Searches for new physics with boosted objects in ATLAS

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06/07/2015

- 2001 – 2005 本科 南京大学
- 2005 – 2011 研究生 南京大学 & 台湾中研院 (Supervisor: Shih-Chang Lee)
- 2011至今 博士后 牛津大学 (Supervisor: Cigdem Issever)

- 2006.10 – 2015. 4 常驻CERN(日内瓦)参与ATLAS实验

- 研究方向
  - Boosted objects R&D, calibration
  - Top quark pair resonance search
  - Exotic heavy quark and Top final state searches (subgroup convener)
  - ATLAS central MC production (computing duty)

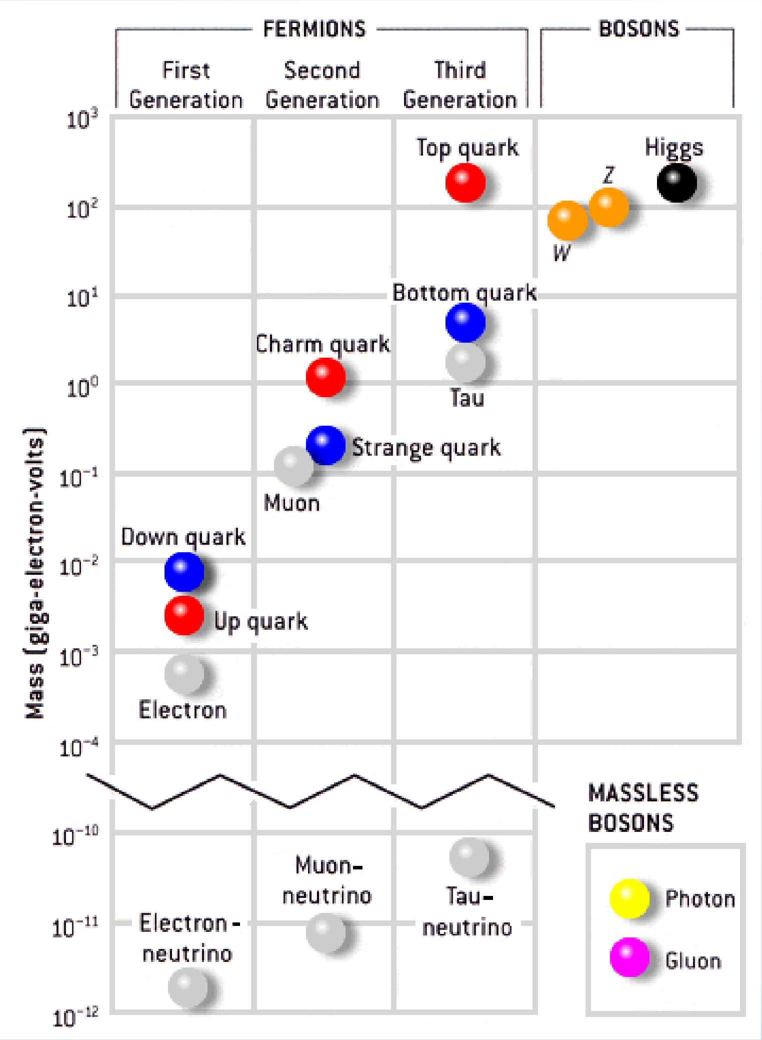
  PhD:
  - Same-sign di-lepton search
  - Pixel detector
  - Multivariate analysis (Neural Network in TMVA)

Outline

- Introduction
  - New physics searches at energy frontier
  - LHC and ATLAS
- Reconstruction & Identification of Boosted Objects
  - Leptons isolation
  - Large-R jet and substructure
  - Flavor-tagging
- Top quark pair resonance search

Introduction

Standard Model and Beyond



It is the worst of times

- The successful **Standard Model** runs out of predictions

It is the best of times

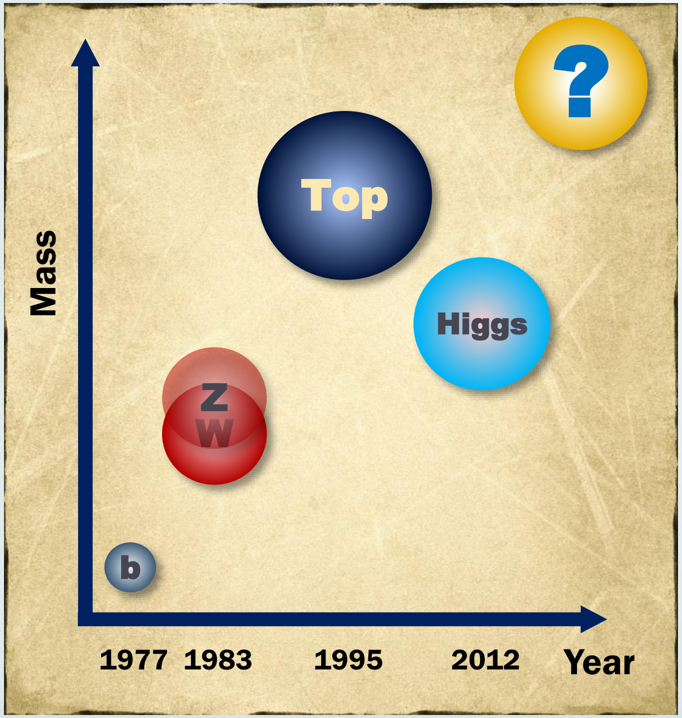
(recall the end of 19th century)

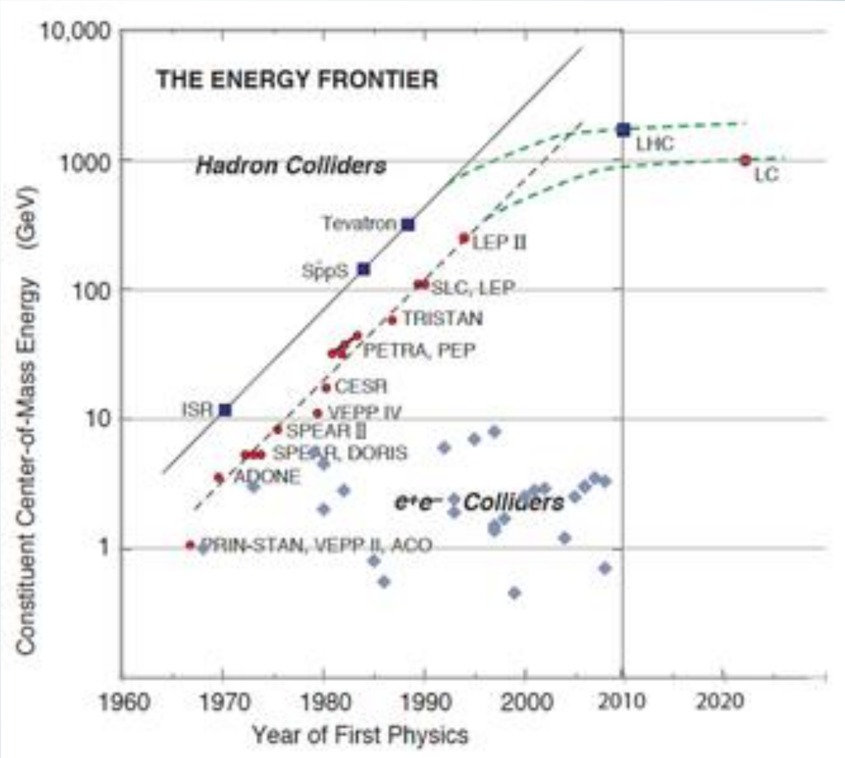
- Hierarchy problem
- Missing gravity in SM
- Mystery of dark matter
- …

Introduction

New physics searches at energy frontier

- High energy frontier
  - Major goal of collider physics
  - Unprecedented energy @LHC

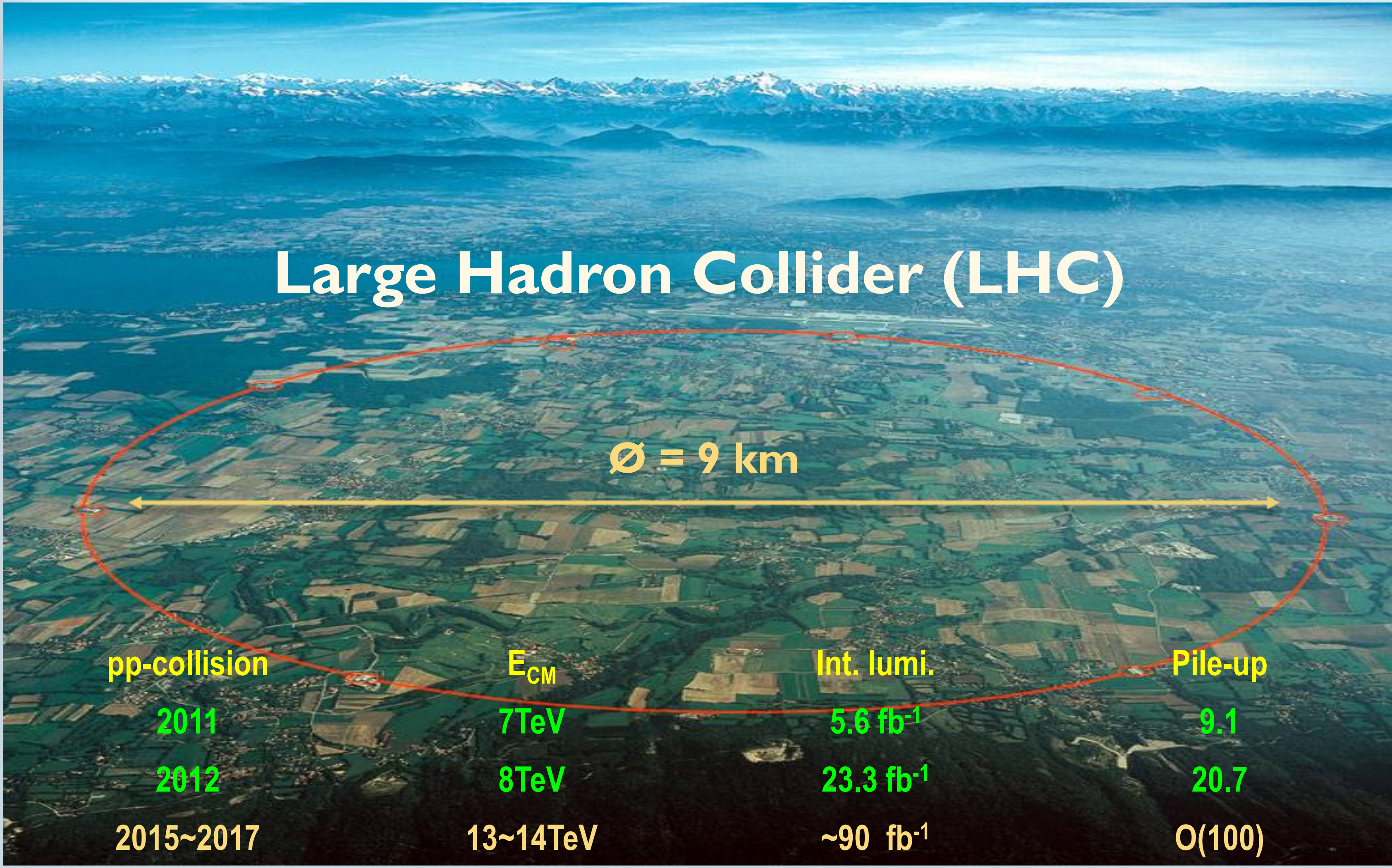




* Particle Accelerator Livingston Chart 2010

Introduction

LHC



pp-collision	E_{CM}	Int. lumi.	Pile-up
2011	7TeV	5.6 fb^{-1}	9.1
2012	8TeV	23.3 fb^{-1}	20.7
2015~2017	13~14TeV	~90 fb^{-1}	O(100)

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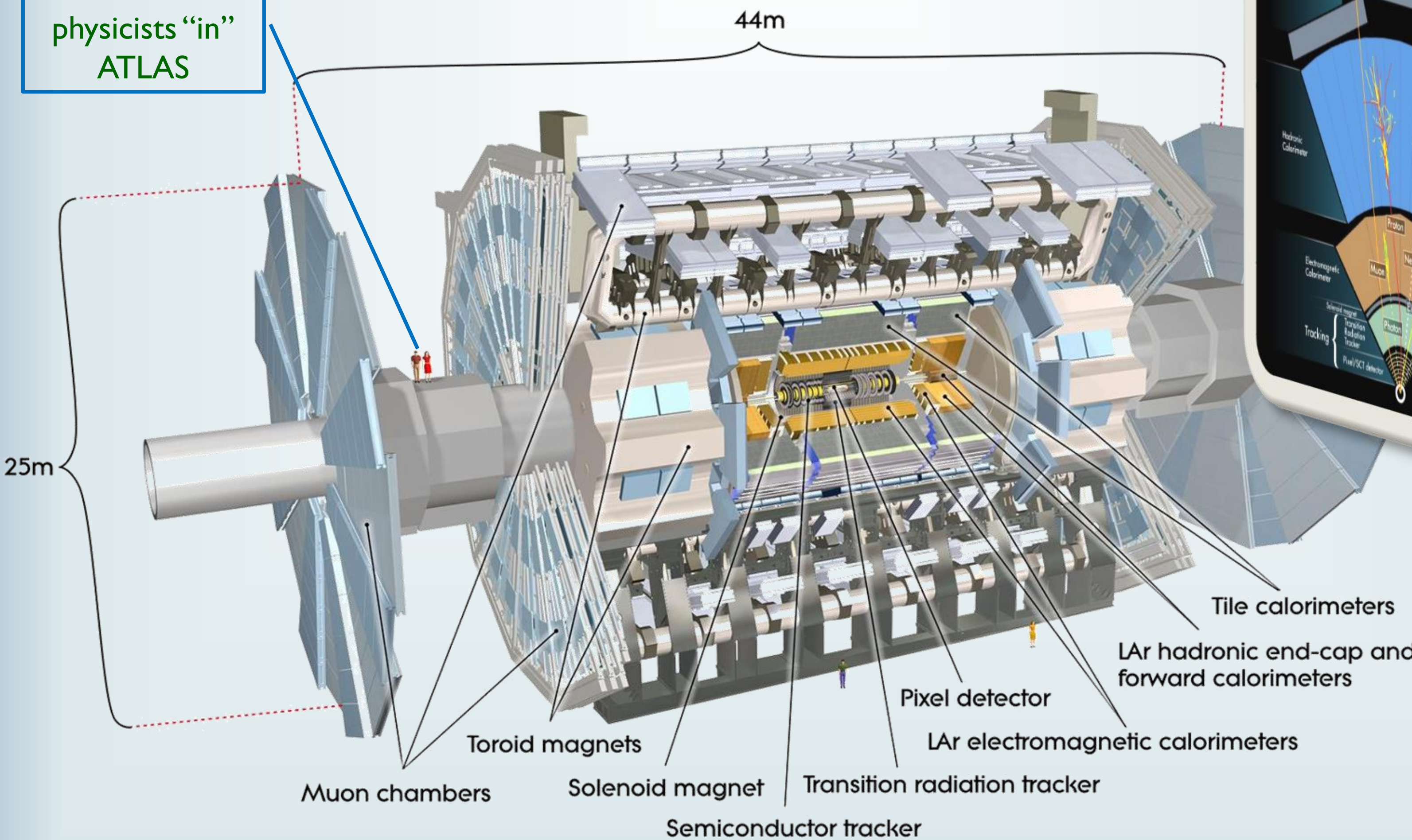
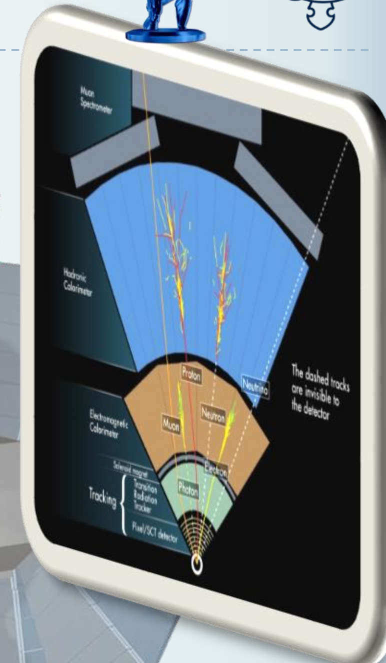
Introduction

ATLAS

~3000 physicists "in" ATLAS





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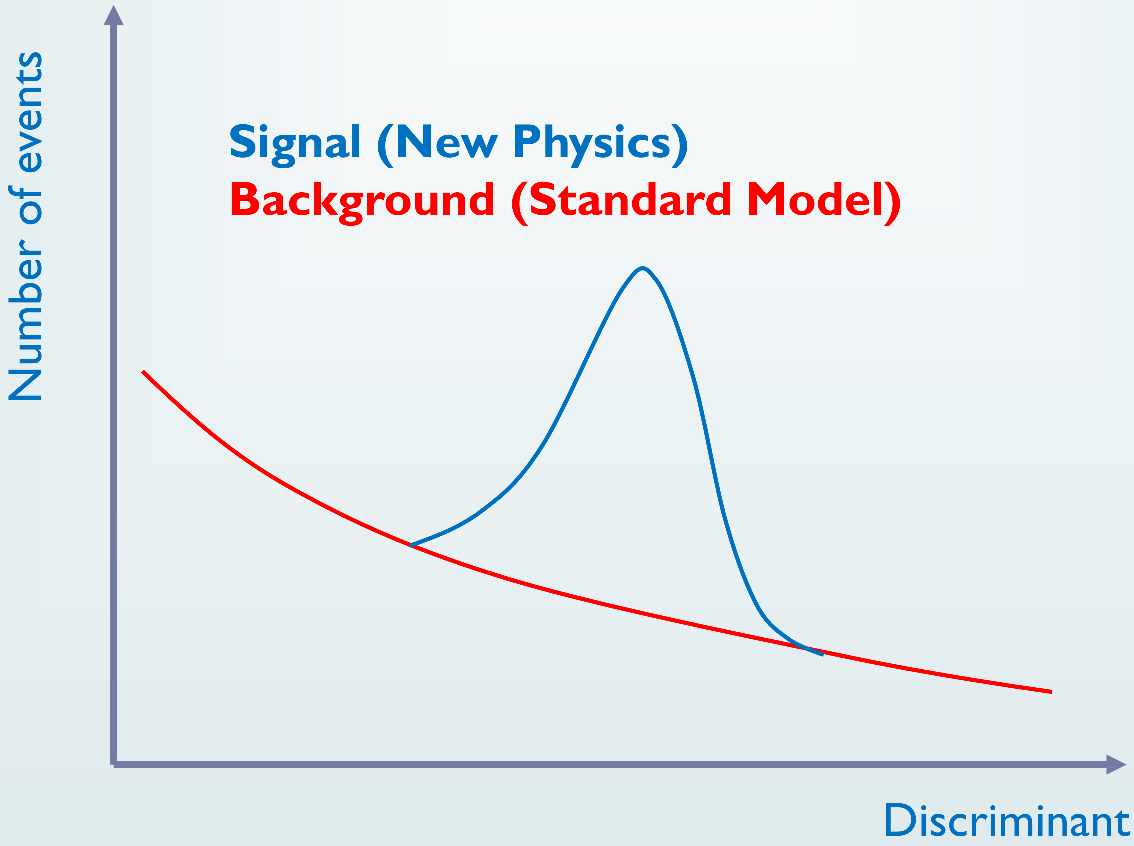
Introduction

New physics searches



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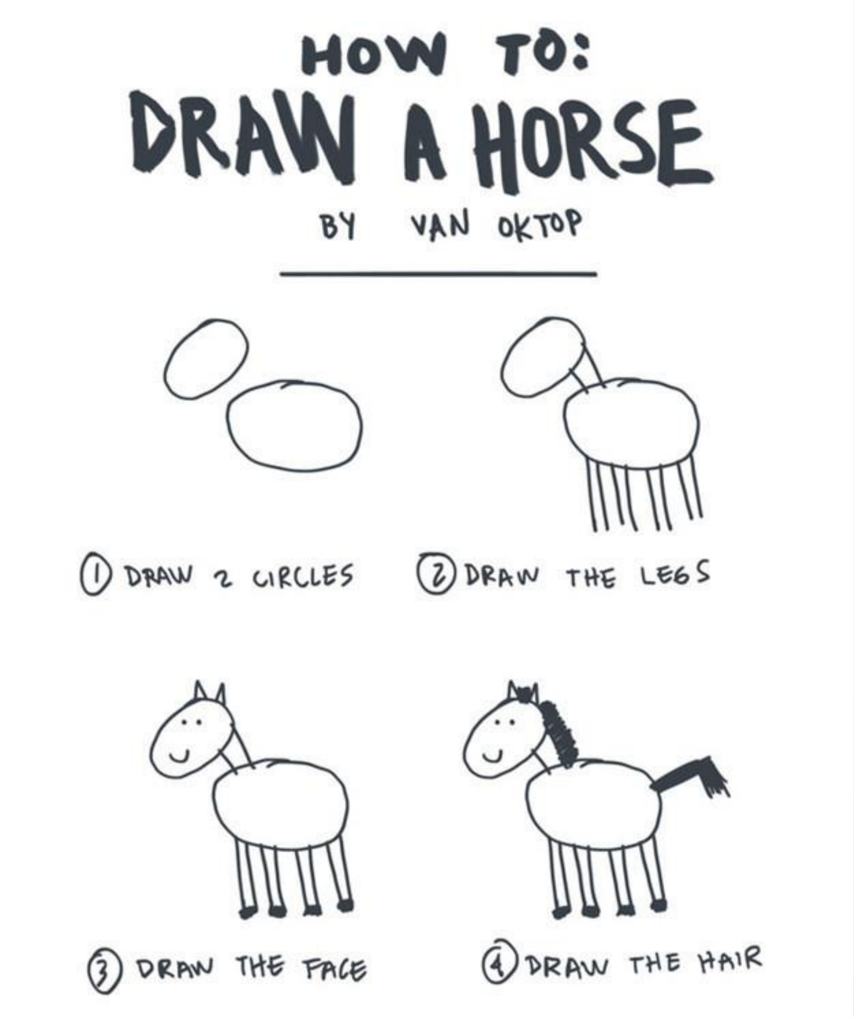
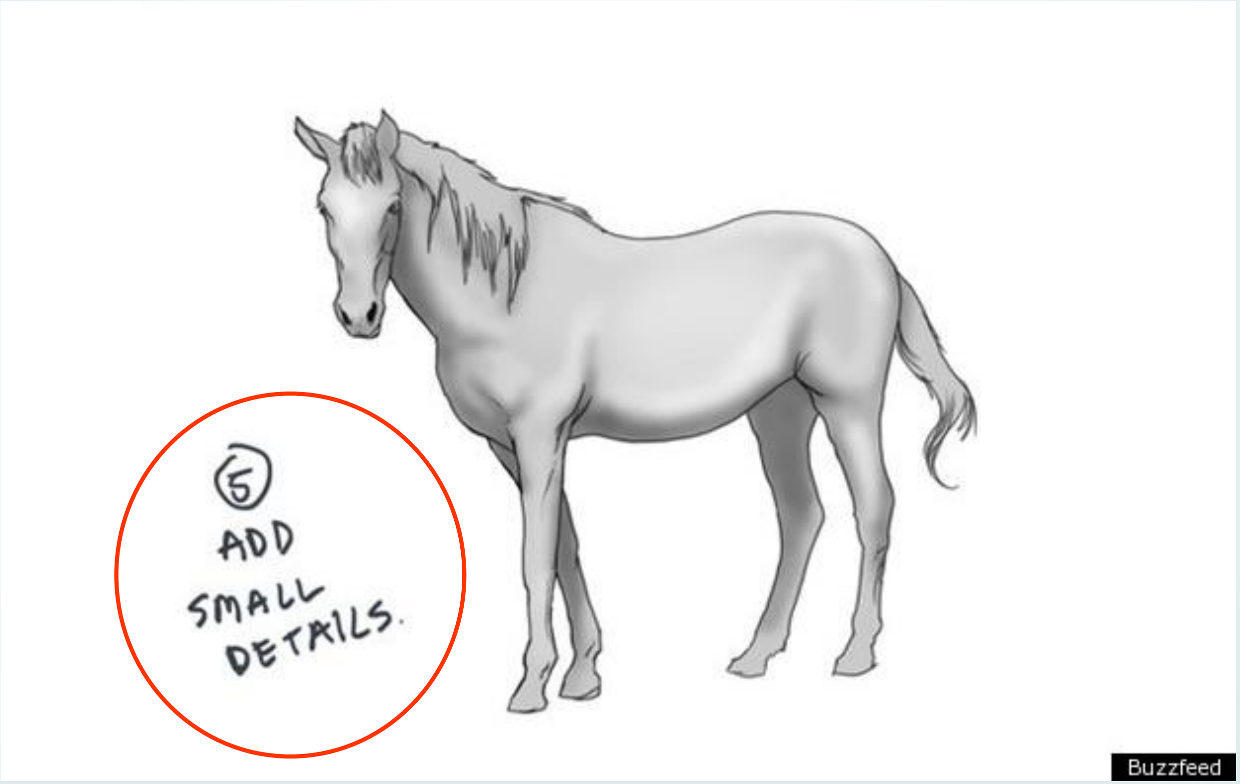
Introduction
New physics searches

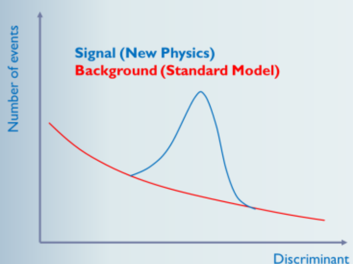


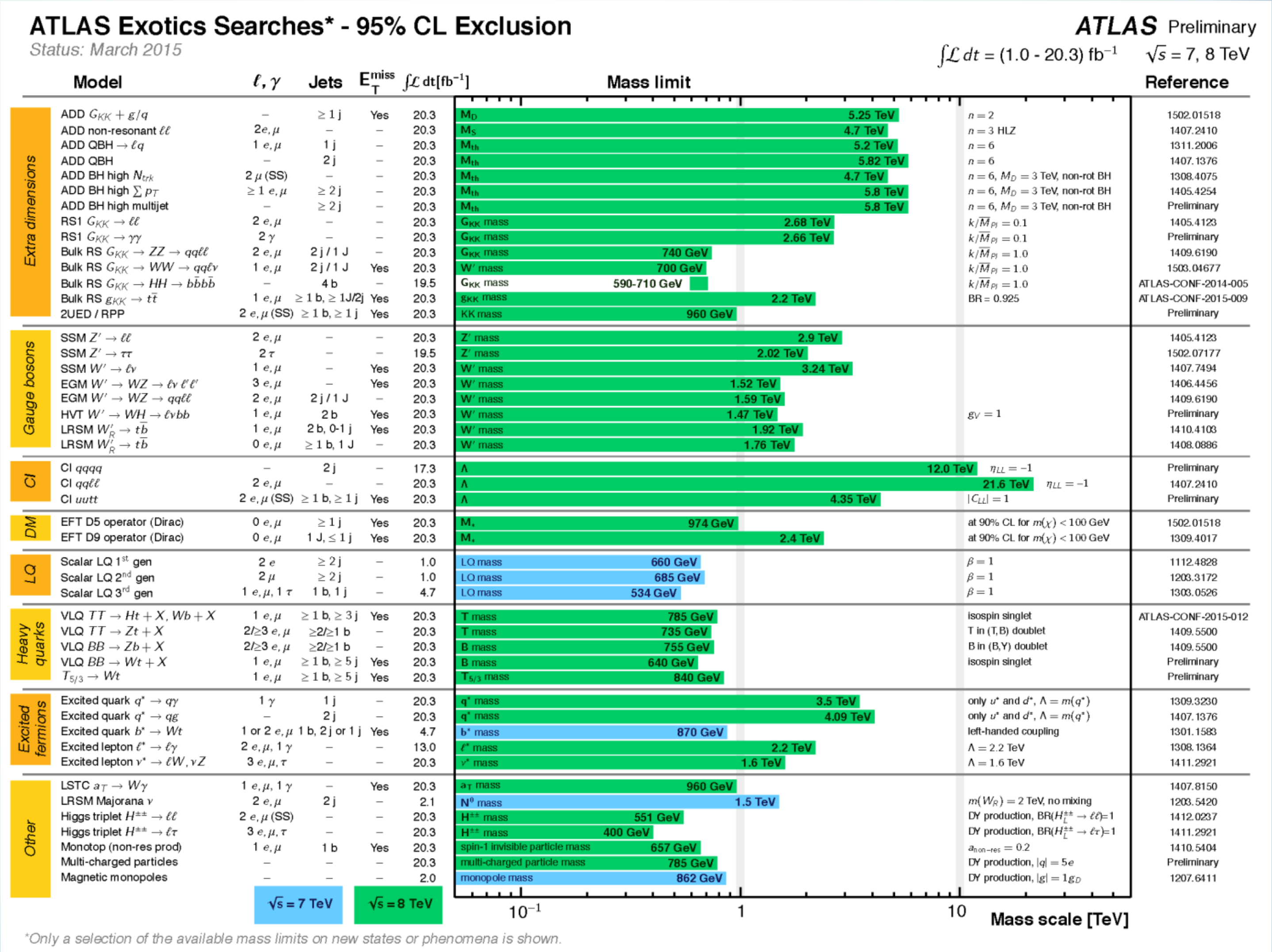
New physics searches



Introduction

New physics searches at energy frontier





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Outline

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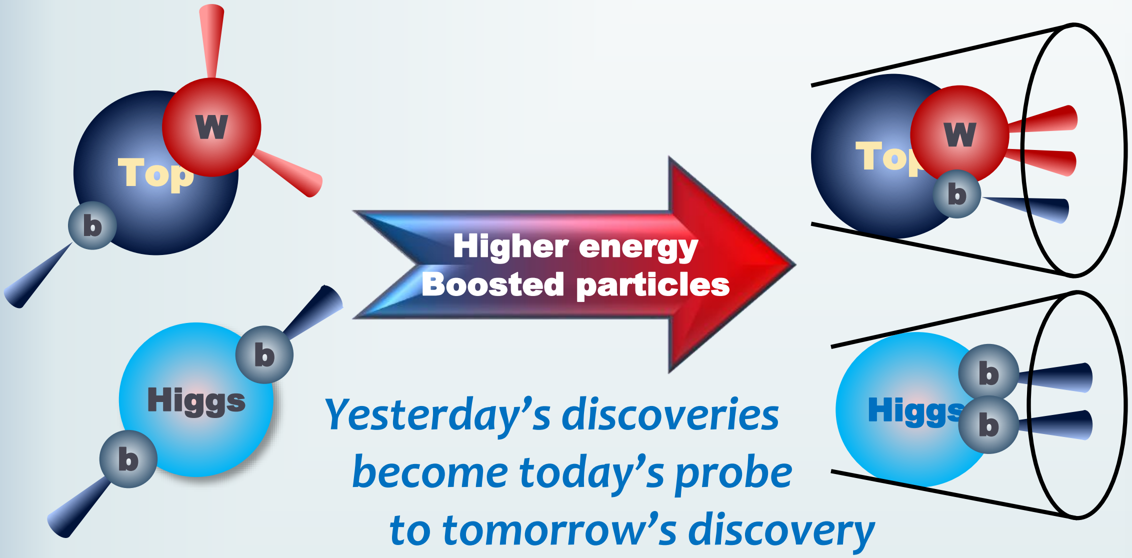
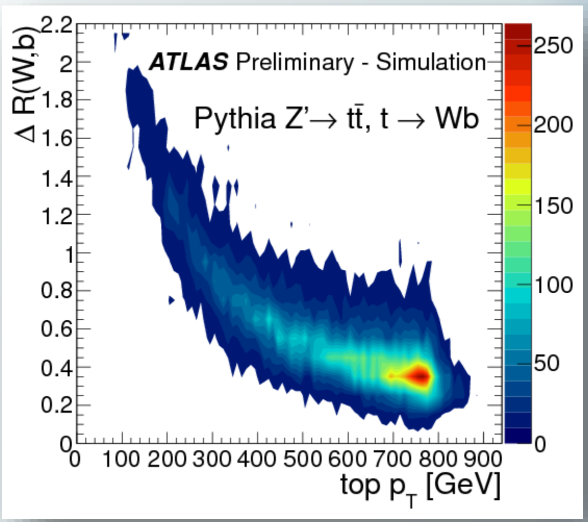
  - LHC and ATLAS
  - New physics searches at energy frontier
- Reconstruction & Identification of Boosted Objects
  - Leptons isolation
  - Large-R jet and substructure
  - Flavor-tagging
- Top quark pair resonance search

Boosted objects

- By now many searches have reached TeV-scale mass limits
- Heavy SM particles (top, W, Z, H, …) highly “boosted”

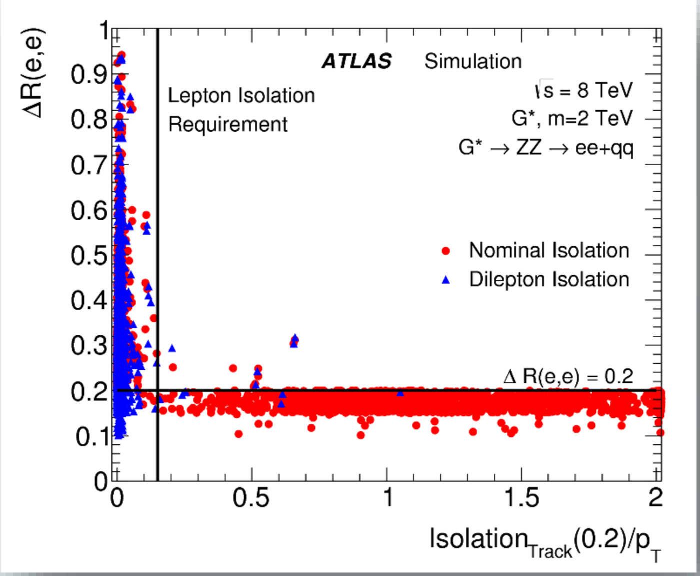


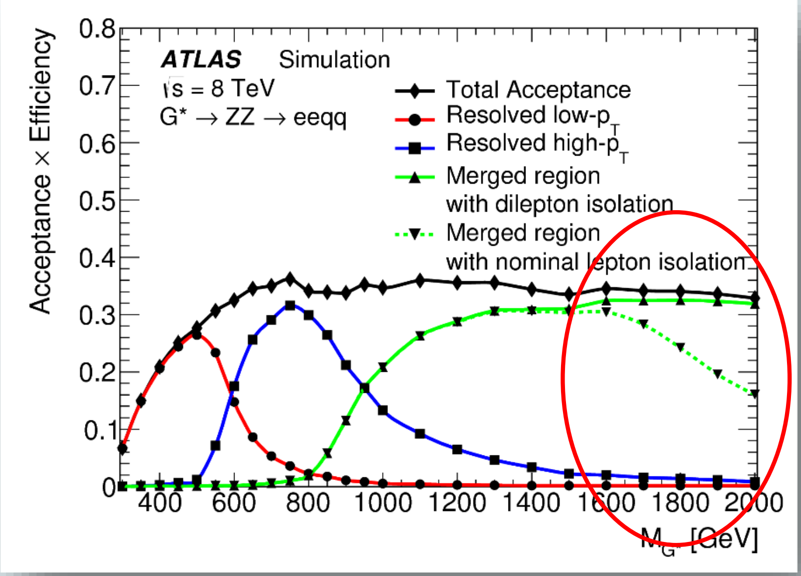


- New challenges to particle reconstruction/identification
- New opportunities to improve sensitivities

Lepton isolation (Z->ll)

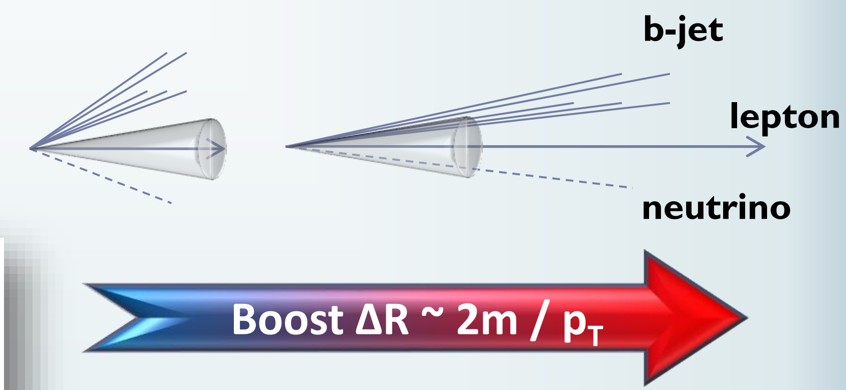
- Lepton pairs from boosted Z boson highly collimated
- Special isolation treatment to subtract contribution from the other lepton



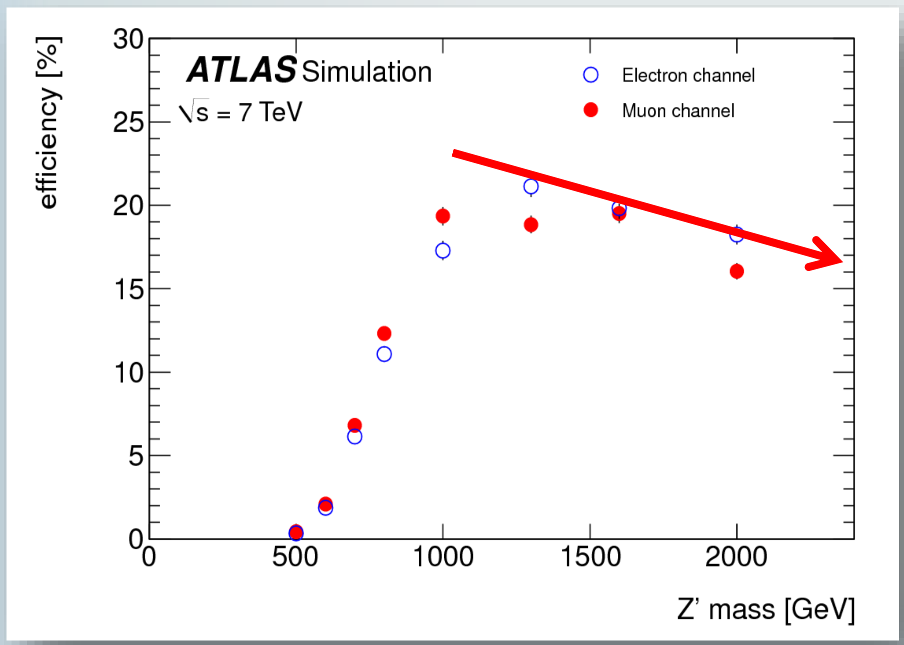


Lepton isolation (leptonic top)

- Lepton and b-jet from boosted top become highly collimated



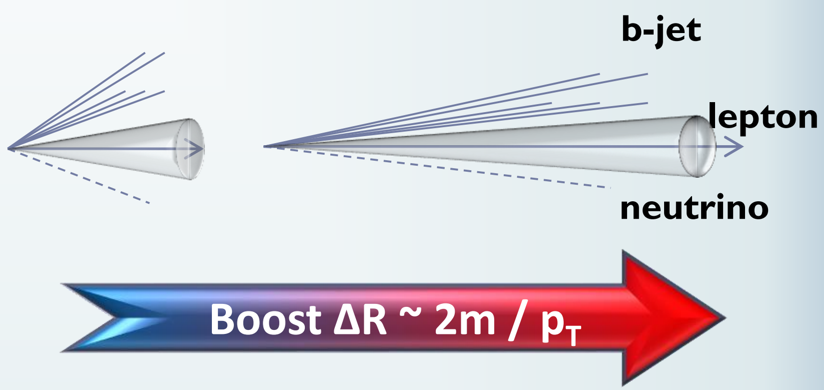
Signal efficiency for Z' ->ttbar with fixed cone isolation



Traditional fixed-cone isolation starts to fail above TeV

Lepton isolation (leptonic top)

- Even boosted, leptons from tops have larger separation from jets than those from lighter quark/gluon



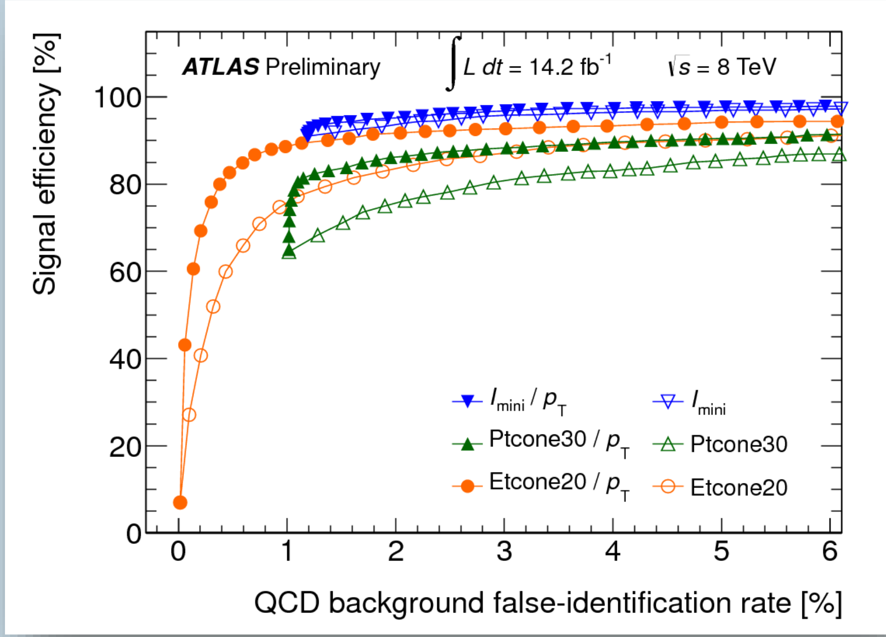
- Mini-isolation
  JHEP 1103:059 (2011)
  Rehermann, Tweedie
  - **Variable cone size**

    $\Delta R = k_T / p_T^{lepton}$, k_T=10 GeV
  - $I_{mini} = \sum P_T$ of tracks within (excluding the track of the lepton)
  - Require $I_{mini} / p_T^{lepton} < 0.05$

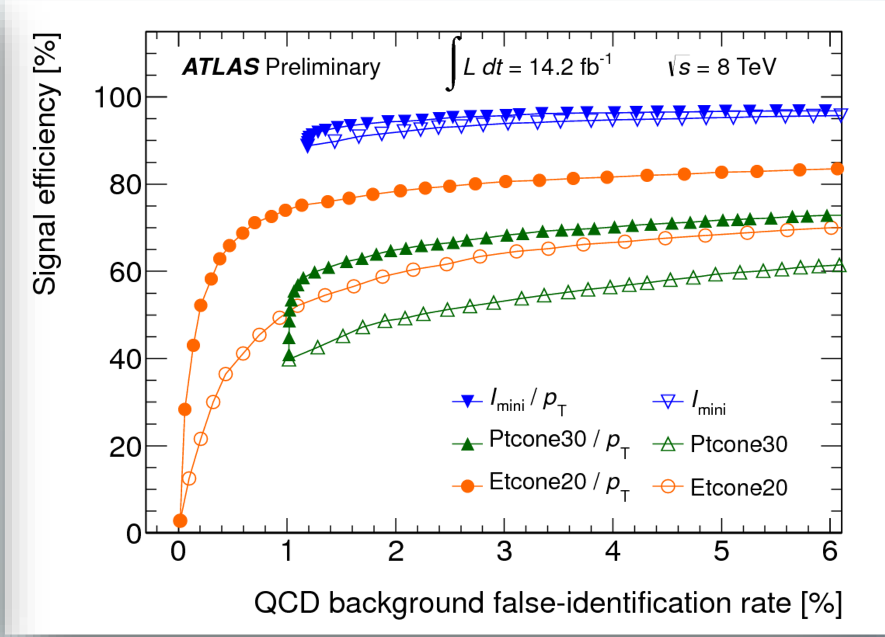
Lepton isolation (leptonic top)

- Recover efficiency for highly boosted top

Z' 1.0 TeV

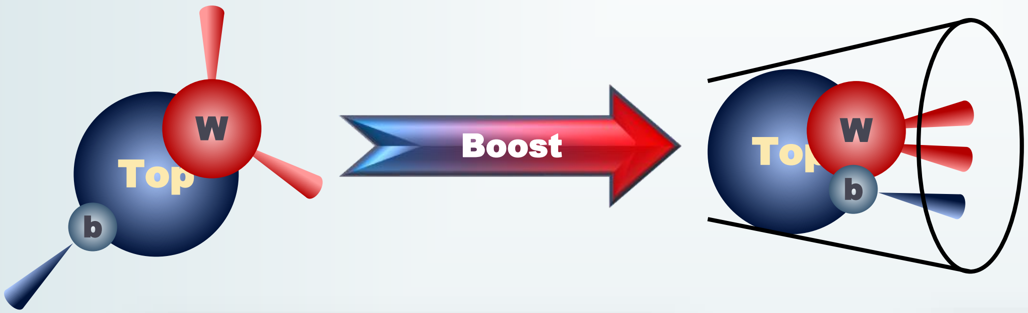


Z' 2.0 TeV

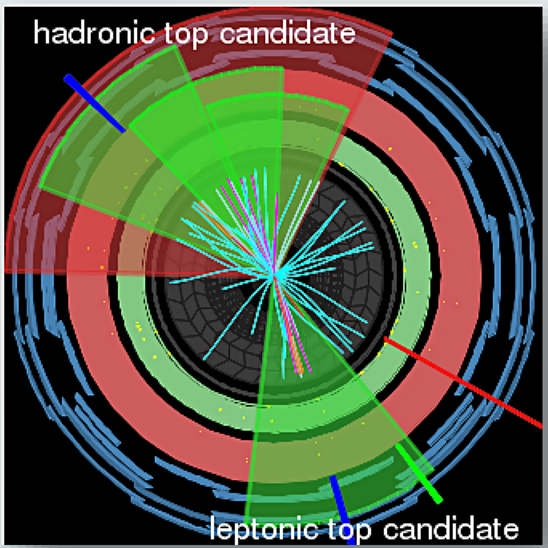


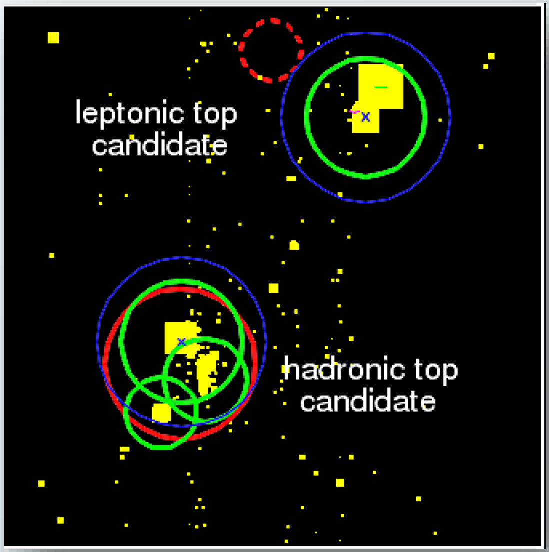
Large-R jet

Reconstruct a hadronic top quark (boson) from three (two) small-radius jets , … or single large-radius jet



- Better acceptance when jets get merged
- Reduce combinatorial backgrounds





Large-R jet substructure

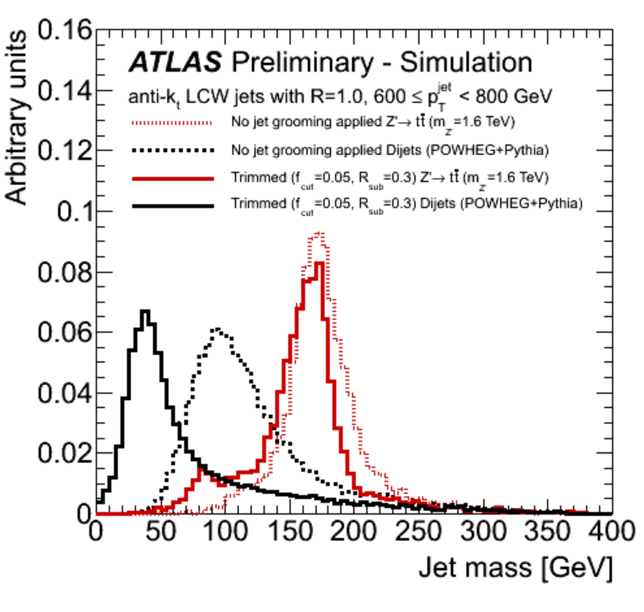
Jet mass

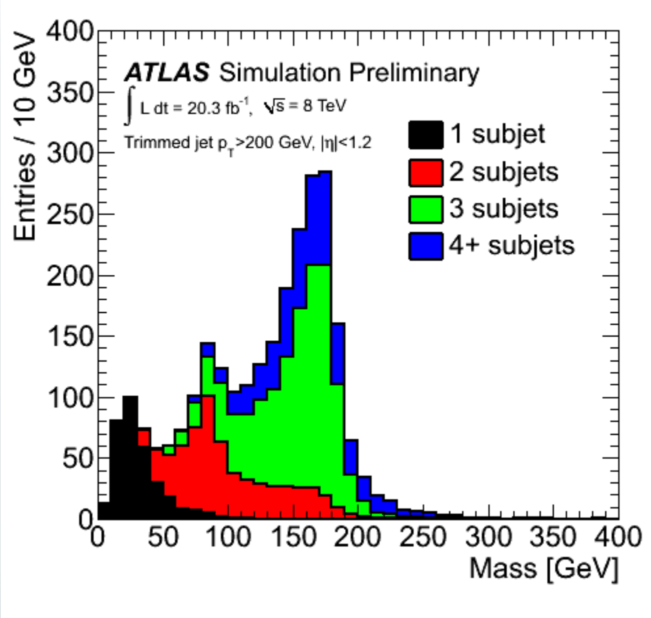
- Simple 4-vector sum of jet constituents

$$(m^{\text{jet}})^2 = (\sum_i E_i)^2 - (\sum_i p_i)^2$$

  Calorimeter clusters, charged tracks, truth particles, …

- Approximate the mass of original particles
- **Subject to pile-up noise** => jet grooming requied





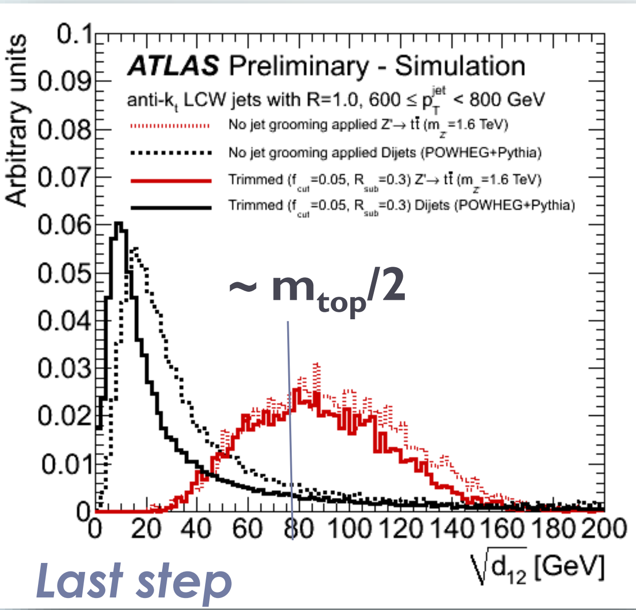
Large-R jet substructure

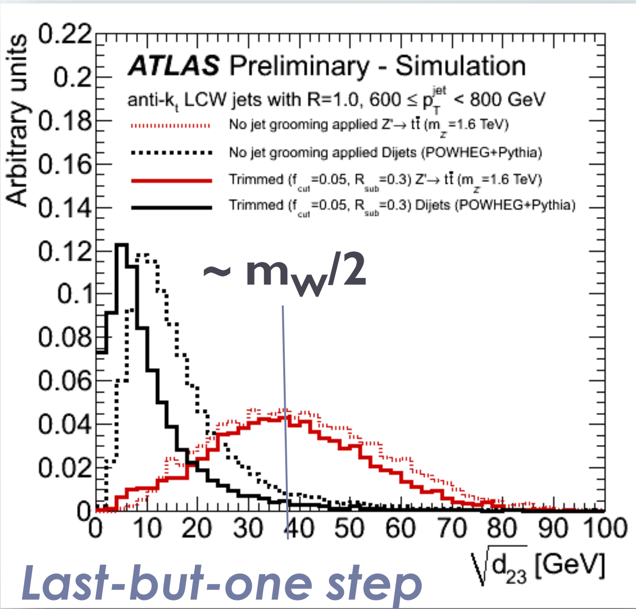
Jet splitting scale

PRD65, 096014 (2002)
Butterworth, Cox, Forshaw

- Re-cluster jet constituents with K_T algorithm
  - Starting from softest constituents to hardest
- Observable: the splitting scale in the last step(s) of clustering

$$\sqrt{d_{ij}} = \min(p_{\mathrm{T}i}, p_{\mathrm{T}j}) \times \Delta R_{ij}$$





Large-R jet substructure

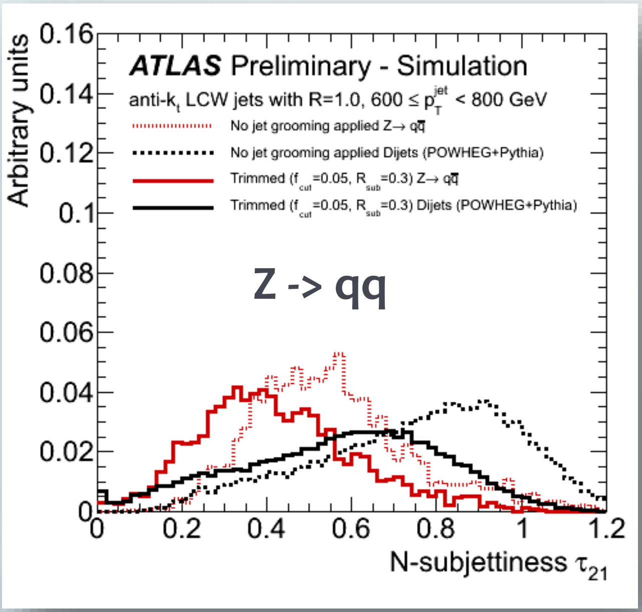
N-subjettiness (τ_N)

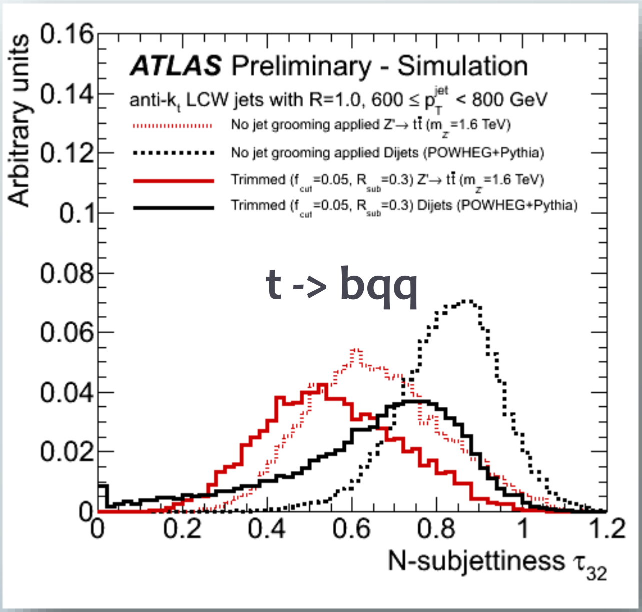
JHEP 1103:015 (2011), JHEP 1202:093 (2012)
J. Thaler, K. Van Tilburg

- Re-clustering with Kt algorithm until exactly N subjets are formed

$$\tau_N = \frac{1}{d_0} \sum_k p_{Tk} \times \min(\delta R_{1k}, \delta R_{2k}, ..., \delta R_{Nk}) \ , \ \text{with} \ \ d_0 \equiv \sum_k p_{Tk} \times R$$

- Observable: τ_{N+1} / τ_N , smaller ratio = more "subjetty"

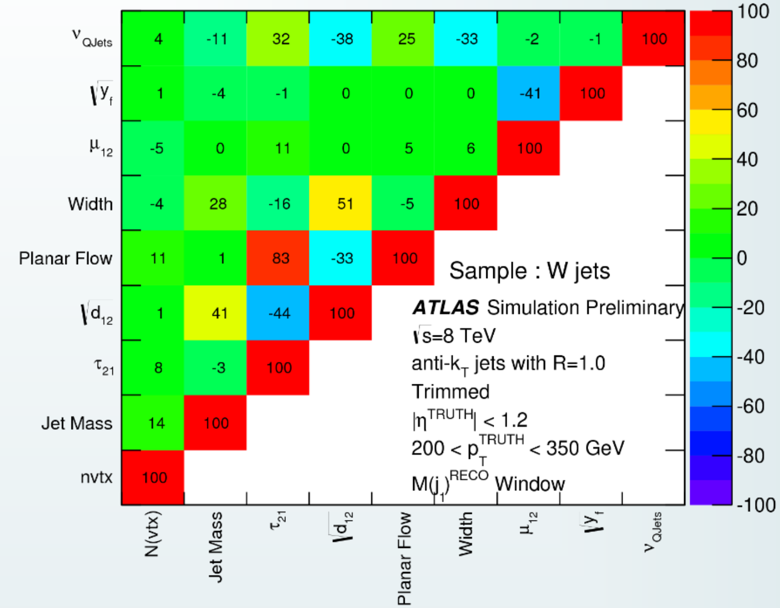




Large-R jet substructure

And more …

- Mass drop, Energy correlation, Momentum balance, Jet width, Planar flow, Q-jets volatility, …

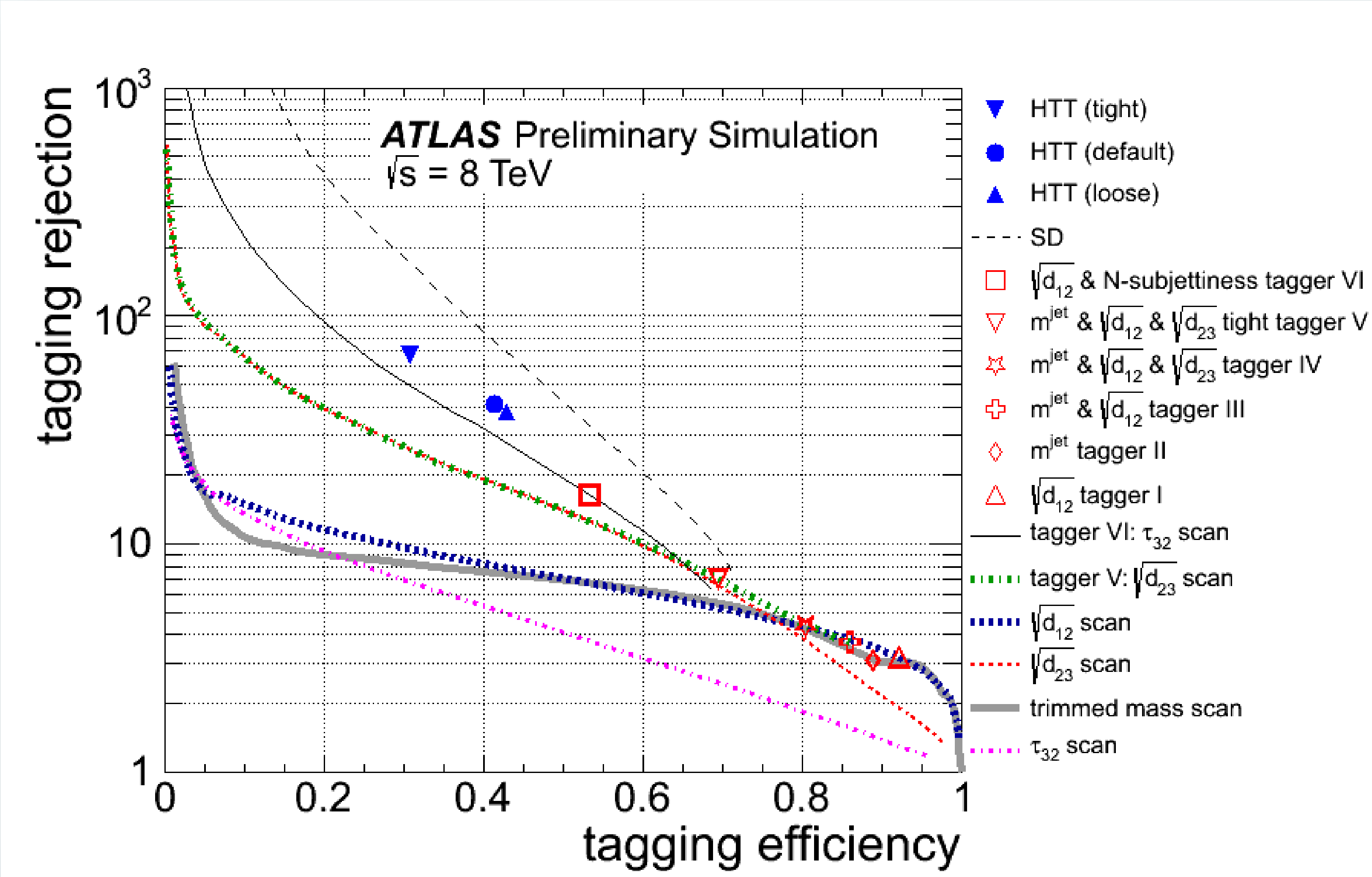


Optimal choice for analysis not always obvious

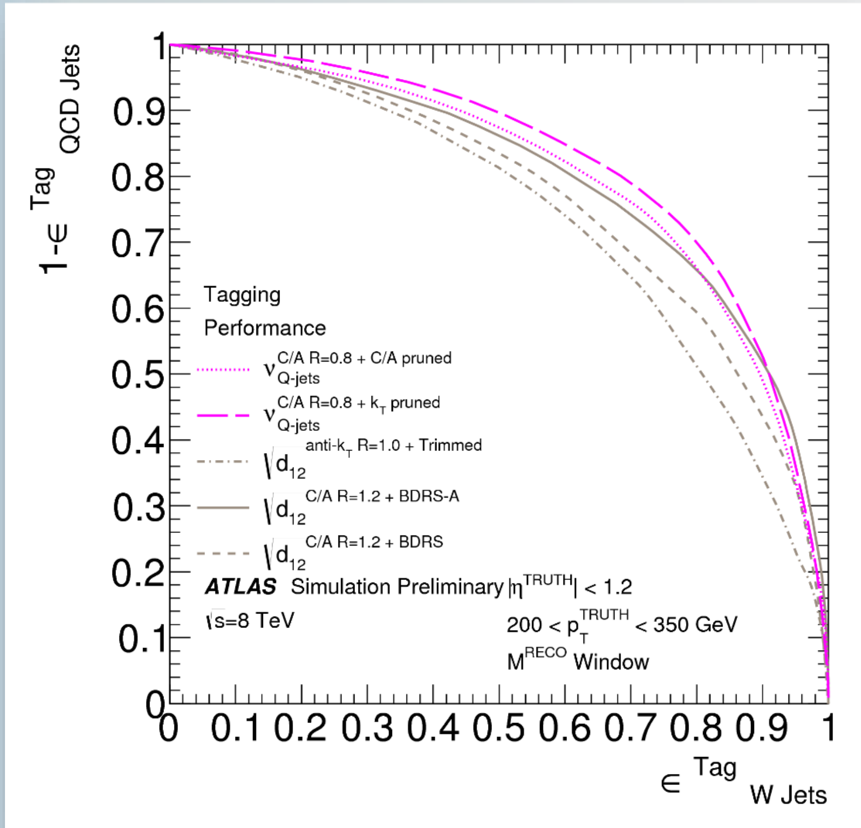
- Topology-dependent applicability
- p_T-dependent performance
- Sensitivities to pile-up
- Correlations between variables

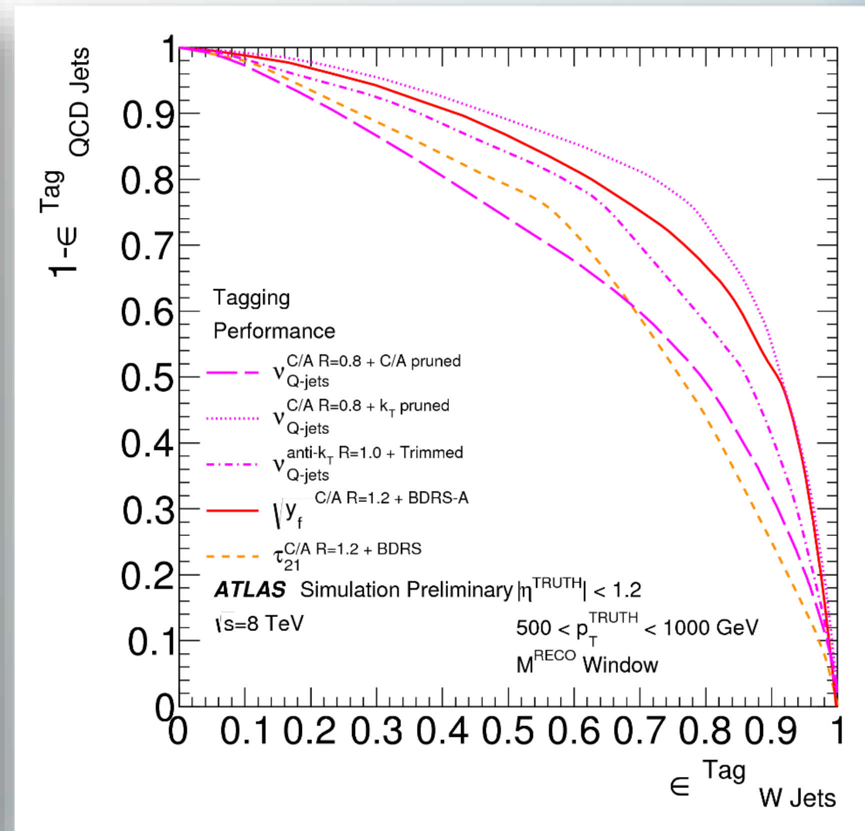
And more complex taggers invented …

Top Taggers Comparison



Boson Taggers Comparison



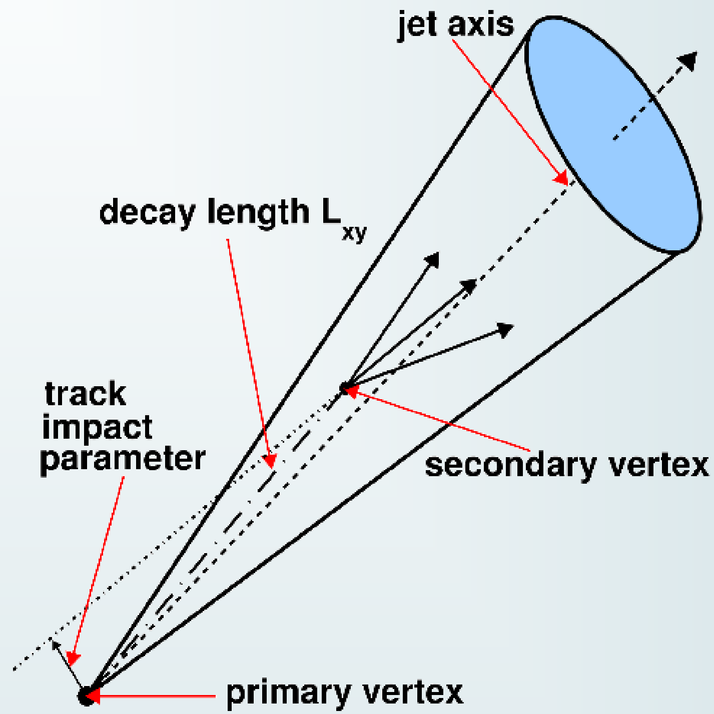


p_T - dependent Substructure performances

Flavor-tagging

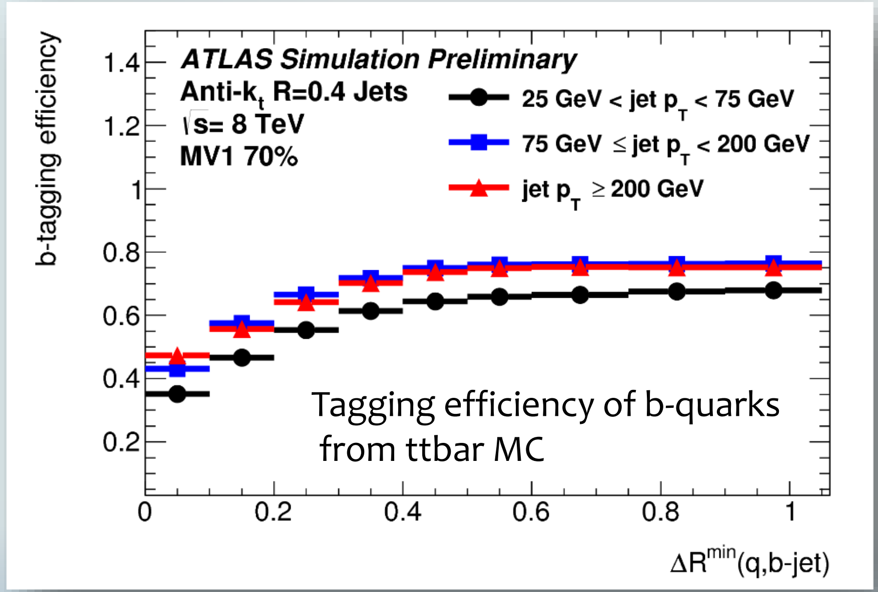
- "Classical" experimental techniques to identify long lifetime b-hadron decays based on track impact parameters and displaced vertex

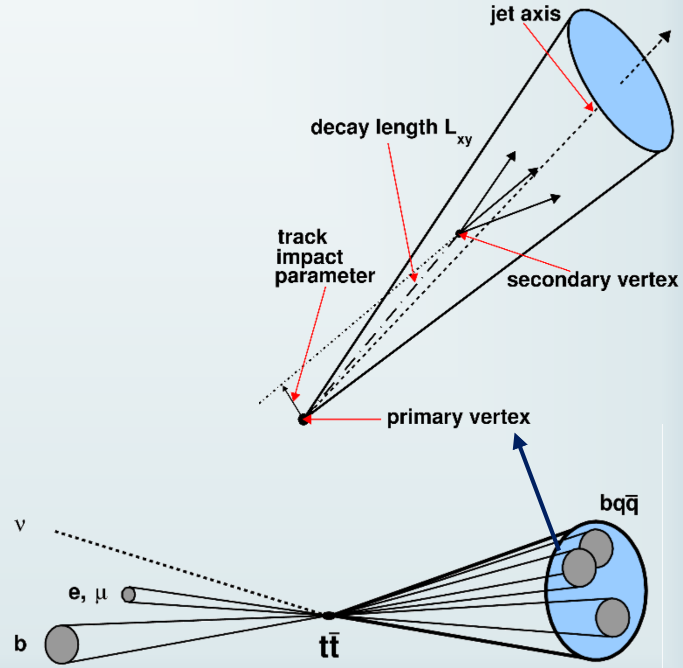
- Vital for physics analyses involving top quark and Higgs boson



Flavor-tagging

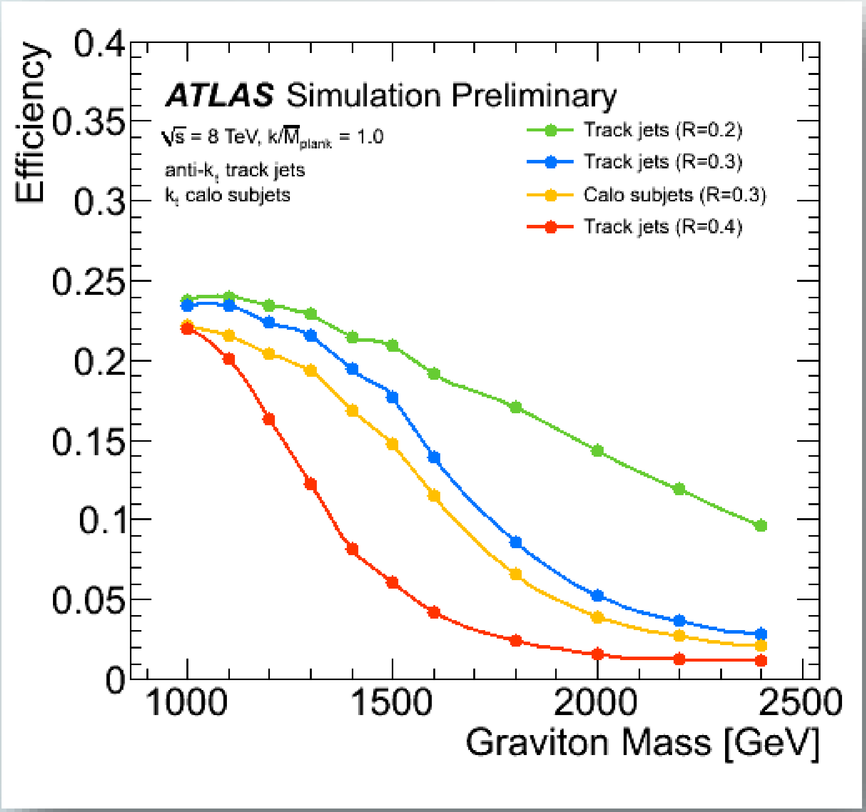
- Tracking/vertexing efficiencies degrade in high pt
- Collimated jets make life difficult even in medium pt range
  - Lower efficiency to identify top quark or Higgs(->bb) boson
  - Dense environment requires dedicated calibration (precision limited by statistics)





Flavor-tagging

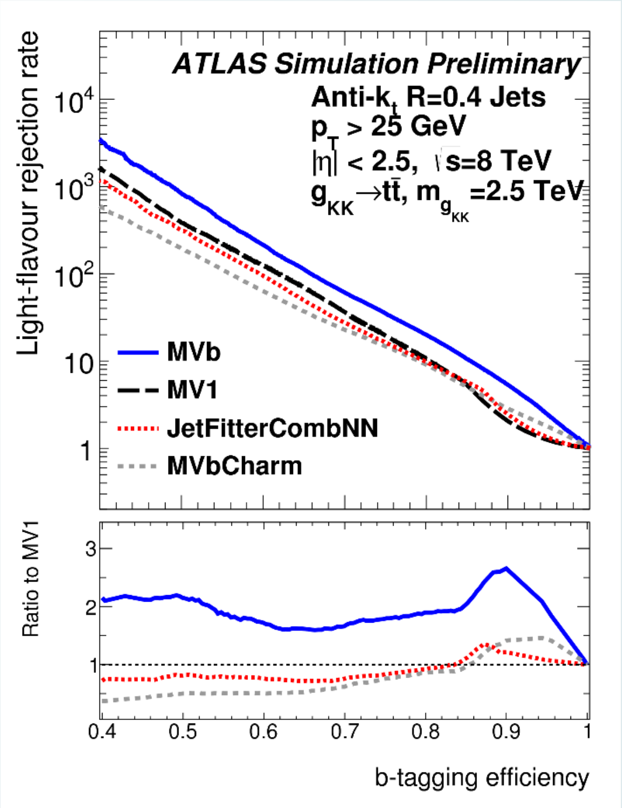
- Solution A: smaller track jets for b-tagging
  - Cons: worse background rejection in low p_T



Efficiency to find **two b-tagged** track jets / subjets in both large-R jets of **RSG->HH->4b** MC events

Flavor-tagging

- Solution A: smaller track jets for b-tagging
  - Cons: worse background rejection in low p_T
- Solution B: dedicated multivariate algorithm trained for dense environment
  - Cons: topology dependent
- Other R&D
  - Variable-radius jets (p_T-dependent)
  - Multi-vertex tagging (for double B-hadron jets)
  - …



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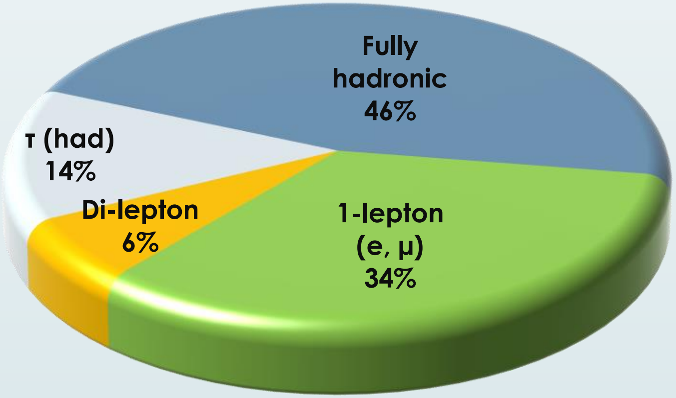
- Top quark pair resonance search

Top pair resonance searches

- Generic search looking for excess on the Mtt spectra
- Interpret results for benchmarks of various widths & spins
  - Affect angular distributions (selection efficiency)

    JHEP 1799 0901 (2009) 047

- Most sensitive in 1-lepton channel
  - Complemented by all-hadronic channel



Top pair resonance searches

1-lepton selection

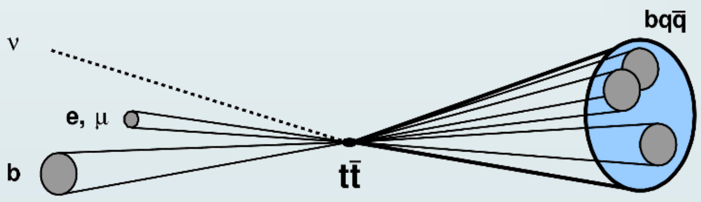
- ==1 Mini-isolated e/μ
- MET => Reconstruct neutrino from W mass constraint
- At least one b-tagged jet

Resolved

- >=4 anti-k_T 0.4 jets
- Ttbar candidate reconstructed based on likelihood combination of jets/lepton/neutrino/b-tagging

Boosted

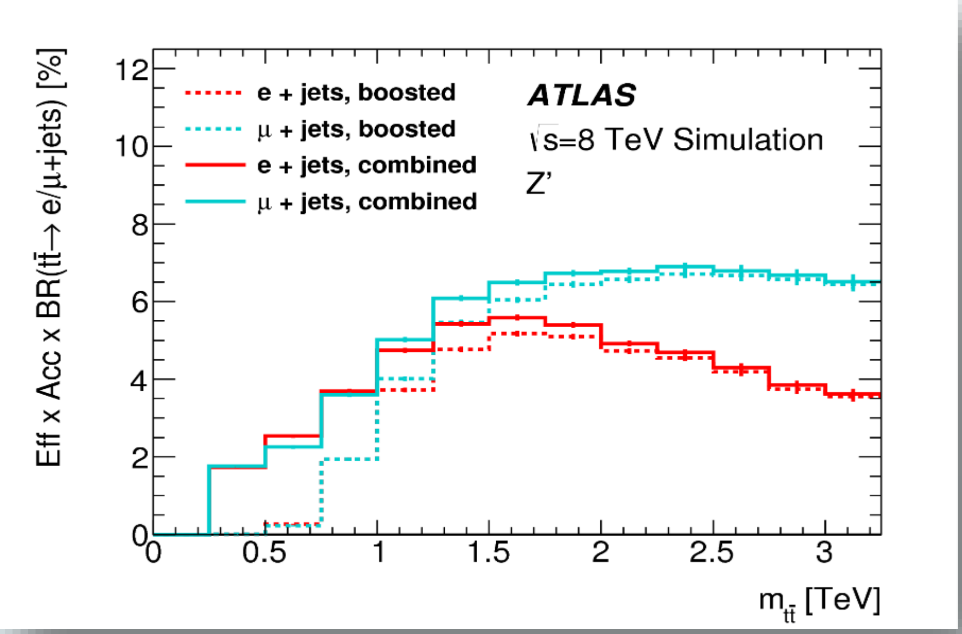
- >=1 anti-k_T 0.4 jet, dR(lep, akt4)<1.5
- >=1 **anti-k_T 1.0 jet**, Pt>350GeV
  - Δφ(lep, akt10)>2.3
  - ΔR(akt10, akt4)>1.5
  - **mass>100GeV, splitting scale>40GeV**



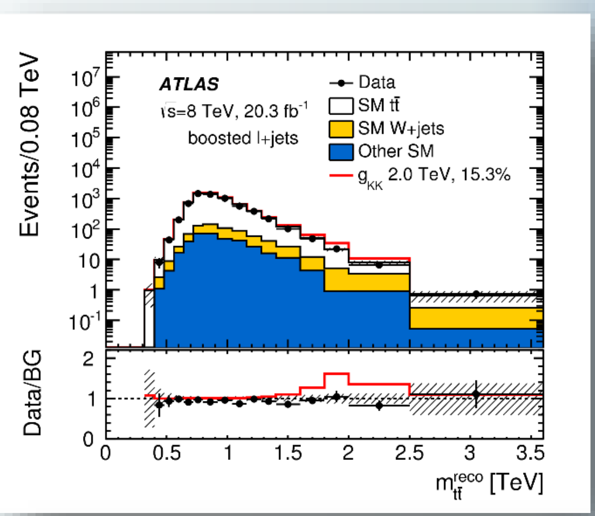
Top pair resonance searches

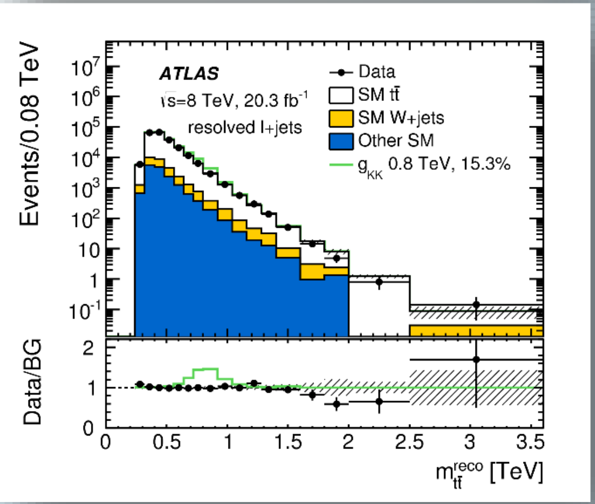
1-lepton selection efficiency

- Boosted channel dominate above 1TeV
  - Priority over resolved channel
  - Less non-ttbar background => Higher sensitivity



(combined=boosted || resolved)





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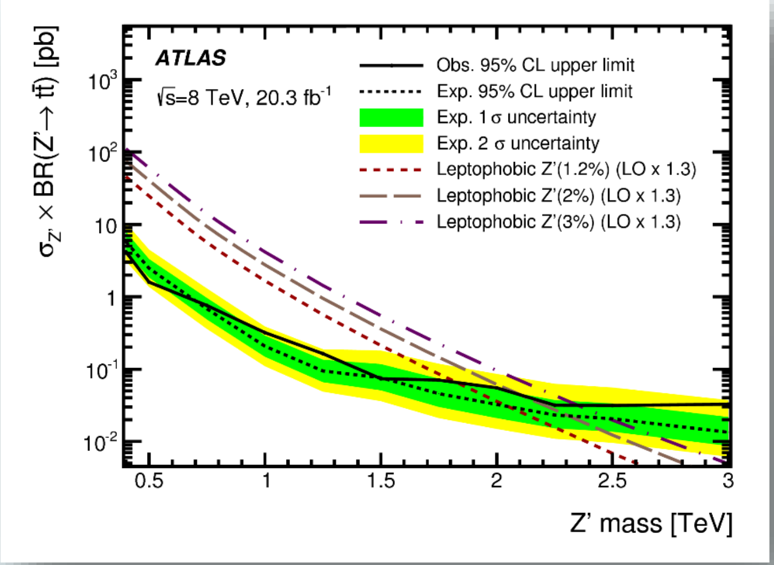
Top pair resonance searches

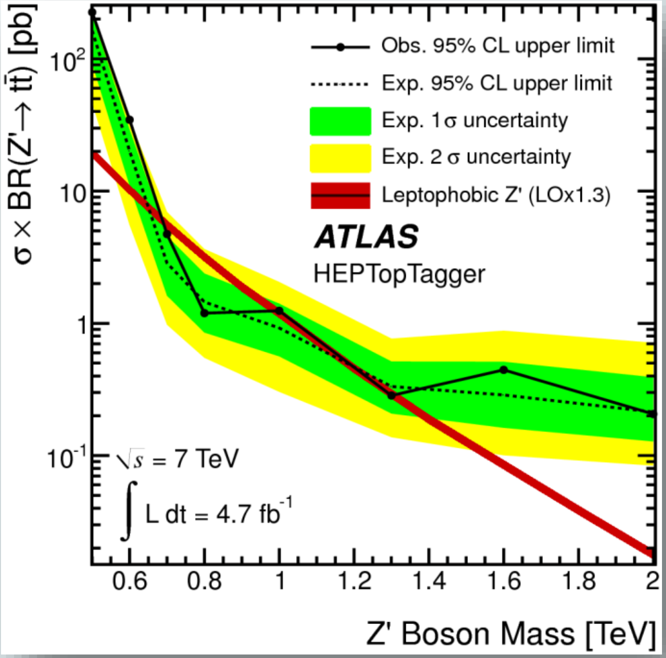
Limit

- Good sensitivity into high mass tails (thanks for the boosted techniques)
- Generally better sensitivity from 1-lepton channel
  - Higher acceptance x BR
  - Less non-ttbar background

1-lepton channel (20/fb@8TeV)

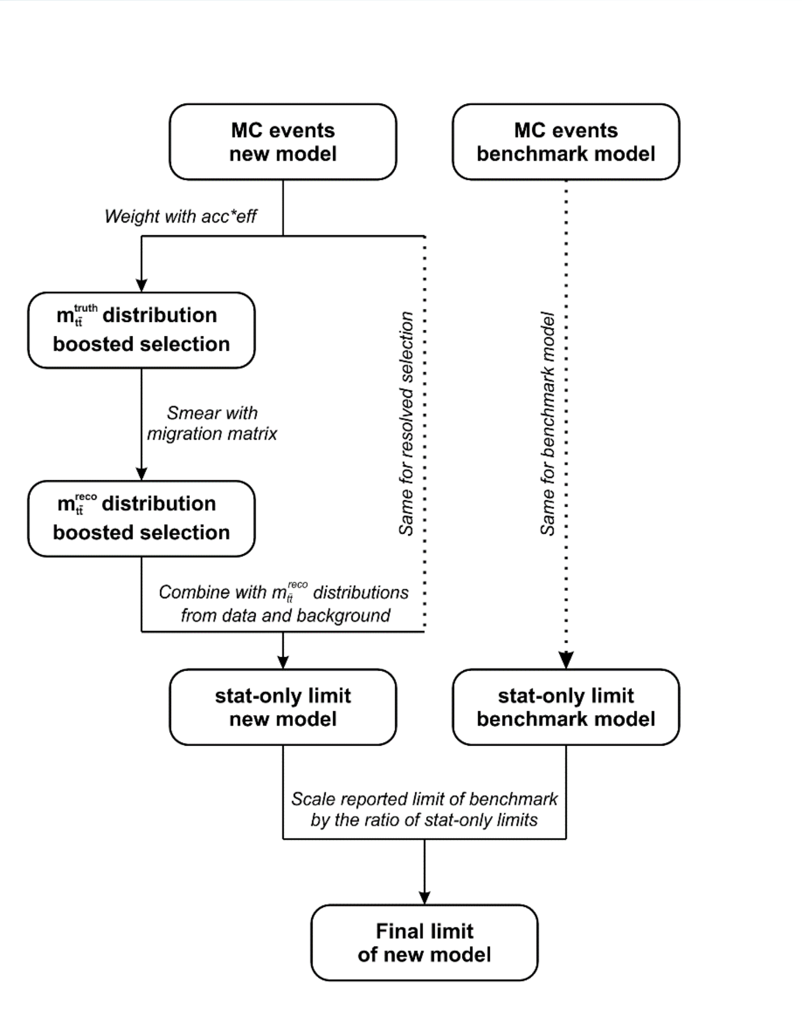


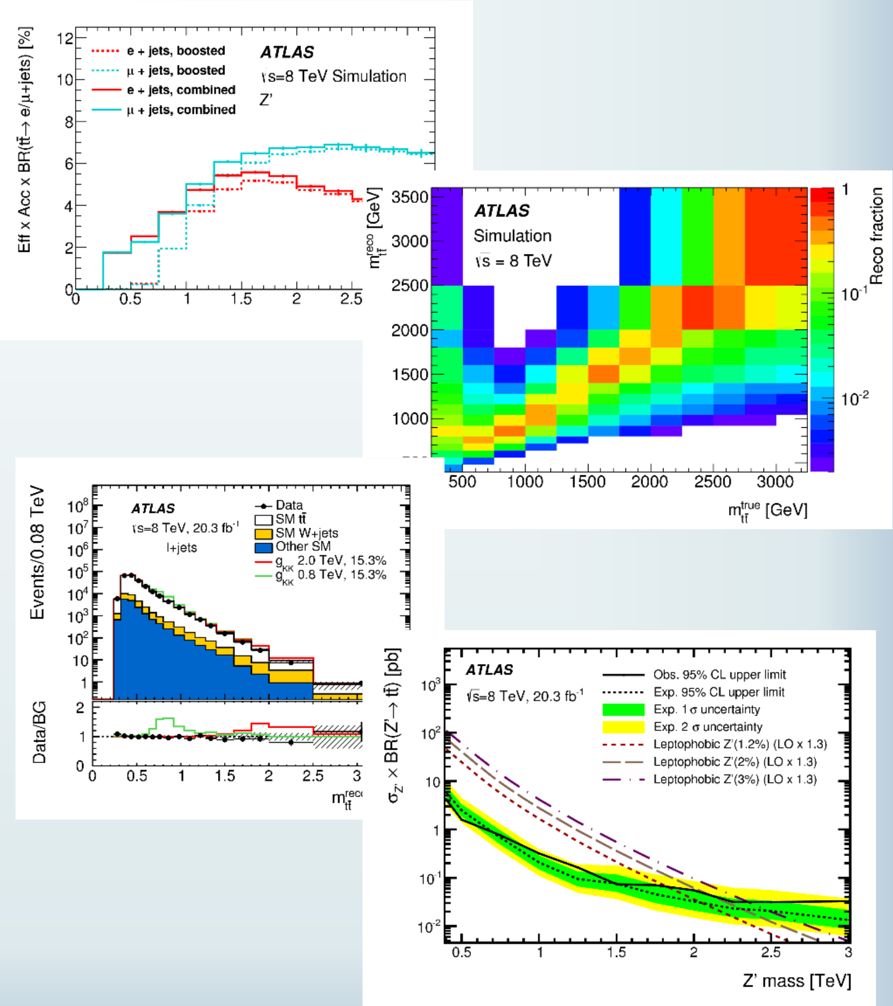
All-had channel (5/fb@7TeV)



!! Not on same footing for comparison

Recasting facility





Summary

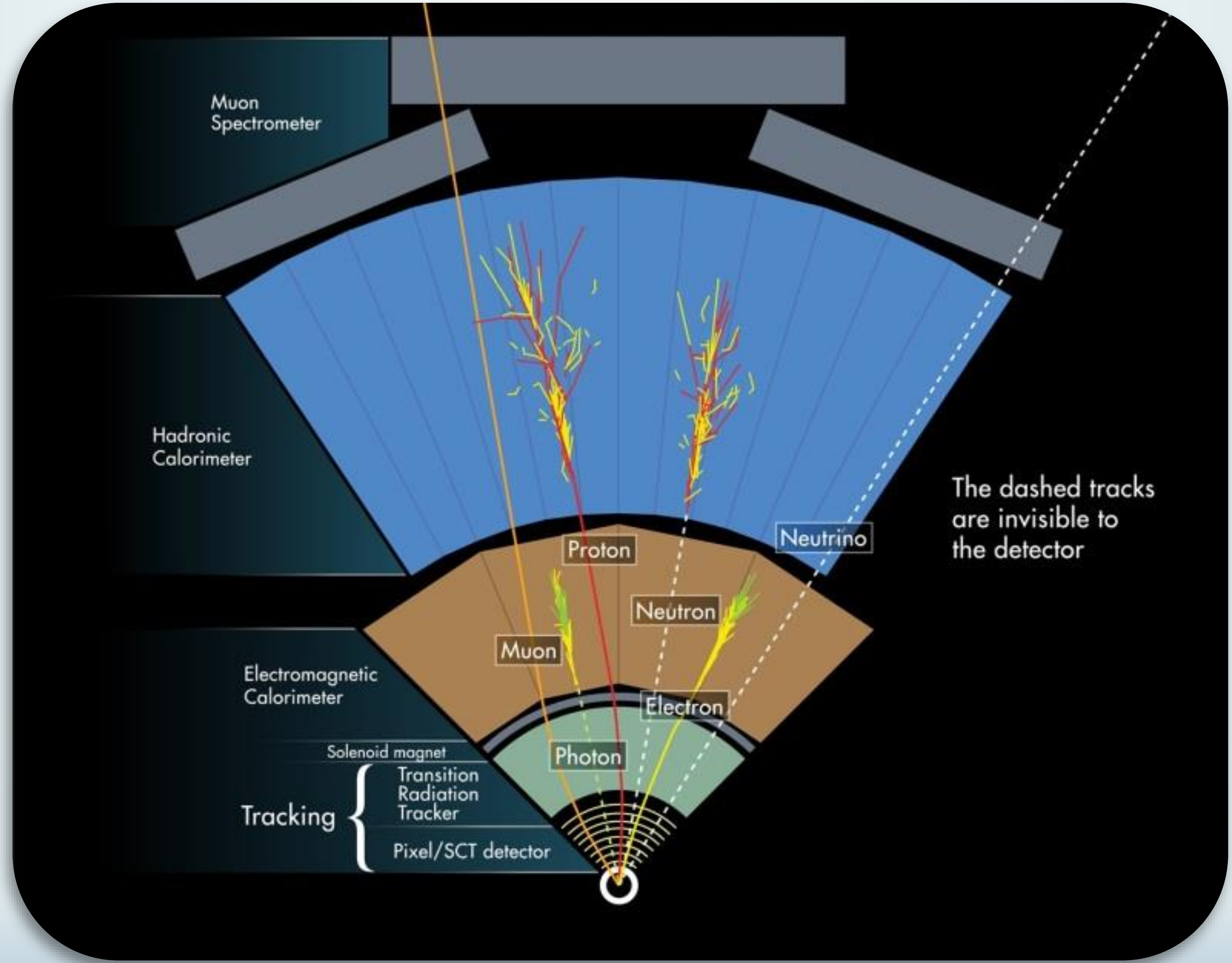
- BSM searches with boosted objects actively evolving in recent years
  - Many new challenges not faced by previous experiments
  - Also provide many exciting opportunities (all-hadronic channels etc)

- A lot of new techniques are developed
  - Yet still lots of rooms to improve
  - Becoming mainstream/standard techniques for analyses (including measurements)

Thanks!!

Backup

Basic reconstruction and identification

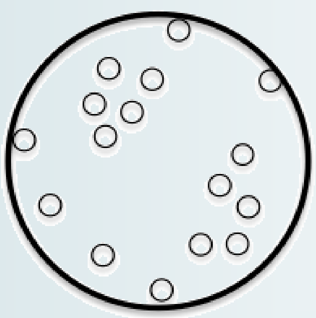


Backup

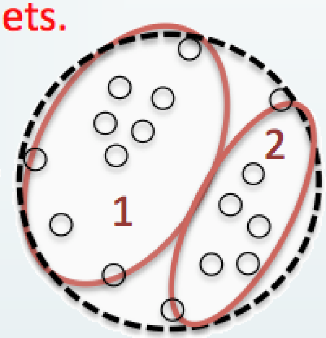
Large-R jet substructure

Jet splitting scale

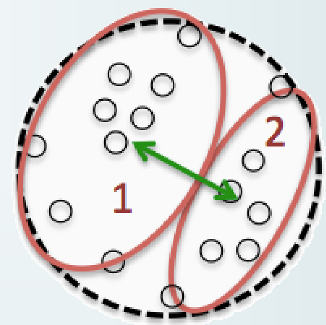
Initial jet



Go back one step in the jet clustering history: you have two subjets.



Measure the dR between them and their pTs.



$\sqrt{d_{12}} = \min(pT(1),pT(2)) \times dR(1,2)$

- If the distance between the subjets is large, $\sqrt{d_{12}}$ is large.
- If the softer of the two subjets in the last clustering has high pT, then $\sqrt{d_{12}}$ is large.
- Both these things indicate large $\sqrt{d_{12}}$ in symmetric two body decays.

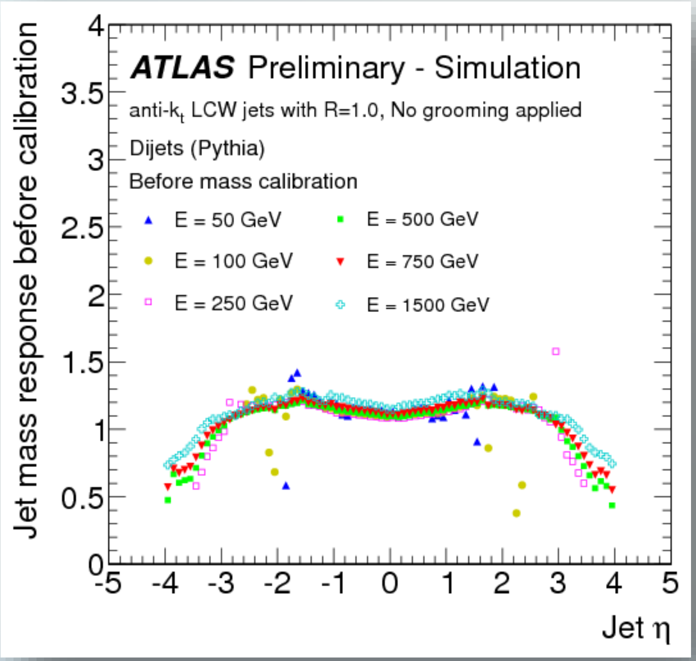
Backup

Large-R jet mass scale calibration

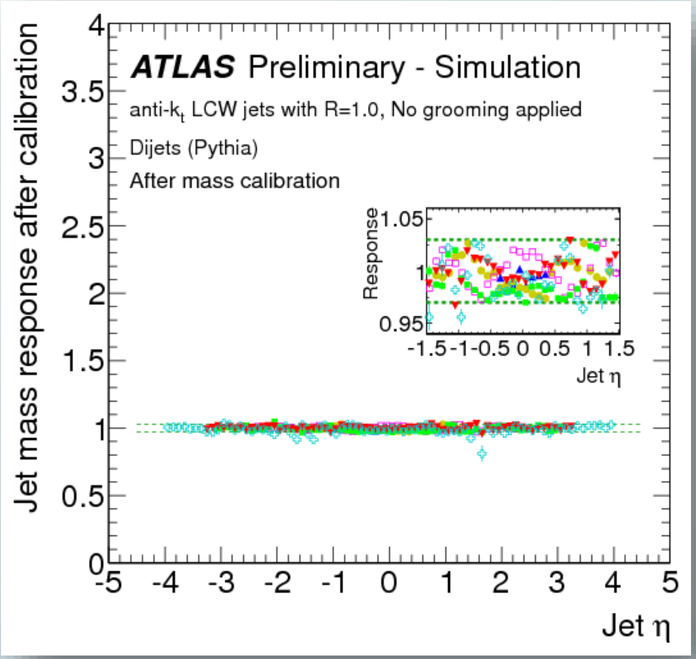
Jet mass

- Sensitive to even very soft contamination from large opening angle
- Calibrated to truth jet mass in MC (after energy calibration)
  - **Response precision within 3%**

Before calibration



After calibration



Large-R jet mass scale uncertainty

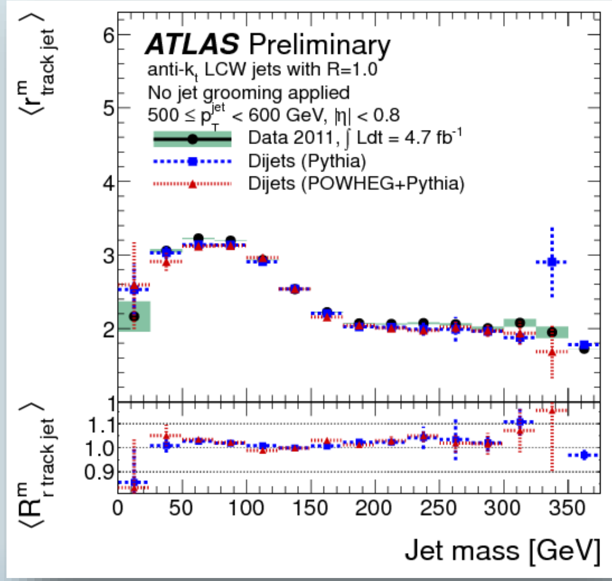
- JMS in-situ validation: Double-ratio method
  - Ratio of mass between the (calo) jet to the track jet matched to it

$$r^{m}_{\text{track jet}} = \frac{m^{\text{jet}}}{m^{\text{track jet}}}$$

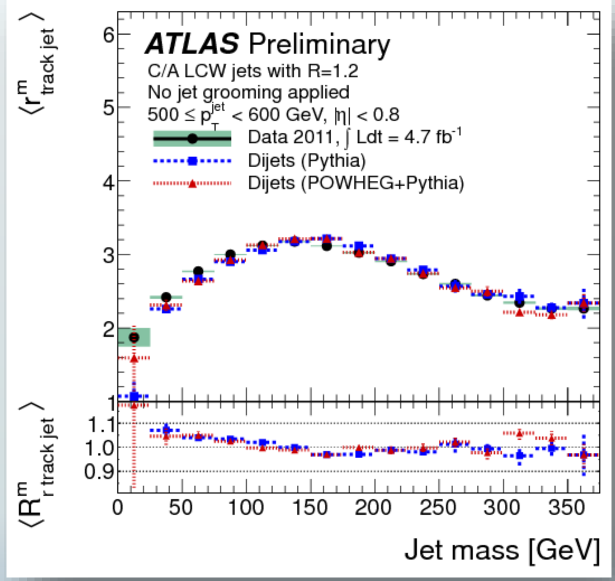
  - Compare the ratio from data vs. MC

$$R^{m}_{r\ \text{track jet}} = \frac{r^{m,\text{data}}_{\text{track jet}}}{r^{m,\text{MC}}_{\text{track jet}}}$$

Anti-K_T 1.0



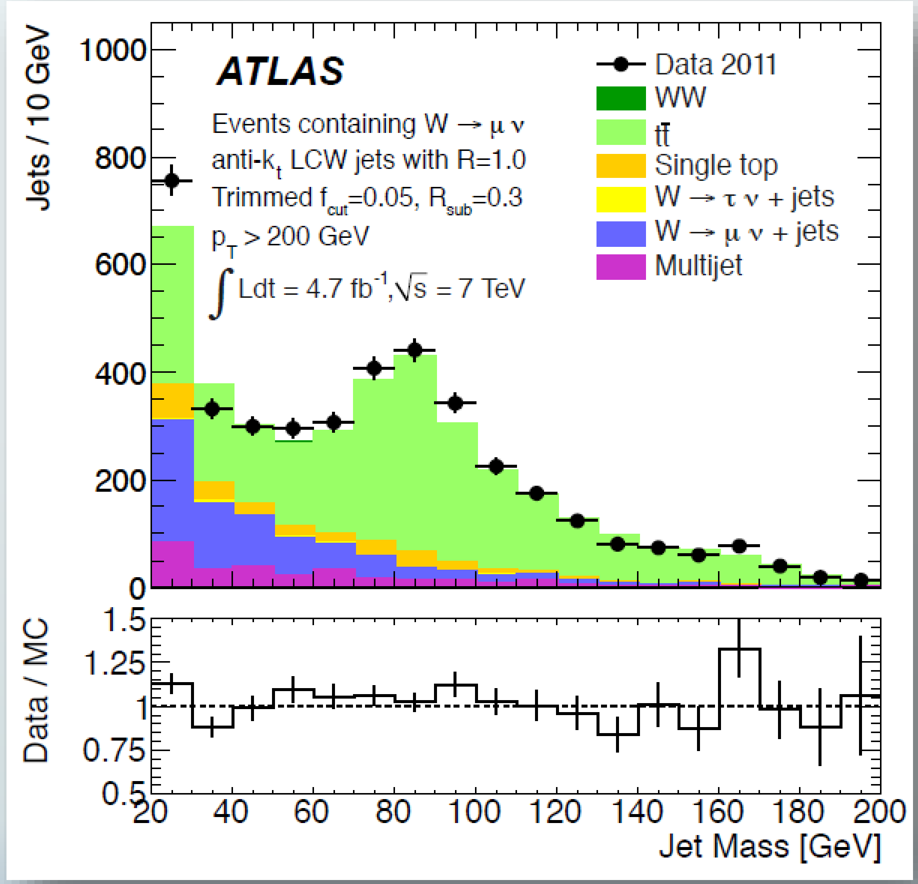
C/A 1.2



Backup

Large-R jet mass scale validation

- JMS in-situ validation: W mass peak in ttbar events



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Backup:

New physics searches at energy frontier

- Searches with boosted objects

Bulk RS $G_{KK} \to ZZ \to qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	G_{KK} mass 740 GeV
Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	2 j / 1 J	Yes	20.3	W′ mass 700 GeV
Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV
Bulk RS $g_{KK} \to t\bar{t}$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV
2UED / RPP	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	KK mass 960 GeV

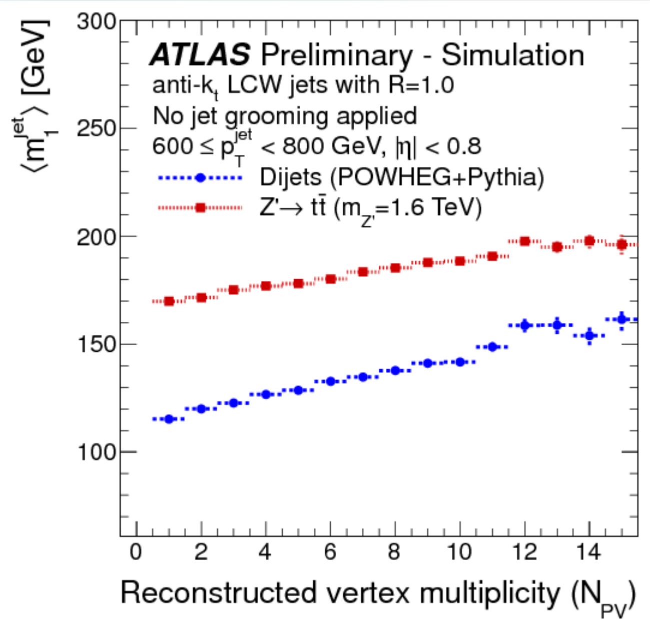
EGM $W' \to WZ \to \ell\nu\, \ell'\ell'$	3 e, μ	–	Yes	20.3	W′ mass 1.52 TeV
EGM $W' \to WZ \to qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	W′ mass 1.59 TeV
HVT $W' \to WH \to \ell\nu bb$	1 e, μ	2 b	Yes	20.3	W′ mass 1.47 TeV
LRSM $W'_R \to t\bar{b}$	1 e, μ	2 b, 0-1 j	Yes	20.3	W′ mass 1.92 TeV
LRSM $W'_R \to t\bar{b}$	0 e, μ	≥ 1 b, 1 J	–	20.3	W′ mass 1.76 TeV

VLQ $TT \to Ht + X, Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	T mass 785 GeV
VLQ $TT \to Zt + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	T mass 735 GeV
VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 755 GeV
VLQ $BB \to Wt + X$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	B mass 640 GeV
$T_{5/3} \to Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV

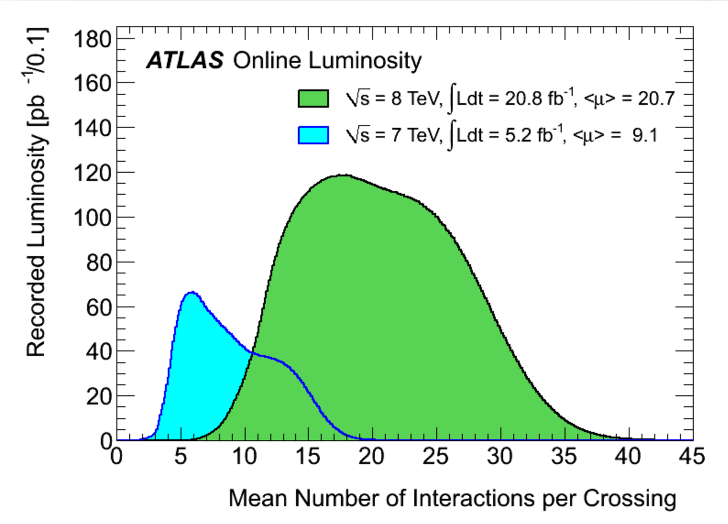
Backup:
Large-R jet grooming

- Large-R jets capture more pile-up noise than small jets
  - Substructures are very sensitive to soft contamination at large angle
- Ever-increasing PU intensity at LHC

jet mass wrt PU in 2011



In 2012 : N_{pv} up to ~40
In 2015 : ???



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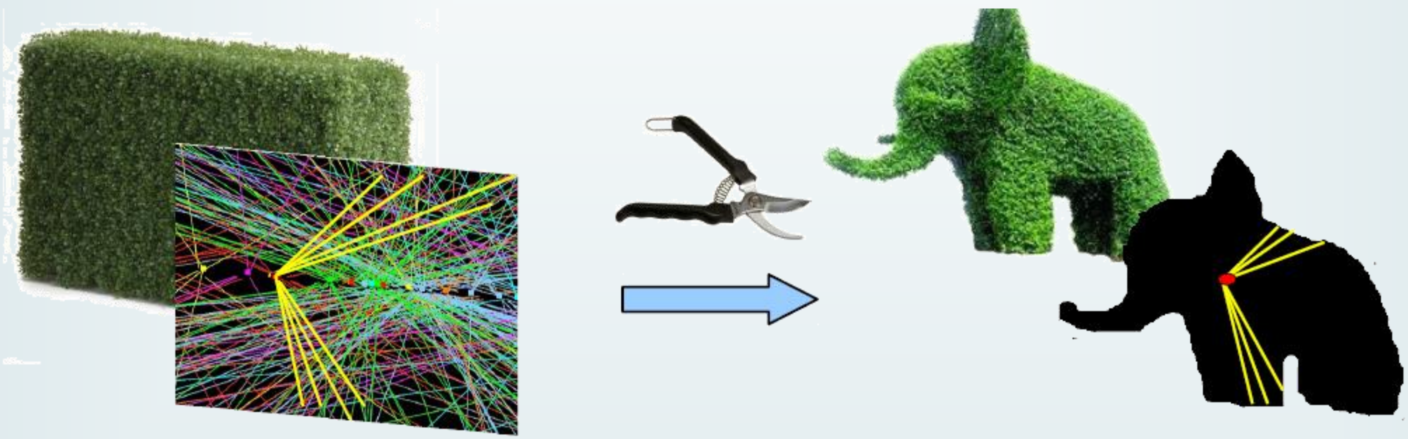
Backup:

Large-R jet grooming

- Algorithms to reduce soft components from UE and PU
  - Jet kinematics more close to the constituents of hard scattering
  - Better resolution/discrimination of the substructure variables



I. **Trimming (adopted in ATLAS)**

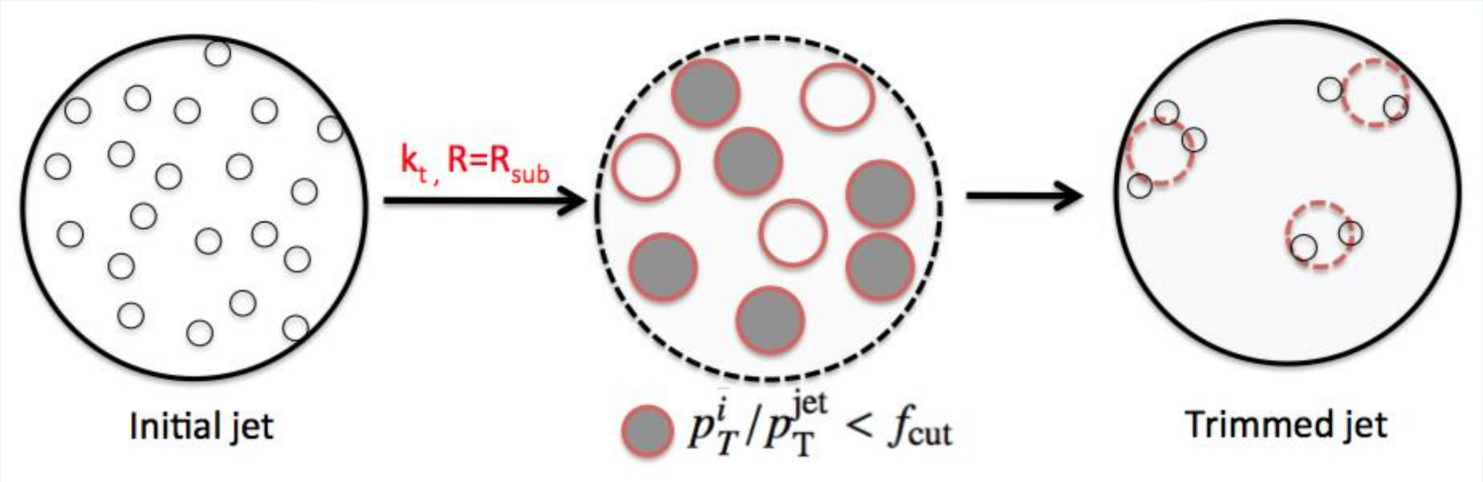
II. Pruning

III. Mass drop/filtering

Backup:
Large-R jet grooming: Trimming

JHEP 1002:084 (2010) D. Krohn, J. Thaler, L.T. Wang

- Use jet constituents to build Kt subjets (e.g. R_{sub}=0.3)
- Remove soft subjets (e.g. *f*=5%)

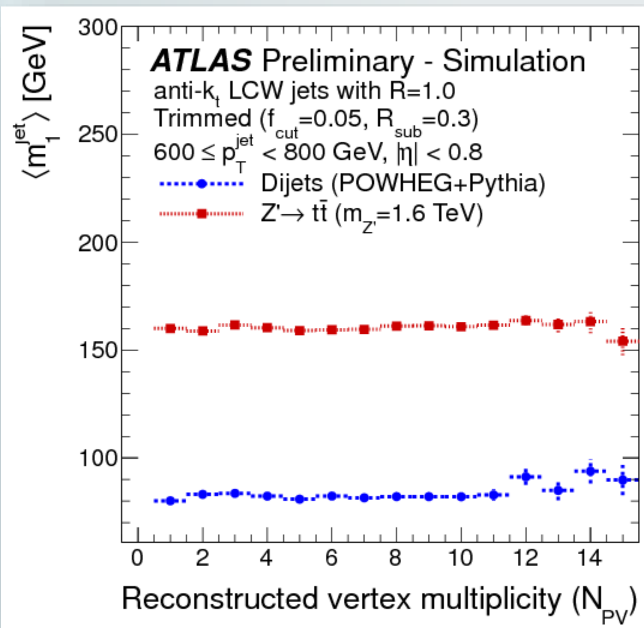


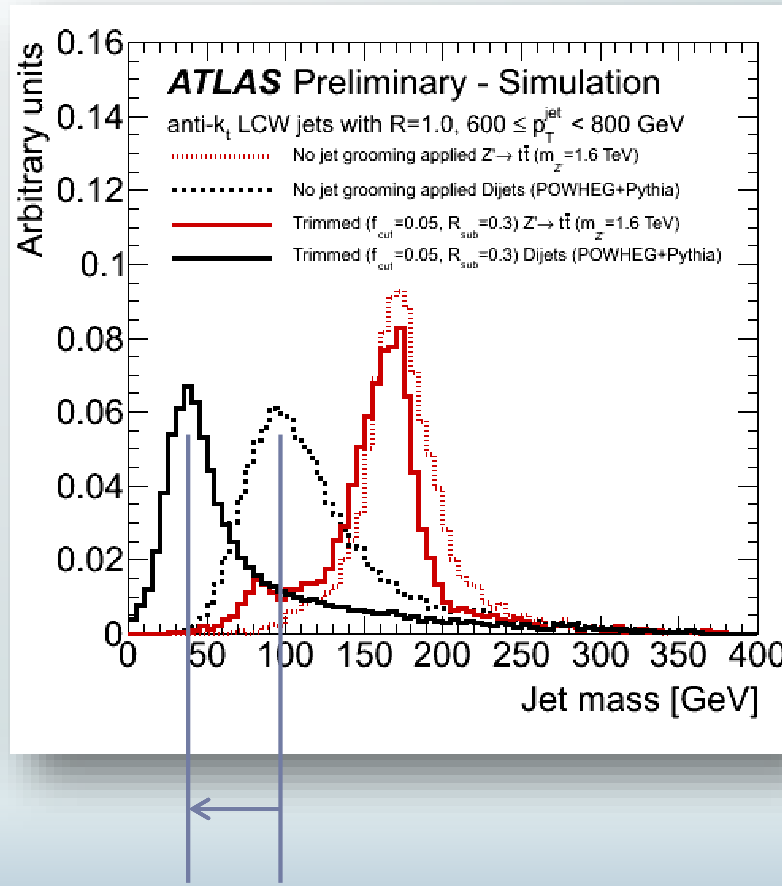
Backup:
Large-R jet grooming: Trimming

Greatly reduce pileup-dependency and restore discriminating power

jet mass wrt PU in 2011

After trimming





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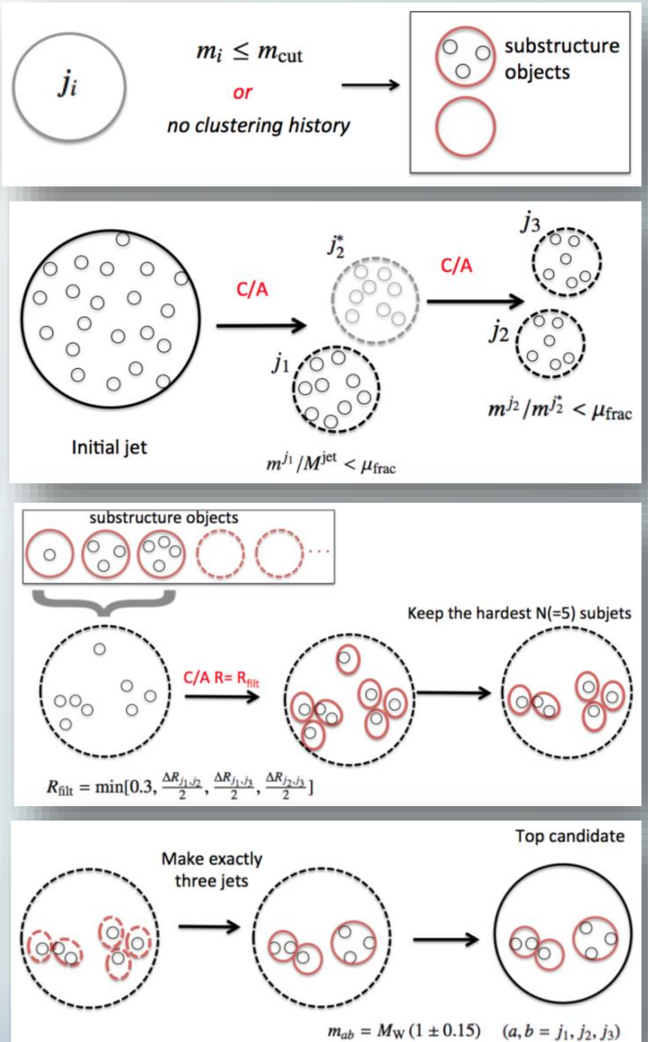
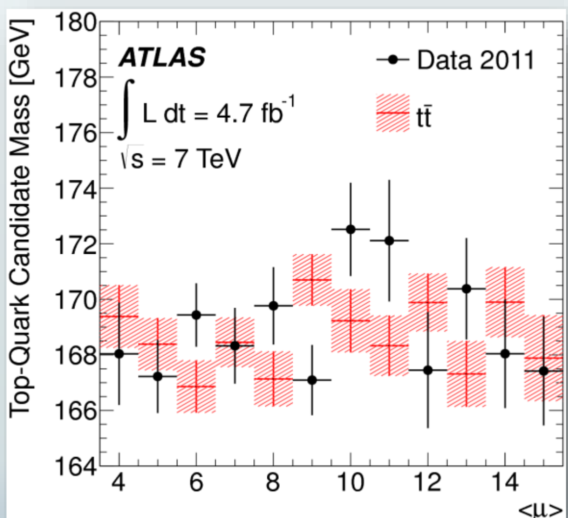
Backup:
Complex taggers: HEPTopTagger

JHEP 1010:078 (2010)
T. Plehn, M. Spannowsky, M. Takeuchi, D. Zerwas

- A multi-step algorithm to identify top-jet
  - Starting from a C/A 1.5 jet
  - Grooming: Mass-drop; Filtering
  - Top and W mass constraints on sub-jets



Robust against pileup



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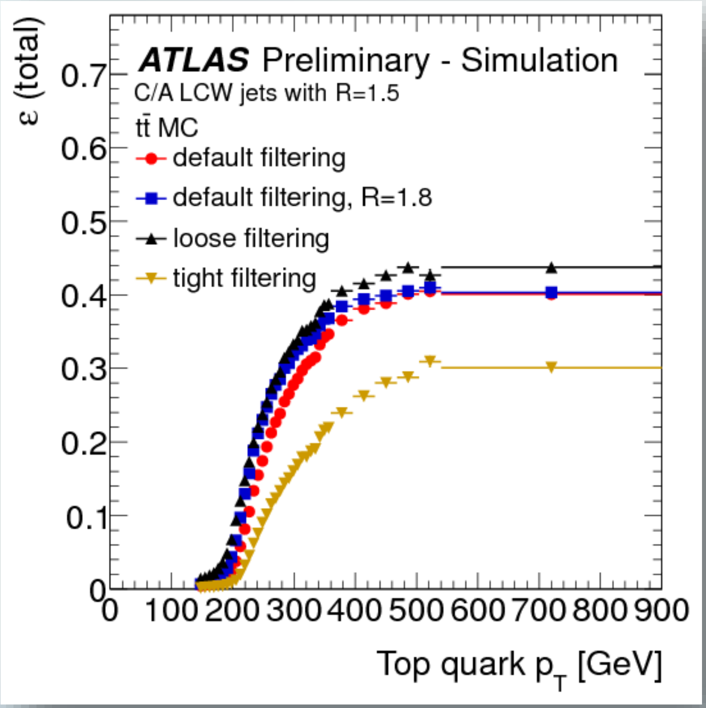
06/07/2015

Backup:

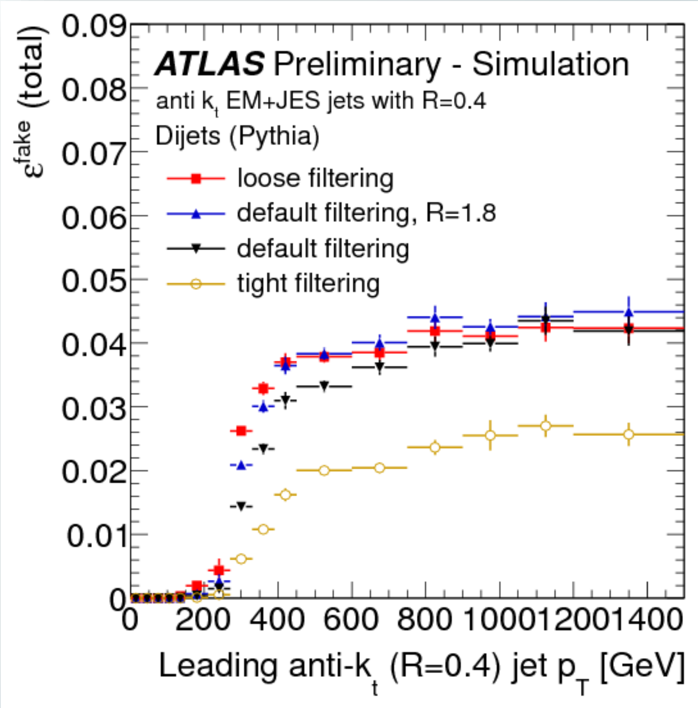
Complex taggers: HEPTopTagger

- Greatly suppress QCD jet background with reasonable signal efficiency

Signal efficiency



Fake rate



Backup:
Complex taggers

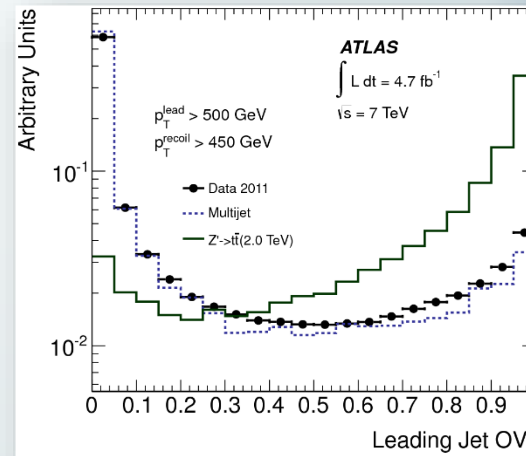
- **Top Template Tagger:**

PRD82,054034(2010); PRD85,114046(2012)
L. G. Almeida, S. J. Lee, G. Perez, et al.

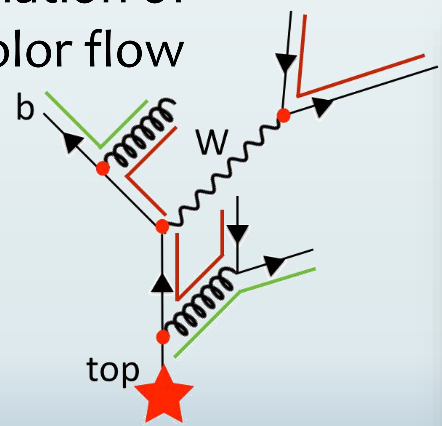
  - Generate templates library based on tops from top decay
  - For each jet candidate, define the overlap function

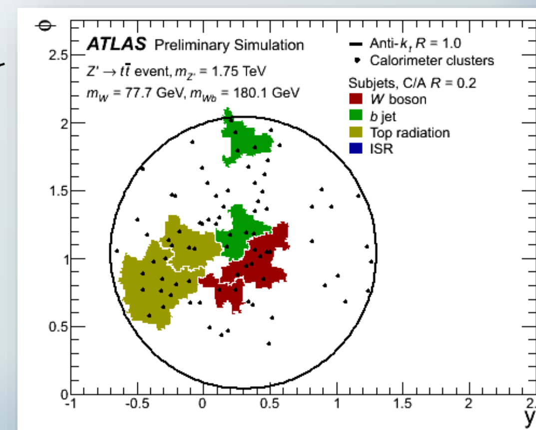
$$OV_3 = \max_{\{\tau_n\}} \exp\left[-\sum_{i=1}^{3} \frac{1}{2\sigma_i^2} \left(E_i - \sum_{\substack{\Delta R(\text{topo},i) \\ <0.2}} E_{\text{topo}} \right)^2 \right]$$

$$\sigma_i = E_i/3$$



- **Shower Deconstruction Tagger:**
  - Algorithm combining information of hard scattering, ISR, FSR, Color flow
  - Discriminant: combined likelihood ratio of the events from S(B) shower histories





Backup:

Ttbar resonance : fully hadronic channel

- Veto events with good lepton (orthogonal to 1-lep analysis)

HepTopTagger

- Two C/A 1.5 jets **p_T>200GeV,** Pass HTT
- b-jets within ΔR=1.4 of each large-R jets

TopTemplateTagger

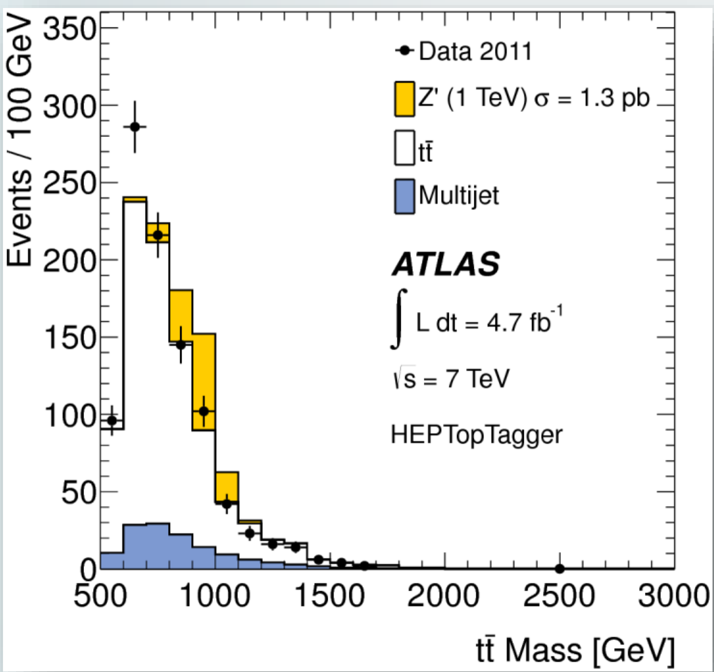
- Two anti-k_T 1.0 jets **p_T^1>500GeV, p_T^2>450GeV,** Pass TTT
- b-jets within ΔR=1.0 of each large-R jets

Model	Total Efficiency (%)	
	HEPTopTagger	Template Tagger
Z' (0.5 TeV)	0.03 ± 0.01	–
Z' (0.8 TeV)	2.96 ± 0.08	–
Z' (1.0 TeV)	4.76 ± 0.09	0.48 ± 0.05
Z' (1.3 TeV)	5.67 ± 0.11	6.37 ± 0.13
Z' (1.6 TeV)	5.40 ± 0.10	8.13 ± 0.16
Z' (2.0 TeV)	4.44 ± 0.10	6.26 ± 0.13
g_{KK} (0.7 TeV)	1.70 ± 0.13	–
g_{KK} (1.0 TeV)	4.13 ± 0.21	0.74 ± 0.10
g_{KK} (1.3 TeV)	5.14 ± 0.23	5.02 ± 0.25
g_{KK} (1.6 TeV)	4.72 ± 0.22	6.43 ± 0.26
g_{KK} (2.0 TeV)	4.44 ± 0.22	5.22 ± 0.21

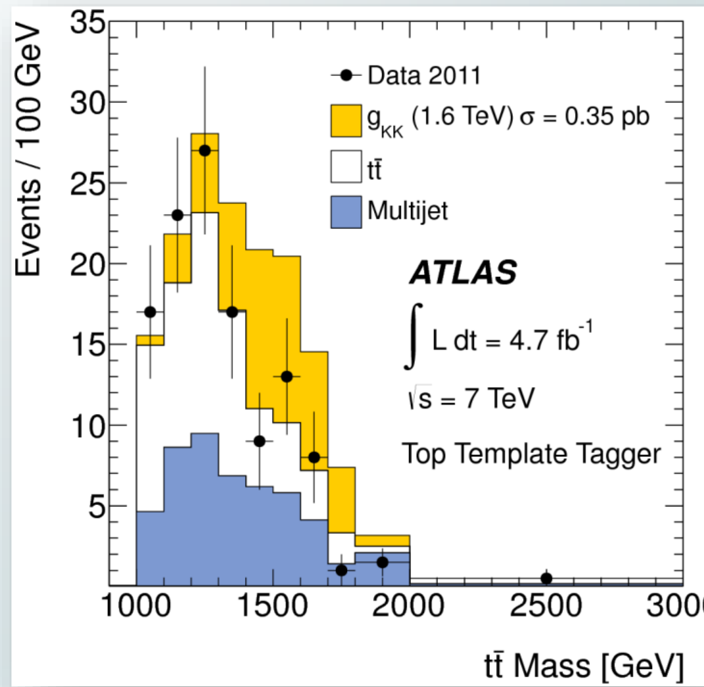
Backup:

Ttbar resonance : fully hadronic channel

- Mtt reconstruction straightforward: j1+j2
- Large multi-jet background



HepTopTagger



TopTemplateTagger

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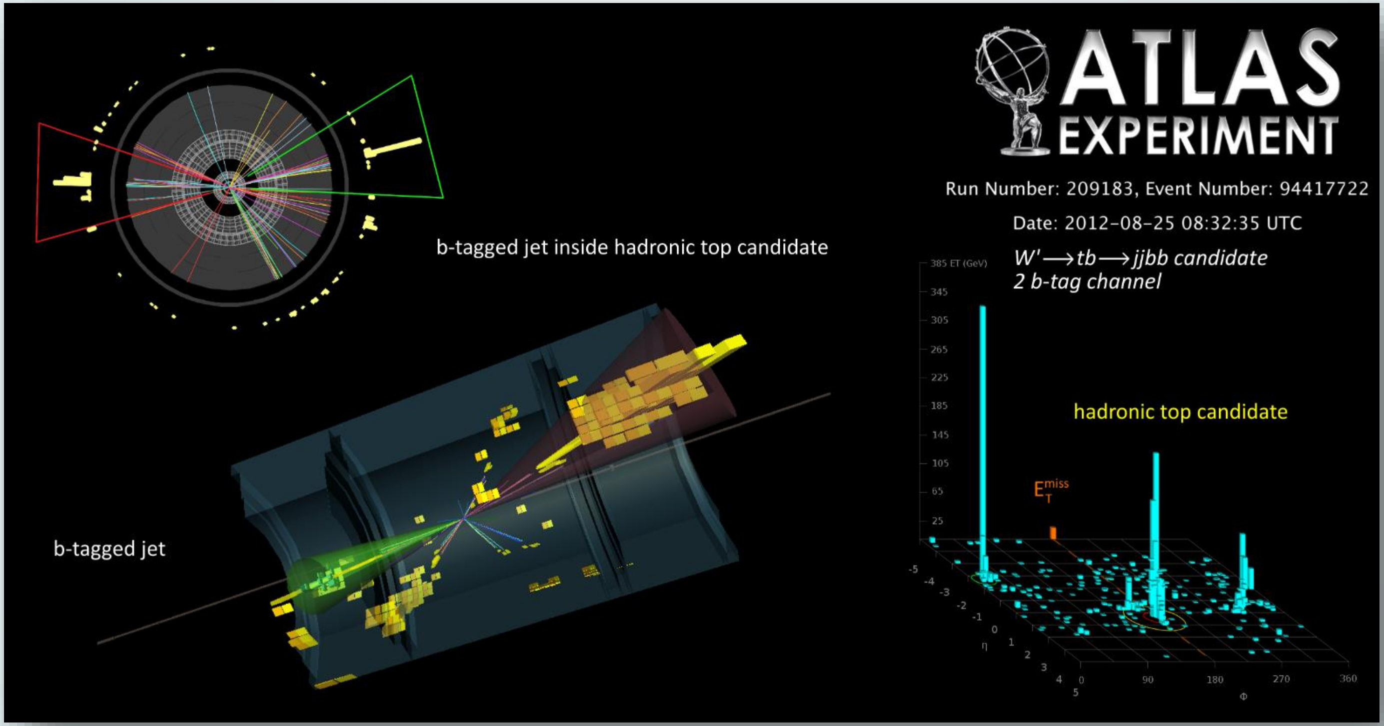
Tb resonance searches

- Leptonic channel
- All hadronic channel
  - Very high pt b-tagged small-R jet + Top tagged large-R jet (splitting scale & nSubjettiness)



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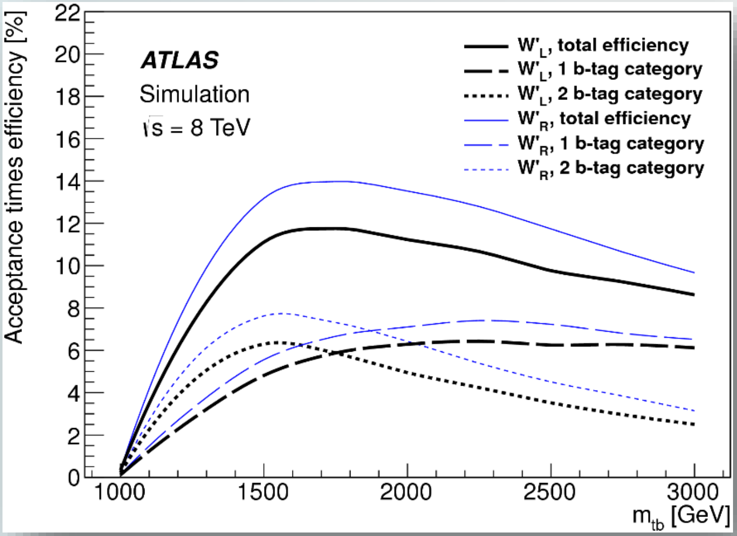
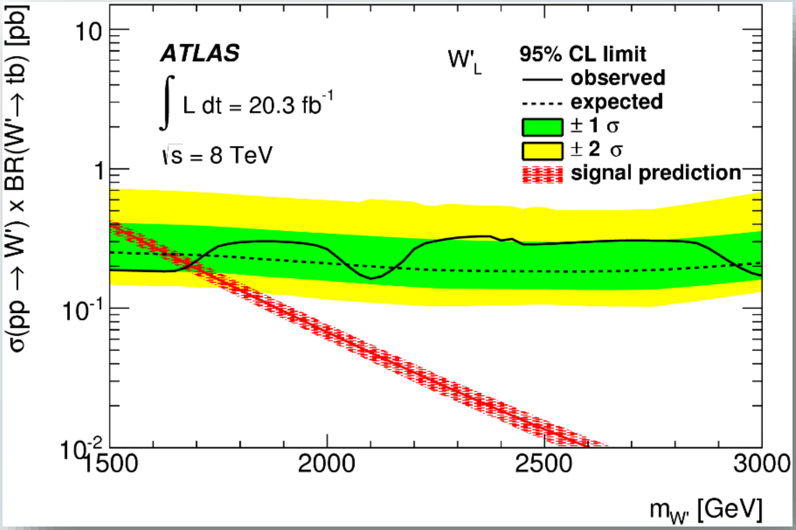
Searches with boosted objects

Tb resonance searches

- b-tagging inefficiency & uncertainties are the major experimental limitations (besides stat)

All-hadronic channel



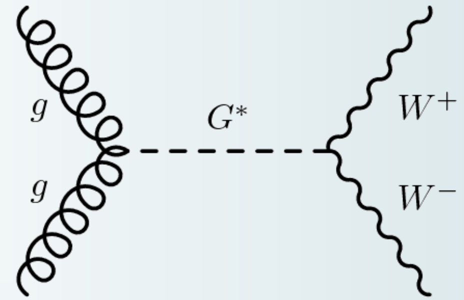


Source	$W'_{\rm R}$ (1.75 TeV)	Background
b-tagging efficiency	27%	6%
Jets	4%	1–4%
Lepton	2%	2–4%
$t\bar{t}$ modelling		8–14%
PDF	9%	3–5%

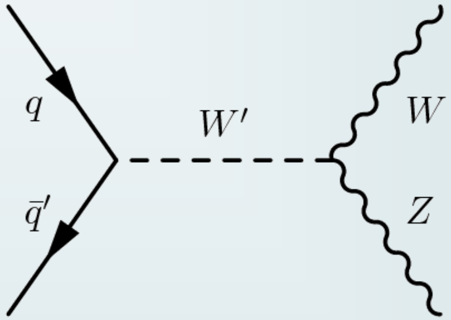
1-lepton channel

Diboson resonance search

- Multiple channels pursued in ATLAS
  - WV->lvjj/lvJ
  - ZV-> lljj/lvJ
  - WZ->lvll
  - VH->ll/lv/vv + bb
  - VV-> JJ all-hadronic
  - HH -> 4b



- Leptonic Z boson identified with special isolation

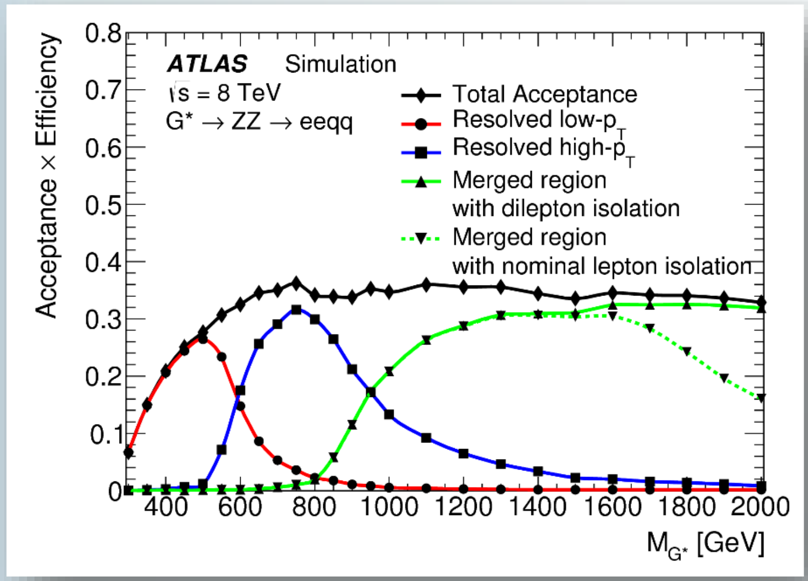


- Hadronic boson
  - 2 small-R jet / 1 large-R jet (depending on boson pt)
  - Mass window on small-R jet pair / large-R jet
  - Further substructure cuts on large-R jet for boson tagging
  - (Boosted) b-tagging for Higgs candidates

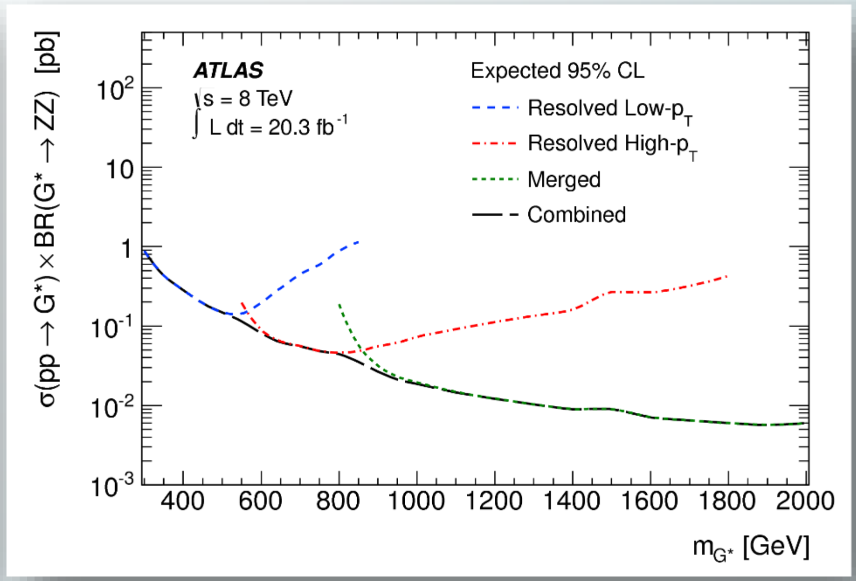
Searches with boosted objects

Diboson resonance search

- Good coverage across mass range achieved by the combination of different strategies



Signal acceptance



Cross-section limits

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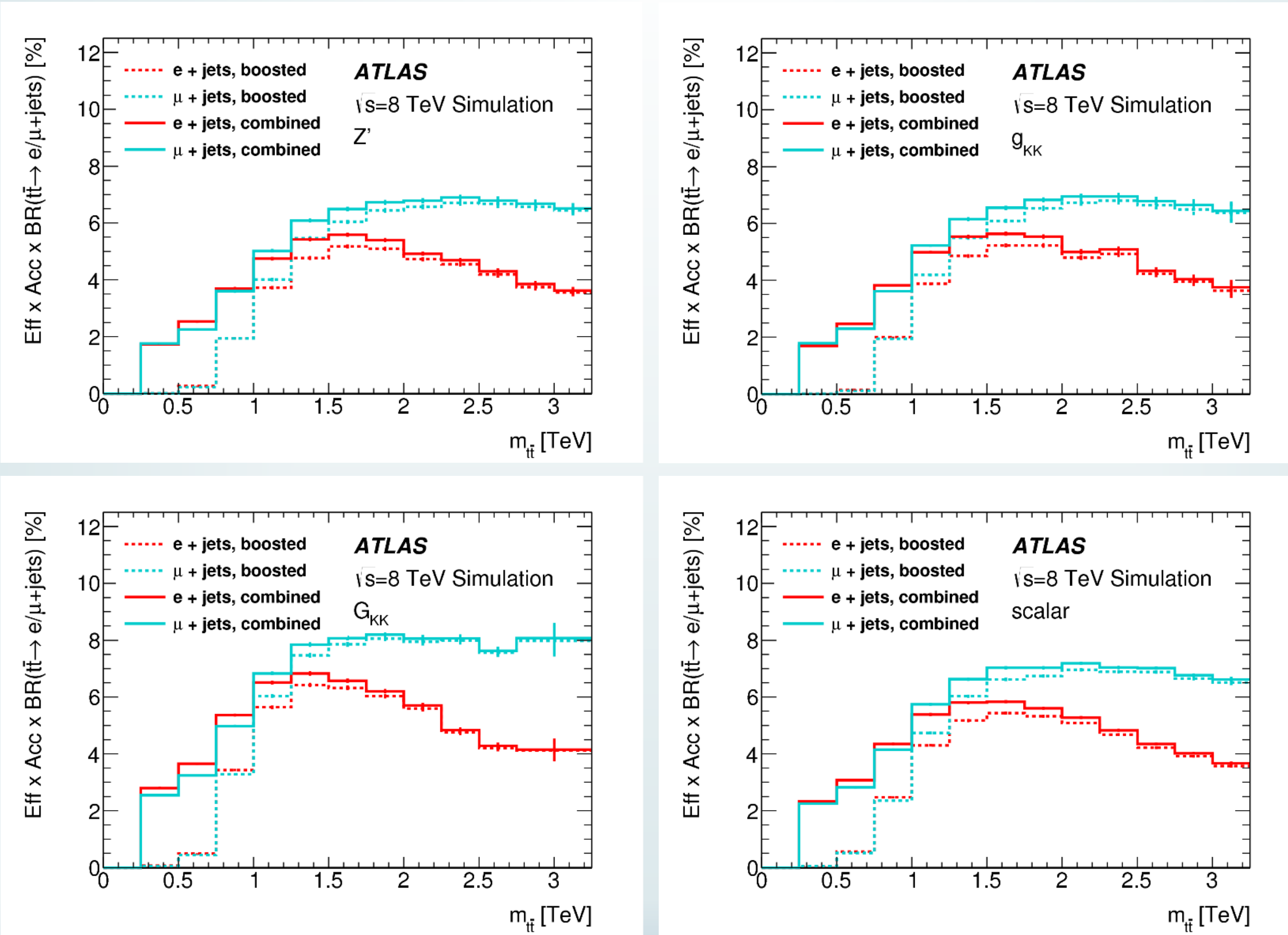
Backup

Ttbar resonance 1-lepton efficiency



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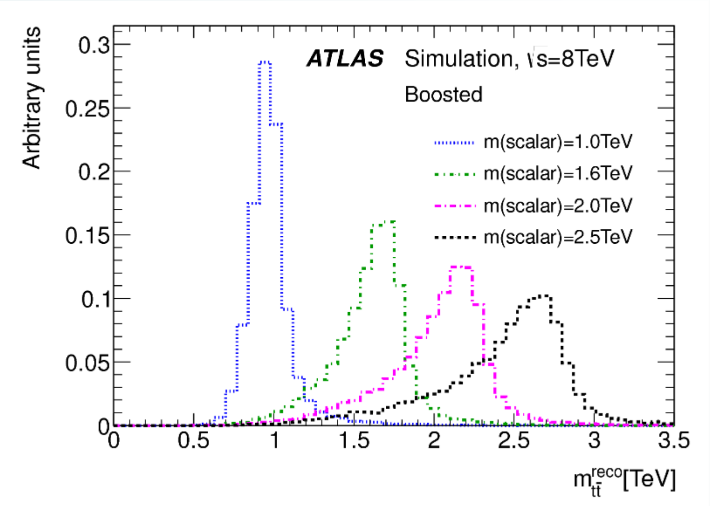
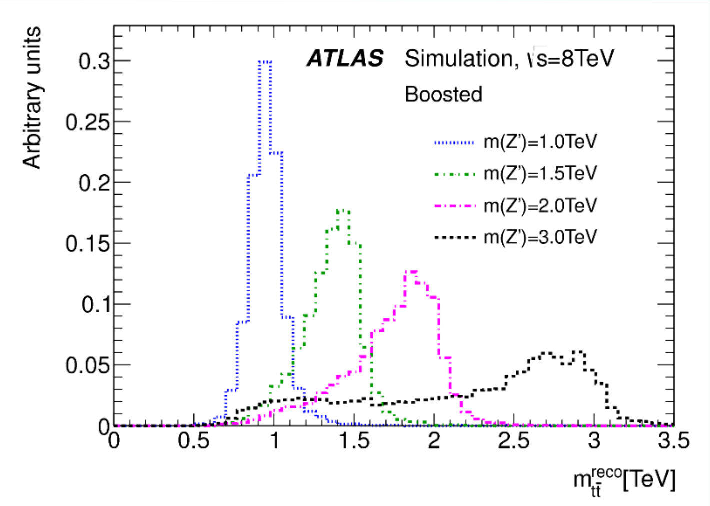
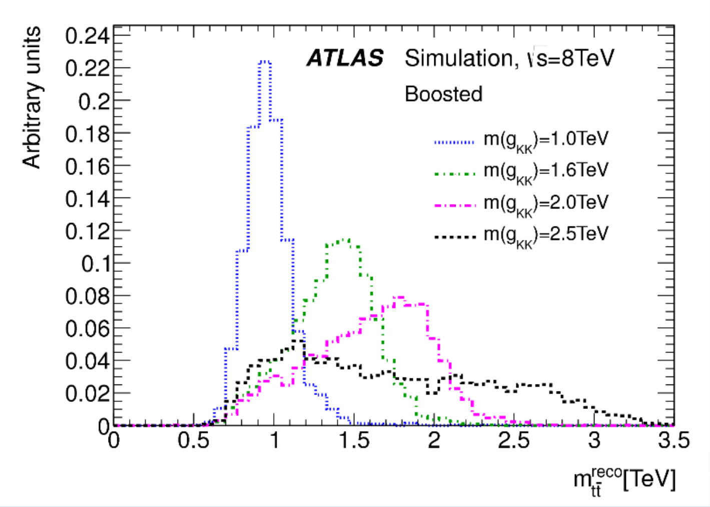
Backup

Ttbar resonance 1-lepton mtt reconstruction





Broader resonance have bigger off-shell production rate in high mass



Backup

2HDM Heavy Higgs interference