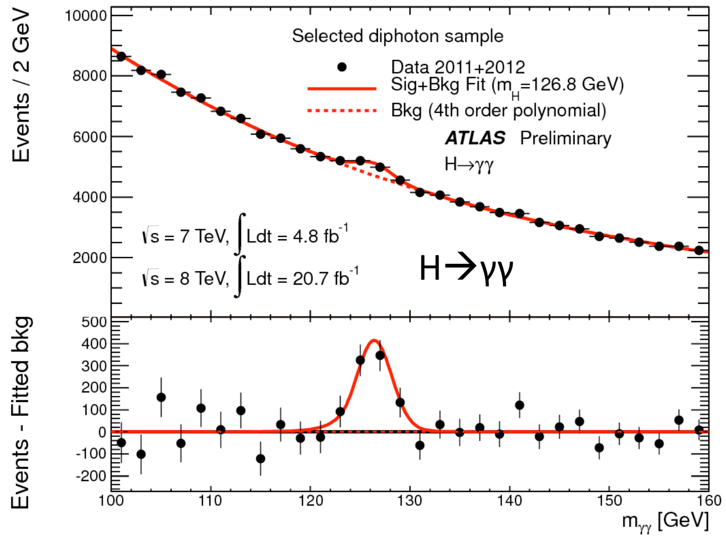
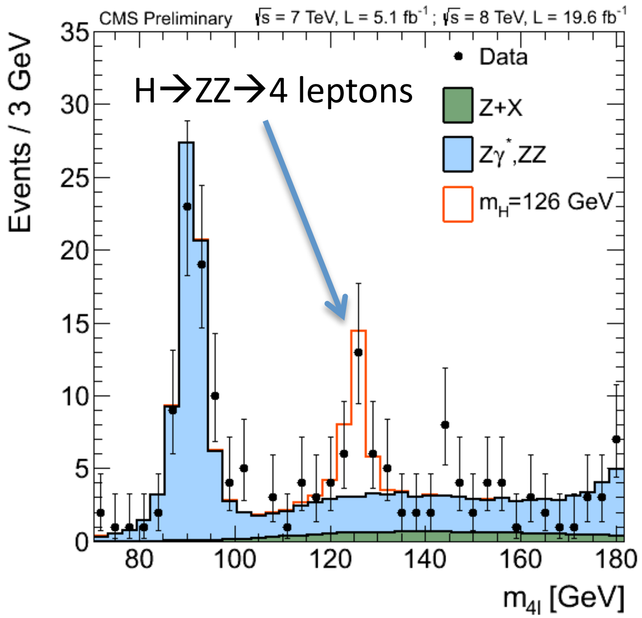
H→ττ in CMS, A Particle Flow Analysis

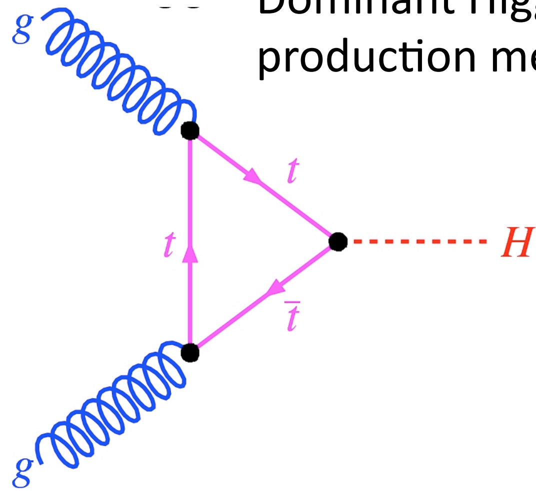
Colin Bernet (CERN, CRNS/LLR)

Discovery of a Higgs boson





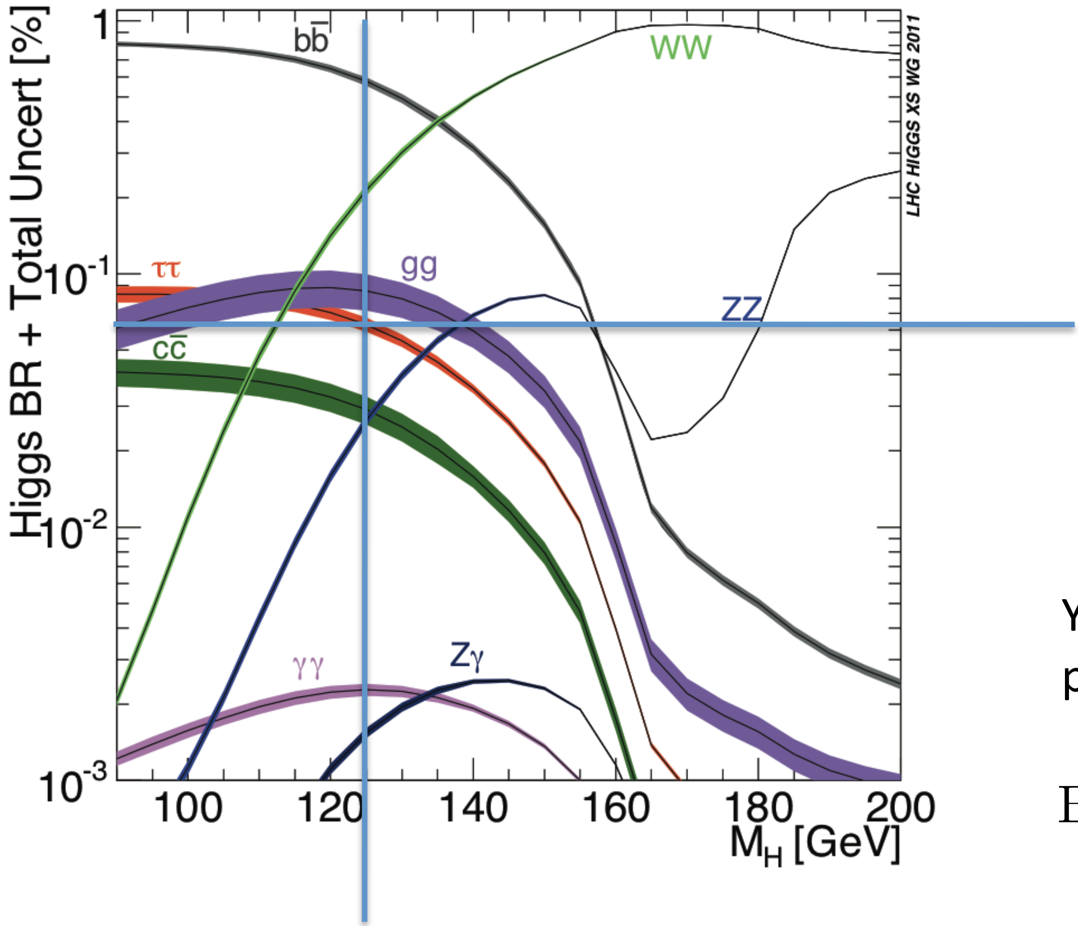
gluon-gluon fusion
Dominant Higgs production mechanism



- mass ~ 125.6 ± 0.5 GeV
- σ x BR compatible with SM
  - couples to Z and W
  - couples to top quark (probably)
- **does it couple to leptons?**

ATLAS-CONF-2013-012, CMS-PAS-HIG-13-002

Probe lepton coupling: H→ττ



$$\mathrm{BR}(H \to \tau\tau) = 6\%$$

Yukawa coupling to fermions proportional to fermion mass m_f

$$\mathrm{BR}(H \to \mu\mu) = \left(\frac{m_\mu}{m_\tau}\right)^2 \mathrm{BR}(H \to \tau\tau)$$

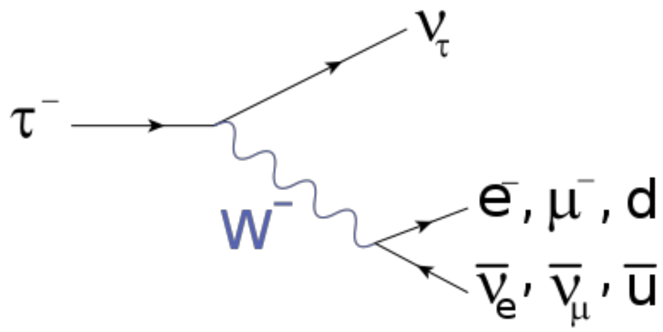
~1/300

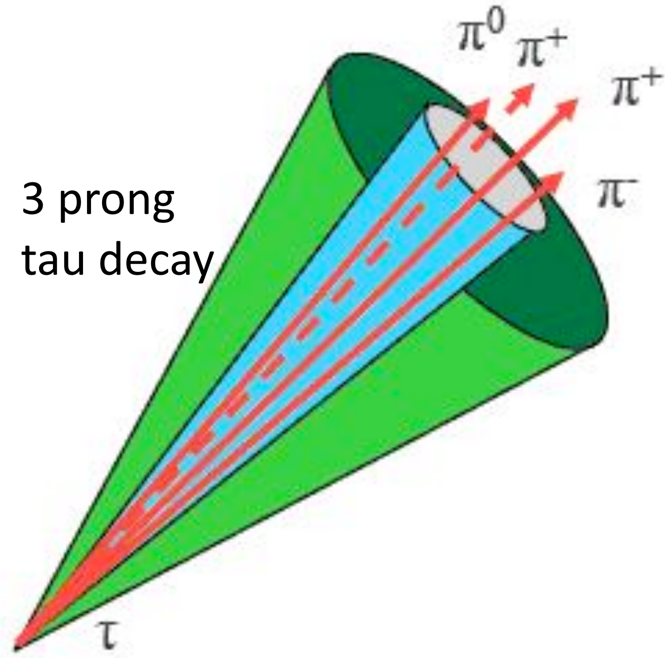
LHC Higgs σ Working Group

Part I

- Principles of the H→ττ search
  - fighting the main background sources
  - need for high-performance physics objects
- Particle flow reconstruction
  - What and why?
  - The algorithm
  - Physics object performance
- The CMS H→ττ analysis
  - specific techniques
  - results

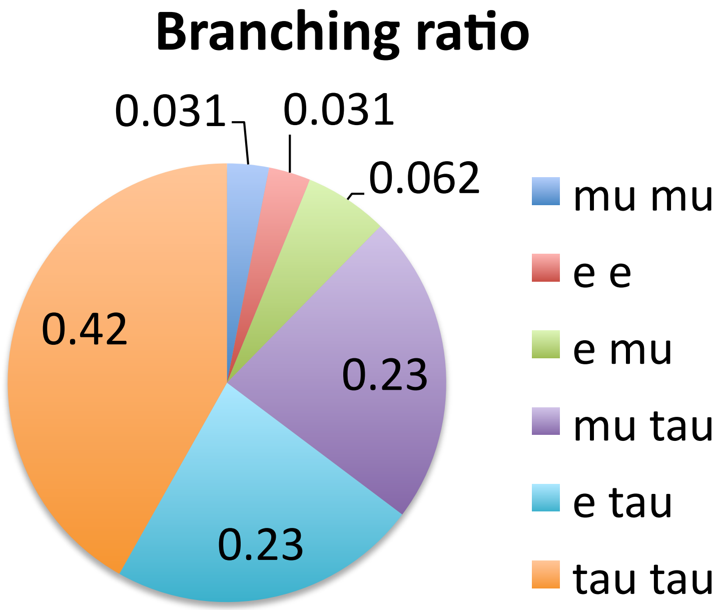
The τ, a massive (and challenging) lepton





- m = 1.78 GeV
- $c\tau$ = 90 μm
- Branching ratios:
  - 65% $\tau^\pm \rightarrow \tau_{had}^\pm \nu_\tau$
    - 75% , $\tau^\pm \rightarrow$ **1** $\pi^\pm$ + [π^0(‘s)] + ν_τ (**1 prong**)
    - 23% , $\tau^\pm \rightarrow$ **3** $\pi^\pm$ + [π^0(‘s)] + ν_τ (**3 prongs**)
  - 35% $\tau^\pm \rightarrow l^\pm \nu_l \nu_\tau$
- Decays into 1 or 2 neutrinos
  → MET in the event
- Narrow “jet”
  with only a few particle
  → high jet to τ fake rate (few %)

$H \to \tau\tau$ channels



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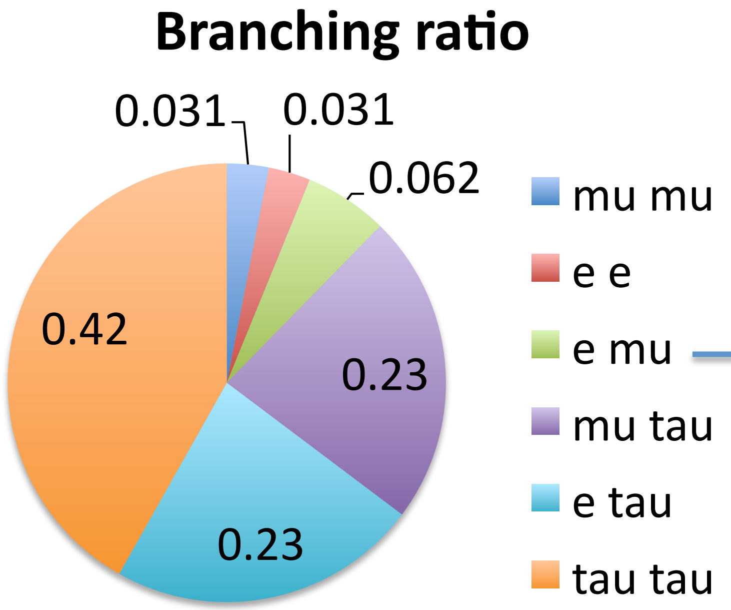
H→ττ channels



low BR and large background
Z→ττ + Z→ll

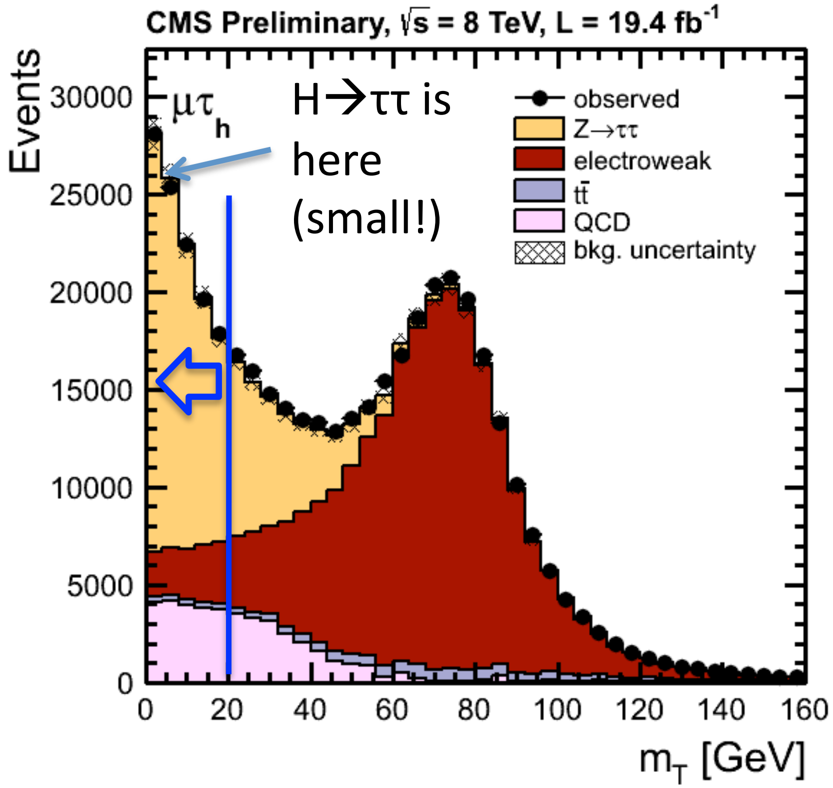
Low BR but very clean
Z→ττ + ttbar

The most powerful channels
Z→ττ, W+jets, QCD

Large BR but large background
Z→ττ, QCD
(jet→τ fake rate ~ few%)

The H→ττ→μτ channel

- Inclusive selection:
  - identified and isolated μ & τ, with pT > 20 GeV
  - rejects QCD & W+jets
    - This background yield is proportional to the jet→τ fake rate



- mT < 20 GeV
  - rejects W+jets & ttbar
    - H→τ τ at low mT like Z→ττ
  - separation performance depends on E_T^{miss} resolution

$$m_T = \sqrt{2 p_T E_T^{miss} (1 - \cos(\Delta\phi))}$$

Transverse mass
mass of the μ + E_T^{miss} system in the transverse plane

CMS-PAS-HIG-13-004

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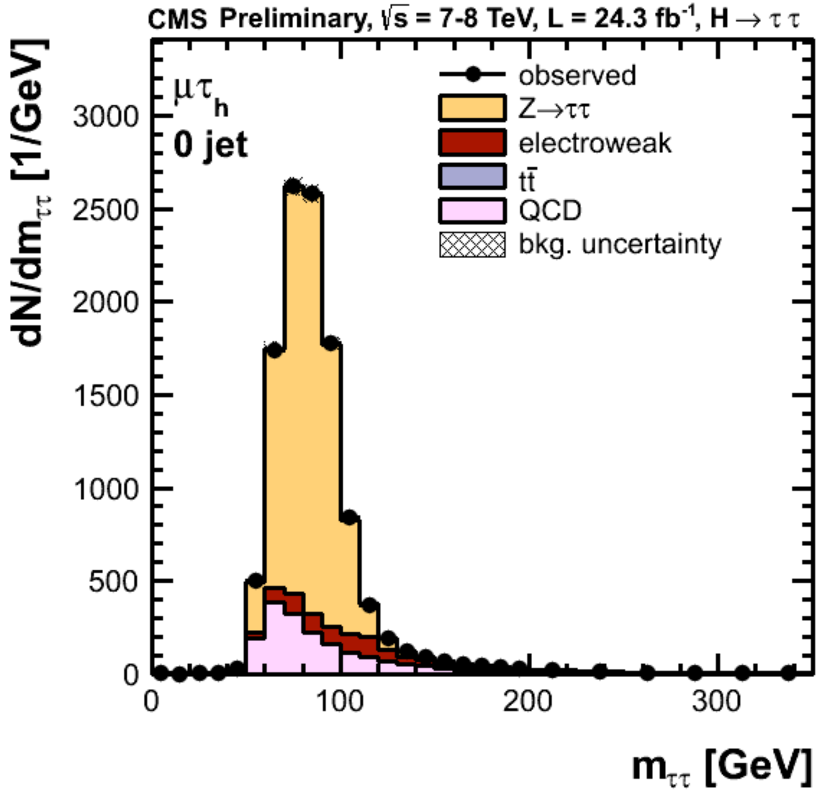

Full ττ mass
includes neutrinos;
reconstructed from μ, τ, E_T^{miss}
(more later)

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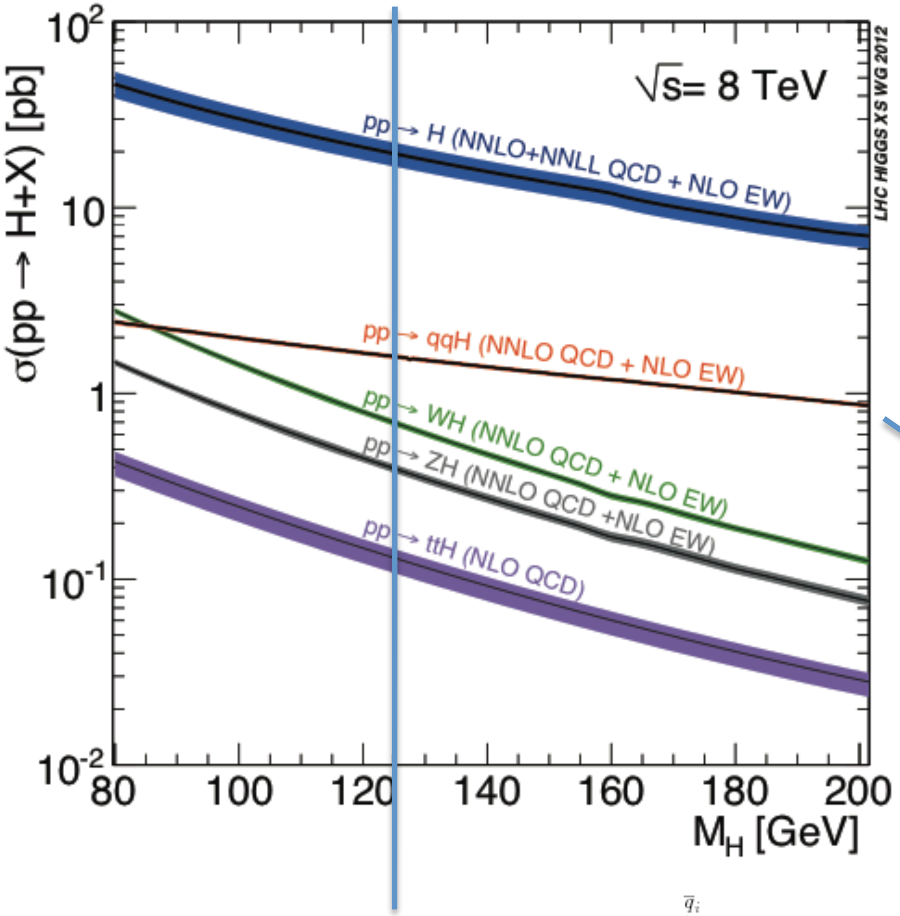
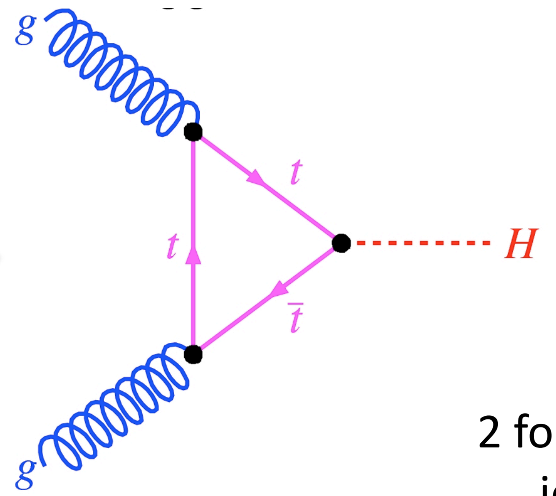
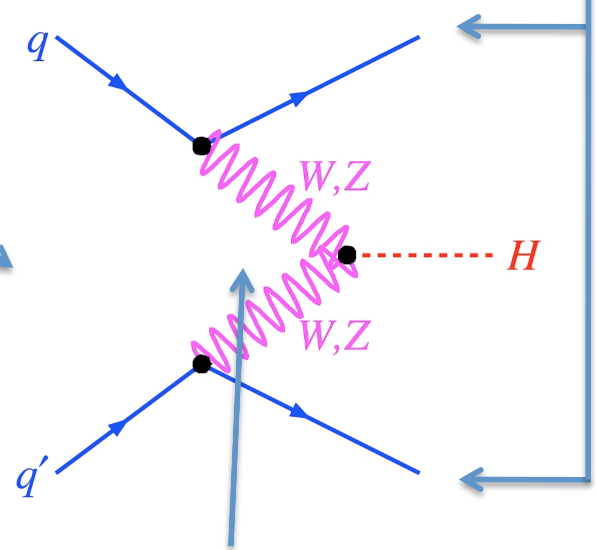
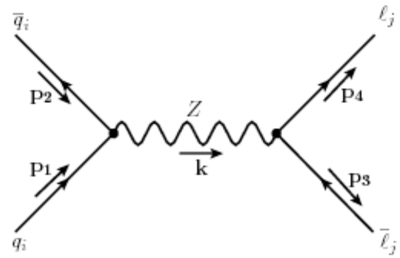
Vector Boson Fusion (VBF)





2 forward jets





No colour flow in between
→ rapidity gap

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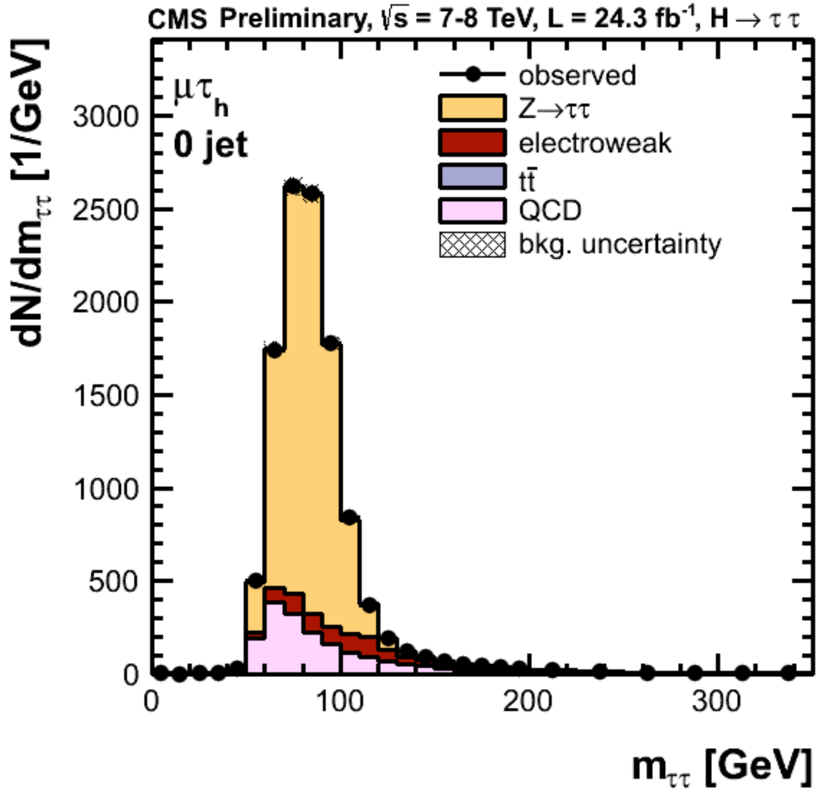
The H→ττ→μτ channel: VBF cuts

- VBF selection:
  - 2 jets pT > 30 GeV
  - |Δη| > 3.5
  - m_{jj} > 500 GeV
  - no jet in between
- Rejects Z→ττ
- Uncertainty in jet energy scale → 5% uncertainty in signal yield

before VBF selection



Full ττ mass
includes neutrinos;
reconstructed from μ, τ, E_T^{miss}
(more later)

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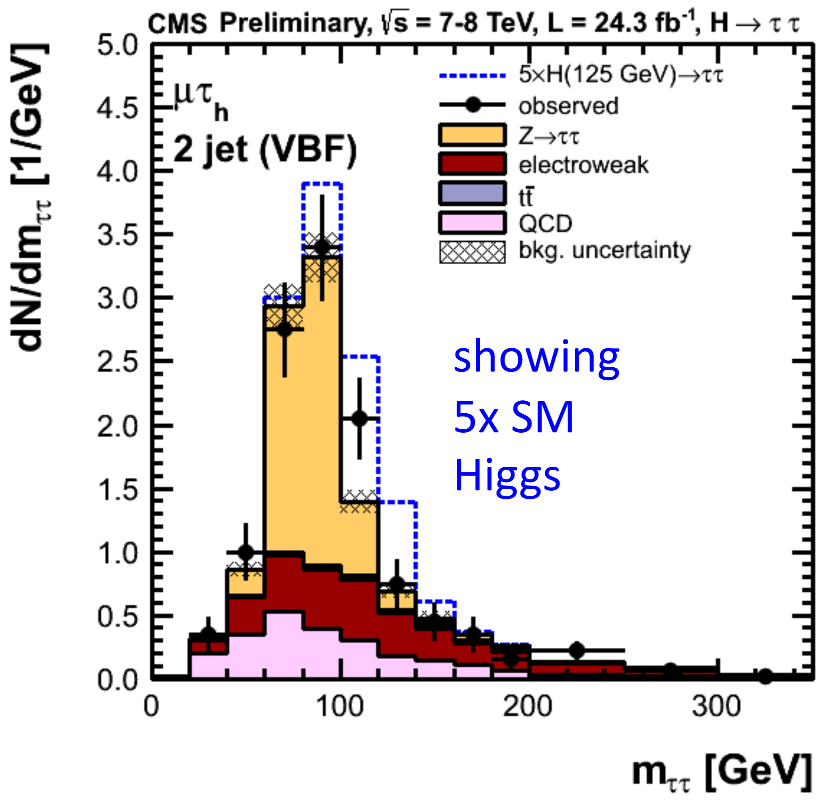

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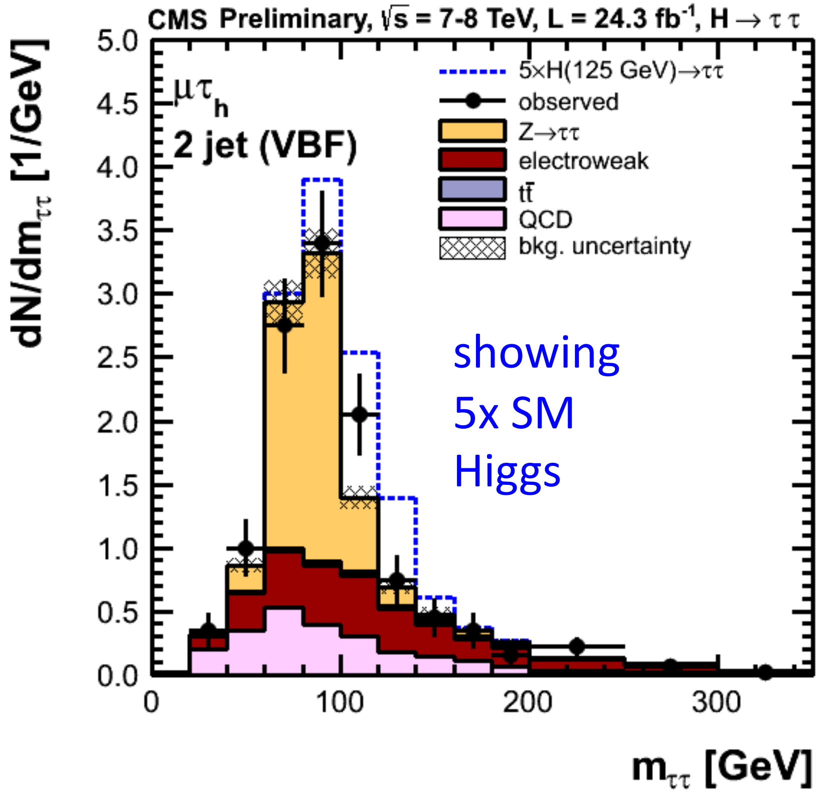
The H→ττ→μτ channel: VBF cuts

- H→ττ separated from Z→ττ using $m_{\tau\tau}$
  - τ energy scale uncertainty
    - error results in shifted peak
  - E_T^{miss} resolution
    - drives the peak width

after VBF selection



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Part II

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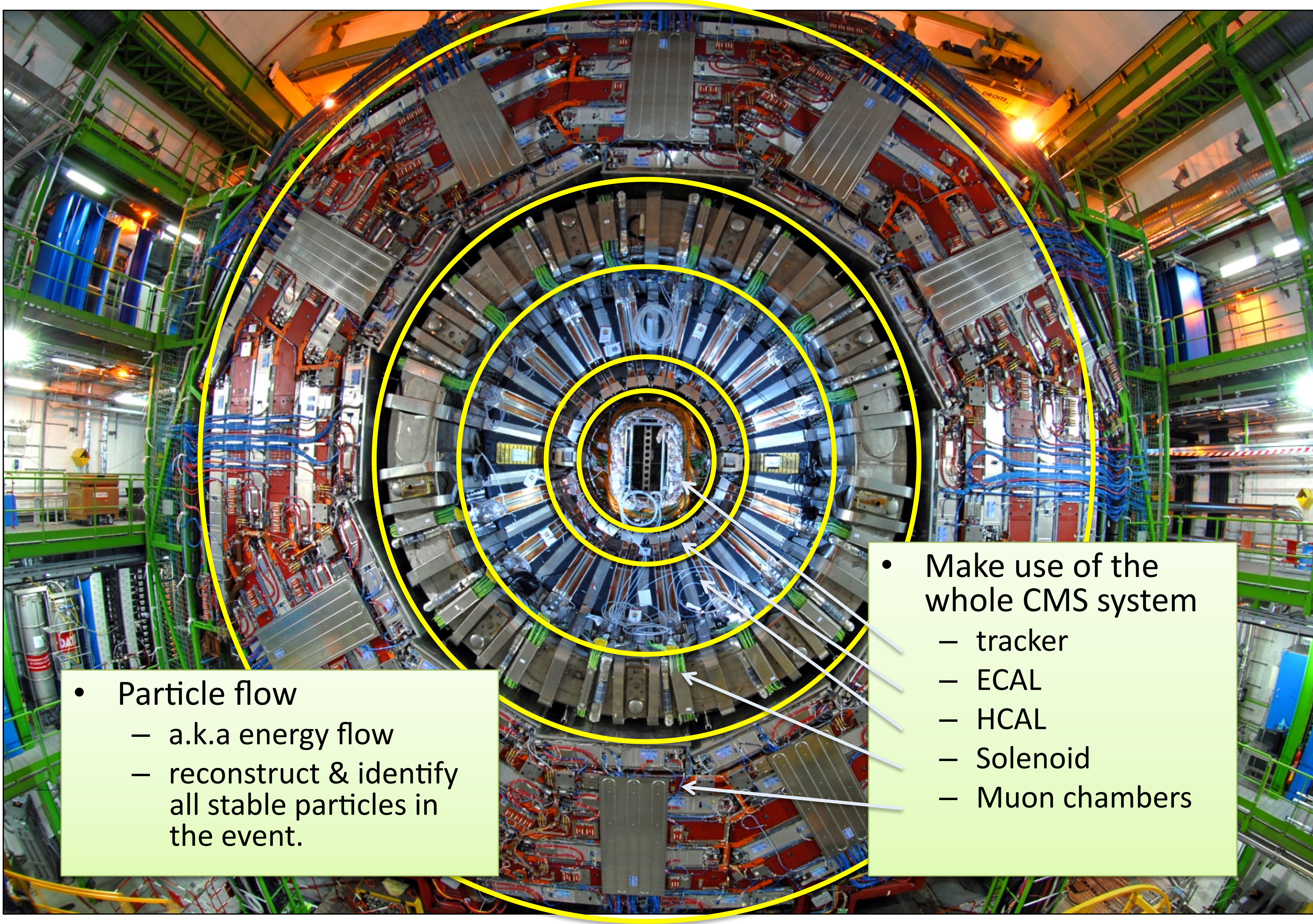
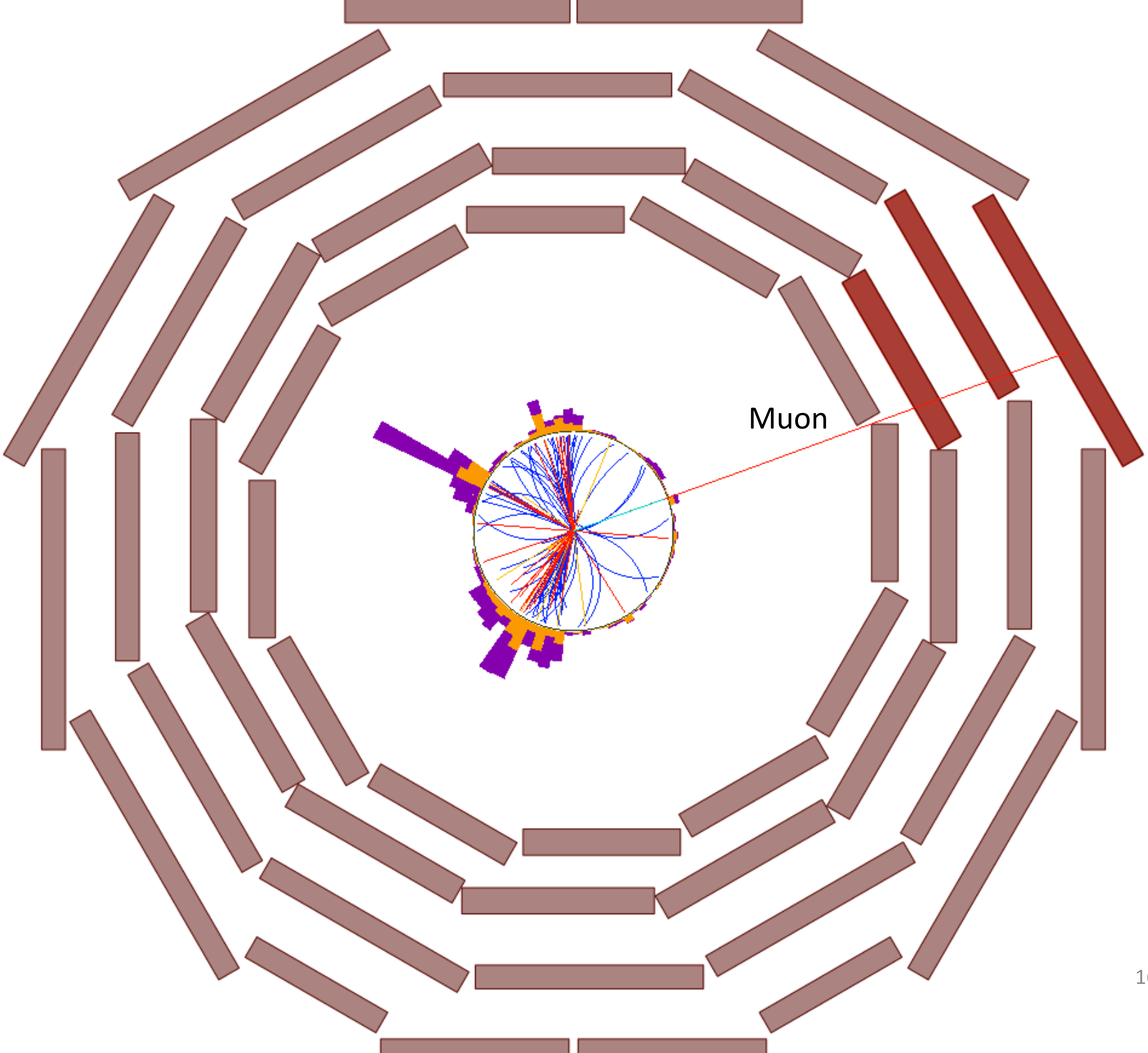
  - fighting the main background sources
  - need for high-performance physics objects
- Particle flow reconstruction
  - What and why?
  - The algorithm
  - Physics object performance

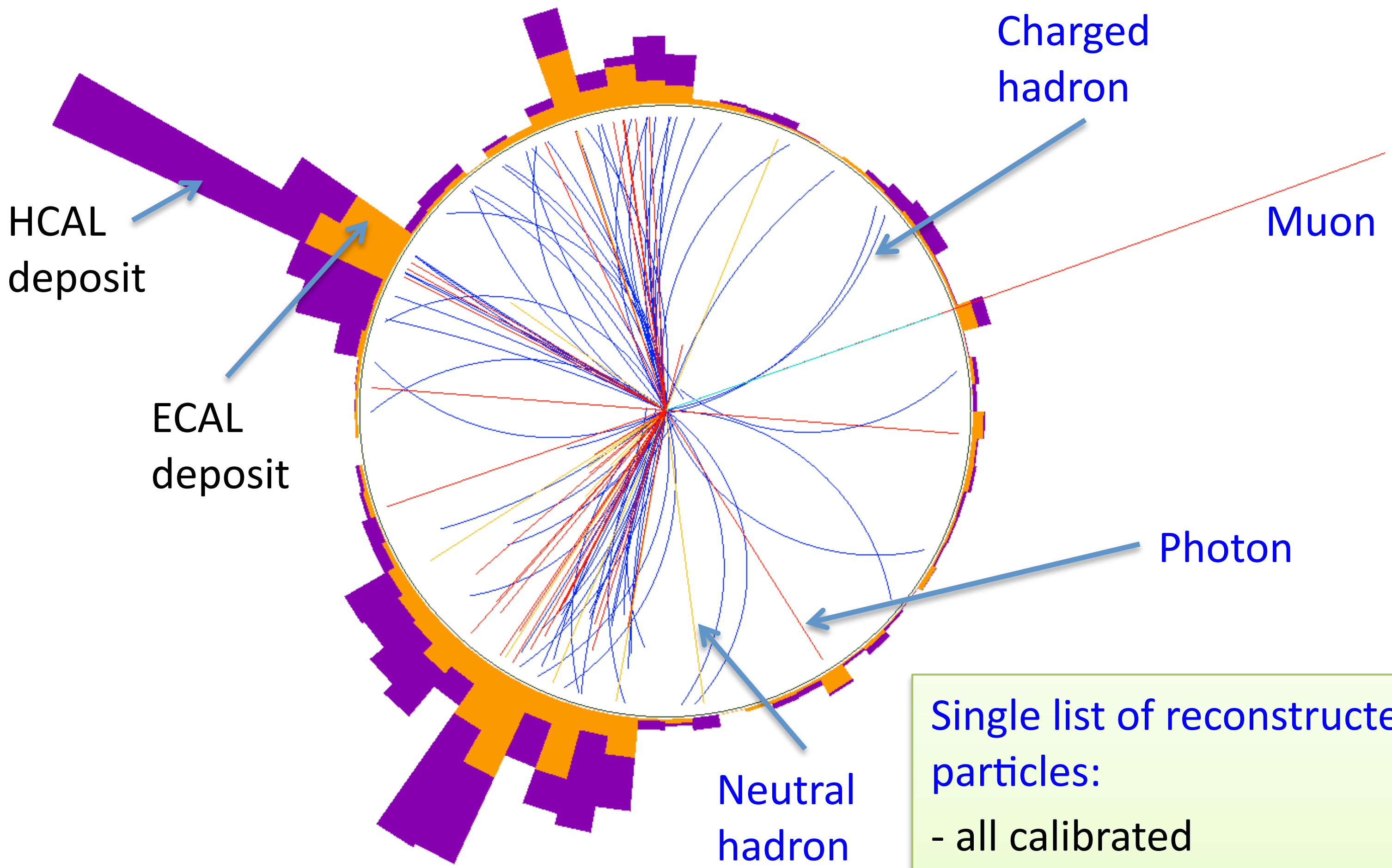
- τ ID efficiency and fake rate
- τ energy scale syst. uncertainty
- E_T^{miss} resolution
- jet energy scale syst. uncertainty
- and much more!

- The CMS H→ττ analysis
  - background estimation & main uncertainties
  - statistical procedure
  - results


• Make use of the whole CMS system
– tracker
– ECAL
– HCAL
– Solenoid
– Muon chambers
• Particle flow
– a.k.a energy flow
– reconstruct & identify all stable particles in the event.


Muon

Zoom

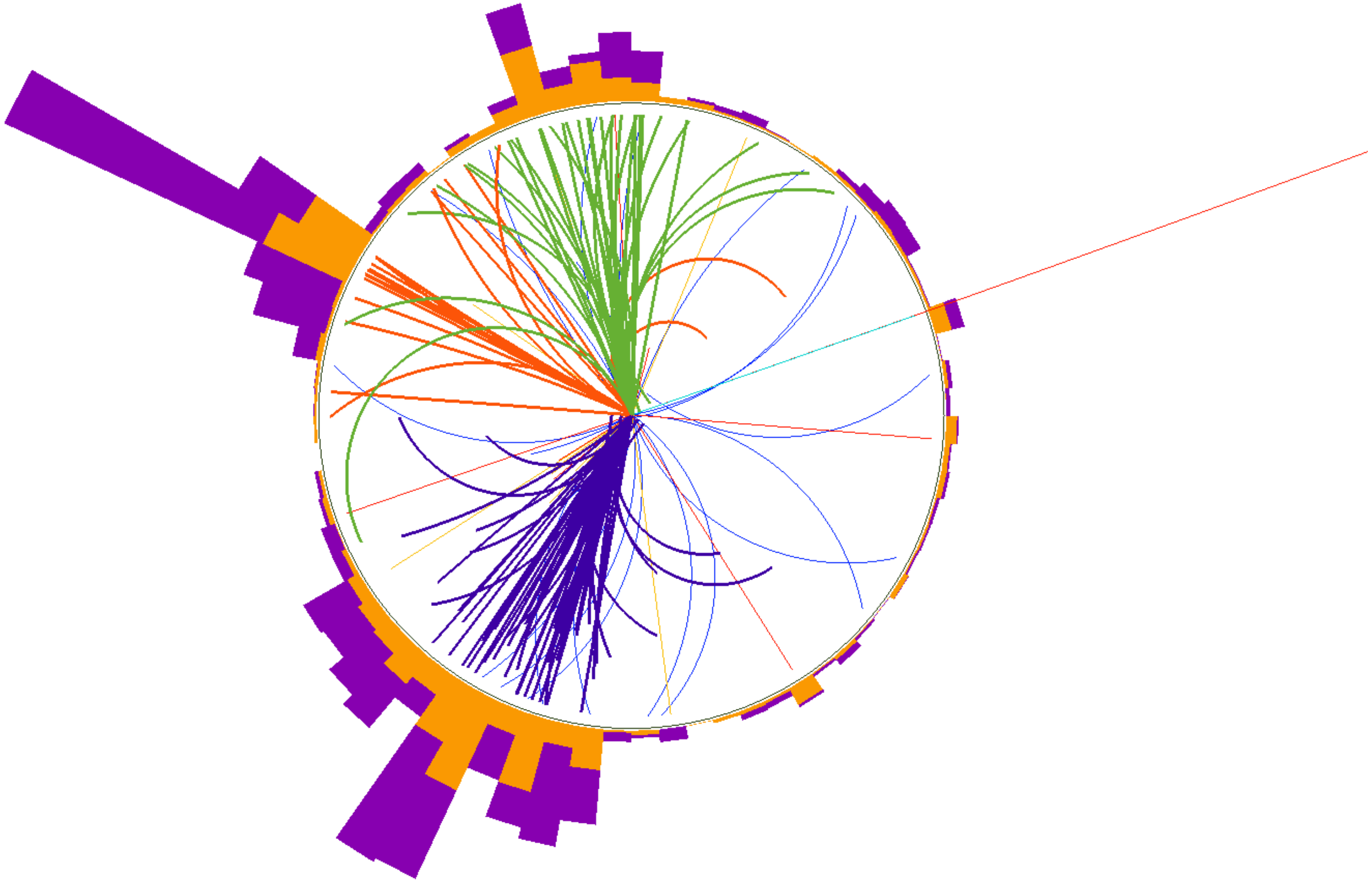


Single list of reconstructed particles:

- all calibrated

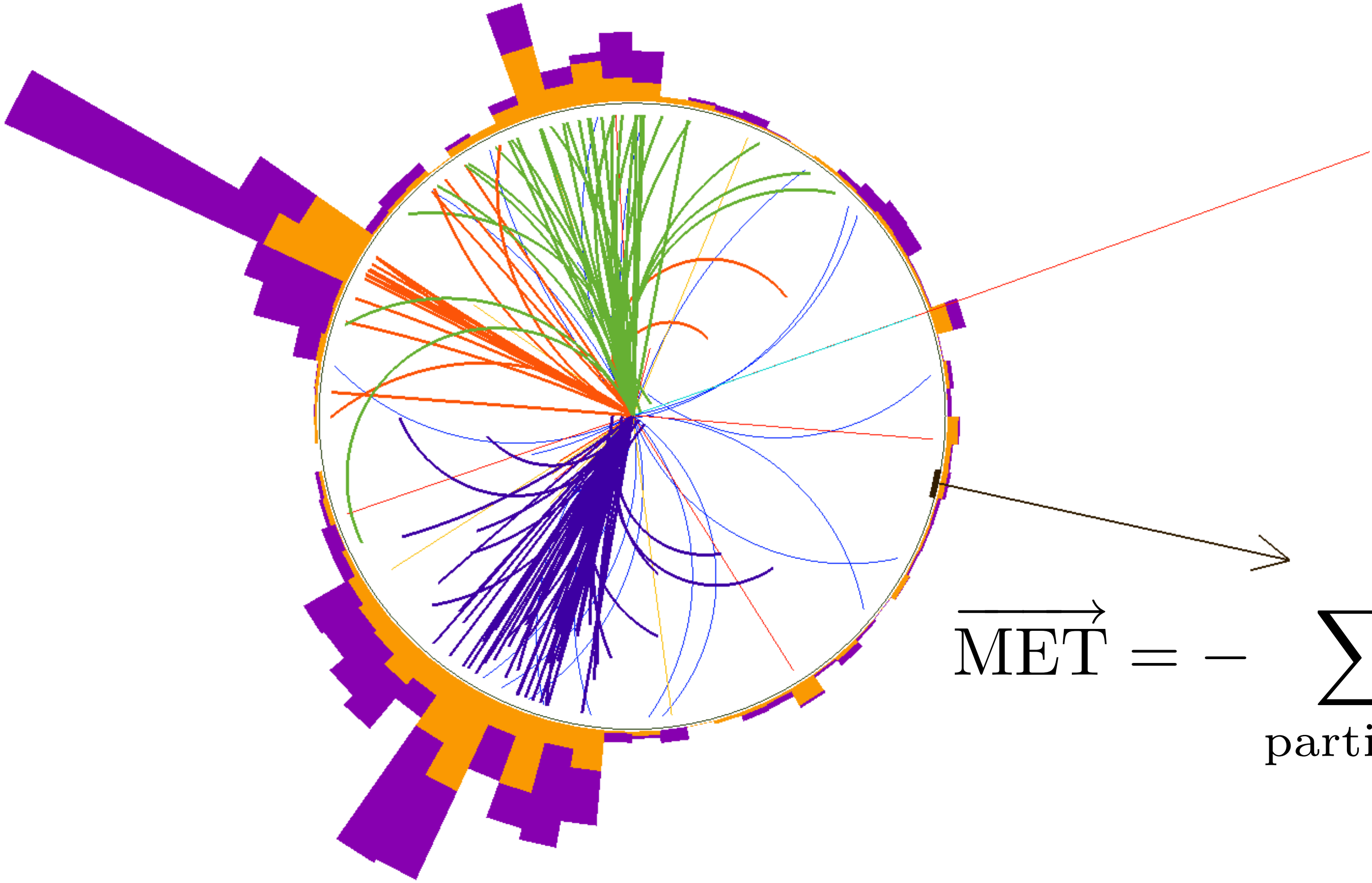
- used to build high-level objects in a consistent way (global event description)

Particle Jets



For the first time in a hadron collider experiment

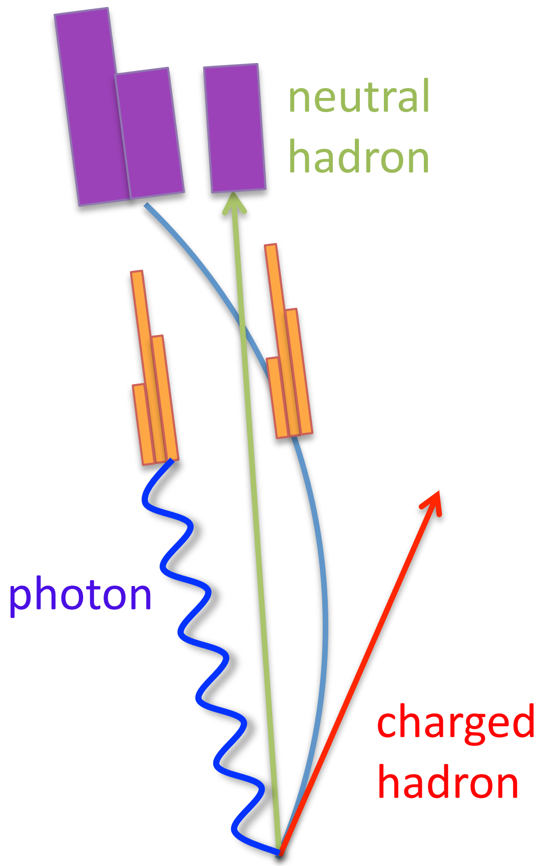
Missing Transverse ~~Energy~~ Momentum



$$\overrightarrow{\mathrm{MET}} = - \sum_{\mathrm{particles}} \vec{p}_{\mathrm{T}}$$

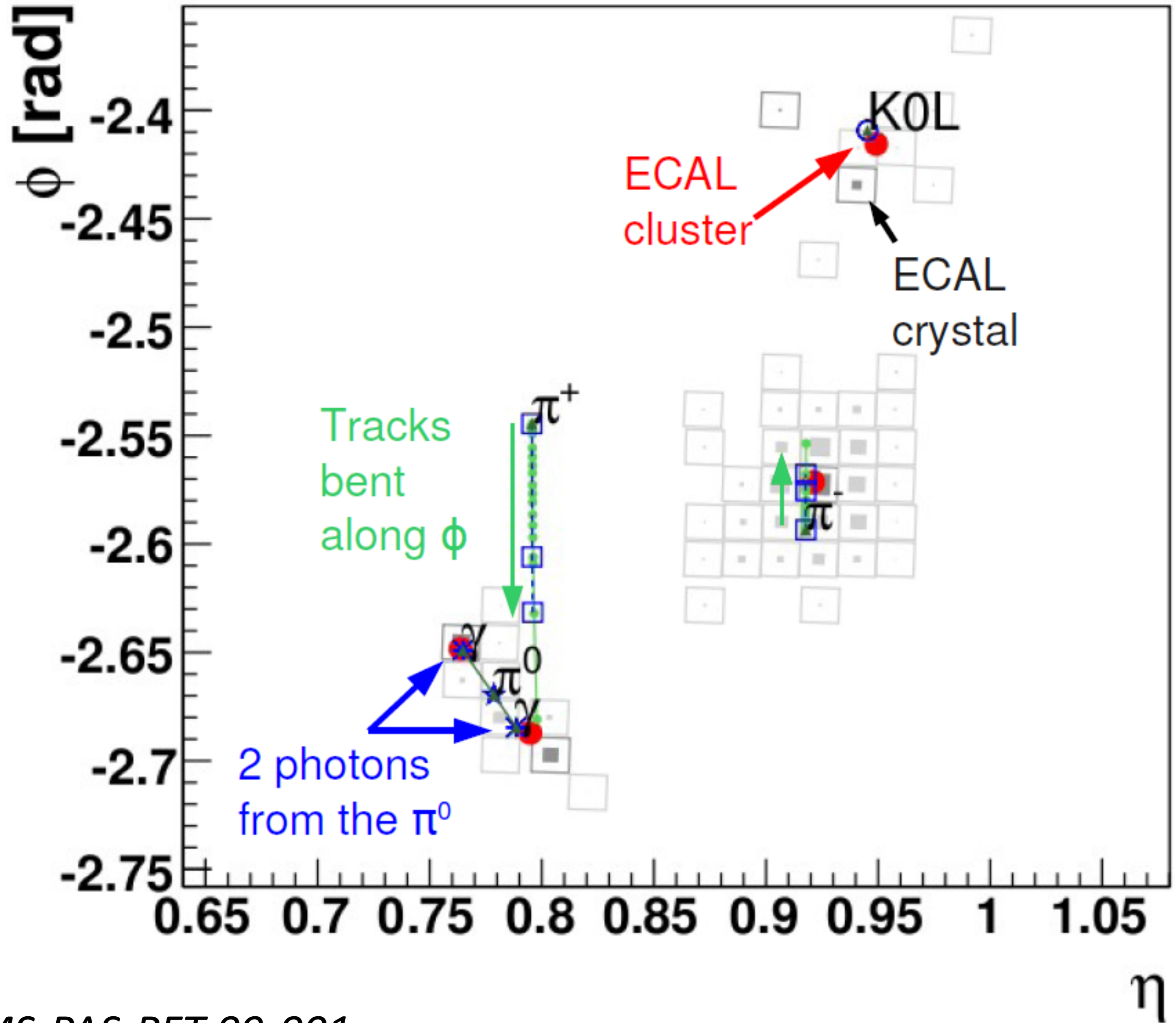
For the first time in a hadron collider experiment

Why Particle Flow?



- Calorimeter jet:
  - $E = E_{HCAL} + E_{ECAL}$
  - σ(E) ~ calo resolution to hadron energy: 120 % / √E
  - direction biased (B = 3.8 T)
- Particle flow jet:
  - 65% charged hadrons
    - σ(pT)/pT ~ 1%
    - direction measured at vertex
  - 25% photons
    - σ(E)/E ~ 1% / √E
    - good direction resolution
  - 10% neutral hadrons
    - σ(E)/E ~ 120 % / √E
  - **Need to resolve the energy deposits from the neutral particles…**

ECAL Surface



- A typical jet
  - pT = 50 GeV/c
- Cell size:
  - 0.017x0.017

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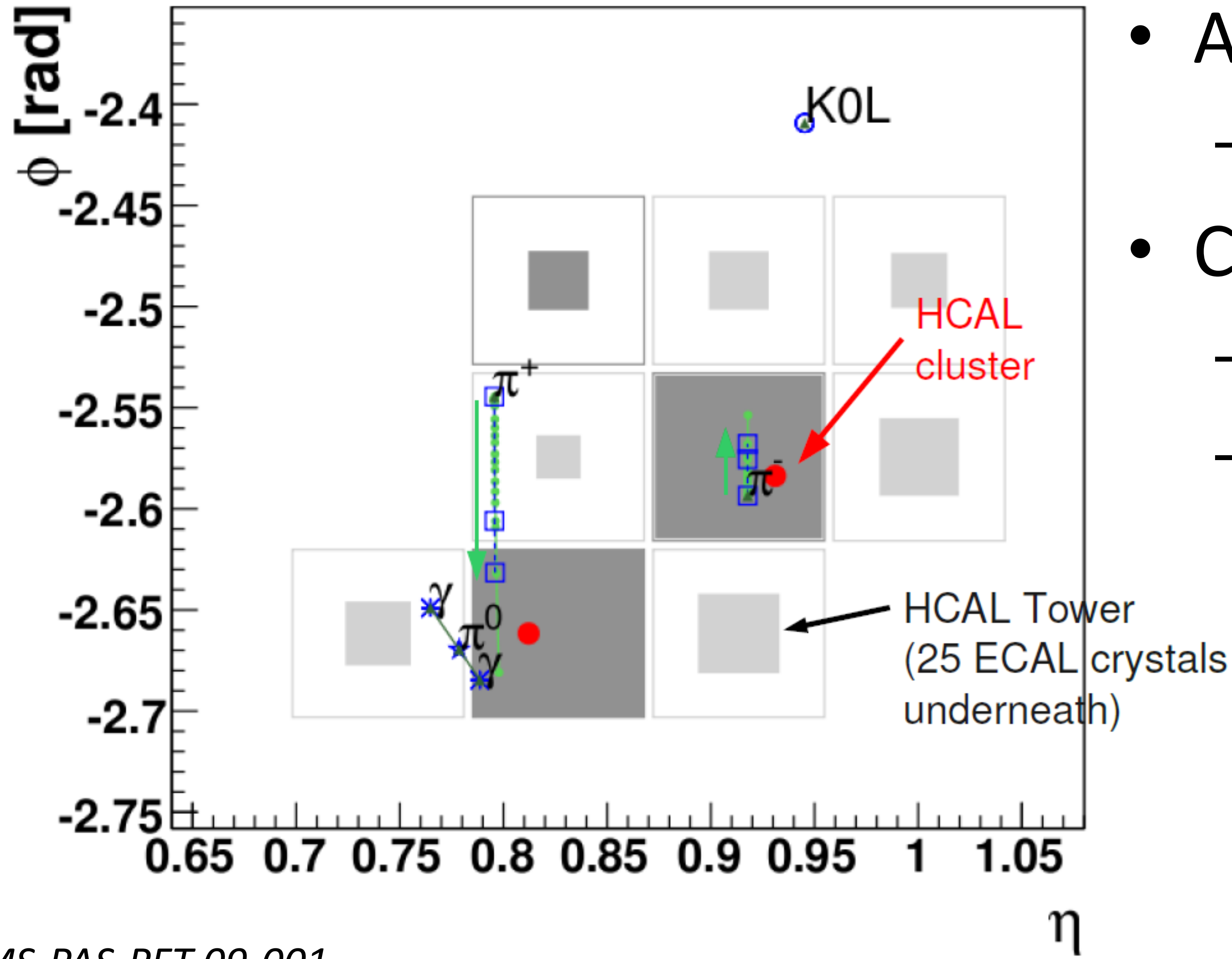
HCAL Surface



- A typical jet
  - pT = 50 GeV/c
- Cell size:
  - 0.085x0.085
  - 5 ECAL crystals

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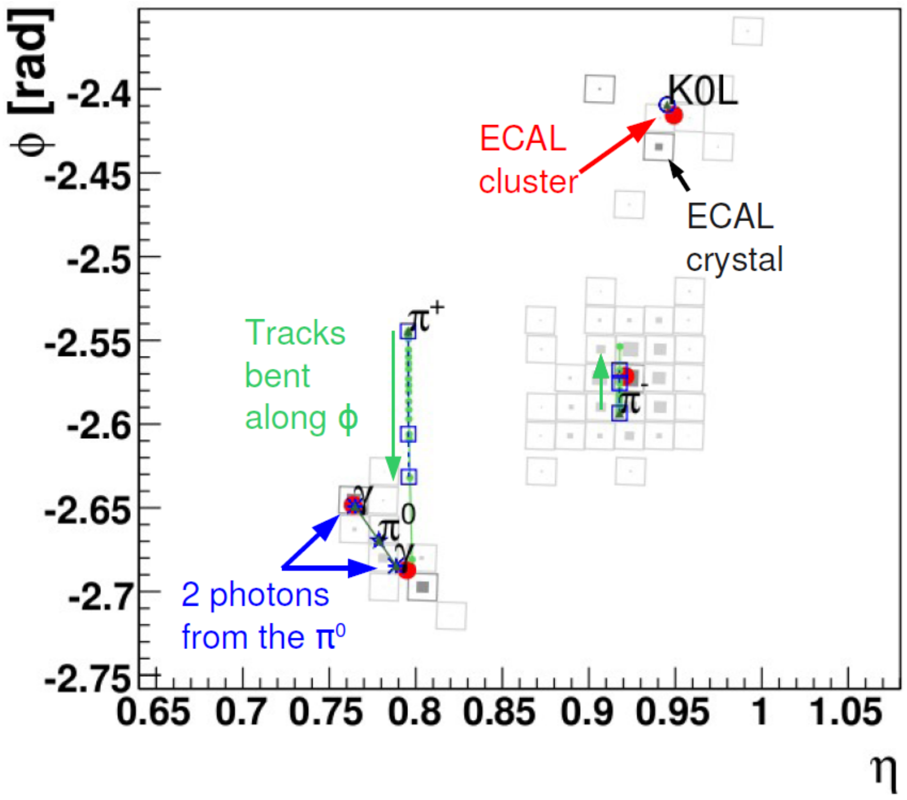
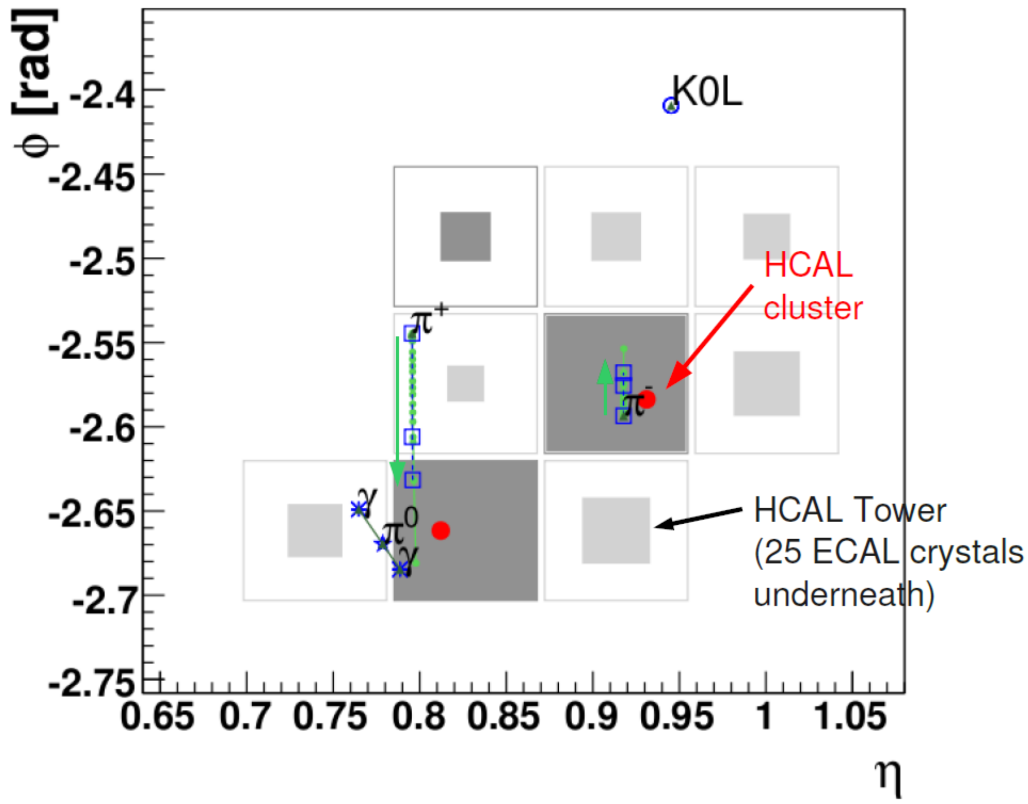
2 charged hadrons, 3 photons

from tracks

from ECAL clusters



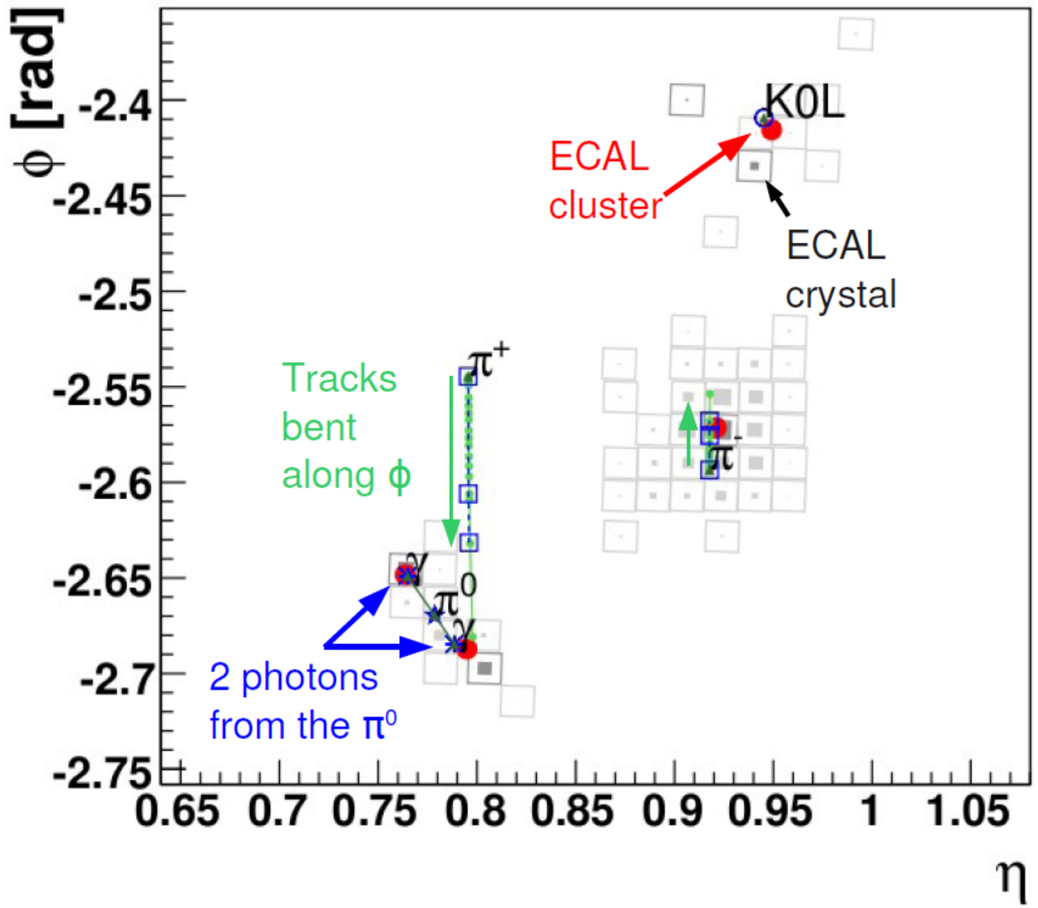


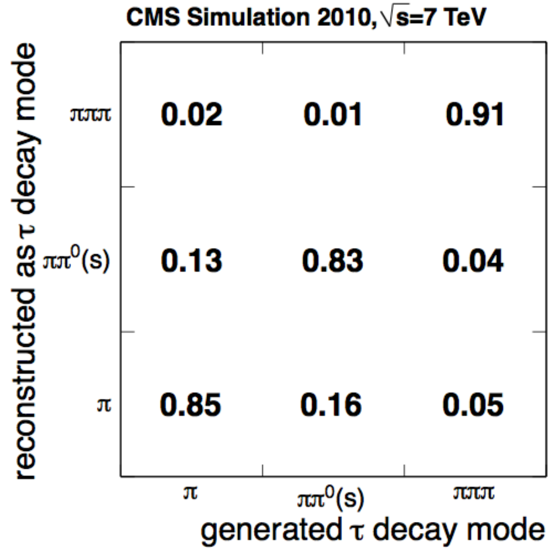
CMS-PAS-PFT-09-001, + instructive backup slides

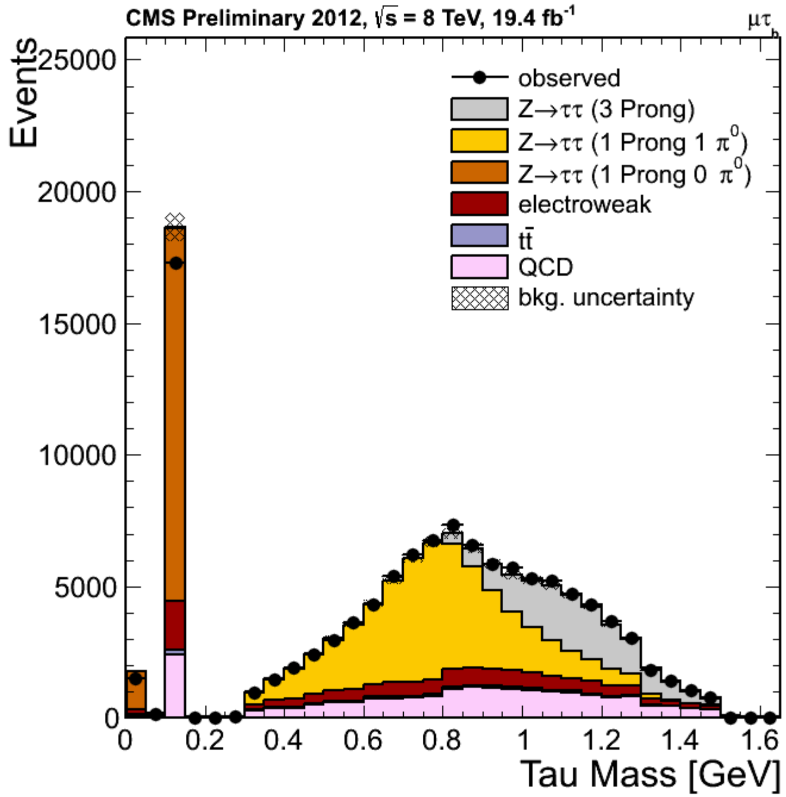
Effects of particle flow in CMS

- **Jets**
  - energy resolution / 2
  - angular resolution / 3
  - Flavour dependence of response / 3
  - Systematic error on JES / 2
  - « electron in jet » b tagging
  - quark-gluon jet tagging
- **MET:**
  - resolution / 2
  - pile-up control
  - smallest tails
- **τ**
  - jet fake rate / 3 @ same eff.
  - energy resolution / 4
- **Electrons**
  - down to pT = 3 GeV
  - in jets
- **μ**
  - 4% more efficient ID @ same bgd rate
  - better momentum assignment at high pT
- **e, μ, τ, γ isolation**
  - pile-up control
- **Physics analyses**
  - Better trigger for jets, MET, taus (PF@HLT)
  - e.g:
    - FSR photon recovery in H→ZZ
    - embedding in H→ττ
    - jet substructure

τ Reco & ID in CMS







- Select decay particles according to decay mode
- Isolation w/r to other particles

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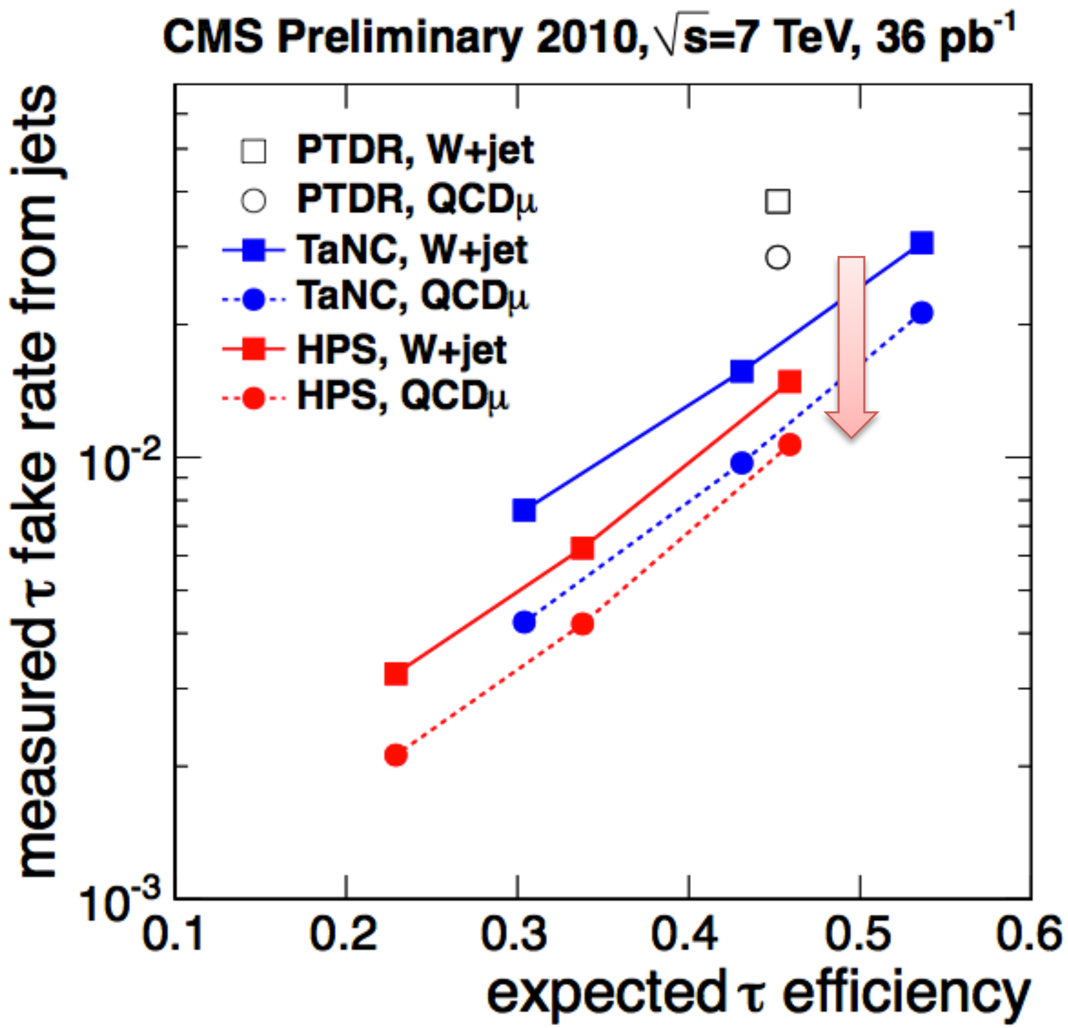
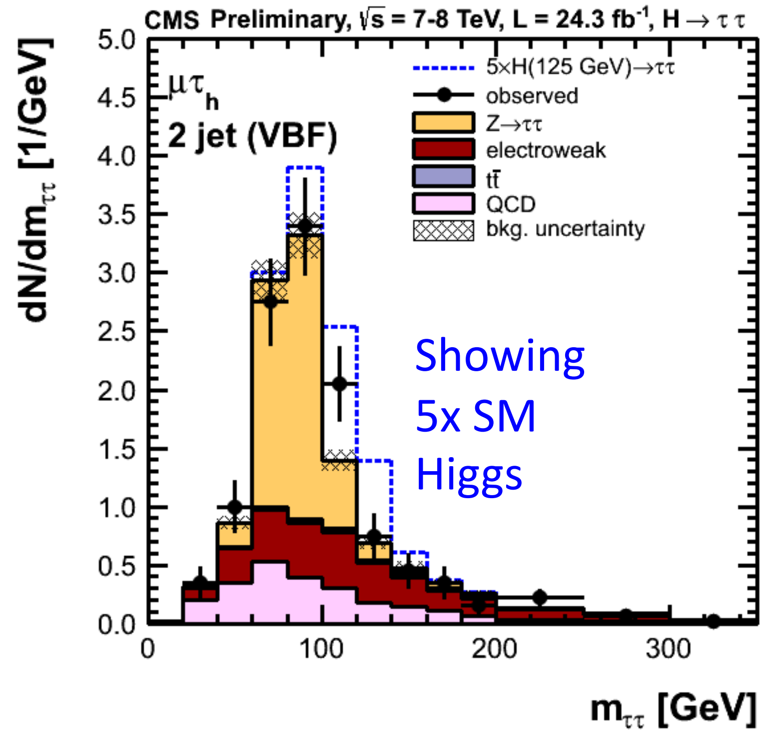
τ ID performance



- 3 times less jet→τ fake rate at same efficiency
  - → 3 times less W+jets and QCD background



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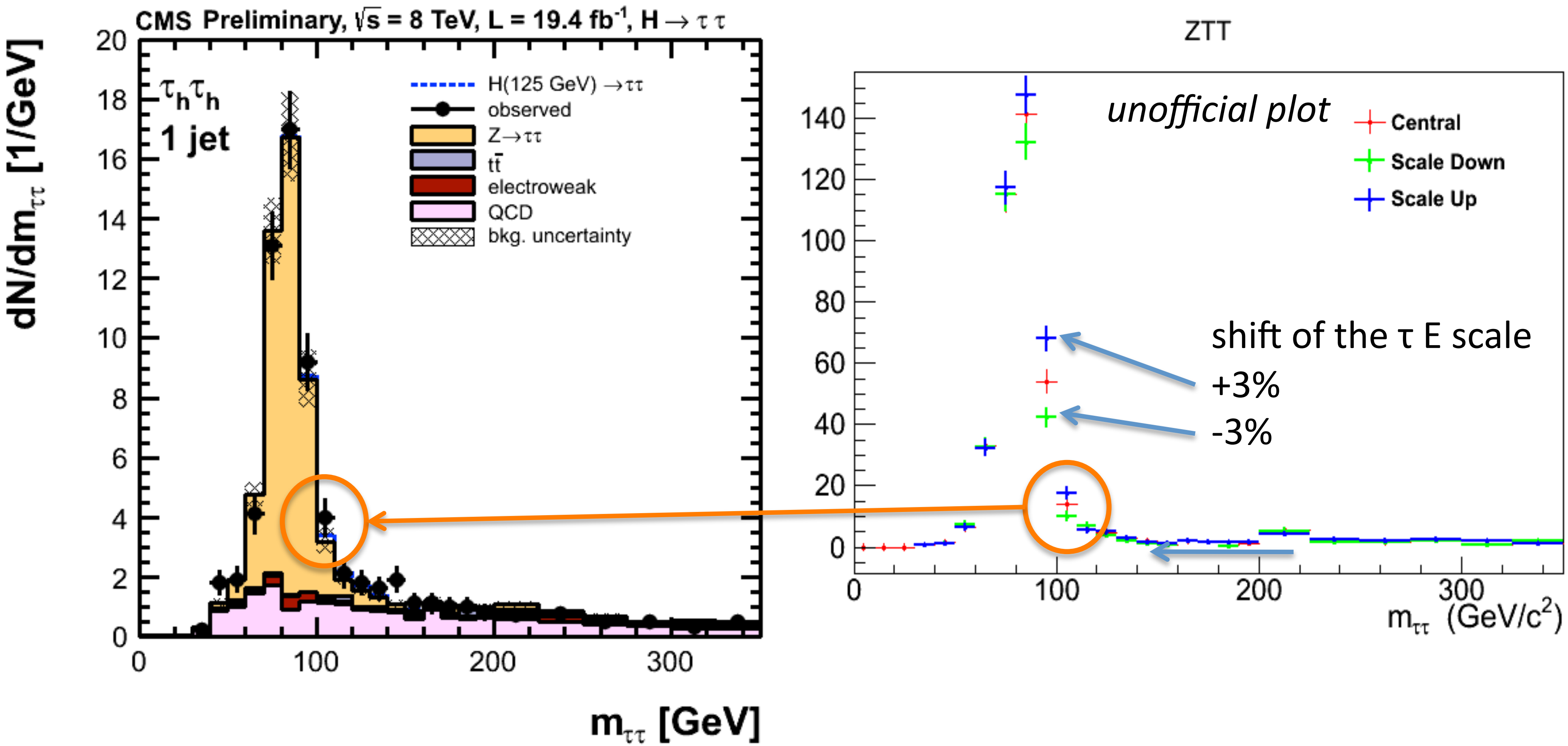
τ Energy Scale



- fully hadronic (ττ) channel
  - 3% shift of τ E scale = 1-2 x signal expectation
- Important to calibrate τ energy
  - done using the τ mass

Unofficial plots

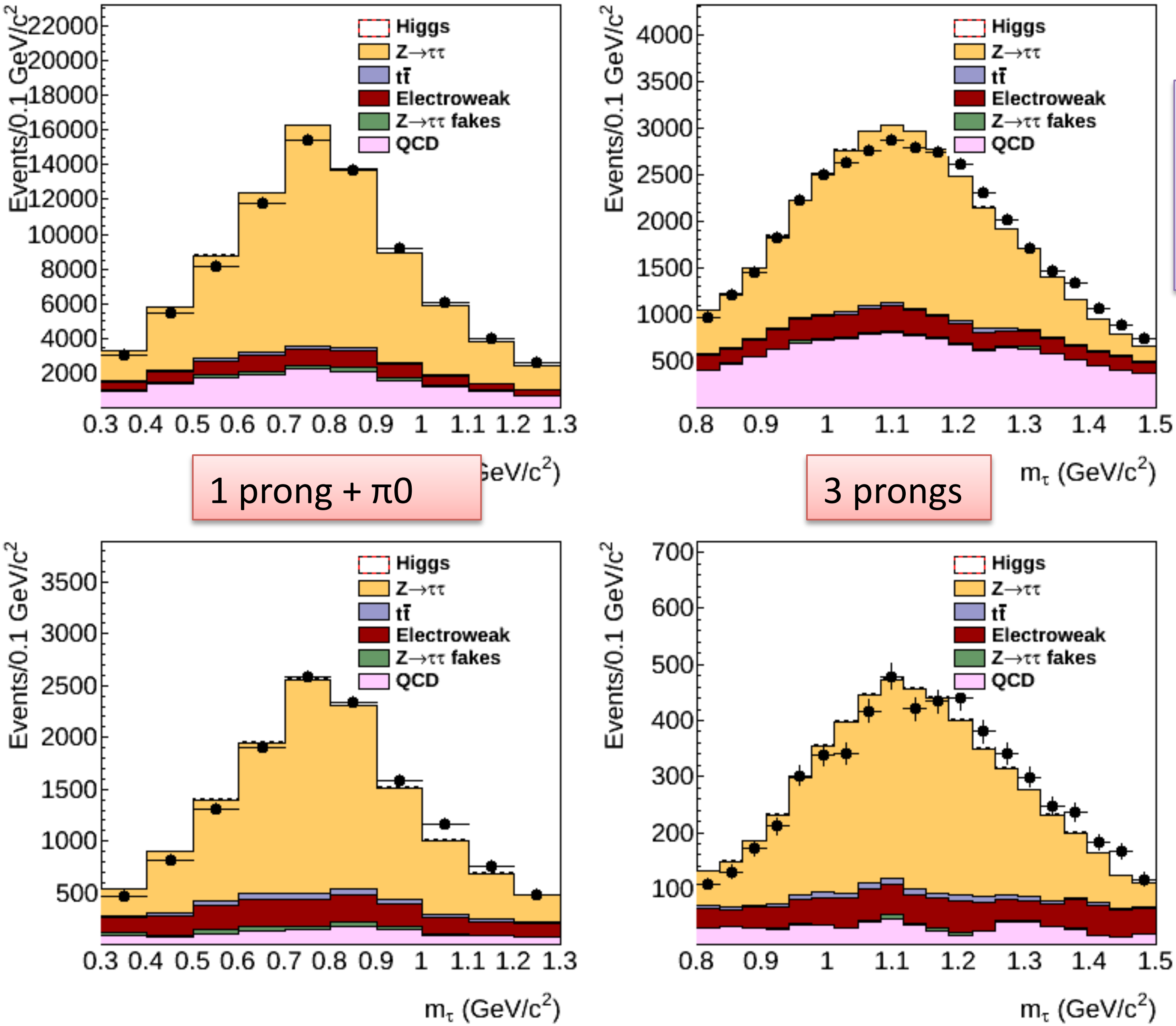
τ mass before calibration

pT<40

pT>40

1 prong + π0

3 prongs



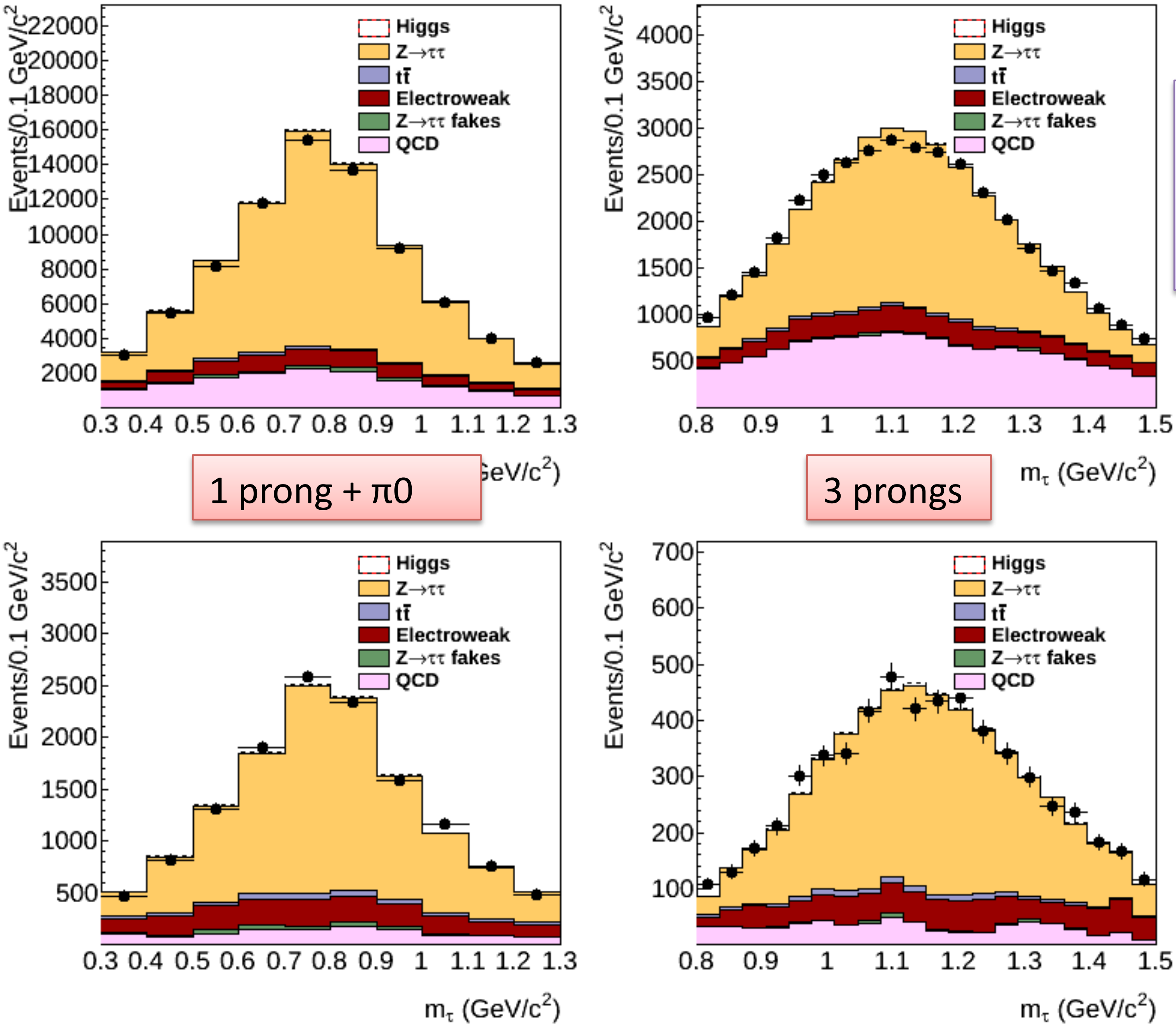
plots and fit done using μτ events.

Unofficial plots

τ mass after calibration

pT<40

pT>40



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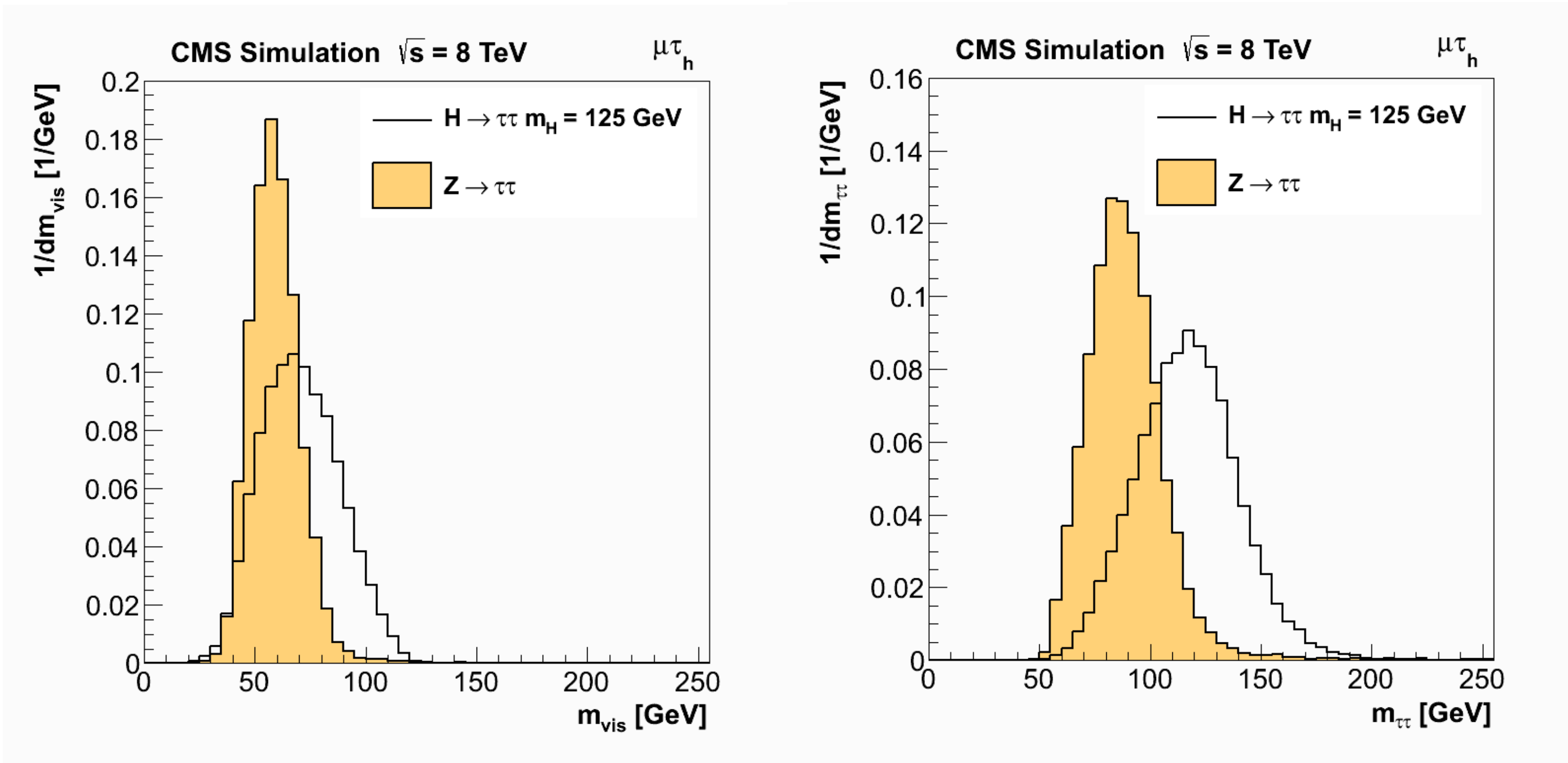
3 prongs

plots and fit done using μτ events.

E_T^{miss} resolution: $m_{\tau\tau}$

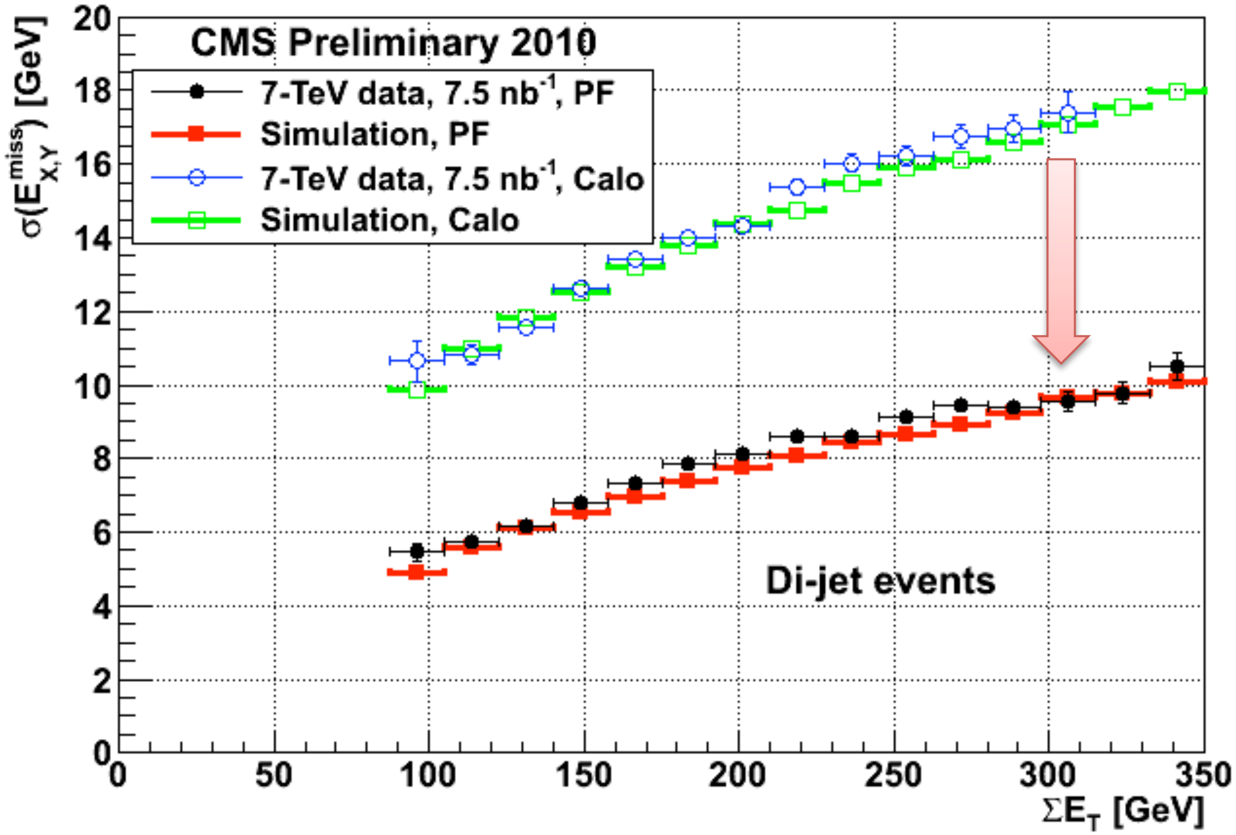


$$m_{\text{vis}}^2 = (p_1 + p_2)^2$$

$$m_{\tau\tau} = f(p_1, p_2, E_{\text{T}}^{\text{miss}})$$

- H→ττ better separated from Z→ττ (main, irreducible background)
- Resolution on $m_{\tau\tau}$ ~ 20% (resolution on E_T^{miss} important)

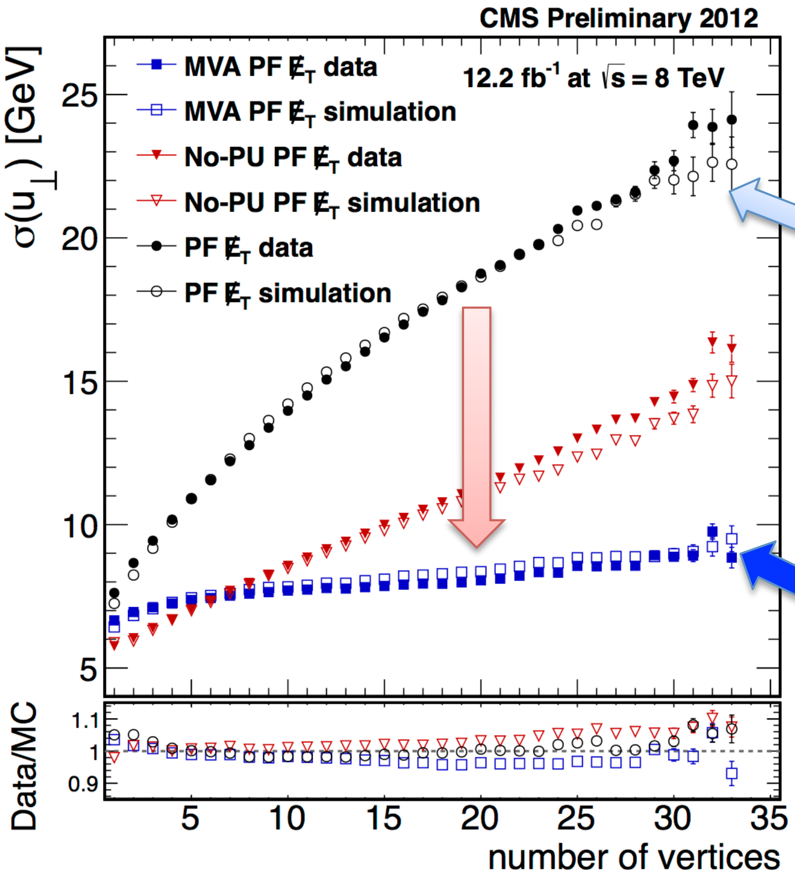
PF vs Calorimeter E_T^{miss}



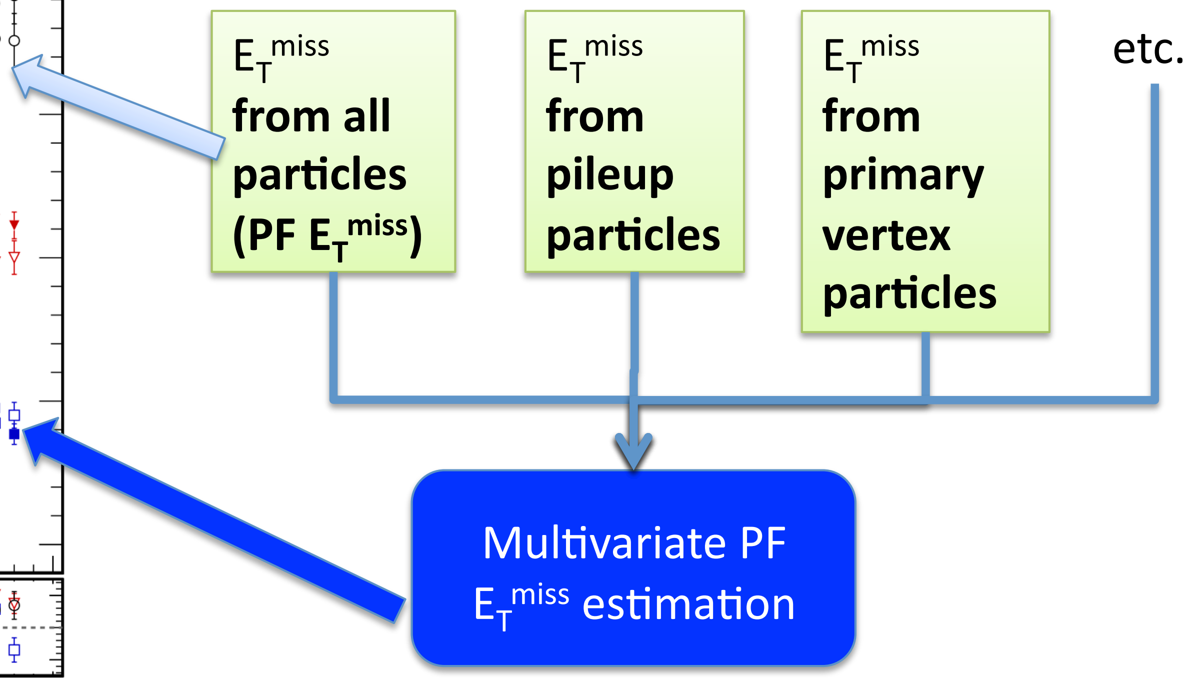
Resolution twice better

CMS PAS PFT-10-002

Multivariate PF E_T^{miss}



several kinds of particle-flow E_T^{miss}:

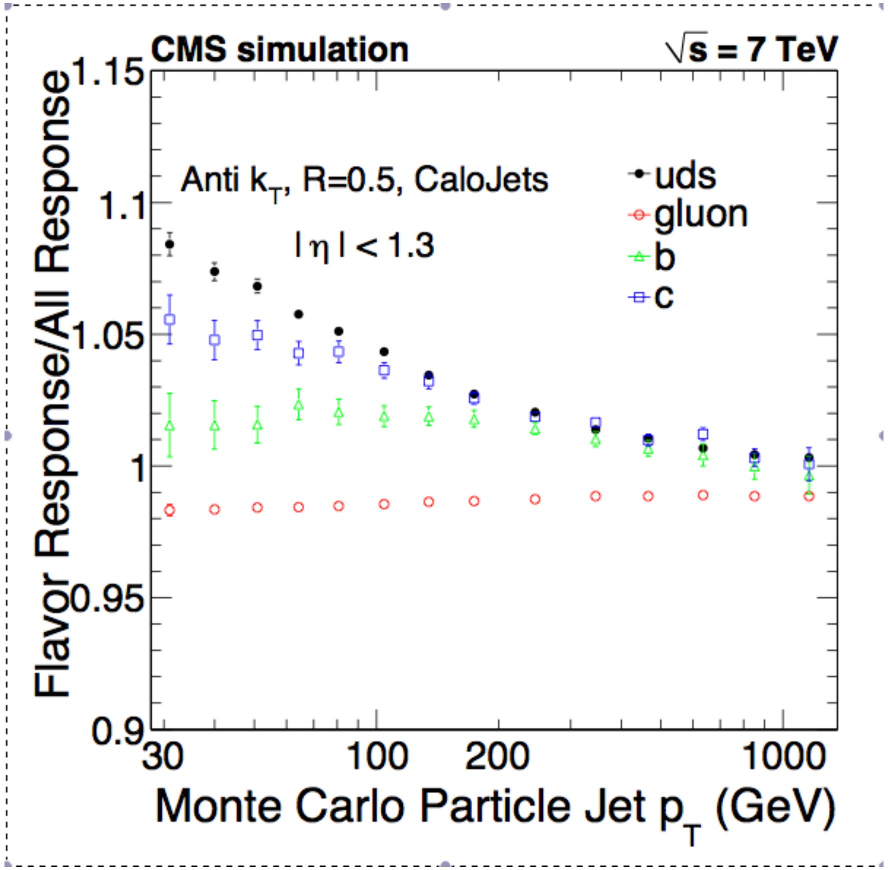


- Additional factor 2 improvement @ 20 pile-up vertices
- MVA PF MET Almost insensitive to pileup

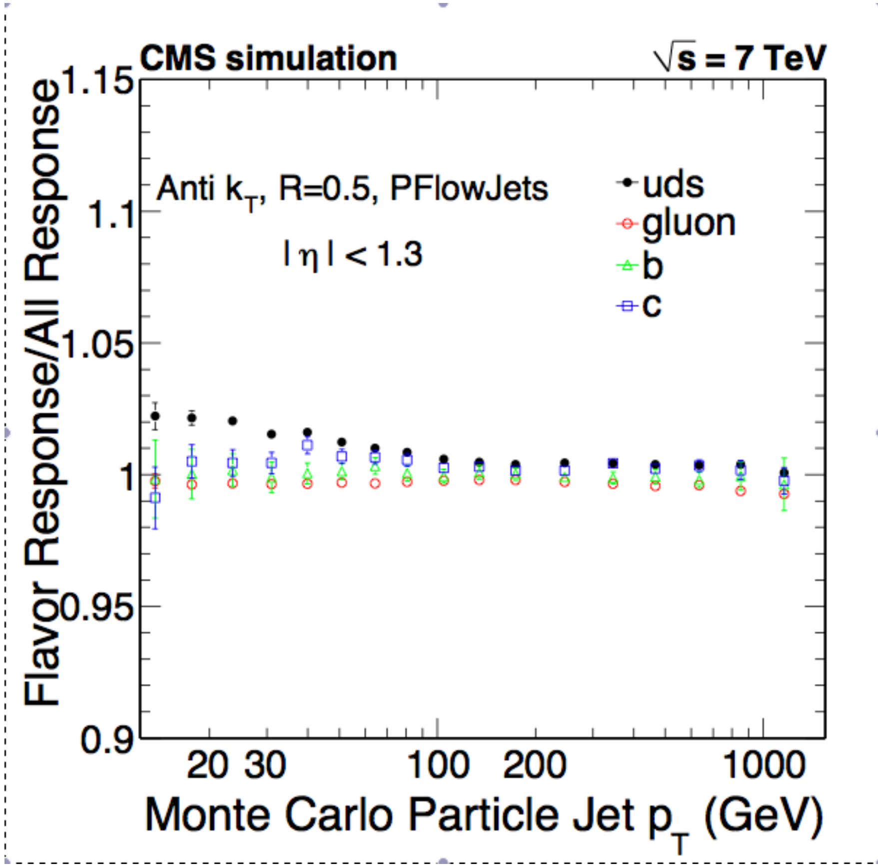
CMS-PAS-JME-12-002

Jet Response: Flavour Sensitivity

Calo Jets



PF Jets



PF jet response almost independent
from the flavour of the jet-initiating parton

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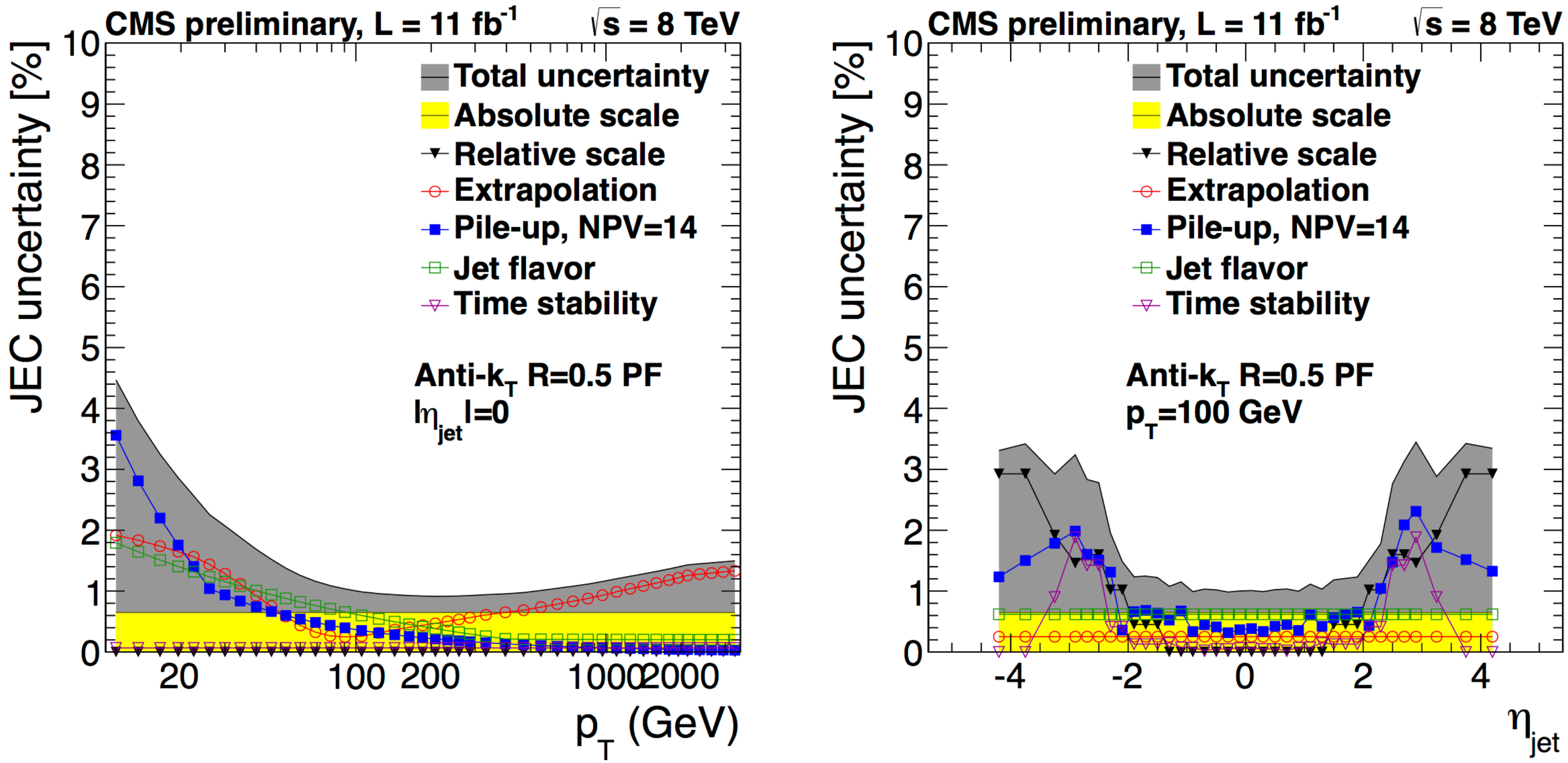
Jet Energy Scale Uncertainty



1-3 % Jet Energy Scale Systematic uncertainty

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME2013JEC

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- E_T^{miss} resolution
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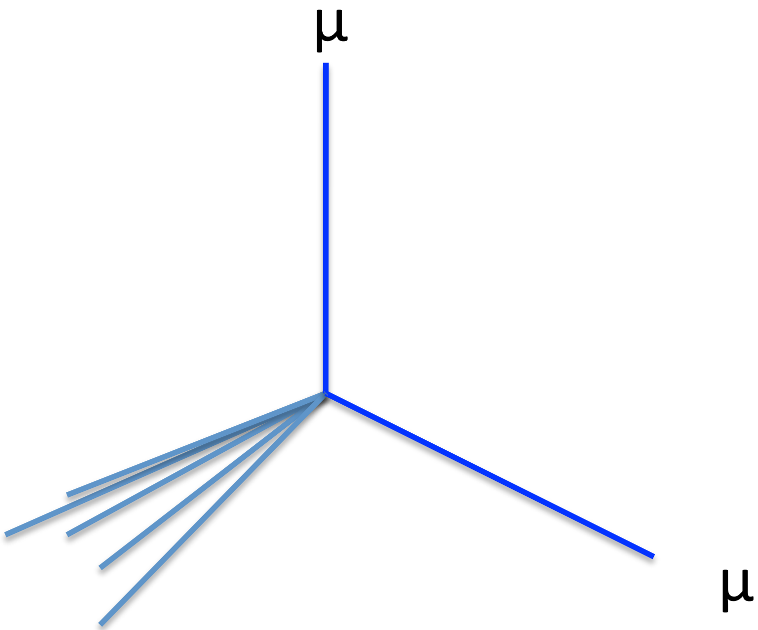
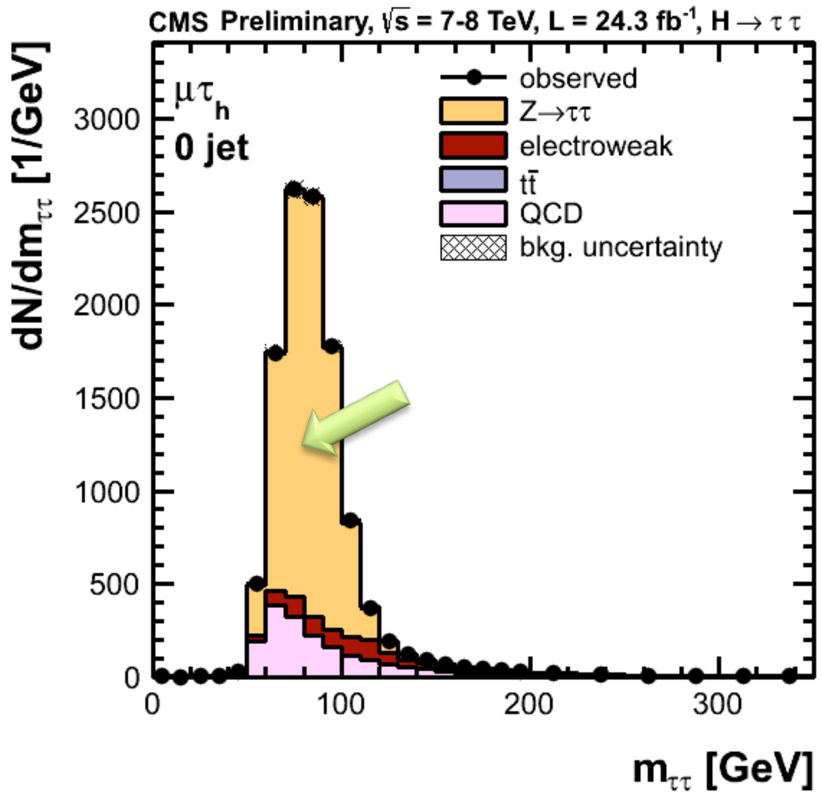
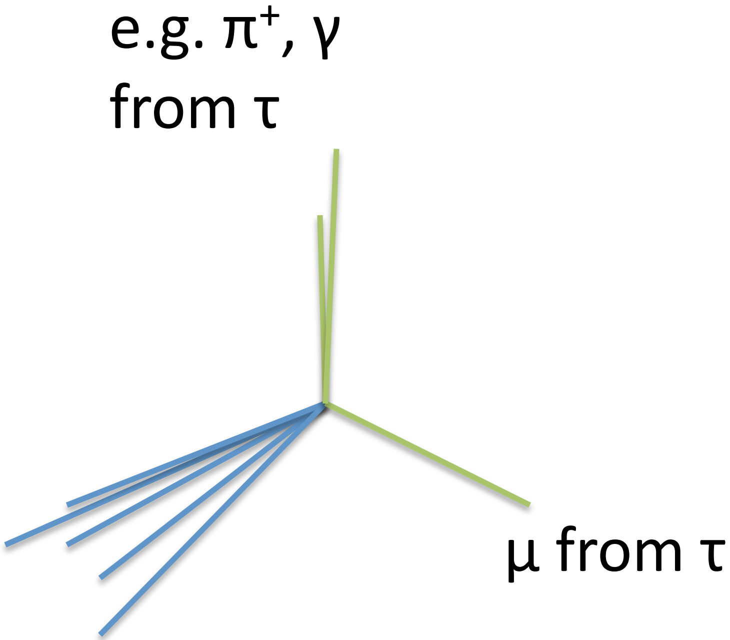
Background : Z→ττ

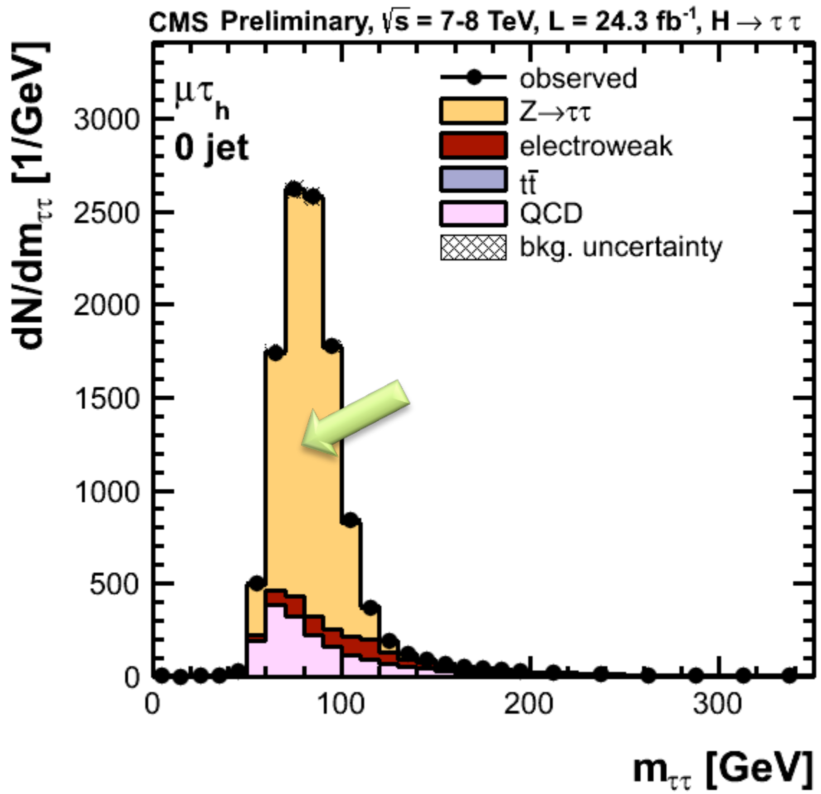




- Select data Z→μμ events
- Replace muons by particles reconstructed from simulated Z→ττ decay, and apply selection
- Jets and E_T^{miss} from data. Main remaining uncertainties:
  - τ ID efficiency uncertainty (8%)→ affects the yield
  - τ energy scale uncertainty (3%)→ affects the shape

Background : Z→ττ





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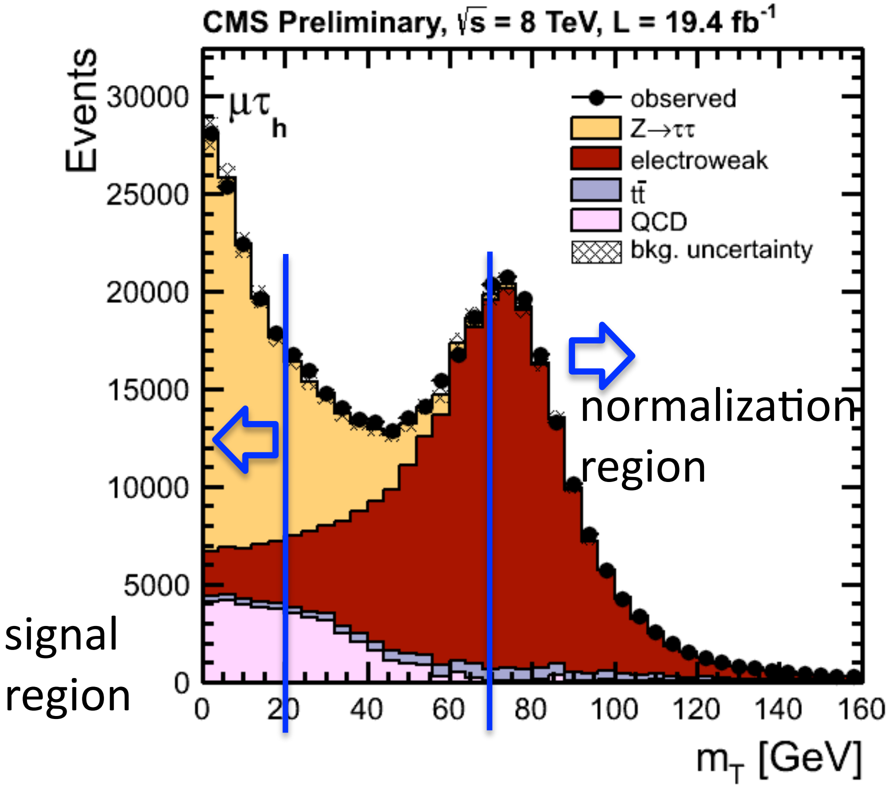
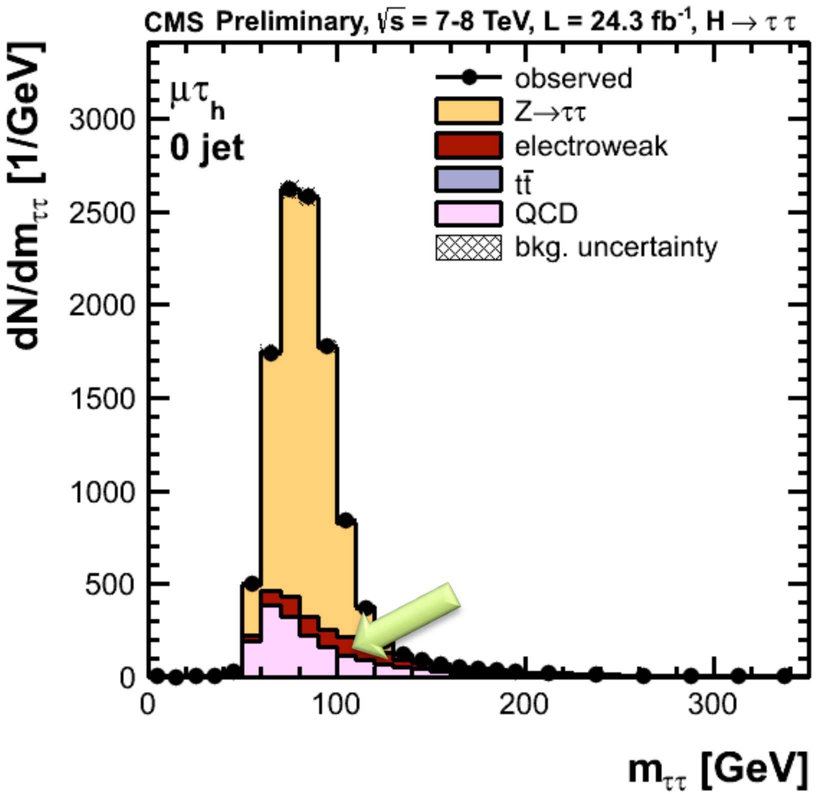
  - τ energy scale uncertainty (3%)→ affects the shape

Background : W+Jets





- normalization to data in high mT region
- assume simulated shape → yield in signal region
  - yield syst. uncertainty = 20%

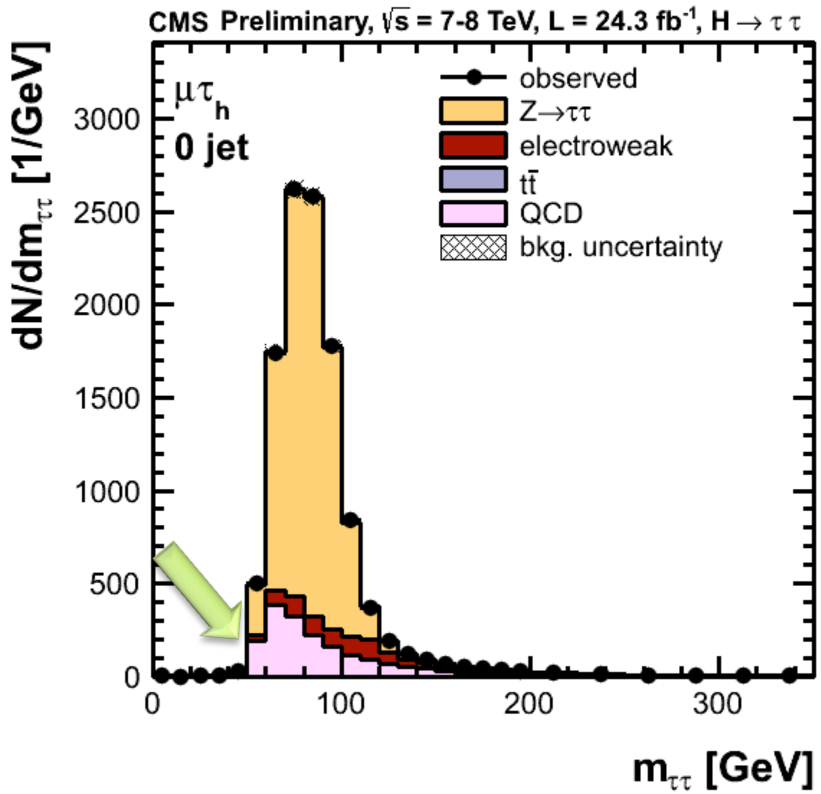
CMS PAS HIG-13-004

Background : QCD

- Select same-sign (SS) μτ events
- QCD_{SS} = data - Bgd_{SS}
- $QCD_{OS} = f_{SS \to OS}\, QCD_{SS}$

10% uncertainty

1.06 ± 0.11 from data

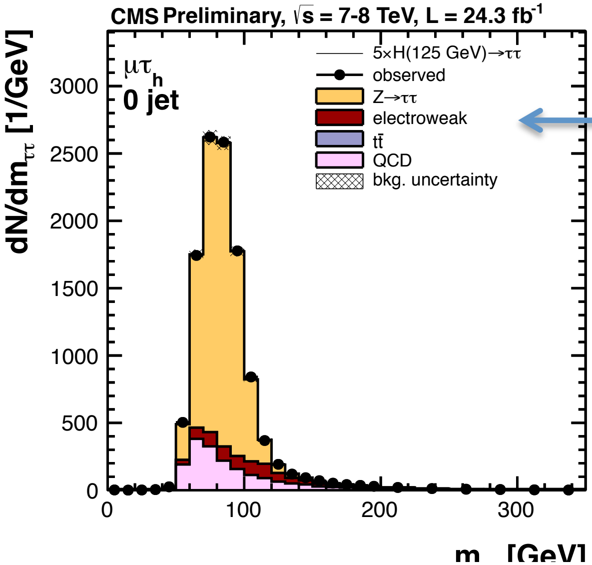


- VBF category: not enough events in SS region
  - yield $QCD_{VBF} = f_{inclusive \to VBF} QCD_{inclusive}$

    20 % uncertainty
  - shape from control region with non-isolated μ

CMS PAS HIG-13-004

Event categories

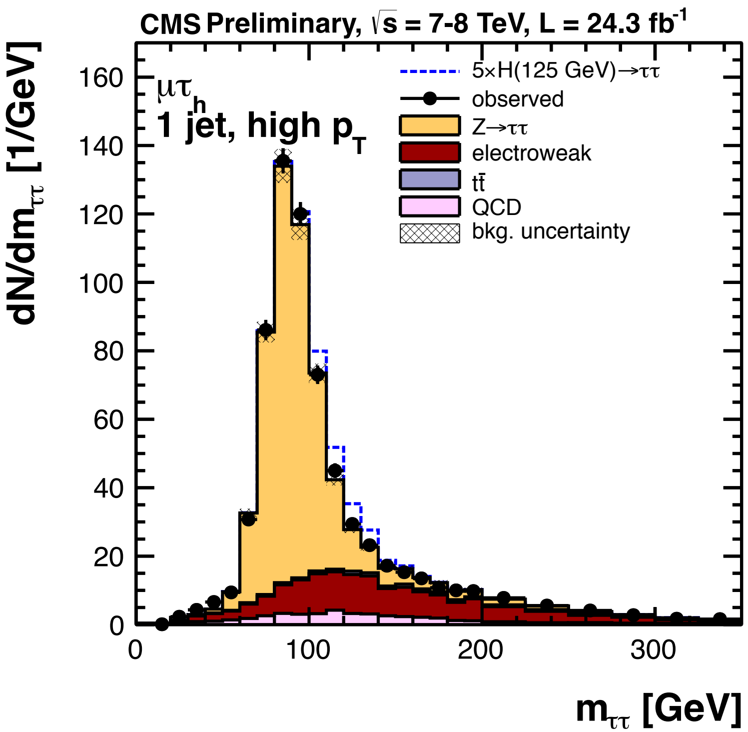


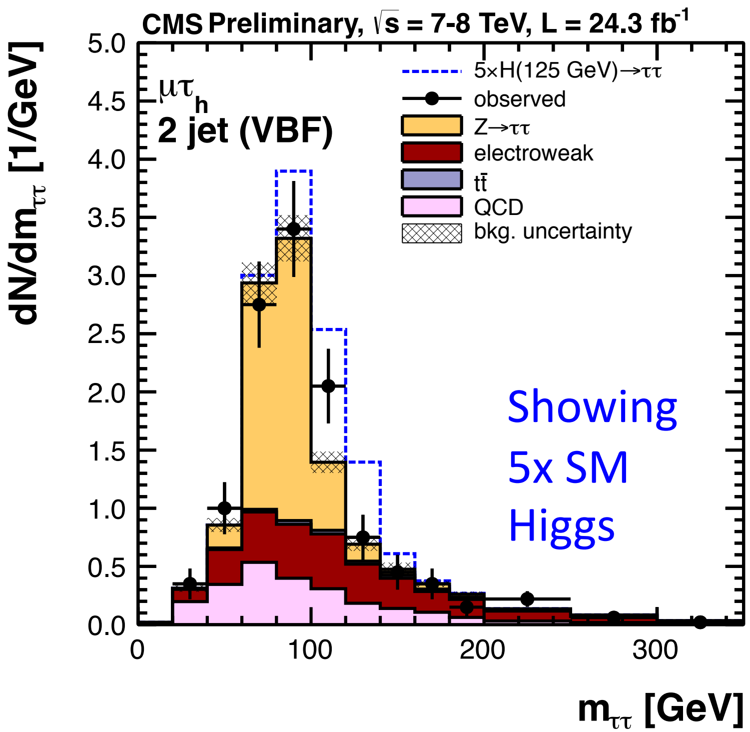
constrains systematic errors

for sensitive categories

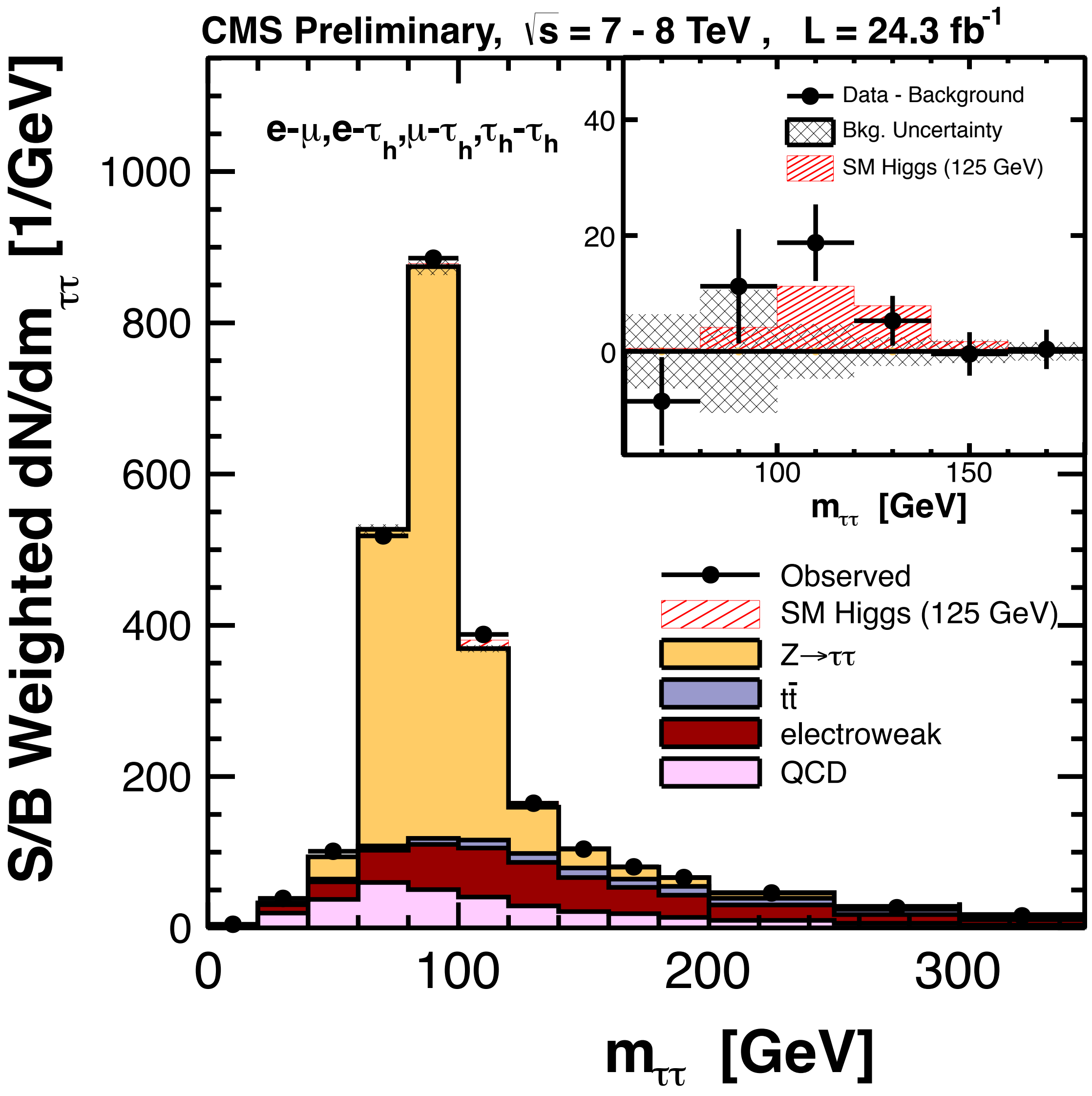
5 channels:

$\mu\tau_h$, $e\tau_h$, $e\mu$, $\tau_h\tau_h$, $\mu\mu$



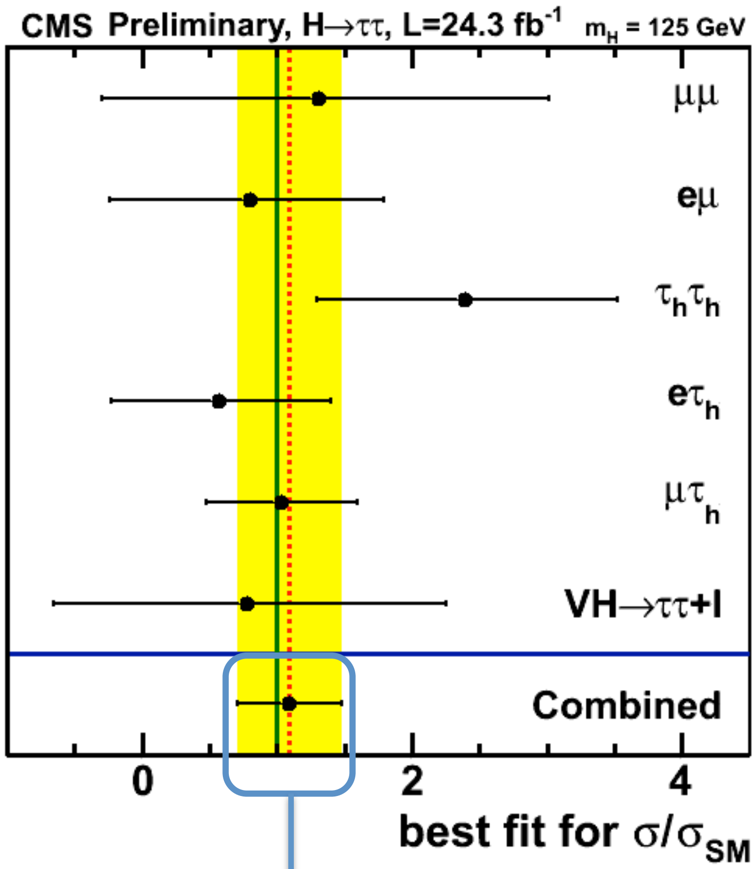


Combined mass distribution



- Combination of all categories of all major channels
- Each is weighted by the expected S/B in the signal region

H → ττ significance

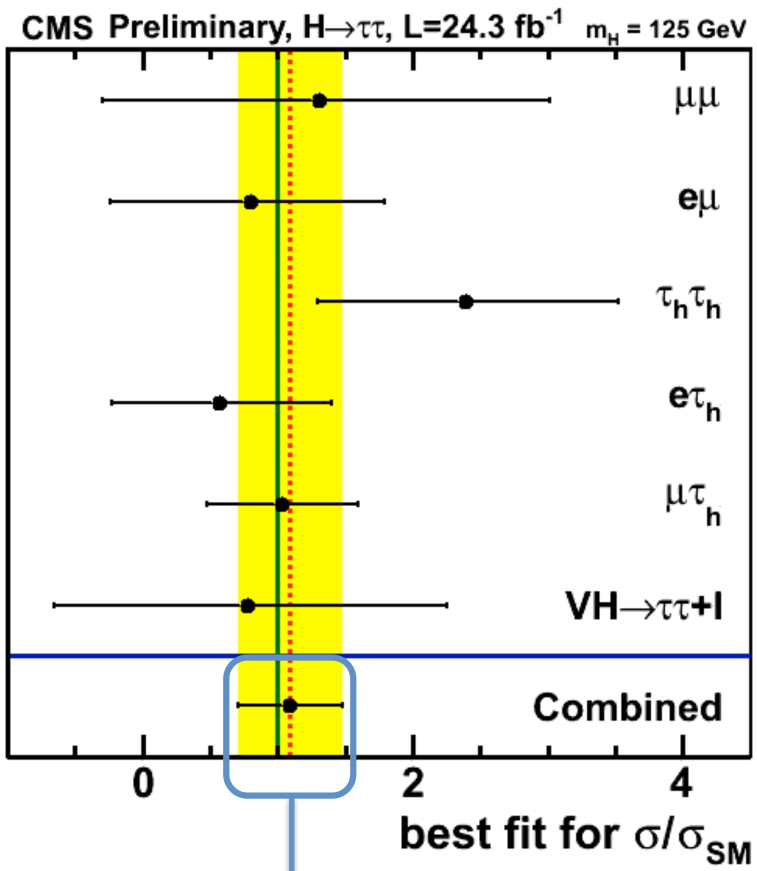


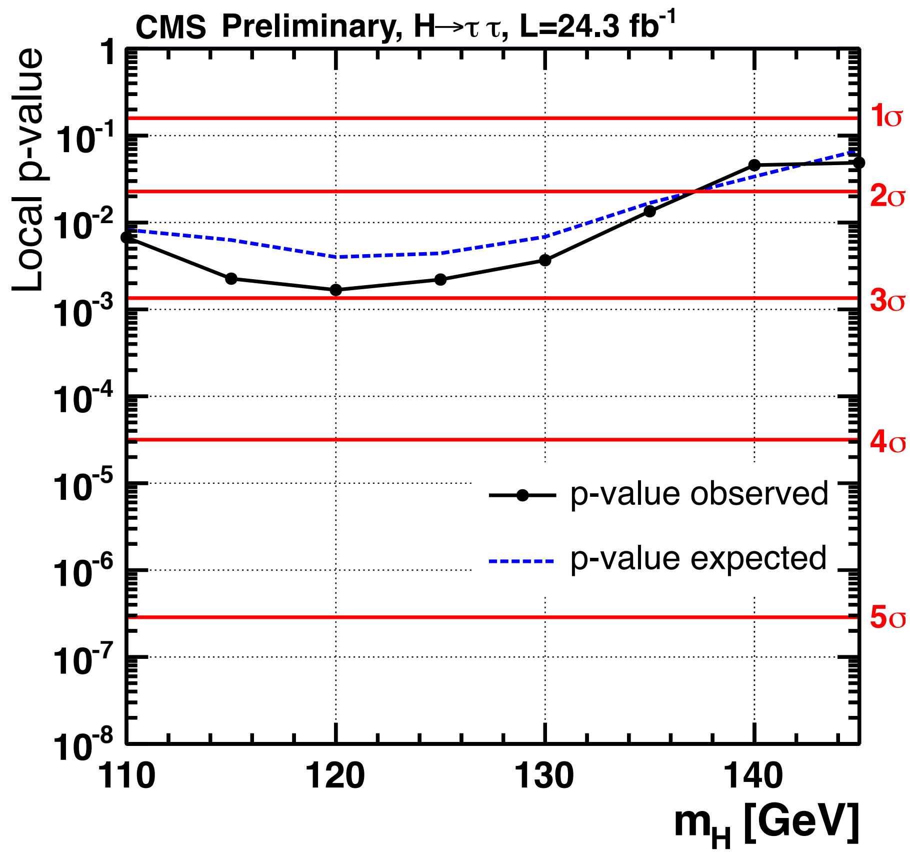
All channels compatible

$\mu = 1.1 \pm 0.4$

CMS PAS HIG-13-004

H → ττ significance





All channels compatible

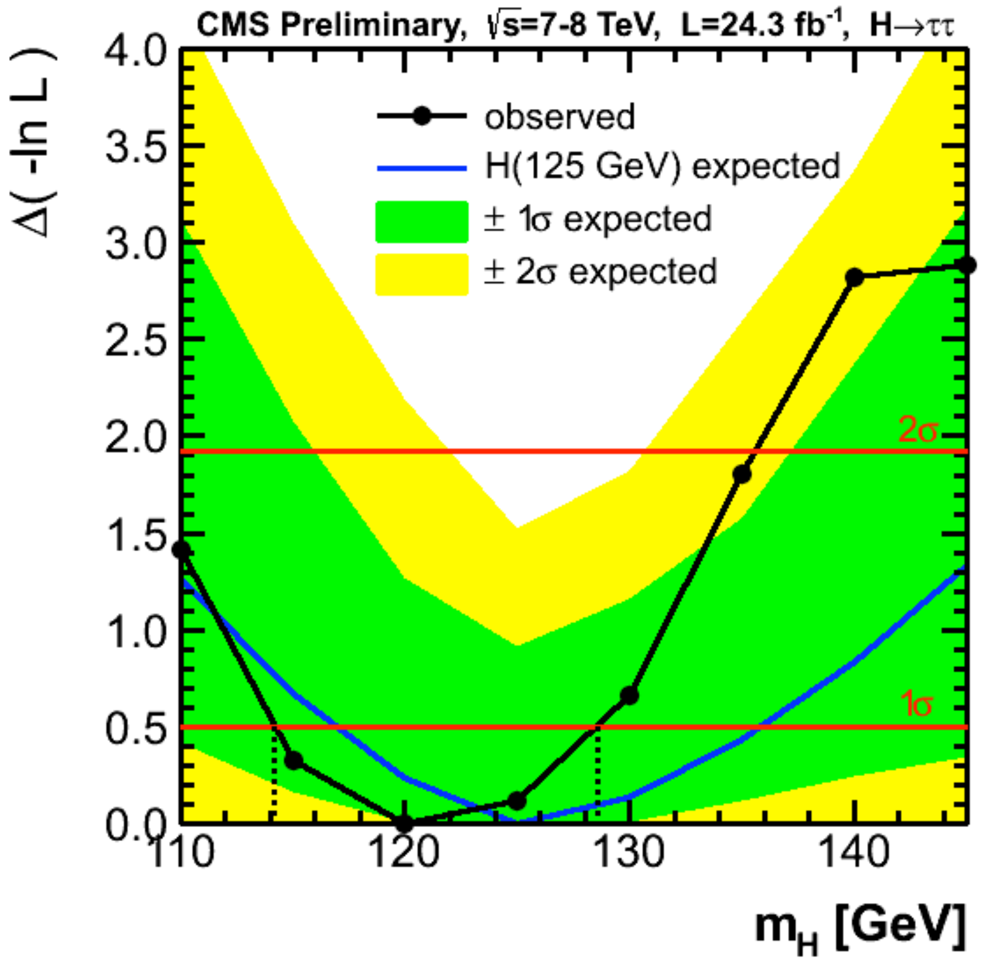
μ = 1.1 ± 0.4

Maximum significance:
2.93 σ @ mH = 120 GeV (2.65 exp.)

First Strong indication that the new boson couples to τ as the SM Higgs

CMS PAS HIG-13-004

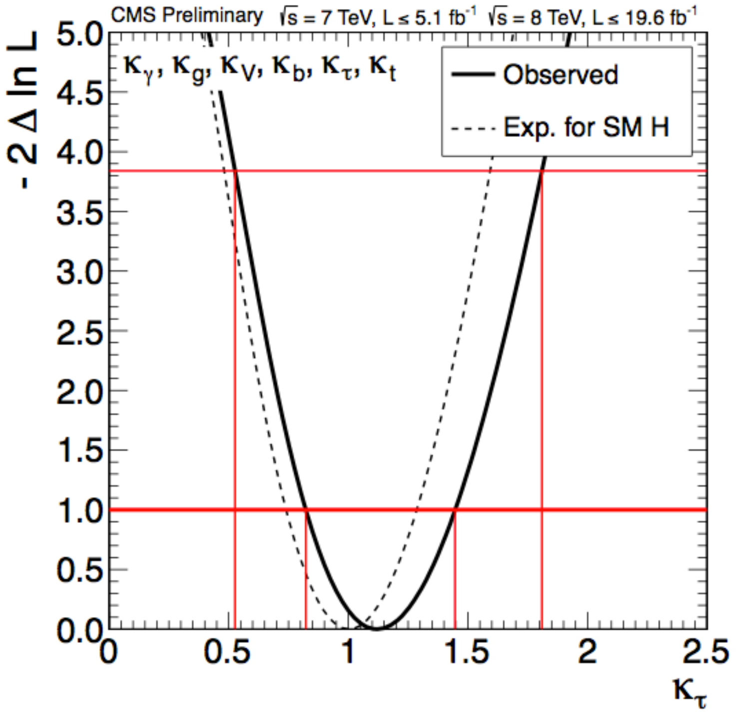
H→ττ mass measurement

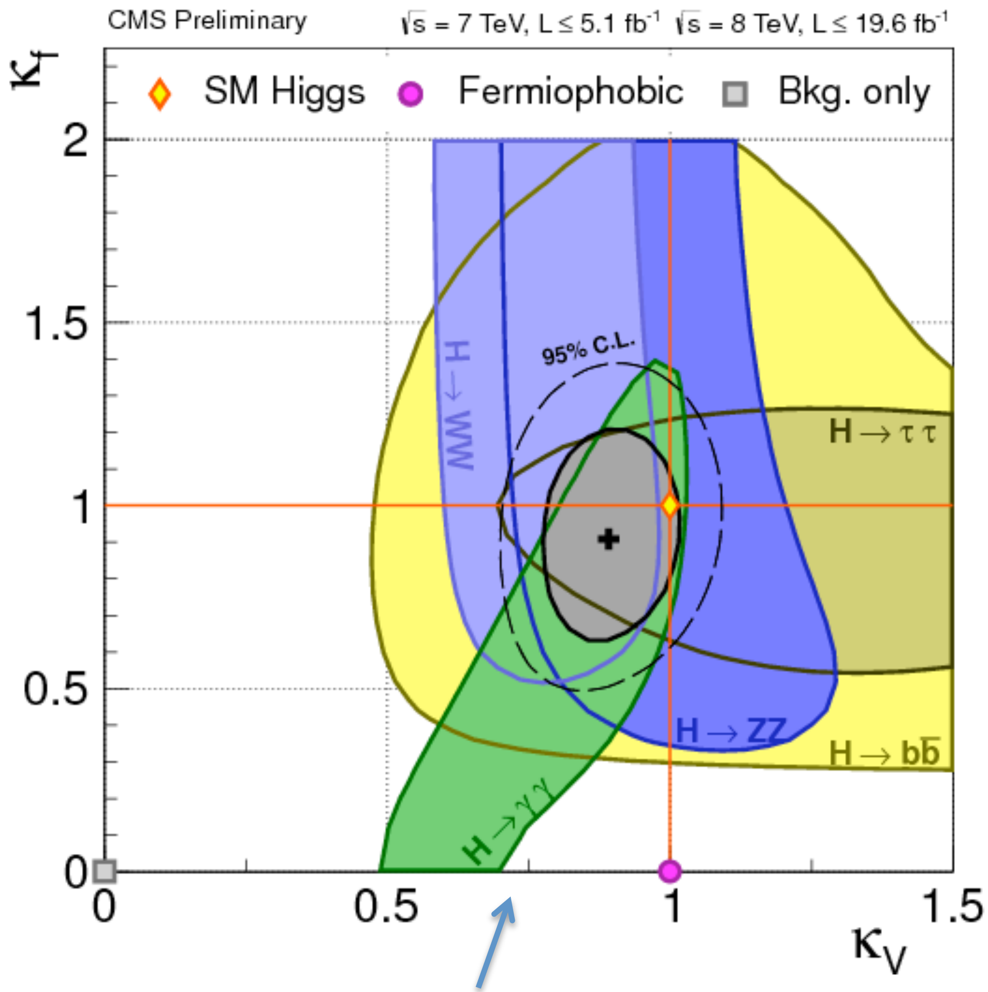


Due to low mττ resolution, compatible with:
- expectation for m_H = 125 GeV
- H→ZZ→4 lepton mass measurement

Summary

- particle flow dramatically improves the performance of CMS
  - used in almost all analyses
    - e.g. only 2 jet-based analyses don't use PF jets
- First strong hint for H→ττ (2.94σ)
- main constraint on the coupling to fermions





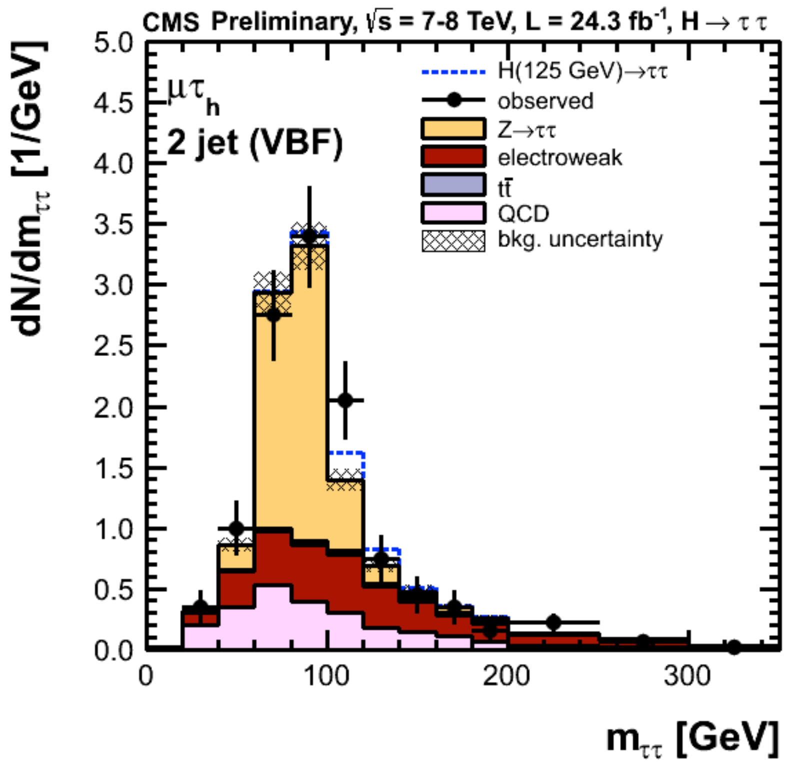
Coupling to fermions VS coupling to bosons, w/r to Standard Model

Coupling to τ, w/r to SM

Back-up

Statistics

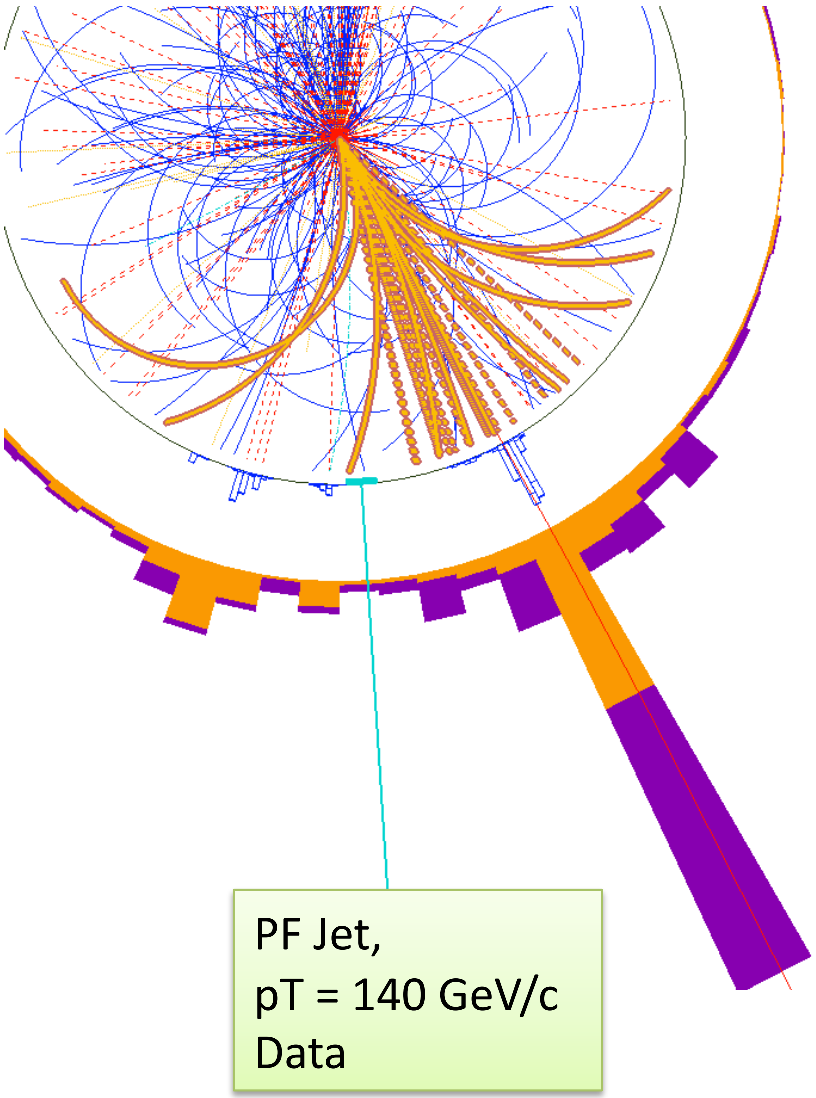
$$\mathcal{L}(\mathrm{obs}|s(\hat{\mu}) + b, \hat{\theta})$$



$$q_0 = -2 \ln \frac{\mathcal{L}(\mathrm{obs}\,|\,b,\,\hat{\theta}_0)}{\mathcal{L}(\mathrm{obs}\,|\,\hat{\mu}\cdot s + b,\,\hat{\theta})},$$

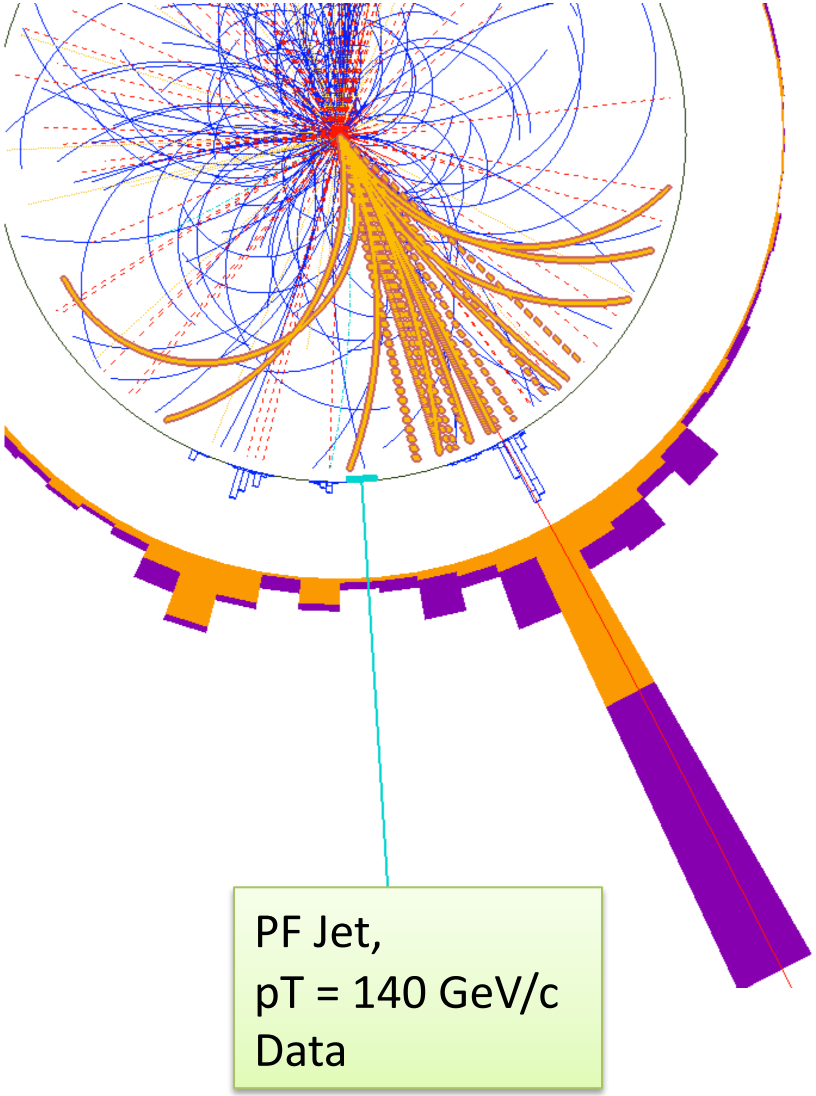
$$p_0 = \mathrm{P}(q_0 \geq q_0^{obs}\,|\,\mathrm{b}).$$

Recipe for a good particle flow



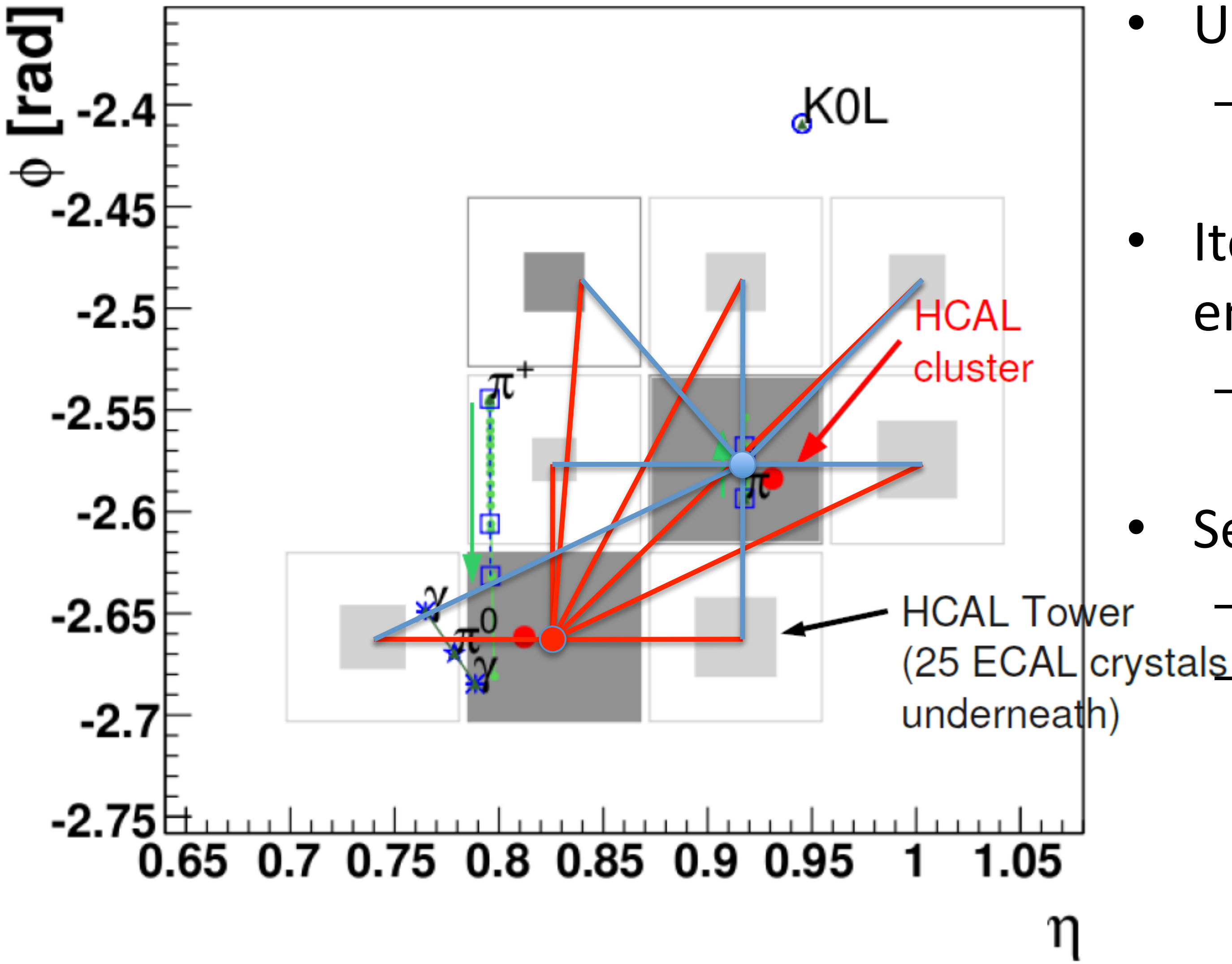
- Separate neutrals from charged hadrons
  - Field integral (BxR)
  - Calorimeter granularity
- Efficient tracking
- Minimize material before calorimeters
- Clever algorithm to compensate for detector imperfections

Neutral/charged separation (1)
Field Integral



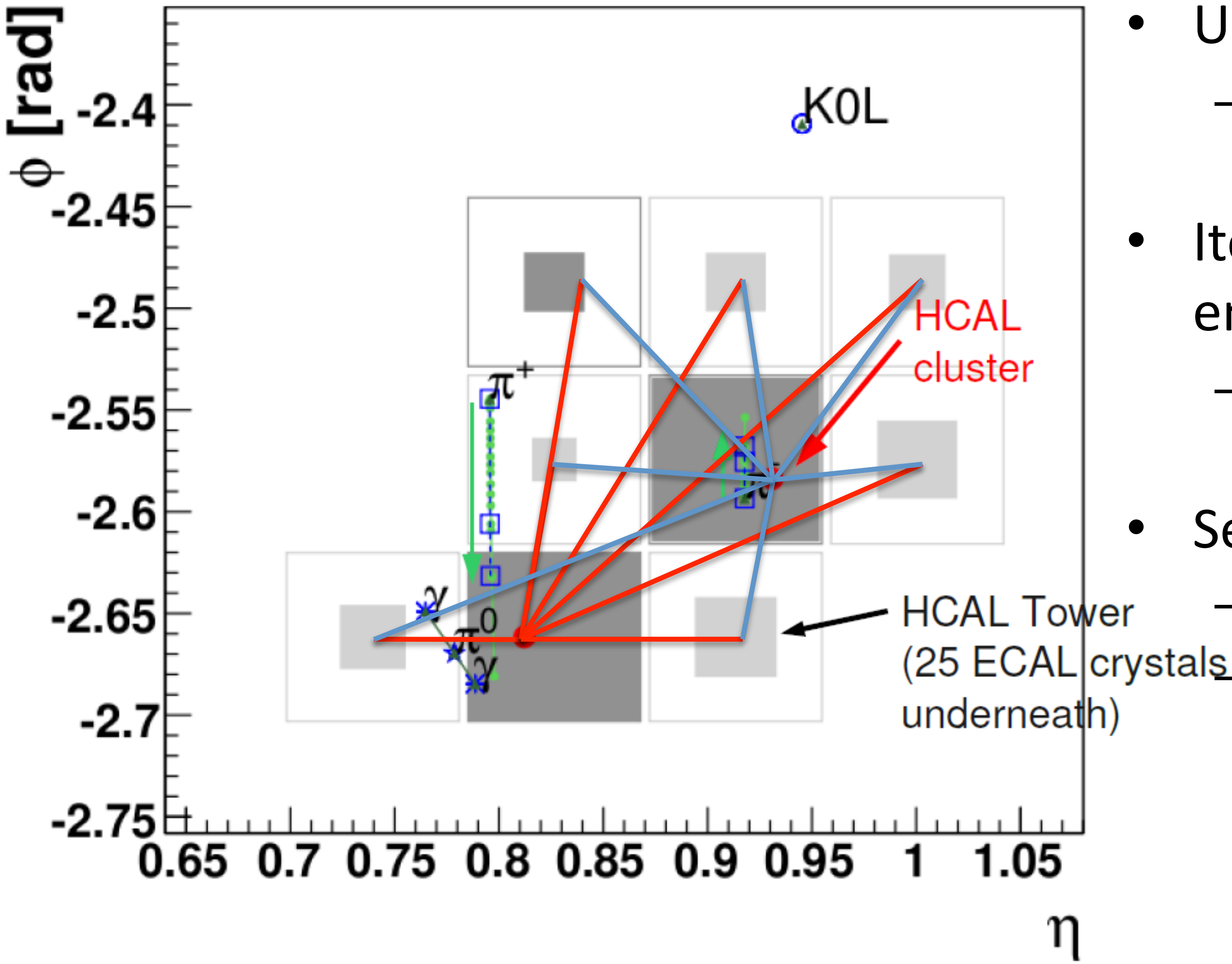
- Strong magnetic field: 3.8 T
- ECAL radius 1.29 m
- BxR = 4.9 T.m
  - ALEPH: 1.5x1.8 = 2.7 T.m
  - ATLAS: 2.0x1.2 = 2.4 T.m
  - CDF: 1.5x1.5 = 2.25 T.m
  - DO: 2.0x0.8 = 1.6 T.m

PF Clustering, HCAL



- Used in:
  - ECAL, HCAL, preshower
- Iterative, energy sharing
  - Gaussian shower profile with fixed σ
- Seed thresholds
  - ECAL : E > 0.23 GeV
  - HCAL : E > 0.8 GeV

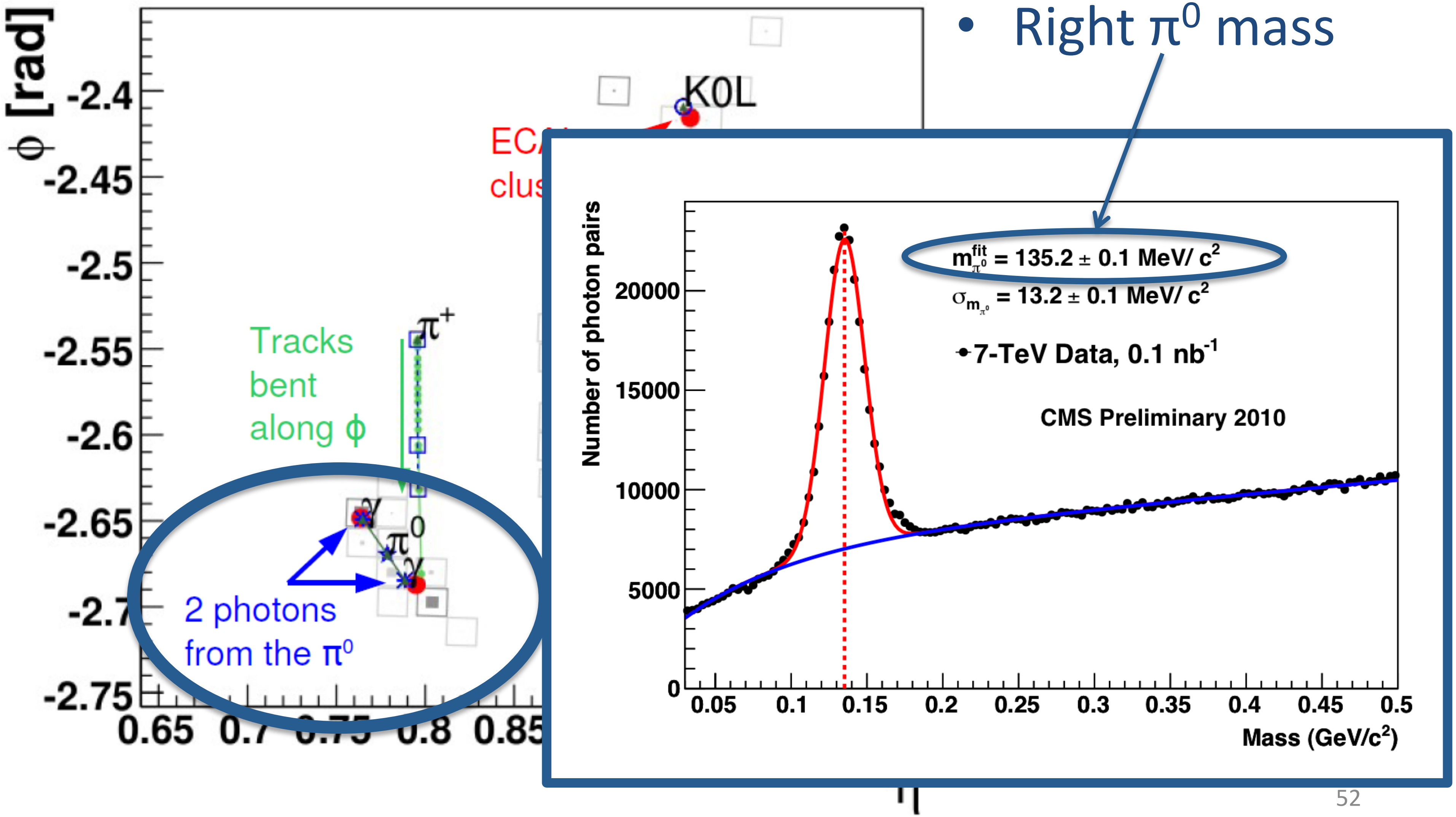
PF Clustering, HCAL



- Used in:
  - ECAL, HCAL, preshower
- Iterative, energy sharing
  - Gaussian shower profile with fixed σ
- Seed thresholds
  - ECAL : E > 0.23 GeV
  - HCAL : E > 0.8 GeV

PF Clustering, ECAL - Validation

- Right π^0 mass

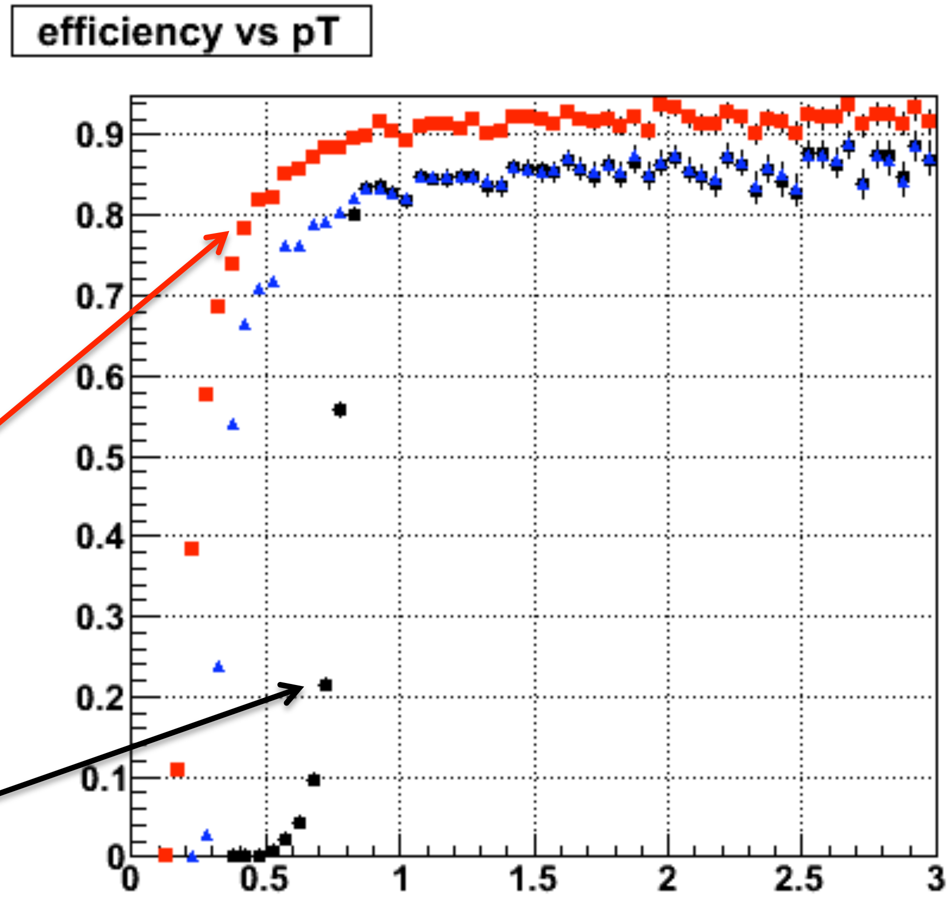


Iterative Tracking (1/2)

- Developed for PF, now standard
- At each iteration:
  - Reconstruct a set of tracks
  - Remove track hits
  - Relax constraints
- Fast (~10 s / event)

- Iterative tracking:
  - 1-2 % fake rate

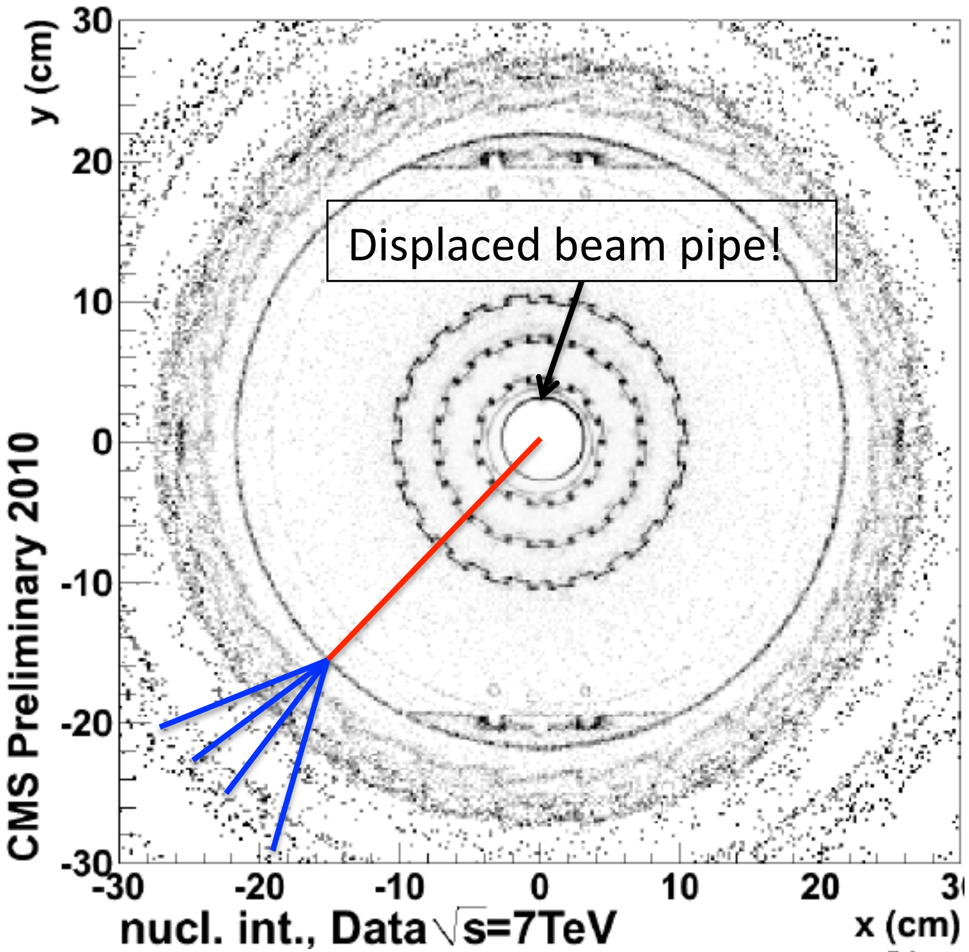
- Old “CTF” tracking:
  - 20 % fake rate



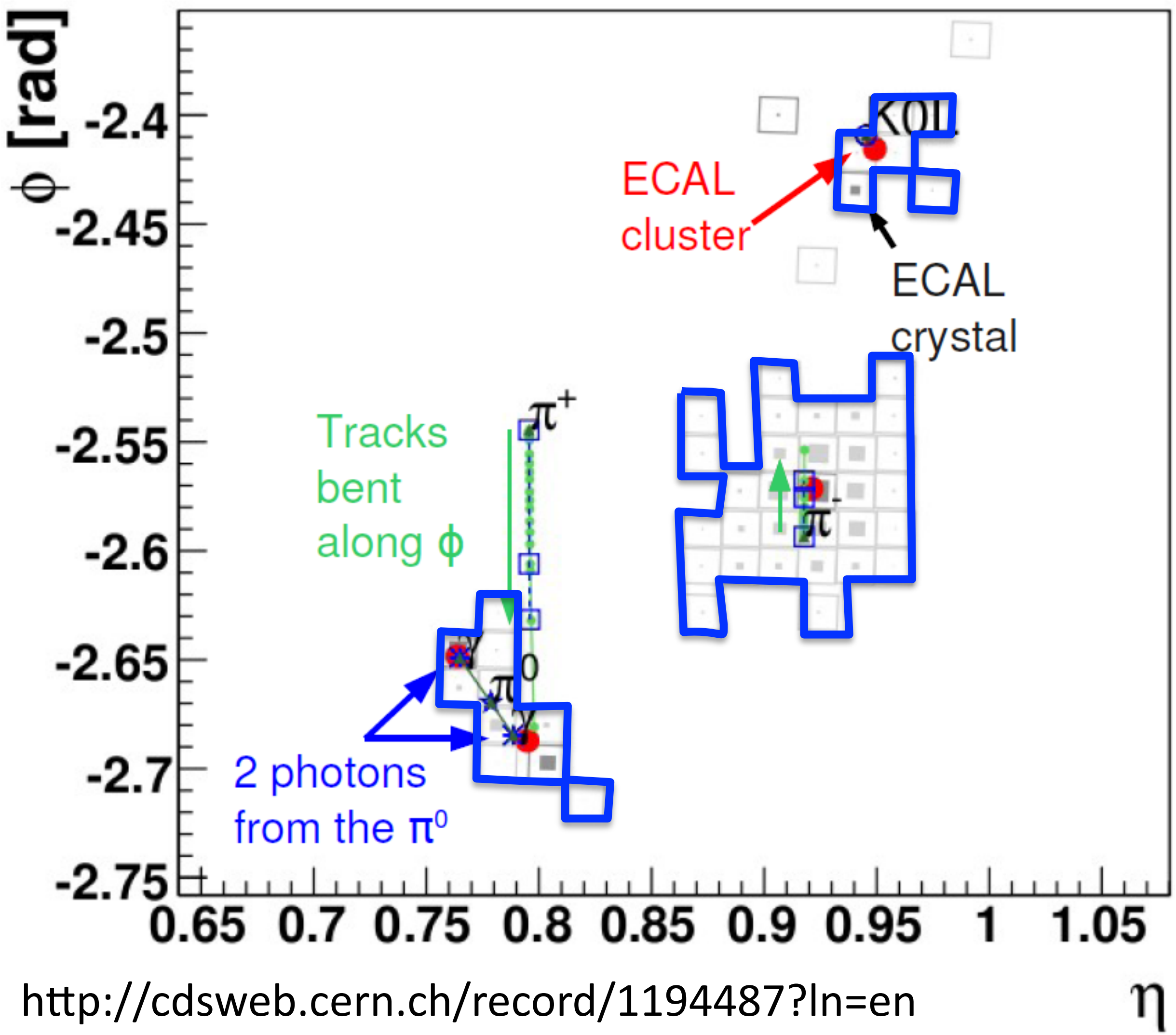
Iterative Tracking (2/2)

- Efficient also for secondary tracks
- Secondary tracks used in PF:
  - Charged hadrons from nuclear interactions
    - No double-counting of the primary track momentum
  - Conversion electrons
    - Converted brems from electrons (cf electron slide later)

Nuclear interaction vertices



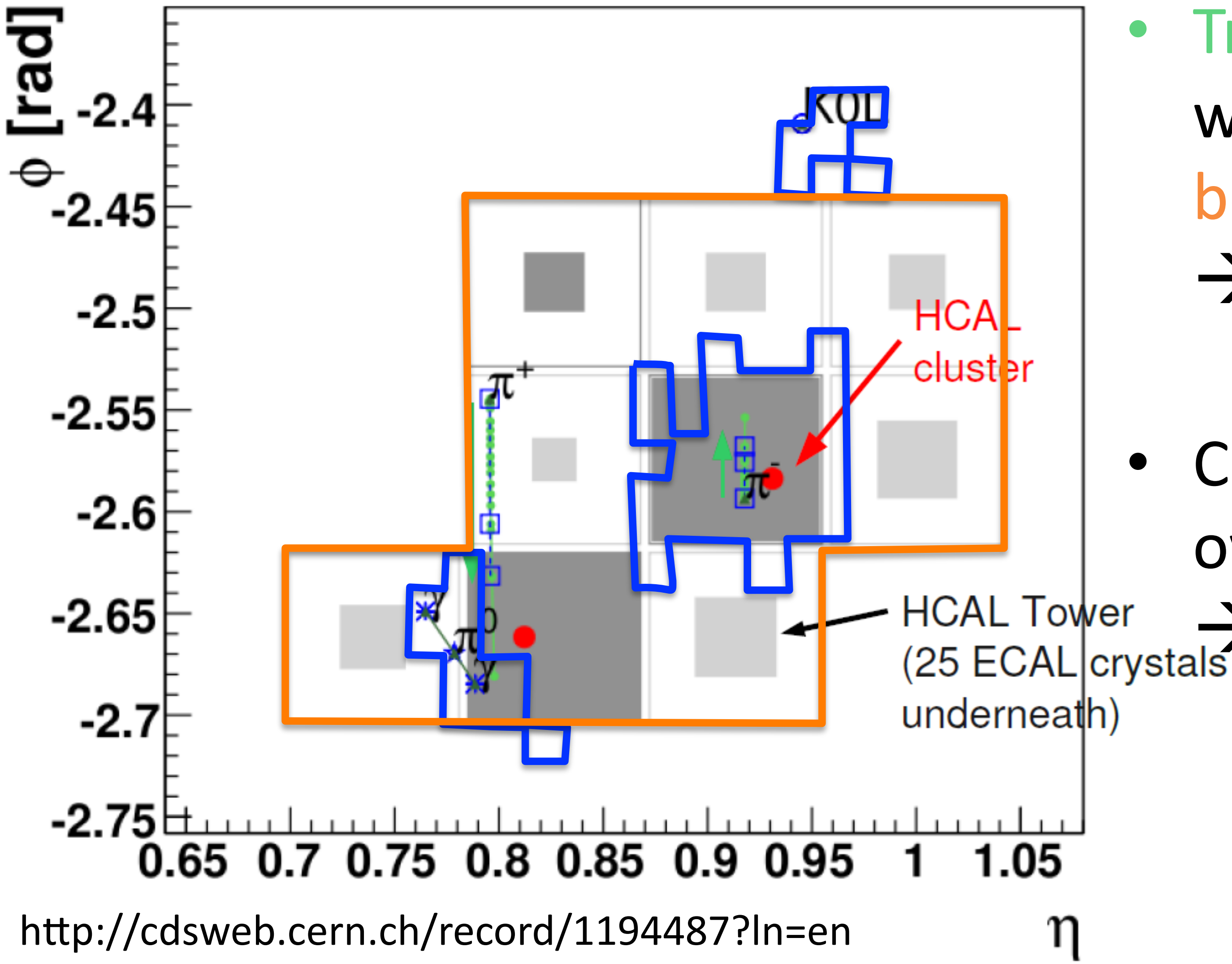
Linking – ECAL view



http://cdsweb.cern.ch/record/1194487?ln=en

- Track impact within cluster boundaries → track & cluster linked

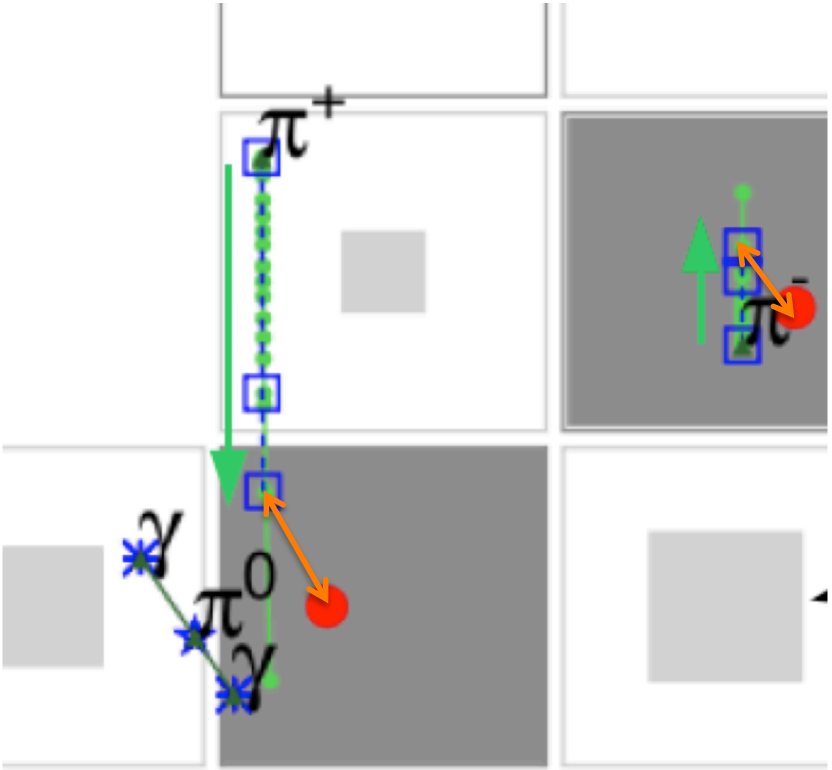
Linking – HCAL view

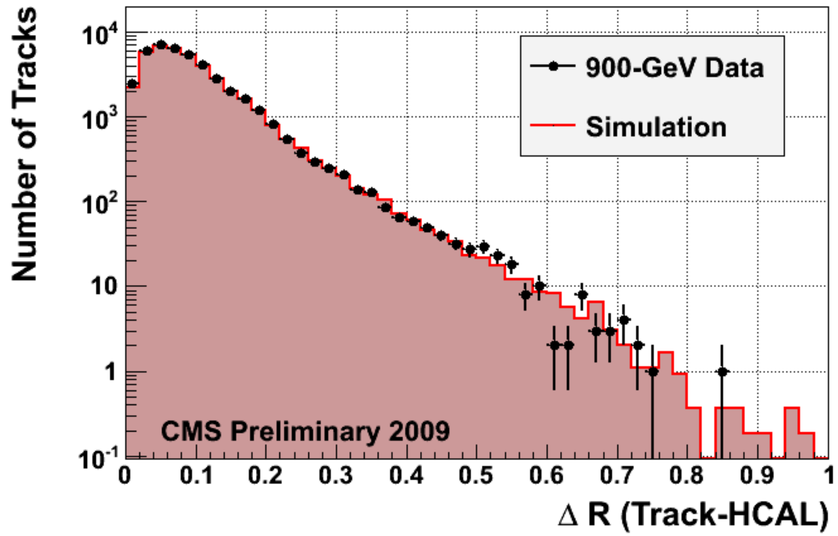


http://cdsweb.cern.ch/record/1194487?ln=en

- Track impact within cluster boundaries
  → track & cluster linked
- Clusters overlapping
  → clusters linked

Link Validation

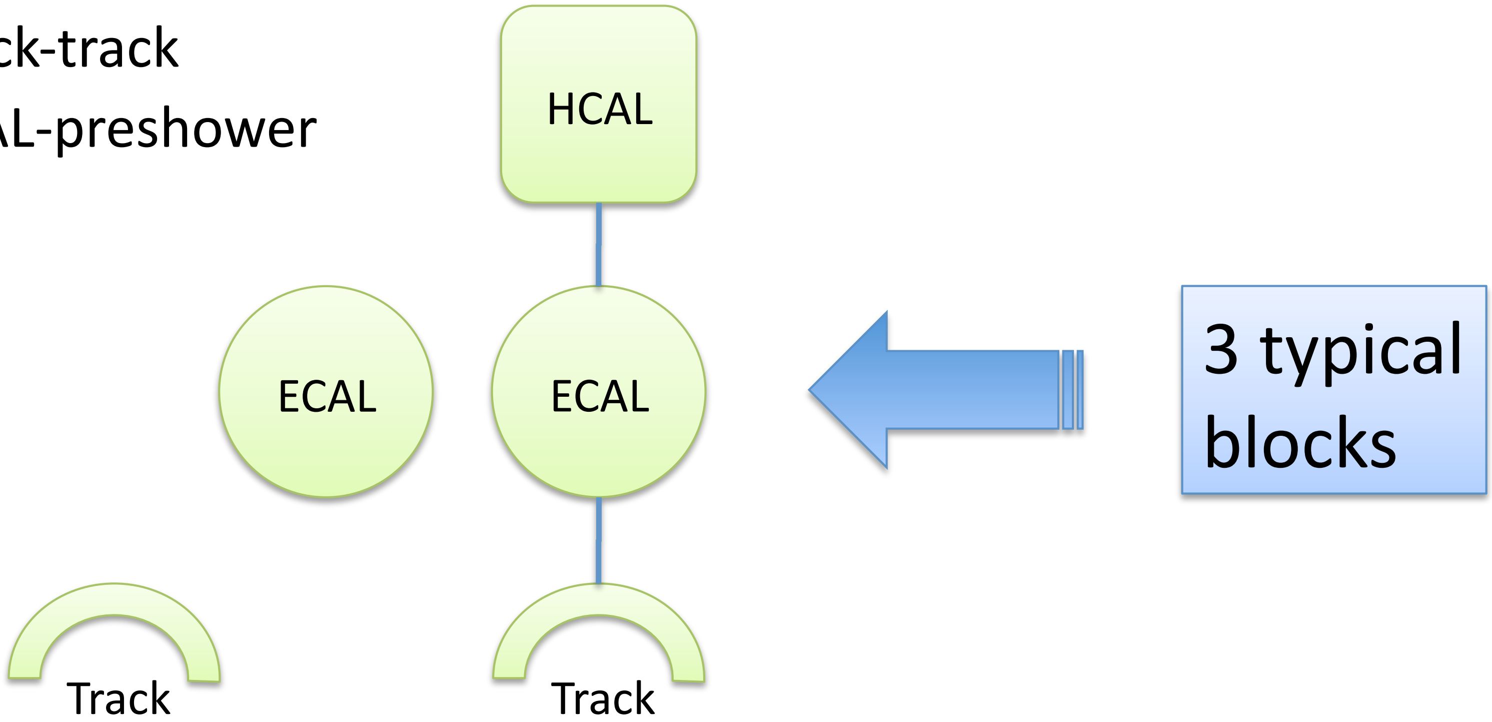




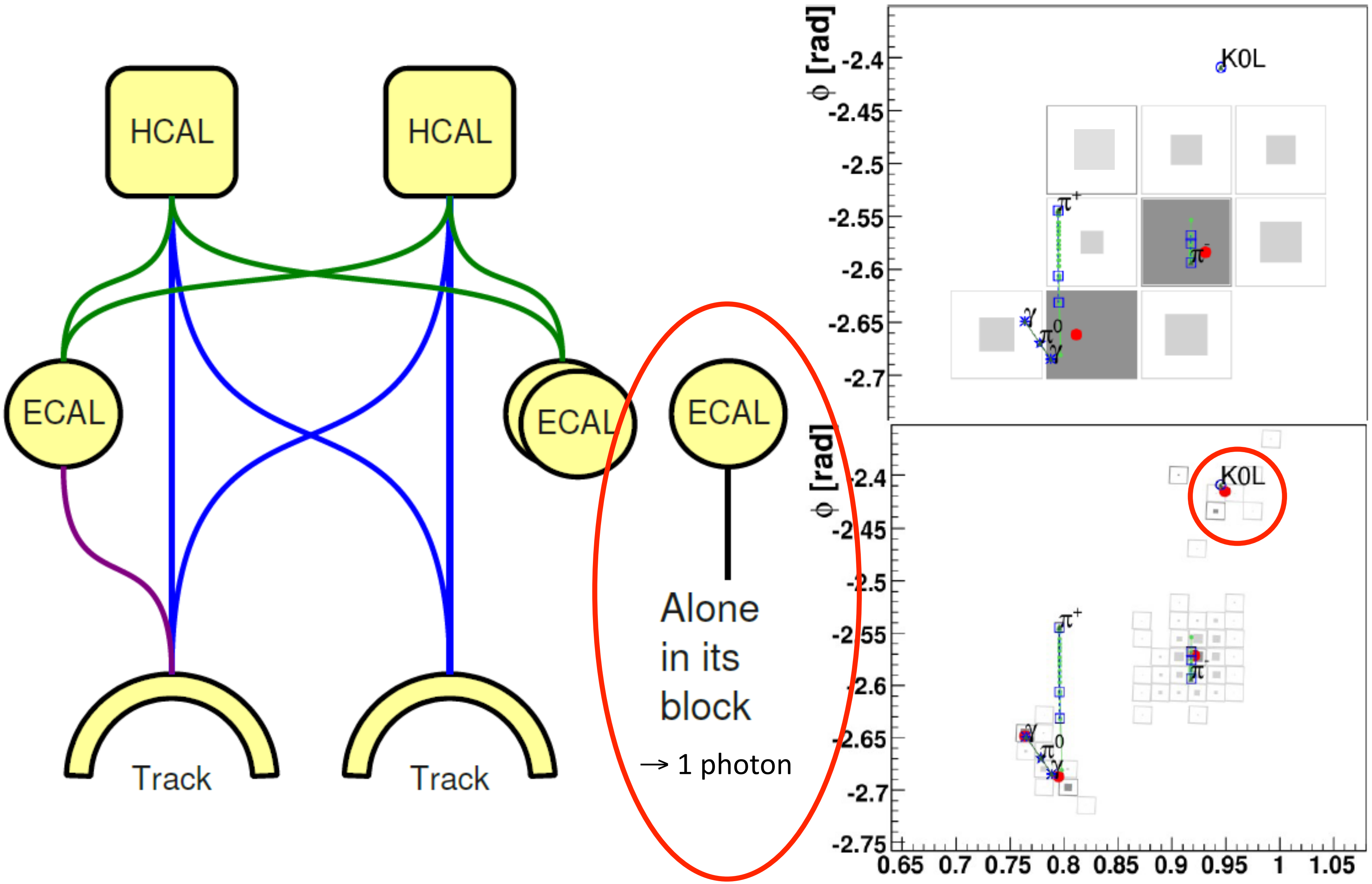
Distance between:
- the track impact and
- the closest HCAL cluster

Links and blocks

- Links:
  - Track-ECAL
  - Track-HCAL
  - ECAL-HCAL
  - Track-track
  - ECAL-preshower
- The block building rule:
  - 2 linked PF elements are put in the same blocks

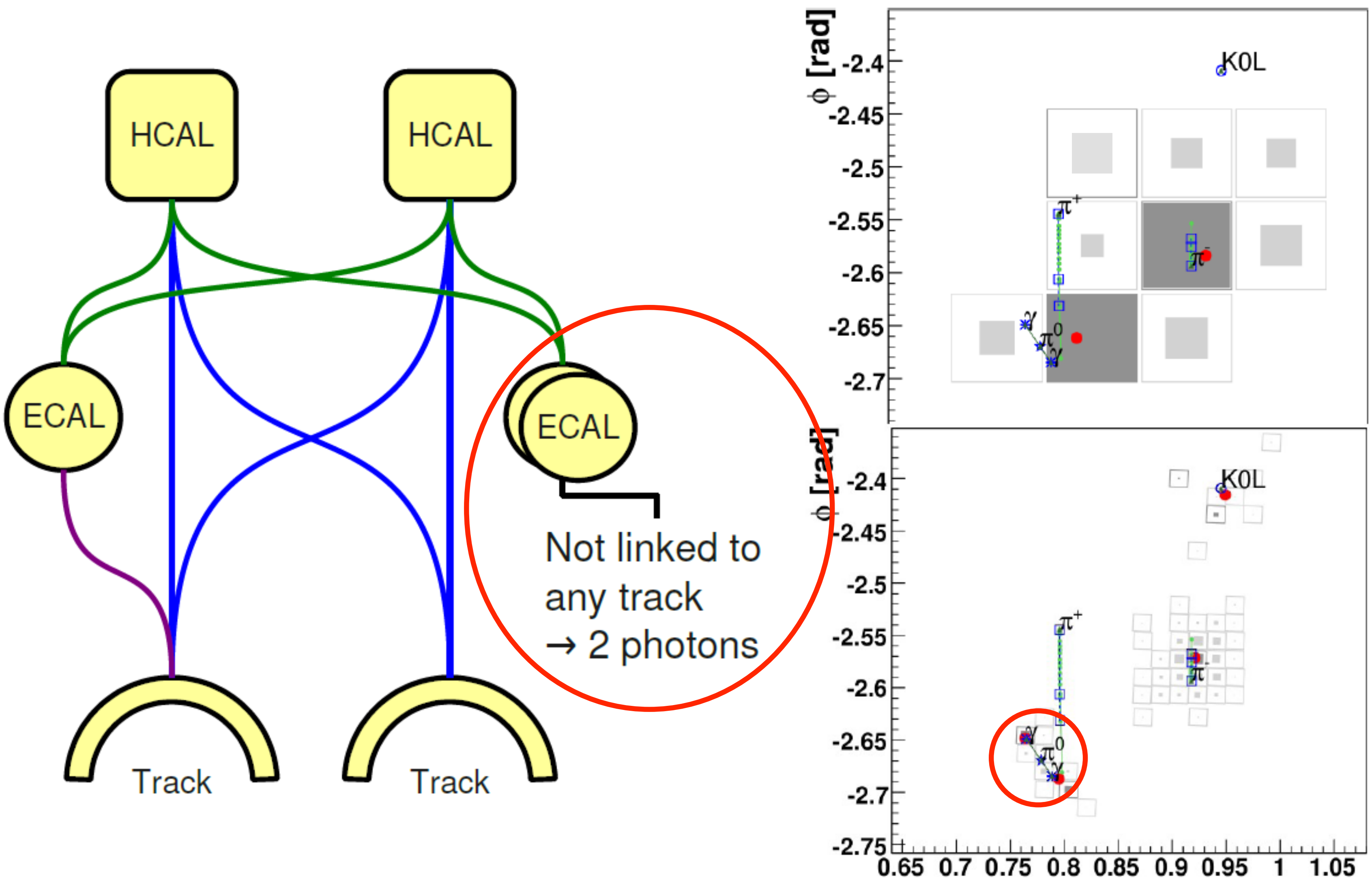


Result: 2 PF “Blocks”



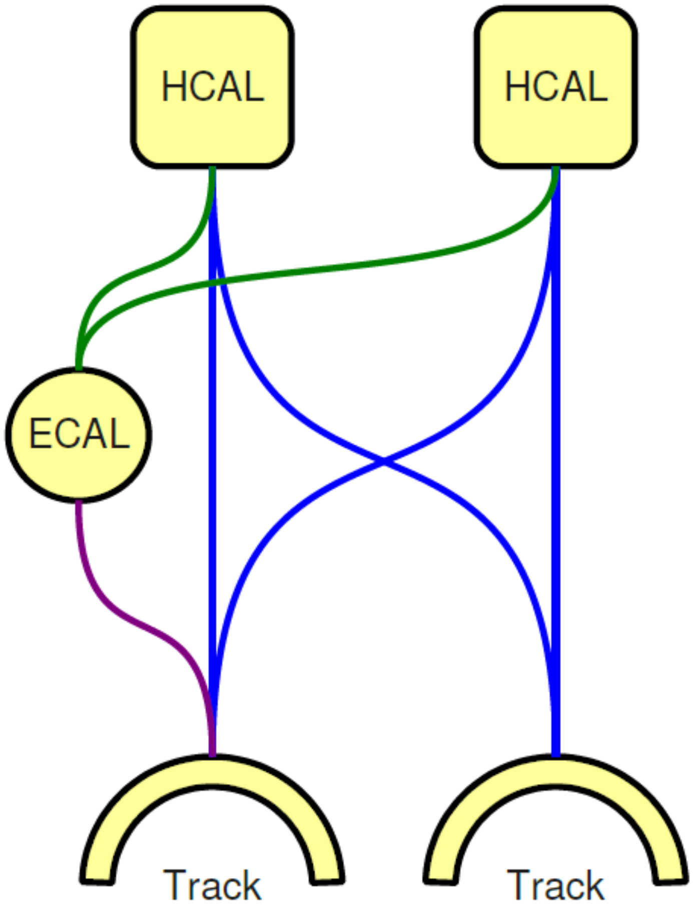
http://cdsweb.cern.ch/record/1194487?ln=en

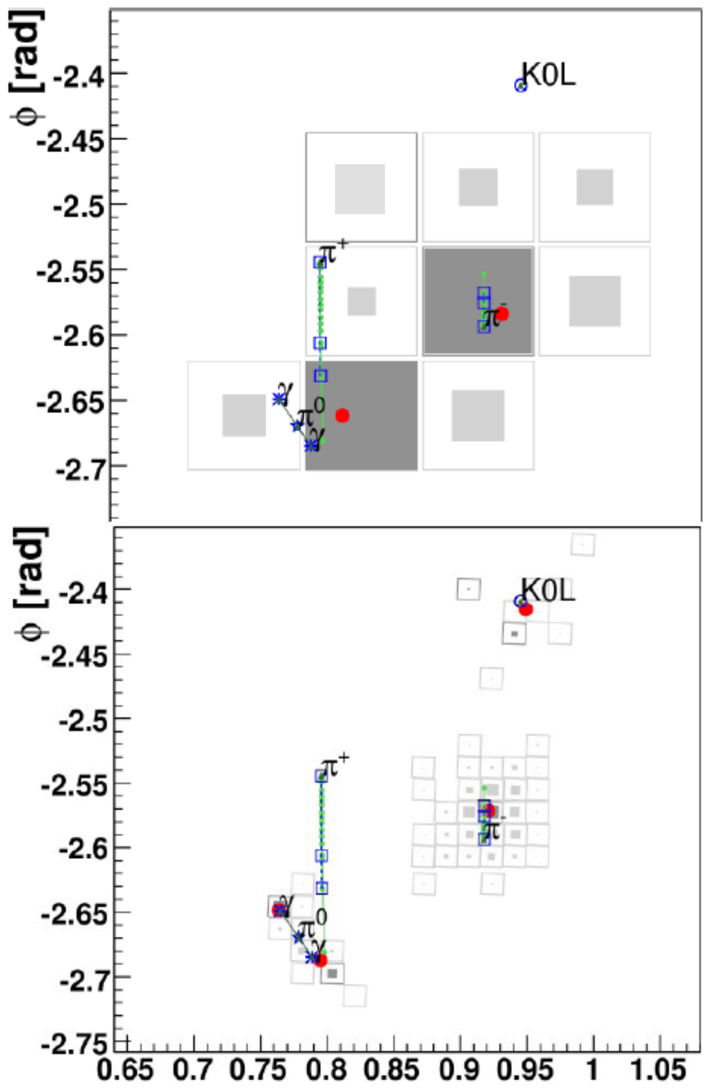
Photons



http://cdsweb.cern.ch/record/1194487?ln=en

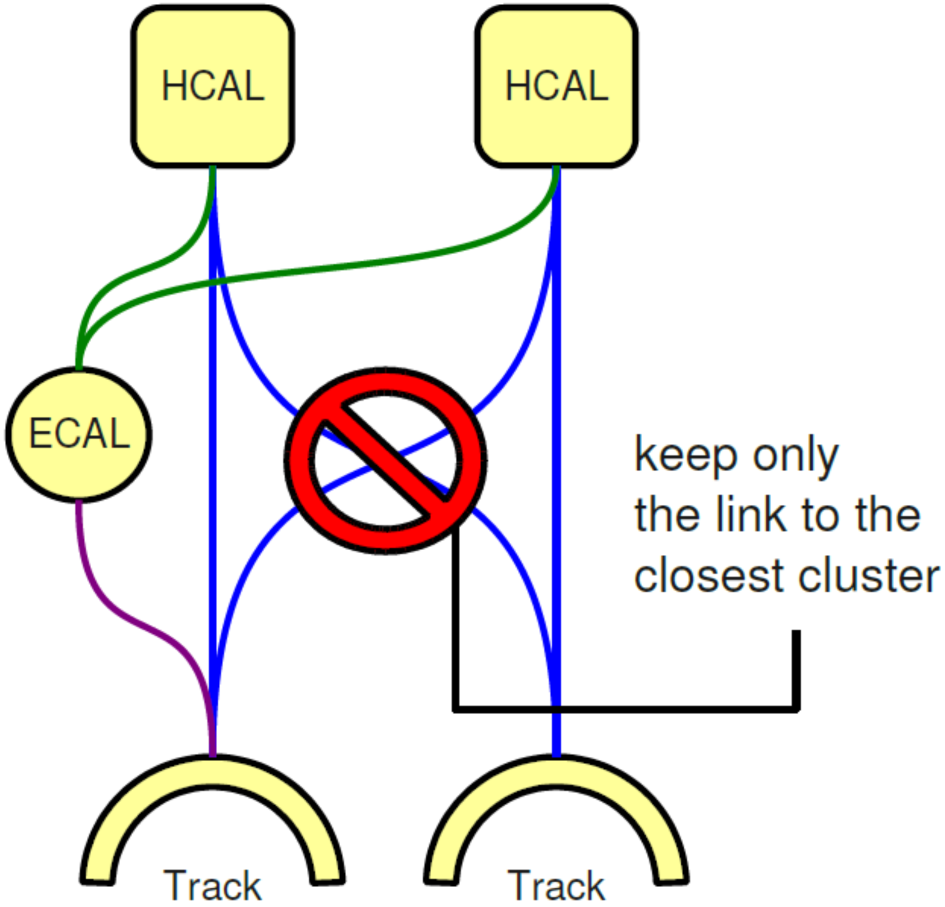
Photons

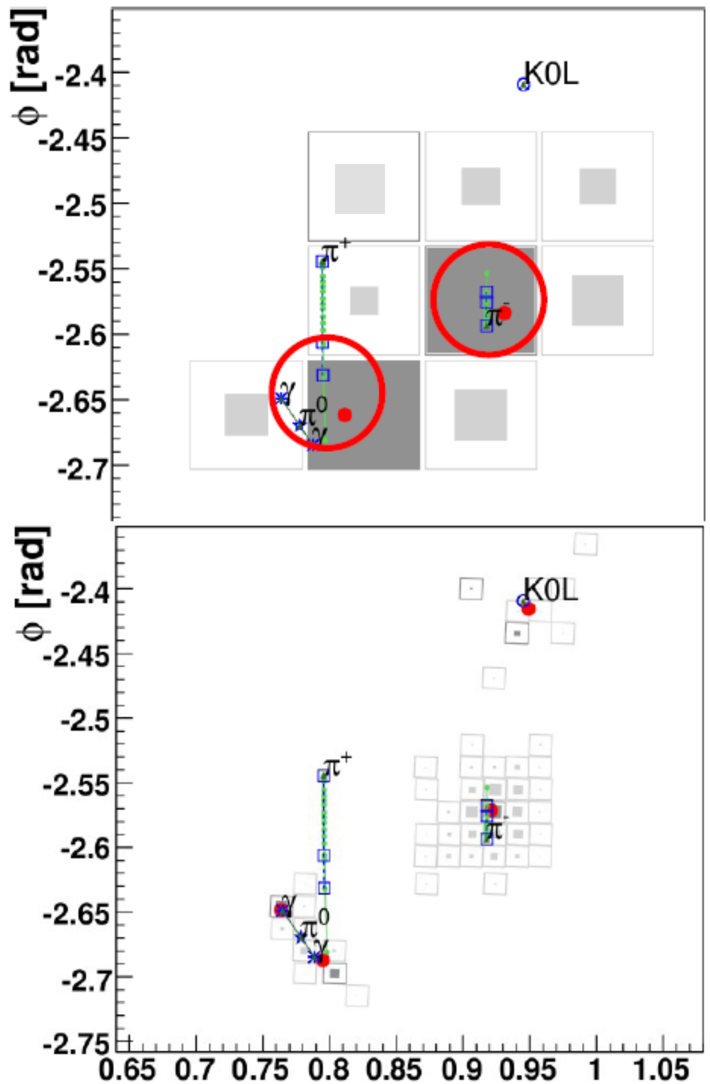




http://cdsweb.cern.ch/record/1194487?ln=en

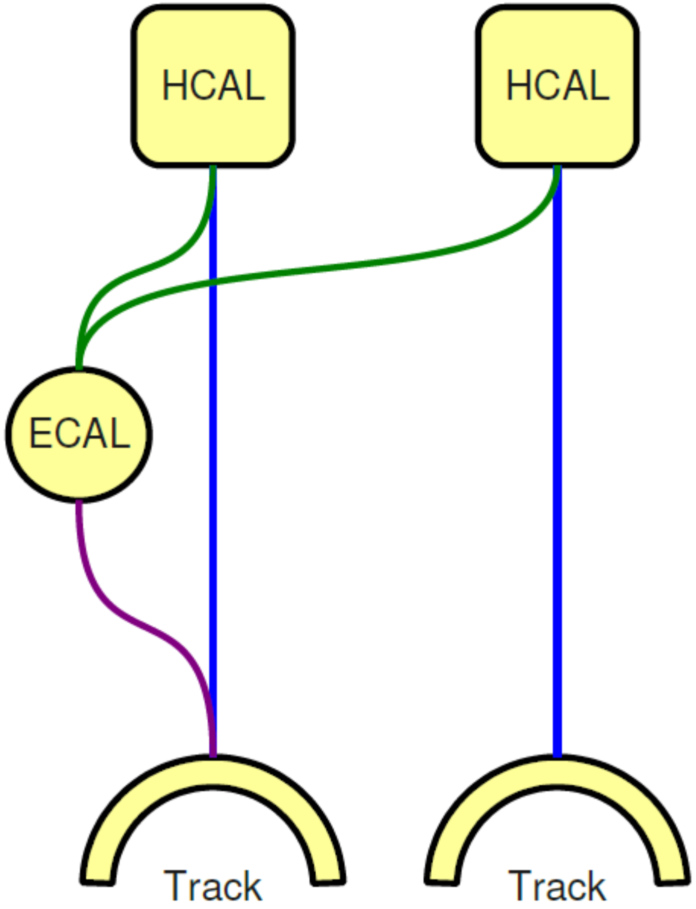
Block simplification

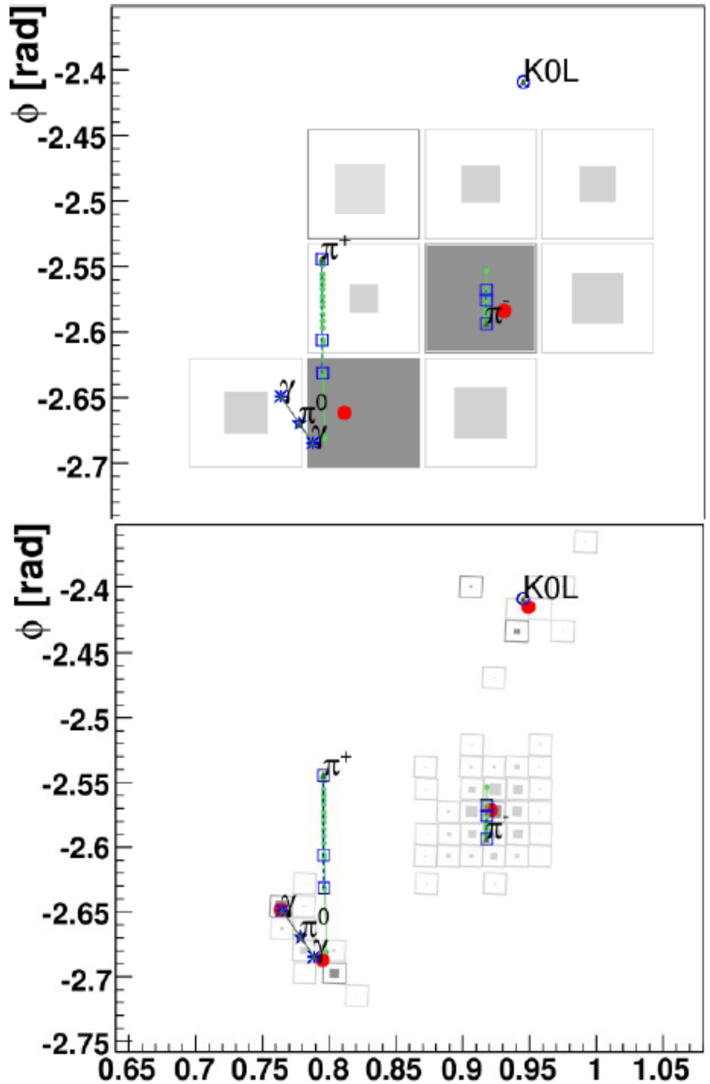




http://cdsweb.cern.ch/record/1194487?ln=en

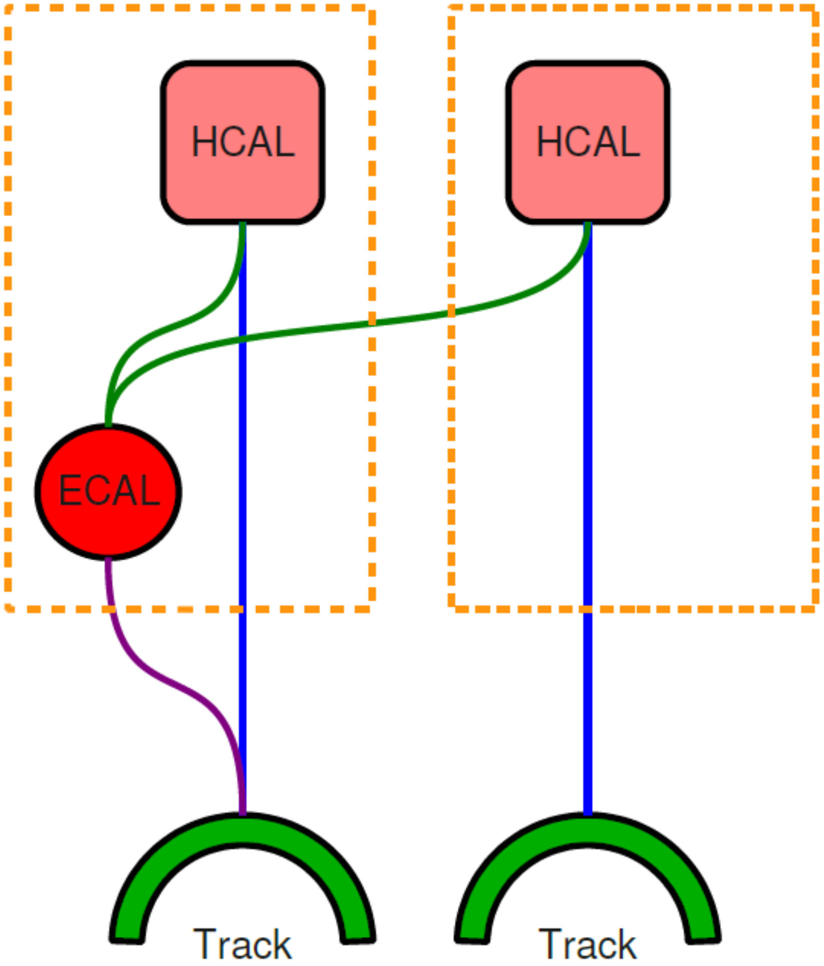
Block simplification





http://cdsweb.cern.ch/record/1194487?ln=en

Charged hadrons, overlapping neutrals



- For each HCAL cluster, compare:
  - Sum of track momenta p
  - Calorimeter energy E
    - Linked to the tracks
    - Calibrated for hadrons

$$E = a + bE_{ECAL} + cE_{HCAL}$$

- E and p compatible
  - Charged hadrons
- E > p + 120% √p
  - Charged hadrons +
  - Photon / neutral hadron
- E<<p
  - Need attention …
  - Rare: muon, fake track

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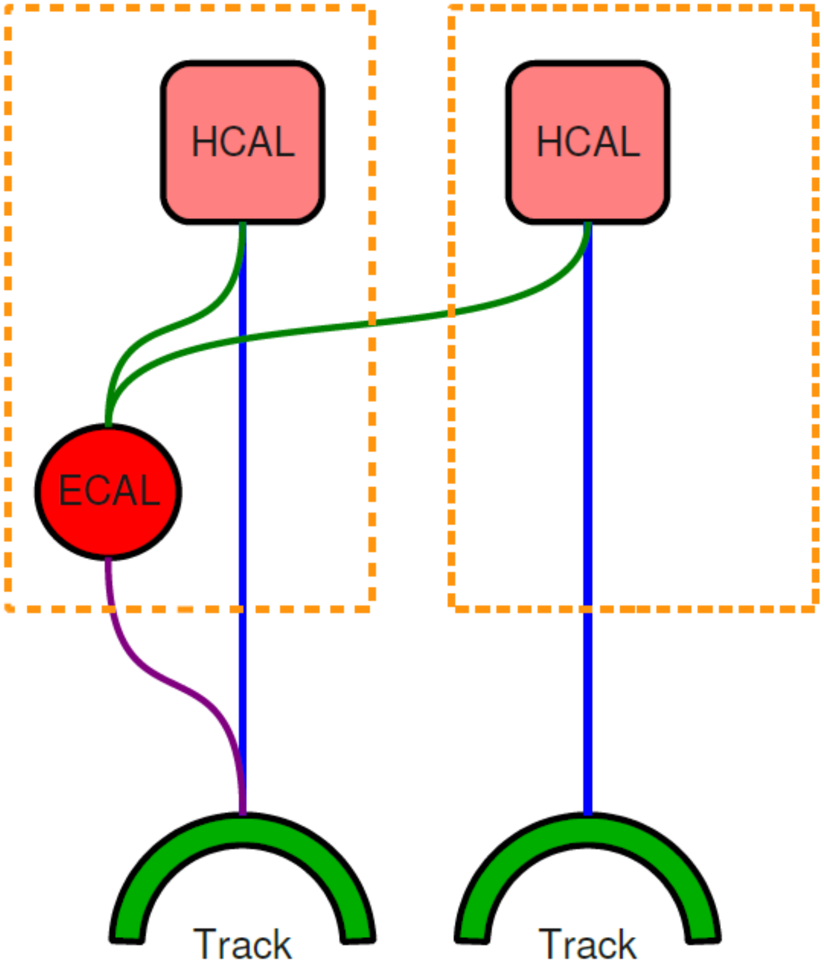
Charged+neutrals: E ≈ p



- Charged hadron energy from a fit of p_i and E
  - i = 1, .. , Ntracks
  - Calorimeter and track resolution accounted for
- Makes the best use of the tracker and calorimeters
  - Tracker measurement at low pT
  - Converges to calorimeter measurement at high E

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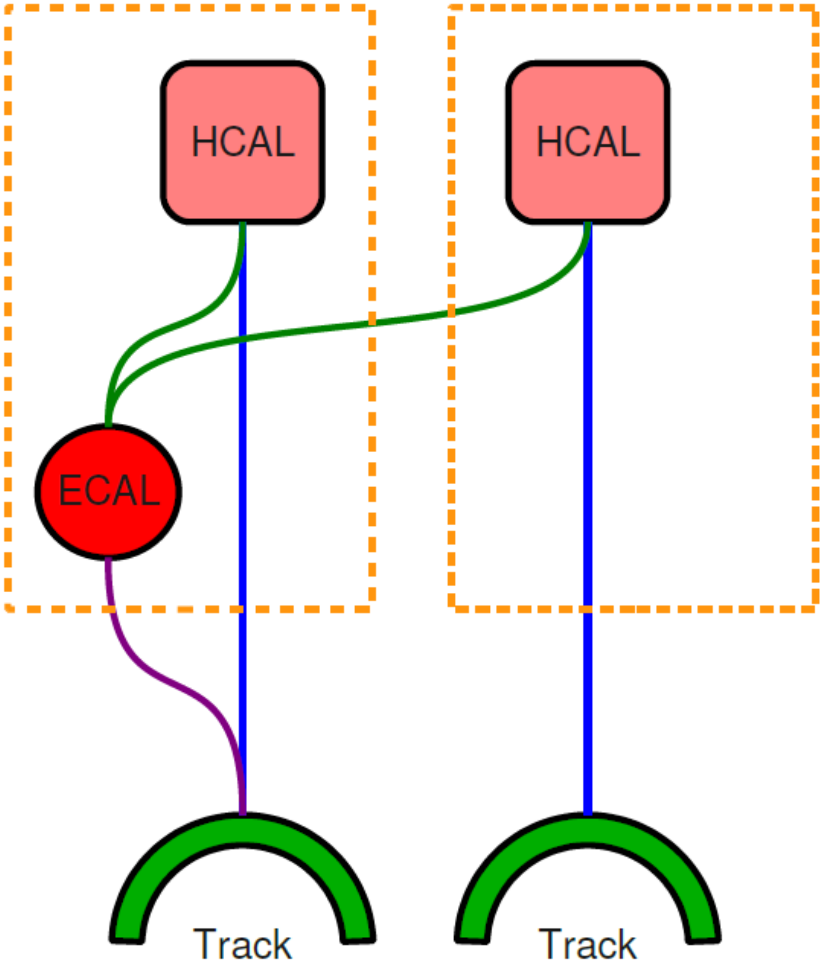
Charged+neutrals: E > p

$$E = a + bE_{ECAL} + cE_{HCAL}$$



- Significant excess of energy in the calorimeters:
  $E > p + 120\% \sqrt{E}$
- Charged hadrons [p_i]
- Neutrals:
  - E from ECAL or HCAL only:
    - HCAL → h^0 [E – p]
    - ECAL → γ [E_{ECAL} – p/b]
  - E from ECAL and HCAL:
    - E-p > E_{ECAL} ?
      - γ [E_{ECAL}]
      - h^0 with the rest
    - Else:
      - γ [(E – p) / b]

Always give precedence to photons

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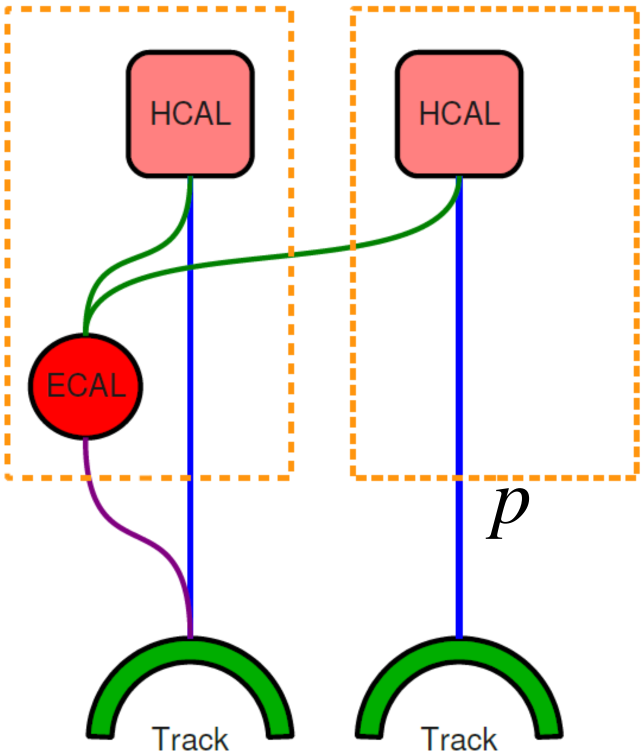
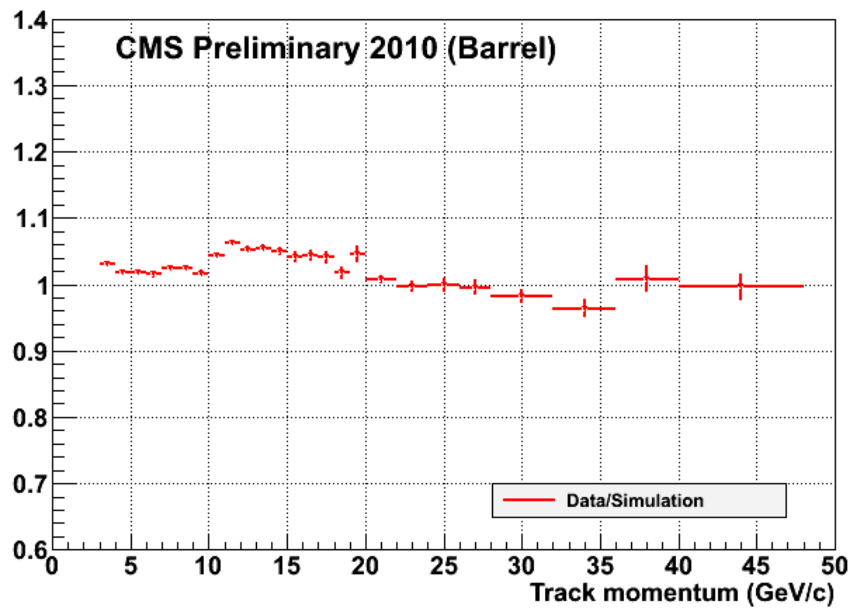
Validation of the calibration



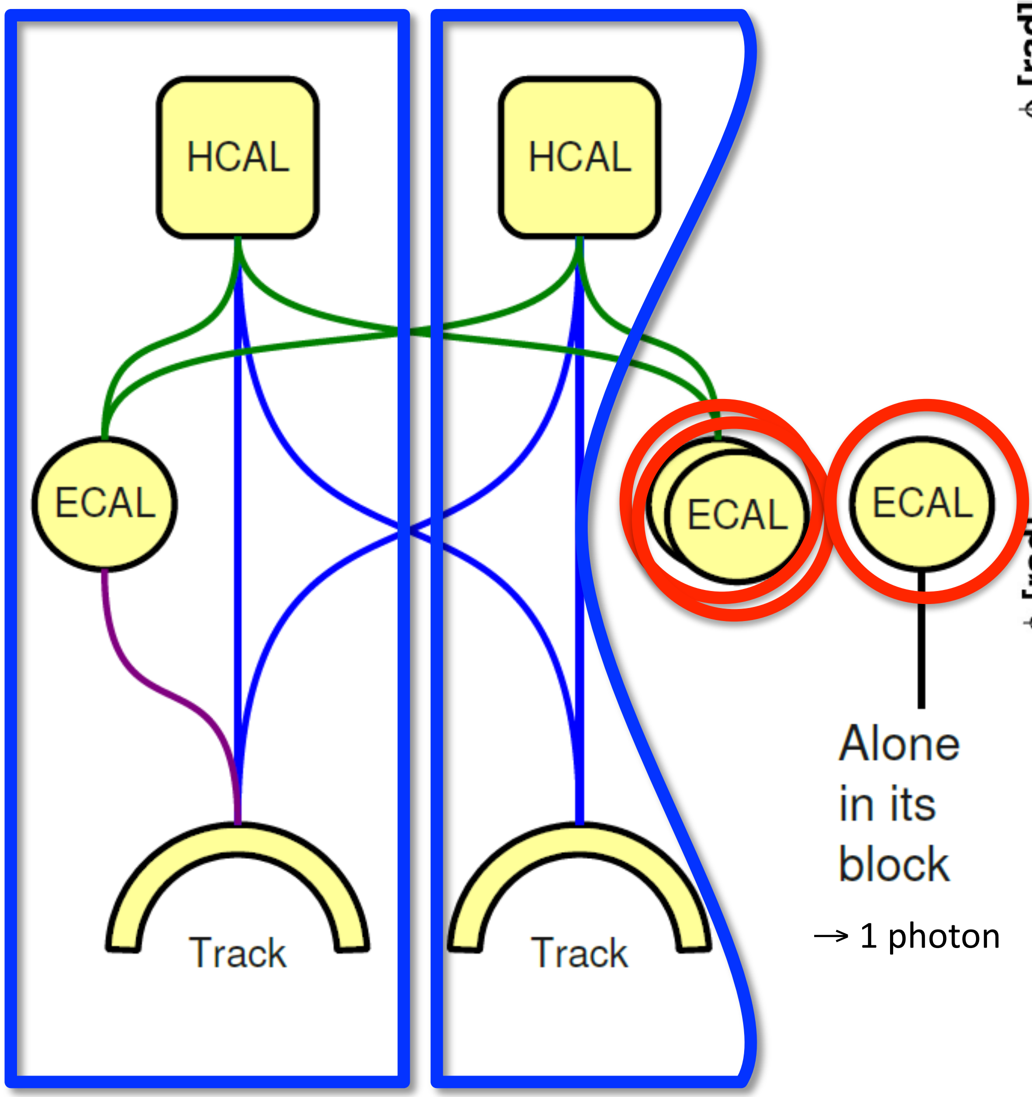
$$E = a + bE_{ECAL} + cE_{HCAL}$$

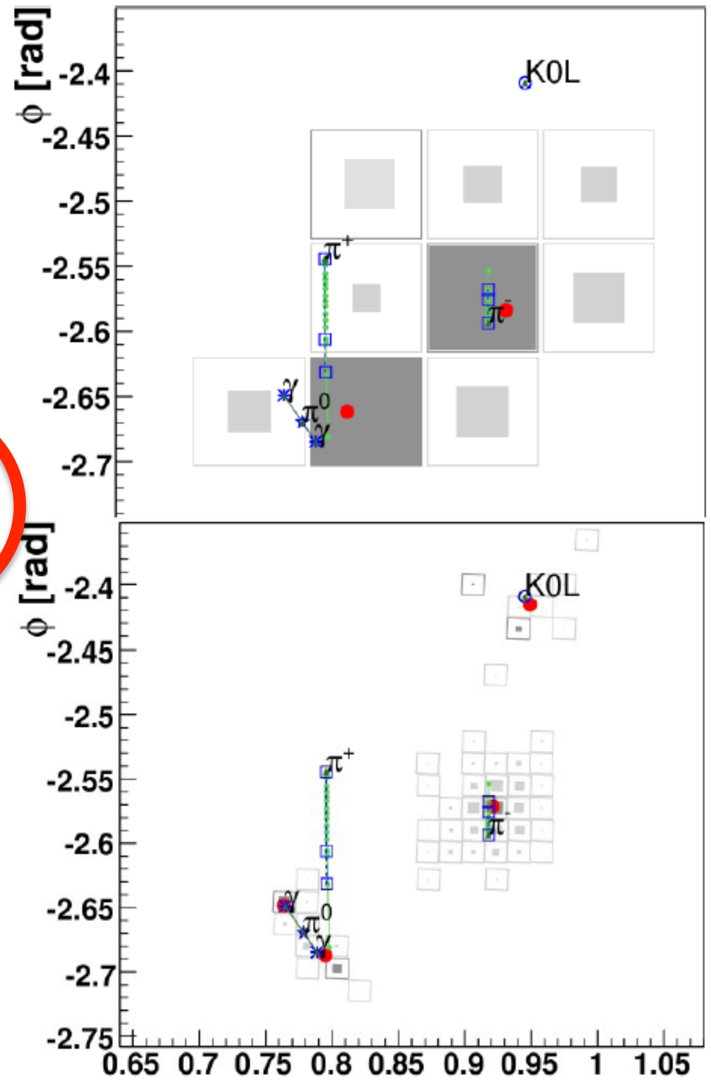
$$\frac{(E/p)_{data}}{(E/p)_{simu}}$$



Ratio of the calorimeter response between data and Monte-Carlo

2 charged hadrons, 3 photons





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