# *PGS 4*

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1. Detector Effects and Simulation
2. LHC Detectors
3. Design of PGS
4. PGS Physics Object Reconstruction
5. Triggers in PGS
6. Future Development

# Contributors

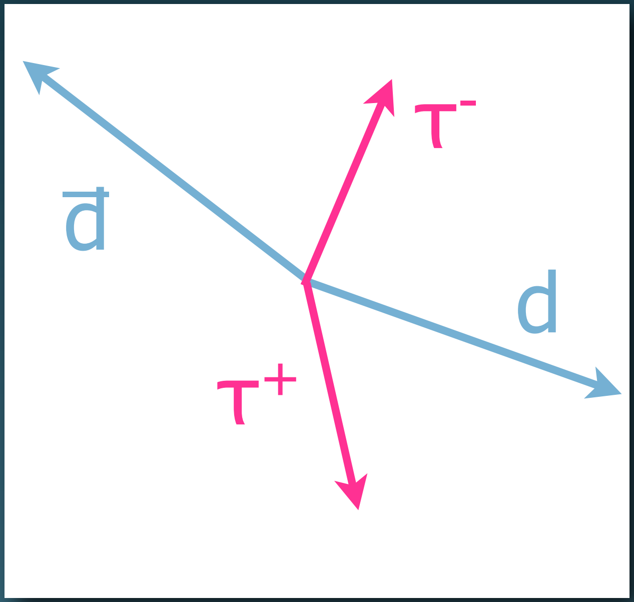
## PGS is the work of many people!

John Conway (UC Davis), Ray Culbertson (FNAL), Regina Demina (U. Rochester), Ben Kilminster (Ohio State), Mark Kruse (Duke), Steve Mrenna (FNAL), Jason Nielsen (LBNL), Maria Roco (now at Lucent), Aaron Pierce and Jesse Thaler (Harvard), Natalia Toro (Harvard), Chris Tully (Princeton).

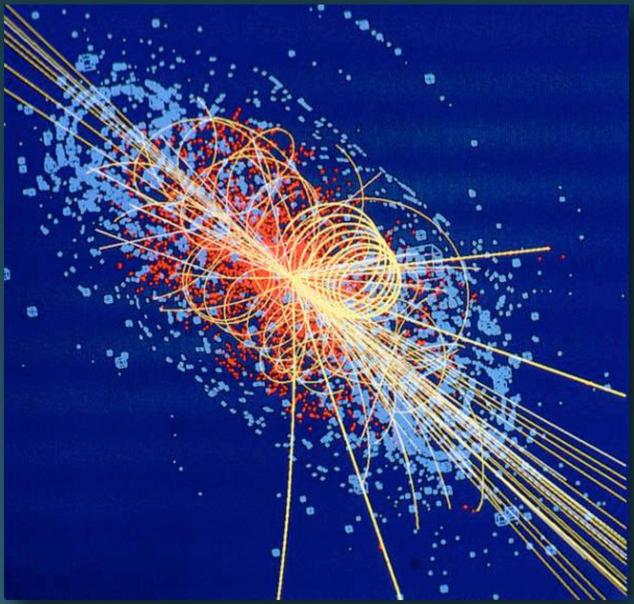
Special thanks to Matt Strassler, Matt Bowen, Nima Arkani-Hamed and Liantao Wang for furthering the use and development of PGS via the LHC Olympics.

# Detector Effects and Simulation

**Ideally a high energy physics detector would tell us the four momenta of all outgoing particles in a hard collision:**



what we want

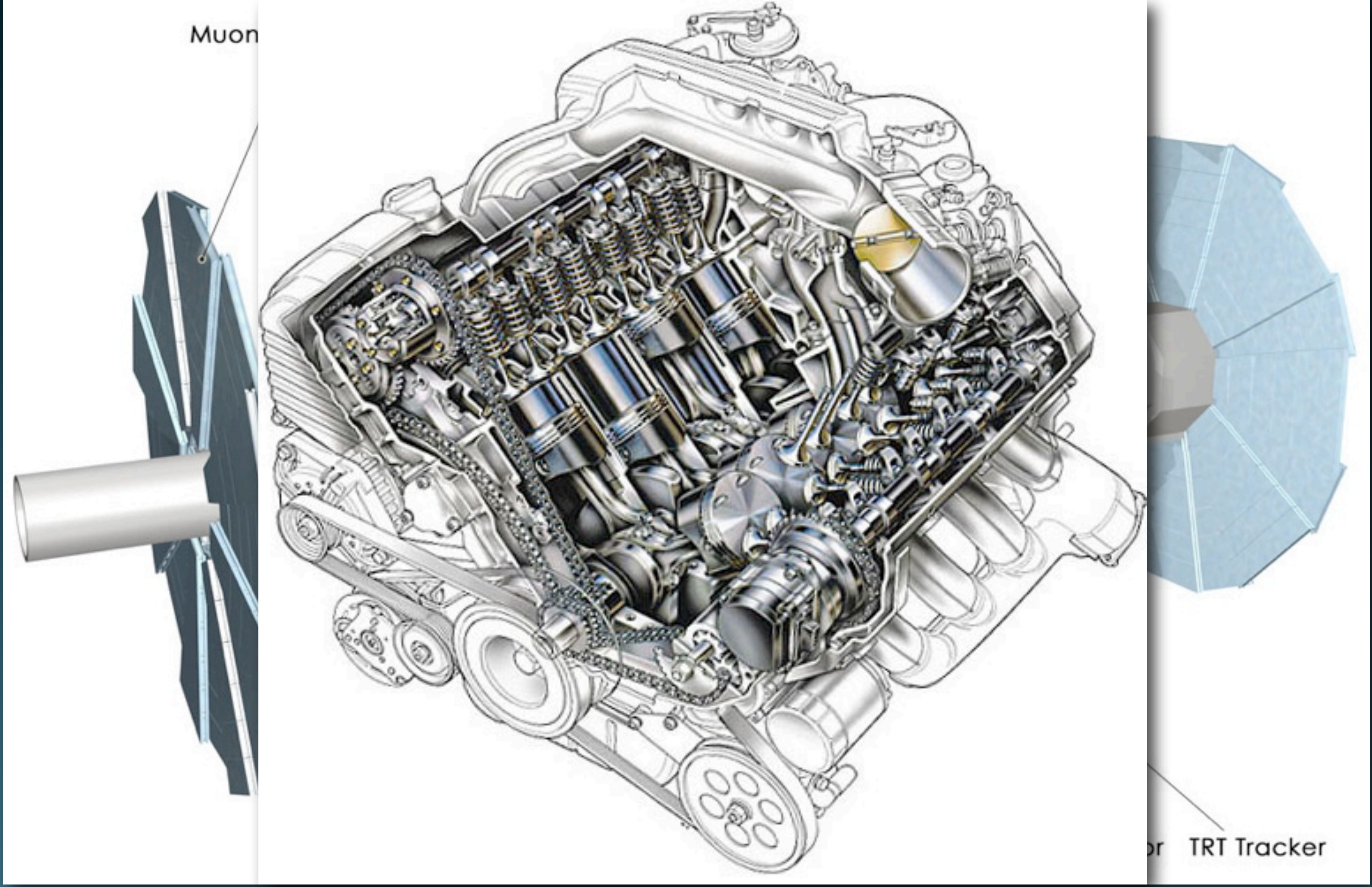


what we get

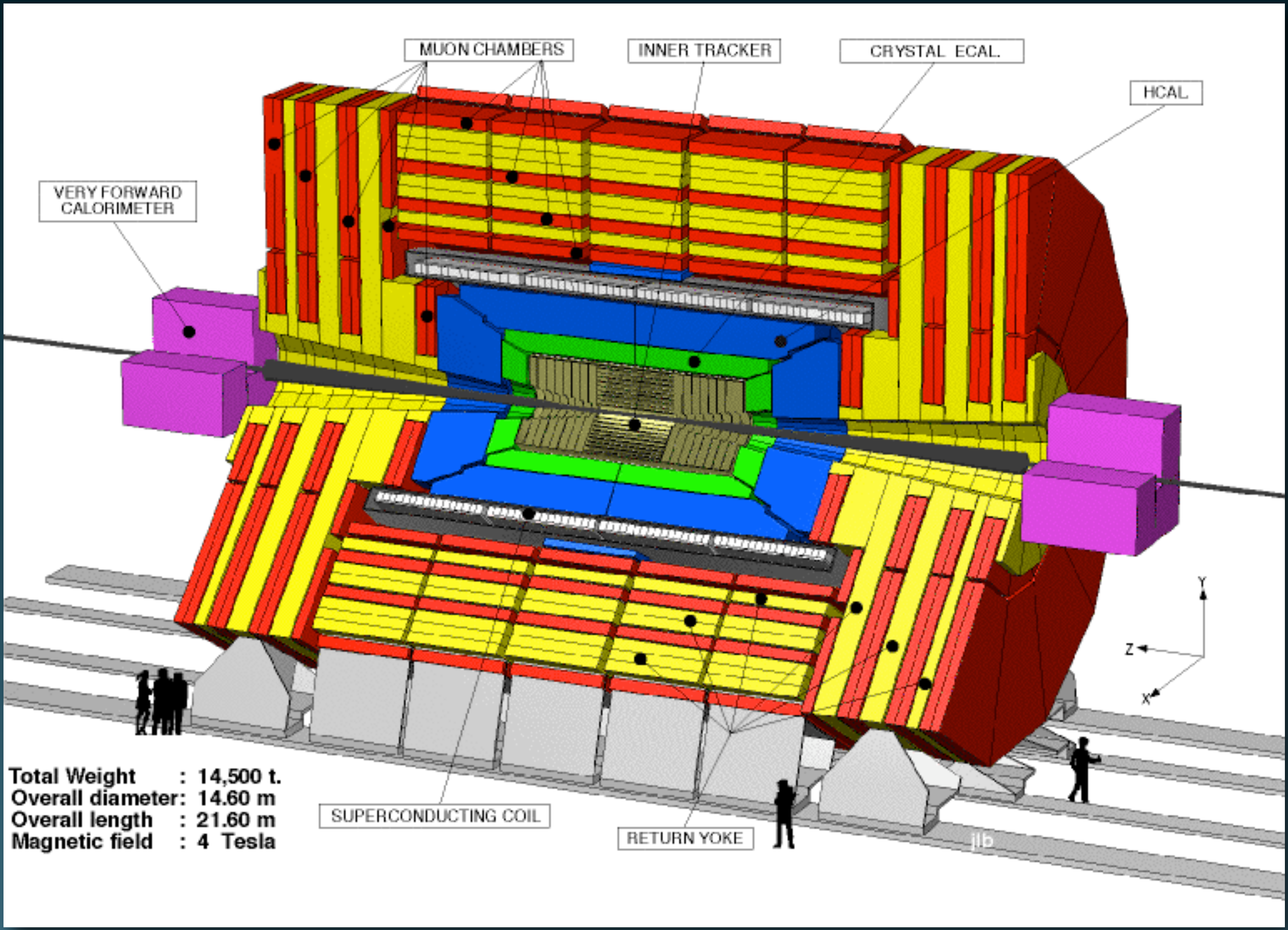
# Detector Simulation: Goals

- detector acceptance
- detector efficiency
- detector resolution
- secondary interactions
  - nuclear interactions
  - brehmsstrahlung
  - pair production
  - multiple scattering
- multiple interactions (pileup)
- event reconstruction effects

# ATLAS



# CMS



Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

# CMS and ATLAS

- **similar, yet different approaches to LHC problem**

| | ATLAS | CMS |
|---|---|---|
| vertexing | Si pixels | Si pixels |
| tracking | Si strips/gas | Si strips |
| em cal | liquid Ar | $PbWO_4$ |
| had cal | steel/scint. | brass/scint. |
| muon | RPCs/drift | RPCs/drift |

# GEANT4

- the gold standard in high energy physics detector simulation software
- treats detector as “slabs” of particular material
- simulates in detail energy deposition from ionization, showering
- simulates all secondary interactions
- problem: takes (many) minutes of CPU per event!

# PGS Philosophy

- interface to standard physics process generators (PYTHIA, HERWIG, ISAJET, ALPGEN, ...)
- perform very basic detector simulation with
  - tracks
  - calorimeter deposits
  - muon ID
- reconstruct physics “objects”: $\gamma$, e, $\mu$, $\tau$, jet (b), MET from tracks/calorimeter
- parametrize where needed

# Detector Simulation Goals

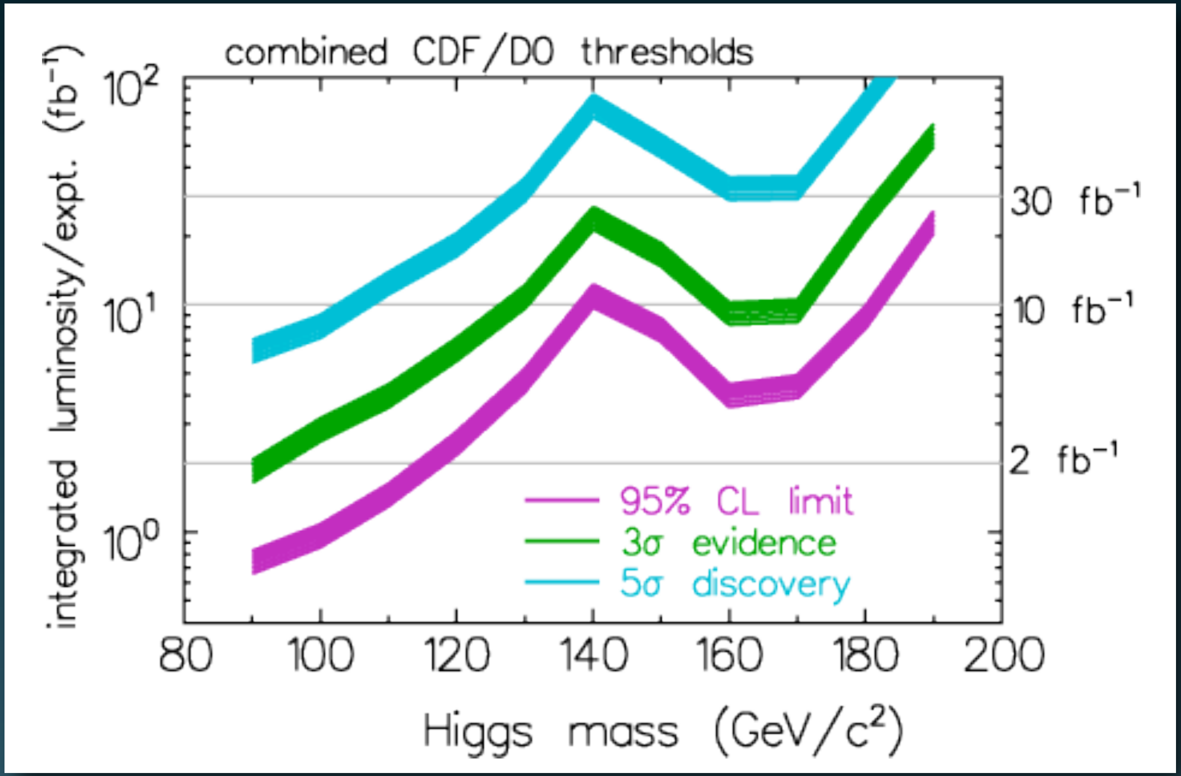
PGS?

- ✓ detector acceptance
- ✓ detector efficiency
- ✓ detector resolution
- secondary interactions
  - ✗ nuclear interactions
  - ✗ brehmsstrahlung
  - ✗ pair production
  - ✓ multiple scattering
- ✗ multiple interactions (pileup)
- ✓ event reconstruction effects

# Origin of PGS

- March 1998: kickoff of the Tevatron Run 2 SUSY/Higgs Workshop
- no Run 2 CDF/D0 simulations available then
- developed “SHW” simulation as average of CDF/D0
- published SHW Higgs report: hep-ph/0010338
- still a reliable resource for Tevatron Higgs reach!
- SHW -> PGS for Snowmass 2001
- used for VLHC, LHC, LC, Tevatron comparisons, especially by theorists

# Tevatron SM Higgs: SHW



Famous result from the 1998 Tevatron Run 2 Susy/Higgs Workshop: from SHW simulation!

# Flow of PGS

event generation

↓

STDHEP common blocks

↓

event simulation, object reconstruction

↓

user analysis

↓

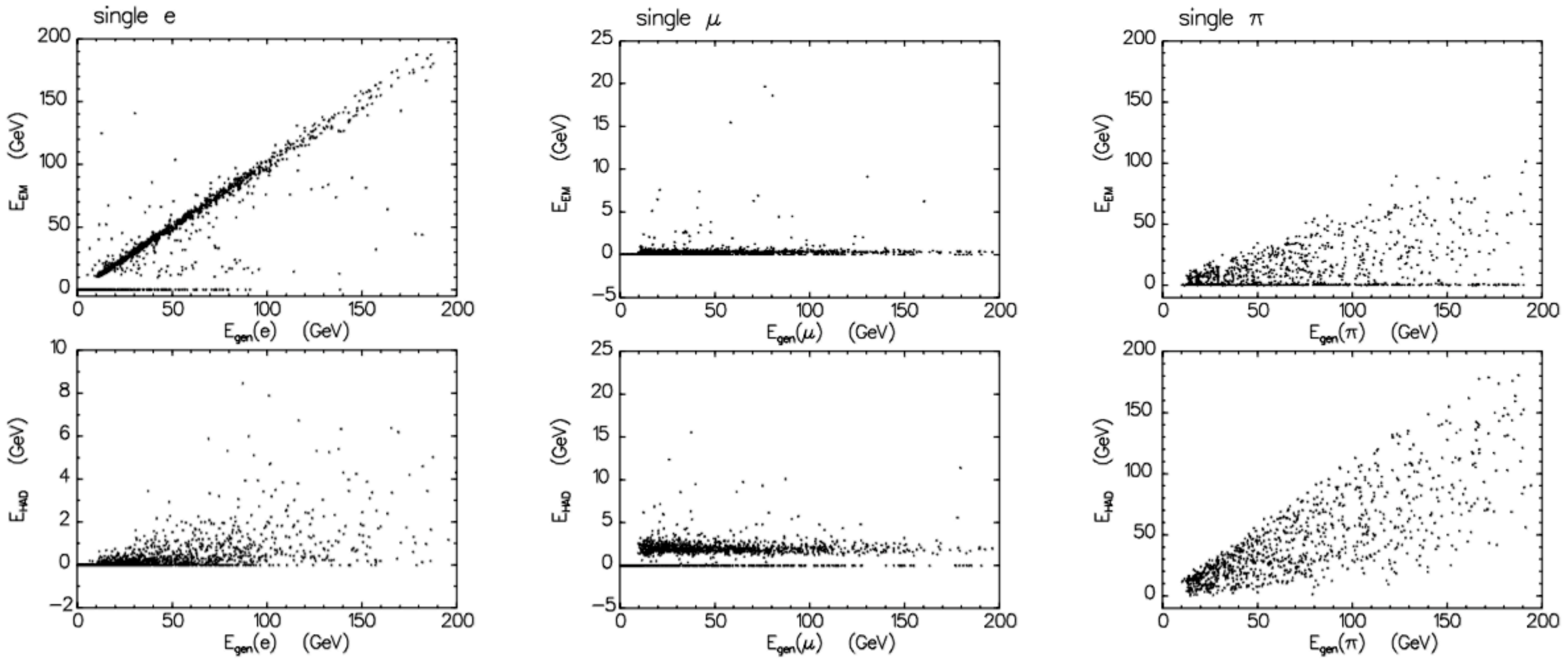
user output

# PGS Detector Simulation

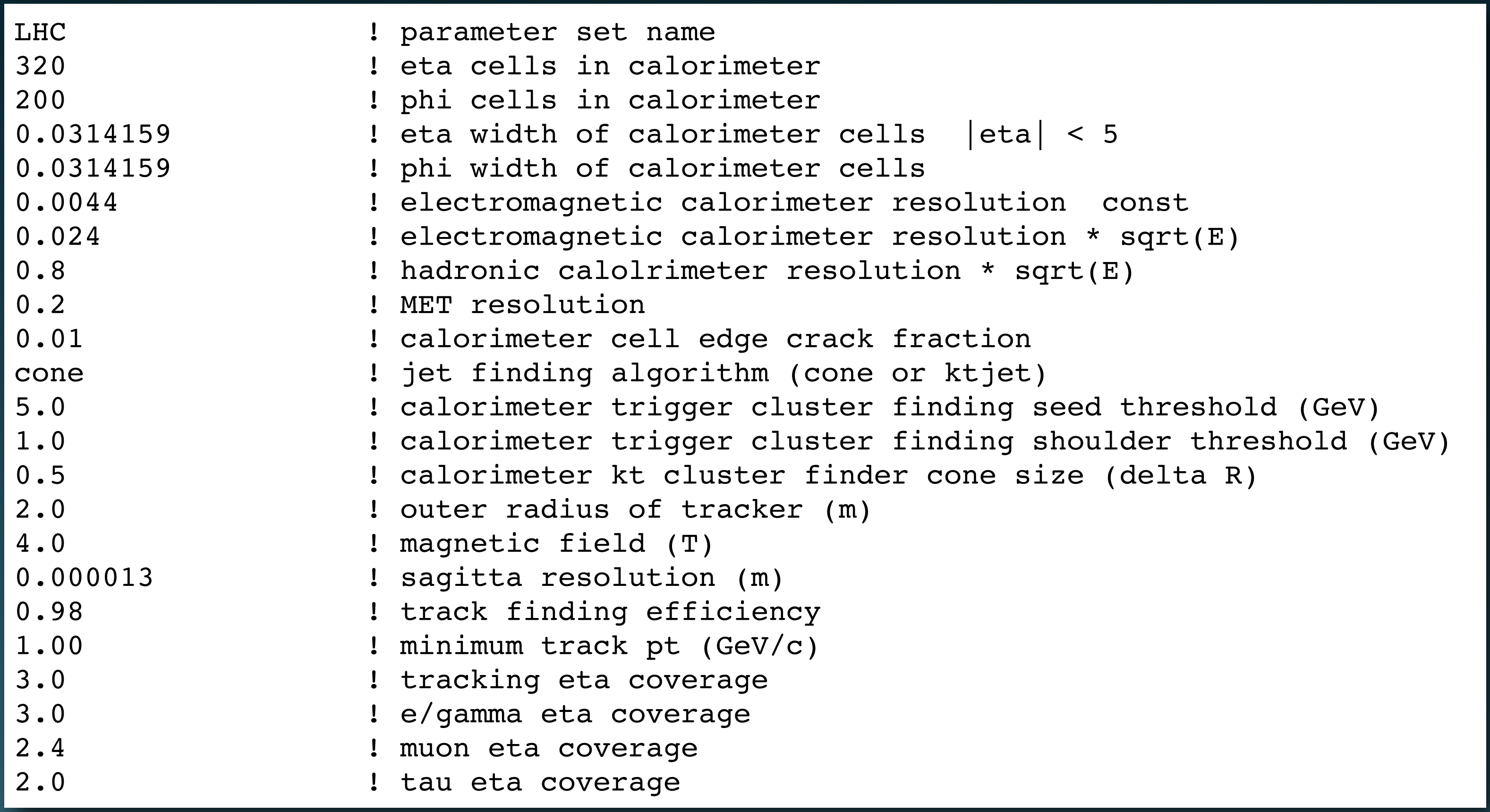
- loop through all final-state HEPEVT particles
- if charged, make charged track (straight...)
- calorimeter deposits:
    - gamma/electron: mostly electromagnetic
    - hadron: mostly hadronic
    - muon: minimum ionizing
- calorimeter is idealized, segmented in eta/phi
- resolutions are controllable parameters

# PGS Event Simulation

- plots of electromagnetic, hadronic, muonic energy deposits as implemented in PGS:



# PGS Parameters



```
LHC                 ! parameter set name
320                 ! eta cells in calorimeter
200                 ! phi cells in calorimeter
0.0314159           ! eta width of calorimeter cells  |eta| < 5
0.0314159           ! phi width of calorimeter cells
0.0044              ! electromagnetic calorimeter resolution  const
0.024               ! electromagnetic calorimeter resolution * sqrt(E)
0.8                 ! hadronic calolrimeter resolution * sqrt(E)
0.2                 ! MET resolution
0.01                ! calorimeter cell edge crack fraction
cone                ! jet finding algorithm (cone or ktjet)
5.0                 ! calorimeter trigger cluster finding seed threshold (GeV)
1.0                 ! calorimeter trigger cluster finding shoulder threshold (GeV)
0.5                 ! calorimeter kt cluster finder cone size (delta R)
2.0                 ! outer radius of tracker (m)
4.0                 ! magnetic field (T)
0.000013            ! sagitta resolution (m)
0.98                ! track finding efficiency
1.00                ! minimum track pt (GeV/c)
3.0                 ! tracking eta coverage
3.0                 ! e/gamma eta coverage
2.4                 ! muon eta coverage
2.0                 ! tau eta coverage
```

User is free to change these...at his or her own risk!

# PGS Resolutions

- tracking (B field, radius, sagitta)
  - ✓ calculate sagitta, smear it, get $p_T$
  - ✓ includes possibility of charge confusion
- em calorimetry

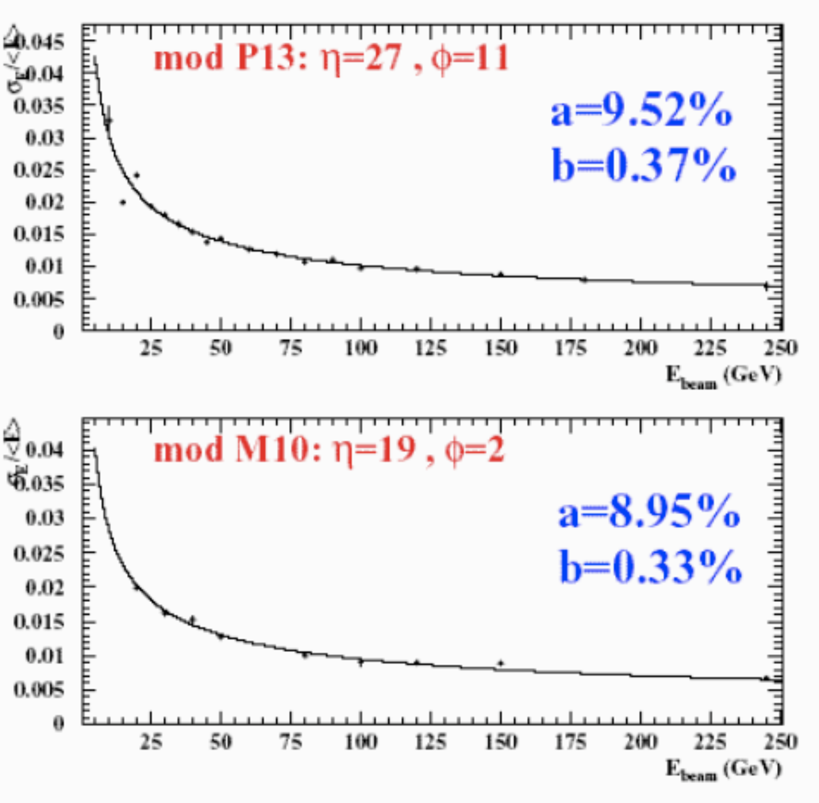
$$\Delta E/E = a + b/\sqrt{E}$$

- hadron calorimetry

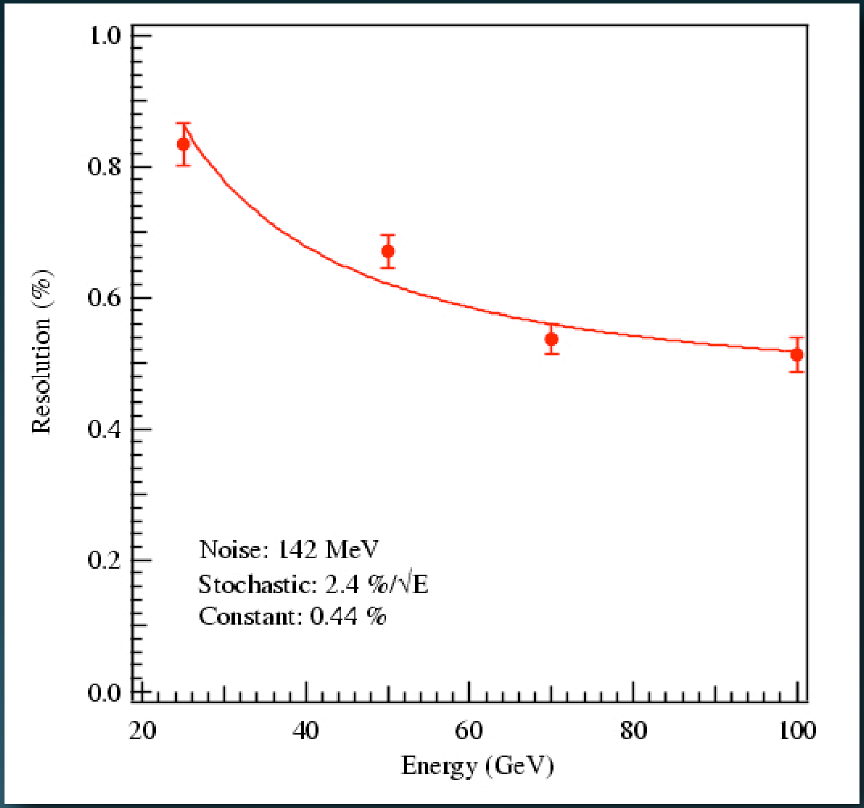
$$\Delta E/E = b/\sqrt{E}$$

# ATLAS/CMS Calorimetry

ATLAS



CMS



This is from test beams - does not tell the whole story!

# PGS e.m. resolution

- presently in PGS (090401 release):

$$\Delta E/E = 0.0044 + 0.024/\sqrt{E}$$

- older releases a lot worse:

$$\Delta E/E = 0.01 + 0.20/\sqrt{E}$$

# PGS Jet Finding

- after second LHC Olympics, request was made to use kt jet algorithm rather than the “JETCLU”-like cone algorithm formerly used
- ended up doing both: top-down cone jets used for trigger objects, and bottom-up kt jets used for physics jet objects
- in PGS this a user-settable switch
- ktjets greatly slows down performance!

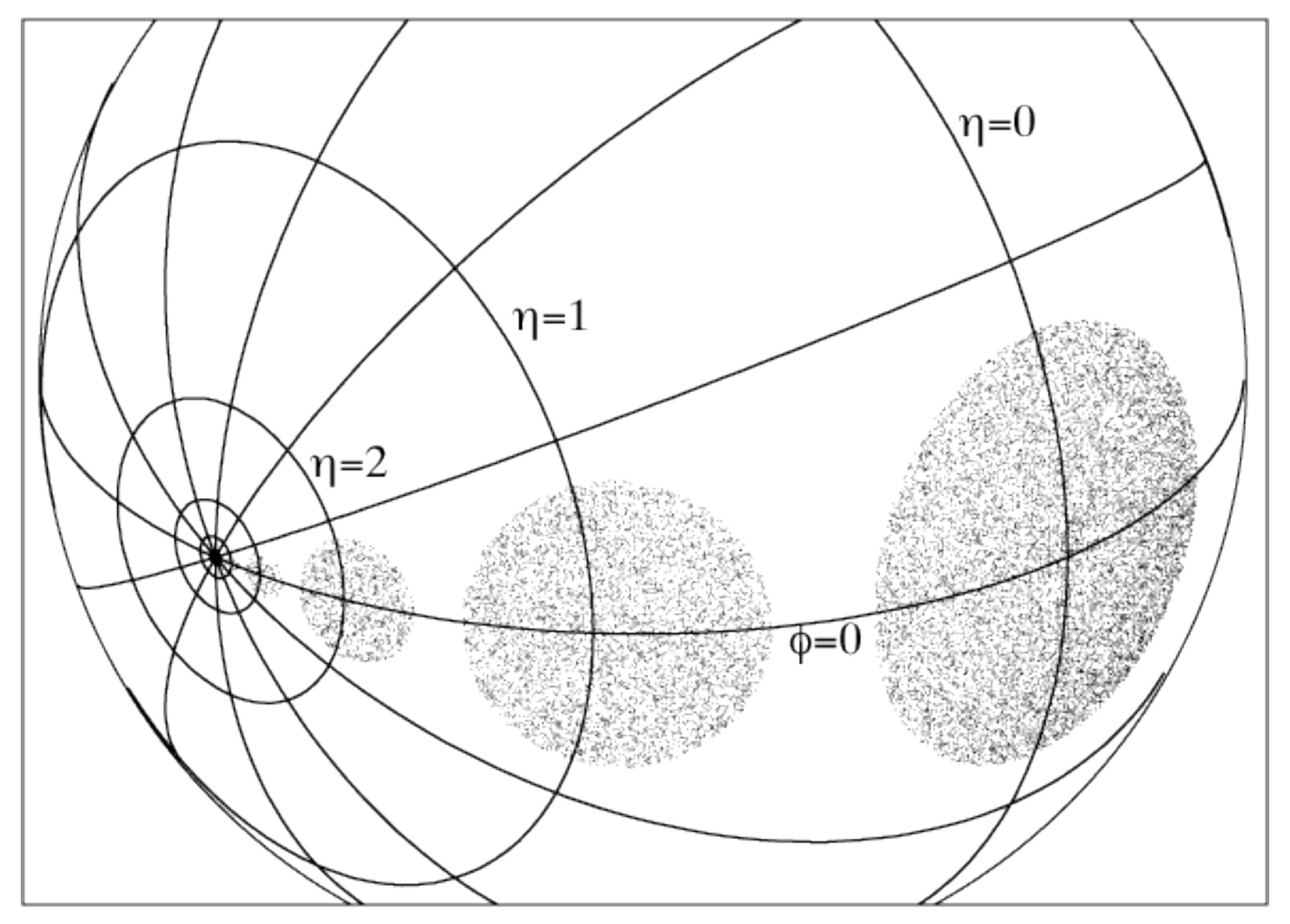
# PGS Jet Finding

- “top-down” (cone): **find highest ET tower, then add to it nearby towers above some threshold, lying within a pre-set cone size ($\Delta R_0$); repeat until remaining highest ET tower is below some threshold**
- “bottom-up” (kt jet): **treat all towers (em+had) as “particles”; find all particle-particle distances $\min(k_{Ti}^2, k_{Tj}^2)\Delta R_{ij}^2/\Delta R_0^2$ and particle-”beam” distances $k_{Ti}^2$ and if the overall minimum is an ij, merge them; repeat until no merge-able pairs remain**

# PGS Jet Finding

- the two algorithms differ in the tails of various distributions
- kt jet clusters all energy above threshold; may not be desirable
- funny-shaped jets (e.g. with g radiation) will always be a difficulty
- is $\Delta R$ even the right measure of separation?
- $\Delta R$ is “z boost invariant” but...

# We plot here random points lying within ΔR of 0.4 from several reference points:



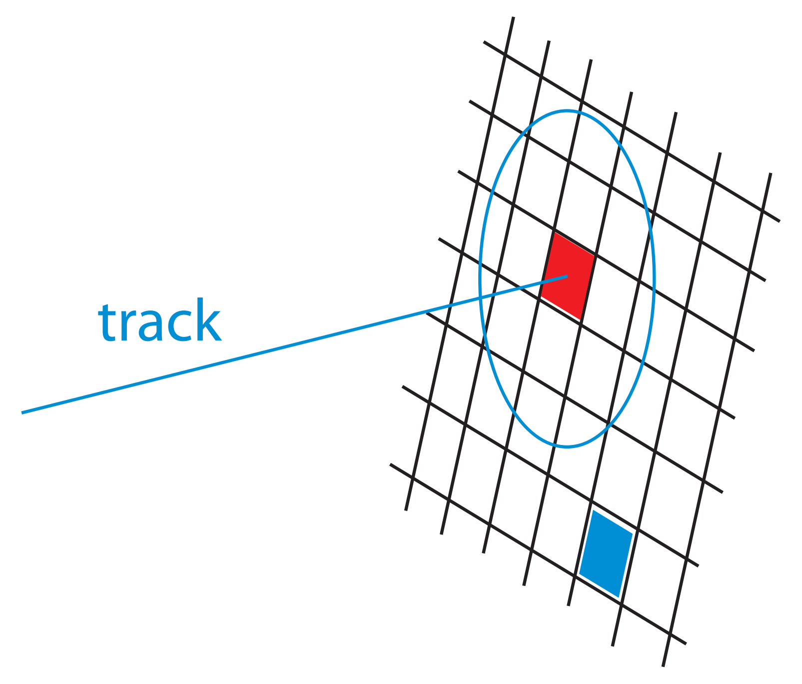
ΔR used for jet finding/merging, isolation, ... is it what we want in all cases?

# PGS Electrons/Photons

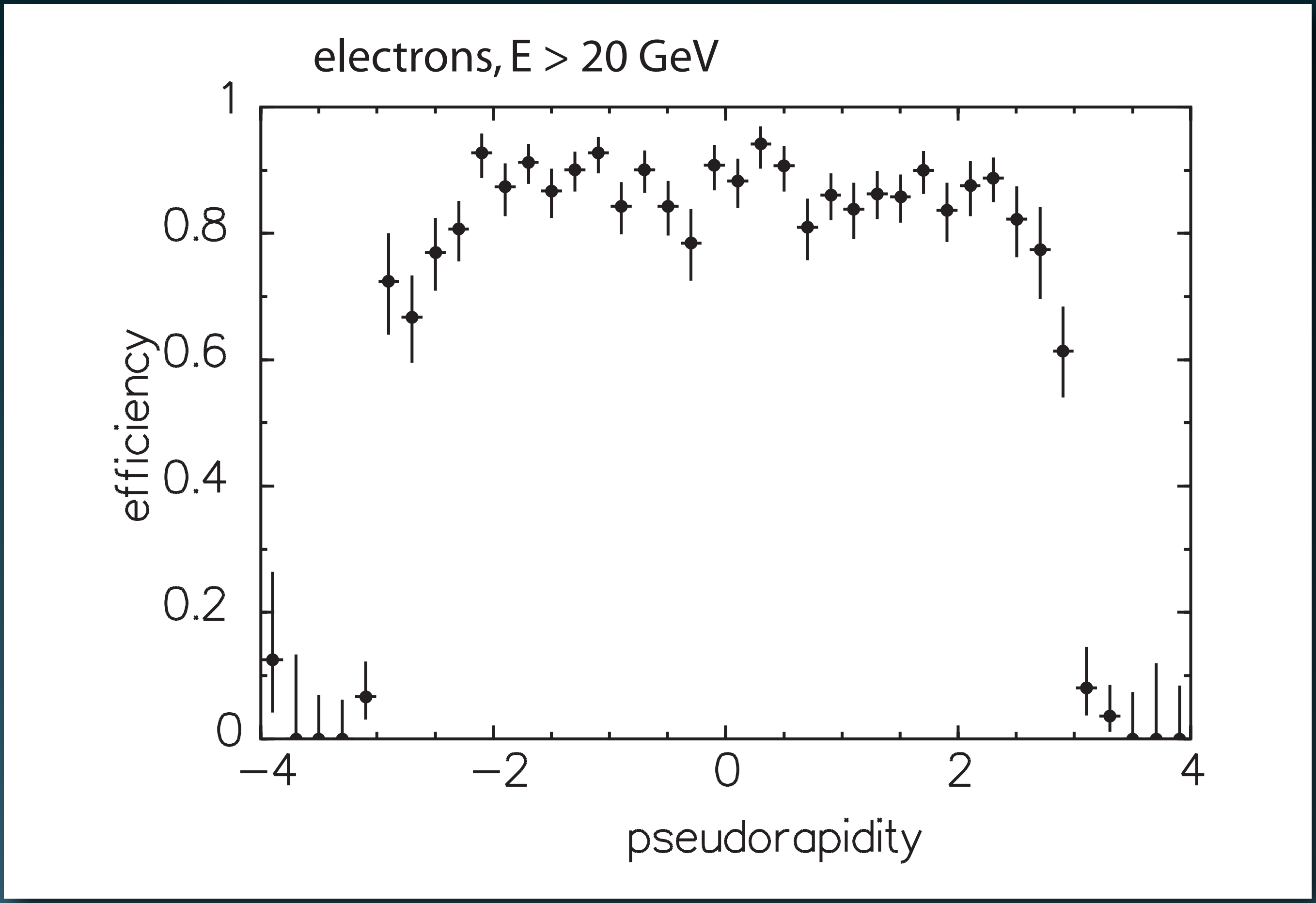
- in real life electromagnetic showers are narrow; hadronic showers are wide
- in PGS, alas, there is no lateral spread
- we simply rely on the fact that the energy is deposited in the em section of the calorimeter
- start with clusters (kt jet alg.) and apply em fraction cuts, match with track
- apply calorimeter isolation cut (3x3 region)

# PGS Electrons/Photons

- look at em fraction of cluster (single tower most likely)
- see if there is a track; no track ⇒ photon
- require sum of $p_T$ of other tracks in $\Delta R$ cone of 0.4 be less than 5 GeV
- require sum of energy in 3x3 collar region < 0.1 E



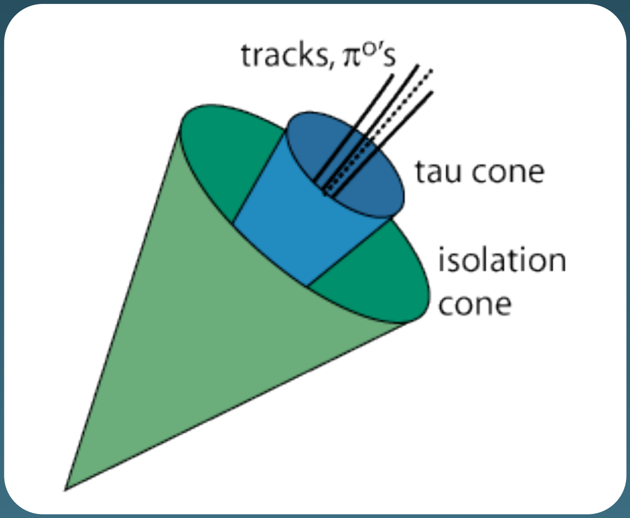
# PGS electron efficiency

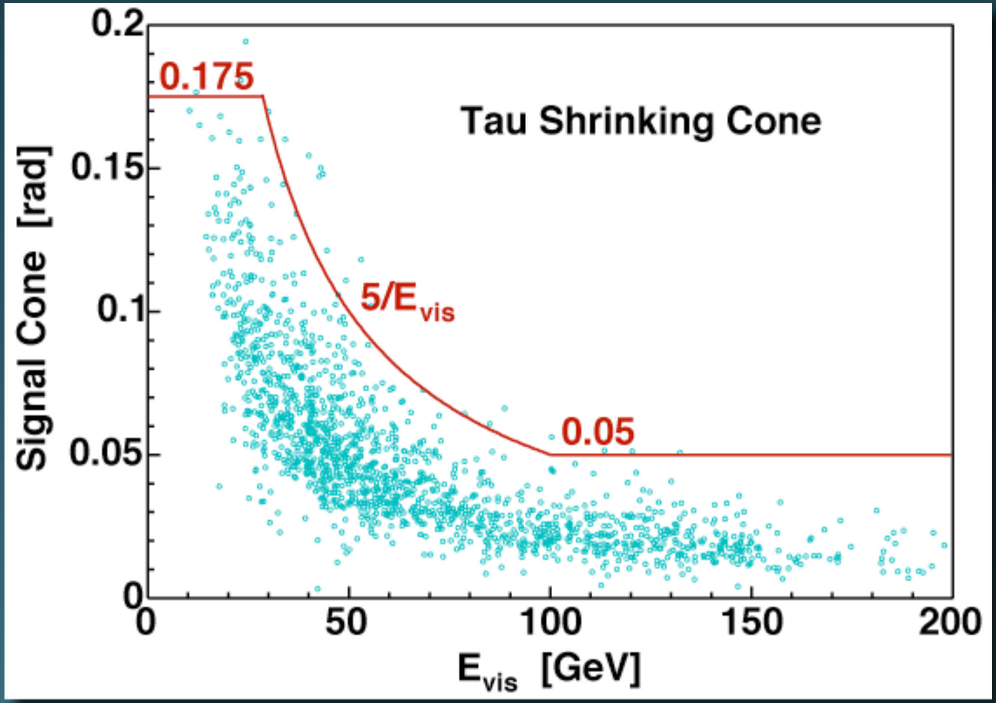


- **efficiency about 87% out to |η| = 3**

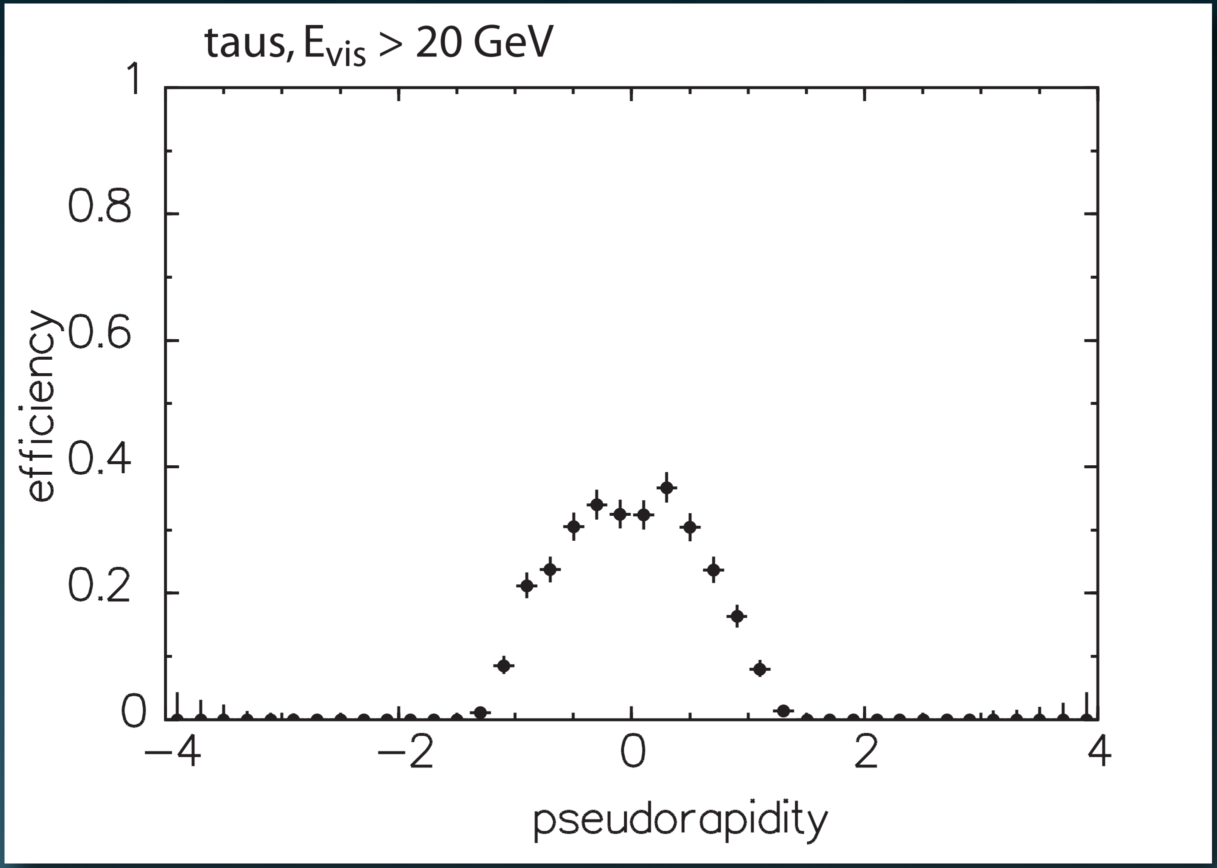
# PGS Tau Reconstruction

- standard approach at hadron colliders: cone based algorithm
- use CDF-style “shrinking cone” surrounding high-$p_T$ seed track
- we “fake” the $\pi^0$ reconstruction





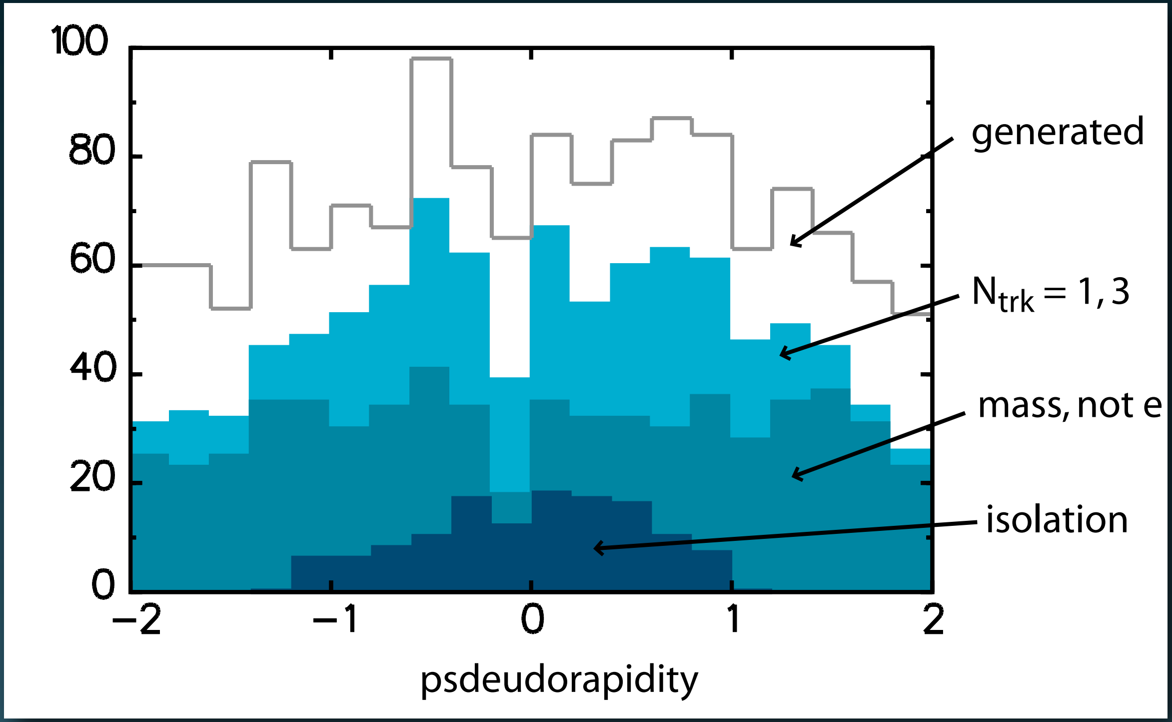
# PGS tau efficiency



- **efficiency much smaller than electrons, falls of rapidly at high pseudorapidity**

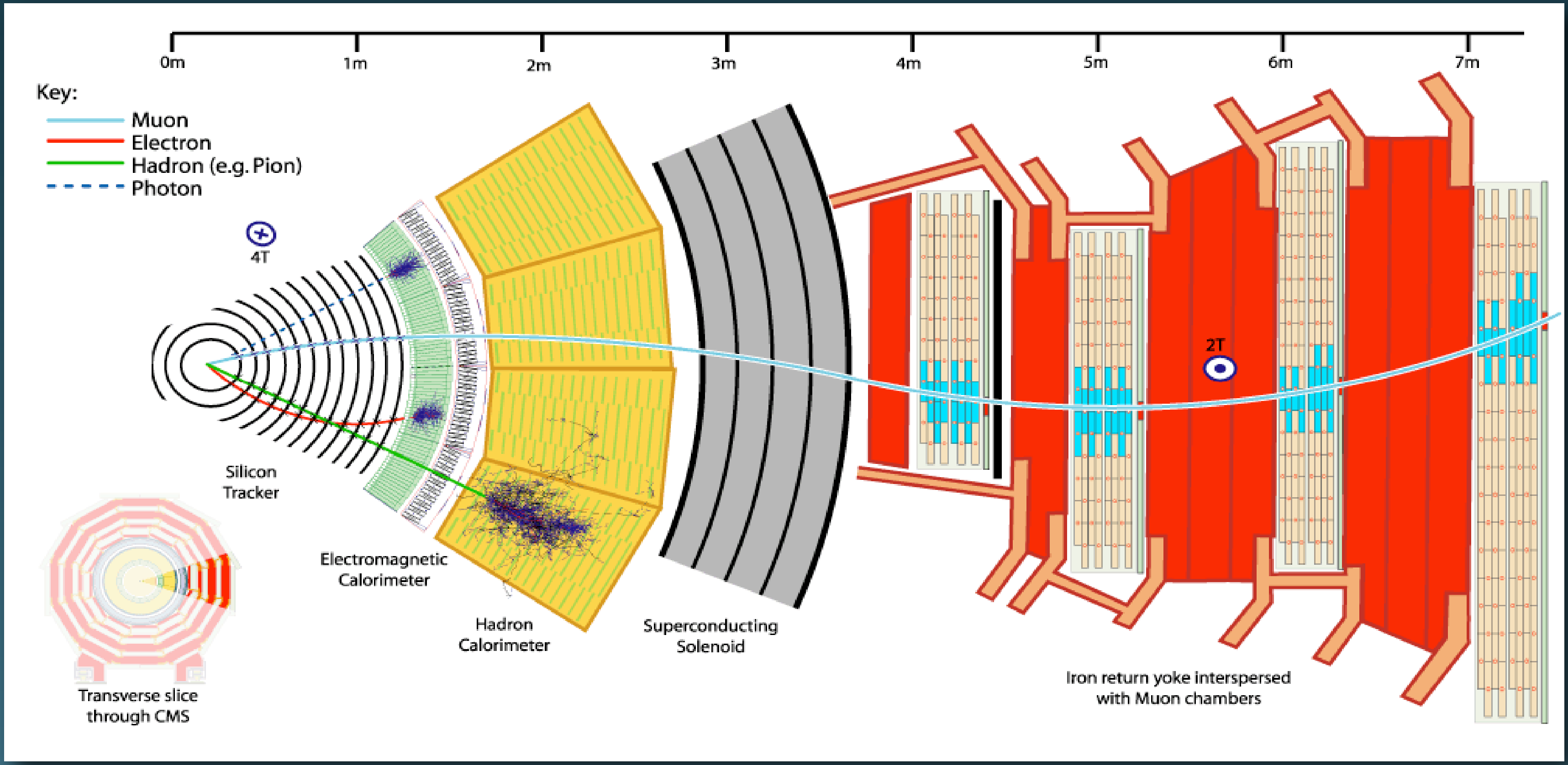
# PGS tau efficiency

- can we understand which cut

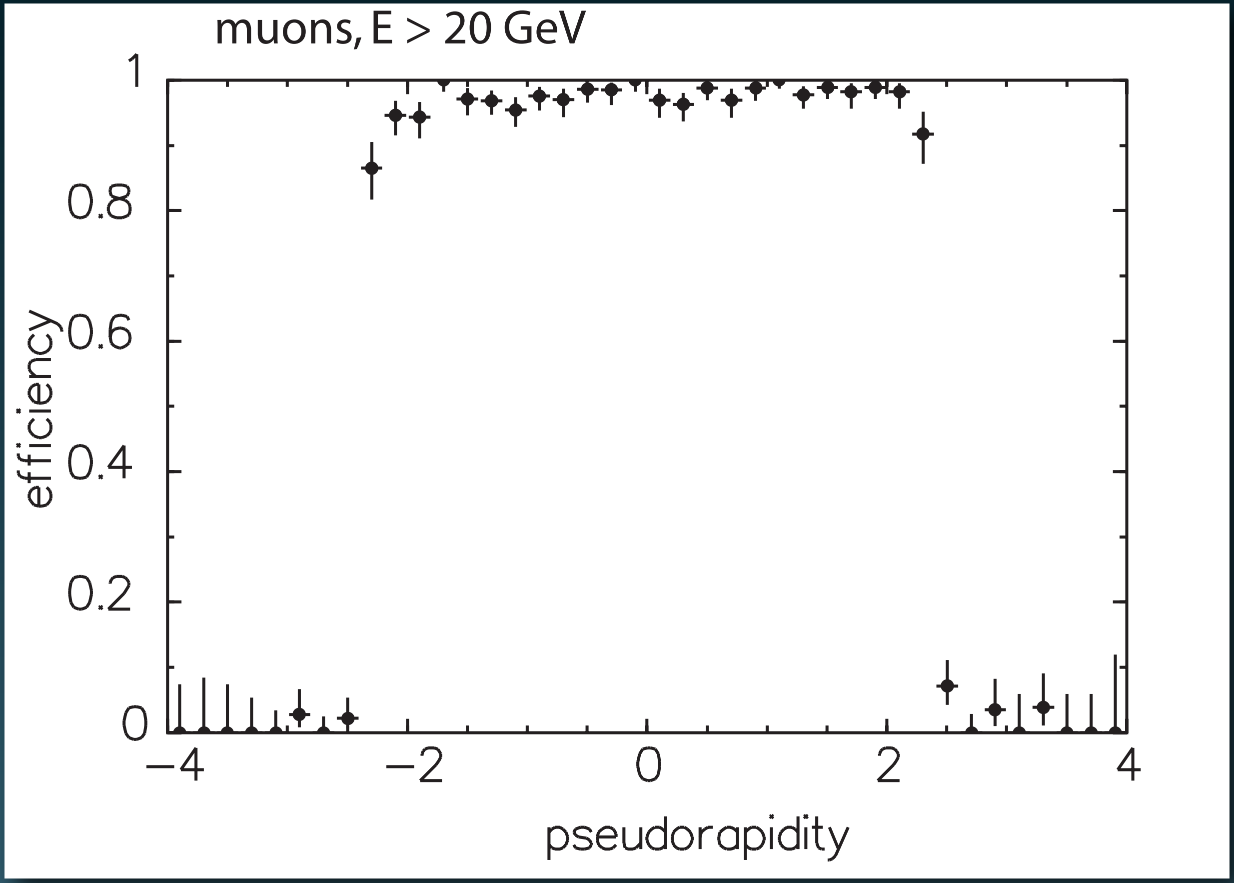


# PGS Muons

- Modern muon systems are highly efficient/redundant!
- We provide a parametrized efficiency function but we do <u>not</u> apply it by default
- Also, we do not apply a muon isolation cut by default, and leave that to the user (applied in the olympics executable)



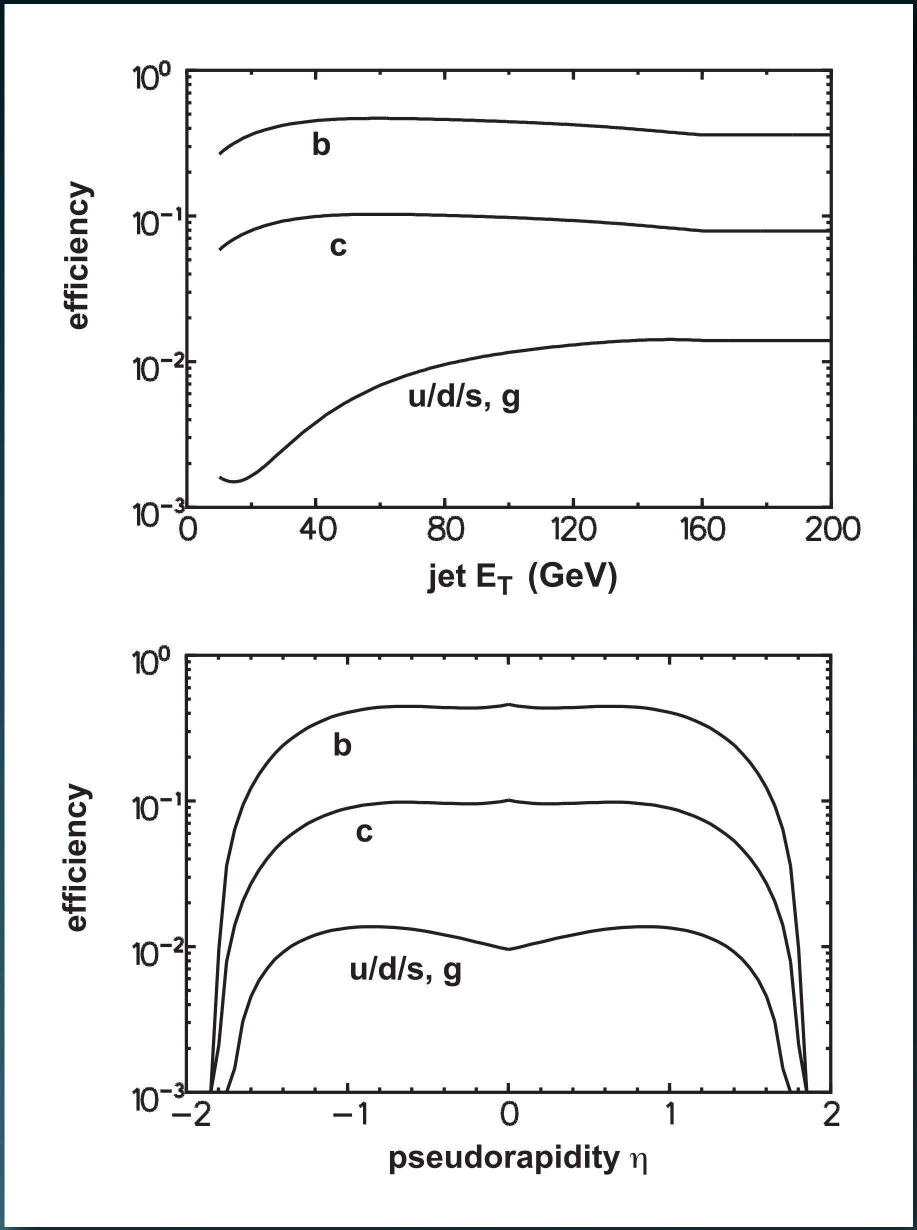
# PGS muon efficiency



- efficiency about 97% out to $|\eta| = 3$ (depends totally on track efficiency)

# PGS b-tagging

- parametrize b-tagging efficiency as a function of jet ET, eta
- use MC truth to tell "true jet type"
- this parametrization based on CDF Run 2
- probably not too far from eventual LHC experience...



# Uniqueness

- a given calorimeter energy (kt jet) cluster can give rise to
  - photon or electron
  - tau
  - jet
- must have algorithm to decide which it is!
- <u>cannot</u> call it two different things!

# Uniqueness

- we define physics object precedence:

$$\gamma > e > \tau > \text{jet}$$

- if object is already identified as an electron it cannot be a tau or a jet; tau cannot be jet
- jet is “catch-all” class
- muons are all “unique”
- we do this using 3D angle of 10°
- enforced as of PGS 4; provide “unique” flag for each object

# PGS for LHC Olympics

- goal of LHC Olympics: simulate the experience of analyzing physics “results” for new physics
- wanted fast (if rudimentary) simulation; PGS fit the bill
- created ASCII file output to store (unique) physics object list with eta, phi, pt, etc.
- for Third LHC Olympics, extended file format to include muon isolation, trigger information
- better-packaged, more-reliable distribution of PGS

# PGS Trigger Objects

- PGS provides crude "trigger objects" formed from cone algorithm cluster and tracks:
  - gamma: em deposit, no track
  - electron: em deposit with track
  - muon: straight 98% on all muons that make tracks
  - tau: subset of tau cuts
  - jet: any cluster
- these are <u>not</u> used in the LHC Olympics!

# LHC Olympics Trigger

- LHC Olympics trigger uses PGS physics objects, not PGS trigger objects
- Chris Tully and Herman Verlinde wrote an LHC-like trigger “table” including single leptons or photons, single jets, MET, lepton +jets, lepton+jets, jets+MET, dileptons, ...
- very complete table!
- divided into “Level 1” (low threshold) and “Level 2” (high threshold)
- record trigger “word” in LHC Olympics output

# Example Olympics Output

```
 #  typ      eta    phi      pt    jmas  ntrk  btag   had/em  dum1  dum2
                         0             1   3585
 1    4   -1.312  3.143  104.54   21.59  19.0   0.0     1.22   0.0   0.0
 2    4   -1.233  0.957   85.10   15.90  11.0   0.0     5.78   0.0   0.0
 3    4   -2.939  1.139   38.38   26.74  20.0   0.0    63.11   0.0   0.0
 4    4    3.226  5.123   37.37   34.33   8.0   0.0     1.10   0.0   0.0
 5    4   -3.718  4.691   21.52    1.55  17.0   0.0     1.35   0.0   0.0
 6    4    0.211  5.752   12.75   15.57   0.0   0.0     1.03   0.0   0.0
 7    4    1.008  3.038   12.60    4.18   3.0   0.0     1.73   0.0   0.0
 8    4   -2.106  4.275    7.93    2.75  19.0   0.0     3.32   0.0   0.0
 9    6    0.000  6.008   15.64    0.00   0.0   0.0     0.00   0.0   0.0
                         0             2   3599
 1    2   -1.317  3.638    3.36    0.11  -1.0   6.0    11.41   0.0   0.0
 2    2   -1.388  1.845   12.23    0.11   1.0  10.0     0.10   0.0   0.0
 3    4   -0.044  5.646   79.40  335.20   0.0   0.0     1.63   0.0   0.0
 4    4   -0.341  1.677   56.31   32.28   8.0   0.0     5.10   0.0   0.0
 5    4   -3.391  5.279   55.44   30.84  20.0   0.0     1.11   0.0   0.0
 6    4   -1.242  3.464   36.02   34.93   9.0   0.0     2.23   0.0   0.0
 7    4    3.875  2.981   23.08   25.33  12.0   0.0     1.78   0.0   0.0
 8    4   -2.934  0.093   11.33    2.15  21.0   0.0     6.17   0.0   0.0
 9    4   -1.584  4.694   11.12    2.39  18.0   0.0     5.91   0.0   0.0
10    4   -1.716  1.913    9.09    2.20  12.0   0.0     0.90   0.0   0.0
                          0             3   3585
 1    4    0.523  0.059  225.21   48.39  19.0   0.0     3.19   0.0   0.0
 2    4    1.336  3.220  228.44    3.75  10.0   0.0    10.04   0.0   0.0
 3    4    2.918  0.007   62.64  123.09  13.0   0.0     1.53   0.0   0.0
 4    4    2.888  3.307   39.08    6.84  13.0   0.0     0.51   0.0   0.0
 5    4   -3.432  6.037   13.55   13.69   4.0   0.0     3.54   0.0   0.0
 6    4   -1.444  2.410   11.78    4.33   4.0   0.0     1.06   0.0   0.0
 7    4    2.065  1.650   11.82    2.55  14.0   0.0     3.07   0.0   0.0
```

# Supported Environments

- OS X: gfortran/gcc 4.x
- Linux: g77/gcc 3.4.x
- Cygwin (must remake libs yourself)

- PGS is CERNLIB-free (and loving it!)
- be mindful of random numbers if you are splitting your jobs into parallel runs!
- can use different seeds for each run

# Future Work

- clear demand for “tuned” versions for CMS, ATLAS, CDF, D0...
- this will take some study
- could improve calorimetry with detailed “particle gun” study
- implement features from prvate hacked PGS versions?