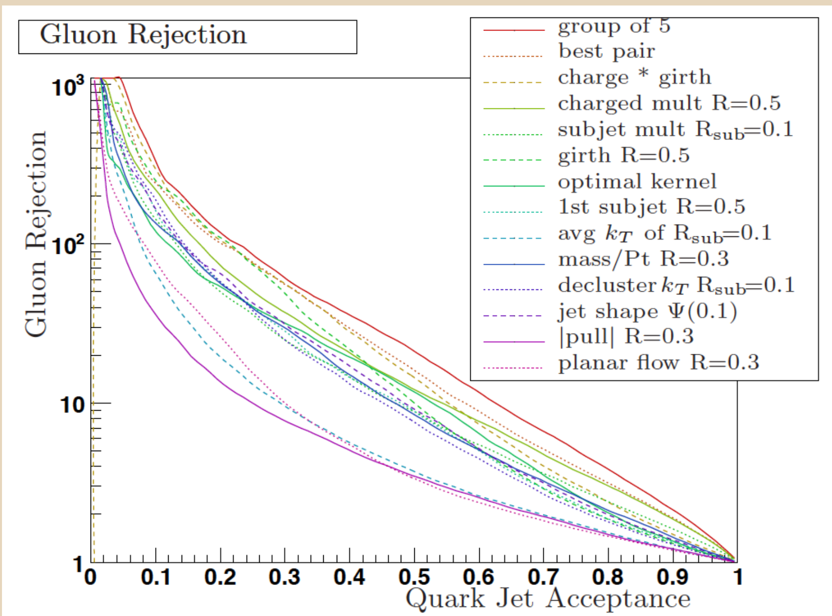




q/g tagger

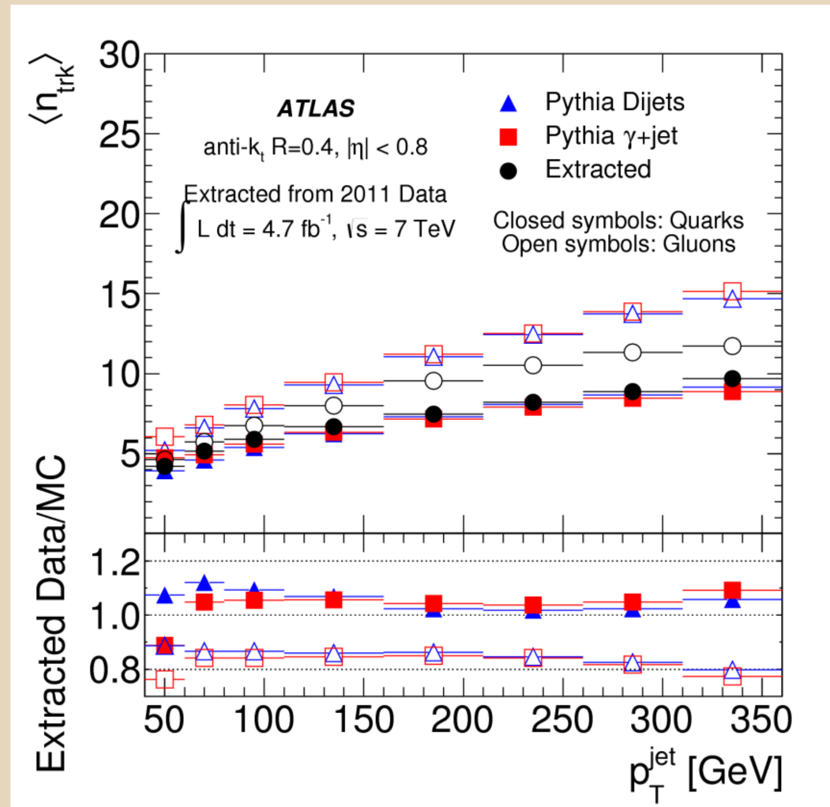
Sensitive variables

Color factor (g=3 vs. q=9/4) in substructure moments leads to many sensitive variables

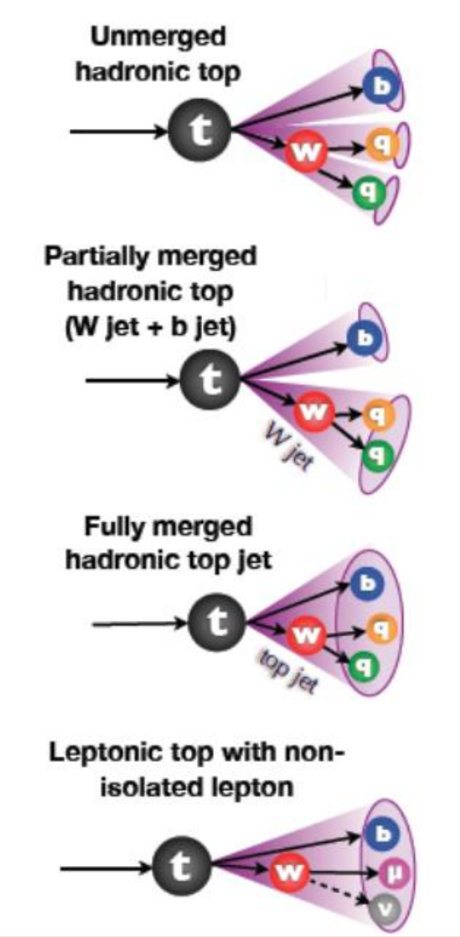


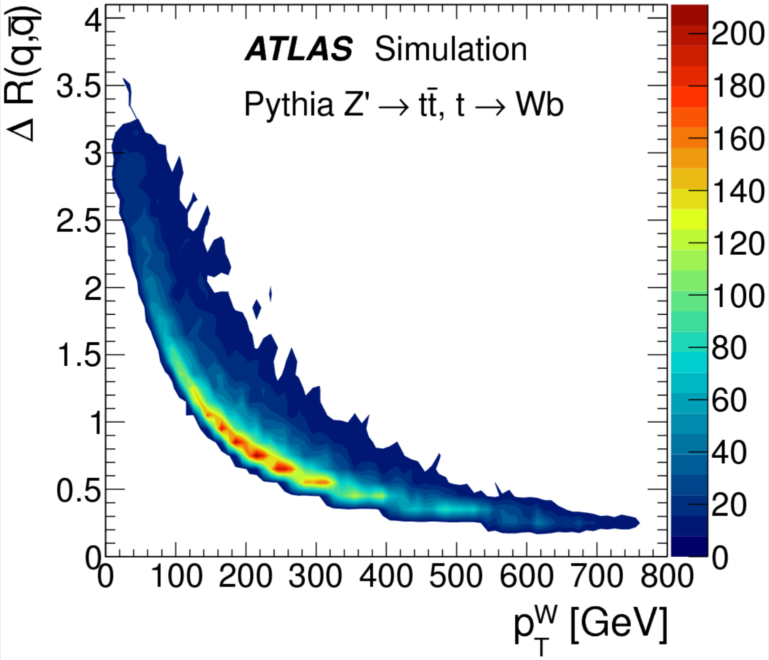
Gallicchio and Schwartz, PRL107 (2011)

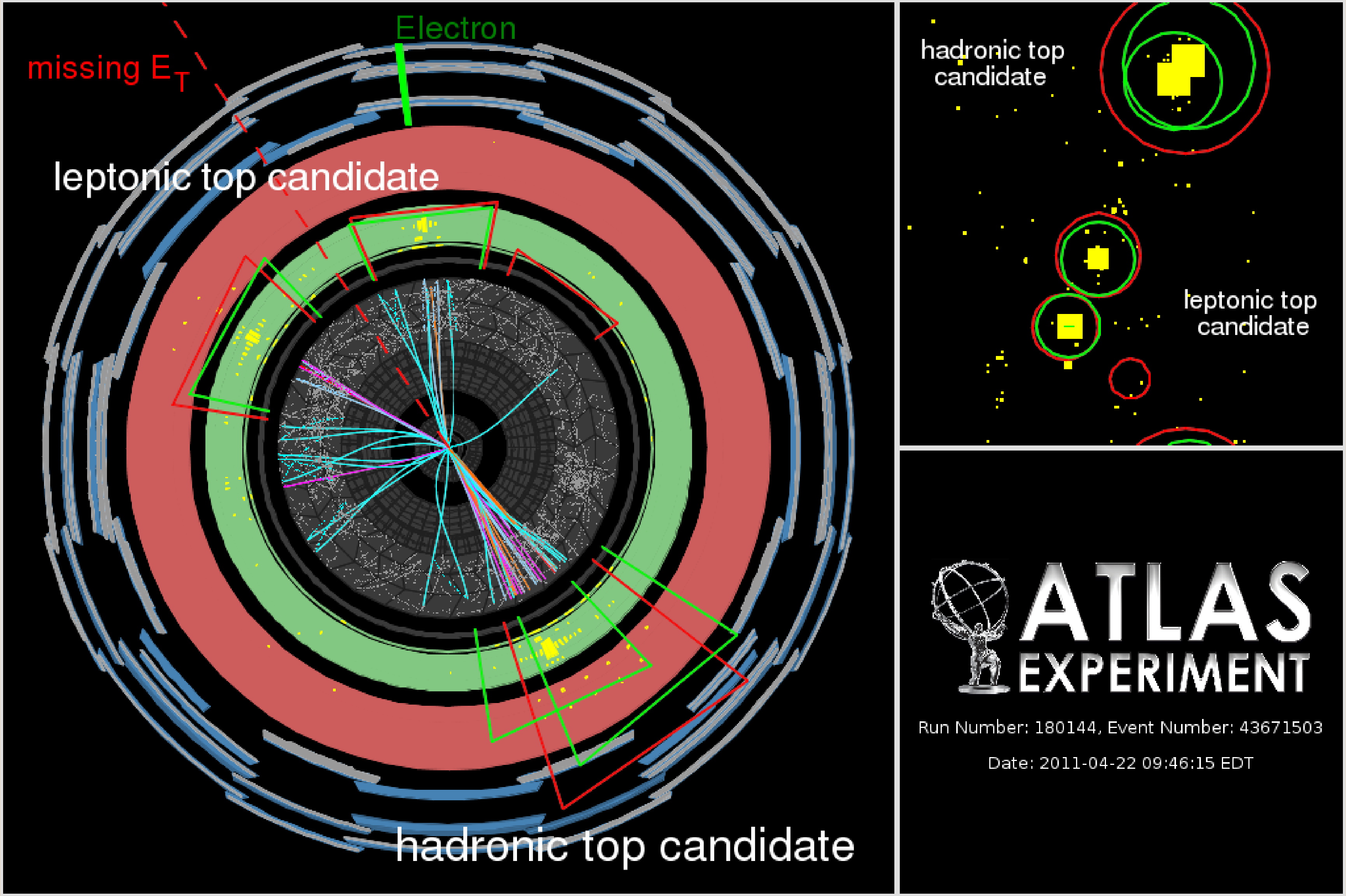
Modeling



High p_T BG are mostly light partons







Electron
missing E_T
leptonic top candidate
hadronic top candidate
hadronic top candidate
leptonic top candidate
ATLAS EXPERIMENT
Run Number: 180144, Event Number: 43671503
Date: 2011-04-22 09:46:15 EDT

top/W tagging variables

Butterworth, Cox, Forshaw (2002)

Splitting scale ~(m/2)^2

$$d_{ij} = \min(p_{ti}^2, p_{tj}^2)\Delta R_{ij}^2$$

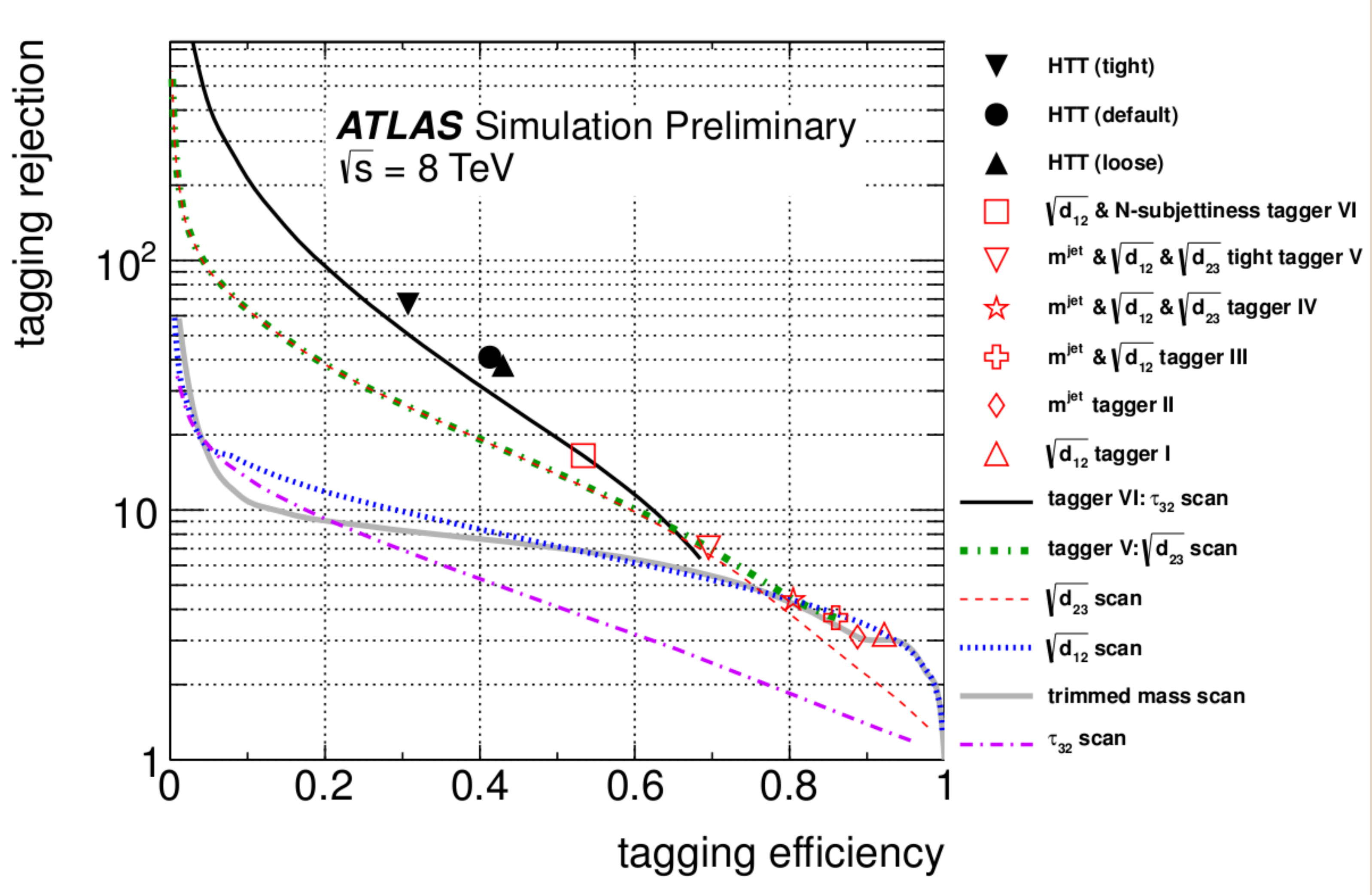
n-subjettiness ~ 0

$$\tau_N = \frac{1}{\sum_k p_{T,k} R_{\text{jet}}^{\beta}} \sum_k p_{T,k} \min(\Delta R_{1,k}^{\beta}, \Delta R_{2_k}^{\beta}, \ldots)$$

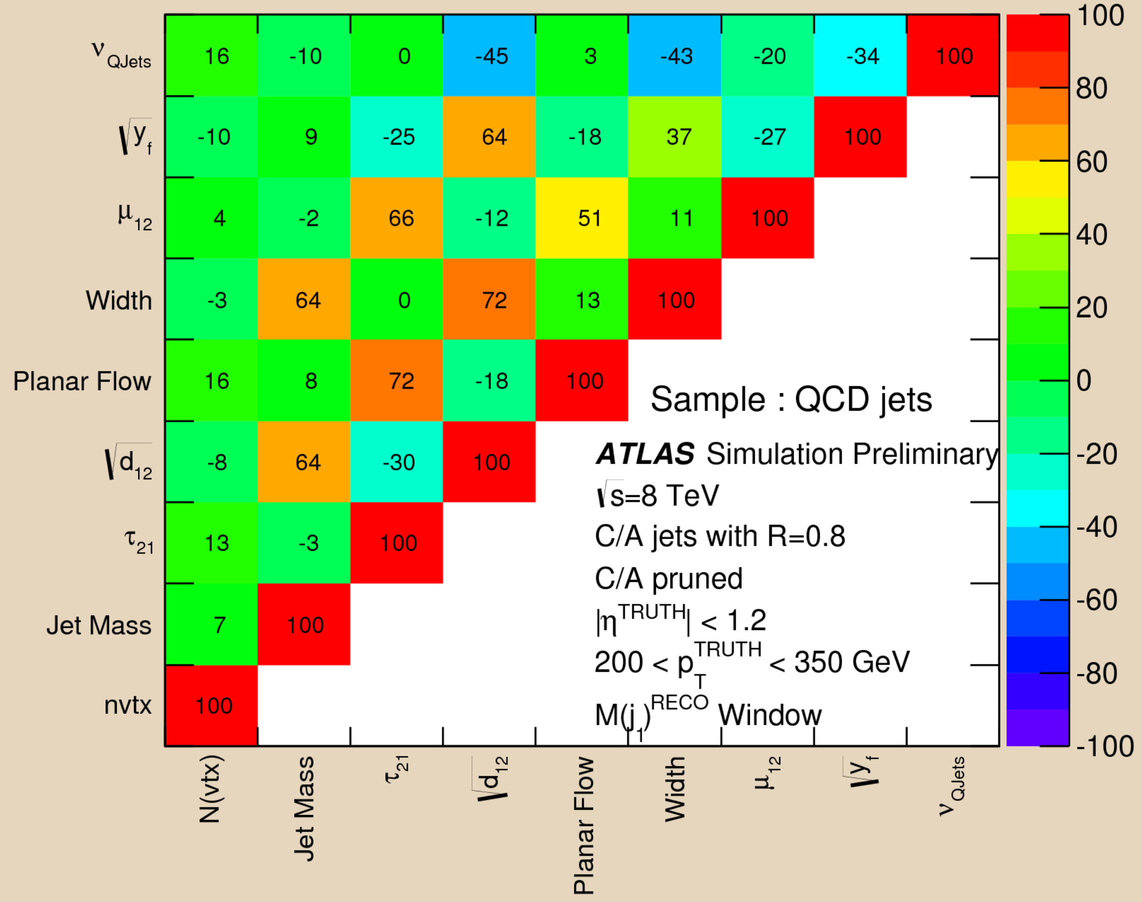
Thaler, Van Tilburg (2011)

typically combined in a “tag”

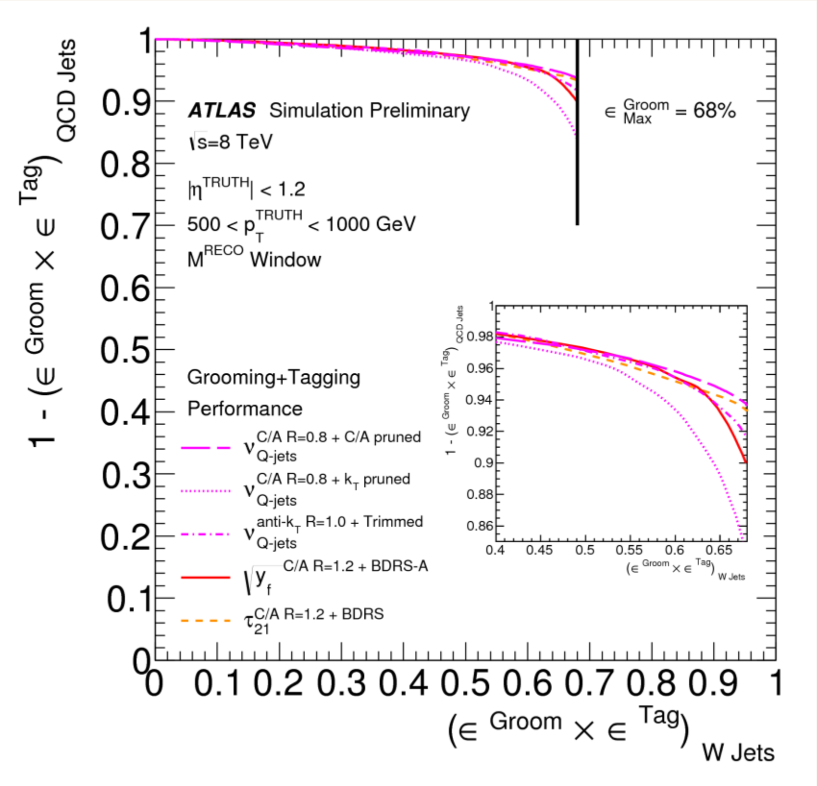
Top-tagging performance

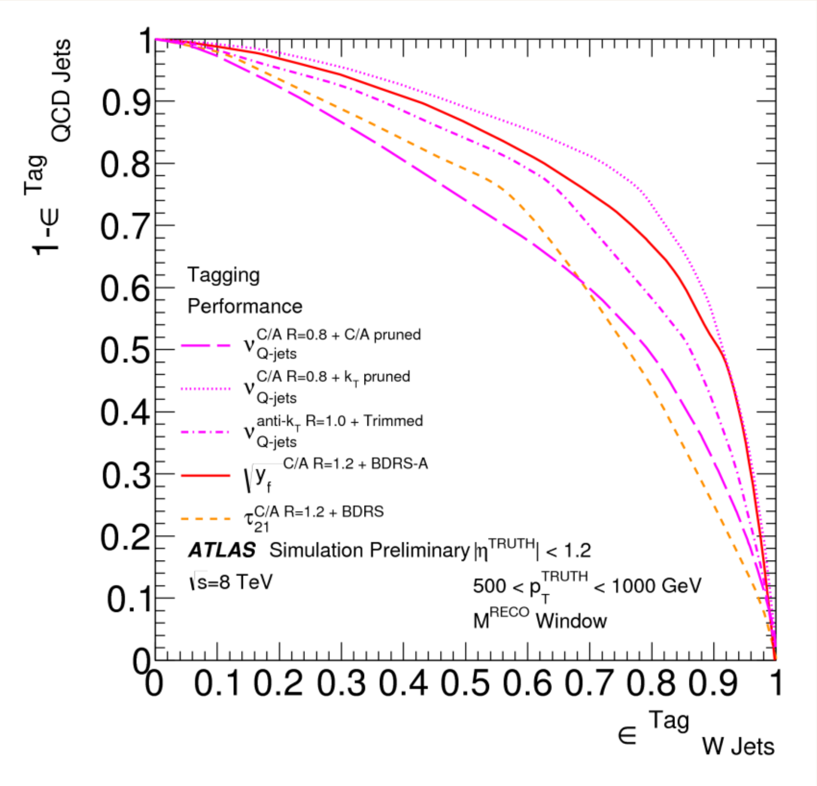


W-tagging correlations



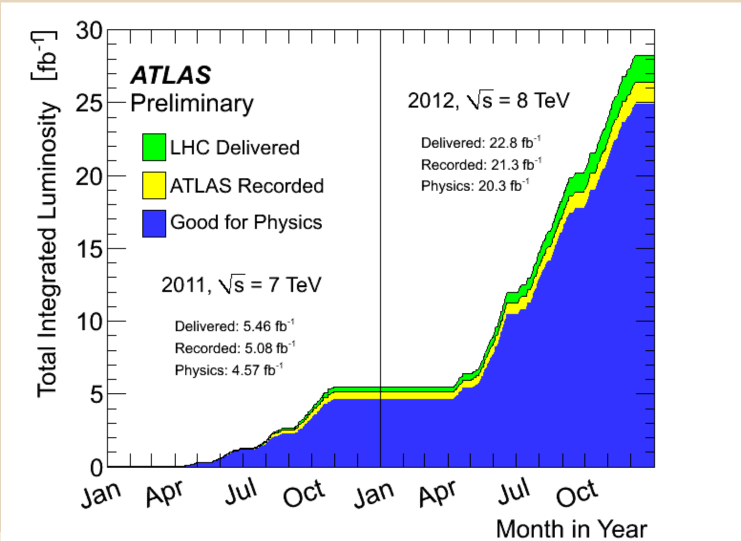
W-tagging performance

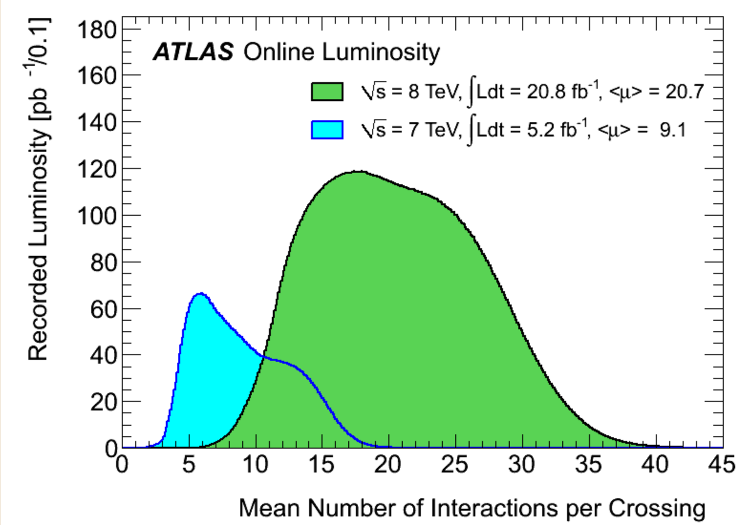


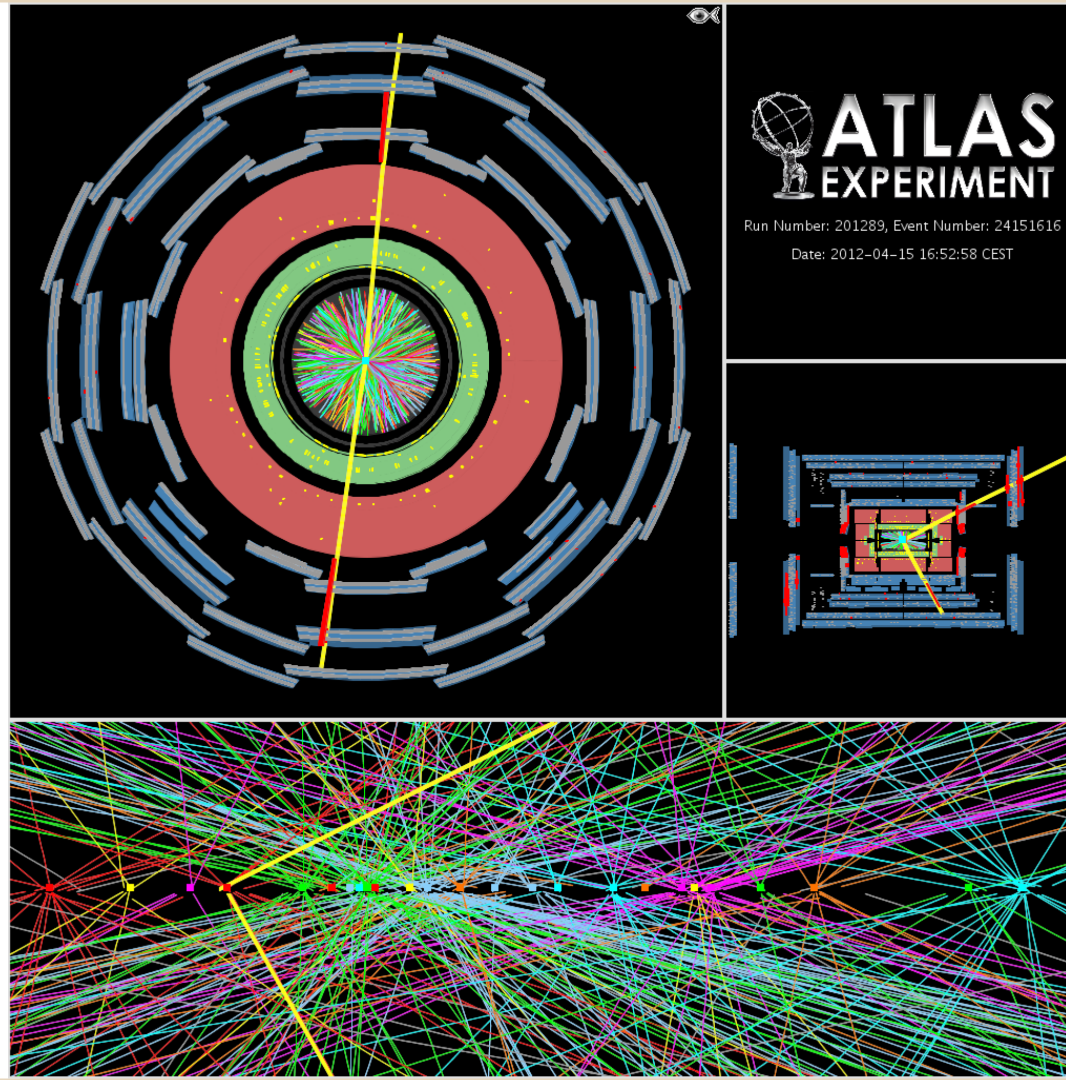


Challenges in substructure tagging

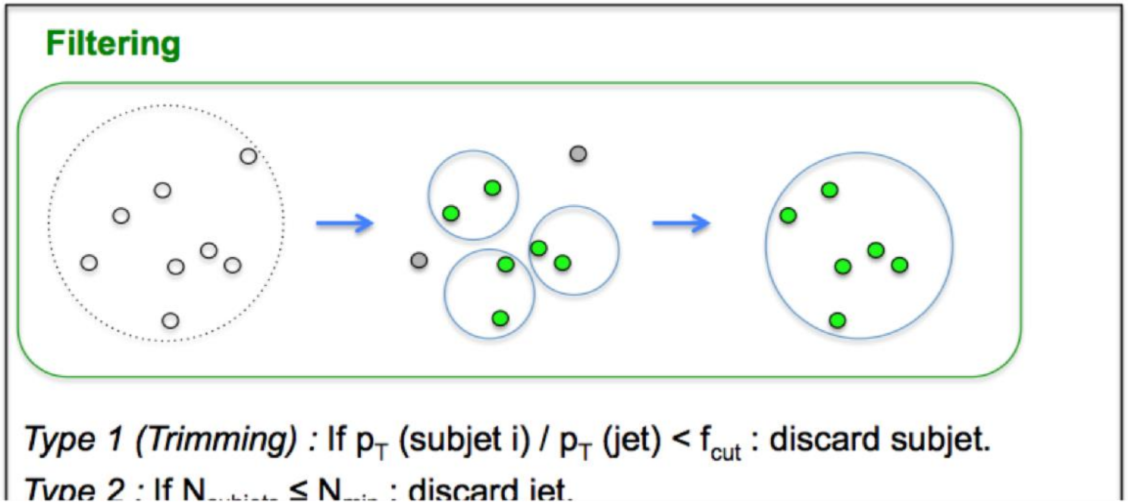
the LHC environment

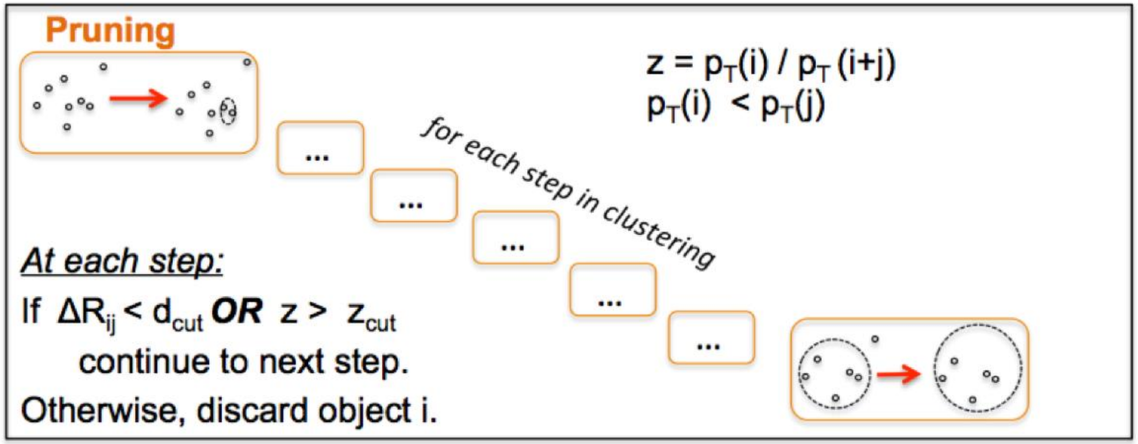






Jet grooming

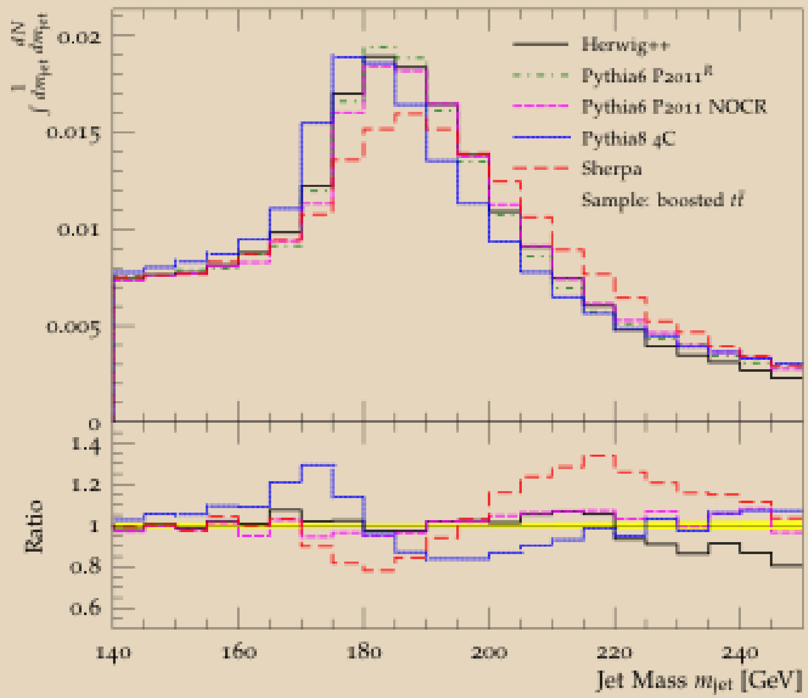




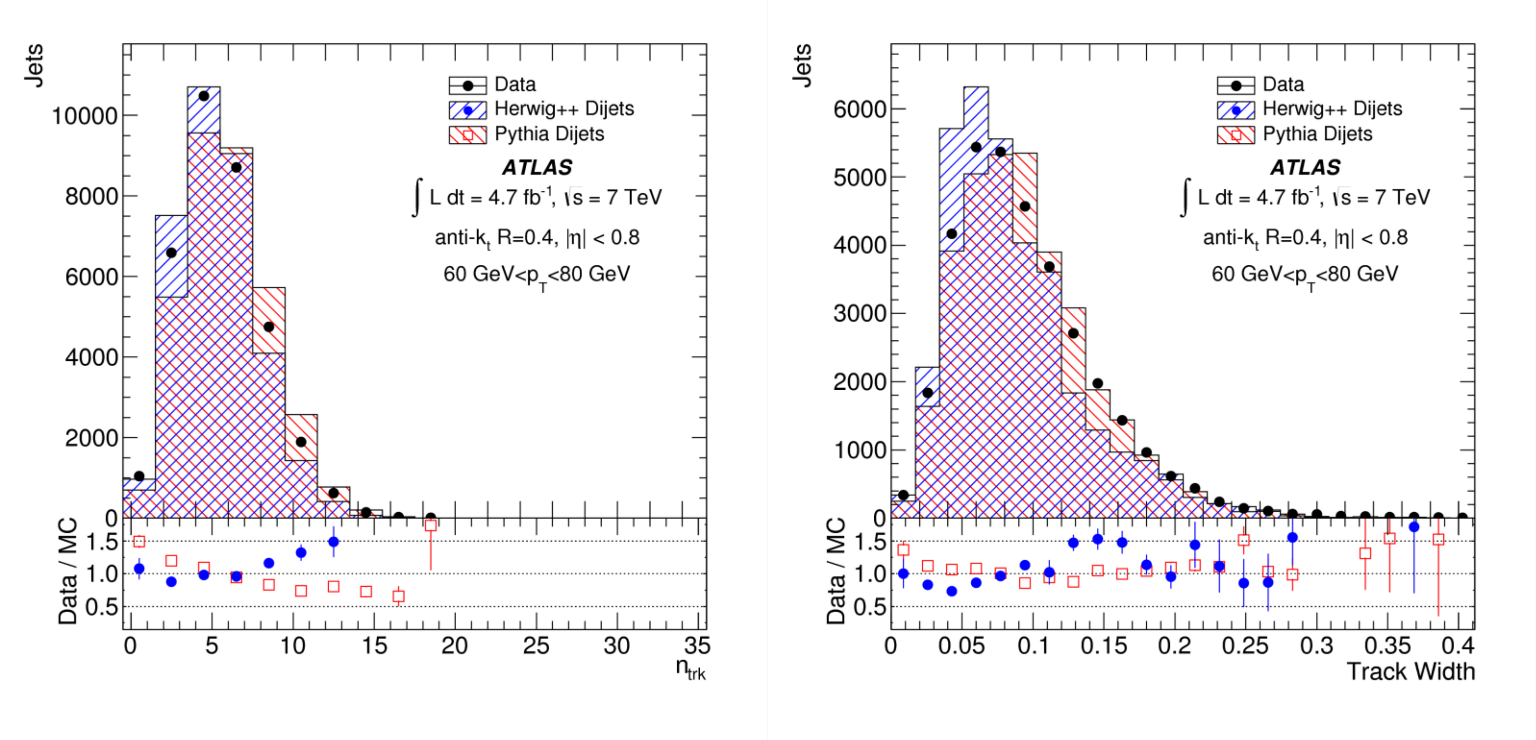
Modeling substructure variables

Theory typically predicts *moments* – tagging uses distributions

Parton showers may disagree, and require tuning



Modeling substructure variables



Data-driven efficiency: q/g tag

artist: M. Swiatlowski

- construct width and n_{trk} distributions expected for pure samples
- bin in jet p_T, η; fix **flavor ratios** to MC predictions
  - also fix heavy flavor templates (shape and normalization)
- Solve to extract pure templates

Data-driven efficiency: jet charge/pull

Opposite to leptonic W charge

Color singlet

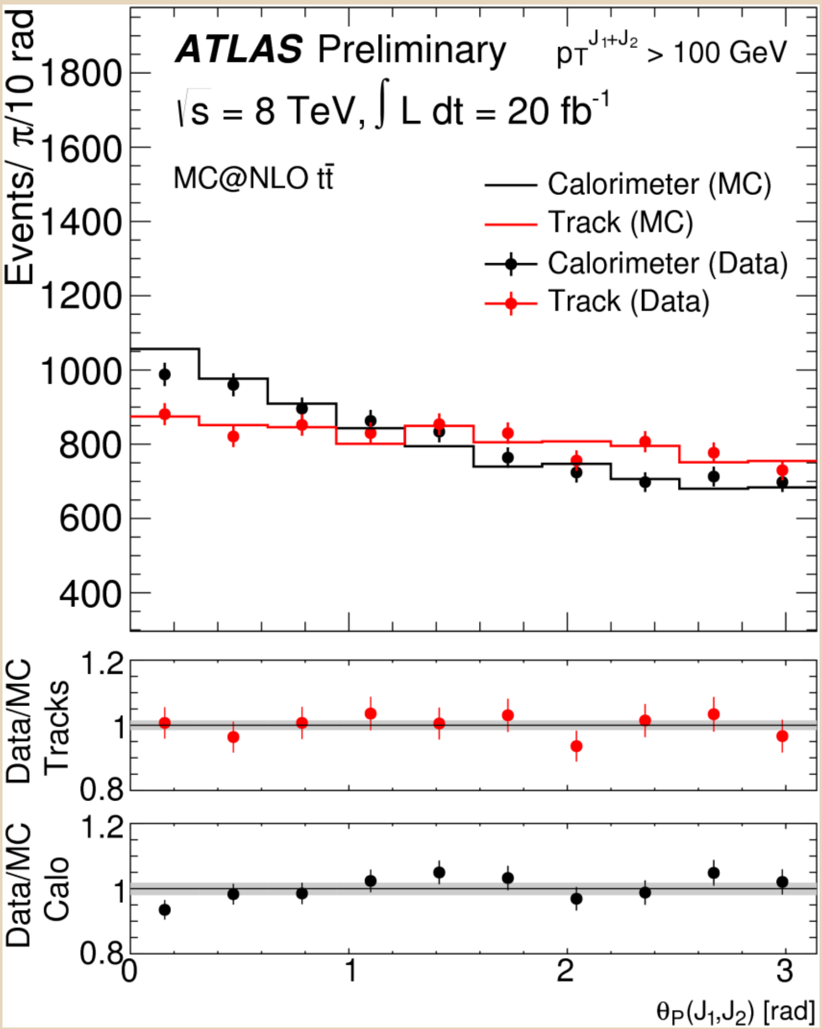
Charge bias also possible in W+jets, dijets

Jet charge validation

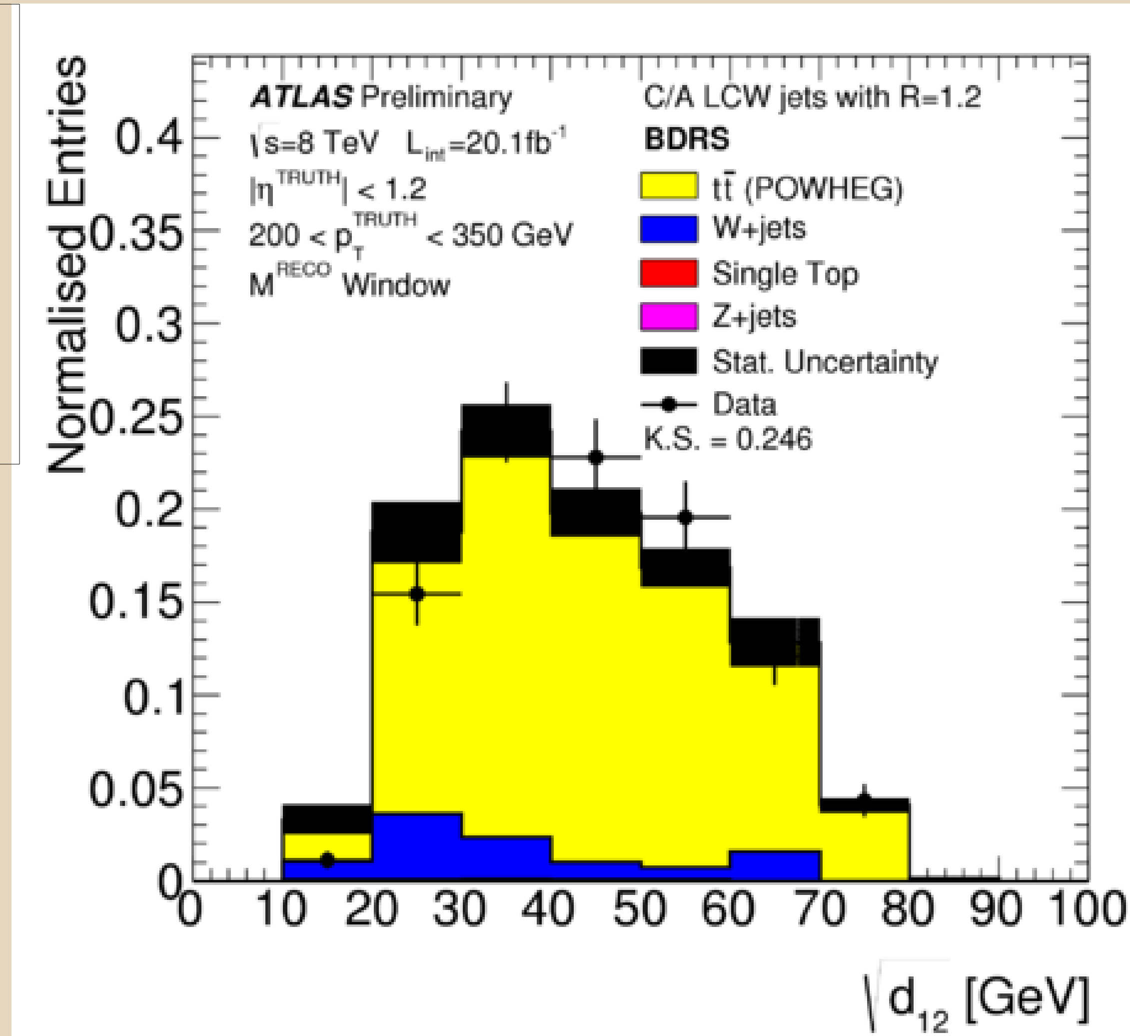
$W \to qq$ candidate charge

Performance of a W+ tagger

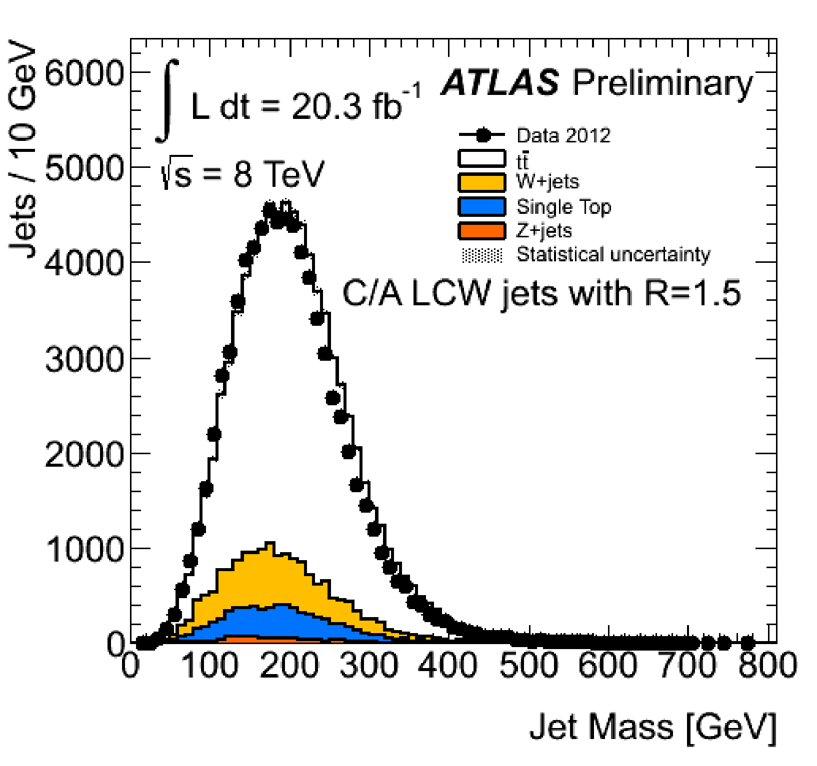
Jet pull validation

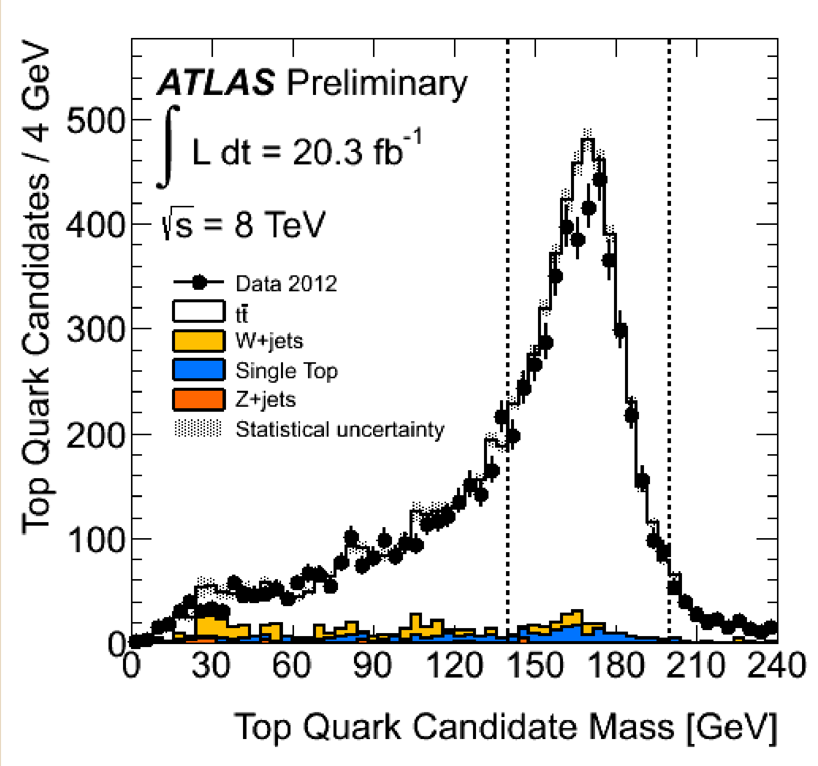


W-tagging validation



top-tagging validation

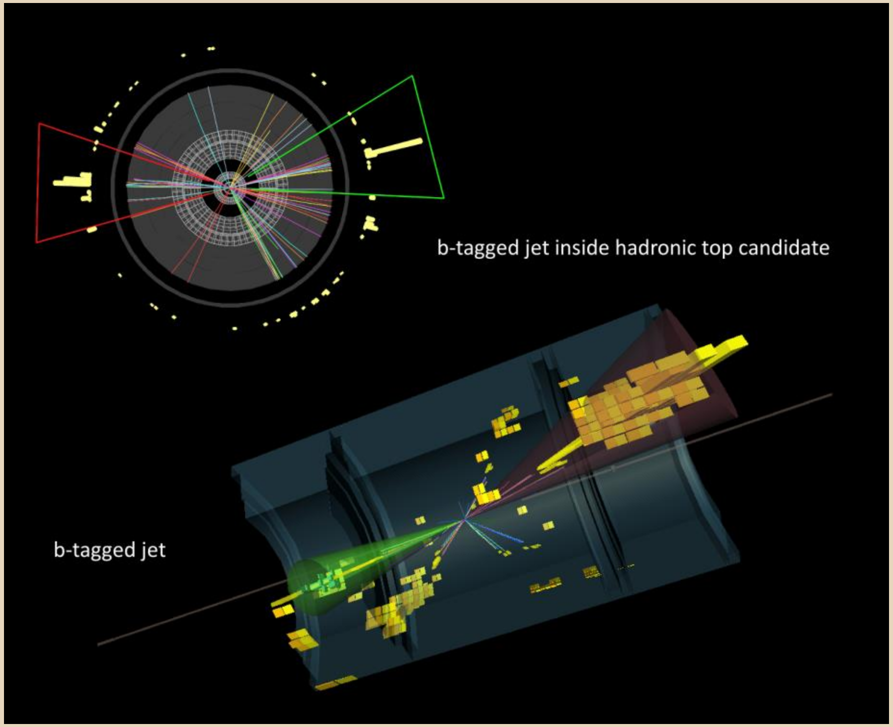


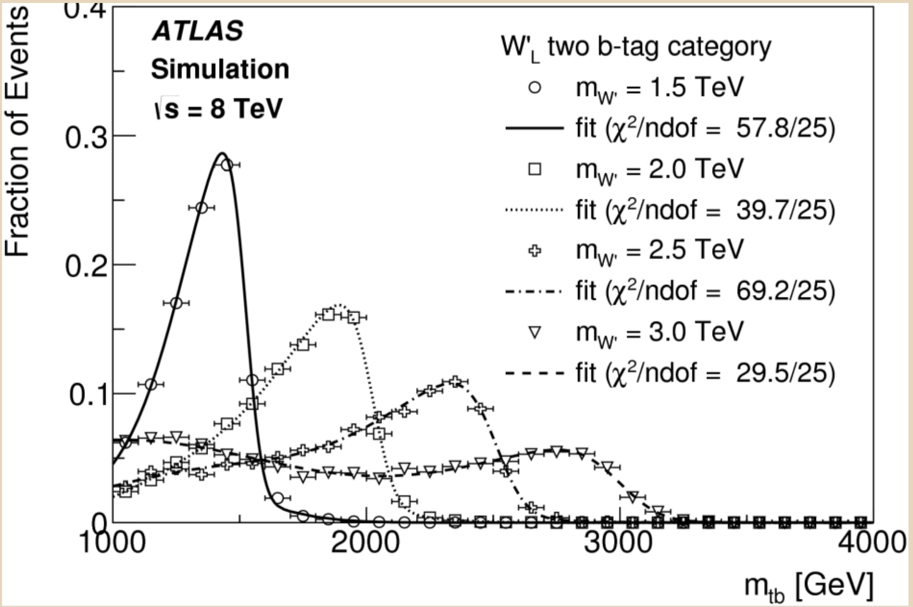


Challenging the SM with substructure tags

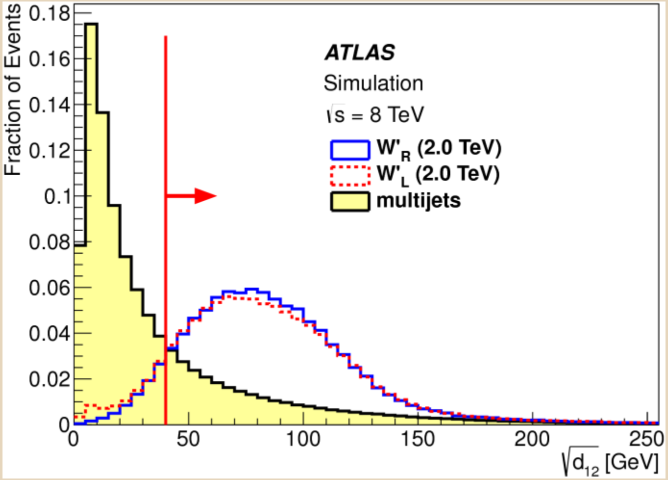
Search for W' → tb in hadronic channel

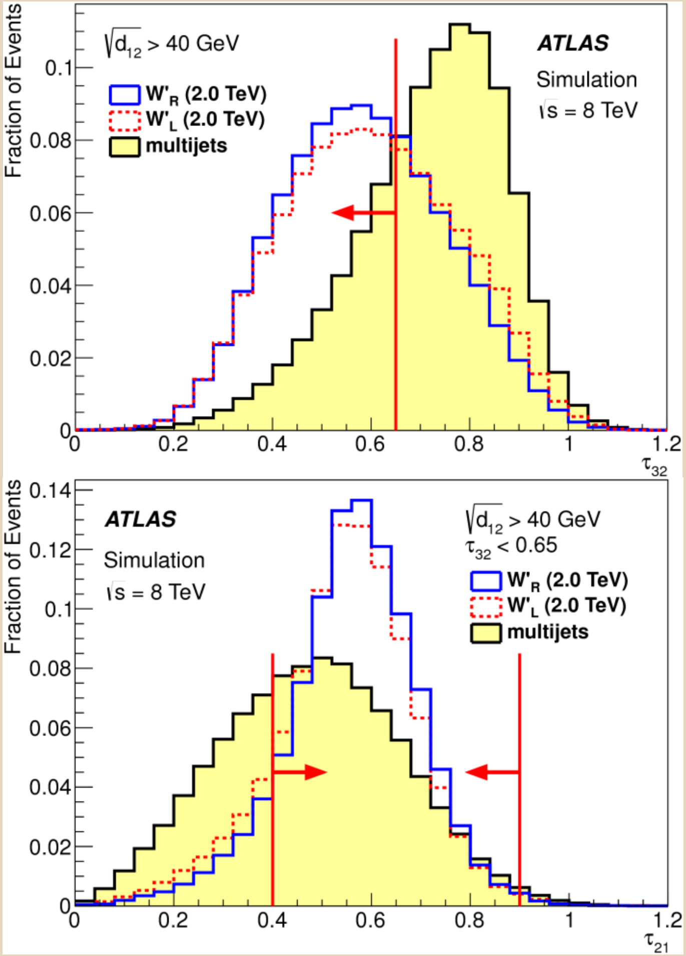
Consider new gauge interactions in models preferring quark/3rd gen couplings





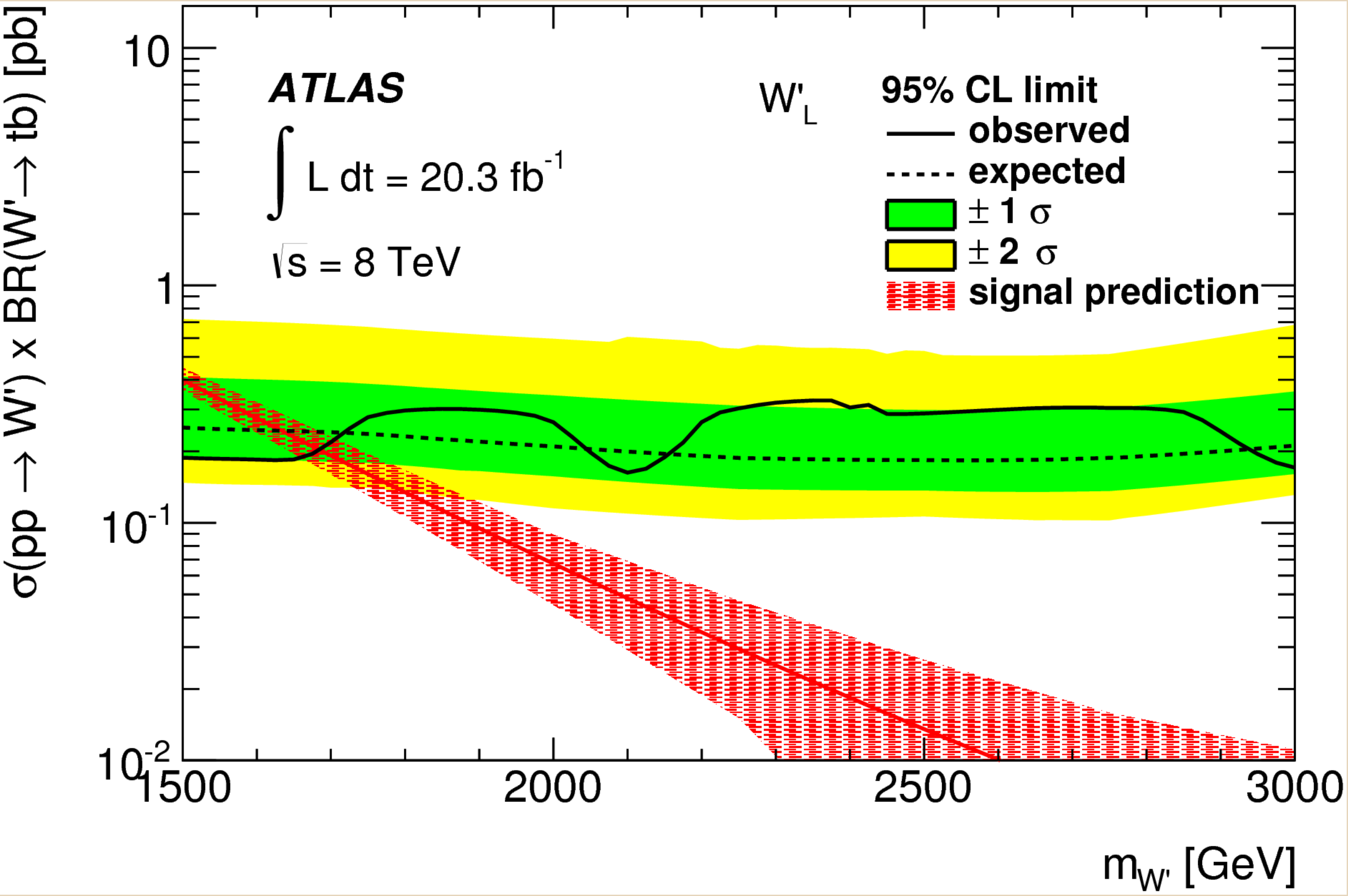
Top tagging variables





small differences in signal distribution for W_L, W_R due to top polarization

Limits on W’

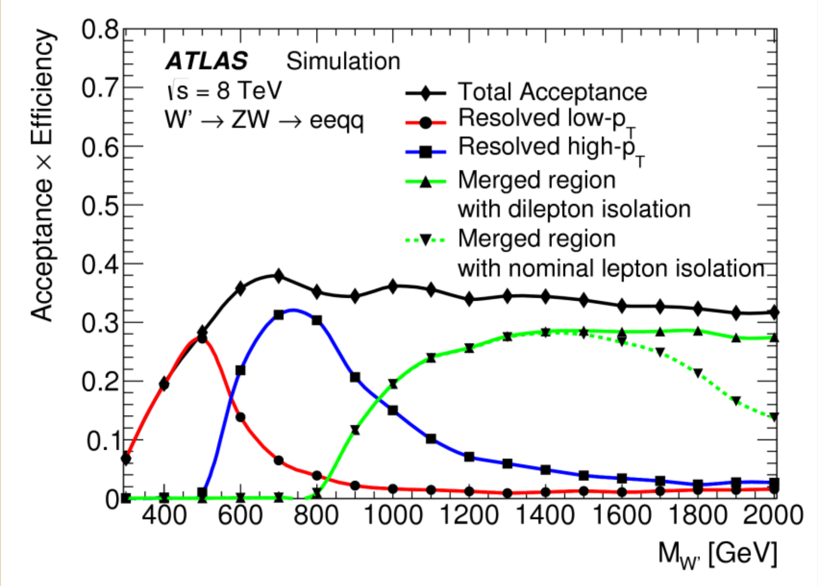


ATLAS
$\int$ L dt = 20.3 fb^{-1}
$\sqrt{s}$ = 8 TeV
W'$_L$
95% CL limit
observed
expected
± 1 σ
± 2 σ
signal prediction
σ(pp → W') x BR(W' → tb) [pb]
10
1
10^{-1}
10^{-2}
1500
2000
2500
3000
m$_{W'}$ [GeV]

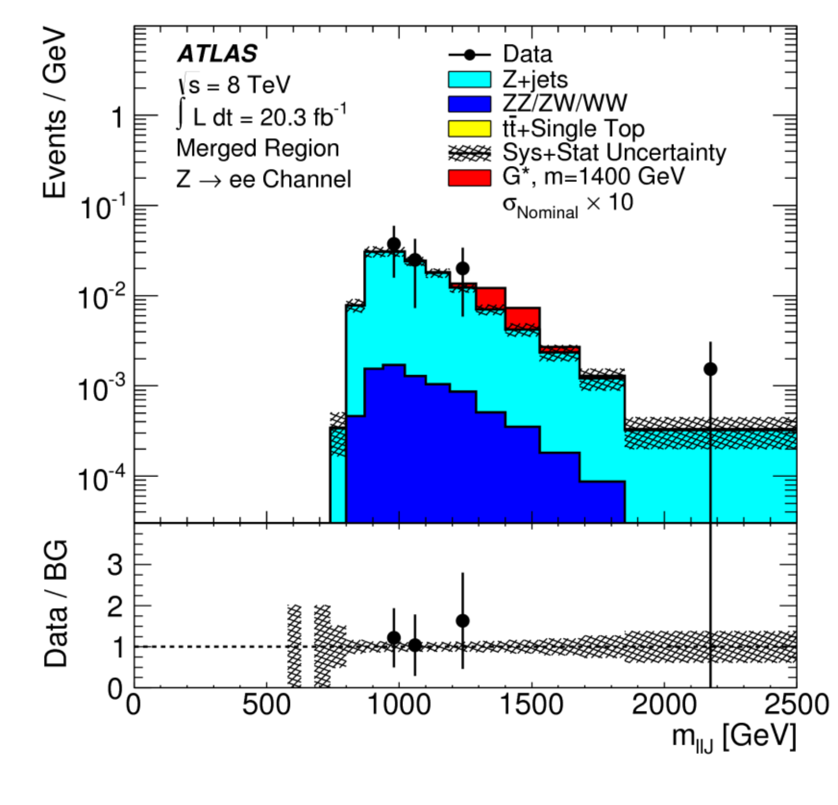
Search for W’ → WZ, G* → ZZ in leptonic Z+jet channel

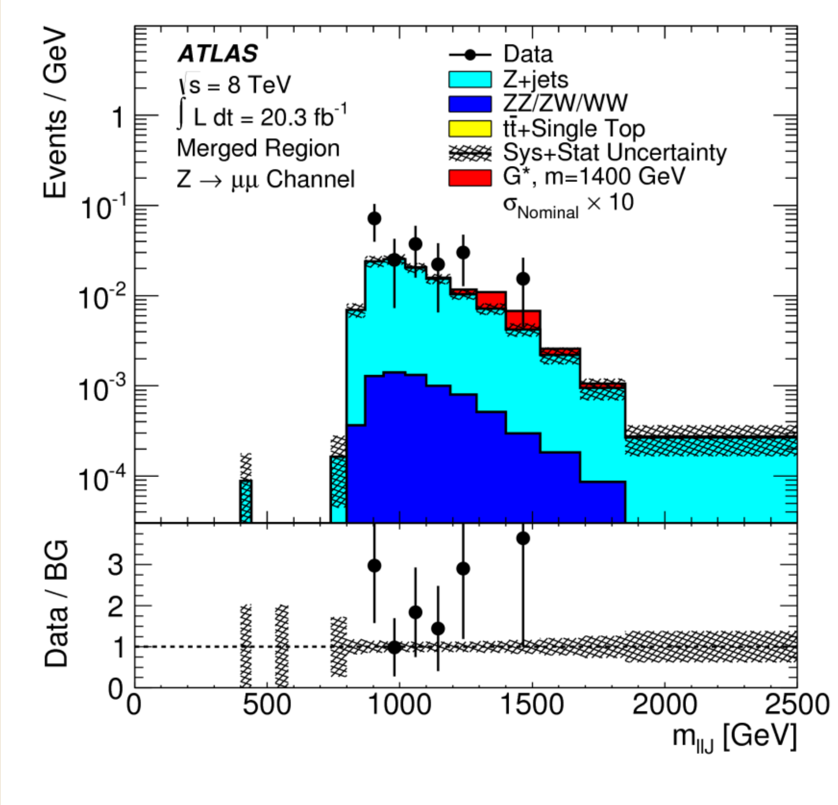
apply three signal regions (2 jet and 1 jet)

Signal region	LR	HR	MR
Trigger	Single lepton/dilepton triggers		
Preselection	Primary vertex exists Event cleaning Exactly two leptons ($p_{\mathrm{T}} > 25$ GeV) Isolated (excluding other leptons) Opposite charge (muon only) $66 < m_{\ell\ell} < 116$ GeV		
Dilepton p_{T}	$p_{\mathrm{T}}^{\ell\ell} > 100$ GeV	$p_{\mathrm{T}}^{\ell\ell} > 250$ GeV	$p_{\mathrm{T}}^{\ell\ell} > 400$ GeV
Jet multiplicity	≥ 2 R=0.4 jets		≥ 1 R=1.2 jets
Dijet p_{T}	$p_{\mathrm{T}}^{jj} > 100$ GeV	$p_{\mathrm{T}}^{jj} > 250$ GeV	-
Dijet mass	$70 < m_{jj} < 110$ GeV		-
Leading jet p_{T}	-		$p_{\mathrm{T}}^{J} > 400$ GeV
Leading jet mass	-		$70 < m_J < 110$ GeV
Leading jet $\sqrt{y_{\mathrm{f}}}$	-		$\sqrt{y_{\mathrm{f}}} > 0.45$

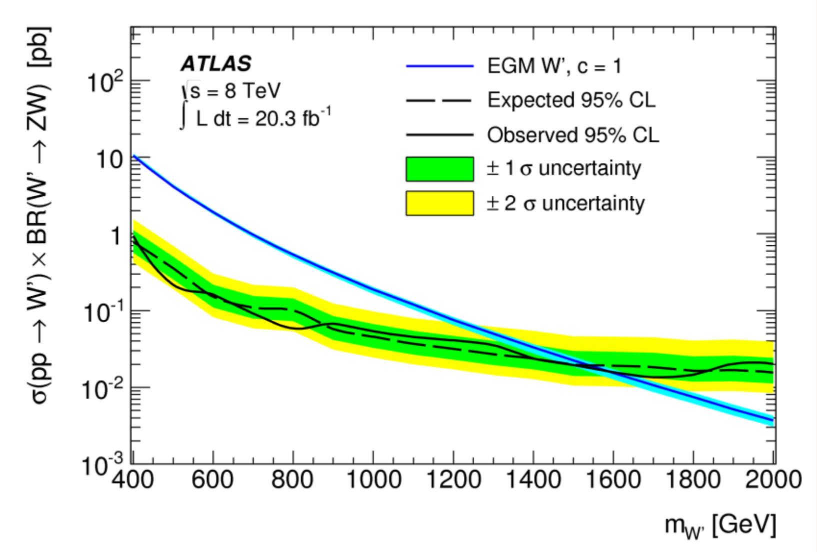


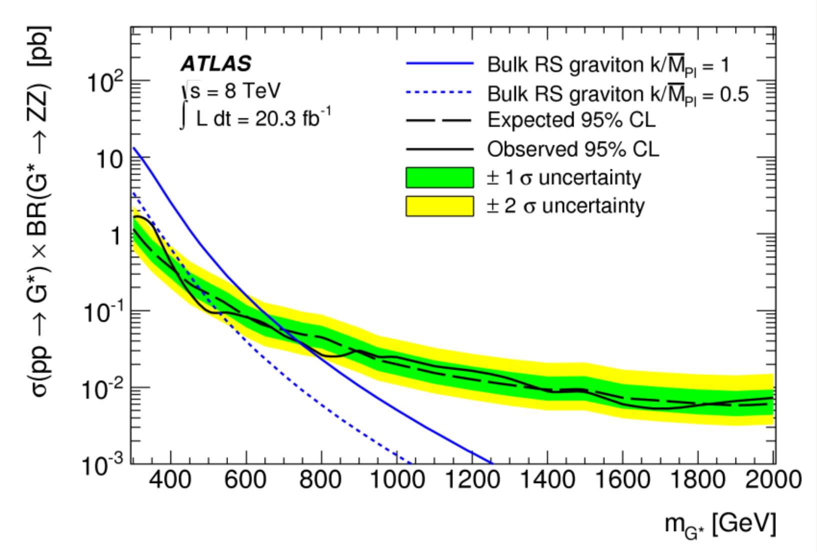
Boosted channel backgrounds





Limits


ATLAS
$\sqrt{s}$ = 8 TeV
$\int$ L dt = 20.3 fb^{-1}
EGM W', c = 1
Expected 95% CL
Observed 95% CL
± 1 σ uncertainty
± 2 σ uncertainty
σ(pp → W') × BR(W' → ZW) [pb]
$m_{W'}$ [GeV]


ATLAS
$\sqrt{s}$ = 8 TeV
$\int$ L dt = 20.3 fb^{-1}
Bulk RS graviton k/$\overline{M}_{Pl}$ = 1
Bulk RS graviton k/$\overline{M}_{Pl}$ = 0.5
Expected 95% CL
Observed 95% CL
± 1 σ uncertainty
± 2 σ uncertainty
σ(pp → G*) × BR(G* → ZZ) [pb]
m_{G*} [GeV]

Outlook

Confronting Run II challenges

Strategy for 2015

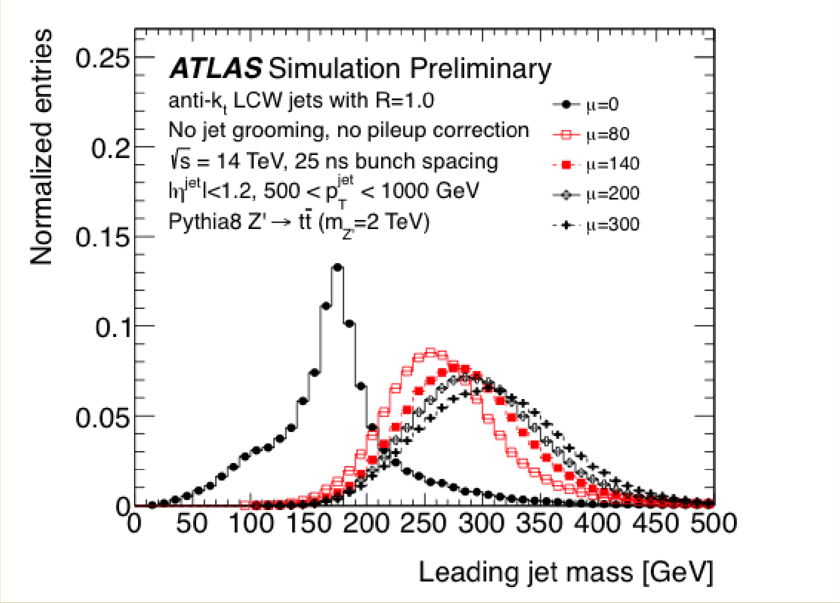
Tagger calibrations:

- *W, top tags:* In-situ efficiency/fake rate measurements from Run I (being completed)
- better *q/g* purified samples

Pileup:

- **grooming** and **area subtraction** perform well
- also: track-based pileup constraints (subjet JVT)

Beyond Run II:



Looking ahead

No evidence of physics beyond the SM in Run I

…but a great laboratory for careful validation of jet tagging observables in data!

Will hadronic final states show us new physics first in Run II?