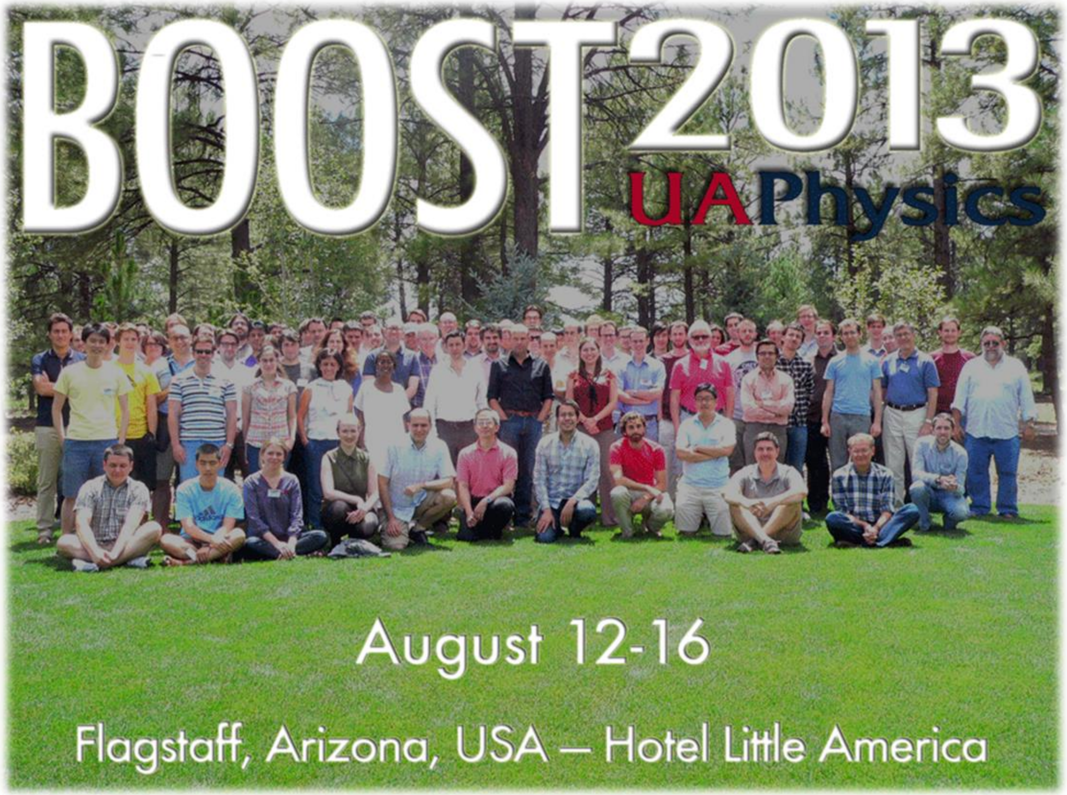
Summary of



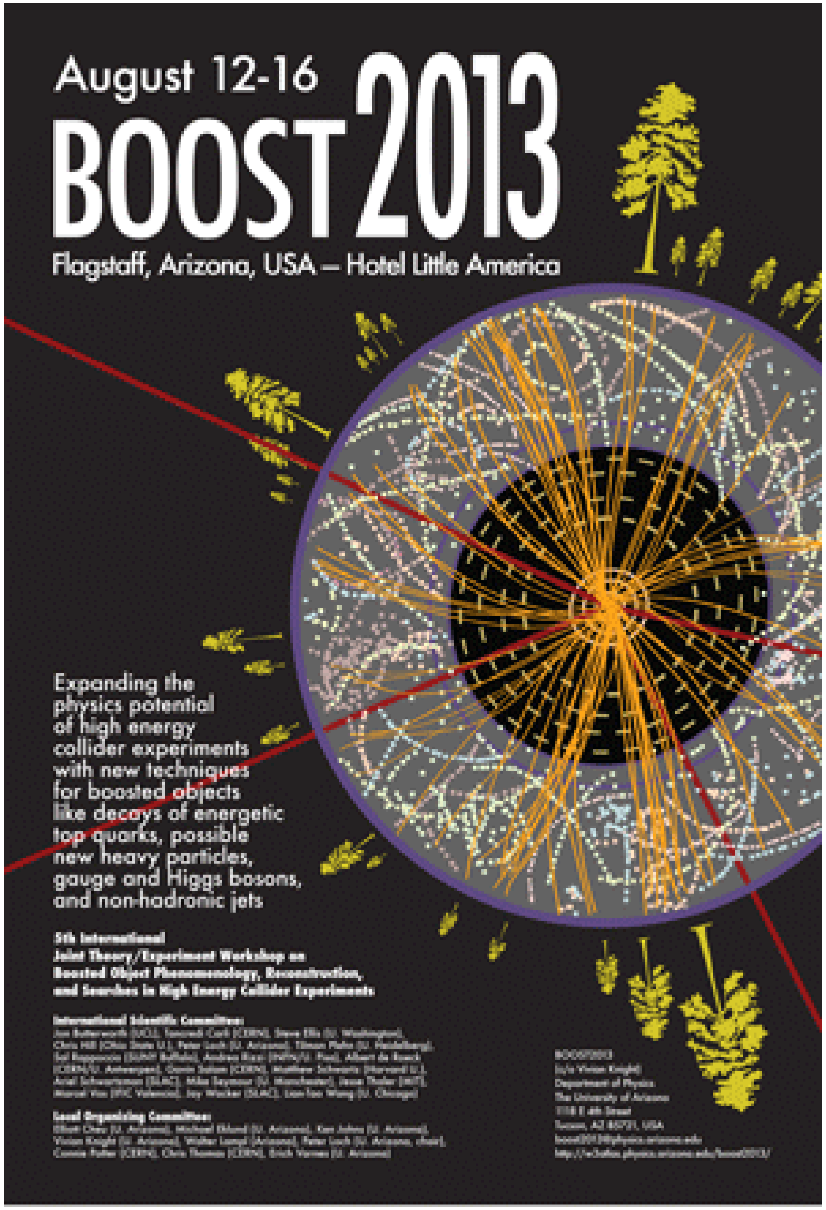
Peter Loch
University of Arizona

XLIII International Symposium on Multiparticle Dynamics
(IIT, Chicago, September 15-20, 2013)

BOOST2013 in Brief

International joint theory/experiment workshop on boosted objects in hadron colliders

- Fifth annual workshop organized by the Experimental Elementary Particle Physics group at the University of Arizona
  - Followed workshops at SLAC (USA), Oxford (UK), Princeton (USA), and Valencia (Spain)
  - About 80 attendants from theory, phenomenology, and experiment (ATLAS & CMS)
  - Format accommodates significant time for discussions
- Addresses all aspects of boosted object phenomenology, reconstruction, and use in searches
  - Hadron and lepton jets and their substructure
  - Recent new aspects include jet and sub-jet characterization in boosted and non-boosted scenarios – light quark/gluon jet separation, sub-jet b-tagging, …



This Talk

Introduction

- Motivations and technologies

Theory and phenomenology

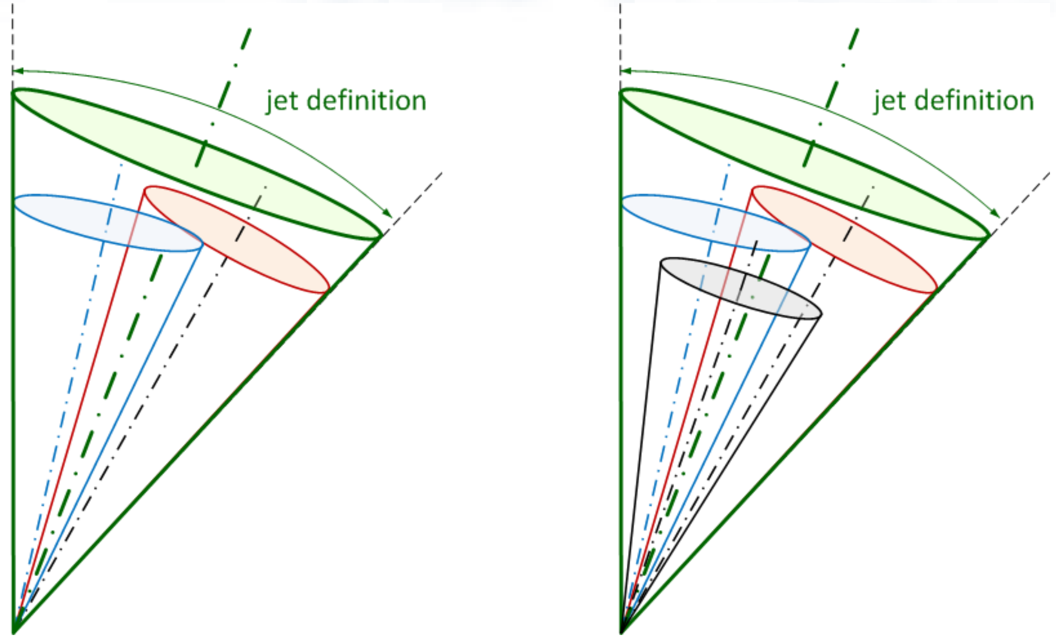
- Emphasis for BOOST2013 and the near future
- Selected first results from calculations
- News from technologies and observables
  - See also Jesse Thaler's talk this morning

Experiment (LHC)

- Performance evaluations in the presence of 2012 pile-up conditions
- Preparation for future challenges at LHC

Conclusions

Introduction



Motivation for Jet Substructure Analysis

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Plots from ATLAS Coll., arXiv:1306.4945 [hep-ex] (2013) (to be published in *JHEP*)

Kinematic reach at LHC

- Allows production of boosted (heavy) particles like W and Higgs bosons, and top quarks decaying into collimated (single-jet like) final states
  - All decay products are collected into one jet with size $R \approx 2m/p_{\mathrm{T}}$
  - Final state not resolvable with standard (narrow jet) techniques anymore
- Searches for new heavy particles with boosted (SM) decay products
  - Single jet mass indicative observable for new particle production

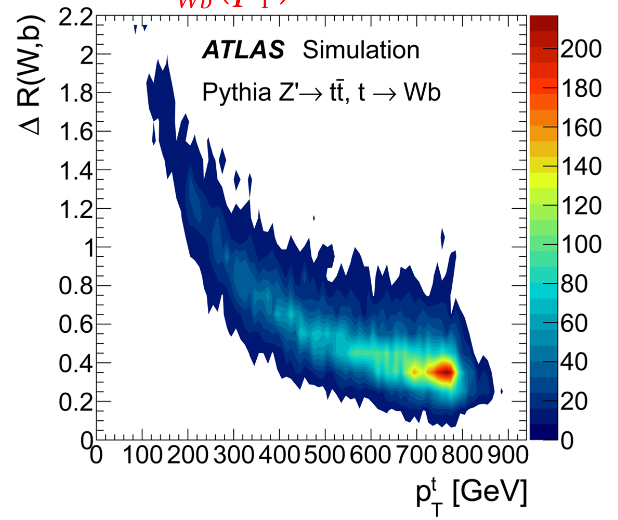
High luminosity

- Presence of additional proton-proton collisions in a bunch crossing can deteriorate single jet mass and shape measurements
  - Needs techniques to extract relevant internal jet energy flow structures for mass reconstruction from diffuse pile-up contributions severely affecting single jet mass scales and resolutions

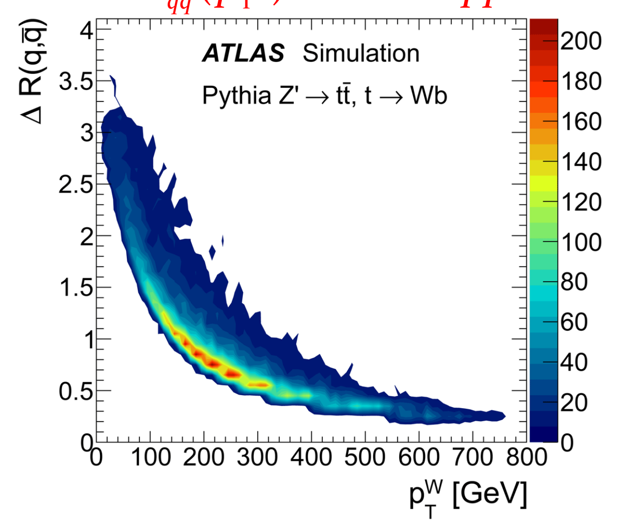
Jet substructure analysis

- Collection of techniques aiming at enhancing two- or three-prong decay patterns in single jets
  - Typically leads to suppression of QCD-like backgrounds from quark- and gluon jets with their typical parton shower and fragmentation driven internal flow structure

$\Delta R_{Wb}(p_{\mathrm{T}}^{t})$ in $t \to Wb$



$\Delta R_{q\bar{q}}(p_{\mathrm{T}}^{W})$ in $W \to q\bar{q}$



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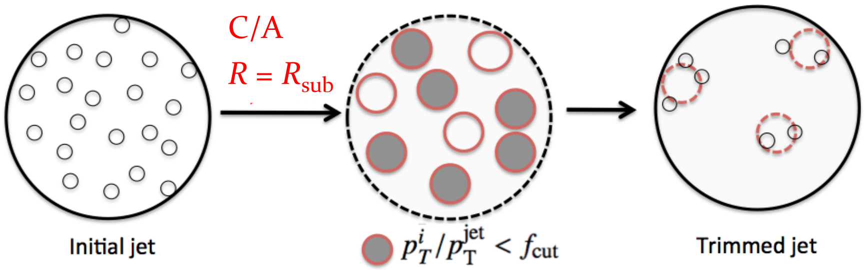
Trimming

D.Krohn, J.Thaler, L.Wang, *JHEP* **02** (2010) 84



$$R_{\mathrm{sub}} = \{0.2, 0.3\}$$

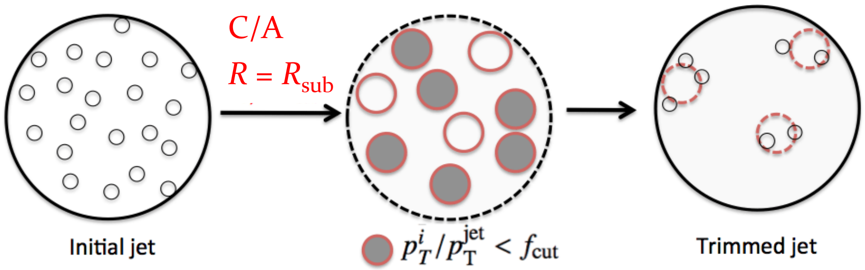
$$f_{\mathrm{cut}} = \{0.01, 0.03, 0.05\}$$

$$p_{\mathrm{T}}^{\mathrm{sub}} > f_{\mathrm{cut}} \times p_{\mathrm{T}}^{\mathrm{jet}}$$

Figures from ATLAS Coll., arXiv:1306.4945 [hep-ex] (2013) (to be published in *JHEP*)

Trimming

D.Krohn, J.Thaler, L.Wang, *JHEP* **02** (2010) 84

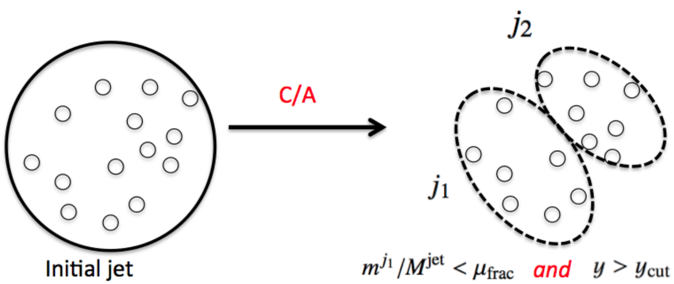


$$R_{sub} = \{0.2, 0.3\}$$

$$f_{cut} = \{0.01, 0.03, 0.05\}$$

Mass drop…

J.M.Butterworth *et al.*, *Phys.Rev.Lett.* **100** (2008) 242001



$$m_{j1} / m_{jet} < \mu_{frac}$$

$$y = \frac{\min[p_{T,j1}^2, p_{T,j2}^2]}{m_{jet}^2} \times \Delta R_{j1,j2} > y_{cut}$$

$$\mu_{frac} = \{0.20, 0.33, 0.67\},\ y_{cut} = 0.09$$

Figures from ATLAS Coll., arXiv:1306.4945 [hep-ex] (2013) (to be published in *JHEP*)

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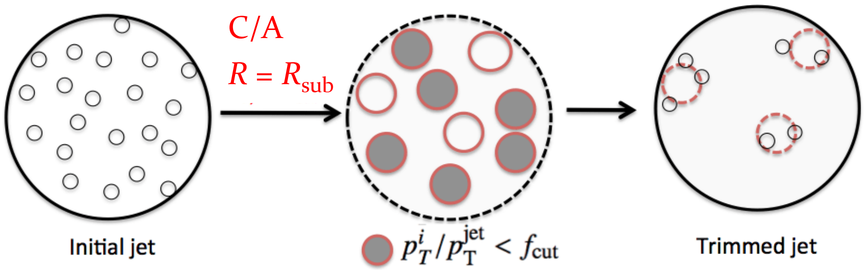
Trimming

D.Krohn, J.Thaler, L.Wang, *JHEP* **02** (2010) 84

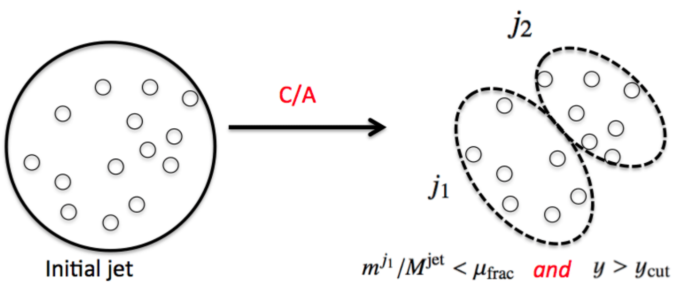


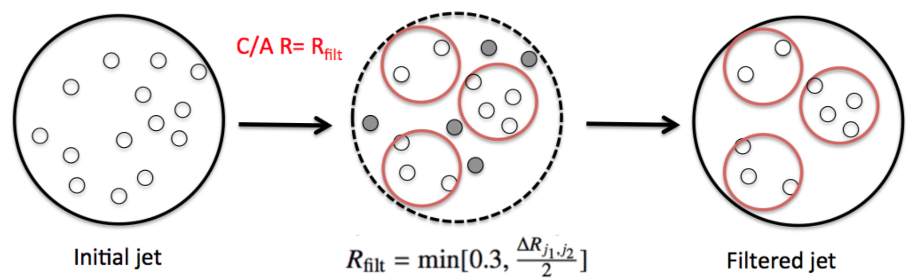
$$R_{sub} = \{0.2, 0.3\}$$

$$f_{cut} = \{0.01, 0.03, 0.05\}$$

Mass drop… … … … … … … …filtering

J.M.Butterworth *et al.*, *Phys.Rev.Lett.* **100** (2008) 242001





$$\mu_{frac} = \{0.20, 0.33, 0.67\},\ y_{cut} = 0.09$$

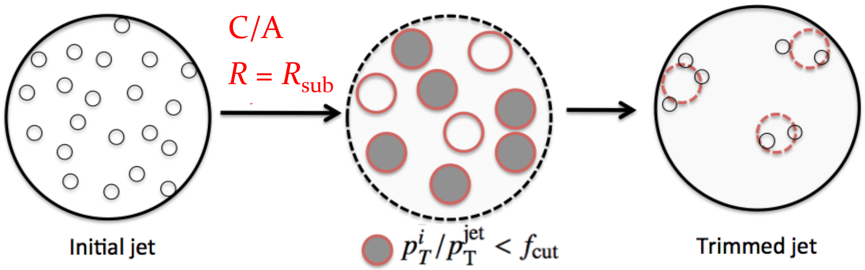
Figures from ATLAS Coll., arXiv:1306.4945 [hep-ex] (2013) (to be published in *JHEP*)

Jet Grooming Techniques

Figures from ATLAS Coll., arXiv:1306.4945 [hep-ex] (2013) (to be published in *JHEP*)

Trimming

D.Krohn, J.Thaler, L.Wang, *JHEP* **02** (2010) 84

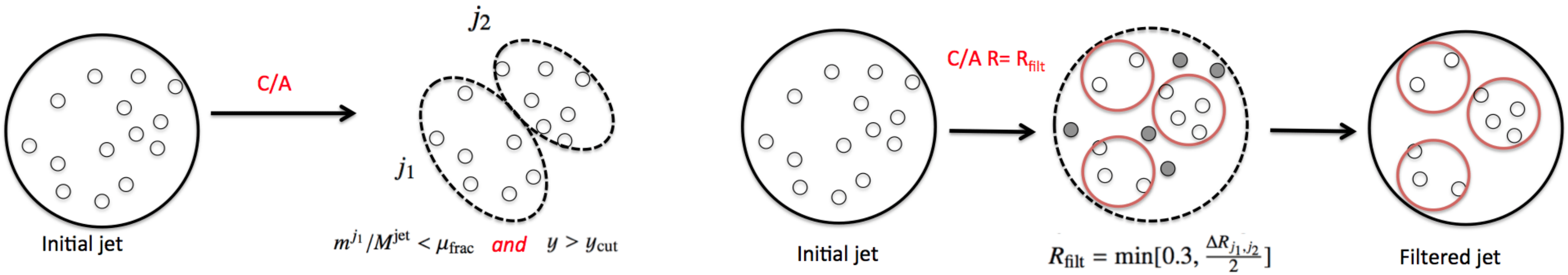


$$R_{\mathrm{sub}} = \{0.2, 0.3\}$$

$$f_{\mathrm{cut}} = \{0.01, 0.03, 0.05\}$$

Mass drop… … … … … … … …filtering

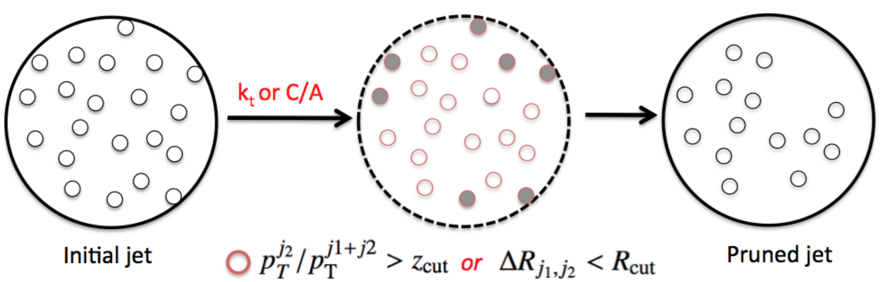
J.M.Butterworth *et al.*, *Phys.Rev.Lett.* **100** (2008) 242001



$$\mu_{\mathrm{frac}} = \{0.20, 0.33, 0.67\},\ y_{\mathrm{cut}} = 0.09$$

Pruning

S.D.Ellis, C.Vermillion, J.Walsh, *Phys.Rev.* **D80** (2009) 051501 & *Phys.Rev*. **D81** (2010) 094023



$$R_{\mathrm{cut}} = \{0.1, 0.2, 0.3\}$$

$$z_{\mathrm{cut}} = \{0.05, 0.1\}$$

Single jet mass

$$m_{\mathrm{jet}} = \sqrt{E_{\mathrm{jet}}^2 - p_{\mathrm{jet}}^2}$$

- Deduced from four-momentum sum of all jet constituents
  - Before and after any grooming
  - Constituents can be massive (generated stable particles, reconstructed tracks) or massless (calorimeter cell clusters)
- Can be reconstructed for any meaningful jet algorithm

k_T splitting scales

J.M.Butterworth, B.E.Cox, J.R.Forshaw, *Phys.Rev.* **D65** (2002) 096014

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

- k_T distance of last (d_{12}) or second-to-last (d_{23}) recombination
  - Hardest and next-to-hardest recombination considered
- Has expectation values for pronged decays
  - $d_{12} \approx (M/2)^2$ for particle with mass M undergoing 2-body decay

N-subjettiness

J.Thaler, K. Van Tilburg, *JHEP* **03** (2011) 15

$$\tau_N = \sum_k p_{\mathrm{T},k} \times \min[\delta R_{1k}, \ldots, \delta R_{Nk}] \Big/ \left(\sum_k p_{\mathrm{T},k} \times R \right)$$

- Measures how well jets can be described assuming N sub-jets
  - Degree of alignment of jet constituents with N sub-jet axes
- Sensitive to two- or three-prong decay versus gluon or quark jet
  - Highest signal efficiencies from N-subjettiness ratios τ_{N+1}/τ_N

Theory & Phenomenology

$$C_F C_A \left[-\frac{8\pi^2}{3} \ln^2\left(\frac{\tau_\omega Q}{2R\omega}\right) + \left(-\frac{8}{3} + \frac{88\pi^2}{9} - 16\zeta_3 \right) \ln\left(\frac{\tau_\omega Q}{2R\omega}\right) \right]$$

$$+ C_F n_f T_F \left(\frac{16}{3} - \frac{32\pi^2}{9} \right) \ln\left(\frac{\tau_\omega Q}{2R\omega}\right) + \cdots$$

The Grand Picture

Back to basics (Salam, Thaler, Schwartz,…)

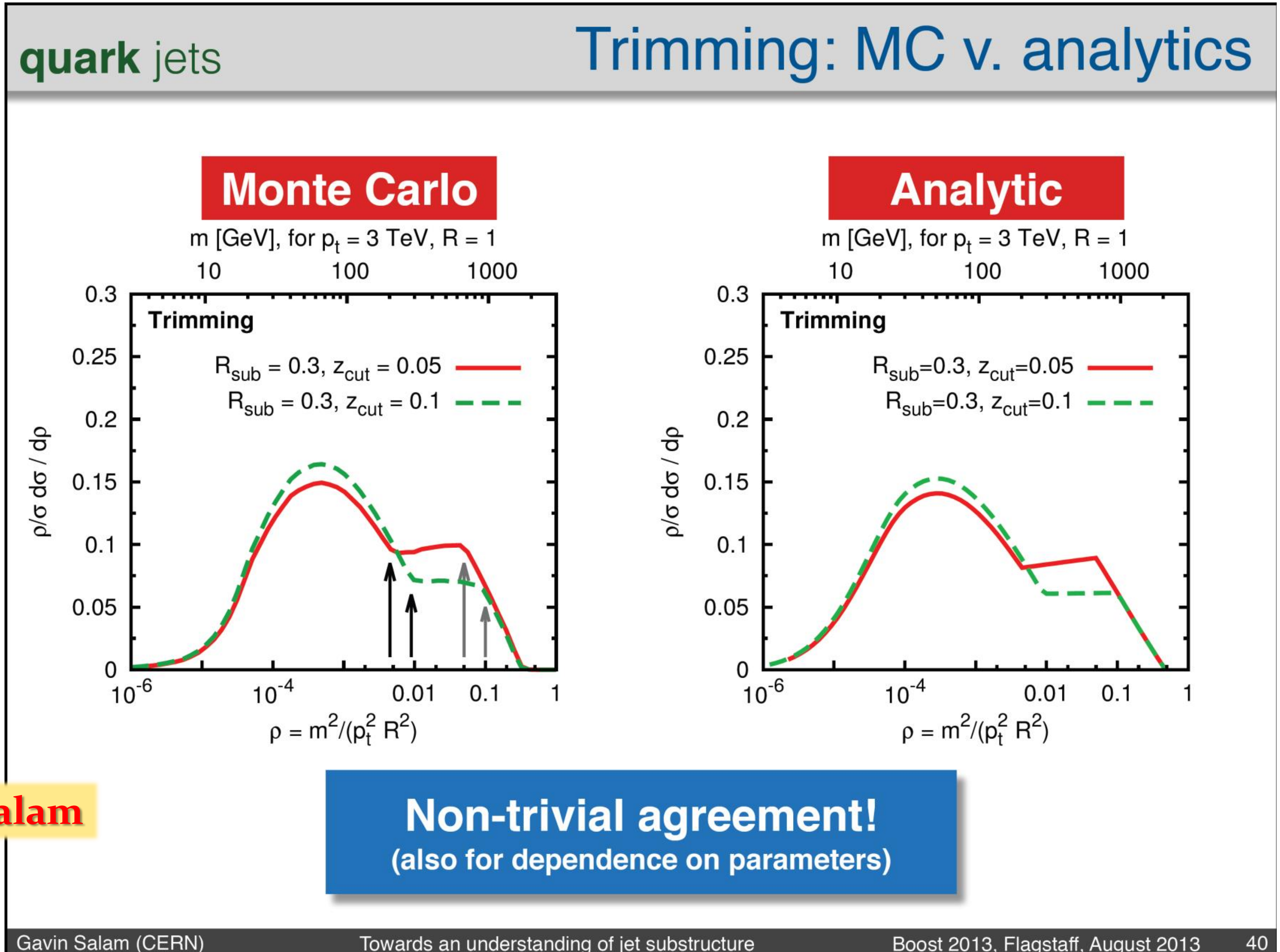
- Past focus on the development of technologies/tools/observables for jet substructure analysis
  - Trimming, (mass drop) filtering, pruning, shower decomposition, *Q*-jet, …
  - *N*-subjettiness, planarity, centrality, energy-energy correlations, …
- Now shift/extend focus to precision calculations for jet substructure observables
  - Check "sanity" of numerical approaches like e.g. Pythia
  - Understand why an algorithm works and re-invest this understanding in better algorithms

Evolution of calculation attempts (Thaler)

- Calculations for precision (BOOST2012) – try to calculate something!
  - Focus on jet mass
- Calculations for insight (BOOST2013) – back to basics!
  - Understanding to which extend the large number of developed jet substructure technologies and observable probe the same physics
- Calculation for liberation (BOOST2014) – relax IR safety requirements!
  - Analytical understanding of IR unsafe observables

Back to Basics Examples I

Calculate effect of trimming



G. Salam

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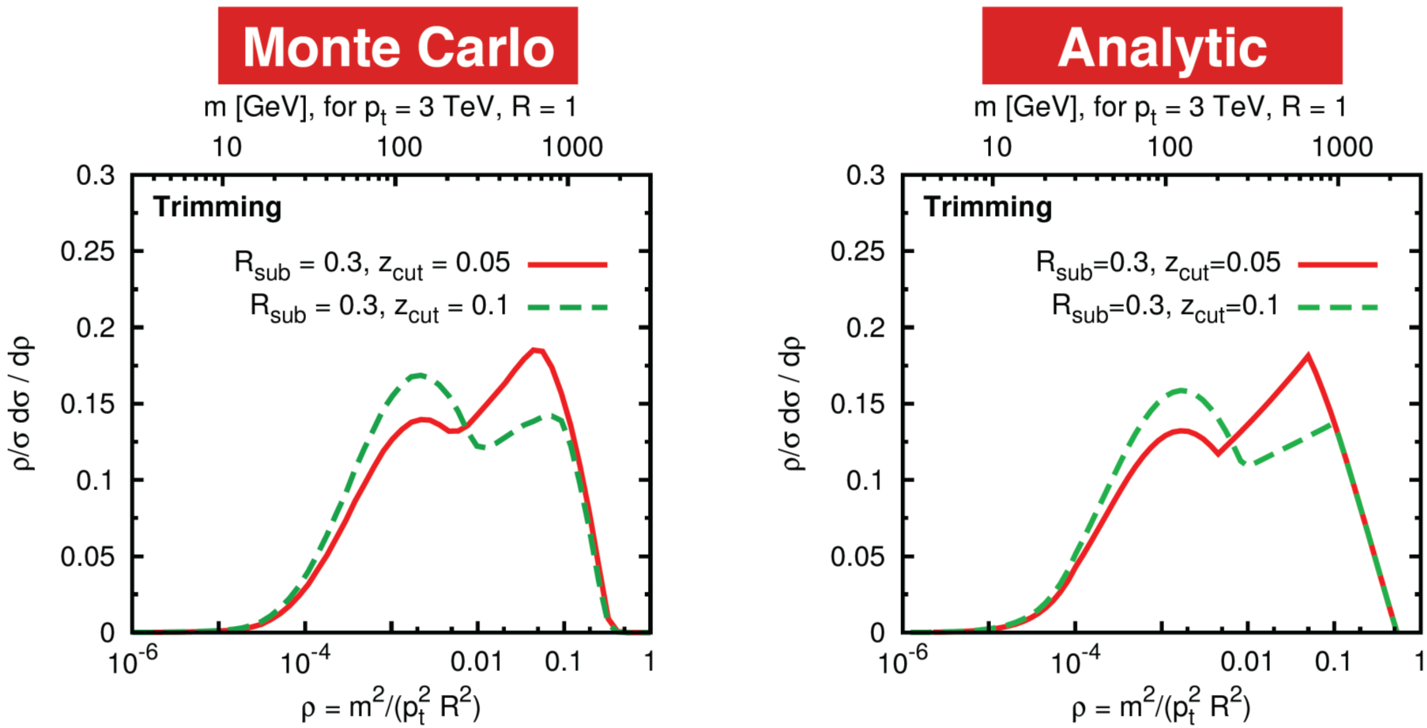
Calculate effect of trimming

gluon jets

Trimming: MC v. analytics



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Non-trivial agreement!
(also for dependence on parameters)

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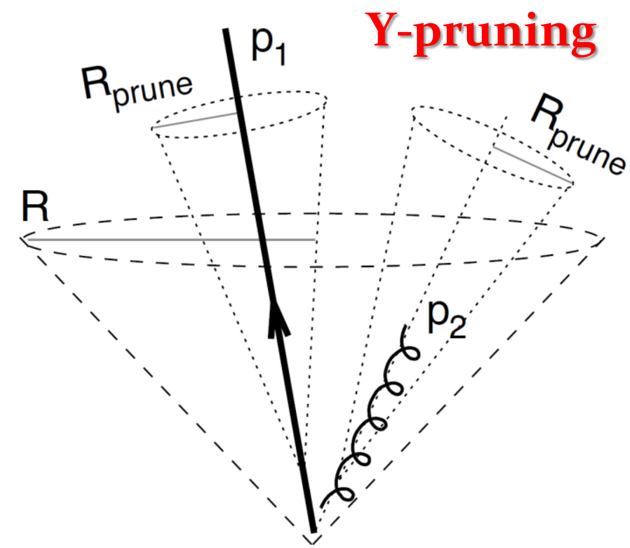
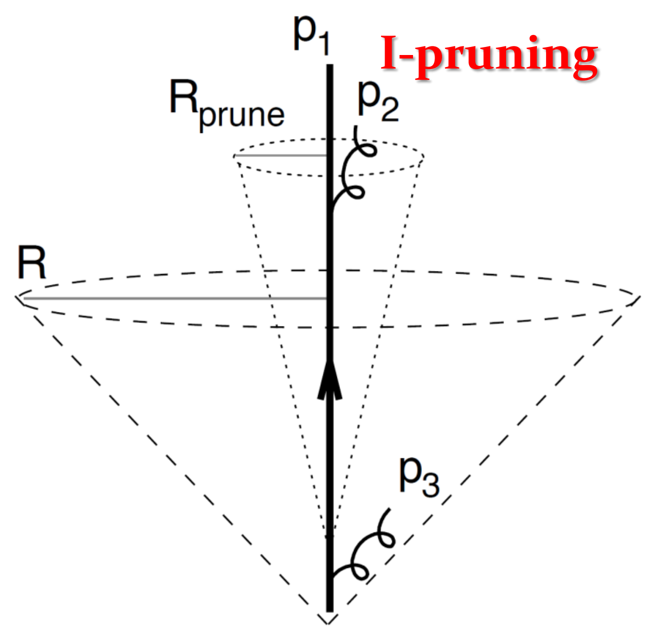
Pruning with analytical methods

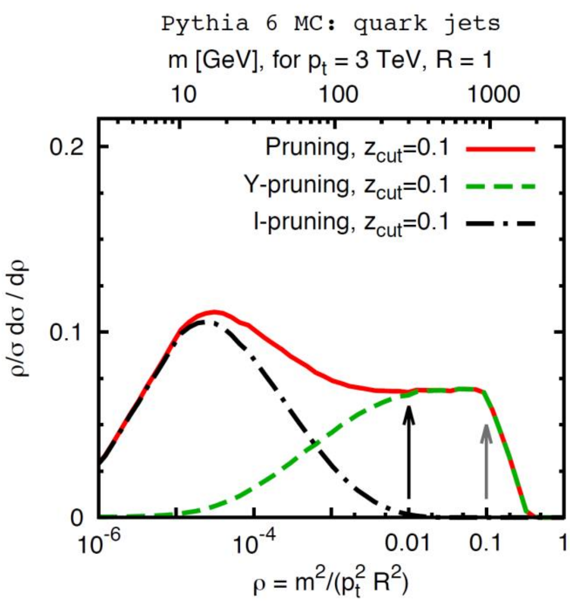
Attempt to reproduce pruned jet mass spectrum from Sudakov calculations

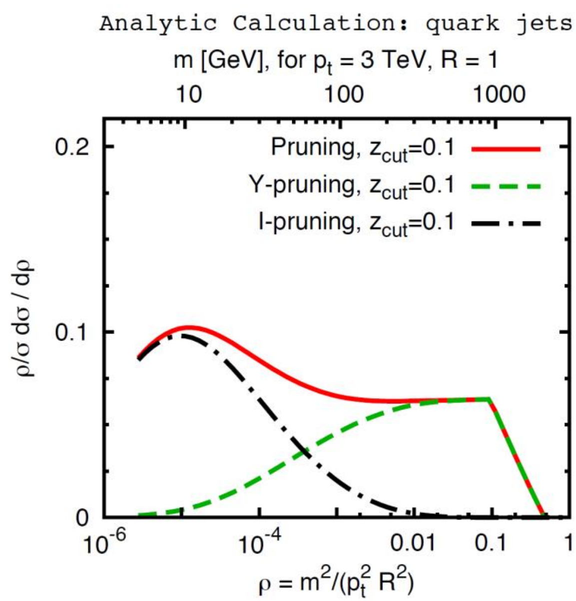
Consider two different pruning scenarios separately – Y-pruning and I-pruning

S. Marzani









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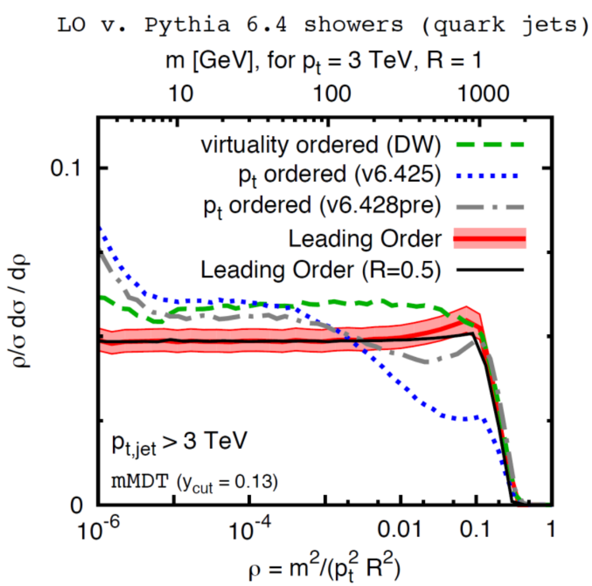
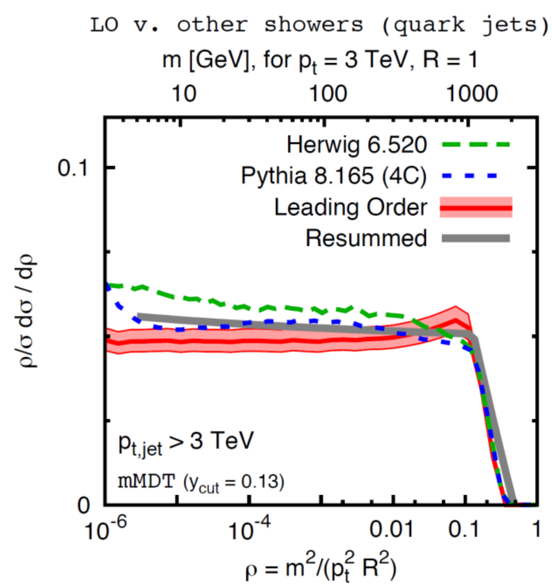
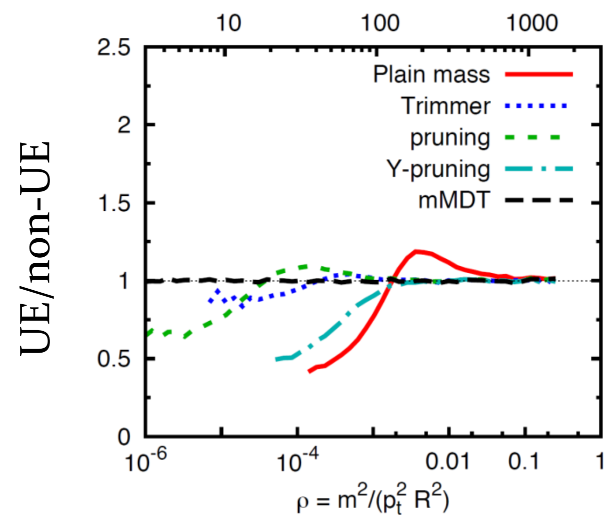
Mass drop tagger with analytical methods

- Inherently complicated to calculate jet mass spectrum after mass drop tagger (MDT)
    - New approach: use transverse mass order to pick sub-jet (not mass) – modified MDT (mMDT)
- mMDT shows interesting features
    - Insensitive to underlying event
    - Can be calculated
    - Unraveled bug in Pythia6.425 (fixed in 6.428pre)

S. Marzani







Other Selected Topics from Theory

Algorithms

- Work on separating hard kinematics from parton shower and fragmentation features in jet (Curtin)
  - Analysis of information content from substructure techniques and observables
- Shower decomposition (Soper et al.)
  - Attempt to decompose jets according to splitting kernels in parton showers – sensitive to jet substructure
- Application of image processing strategies to jet structure (Cogan et al.)
  - Fisher discriminant based technique
- Telescoping jets (Chien et al.)
  - Analyze jets with increasing size *R* and evaluate (change of) substructure information

Precision calculations

- Calculate substructure from tracks in jets (Waalewijn)
  - Attempt to analytically understand substructure using tracks only – highly resistant to pile-up effects
- Semi-classical approach to jet substructure (Tseng)
  - Variation of distance scale motivated by semi-classical approaches – R^3 and transverse mass scales

Experiment

The experimental progression*:

BOOST2010: *"These aren't your daddy's jets"*

BOOST2011: *"First data"*

BOOST2012: *"Kids in a candy store"*

BOOST2013: *"Bringing substructure into the mainstream"*

*according to D. Miller (U Chicago) in his summary for BOOST2013

Experimental Contributions

Precision measurements

- Detailed calibration and validation schemes
  - Jet mass, internal distance scales, *N*-subjettiness
- New approaches
  - Q-jets

Jet substructure at work

- Tagging
  - New tagging schemes using substructure techniques and/or sub-jets
  - Final state (W, top) tagger performance evaluations
- Searches for new physics
  - Looking for e.g. massive particles decaying into a jet in resolved and boosted scenarios

Pile-up mitigation in high luminosity environments

- Can techniques refined for today's (2012) LHC conditions still be successfully applied in the future (2015 and beyond)?
  - Loss of precision in reconstruction of observables – effect on discovery potential (e.g., signal/background)

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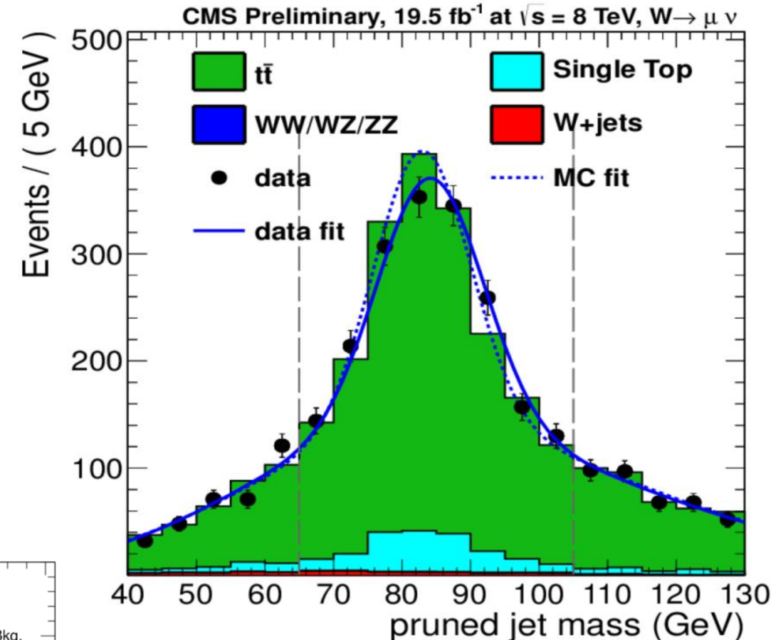
Jet mass measurements

Jet mass good discriminator in searches – calibrated mass scale important

Calibration requires validation!

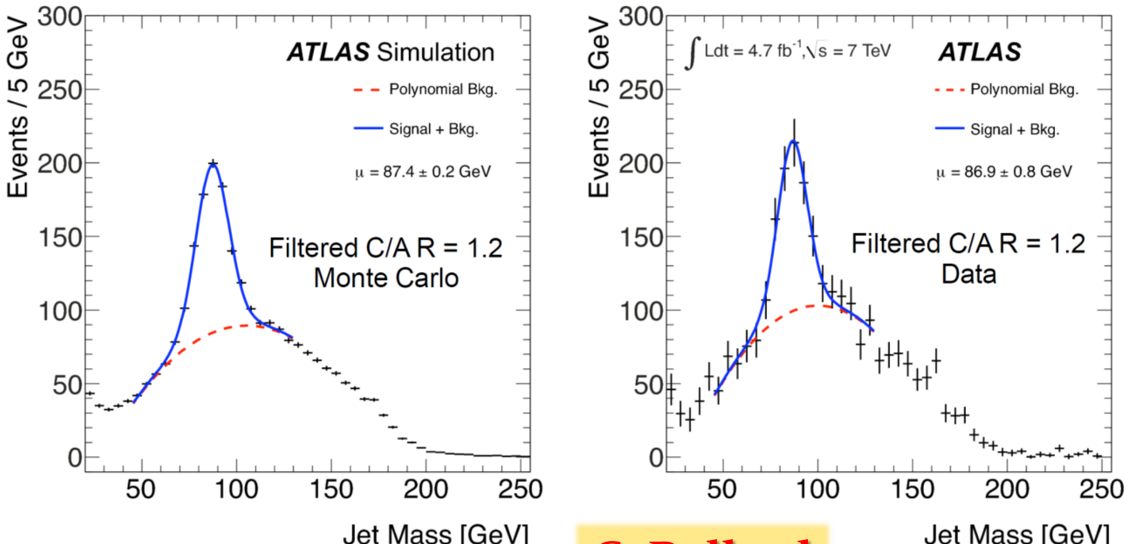
Hadronic W decays provide reference for jet mass

CMS JME-13-006



P. Maksimovic

ATLAS-PERF-2012-02 (arXiv:1306.4945)

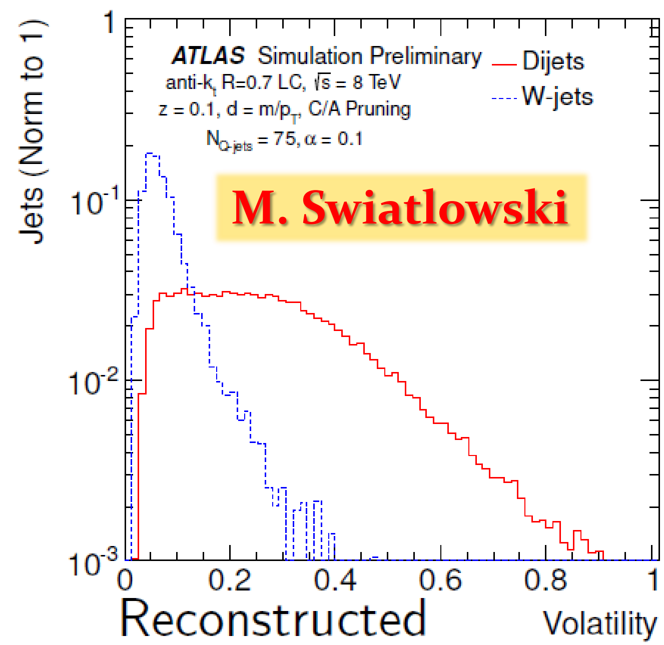


C. Pollard

Applying New Approaches

Q-jets

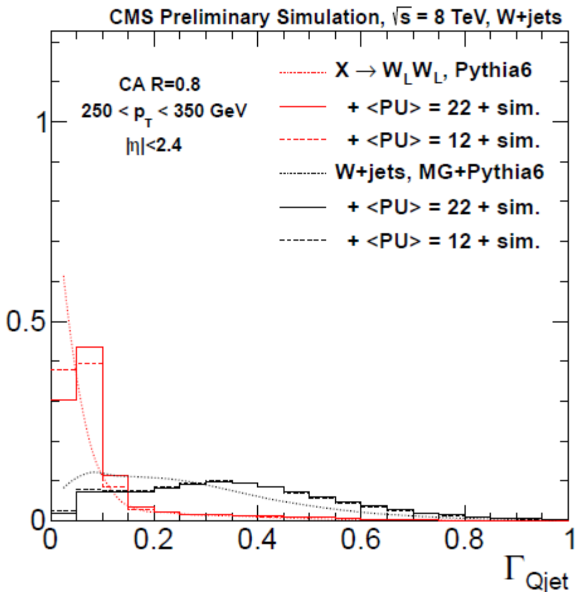
- Tests several possible recombinations in a given jet
  - Parton shower/fragmentation cannot be exactly undone in experiment
  - With some respect any recombination attempt is arbitrary
  - Jet is unchanged if all inputs are always included – need to introduce randomness in jet grooming to change e.g. the jet mass
- Based on pruning
  - Select random pairs instead of minimum distance pairs – randomness controlled by rigidity α
  - Calculate scoring variable "volatility" describing the relative width of the jet mass distribution arising from the various combinations – still for one jet only!
- Analysis
  - Distribution of volatilities in jet sample is expected to be sensitive to jet origin – massive particle or light quark/gluon jet

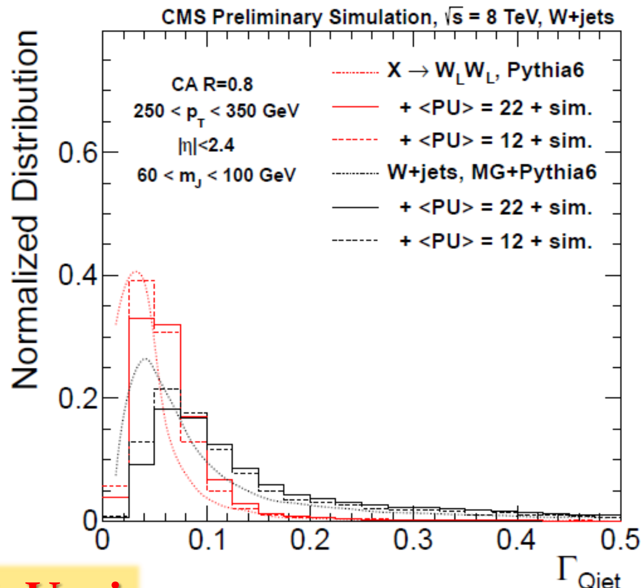


Q-jets in the Experiment I

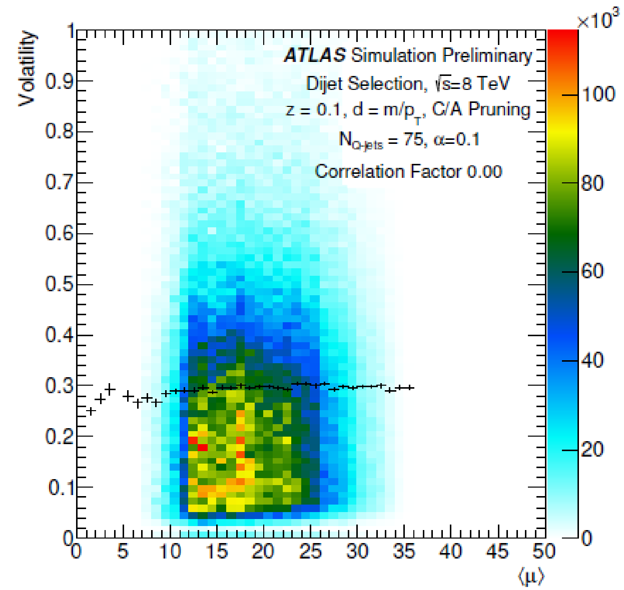
Volatility rather insensitive to pile-up

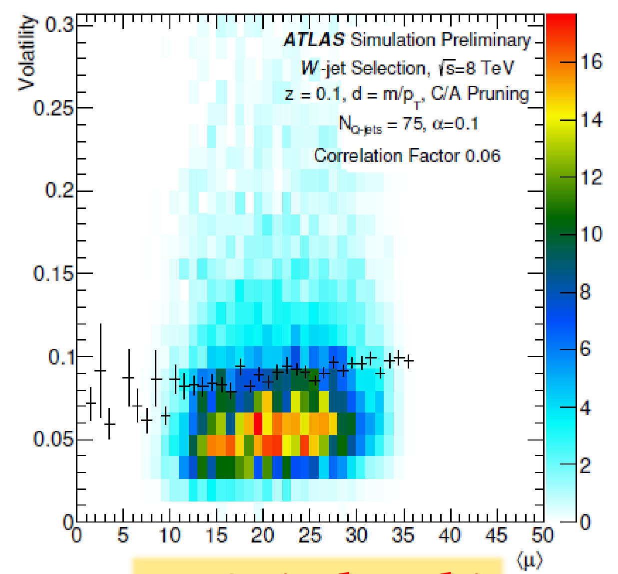
Diffuse pile-up contribution in jets is even more randomized





E. Usai





M. Swiatlowski

Excellent signal versus background discrimation

Also after full detector simulation

Q-jets in the Experiment II

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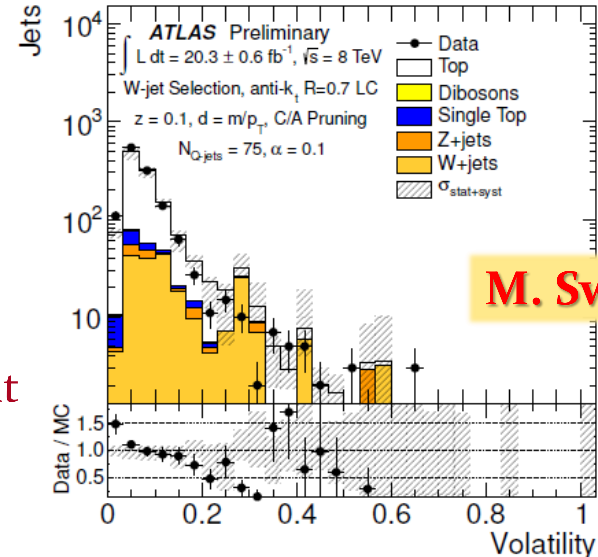
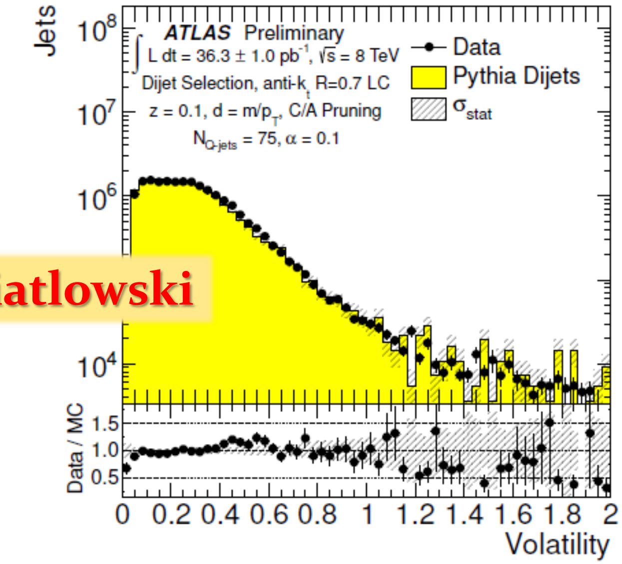
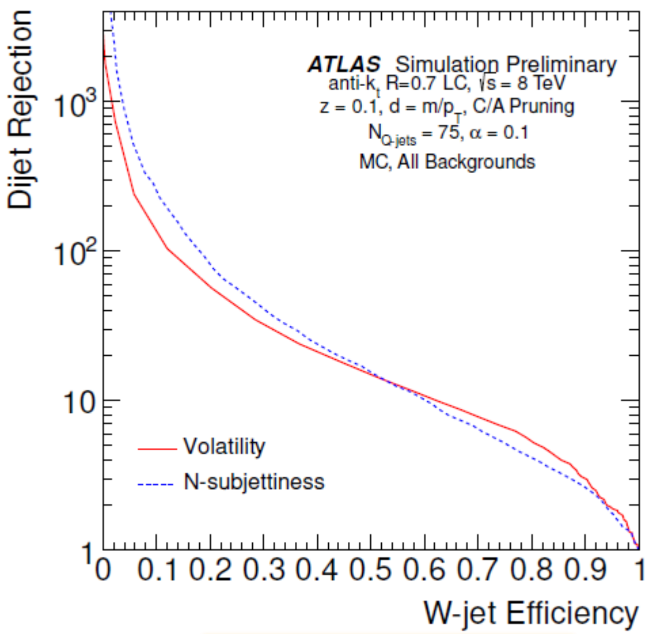
Volatility is well described by MC

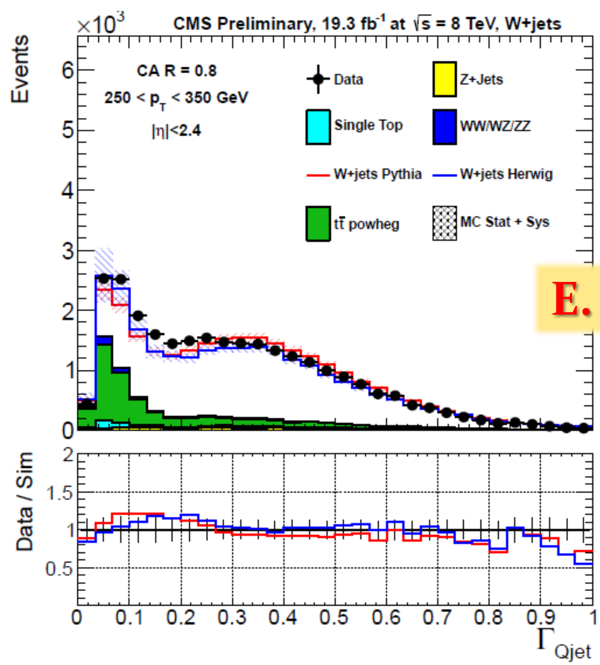
- Performance comparable to *N*-subjettiness ratio
  - Better at low efficiency
  - Turn-over point under study

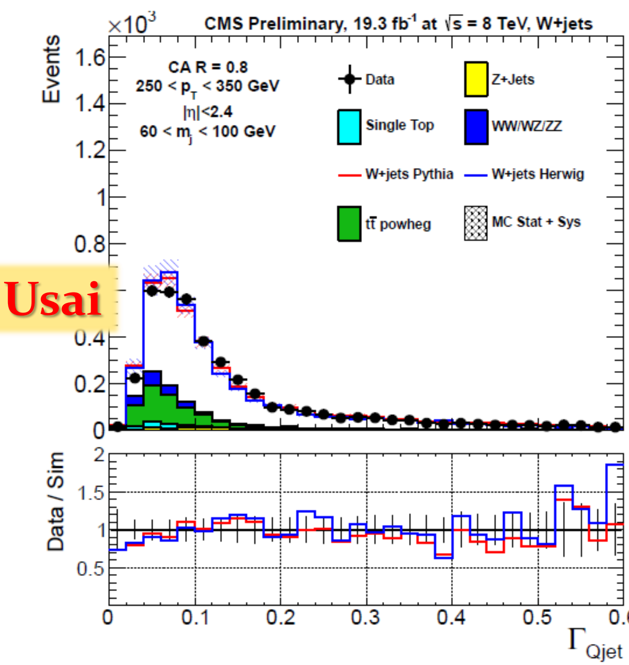




M. Swiatlowski







E. Usai

M. Swiatlowski

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Jet area method (scalar)

- Corrects pile-up contribution to jet p_T
  - Subtract p_T from pile-up estimated using transverse momentum flow density and jet area
  - Transverse momentum density determined from "soft" event components (least affected by hard scattering in event)
  - Jet area determined using "ghost area"
- Does not correct mass or substructure
  - Mass scale changes according to change in p_T but still sensitive to pile-up
  - Same for substructure observables depending on the global jet energy (p_T) scale
- Use a vector area quantity to correct observables related to its composition
  - See next slides…

Jet Shapes

S. Menke

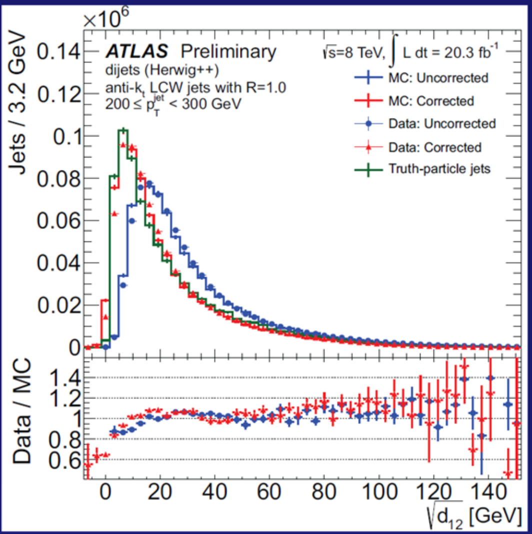
ATLAS-CONF-2013-85

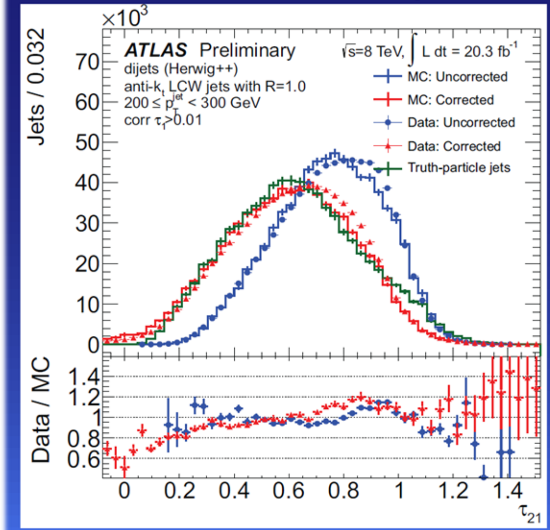
- pile-up subtraction for jet shapes (arXiv:1211.2811) is an extension of the jet area correction approach beyond the $p_\perp$ of the jet
  - first ingredient is the ghost's 4-vectors $g_\mu = g_\perp[\cos\phi, \sin\phi, \sinh y, \cosh y]$ with area $A_g = 1/\nu_g$
  - their addition during the jet forming change jet shapes $\mathcal{V}(\rho, g_\perp)$ slightly
  - by varying the ghost's transverse momentum scale $g_\perp$ the effect on any shape can be evaluated
  - and eventually subtracted
- instead of subtracting the average $\rho \times A_{\text{jet}}$ from the jet $p_\perp$ the corresponding subtraction is done for the ghosts
  - measured shape: $\mathcal{V}(\rho = \rho_0, g_\perp = 0)$
  - desired shape: $\mathcal{V}(\rho = 0, g_\perp = 0)$
  - correction principle: $\mathcal{V}(\rho + \delta, g_\perp) = \mathcal{V}(\rho, g_\perp + \delta \times A_g)$
  - evaluate: $\mathcal{V}(\rho = 0, g_\perp = 0) = \mathcal{V}(\rho = \rho_0, g_\perp = -\rho_0 \times A_g)$
- calculated with first 3 terms of Taylor expansion

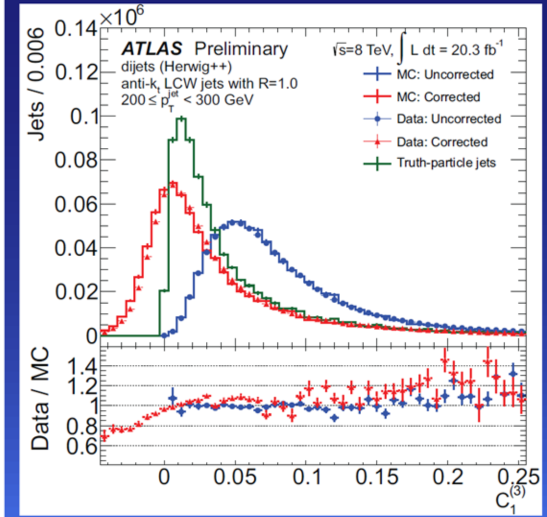
Jet Shapes ► Performance

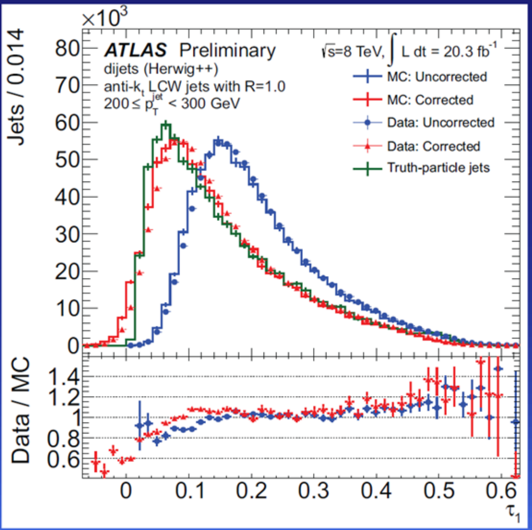
S. Menke

- several shapes tested in 2012 data and MC
  - splitting scale $\sqrt{d_{ij}} = \min(p_{\perp,i}, p_{\perp,j})\Delta R_{ij}$, with the distance of two subjets ΔR_{ij}
    $i = 1, j = 2$ for the last two sub-jets in jet forming
  - N-subjettiness
    $\tau_N = \sum_k p_{\perp,k} \min(\Delta R_{1,k}, \ldots, \Delta R_{N,k}) / \sum_k p_{\perp,k} R$, close to 0 if the jet can be described by N or less sub-jets
  - ratios of τ_N, $\tau_{ij} = \tau_i/\tau_j$
  - energy-energy correlations (EEC) of the jet constituents,
    $C_1^{(\beta)} = \left(\sum_{i<j} p_{\perp,i} p_{\perp,j} (\Delta R_{ij})^\beta\right) / \left(\sum_k p_{\perp,k}\right)^2$
- examples for di-jet events
- corrected shapes closer to truth









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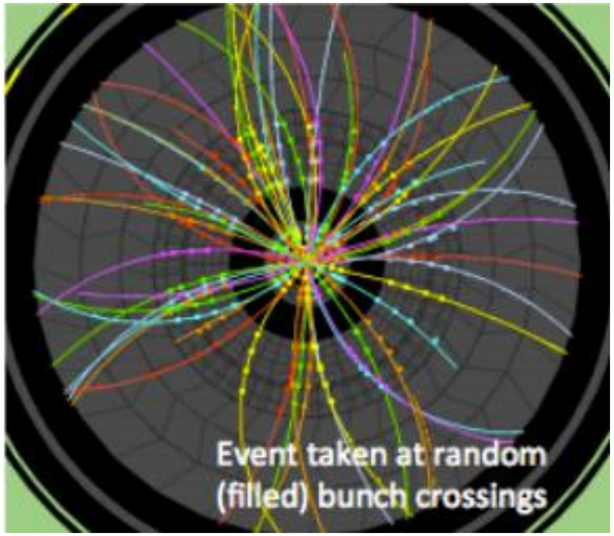
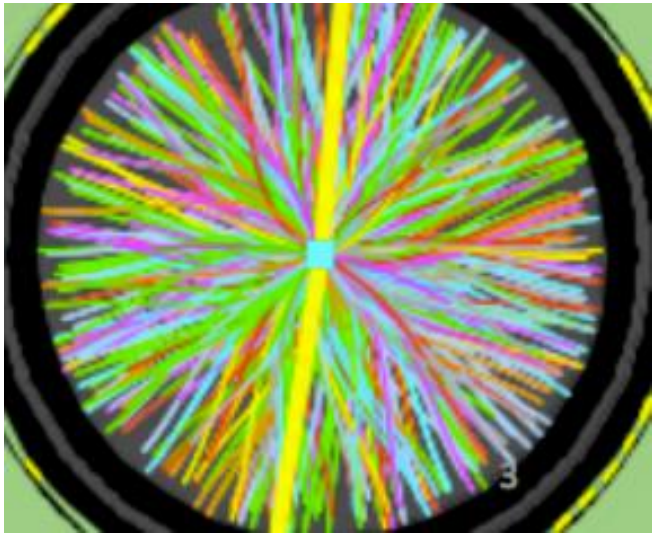
Future Prospects for LHC

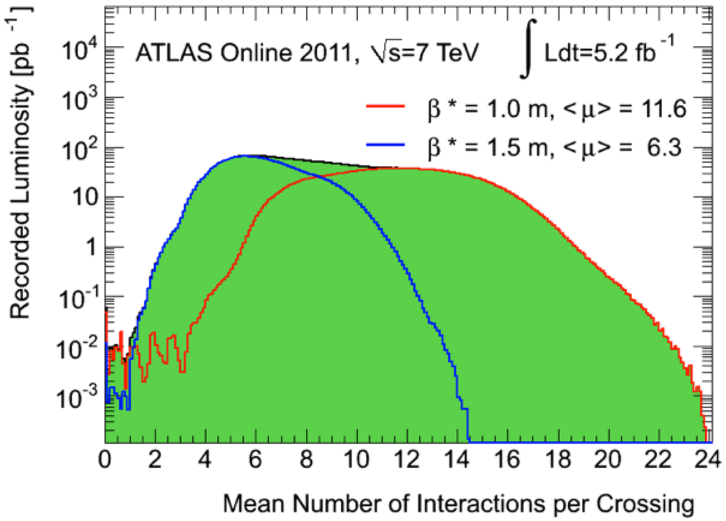
LHC 2010 (PU ~0)

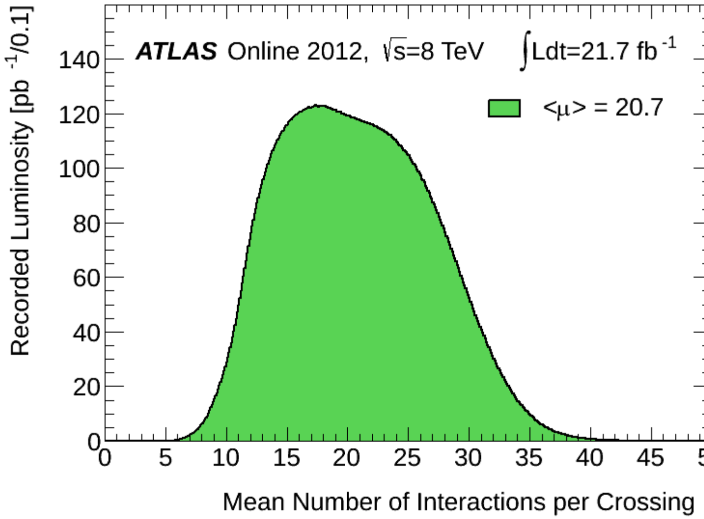


LHC 2011 (PU ~12)

LHC 2012 (PU ~21)







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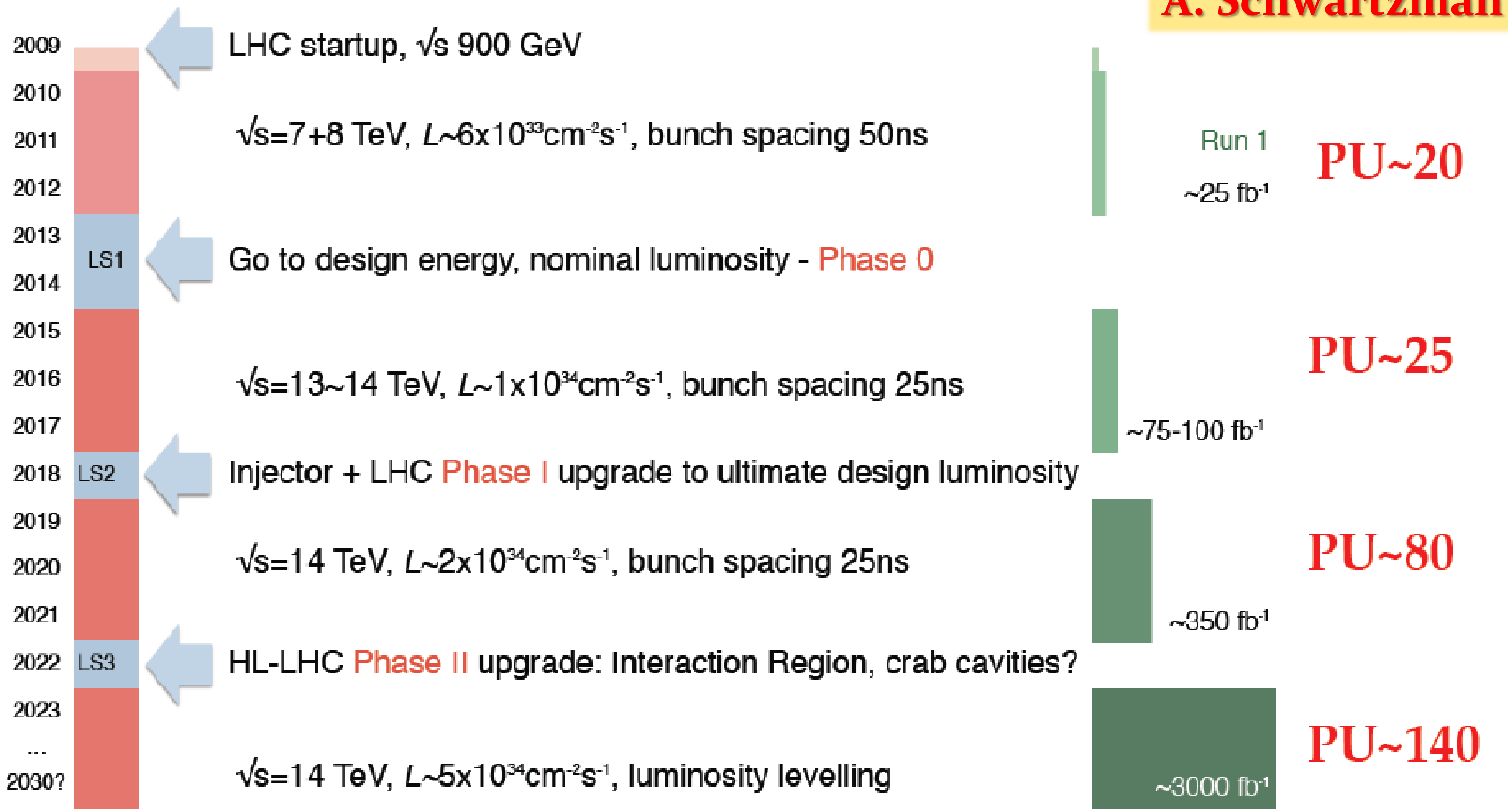
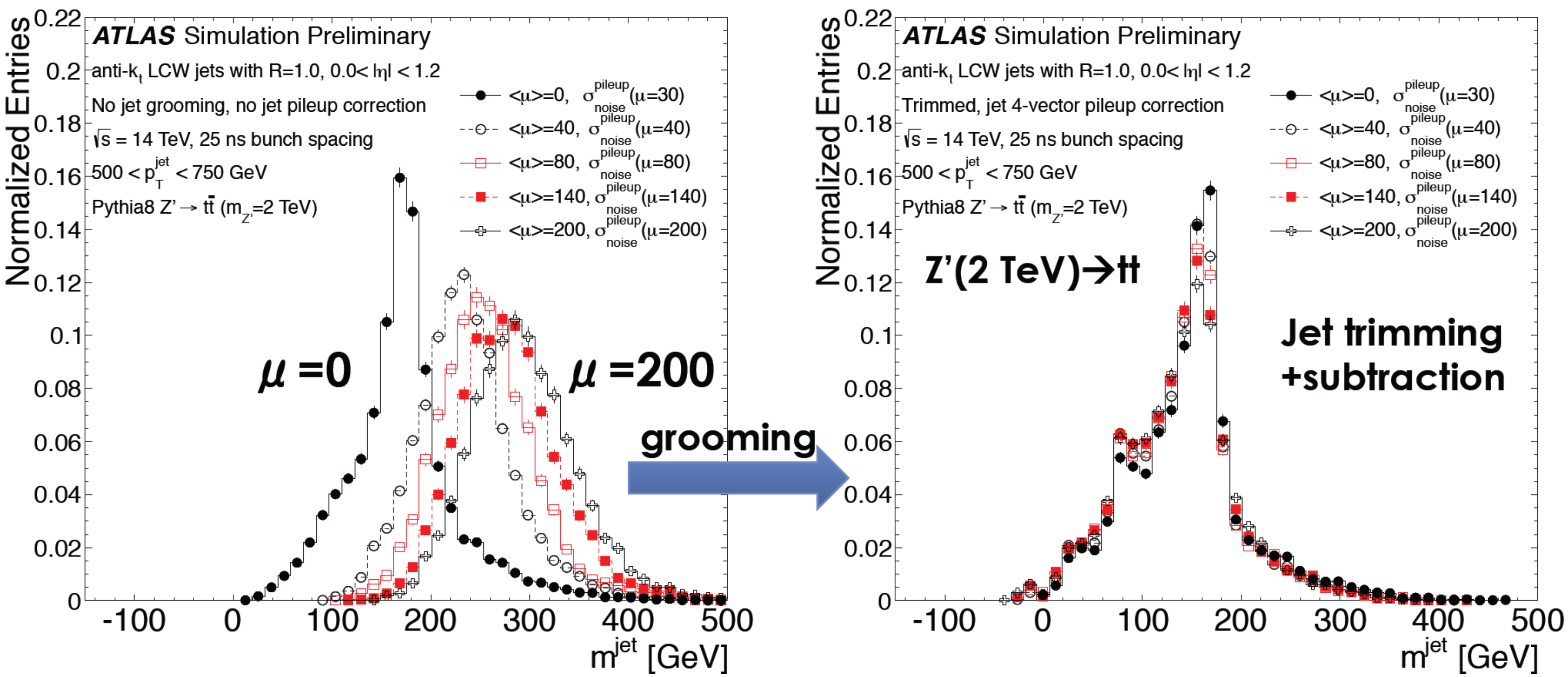
LHC beyond Run 1

A. Schwartzman



4

Future Prospects for LHC



A. Schwartzman

First impressions from full simulations

Jet substructure techniques can mitigate pile-up – jet mass spectrum can be restored

Other observables under study…

Conclusions

Very selective and biased summary

- My apologies – wealth of material required hard (biased) selections
  - Personal preference for performance probably shows….

Theory and phenomenology

- Impressive results from recent calculations
- Suggestions for new observables with promising features
- Ongoing investigations of internal jet structure and correlations between information content from various substructure techniques
- Alternative technologies for structural analysis not only of jets but also of the whole event

Experiment

- Distance and energy scales can be resolved with sufficient precision for most substructure techniques
- Environmental effects like pile-up can be controlled in 2012 LHC environment
- Sub-jet tagging and searches using substructure become more "routine"

Outlook & Acknowledgments

BOOST workshop series is alive!

- High level of synergy between theory and experiments, and between experiments
- BOOST2014 at UCL, London, UK
- Related "mid-term" workshop: Boston jet meeting January 2014

Report

- BOOST reports present work started/set up at the workshop
  - No proceedings!
- Optimistic goal: public early January/February 2014

Thank you!

- All attendants for the interesting contributions and constructive discussions!
- D. Miller (Chicago) and M. Schwartz (Harvard) for the excellent experiment and theory summaries

Also see substructure related presentations at ISMD13

- Tagging, searches and performance…

Links

- Main workshop page
  - http://w3atlas.physics.arizona.edu/boost2013
- Agenda
  - https://indico.cern.ch/conferenceTimeTable.py?confId=215704#20130812