



From RAW data to the Higgs and beyond

Physics Object ID,
Analyses techniques,
Higgs results and future
prospects

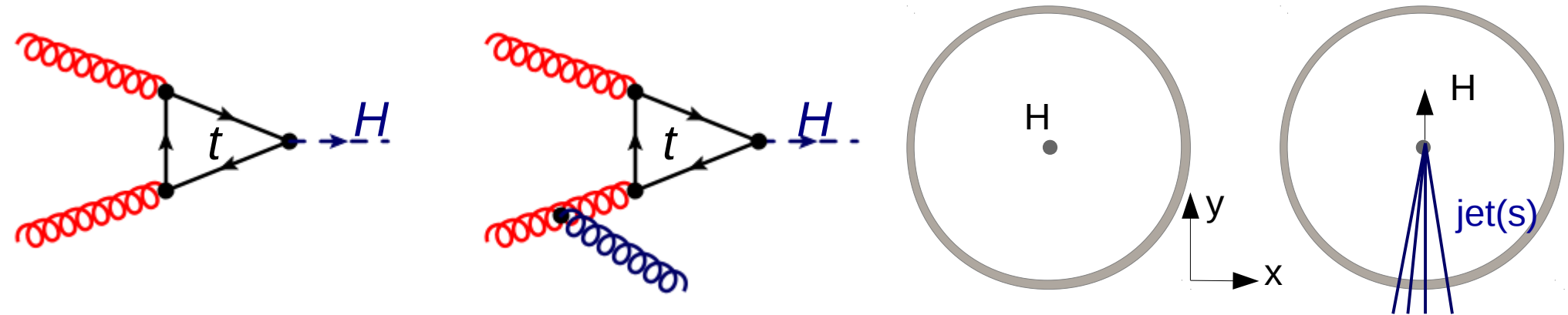
M.Bachtis (CERN-PH)

Outline of the lectures

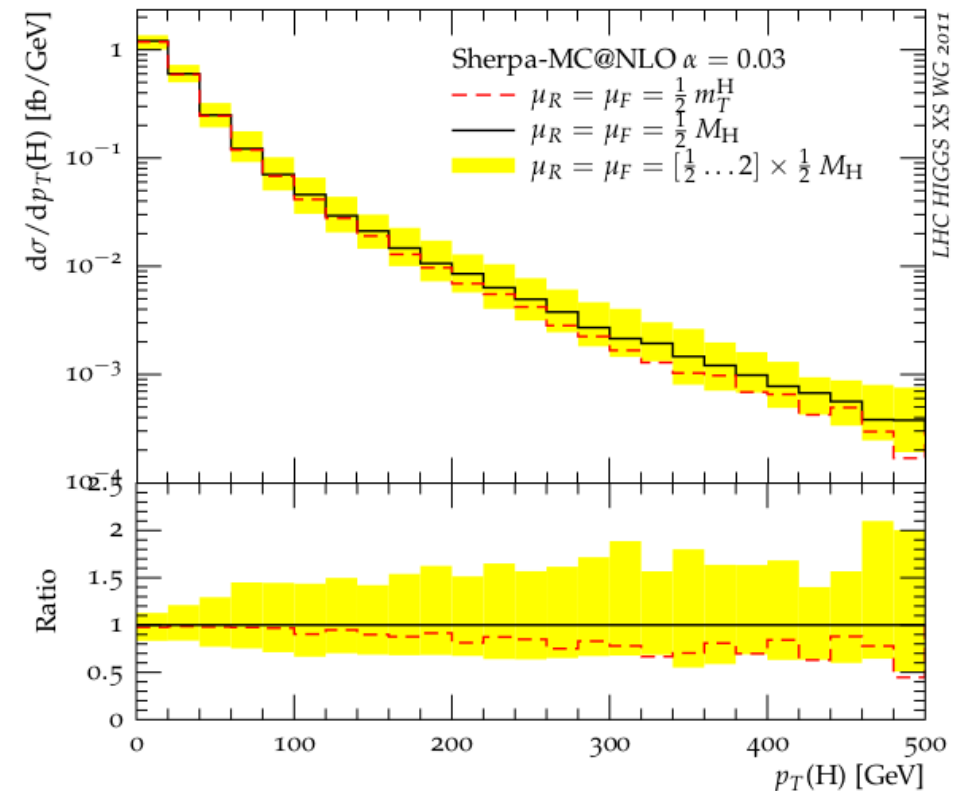
- Part I
 - Experimental signatures of Higgs events
 - Search feasibility and detector requirements
 - Physics Object Identification techniques
- Part II
 - Higgs analyses in ATLAS and CMS and the respective analyses techniques
 - Recent Higgs results
- Part III
 - Future prospects of Higgs measurements at HL-LHC, ILC and FCC ee/pp

Higgs Production @ the LHC(I)

- Gluon fusion [19.3 pb @ 8TeV]

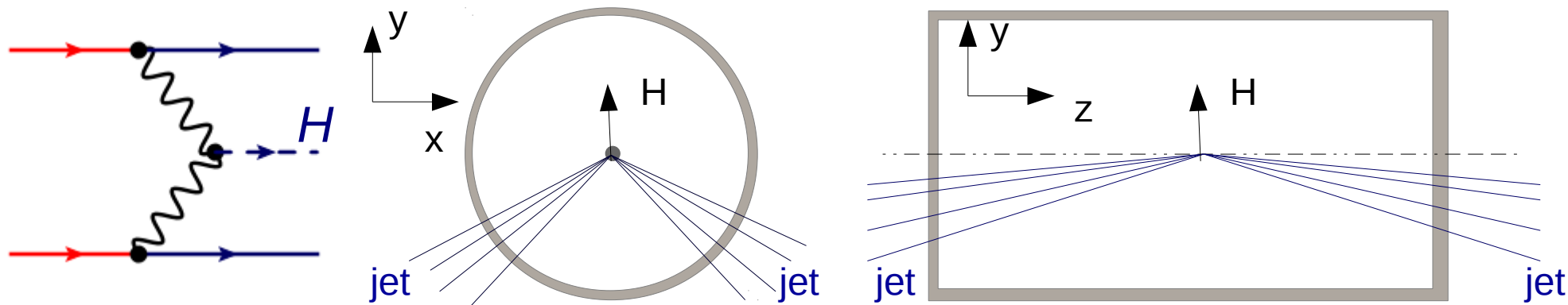


- Dominant production mechanism
- Loop dominated by top
- Often accompanied by radiation
 - presence of jets in the final state

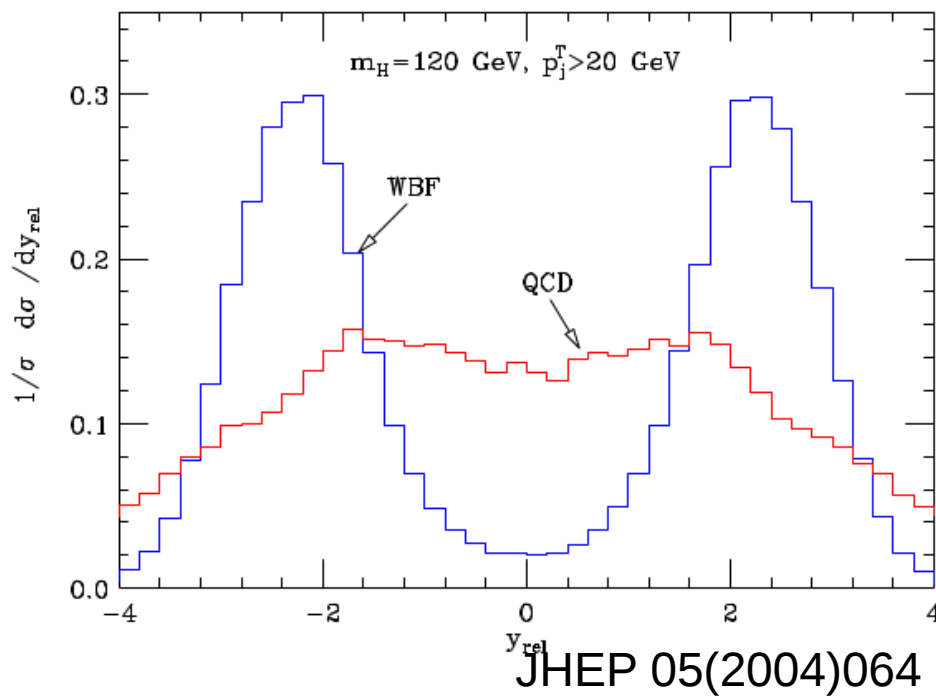


Higgs Production @ the LHC (II)

- Vector boson fusion [1.6 pb @ 8TeV]

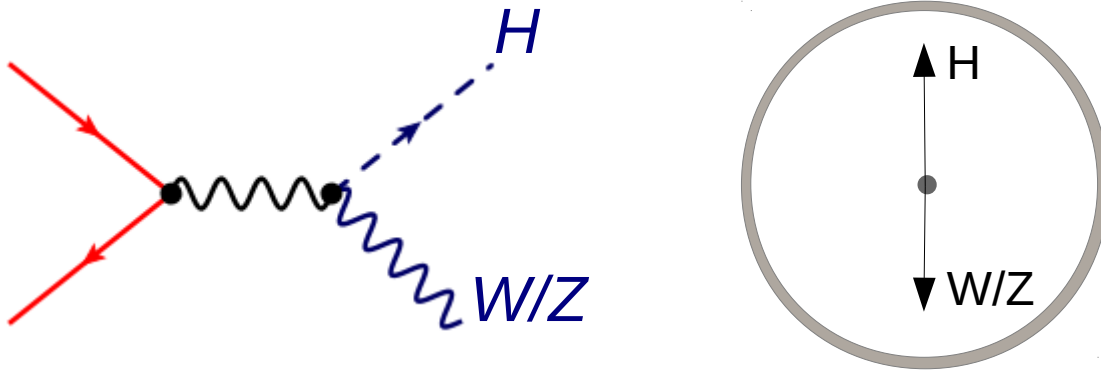


- 10x lower cross section than gluon fusion
- Distinct experimental signature
 - Two jets in the final state
 - Large opening angle between the jets



Higgs Production @ the LHC (III)

- Associated production with a vector boson (W/Z)
- WH : 0.70 pb , ZH: 0.40 pb @ 8 TeV

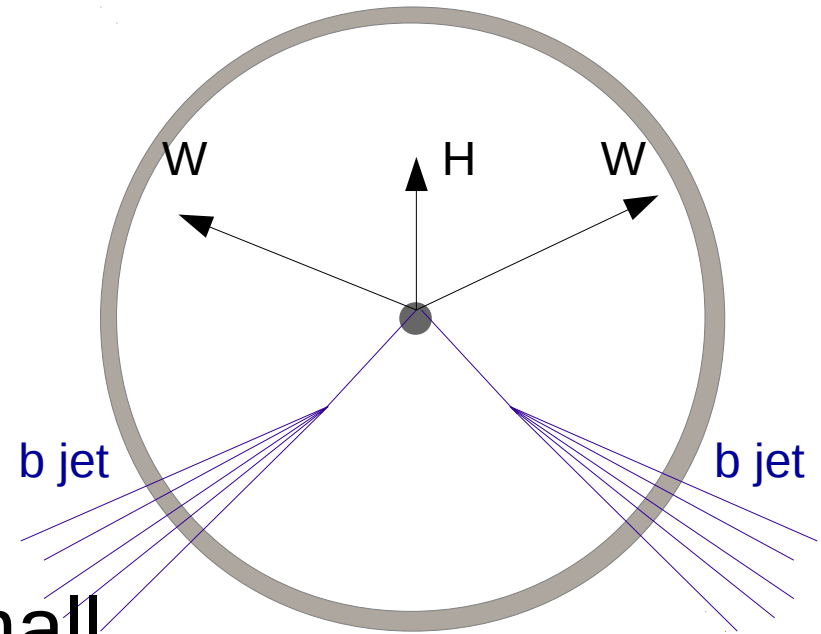
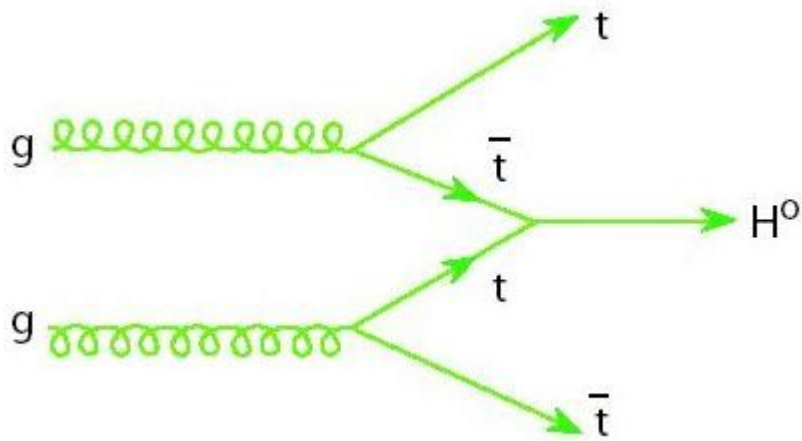


- Cross section very small
- However presence of vector boson in the final state makes the final state clean - reducing backgrounds

Higgs Production @ the LHC (IV)

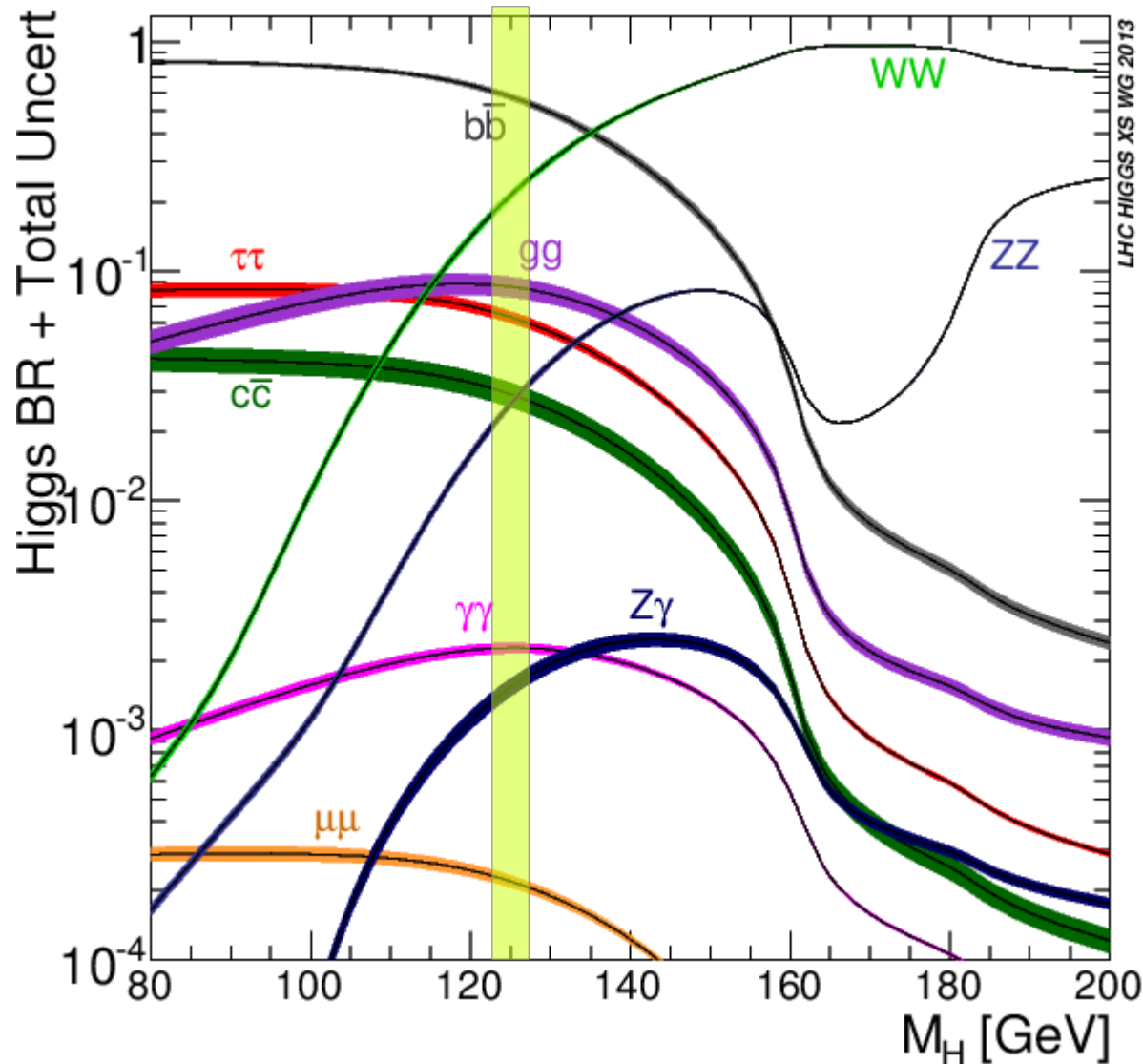
- Associated production with a top pair

[0.12pb @8TeV]



- Cross section extremely small
 - 120 events per fb^{-1}
- Unique final state with 2 b jets , 2 W bosons and a Higgs boson
 - Major background is $t\bar{t}$ pairs + X

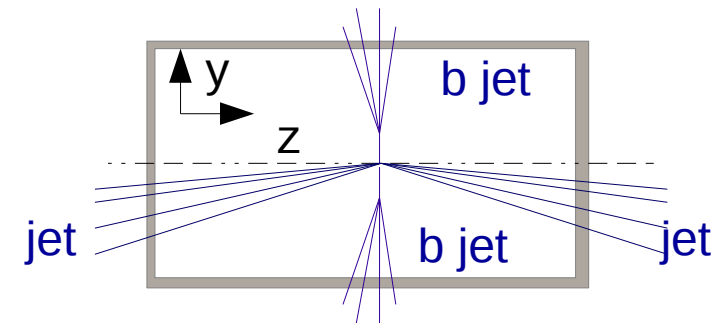
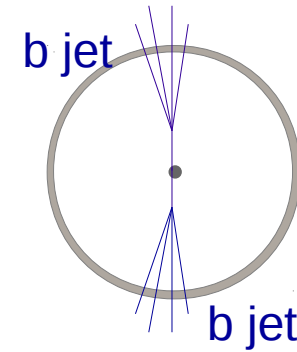
Higgs decays for M_H around 125 GeV



- A plethora of decay modes @125 GeV
 - Lets take them one by one...

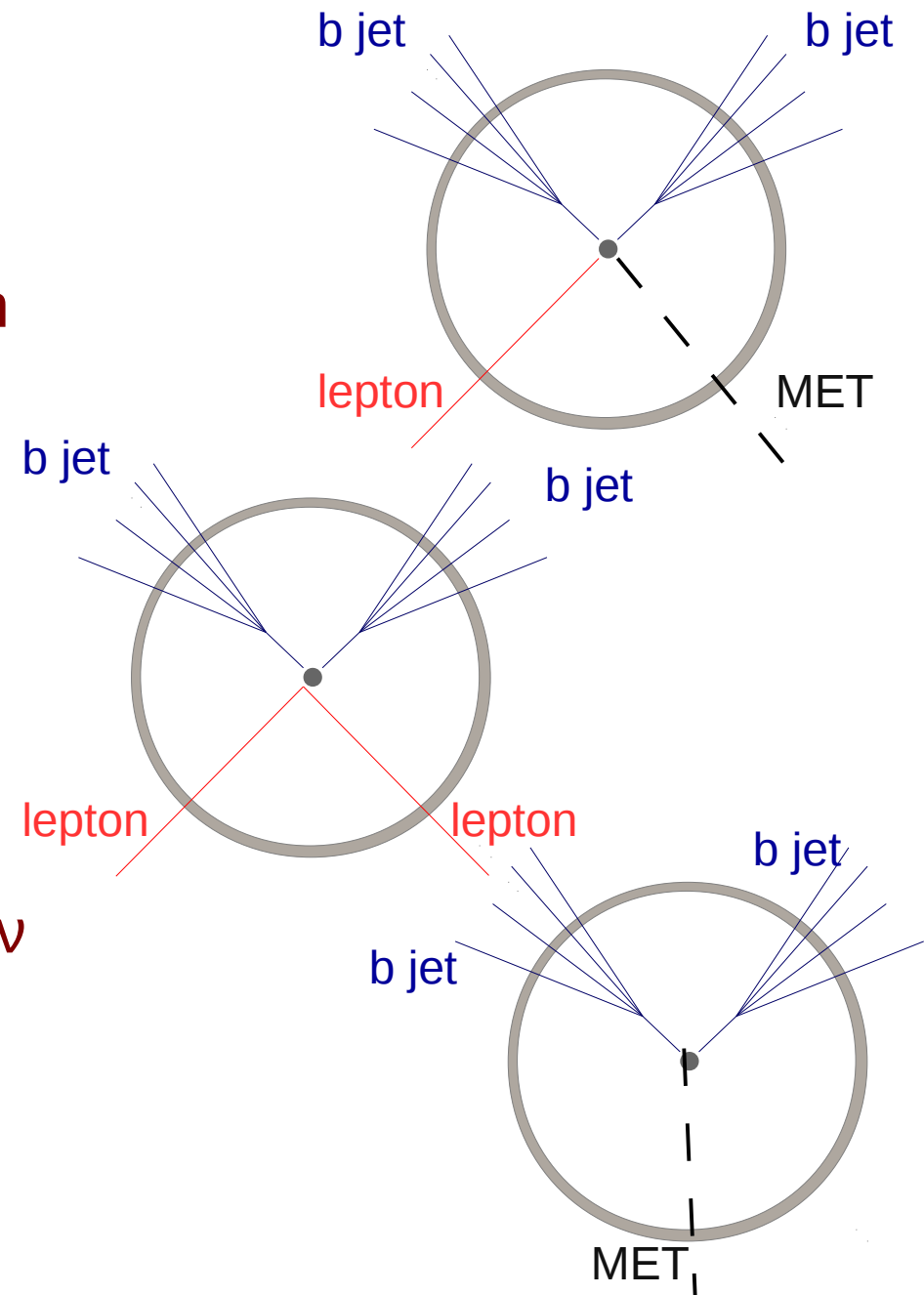
$H \rightarrow bb$ [BR = 57% @ 125 GeV]

- Fully reconstructed final state
 - Dominated by jet resolution
- $ggH \rightarrow bb$ not feasible
 - Direct bb production 10^7 times larger
 - Impossible to even trigger the events
- VBF $H \rightarrow bb$ probably feasible
 - But very hard since background is direct $2b 2jet$ production
 - Angular separation and bb mass peak can decrease the background but not enough to be competitive to other modes



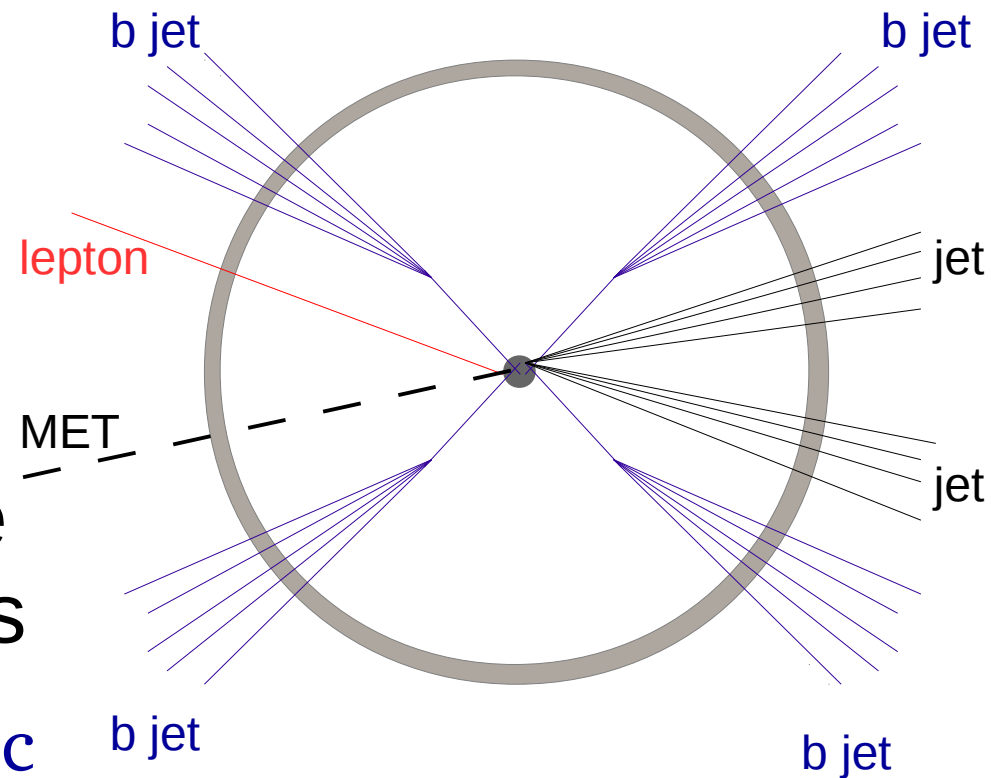
$H \rightarrow bb$ [BR = 57% @ 125 GeV]

- WH feasible
 - But W needs to decay to lepton+neutrino
 - ~ 40 events per fb^{-1} per lepton flavor [e,mu,tau]
 - Backgrounds : W+bb ,WZ
- ZH feasible
 - Z needs to decay to two charged leptons or two neutrinos
 - 8 events per fb^{-1} per lepton flavor, 46 events for the $Z \rightarrow \nu\nu$
 - Backgrounds Z+bb, Z+fake MET



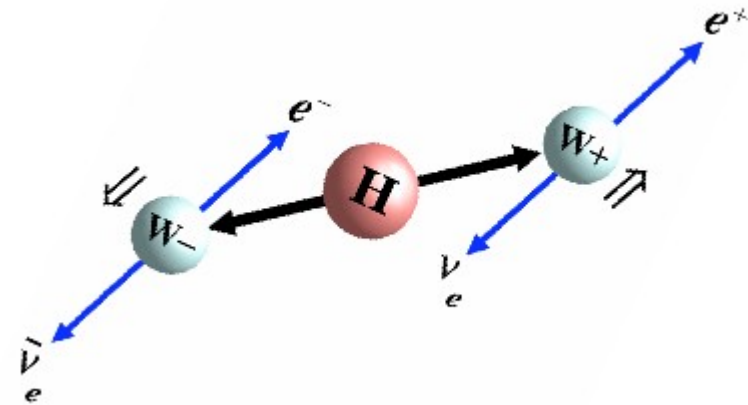
$H \rightarrow bb$ [BR = 57% @ 125 GeV]

- ttH is also possible with enough statistics
 - Main background is $tt + bb$
 - Normally at least one W needs to decay to leptons
 - to reduce QCD background
 - to trigger the event
- ~ 68 events per fb^{-1} before requirements on W decays
 - ~ 7 events for a semileptonic decay [per lepton flavor]

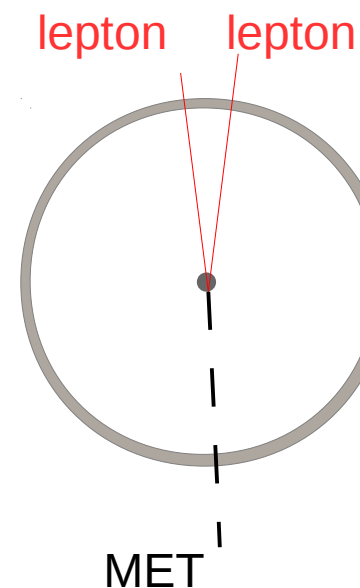


$H \rightarrow WW^*$ [BR = 22% @ 125 GeV]

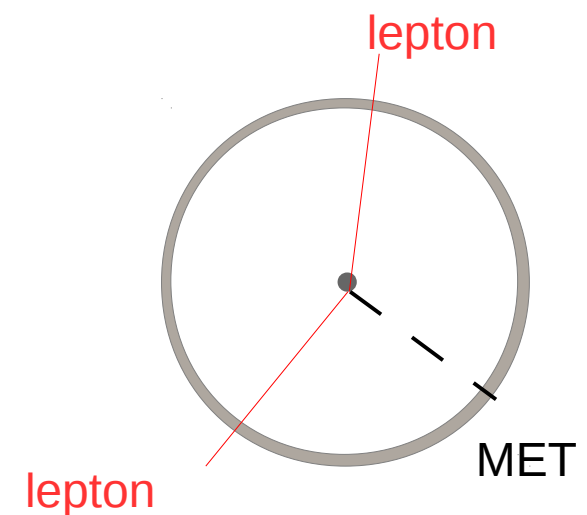
- Not fully reconstructed state
 - 2 neutrinos
- Most final states require a di-leptonic WW decay
 - Or else overwhelmed by W+jets
- Requiring both W decays electrons or muons
 - Makes effective BR $\sim 0.9\%$
- Higgs \rightarrow spin 0
 - Spin correlations give collinear lepton signature
 - Can be exploited experimentally



H \rightarrow WW

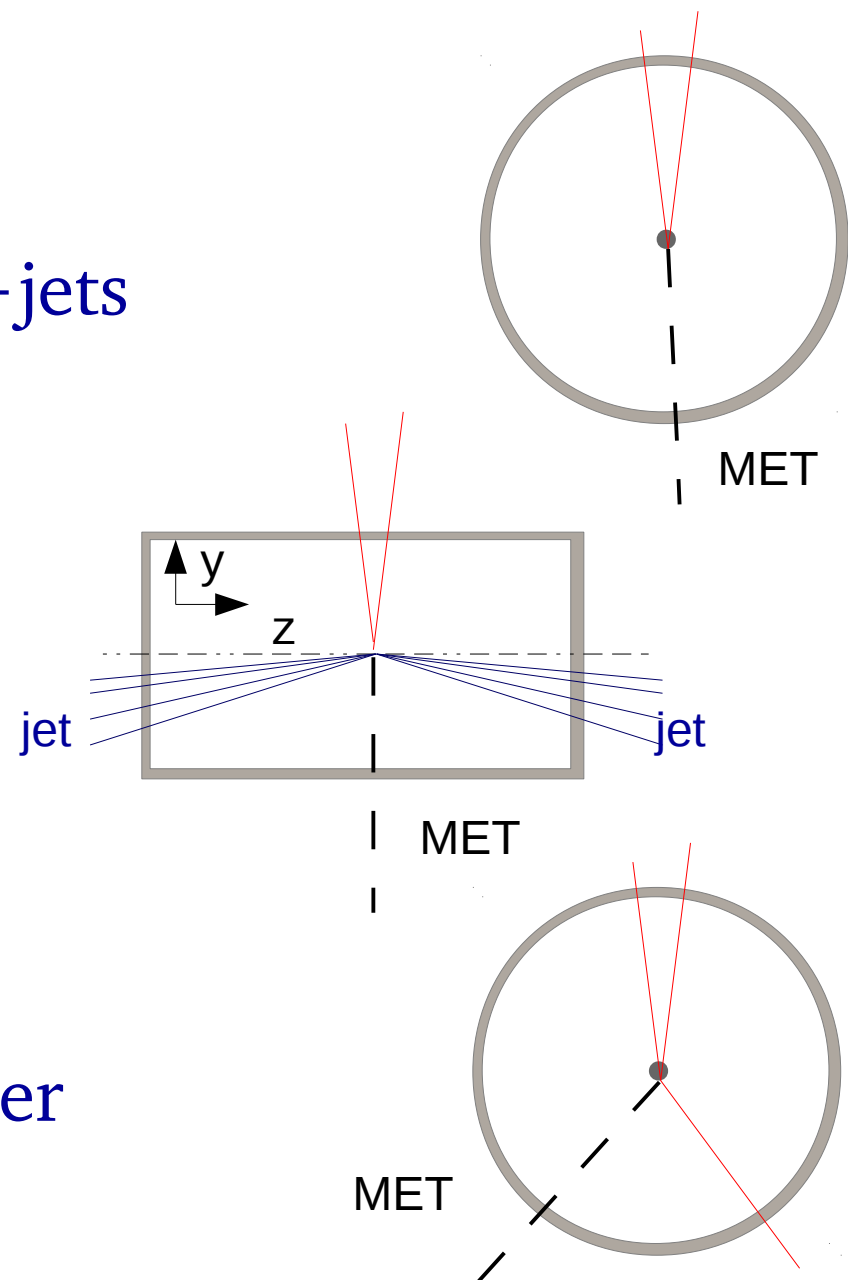


SM WW



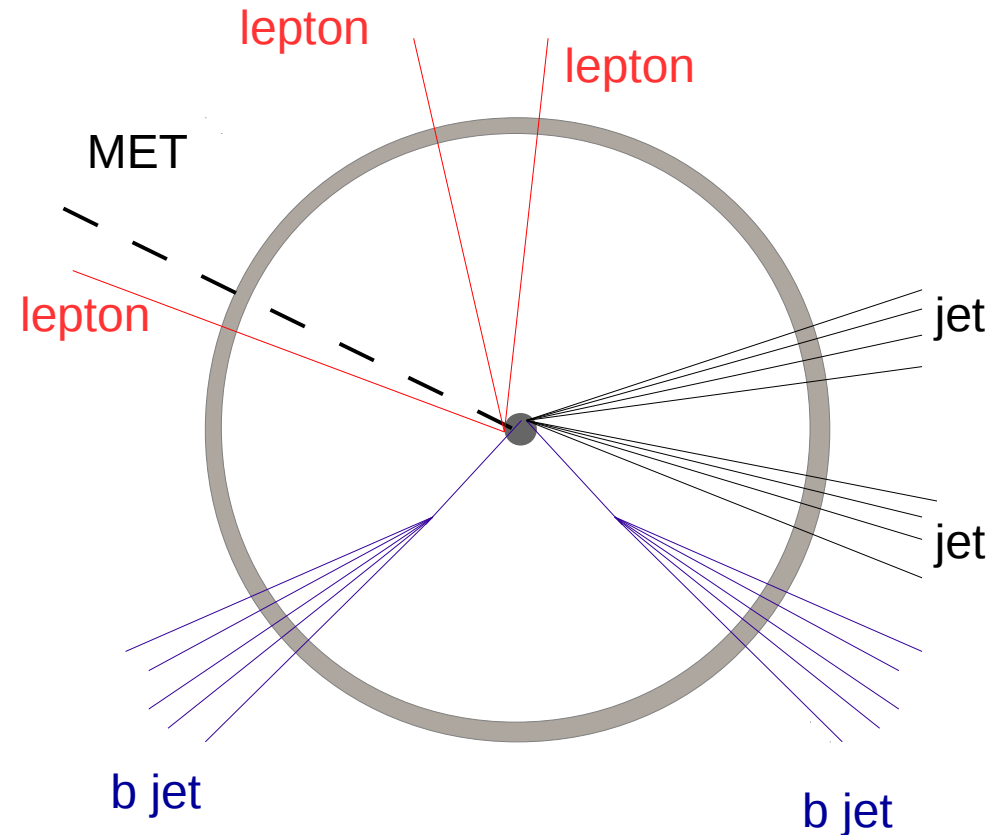
Feasible $H \rightarrow WW^*$ signatures

- $gg \rightarrow H \rightarrow WW^*$
 - 170 events / fb^{-1}
 - Backgrounds: SM WW , tt , W +jets [with fake leptons]
- VBF $H \rightarrow WW^*+2$ jets
 - 14 events / fb^{-1}
 - Backgrounds: $WW+2$ jets, tt , $W+3$ jets
- $WH \rightarrow WWW^*$
 - For all W leptonic, 1.7 events per fb^{-1}
 - Backgrounds: WZ , WW +jets



Feasible $H \rightarrow WW^*$ signatures

- Associated production with top also possible
 - $2b + 4W$ final states
 - Any of the 4 W can decay leptonically leading to final states of 1 – 4 leptons
 - 26 events/fb-1 before any W decay
- A lot of combinatorics/
multilepton based search
- Main backgrounds
 $ttZ/ttW/tt$ +fake leptons



H \rightarrow gg and H \rightarrow cc

- H \rightarrow gg impossible at LHC due to very large jet backgrounds
- H \rightarrow cc practically impossible @ LHC
 - With much lower branching ratio to bb, higher background cross sections and less performant c jet vs b jet identification
 - b-jet identification relies to the long lifetime of B hadrons
 - Lifetime of c hadrons smaller \rightarrow need much better vertex capabilities
- Both of those modes can however be studied in an e^+e^- collider

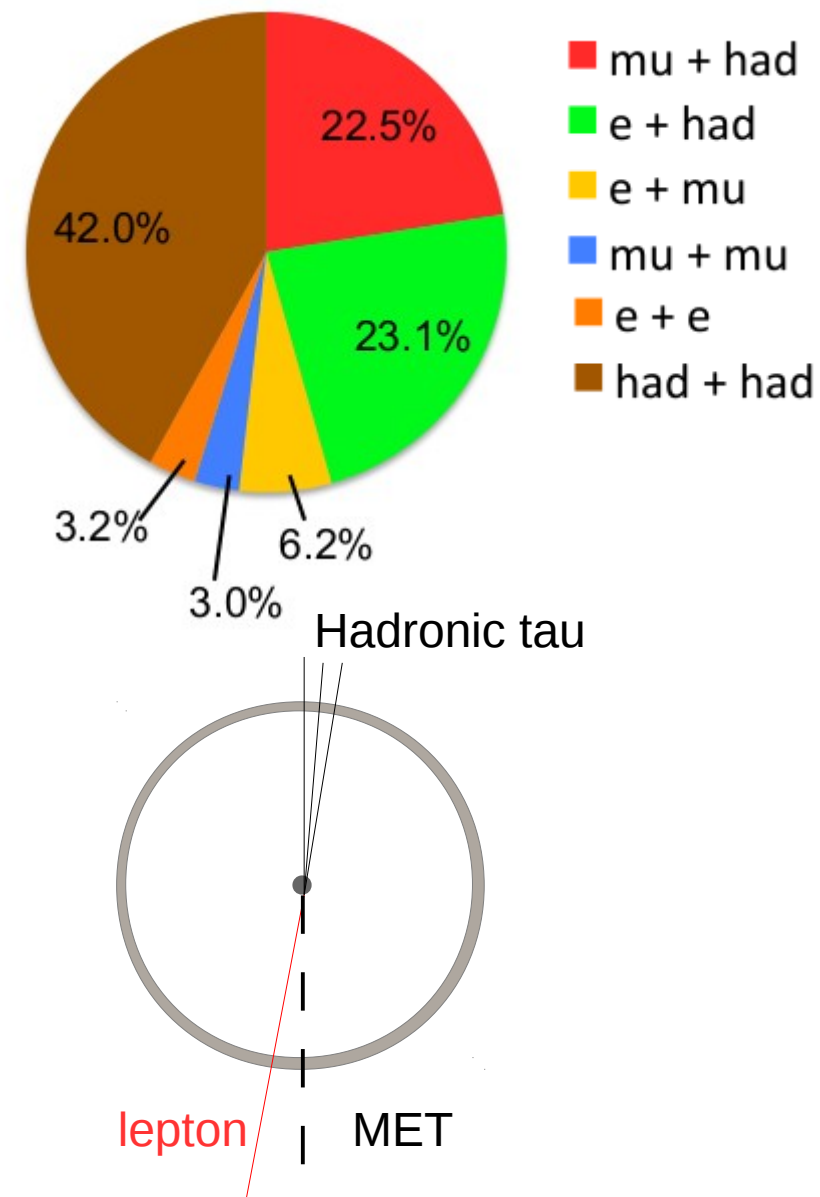
$H \rightarrow \tau\tau$ [BR = 6.3% @ 125 GeV]

- Due to heavy tau mass [1.78 GeV] easiest accessible leptonic final state
- Tau lepton decays to an electron or a muon and two neutrinos about 20% of the time
- Taus decay to hadrons ~60% of the time
- In addition since tau is boosted it appears as a very collimated jet in the detector
 - Crucial to identify the tau decays and discriminate against jets to be able to exploit the significant di-tau branching ratio

Decay Mode	Resonance	Mass (MeV/c ²)	Branching ratio(%)
$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$			17.8 %
$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$			17.4 %
$\tau^- \rightarrow h^- \nu_\tau$			11.6 %
$\tau^- \rightarrow h^- \pi^0 \nu_\tau$	ρ	770	26.0 %
$\tau^- \rightarrow h^- \pi^0 \pi^0 \nu_\tau$	a_1	1200	10.8 %
$\tau^- \rightarrow h^- h^+ h^- \nu_\tau$	a_1	1200	9.8 %
$\tau^- \rightarrow h^- h^+ h^- \pi^0 \nu_\tau$			4.8 %
Other hadronic modes			1.7%

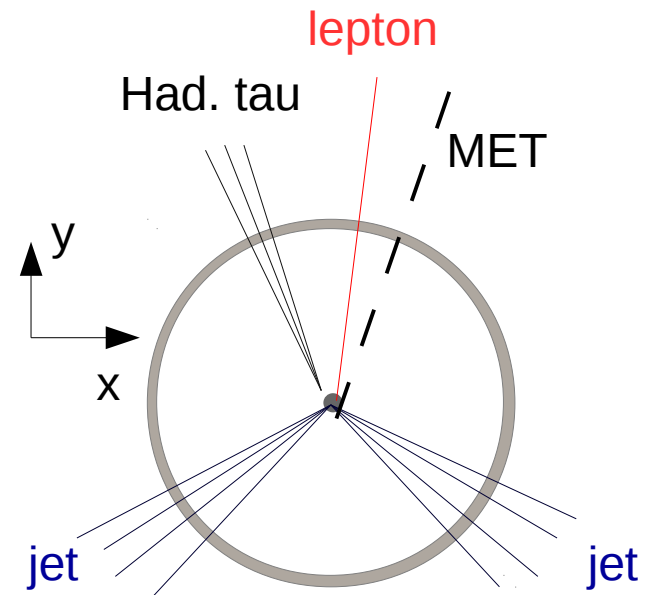
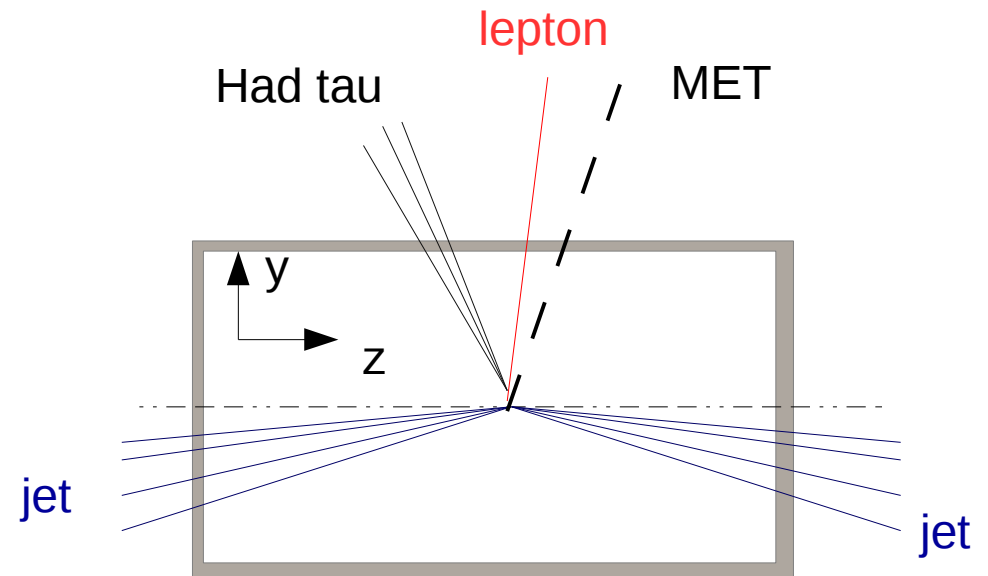
H \rightarrow $\tau\tau$ final states

- Depending on the tau decays, several final states with 2-4 neutrinos occur
 - Final state mass not fully reconstructed
 - Lepton spectrum softer so selection efficiency much lower [i.e than WW]
- In gluon fusion 1200 evts/fb-1
 - Before tau decays
 - Overwhelmed by Z \rightarrow tautau
 - Need hard cuts and good mass reconstruction to reject it



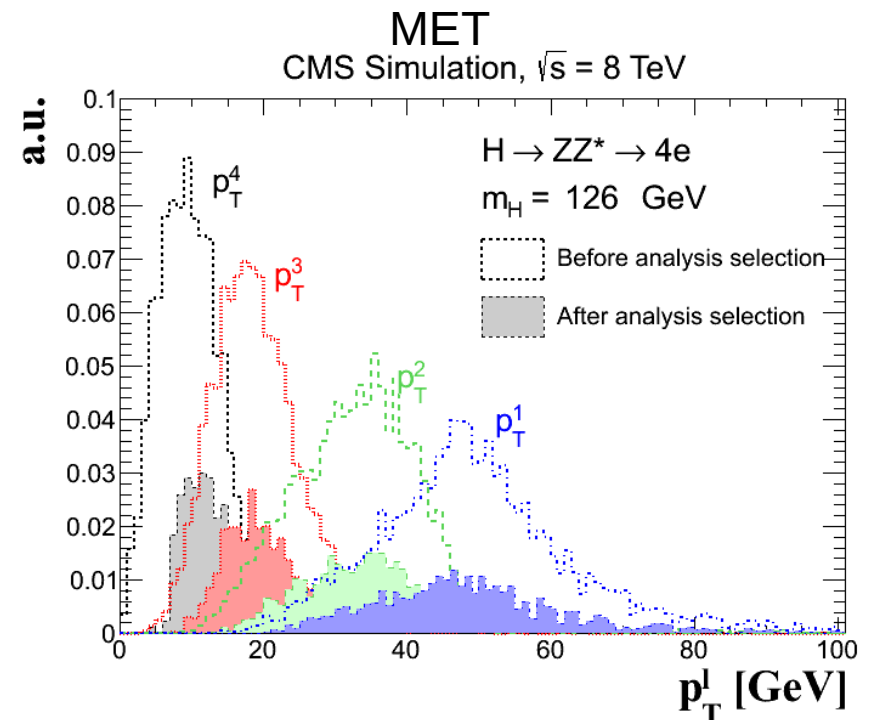
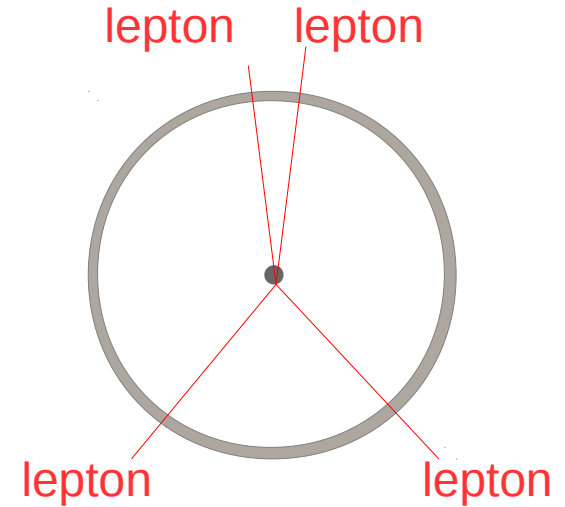
VBF $H \rightarrow \tau\tau$

- Promising final state!
 - ~ 100 events /fb-1 before tau decays
- Main background: $Z \rightarrow \tau\tau + 2$ jets
 - can be suppressed by exploiting VBF signature
- VH also possible but lower performance due to $V + \text{jets}$ background



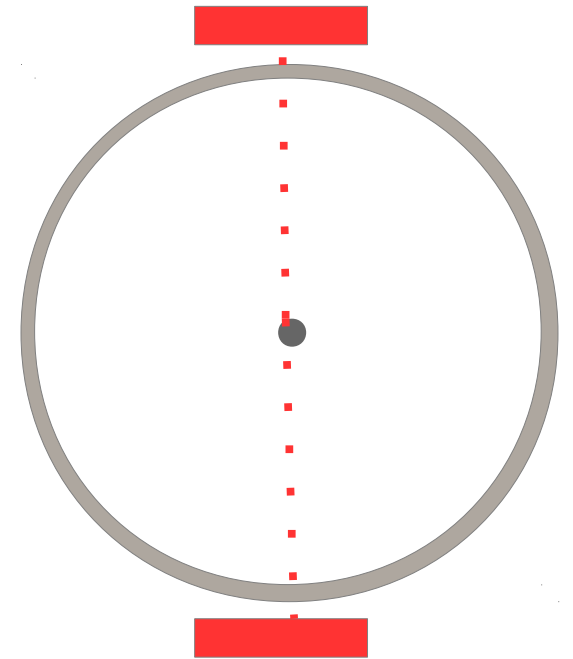
$H \rightarrow ZZ^*$ [BR = 2.6% @ 125 GeV]

- Fully reconstructed final state with excellent resolution in the case of 4 leptons
- At low mass both Z need to decay to leptons [e/mu] to avoid Z+jets background
 - Effective BR = 1.25×10^{-4}
 - Background dominated by SM ZZ production
 - Very small for mass $< 2M_Z$
- At gluon fusion 2.5 events/fb⁻¹
 - But very clean final state with fully reconstructed mass
- VBF harder [0.2 events/fb⁻¹]
- Challenge: excellent lepton efficiency and large detector coverage



$H \rightarrow \gamma\gamma$ [BR = 2.2×10^{-3} @ 125 GeV]

- Fully reconstructed final state with excellent resolution
- Background dominated by direct di-photon production + QCD with fake photon
- Experimentally challenging
 - Photon identification
 - Identification of the primary vertex
 - Rejection of jet background



H \rightarrow $\gamma\gamma$ final states

- At gluon fusion, 40 events /fb⁻¹ expected
 - Large falling di-photon background
- With VBF \sim 3.5 events/fb⁻¹ expected
 - Large di photon background suppressed by VBF requirements
- VH/ttH also possible
 - With lower sensitivity but very small background

$H \rightarrow Z\gamma$ and $H \rightarrow \mu\mu$

- $H \rightarrow Z\gamma$ has a similar branching ratio to $\gamma\gamma$ [1.5×10^{-3} @ 125 GeV]
 - However for exploiting the experimental signature Z needs to decay to leptons
 - 6% of the branching ratio available. Need very high luminosity to observe it
- $H \rightarrow \mu\mu$ has very low BR [2.2×10^{-4} @ 125 GeV]
 - Overwhelmed by huge $Z \rightarrow \mu\mu$ background
 - Maybe possible at very high luminosity with tight VBF selection

Summary of the feasible LHC searches

The big five

- $H \rightarrow ZZ^* \rightarrow 4l$ [ggH/VBF]
- $H \rightarrow WW^* \rightarrow 2l2\nu$ [ggH/VBF/VH/ttH]
- $H \rightarrow \gamma\gamma$ [ggH/VBF/VH/ttH]
- $H \rightarrow \tau\tau$ [ggH/VBF/VH/ttH]
- $H \rightarrow bb$ [VH/ttH]

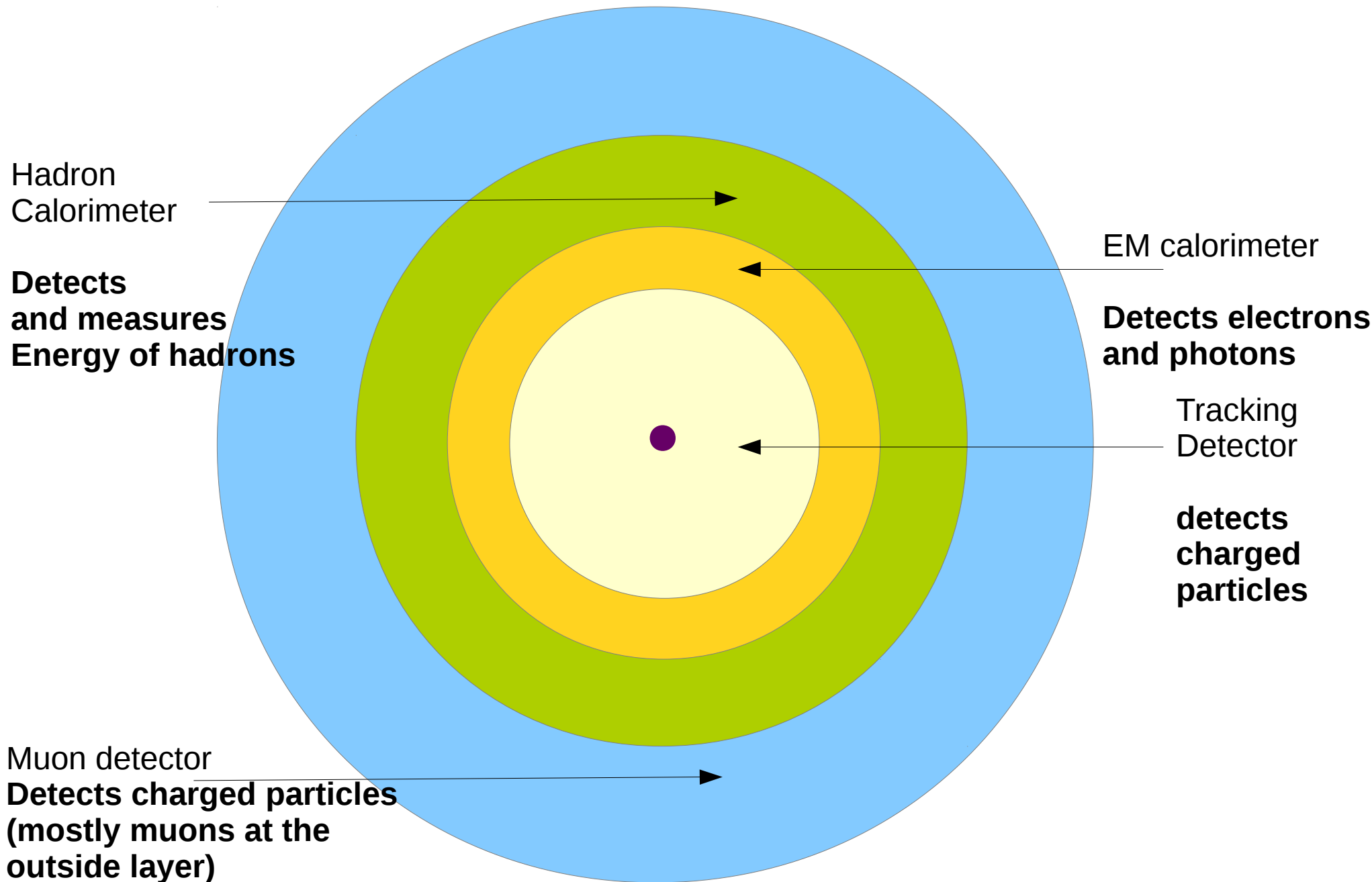
Prospects for High Luminosity

- $H \rightarrow Z\gamma$ [ggH/VBF]
- $H \rightarrow \mu\mu$ [ggH/VBF]

Experimental requirements

- Excellent lepton identification performance even at low p_T
 - To identify leptons in ZZ , WW and tautau
- Excellent lepton momentum resolution
 - To reconstruct a narrow ZZ \rightarrow 4l peak
- Excellent photon identification performance and resolution
 - To reconstruct the H \rightarrow gamma gamma events and reject fake photon background
- Good jet energy resolution
 - To reconstruct bb pairs and form VBF observables
- Good b-tagging performance
 - To remove the light jet background in bb /ttH
- Good MET resolution
 - To reconstruct the WW and tautau final states

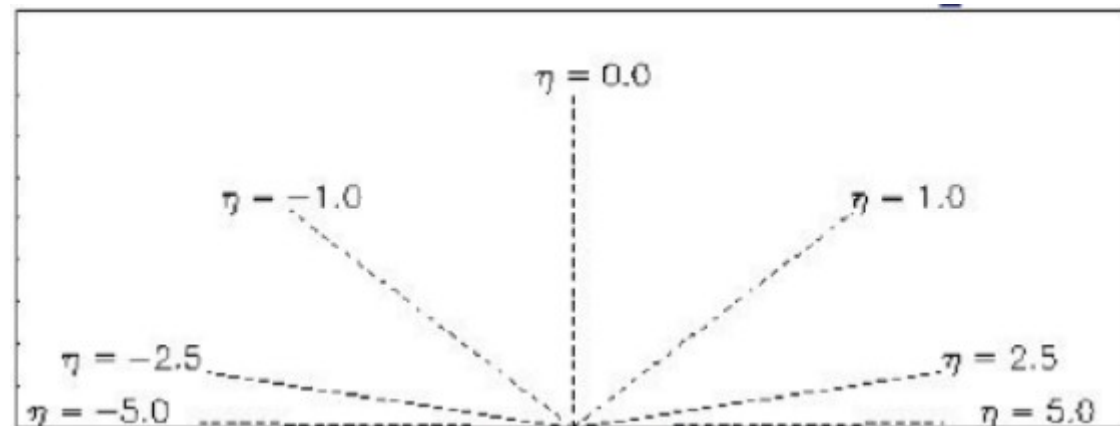
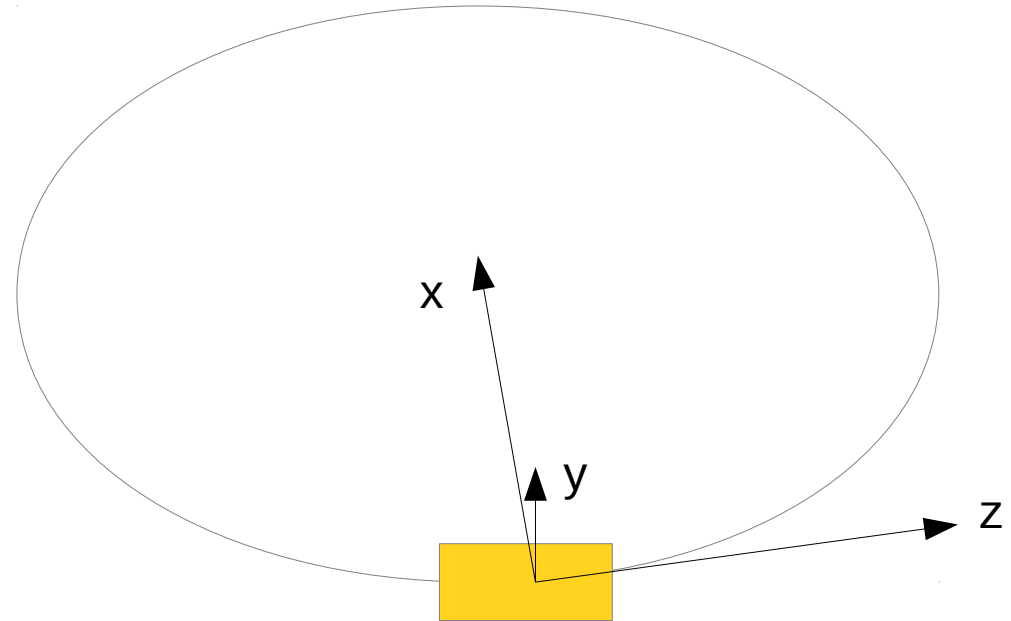
The basic principle of HEP detector



Coordinate systems

- Coordinate system
 - X axis pointing to the center of the ring
 - Y axis upwards
 - Z axis along the beam
- Instead of the polar angle θ , the pseudorapidity η is used

$$\eta = -\ln \tan \frac{\theta}{2}$$



Principles of Particle Identification

Charged hadrons

Leave track in inner tracker and deposit most of the energy in HCAL

Electrons

leave a track in the inner tracker and deposit almost all their energy in the ECAL

Neutral hadrons

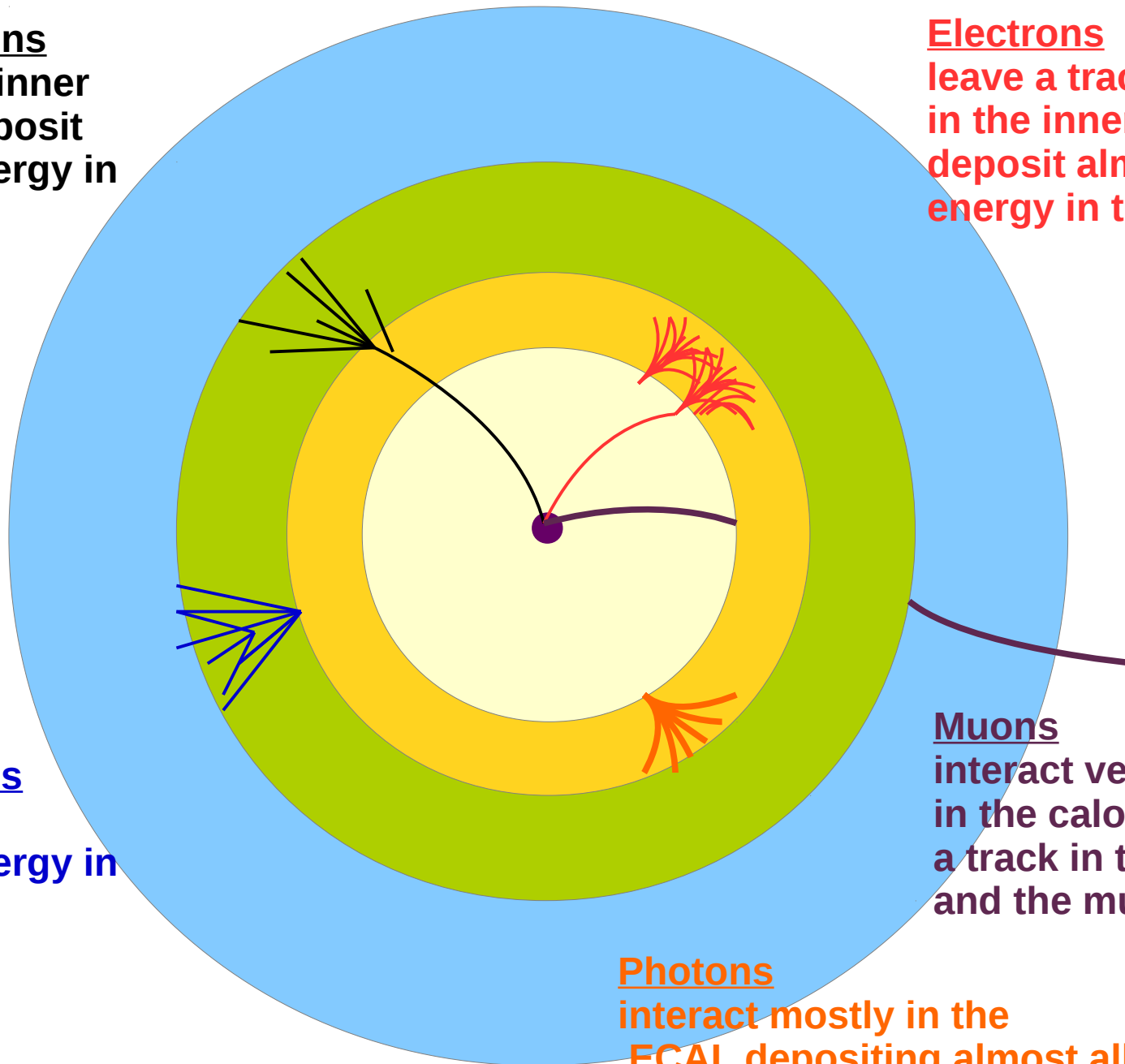
deposit most of the energy in HCAL

Muons

interact very little in the calorimeters leaving a track in the inner tracker and the muon system

Photons

interact mostly in the ECAL depositing almost all their energy



Measurement of track momentum

Track trajectory $y=f(x)$ reconstructed from N measurement points

In the case of a straight line

$$y = \tan\theta x + d \approx \theta x + d$$

Track parameters and errors estimated by minimizing a Chi2

$$\chi^2 = \sum_i \frac{(y_i - f(x_i))^2}{\sigma_i^2} \leftarrow \text{Error of each point}$$

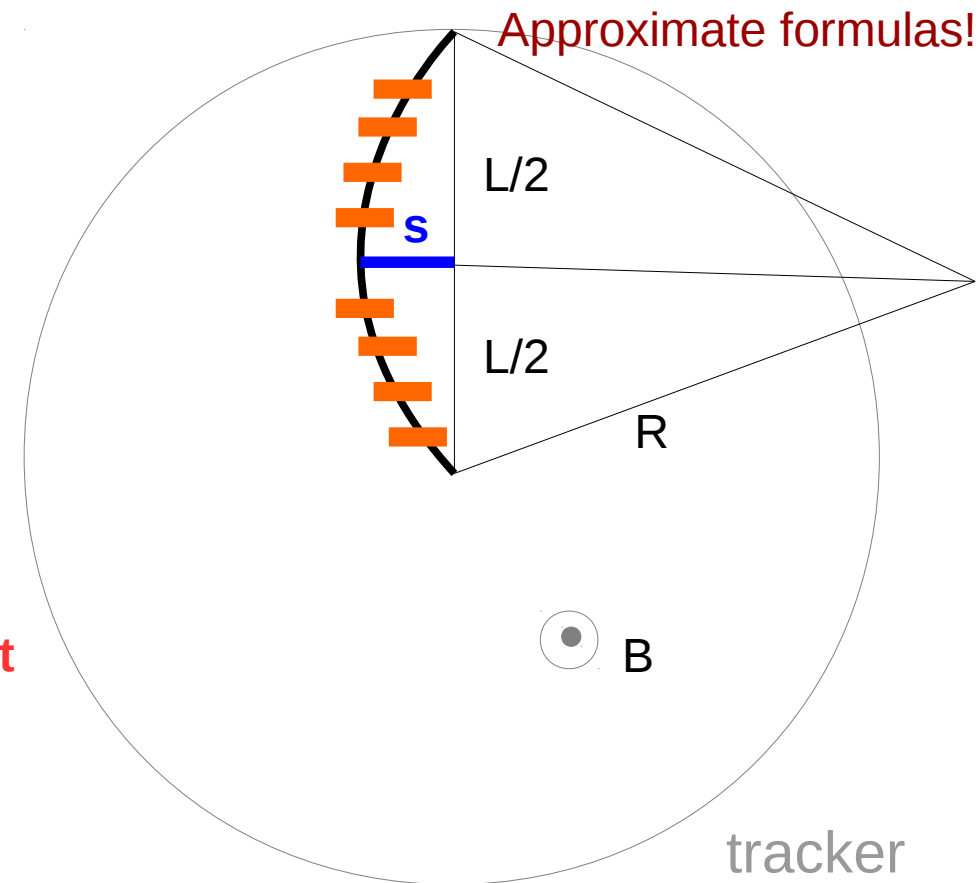
In uniform magnetic field

$$p_T = 0.3BR$$

The helix can be parameterized by a parabola

$$y = \frac{1}{2R}x^2 + \theta x + d \xrightarrow{\text{After minimization}}$$

$$\begin{aligned} \delta d &\approx \sigma / \sqrt{N} && \sim \text{microns} \\ \delta \theta &\approx \frac{\sigma}{L\sqrt{N}} && \ll \text{mrad} \\ \delta \frac{1}{2R} &\approx \frac{\sigma}{L^2\sqrt{N}} \end{aligned}$$



Transverse momentum resolution

$$p_T = 0.3BR \longrightarrow \frac{\delta p_T}{p_T} = \frac{\delta R}{R} = 2R\delta \frac{1}{2R} = \frac{2R\sigma}{L^2\sqrt{N}}$$

$$\frac{\delta p_T}{p_T} = \frac{2\sigma p_T}{0.3BL^2\sqrt{N}}$$

Measurement degrades as tracks become straight

Large magnetic field

Many measurement points

Large tracker size

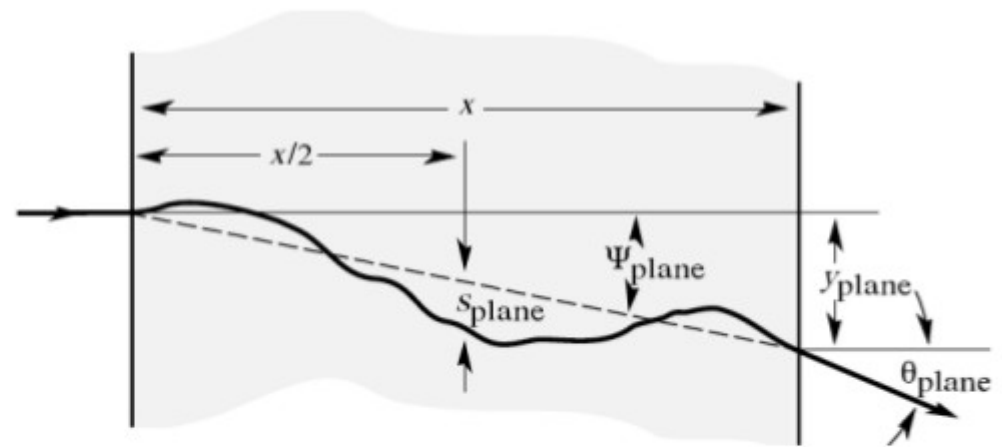
Multiple scattering(M.S.)

- Charged particles deflected in the material by an angle

$$\sqrt{\langle \theta_{MS}^2 \rangle} = \frac{15 \text{ MeV}/c}{\beta p} \sqrt{\frac{\text{thickness}}{X_{rad}}}$$

~ 0.9 mrad/(βp) for a 300 μm silicon detector

- The track propagation can be done iteratively by using the M.S. information in the chi² !
- The momentum resolution can be limited by M.S



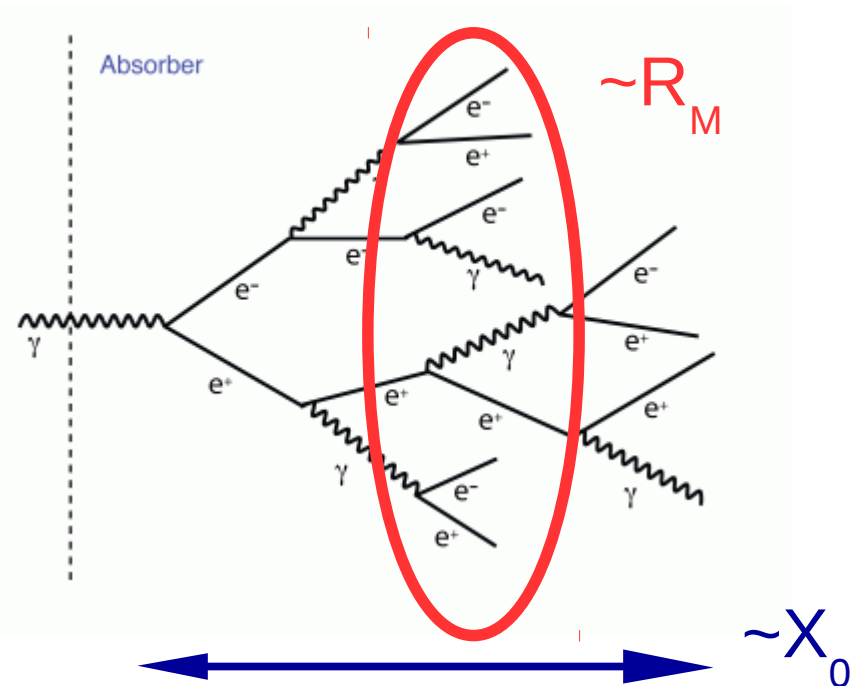
- if the uncertainties on the material are large compared to module position uncertainties

$$\frac{\delta p}{p} = \frac{1}{0.3BL} \frac{0.015 \text{ Mev}}{\beta} \sqrt{\frac{L}{X_{rad}}}$$

EM interactions

- EM interactions characterized by the radiation length(X_0):
 - Mean distance over a high energy electron loses all by $1/e$ of its energy
 - or $7/9$ of the mean free path for pair production of a high energy photon
- EM Calorimeters need to be $\sim 15-30 X_0$ to contain the shower

- Transverse position resolution of the shower depending on the Moliere radius(R_M)
 - Contains 90% of the shower energy



Calorimeter resolution

- The EM energy resolution is parameterized as

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2$$

Noise term

- Electronics or physics noise

Constant term

Statistical term

- Related to the photon counting in the photodetectors!
- Intrinsic shower fluctuations, material in front of the calorimeter, sampling fluctuations

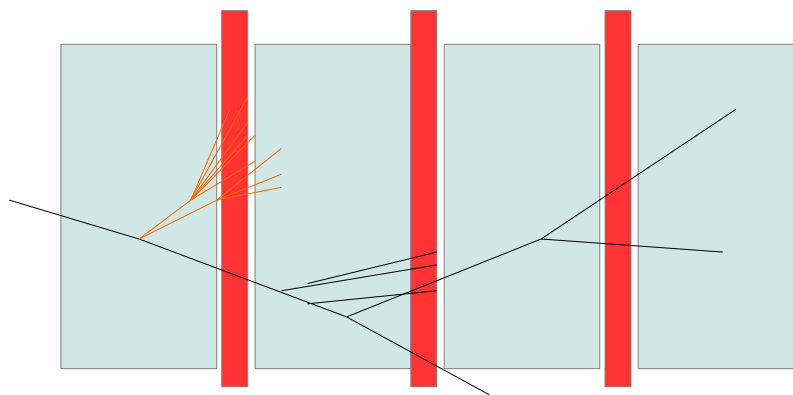
- Radiation damage, non uniformity, calibration uncertainty and energy leakage

Hadron Interactions

- Hadron interactions characterized by the interaction length (λ_I)
 - Mean free path of a hadron before ongoing a hadronic interaction
 - Typical hadron calorimeters span from 8-12 interaction lengths

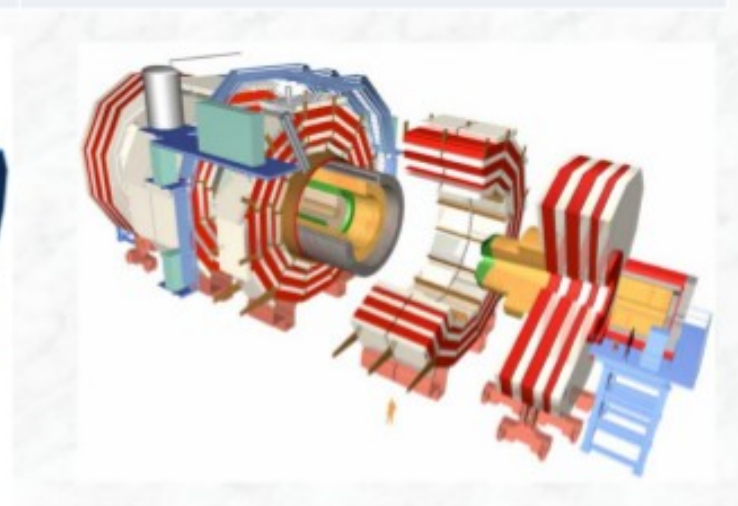
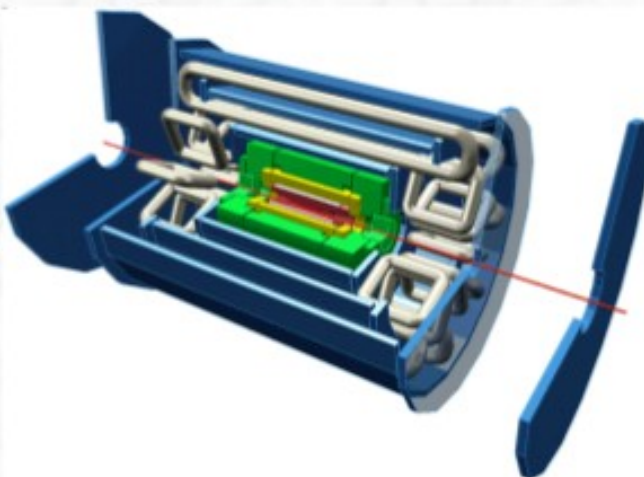
Hadron interactions \rightarrow low # particles

- In case of neutral pions, photons \rightarrow EM showers
- Charged deposit energy by ionization, excitation, interaction with nuclei
- Significant fraction of energy lost!



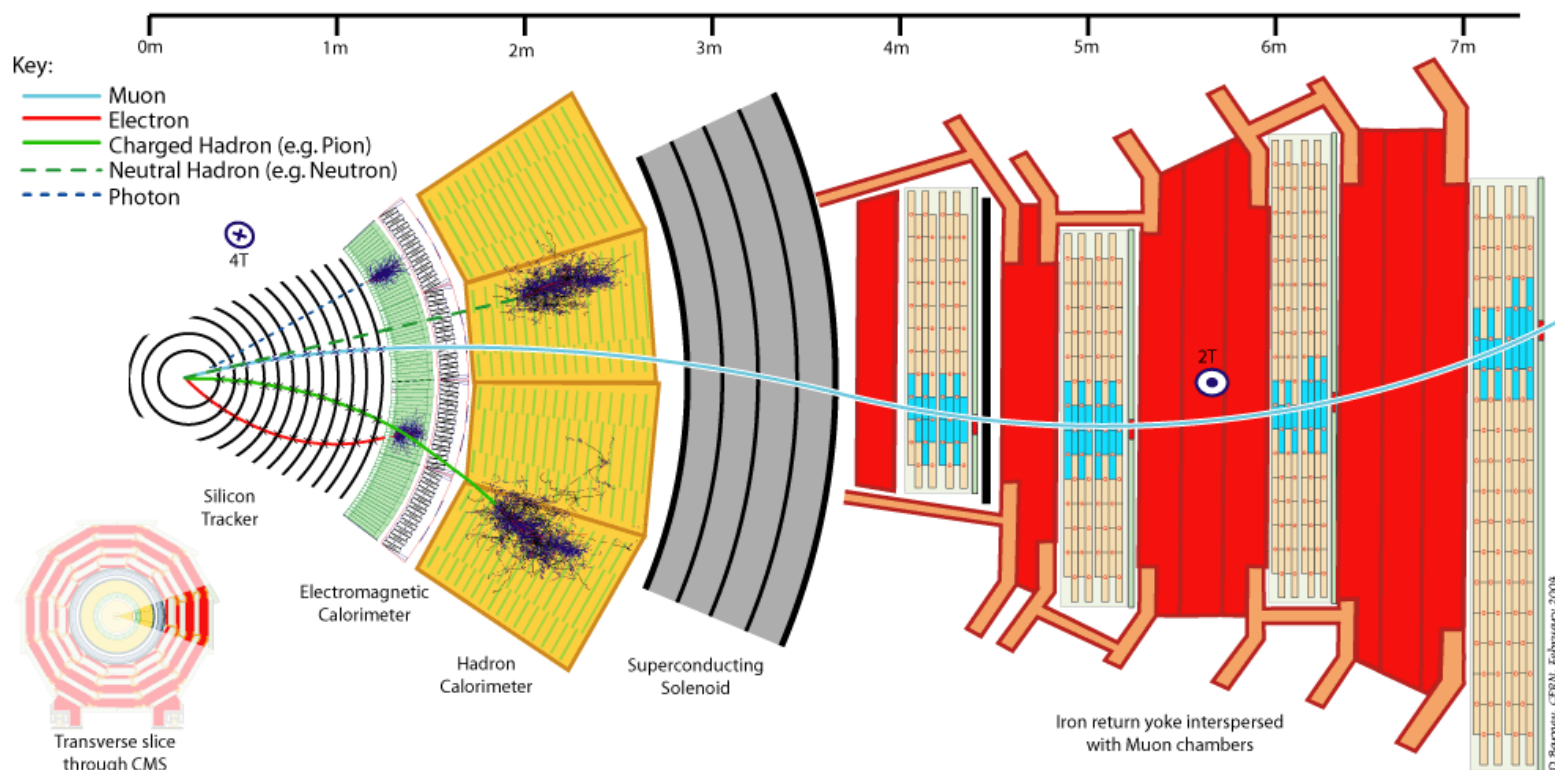
The ATLAS and CMS Detectors

	ATLAS	CMS
Magnetic field	2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)	4 T solenoid + return yoke
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$	Silicon pixels and strips (full silicon tracker) $\sigma/p_T \approx 1.5 \cdot 10^{-4} p_T + 0.005$
EM calorimeter	Liquid argon + Pb absorbers $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO ₄ crystals $\sigma/E \approx 3\%/\sqrt{E} + 0.003$
Hadronic calorimeter	Fe + scintillator / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Brass + scintillator (7 λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)	$\sigma/p_T \approx 1\%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)
Trigger	L1 + HLT (L2+EF)	L1 + HLT (L2 + L3)



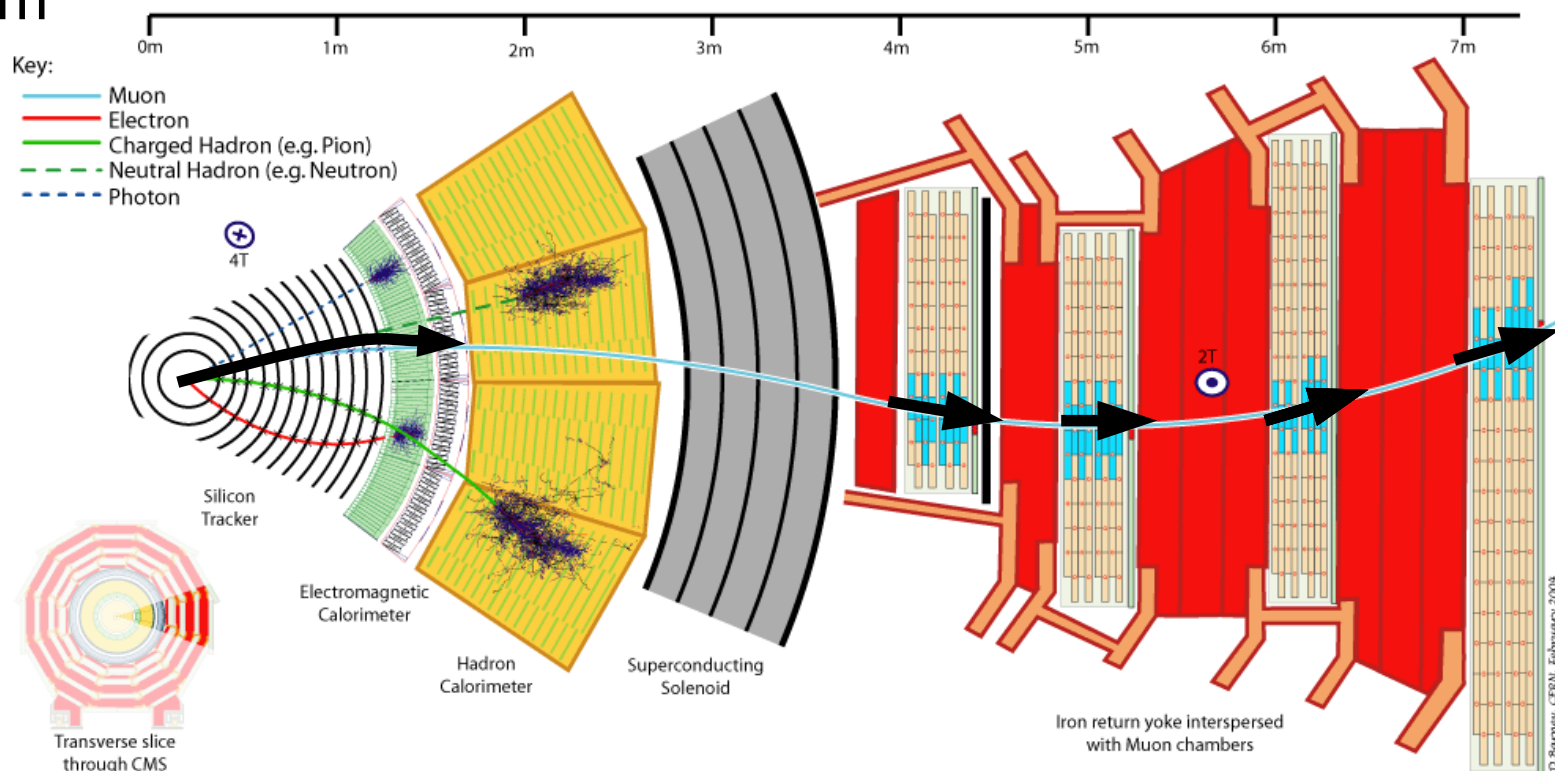
Muon Identification

- Muons identified as penetrating tracks through the whole detector
 - Starting from an inner track and reconstructed local segments in the muon system
- Different reconstruction philosophies used based on the transverse momentum and required purity



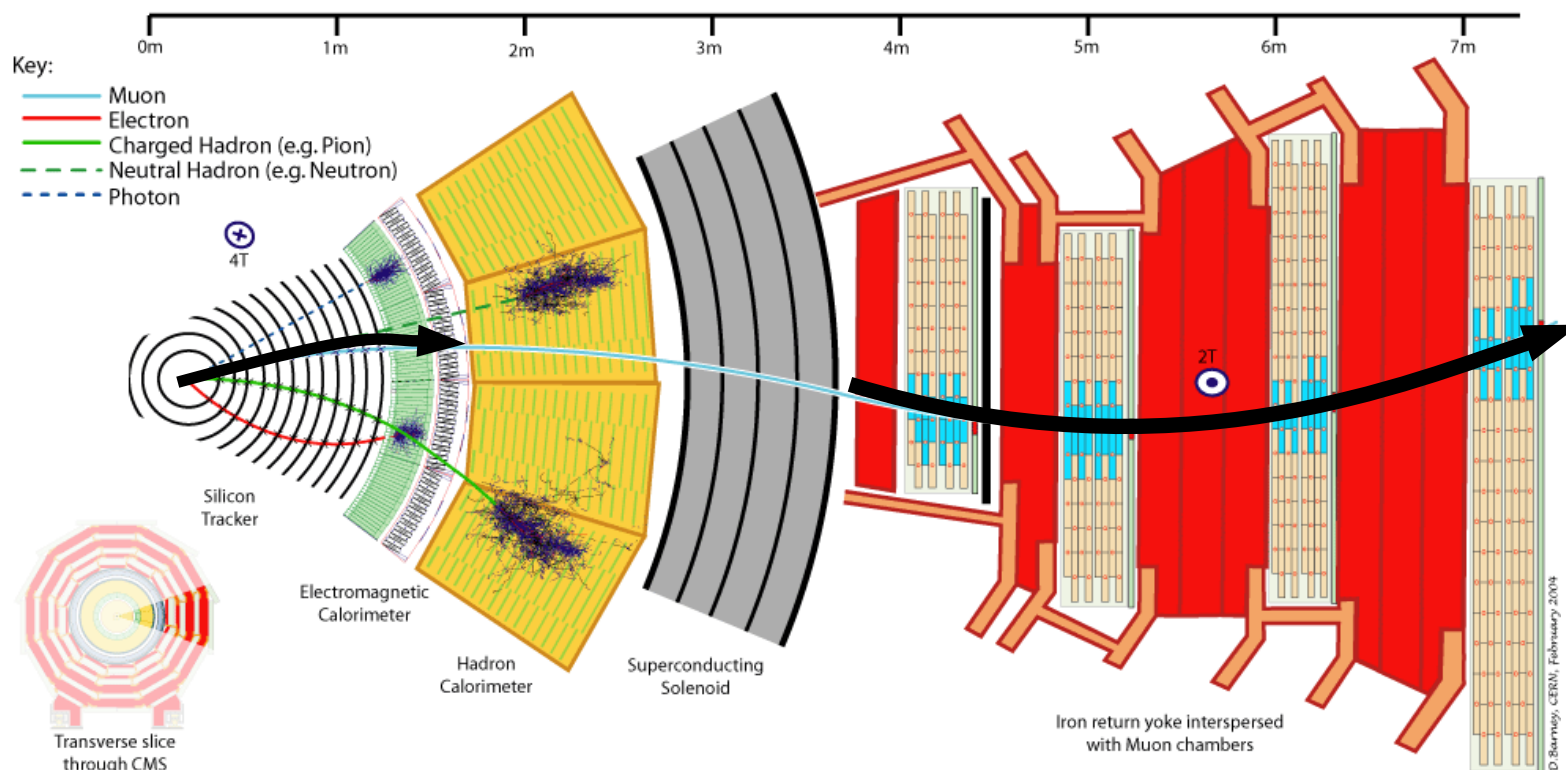
Inside-Out muons

- Segments are reconstructed in the muon system
- Inner tracks are extrapolated [taking into account the material] and are matched to segments
- The muon momentum is derived by the tracker track
- Suitable for low pt muons that do not penetrate the whole muon system



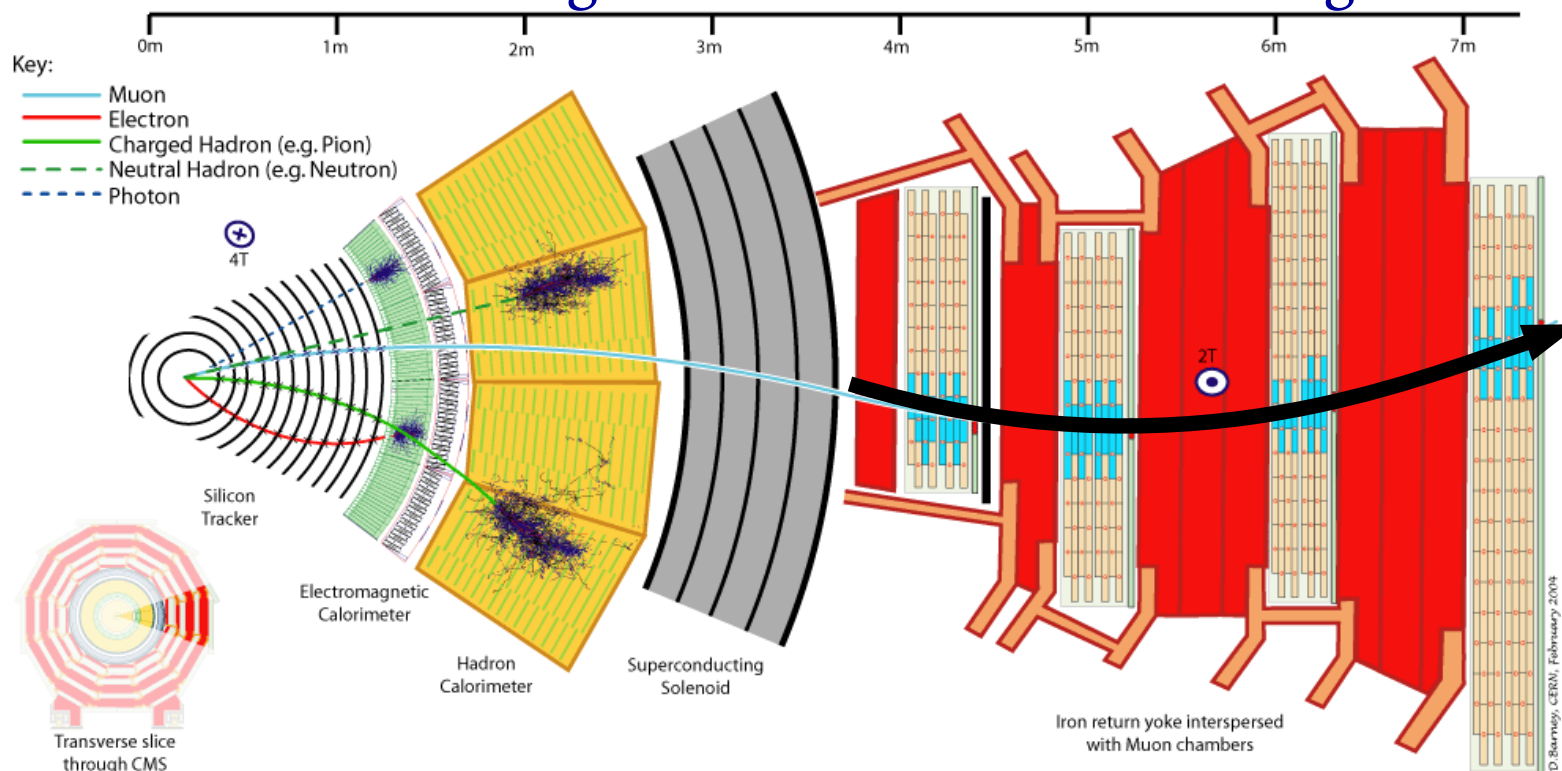
Combined muons

- Full standalone tracks are reconstructed in the muon system
- Inner and standalone tracks are extrapolated and matched
- Combined tracks are made
- Muon momentum comes from the combined track at high P_t or from inner track in the region that the tracker dominates



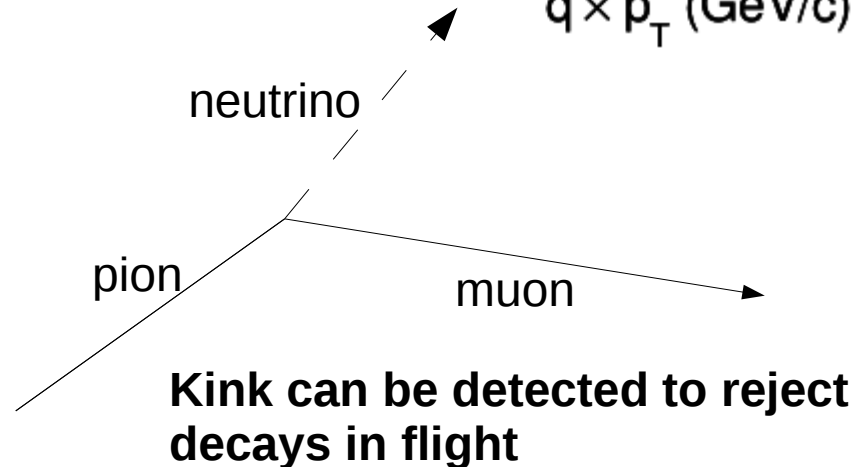
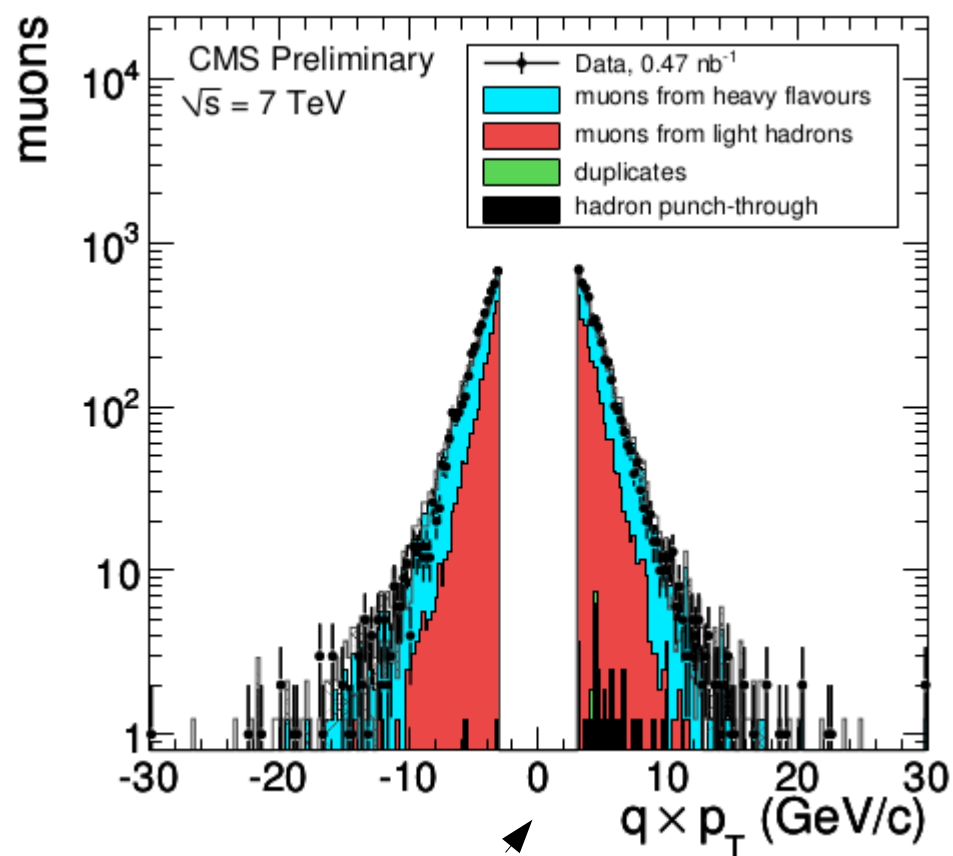
Standalone Muons

- Tracks only in the muon system (extrapolated to vertex)
 - Not very much used due to the low purity
- In the case of CMS, standalone resolution limited by muon detector resolution and M.S. in iron yoke
- In the case of ATLAS standalone track has very good resolution
 - Used in the forward region outside tracker coverage



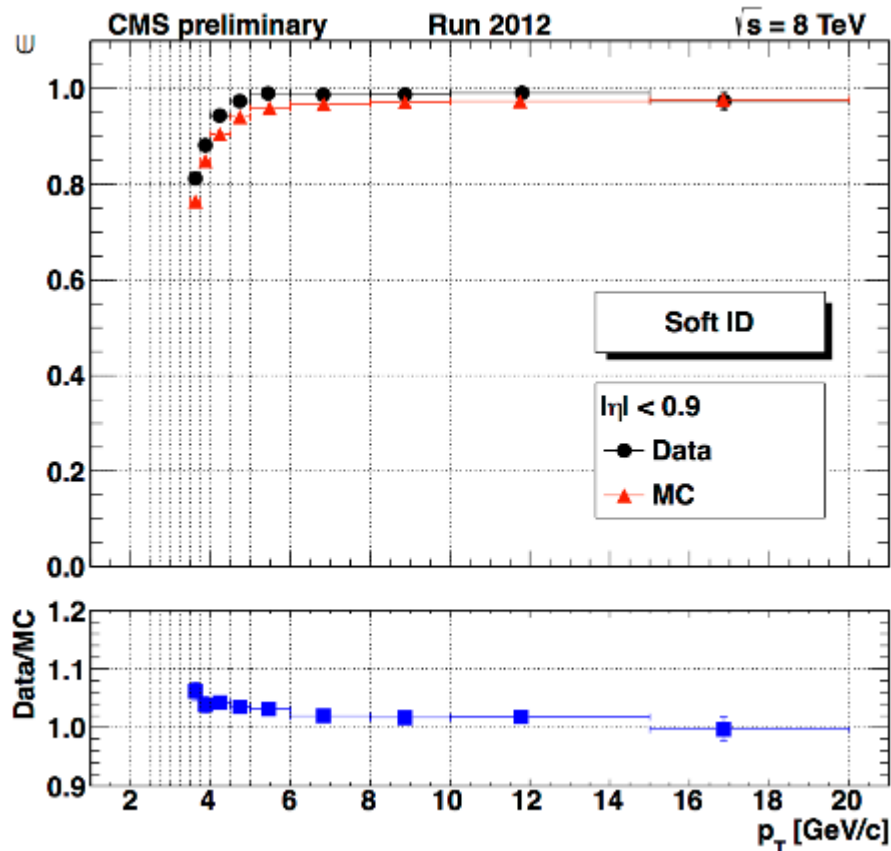
Muon backgrounds

- Semileptonic decays of heavy quarks
 - Real muons inside jets
- Decays in flight of pions and Kaons
 - Pion becoming a muon far from the vertex and penetrates the muon system
- Punch through hadrons
 - Particles that escape the calorimeter into the muon system

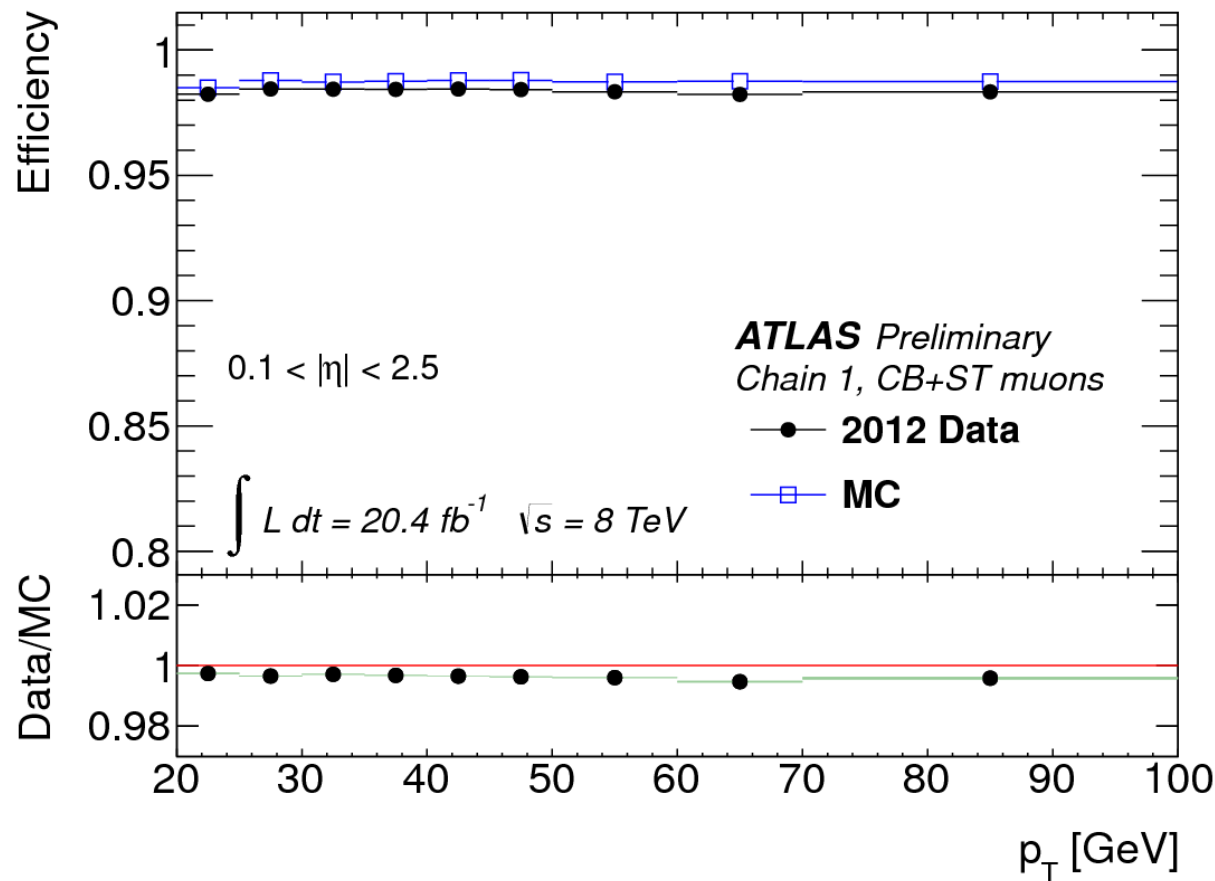


Muon Identification efficiency

Low pt muons @ CMS

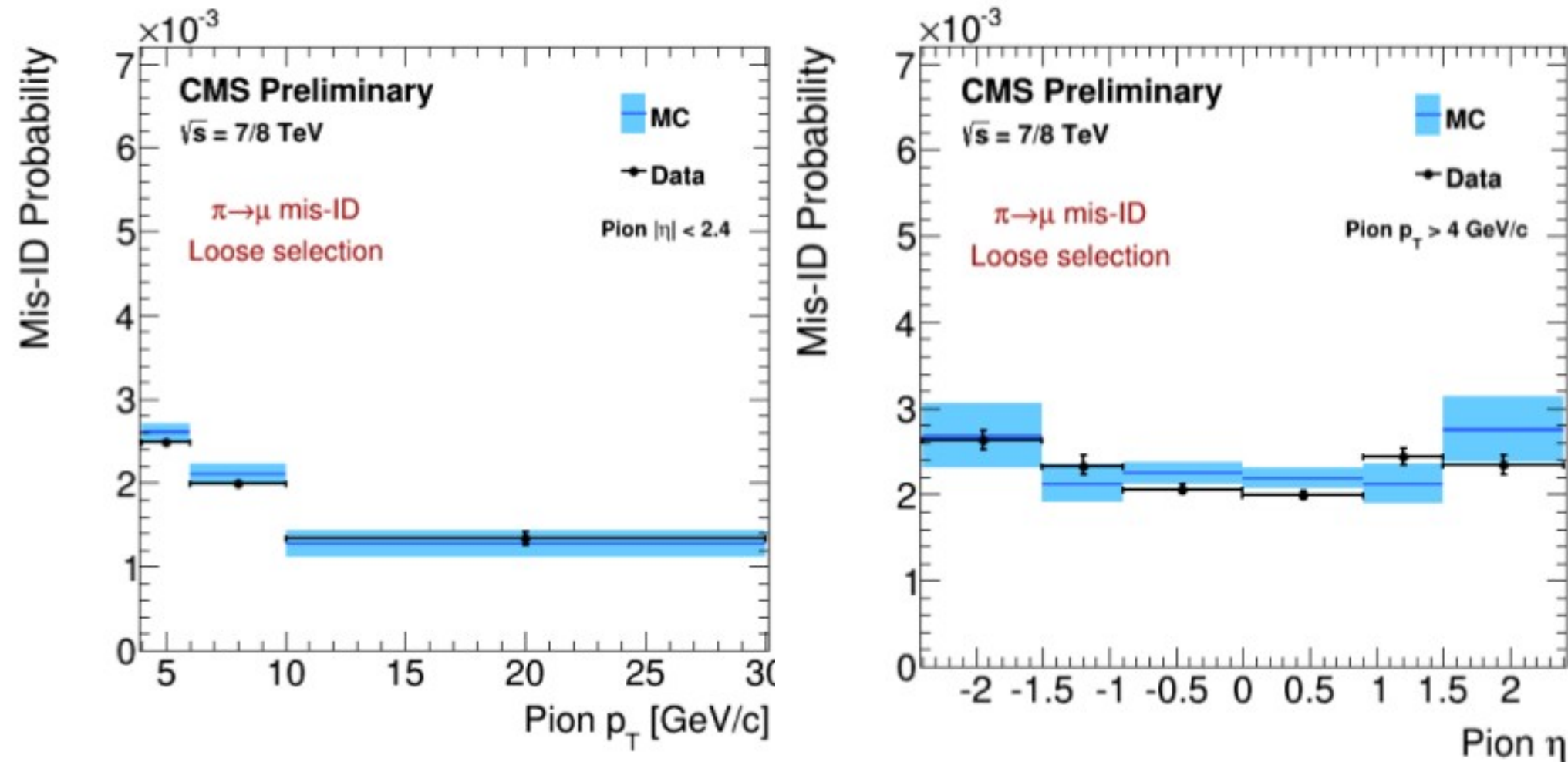


High pt muons at ATLAS



- Muons are the workhorse of major physics searches!
- Extremely pure and very precisely measured!

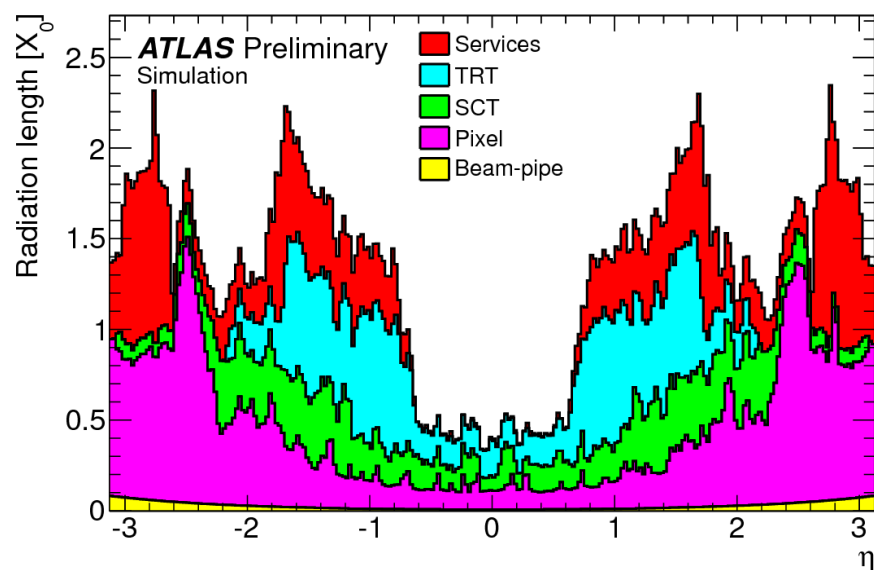
Muon fake rate from pions



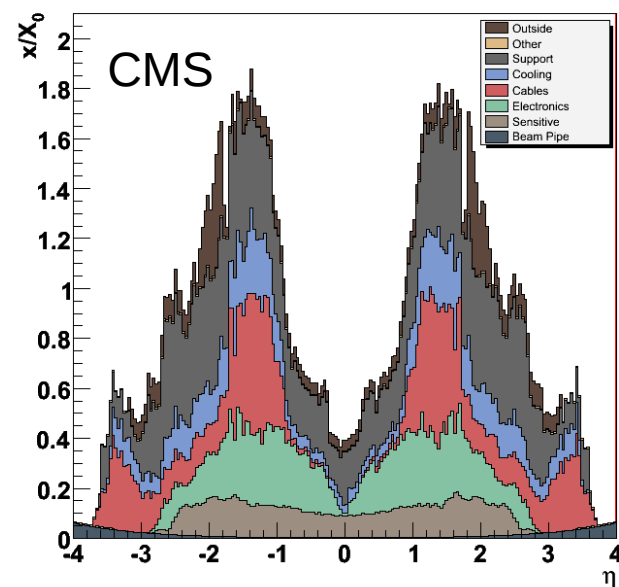
- Fake rate from pions @ 10^{-3} level
- Main background in the muon final states from real muons in other processes

Electron Identification

- Electrons are identified by a track connected to an EM deposit.
 - EM deposit often broad due to shower in the tracker material
- Tracker material budget → crucial for electron ID
 - Both ATLAS/ CMS → a lot of material



Tracker Material Budget

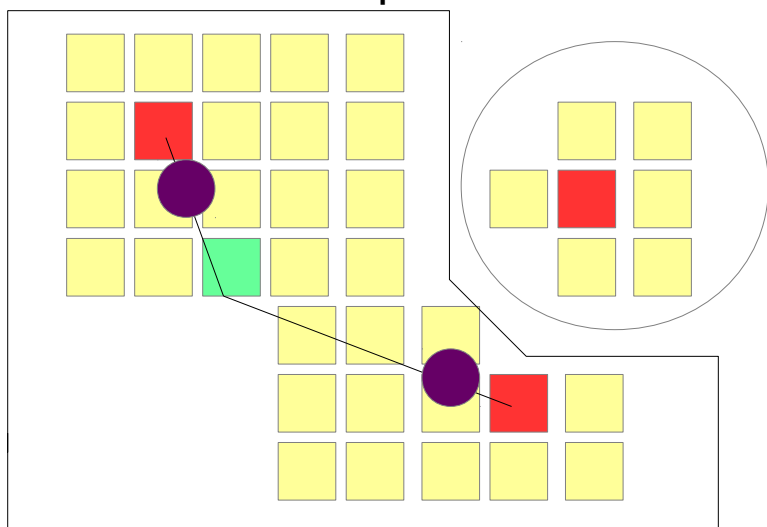


Calorimeter clustering

- Identify individual energy deposits in the calorimeters
 - Specific algorithm depends on calorimeter technology + granularity

- **Example: CMS ECAL**

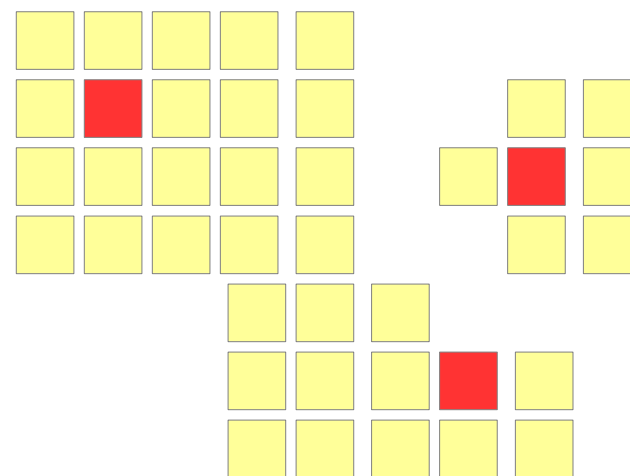
3. Make clusters from seeds and share hits in the same topo cluster



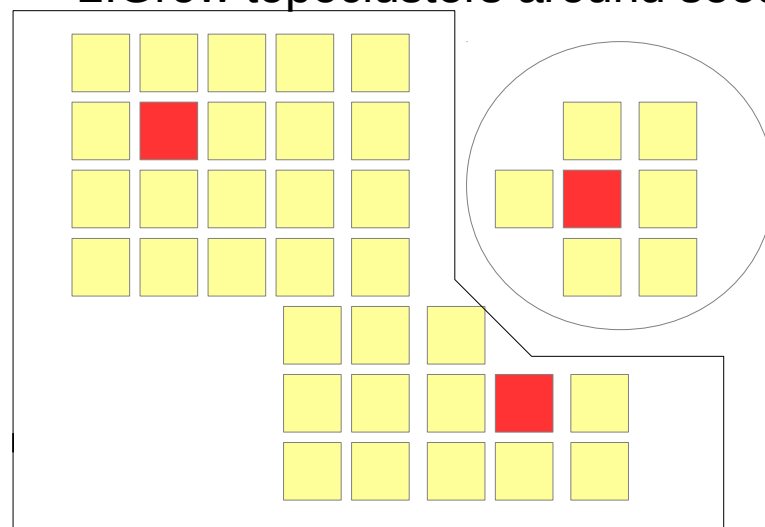
seed

active cell

1. Identify local maxima as seeds

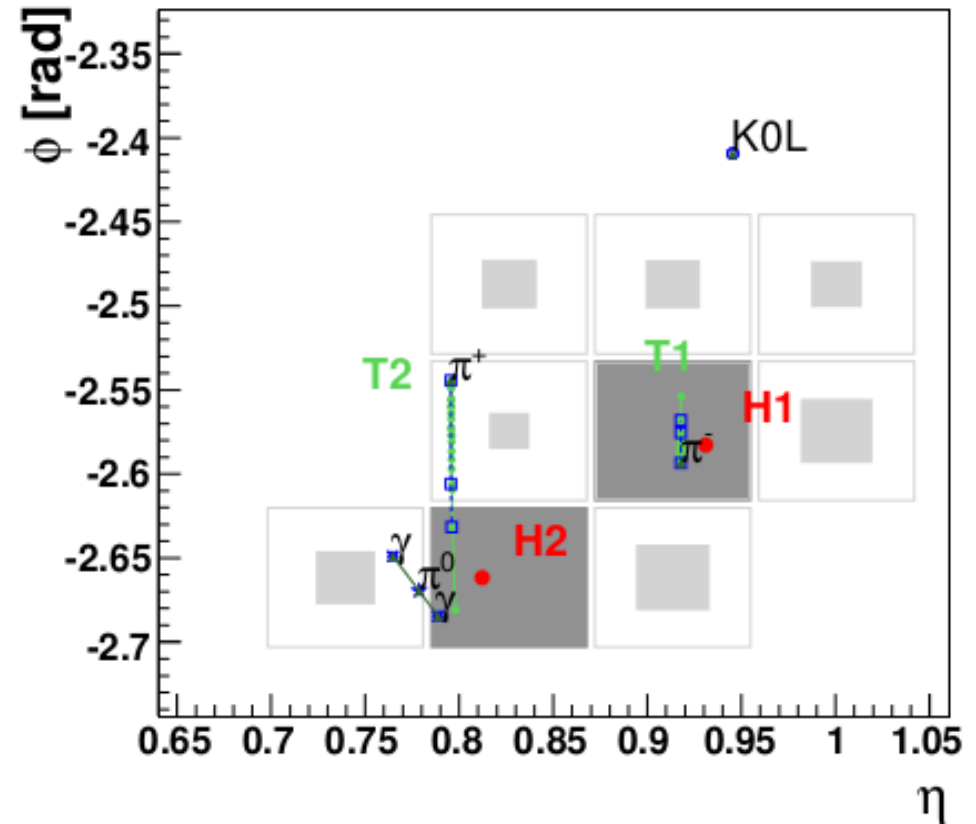
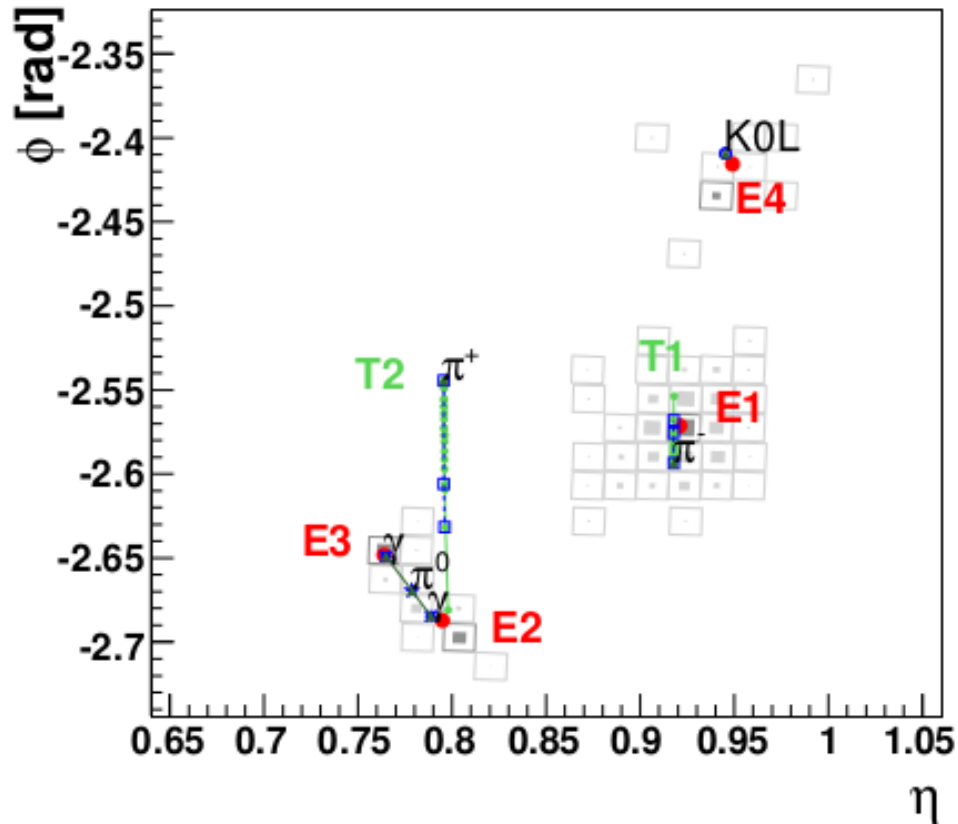


2. Grow topoclusters around seeds



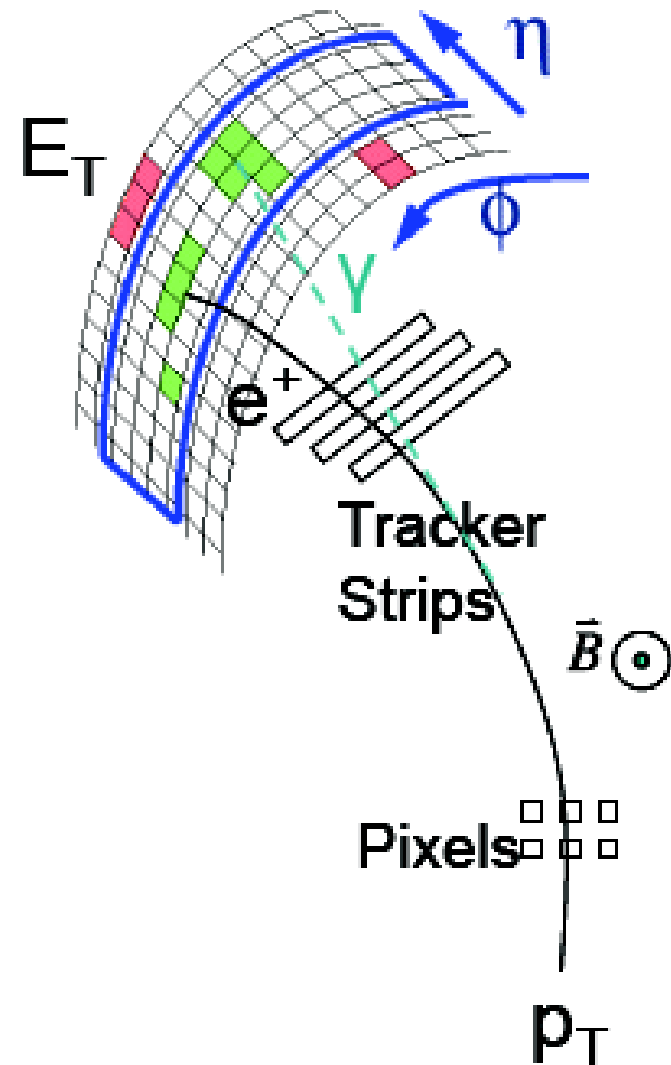
Clustering in reality

- Calorimeter clustering in CMS ECAL and HCAL



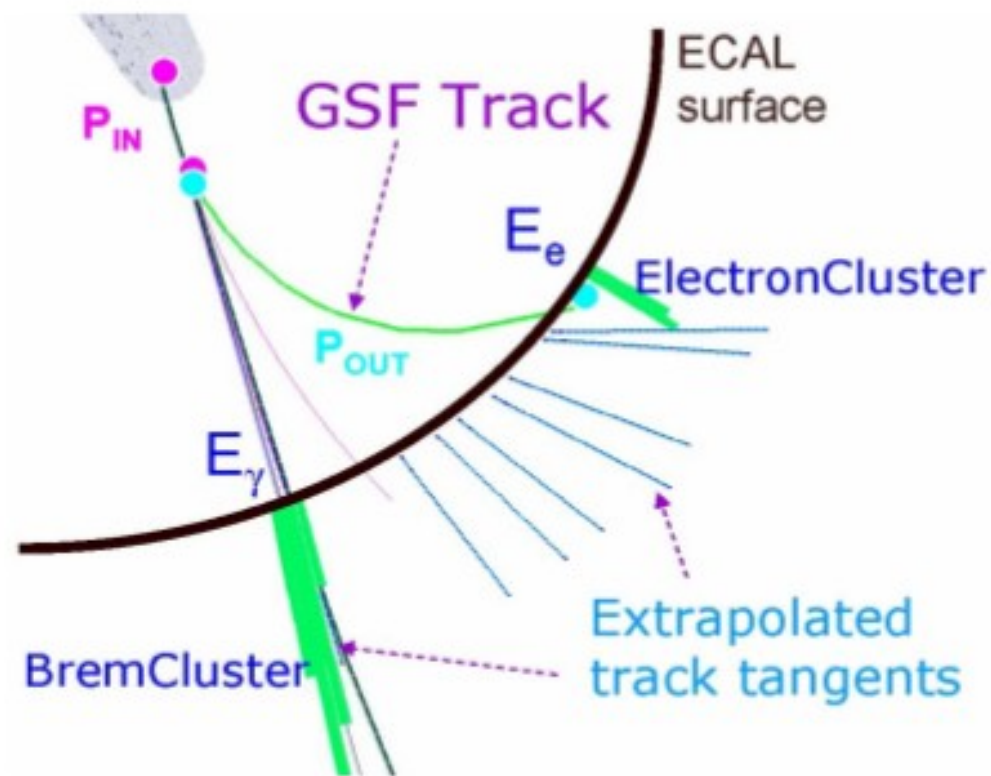
Outside -In Electrons

- Used in ATLAS and CMS
- An EM cluster is built in the ECAL
 - In case of high granularity, a cluster of clusters is made
 - by growing in phi to account radiation
- Cluster seeds tracking with the GSF algorithm
 - Takes into account energy loss
- Track -Calorimeter observables are created for ID

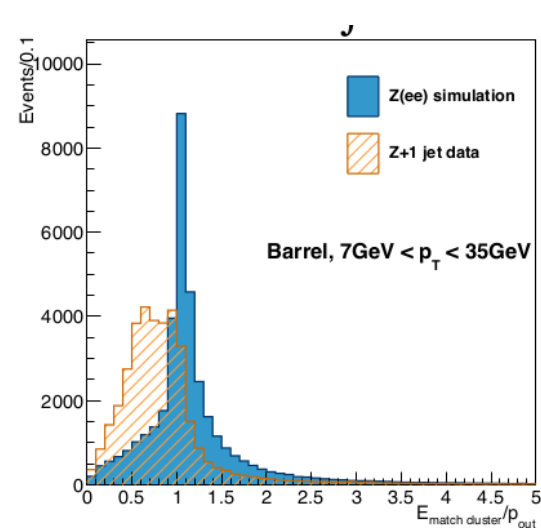
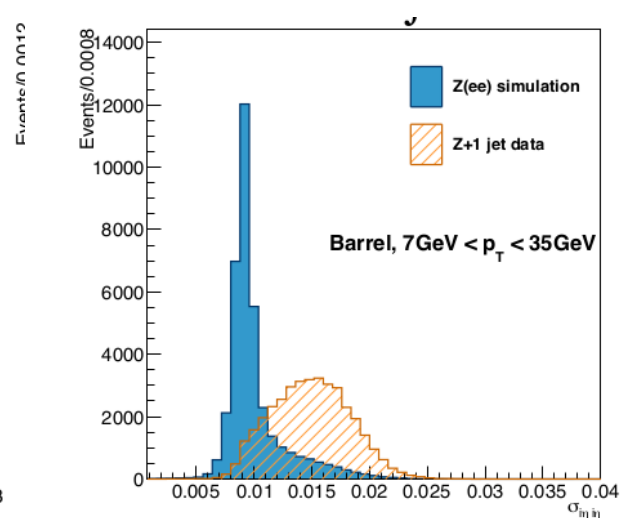
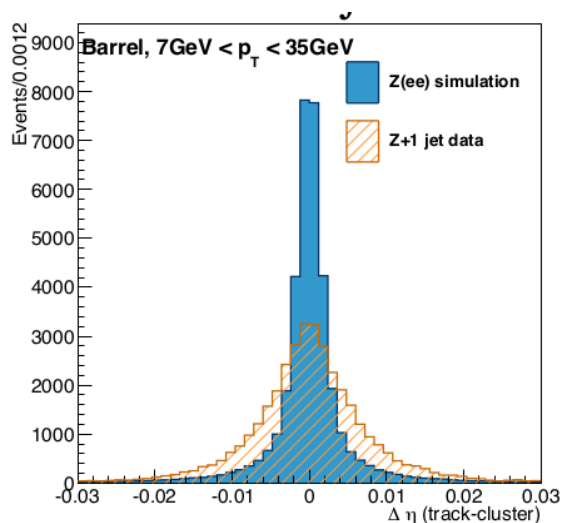


Inside-Out Electrons

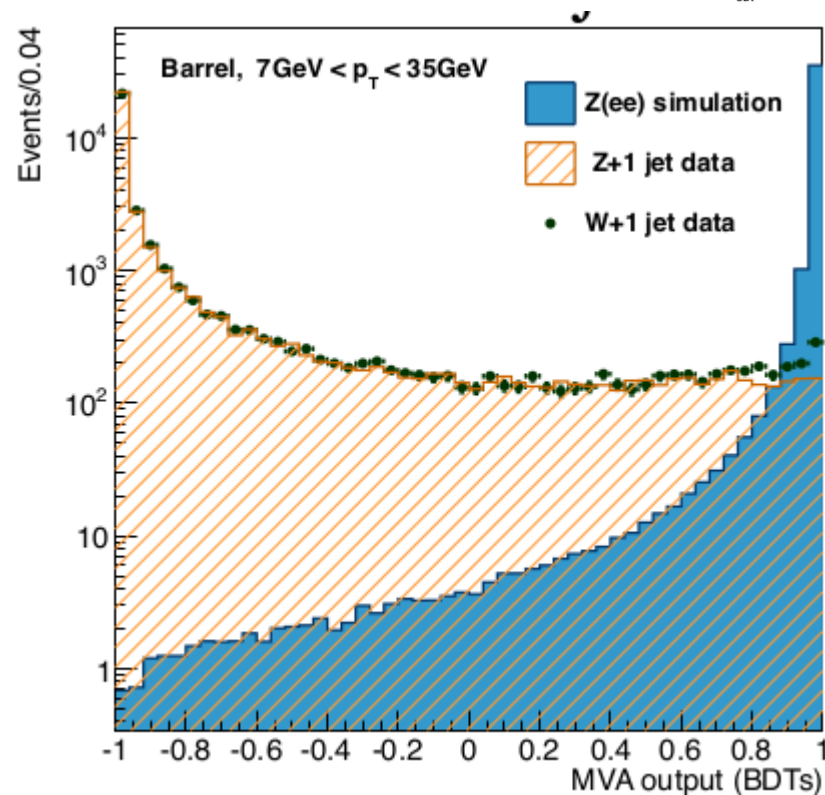
- Used at CMS at low p_t
- Starting from a track extrapolate tangents to collect brem photons
- Then a GSF track is built from the standard track
- Track and clusters are linked and combined observables are formed



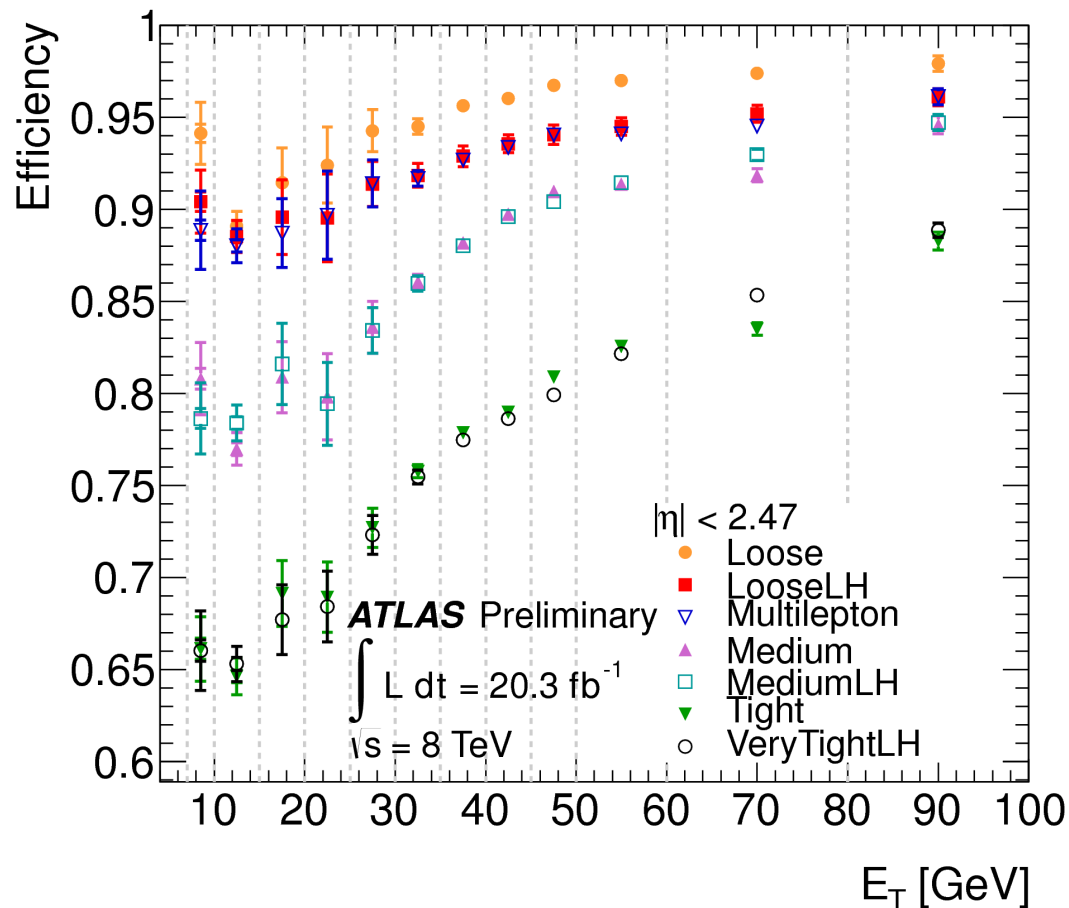
Electron ID observables



- Good discrimination for the electron observables
- Can be combined through a MVA technique [BDT/LHR] to boost performance

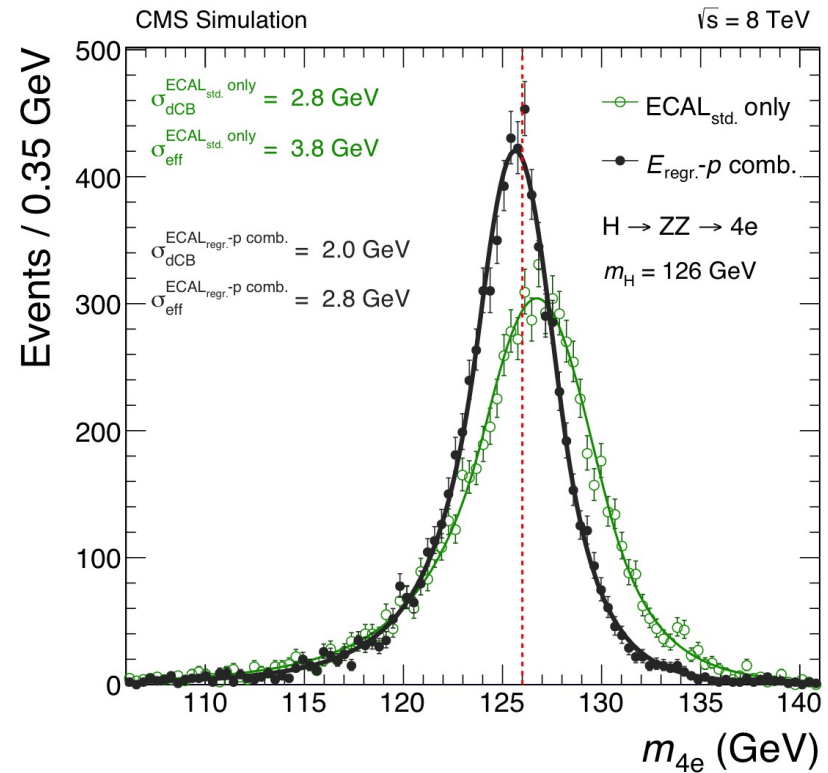
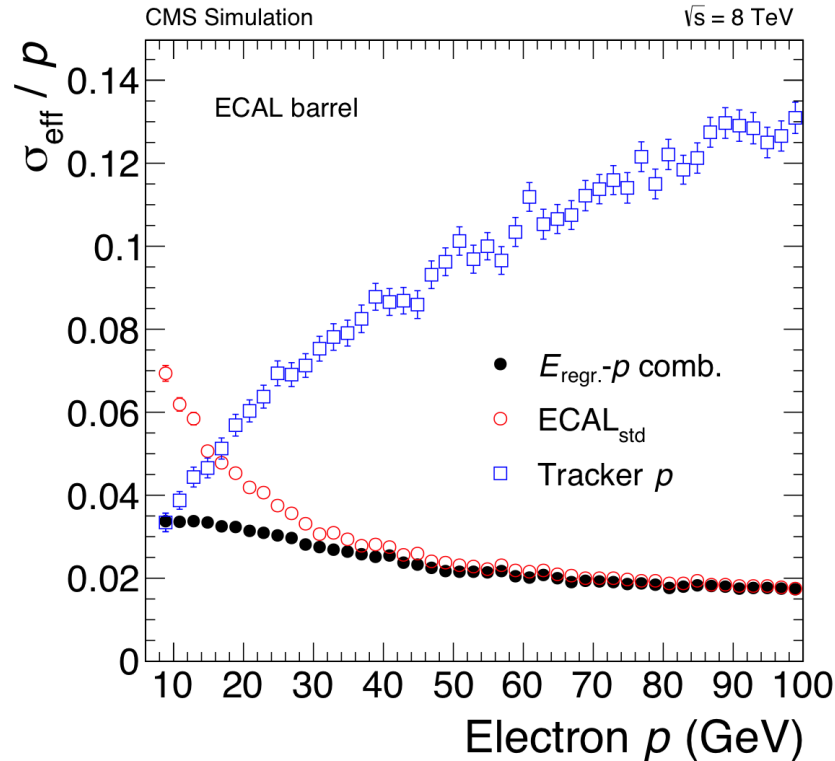


Electron Identification efficiency



- Several working points are used based on the required background rejection in the analysis!
- In the case of electrons backgrounds come from EM fluctuations in jets

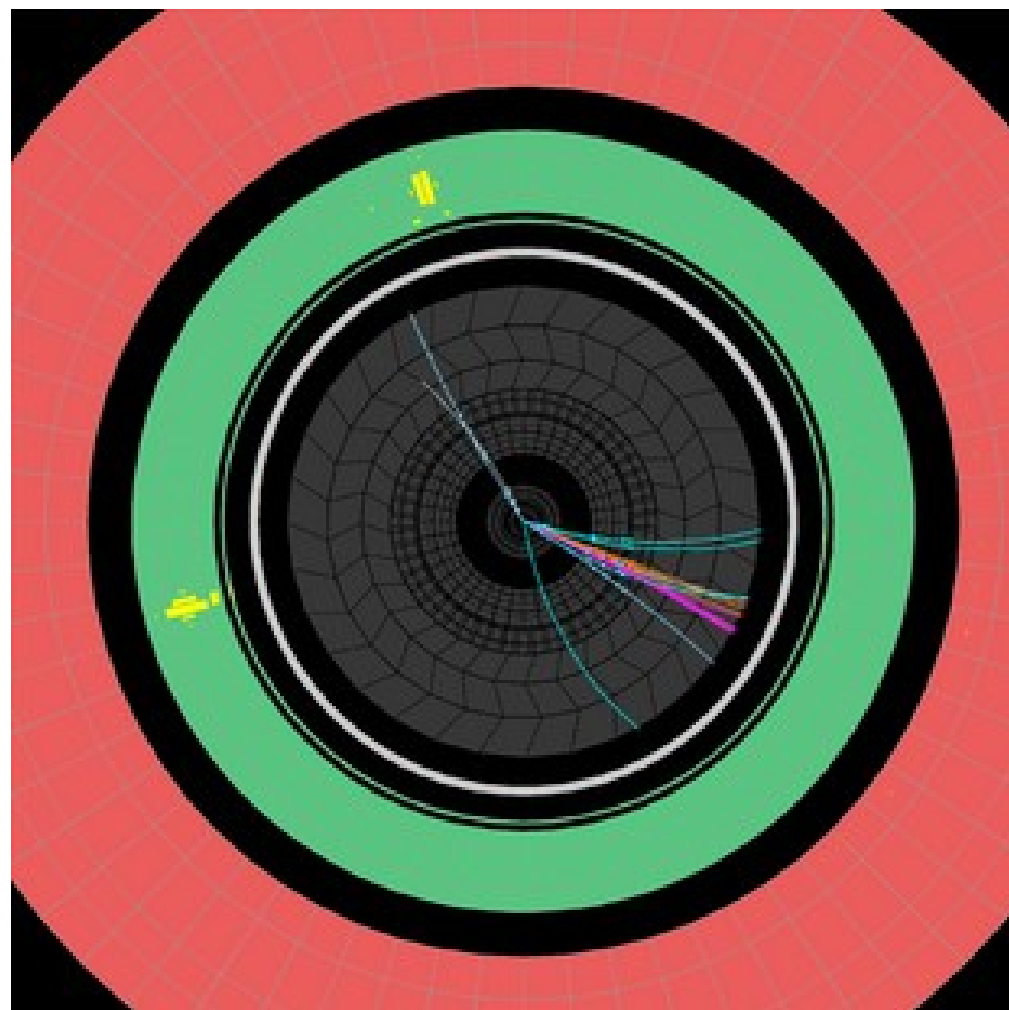
Electron momentum measurement



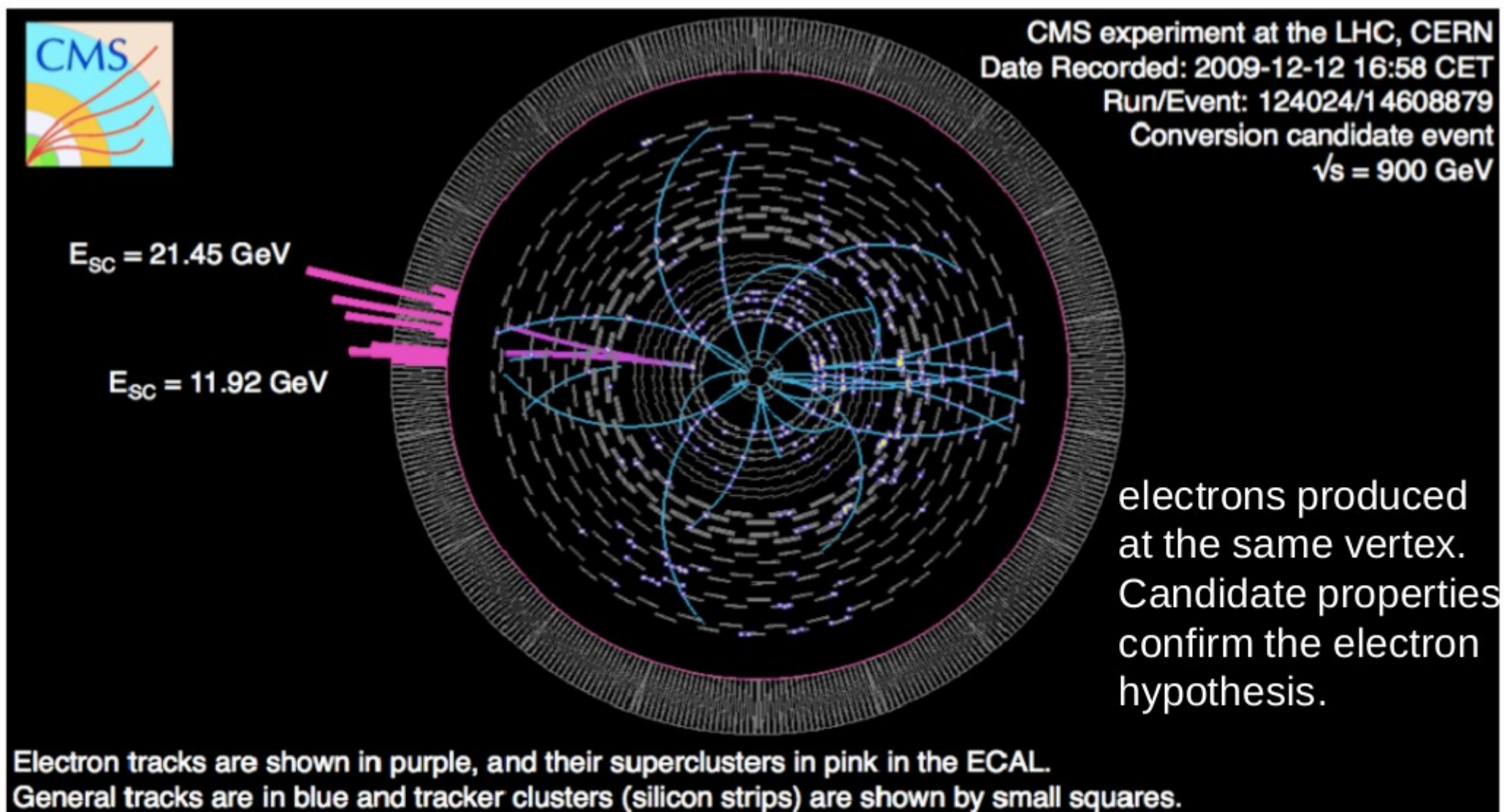
- ECAL is dominating the measurement at higher Pt
 - Tracker dominates at low pt!
- Combine both using a simple combination or MVA technique to get best performance!

Photon reconstruction

- Exactly the same technique as the electron in the calorimeter
 - Broad cluster is used to account for conversions in the tracker material
- Conversions can also be tagged by reconstructing electron tracks
 - And their invariant mass



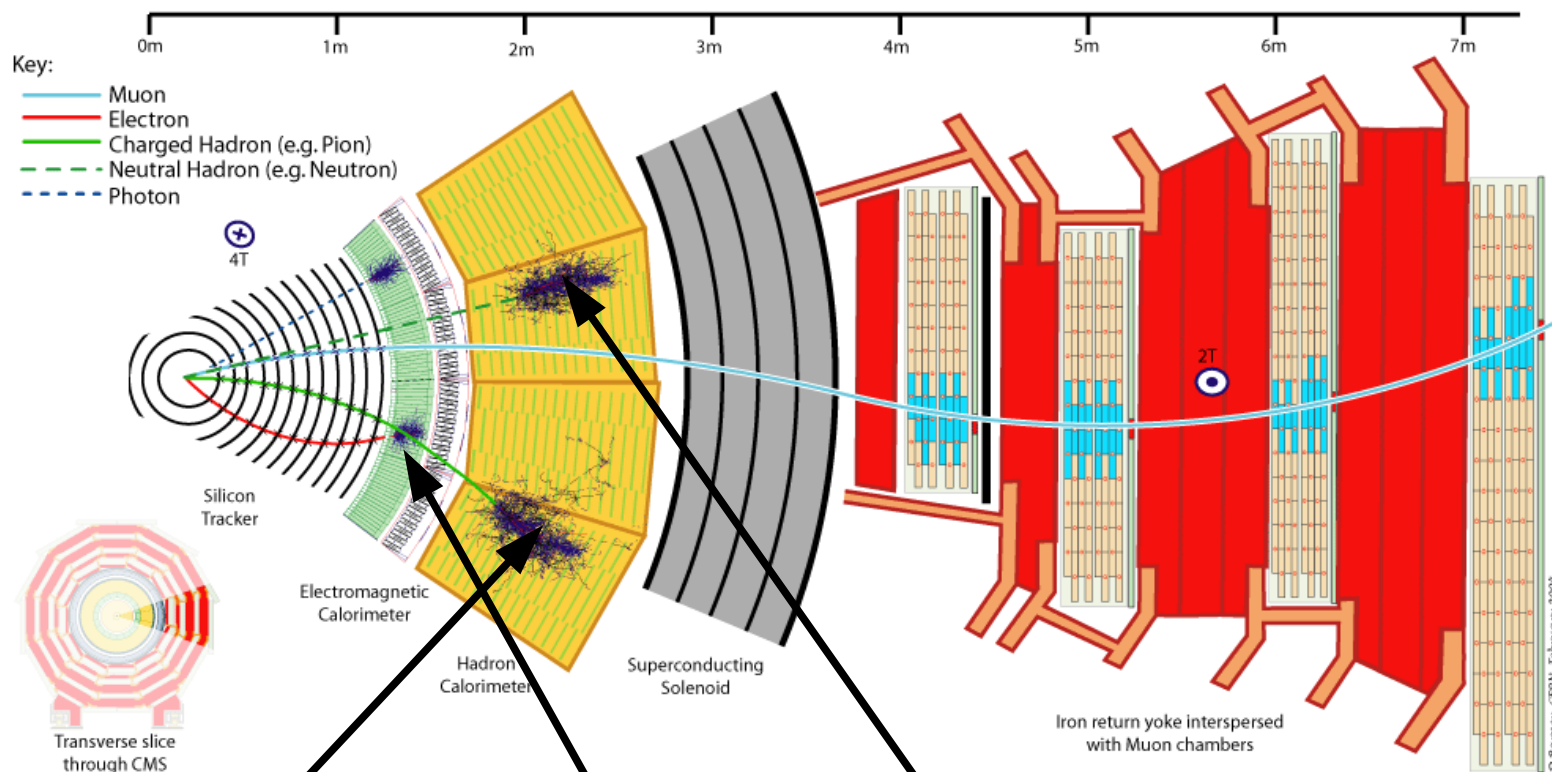
Conversion reconstruction



The Particle Flow approach

- The idea of Particle Flow is to combine information from all sub-detectors to reconstruct a mutually exclusive list of particles(PF candidates)
 - Charged hadrons
 - Neutral Hadrons
 - Photons
 - Electrons
 - Muons
- The list of PF candidates can be used to create higher level physics objects such as Jets, hadronic tau decays, MET

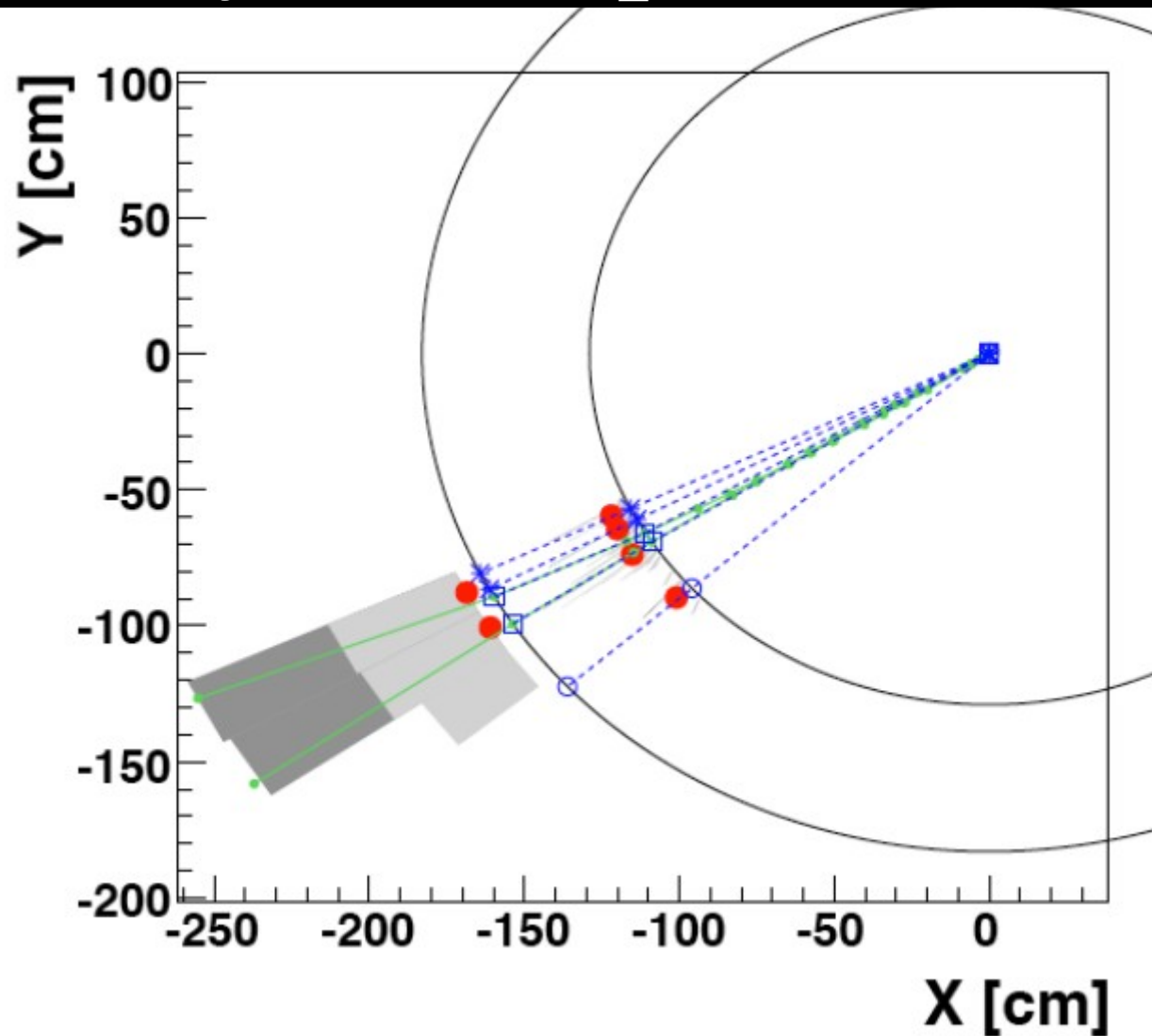
The gains of PF



- HCAL resolution much worse than tracker
 - In case of charged hadrons the momentum is calculated from the track
 - More precise

- Low HCAL resolution affects only neutral hadrons
 - 10% of a jet energy
- Photons are measured with very precise and high granularity ECAL

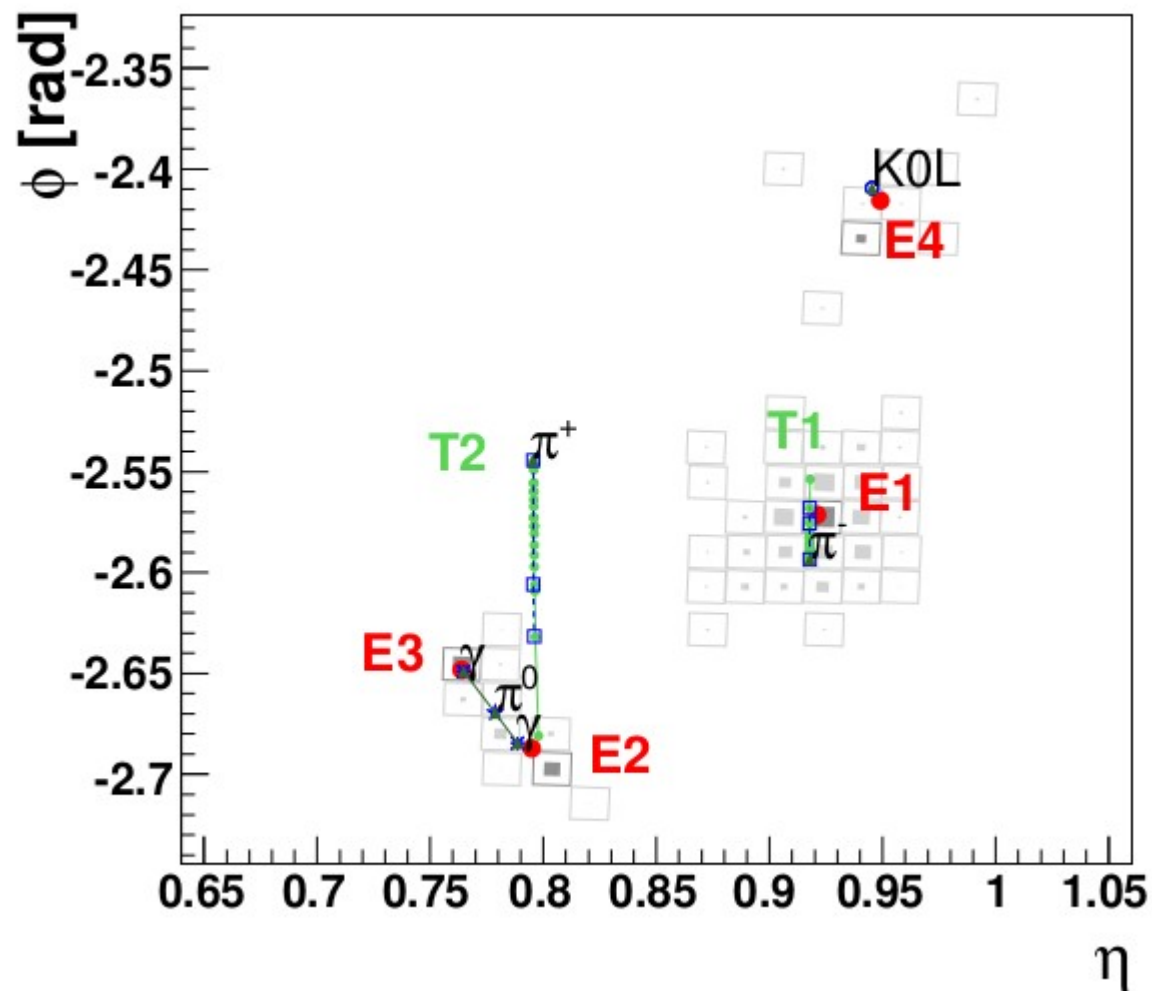
Example : a jet of 4 particles



- A 65 GeV jet of a K^0 , π^+ , π^- , π^0

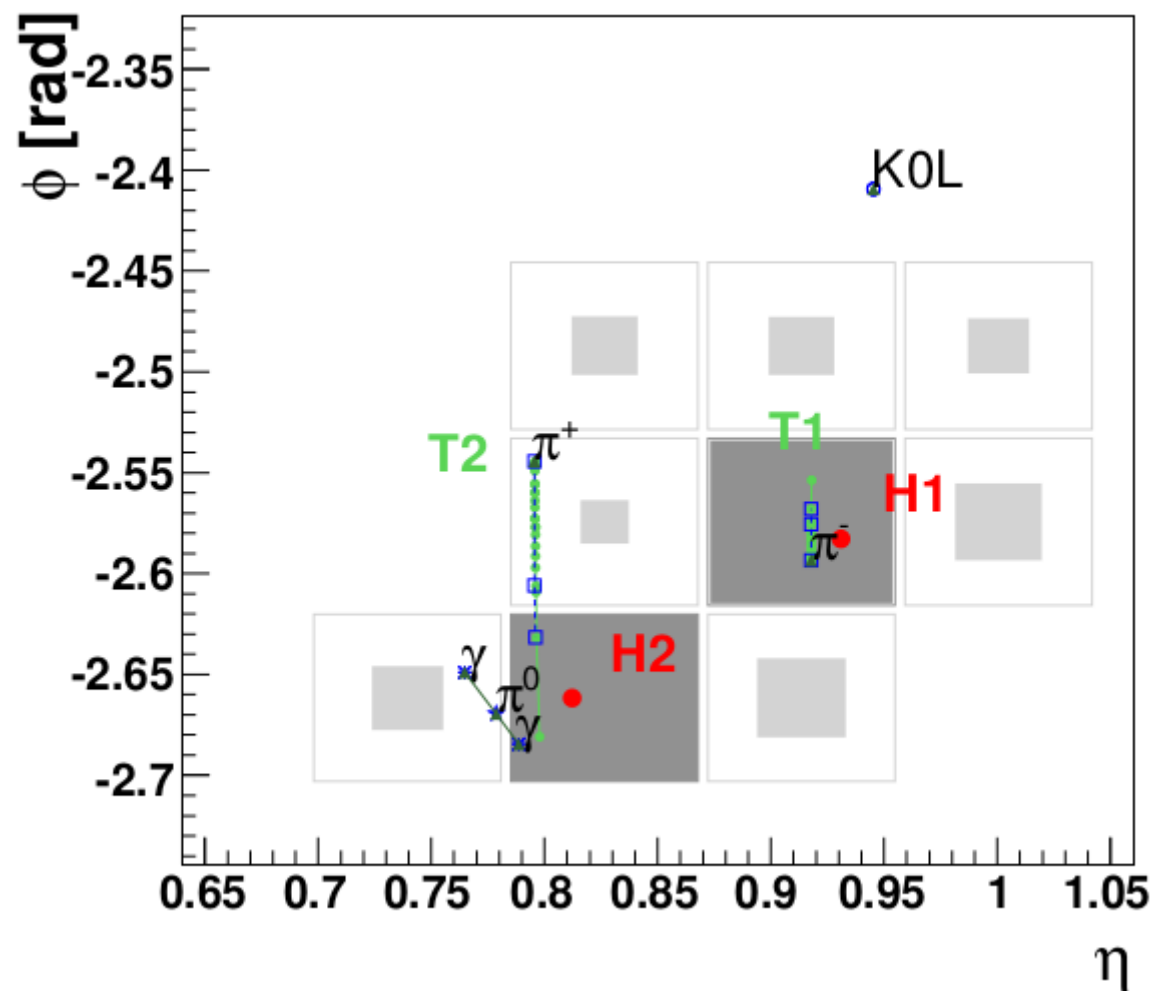
ECAL deposits

- The neutral pion forms two clusters for the two photons
- The K_0 interacts mainly in ECAL forming a cluster
- The π^- deposits also some ECAL energy forming another cluster

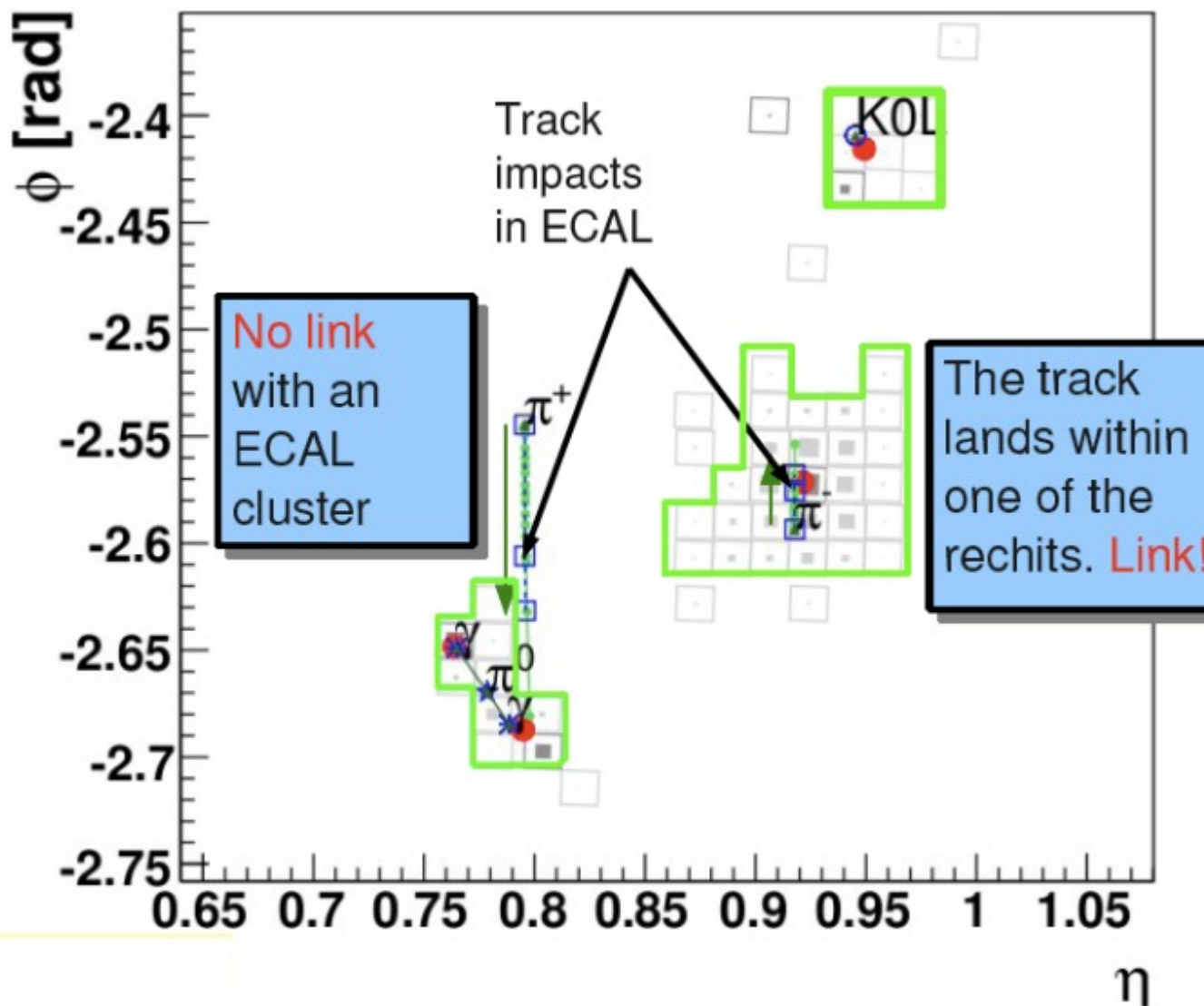


HCAL deposits

- HCAL much lower granularity
- Two clusters formed by two charged pions
- K^0 doesn't deposit significant energy



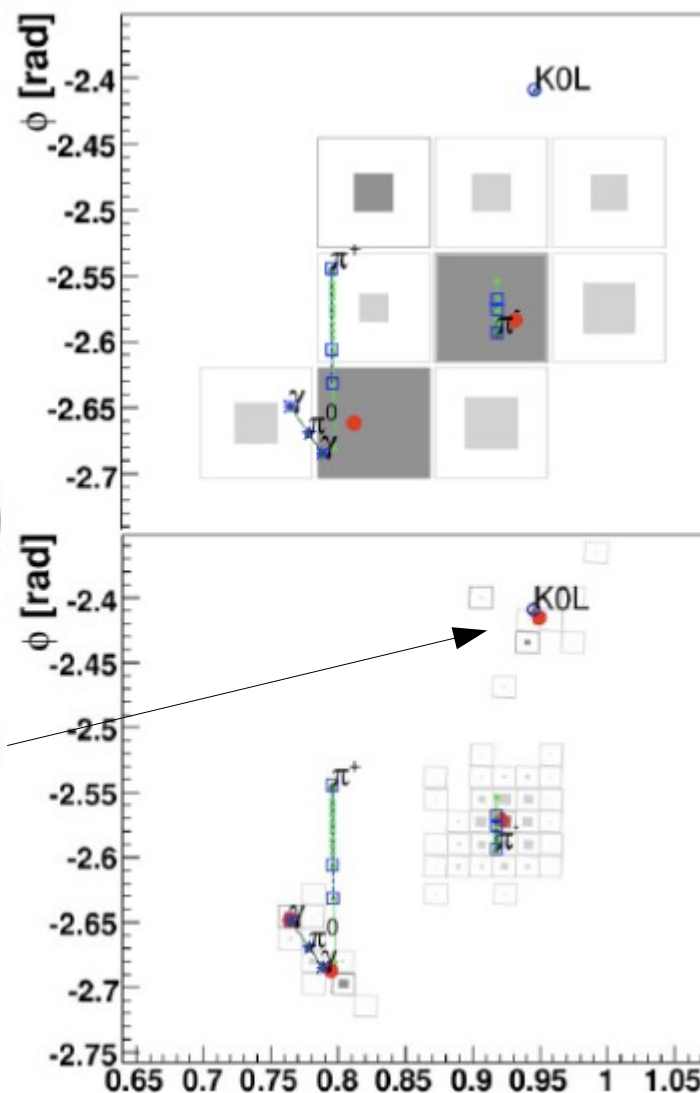
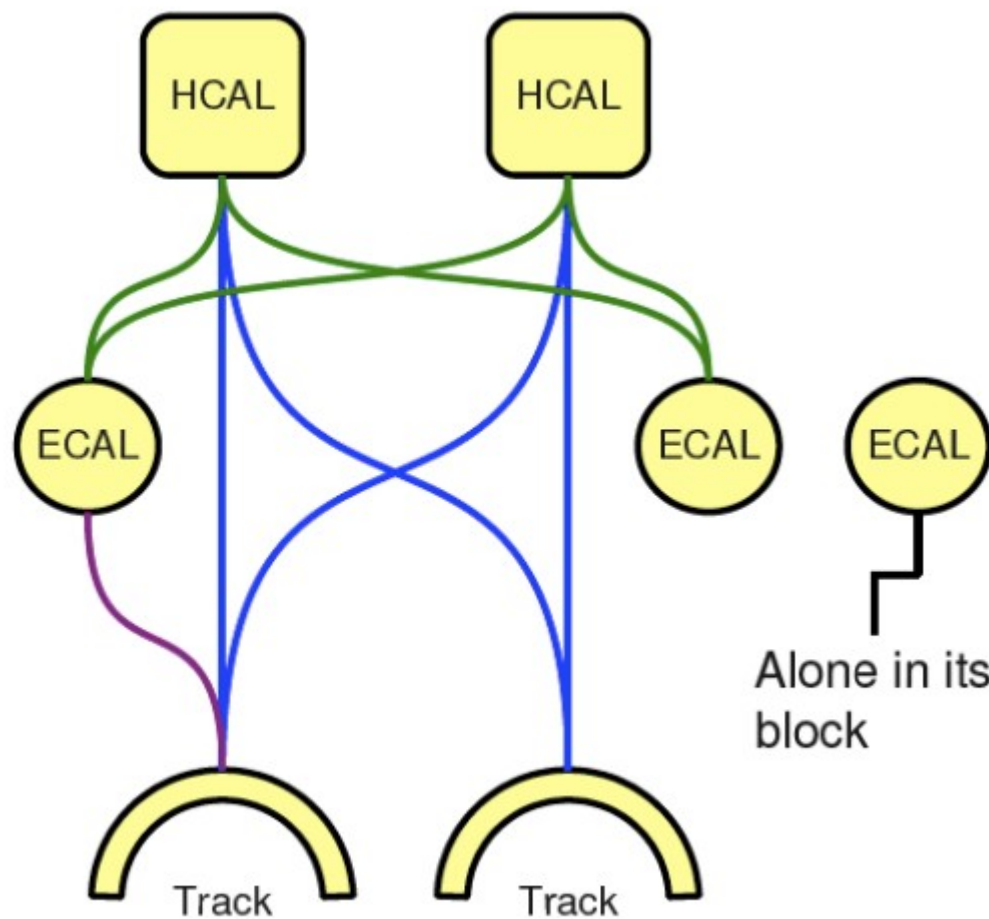
Track -ECAL linking



- If track lands on one of the rechits link track+ECAL
 - Happens only for the π^- in this example

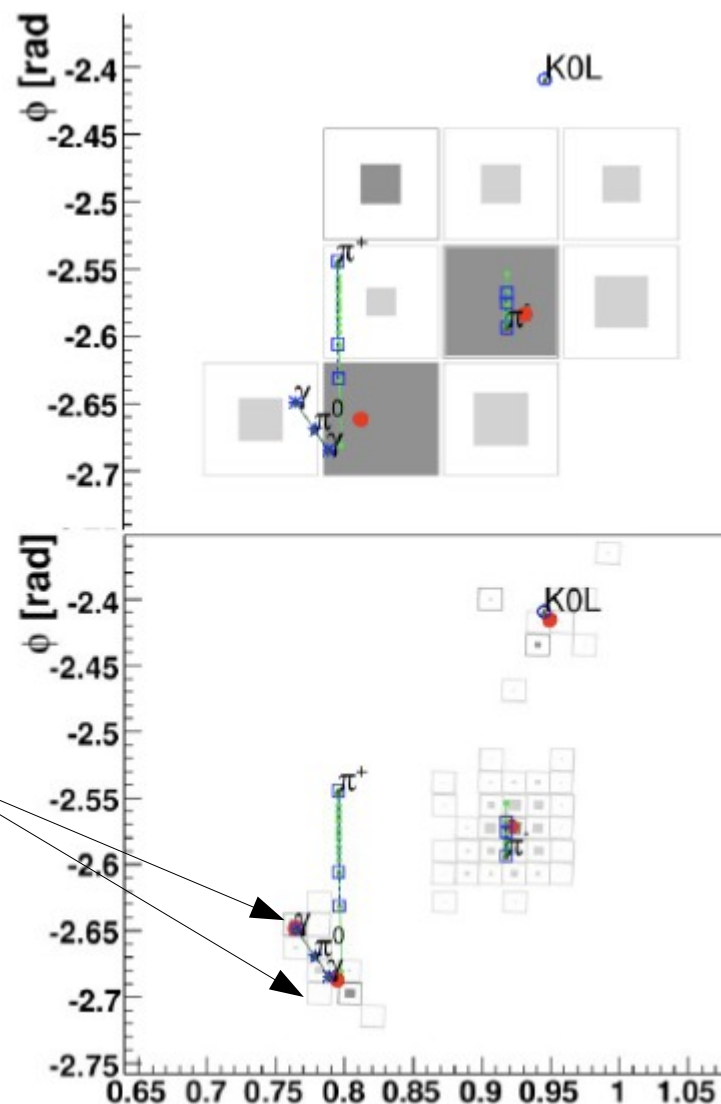
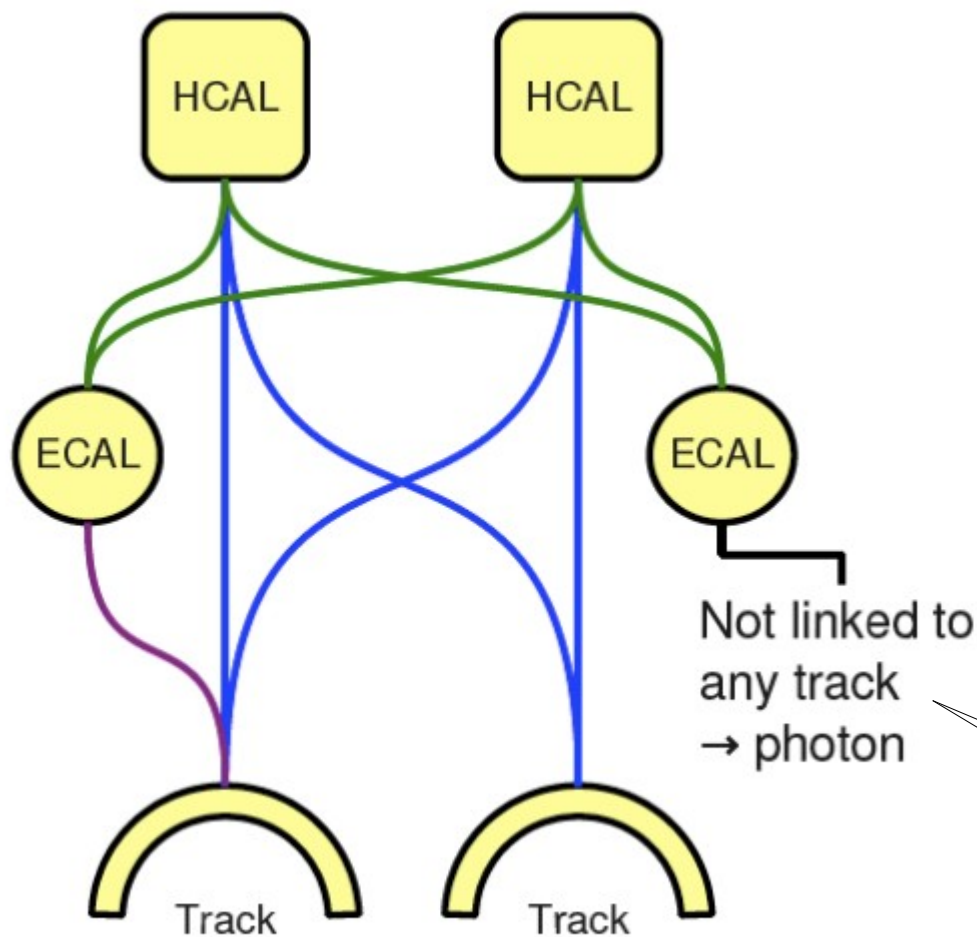
Links summary

A tree of links forms a block



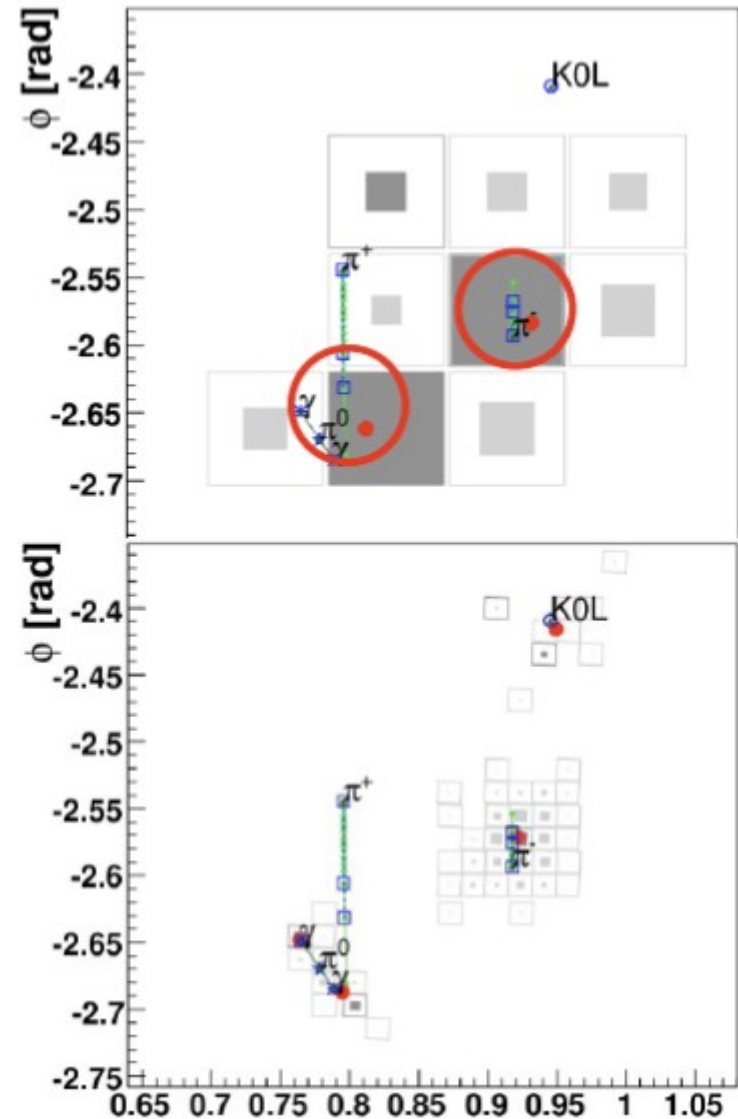
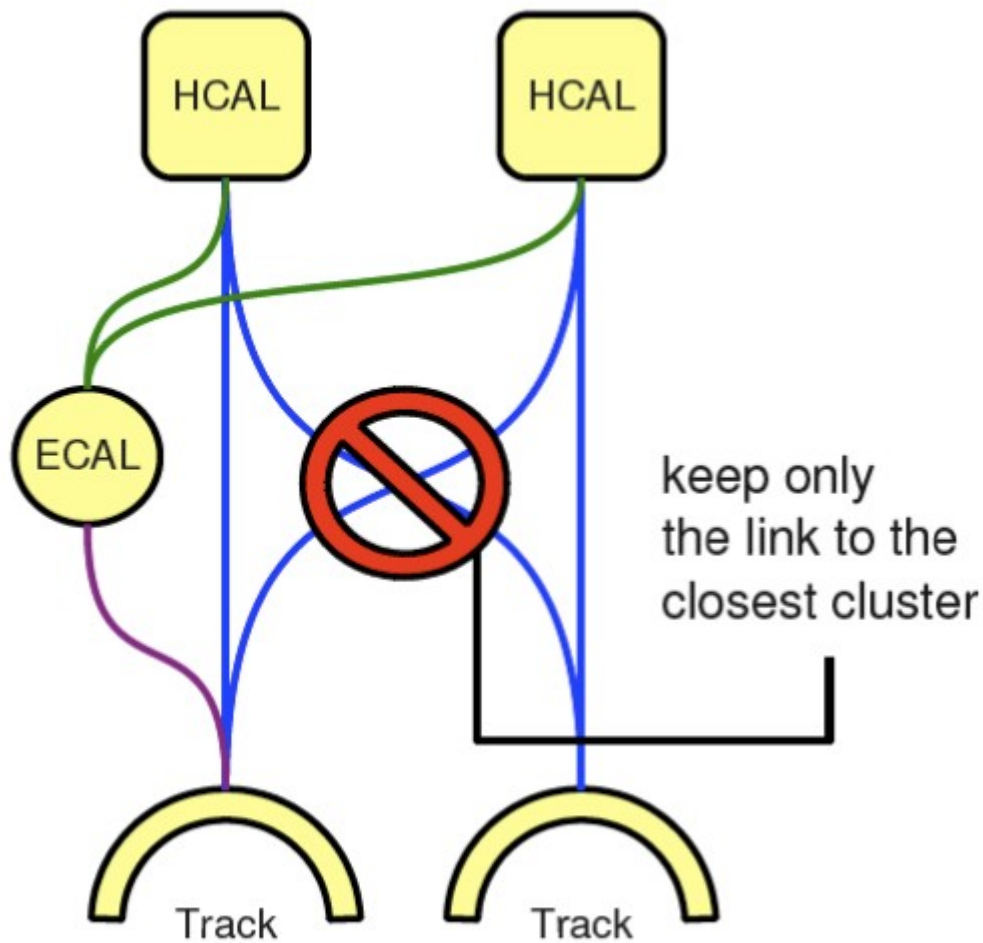
- K0 ECAL only \rightarrow becomes PF photon

Particle creation → step 1



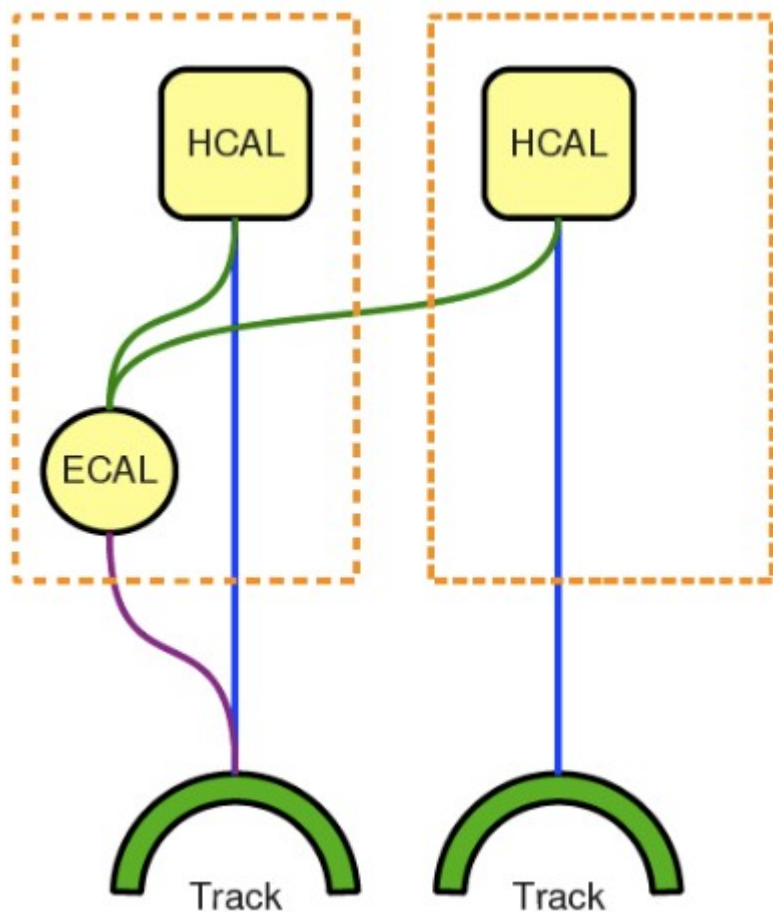
- Photons from π^0 not linked to track → PF photons
- In the tracker boundary ECAL+HCAL = photon+ neutral hadron

Particle creation → step 2



- If tracks linked to multiple HCAL keep only the closest

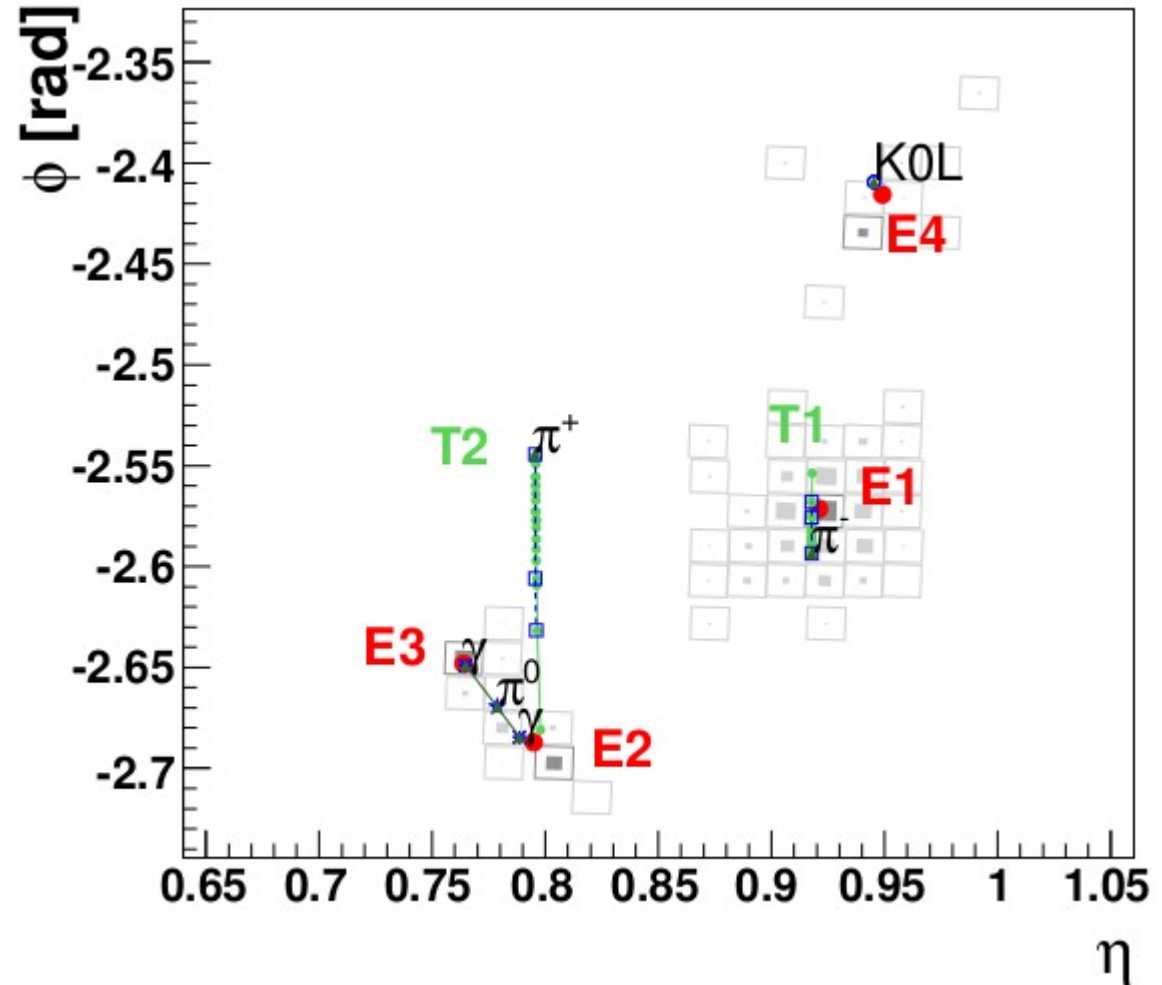
Particle creation → step 3



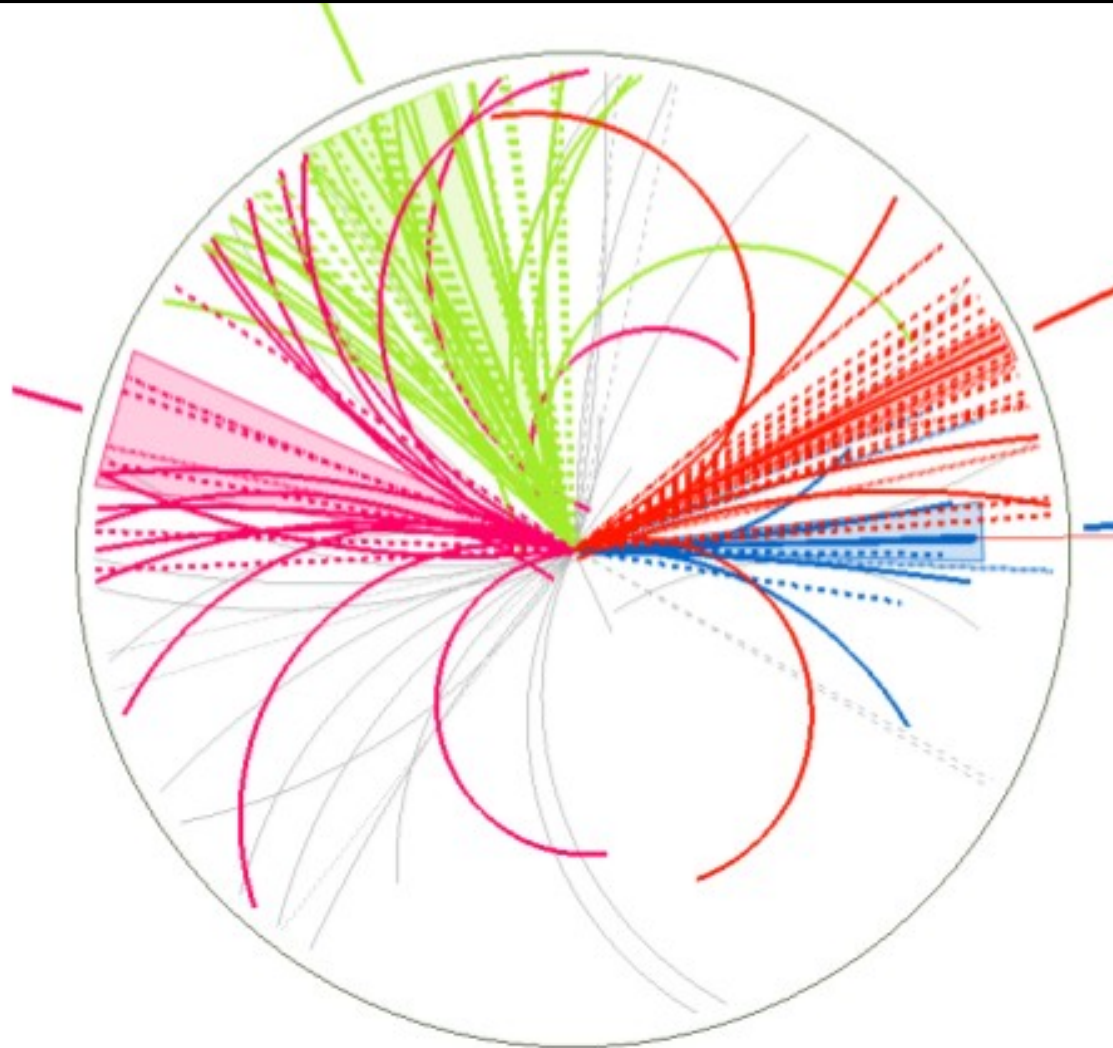
- For the track + HCAL elements compare the HCAL energy to the expected calorimeter resolution for this track
 - If no excess make charged hadron
- For the track+ECAL +HCAL elements compare track momentum with expected charged hadron resolution in ECAL and HCAL
 - If compatible make charged hadron
 - If ECAL excess create photon+charged hadron
 - If HCAL excess create charged +neutral hadron
 - If track excess and loose muon ID make muon+photon+neuytral hadron

Summary of the PF reconstruction

- The real event had
 - K^0, π^+, π^-, π^0
- PF will create
 - Two PF photons from π^0 decay
 - Two charged hadrons for the two pions
 - One PF photon corresponding to the K^0
 - Since no HCAL deposit PF cannot predict a neutral hadron



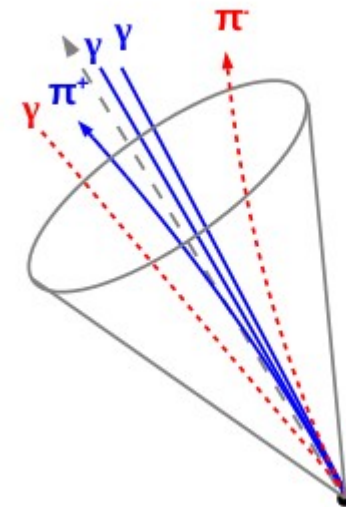
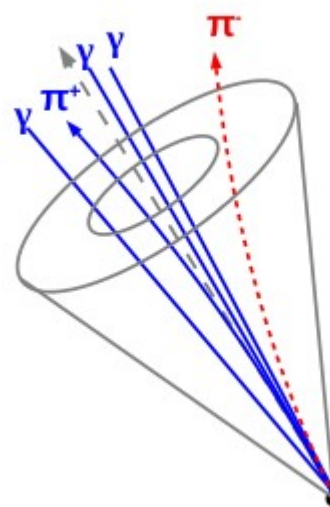
Reconstruction of a full event



Showing jets >50 GeV made out of PF particles

Hadronic tau identification

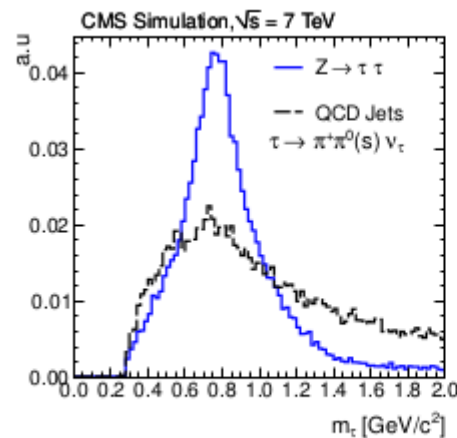
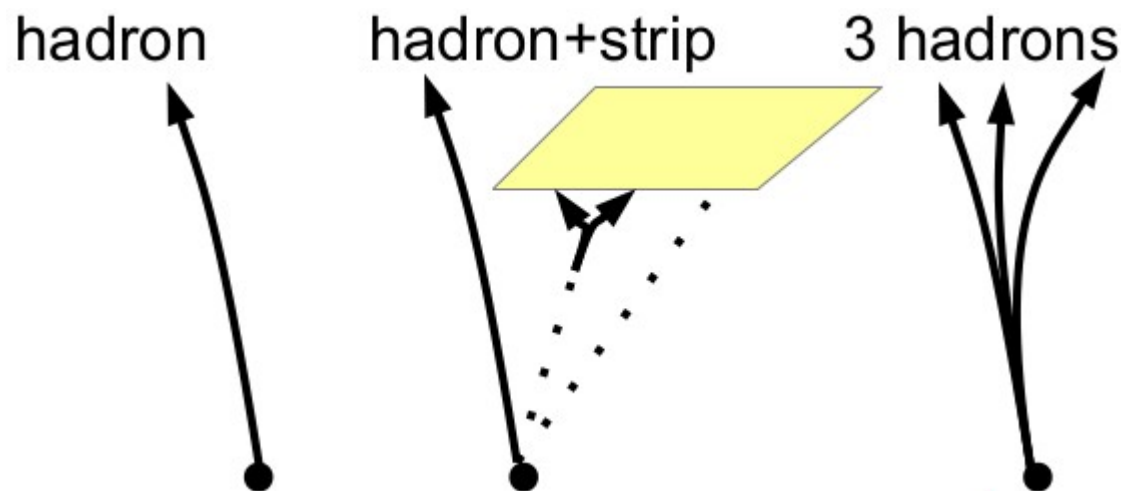
- A collimated jet with one or three charged particles
- Two philosophies
 - Cone based approach
 - Define a signal cone and an isolation cone
 - Check the number of charged particles in the cone
 - Decay mode approach
 - Reconstruct individual tau decay mode
 - Define everything else as isolation



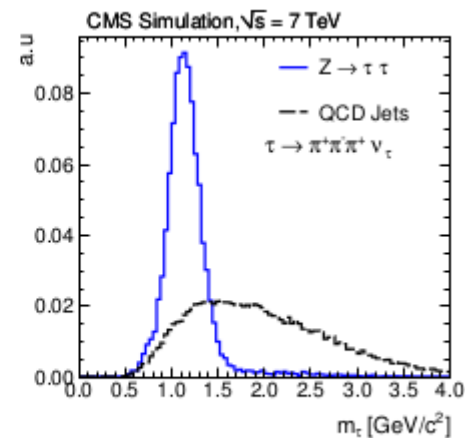
Decay mode reconstruction favored in Particle Flow!

Decay mode: Tau ID in CMS

- Create 3 decay modes combinatorially around jets
 - A single charged hadron
 - A charged hadron+ an EM strip of PF photons
 - To account for material effects
 - Three charged particles
- In case of multiple decay modes pick the one with highest Pt
- Use the mass of the intermediate meson to reject background
- All other particles in the vicinity are used for isolation

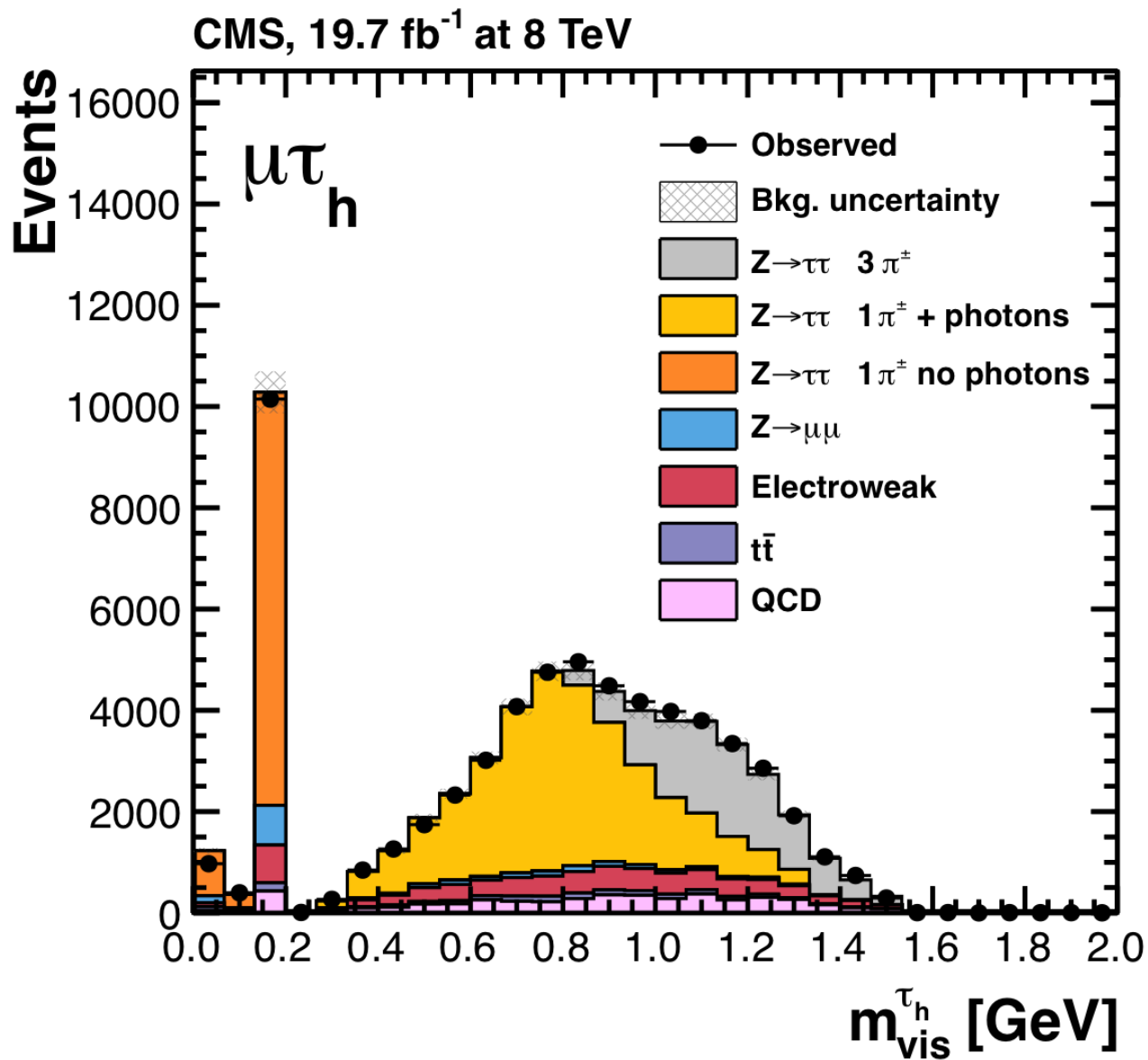


(a) one prong + strip

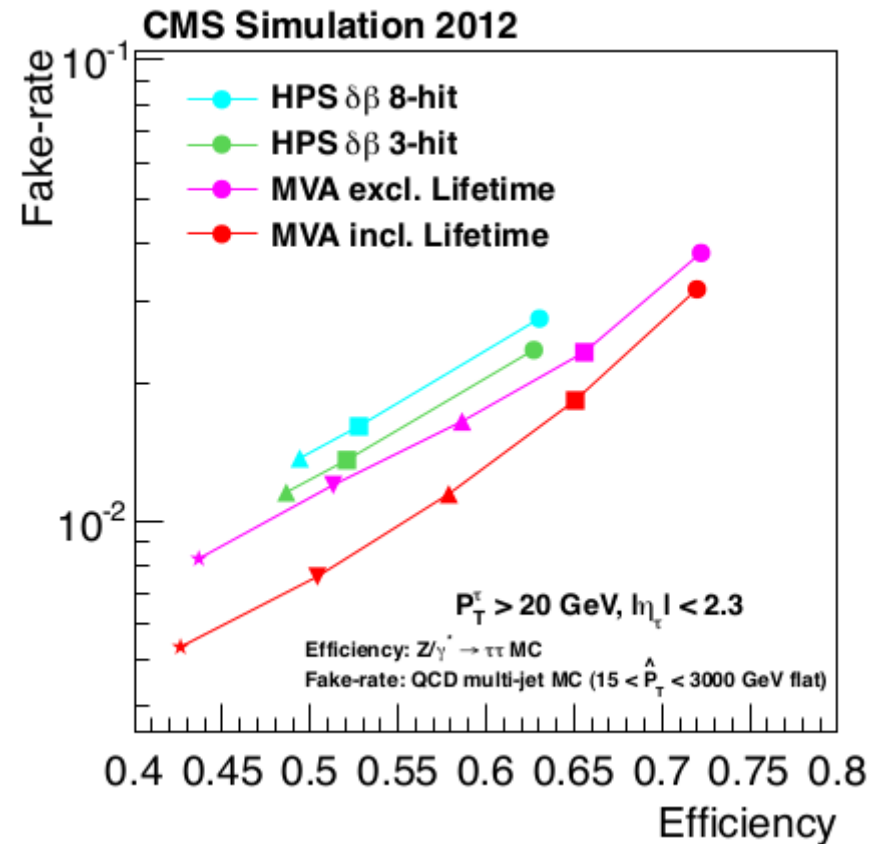
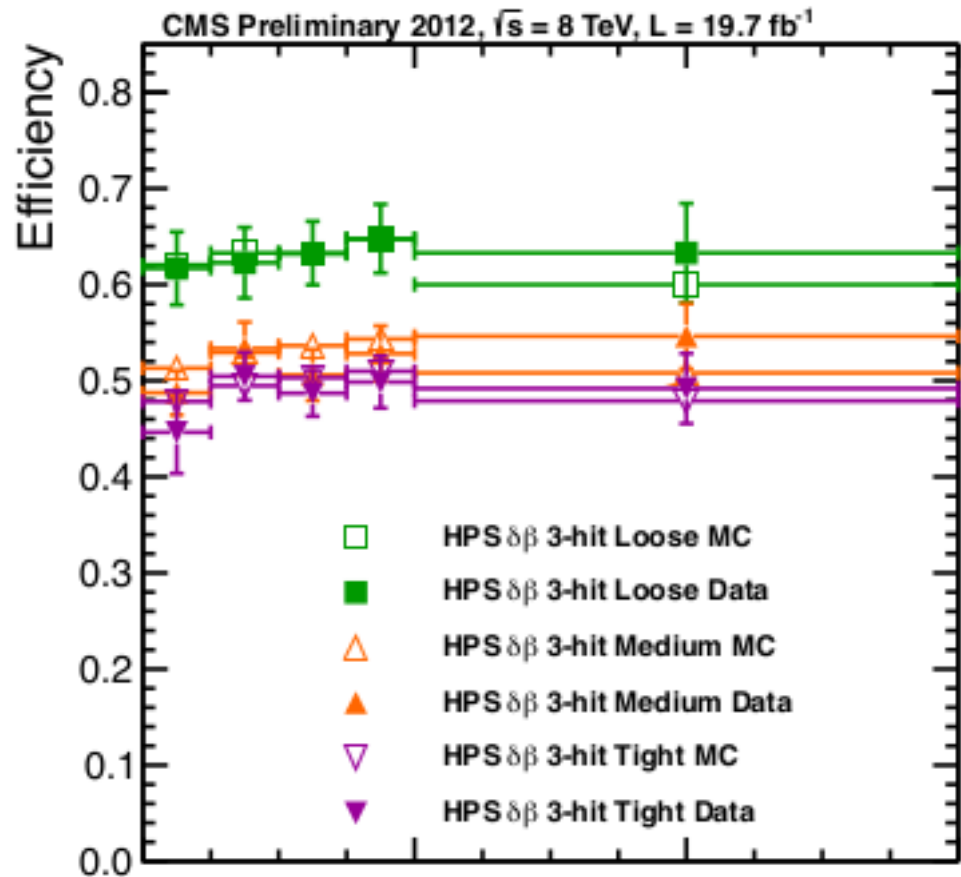


(b) three prongs

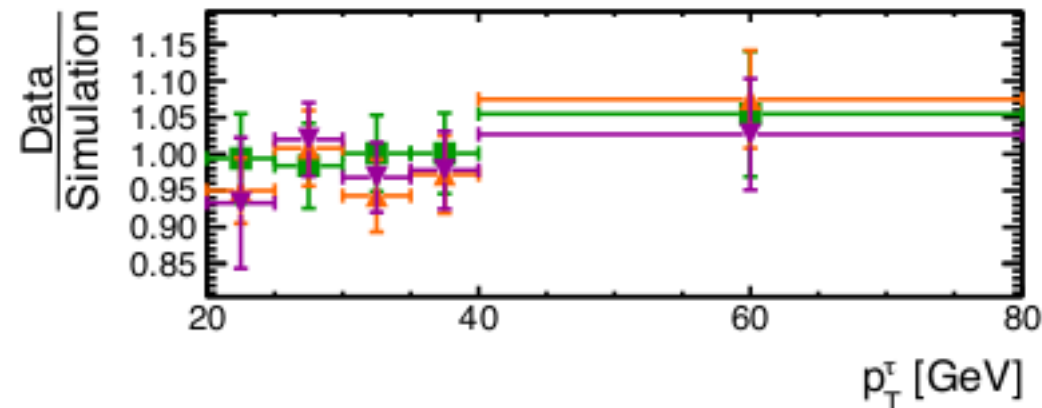
Validation with data: Tau mass



Tau identification efficiency and fakes



- ~50% efficiency for fake rate of 1%
 - Background is from jets!
- Additional information from lifetime improves performance



Jet reconstruction

- Jet reconstruction identifies the signatures of quarks and gluons in the detector
- Jet algorithms cluster detector elements to form jets
 - Detector elements can be Calorimeter cells [e.g ATLAS] and the resulting jets are Calorimeter jets
 - Particles from Particle Flow are also used [e.g CMS]
 - Good correspondence with the MC quantities
 - Large improvement since tracker is used to measure most particles [charged hadrons] especially at low p_t
 - At high jet energies, calorimeter resolution comparable with tracker
 - PF and Calorimeter jets converge to the same performance

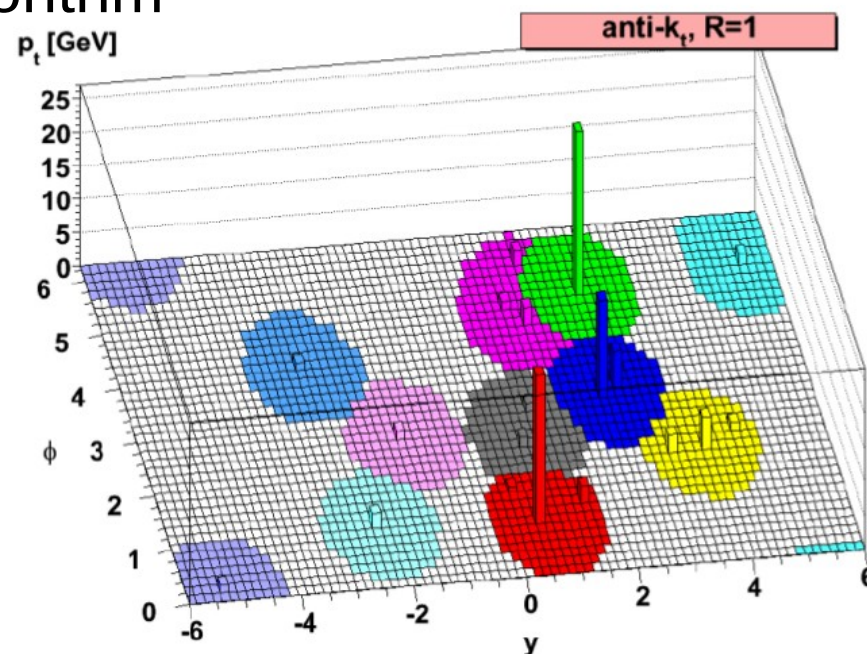
Jet algorithms

- Several algorithms to cluster particles into jets
- Requirements
 - IR safe: robust against the presence of low energy particles radiated by the partons
 - Collinear safe: Parton splits into pair of collinear partons recombined into the original one
- ATLAS and CMS use the anti-kt algorithm

$$d_{ij} = \min \left(\frac{1}{k_{T,i}^2}, \frac{1}{k_{T,j}^2} \right) \frac{\Delta_{ij}^2}{R^2},$$

$$d_{iB} = \frac{1}{k_{T,i}^2},$$

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$



Missing transverse energy

- Neutrinos cannot be identified in the detector
- Their contribution is approximated by looking at the missing transverse energy

$$E_T^{\text{miss}} = \sum_i \vec{E}_T$$

- Specific corrections to the missing transverse energy and multivariate techniques are also employed

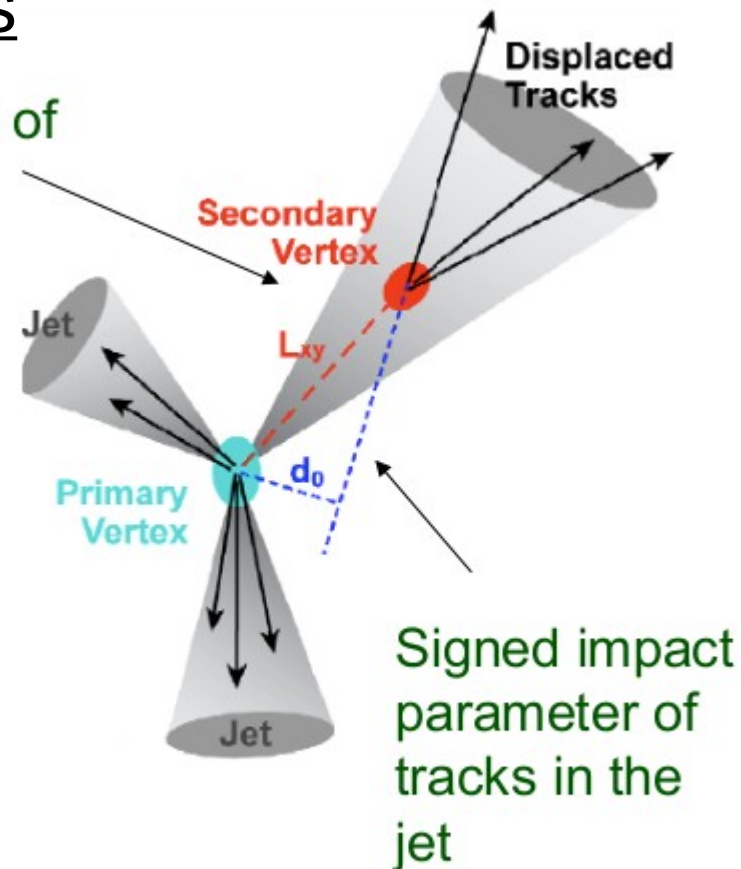
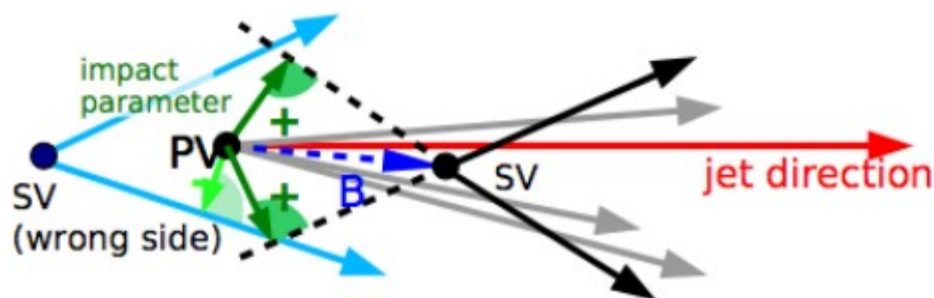
Tagging of jets from b-quarks

- Exploiting the lifetime of B hadrons
 - Producing displaced vertices

Observables

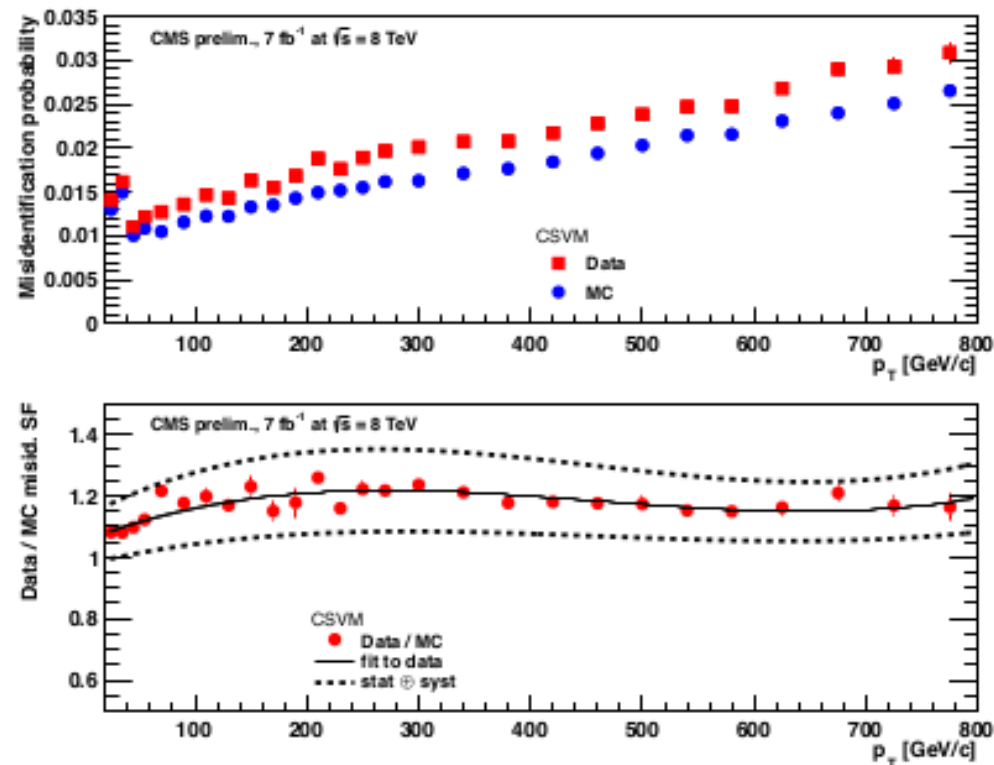
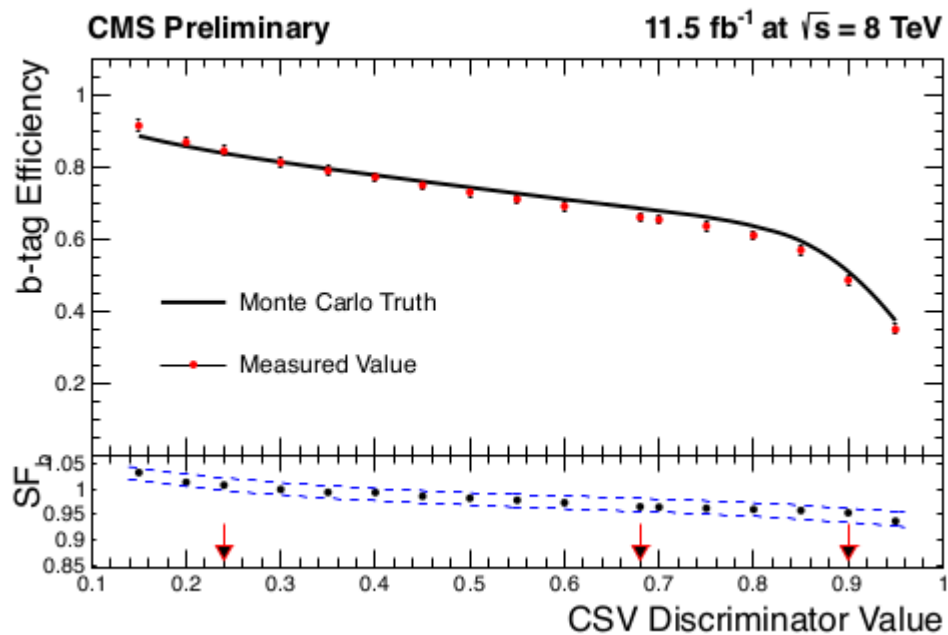
Signed decay length of secondary vertexes

Signs of Impact parameter and of vertex decay length are defined according to jet direction



Observables often combined in MVA discriminants

b-tagging performance



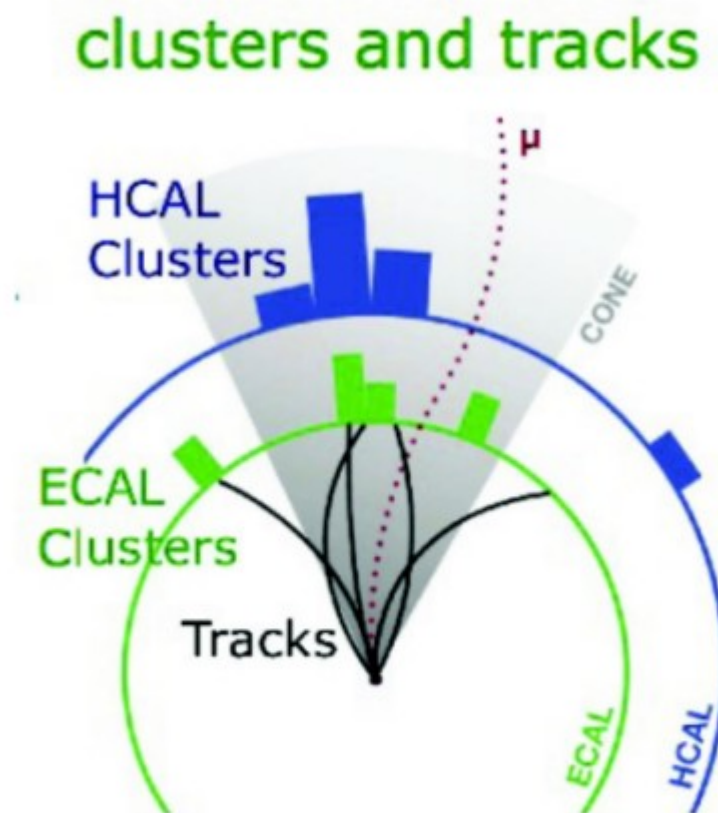
- Typical efficiency of 50% with a mistag probability of 1-2%

Lepton and Photon Isolation

- Leptons and photons from interesting processes are isolated in the detector
 - Isolation is a handle to reject backgrounds from non-prompt objects
 - Which can be real
 - i.e muons from b decays
 - or fake
 - jet misidentified as electron
- Definition of combined Isolation

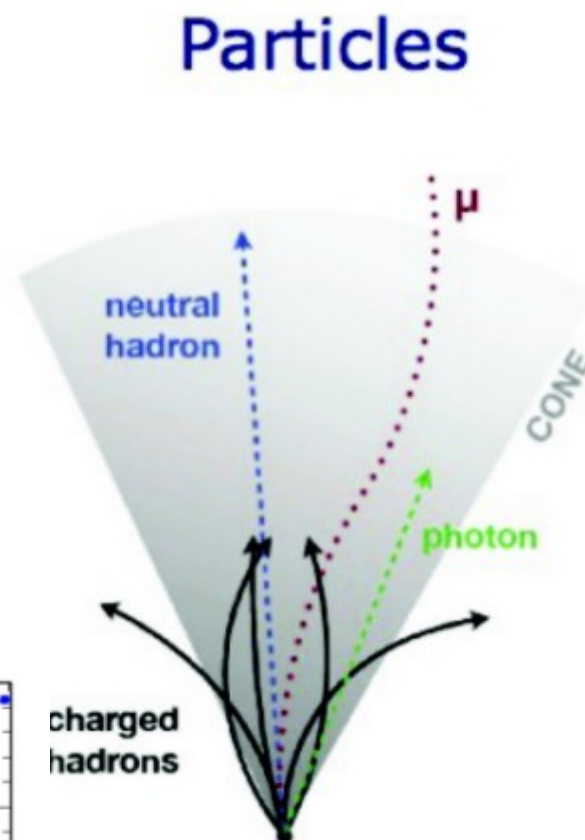
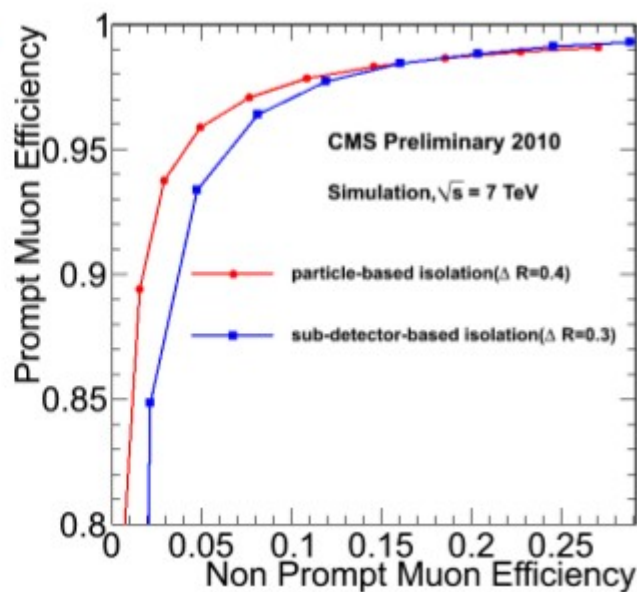
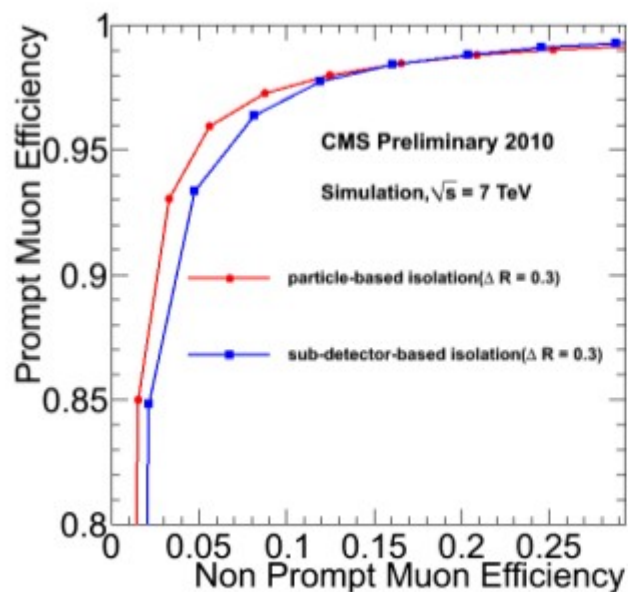
$$I = \frac{I_{ch} + I_{ECAL} + I_{HCAL}}{p_T}$$

- Sum of tracks and hits in a cone

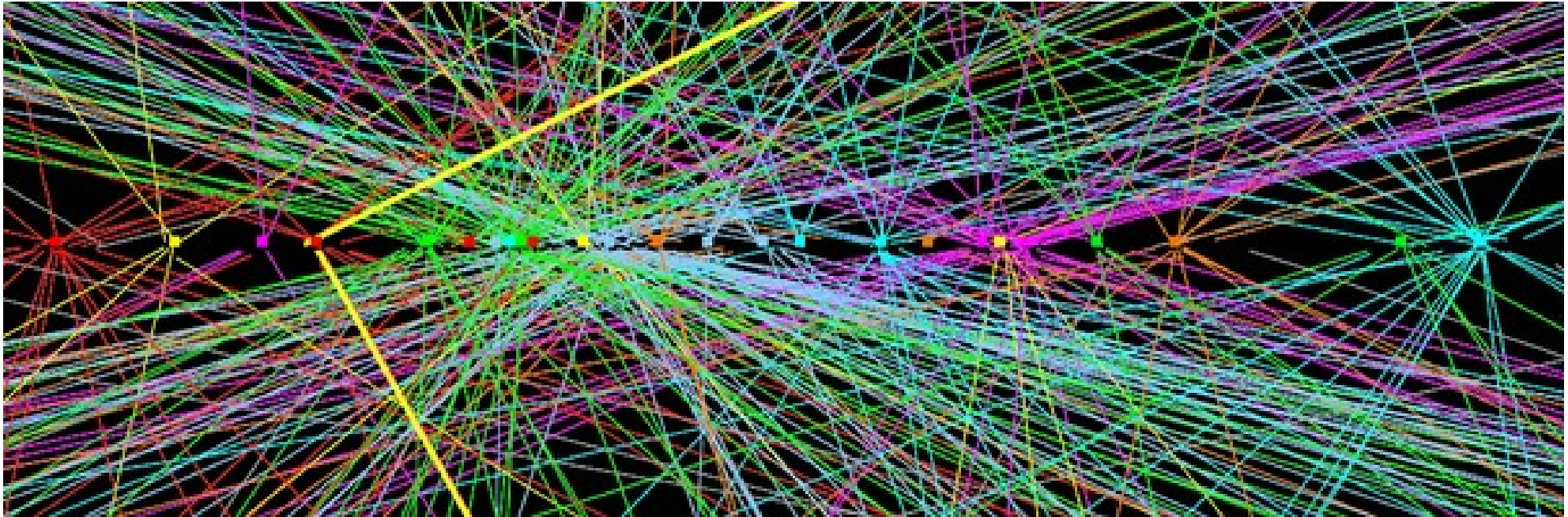


Isolation with Particle Flow

- Isolation with PF candidates also possible
- improves performance
 - Does not double count the calorimeter deposits of the charged hadrons



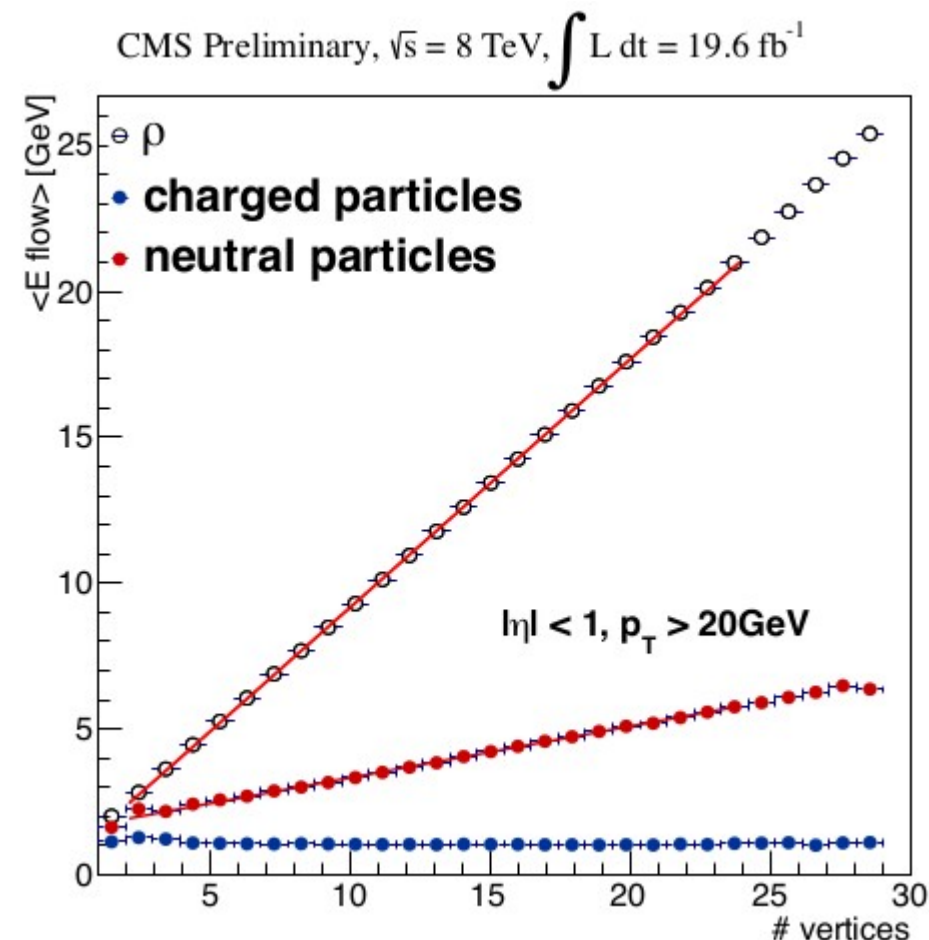
The challenge of pileup



- At high luminosity several pairs of protons can interact
 - Producing multiple interactions in the detector
 - Event of interest overlaid with other events
- We need to separate them in analysis level

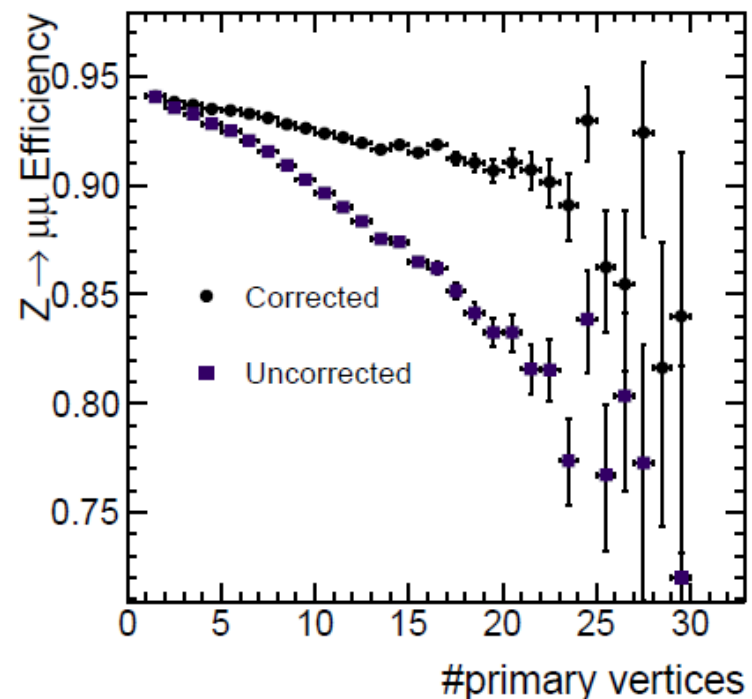
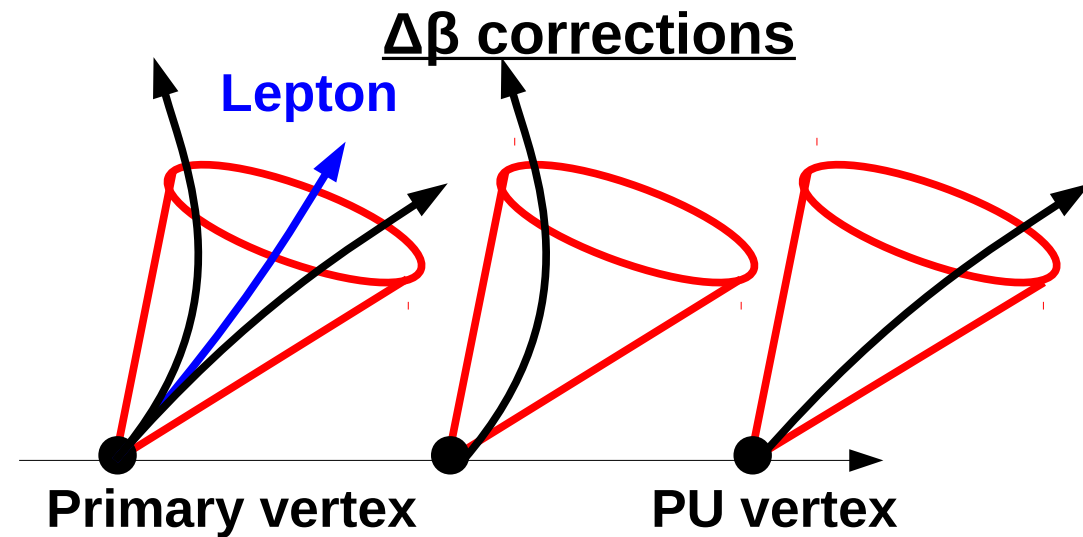
Effects of PU in the analysis

- Particles from additional collisions degrade analysis performance
 - Isolation is spoiled for prompt leptons
 - Particles degrade Jet and MET resolution
 - Electron ID variables spoiled by PU hadronic deposits
- Special techniques needed for PU mitigation



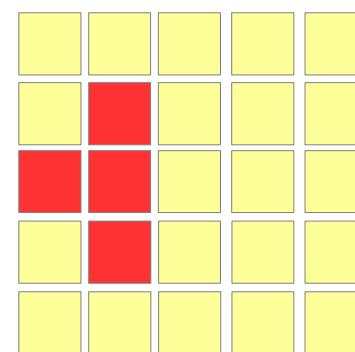
Example: PU mitigation in isolation

- Charged particles are selected by vertex requirements
 - Problem is the neutrals
- Neutrals from PU can be predicted by measuring the charged deposit from PU in the same cone
 - And assuming charged:neutral = 2:1



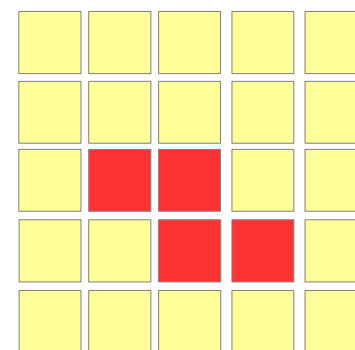
Out of time PU

- In case a detector is slower than a bunch crossing particles in previous bunch create PU in the detector
 - Mostly affecting Calorimeters
- With LHC running @25ns OOT PU becomes major issue
 - Can be mitigated at low level by looking at the pulses in the detector



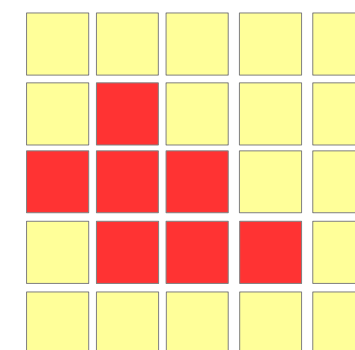
BX -1

+



BX 0

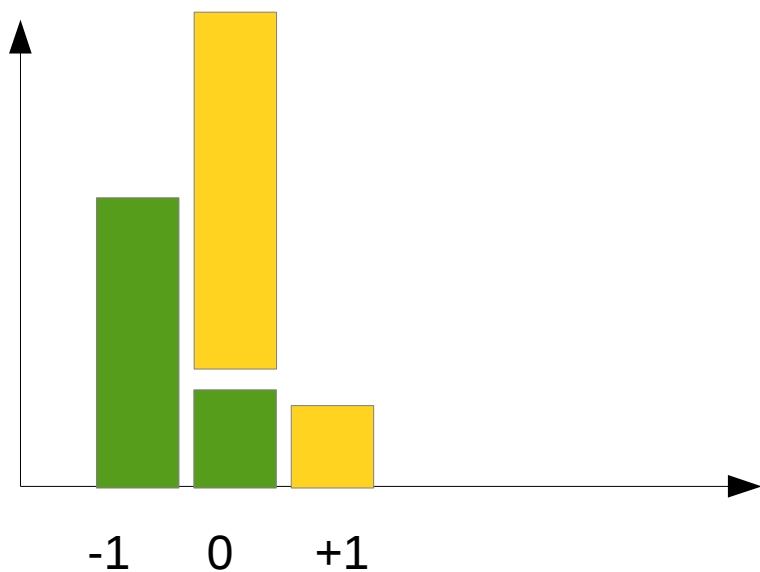
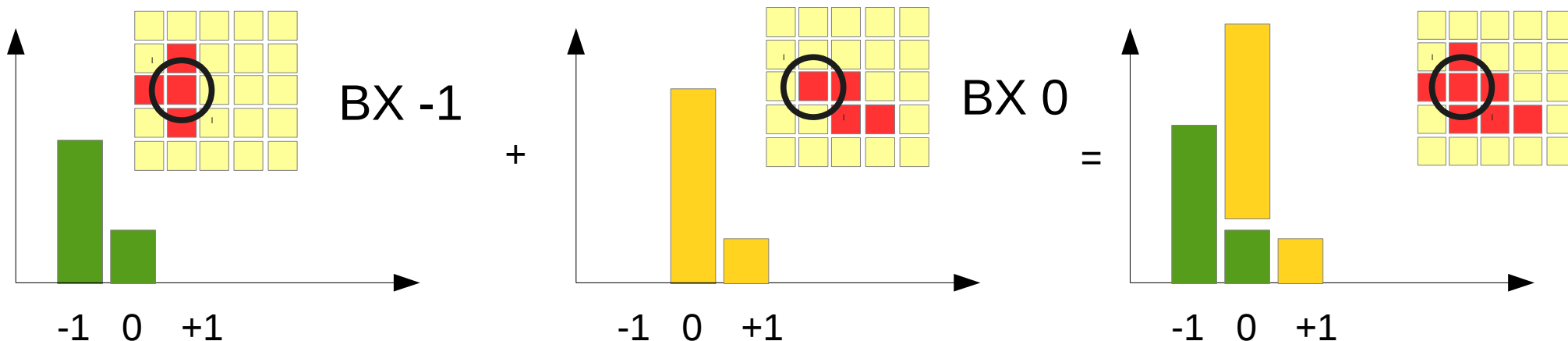
=



Hits @ BX0

OOT PU: Time samples

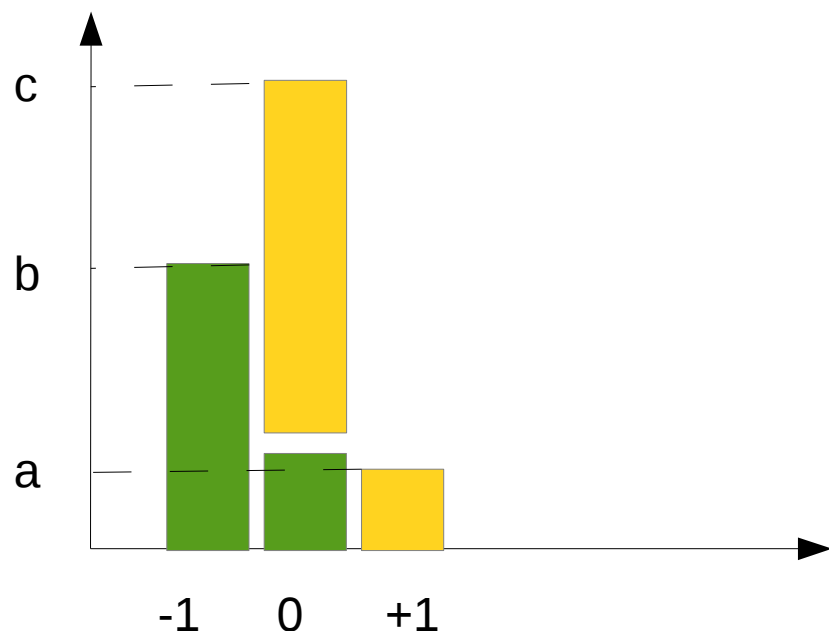
Looking at a specific calorimeter hit vs time



- Reconstructing time sample 0 has 20% OOT contribution
- Granularity of the calorimeter helps! → less chance of overlap
- Need smart technique to estimate the bx0 contribution

Example OOT PU mitigation

- Assumption that we know the pulse shape
 - e.g 20% of the energy in the next bx
 - This ratio could vary in the detector → hit calibration



$$0.8BX(0) + 0.2BX(-1) = c$$

$$0.8BX(-1) = b$$

$$0.2BX(0) = a$$

BX0 energy estimated from pulse shape

- Realistic case harder!
 - Deposits in continuous bunch crossings
 - Complicated pulse fits and looking at neighboring hits!

Summary of the first lecture

- Reviewed the Higgs phenomenology
 - What we expect at LHC and which modes are relevant
- Looked at the detector requirements for the Higgs search
 - How we identify objects
 - What is the typical performance
 - How we solve experimental problems to improve sensitivity of the analyses
- Next : Look at the main Higgs analyses in depth and review the higher level techniques