Peering Inside Protons and Nuclei

ORNL Seminar

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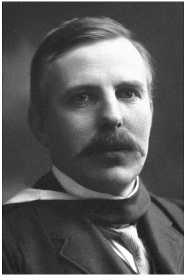
February 18, 2019

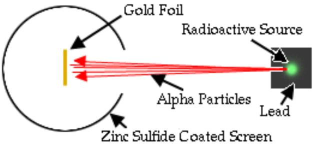
Outline

1. Introduction to the structure of the proton
2. Experimental facilities
3. Software challenges particle physicists face

Rutherford's Gold Scattering

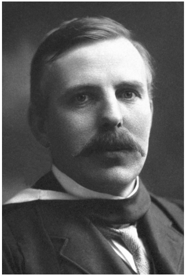
- Symbolic beginning of particle physics - Rutherford gold foil scattering
- Most particles go through the foil, but some scatter at very large angles

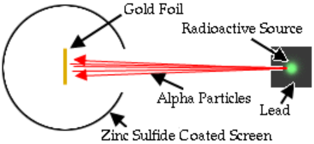




Rutherford's Gold Scattering

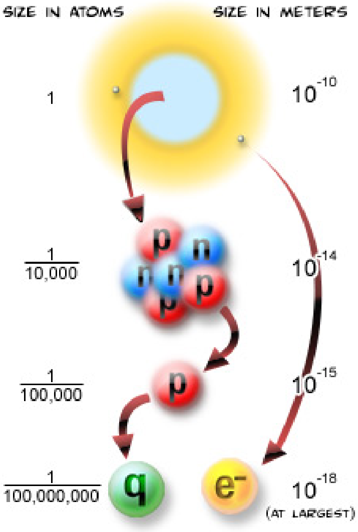
- Symbolic beginning of particle physics - Rutherford gold foil scattering
- Most particles go through the foil, but some scatter at very large angles
- Atoms are mostly empty space, with a dense core at the middle!





Atomic Scales

- The next decades saw experimentalists go smaller and smaller...



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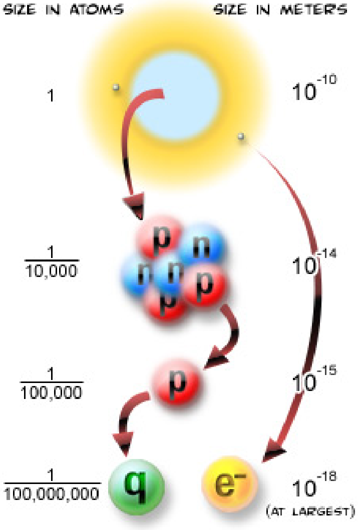
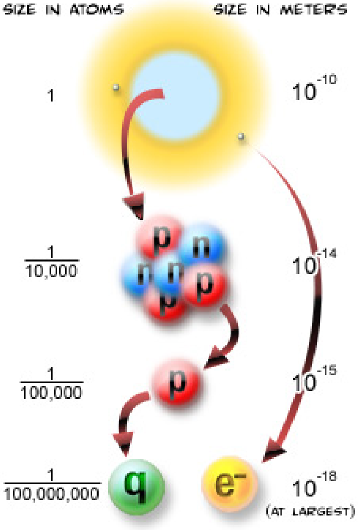
- In the 1960's, physicists at the Stanford Linear Accelerator found electrons scatter off subcomponents of protons

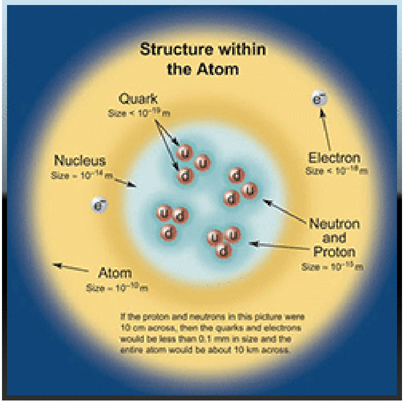


Atomic Scales

- The next decades saw experimentalists go smaller and smaller...
- In the 1960's, physicists at the Stanford Linear Accelerator found electrons scatter off subcomponents of protons
- Protons have constituents, generically called "partons"
- 8 orders of magnitude smaller than Rutherford (!!)

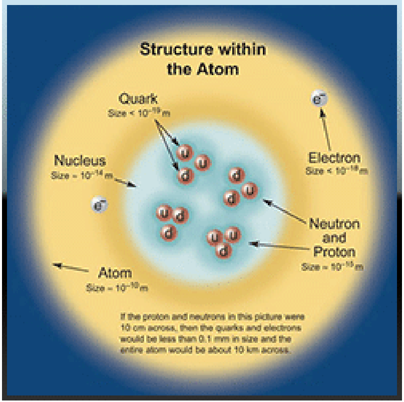


Modern Structure of Atom



- Conventional view of the atom
- Protons and neutrons composed of three quarks
- Quarks, protons, neutrons held together by gluons

Modern Structure of Atom



- Conventional view of the atom
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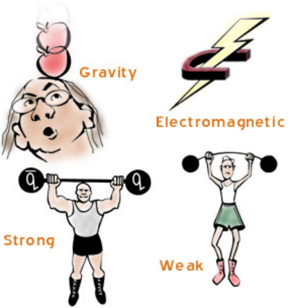
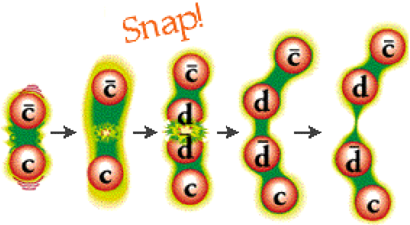
- "Strong" force counteracts repelling force of electromagnetic force

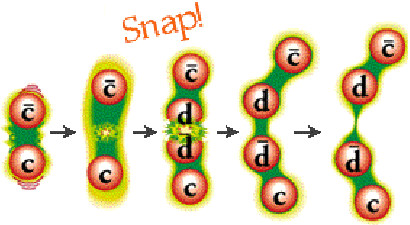


- However, quarks and gluons are confined within protons
- Impossible to observe a free quark or gluon!



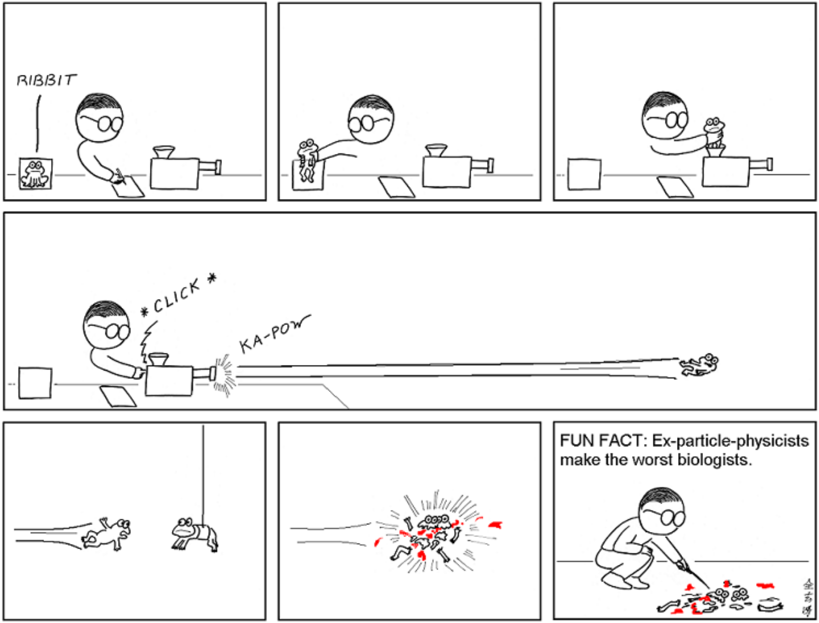
Confinement

- However, quarks and gluons are confined within protons
- Impossible to observe a free quark or gluon!
- When they get pulled apart, strong force becomes stronger and new particles can be produced from $E = mc^2$



So how do we study quarks if they can never be observed freely??

The only way physicists know how - smashing them into each other



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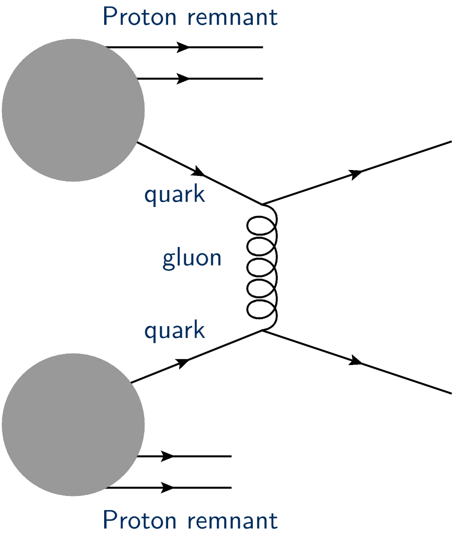
High Energy Proton-Proton Collisions



- Proton-proton collisions "schematically" drawn out like this example
- A quark interacts with another quark via the exchange of a gluon

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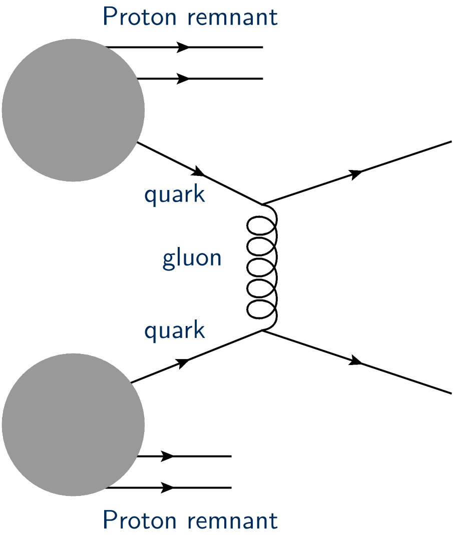
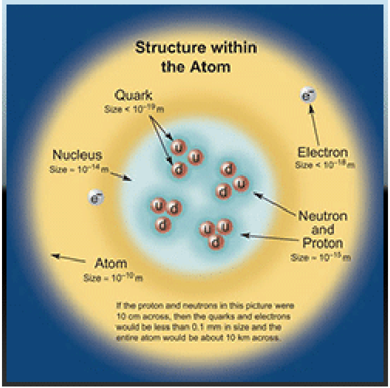


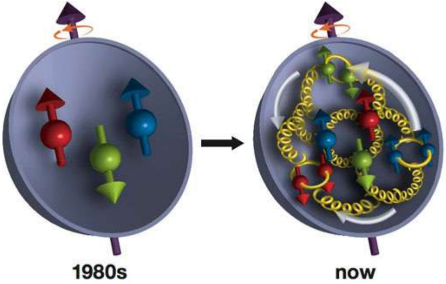
- Proton-proton collisions "schematically" drawn out like this example
- A quark interacts with another quark via the exchange of a gluon
- Gluon "mediates" strong interaction
- Final-state quark then fragments into many other particles via $E = mc^2$ (confinement!)
  - This is called a jet - spray of particles resulting from a quark or gluon that gets ripped out of the proton

“Modern” Structure of Atom



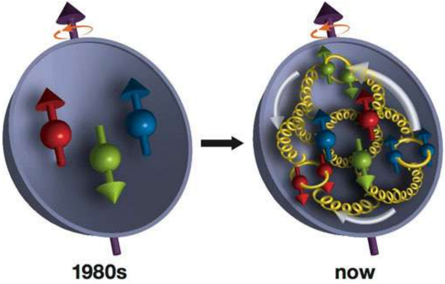
- Proton structure is simple - 3 quarks confined within proton “radius”
  - This warrants another talk!

Modern Structure of Atom



- Proton structure is *complicated*

Modern Structure of Atom



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- We now know that there are many, many quarks and gluons within the proton

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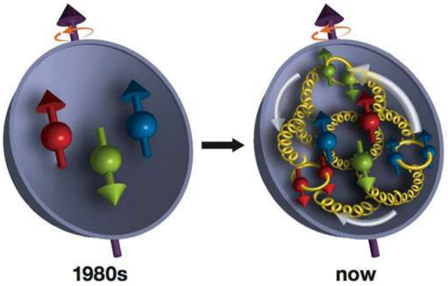

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- Each of them has a quantum mechanical spin (magnetic property), complicating things further

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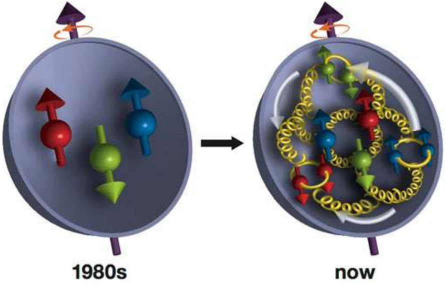
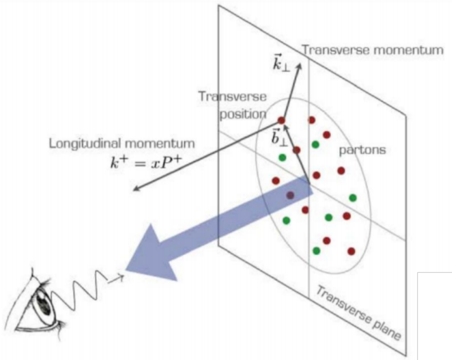


- Proton structure is *complicated*
- We now know that there are many, many quarks and gluons within the proton
- Each of them has a quantum mechanical spin (magnetic property), complicating things further
- How do all of these particles combine together to form one of *the* most basic building blocks of the universe?

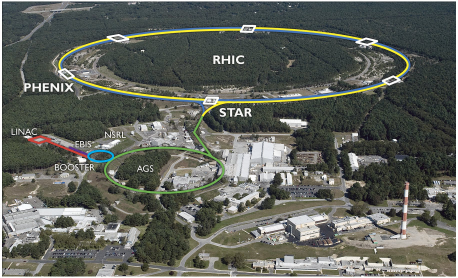
Multidimensional Proton Structure

- The last two decades have seen strong force research push towards measurements of quark and gluon dynamics
- What does the proton look like in terms of the quarks and gluons inside of it?
    - Position (2D)
    - Momentum (3D)
    - Quark flavor content
    - Spin
    - ...



The LHC and RHIC

The Large Hadron Collider (LHC) at CERN (Geneva, Switzerland)



The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab (New York)

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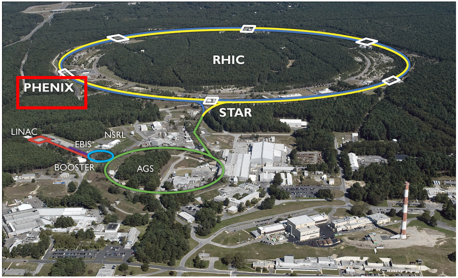

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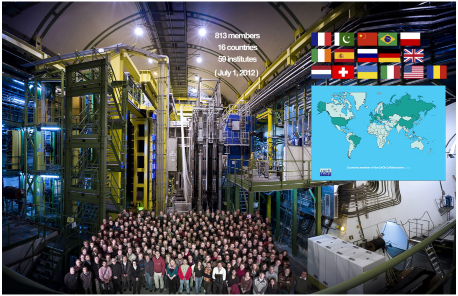
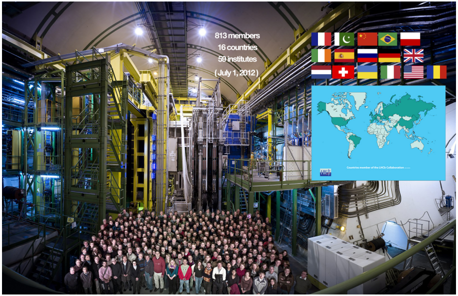
Experimental Facilities



- LHCb measures electrons, photons, muons, and hadrons (strongly interacting particles)
- Experiment is several stories tall!
- International collaboration of ~ 900 people (not all shown in picture)

Experimental Facilities



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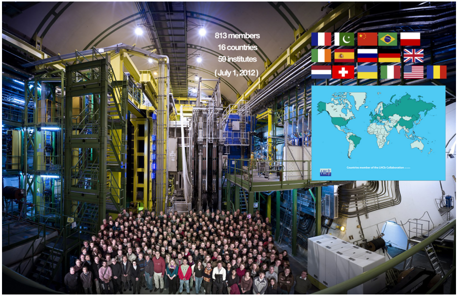

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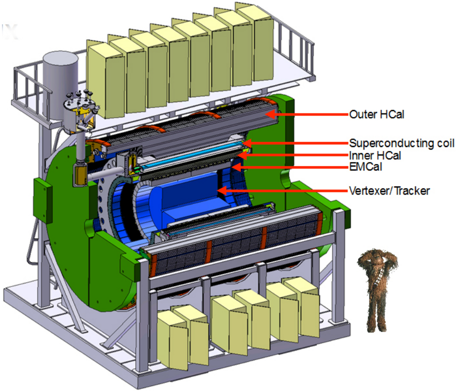

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LHCb collaboration

R. Aaij[28], C. Abellán Beteta[46], B. Adeva[43], M. Adinolfi[50], C.A. Aidala[78], Z. Ajaltouni[6],
S. Akar[61], P. Albicocco[19], J. Albrecht[11], F. Alessio[44], M. Alexander[55], A. Alfonso Albero[42],
G. Alkhazov[34], P. Alvarez Cartelle[57], A.A. Alves Jr[43], S. Amato[2], S. Amerio[24], Y. Amhis[8],
L. An[18], L. Anderlini[18], G. Andreassi[45], M. Andreotti[17], J.E. Andrews[62], F. Archilli[28],
P. d'Argent[13], J. Arnau Romeu[7], A. Artamonov[41], M. Artuso[63], K. Arzymatov[38], E. Aslanides[7],
M. Atzeni[46], B. Audurier[23], S. Bachmann[13], J.J. Back[52], S. Baker[57], V. Balagura[8,b],
W. Baldini[17], A. Baranov[38], R.J. Barlow[58], G.C. Barrand[8], S. Barsuk[8], W. Barter[58],
M. Bartolini[20], F. Baryshnikov[74], V. Batozskaya[32], B. Batsukh[63], A. Battig[11], V. Battista[45],
A. Bay[45], J. Beddow[55], F. Bedeschi[25], I. Bediaga[1], A. Beiter[63], L.J. Bel[28], S. Belin[23], N. Beliy[66],
V. Bellee[45], N. Belloli[21,i], K. Belous[41], I. Belyaev[35], E. Ben-Haim[9], G. Bencivenni[19],
S. Benson[28], S. Beranek[10], A. Berezhnoy[36], R. Bernet[46], D. Berninghoff[13], E. Bertholet[9],
A. Bertolin[24], C. Betancourt[46], F. Betti[16,44], M.O. Bettler[51], M. van Beuzekom[28],
Ia. Bezshyiko[46], S. Bhasin[50], J. Bhom[30], M.S. Bieker[11], S. Bifani[49], P. Billoir[9], A. Birnkraut[11],
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H. Cai[68], R. Calabrese[17,g], R. Calladine[49], M. Calvi[21,i], M. Calvo Gomez[42,m], A. Camboni[42,m],
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E. Dall'Occo[28], J. Dalseno[43,v], A. Danilina[35], A. Davis[58], O. De Aguiar Francisco[44],
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F. Dettori[56], B. Dey[69], A. Di Canto[44], P. Di Nezza[19], S. Didenko[74], H. Dijkstra[44], F. Dordei[23],
M. Dorigo[44,y], A. Dosil Suárez[43], L. Douglas[55], A. Dovbnya[47], K. Dreimanis[56], L. Dufour[28],
G. Dujany[9], P. Durante[44], J.M. Durham[79], D. Dutta[58], R. Dzhelyadin[41,†], M. Dziewiecki[13],
A. Dziurda[30], A. Dzyuba[34], S. Easo[53], U. Egede[57], V. Egorychev[35], S. Eidelman[40,x],
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S. Esen[28], T. Evans[61], A. Falabella[16], N. Farley[49], S. Farry[56], D. Fazzini[21,44,i],
P. Fernandez Declara[44], A. Fernandez Prieto[43], F. Ferrari[16], L. Ferreira Lopes[45],
F. Ferreira Rodrigues[2], M. Ferro-Luzzi[44], S. Filippov[37], R.A. Fini[15], M. Fiorini[17,g], M. Firlej[31],
C. Fitzpatrick[45], T. Fiutowski[31], F. Fleuret[8,b], M. Fontana[44], F. Fontanelli[20,h], R. Forty[44],
V. Franco Lima[56], M. Frank[44], C. Frei[44], J. Fu[22,q], W. Funk[44], C. Färber[44], M. Féo[44],
E. Gabriel[54], A. Gallas Torreira[43], D. Galli[16,e], S. Gallorini[24], S. Gambetta[54], Y. Gan[3],
M. Gandelman[2], P. Gandini[22], Y. Gao[3], L.M. Garcia Martin[76], B. Garcia Plana[43],
J. García Pardiñas[46], J. Garra Tico[51], L. Garrido[42], D. Gascon[42], C. Gaspar[44], L. Gavardi[11],
G. Gazzoni[6], D. Gerick[13], E. Gersabeck[58], M. Gersabeck[58], T. Gershon[52], D. Gerstel[7],
Ph. Ghez[5], V. Gibson[51], O.G. Girard[45], P. Gironella Gironell[42], L. Giubega[33], K. Gizdov[54],

Experimental Collaborations

V.V. Gligorov[9], D. Golubkov[35], A. Golutvin[57,74], A. Gomes[1,a], I.V. Gorelov[36], C. Gotti[21,i],
E. Govorkova[28], J.P. Grabowski[13], R. Graciani Diaz[42], L.A. Granado Cardoso[44], E. Graugés[42],
E. Graverini[46], G. Graziani[18], A. Grecu[33], R. Greim[28], P. Griffith[23], L. Grillo[58], L. Gruber[44],
B.R. Gruberg Cazon[59], O. Grünberg[71], C. Gu[3], E. Gushchin[37], A. Guth[10], Yu. Guz[41,44],
T. Gys[44], C. Göbel[65], T. Hadavizadeh[59], C. Hadjivasiliou[6], G. Haefeli[45], C. Haen[44],
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D. Johnson[44], C.R. Jones[51], C. Joram[44], B. Jost[44], N. Jurik[59], S. Kandybei[47], M. Karacson[44],
J.M. Kariuki[50], S. Karodia[55], N. Kazeev[39], M. Kecke[13], F. Keizer[51], M. Kelsey[63], M. Kenzie[51],
T. Ketel[29], E. Khairullin[38], B. Khanji[44], C. Khurewathanakul[45], K.E. Kim[63], T. Kirn[10],
V.S. Kirsebom[45], S. Klaver[19], K. Klimaszewski[32], T. Klimkovich[12], S. Koliiev[48], M. Kolpin[13],
R. Kopecna[13], P. Koppenburg[28], I. Kostiuk[28,48], S. Kotriakhova[34], M. Kozeiha[6], L. Kravchuk[37],
M. Kreps[52], F. Kress[57], P. Krokovny[40,x], W. Krupa[31], W. Krzemien[32], W. Kucewicz[30,l],
M. Kucharczyk[30], V. Kudryavtsev[40,x], A.K. Kuonen[45], T. Kvaratskheliya[35,44], D. Lacarrere[44],
G. Lafferty[58], A. Lai[23], D. Lancierini[46], G. Lanfranchi[19], C. Langenbruch[10], T. Latham[52],
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B. Leverington[13], P.-R. Li[66,ab], Y. Li[4], Z. Li[63], X. Liang[63], T. Likhomanenko[73], R. Lindner[44],
F. Lionetto[46], V. Lisovskyi[8], G. Liu[67], X. Liu[3], D. Loh[52], A. Loi[23], I. Longstaff[55], J.H. Lopes[2],
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S. Maddrell-Mander[50], O. Maev[34,44], K. Maguire[58], D. Maisuzenko[34], M.W. Majewski[31],
S. Malde[59], B. Malecki[44], A. Malinin[73], T. Maltsev[40,x], H. Malygina[13], G. Manca[23,f],
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Experimental Collaborations

S. Ponce[44], A. Popov[41], D. Popov[49,12], S. Poslavskii[41], E. Price[50], J. Prisciandaro[43],
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Challenges in Particle Physics

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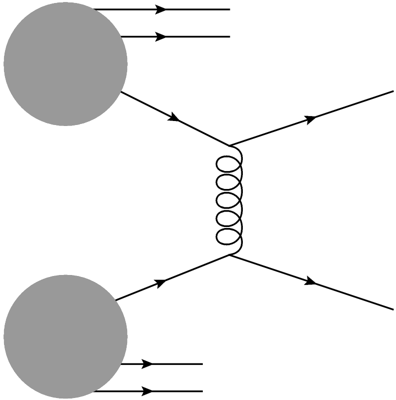

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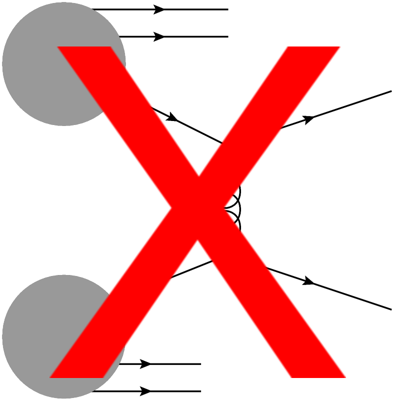

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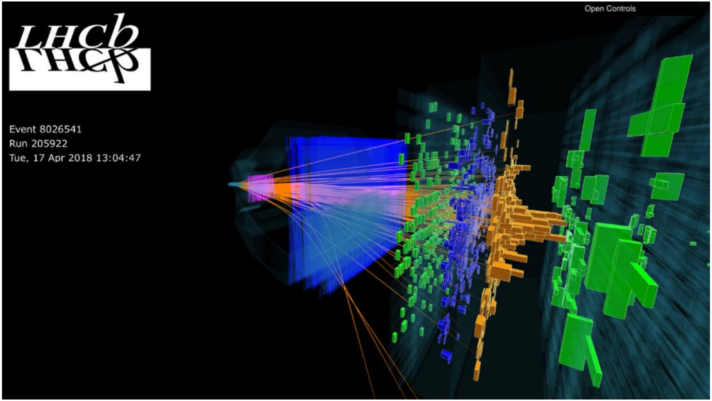

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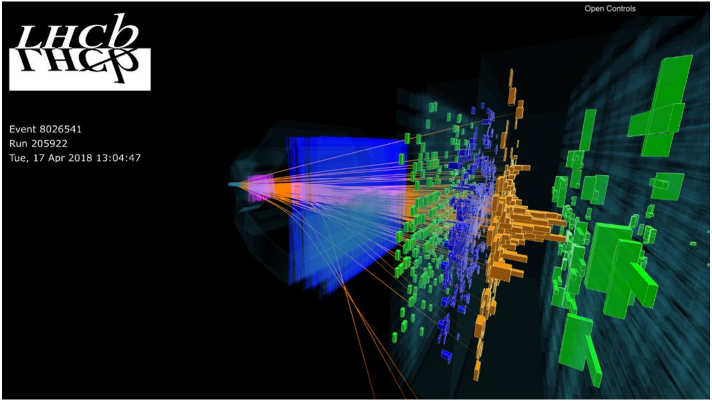
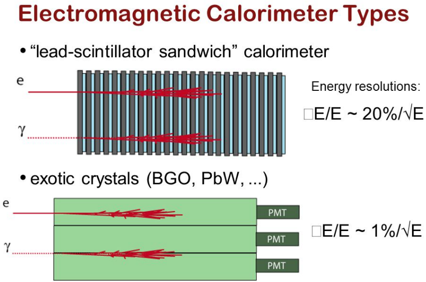


- How to distinguish particles from one another?
- How to distinguish which are electrons/hadrons/photons etc.?
- ...

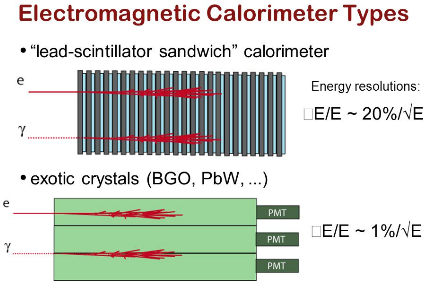
sPHENIX Photon Calibration

- Electromagnetic calorimeters in experiments measure photons and electrons
- Basic idea - photons scatter off electrons in materials, which then scatter again, and again...



sPHENIX Photon Calibration

- Electromagnetic calorimeters in experiments measure photons and electrons
- Basic idea - photons scatter off electrons in materials, which then scatter again, and again...
- Collect light yield at the end of this "shower"
- Need to be calibrated and corrected
  - Impossible to collect all of the energy



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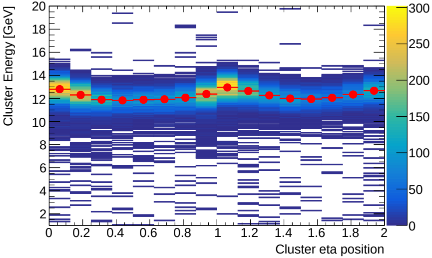
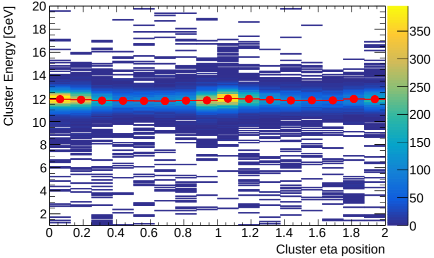
  - Interference from other energy deposits
- Crucial for improving detector performance

New Method: Position Recalibration

Before Recalibration



After Recalibration



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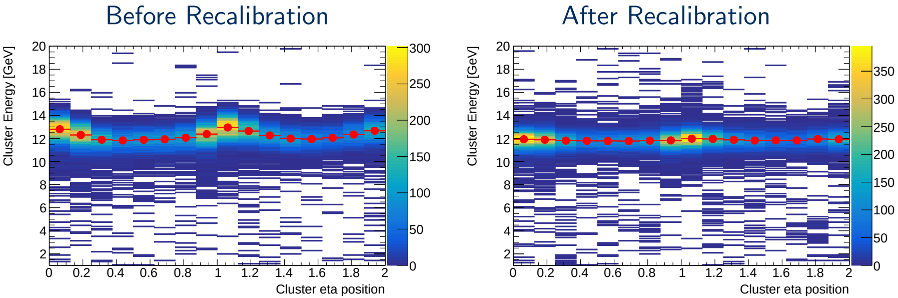
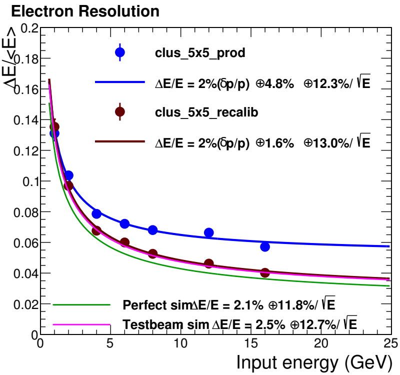


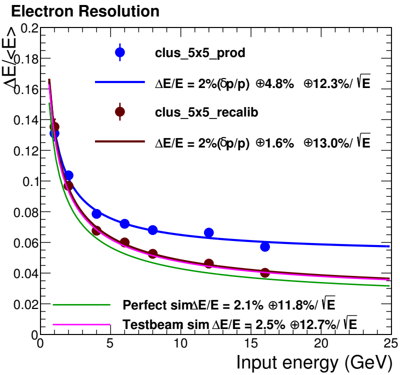
- Analysis method introduces new correction
- Previous method required outside information
- My method utilizes only energy deposits left in calorimeter

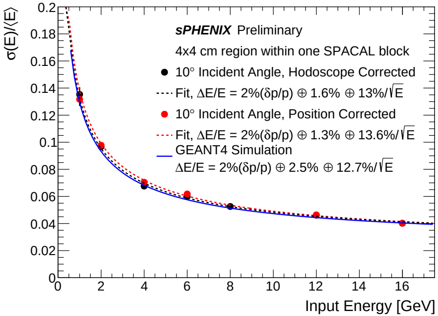
Resulting Performance of Detector



- Resolution shows improvement with implementation of method (lower $\rightarrow$ better)

Resulting Performance of Detector

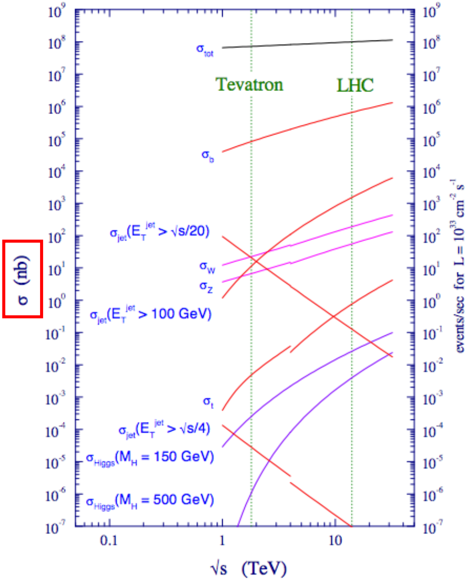




- Resolution shows improvement with implementation of method (lower → better)

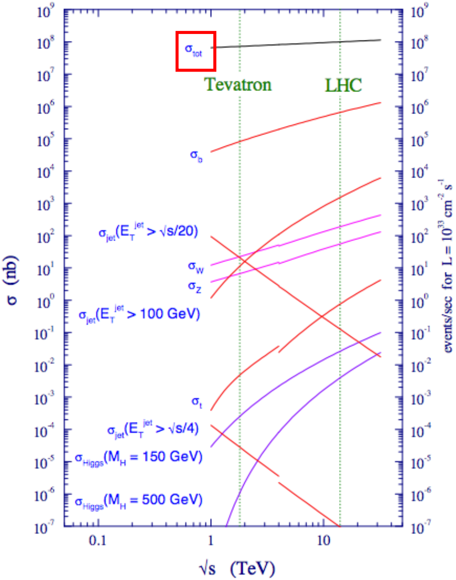
- New method matches previous method which requires outside information (red and black)
- Software package that performs corrections implemented and still used in sPHENIX github repository

Challenges in Particle Physics



Rept.Prog.Phys., 70:89, 2007

- Cross section (σ) is the probability for a particular process to happen



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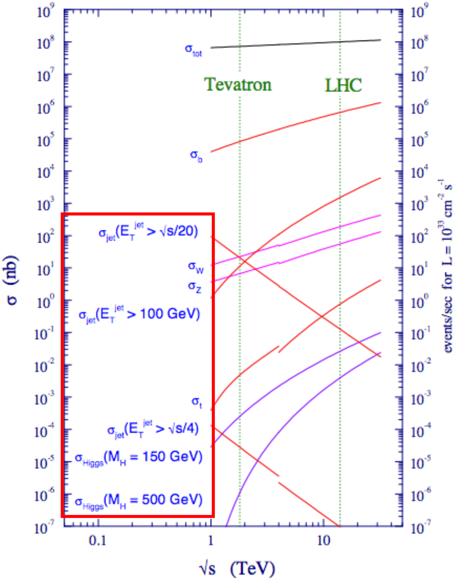

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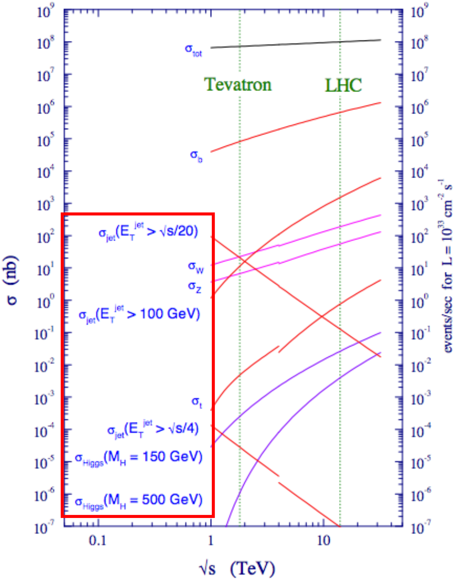

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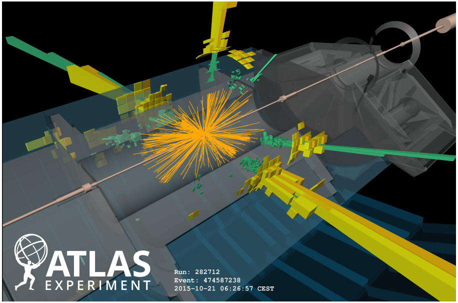
- With data rates of $\mathcal{O}(1)$ GB per second, it is impossible to keep everything

Physics Triggers

- Implement "triggers" at the hardware and software level
- Helps pick through data to find the "needle in a haystack"



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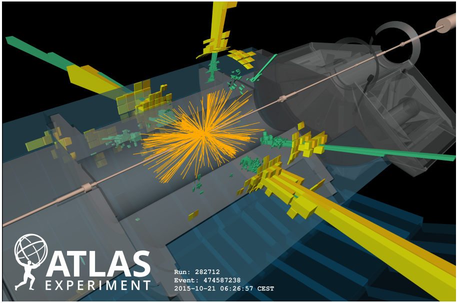

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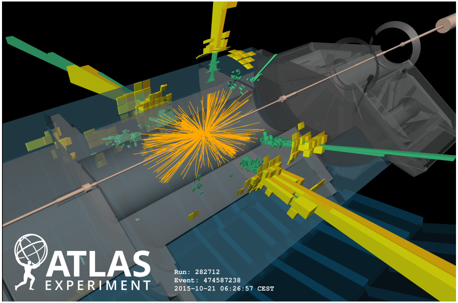

  - Iterate over energy deposits in real time, trigger on large, collimated energy deposits

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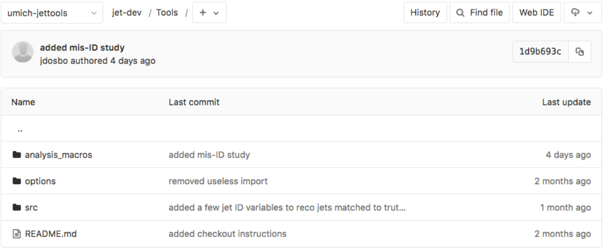
- Requires complex analysis packages (each directory has many different classes)



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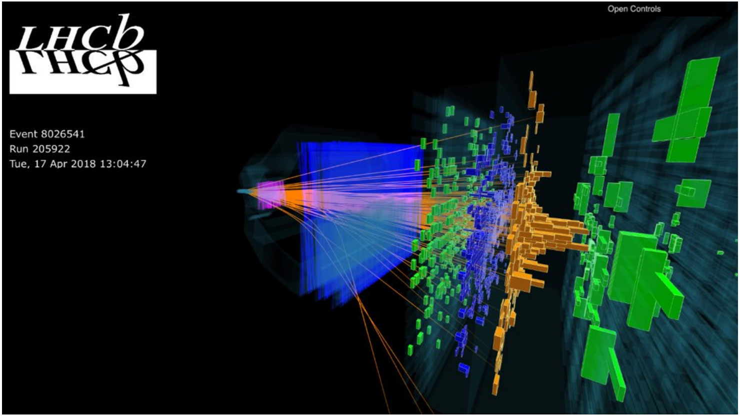
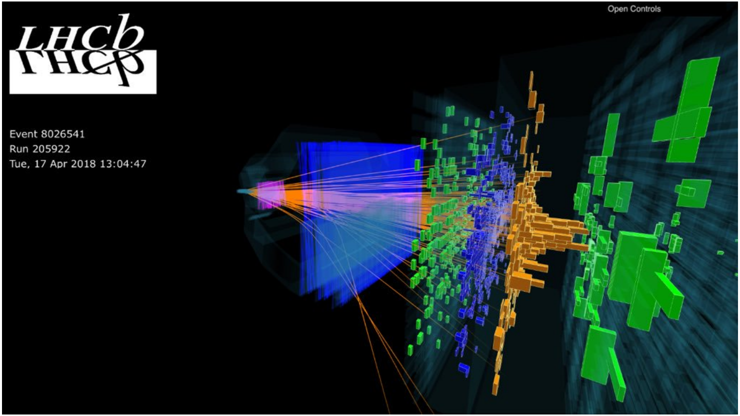


- Question: how do you go from this image to actually concluding something physical about the structure of the proton??

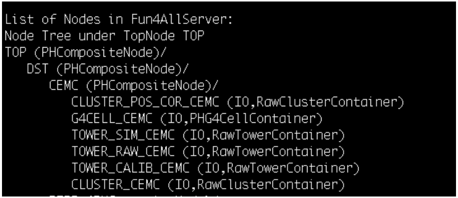
Challenges in Particle Physics



- Question: how do you go from this image to actually concluding something physical about the structure of the proton??
- Answer: reduce your data rate step-by-step until you have something manageable

Analysis Frameworks

- General analysis trunk is the "node tree"
  - Example shown here from sPHENIX, open source on github
- Nodes inherit from `PHCompositeNode`



```
List of Nodes in Fun4AllServer:
Node Tree under TopNode TOP
TOP (PHCompositeNode)/
   DST (PHCompositeNode)/
      CEMC (PHCompositeNode)/
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         G4CELL_CEMC (IO,PHG4CellContainer)
         TOWER_SIM_CEMC (IO,RawTowerContainer)
         TOWER_RAW_CEMC (IO,RawTowerContainer)
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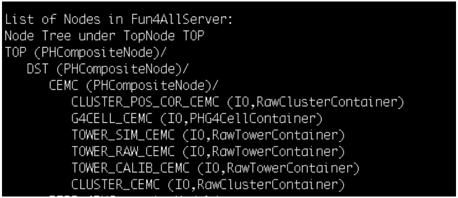

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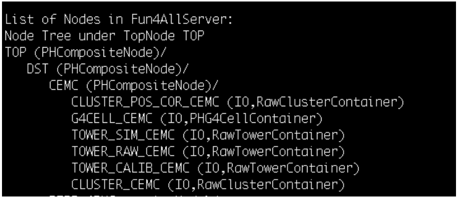

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```

  - `PHCompositeNode` has containers (e.g. `RawClusterContainer`), which is a more general class corresponding to actual physical data

Analysis Frameworks

- Develop analysis packages to analyze the NodeTree
- Allows users to loop over the containers of interest

```
RawClusterContainer::ConstRange begin_end = clusters->getClusters();
RawClusterContainer::ConstIterator clusiter;

//loop over the emcal clusters
for (clusiter = begin_end.first;
     clusiter != begin_end.second;
     ++clusiter)
{
  //get this cluster
  RawCluster *cluster = clusiter->second;

  //get cluster characteristics
  //this helper class determines the photon characteristics
  //depending on the vertex position
  //this is important for e.g. eta determination and E_T determination
  CLHEP::Hep3Vector vertex(vtx->get_x(), vtx->get_y(), vtx->get_z());
  CLHEP::Hep3Vector E_vec_cluster = RawClusterUtility::GetECoreVec(*cluster, vertex);
  clus_energy = E_vec_cluster.mag();
```

Analysis Frameworks

- Develop analysis packages to analyze the NodeTree
- Allows users to loop over the containers of interest
- Example - loop over clusters (energy deposits) in electromagnetic calorimeter for energy calibration method!
- Write selected data out to ROOT trees - organized data tables

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  //get cluster characteristics
  //this helper class determines the photon characteristics
  //depending on the vertex position
  //this is important for e.g. eta determination and E_T determination
  CLHEP::Hep3Vector vertex(vtx->get_x(), vtx->get_y(), vtx->get_z());
  CLHEP::Hep3Vector E_vec_cluster = RawClusterUtility::GetECoreVec(*cluster, vertex);
  clus_energy = E_vec_cluster.mag();
```

ROOT: Data Analysis Framework

- Common software tool in particle physics - ROOT
- Data analysis package developed at CERN in Geneva, Switzerland (probably by research software engineers...)
  - "A modular scientific software toolkit. It provides all the functionalities needed to deal with big data processing, statistical analysis, visualisation and storage. It is mainly written in C++ but integrated with other languages such as Python and R."

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  - "A modular scientific software toolkit. It provides all the functionalities needed to deal with big data processing, statistical analysis, visualisation and storage. It is mainly written in C++ but integrated with other languages such as Python and R."
- Excellent documentation, tons of tutorials, free download at root.cern.ch - I highly recommend checking it out

Analysis Frameworks

- From ROOT trees, one can develop (another) analysis package
- Smaller classes that actually do data analysis, systematic studies. . .
- This is an additional step in parsing data down to final result

efficiency_rootfiles	adding efficiency rootfiles	3 weeks ago
systematics	removed spurious .C~ files accidentally commi...	5 days ago
README.md	updated README	3 weeks ago
analyze_truthmc.C	Updated macros with unfolding and systemati...	3 weeks ago
analyze_truthmc.h	Updated macros with unfolding and systemati...	3 weeks ago
cuts.h	Updated macros with unfolding and systemati...	3 weeks ago
do_spd_hit_study.C	add a short macro to look at spd hit distributio...	2 months ago
do_spd_hit_study.h	add a short macro to look at spd hit distributio...	2 months ago
make_constituent_distributions.C	added mis-ID study	5 days ago
make_constituent_distributions.h	added mis-ID study	5 days ago

Analysis Frameworks

- Leading group at University of Michigan in new research area
- Brand new code framework within collaboration!
- Documentation important for future graduate student use

TWiki page

A twiki page with some documentation of e.g. ANA note development can be found at the following link

Environment setup

Setting up the environment on lxplus to run the jobs is straightforward. The jobs were run with DaVinci v36r7p6, which is the same DaVinci version as the Zjet cross section analysis used. This was chosen to maintain consistency with the previous analysis. The TupleTools under src can be copied into e.g.

```
Phys/DecayTreeTuple/src/
```

in your local DaVinci setup. Execute

```
. LbLogin.sh -c x86_64-slc6-gcc48-opt
```

to get the proper environment, and then do a `make` and `make install` like usual as discussed in e.g. the starterkit tutorial

Analysis Frameworks

- Recent push amongst collaboration to better preserve analysis frameworks
- Science out to be reproducible...

make_jet_efficiencies.C	Committing analysis code to QEE repository, ...
make_jet_efficiencies.h	Committing analysis code to QEE repository, ...
make_misID_sys.C	automated workflow
make_quad_sum.C	automated workflow
make_systematic_uncertainties.py	automated workflow
make_track_efficiency.C	automated workflow
make_track_efficiency.h	automated workflow
make_trackeff_smooth.C	automated workflow

Analysis Frameworks

- Recent push amongst collaboration to better preserve analysis frameworks
- Science out to be reproducible...
- Automated workflow using (python) scripts, which run other macros
- Good for documentation, ease to use, amongst many other things. . .

make_jet_efficiencies.C	Committing analysis code to QEE repository, ...
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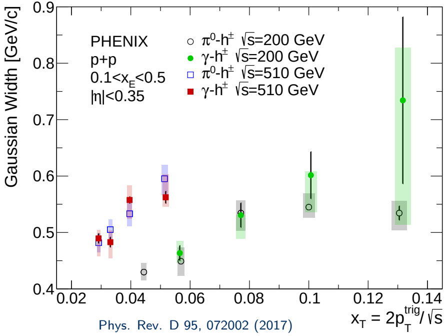
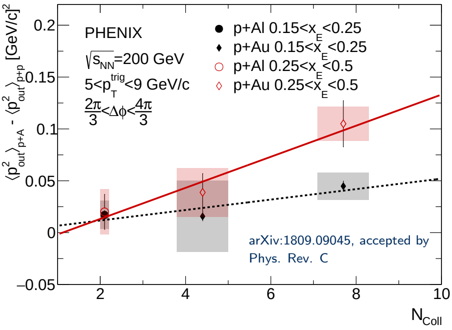
make_trackeff_smooth.C	automated workflow

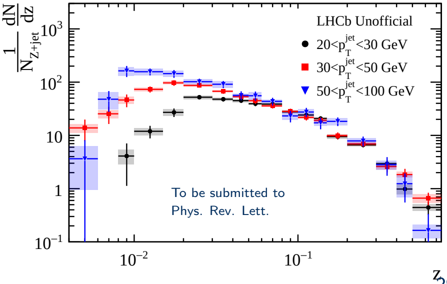
Analysis → Results

- Analysis frameworks lead to results which get published
- Physics gets documented in publications, analysis packages are saved in collaboration repositories



Phys. Rev. D 95, 072002 (2017)
Phys. Rev. D. 98, 072004 (2018)





Conclusions

- Proton structure research a vibrant field of high energy particle physics
  - Aiming to answer basic fundamental questions about the universe - how is the most basic building block of matter composed?
- Major software challenges to overcome in particle physics research
  - Huge data rates and data storage, finding rare processes in MHz data rates
  - Identifying particles in large backgrounds
  - Analysis packages that are reproducible and usable by other members of collaborations
  - Many, many others that I have not discussed
- Ultimately work leads to publications
  - Recent focus within collaborations on analysis preservation and reproducibility

Thank you!

References

- Many unreferenced figures taken from http://www.particleadventure.org

Basic Structure of Node Tree