Sensitivity to New High-Mass States in the 3rd Generation at Future Proton Colliders

J. Love

Contributions by: B. Auerbach, S. Chekanov, A. V. Kotwal, M. Low, J. Proudfoot

Motivation

- Learn how to test 3rd Generation interactions at beyond LHC energies
  - Reconstruct high-p_T b, top, and τ's
- MC Truth-level study of the sensitivity to new high mass states at a 100 TeV proton-proton collider
  - Using Z' and g_{kk} decaying to ttbar as signal models
    - Implications for detector design in S. Chekanov's talk

Phys. Rev. D 91, 034014 (2015)

  - VBS Resonant di-Higgs production in the 4τ final state
  - Using η to HH with varying width as model

Phys. Rev. D 91, 114018 (2015)

Outline

- Motivation
- Outline
- Ttbar Resonances
  - Hadronic vs Leptonic Final States
  - Jet Substructure variables
    - MC comparisons
    - Performance
  - Sensitivity to new high mass states
  - Impact of granularity on τ_{21}
- VBS Resonant di-Higgs production to 4τ
  - Model description
  - Background vs Signal kinematic distributions and BDT Discriminant
  - Sensitivity and scaling
- Summary

Resonances Decaying to ttbar

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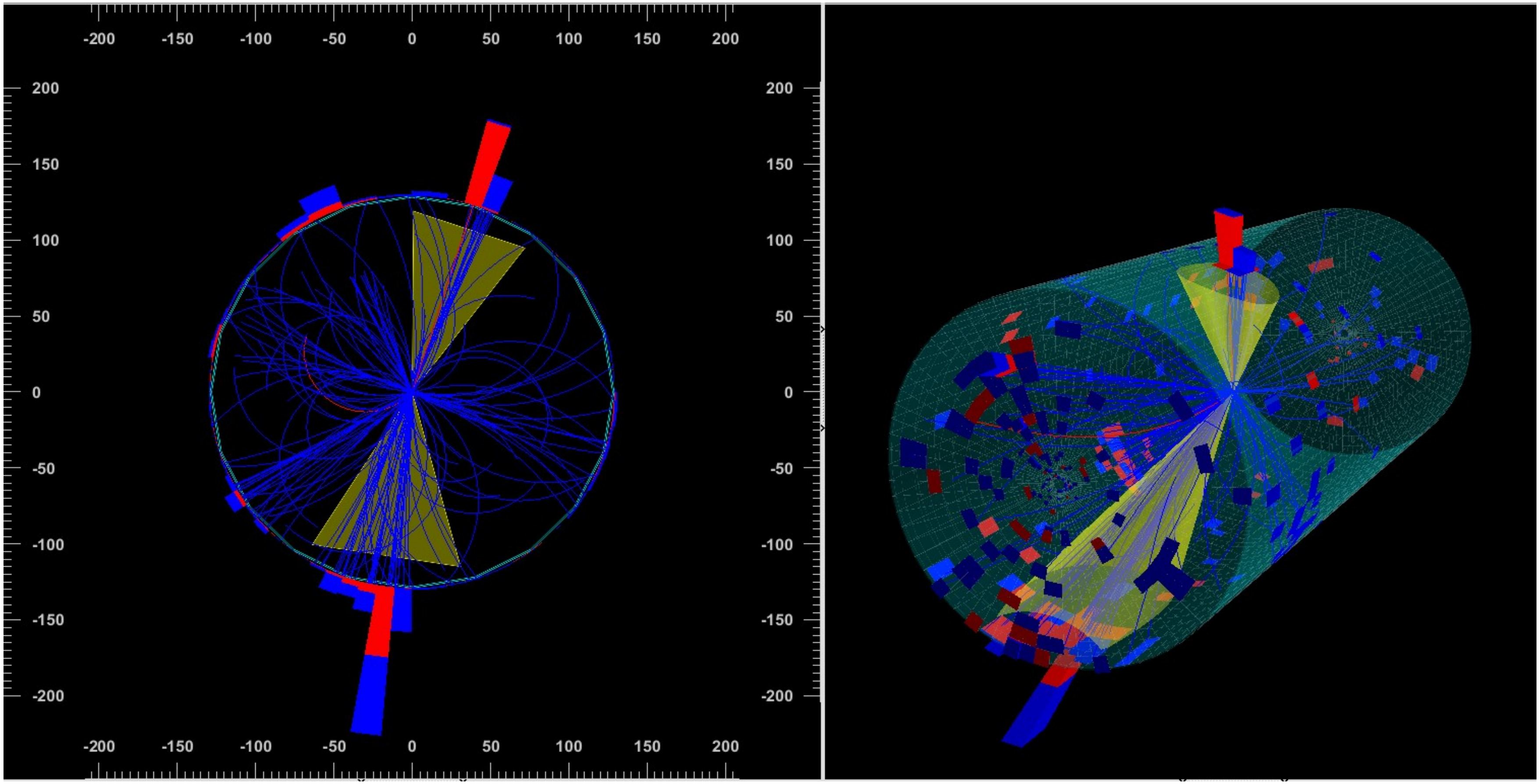
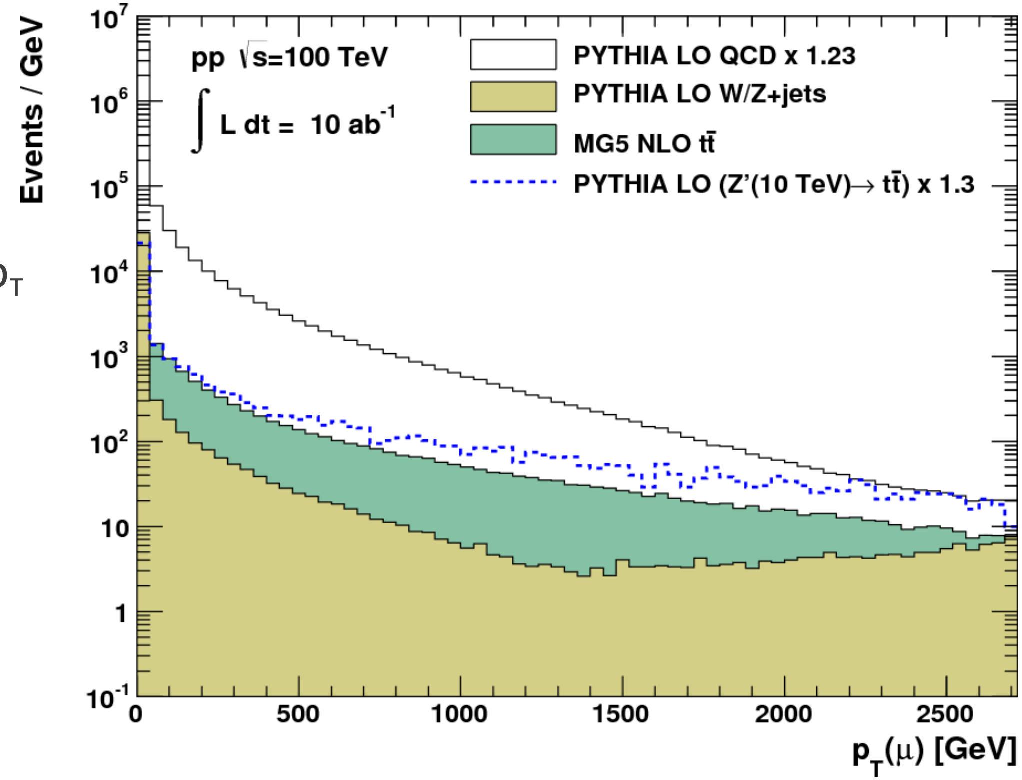


Delphes Sim.

Top Reconstruction: Hadronic vs Leptonic?

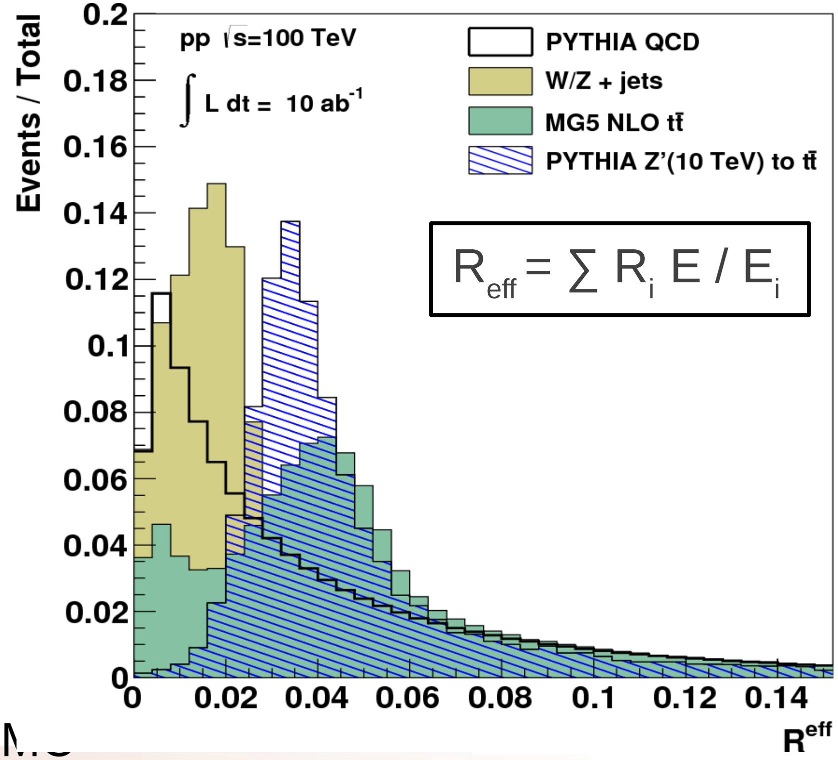
- Leptonic final states are a sure sign of electroweak interactions
  - But at the cost of limited BR
- Leptons from top quarks with >3 TeV p_T fail standard isolation requirement
  - Electrons may not be easily distinguishable from the b-quark initiated jet
- QCD di-jet events contain high-p_T muons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



Jet Substructure Variables

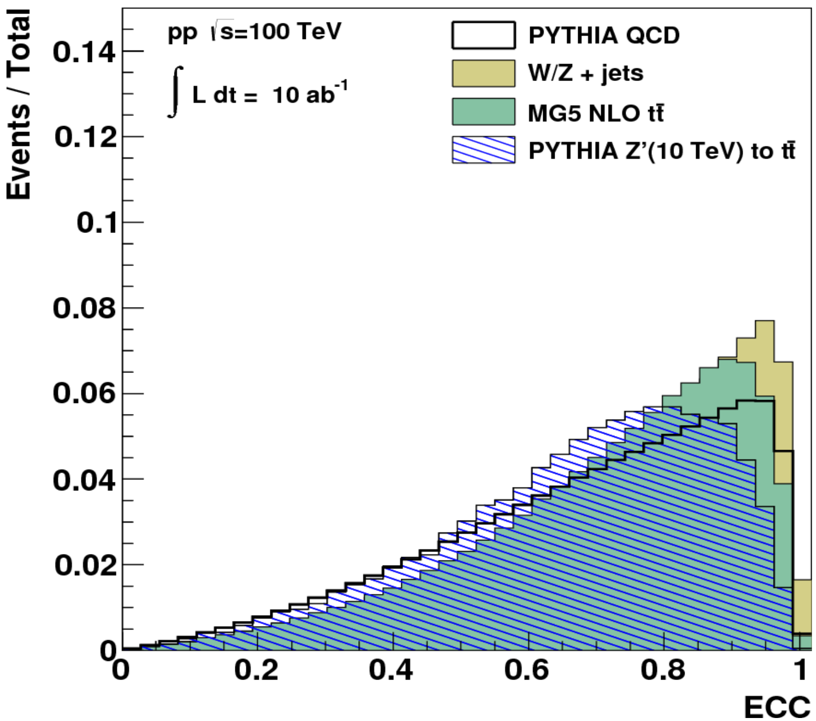
- Used jet substructure variables to test if substructure can provide needed background rejection
  - Jet Mass
  - Splitting scale d_{12} Phys. Rev. D65 (2002) 96014
  - N-subjettiness variables τ_{32} τ_{21} JHEP 1103:015, 2011
  - Jet Eccentricity Phys. Rev. D81 (2010) 114038
  - R_{Eff} – Energy Averaged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

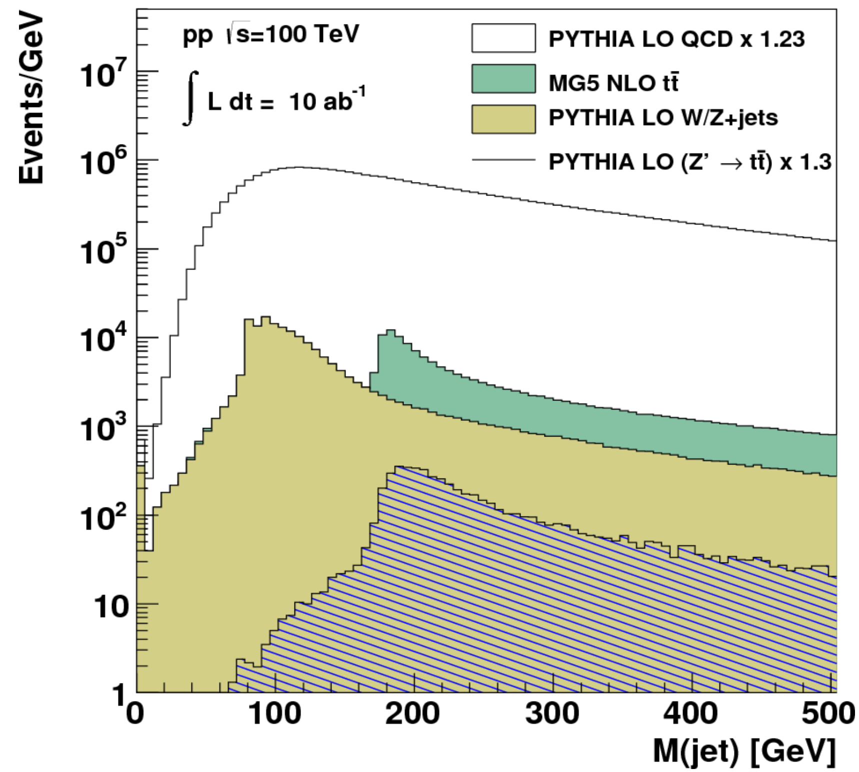
- Anti-k_T jets with radius 0.5
  - Built from truth record particles minus neutrinos
  - An infinite and perfect detector



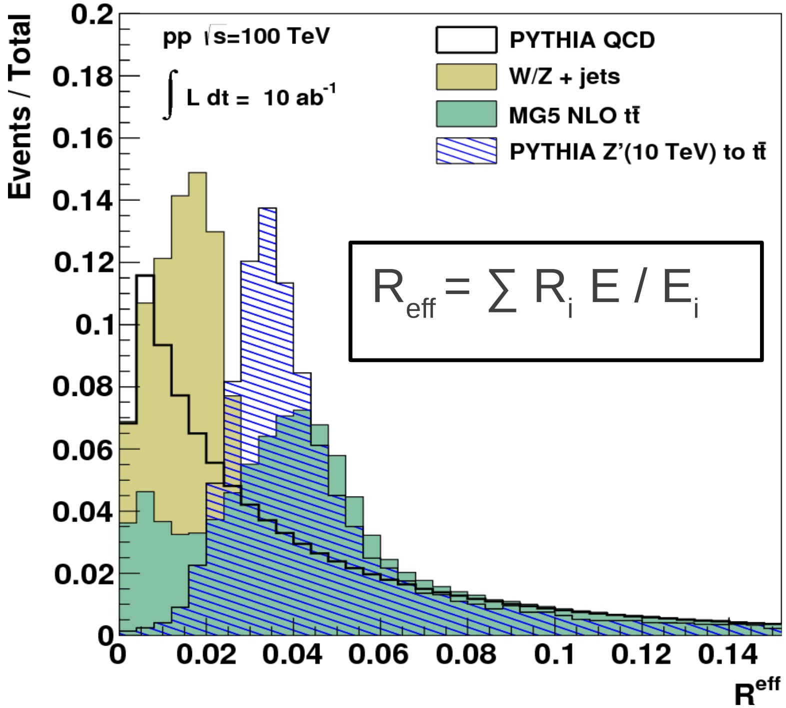
Jet Substructure Variables

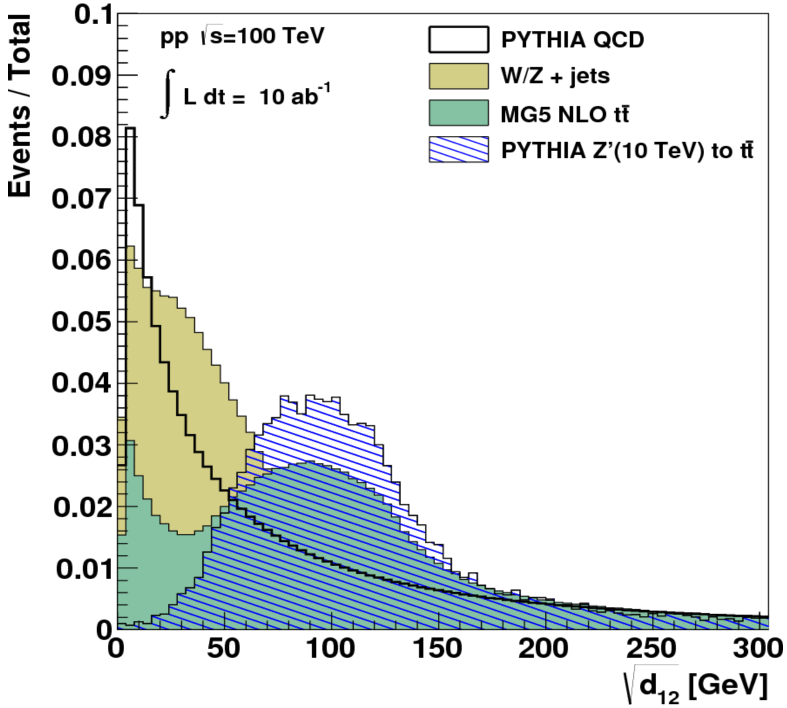
- ECC degree of elongation of jet shape
  - Optimized cut above ECC > 0.9
- Clear peak at Jet mass distribution at W/Z and top mass
  - Optimized cut above 140 GeV





Jet Substructure Variables



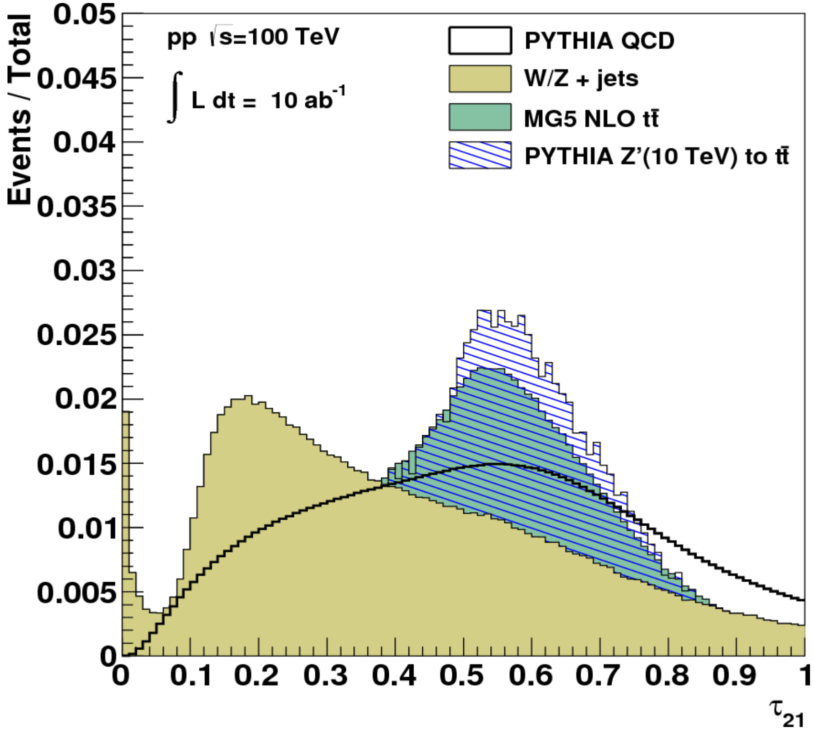


- R_{eff} – larger for jets initiated by massive particles
  - Optimized cut $R_{eff} > 0.03$
  - Highly correlated with Jet Mass
- Splitting scale d_{12} peaks at 1/2 Top Mass
  - Optimized cut $d_{12} > 50$ GeV

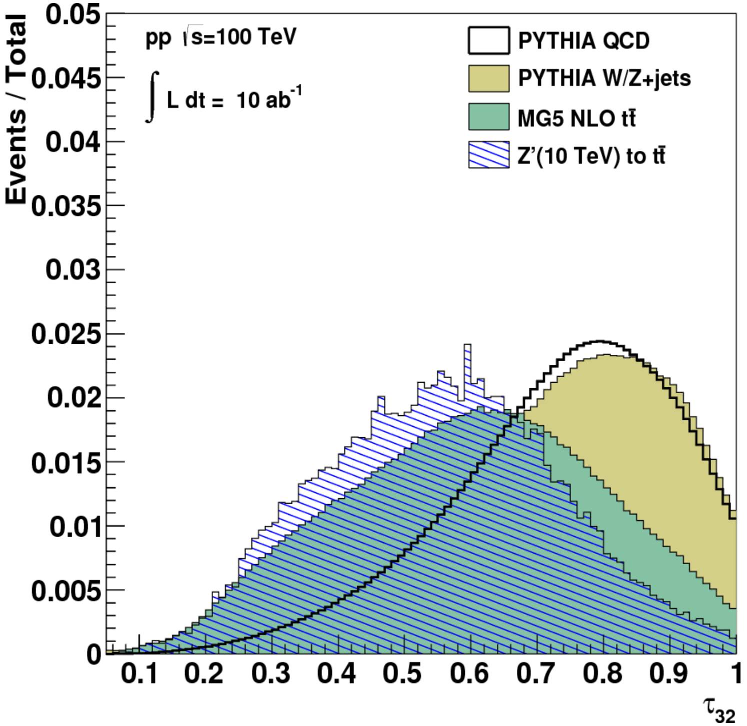
Jet Substructure Variables

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

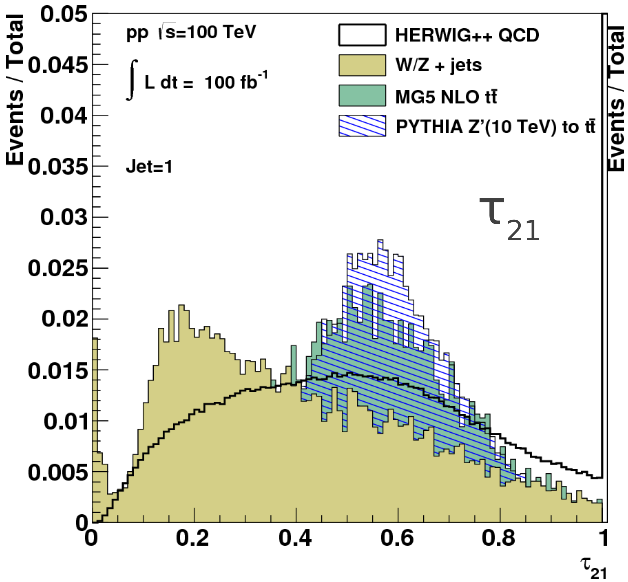
τ_{21}

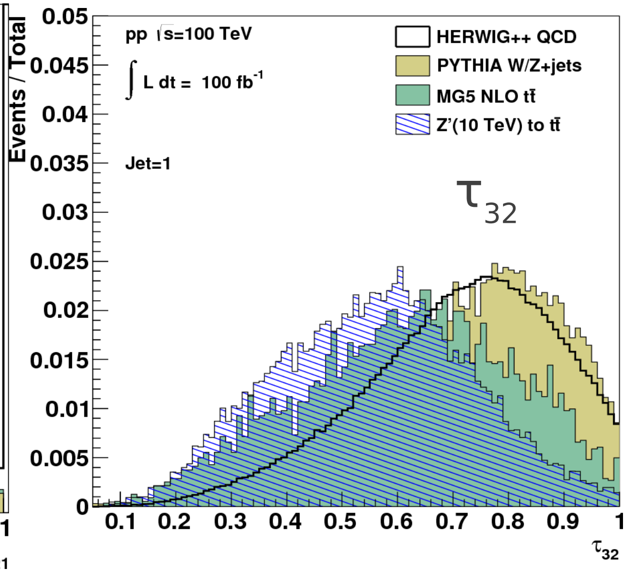


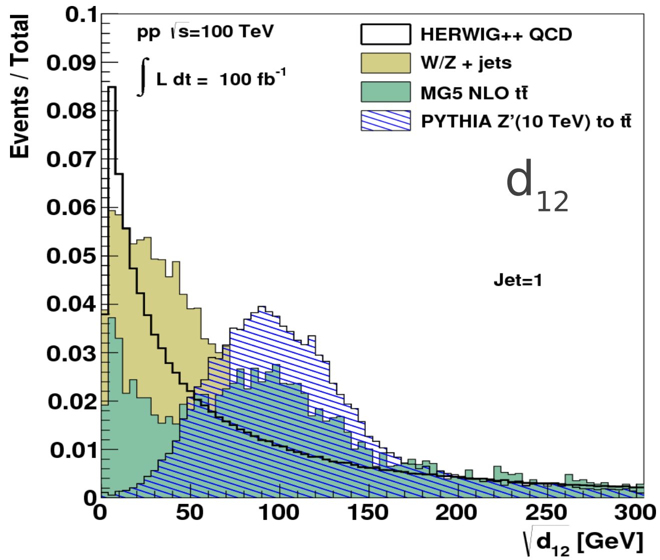
τ_{32}

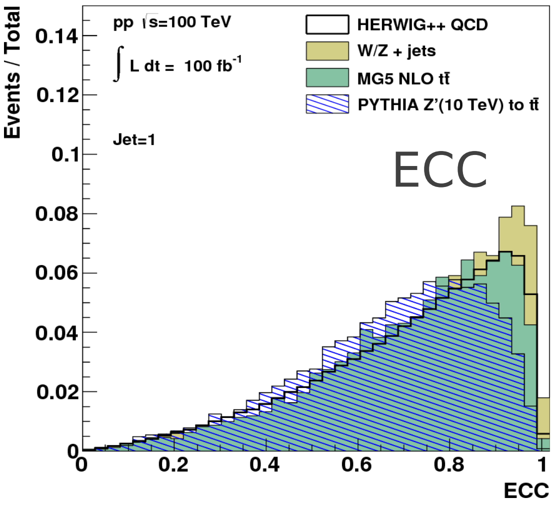


A Quick Look at Herwig++





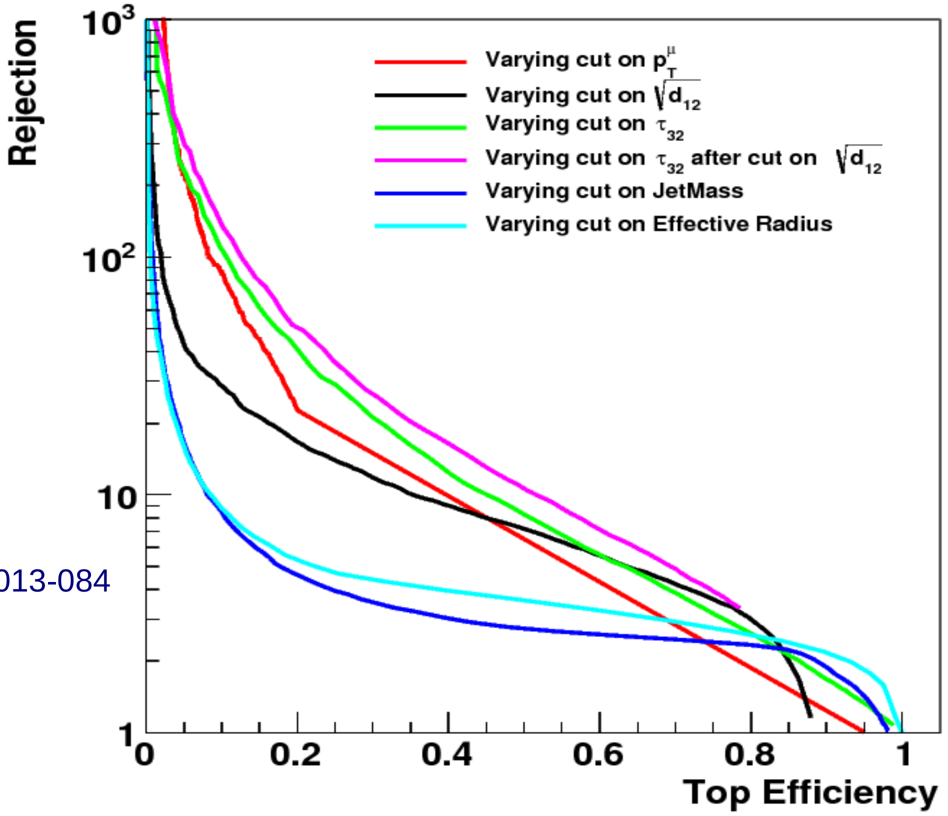




- HERWIG++ QCD dijet events give similar distributions to PYTHIA
  - Also include W/Z Brem. Events
  - Optimized selections at same values

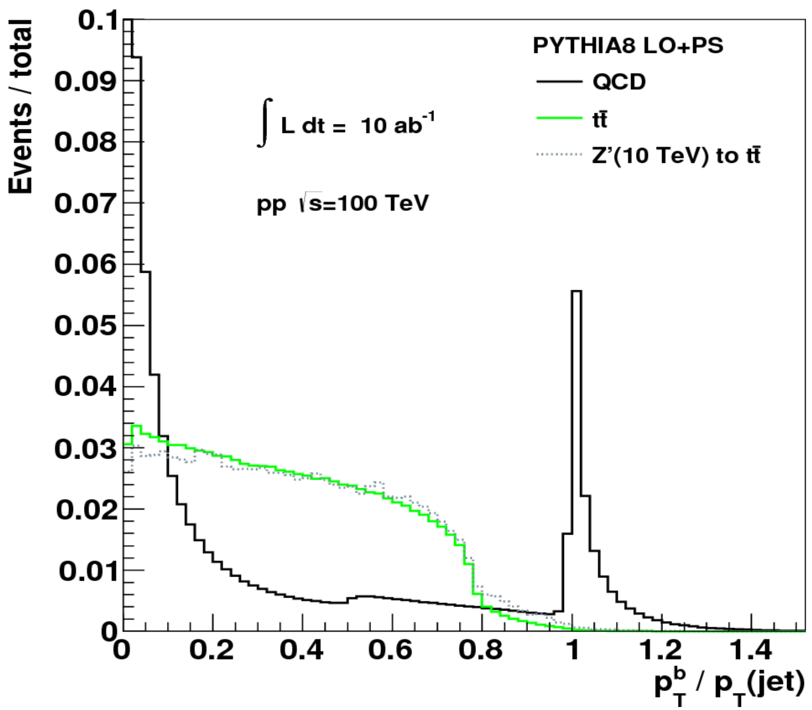
Identifying Top Jets

- 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 give best performance
  - 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
- Efficiency reduction from requiring a muon of any p_T in event
  - Excellent rejection power at low efficiency



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 p_T > 0.2 of jet



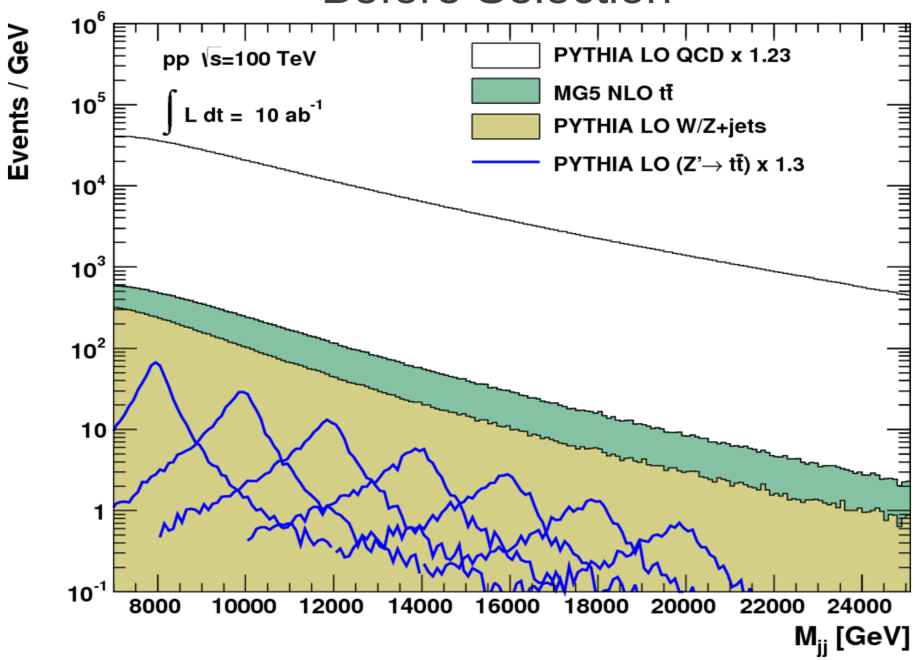
Physics Reach

- 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

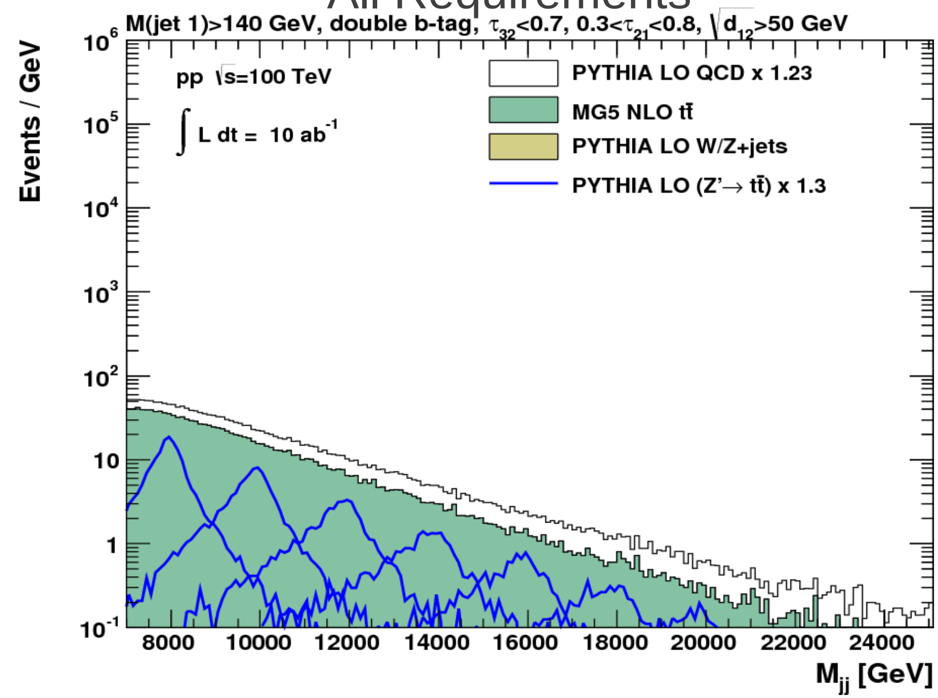
Cross Section X BR 95 %CL Limit

mass (TeV)	$\sigma \times$Br (fb) $Z^{0\prime}$ (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

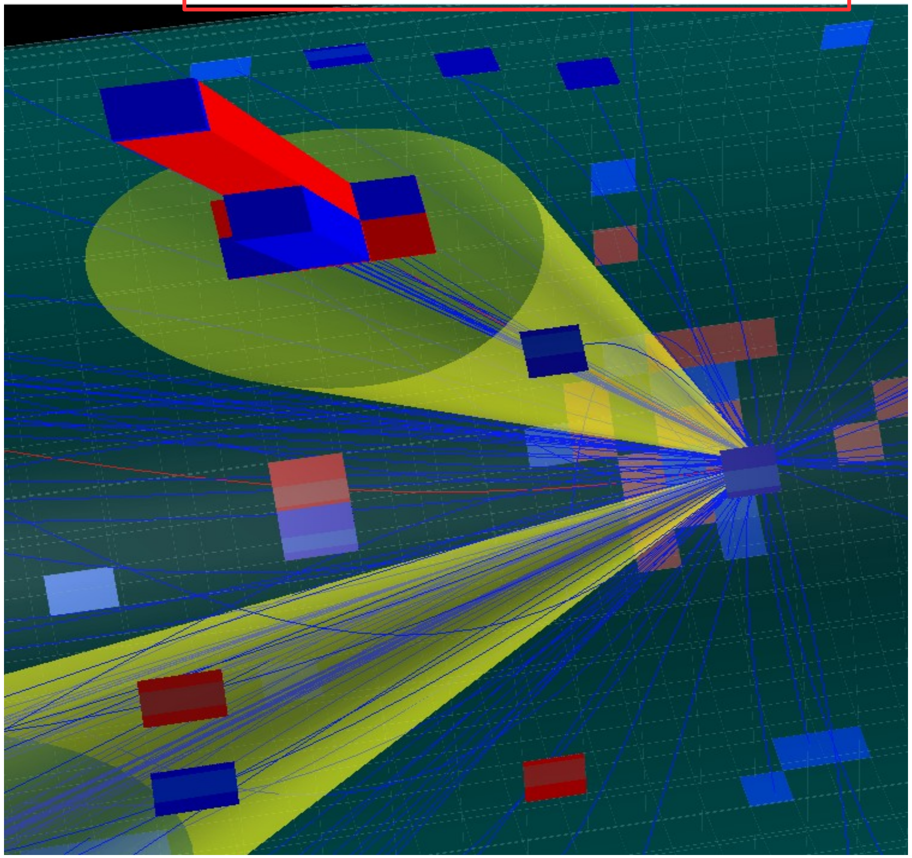


Implications on Detector Performance

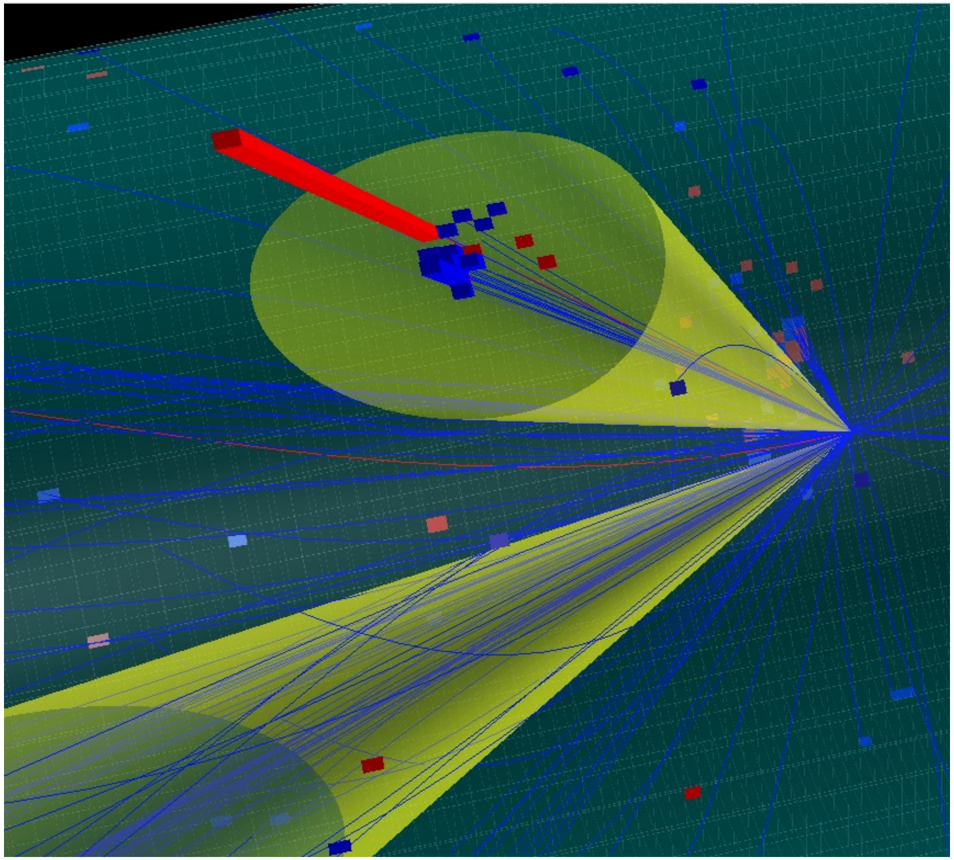
- **Precise tracking for high-efficiency b-tagging with small fake rate**
  - 70% efficiency & 1% fake rate for jets with $2 < p_T < 10$ TeV assumed in this study
- **High-granularity calorimeter to maintain LHC-like sensitivity to jet substructure variables for 10 TeV top's**
- **Large dynamic range for jet energy resolution**
- See S. Chekanov's talk for more implications!

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

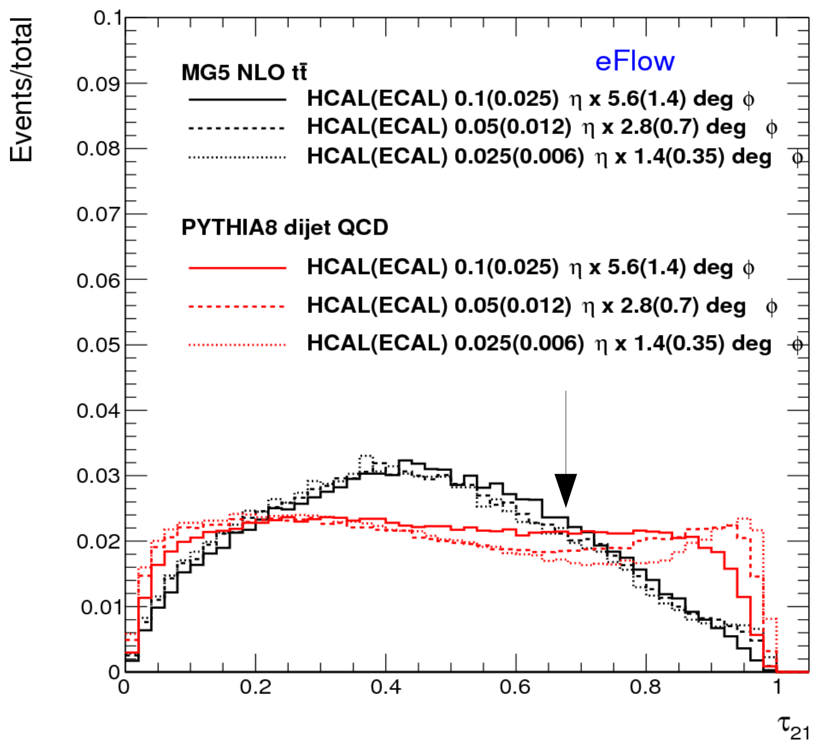
Note: this study uses a fast simulation.
We ignore effects from Molière radius when considering transverse profile of showers!

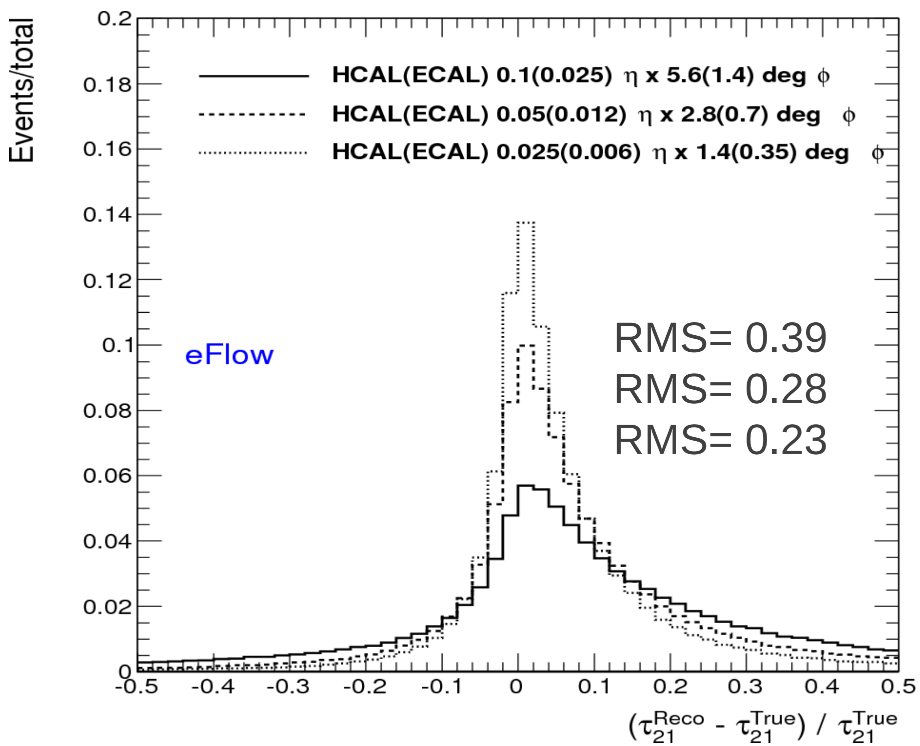
From S. Chekanov

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 for Snowmass Detector
- x2 (x4) granularity leads to 36% (67%) improvement in resolution

HepSim MC input + Delphes 3.2



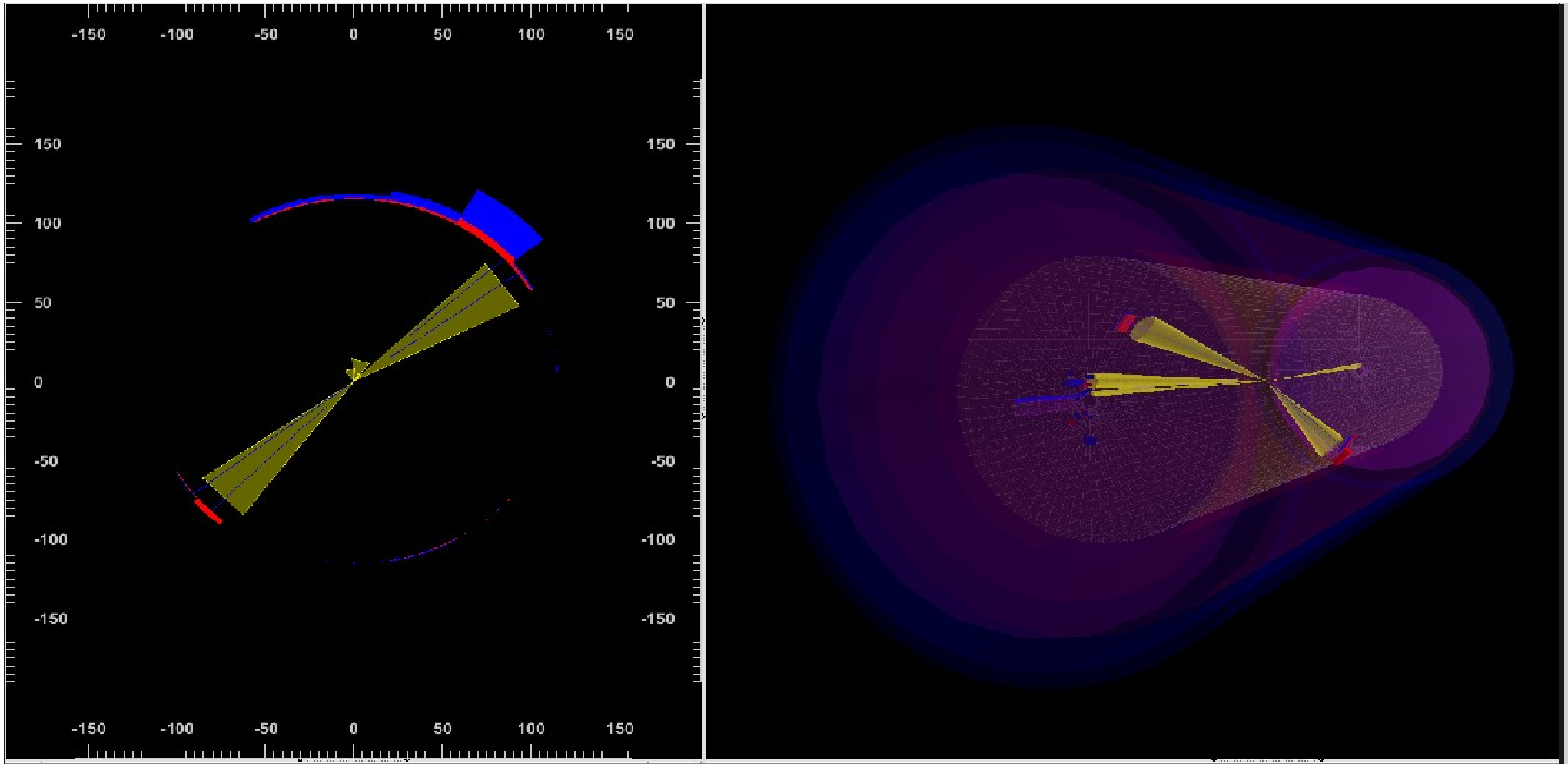


From S. Chekanov

Resonant VBS Di-Higgs Production in 4τ Final State

Phys. Rev. D 91, 114018 (2015)

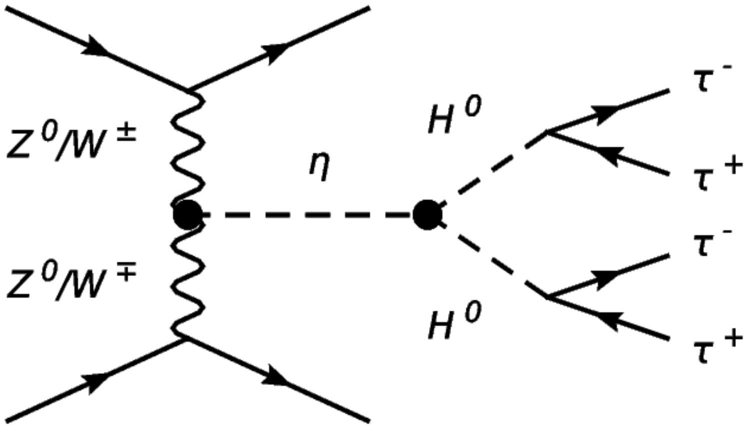
S. Chekanov, A. V. Kotwal, M. Low

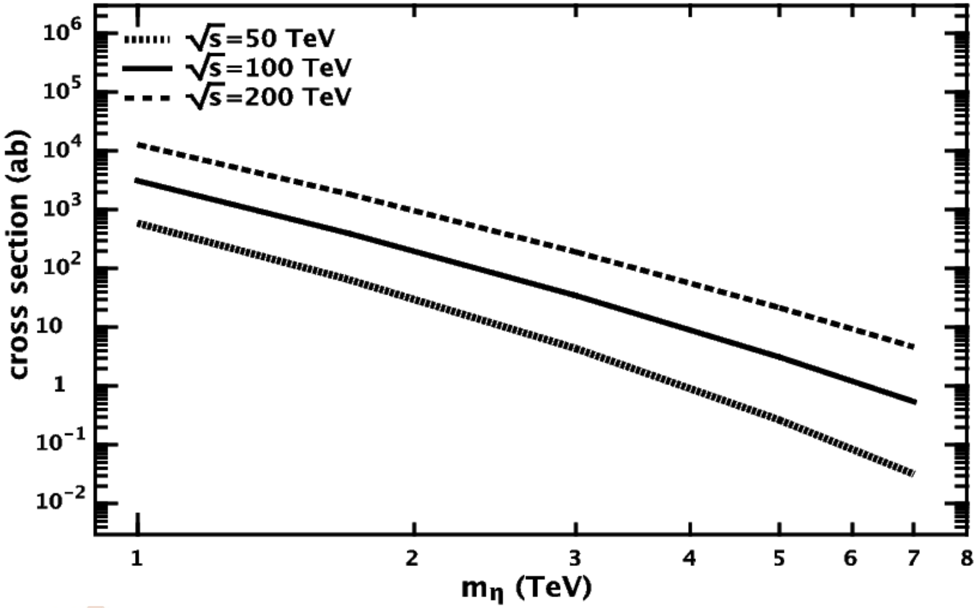


Delphes Sim.

Resonant VBS to di-Higgs

- **New composite η decays to SM Higgs**
  - Only longitudinal bosons contribute
  - Each Higgs decays to ττ
  - Final state two jets and 4τ's
    - Possible to use Large-R Higgs to ττ jets
    - Anti-k_T R=0.2 jets used for τ's
- **Main backgrounds**
  - SM processes:
    VV, HH, and VBS VV, HH

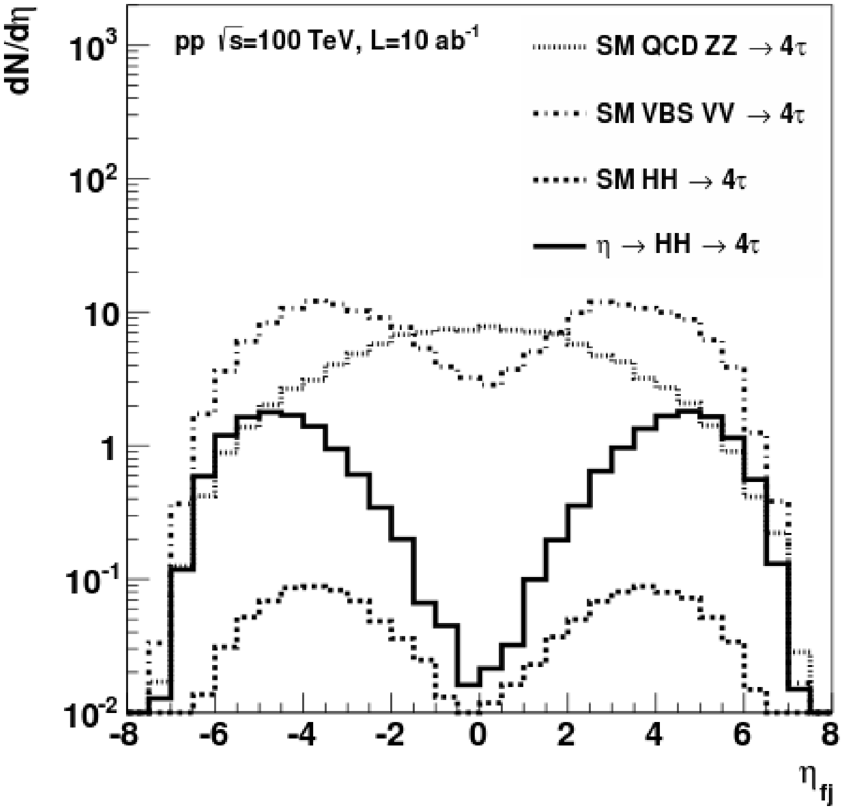




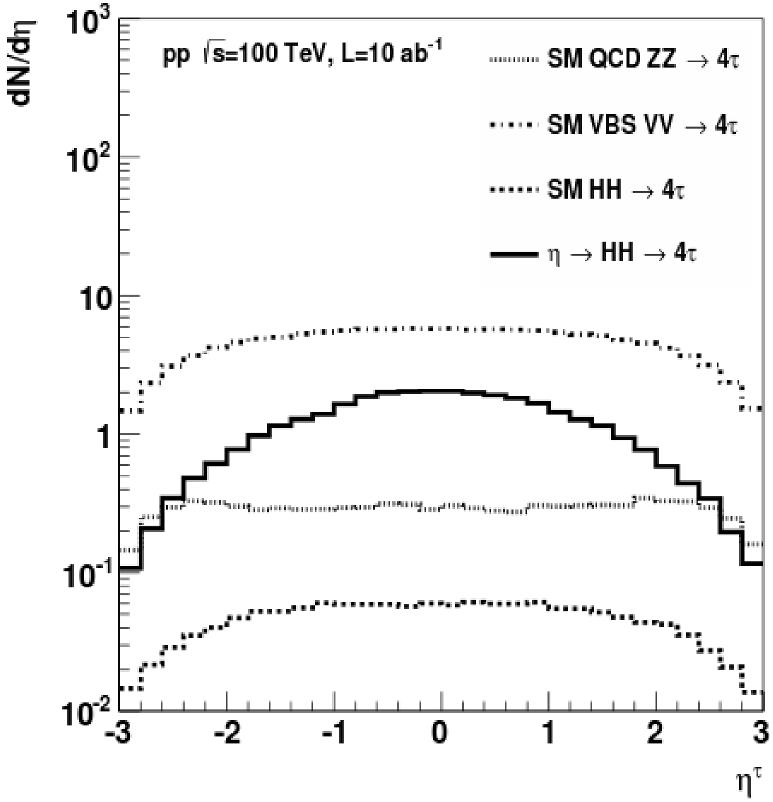
- **Assume LHC-like τ-ID performance**
  - Efficiency - 60%
  - QCD Fake rate ~2%
- τ-decays extremely collimated
  - For 1 TeV p_T ~2mm spread 1 m from interaction point
    - 85% One charged track plus EM showers

Pseudo-rapidity Distributions

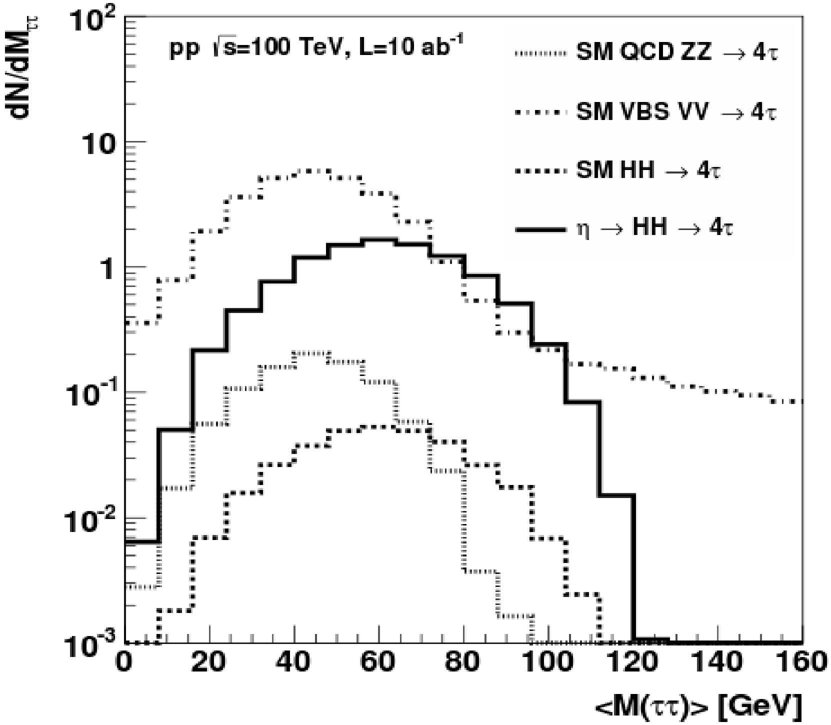
- Jets in VBS process dominantly forward
  - At 100 TeV Collider <η> ~5



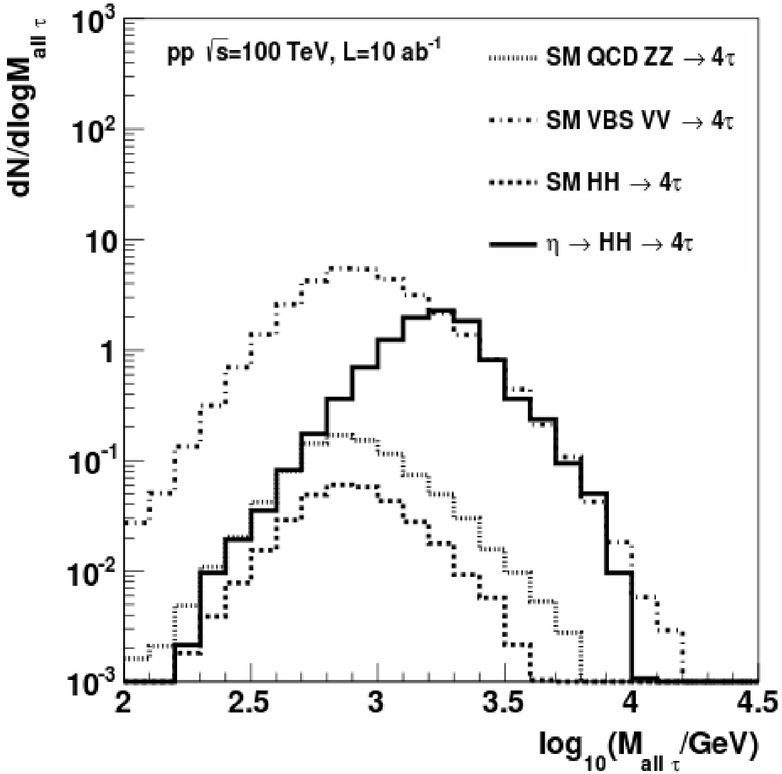
- Final τ's from η to HH more central than backgrounds
  - Generator level requirement $|\eta^\tau| < 3$



Two- and Four-τ Mass Distributions



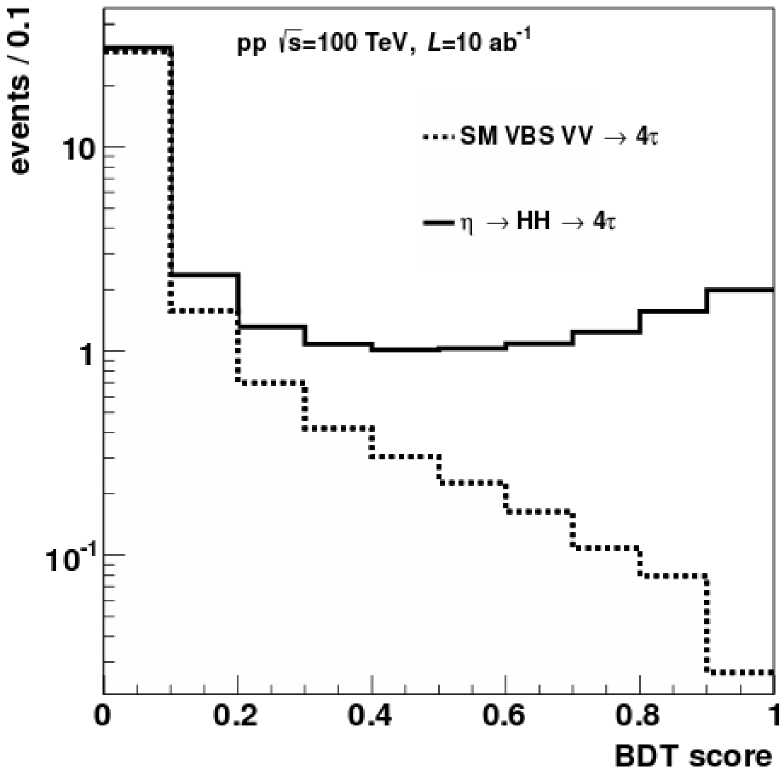
- All combinations of tagged jets tested to give masses consistent with Higgs
  - Four-τ mass shows peak for η
    - Further improved with E_T^{miss} included



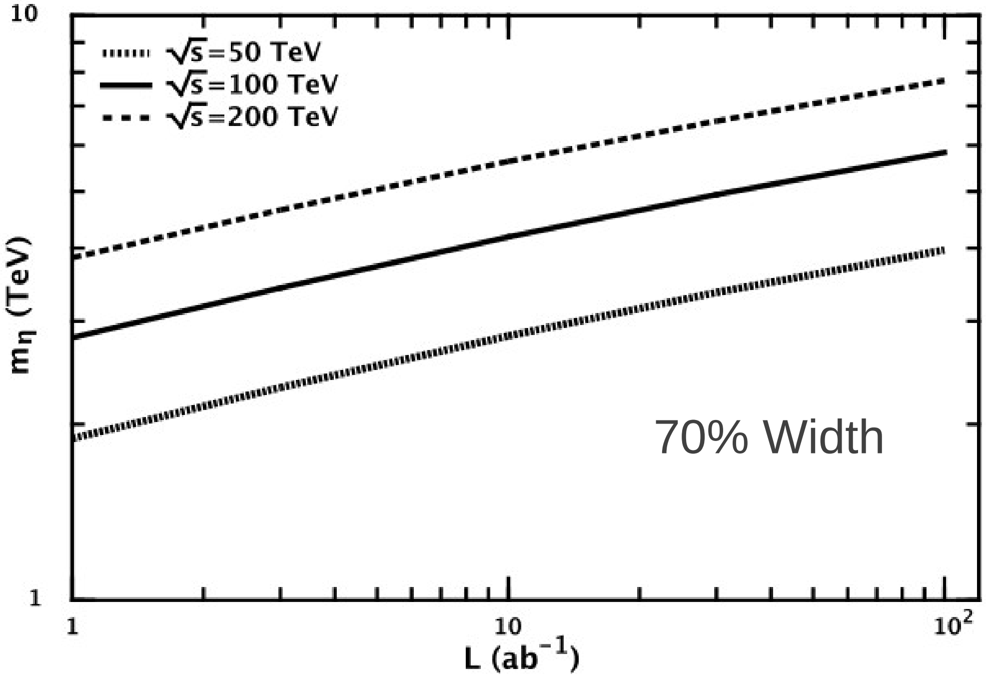
- Missing transverse momentum results in Higgs peak shifted off resonance

Boosted Decision Tree Performance

- SM backgrounds make hard cuts inefficient
- BDT built from event level kinematic distributions
  - TMVA BDT trained against irreducible SM VBS VV→4τ
- Used to compute likelihood of the background only hypothesis and test signal significance



Discovery Potential



$\mathcal{L}$ (ab^{-1})	$\sqrt{s} = 50$ TeV	m_η (TeV) $\sqrt{s} = 100$ TeV	$\sqrt{s} = 200$ TeV
1	1.89	2.81	3.85
3	2.31	3.42	4.65
10	2.83	4.18	5.63
30	3.36	4.94	6.60
100	3.97	5.83	7.74

- 5σ discovery sensitivity for 70% width η
  - Sensitivity follows power law scaling with Luminosity

$$m_\eta^{5\sigma} \propto \mathcal{L}^\alpha$$

    - Where α= 0.2 (0.16) for 20% (70%) width η
  - Sensitivity follows power law scaling with COM

$$m_\eta^{5\sigma} \propto (\sqrt{s})^\beta$$

    - For √s < 100 TeV, β = 0.5 (0.56) for 20% (70%) width η
    - For √s between 100-200 TeV β = 0.34 (0.43) for 20%(70%) width η

Summary

- Future proton colliders have great potential for searches for new resonances decaying to 3rd generation final states
  - For ttbar resonances the hadronic final state seems most promising
    - Jet substructure mass+shower variables combined with high efficiency b-tagging give sensitivity in the fully hadronic final state
    - **Possible 5σ discovery of up to 20 TeV Z' decaying to ttbar in 100 TeV pp data**
  - For τ-ID LHC-like performance critical
    - High-p_T τ-tagging must maintain LHC-like performance
    - **Possible 5σ discovery of up to 6 TeV η in di-Higgs to 4τ final state in 100 TeV pp data**
- These performance requirements have serious implications on detector design
  - Extremely fine granularity calorimetry well motivated by jet substructure variable resolution
  - Large pseudo-rapidity coverage needed to capture forward jets of VBS processes
  - Precision tracking to maintain b-tagging performance in increasingly dense environment
- Thank you!

Additional Material

MC Samples

- **Signal (LO QCD). PYTHIA8, MADGRAPH5**
  - $f \bar{f} \to$ Z0' with M=8,10,12,14,16,18,20 TeV. Pure Z' contribution. Γ/M=3%
  - $q \bar{q} \to g_{KK}$ with M=8,10,12,14,16,18,20 TeV. Pure g_{KK} contribution. Γ/M=16%
  - pp $\to \eta$ jj with $\eta \to$ HH $\to 4\tau$ with Γ/M= 20% and 70%
- **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 H/Z/W+jets)
    - Not too realistic, but the usage of “realistic” ALPGEN should not change conclusions

- **Monte Carlo samples from the HepSim repository:**
  - http://atlaswww.hep.anl.gov/hepsim/

hep-ph > arXiv:1403.1886

From S. Chekanov

Software Monte Carlo toolkit for this study

- **Monte Carlo samples from the HepSim repository:**
  - http://atlaswww.hep.anl.gov/hepsim/
  - Select p → ← p then 100 TeV

hep-ph > arXiv:1403.1886

- *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

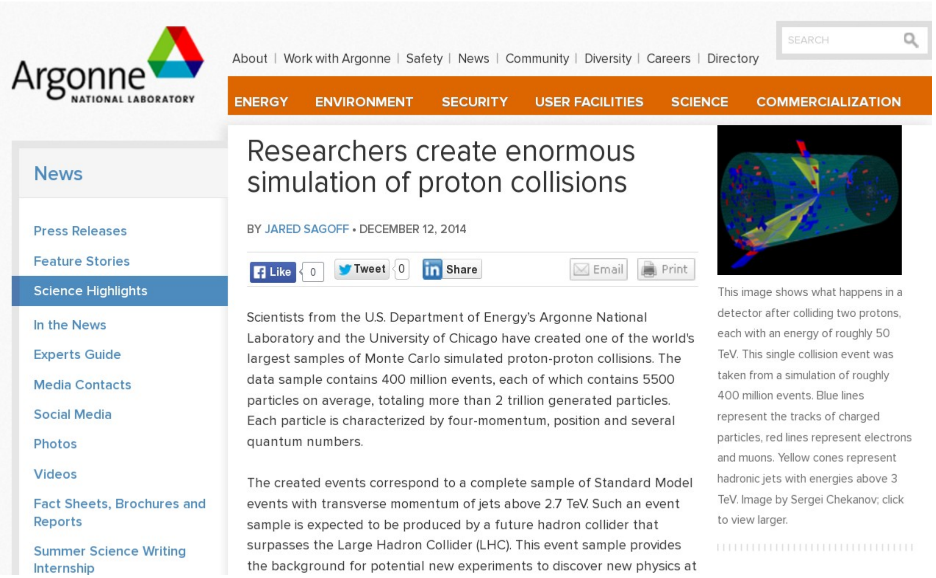
MC samples for this study

- 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

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.

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

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

From S. Chekanov