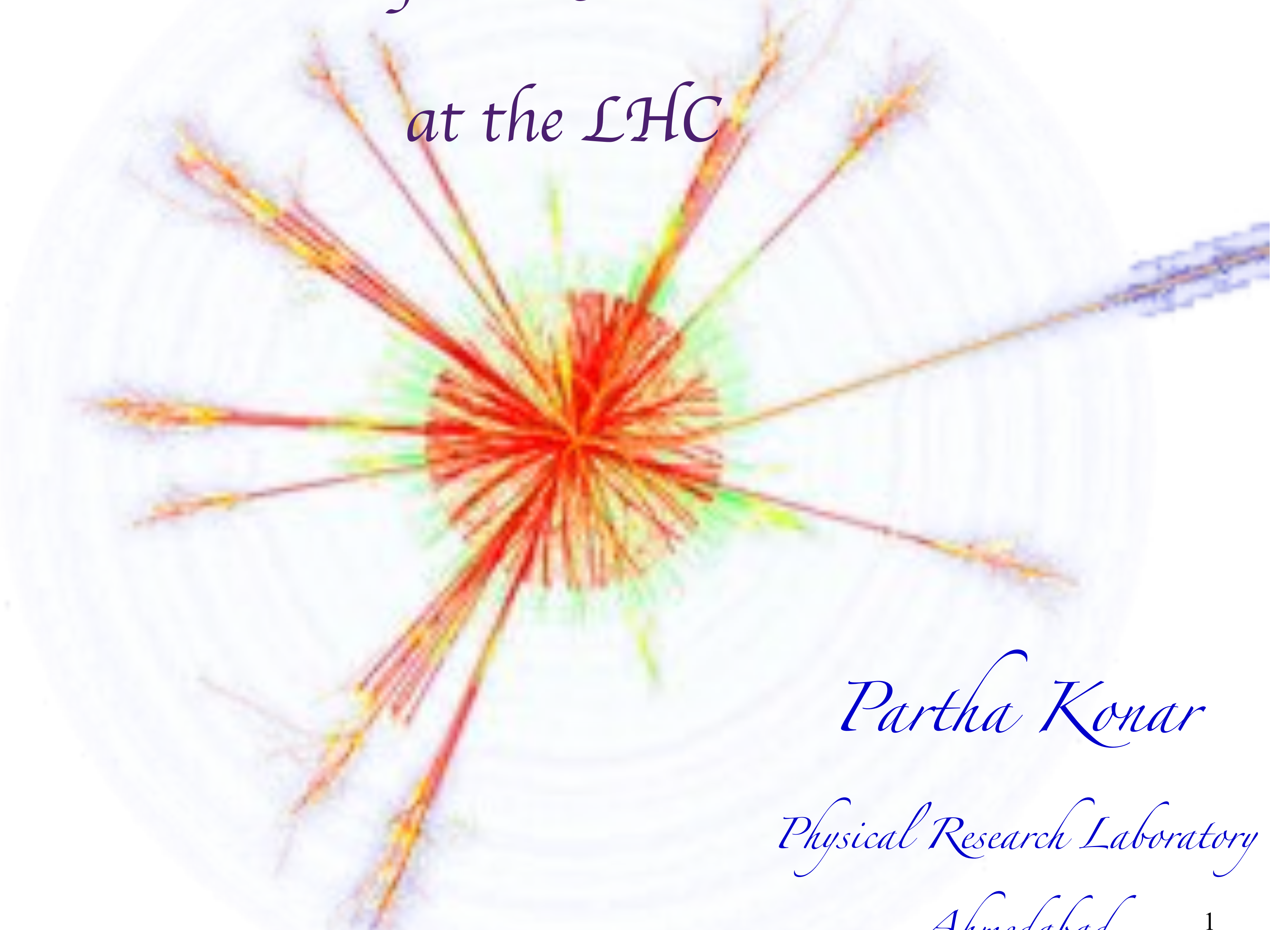
Boosted objects - Jet substructure at the LHC



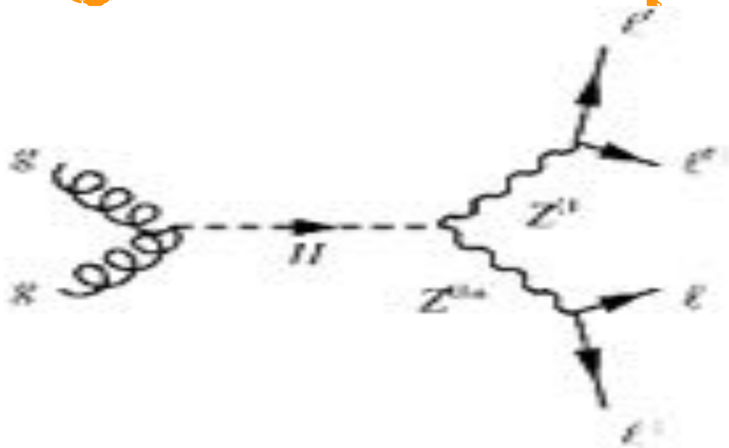
Partha Konar

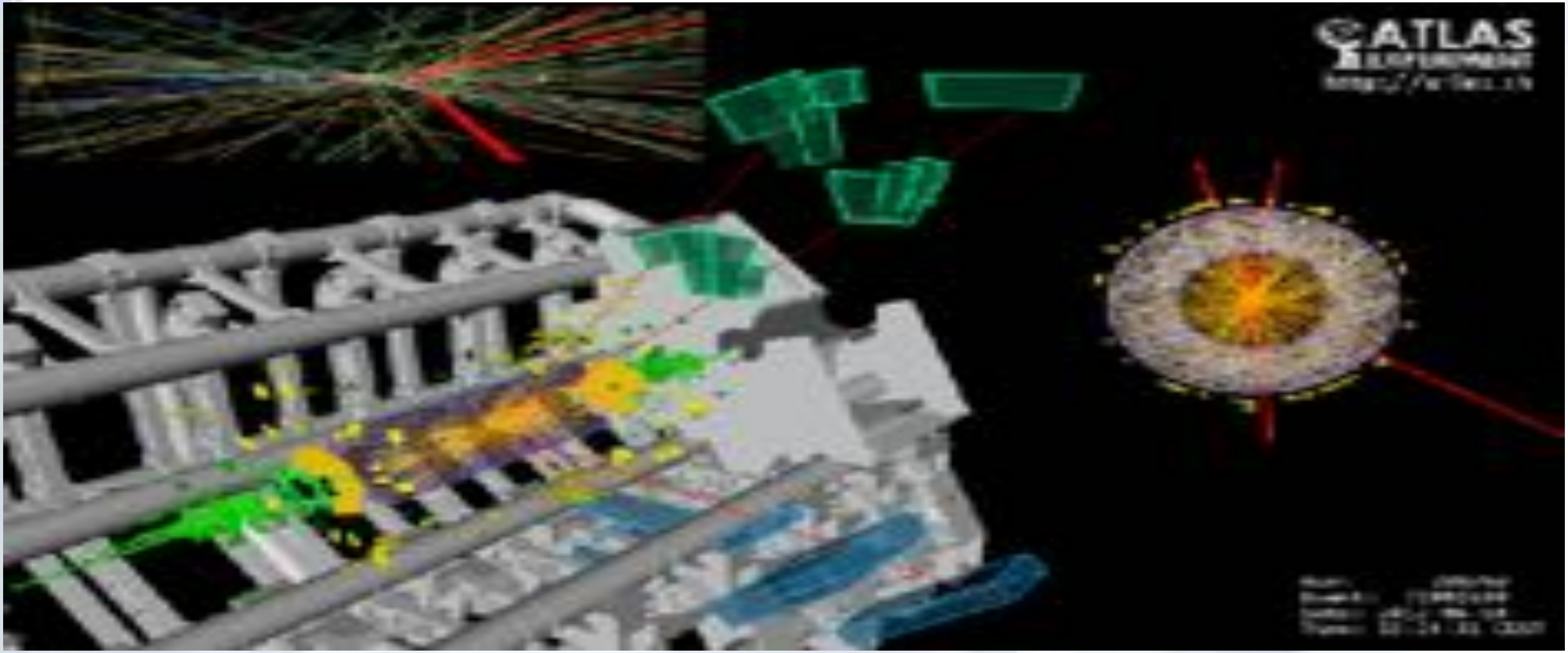
Physical Research Laboratory

Ahmedabad

WHEPP 2017 : Bhopal, Dec 14-23, 2017

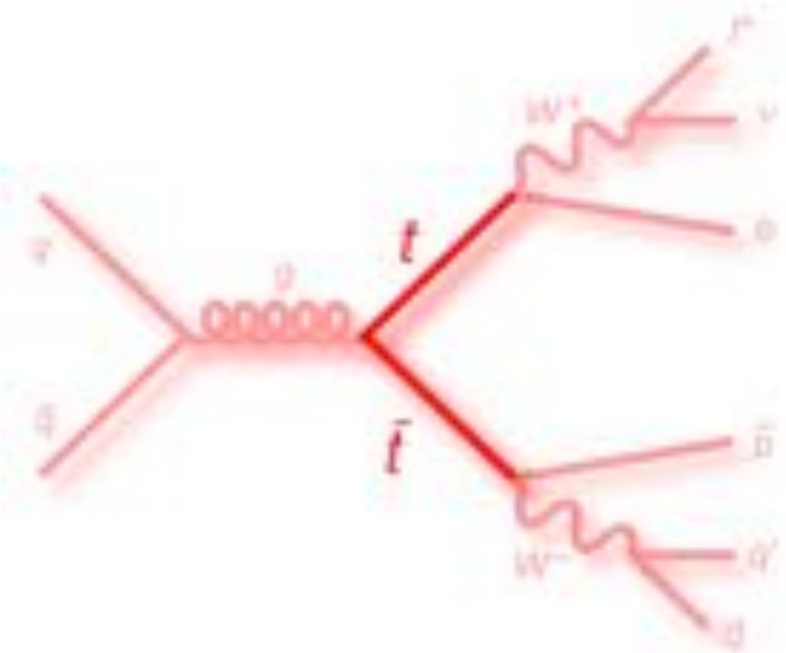
Looking at new particle



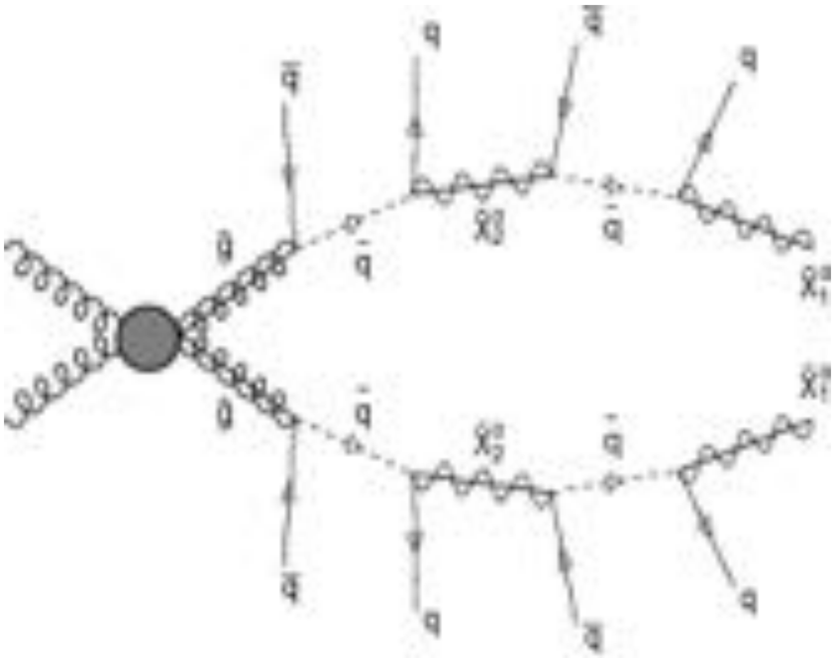


Looking at new particle with jets

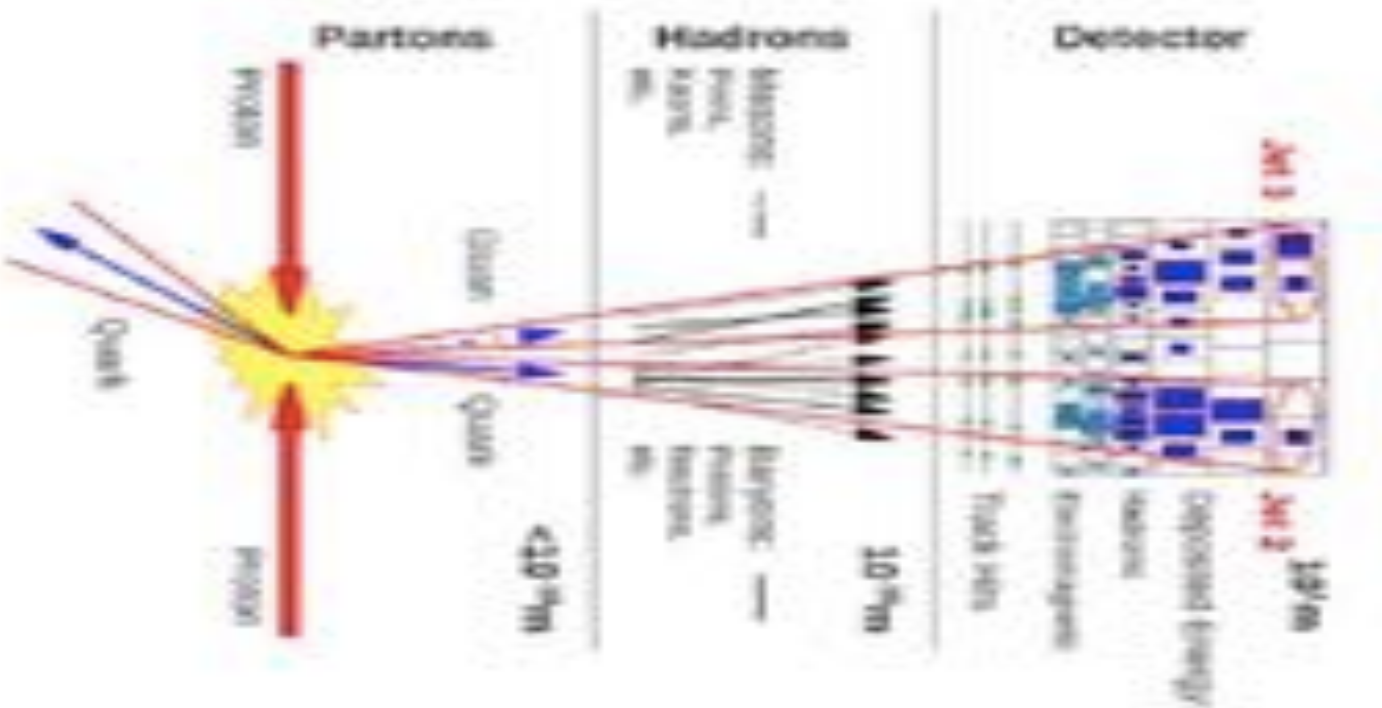
SM



BSM



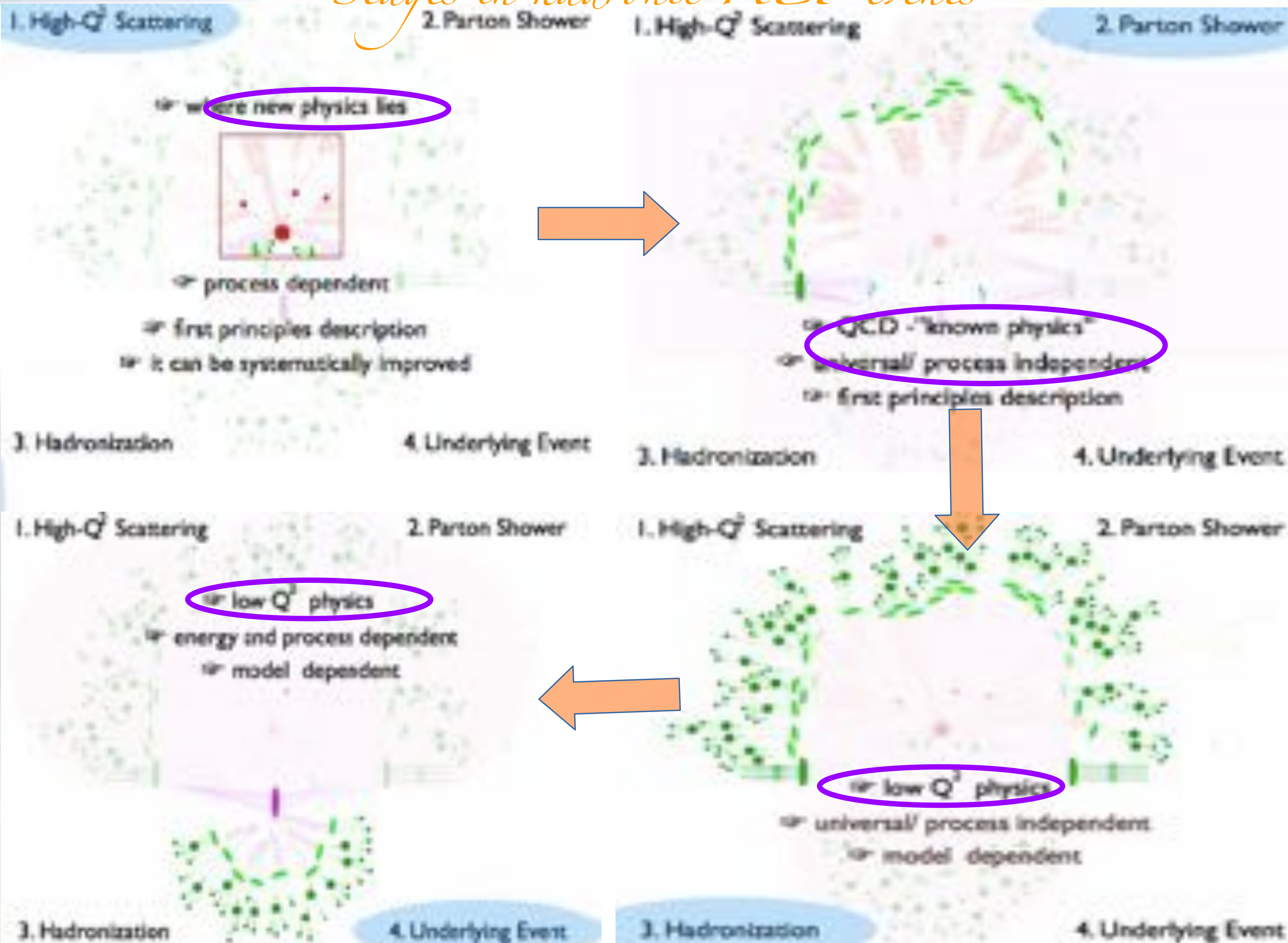
Looking for new resonance with jets



- *LHC having hadronic environment*
  - *Over the hard partons, we study, there are showering and hadronization*
  - *+ large amounts of soft, unassociated radiation from =>*
  - (i) *underlying event* (ii) *multiple interactions* (iii) *pile-up*

Rabbertz

Stages in hadronic HEP events

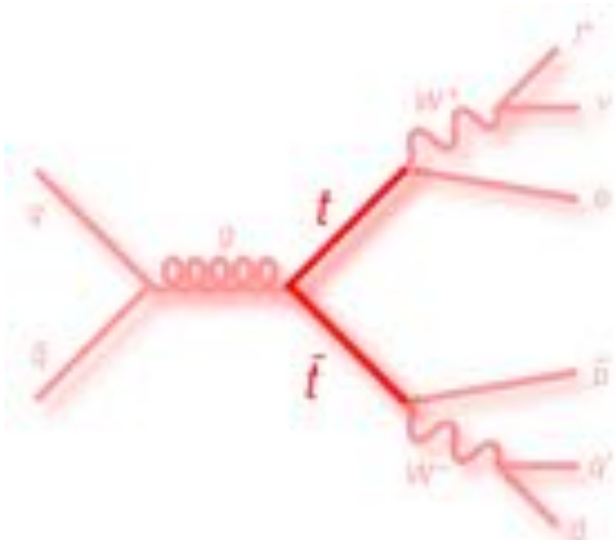


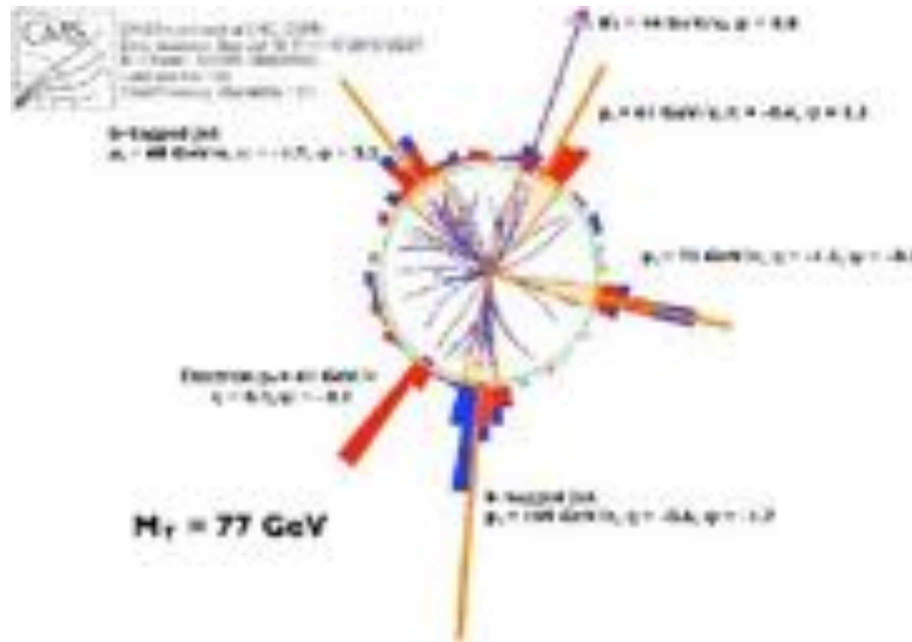
Maltoni '10

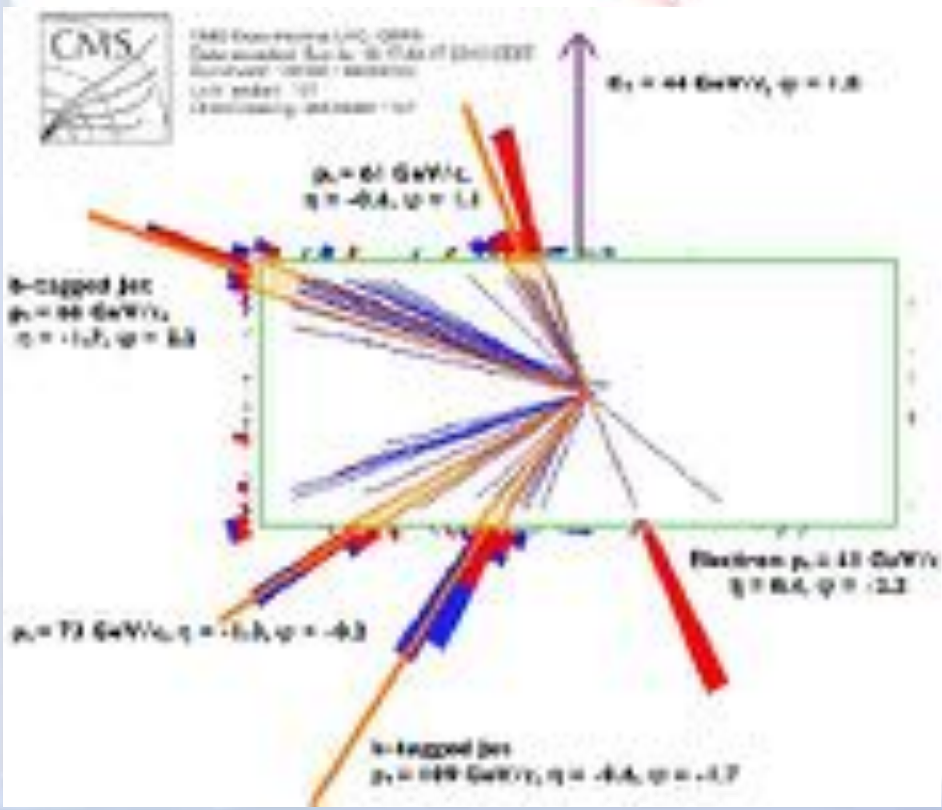
HEP events

Maltoni '10

Looking for new resonance with jets







Observable - Jet

Collimated bunches of stable hadrons, originating from partons (quarks & gluons) after fragmentation and hadronization

Looking for new resonance with jets

- *JETS*
  - Collimated bunch of stable final hadrons
  - Originating from parton

    => fragmentation and hadronization

- *How to find one?*
  - Approximate attempt to reverse engineering
  - Jet algorithm (not unique)

Data ~ Jet objects ~ partons + QCD

Experiment	*Theory*
H–cal / EM–cal tower	**Particle 4–momenta**

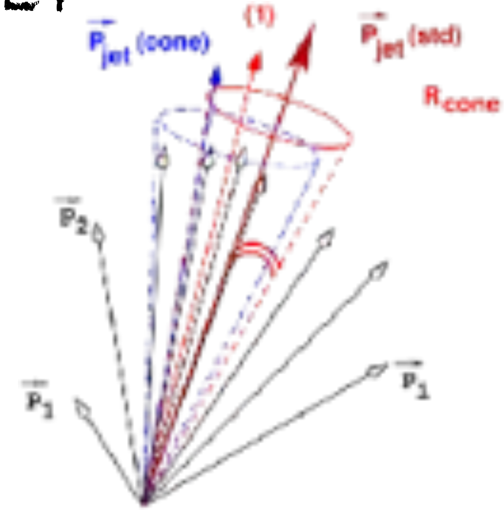
Looking for new resonance with jets

- **Cone algorithms** // QCD modifies energy flow in small scale
  - Present a very intuitive picture of parton radiation
  - Typically not Infrared- & Collinear-Safe
  - Midpoint Cone(Tev), Iterative Cone (CMS), SISCone (LHC)
  - Clumsy in practice, not used much now
- **Sequential recombination algorithms** // QCD divergence in small separation
  - Measure in terms of separation between final state particles ~ $\frac{m_{ij}^2}{Q^2} \sim \frac{2E_iE_j(1-\cos^2\theta_{ij})}{Q^2}$
  - Vanishes infrared ($E \to 0$) or collinear ($\cos \to 1$)
  - Infrared- & Collinear-Safe by construction
  - ★ kT, Cambridge/Aachen, Anti-kT

Cone Algorithm

- *Find most energetic particle in event -> SEED*

- Put a cone of radius R around the seed, sum up momenta of all particles enveloped by cone -> TRIAL JET



- Compare trial jet axis with seed axis
- Nearly identical within precision?

YES => Set this Stable cone as Jet

remove all entries belong to the jet;

start with next most energetic particle as seed

NO =>

iterate with trial jet axis as new seed until convergence

Until no seeds above certain threshold (CMS: 1GeV) are left

Sequential Algorithm

- *Based on distance measure*

$$d_{ij} = \min\left(k_{Ti}^{2p}, k_{Tj}^{2p}\right)\frac{\Delta_{ij}}{D}$$

$$d_{iB} = k_{Ti}^{2p}$$

P = 1[KT], 0[C/A], -1[Anti-KT]

- Compute all distances dij and diB; Find smallest

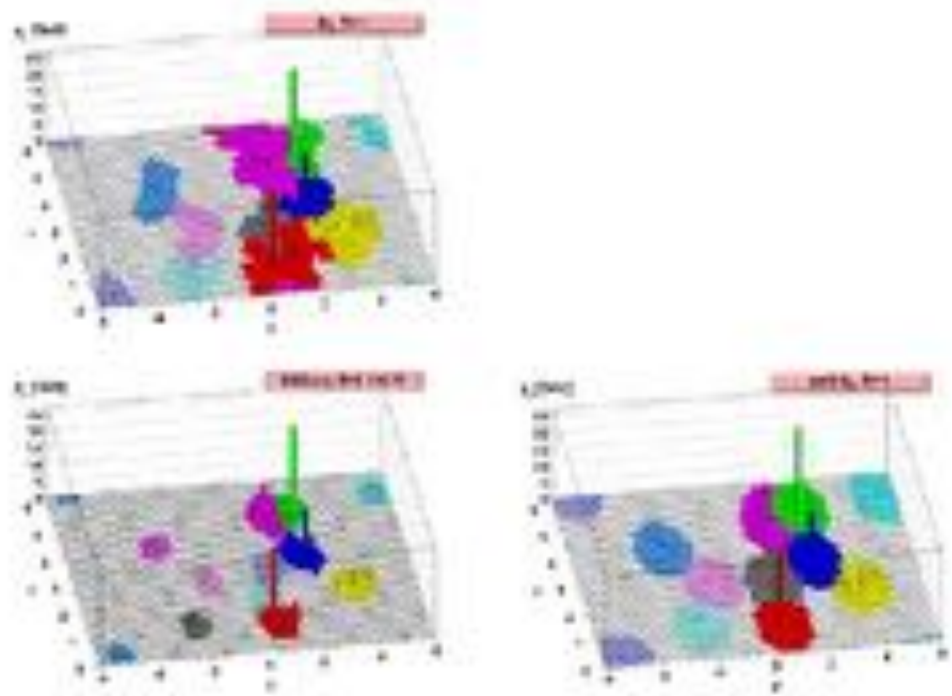
If dij smallest =>

Combine i and j, update distance, find next smallest

If diB smallest =>

Remove i and call it a jet

- Repeat till all particle clustered



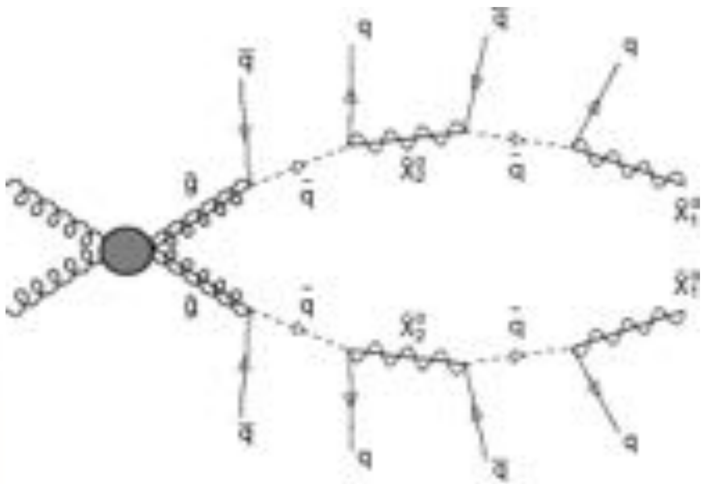
>> Returns not only a list of jets + clustering sequence

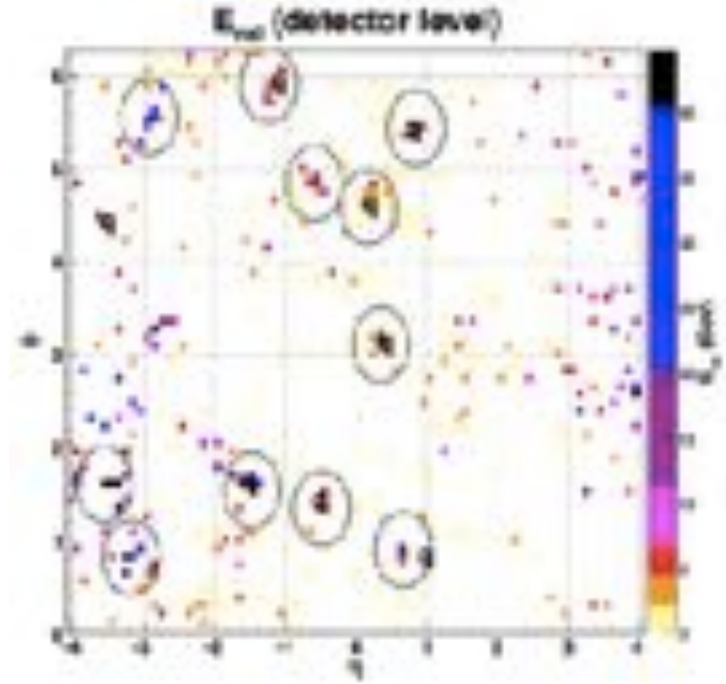
Easy to test multiplicity with "D"

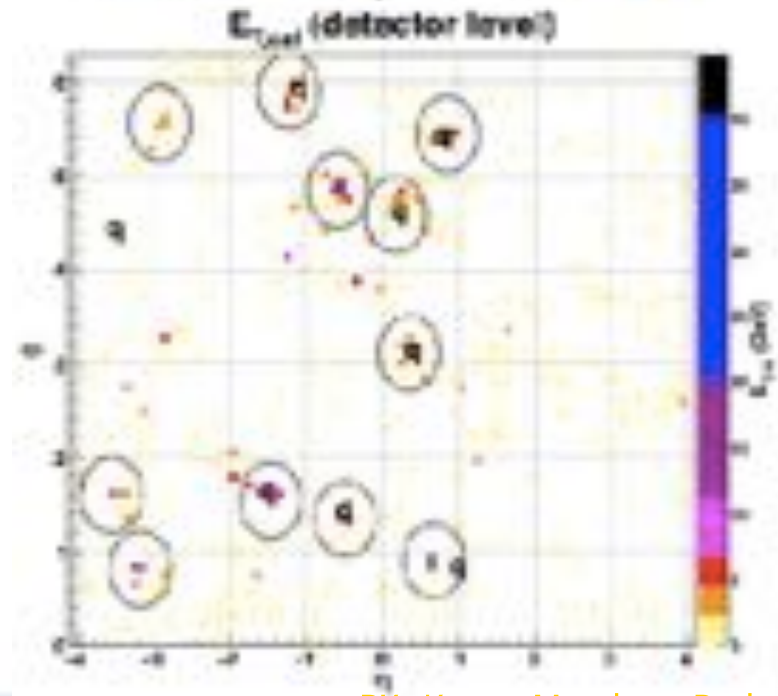
D → angular resolution

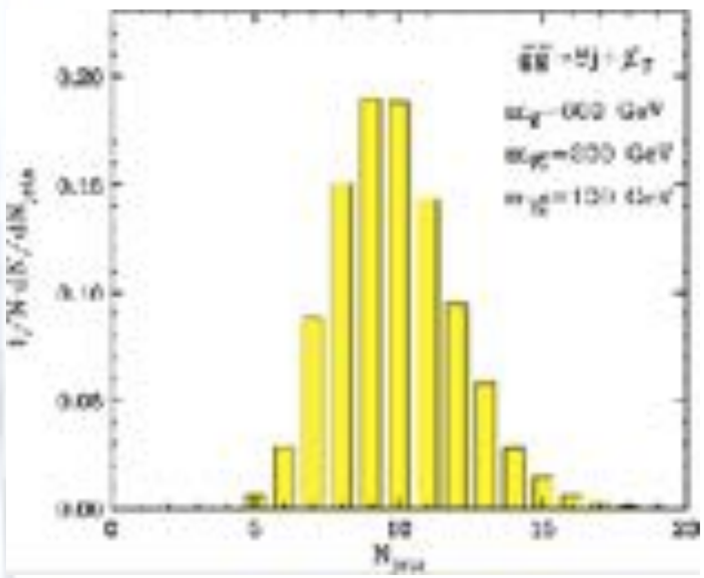
HEP events

BSM









PK, Kong, Matchev, Park 2010

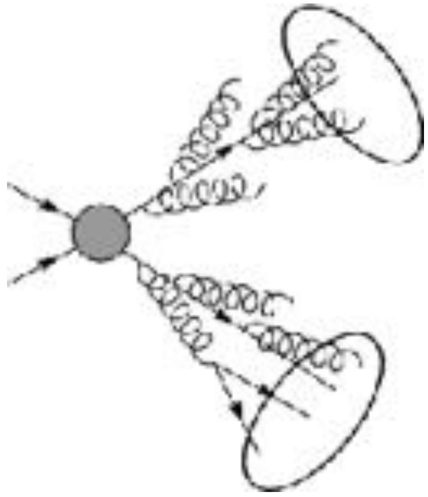
"New" jets @ LHC

- High and ultra-high energy collider

  : if PT<2TeV ~ 100 GeV splitting distinguishable with cell size 0.1

- Present calorimeters at ATLAS and CMS have much finer resolution

  : ~ 50 E_cell of .1 in R=0.4



- Computations in fast sequential algorithms

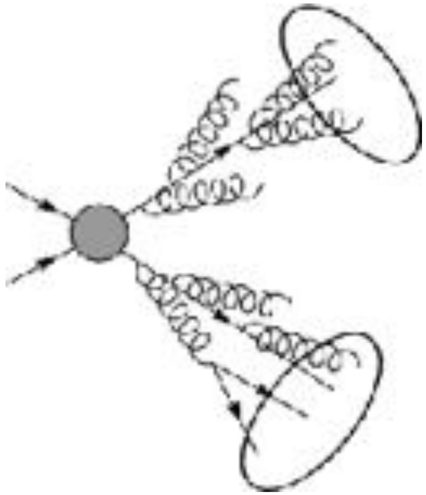
  : fast jet algorithm

GavinSalam, Butterworth, Davison, Thaler, Wang, Nojiri, Gavin P. Salam, Kaplan.....;2008

"New" jets @ LHC

=> production and analysis of boosted objects & fat jet

Decay & fragmentation of boosted object Produce a collimated spray of hadron, standard Algorithm consider it as single jet



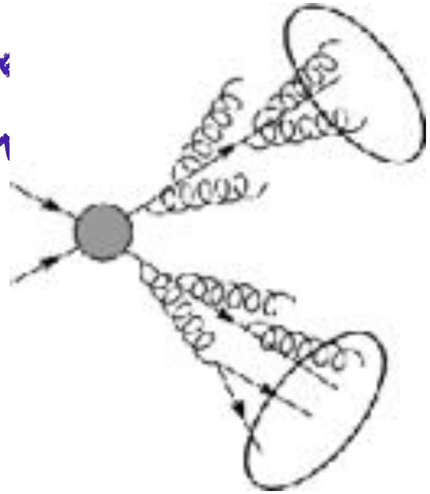
☑ How can this be useful =>

- Natural candidates with increased CM energy
- Exploring heavy resonance
    - Can it reduce background?
    - Internal feature of these jets?

GavinSalam, Butterworth, Davison, Thaler, Wang, Nojiri, Gavin P. Salam, Kaplan.....;2008

"New" jets @ LHC

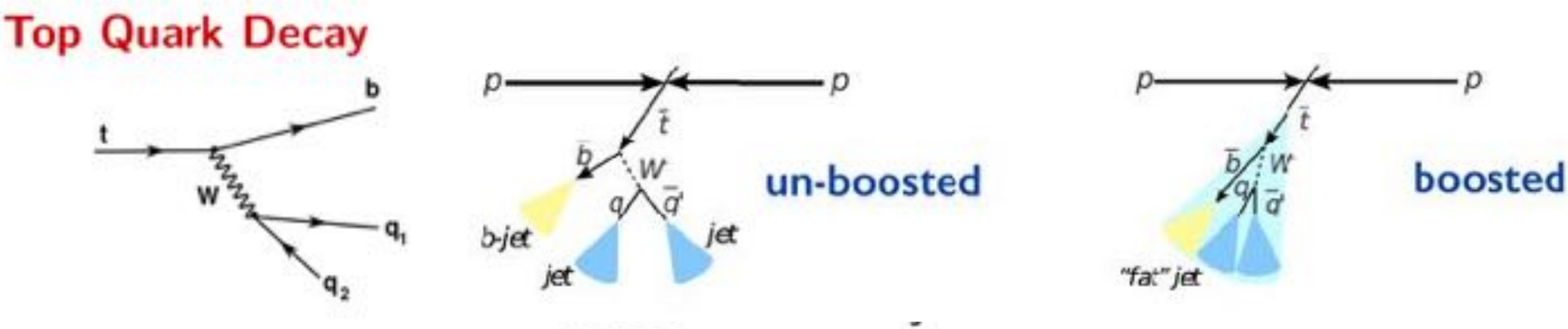
- => production and analysis of boosted objects & fat jet
- # Decay & fragmentation of boosted object Produce collimated spray of hadron, standard Algorithm it as single jet

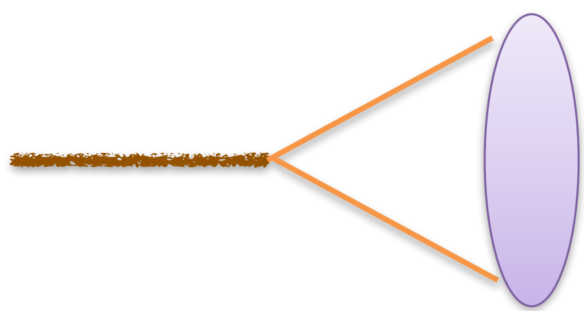


- Way out =>
  - With same jet mass: Boosted hadronic objects have a fundamentally different energy pattern Vs to QCD jets
  - Clean up smearing effect of jet contamination from IRS, UE, Pileups
  - Exploit the characteristics and kinematic properties for
  - Boosted Top-jets / Higgs-jets / W-jets

GavinSalam, Butterworth, Davison, Thaler, Wang, Nojiri, Gavin P. Salam, Kaplan.....;2008

boosted "New" jets @ LHC





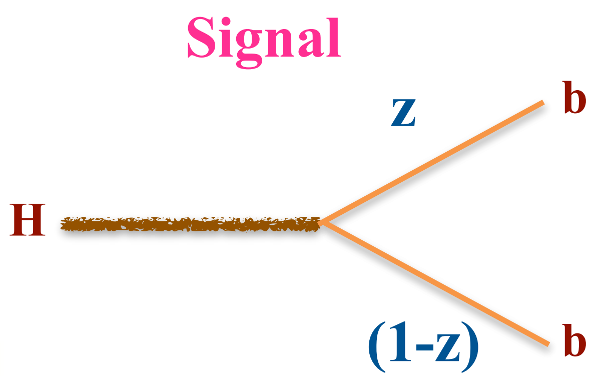
$$\Delta R \sim \frac{1}{\sqrt{z(1-z)}}\frac{M_H}{P_T^H} \sim \frac{2M_H}{P_T^H}$$

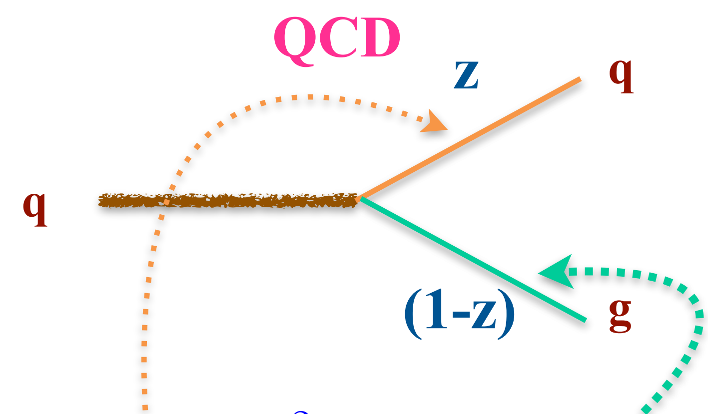
Top quarks at fixed center of mass energy

$\sqrt{\hat{s}}$	R_0	3	2	1
1.5 TeV	0.4	0.55	0.45	—
1.5 TeV	0.6	0.2	0.6	0.2
2.0 TeV	0.6	0.1	0.45	0.45

1011.2268, 1302.0260

Characteristics of “New” jets

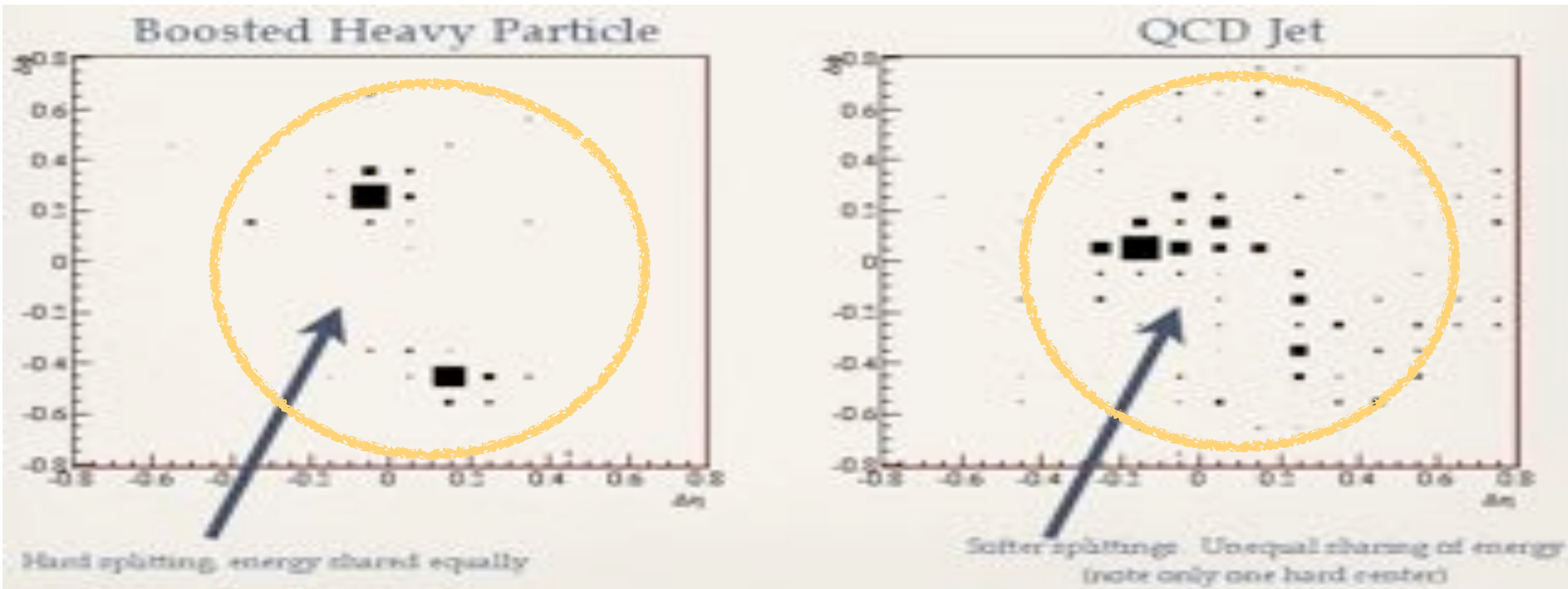




$$d\sigma_{n+1} \approx d\sigma_n \, dz \, \frac{dt}{t} \frac{\alpha_s}{2\pi} P(z)$$

$P(z) \sim 1$

Splitting function $P(z) \sim \frac{1+z^2}{1-z}$ $\quad P(z) \sim \frac{1+(1-z)^2}{z}$



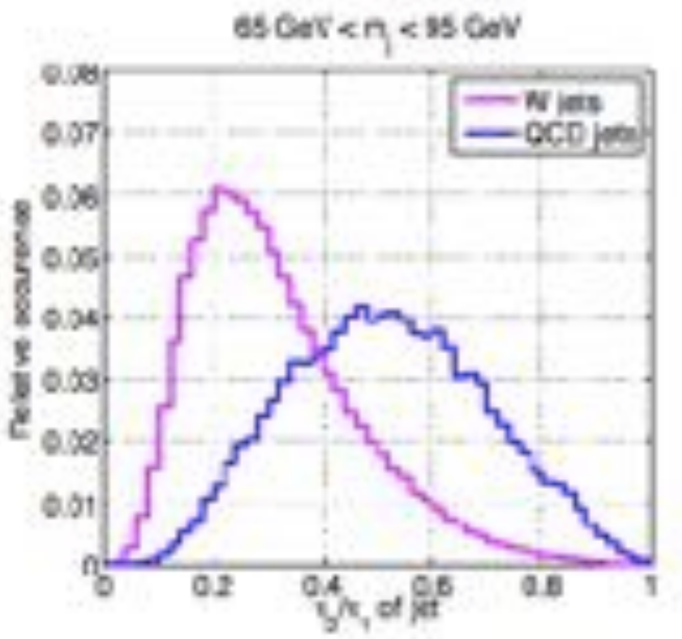
N-subjettiness

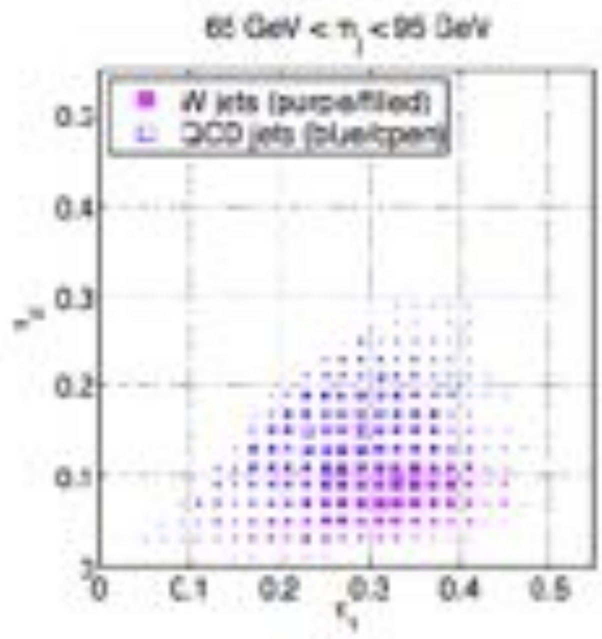
Minimize over all possible candidate sub-jet directions (analogous to event shape thrust)

$$\tau_N = \frac{1}{\mathcal{N}_0} \sum_i p_{i,T} \min \{\Delta R_{i1}, \Delta R_{i2}, \cdots, \Delta R_{iN}\}; \quad \mathcal{N}_0 = \sum_i p_{i,T} R_0$$

- Quantify how original jet seem to be composed of N daughter subjets
- $\tau_N \sim 0$ => Original jet consist of N or fewer sub-jets
- $\tau_N >> 0$ => Large fraction of energy diluted from candidate N sub-jets
- A good discriminant the ratios of adjacent N-subjettiness values

N-subjettiness

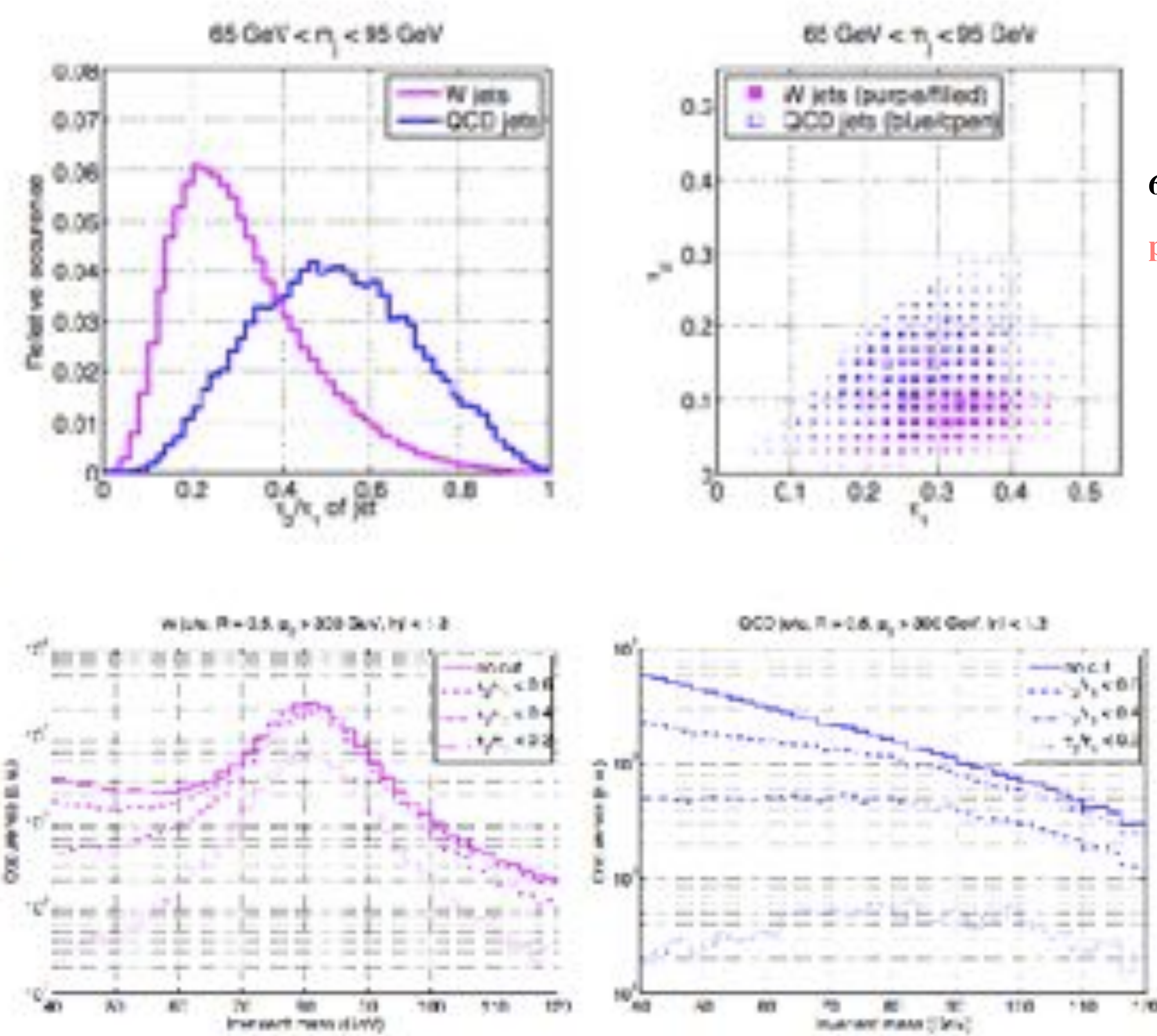




65 GeV < m_{jet} < 95 GeV ; R = 0.6,

p_T > 300 GeV, and |η| < 1.3

N-subjettiness



65 GeV < m_{jet} < 95 GeV ; R = 0.6, p_T > 300 GeV, and |η| < 1.3

Thaler, Tilburg 2011

Characteristics of top jets

- *Boosted top : difficult b-tag, W-decay products not isolated*

Leptonic channel: lepton isolation discard ~90% ttbar event!

=> t tbar Signal : boosted two jet events + huge QCD BG

Symmetric declustering, by throwing softer among two (reversing the C.A.)

Repeated to reach at two hard objects or irrducible

Repeated to reach 3 sub-jet

Additional kinematic selections => M_t, M_W, W helicity angle

Kaplan, Schwartz.. PRL 2008

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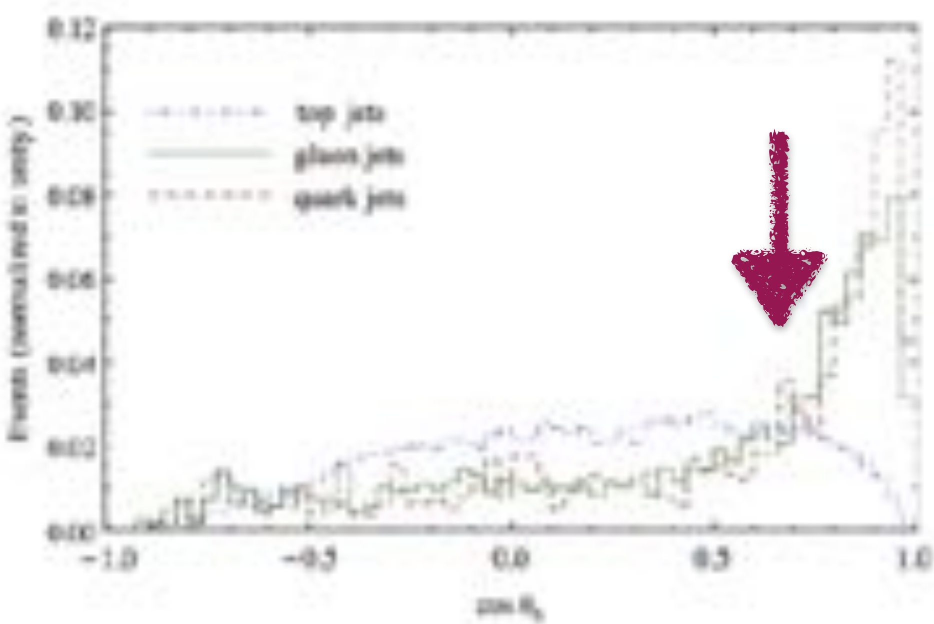
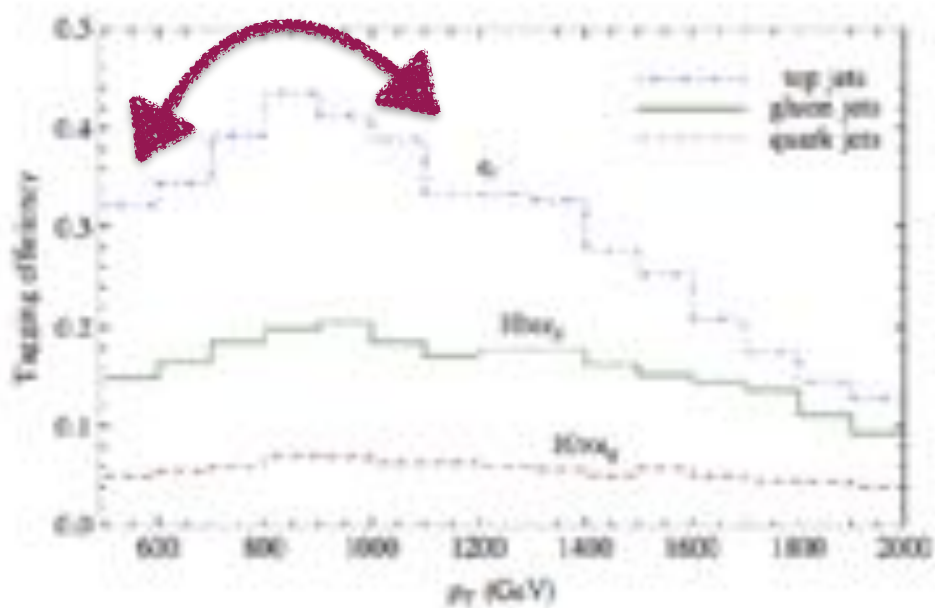


Helicity angle, measured in the rest frame of the reconstructed W, between the reconstructed top's flight direction and one of the W decay products



The efficiencies for correctly tagging a top jet (ϱ_t), and mistagging a gluon jet (ϱ_g) or light quark jet (ϱ_q)

Characteristics of Higgs jets

- BR[$H \rightarrow b\ \bar{b}$] ~ 60% for 125 GeV Higgs

Not useful: Overwhelmingly large background

Not much help: even with associated production with Z..

New approach - Higgs with high PT>200 GeV

=> Signal : leptons from Z + 'Higgs-Like' fat jet

Higgs like jet =>

Symmetric splitting structure

Salam, Butterworth, Davison PRL 2008

Sharp drop in parton mass

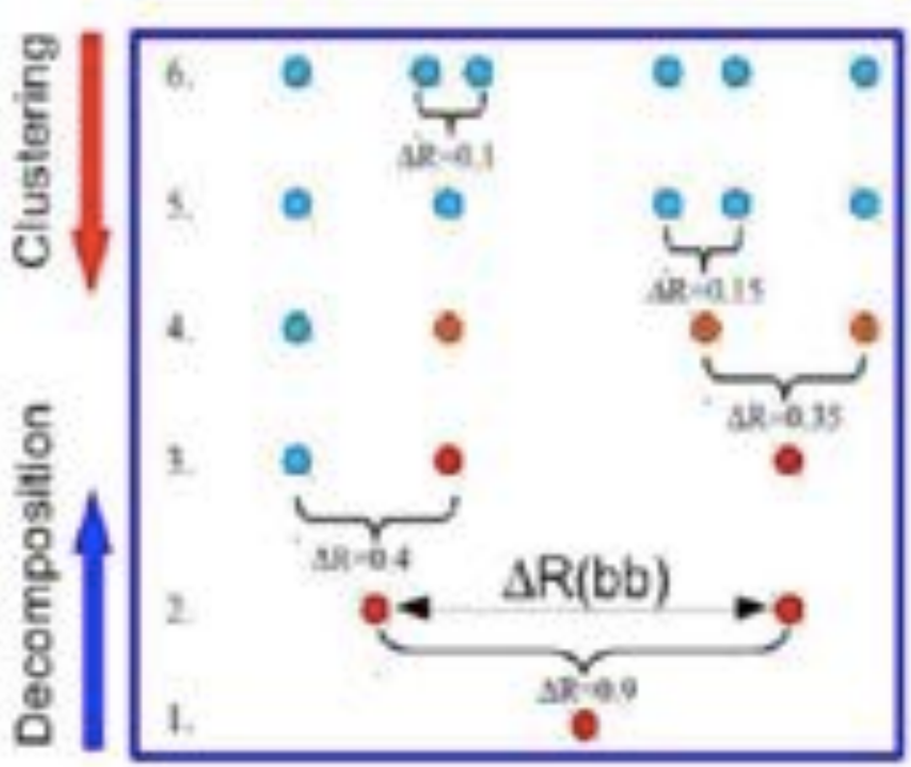
Now 'unwinding/filtering' the 'fat jet' with such features

Get back Higgs like H -> b b splitting

Projected Higgs discovery at 5 sigma in 30 fb-1 (14 TeV)

"New" jet cleaning

- *Filtering or mass-drop method in case of h->bb*
- *Trimming : recluster the fat jet & retain a subset of subjets*
- *Pruning : check the soft and wide angle splitting*



Recombination algorithms - Follow the History of jet clustering algorithm

BOOST2010: arXiv:1012.5412

"New" jet cleaning

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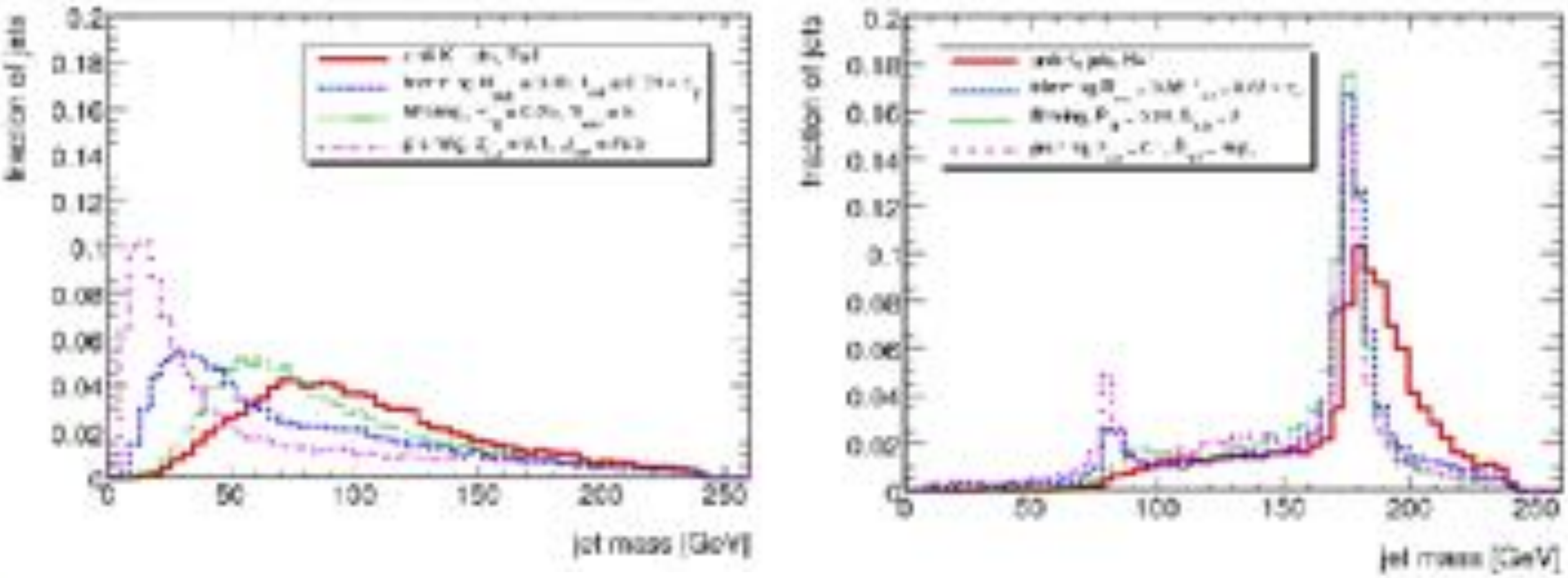

Di-jet / t t-bar event sample in 500-600 GeV: effect of different grooming

BOOST2010: arXiv:1012.5412

"New" jets @ LHC

- Inevitable with high-energy collider/ exploration of multi TEV exotics at collider (other experiments?)
- Fat jet and substructure can provide additional tool for discovery of new physics
- Carry signature of new particle in internal structure
- Control background after unwinding fat jets
- Jet kinematics and grooming can provide more handle
- Progress done last few years – looks exciting !
- BSM search with E (NP) >> E (EW) >> E (QCD)

BOOST2010: arXiv:1012.5412