Sensitivity to New High-Mass States Decaying to ttbar at a 100 TeV Collider: Lessons learned about high-p_T top-quarks from MC Studies

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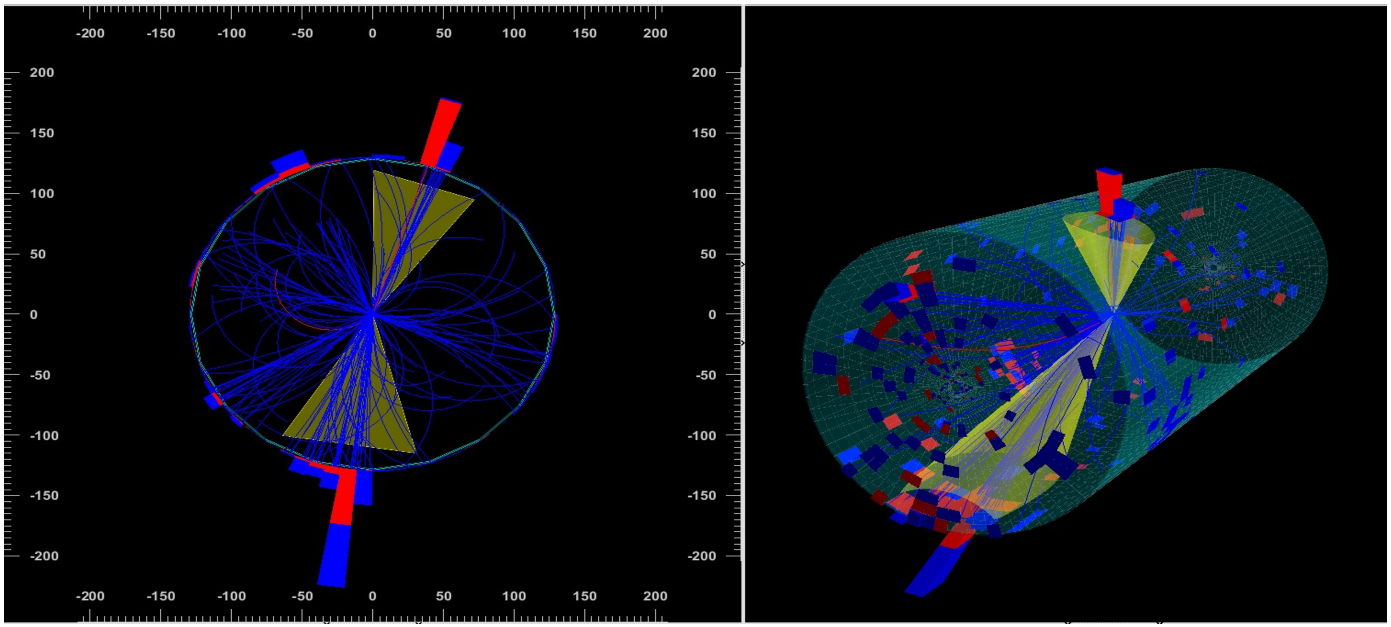
J. Proudfoot, A. V. Kotwal

Motivation

- MC Truth-level study of the sensitivity of new high mass states decaying to ttbar at a 100 TeV Collider
  - Extract model independent limits for observation of a generic resonance with 10 ab^{-1} of 100 TeV pp collisions
    - Using Z' and g_{kk} as signal models arxiv:1412.5951
  - Use jet substructure to identify top quarks
  - Look at impact on detector resolution

Delphes Sim.



Outline

- Motivation
- Outline
- Physics
  - MC Framework
    - Signals
    - Backgrounds
  - Hadronic vs Leptonic Final States
    - Current limits
  - Top Quark Selections
    - Jet Substructure variables
      - MC comparisons
    - Performance
  - Sensitivity to new states
- Implications on detector performance
  - Segmentation
  - Impact of finer granularity

MC Samples

- **Signal (LO QCD). PYTHIA8**
  - $f \bar{f} \rightarrow Z0'$ with M=8,10,12,14,16,18,20 TeV. Code 3001. Pure Z' contribution. Γ/M=3%
    - cross section scaled by the k-factor 1.3 (careful here → using 8 TeV CM energy!)
  - $q \bar{q} \rightarrow g_{KK}$ with M=8,10,12,14,16,18,20 TeV. Code 5006. Pure g_{KK} contribution. Γ/M=16%
    - cross section is at LO

- **Background processes:**
  - PYTHIA8 for QCD backgrounds
    - NLOjet++ (NLO) to extract the k-factor (MSTW2008nlo68cl for PDF)
  - HERWIG++ x k-factor as alternative (contain W/Z brem. events)
  - SM $t\bar{t}$ process was generated with Madgraph (MSTW2008nlo68cl for PDF)
    - NLO QCD+ HERWIG6
  - PYTHIA8 for all SM boson processes (like Z/W+jets)
    - Not too realistic, but the usage of “realistic” ALPGEN should not change conclusions

From S. Chekanov

Software Monte Carlo toolkit for this study

- **Monte Carlo samples from the HepSim repository:**

hep-ph > arXiv:1403.1886

  - http://atlaswww.hep.anl.gov/hepsim/
  - Select p → ← p then 100 TeV

Show all

p →← p
7 TeV
8 TeV
13 TeV
14 TeV
33 TeV
100 TeV

e →← e
500 GeV

e →← p
920 GeV

HepSim

Repository with predictions for HEP experiments

Selected: pp collisions, 100000 GeV energy, all type

This is a new HepSim database. For more datasets use the Old HepSim repository

Show 25 entries Previous 1 2 Next Search:

Id	→←	E (GeV)	Name	Generator	Process	Topic	Info	Url
1	pp	100000.0	higgs_pythia8_100tev	PYTHIA8	gg2Httbar and qqbar2Httbar	Higgs	Info	URL link
2	pp	100000.0	higgs_ttbar_mg5	MADGRAPH+HERWIG6	Higgs+ttbar (NLO+PS)	Higgs	Info	URL link
3	pp	100000.0	kkgluon_ttbar_1tev_pythia8	PYTHIA8	KKgluon (1 TeV) to ttbar	Exotic	Info	URL link
4	pp	100000.0	kkgluon_ttbar_4tev_pythia8	PYTHIA8	KKgluon (4 TeV) to ttbar	Exotic	Info	URL link
7	pp	100000.0	qcd_herwigpp_pt2700	HERWIG++	All dijet QCD events	SM	Info	URL link
8	pp	100000.0	kkgluon_ttbar_8tev_pythia8	PYTHIA8	KKgluon(8 TeV) to ttbar	Exotic	Info	URL link
9	pp	100000.0	kkgluon_ttbar_16tev_pythia8	PYTHIA8	KKgluon (16 TeV) to ttbar	Exotic	Info	URL link
10	pp	100000.0	kkgluon_ttbar_20tev_pythia8	PYTHIA8	KKgluon (20 TeV) to ttbar	Exotic	Info	URL link
11	pp	100000.0	qcd_pythia8_pt300	PYTHIA8	All dijet QCD events	SM	Info	URL link
12	pp	100000.0	qcd_pythia8_pt900	PYTHIA8	All dijet QCD events	SM	Info	URL link
13	pp	100000.0	qcd_pythia8_pt2700	PYTHIA8	All dijet QCD events	SM	Info	URL link
14	pp	100000.0	qcd_pythia8_pt8000	PYTHIA8	All dijet QCD events	SM	Info	URL link
15	pp	100000.0	ttbar_mg5	MADGRAPH+HERWIG6	p p > t t~ [QCD] (ttbar at NLO)	Top	Info	URL link
16	pp	100000.0	ttbar_pt2500_mg5_lo	MADGRAPH+HERWIG6	p p > t t~ (ttbar at LO)	Top	Info	URL link
20	pp	100000.0	ttbar_pythia8_pt900	PYTHIA8	g g -> t tbar, q qbar -> t tbar	Top	Info	URL link
21	pp	100000.0	ttbar_pythia8_pt300	PYTHIA8	g g -> t tbar, q qbar -> t tbar	Top	Info	URL link
22	pp	100000.0	ttbar_pythia8_pt2700	PYTHIA8	g g -> t tbar, q qbar -> t tbar	Top	Info	URL link
23	pp	100000.0	ttbar_pythia8_pt8000	PYTHIA8	g g -> t tbar, q qbar -> t tbar	Top	Info	URL link
24	pp	100000.0	ttbar_mcfm_100tev	MCFM	ttbar production at NLO	Top	Info	URL link

Data samples & analysis program are public

From S. Chekanov

MC samples for this study

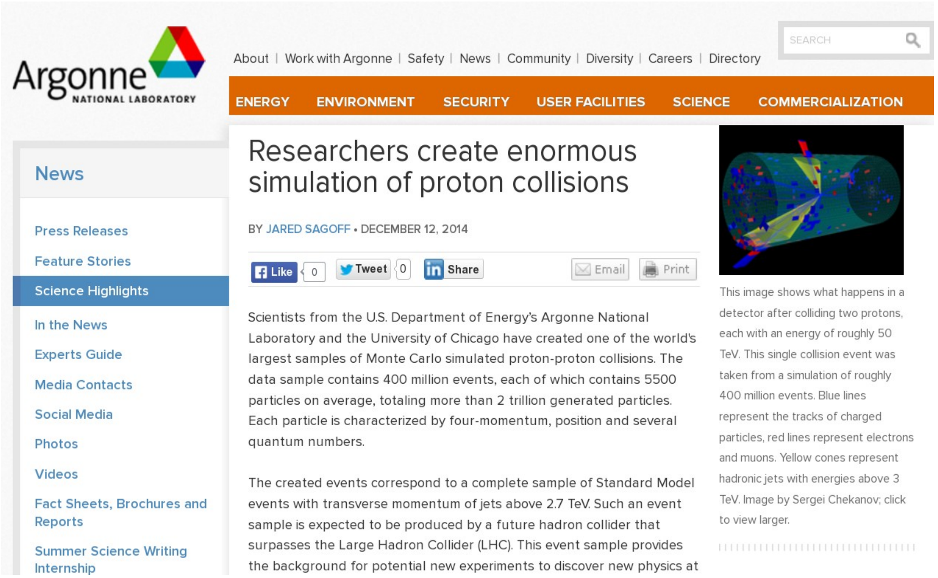
- http://atlaswww.hep.anl.gov/hepsim/

MC event samples for Z' / g_{KK} studies:

- qcd_herwigpp_pt2700
- qcd_pythia8_pt2700
- ttbar_pythia8_pt2700
- pythia10tev_wjet2700
- ttbar_pt2500_mg5
- ttbar_pt2500_mg5_lo
- zprime*_pythia8
- kkgluon_ttbar*_pythia8

Includes the description of how to:
- *download samples*
- *build an analysis program*
- *run fast detector simulation (Delphes)*

World's largest public MC sample hosted by HepSim used in this study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Researchers create enormous simulation of proton collisions

BY JARED SAGOFF • DECEMBER 12, 2014

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Scientists from the U.S. Department of Energy's Argonne National Laboratory and the University of Chicago have created one of the world's largest samples of Monte Carlo simulated proton-proton collisions. The data sample contains 400 million events, each of which contains 5500 particles on average, totaling more than 2 trillion generated particles. Each particle is characterized by four-momentum, position and several quantum numbers.

The created events correspond to a complete sample of Standard Model events with transverse momentum of jets above 2.7 TeV. Such an event sample is expected to be produced by a future hadron collider that surpasses the Large Hadron Collider (LHC). This event sample provides the background for potential new experiments to discover new physics at

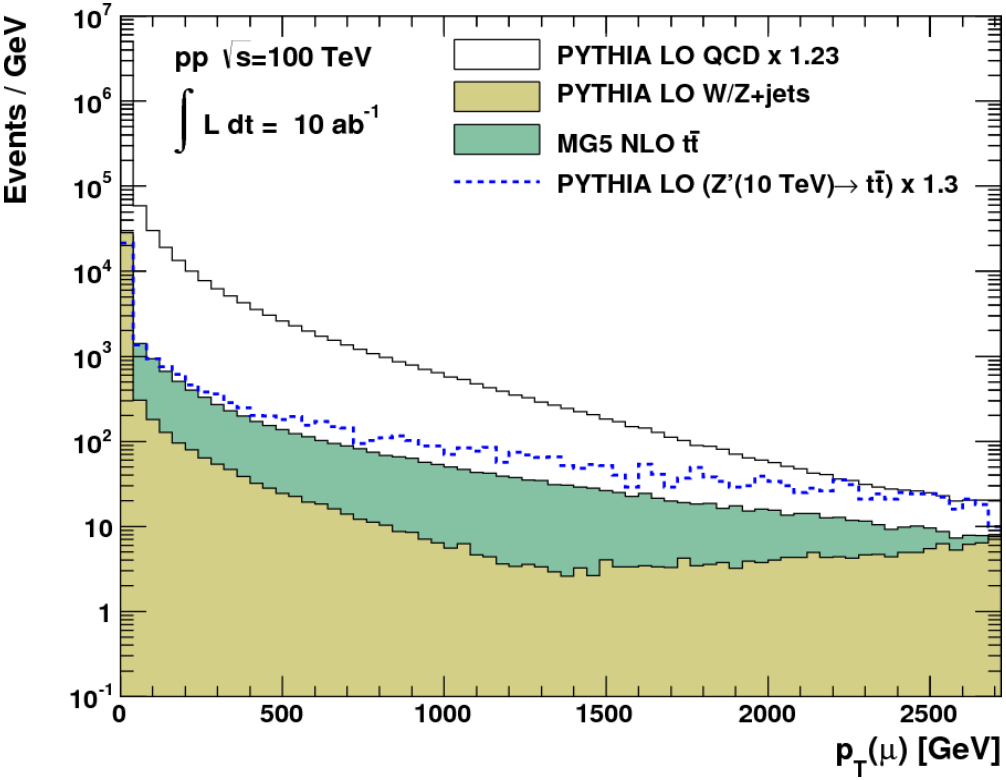
This image shows what happens in a detector after colliding two protons, each with an energy of roughly 50 TeV. This single collision event was taken from a simulation of roughly 400 million events. Blue lines represent the tracks of charged particles, red lines represent electrons and muons. Yellow cones represent hadronic jets with energies above 3 TeV. Image by Sergei Chekanov; click to view larger.

Pythia8 dijets. Int. luminosity ~10 ab^{-1}
0.4 billion pp events at 100 TeV

From S. Chekanov

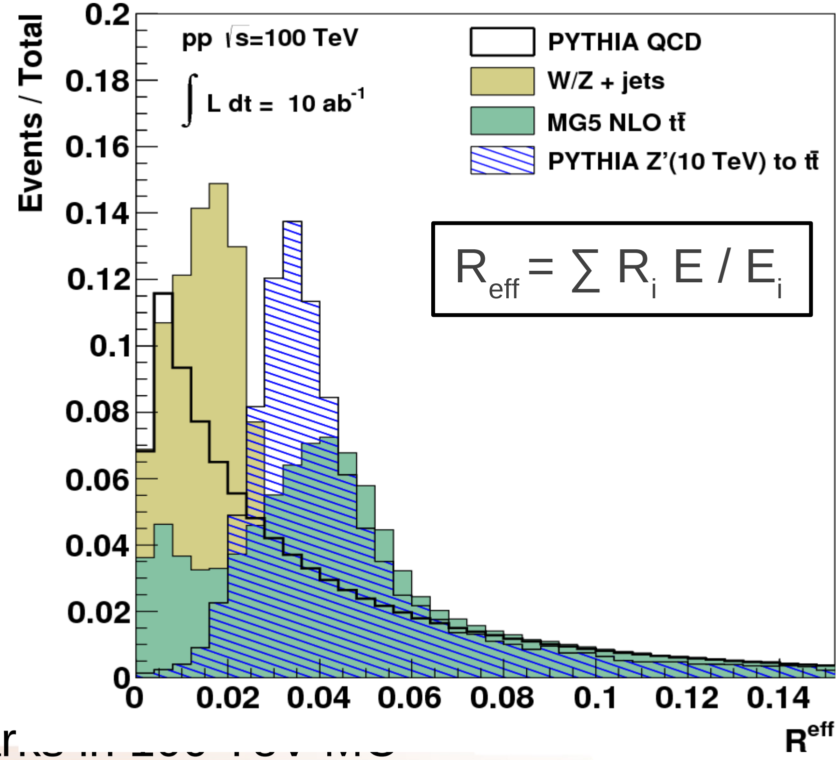
Top Reconstruction: Hadronic vs Leptonic?

- Leptonic final states are a sure sign of electroweak interactions
  - But at the cost of limited BR
  - Must be identified?
- Leptons from top quarks with >3 TeV p_T fail isolation requirement
  - Electrons may not be easily distinguishable from the b-quark initiated jet
- QCD di-jet events contain high-p_T muons too
  - Must require muon p_T > 2 TeV to improve S/B



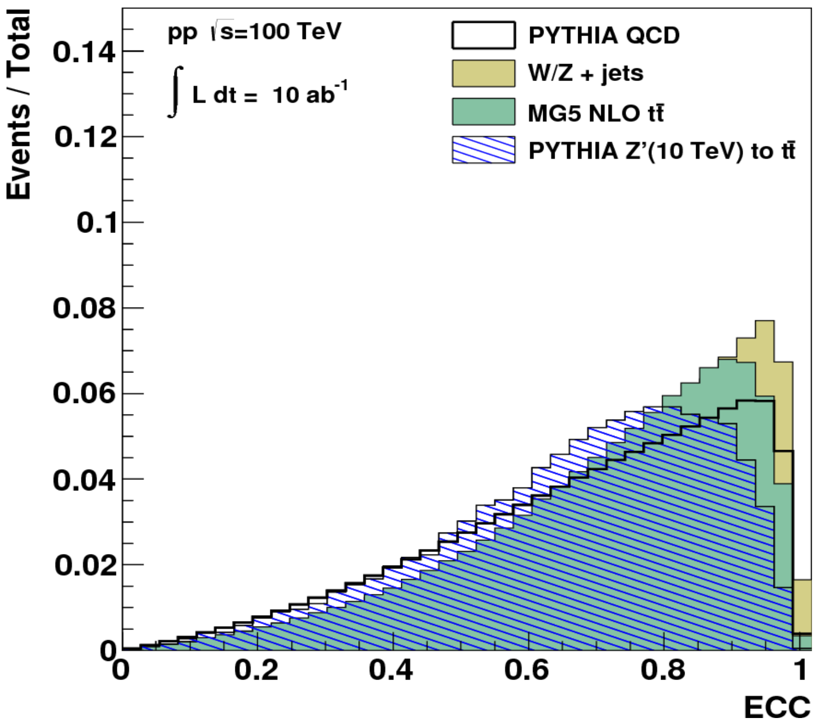
Jet Substructure Variables

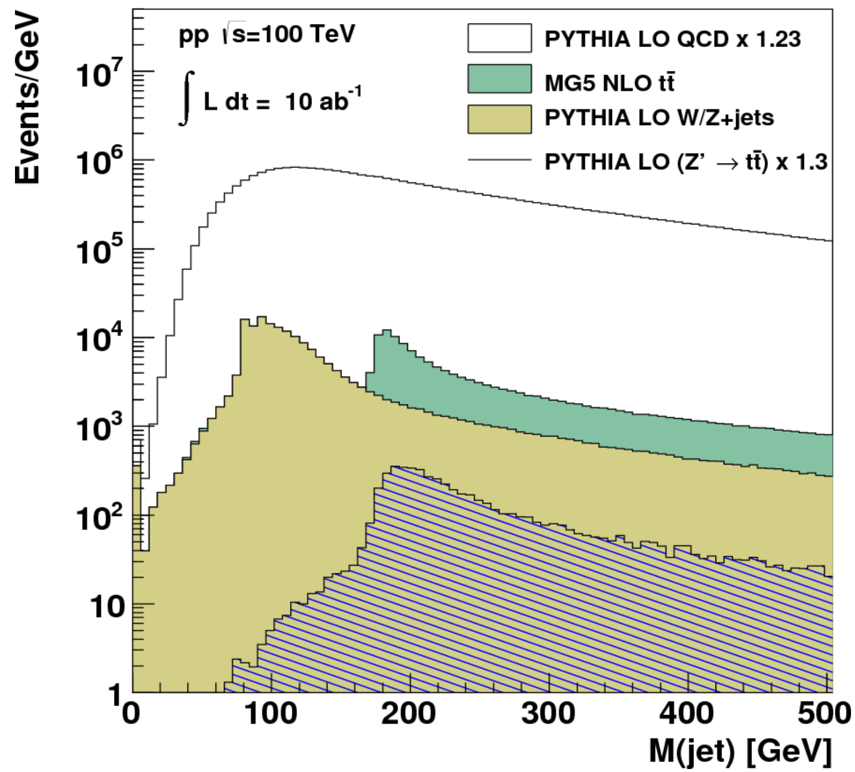
- Used jet substructure variables to test if substructure can provide needed background rejection
  - Jet Mass
  - Splitting scale d_{12} Phys. Rev. D65 (2002) 96014
  - N-subjettiness variables τ_{32} τ_{21} JHEP 1103:015, 2011
  - Jet Eccentricity Phys. Rev. D81 (2010) 114038
  - R_{Eff} – Energy Averaged Distance from Radius
  - And combinations thereof
- Anti-k_T jets with radius 0.5



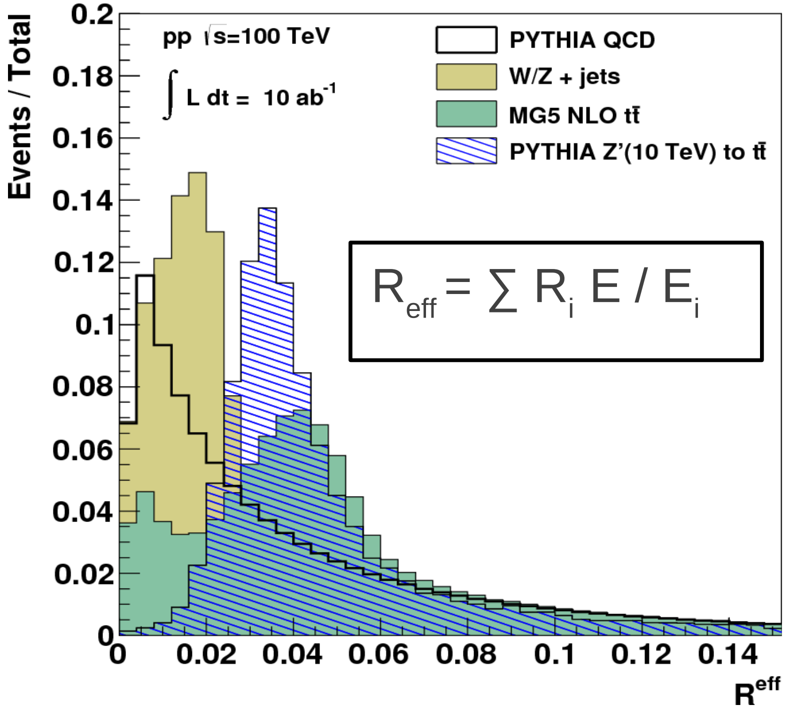
Jet Substructure Variables

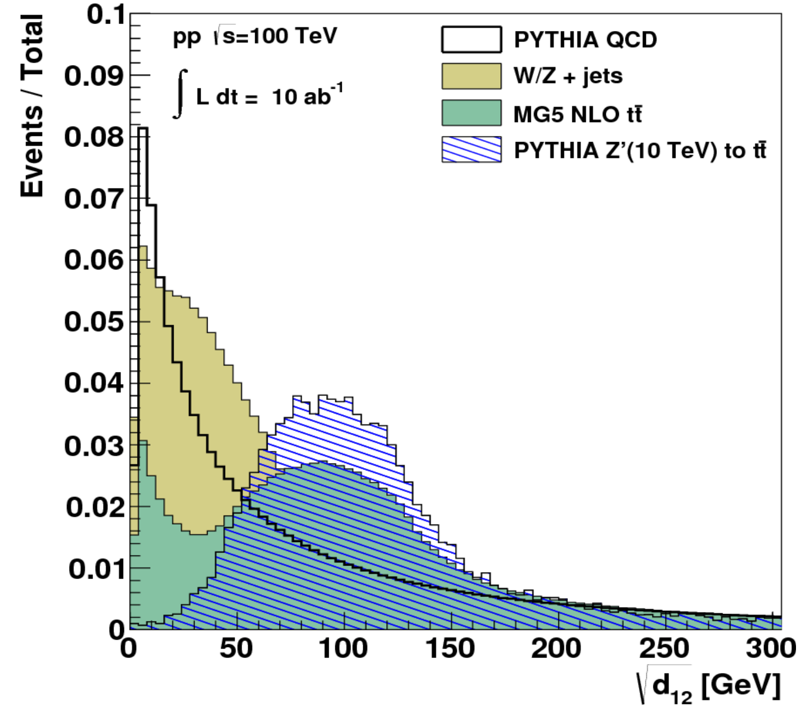
- Clear peak at Jet mass disribution at W/Z and top mass
  - Optimized cut above 140 GeV
- ECC degree of elongation of jet shape
  - Optimized cut above ECC > 0.9





Jet Substructure Variables



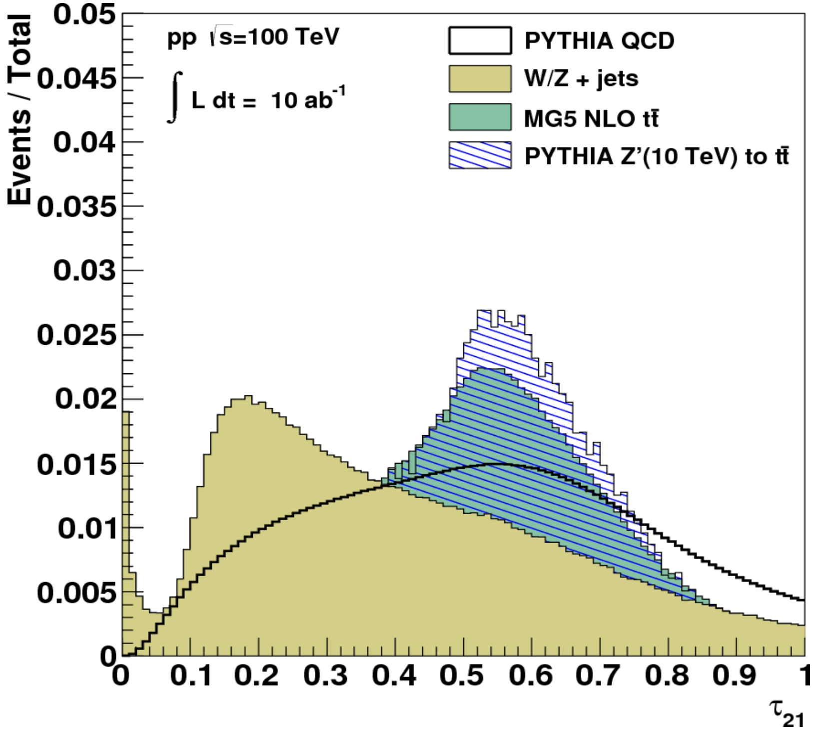


- Splitting scale d_{12} peaks at 1/2 Top Mass
  - Optimized cut $d_{12} > 50$ GeV
- R_{eff} – larger for jets initiated by massive particles
  - Optimized cut $R_{eff} > 0.03$
  - Highly correlated with Jet Mass

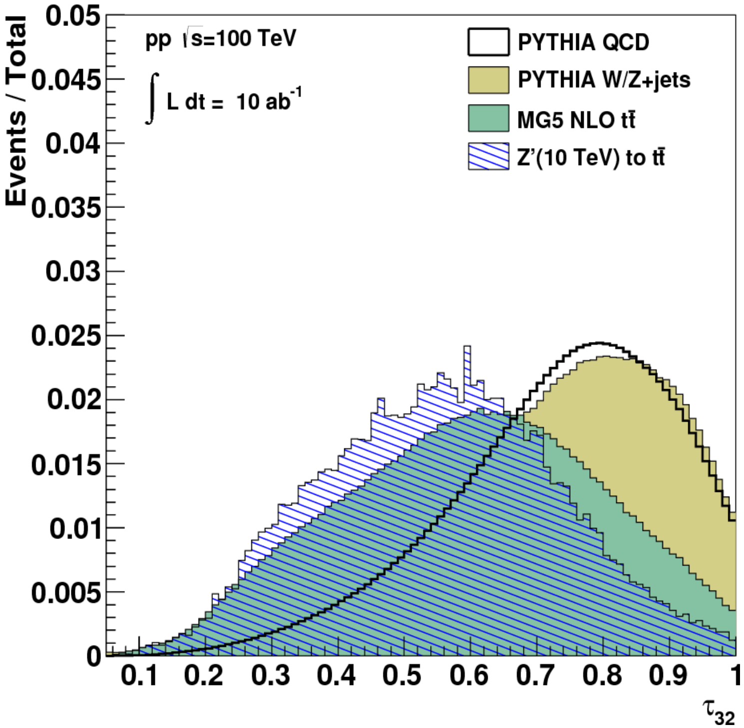
Jet Substructure Variables

- N-subjettiness – measure of how well a jet is described by N-subjets and ratios formed from these variables
  - Cut $\tau_{32} < 0.75$
  - Cut $\tau_{21} > 0.3$ reject boosted W/Z and $\tau_{21} < 0.8$ to reject QCD dijets

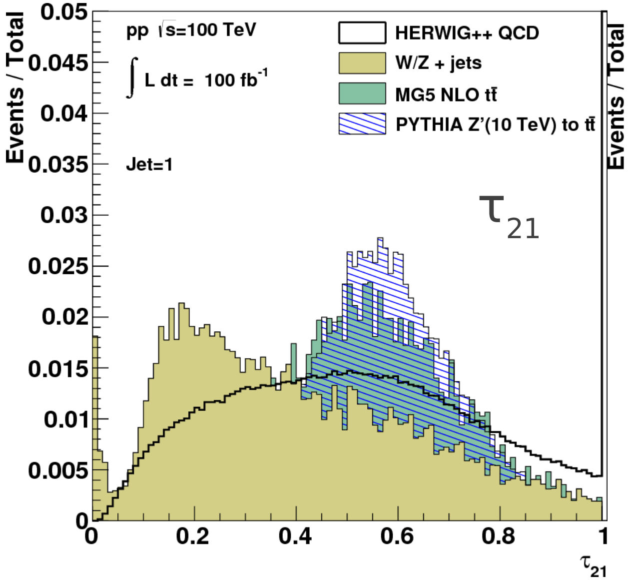
τ_{21}

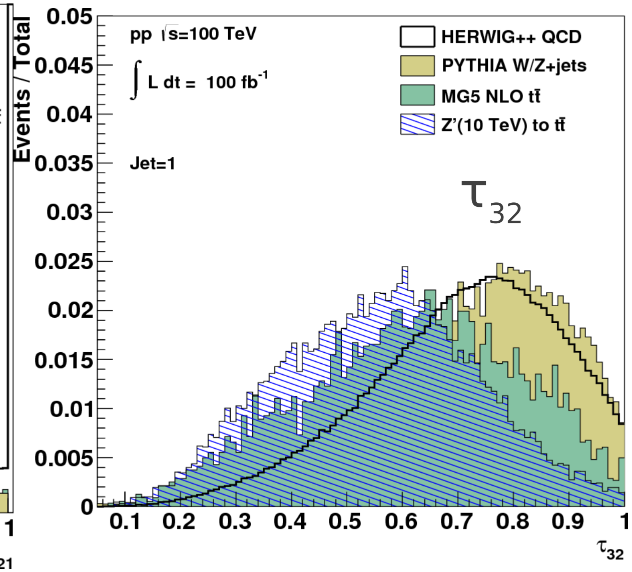


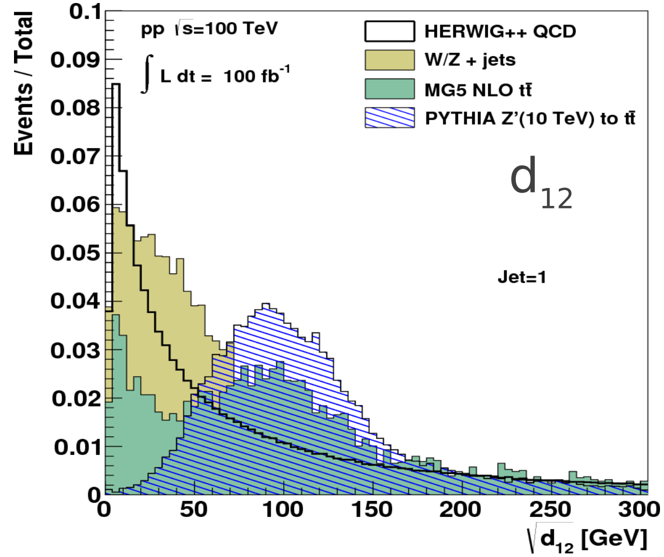
τ_{32}

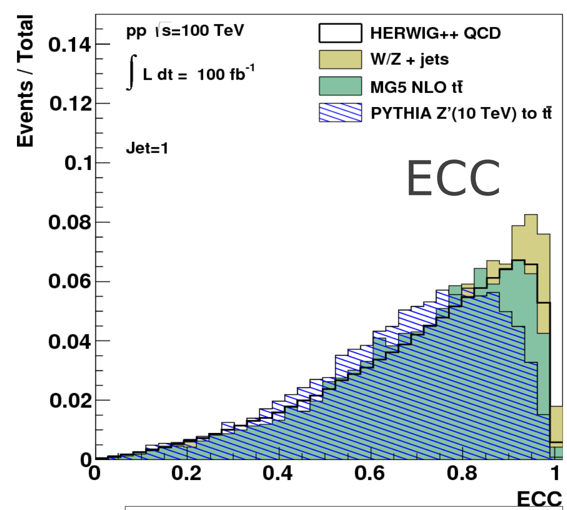


A Quick Look at Herwig++







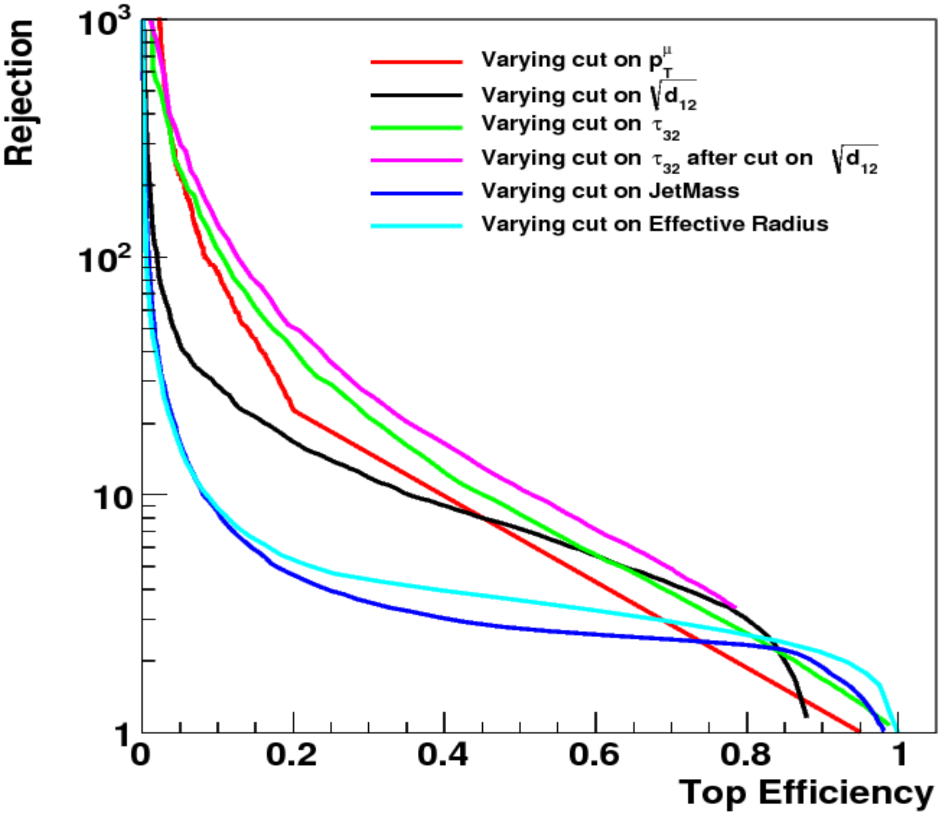


- HERWIG++ QCD dijet events give similar distributions to PYTHIA
  - Also include W/Z Brem. Events
  - Optimized cut values at same values

From S. Chekanov

Identifying Top Jets

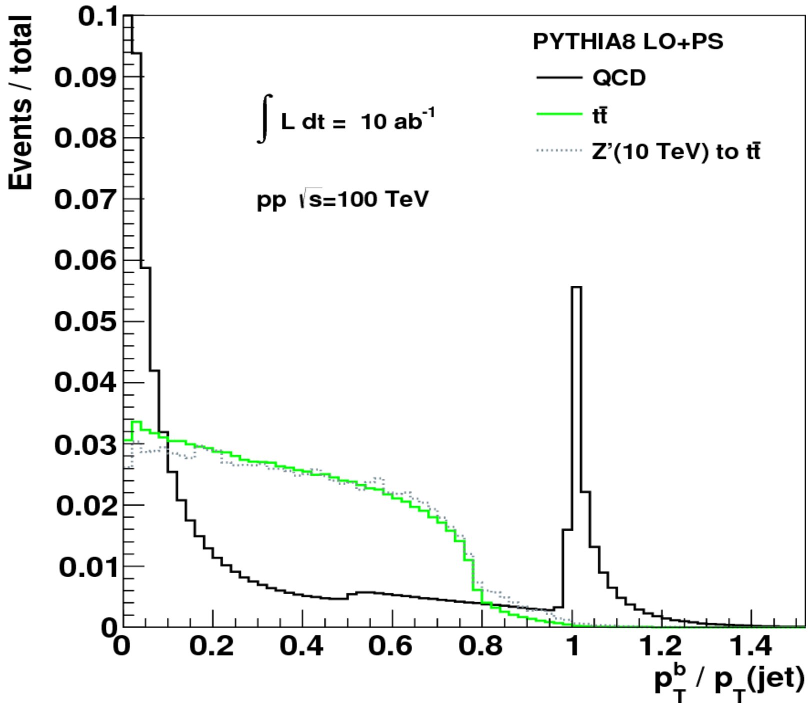
- Efficiency vs rejection curve as top quark substructure requirements are tightened
  - Rejection is one over QCD dijet efficiency
- For very high efficiency (> 60 %) mass-like variables are most performant
  - Splitting scale, Effective Radius, Jet Mass
- Combination of n-subjettiness and Splitting Scale works well over large range
  - ATLAS W' Top Tagger
    - In full sim MC ATLAS AWTT has 50% Efficiency Rejection of 18x



ATLAS-CONF-2013-084

Additional Information – b-tagging

- After jet substructure requirements S/B has improved by ~10x
  - QCD backgrounds are still ~10x too large.
- Must include b-tagging
  - Match a b-quark to a jet dR <0.1
  - Use Snowmass-like 70% b-quark tagging efficiency to tag 1% light-quark jet fake efficiency, and 10% charm
- Require b-quark to have 0.2 < p_T of jet



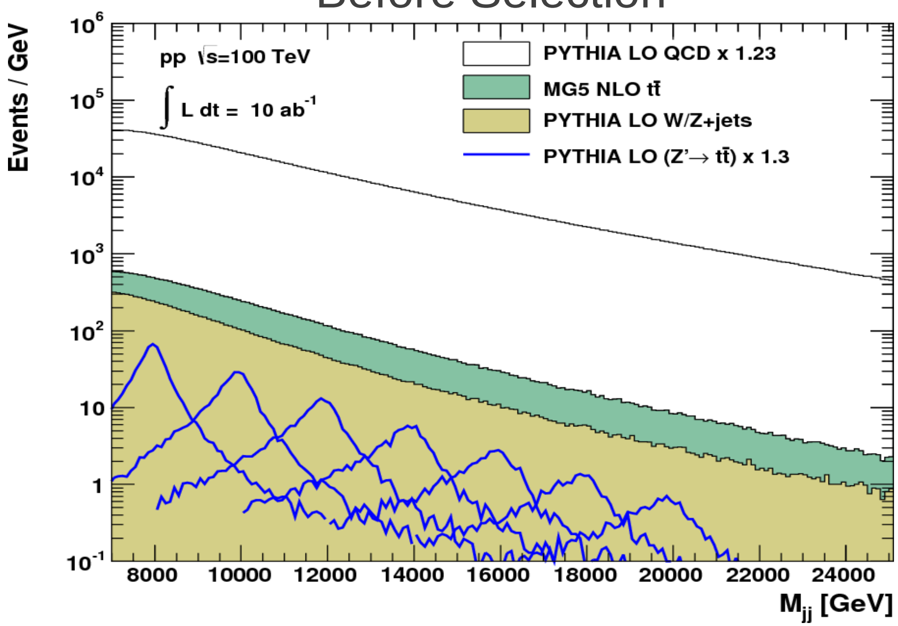
Physics Reach

- After jet substructure and b-tagging requirements sensitivity to new resonances decaying to ttbar are calculated
  - With 10 ab^{-1} can discover 12 TeV signal
  - With 150 ab^{-1} can discover 20 TeV signal

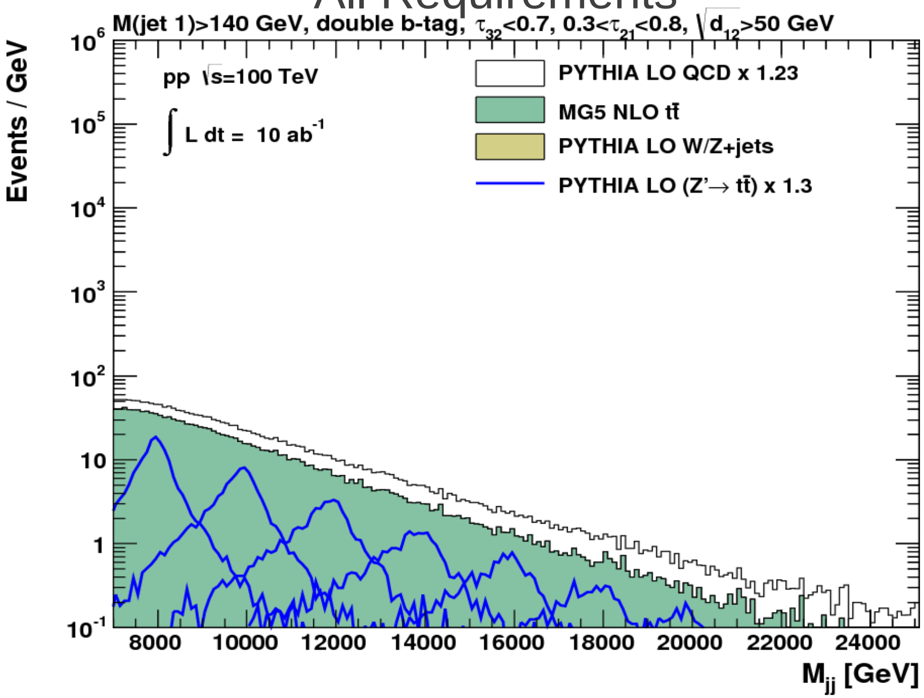
Cross Section X BR 95 %CL Limit

mass	$\sigma\times$Br (fb)			
(TeV)	$Z^{0\prime}$ (th.)	$Z^{0\prime}$ (exp.)	g_{KK} (th.)	g_{KK} (exp.)
8	18.46	7.00	262.3	20.2
10	7.03	3.97		
12	3.02	2.54	45.4	7.7
14	1.44	1.75		
16	0.73	1.27	12.2	4.7
18	0.39	1.10		
20	0.21	0.98	4.2	4.1

Before Selection



All Requirements



Implications on Detector Performance

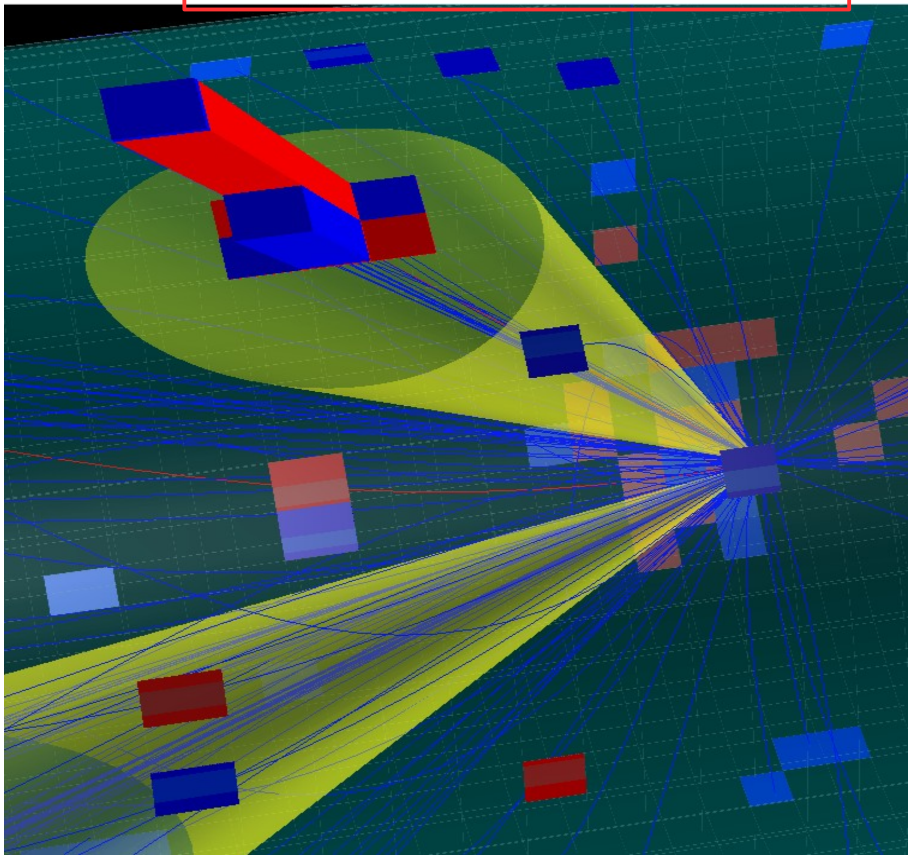
- **High-efficient b-tagging with small fake rate for light-flavor jets**
  - 70% efficiency & 1% fake rate for jets with $2.7<p_T<10$ TeV assumed in this study
- **High-granularity calorimeter**
- **Good jet energy resolution**

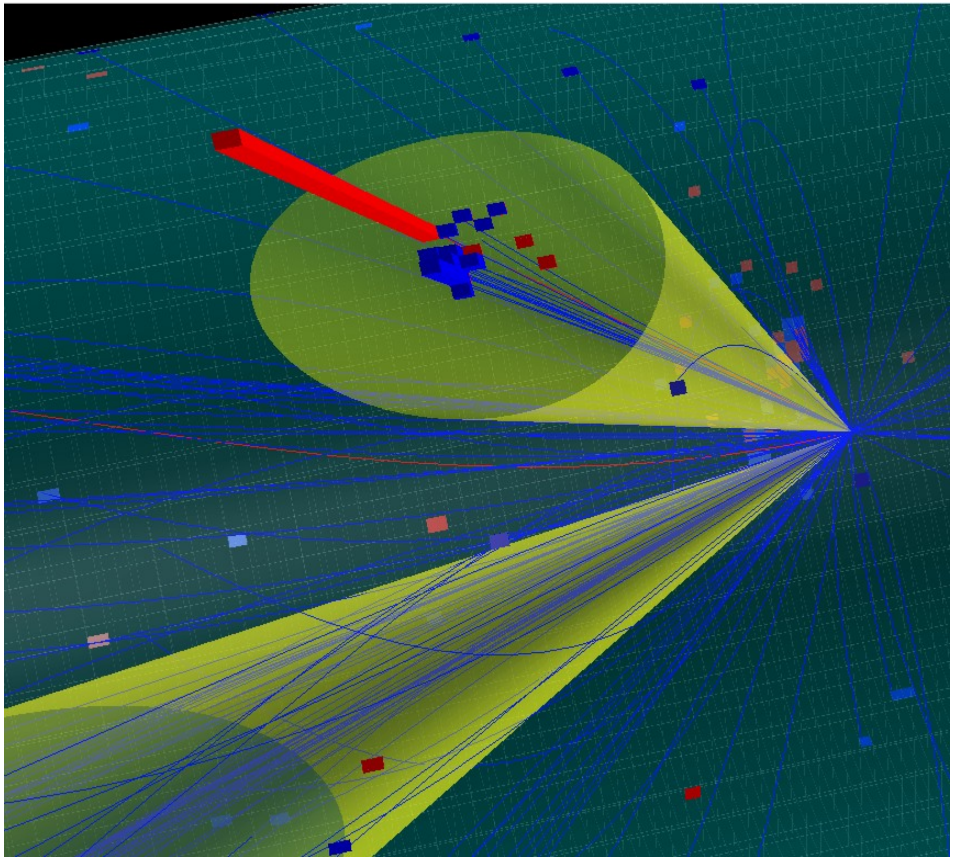
From S. Chekanov

Example: Z'(10 TeV) → $t\bar{t}$ → 2 antiKT05 jets (pT> 3 TeV)

Snowmass-like CAL geometry
'ATLAS'-like

x4 smaller CAL cells





~ 5 deg :
Phi ~ 5 deg, Eta ~ 0.1

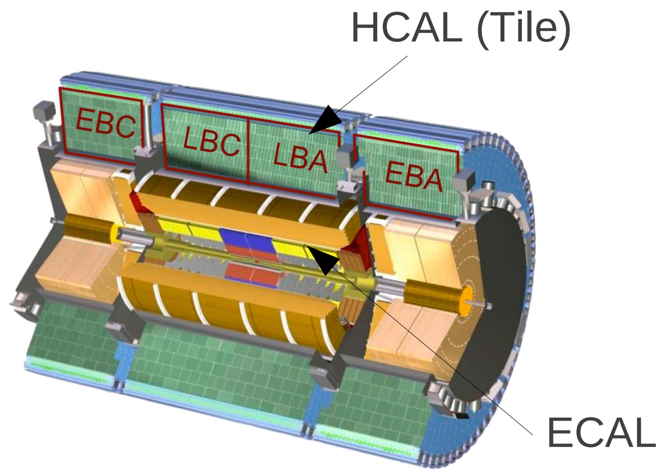
x 4 better →

~ 1.25 deg :
Phi ~ 1.25 deg, Eta ~ 0.025

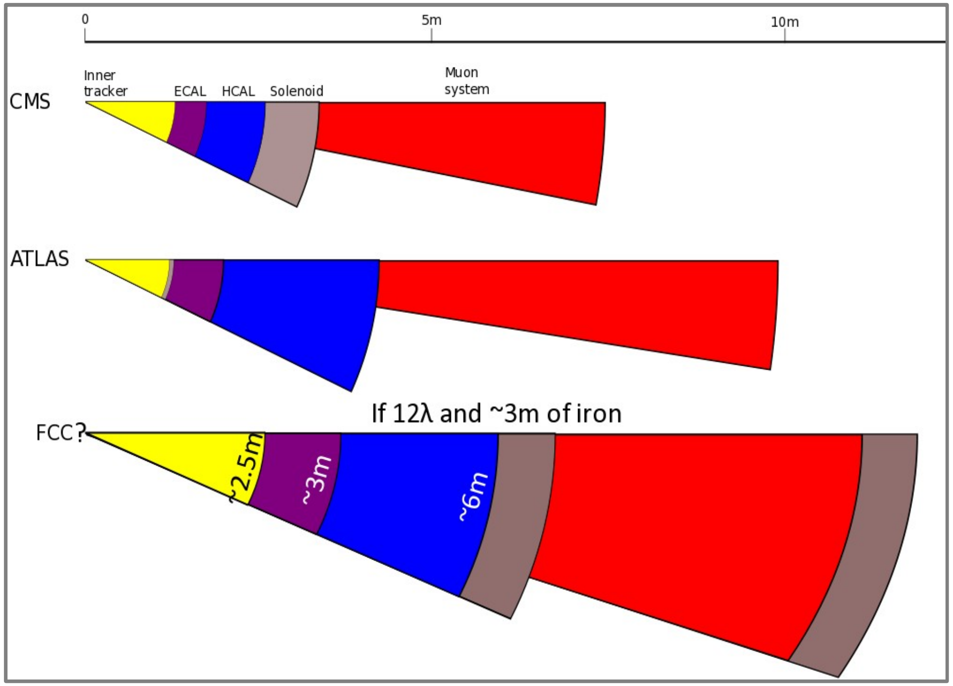
Note: this study uses a fast simulation.
We ignore effects from Molière radius when considering transverse profile of showers!

From S. Chekanov

Calorimeter segmentation



- **ATLAS:**
  - HCAL (TileCal) has 64 modules in **φ** and **η=0.1** in the central region
  - ECAL has x4 better segmentation
  - HCAL ~2m away from IP
- **x2 better segmentation for a detector that has x2 larger distance from IP requires same instrumentation (cell sizes) as for ATLAS LArg and Tile calorimeter**
- **Increasing segmentation by x4, x6 or more may require different instrumentation and technology!**
- **Can be studies using HepSim MC event samples + Delphes fast simulation**



C.Barnet, C.Helsens

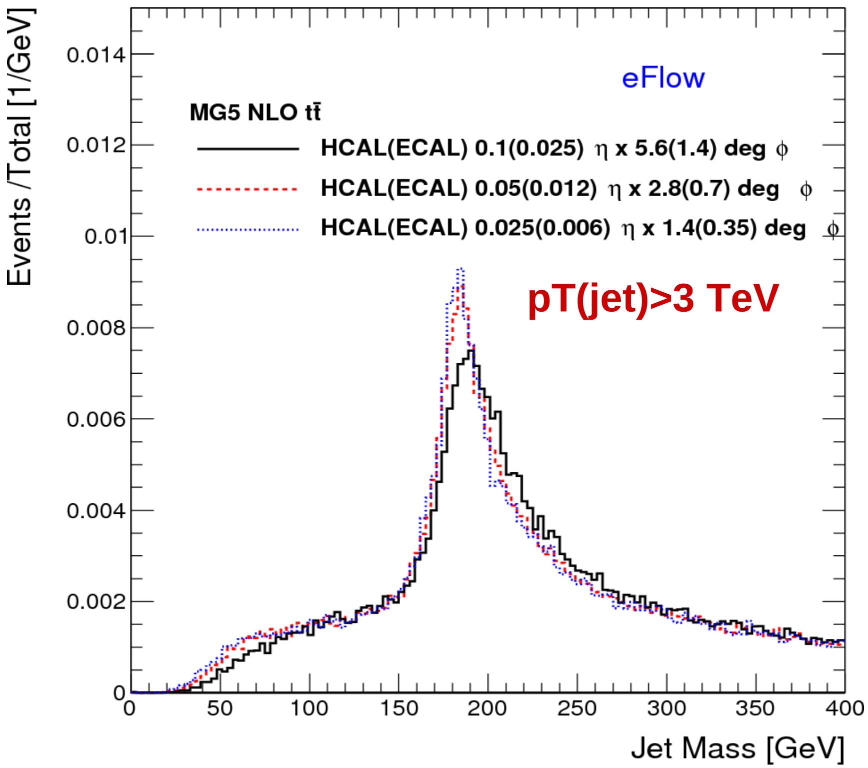
Thanks to A. M. Henriques Correia for discussion

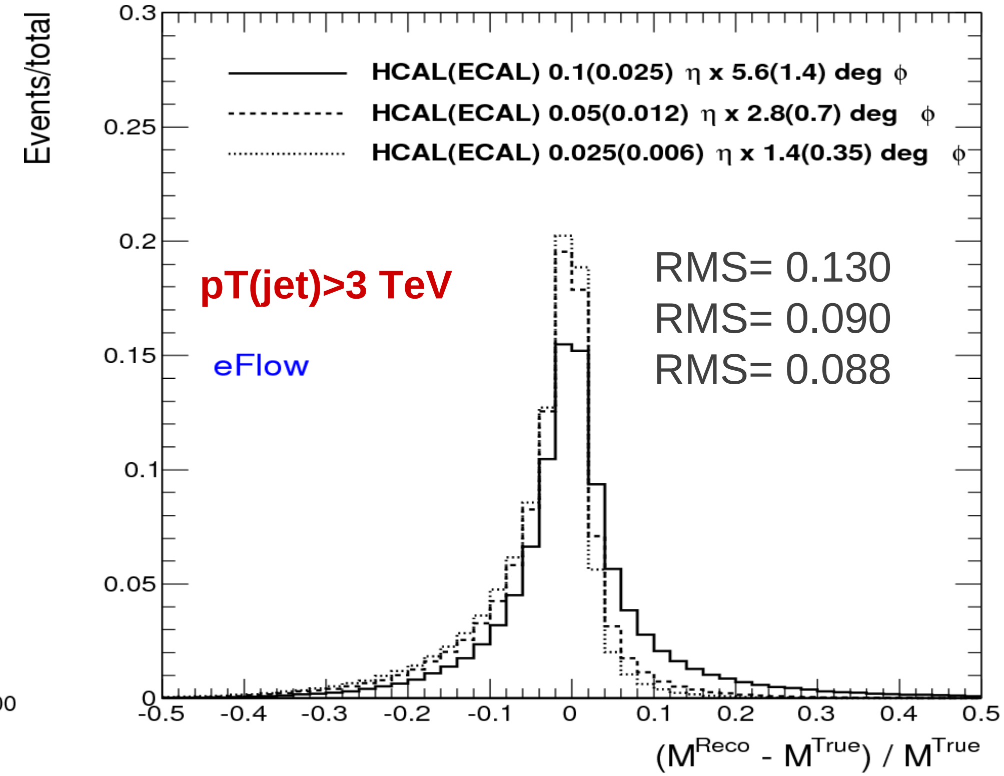
From S. Chekanov

Jet mass Finer HCAL & ECAL cells

- Assume x2 and x4 finer granularity of both ECAL and HCAL
- x2 (x4) granularity leads to 44% (48%) improvement in resolution

HepSim MC input + Delphes 3.2



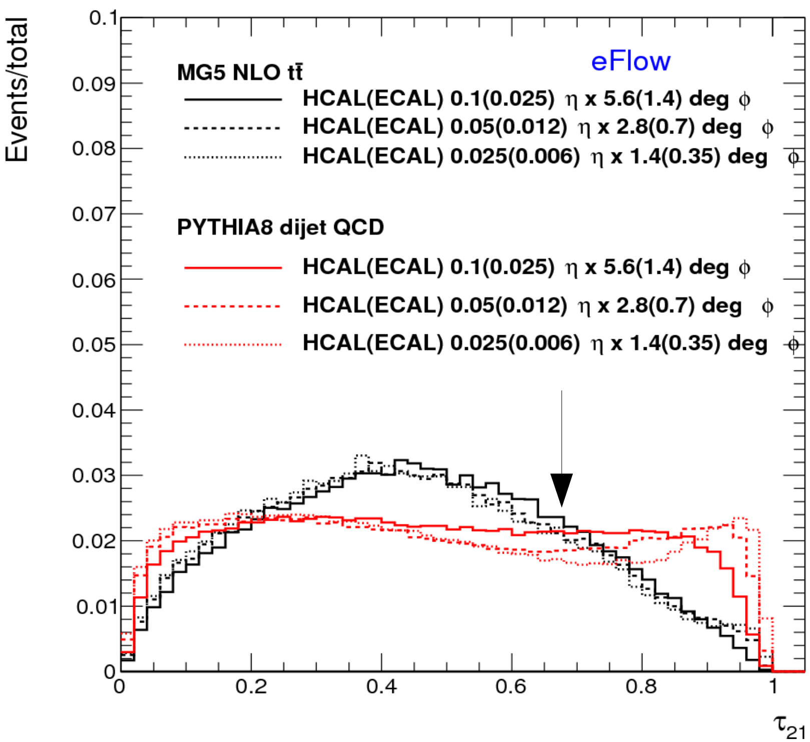


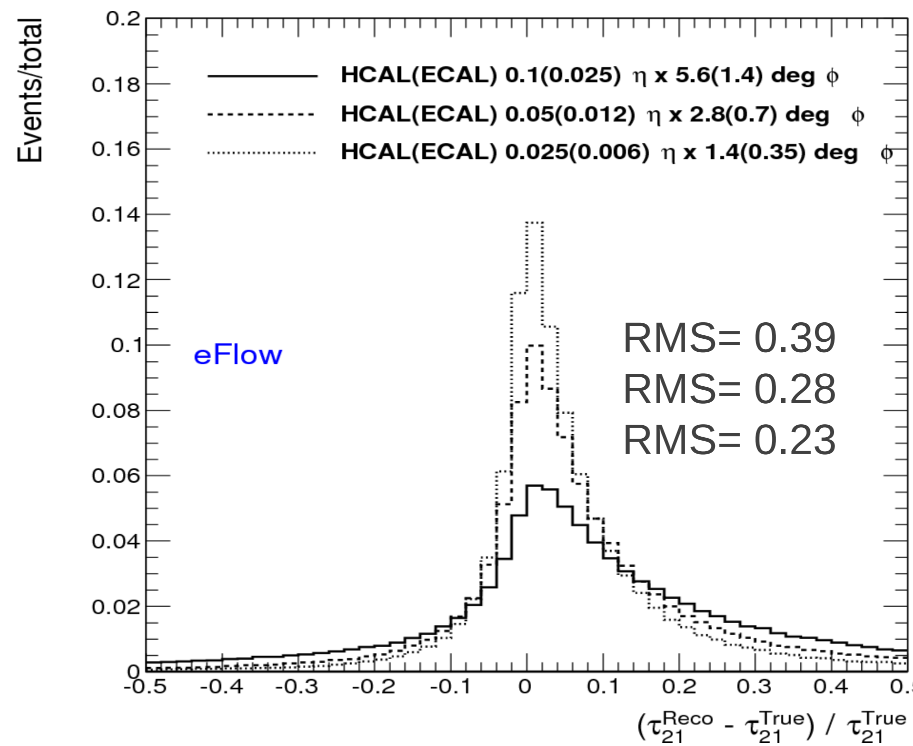
From S. Chekanov

τ_{21} Finer HCAL & ECAL cells

- Using Delphes Fast Simulation with p_T^{jet} >3 TeV
- Assume x2 and x4 finer granularity of both ECAL and HCAL
- x2 (x4) granularity leads to 36% (67%) improvement in resolution

HepSim MC input + Delphes 3.2





From S. Chekanov

Summary

- A 100 TeV pp collider has great potential for searches for new resonances decaying to ttbar
  - Hadronic final state promising
- Jet substructure mass+shower variables combined with high efficiency b-tagging give sensitivity in the fully hadronic final state
  - Substructure gives efficiency of ~50% with a rejection of 10x
  - B-tagging assumes efficiency of 70% with a rejection of 100x
  - Serious implications on the detector
- Calorimeter granularity significantly impacts resolution of substructure variables
  - A 4x increase in granularity compared to ATLAS-like calorimeter
  - Gives 67% improvement on resolution on Jet Mass
  - Gives 48% improvement on n-subjettiness τ_{21}

- Thank you!