Searches for new physics with boosted objects in ATLAS

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- > 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

> ...



06/07/2015

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





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Introduction New physics searches



Number of events Signal (New Physics) **Background (Standard Model)**

Discriminant

Introduction New physics searches





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Introduction New physics searches





Introduction New physics searches at energy frontier

AILAS EXOLICS	Searches*	- 95%	% CL	xclusion	ATL	4S Preliminar
Status: March 2015		r mier			$\int \mathcal{L} dt$ = (1.0 - 20.3) fb $^{-1}$	\sqrt{s} = 7, 8 TeV
Model	ℓ, γ Jets	3 E ^{miss}	'∫£dt[fl	Mass limit		Reference
$\begin{array}{c} \text{ADD } \mathcal{G}_{KK} + g/q \\ \text{ADD non-resonant } \ell\ell \\ \text{ADD OBH} \to \ell q \\ \text{ADD OBH} \to \ell q \\ \text{ADD OBH high Netk} \\ \text{ADD BH high Netk} \\ \text{ADD BH high Nullist} \\ \text{ADD BH high Nullist} \\ \text{RSI } \mathcal{G}_{KK} \to \ell\ell \\ \text{RSI } \mathcal{G}_{KK} \to \ell\ell \\ \text{Bulk RS } \mathcal{G}_{KK} \to 2Z \to q\ell\ell\ell \\ \text{Bulk RS } \mathcal{G}_{KK} \to WW \to qq\ell \\ \text{Bulk RS } \mathcal{G}_{KK} \to \ell\bar{t} \\ \end{array}$	$\begin{array}{cccc} - & \geq 1 \\ 2e, \mu & - \\ 1 & e, \mu & 1 \\ - & 2j \\ 2\mu(SS) & - \\ \geq 1 & e, \mu & \geq 2 \\ 2 & e, \mu & - \\ 2 & 2e, \mu & - \\ 2 & e, \mu & 2j/1 \\ - & - & 4b \\ 1 & e, \mu & 2j/1 \\ - & - & 4b \\ 1 & e, \mu & \geq 1 & b, \\ 2 & e, \mu(SS) \geq 1 & b, \end{array}$	j Yes – – j – j – J – J – J – J – 1J/2j Yes ≥ 1 j Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3	0 5.25 Te 3 4.7 TeV 14 5.2 Te 15 5.82 16 5.85 16 5.85 16 5.85 16 5.85 16 5.8	$ \begin{array}{llllllllllllllllllllllllllllllllllll$	1502.01518 1407.2410 1311.2006 1407.1376 1308.4075 1405.4254 Preliminary 1405.4123 Preliminary 1409.6190 1500.01677 ATLAS-CONF-2015-00 Preliminary
$\begin{array}{c} \text{SSM } Z' \rightarrow \ell\ell \\ \text{SSM } Z' \rightarrow \tau\tau \\ \text{SSM } W' \rightarrow \delta\tau \\ \text{SSM } W' \rightarrow \delta\tau \\ \text{EGM } W' \rightarrow WZ \rightarrow \ell\tau\ell\ell' \\ \text{EGM } W' \rightarrow WZ \rightarrow qq\ell\ell \\ \text{HVT } W' \rightarrow WH \rightarrow \delta\tau bb \\ \text{LRSM } W_R' \rightarrow t\bar{b} \\ \text{LRSM } W_R' \rightarrow t\bar{b} \end{array}$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	– Yes J – Yes 1 Yes 1 J –	20.3 19.5 20.3 20.3 20.3 20.3 20.3 20.3	mass 2.9 TeV mass 2.02 TeV '' mass 3.24 TeV '' mass 1.52 TeV '' mass 1.59 TeV '' mass 1.29 TeV '' mass 1.92 TeV '' mass 1.76 TeV	$g_V = 1$	1405.4123 1502.07177 1407.7494 1406.4456 1409.6190 Preliminary 1410.4103 1408.0886
CI qqqq CI qqℓℓ CI uutt	$\begin{array}{ccc} - & 2 \mathrm{j} \\ 2 e, \mu & - \\ 2 e, \mu (\mathrm{SS}) \geq 1 \mathrm{b}, \end{array}$	_ ≥1jYes	17.3 20.3 20.3	4.35 TeV	12.0 TeV $\eta_{LL} = -1$ 21.6 TeV $\eta_{LL} = -1$ $ C_{LL} = 1$	Preliminary 1407.2410 Preliminary
EFT D5 operator (Dirac) EFT D9 operator (Dirac)	$egin{array}{ccc} {\sf 0} \ e, \mu & \geq 1 \ {\sf 0} \ e, \mu & {\sf 1} \ {\sf J}, \leq \end{array}$	j Yes 1j Yes	20.3 20.3	. 974 GeV . 2,4 TeV	at 90% CL for $m(\chi) < 100$ GeV at 90% CL for $m(\chi) < 100$ GeV	1502.01518 1309.4017
Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen	$\begin{array}{ccc} 2 \ e & \geq 2 \\ 2 \ \mu & \geq 2 \\ 1 \ e, \mu, 1 \ \tau & 1 \ b, \end{array}$	j – j – Ij –	1.0 1.0 4.7	D mass 660 GeV D mass 685 GeV D mass 534 GeV	$\begin{array}{l} \beta = 1 \\ \beta = 1 \\ \beta = 1 \end{array}$	1112.4828 1203.3172 1303.0526
$\begin{array}{c} \text{VLQ } TT \rightarrow Ht + X, Wb + X \\ \text{WLQ } TT \rightarrow Zt + X \\ \text{VLQ } BB \rightarrow Zb + X \\ \text{VLQ } BB \rightarrow Wt + X \\ \text{T}_{5/3} \rightarrow Wt \end{array}$	$\begin{array}{c c} 1 \ e, \mu & \geq 1 \ b, \\ 2l \geq 3 \ e, \mu & \geq 2l \geq \\ 2l \geq 3 \ e, \mu & \geq 2l \geq \\ 1 \ e, \mu & \geq 1 \ b, \\ 1 \ e, \mu & \geq 1 \ b, \end{array}$	≥3j Yes b – b – ≥5j Yes ≥5j Yes	20.3 20.3 20.3 20.3 20.3 20.3	mass 785 GeV mass 735 GeV mass 755 GeV mass 640 GeV w3 mass 840 GeV	isospin singlet T in (T,B) doublet B in (B,Y) doublet isospin singlet	ATLAS-CONF-2015-012 1409.5500 1409.5500 Preliminary Preliminary
$ \begin{array}{c} & \mbox{Excited quark } q^* \rightarrow q\gamma \\ \hline \begin{tabular}{lllllllllllllllllllllllllllllllllll$	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	– or1jYes –	20.3 20.3 4.7 13.0 20.3	mass 3.5 TeV mass 4.09 TeV mass 870 GeV mass 2.2 TeV mass 1.6 TeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ left-handed coupling $\Lambda = 2.2$ TeV $\Lambda = 1.6$ TeV	1309.3230 1407.1376 1301.1583 1308.1364 1411.2921
$\label{eq:starsess} \begin{array}{c} \text{LSTC} a_T \to W\gamma \\ \text{LRSM} \text{Majorana} \nu \\ \text{Higgs triplet} H^{\pm\pm} \to \ell\ell \\ \text{Higgs triplet} H^{\pm\pm} \to \ell\tau \\ \text{Monotop (non-res prod)} \\ \text{Multi-charged particles} \end{array}$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Yes - - Yes -	20.3 2.1 20.3 20.3 20.3 20.3	mass 960 GeV mass 1.5 TeV ** mass 551 GeV ** mass 400 GeV in-1 invisible particle mass 657 GeV ulti-charged particle mass 785 GeV	$m(W_S) = 2$ TeV, no mixing DY production, $BR(H_L^{\pm\pm} \rightarrow \ell \ell) = 1$ DY production, $BR(H_L^{\pm\pm} \rightarrow \ell \tau) = 1$ $a_{80n-460} = 0.2$ DY production, $ a = 5 = 0$	1407.8150 1203.5420 1412.0237 1411.2921 1410.5404 Preliminary
	Status: March 2015 Model ADD $G_{KX} + g/q$ ADD non-resonant $\ell\ell$ ADD OBH - ℓq ADD OBH - ℓq ADD BH high Σp ADD BH high Σp BI SSM Z' $\rightarrow \ell \ell$ SSM Z' $\rightarrow \ell \ell$ EGM W' $\rightarrow WZ \rightarrow d\mu \ell \ell'$ EGM W' $\rightarrow WZ \rightarrow d\mu \ell' \ell'$ EGM U' $\rightarrow WZ \rightarrow d\mu \ell' \ell' \ell'$ EGM U' $\rightarrow UZ \rightarrow d\mu \ell' \ell' \ell' \ell'$ EGM U' $\rightarrow UZ \rightarrow d\mu \ell' \ell' \ell' \ell'$ EGM U' $\rightarrow UZ \rightarrow d\mu \ell' \ell' \ell' \ell'$ EGM U' $\rightarrow UZ \rightarrow d\mu \ell' \ell' \ell' \ell'$ EGM U' $\rightarrow UZ \rightarrow d\mu \ell' \ell' \ell' \ell'$ EGM U' $\rightarrow UZ \rightarrow d\mu \ell' \ell' \ell' \ell'$ Higs triplet $\ell^{+\mu} \rightarrow \ell'$ Higs triplet $\ell^{+\mu} \rightarrow \ell'$ Higs triplet $\ell^{+\mu} \rightarrow \ell'$	Status: March 2015 Model ℓ, γ Jeta ADD $G_{KK} + g/q$ $- \geq 1$ ADD $OBH - \ell q$ $1e, \mu$ $1j$ ADD $OBH - \ell q$ $1e, \mu$ $1j$ ADD $OBH - \ell q$ $1e, \mu$ $1j$ ADD $BH high N_{tk}$ $2\mu(SS)$ $-$ ADD $BH high \Sigma p_T$ $\geq 1e, \mu \geq 2$ ADD $BH high \Sigma p_T$ $2 = \ell, \mu \geq 2$ ADD $BH high N_{tk}$ $2\mu(SS)$ $-$ Bulk RS $G_{KK} \rightarrow \ell\ell$ $2e, \mu$ $2j/1$ Bulk RS $G_{KK} \rightarrow \ell\ell$ $1e, \mu$ $-2b, 2e, \mu$ (SS) $\geq 1b, 3$ $2ED / RPP$ $2e, \mu(SS) \geq 1b, 3$ $2ED / RPP$ $2e, \mu(SS) \geq 1b, 3$ $1e, \mu \geq 2b, 2e, \mu$ $2b, 2e, 2e, 2e, 2e, 2e, 2e, 2e, 2e, 2e, 2e$	Status: March 2015Model ℓ, γ Jets E_T^{miss} ADD $G_{KK} + g/q$ $ \geq 1j$ YesADD OBH $\neq q$ $1 e, \mu$ $1j$ $-$ ADD OBH $\neq q$ $1 e, \mu$ $1j$ $-$ ADD BH high N_{tk} $2\mu(SS)$ $ \geq 2j$ ADD BH high N_{tk} $2e, \mu$ $2i + \mu \geq 2j$ $-$ ADD BH high N_{tk} $2e, \mu$ $2e, \mu$ $-$ ADD BH Nigh N_{tk} $2e, \mu$ $2e, \mu$ $-$ Bil $G_{KK} \rightarrow \ell\ell$ $2e, \mu$ $2e, \mu$ $-$ Buk RS $G_{KK} \rightarrow \ell\ell$ $2e, \mu$ $2e, \mu$ $-$ Buk RS $G_{KK} \rightarrow \ell\ell$ $2e, \mu$ $2e, \mu$ $-$ Buk RS $G_{KK} \rightarrow \ell\ell$ $2e, \mu$ $ -$ SSM $Z' \rightarrow \ell\ell$ $2e, \mu$ $ -$ SSM $W' \rightarrow VZ \rightarrow qq\ell\ell$ $2e, \mu$ $ -$ SSM $W' \rightarrow VZ \rightarrow qq\ell\ell$ $2e, \mu$ $2i + J/2$ $-$ SSM $W' \rightarrow VZ \rightarrow qq\ell\ell$ $2e, \mu$ $2i + J/2$ $-$ SSM $Z' \rightarrow d\ell$ $2e, \mu$ $2i + J/2$ $-$ SSM $Z' \rightarrow d\ell$ $2e, \mu$ $2i + J/2$ $-$ SSM $Z' \rightarrow d\ell$ $2e, \mu$ $2i + J/2$ $-$ SSM $W' \rightarrow UZ \rightarrow qq\ell\ell$ <	Status: March 2015 Model ℓ, γ Jets \mathbf{F}_{T}^{miss} $f\mathcal{L} dt[fb^{-1}]$ ADD $G_{KK} + g/q$ $ \geq 1$ Yes 20.3 M ADD OBH + ℓq $1e, \mu$ 1 $ \geq 2i$ $ \geq 23.3$ M ADD OBH + ℓq $1e, \mu$ 1 $ \geq 2i$ $ \geq 20.3$ M ADD BH high N_{trk} $2\mu(SS)$ $ \geq 23.3$ M AD ADD BH high N_{trk} $2\mu(SS)$ $ \geq 23.3$ M ADD BH high N_{trk} $2\mu(SS)$ $ \geq 23.3$ M M ADD BH high N_{trk} $2\mu(SS)$ $ \geq 23.3$ M Bulk RS $G_{KK} \rightarrow WW - qrdv$ $2e, \mu$ $ \geq 23.3$ M $=$ $= 23.$	Status: March 2015 Model (4, γ Jets Erris f/C dt(fb^-1) Mass limit ADD Gord + E(q) 2 + β No. 4 + β ADD Gord + E(q) 2 + β No. 4 + β ADD Gord + E(q) 2 + β No. 4 + β ADD BH High Corp + 2 2 + β No. 4 + β ADD BH High Corp + 2 2 + β No. 4 + β No. 4 + β ADD BH High Corp + $d\ell$ 2 + β 3 + β Mass 2 + β 3 + β ADD BH High Corp + $d\ell$ 2 + β Mass 3 + β Mass 2 + β 2 +	Status: March 2015 $\int \mathcal{L} dt = (1, 0, -20, 0) \text{ b}^{-1}$ Status: March 2015 $\int \mathcal{L} dt = (1, 0, -20, 0) \text{ b}^{-1}$ Model $\int \mathcal{L} dt = (1, 0, -20, 0) \text{ b}^{-1}$ Model $\int \mathcal{L} dt = (1, 0, -20, 0) \text{ b}^{-1}$ ADD Grap + Erig $\mathcal{L} = 0$ March $\mathcal{L} = 0$

Signal (New Physics) Background (Standard

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Outline



- Introduction
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 - 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

Reconstruction & Identification of Boosted Objects 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

Reconstruction & Identification of Boosted Objects Lepton isolation (Z->II)

Lepton pairs from boosted Z boson highly collimated

Special isolation treatment to subtract contribution from the other lepton



Reconstruction & Identification of Boosted Objects Lepton isolation (leptonic top)

Lepton and b-jet from boosted top become highly collimated



Reconstruction & Identification of Boosted Objects Lepton isolation (leptonic top)

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



Variable cone size

 $\Delta R = k_T / p_T^{lepton}$, $k_T = 10 \text{ GeV}$

- > $I_{mini} = \sum P_T$ of tracks within (excluding the track of the lepton)
- > Require $I_{mini} / p_T^{lepton} < 0.05$

Reconstruction & Identification of Boosted Objects Lepton isolation (leptonic top)

> Recover efficiency for highly boosted top



Z' 1.0 TeV

Z' 2.0 TeV

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

Better acceptance when jets get merged W Boost Reduce combinatorial backgrounds hadronic top candidate leptonic top candidate hadronic top candidate eptonic top candidate

Jet mass

Simple 4-vector sum of jet constituents Calorimeter clusters, charged tracks, truth particles, ...

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

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



Jet splitting scale

> Re-cluster jet constituents with K_T algorithm

PRD65, 096014 (2002) Butterworth, Cox, Forshaw

- Starting from softest constituents to hardest
- Observable: the splitting scale in the last step(s) of clustering

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



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N-subjettiness ($\tau_{\rm N}$)

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

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

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

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



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V QJets

¥۷,

 μ_{12}

Width

1d12

τ₂₁

nvtx

N(vtx)

Mass

Jet Mass

Planar Flow

And more ...

. . .

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



Optimal choice for analysis not always obvious

vs=8 TeV

Trimmed

 $|\eta^{\text{TRUTH}}| < 1.2$

Width

M(j_)^{RECO} Window

Sample : W jets **ATLAS** Simulation Preliminary

anti-k_T jets with R=1.0

 $200 < p_{-}^{TRUTH} < 350 \text{ GeV}$

×,

100

80

60

40

20

0

-20

-40

-60

-80

-100

> Topology-dependent applicability

-33

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

And more complex taggers invented ...

Reconstruction & Identification of Boosted Objects Top Taggers Comparison



Reconstruction & Identification of Boosted Objects Boson Taggers Comparison



 p_T - dependent Substructure performances

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- "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



- > 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)



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jet axis

- 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

- 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 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 <u>1-lepton channel</u>
 - Complemented by <u>all-hadronic channel</u>



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</p>
- >=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





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



!! Not on same footing for comparison

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Top pair resonance searches Recasting facility



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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



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Backup Large-R jet substructure

Jet splitting scale



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

- If the distance between the subjets is large, Vd_{12} is large.
- If the softer of the two subjets in the last clustering has high pT, then Vd_{12} is large.
- Both these things indicate large Vd_{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

Backup 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
 - Compare the ratio from data vs. MC



C/A 1.2

Anti- K_T 1.0



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Backup Large-R jet mass scale validation

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



Backup: New physics searches at energy frontier



Bulk DC C	2	0:711		00.0	C	740.0-14	
Durk RS $G_{KK} \rightarrow ZZ \rightarrow qqtt$	$2 e, \mu$	2]/]	_	20.3	G _{KK} mass	740 Gev	
Bulk RS $G_{KK} \to WW \to qq\ell v$	$1 e, \mu$	2j/1J	Yes	20.3	W' mass	700 GeV	
Bulk RS $G_{K\!K} o H\!H o bar{b}bar{b}$	_	4 b	_	19.5	G _{KK} mass	590-710 GeV	
Bulk RS $g_{{ m K}{ m K}} ightarrow tar t$	$1 e, \mu$	≥ 1 b, ≥ 1 J/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 <i>e</i> , μ	_	Yes	20.3	W' mass	1.5	52 TeV
EGM $W' o WZ o qq\ell\ell$	2 e,μ	2j/1J	—	20.3	W' mass	1.	59 TeV
HVT $W' \to WH \to \ell \nu bb$	$1~e,\mu$	2 b	Yes	20.3	W' mass	1.4	7 TeV
LRSM $W_{\scriptscriptstyle R}^\prime ightarrow t \overline{b}$	$1~e,\mu$	2 b, 0-1 j	Yes	20.3	W' mass		1.92 TeV
LRSM $W_R^{'\prime} ightarrow t \overline{b}$	0 e, µ	≥ 1 b, 1 J	—	20.3	W' mass		1.76 TeV
VLQ $TT \rightarrow Ht + X, Wb + X$	1 e,µ	≥ 1 b, ≥ 3 j	Yes	20.3	T mass	785 GeV	
VLQ $TT \rightarrow Zt + X$	2/≥3 e, µ	≥2/≥1 b	_	20.3	T mass	735 GeV	
VLQ BB o Zb + X	2/≥3 e, μ	≥2/≥1 b	_	20.3	B mass	755 GeV	
VLQ BB o Wt + X	$1 e, \mu$	≥ 1 b, ≥ 5 j	Yes	20.3	B mass	640 GeV	
$T_{5/3} \rightarrow Wt$	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



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



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



Backup: Complex taggers: HEPTopTagger

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

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



Robust against pileup

 $m_i \leq m_{\rm cut}$

no clustering history

C/A

Ji

substructure

objects

0

C/A

Backup: Complex taggers: HEPTopTagger

Greatly suppress QCD jet background with reasonable signal efficiency



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

- > Two anti- k_{T} 1.0 jets **p_T¹>500GeV, p_T²>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			
$g_{\rm KK}$ (0.7 TeV)	1.70 ± 0.13	_			
$g_{\rm KK}$ (1.0 TeV)	4.13 ± 0.21	0.74 ± 0.10			
$g_{\rm KK}$ (1.3 TeV)	5.14 ± 0.23	5.02 ± 0.25			
$g_{\rm KK}$ (1.6 TeV)	4.72 ± 0.22	6.43 ± 0.26			
$g_{\rm KK}$ (2.0 TeV)	4.44 ± 0.22	5.22 ± 0.21			

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Backup: Ttbar resonance : fully hadronic channel

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



Searches with boosted objects Tb resonance searches

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



Searches with boosted objects Tb resonance searches

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



All-hadronic channel

Source	$W'_{\rm R} \ (1.75 \ {\rm TeV})$	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

Searches with boosted objects Diboson resonance search

- Multiple channels pursued in ATLAS
 - ≻ WV->lvjj/lvJ
 - > ZV-> lljj/lvJ
 - > WZ->lvll
 - > VH->II/Iv/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



Backup Ttbar resonance 1-lepton efficiency



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Backup **Ttbar resonance 1-lepton mtt reconstruction**





ATLAS Simulation, vs=8TeV

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

Backup 2HDM Heavy Higgs interference

