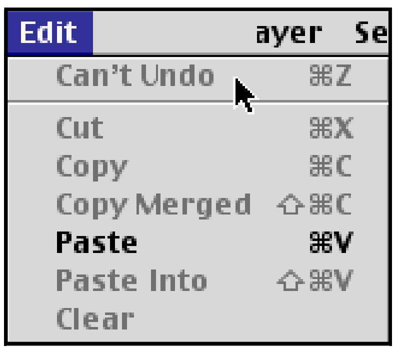
Metody eksperymentalne w fizyce wysokich energii

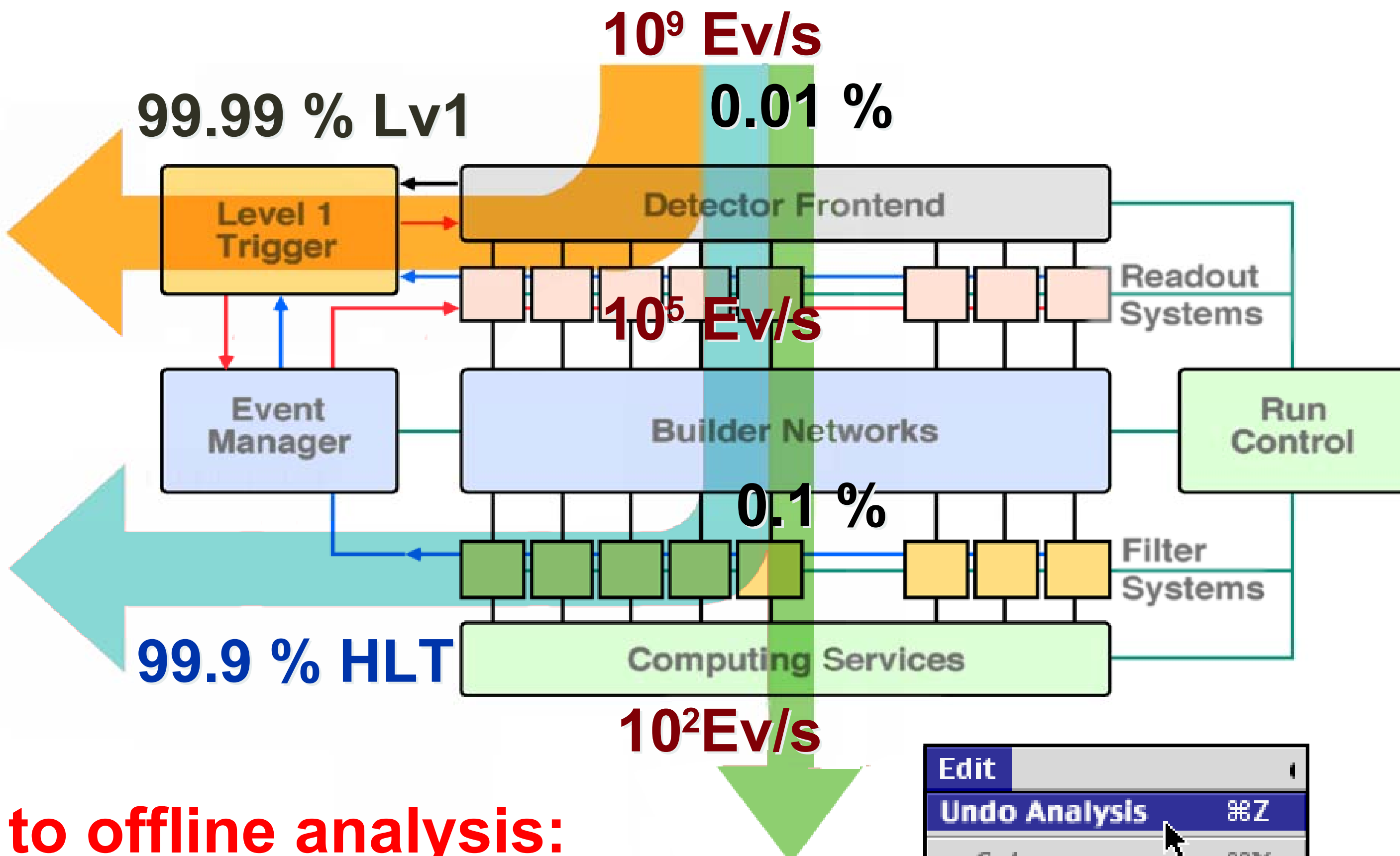
prof. dr hab. A.F.Żarnecki
Zakład Cząstek i Oddziaływań Fundamentalnych IFD

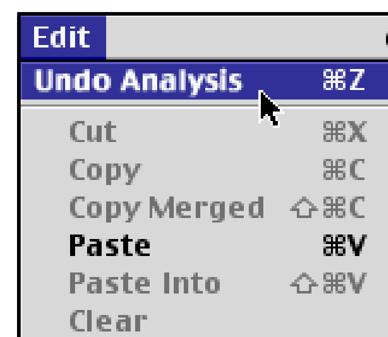
Wykład XII

- Rekonstrukcja przypadków

A parting thought







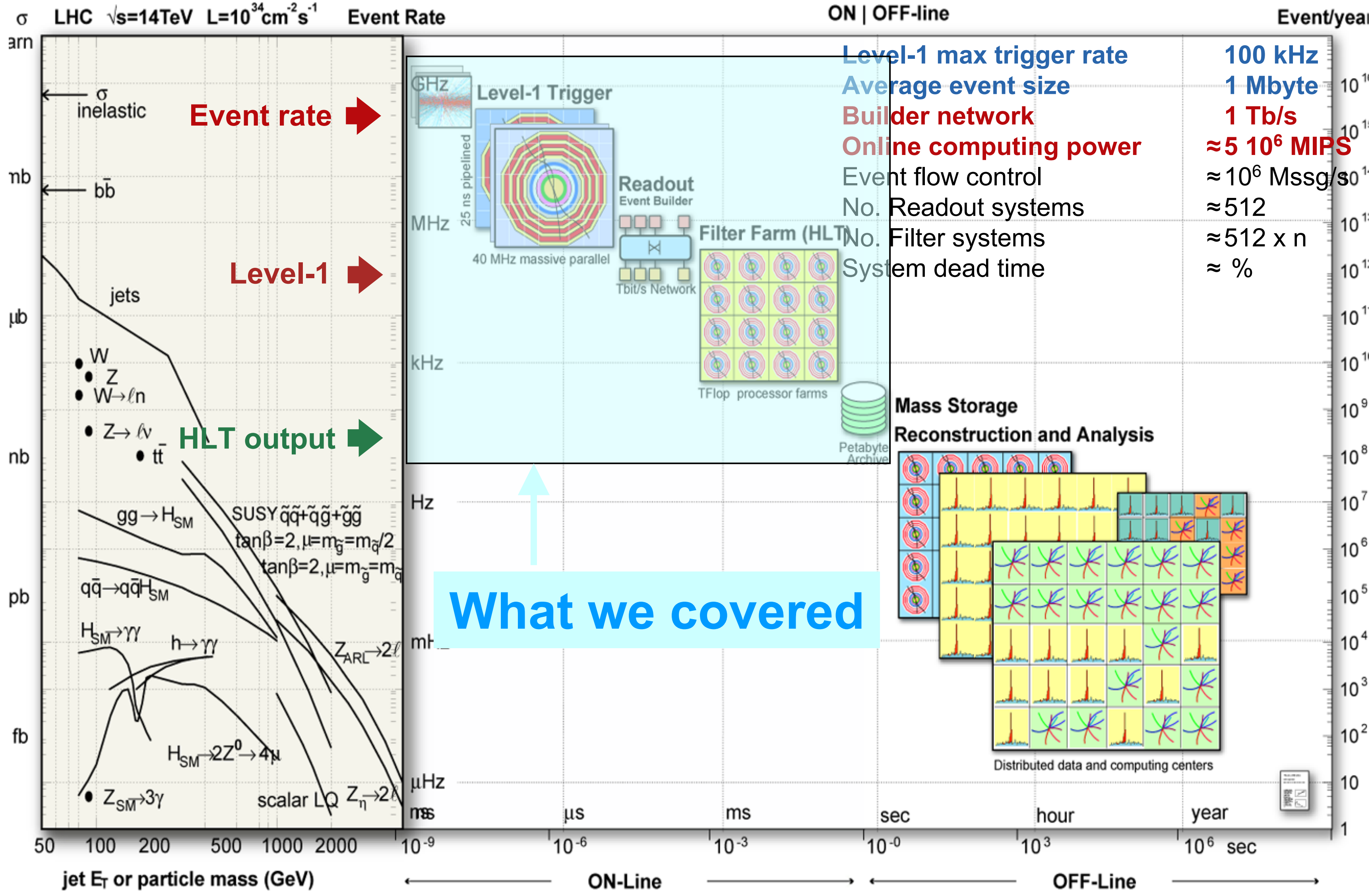
With respect to offline analysis:

Same hardware (Filter Subfarms)

Same software

But different situations

Online Physics Selection: summary



Dane odczytywane z detektora:

- "zapalone" cele kalorymetru
  - ID celi + sygnał
  - + ew. informacja o profilu podłużnym lub poprzecznym w przypadku wielokrotnych odczytów

- "hity" w detektorach śladowych
  - ID/pozycja drutu/paska/piksla
  - + ew. sygnał (~dE/dx)
  - + ew. czas (komory dryfowe, TPC)

Co potrzebujemy do analizy fizycznej:

- zidentyfikowane fotony: energia, kierunek emisji (=> wektor pędu)
- zidentyfikowane leptony (elektrony/miony/taony): energia, pęd, znak
- zrekonstuowane jety: energia, pęd, masa niezm., zapach (!)
- zrekonstuowany brakujący pęd poprzeczny, energia, masa...

Dodatkowe dane wejściowe

Wyznaczane na podstawie zebranych danych (w tym w odpowiedzi na detykowane triggery), parametrów pracy detektora itp.:

- parametry kalibracji
- parametry pozycjonowania
- parametry efektywności

Niezbędne do rekonstrukcji danych.

Rzadko/powoli się zmieniają - w skalach dni, tygodni.
W najgorszym przypadku co napełnienie (fill).
Czasami raz na rok (od shutdownu do shutdownu).

Zazwyczaj przechowywane w dedykowanych bazach danych.

Kolejne kroki rekonstrukcji

Krok I: "normalizacja" na poziomie poszczególnych detektorów

kalorymetry

ID celi => pozycja w detektorze, z uwzględnieniem pozycjonowania

sygnał => depozyt energii w GeV, z uwzględnieniem kalibracji, tła

detektory śladowe

ID elementu, ew. czas dryfu

=> pozycja w detektorze, z uwzgl. pozycjonowania

Krok II: rekonstukcja podstawowych "elementów"

wciąż na poziomie poszczególnych detektorów

kalorymetry

"klastry"/"wyspy" energii (pojedyncze cząstki ?)

detektory śladowe

"klastry"/punkty, ew. elementy/fragmenty toru (punkt + kierunek)

Krok III: rekonstrukcja obiektów na na poziomie globalnym
- rekonstrukcja torów
- rekonstrukcja wierzchołka pierwotnego i w. wtórnych
- rekonstrukcja jetów

Krok IV: identyfikacja obiektów (na poziomie globalnym
łączenie tor-klaster (i ew. korekta energii: PFA)
- identyfikacja leptonów
- znaczenie zapachów jetów (ciężkie kwarki)

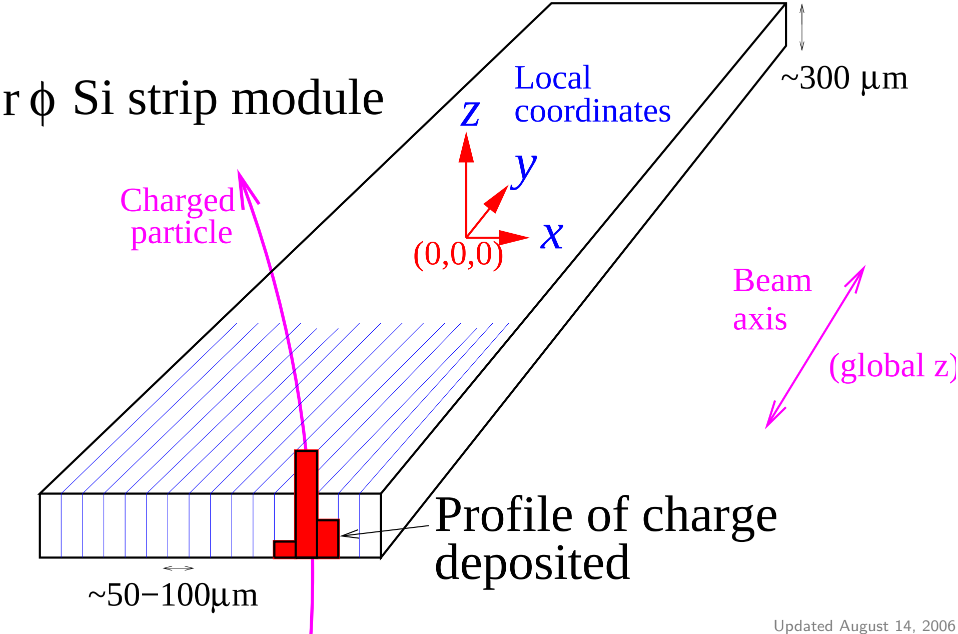
Rekonstrukcja torów

Tracking: basic idea

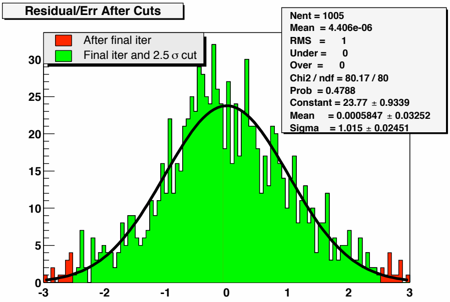
When we talk about "tracking," we want to do the following:

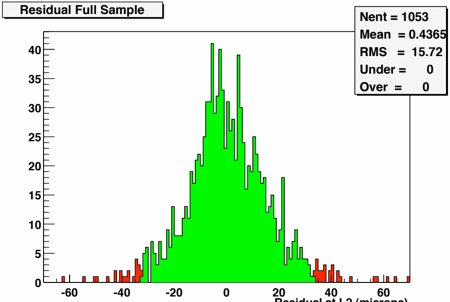
- Measure the true path of the charged particle, which let's us know...
- The momentum (3-momentum) if we know the magnetic field
- The sign of the charge of the particle
- With other constraints or assumptions, the "origin" in space of the particle
- Without some other detector though, we can't measure the mass independently just with a tracker

2D Point ($r\phi$ or rz): $\bar{x} = (\sum i * q_i) / \sum q_i$



Typical Resolution of 50 μm Strips (CDF)





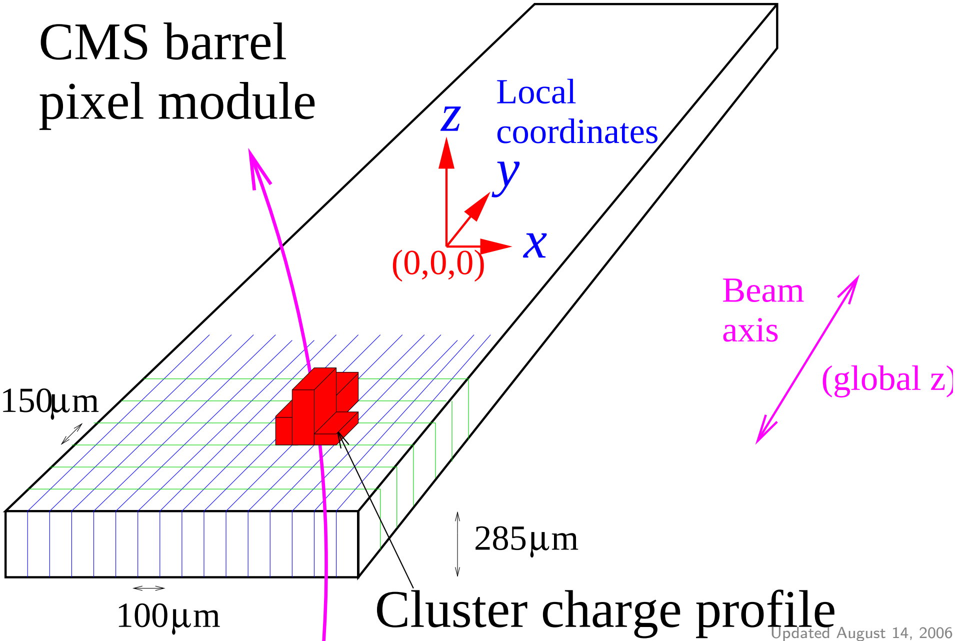
Cluster Width	Resolution
1	12 μm
2	9 μm
3	14 μm
4+	22 μm

- *rz* strips are either shallow stereo (2°), or 90° stereo but larger pitch
- Intrinsic resolution of larger pitch stereo usually factor of 2+ worse than $r\phi$

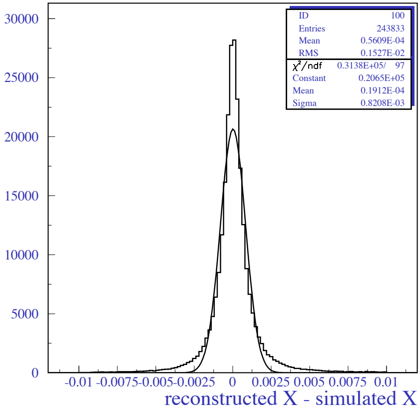
Resolution of Si Strip Detector

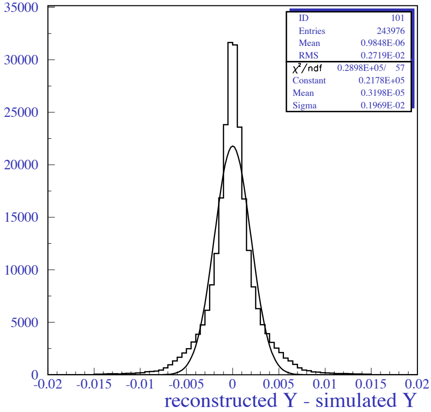
- The resolution of a Si hit depends on the number of strips in the cluster (2-strip most precise)
- Charge drifts with Lorentz force: $q(\vec{\boldsymbol{E}} + \vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}})$
- Thin material: Landau distribution of charge [2]
- Track impact angle & position makes a difference [3]
- Delta rays (hard knock e^-) can bias charge distribution
- Dead channels, noise, V_{dep}, temperature all could affect this too
- Radiation damage changes
- Pileup from previous event
- Multiple particles passing through same strips

3D Space Point from Pixel Detector



Typical Pixel Resolution (CMS): $8 - 20\ \mu\mathrm{m}$ (with 100/150 µm pitch !)





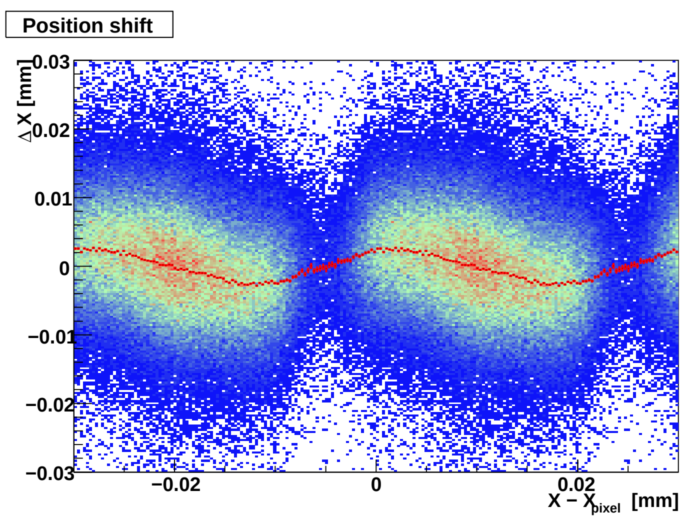
Detektory pixlowe

MAPS

Wyniki testów detektora MAPS, rozmiar pixla 30 $\times$ 30μm

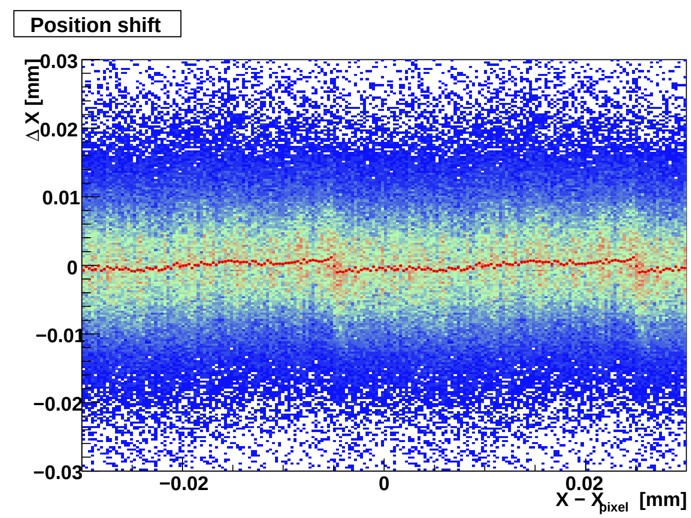
Błąd pozycji vs pozycja na pikslu.

Pozycja wyznaczana metodą środka ciężkości (CoG)



Pojedyncza cząstka "zapala" średnio 4 pixle $\Rightarrow$ systematyczny błąd pozycji zależny od punktu przejścia cząstki

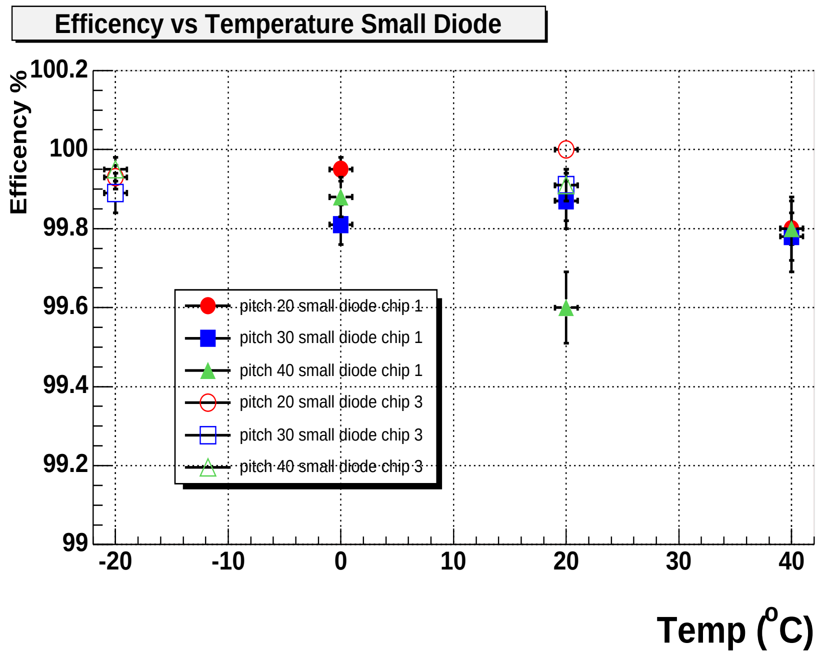
Pozycja CoG po zastosowaniu poprawki (tzw. funkcja Eta)



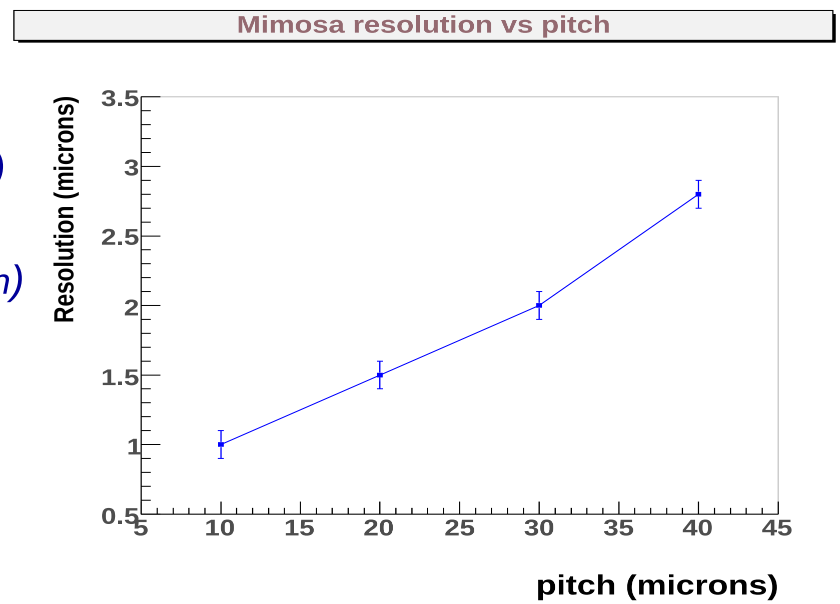
wyznaczana z danych poprawka prawie całkowicie eliminuje efekty systematyczne

Detection Efficiency & Spatial Resolution

- **Detection efficiency:**
  - *Ex: MIMOSA-9 data (20, 30 & 40 μm pitch)*
  - $\epsilon_{det} \gtrsim$ *99.5–99.9 % repeatedly observed at room temperature (fake rate $\sim 10^{-5}$)*
  - $T_{oper.} \gtrsim$ *40 °C*



- **Single point resolution versus pixel pitch:**
  - *clusters reconstructed with eta-function, exploiting charge sharing between pixels (12-bit ADC)*
  - $\sigma_{sp} \sim \mathbf{1}\ \mu\mathbf{m}$ *(10 μm pitch)* $\rightarrowtail \lesssim \mathbf{3}\ \mu\mathbf{m}$ *(40 μm pitch)*
  - *4-bit ADC simul.* $\Rightarrow \sigma_{sp} \lesssim \mathbf{2}\ \mu\mathbf{m}$ *(20 μm pitch)*
  - *measured binary output resolution (MIMOSA-16, -22):* $\sigma_{sp} \gtrsim$ *3.5 & 4.5 μm (18.4 & 25 μm pitch)*



Pattern Recognition & Track Fitting

Typically, pattern recognition algorithms are either "inside-out" or "outside-in."

- You have to start with some idea of the path of the particle to bootstrap your algorithm: a track seed
- Then you take this candidate, this seed, can try to find compatible hits in other layers
- Continue this process until you've met some criteria for what a "good track" should have
- Once you've got your hits for your track, try to do a good job of fitting your pseudohelix
- Psuedohelix because there is energy loss and multiple scattering
- There are also spurious hits from detector noise and low momentum, unreconstructable tracks. These will mess up your "true" helix

Helix Parameters

We can decompose the momentum of a track in spherical coordinates [1]:

$$p_x = p \cos\phi \sin\theta$$
$$p_y = p \sin\phi \sin\theta$$
$$p_z = p \cos\theta$$

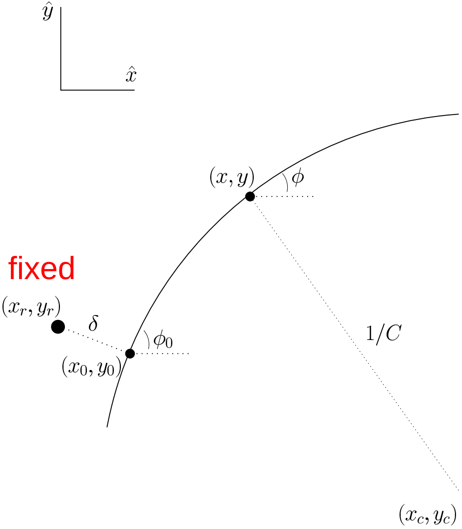
Different experiments choose different ranges for the angles, it's important that you figure out what they are using:

$$\phi \in [-\pi, \pi] \qquad \theta \in [0, \pi]$$

There must also be some "reference point" in space to uniquely define our helix: (x_r, y_r, z_r)

Helix Parameters in $x - y$ Plane

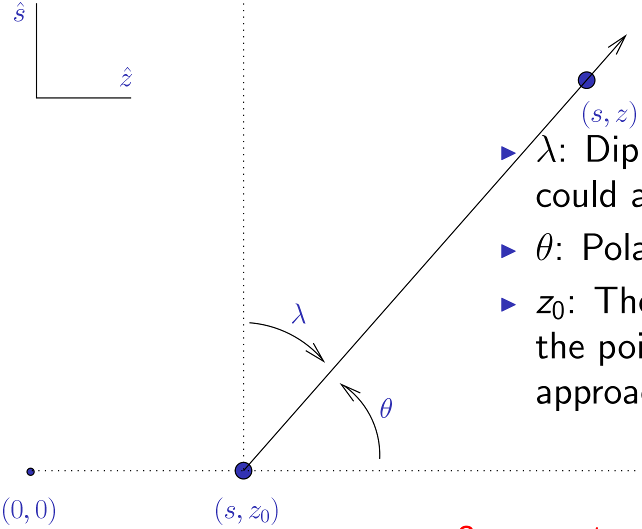
This parameterization is more closely related to things we actually measure with our trackers



- C: Curvature of the track. Signed with charge.
- ϕ_0: Azimuthal angle of the momentum at the point of closest approach
- δ: Distance of closest approach. (Also signed, but differently.)

3 parameters in x-y

$z = z_0 + s \tan \lambda$



- λ: Dip angle of track, or could also use
- θ: Polar angle of track
- z_0: The z of the track at the point of closest approach in $x - y$

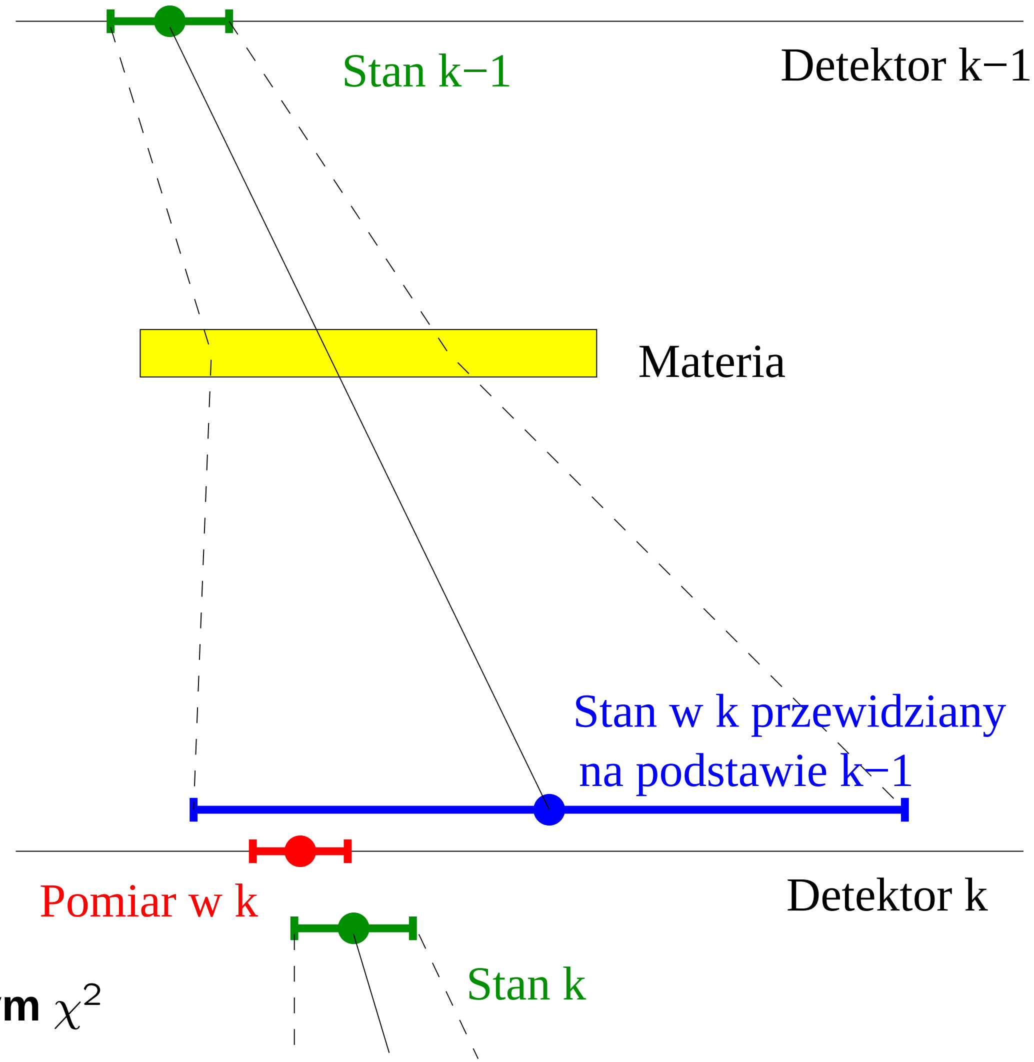
+ 2 parameters in r-z

Kalman Filter

- The Kalman Filter [4] is an iterative procedure
- You start with a seed track. For example, a pair of hits in the pixel detector that line up within 5σ of the primary interaction region
- Then you add points on successive layers, taking into account projected error from current hypothesis track and multiple scattering
- Finally, if this track passes some requirements for a minimum number of hits, you refit it (smooth) again with the filter using a better starting point

Filtr Kalmana - sposób na dopasowywanie torów

- **Algorytm oblicza parametry toru używając punktów "pasujących" do toru:**
- **Punkty są dodawane zaczynając od najbardziej zewnętrznych**
- **Stan początkowy jest brany z zewnętrznych detektorów śladowych**
- **Stan obliczony dla detektora k-1 jest ekstrapolowany do detektora k z uwzględnieniem wpływu materii.**
- **Punkty w znalezione w detektorze k są porównywane z przewidywaniem i są dodawane jeżeli nie wprowadzaja dużego wzrostu χ^2 przy dopasowaniu toru - obliczany jest stan k**
- **Jezeli więcej niż jeden punkt "pasuje" brane są pod uwagę wszystkie możliwości i ostatecznie wybierany jest tor z największą liczbą punktów i najmniejszym χ^2**



Tracking Resolution

The resolution of the various helix parameters depends on a number of things

- The number of hits used from various subdetectors (hopefully, more is better)
- The momentum of the particle. Higher momentum particles deflect less from multiple scattering
- The polar angle of the track (η)
- Quality of alignment
- Presence of other tracks!
- Detector noise

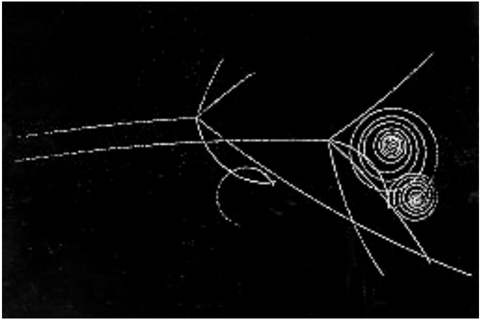
High Multiplicity Strategies

- If your inner layers are being swamped, use an outside-in algorithm instead of an inside-out algorithm
- Try to boost efficiency for higher p_T tracks by reconstructing them first, and then remove these hits from consideration
- Upgrade your detector

Rekonstrukcja wierzchołków

Vertexing: Basic Idea

The basic idea of vertexing is to figure out where the particles came from. We can associate tracks to particle decays and interactions this way.



Vertexing Strategy

- A vertex is a point where more than one particle comes from
- If there is more than one track coming from the same place, then the helixes should cross each other, right?
- Look for places where helixes cross
- Caveat: The track parameters $\vec{\boldsymbol{p}}_i = (C, \phi, d_0, \tan\lambda, z_0)$ are different in different parts of the helix

Vertexing Algorithm

- If helixes cross, that means the track parameters must be the same at some point
- In 2D, this is as simple as looking for crossing circles
- But you can take full advantage of full track parameterization and covariance matrix to look for vertexes
- Most methods are built on some kind of χ^2 of track parameters

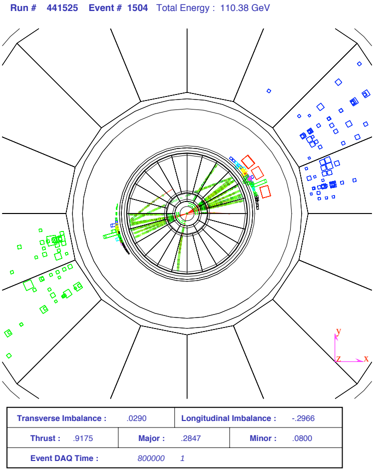
$$\chi^2 = \sum_{i}^{N_{\mathrm{trk}}} (\vec{\boldsymbol{x}} - \vec{\boldsymbol{g}}(\vec{\boldsymbol{p}}_i))^{\mathrm{T}} \mathbf{J}^{\mathrm{T}} \mathbf{M}_i^{-1} \mathbf{J} (\vec{\boldsymbol{x}} - \vec{\boldsymbol{g}}(\vec{\boldsymbol{p}}_i))$$

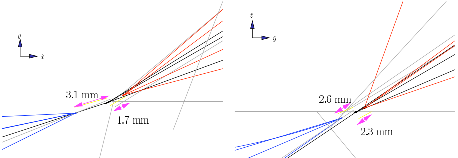
Vertex Algorithm Continued

- Again, we have a problem of pattern recognition
- The χ^2 can be defined for any collection of tracks
- Vertex algorithms are usually iterative however, pruning or down-weighting tracks which make large contributions to the χ^2 (outliers)
- Clumps, or clusters of tracks are what is searched for in this way

Rekonstrukcja wierzchołków wtórnych

B-Tagging: Basic Idea

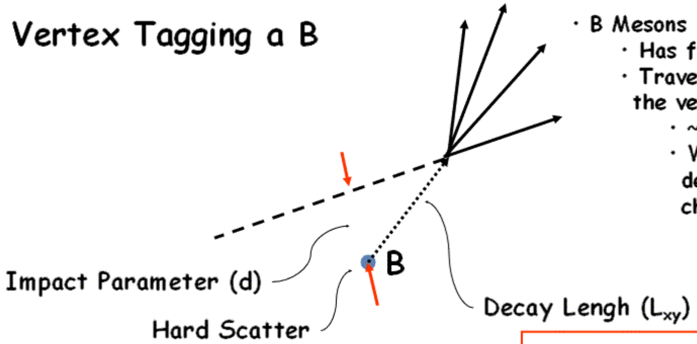




- B hadrons have lifetimes and decay lengths distinct from other species
- Decay length is measurable in a given event by finding a vertex ("secondary") and taking the distance to the "primary" vertex
- Can look for B hadrons by finding these vertexes which are compatible with known properties of B hadrons

Example B-Tag (D0)

Vertex Tagging a B



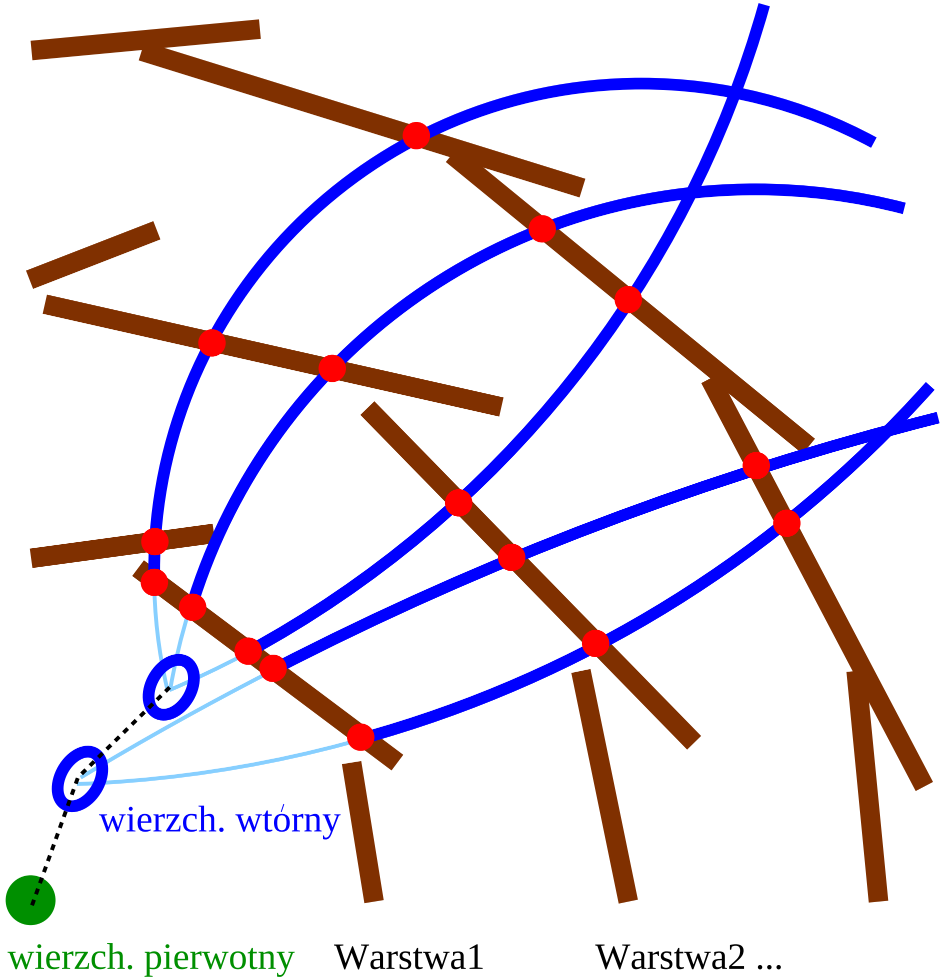
- B Mesons
  - Has finite life time
  - Travels some distance from the vertex before decaying
    - ~ 1mm
    - With charm cascade decay, about 4.2 charged tracks

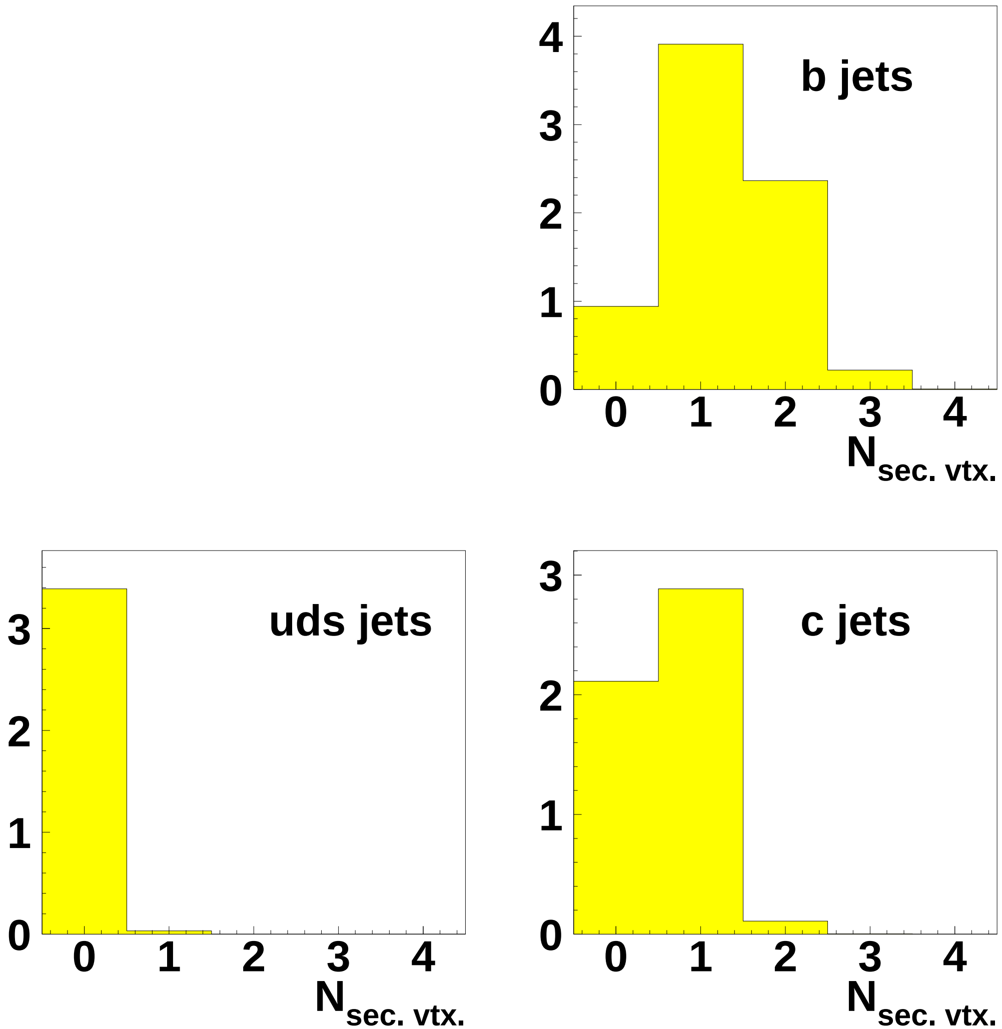
Several algorithms under active development

- Impact Parameter Resolution: $d/\sigma(d)$
- Decay Length Resolution: $L_{xy}/\sigma(L_{xy})$

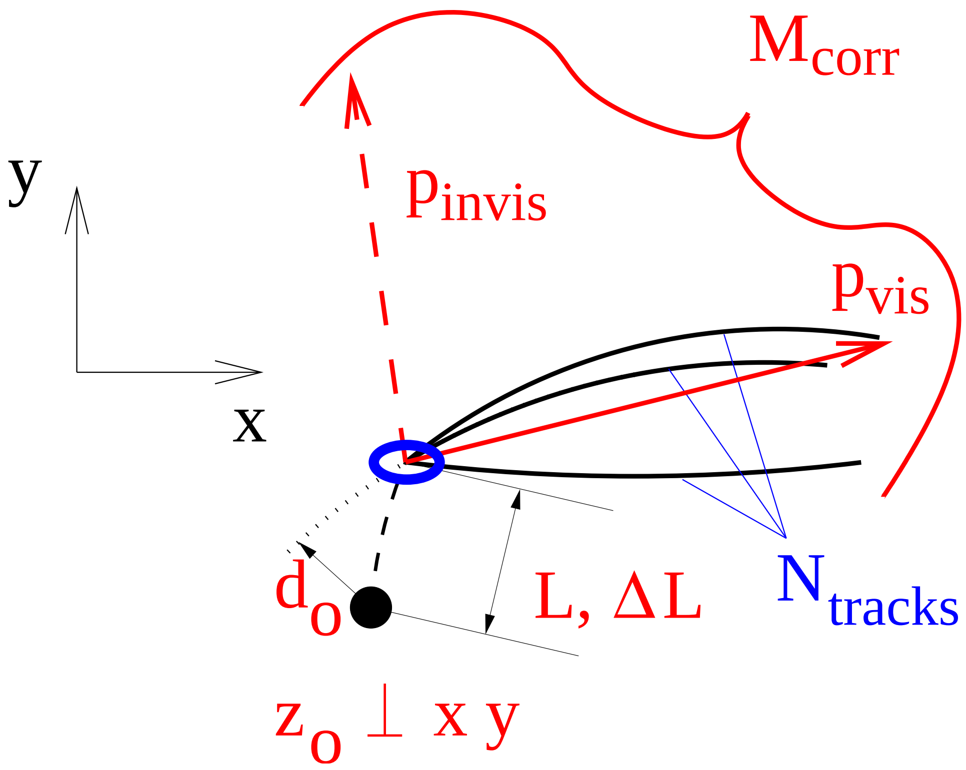
“Jet tagging” - 1

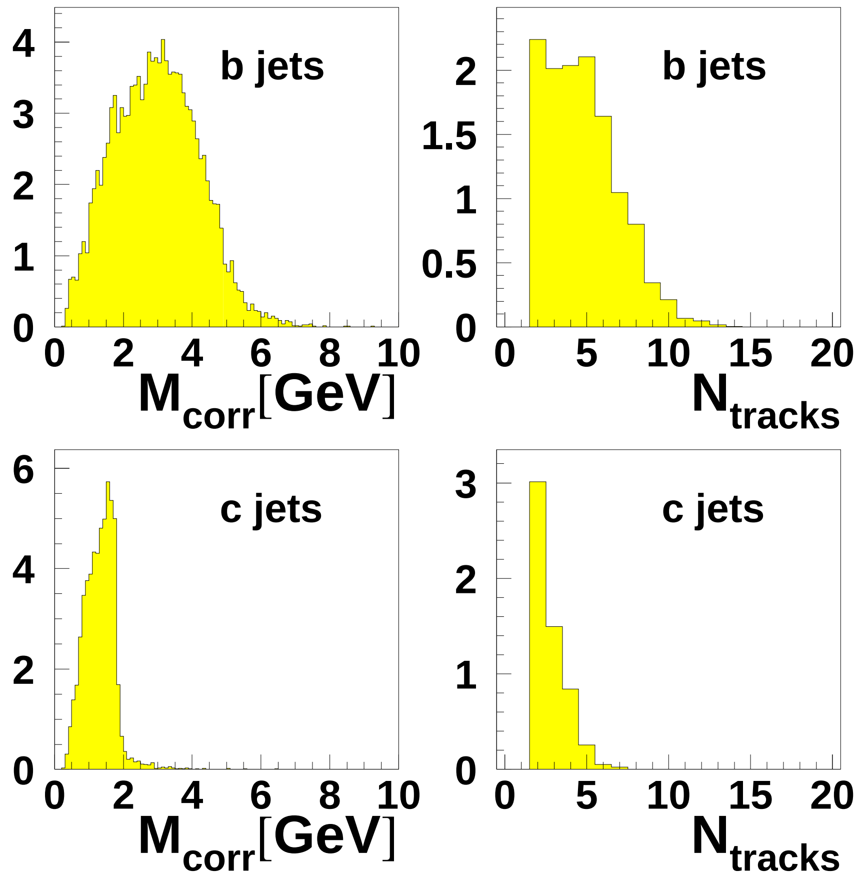
- **Dla każdego dżetu wierzchołki wtórne są wyznaczane za pomocą ZVTOP**





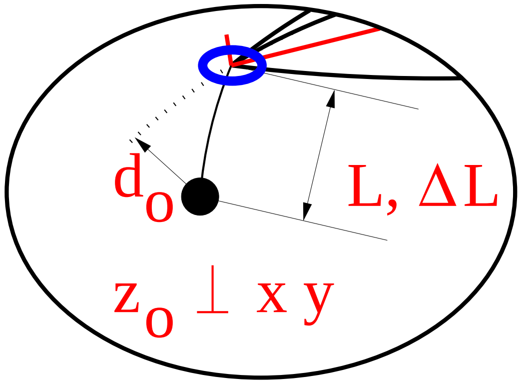
“Jet tagging” - 2

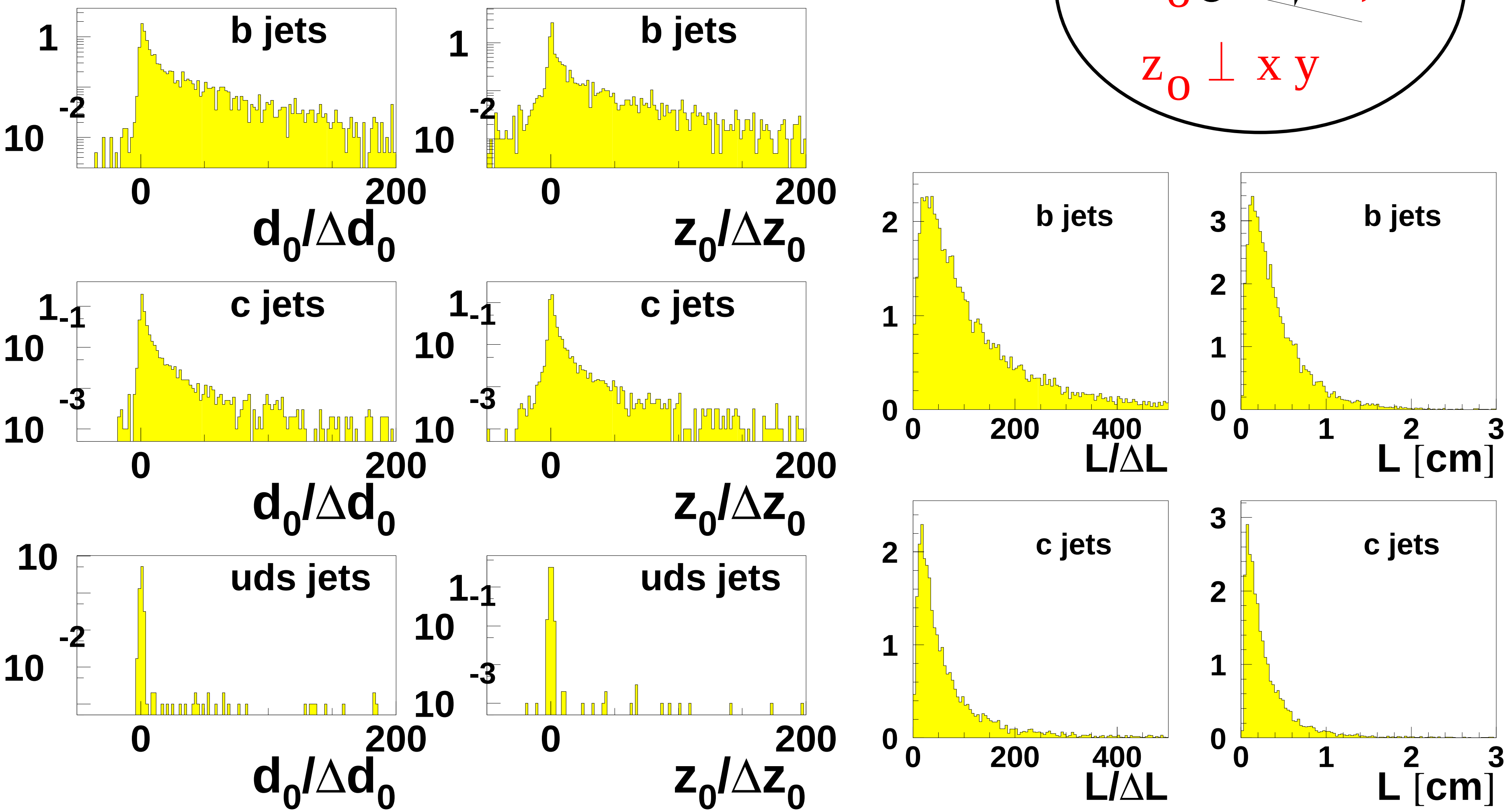




- Dla każdego dżetu **sieć neuronowa** (na podstawie powyższych wielkości) zwraca **b-tag** i **c-tag** $\in (0, 1)$ - wielkości mówiące na ile jet jest podobny do dżetu **“b”** lub **“c”**

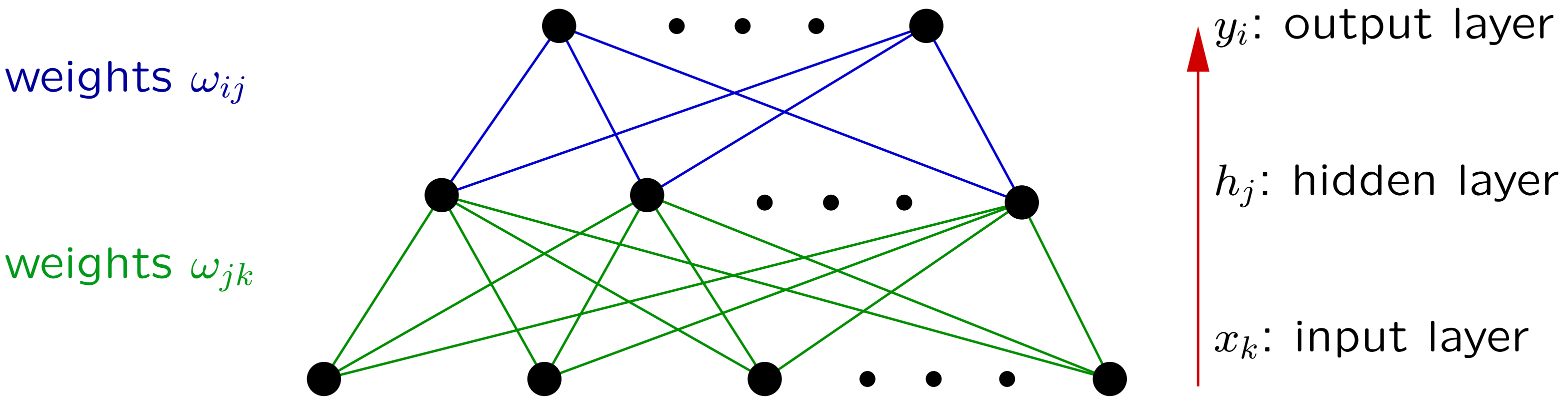
"Jet tagging" - 3





What is a neural network?

Feed-Forward Neural Network

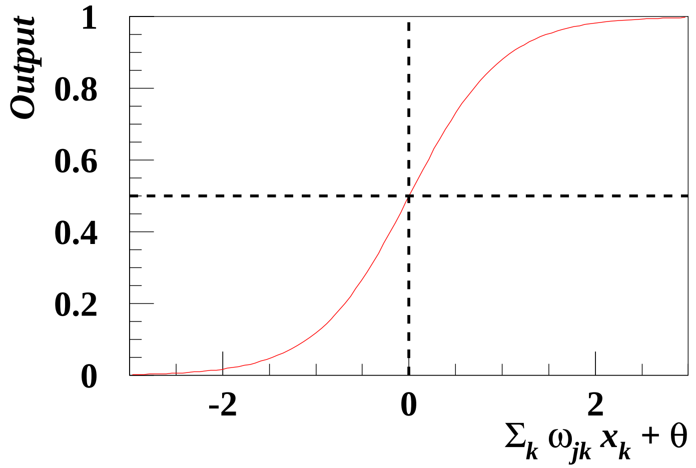


$+$ a threshold θ_j for each neuron

Output of a neuron:

$$O_j = g(\sum_k \omega_{jk}\ x_k + \theta_j)$$

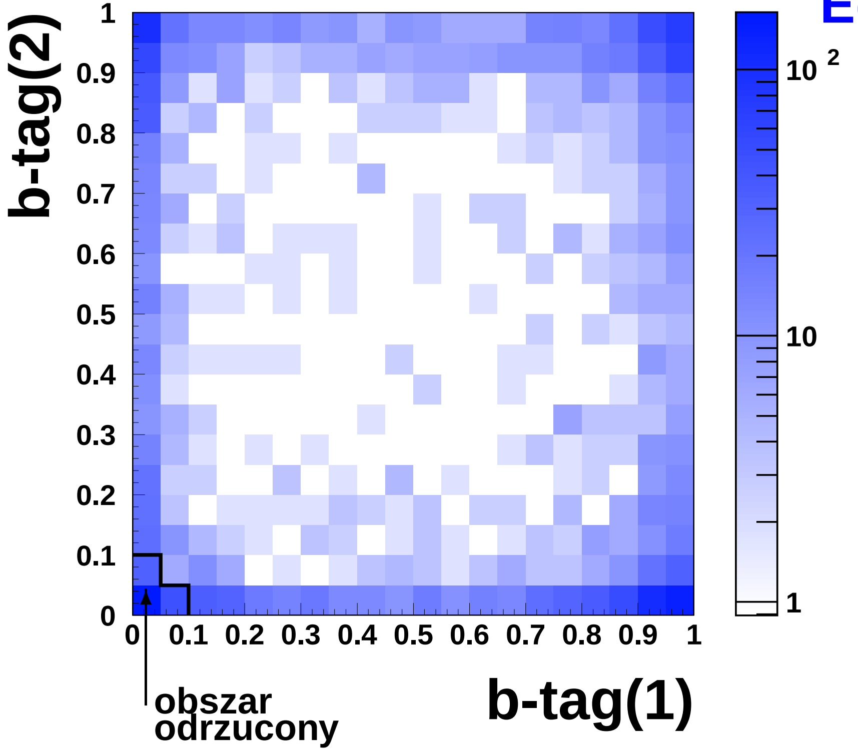
with $g(x) = \frac{1}{1+e^{-2x}}$



Training: adjust weights
$\rightarrow NN_{\text{out}}$ el. ~ 1 and had. ~ 0

b-tag dla h $\rightarrow$ jet(1) jet(2)

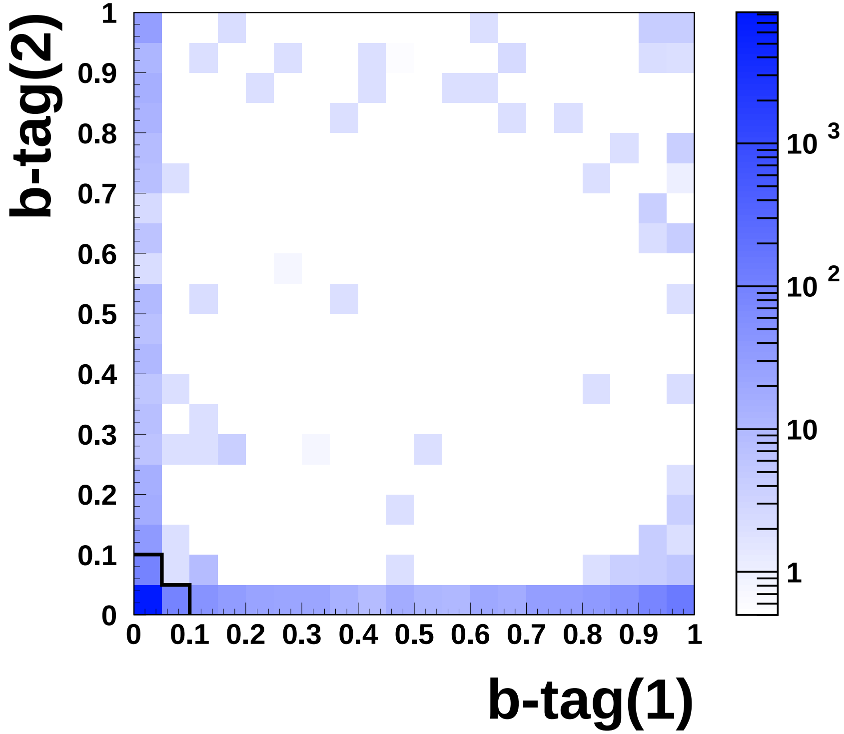
Signal: h$\rightarrow$ b$\bar{\text{b}}$



E(1) $>$ E(2)

500 fb^{-1}

Background



Cięcia optymalizujące $\Delta\Gamma/\Gamma$

Sygnał:	**2414 przypadków**
Tło:	**785 przypadków**

Precyzja pomiaru:

$$\frac{\Delta\Gamma(h \rightarrow b\bar{b})}{\Gamma(h \rightarrow b\bar{b})} = 2.3\%$$

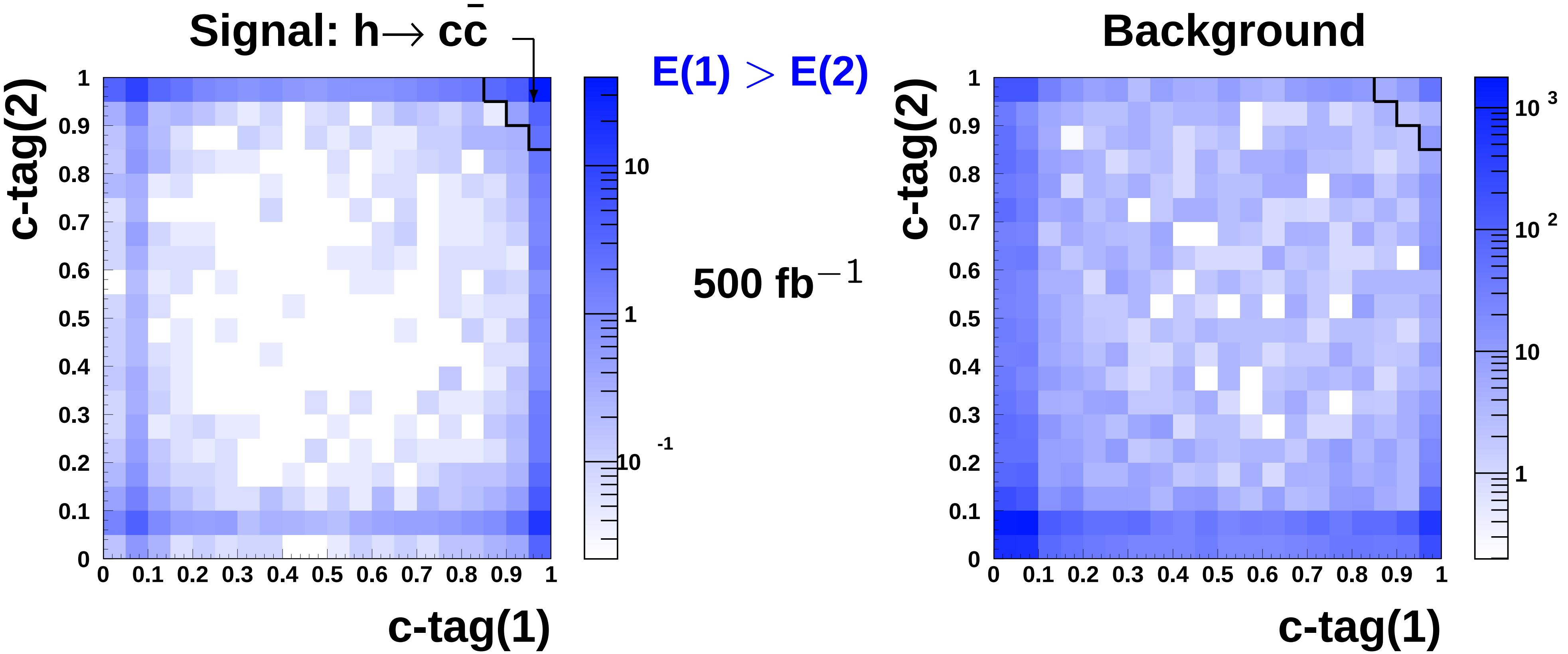
Przykładowe rozkłady dla :

warstwy: 1 - 5

grubość warstwy $50\mu m$

rozdzielczość warstwy $2\mu m$

c-tag dla h $\longrightarrow$ jet(1) jet(2)



Cięcia optymalizujące $\Delta\Gamma/\Gamma$

Sygnał: 42 przypadków

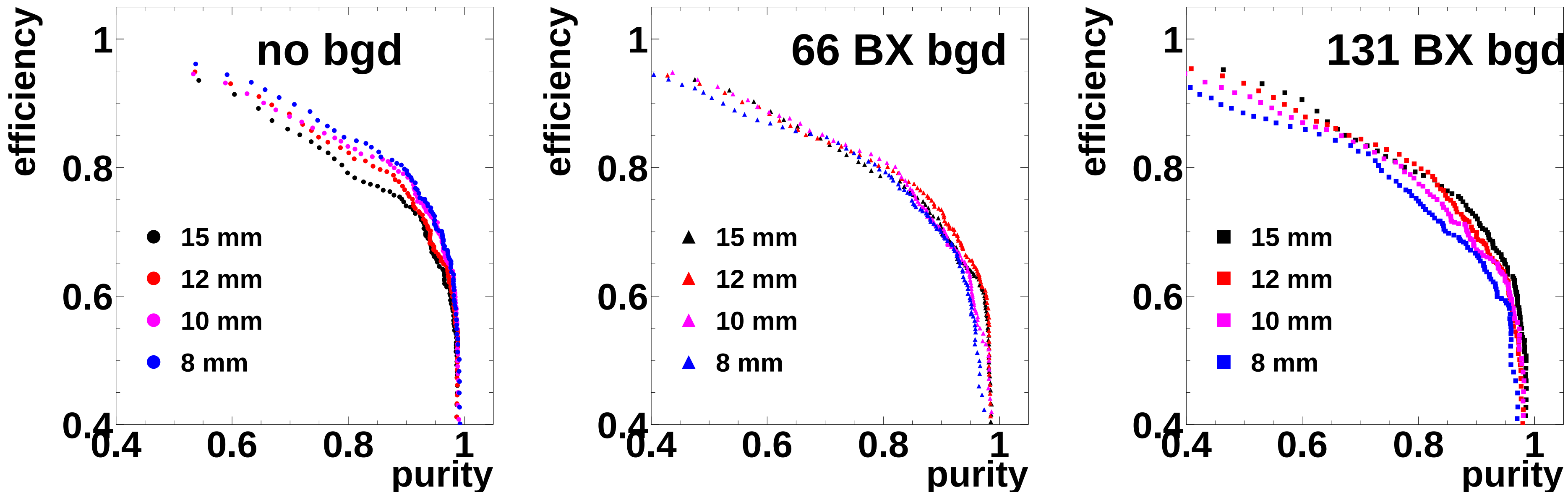
Tło: 79 przypadków

Precyzja pomiaru:

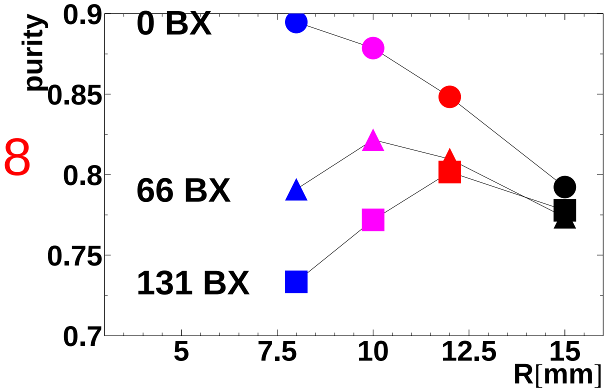
$$\frac{\Delta\Gamma(h \to c\bar{c})}{\Gamma(h \to c\bar{c})} = 26\%$$

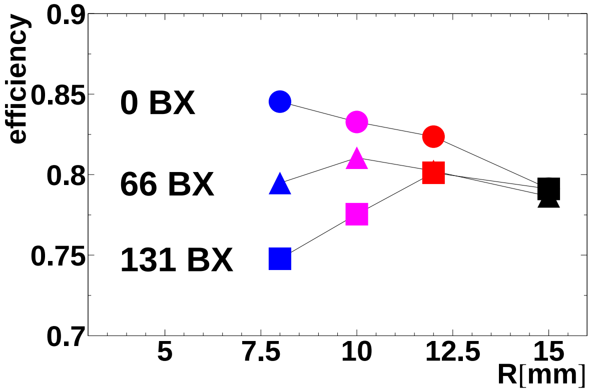
Przykładowe rozkłady dla :
warstwy: 1 - 5
grubość warstwy $50\mu m$
rozdzielczość warstwy $2\mu m$

Wpływ tła na identyfikację kwarków b



Efficiency 0.8



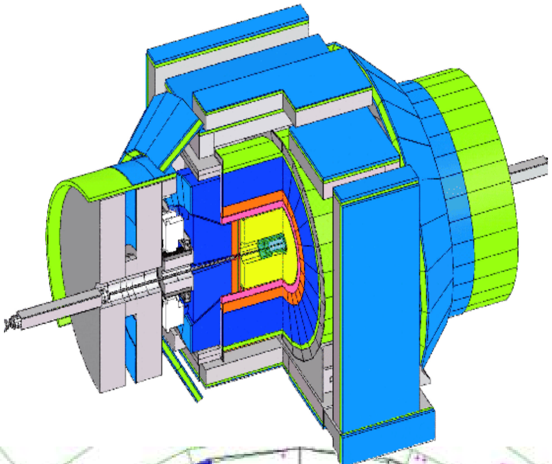


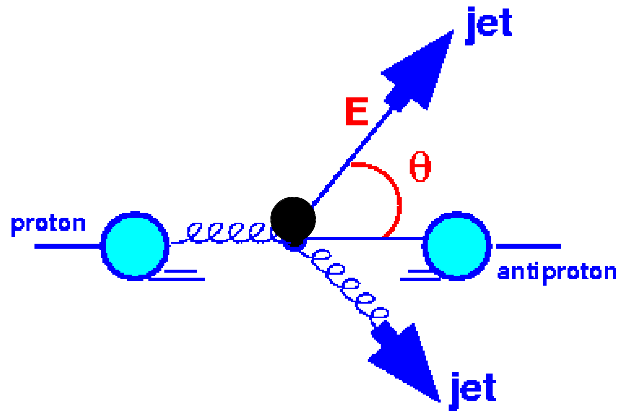
Purity 0.8

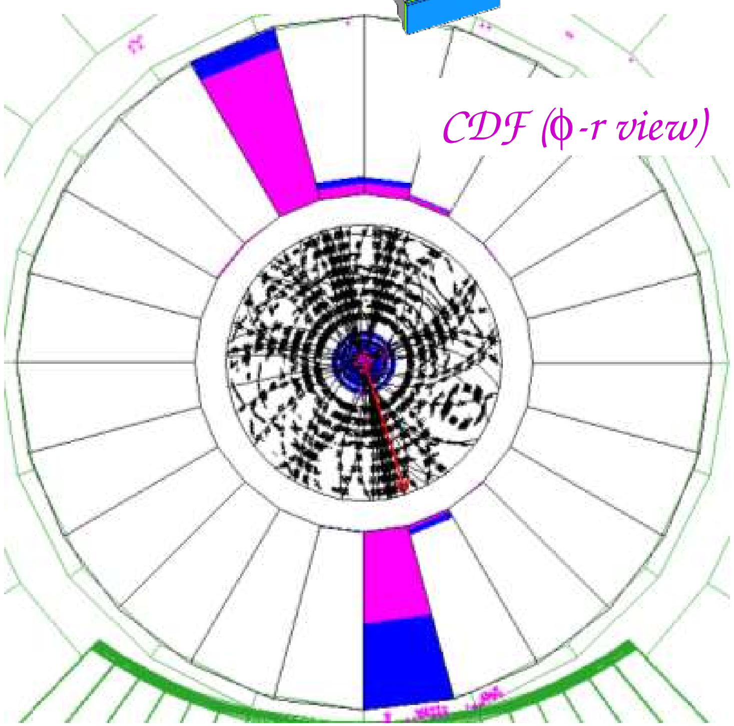
Rekonstrukcja jetów

What do Jets Look Like ?

(the highest P_T jet event from CDF)

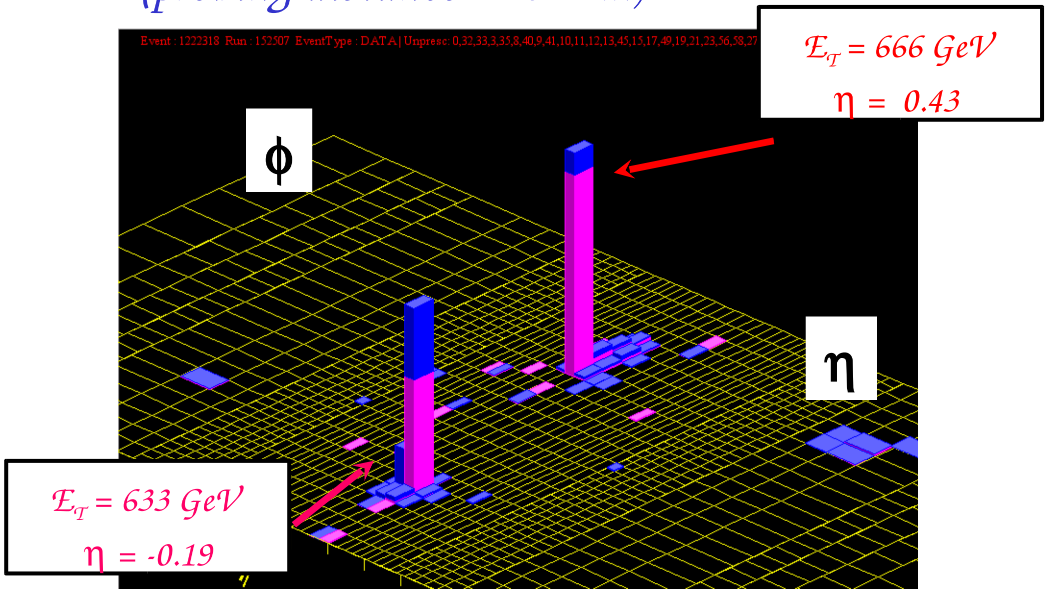






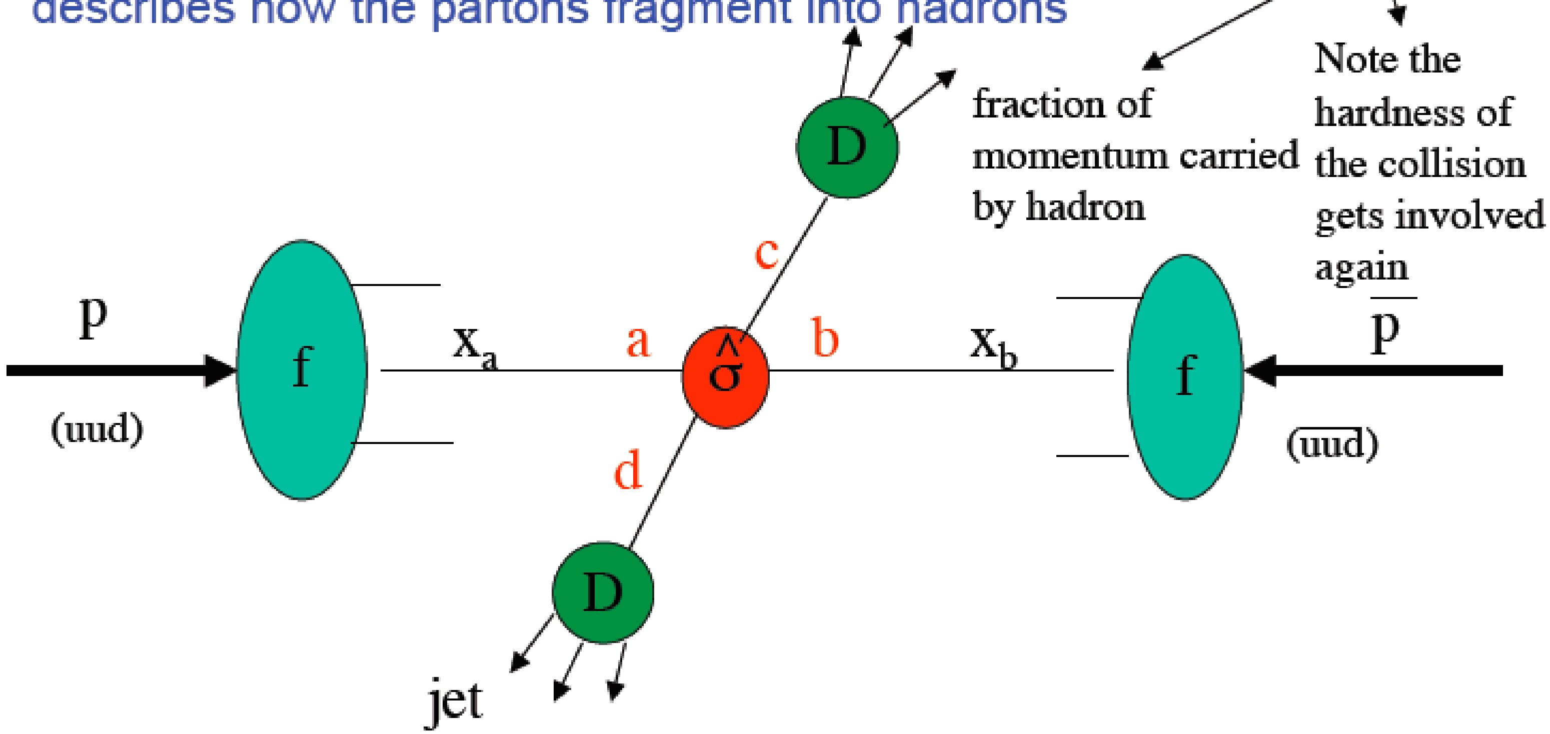
Dijet Mass = 1.36 TeV

(probing distance ~10^{-19} m)



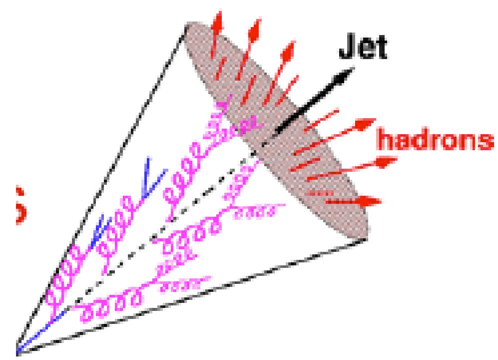
2->2 hard scattering

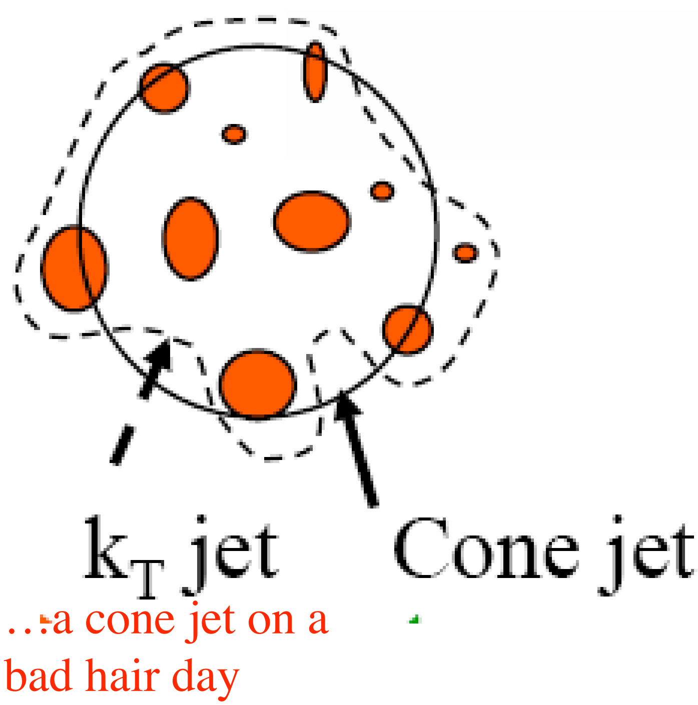
- c and d are the outgoing partons, but problem: they carry color; we don't observe the quarks or gluons themselves (don't see naked color) but instead the partons fragment into jets of hadrons (pions, kaons, and protons)
- it's the jets of hadrons that we can observe experimentally; $D(z,Q^2)$ describes how the partons fragment into hadrons



What is a jet?

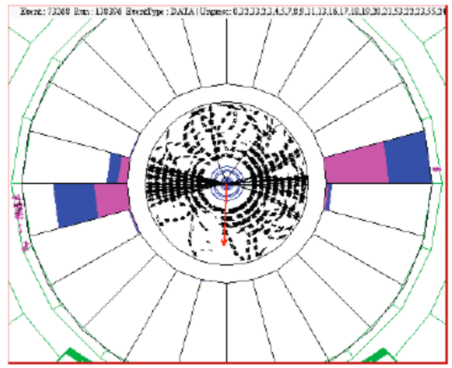
- Jets are the experimental signatures of quarks and gluons
- Jets manifest themselves as localized clusters of energy
- It is the role of the jet algorithm to identify and measure the properties of a jet
- A jet algorithm can either measure
  - closeness in momentum space: k_T algorithm
    - most often used at LEP and HERA
  - closeness in coordinate space: cone algorithm
    - most often used at the Tevatron
  - at the LHC, hopefully both will be equally used
- Can apply these jet algorithms to calorimeter towers or particles or partons…and would like to get a similar answers, as much as possible

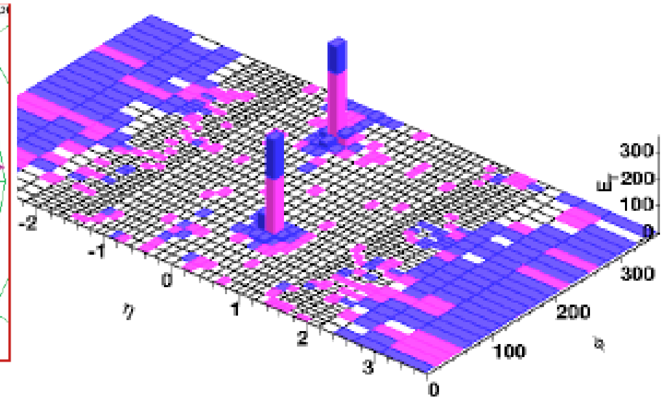


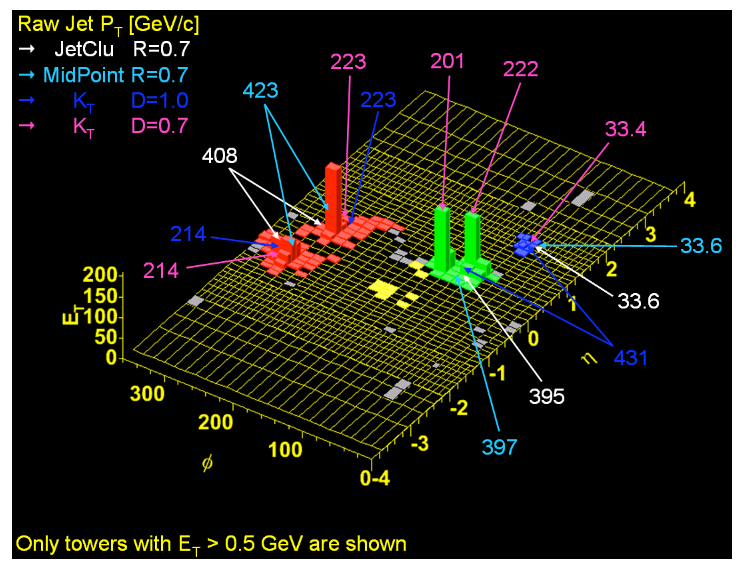


Jet algorithms

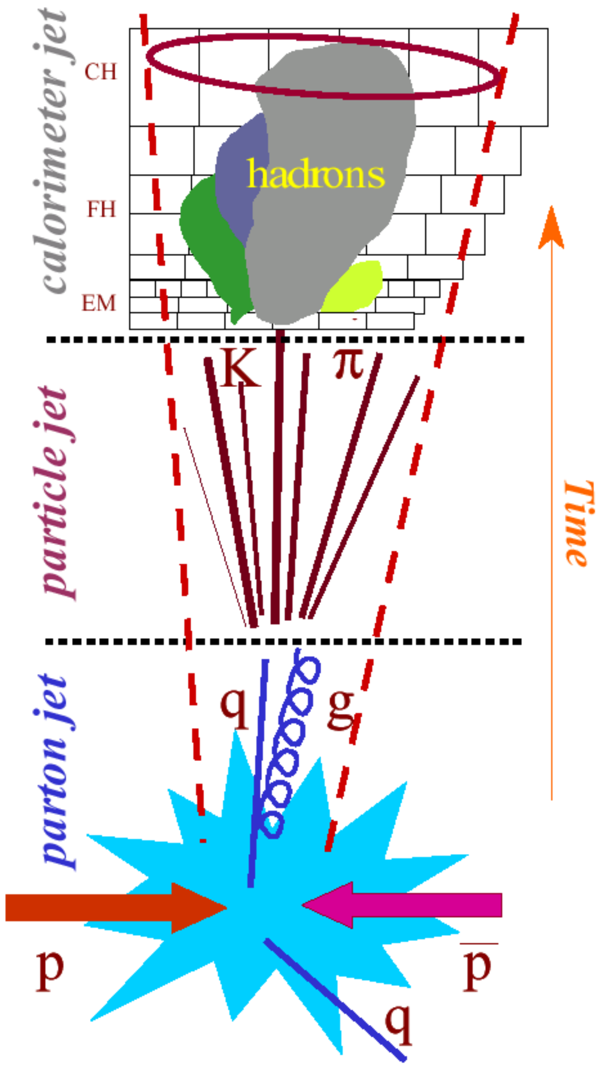
- For some events, the jet structure is very clear and there's little ambiguity about the assignment of towers/particles to the jet
- But for other events, there is ambiguity and the jet algorithm must make decisions that impact precision measurements
- If comparison is to hadron-level Monte Carlo, then hope is that the Monte Carlo will reproduce all of the physics present in the data and influence of jet algorithms can be understood
    - more difficulty when comparing to parton level calculations







Jet Finding



- Calorimeter jet (cone)
  - jet is a collection of energy deposits with a given cone *R*: $R = \sqrt{\Delta\varphi^2 + \Delta\eta^2}$
  - cone direction maximizes the total E_T of the jet
  - various clustering algorithms

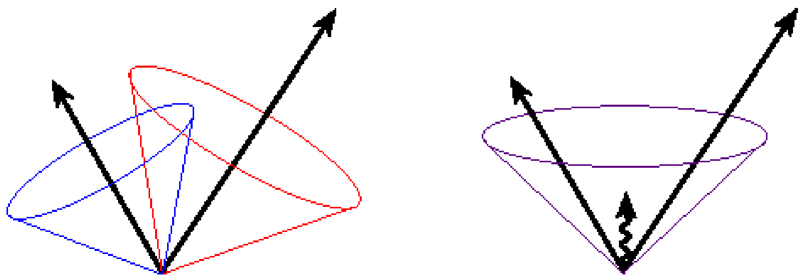
→ correct for finite energy resolution
→ subtract underlying event
→ add out of cone energy

- Particle jet
  - a spread of particles running roughly in the same direction as the parton after hadronization

Jet Algorithms: Cone

- **Cone algorithms**
  - **draw a cone of fixed size around a seed**
  - **compute jet axis**
  - **draw a new cone around the new jet axis and recalculate axis and new E_T**
  - **iterate until stable**

  →In addition:
  - **add additional midpoint seeds between pairs of close jets**
  - **split/merge after stable proto-jets found**



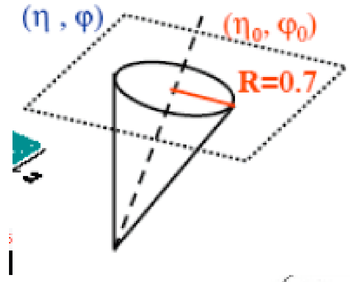
Midpoint cone algorithm

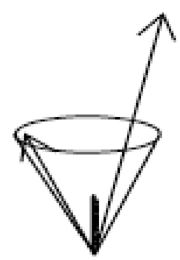
- Generate p_T ordered list of towers (or particles/partons)
- Find proto-jets around seed towers (typically 1 GeV) with p_T>threshold (typically 100 MeV)
  - include tower k in cone if

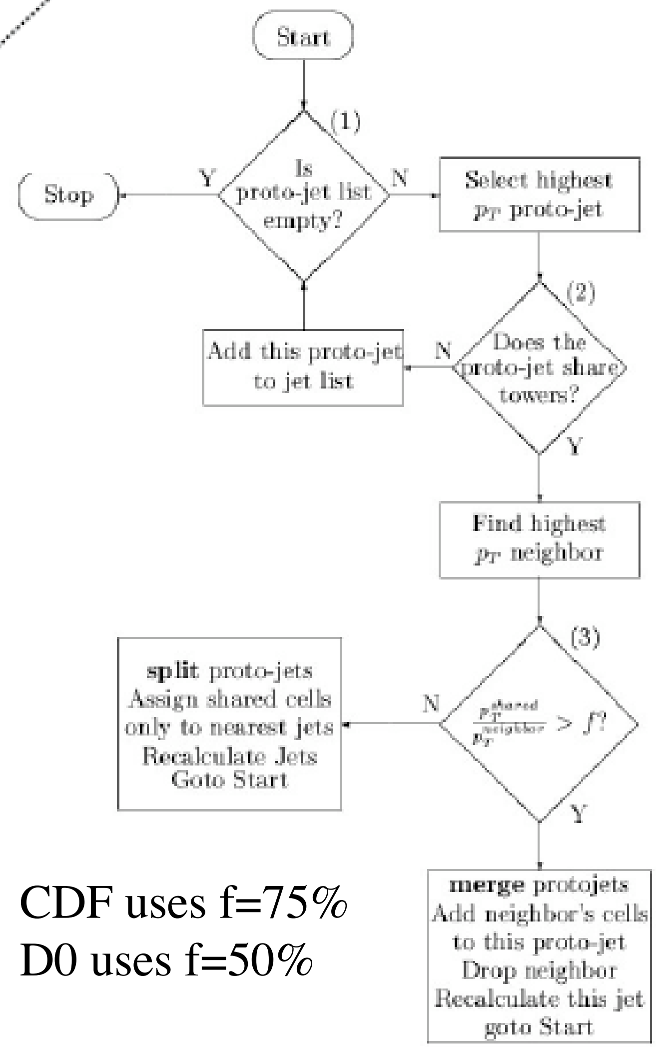
$$k \subset C \text{ iff } \sqrt{(y_k - y_C)^2 + (\phi_k - \phi_C)^2} \le R_{cone},$$

$$p_C = (E_C, \vec{p}_C) = \sum_{k \subset C} (E_k, \vec{p_k}),\ \ \overline{y}_C \equiv \frac{1}{2}\ln\frac{E_C + p_{z,C}}{E_C - p_{z,C}},\ \ \overline{\phi}_C \equiv \tan^{-1}\frac{p_{y,C}}{p_{x,C}}$$

  - iterate if $(\overline{y}_C, \overline{\phi}_C) \neq (y_C, \phi_C)$
  - NB: use of seeds creates IR-sensitivity
- Generate midpoint list from proto-jets
  - using midpoints as seed positions reduces IR-sensitivity
- Find proto-jets around midpoints
- Go to splitting/merging stage
  - real jets have spatial extent and can overlap; have to decide whether to merge the jets or to split them
- Calculate kinematics (p_T,y,ϕ) from final stable cones







CDF uses f=75%
D0 uses f=50%

Jet Algorithms: k_T

For each object and pair of objects:

$$d_{ii} = k_{T,i}^2$$

$$d_{ij} = \min(k_{T,i}^2, k_{T,j}^2)\frac{\Delta R_{ij}^2}{D^2}$$

Soft — $\min(k_{T,i}^2, k_{T,j}^2)$

Collinear (if $\Delta R << 1$) — ΔR_{ij}^2

Resolution parameter (D=1) — D^2

order all d_{ii} and d_{ij}:

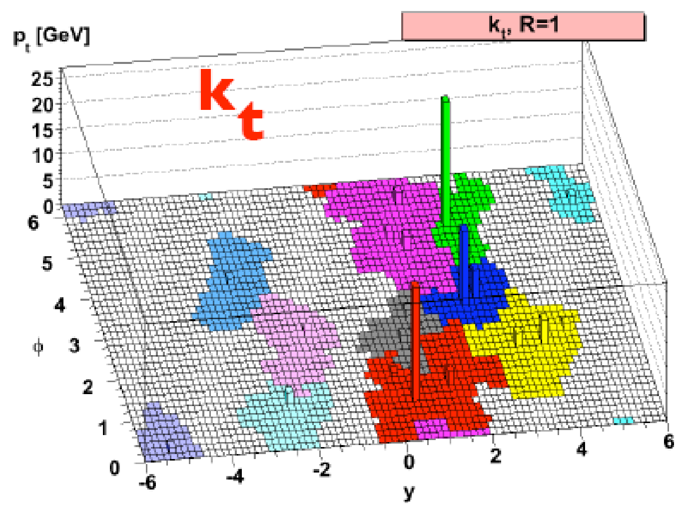
If $d_{min} = d_{ij}$

$\Rightarrow$ merge particles

If $d_{min} = d_{ii}$

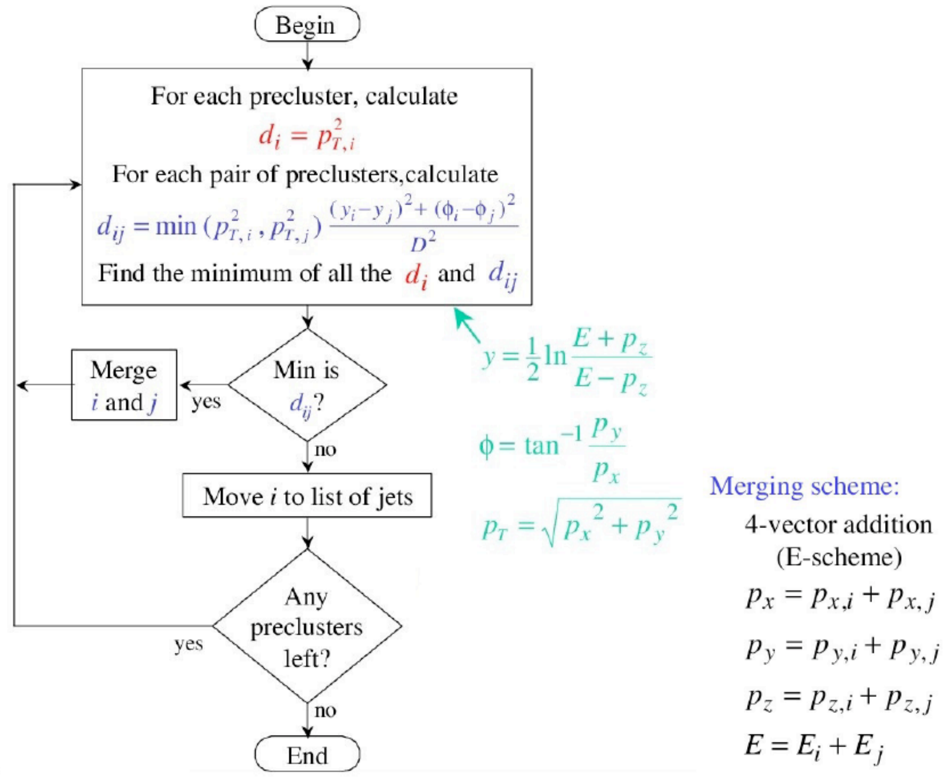
$\Rightarrow$ jet

- **theoretically favored, no split-merge**
- **to reduce computation time, start with 0.2 x 0.2 pre-clusters**



k_T algorithm

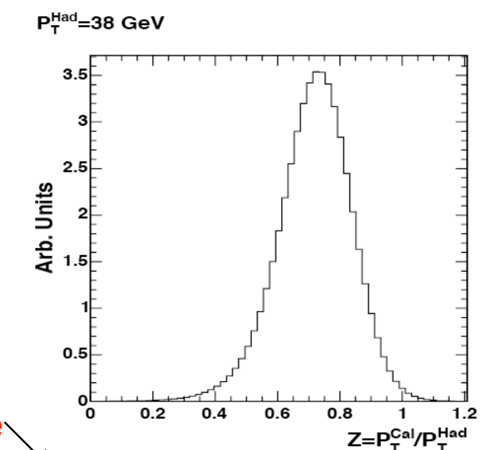
- The k_T jet algorithm successively merges pairs of partons, particles or calorimeter towers in order of increasing relative transverse momentum
- The algorithm typically contains a parameter D that controls the termination of the merging and characterizes the approximate size of the resulting jets
- Since the k_T algorithm fundamentally merges nearby particles,there is a correspondence of jets reconstructed in a calorimeter to jets reconstructed from individual hadrons, leptons, and photons
- As the jet does not have a fixed area, the underlying event subtraction is more problematic

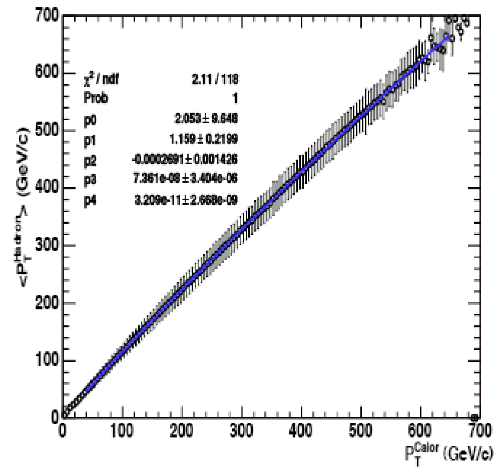


Rekonstrukcja energi jetów

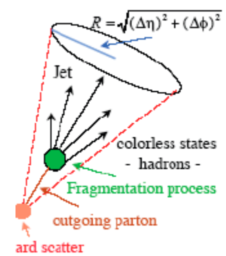
Jet Corrections

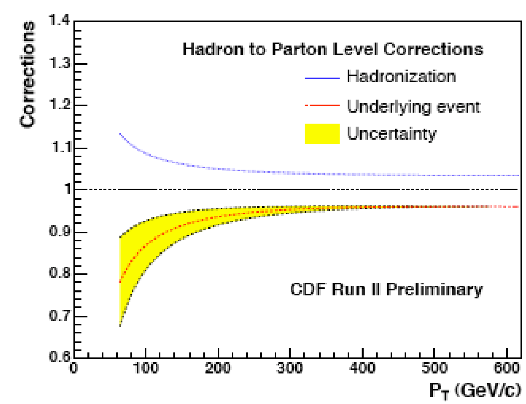
- Need to correct from calorimeter to hadron level (different response of calorimeter to EM and HAD energy)
  - and for resolution effects
- And from hadron to parton level for other observables (such as comparisons to parton level cross sections)
  - underlying event and out-of-cone
    - can correct data to parton level or theory to hadron level…or both and be specific about what the corrections are
  - note that loss due to hadronization is basically constant at 1 GeV/c for all jet p_T values at the Tevatron (for a cone of radius 0.7)
    - for a cone radius of 0.4, the two effects cancel to within a few percent
  - interesting to check over the jet range at the LHC

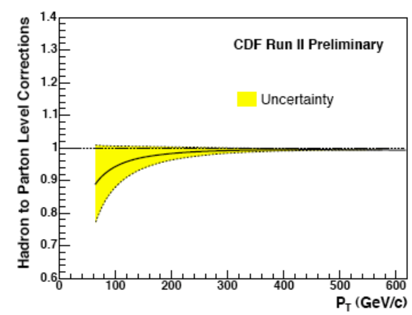




partons in cone give rise to hadrons outside the cone







for cone of 0.7, UE correction wins

Response correction

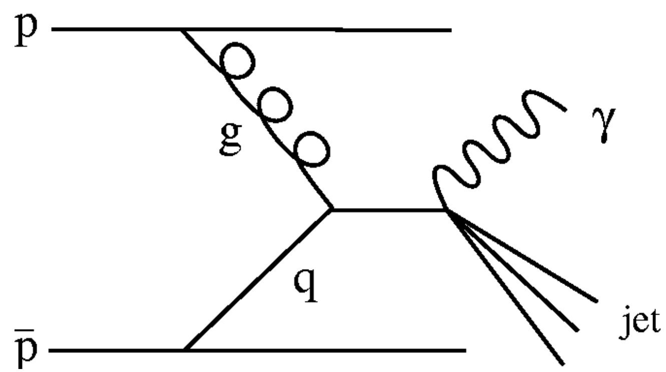
One possibility:

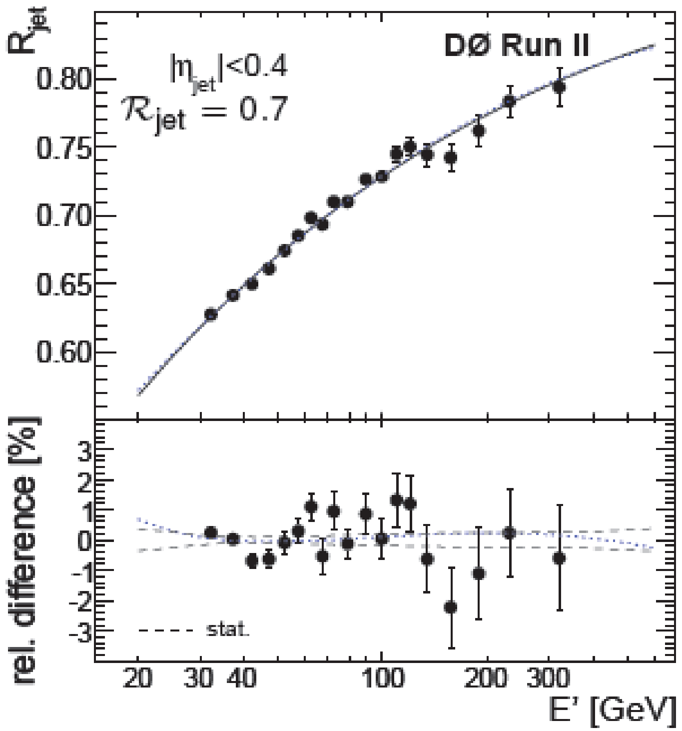
use γ+jet events

-γ well measured and calibrated

- missing transverse energy projection:

$$R_{\text{had}} = 1 + \frac{\vec{E}_T \cdot \vec{p}_{T,\gamma}}{\vec{p}^{\,2}_{T,\gamma}}$$





The 25% correction to the response is the largest of all energy scale contributions

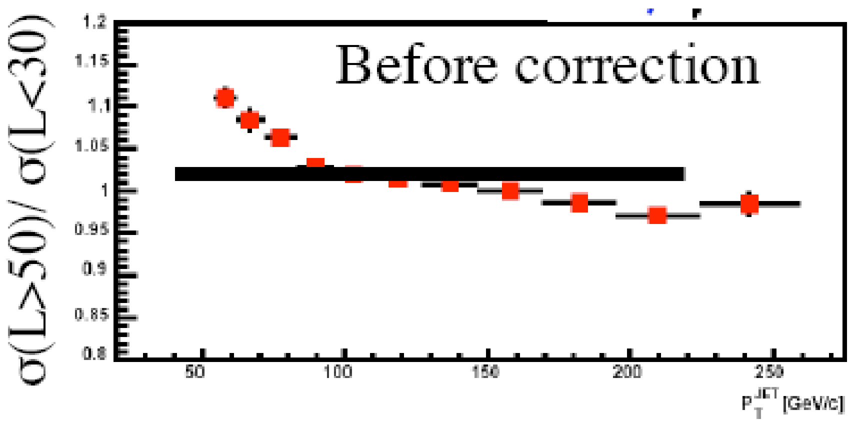
JES for k_T algorithm

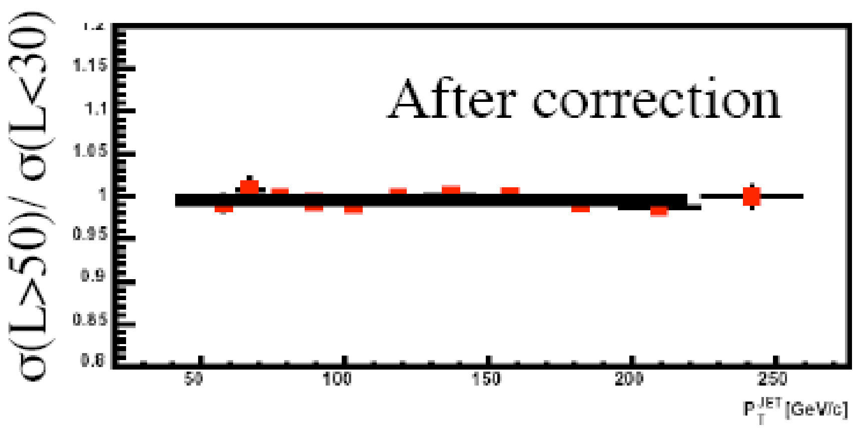
Problem of k_T algorithm in hadron colliders: Multiple interactions

•k_T algorithm is attracted to energy deposits and picks up the energy from MI, UE etc<.

• k_T algorithm has now been used by CDF to measure a cross-section for Run2:

• emiprical energy correction factor used using the fact that the cross-section is luminosity independent



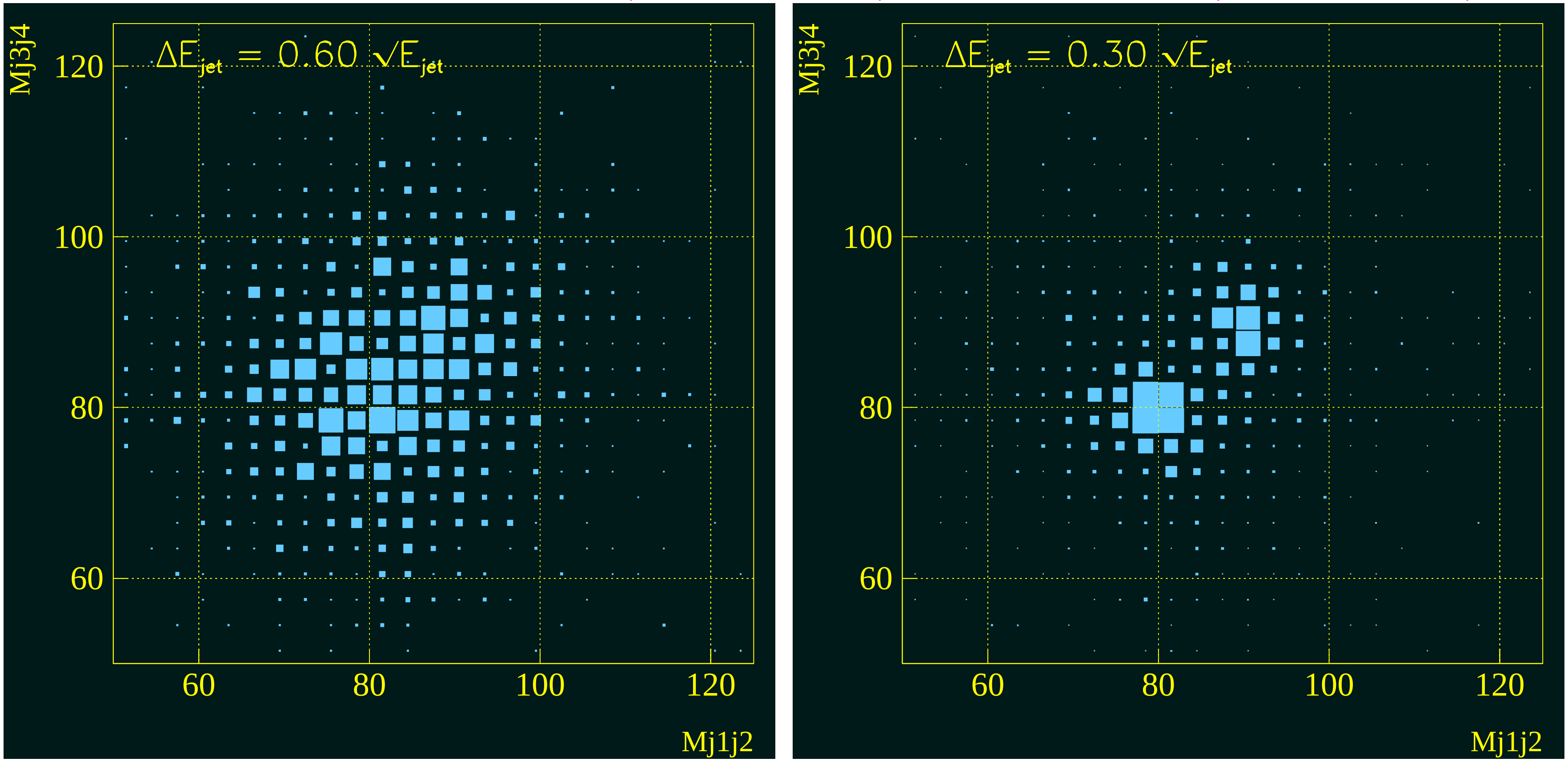


Rekonstrukcja obiektów

Energy flow in jets

- Some processes where WW and ZZ need to be separated without beam constraints (e.g. $e^+e^- \rightarrow \nu\nu WW$, $\nu\nu ZZ$)
- This requires a resolution of about $\Delta E/E = 30\%/\sqrt{E}$

WW-ZZ separation for $\Delta E/E = 60\%/\sqrt{E}$ and $\Delta E/E = 30\%/\sqrt{E}$



Jet Reconstruction @ ILC

- Q. How to achieve the best attainable jet energy resolution?

- A. Since the momentum resolution for the charged particle measured by trackers is much better than the energy resolution of calorimeters, the best energy resolution is obtained by reconstructing momenta of individual particles avoiding double counting among Trackers and Calorimeters.
  - Charged particles (~60%) measured by Tracker.
  - Photons (~30%) by electromagnetic CAL (ECAL).
  - Neutral hadrons (~10%) by ECAL + hadron CAL (HCAL).

$$E_{TOT} = \underbrace{p_e + p_\mu + p_{charged\ hadron}}_{\text{[tracks only]}} + \underbrace{E_\gamma + E_{neutral\ hadron}}_{\text{[calorimeter only]}}$$

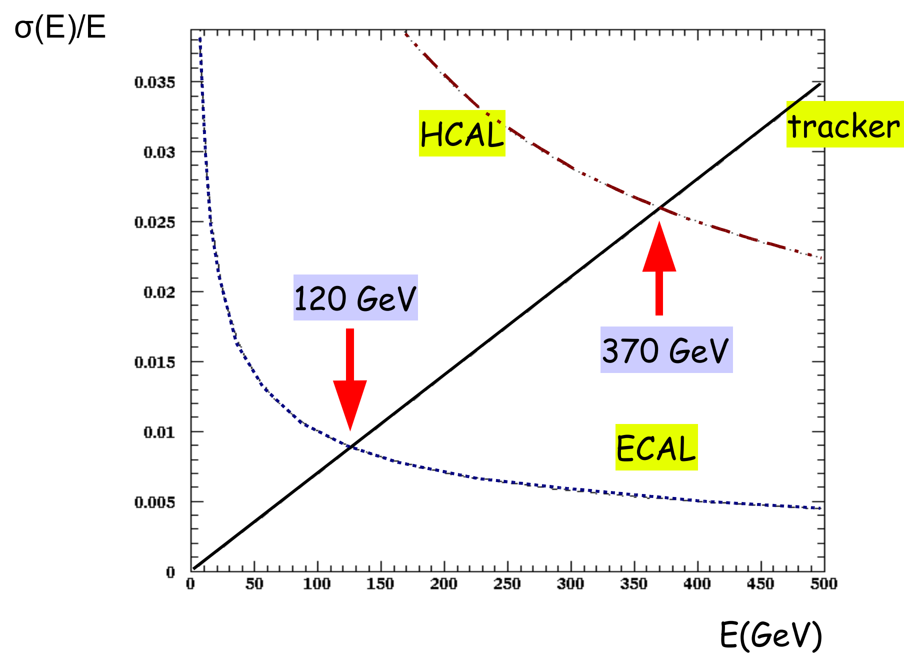
Particle Flow Algorithm (PFA)

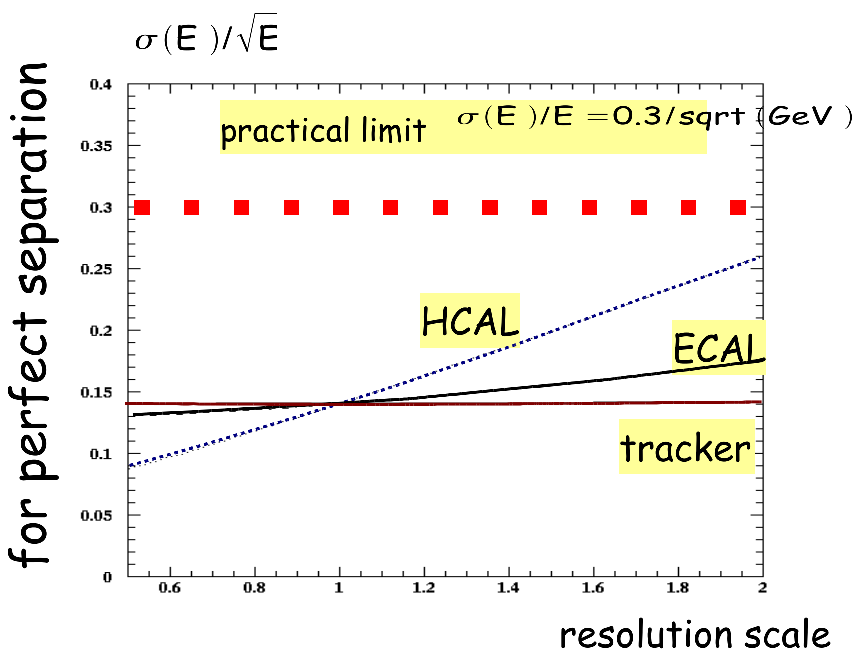
Particle Flow: Basics

$$\sigma(Jet) = \sqrt{\sum \epsilon_T^2 E_i^4 + \sum \epsilon_{ECAL}^2 E_i + \sum \epsilon_{HCAL}^2 E_i}$$

Resolution is dominated by HCAL and by "confusion" term

Resolution tracker - Calorimeter

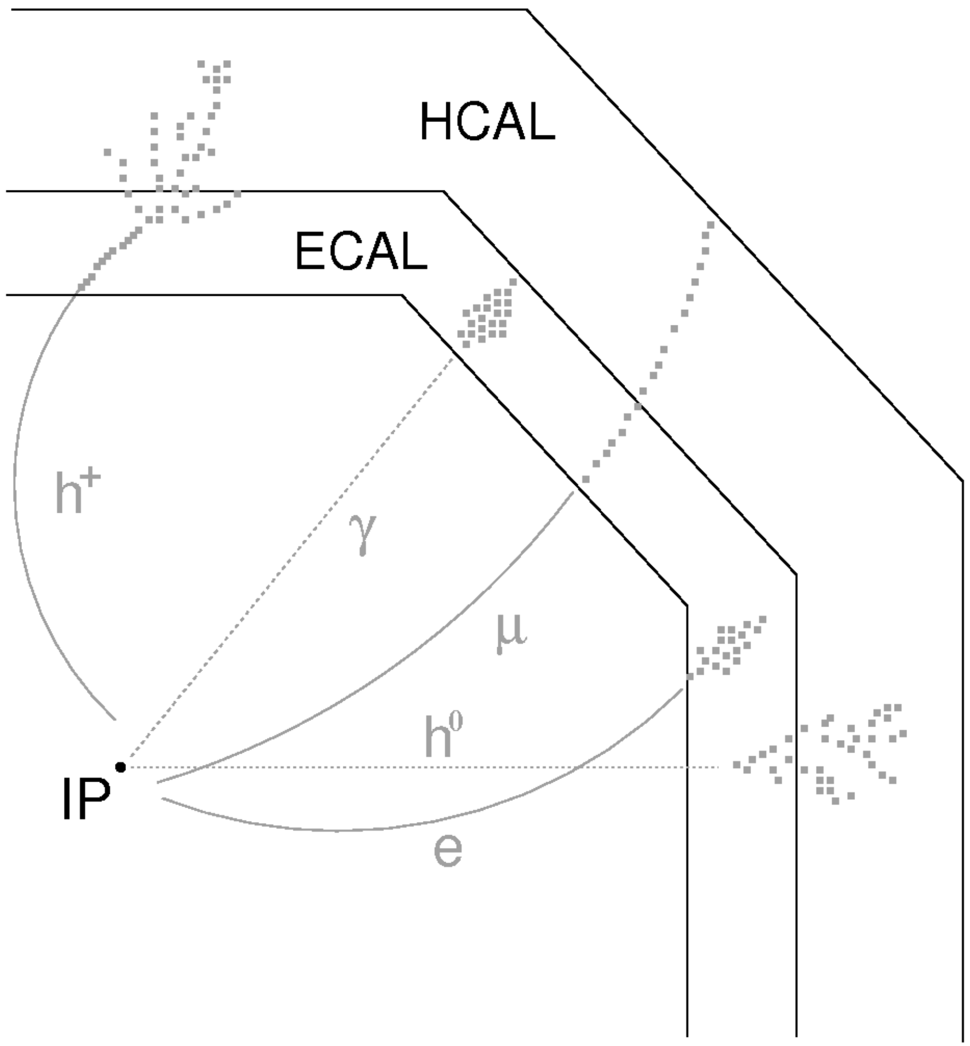




Effect of changing the resolutions by a scale factor

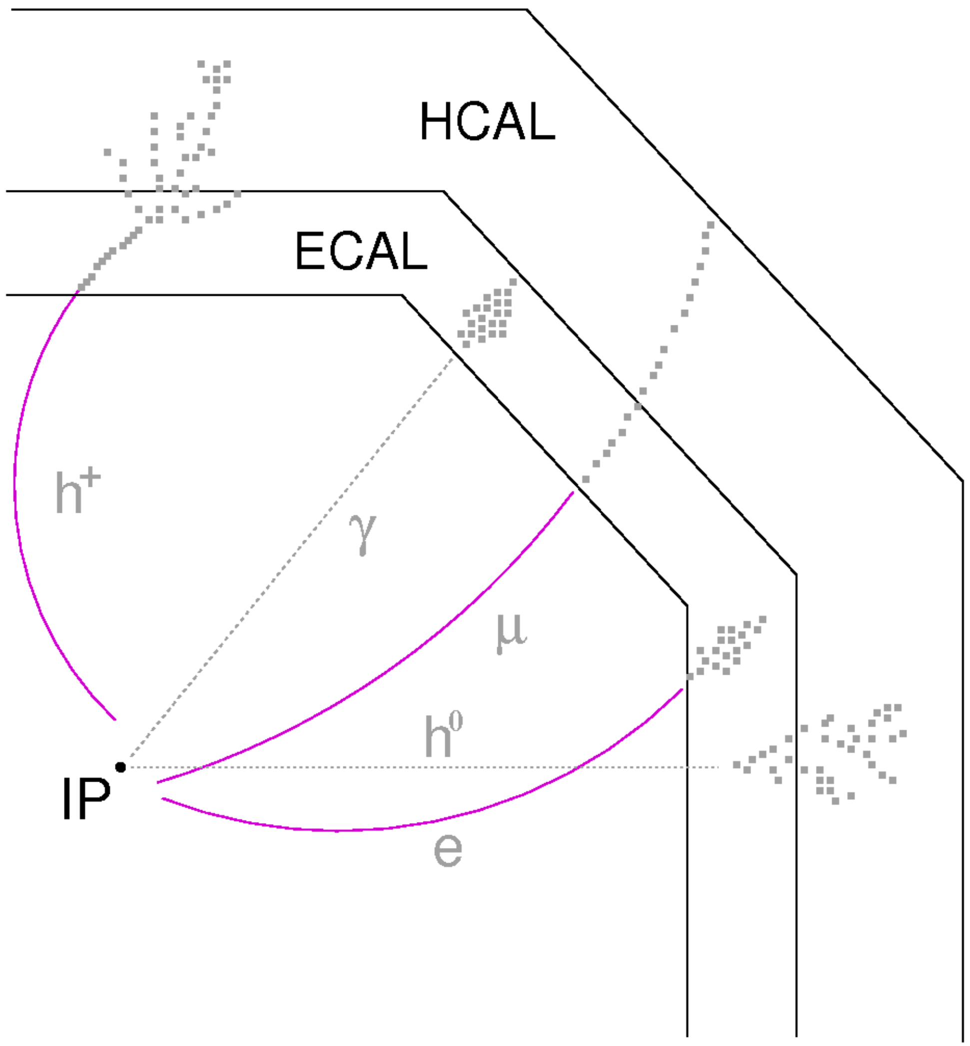
design detector to
- minimize confusion term
- minimize the role of the HCAL
- for the rest: build the best HCAL possible

Track-Based Particle Flow Concept



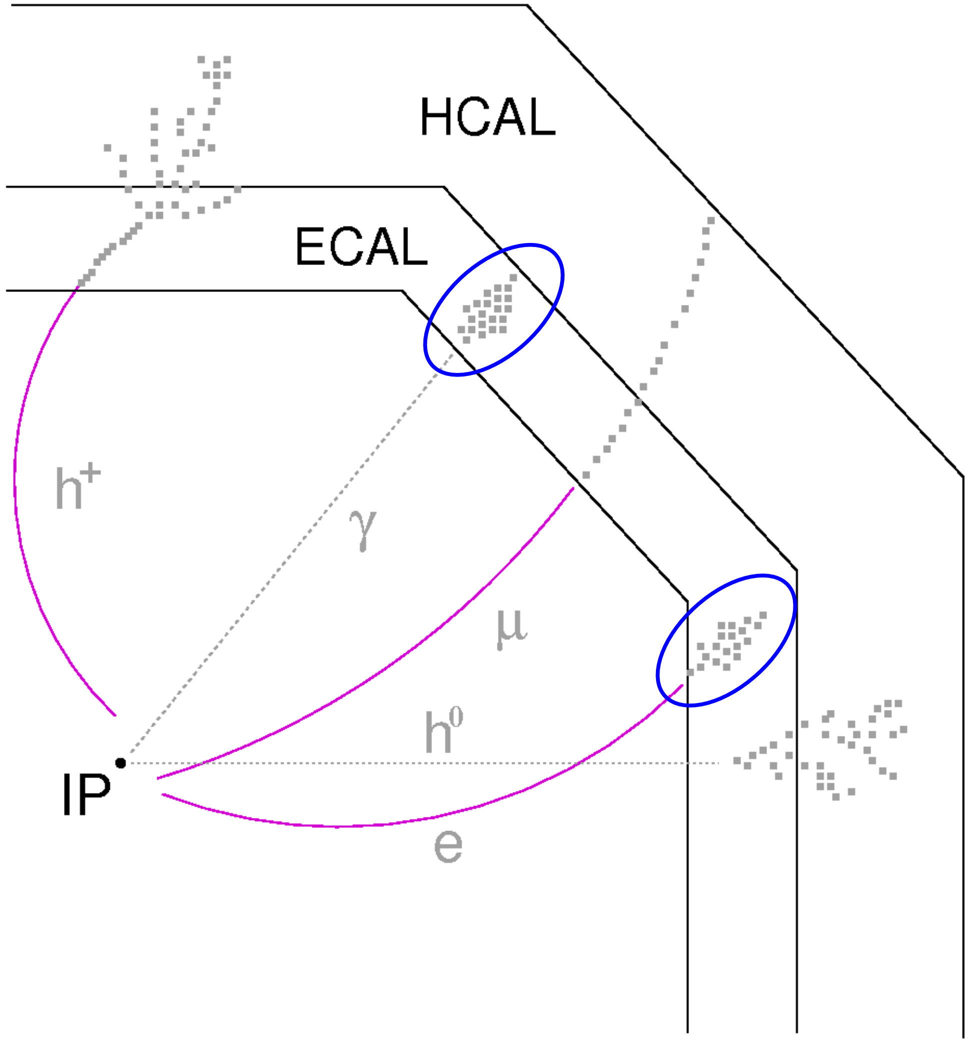
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)



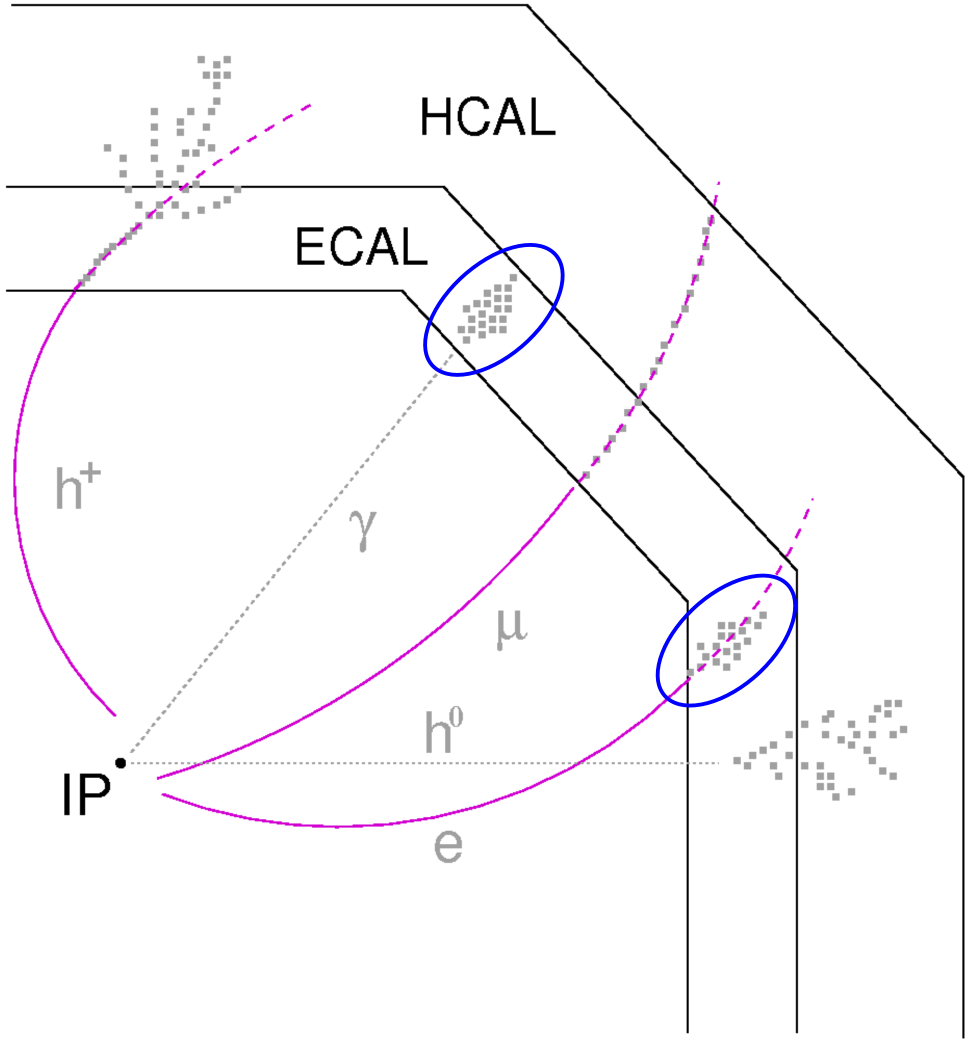
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)
2. find photon candidates



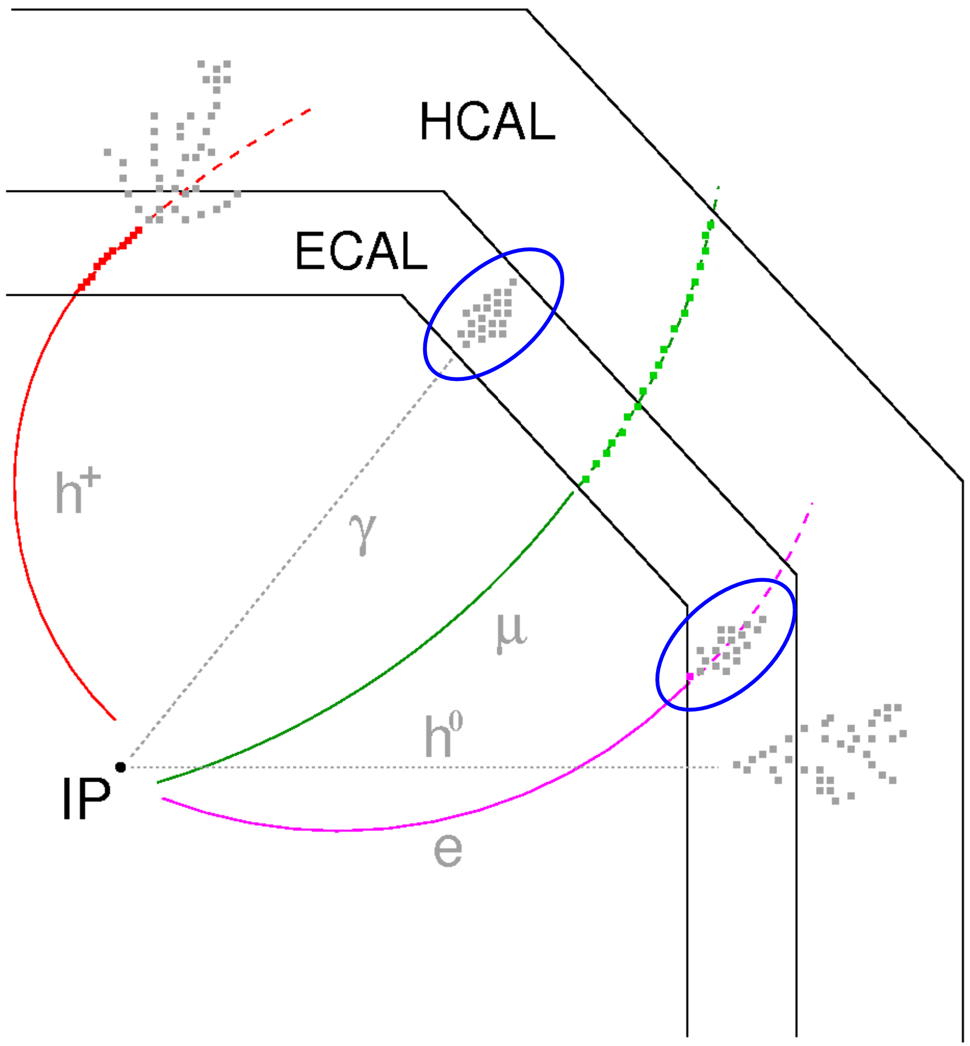
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)
2. find photon candidates
3. extrapolate tracks into Calorimeter
   - different models, with and w/o energy loss, multiple scattering, ...
   - dedicated Geometry description needed



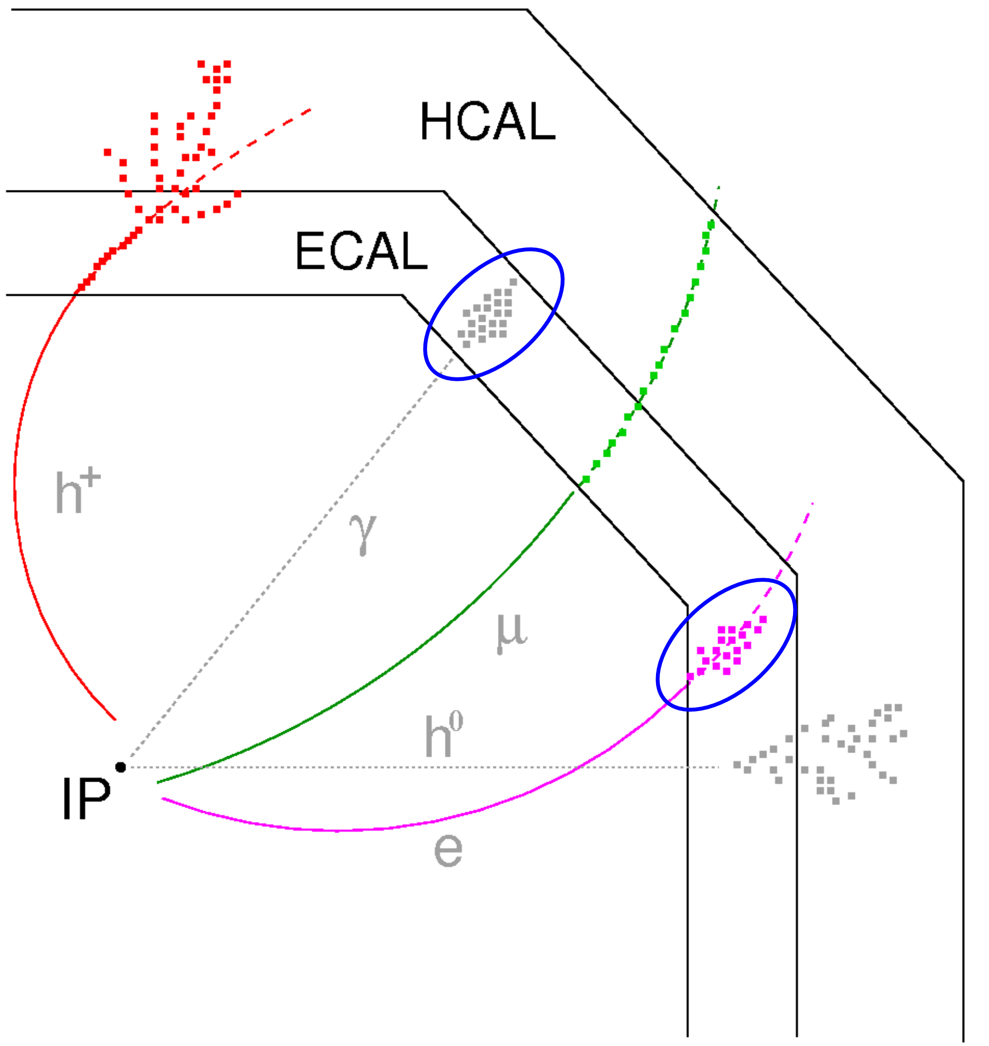
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)
2. find photon candidates
3. extrapolate tracks into Calorimeter
   - different models, with and w/o energy loss, multiple scattering, ...
   - dedicated Geometry description needed
4. assign MIP stub to track, find muons



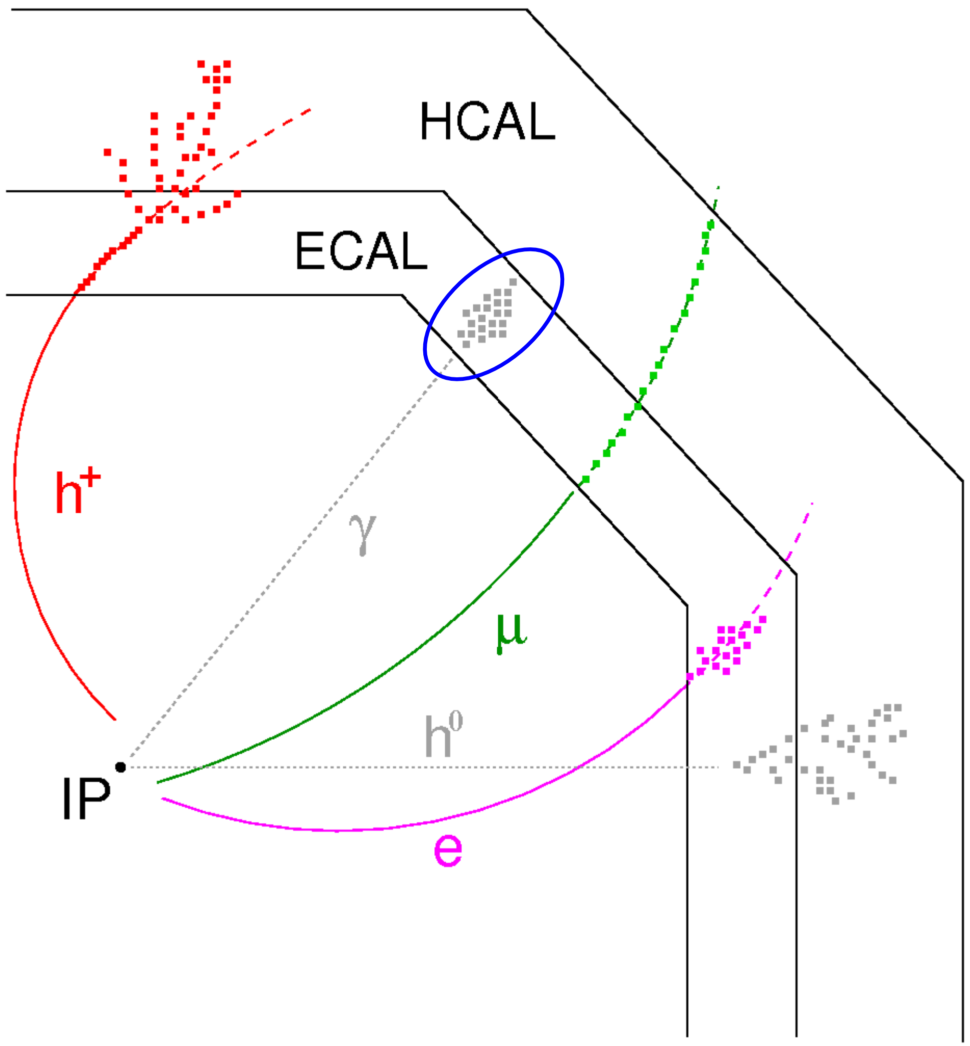
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)
2. find photon candidates
3. extrapolate tracks into Calorimeter
   - different models, with and w/o energy loss, multiple scattering, ...
   - dedicated Geometry description needed
4. assign MIP stub to track, find muons
5. clustering (ECAL and HCAL)
   - variable, depending on track and photon candidates
   - different algorithms



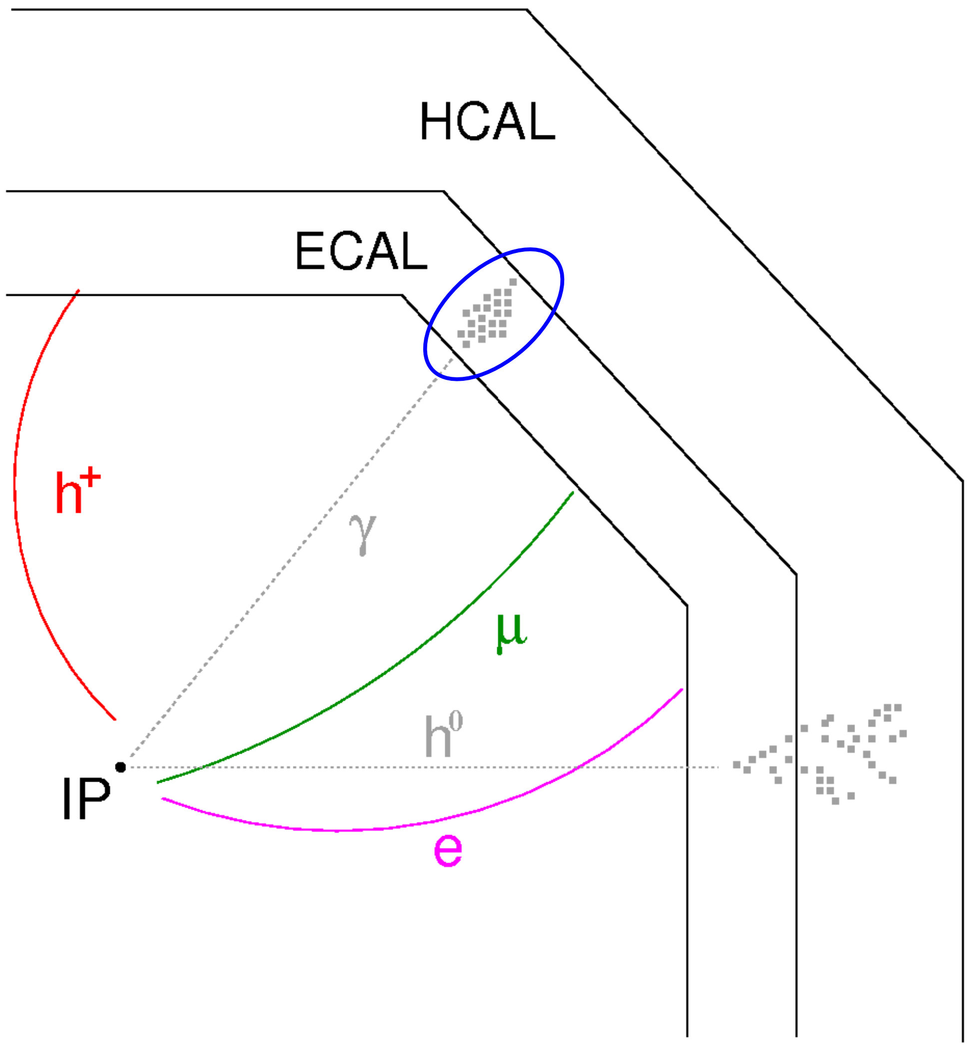
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)
2. find photon candidates
3. extrapolate tracks into Calorimeter
   - different models, with and w/o energy loss, multiple scattering, ...
   - dedicated Geometry description needed
4. assign MIP stub to track, find muons
5. clustering (ECAL and HCAL)
   - variable, depending on track and photon candidates
   - different algorithms
6. particle ID for $e^{+/-}$, $h^{+/-}$



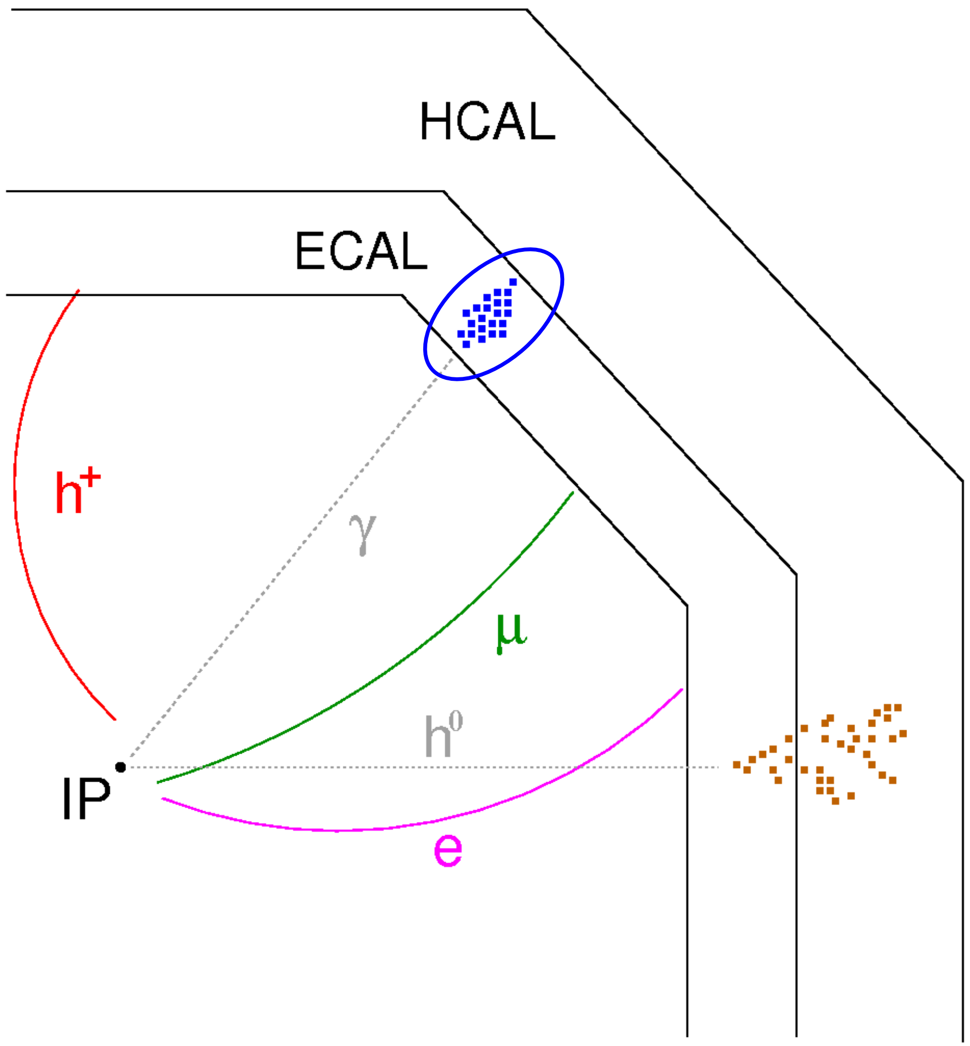
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)
2. find photon candidates
3. extrapolate tracks into Calorimeter
   - different models, with and w/o energy loss, multiple scattering, ...
   - dedicated Geometry description needed
4. assign MIP stub to track, find muons
5. clustering (ECAL and HCAL)
   - variable, depending on track and photon candidates
   - different algorithms
6. particle ID for $e^{+/-}$, $h^{+/-}$
7. remove 'charged' Calorimeter hits



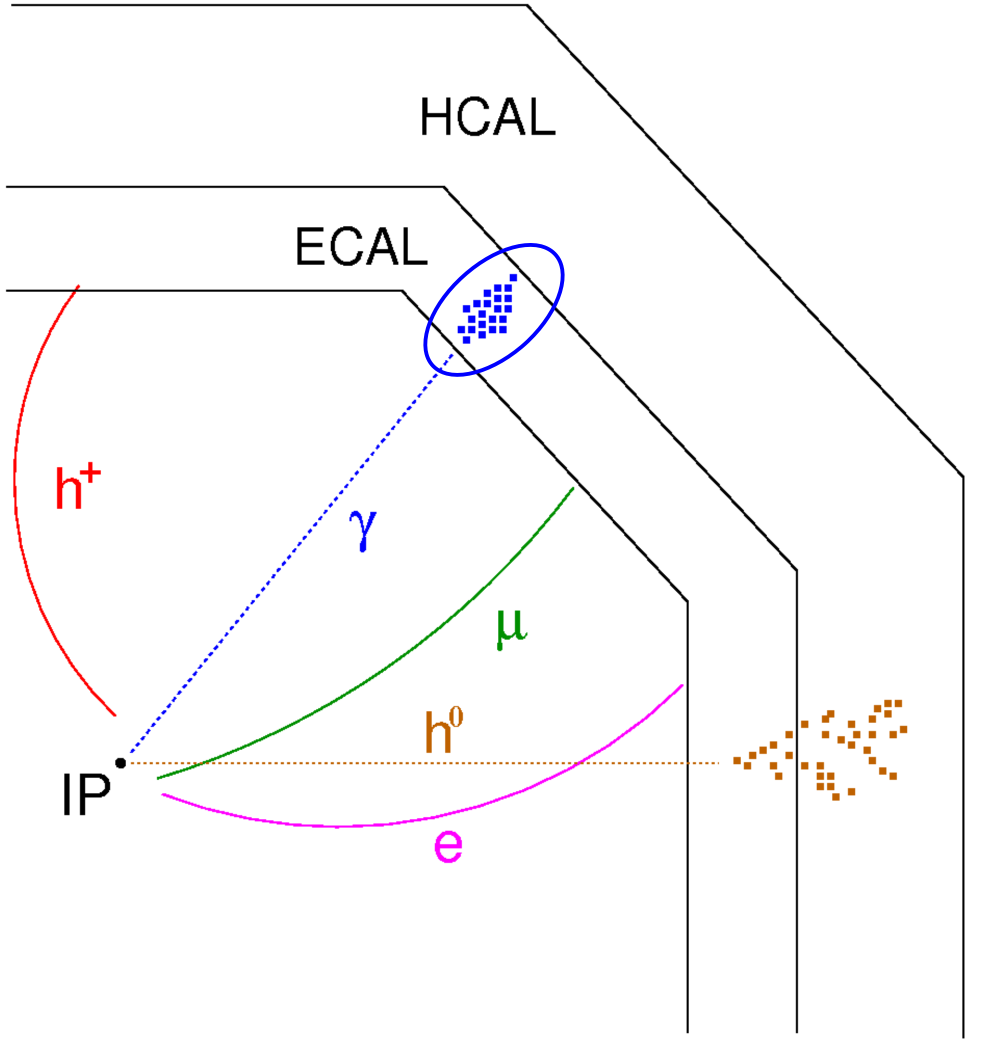
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)
2. find photon candidates
3. extrapolate tracks into Calorimeter
   - different models, with and w/o energy loss, multiple scattering, ...
   - dedicated Geometry description needed
4. assign MIP stub to track, find muons
5. clustering (ECAL and HCAL)
   - variable, depending on track and photon candidates
   - different algorithms
6. particle ID for $e^{+/-}$, $h^{+/-}$
7. remove 'charged' Calorimeter hits
8. clustering on 'neutral' hits



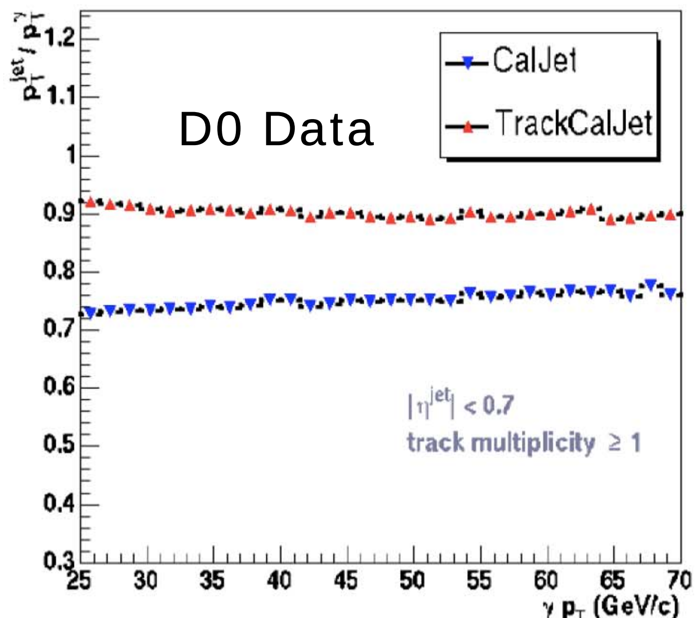
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)
2. find photon candidates
3. extrapolate tracks into Calorimeter
   - different models, with and w/o energy loss, multiple scattering, ...
   - dedicated Geometry description needed
4. assign MIP stub to track, find muons
5. clustering (ECAL and HCAL)
   - variable, depending on track and photon candidates
   - different algorithms
6. particle ID for $e^{+/-}$, $h^{+/-}$
7. remove 'charged' Calorimeter hits
8. clustering on 'neutral' hits
9. particle ID for photons and h^0



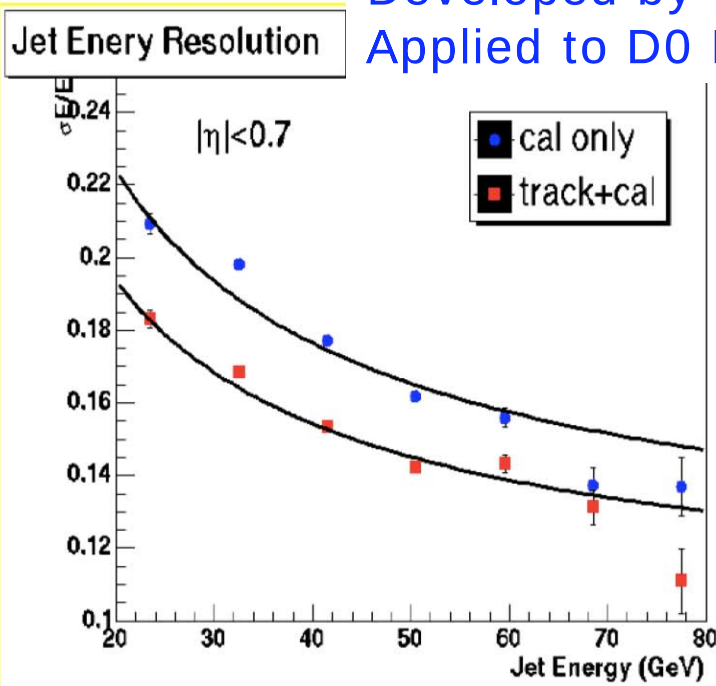
Jet Plus Track

- No track-cluster matching required
  - Expected e/π non-linearity is subtracted from calorimeter measurement and replaced with track momentum



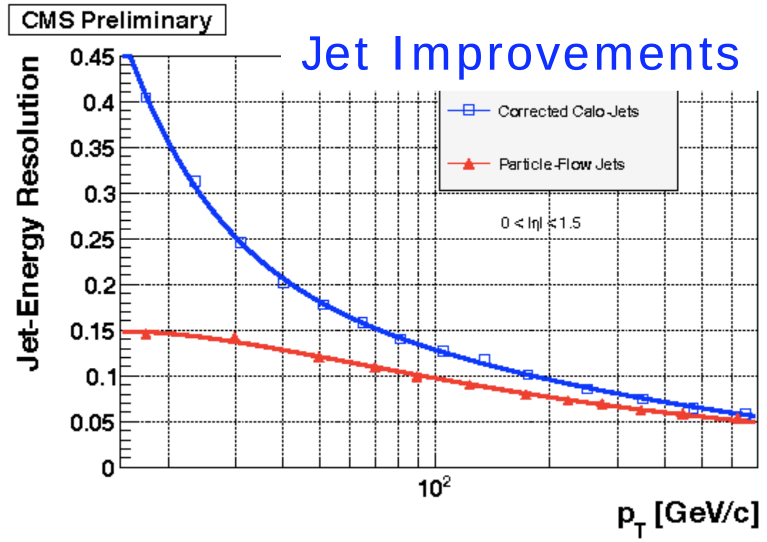
(Courtesy of A. Schwartzman)

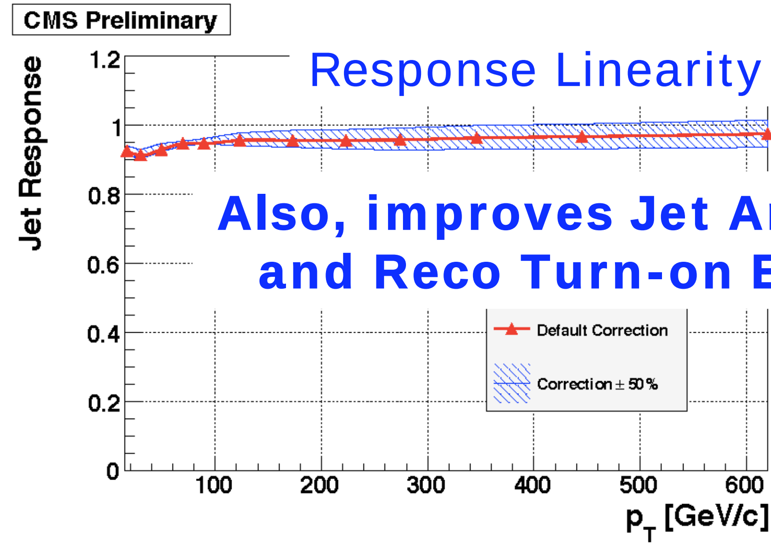
Developed by CMS
Applied to D0 Data



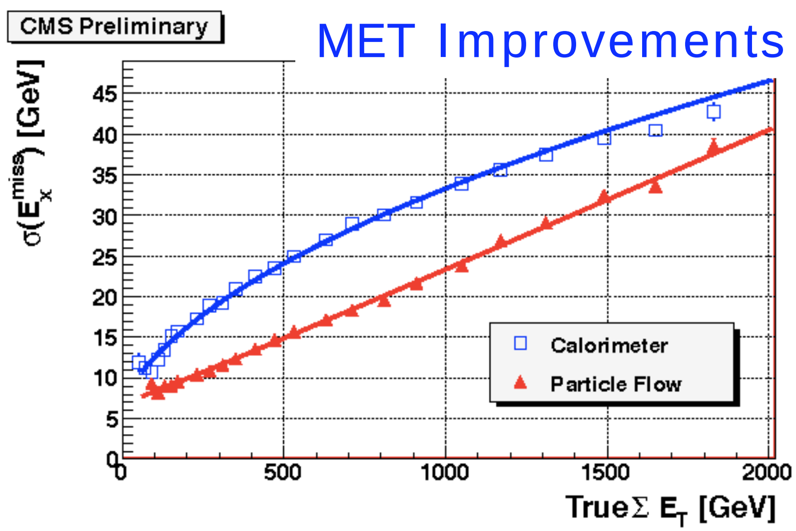
Magnitude of improvement is much larger for calorimeters with large e/π non-linearity

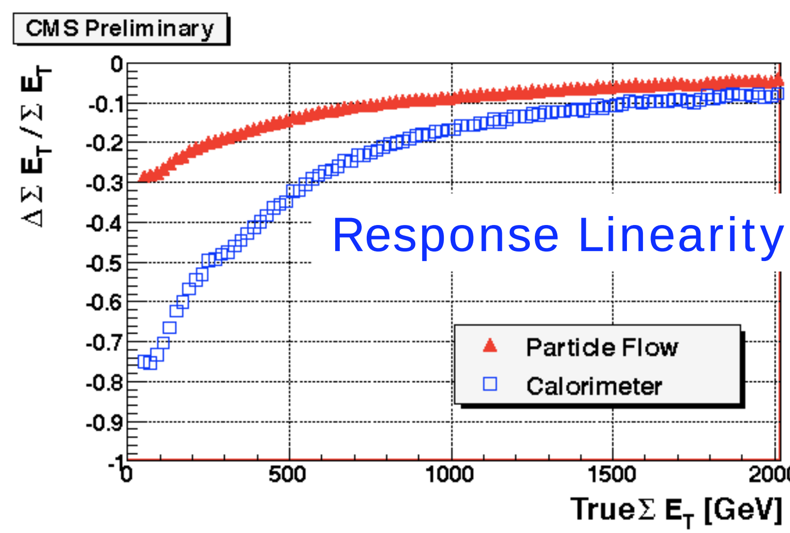
Particle Flow





Also, improves Jet Angle and Reco Turn-on Eff.





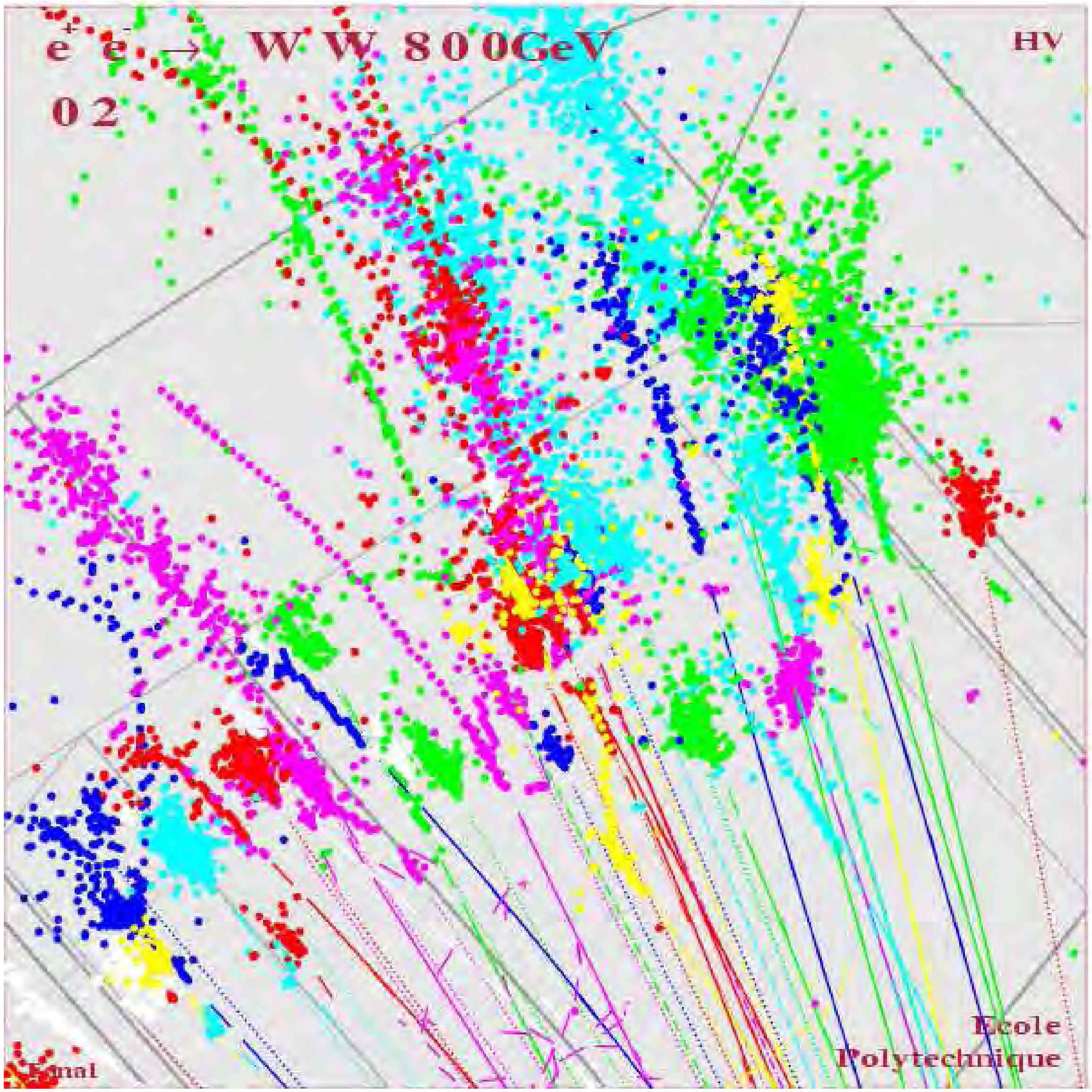
Main problem: Confusion

- At high energy jets are very narrow

➠ Tracks are very close at the calorimeter

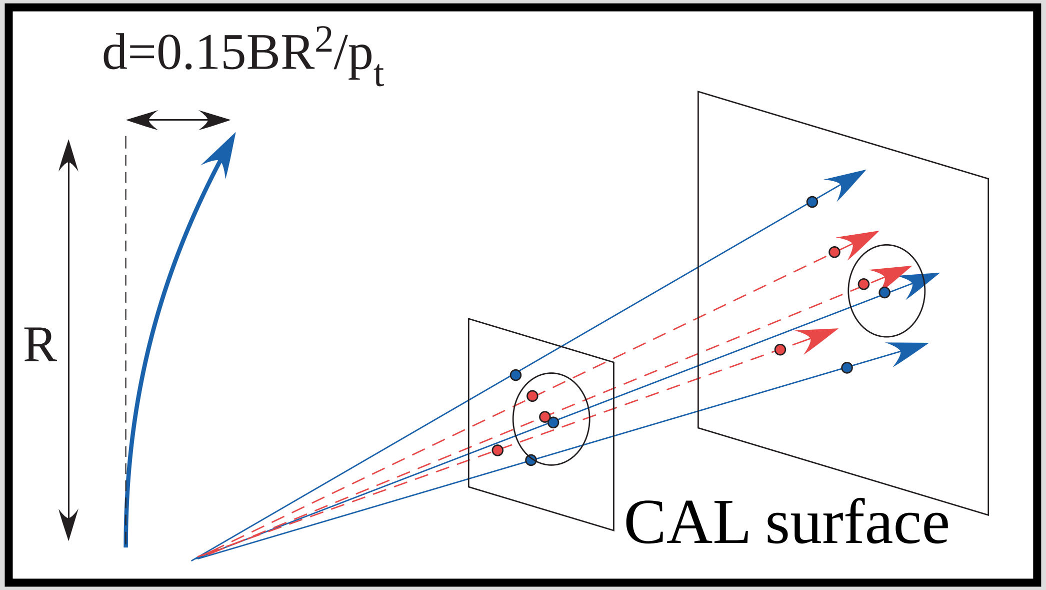
- Need very fine granularity of calorimeter and sophisticated software to separate showers

- Energy resolution still dominated by confusion term



Particle Flow Algorithm

- In order to get good energy resolution by PFA, separation of particles is important. → Reduce the density of charged and neutral particles at calorimeter surface.



Often quoted "Figure of Merit"

$$\frac{BR^2}{\sqrt{\sigma^2 + R_M{}^2}}$$

B : Magnetic field
R : CAL inner radius
σ: CAL granularity
R_M : Effective Moliere length

- For transverse separation of particles at the ECAL surface, stronger B-field and/or large ECAL radius are preferable.

 * Fine segmentation of CAL is also important for pattern recognition.

Radius vs. B-field