X → diHiggs → 4b

Boosted Analysis
Preparations for Run 2

REU work at CERN winter 2015 with the Atlas Exotics group

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20 March 2015

Outline

I.) Introduction & short recap on motivation for boosted analysis

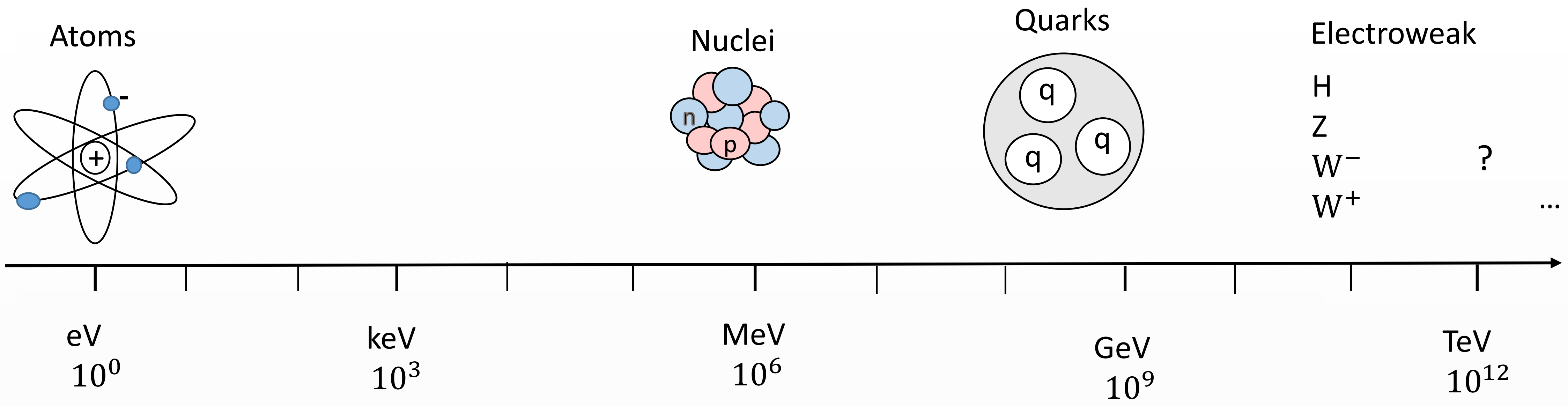
II.) XhhBoosted package development update

III.) Preliminary results of 13 TeV sample jet cuts study

IV.) Happening Now & Near future goals : background studies, QCD, ttbar with signal 20 release samples

V.) Backup slides on some cool things I learned

I.)



The universe at different energy scales: atomic physics to modern particle physics at the TeV scale.

Discovery of the Higgs boson opens new possibilities of probing the Electroweak scale and the production of heavy particles at the LHC

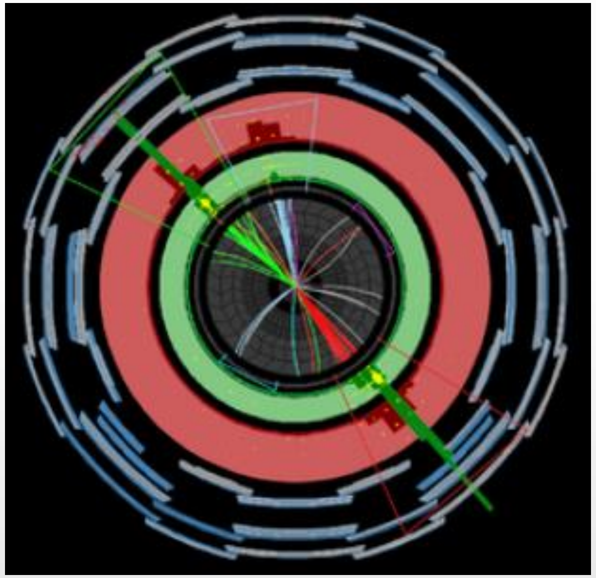
- Use the Higgs boson as a tool for further discovery
- Many new physics models predict significant rates of Higgs pair production
  - New resonances: Kaluza-Klein graviton $G_{KK} \rightarrow hh$
  - Extended Higgs sector, 2 Higgs doublet model, $H \rightarrow hh$ …
  - Non-resonant production: New coloured scalars, direct tthh vertices…

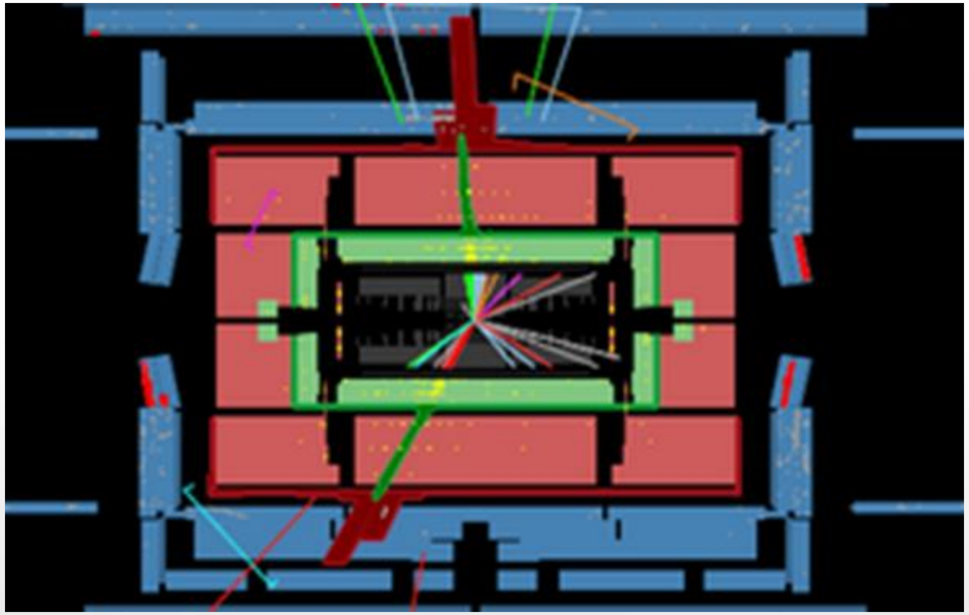
II.) Jets in ATLAS

- Transverse view (left): since the colliding partons have no momentum transverse to the beam axis, the jets are produced back to back in the transverse plane and have equal and opposite momenta.
- RZ-view (right): jets are not back to back due to the boost of the final-state system from the net momenta of the colliding partons along the beam axis, $(x_1 - x_2)\frac{\sqrt{s}}{2}$.

- “Jets are not just smeared partons”: they are matched by the number of degrees of freedom in the hard radiation that interferes at the amplitude level with the matrix element part of the calculation.
  (check out perturbation theory in backup)

- “Jets have no existence independent of the algorithm”: jet algorithms do not find jets, they define them.



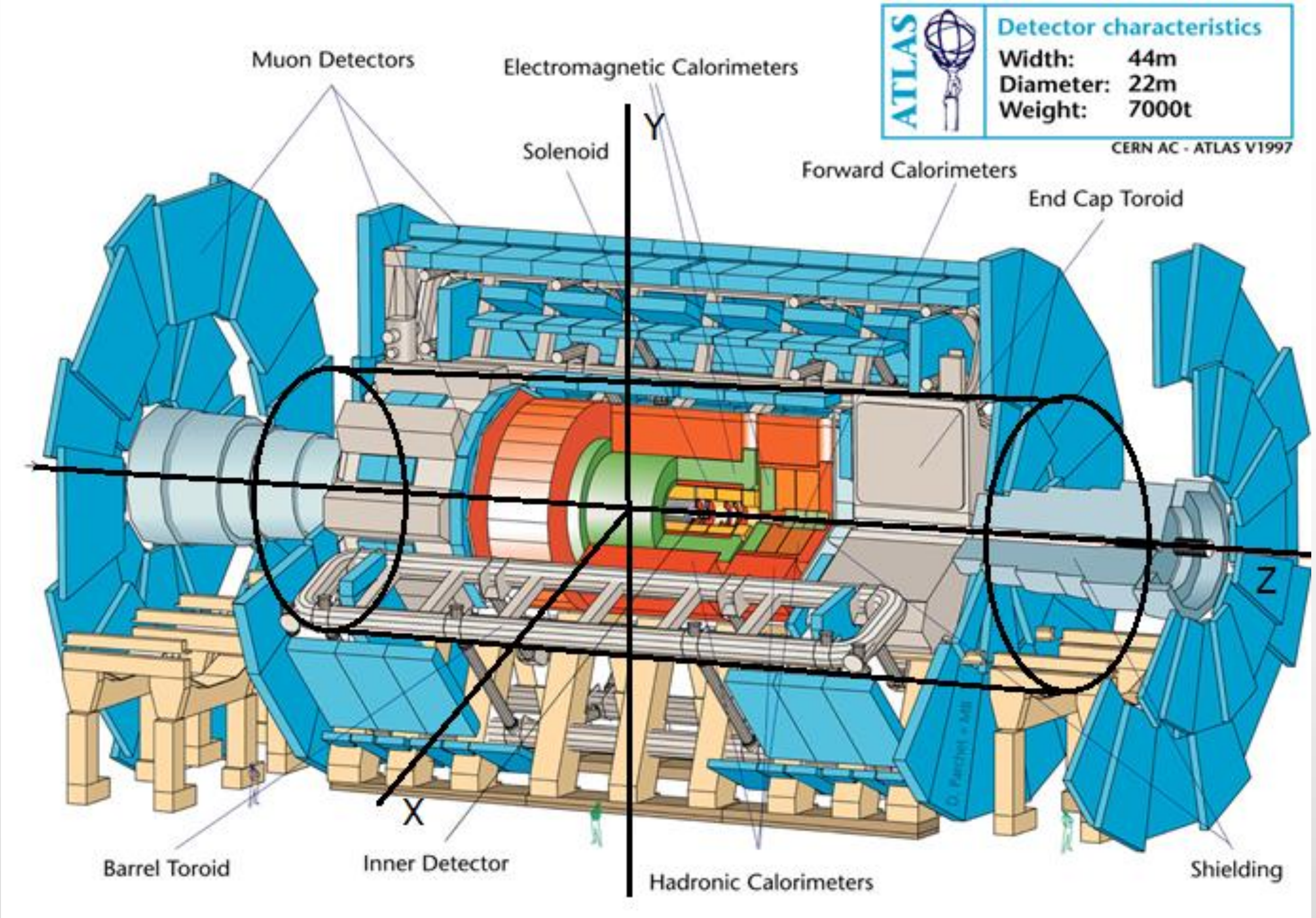


Atlas note: Performance of Jet Algorithms in the Atlas Detector

High mass jet event with dijet mass 3350 GeV and leading jets with (pT, eta, phi, color) of (1800 GeV, -0.51, -0.85, red) and subleading jets with (1470 GeV, -0.05, 2.4, green).
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayCONFnotes#Search_for_New_Phenomena_in_the

Measured Quantities, and the ATLAS detector… know it… love it

- rapidity (y), transverse momentum (p_T)



- Θ = polar angle measured with respect to the beam line.
- ϕ = azimuthal angle measured with respect to x axis.
- Rapidity: $y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$
- Pseudorapidity: $\eta = -\ln\frac{\theta}{2}$
- Transverse momentum: $p_T = p \times sin\theta$
- Transverse energy: $E_T = E \times sin\theta$

Detector → measurements → particle interactions & cross sections → compare to pertubative QCD fit → compare to PDFs

Given all this how do we look for new physics and continue to investigate fundamental particles?

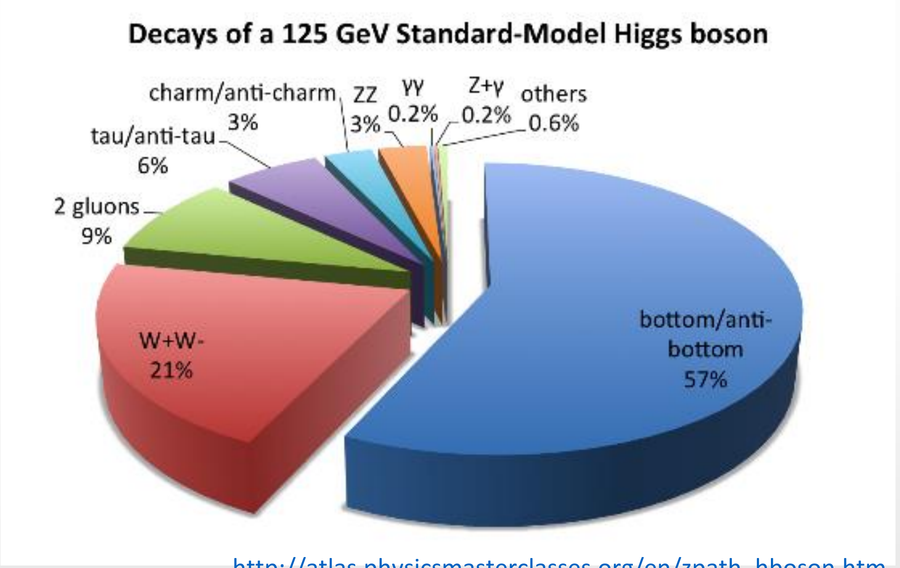
- If a b-quark is produced, the hadronization process will create a jet of hadrons, one of which will contain the b-quark, known as b hadrons.
- The b-quarks are relatively long lived with lifetimes of order 1.5×10^{-12}s.

Discovery of the Higgs boson and measured properties are consistent with the Standard Model

- Branching ration (BR) : BR(j) = $\frac{\Gamma_j}{\Gamma}$
- BR of H→bb $\approx 57.7\ \%$ at Higgs mass of 125 GeV
- Compare to BR of H → WW $\approx 21.6\ \%$

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR

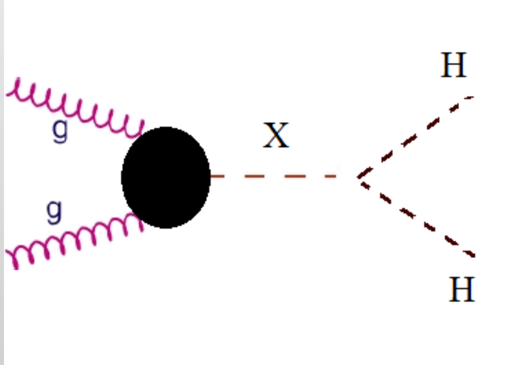
- This gives an intuition that b flavor tagging and jet reconstruction will help increase sensitivity for searches and analysis



http://atlas.physicsmasterclasses.org/en/zpath_hboson.htm

Leading to opportunities for searches with new physics models

- Many models predict significant Higgs pair production rates at high invariant mass
- Kaluza-Klein graviton G^*_{KK} in Randall-Sundrum framework
- Warped Extra Dimensions
- 2Higgs Double Model (2HDM)



Motivation for Boosted Analysis

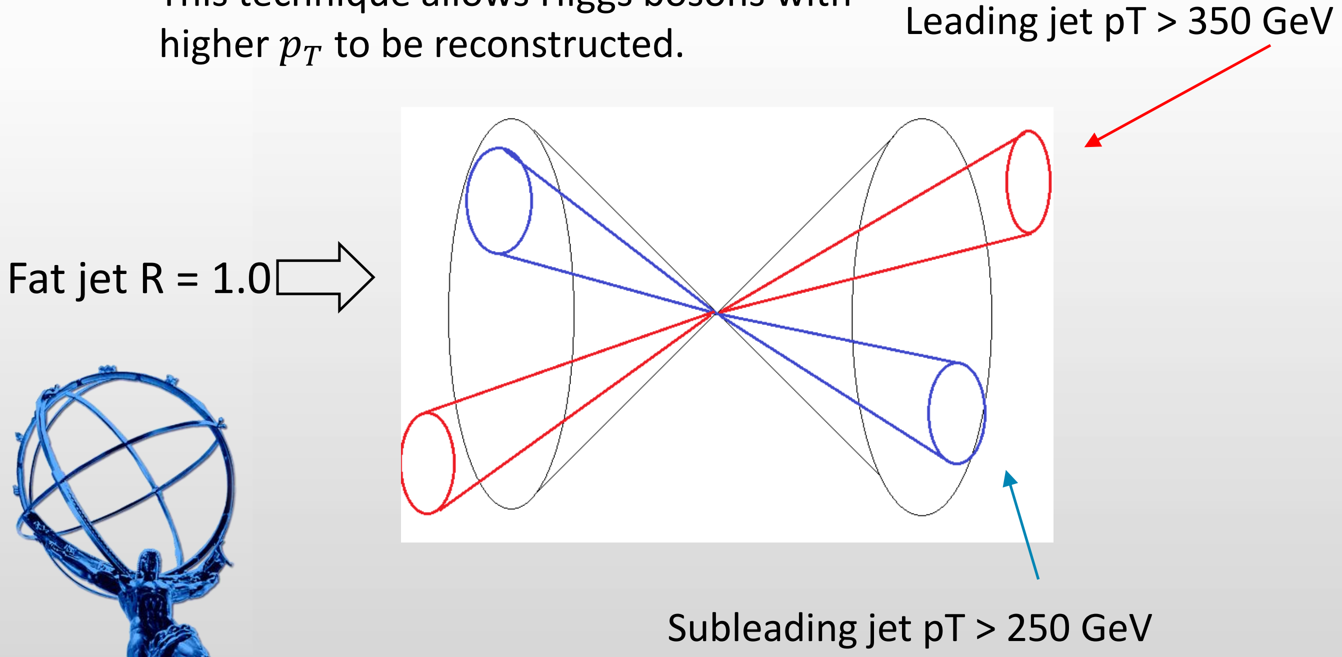
- Angular separation for 2-body decay products of a heavy particle is approximately $\Delta R \approx \frac{2m}{p_T}$,

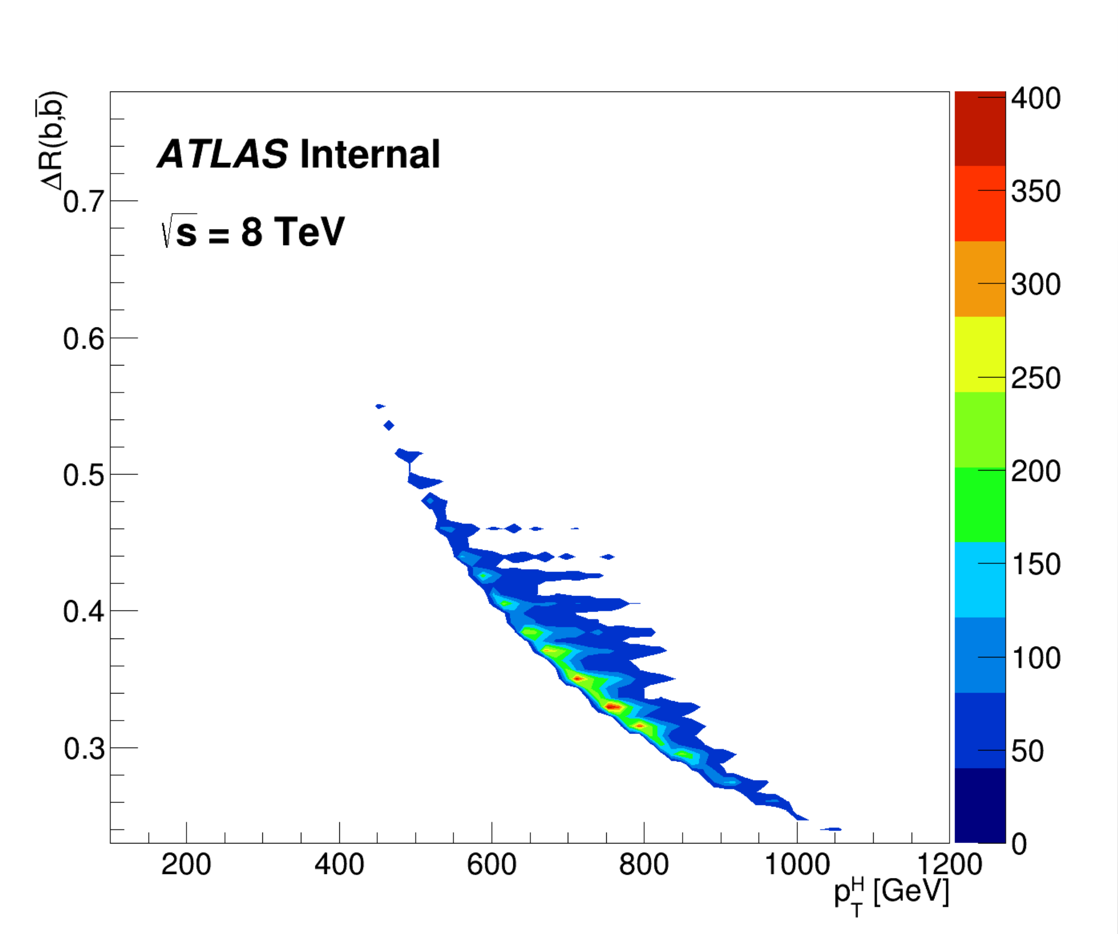
  where $\Delta R = \sqrt{\eta^2 + (\Delta\phi)^2}$.

- For a Higgs with $p_T \gtrsim$ 625 GeV, the threshold where jets would begin to merge in the detector is R = 0.4

Analysis Strategy from run1 Boosted Analysis

- Large-R trimmed jets with R = 1.0
- Two b-tagged small R, R = 0.3 track jets ghost associated to each Large-R jet.
- This technique allows Higgs bosons with higher p_T to be reconstructed.

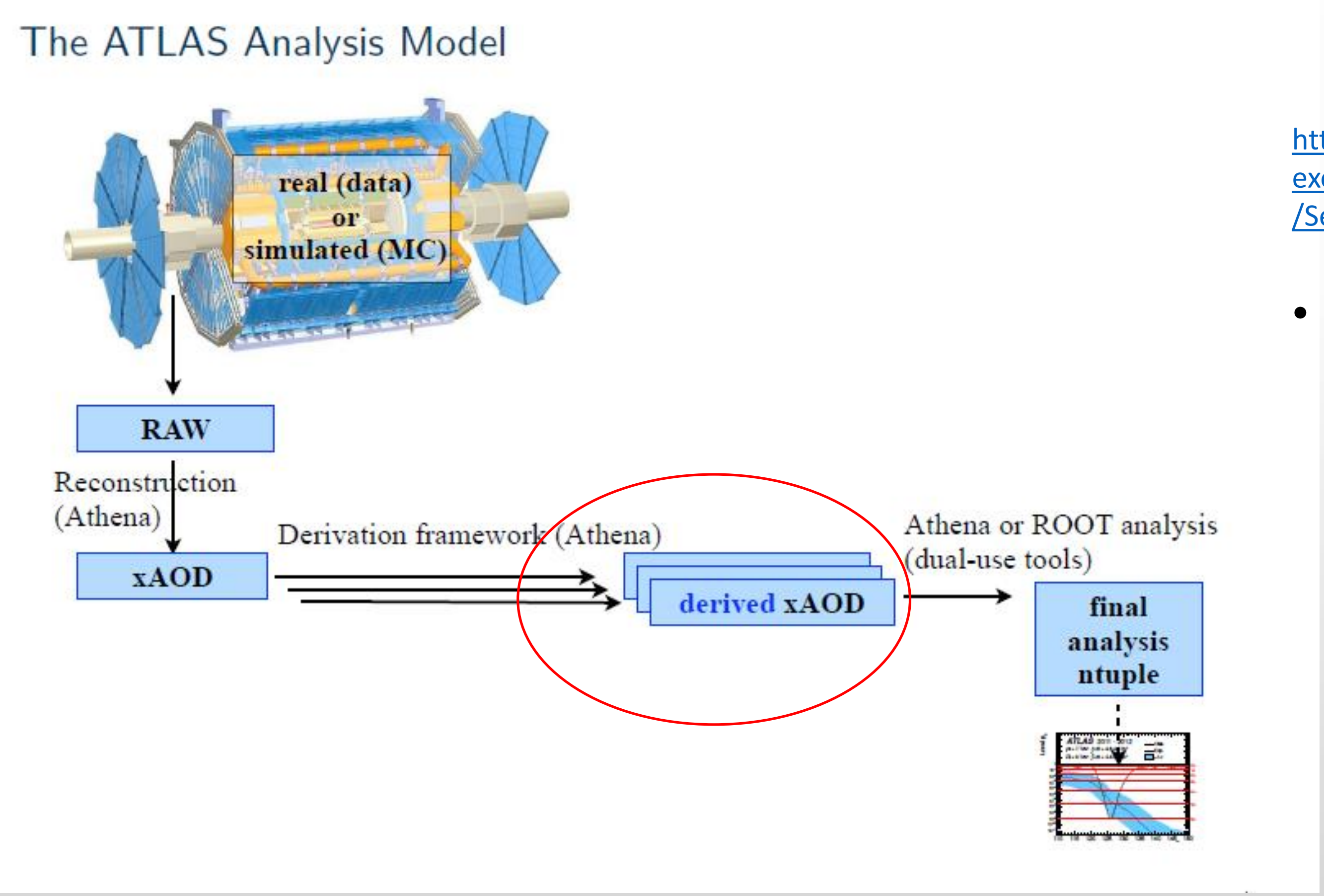




III.) Analysis :

- Actively developing package with Max : XhhBosted that works with xAODAnaHelpers package

https://svnweb.cern.ch/trac/atlasphysexo/browser/Physics/Exotic/JDM/hh4b/Run2/Code/XhhBoosted



Schema proposed :
https://svnweb.cern.ch/trac/atlasphys-exo/browser/Physics/Exotic/JDM/hh4b/Run2/Code/XhhBoosted/trunk/util/runXhhBoosted.cxx

- Run common basic event selection, GRL
- Apply specific Boosted Event Selection functions, seen defined in AnalysisMacros.h here :

https://svnweb.cern.ch/trac/atlasphys-exo/browser/Physics/Exotic/JDM/hh4b/Run2/Code/XhhBoosted/trunk/Root/SetXhhEventCuts.cxx

- The outputs of this algorithm are:
  - A set of flags in EventInfo to check which cuts were passed
  - A container in Tevent holding xAOD::Iparticle links to the 2 large jets, which are linked to 2 small R track jets

  - Proposal to code a common package to make plots/tables out of this information
  - Allow for code flexibility in development and better processing

The Algorithm :

```
EL::Job basicJobSetup(int argc, char* argv[])
{
  //
  // Grab the configuration file
  //
  std::string configName = "./XhhBoosted/data/steer.config";
  if( argc > 1 ){
    std::cout << "Config file is set to: " << configName << std::endl;
    configName= argv[ 1 ];
  }else{
    std::cout << "Config file defaults to: " << configName << std::endl;
  }

  TEnv* config = new TEnv(configName.c_str());

  //
  // Determine the run Mode
  //
  TString m_runMode   = config->GetValue("RunMode",       "local");
  std::string faxDSName = config->GetValue("FAXDataSetName",  "Set DC Name in Config file");
```

Configures input data & determines run mode

Configuration files encapsulated from steering macros and class functions to increase close versatility

```
//
// Set up the job for xAOD access:
//
xAOD::Init().ignore();

//
// Construct the samples to run on:
//
SH::SampleHandler sh;

if(m_runMode.Contains("fax",TString::kIgnoreCase)){
  std::cout << " Running on fax over. " << faxDSName << std::endl;
  SH::scanDQ2 (sh, faxDSName);
}else{
  std::cout << " Running locally over one file. " << std::endl;
  // this takes one single file (to be used for testing)

  //
  // Grab the Path from the config
  //
```

Follows the ASG guidelines and is fully supported

Here using Sample Handler as recommendation

```
 std::stringinputFilePath=config>GetValue("LocalFilePath",  "/share/t3data3/johnda/samples/mc14_13Te
V.203496.MadGraphPythia8_AU2MSTW2008LO_RSG_hh_bbbb_m500.merge.AOD.e3219_s1982_s2008_
r5787_r5853_tid01604035_00/");

  std::string inputFileName = config->GetValue("LocalFileName",  "AOD.01604035._000002.pool.root.2");

   SH::DiskListLocal list (inputFilePath);
   SH::scanDir (sh, list, inputFileName);
 }

 //
 // Set the name of the input TTree. It's always "CollectionTree"
 // for xAOD files.
 //
 sh.setMetaString( "nc_tree", "CollectionTree" );

 //
 // Print what we found:
 //
 sh.print();
```

```
//
  // Create an EventLoop job:
  //
  EL::Job ;
  job.sampleHandler( sh );

  //
  //  Set the number of events
  //
  int nEvents = config->GetValue("maxEvents",       -1);
  if(nEvents > 0)
    job.options()->setDouble(EL::Job::optMaxEvents, nEvents);

  return job;
}

void runLocalDriver(EL::Job& job, int argc, char* argv[])
{
```

Create Event Loop job
and
preliminary job options

```
//
 // Grab the configuration
 //
 std::string configName = "./XhhBoosted/data/steer.config";
 if( argc > 1 ){
   std::cout << "Config file is set to: " << configName << std::endl;
   configName= argv[ 1 ];
 }else{
   std::cout << "Config file defaults to: " << configName << std::endl;
 }

 TEnv* config = new TEnv(configName.c_str());

 //
 // Set the output directory
 //
 std::string submitDir = config->GetValue("SubmitDir",   "runXhhBoostedOutput");
 if( argc > 2 ){
   submitDir = argv[ 2 ];
 }
 std::cout << "Output (Submit) Dir is: " << submitDir << std::endl;
```

Makes use of Tevent and Tstore to hold and store particles, these are classes from the RootCore skeleton

```
EL::DirectDriver driver;
  driver.submit( job, submitDir );
  return;
}

void basicEventSelection(EL::Job& job, std::string name, std::string configFile)
{
  BasicEventSelection* baseEventSel = new BasicEventSelection(name, configFile);
  job.algsAdd( baseEventSel );
}

void calibrateJets(EL::Job& job, std::string name, std::string configFile)
{
   JetCalibrator* jetCalib      = new JetCalibrator("jetCalib_"+name,configFile);
   job.algsAdd( jetCalib );
}

void selectCaloJets (EL::Job& job, std::string name, std::string configFile)
{
   JetSelector*   jet_selection    = new JetSelector  ("selCaloJets_"+name,configFile);
   job.algsAdd( jet_selection );
}
```

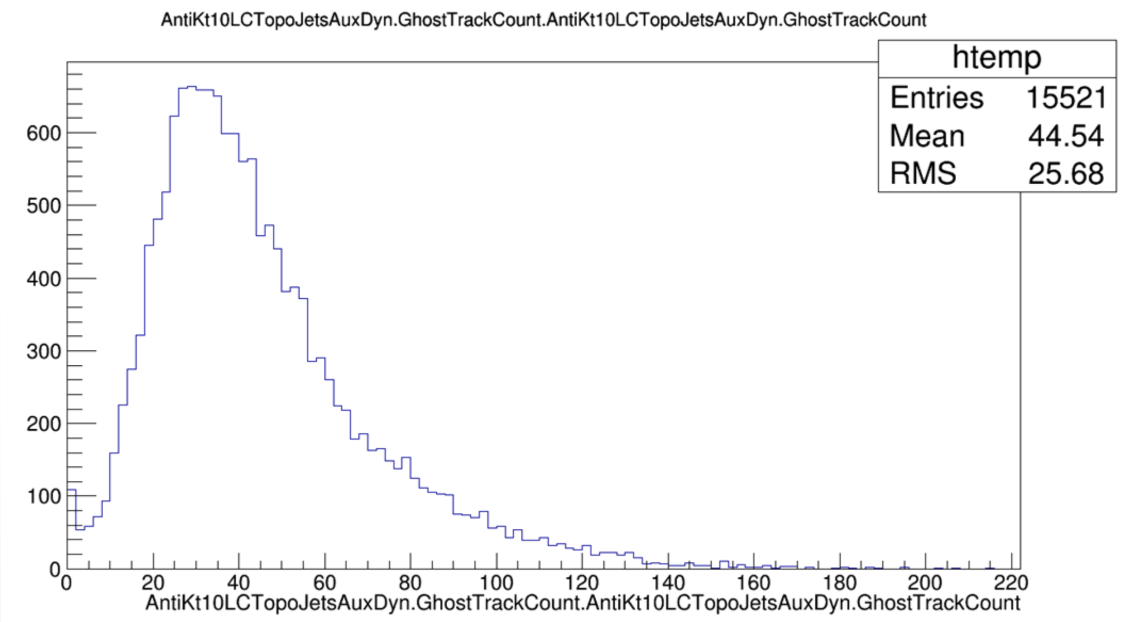
The algorithm for the Boosted Analysis

```
void setXhhEventCuts(EL::Job& job, std::string name, std::string configFile)
{
  SetXhhEventCuts* setXhhEventCuts    = new SetXhhEventCuts(name, configFile);
   job.algsAdd( setXhhEventCuts );
}

void eventCount(EL::Job& job, unsigned int eventsPerPrint = 100, bool debug=false)
{
 EventCount* eventCount       = new EventCount();
 eventCount->m_eventsPerPrint = eventsPerPrint;
 job.algsAdd( eventCount );
}

// to be implemented still
/*void calibrateMuons(EL::Job& job, std::string name, std::string configFile)
  {
    MuonCalibrator* muonCalib    = new MuonCalibrator("muonCalib_"+name, configFile);
    job.algsAdd( muonCalib );
  }
void selectMuons(EL::Job& job, std::string name, std::string configFile)
  {
    MuonSelector*   muon_selection  = new MuonSelector  ("muons_"+name, configFile);
    job.algsAdd( muon_selection );
  }*/
```

Right now most testing is being done in setXhhEventCuts

Signal sample using:

- Mass of the G_{KK} at resonance of 500 GeV (working on obtaining different mass resonances presently)
- DC14 release 19, $\sqrt{s} = 13$ TeV
- EventCount and SetXhhEventCuts are the classes accessed by macros



Directly from signal sample, count of events after AntiKt10LCTopo algorithm applied.

- Console output after running XhhBoosted :

```
Info in <BasicEventSelection::finalize()>: Number of events          = 5000
Info in <JetSelector::finalize()>: selCaloJets_selCaloJets
Info in <JetSelector::histFinalize()>: Filling cutflow
Total Events Processed...  5000 Events  (Rate: 220.751 Hz)
Cut PassAssoTrackJets 315 0.063
Cut PassAtLeast2Jets 538 0.1076
Cut PassLeadJetPt 343 0.0686
Cut PassSubLeadJetPt 538 0.1076
Cut PassTrackJetEta 45 0.009
Cut PassTrackJetPt 45 0.009
Cut PassXhhTrig 0 0
Info in <BJetSelector::finalize()>: Deleting tool instances...

Info in <BJetSelector::finalize()>: Deleting tool instances...

DiJets: Number of passed di-jets: 2576980377/(858993466)
Info in <JetSelector::histFinalize()>: Calling histFinalize
```

- AntiKt R = 1.0 jet trimming
- Pass 2 Jets : Leading and subleading with p_T > 350 GeV and p_T > 250 GeV respectively, both with η < 2.0 (between fat jets)
- Tracks jet with R = 0.3 are ghost associated to large R ungroomed jets
- Track jets must have p_T > 20 GeV and η < 2.5 (trimmed calorimeter jet and originate from primary vertex)
- Last step to be implemented before b-tagging delta η < 1.7 cut between 2 fat jets

Console output:

*printing out some information about the jets that are in the sample and that pass the cuts.

*actively working on getting different mass samples

```
Info in <SetXhhEventCuts::execute()>:   jet pt  = 386.99 GeV
Info in <SetXhhEventCuts::execute()>:   jet eta = 0.26
Info in <SetXhhEventCuts::execute()>:   jet pt  = 333.15 GeV
Info in <SetXhhEventCuts::execute()>:   jet eta = 0.54
Info in <SetXhhEventCuts::execute()>: trackJetPt1 = 12.92 GeV
Info in <SetXhhEventCuts::execute()>: trackJetPt2 = 174.34 Ge
Info in <SetXhhEventCuts::execute()>: trackJetPt3 = 12.92 GeV
Info in <SetXhhEventCuts::execute()>: trackJetPt4 = 174.34 Ge
Info in <SetXhhEventCuts::execute()>:   jet pt  = 267.74 GeV
Info in <SetXhhEventCuts::execute()>:   jet eta = 0.77
Info in <SetXhhEventCuts::execute()>:   jet pt  = 257.73 GeV
Info in <SetXhhEventCuts::execute()>:   jet eta = 0.36
Info in <SetXhhEventCuts::execute()>:   jet pt  = 368.73 GeV
Info in <SetXhhEventCuts::execute()>:   jet eta = 0.85
Info in <SetXhhEventCuts::execute()>:   jet pt  = 287.15 GeV
Info in <SetXhhEventCuts::execute()>:   jet eta = 0.18
Info in <SetXhhEventCuts::execute()>: trackJetPt1 = 2.11 GeV
Info in <SetXhhEventCuts::execute()>: trackJetPt2 = 3.32 GeV
Info in <SetXhhEventCuts::execute()>: trackJetPt3 = 2.11 GeV
Info in <SetXhhEventCuts::execute()>: trackJetPt4 = 3.32 GeV
Info in <SetXhhEventCuts::execute()>:   jet pt  = 682.92 GeV
Info in <SetXhhEventCuts::execute()>:   jet eta = 0.16
Info in <SetXhhEventCuts::execute()>:   jet pt  = 671.33 GeV
Info in <SetXhhEventCuts::execute()>:   jet eta = 1.22
Info in <SetXhhEventCuts::execute()>: trackJetPt1 = 15.11 GeV
Info in <SetXhhEventCuts::execute()>: trackJetPt2 = 14.13 GeV
Info in <SetXhhEventCuts::execute()>: trackJetPt3 = 15.11 GeV
Info in <SetXhhEventCuts::execute()>: trackJetPt4 = 14.13 GeV
Info in <SetXhhEventCuts::execute()>:   jet pt  = 496.34 GeV
Info in <SetXhhEventCuts::execute()>:   jet eta = 0.09
Info in <SetXhhEventCuts::execute()>:   jet pt  = 362.89 GeV
Info in <SetXhhEventCuts::execute()>:   jet eta = 0.52
```

```
Info in <SetXhhEventCuts::execute()>:   jet pt  = 379.72 GeV
Info in <SetXhhEventCuts::execute()>:   jet eta = 0.06
Info in <SetXhhEventCuts::execute()>:   jet pt  = 354.35 GeV
Info in <SetXhhEventCuts::execute()>:   jet eta = 0.68
Info in <SetXhhEventCuts::execute()>: trackJetPt1 = 10.03 GeV
Info in <SetXhhEventCuts::execute()>: trackJetPt2 = 2.56 GeV
Info in <SetXhhEventCuts::execute()>: trackJetPt3 = 10.03 GeV
Info in <SetXhhEventCuts::execute()>: trackJetPt4 = 2.56 GeV
Warning in <xAOD::THolder::getAs>: Trying to retrieve ConstDataVe
et_v1> pointer
Warning in <xAOD::THolder::getAs>: Trying to retrieve ConstDataVe
et_v1> pointer
Warning in <xAOD::THolder::getAs>: Trying to retrieve ConstDataVe
et_v1> pointer
Warning in <xAOD::THolder::getAs>: Trying to retrieve ConstDataVe
et_v1> pointer
Warning in <xAOD::THolder::getAs>: Trying to retrieve ConstDataVe
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et_v1> pointer
Warning in <xAOD::THolder::getAs>: Trying to retrieve ConstDataVe
et_v1> pointer
Warning in <xAOD::THolder::getAs>: Trying to retrieve ConstDataVe
et_v1> pointer
Info in <SetXhhEventCuts::execute()>:   jet pt  = 382.62 GeV
Info in <SetXhhEventCuts::execute()>:   jet eta = 1.09
Info in <SetXhhEventCuts::execute()>:   jet pt  = 287.25 GeV
Info in <SetXhhEventCuts::execute()>:   jet eta = 0.62
Info in <SetXhhEventCuts::execute()>: trackJetPt1 = 7.93 GeV
Info in <SetXhhEventCuts::execute()>: trackJetPt2 = 7.38 GeV
Info in <SetXhhEventCuts::execute()>: trackJetPt3 = 7.93 GeV
Info in <SetXhhEventCuts::execute()>: trackJetPt4 = 7.38 GeV
```
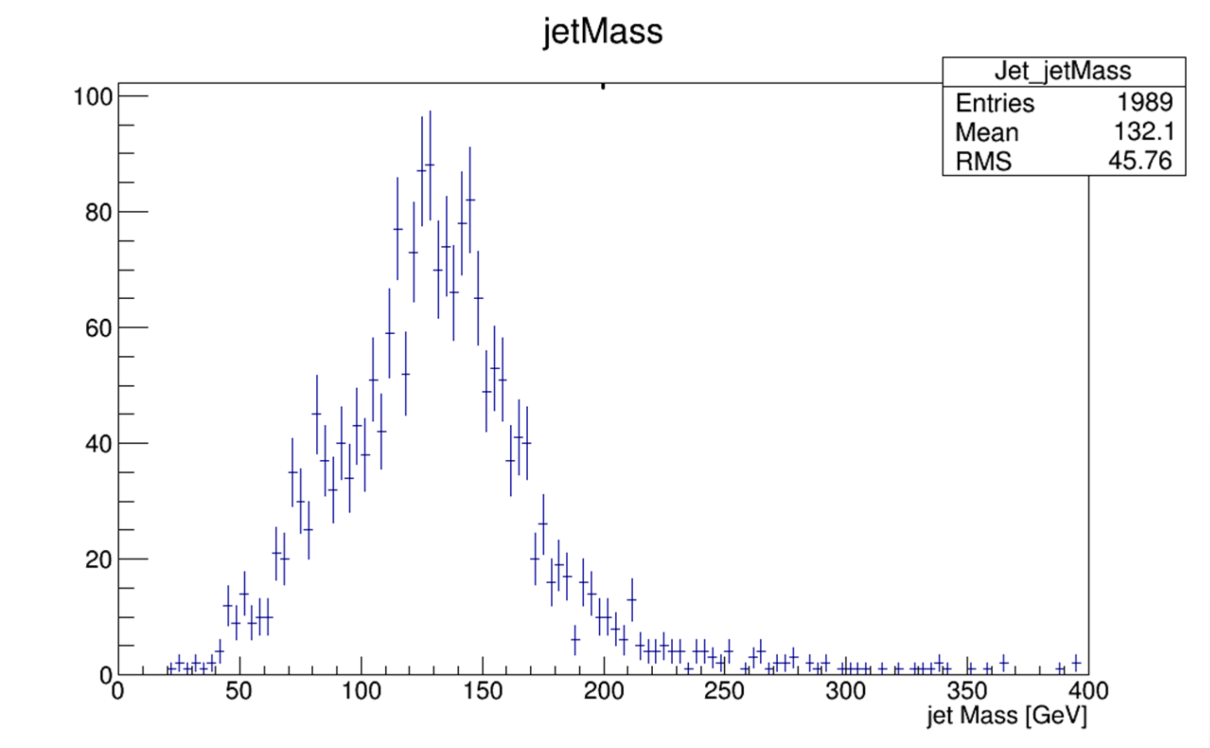
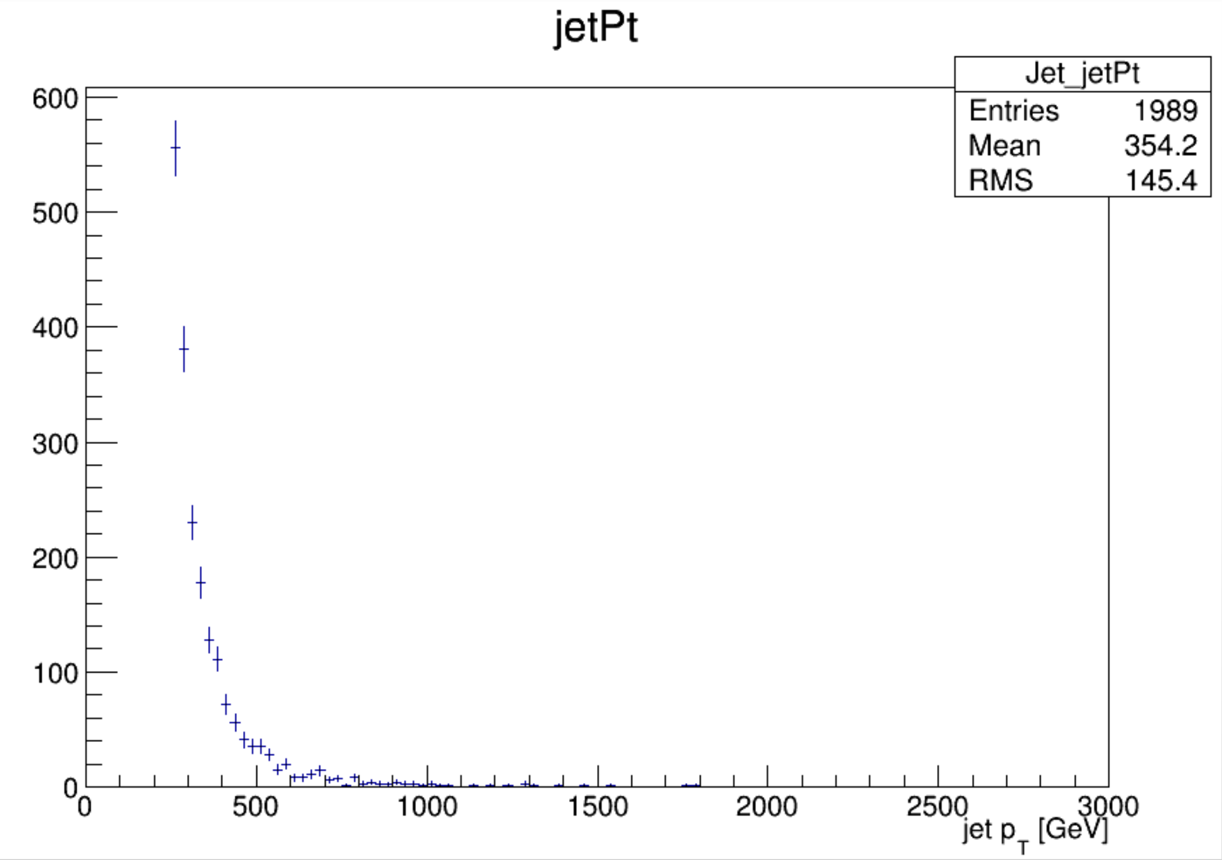
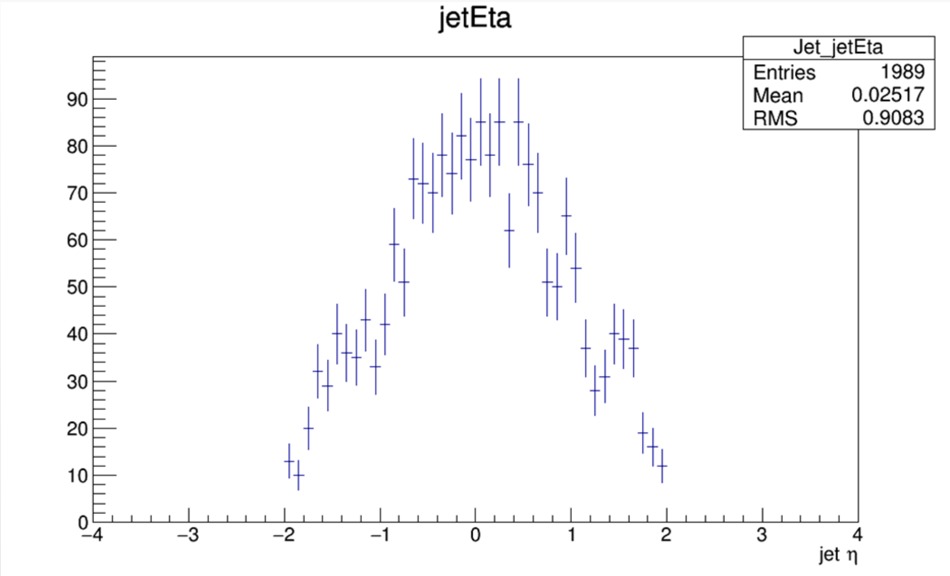

After running package:

- After Leading p_T > 350 GeV cut
- 1989 out of 5000 events pass the cut
- Jet mass peaks about 8 GeV greater than the Higgs mass
- Preliminary efficiency for 500 GeV resonance mass approximately 40 %
- Statistical error and different masses will be studied







IV.) Happening now & Near Future Goals :

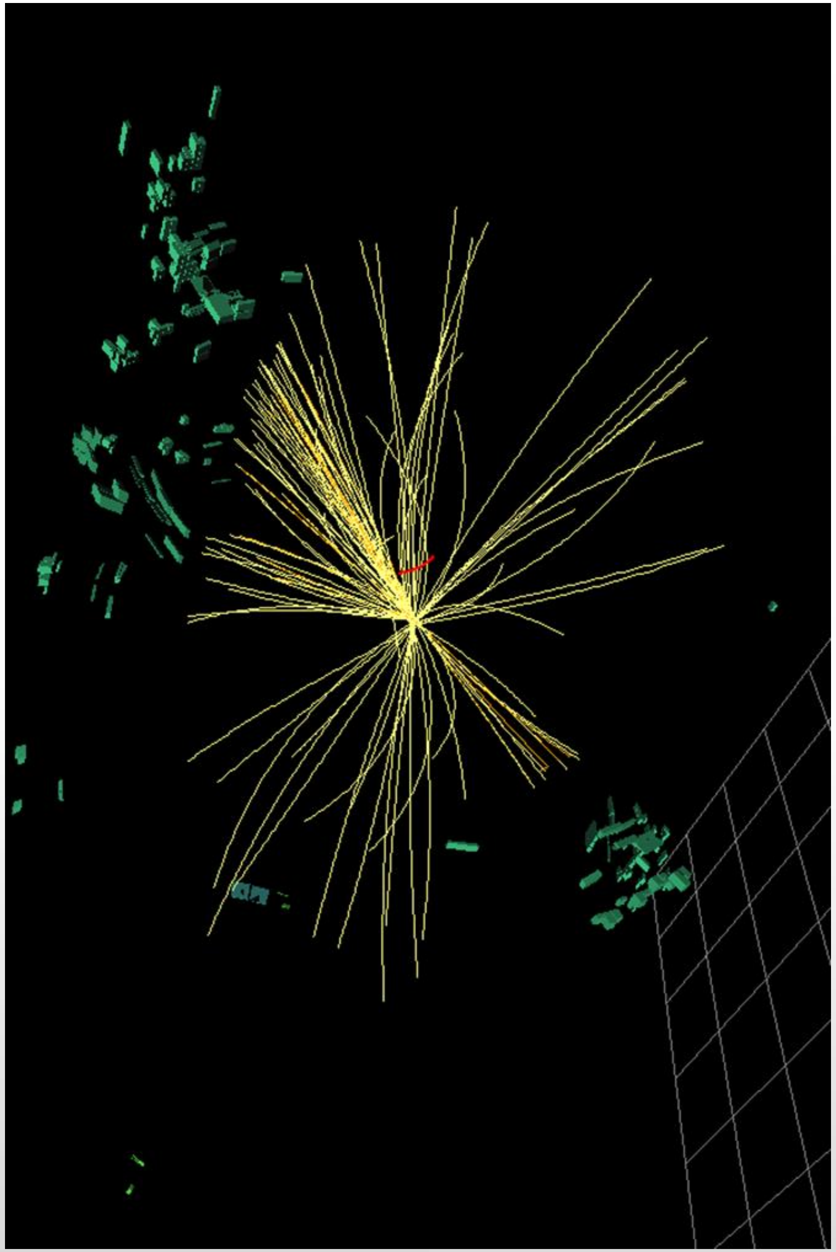
- Working with Max on building XhhBoosted package, this is an xAOD Event loop based algorithm to be complete by May

- Working with Reina Camacho & Michael Kagan in the Boosted X → bb tagging group (collaboration including Max and many others) https://twiki.cern.ch/twiki/bin/viewauth/AtlasProtected/BoostedHiggsToBBTagging

- Study performance for anti-kt trimmed R = 1.0, R_sub = 0.3 and R_sub = 0.2, and f = 5% study performance at 13 TeV : signal versus QCD and top background.

- This is in alignment with what is needed in Diboson → 4b Exotics Analysis studies as well. (the goal is not to create more work, but to work more efficiently as a collaboration and to help ensure an excellently prepared and tested analysis for run2)

    - **Plot efficiency and define signal, control, sideband regions**
    - **Rel20 13TeV samples to work with B-tagging**
    - **Background QCD and ttbar studies**



Just some playing around with the useful features of vp1 for visualizing jets in hadronic collisions : yellow are tracks of particle collisions, red are muon tracks, and green are calorimeter energy deposits. One can get a visual sense of where jets may be reconstructed.

Jump | Search | Atlas | All webs

ChristinaNelson
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ATLAS Collaboration

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TWiki > AtlasProtected Web > AtlasPhysics > FlavourTagging > BoostedBTagging > BoostedHiggsToBBTagging (2015-03-10, ReinaCamacho)

Edit Attach PDF

Boosted X--> bb tagging

Not yet Certified as ATLAS Documentation

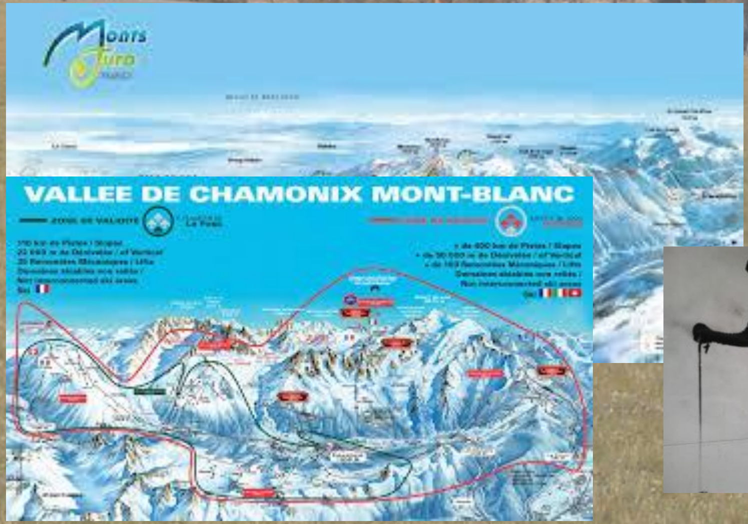
Responsible: MichaelKagan

https://twiki.cern.ch/twiki/bin/viewauth/AtlasProtected/BoostedHiggsToBBTagging

Task ID	TODO Task description	Assignment	Status	Deadline
	Short term tasks			
A	B-tagging - Define working points and study performance for b-tagging using track jets			
A-1	Optimisation and performance at 8 and 13 TeV	M. Kagan, Q. Zeng	Complete:	Before Data
A-2	b-tagging calibration and extrapolation from 8 to 13 TeV	Unassigned?	Complete:	Before data
B	Jet algorithms - Study performance for anti-kt trimmed R=1.0, R_sub=0.2 and f=5%			
B-1	Performance at 8 and 13 TeV: signal vs QCD/top background	Christina Nelson	Complete:	Before Data
B-2	JMS and JES using QCD jets at 13 TeV	C. Delitzsch	Complete:	Before data
B-3	Cross-calibration using QCD jets 13 TeV samples	Unassigned?	Complete:	Before data
B-4	JES and JMS flavour uncertainty from H->bb using 13 TeV samples	Unassigned?	Complete:	Before data
C	Substructure - Using substructure variables adds on top of b-tagging?			
C-1	Performance at 8 and 13 TeV before and after b-tagging	Q. Zeng, Chiao-Ying Lin, T. Lenz, S. Ballensiefen	Complete:	Before Data

Special thanks to my mentors :
Massimiliano Bellomo and
Stephane Willocq


Petzi tickets.ch
NELSON CHRISTINA
PEACE - THE FAMILY RAIN - POLAR CIRCLES - THE
BURNING BEGGARS
LES HIVERNALES
SATURDAY 28/02/2015
START: 21:30
DOORS: 20:30
PRICE: CHF 28.00
Petzi tickets
N° 3047400234656
LES HIVER-NALES

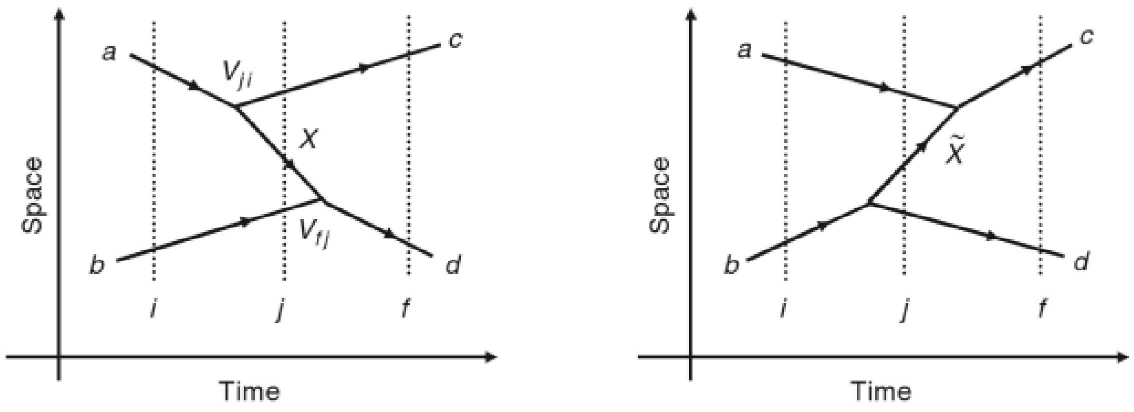

VALLEE DE CHAMONIX MONT-BLANC

C. Nelson

Cool & useful things I learned

Perturbation Theory

- The process of understanding interactions between particles by the exchange of force carrying gauge bosons.
- Two possible time-orderings for the process a+b → c+d which can occur via an intermediate state corresponding to the exchange of particle X.



Initial state $|i\rangle$ corresponds to particles $a + b$, intermediate state $|j\rangle$ corresponds to $c + b + X$, and final state $|f\rangle$ corresponds to $c + d$.

- Left diagram: particle a can be thought of as emitting the exchanged particle X, and then at a later time X is absorbed by b.
- Right diagram: particle b emitting the exchanged particle $\tilde{X}$, which is then absorbed by a. $\tilde{X}$ has the same mass as X but opposite charge.

- Rewriting the four-momentum of the exchanged particle X, as $q = p_a - p_c$ we find that

$$M_{fi} = \frac{g_a g_b}{q^2 - m_X^2}.$$

This remarkable result shows that the interaction matrix, depending on four momentum, is Lorentz invariant and is the sum of different time ordered processes !

Mark Thompson “Modern Particle Physics”. Cambridge University Press 2013, p115-118.

Parton Distribution Functions :

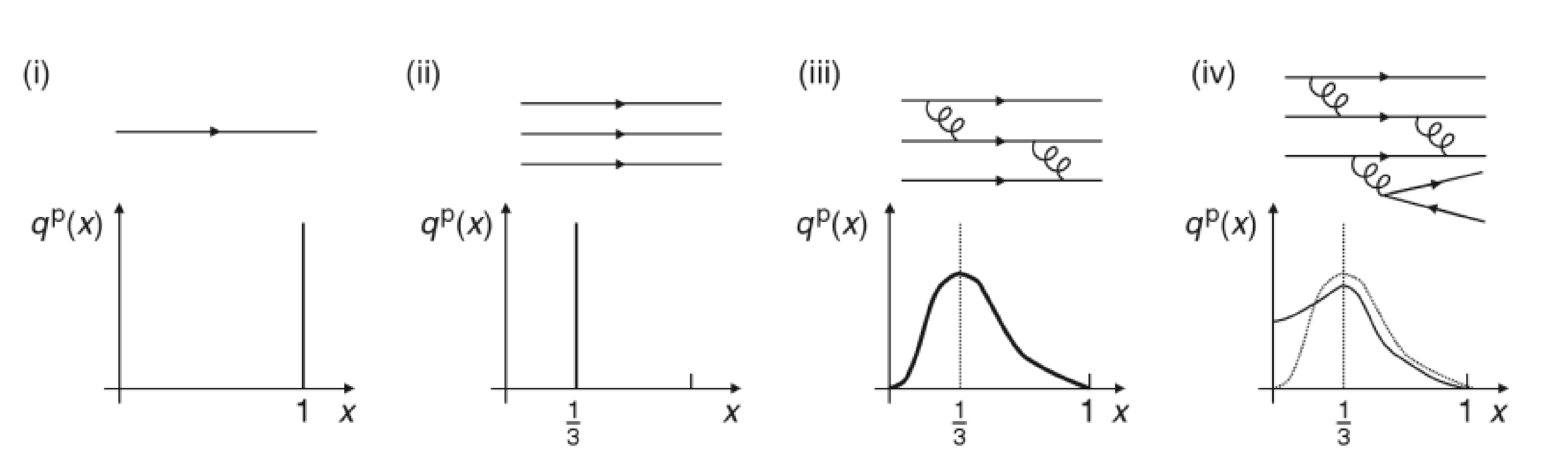
- PDFs are obtained from experiment.

  The dynamics of quarks interacting with each other inside a proton through the exchange of gluons results in a distribution of quark momenta within the proton. The distributions are expressed in terms of PDFs. For example, the bottom-quark PDF for the proton $b^p(x)$ is defined such that

$$b^p(x)\delta x$$

  represents the number of bottom quarks within the proton with momentum fraction between x and $x+\ \delta x$.

Illustrating a few possible forms of PDFs:

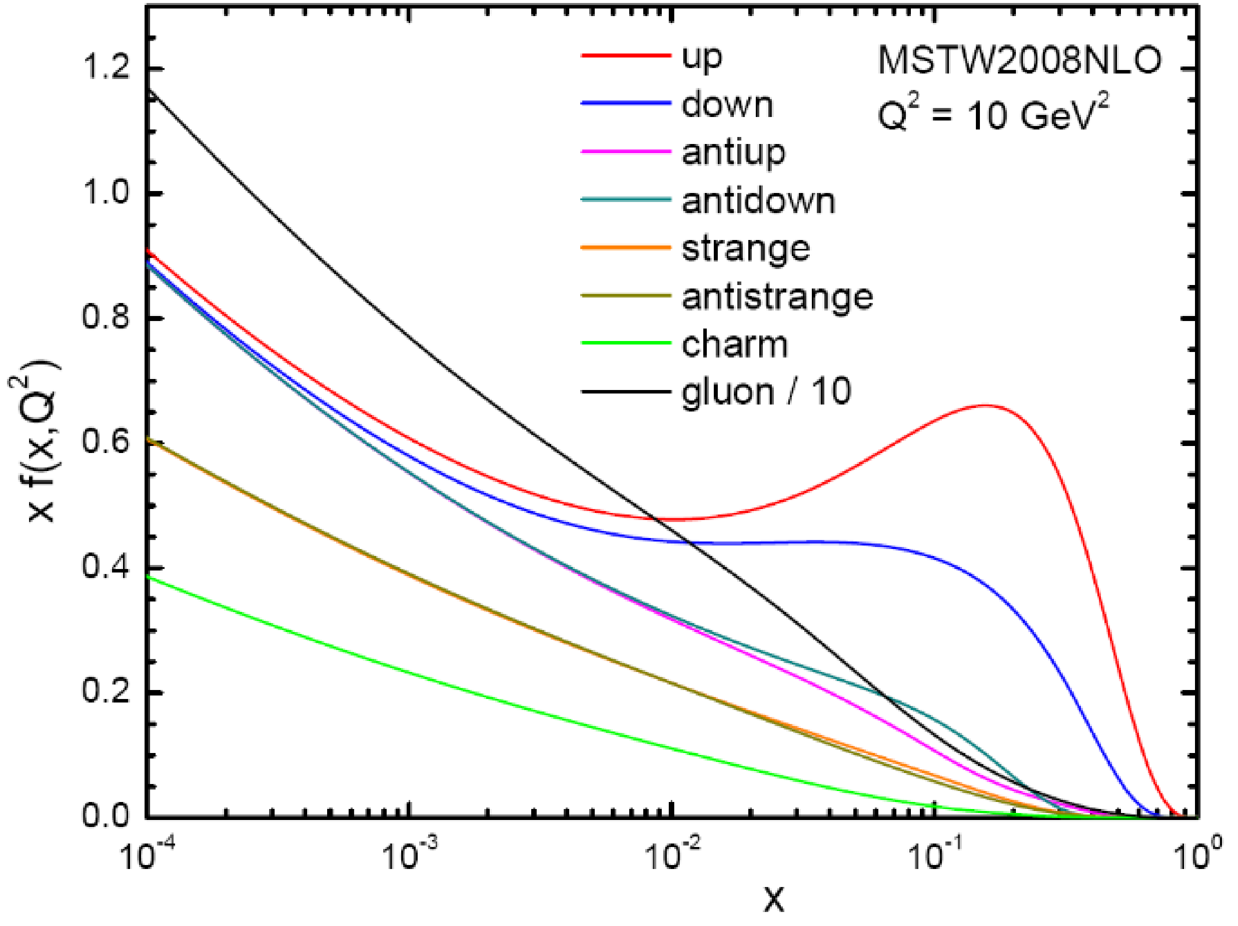


(i) Proton a single point like particle which carries all the momenta of proton, at Dirac delta function $x = 1$.
(ii) Proton contains 3 static quarks each carrying $\frac{1}{3}$ the momenta of the proton, at Dirac delta function $x = \frac{1}{3}$
(iii) Three quarks interact with each other and delta-function at $x = \frac{1}{3}$ is smeared out as the quarks exchange momentum
(iv) Higher-order processes, e.g. virtual quark pairs being produced from gluons inside the proton, tend to result in an enhancement of the PDFs at low x, reflecting the $\frac{1}{q^2}$ nature of the gluon propagator.
Thomson pp.192.

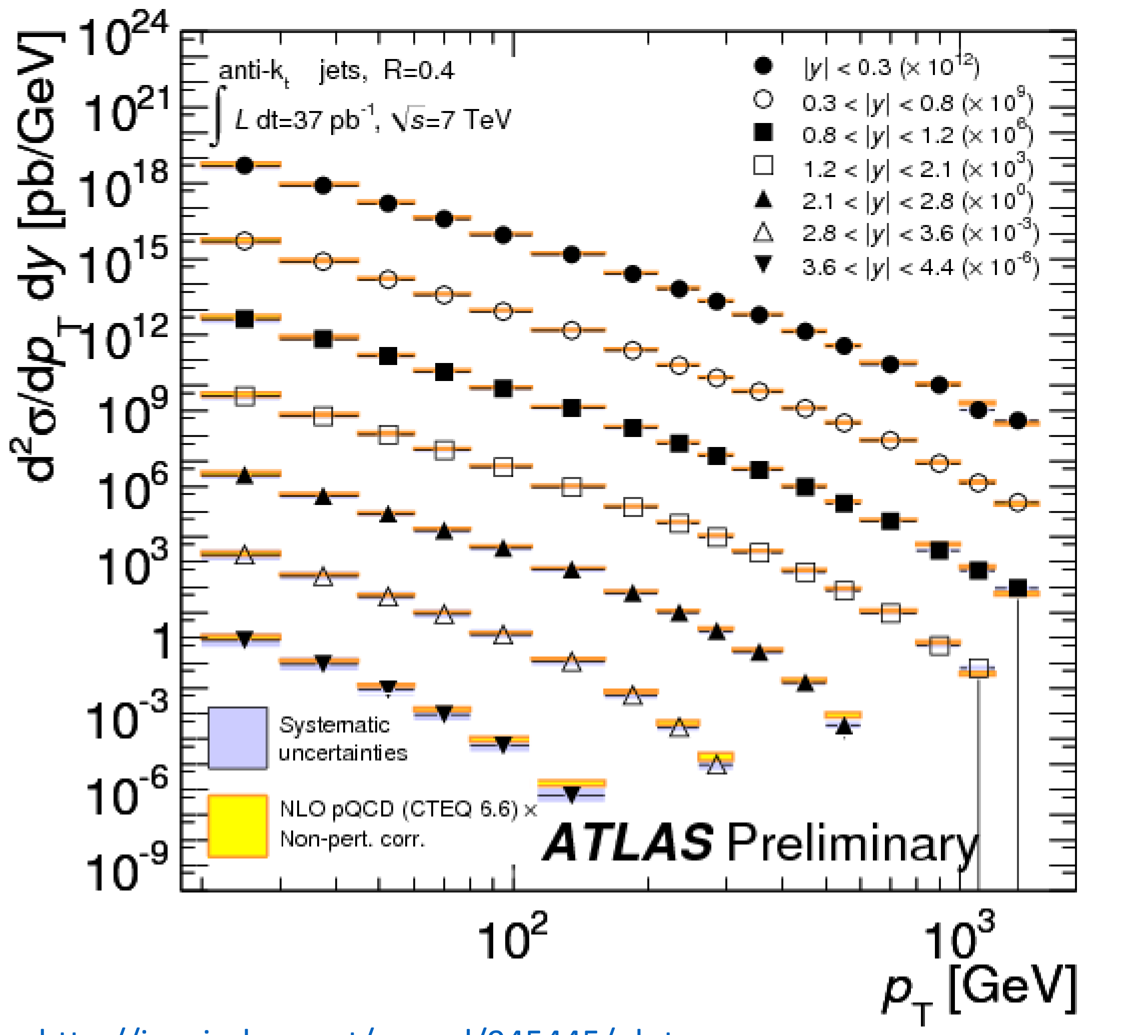
Note: shape of function as approaching higher order processes

Parton Distribution Functions

PDFs reflect the underlying structure of the proton. At present they cannot be calculated from first principles. This is because the theory of QCD has a large coupling constant, and perturbation theory cannot be applied. Therefore the PDFs are extracted from measurements of the structure functions in deep inelastic scattering experiments (fixed target experiments) and other experimental data.



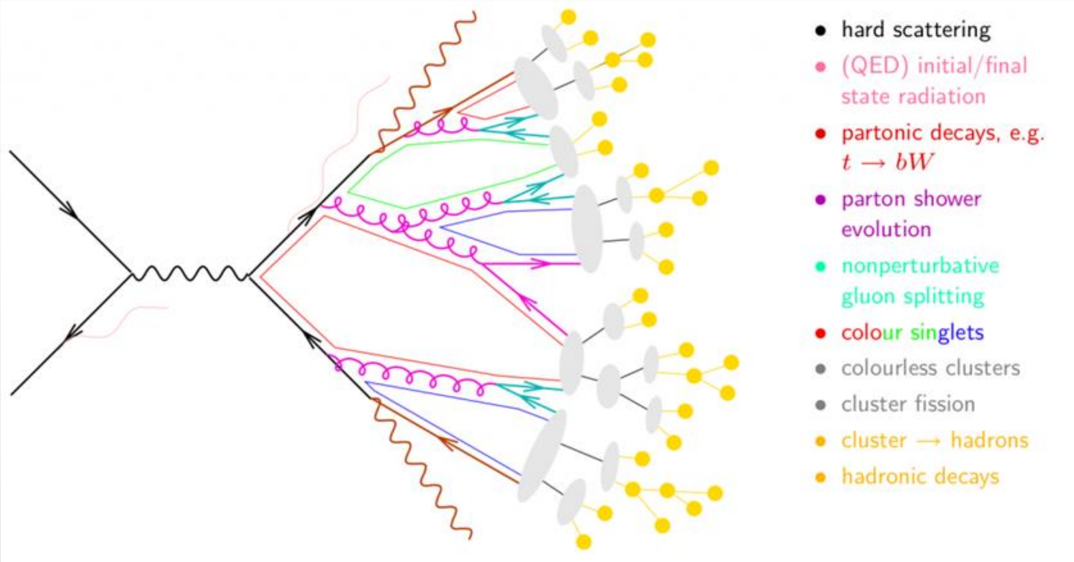
http://lhc.fuw.edu.pl/Stirling.pdf



http://inspirehep.net/record/945445/plots

- Inclusive jet double-differential cross section as a function of jet p_T compared to next-leading-order (NLO) pQCD predictions, using current knowledge of PDFs corrections have been applied.

- QCD is found to provide excellent description of jet phenomena in hadron hadron collisions.
- Owing to the nature of QCD, quarks are always confined in hadrons. However, in high every collisions, it is quarks that are produced, not hadrons.
- As a result of QCD interaction, the strong interaction field between the quarks produce further quarks and antiquarks, known as hadronization
- From hadronization, each quark produced in a collision produces a jet of hadrons.



Derivation of Time-ordered perturbation theory to the second order (for fun ☺) :

In quantum mechanics, the transition rate between an in initial state, i, and final state, f, is given by Fermi's golden rule $\Gamma_{fi} = 2\pi |T_{fi}|^2 \rho(E_f)$, where T_{fi} is the transition matrix element, given by the perturbation expansion $T_{fi} = \langle f|V|i\rangle + \sum_{j\neq i} \frac{\langle f|V|j\rangle\langle j|V|i\rangle}{E_i - E_j} + \; \ldots$. Referring to left diagram on slide 3 & 4,

the quantum mechanical perturbation expansion is
$T_{fi}^{ab} = \frac{\langle f|V|j\rangle\langle j|V|i\rangle}{E_i - E_j} = \frac{\langle d|V|X+b\rangle\langle c+X|V|a\rangle}{(E_a+E_b)-(E_c+E_X+E_b)}$, where T_{fi}^{ab} is the time ordering where the interaction between a and X occurs before that between X and b. Allowed by the energy-time uncertainty relation of quantum mechanics $E_j \neq E_i$. The non-invariant matrix element $V_{ji} = \langle c+X|V|a\rangle$ is related to the Lorentz Invariant (LI) matrix element M_{ji}, by normalizing the phase space wave function. Then,

$$V_{ji} = M_{ji} \prod_k (2E_k)^{-\frac{1}{2}}$$

and the index k runs over the particles involved. Here, we have

$$V_{ji} = \langle c+X|V|a\rangle = \frac{M_{a\to c+X}}{(2E_a 2E_c 2E_X)^{\frac{1}{2}}}$$

where $M_{a\to c+X}$ is the LI matrix element for the fundamental interaction $a \to c + X$. The requirement of LI on $M_{a\to c+X}$ places strong constraints on its possible mathematical structure. To give an example of particle exchange, the simplest possible Lorentz-Invariant coupling is here assumed to be a scalar. In this case, the matrix element is $M_{a\to c+X} = g_a$. Thus,

$$V_{ij}\langle c+X|V|a\rangle = \frac{g_a}{(2E_a 2E_c 2E_X)^{\frac{1}{2}}}.$$

Where the magnitude of the coupling constant g_a is a measure of the strength of the scalar interaction. Similarly we can express $g_b$as the coupling strength in the $b + X \to d$ interaction vertex,

$$V_{fj} = \langle d|V|X+b\rangle = \frac{g_b}{(2E_b 2E_d 2E_X)^{\frac{1}{2}}}.$$

Therefore, with the assumed scalar interaction, the second-order term in the perturbation series is

$$T_{fi}^{ab} = \frac{\langle d|V|X+b\rangle\langle c+X|V|a\rangle}{(E_a+E_b)-(E_c+E_X+E_b)} = \frac{1}{2E_X}\cdot\frac{1}{(2E_a 2E_b 2E_c 2E_d)^{\frac{1}{2}}}\cdot\frac{g_a g_b}{(E_a-E_c-E_X)} \ .$$

The LI matrix element for the process $a + b \to c + d$ is related by the corresponding transition matrix element by

$$M_{fi}^{ab} = (2E_a 2E_b 2E_c 2E_d)^{\frac{1}{2}} T_{fi}^{ab}$$

and thus,

$$M_{fi}^{ab} = \frac{1}{2E_X}\cdot\frac{g_a g_b}{(E_a-E_c-E_X)} \ .$$

The matrix element M_{fi}^{ab} is Lorentz invariant as a scalar interaction and defined in terms of wave functions with an appropriate LI normalization. For this second-order process in perturbation theory momentum is conserved at the interaction vertices but energy is not. Also, the exchanged particle X satisfies $E_X^2 = \boldsymbol{p}_x^2 + m_x^2$, and is called "on-mass shell". Similarly for the right hand side diagram on slides 3 and 4, we have

$$M_{fi}^{ba} = \frac{1}{2E_X}\cdot\frac{g_a g_b}{(E_b-E_d-E_X)} \ .$$

To obtain total amplitude of particle interaction, different amplitudes for a process are summed, giving

$$M_{fi} = M_{fi}^{ab} + M_{fi}^{ba} = \frac{g_a g_b}{2E_X} \cdot \left(\frac{1}{E_a - E_c - E_X} + \frac{1}{E_b - E_d - E_X} \right).$$

Applying conservation of energy $E_b - E_d = E_c - E_a$, we have

$$M_{fi} = \frac{g_a g_b}{(E_a - E_c)^2 - E_X^2}.$$

For both diagrams the exchanged particles momenta is related by the Einstein energy-momenta relation $E_X^2 = \boldsymbol{p}_X^2 + m_X^2$. Momentum is conserved at each interaction vertex giving $\boldsymbol{p}_X = (\boldsymbol{p}_a - \boldsymbol{p}_c)$ for the first (left) time ordered process and $\boldsymbol{p}_{\tilde{X}} = (\boldsymbol{p}_b - \boldsymbol{p}_d) = -(\boldsymbol{p}_a - \boldsymbol{p}_c)$ for the second (right) time ordered process. For both processes energy of the exchanged particle can then be written $E_X^2 = \boldsymbol{p}_X^2 + m_X^2 = (\boldsymbol{p}_a - \boldsymbol{p}_c)^2 + m_X^2$. The matrix element becomes

$$M_{fi} = \frac{g_a g_b}{(p_a - p_c)^2 - m_X^2}$$

Where p_a and p_c are the respective four-momenta of particles a and c. Writing the four-momentum of the exchanged virtual particle X as $q = p_a - p_c$, we have

$$M_{fi} = \frac{g_a g_b}{q^2 - m_X^2}.$$

The term $\frac{1}{q^2 - m_X^2}$ is referred to as the propagator and is associated with the exchanged particle with terms g_a and g_b associated with the interaction vertices.

■

Cross section for the production of two jets from t-channel gluon to gluon exchange process qq→qq is :

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha_s^2}{9Q^4}\left[1 - \left(1 - \frac{Q^2}{\hat{s}}\right)^2\right]$$

where $Q^2 = -q^2$ and $\hat{s} = x_1 x_2 s$ is the center of mass energy of the colliding quarks. In terms of PDFs :

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha_s^2}{9Q^4}\left[1 + \left(1 - \frac{Q^2}{s x_1 x_2}\right)^2\right] g(x_1, x_2)\, dx_1 x_2$$

where $g(x_1, x_2)$ is the sum over the products of the relevant PDF process for scattering qq→ qq.

Conservation of energy and momenta implies
$x_1 = \frac{p_T}{\sqrt{s}}(e^{+y_3} + e^{+y_4})$ and $x_2 = \frac{p_T}{\sqrt{s}}(e^{-y_3} + e^{-y_4})$

Hence, $Q^2 = p_T^2(1 + e^{y_4 - y_3})$