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Introduction to Hadronic Final State Reconstruction in Collider Experiments

Introduction to Hadronic Final State Reconstruction in Collider Experiments (Part V)

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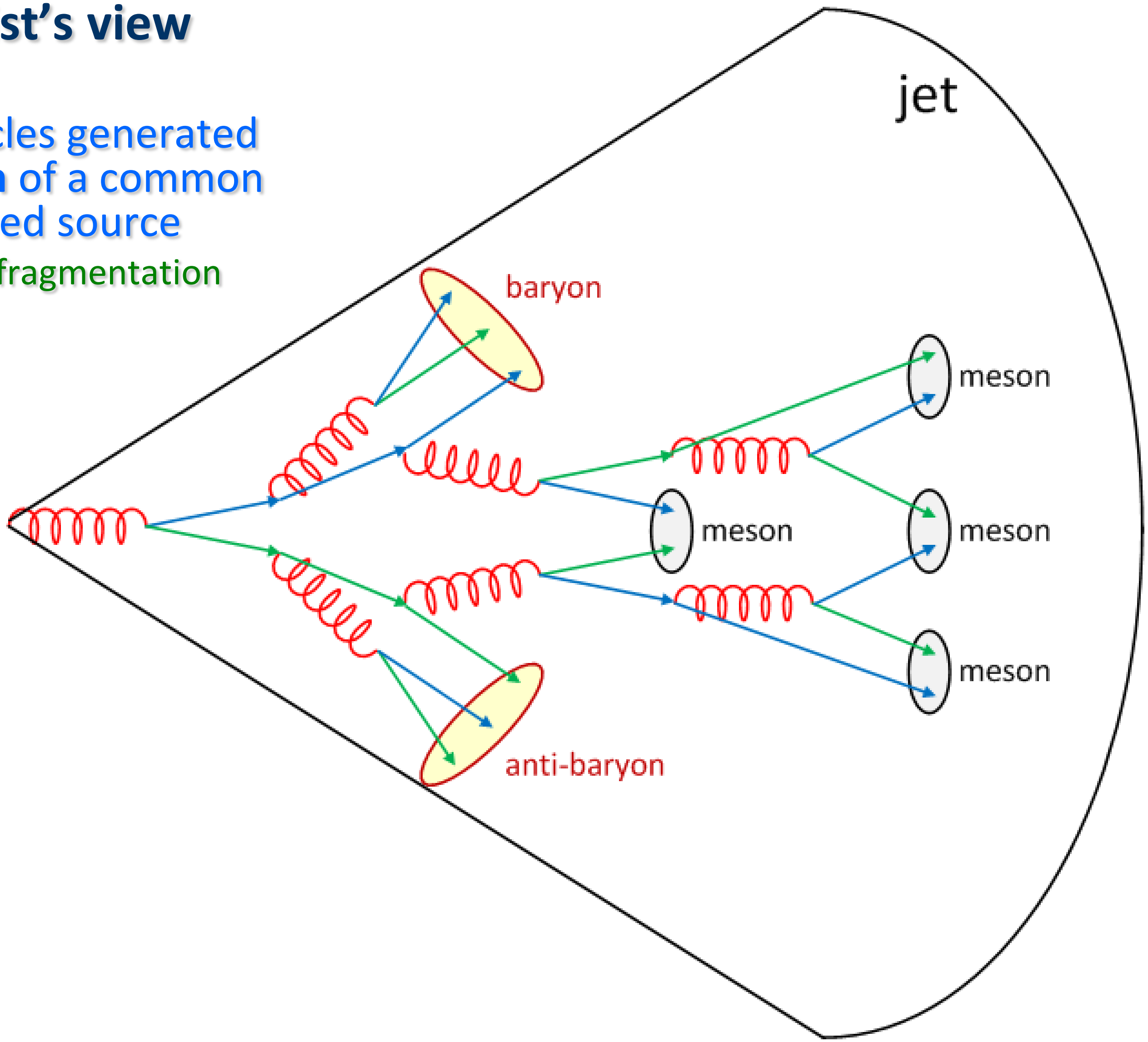
ATLAS

The experimentalist's view (…my view)

- A bunch of particles generated by **hadronization** of a common otherwise confined source
  - Quark-, gluon fragmentation



What Are Jets?

The experimentalist's view (…my view)

- A bunch of particles generated by **hadronization** of a common otherwise confined source
  - Quark-, gluon fragmentation
- Consequence of **common source**
  - Correlated kinematic properties
  - Jet reflects the source by sum rules and conservation
- Interacting particles in jet generate observable signal in detector
  - Protons, neutrons, pions, kaons, photons, electrons, muons, and others with laboratory lifetimes > 10 ps (incl. corresponding anti-particles
- Non-interacting particles in jet do not contribute to directly observable signal
  - Neutrinos, mostly

$$\left(E_{\text{jet}},\vec{p}_{\text{jet}}\right)=\sum_{\text{all particles}}\left(E_{\text{particle}},\vec{p}_{\text{particle}}\right)=\left(E_{\text{parton}},\vec{p}_{\text{parton}}\right)$$

$$q_{\text{jet}}=\sum_{\text{all particles}}q_{\text{particle}}=q_{\text{parton}}$$

$$m_{\text{jet}}=\sqrt{E_{\text{jet}}^{2}-\left|\vec{p}_{\text{jet}}\right|^{2}}=\sqrt{\left[\sum_{\text{all particles}}E_{\text{particle}}\right]^{2}-\left|\sum_{\text{all particles}}\vec{p}_{\text{particle}}\right|^{2}}=\sqrt{E_{\text{parton}}^{2}-\left|\vec{p}_{\text{parton}}\right|^{2}}=m_{\text{parton}}$$

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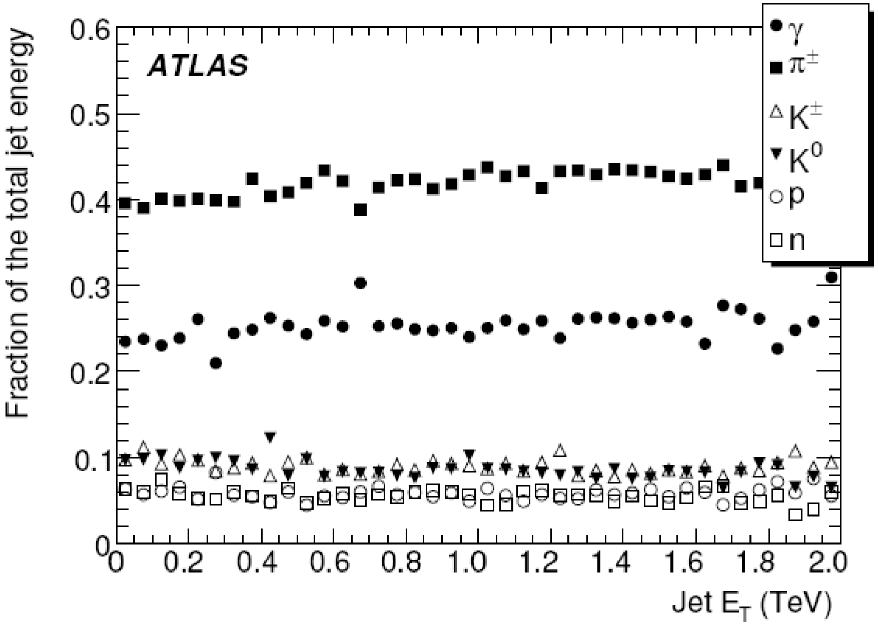
$$\left(E_{\text{jet}},\vec{p}_{\text{jet}}\right)^{\text{obs}} = \sum_{\text{interacting particles}} \left(E_{\text{particle}},\vec{p}_{\text{particle}}\right)$$

$$\neq \left(E_{\text{parton}},\vec{p}_{\text{parton}}\right)$$

$$q_{\text{jet}}^{\text{obs}} \neq q_{\text{parton}}$$

$$m_{\text{jet}}^{\text{obs}} \neq m_{\text{parton}}$$



Particle jet composition generated by PYTHIA

Jet Fragmentation

What is fragmentation?

- Hadronization of partons into particles
  - Confinement in QCD: gluon pair production
  - Gluon radiation

How can fragmentation be measured in an experiment?

- Reconstruct charged tracks in a given jet
  - Momentum fraction carried by these tracks reflects charged (hadron) production in hadronization
- High track reconstruction efficiency and low momentum acceptance needed!
  - Final state in e^+e^- collisions at LEP ideal – very clean collision environment without underlying event, at center-of-mass energies from 90 to 209 GeV
- Fragmentation function are derived from LEP data (1989-2000)

Can we measure the fragmentation of a given jet in hadron colliders?

- Basically impossible, as collision environment is too "messy"
  - Accidental inclusion of charged tracks not from jet (underlying event, pile-up)
  - Loss of relevant tracks hard to detect
- Need to rely on models fully describing collision event
  - Compare composition of detector jets with particle jets from simulations (generators) like PYTHIA, which implement the LEP fragmentation functions!

Parton jets – what is this?

- Basically a representation of an individual final state parton before hadronization
  - Still called a jet because a jet finding algorithm is applied to the simulated partonic final state
- Jet finders explicitly or implicitly apply spatial and kinematic resolution parameters and (kinematic) thresholds to the interactions
  - Two or more close-by partons can be combined to one jet
  - A parton may not make it into a jet because it is below threshold
- Parton jets are "biased" with respect to the jet finding algorithm and its configuration
  - Two different jet finders may generated two different views on the partonic event

Particle jets

- These are jets from final state particles with lifetime > 10 ps
  - E.g., after hadronization of partons
  - Sometimes non-observable particles like neutrinos or particles with very specific signal characteristics (muons) may not be included
    - E.g., the muon generated in semi-leptonic b-decays may not be considered part of the b-jet
- Here a jet finder is mandatory to produce these jets
  - Needs to recombine the bundle of particles coming from the same source (parton)
  - Subjects particles to the same resolution parameters and thresholds as used for parton jets
  - Attempt to match parton and particle jets may allow to understand effect of fragmentation on jet finding efficiencies, mis-clustering (wrong particles combined), and bias on kinematic reconstruction
- Particle jets are a good "truth" reference for detector jets
  - After all , particles generate the detector signal

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Parton “Jets”

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Parton “jets”

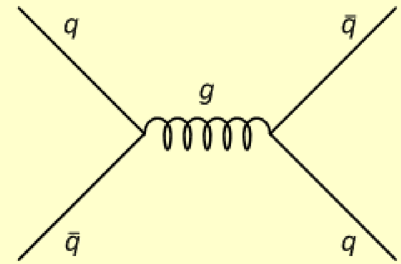
- Theoretical concept converting matrix element calculations in to jet picture
  - Depends on the order of the calculation
- Useful tool to link experimental results to calculations in di-quark resonance reconstruction
  - E.g., hadronic decays of the *W* boson and heavier new particles like *Z′*

Much less meaningful concept in QCD analysis like inclusive jet cross-section

- Jet counting as function of pT
- Number of parton jets not strictly linked to number of particle jets
  - Boundary between matrix element, radiation, parton showering, and underlying event washed out at particle level

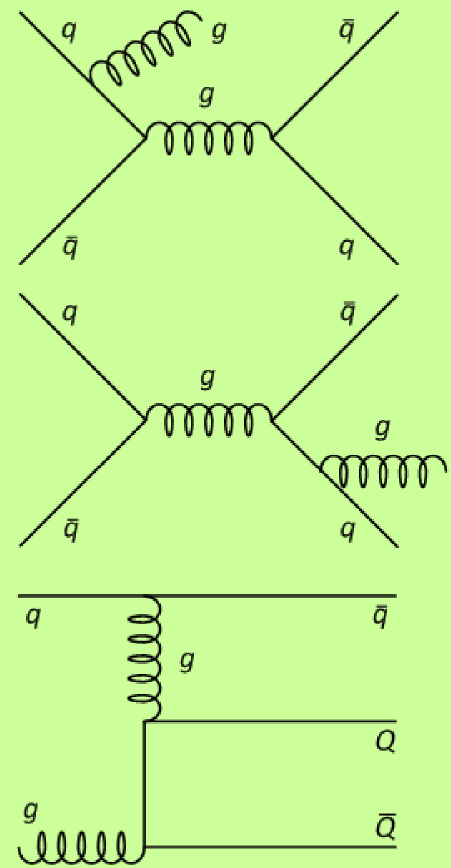
QCD LO:

$N_{\text{jets}} = 2$



QCD NLO:

$N_{\text{jets}} = 3$



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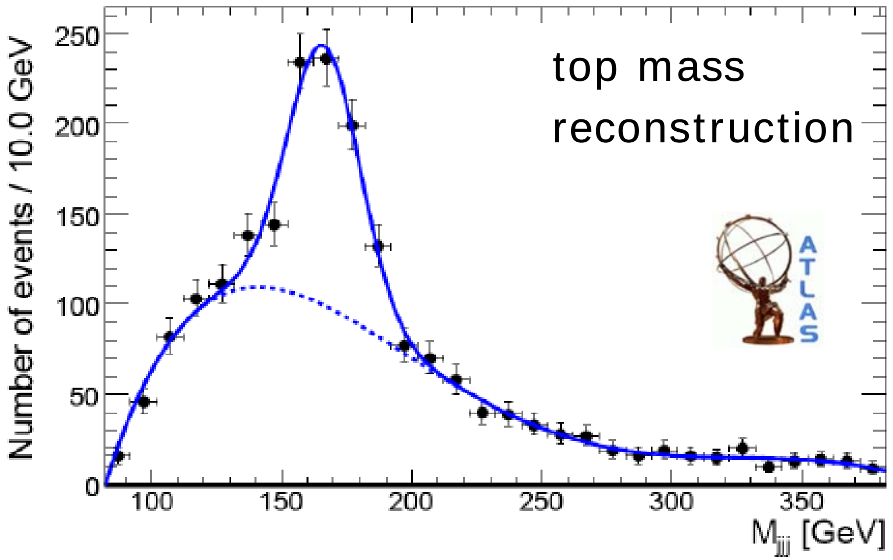
LO decays are easy to tag:

$W \rightarrow q\overline{q}'$ (2-prong decay)

$Z' \rightarrow q\overline{q}'$ (2-prong decay)

$t \rightarrow Wb \rightarrow q\overline{q}'b$ (3-prong decay)

$\rightarrow$ expectations for number of jets from decayed particle hypothesis at given order + mass of jet system pointing to certain source!



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Basic QCD 2 $\rightarrow$ 2 processes at LO:

$gg \rightarrow gg,\; gq \rightarrow gq,\; q\bar{q} \rightarrow q'\bar{q}'$

but often observe more than 2 jets in final state due to higher order contributions, initial and final state radiation, and additional interactions from the underlying event

$\rightarrow$ no obvious additional constraint on the appropriate parton level model from the observable final state, like in case of heavy particle decays!

$\rightarrow$ experimental final state "includes" all orders of calculations and collision environment!!

Particle Jets

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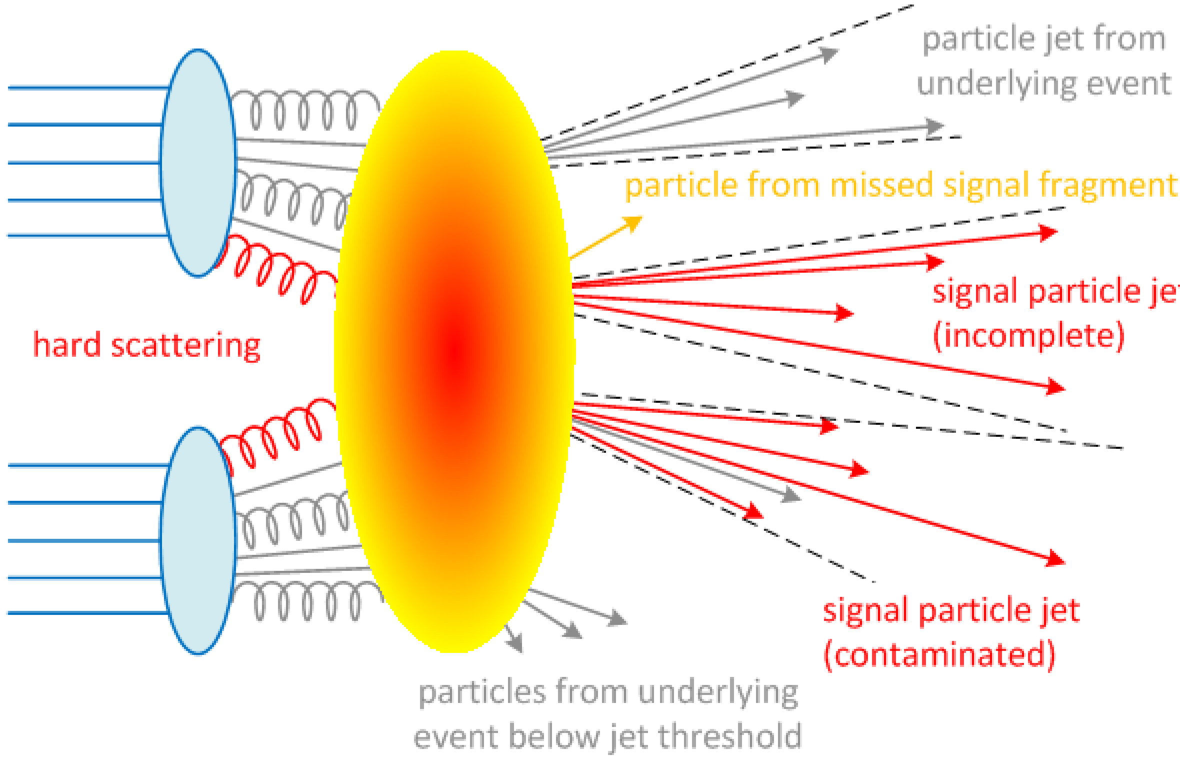
Collection of particles from common source

- Several sources in each collision
  - Hard scattering, multiple parton interactions in the underlying event, initial and final state radiation
- Describe the simulated collision viewed with a microscope (idealized)
  - Microscope **technology** – jet finding algorithm
  - **Resolution** – ability of a jet finder to (spatially) resolve jet structures of collision, typically a configuration parameter of the jet finder
  - **Sensitivity** – kinematic threshold for particle bundle to be called a jet, another configuration parameter of the jet finder



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Usefulness of Particle Jets

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Good reconstruction reference for detector jets

- Provide a truth reference for the reconstucted jet energy and momentum
  - E.g., can be used in simulations together with fully simulated detector jets to calibrate those (we will follow up on this point later!)
- Extract particle jets from measurement by calibration and unfolding signal characteristics from detector jets
  - Understand effect of experimental spatial resolution and signal thresholds at particle level
    - Remember: electromagnetic and hadronic showers have lateral extension → diffusion of spatial particle flow by distributing the particle energy laterally!
    - Remember: noise in calorimeter imply a “useful” signal threshold → may introduce acceptance limitations for particle jets!

Good reference for physics

- Goal of all selection and unfolding strategies in physics analysis
  - Reproduce particle level event from measurement as much as possible!
- Require correct simulations of all aspects of particle spectrum of collision right
  - Matrix element, parton showers, underlying event (non-pertubative soft QCD!), parton density functions,…
    - Parton shower matching to higher order matrix calculation in complex *pp* collision environment is a hot topic among theorists/phenomenologists today!
- Allow to compare results from different experiments
  - Specific detector limitations basically removed
  - Also provides platform for communication with theorists (LO and some NLO)
- Important limitations to be kept in mind
  - NLO particle level generators not available for all processes (more and more coming)
  - NNLO etc. not in sight

Basic idea

- Attempt to collect all particles coming from the same source in a given collision
  - Re-establishing the original correlations between these particles to reconstruct the kinematics and possibly even the nature of the source
- Is an algorithmic challenge
  - Many algorithms on the market, with different limitations
  - No universal algorithm or algorithm configuration for all final state analysis
    - More later, but good to know right away!
- Requires theoretical and experimental guidelines
  - Theory – physical features of particle jets addressed by sum (recombination) rules, stability of algorithm, validity for higher order calculations,…
  - Experiment – requirements for features of measured jets to allow most precise unfolding of particle jet, drives detector designs!
- Guidelines often not very appreciated by older analysis/experiments
  - Often focus on extracting signal structures from experiment without worrying too much about theoretical requirements
    - LO analysis: apply any jet algorithm to measured signals and corresponding simulations with expectations to get the same physics
  - LHC kinematic reach and phase space need considerations of higher order calculations – need jet finders valid to (arbitrary!) order!

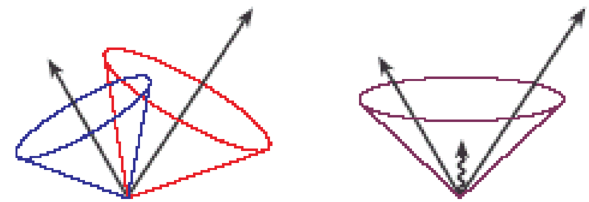
Theoretical Requirements For Jet Finders

Very important at LHC

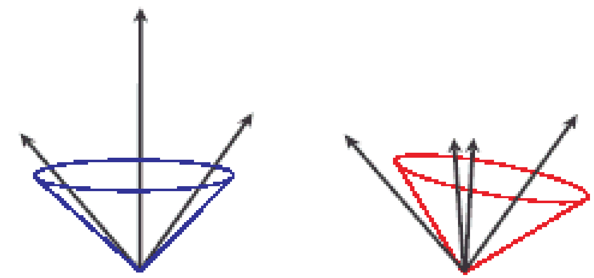
- Often LO (or even NLO) not sufficient to understand final states
  - Potentially significant K-factors can only be applied to jet driven spectra if jet finding follows theoretical rules
    - E.g., jet cross-section shapes
- Need to be able to compare experiments and theory
  - Comparison at the level of distributions
    - ATLAS and CMS will unfold experimental effects and limitations independently – different detector systems

Theoretical guidelines

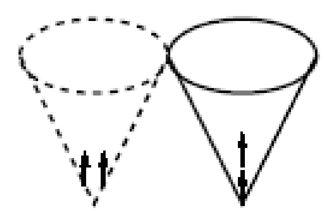
- Infrared safety
  - Adding or removing soft particles should not change the result of jet clustering
- Collinear safety
  - Splitting of large pT particle into two collinear particles should not affect the jet finding



infrared sensitivity
(soft gluon radiation merges jets)



collinear sensitivity (1)
(sensitive to E_t ordering of seeds)



collinear sensitivity (2)
(signal split into two towers below threshold)