Search for Supersymmetry at the LHC

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- Part I: Motivation and Physics Objects ID

  Why we search for SUSY. Detector properties and Physics Object reconstruction . The Standard Model benchmarks.

- Part II: Data analysis in SUSY Searches

  Elements of a SUSY analysis and their integration in a search result. Concepts of data selection, background estimation, control and signal samples, event excess, mass and cross section limits

- Part III: Search for SUSY in CMS

  Recent public results of SUSY searches in CMS (mostly) based on a 36 pb^{-1} data sample collected during 2010. Comparison with results from ATLAS.

Bibliography

CMS Physics Results

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

- Plots and Results
- Journal Publications
- Physics Analysis Summaries – public documents

ATLAS Physics Results

https://twiki.cern.ch/twiki/bin/view/AtlasPublic

The Motivation:
Why do we search for Supersymmetry ?

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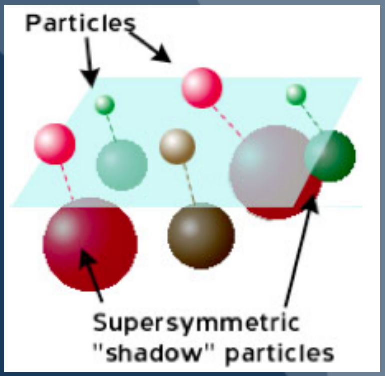
Supersymmetry



SUSY Hypothesis: there is a relation between bosons and fermions

- ➢ Predicts that each boson has an opposite spin fermion super-partner and vice versa

Who ordered this zoo of particles beyond the SM?

Theorists find SUSY very compelling:

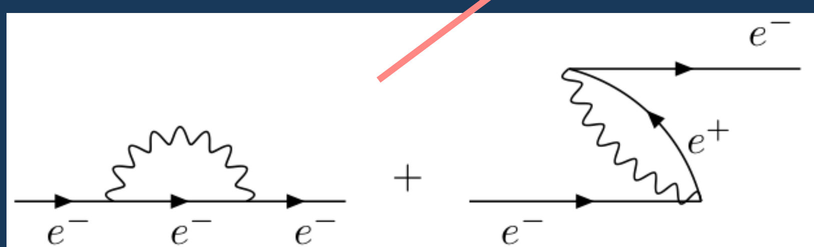
- ➢ Provides a solution to the hierarchy problem
- ➢ Allows unification of gauge couplings
- ➢ Can predict a dark matter particle candidate

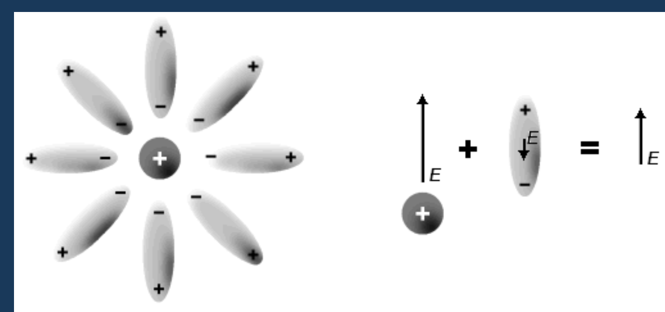
The Hierarchy Problem: Analogy

QED correction to the electron mass

- Classical electrostatic contribution of point-like electron to its energy is infinite

$$m_{e,physical} = m_{e,bare} + \Delta m_e, \quad \Delta m_e = \Delta E_{Coulomb}/c^2 = \frac{3e^2}{20\pi\varepsilon_0 R}$$





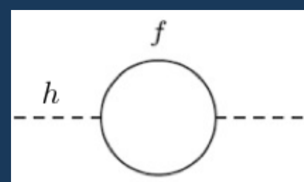
- The electron "partner", the positron, is responsible for eliminating the large divergence $m_{e,physical} = 0.511\ MeV/c^2$

The Hierarchy Problem: Higgs Mass

Radiative corrections to the Higgs mass

- The contribution from a Dirac fermion loop diverges

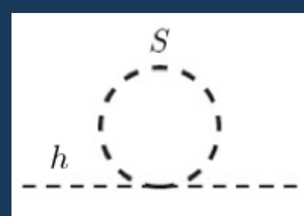
$$(\Delta m_h^2)_{SM} =$$



$$\sim -\frac{\lambda^2}{16\pi^2} M_{cutoff}^2$$

- The contribution from opposite spin super-partners would cancel the divergence resolving the hierarchy problem

$$(\Delta m_h^2)_{MSSM} =$$

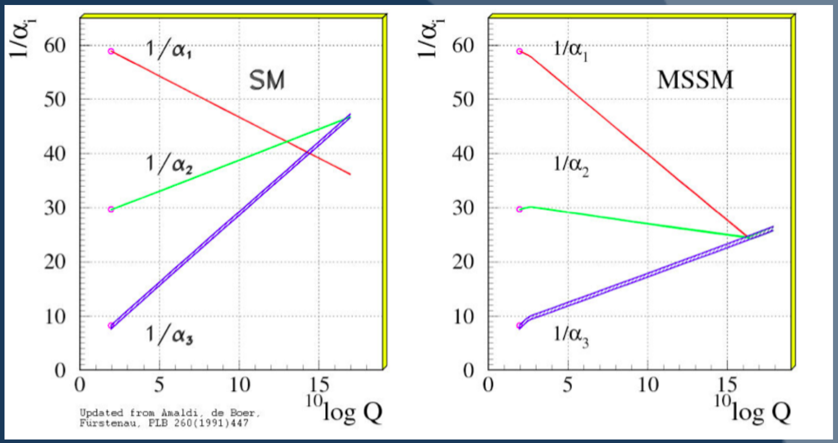


$$\sim \frac{\lambda^2}{16\pi^2} M_{cutoff}^2$$

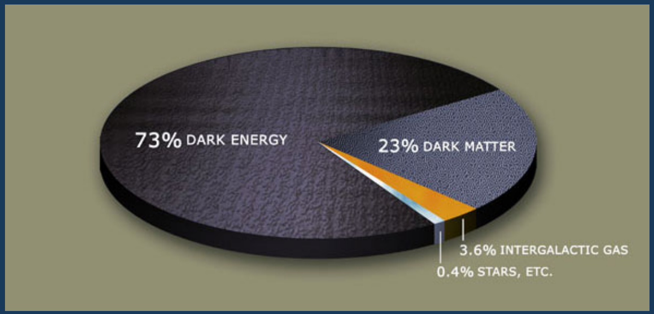
Gauge Couplings, Dark Matter

- Gauge couplings unify at the percent level in MSSM, much better than in SM

- High-scale SUSY breaking scenarios coupled to MSSM with R-parity conservation: LSP can be the WIMP – Dark Matter



$R=(-1)^{3(B-L)+2S}$
1 (SM particles)
-1 (SUSY particles)



SUSY Models

- SUSY predicts degenerate masses for fermions and scalars in a multiplet
  - Superpartners have not been observed – SUSY would be broken symmetry
  - SUSY particles more massive than SM particles but, how massive?

- Scale of SUSY breaking and mediation
  - SUGRA: Gravity mediation (high scale, $m_{3/2}$~100 GeV)
    - ✓ LSP is the lightest neutralino
  - AMSB: Anomaly mediation (very high scale, $m_{3/2}$~10^6 GeV)
    - ✓ LSP is neutralino or sneutrino
  - GMSB mediation (low scale, $m_{3/2}$<<100 GeV)
    - ✓ NLSP is neutralino or stau, LSP is gravitino

LSP weakly interacting – missing energy signal in a detector

The SUSY Particle Zoo (MSSM)

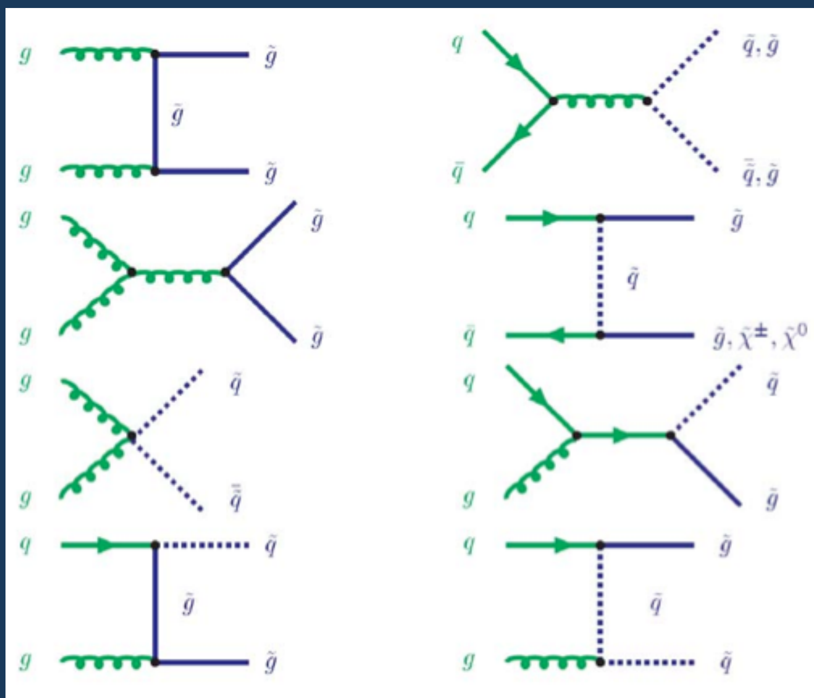
- Superpartners created in pairs
- LSP is stable and neutral
  - Neutralino (photino, higgsino) is best candidate
- LPS can survive from the Big Bang and is a candidate for Dark Matter

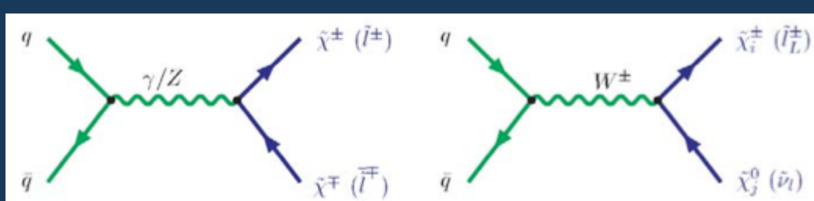
Names	Spin	P_R	Mass Eigenstates	Gauge Eigenstates
Higgs bosons	0	$+1$	h^0 H^0 A^0 $H^\pm$	H_u^0 H_d^0 H_u^+ H_d^-
squarks	0	-1	$\widetilde{u}_L$ $\widetilde{u}_R$ $\widetilde{d}_L$ $\widetilde{d}_R$	" "
			$\widetilde{s}_L$ $\widetilde{s}_R$ $\widetilde{c}_L$ $\widetilde{c}_R$	" "
			$\widetilde{t}_1$ $\widetilde{t}_2$ $\widetilde{b}_1$ $\widetilde{b}_2$	$\widetilde{t}_L$ $\widetilde{t}_R$ $\widetilde{b}_L$ $\widetilde{b}_R$
sleptons	0	-1	$\widetilde{e}_L$ $\widetilde{e}_R$ $\widetilde{\nu}_e$	" "
			$\widetilde{\mu}_L$ $\widetilde{\mu}_R$ $\widetilde{\nu}_\mu$	" "
			$\widetilde{\tau}_1$ $\widetilde{\tau}_2$ $\widetilde{\nu}_\tau$	$\widetilde{\tau}_L$ $\widetilde{\tau}_R$ $\widetilde{\nu}_\tau$
neutralinos	$1/2$	-1	$\widetilde{N}_1$ $\widetilde{N}_2$ $\widetilde{N}_3$ $\widetilde{N}_4$	$\widetilde{B}^0$ $\widetilde{W}^0$ $\widetilde{H}_u^0$ $\widetilde{H}_d^0$
charginos	$1/2$	-1	$\widetilde{C}_1^\pm$ $\widetilde{C}_2^\pm$	$\widetilde{W}^\pm$ $\widetilde{H}_u^+$ $\widetilde{H}_d^-$
gluino	$1/2$	-1	$\widetilde{g}$	" "

S. Martin

Neutralinos, charginos also symbolized as: $\tilde{\chi}_i^0$ $\tilde{\chi}_i^\pm$

SUSY Production in Hadron Colliders





D. Kazakov

- Strong production
  - Gluon fusion, quark anti-quark, quark-gluon scattering

  Dominant at the LHC

  (no valence anti-quarks in pp collisions)

- EWK production
  - Quark anti-quark annihilation

SUSY Production in Hadron Colliders

Production	Key Decay Modes	Signatures
$\tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q}$	$\left.\begin{array}{l}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 \\ \quad q\bar{q}'\tilde{\chi}_1^\pm \\ \quad g\tilde{\chi}_1^0\end{array}\right\} m_{\tilde{q}} > m_{\tilde{g}}$ $\left.\begin{array}{l}\tilde{q} \to q\tilde{\chi}_i^0 \\ \tilde{q} \to q'\tilde{\chi}_i^\pm\end{array}\right\} m_{\tilde{g}} > m_{\tilde{q}}$	$\not{E}_T$ + multijets (+leptons)
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 l^\pm \nu,\ \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 ll$ $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}', \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 ll,$	Trilepton + $\not{E}_T$ Dilepton + jet + $\not{E}_T$
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	$\tilde{\chi}_1^+ \to l\tilde{\chi}_1^0 l^\pm \nu$	Dilepton + $\not{E}_T$
$\tilde{\chi}_i^0\tilde{\chi}_i^0$	$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 X, \tilde{\chi}_i^0 \to \tilde{\chi}_1^0 X'$	$\not{E}_T$ + Dilepton + (jets) + (leptons)
$\tilde{t}_1\tilde{t}_1$	$\tilde{t}_1 \to c\tilde{\chi}_1^0$ $\tilde{t}_1 \to b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 l^\pm \nu, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}'$ $\tilde{t}_1 \to b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 l^\pm \nu, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 l^\pm \nu$	2 acollinear jets + $\not{E}_T$ single lepton + $\not{E}_T$ + $b's$ Dilepton + $\not{E}_T$ + $b's$
$\tilde{l}\tilde{l}, \tilde{l}\tilde{\nu}, \tilde{nu}\tilde{\nu}$	$\tilde{l}^\pm \to l \pm \tilde{\chi}_i^0, \tilde{l}^\pm \to \nu_l \tilde{\chi}_i^\pm$ $\tilde{\nu} \to \nu\tilde{\chi}_1^0$	Dilepton + $\not{E}_T$ Single lepton + $\not{E}_T$ + $(jets)$ $\not{E}_T$

D.I. Kazakov

Commonality: Missing Transverse Energy from weakly interacting LSP

Experimental Search Strategy

- Events with may jets and missing transverse energy (MET)
- Add one, two, three leptons
- Add heavy flavor

Proliferation of SUSY models predicting different particle types, mass scales, kinematics

- Inclusive event selection for model independent search

Experimentalist goal: find an excess of events with respect to standard model predictions as evidence of new physics

The Ingredients:

What do we measure in the detector and how?

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What do we look for?

Events with many jets, missing transverse energy (MET), leptons, electrons, photons

- Good understanding of how these "physics objects" leave their mark in the detector

Design detectors with the capability to identify and measure these "physics objects"

- High identification efficiency and low fake rate
- Linear energy response and excellent energy and position resolution
- High particle isolation efficiency
- Full angular coverage and hermeticity

Main challenge is Background

Events with the same detector signature (same physics objects, similar kinematics) as signal events

Detector Performance Definitions

Concepts

Object Identification Efficiency:

- Probability to reconstruct a physics object in the detector and identify it as the real particle that originated the signature (e, γ, μ, τ, hadron, jet)

Object Fake Rate:

- Probability to reconstruct a physics object in the detector and identify it incorrectly as a real particle of a different type that the one that originated the signature

Object Isolation Efficiency:

- Isolation is a requirement for a physics object to be separated in space from others. Isolation Efficiency is the probability for an event with an isolated object to pass a given isolation requirement

Object Response/Resolution:

- Energy/momentum response is the fraction of energy/momentum reconstructed by the detector. Resolution is the variance of the response distribution

Angular Coverage & Hermeticity:

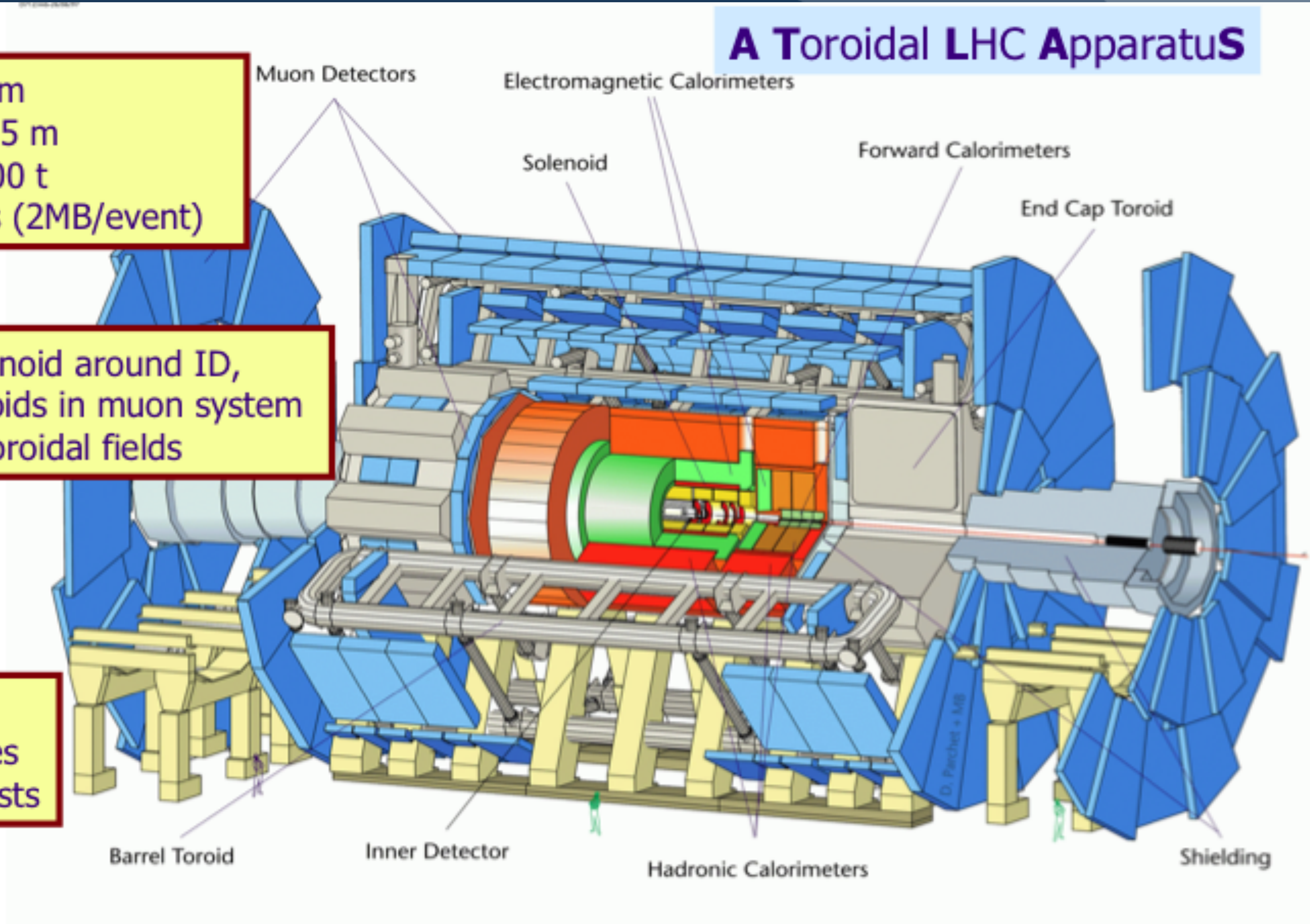
- Angular Coverage refers to the solid angle covered by the detector. A detector is Hermetic if no particle escapes beyond its boundaries

The ATLAS Detector

- Length ~40 m
- Diameter ~25 m
- Weight ~7000 t
- 10^8 channels (2MB/event)

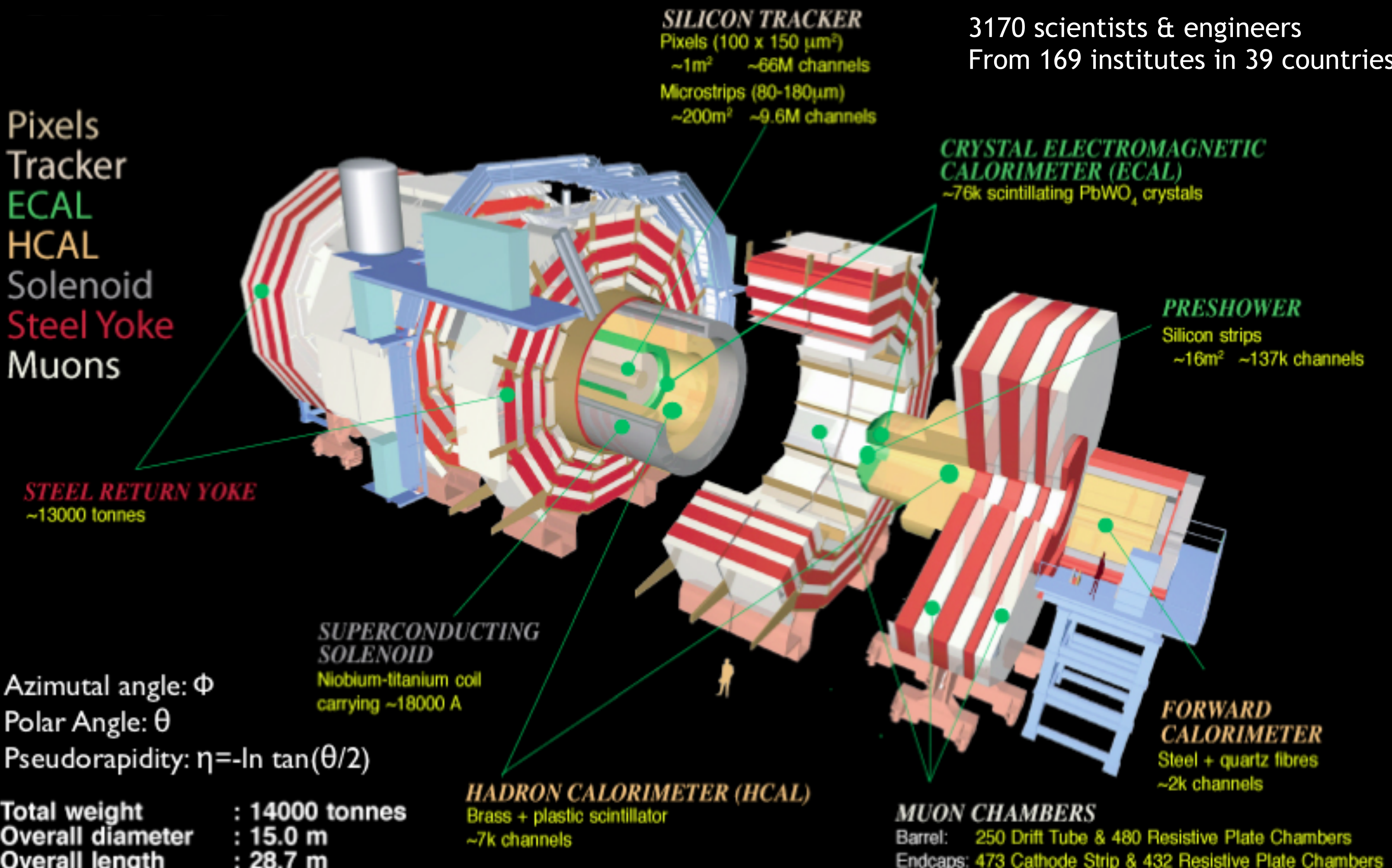
- Central: solenoid around ID, Toroids in muon system
- End caps: Toroidal fields

~40 Nations
~150 Institutes
~2000 physicists



The CMS Detector

3170 scientists & engineers
From 169 institutes in 39 countries



Azimutal angle: Φ
Polar Angle: θ
Pseudorapidity: $\eta=-\ln\tan(\theta/2)$

Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

ATLAS/CMS Detector Comparison

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixels + strips TRD → particle identification B= 2T $\sigma/p_T \sim 5 \times 10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.01$	Si pixels + strips No particle identification B= 4T $\sigma/p_T \sim 1.5 \times 10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 3\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeV standalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

Fabiola Gianotti's

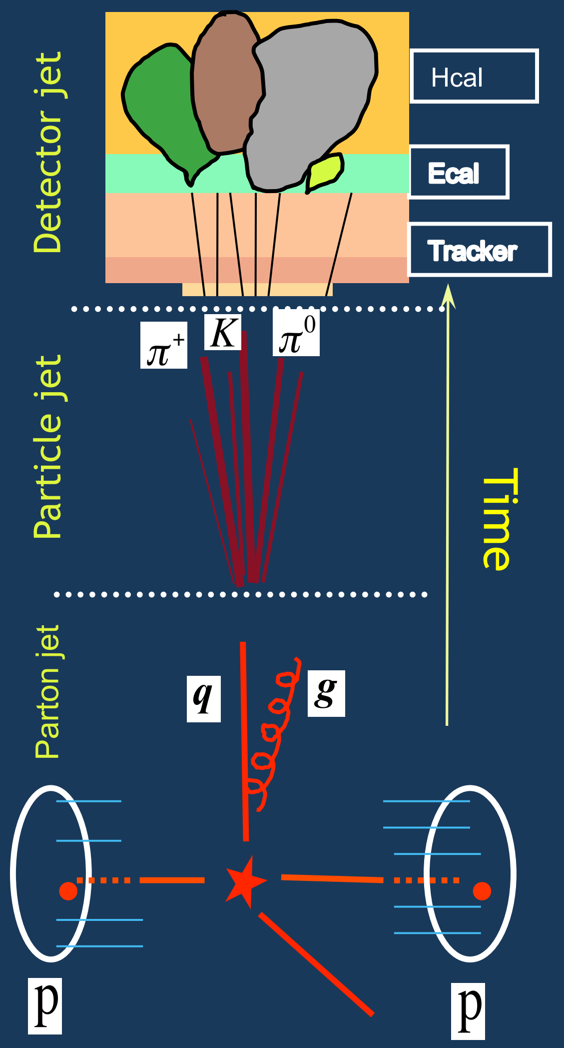
Jet Reconstruction & ID

- What is a jet ?

Jet Reconstruction & ID

- What is a jet ?

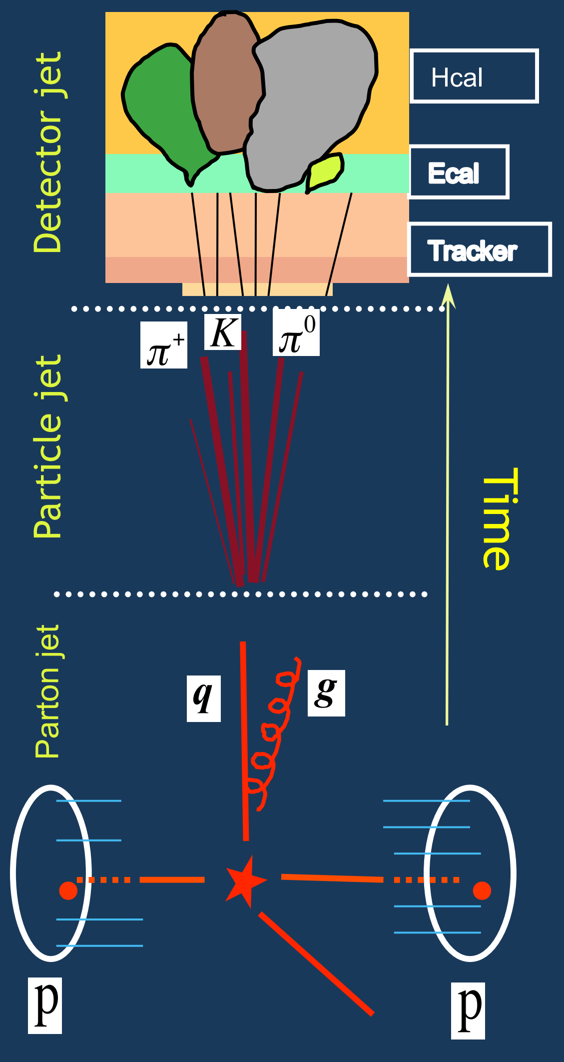
Jet Reconstruction & ID



Jets are the experimental signature of quarks and gluons: spray of collimated colorless particles.

- Parton jet: made of quarks and gluons (after hard scattering and before hadronization).
- Particle jet: composed of final state colorless particles (after hadronization).
- Detector jet: reconstructed from measured energy depositions and tracks.

Jet Reconstruction & ID



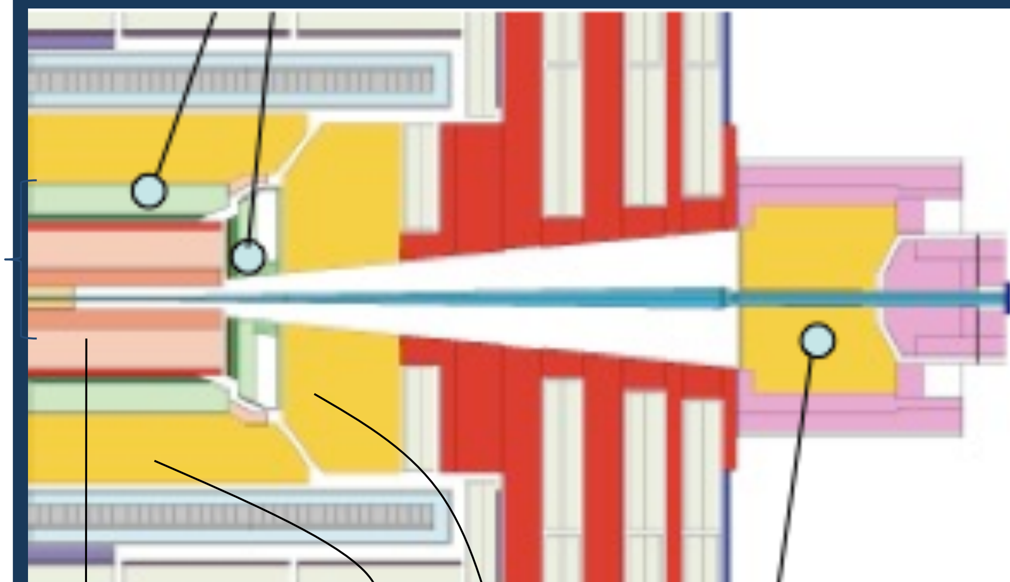
In CMS, we define detector jet types as:

- TrackJets: from tracks only (not discussed today).
- CaloJets: from calorimeter towers only.
- JetPlusTracks (JPT): Track corrections to CaloJets
- PFlow Jets: from individually reconstructed particles using the full detector.

A clustering algorithm defines the jet and may be applied at any level (parton, particle, detector):

Fixed Cone | Sequential Clustering

Jets in the CMS Detector



- Ecal: lead tungstate
  24.7 X_0
  $\phi \times \eta = 0.0175 \times 0.0175$
  e resolution: <0.5%, E>120 GeV
- Hcal: HF (Steel/quartz fibres)
  10 λ_{int}
  $\phi \times \eta = 0.175 \times 0.175$
- Hcal: HB/HE (Brass/Scint)
  5.8 λ_{int} (at η=0)
  $\phi \times \eta = 0.087 \times 0.087$
- Tracker: 0.4-1.7 X_0 ,
  $\sigma(p_T)/p_T = 1.0(2.0) \times 10^{-4}\, p_T \oplus 0.008(0.002)$
  for muons (pions).

Ecal+Hcal non-compensating

- Non-linear response to hadrons.
- Poor hadronic energy resolution.

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{110\%}{\sqrt{E}}\right)^2 + 8.5\%^2$$

➡ Particle Flow improves jet and MET measurements using CMS' high Ecal granularity and excellent tracking.

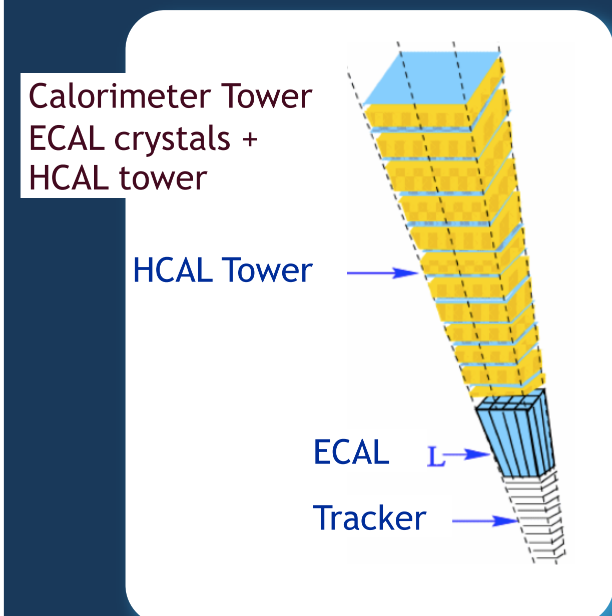
Detector Jet Types: CaloJets

CaloJets defined by a clustering algorithm run on calorimeter towers.

Calorimeter towers are reconstructed from Ecal, Hcal, and HF towers with energy depositions above a given threshold, 0.2-0.85 GeV, to minimize noise.

For example, in the Barrel region:

- **HB tower** is a 0.087x0.087 channel (no longitudinal segmentation).
- **EB tower** is a 5x5 crystal matrix coincident with an HB tower.

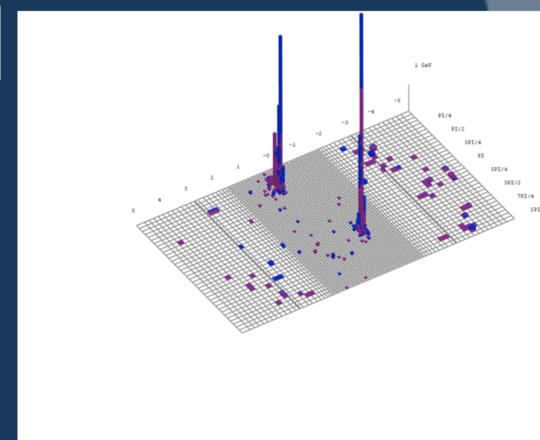


$$(\vec{p},E)_{\text{CaloTower}} = (\vec{p},E)_{\text{EBTower}} + (\vec{p},E)_{\text{HBTower}}$$

$$(\vec{p},E)_{\text{EBTower}} = \sum_{\text{5x5 crystal matrix}} (\vec{p},E)_{\text{crystal}}$$

$\vec{x}_{\text{EBTower}}$: Energy weighted crystal positions

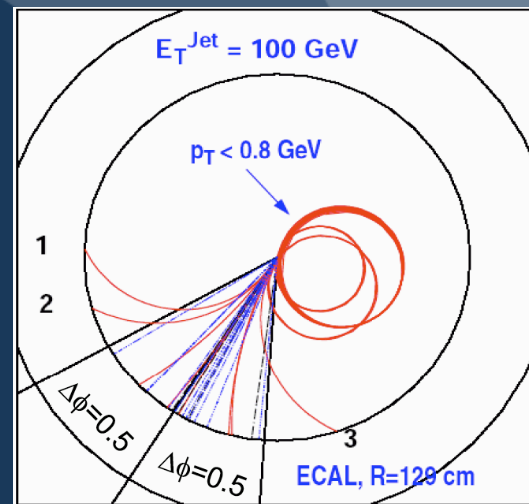
$\vec{x}_{\text{HBTower}}$: Tower axis



Detector Jet Types: JetPlusTracks

The JPT corrections improve CaloJets by using the measured track momentum of charged particles.

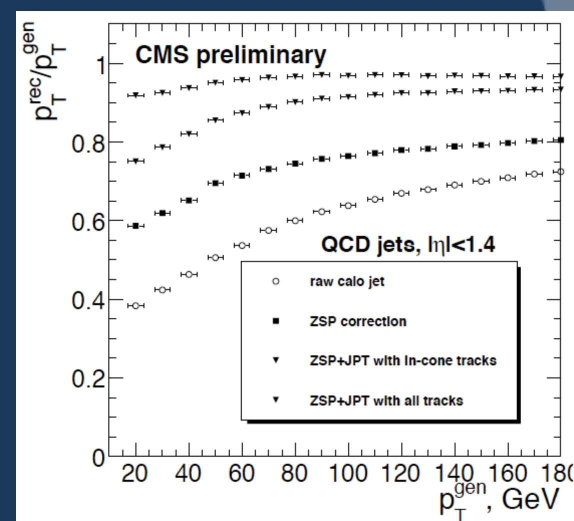
- Add to a CaloJet the momentum of selected charged tracks.
- Subtract from a CaloJet (for each track) the mean calorimeter response to the hadron associated to a track.



Track momentum / single particle response to be measured from Collider data.

JPT Corrections steps:

- ZSP correction for energy lost due to the suppression of low energy calorimeter cells.
- In-cone track response correction.
- Addition of out-of-cone track momenta.
- Track finding efficiency correction.
- Track based muon correction.



CMS-PAS-JME-09-002

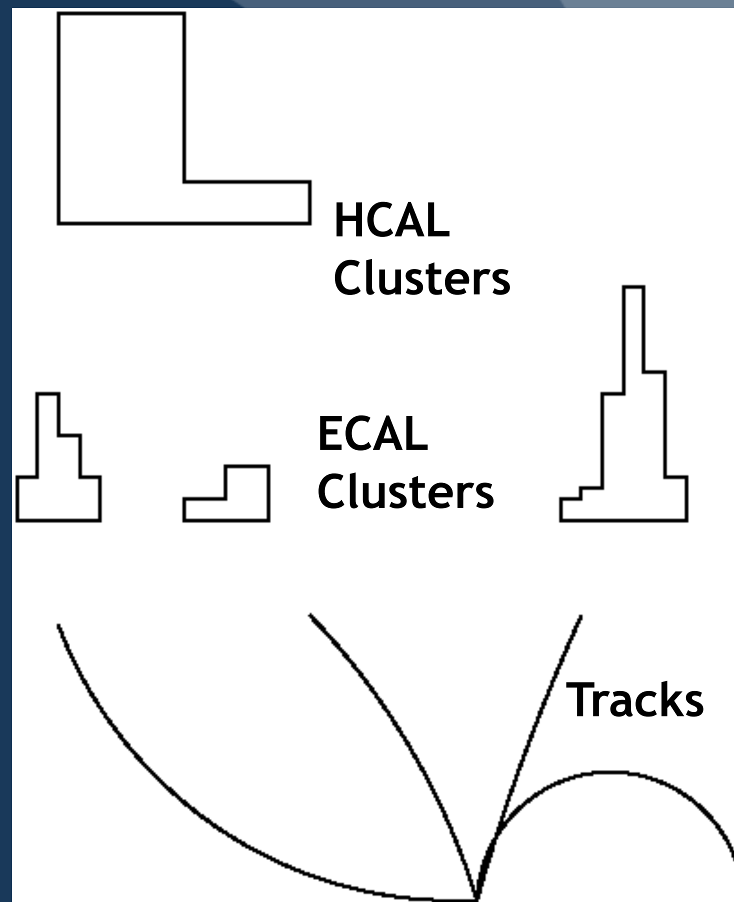
Detector Jet Types: PFlow (PF)

The PFlow algorithm is designed to:

• Reconstruct & identify all particles: γ, e, μ, charged & neutral hadrons, pileup, and converted photons & nuclear interactions

• Use a combination of all CMS sub-detectors to get the best estimates of energy, direction, particle ID

1. Associate hits within each detector



CMS-PAS-PFT-09-001

Detector Jet Types: PFlow (PF)

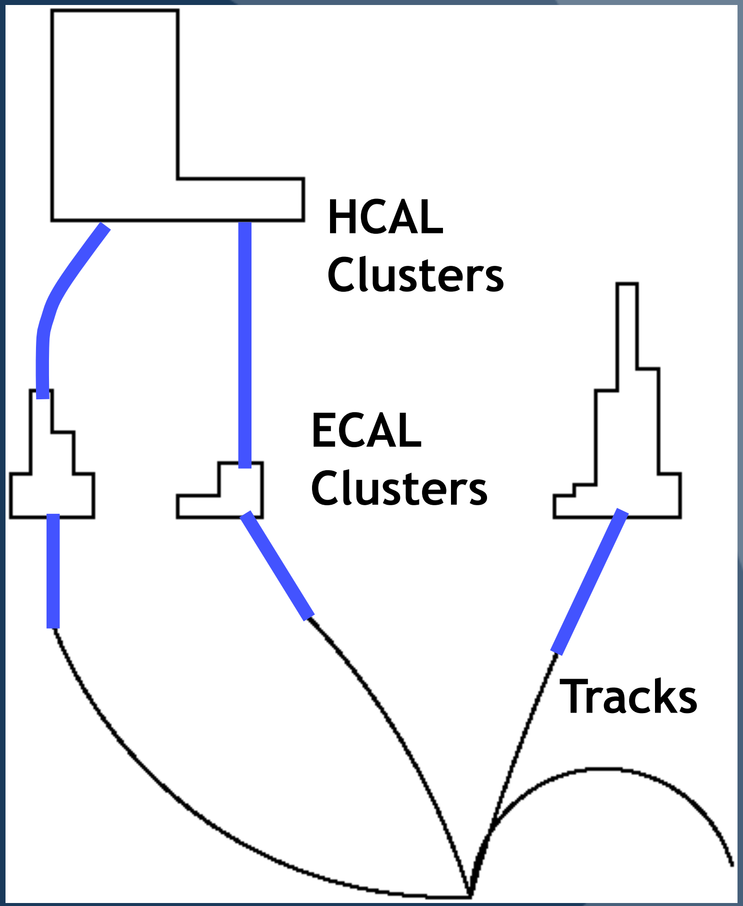
The PFlow algorithm is designed to:

• Reconstruct & identify all particles: γ, e, μ, charged & neutral hadrons, pileup, and converted photons & nuclear interactions

• Use a combination of all CMS sub-detectors to get the best estimates of energy, direction, particle ID

1. Associate hits within each detector
2. Link across detectors

CMS-PAS-PFT-09-001



Detector Jet Types: PFlow (PF)

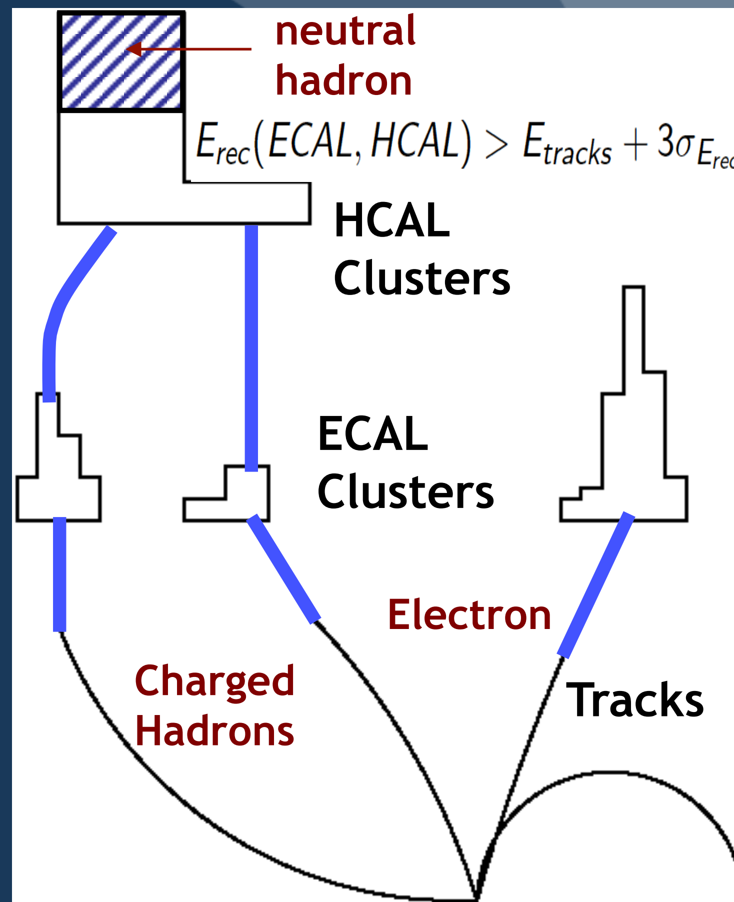
The PFlow algorithm is designed to:

- Reconstruct & identify all particles: γ, e, μ, charged & neutral hadrons, pileup, and converted photons & nuclear interactions

- Use a combination of all CMS sub-detectors to get the best estimates of energy, direction, particle ID

1. Associate hits within each detector
2. Link across detectors
3. Particle ID and separation.

CMS-PAS-PFT-09-001



PFlow jets are reconstructed by running any of the jet clustering algorithms on PFlow particles.

Jet Clustering Algorithm

A jet clustering algorithm should be:

• Simple, easy to calibrate, robust against contributions from pileup and underlying event.

• Infrared safe: the output is stable against adding soft parton emission.

• Collinear safe: the output is stable against replacing any parton by a collinear pair of partons.

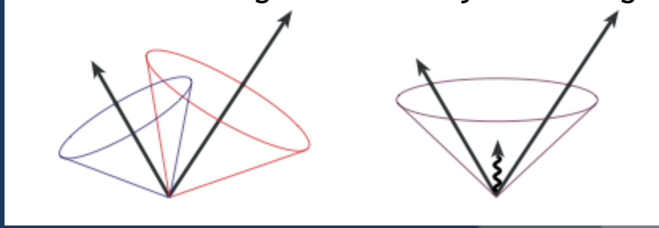
Two classes of jet clustering algorithms:

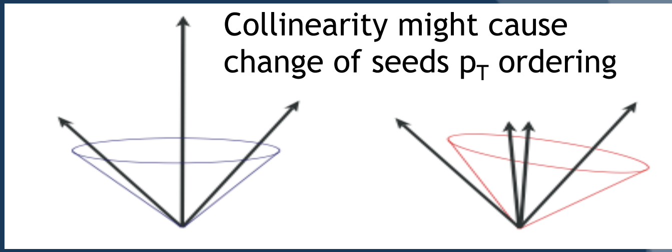
• Fixed cone, with $R^2 = \eta^2 + \phi^2$

– Iterative cone (non-safe).
– Seedless Infrared Safe Cone or SISCone (safe).

• Sequential clustering (non-fixed shape).

– k_T, Anti-k_T, Cambridge-Aachen (safe).





In CMS: (ATLAS)

• Icone, SISCone R=0.5, 0.7 (0.4,0.6)
• Anti-k_T R=0.5, 0.7 (0.4, 0.6)
• k_T R=0.4, R=0.6

Both experiments use Anti-k_T for the searches

Sequential Clustering: k_T, Anti-k_T

- List of input elements (particles, detector elements) and compute: $$k_T^2 = p_x^2 + p_y^2, \quad y = \frac{1}{2}\ln\frac{E+p}{E-p}$$

- For each element, define: $d_i = k_{T,i}^{2p}$

- For each pair (i,j) of different elements, define

$$d_{ij} = \min(k_{T,i}^{2p}, k_{T,j}^{2p})\frac{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}{D^2}$$

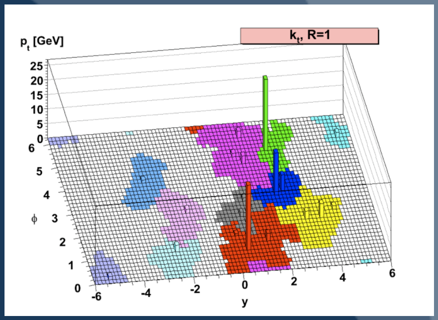
- Determine $d_{\min} = \min(d_i, d_{ij})$

  – if $d_{\min} = d_{ij}$ → cluster objects i and j , form new object jet k_T.

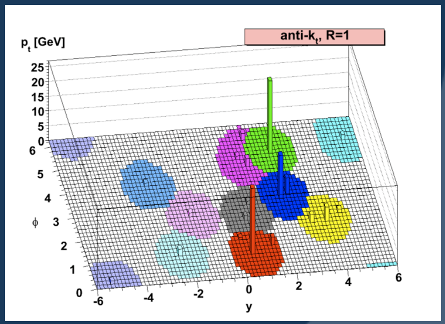
  – if $d_{\min} = d_i$ → add object to list of jets.

- Stop clustering when there are only jets in the list.

JHEP 9708:001 (1997) **JHEP 0804:063 (2008)**



k_T algorithm: p=1
- Clustering of low p_T elements is favored.
- Irregular shape.



Anti-k_T algorithm: p=-1
- Clustering of high p_T elements is favored.
- cone-like shape.

Fixed Cone: ICone, SISCone

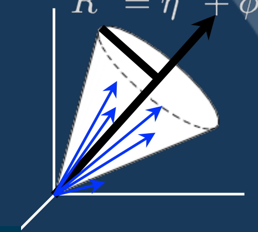
Iterative Cone:

1. List all input elements ($E_{CaloTower}$> 1 GeV), define a proto-jet by drawing a cone of size R around the highest p_T seed. Calculate the proto-jet 4-Momentum vector using the <u>E_T-scheme</u>.
2. Draw a cone of size R around the new position of the proto-jet and iterate until the position of the jet axis is stable. Calculate 4-Momentum using <u>E-scheme.</u>
3. Remove the proto-jet input elements from the list.
4. Move to the next seed and repeat steps 2-5 until done with the list. CaloJets with p_T > 1 GeV are retained.

$$\left\{ \begin{array}{rcl} P_T & = & \sum_i P_{T,i} \\ \eta & = & \frac{1}{P_T} \sum_i P_{T,i}\, \eta_i \\ \phi & = & \frac{1}{P_T} \sum_i P_{T,i}\, \phi_i \end{array} \right.$$

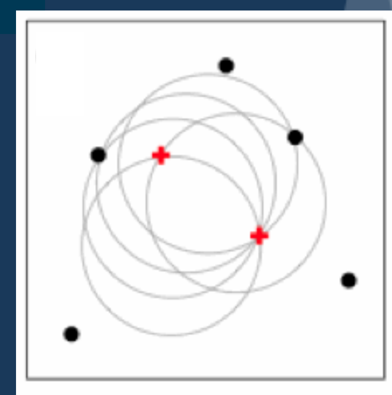
$$\left\{ p^\mu_{kl} = p^\mu_k + p^\mu_l \right.$$

$$R^2 = \eta^2 + \phi^2$$



SISCone:

- All stable cones are sought for proto-jets; no seeds involved. (computationally possible thanks to an innovative implementation that reduces the execution time from $N \cdot 2^N$ to $N^2 \ln N$.)
- Merge-Split mechanism for overlapping proto-jets.
  - If $p_{T,shared}$ < 0.75 $p_{T,j}$, shared input elements are assigned to the closest proto-jet i or j.
  - Otherwise, i and j are merged into one jet.



JHEP 0705:086 (2007)

Jet Energy Calibration

Jet Energy is corrected, in average, to the particle level for SUSY searches

Raw Jet × Offset Correction (pile up) × Relative Response (vs. η) × Absolute Response (vs. p_T) = Calibrated Jet

$$E^{\text{corrected}} = (E^{\text{raw}} - E_{\text{offset}}) \times C(\text{Rel}:\eta) \times C(\text{Abs}:p_T)$$

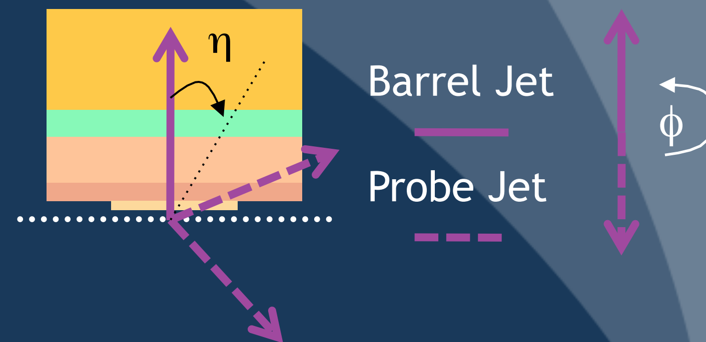
$$\text{Total Response} = \left\langle E_{Raw\ Jet} \right\rangle / E_{Particle\ Jet \equiv Calibrated\ Jet}$$

- Offset: removes detector noise and pileup
- Relative response: removes the η dependence ("uniform detector")
- Absolute response: removes the p_T dependence ("linear detector")

In CMS, the JEC is derived from Monte Carlo and corrected by a residual data/MC ratio as determined with Data Driven Methods

JEC: Relative Response

<u>Measured from data</u> with a *p_T balance method* using a dijet trigger.



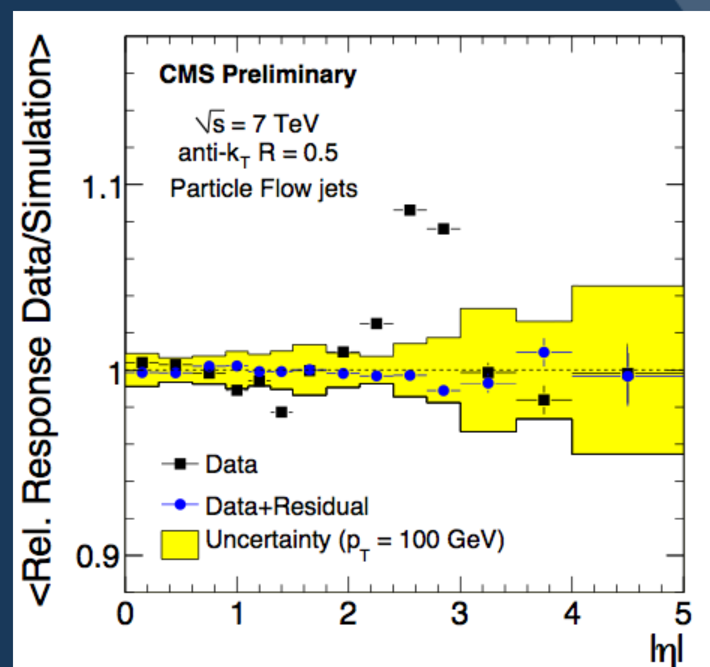
$$p_T^{dijet} = \frac{p_T^{probe} + p_T^{barrel}}{2}$$

$$B = \frac{p_T^{probe} - p_T^{barrel}}{p_T^{dijet}}$$

$$r = \frac{2 + \langle B \rangle}{2 - \langle B \rangle}$$

"Data Driven" (DD) technique

$$c(\eta, \langle p_T^{probe} \rangle) = \frac{1}{r(\eta, \langle p_T^{probe} \rangle)}$$

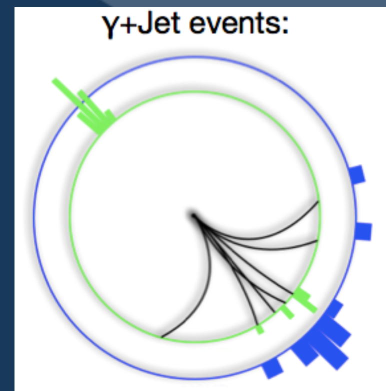


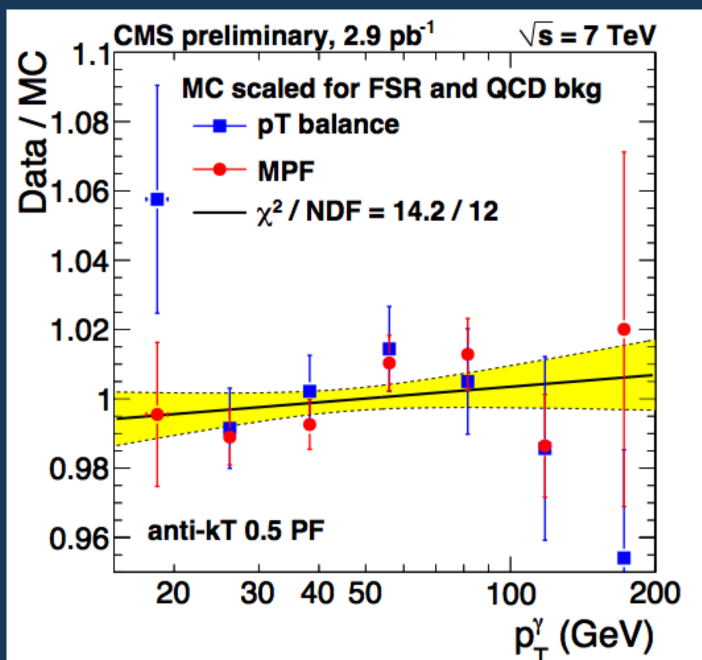
CMS-PAS-JME-10-010

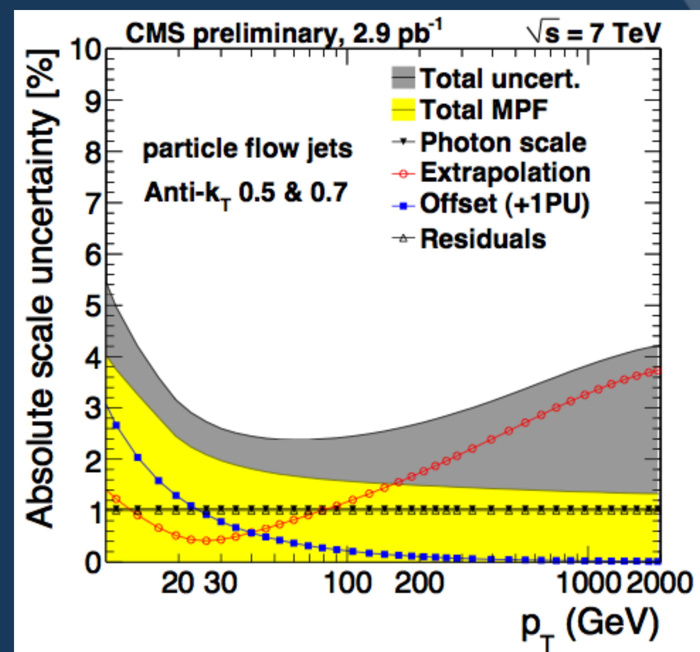
JEC: Absolute Response

<u>Measured from data</u> with a *p_T balance/MPF methods* using a photon+jets events

"Data Driven" (DD) technique







CMS-PAS-JME-10-010

Jet Energy Resolution

Measured from data using the Dijet Asymmetry Method on a dijet inclusive sample

CMS-PAS-JME-09-007

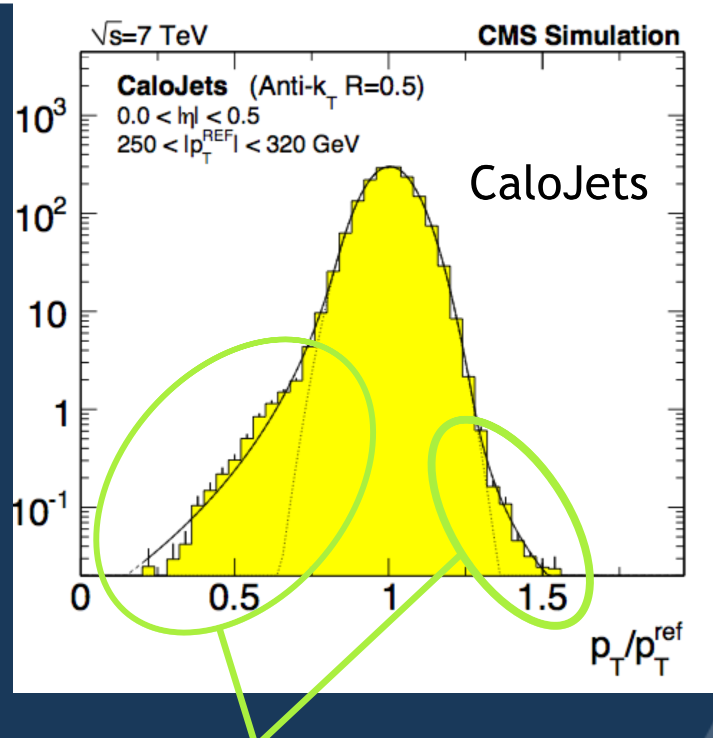
$$A = \frac{(p_T^{\mathrm{jet1}} - p_T^{\mathrm{jet2}})}{(p_T^{\mathrm{jet1}} + p_T^{\mathrm{jet2}})}$$

"Data Driven" (DD) technique

$$\left(\frac{\sigma_{p_T}}{p_T}\right) = \sqrt{2}\sigma_A$$

$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 = \left(\frac{\sigma_{p_T}}{p_T}\right)^2_{\mathrm{Calo}} - \left(\frac{\sigma_{p_T}}{p_T}\right)^2_{\mathrm{Part}}$$

JEC corrected Total Response Distribution



Understanding tails critical for SUSY searches: events with fake large MET

CMS-PAS-JME-10-014

Jet Energy Resolution

Measured from data using the Dijet Asymmetry Method on a dijet inclusive sample

CMS-PAS-JME-09-007

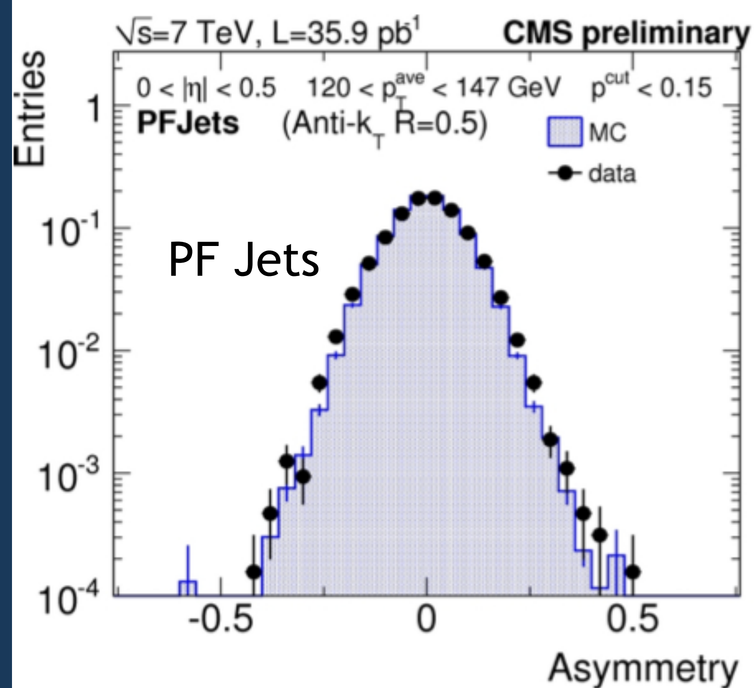
$$A = \frac{(p_T^{jet1} - p_T^{jet2})}{(p_T^{jet1} + p_T^{jet2})}$$

"Data Driven" (DD) technique

$$\left(\frac{\sigma_{p_T}}{p_T}\right) = \sqrt{2}\sigma_A$$

$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 = \left(\frac{\sigma_{p_T}}{p_T}\right)^2_{Calo} - \left(\frac{\sigma_{p_T}}{p_T}\right)^2_{Part}$$

Asymmetry Distribution (A)

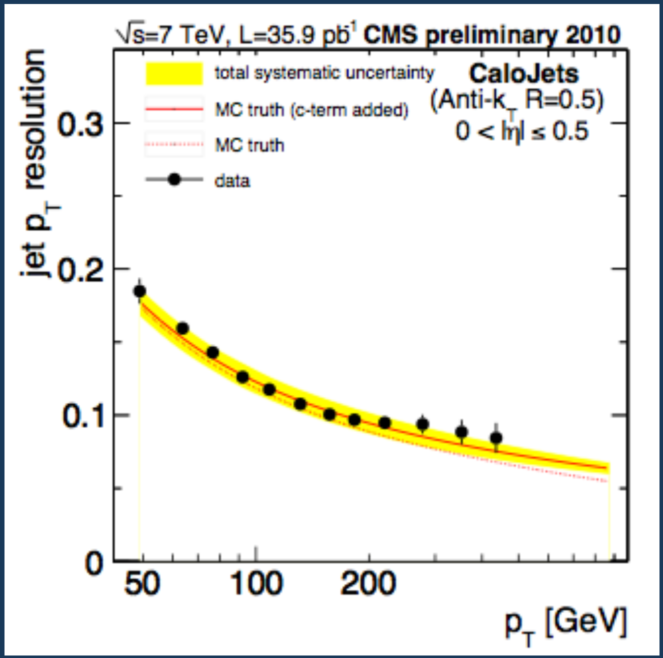


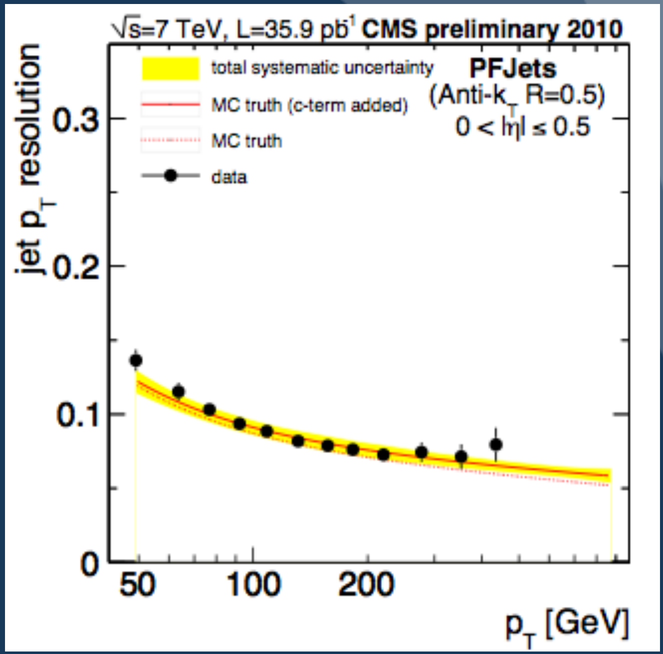
Lost left/right tail information in the measurement

CMS-PAS-JME-10-014

Jet Energy Resolution

Measured from data using the Dijet Asymmetry Method (dijet sample)





$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 = \left(\frac{\sigma_{p_T}}{p_T}\right)^2_{\mathrm{Calo}} - \left(\frac{\sigma_{p_T}}{p_T}\right)^2_{\mathrm{Part}}$$

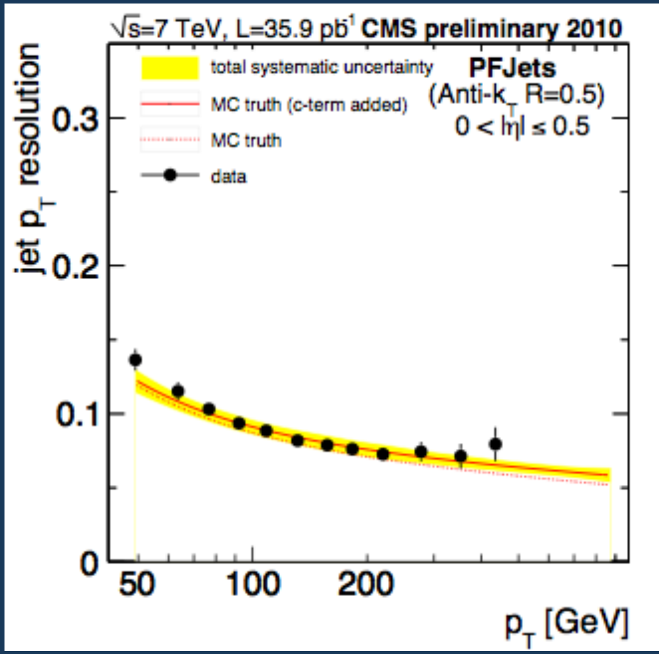
Excellent MC modeling

JPT and PFlow jets significantly better than CaloJets

CMS-PAS-JME-10-014

Jet Energy Resolution

<u>Measured from data</u> using the Dijet Asymmetry Method (dijet sample)



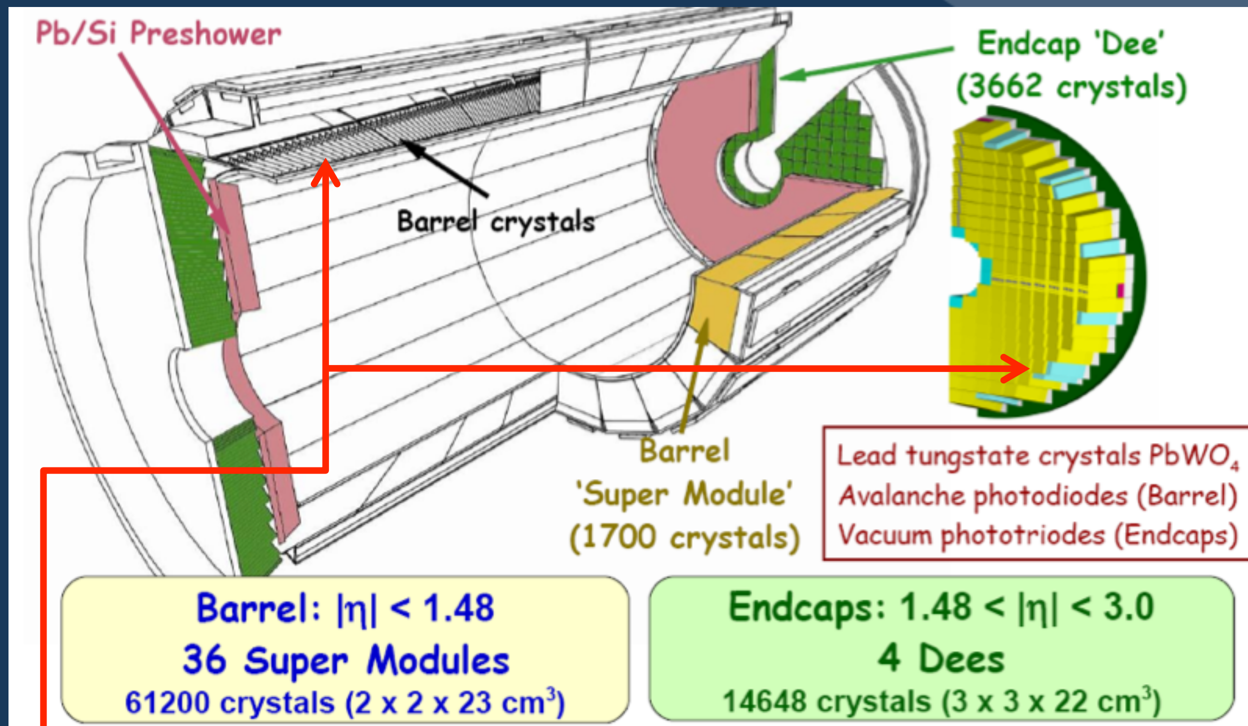
$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 = \left(\frac{\sigma_{p_T}}{p_T}\right)^2_{\mathrm{Calo}} - \left(\frac{\sigma_{p_T}}{p_T}\right)^2_{\mathrm{Part}}$$

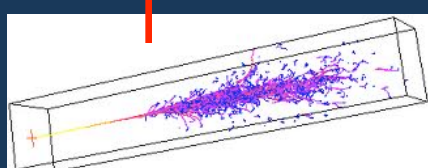
Excellent MC modeling

JPT and PFlow jets significantly better than CaloJets

CMS-PAS-JME-10-014

γ/e in the CMS Detector





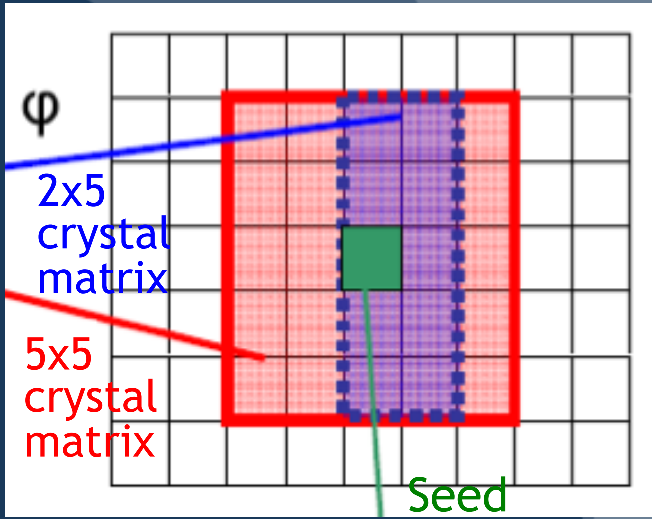
compact & high granularity:
radiation length = 0.89 cm
Moliere Radius = 2.2cm
$\Rightarrow$ good jet rejection

26 rad. lengths
90% of shower contained in one crystal

e/γ resolution: <0.5%, E>120 GeV

γ/e Reconstruction & ID

- 97% of unconverted photon is contained in a 5x5 crystal matrix.
- The electron energy is spread in ϕ due to the solenoidal magnetic field
  - ✓ Electrons radiate by bremsstrahlung
  - ✓ Photons have 50% probability to convert into electrons in the tracker



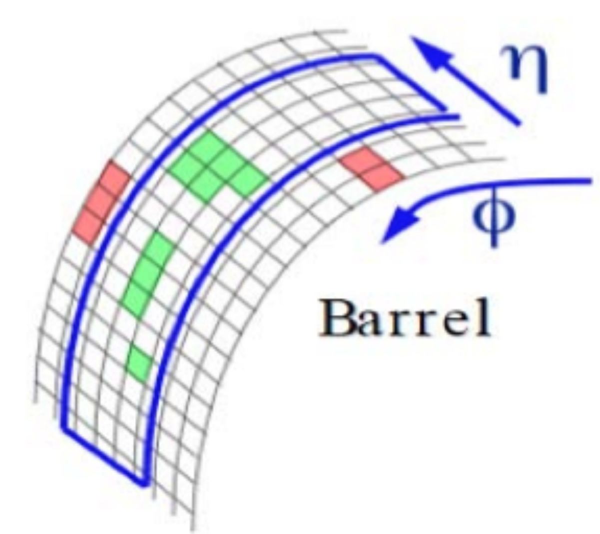
Define Superclusters to recover energy

Barrel: use dynamic algorithm

- ✓ Start with seed crystal (highest p_T)
- ✓ Narrow rows in η, long in bending direction ϕ

Endcap: use 5x5 crystal matrix, preshower E added

- ✓ Start with seed crystal (highest p_T)
- ✓ Narrow rows in η, long in bending direction ϕ

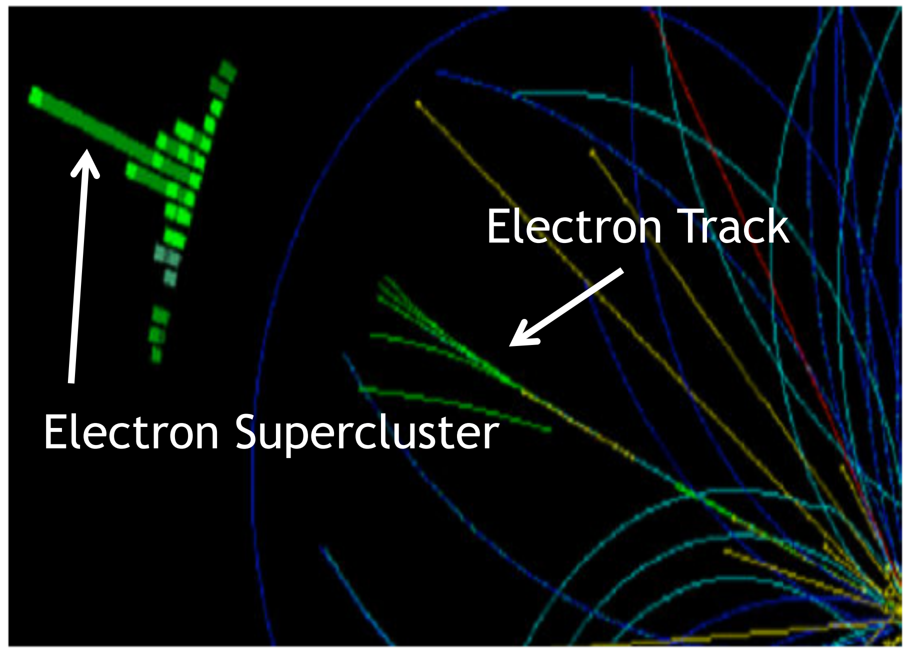


$$E_{hcal}/E_{ecal}<0.05$$

γ/e Reconstruction & ID

γ and e ID criteria are quite similar. For example (loose γ ID):

- Ecal iso: E_T in 0.06<R<0.4 less than $(4.2+0.006*E_T^{\gamma})$ GeV
- Hcal iso: E_T in 0.15<R<0.4 less than $(2.2+0.0025*E_t^{\gamma})$ GeV
- Tracker iso: E_T of tracks in 0.04<R<0.4 less than $2+0.001*E_t^{\gamma}$) GeV
- $\sigma_{i\eta i\eta}$ measures the size of the supercluster in η, with $\sigma_{i\eta i\eta}$< 0.013 (0.03) in the Barrel (Endcap)
- E2/E9 ratio of E in two highest E crystals and in 3x3 matrix < 0.95
- Signal seed crystal time with 3 ns of interaction time (remove beam halo)



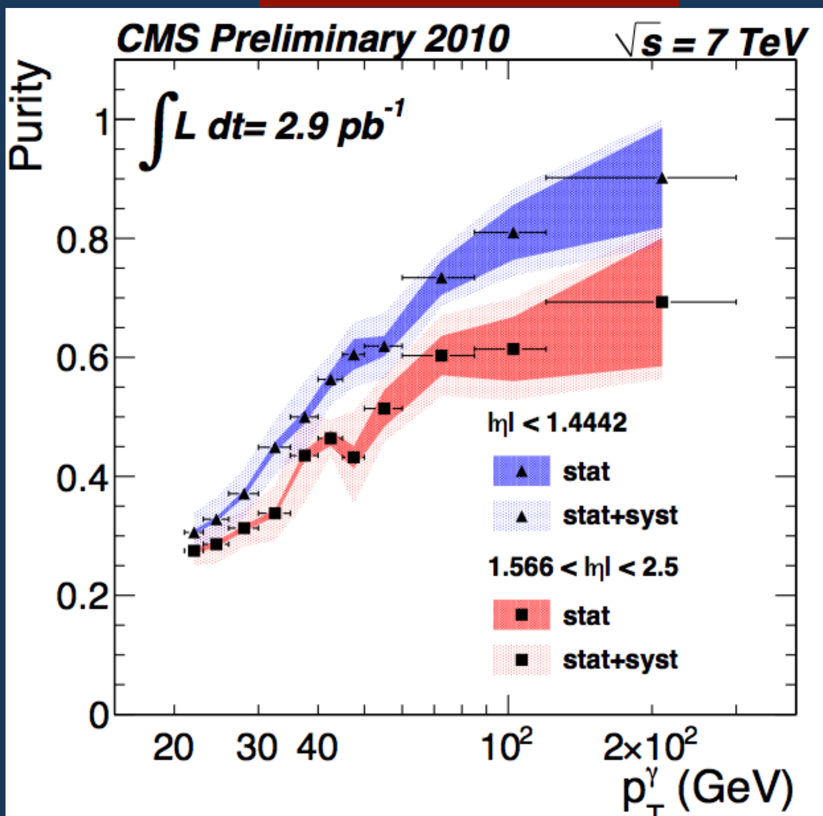
Photons: no pixel hits consistent with track from interaction region

Electrons: pixel match required, E & p_T is a combination of Ecal and tracking information, Bremsstrahlung correction estimated using tracks

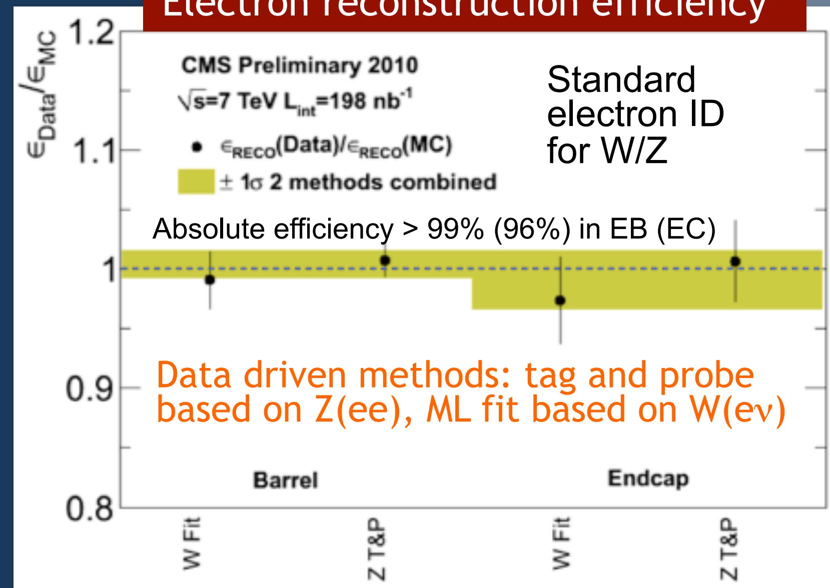
Small differences in γ/e ID used in different analyses

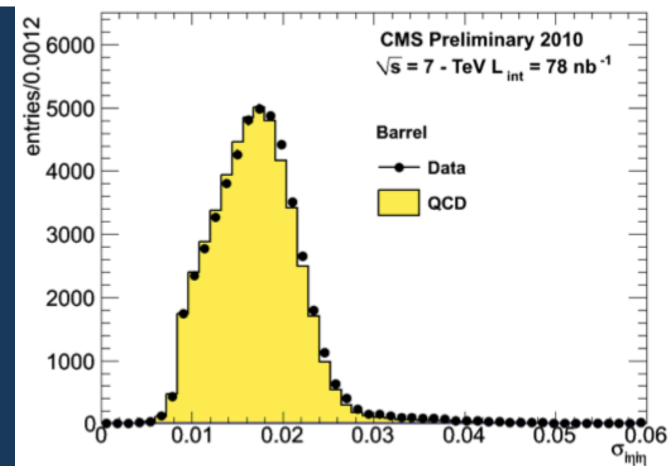
γ/e Performance

Photon Purity



Electron reconstruction efficiency

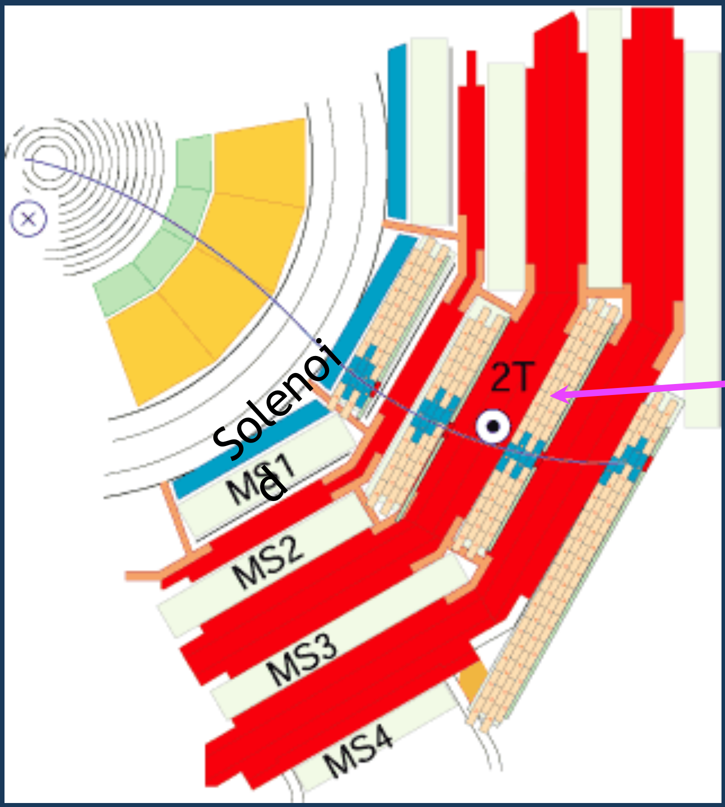


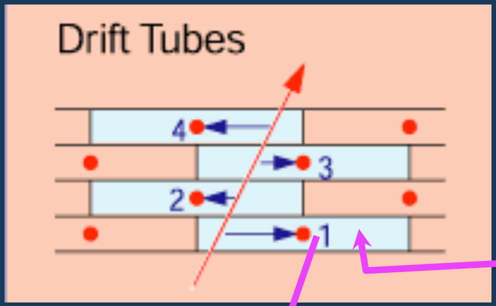


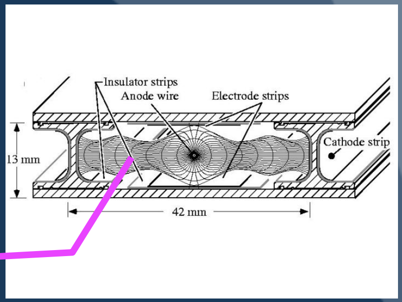
Other important numbers to measure are efficiency and fake rate

CMS-PAS-EGM-10-006

Muons in the CMS Detector







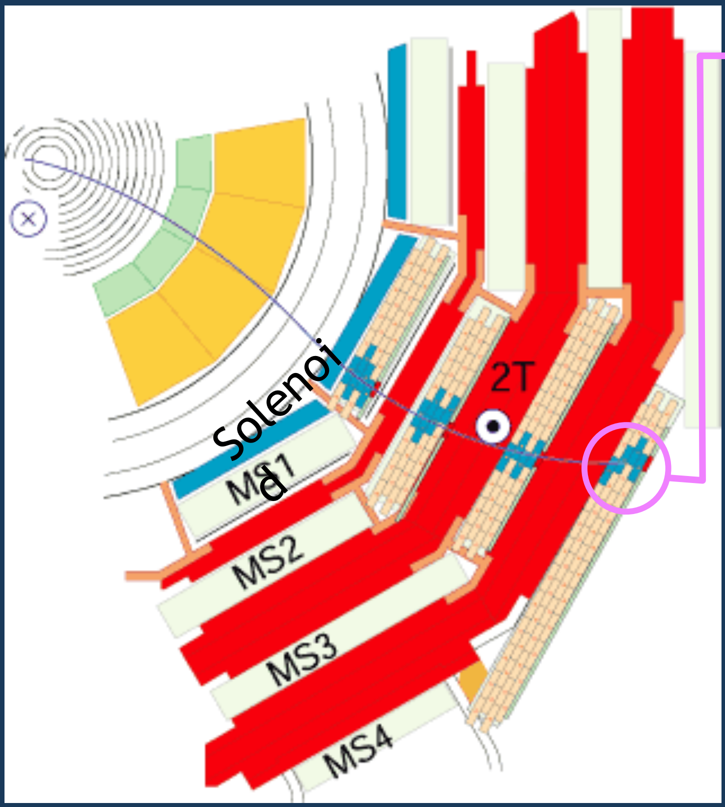
Drift Tubes (DT) outside solenoid and interleaved with iron "return yoke" plates:

- ✓ distance to wire
- ✓ position along the wire

Muons bend in powerful magnetic field:

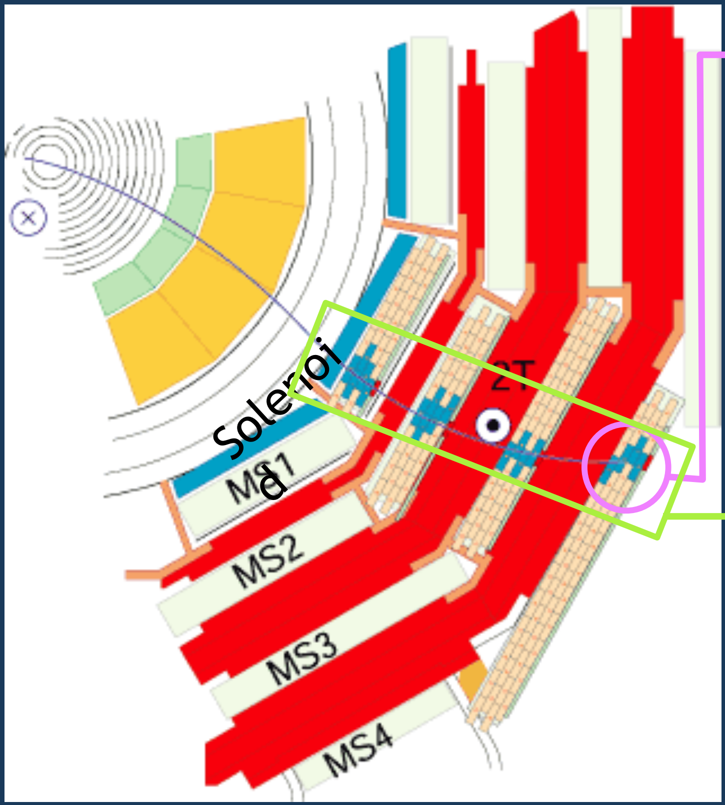
- ✓ Accurate p_T measurement

Muon Reconstruction



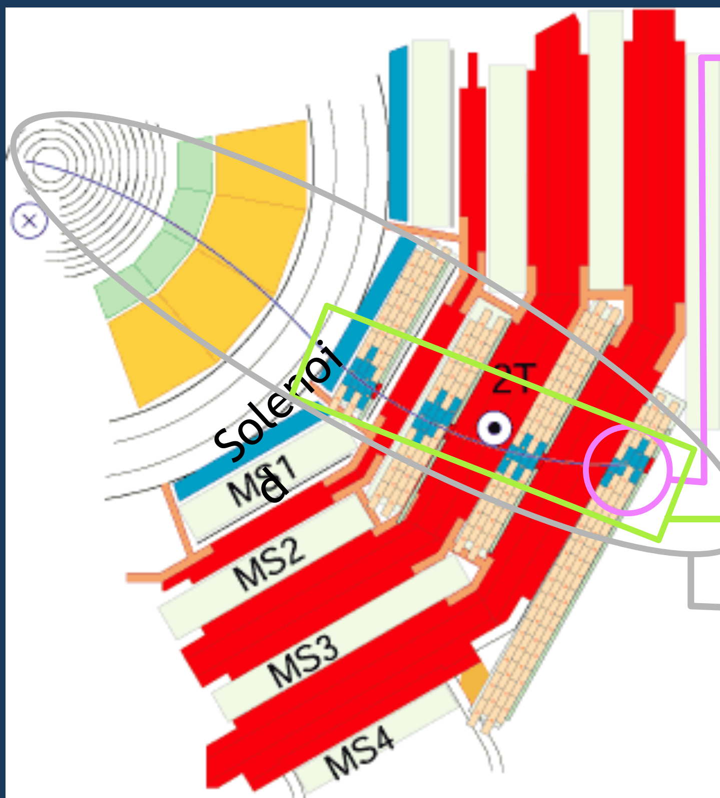
- Local Muon
  - ✓ Hits from subdetectors
  - ✓ Track Segments from hits

Muon Reconstruction & ID



- Local Muon
  - ✓ Hits from subdetectors
  - ✓ Track Segments from hits
- Standalone Muon
  - ✓ Combine track segments into a muon trajectory in muon system

Muon Reconstruction & ID



- Local Muon
  - ✓ Hits from subdetectors
  - ✓ Track Segments from hits
- Standalone Muon
  - ✓ Combine track segments into a muon trajectory in muon system
- Global Muon
  - ✓ Reconstruct Muon Tracker Track
  - ✓ Combine Standalone muon and Muon Tracker Track into a Global Muon (global fit)

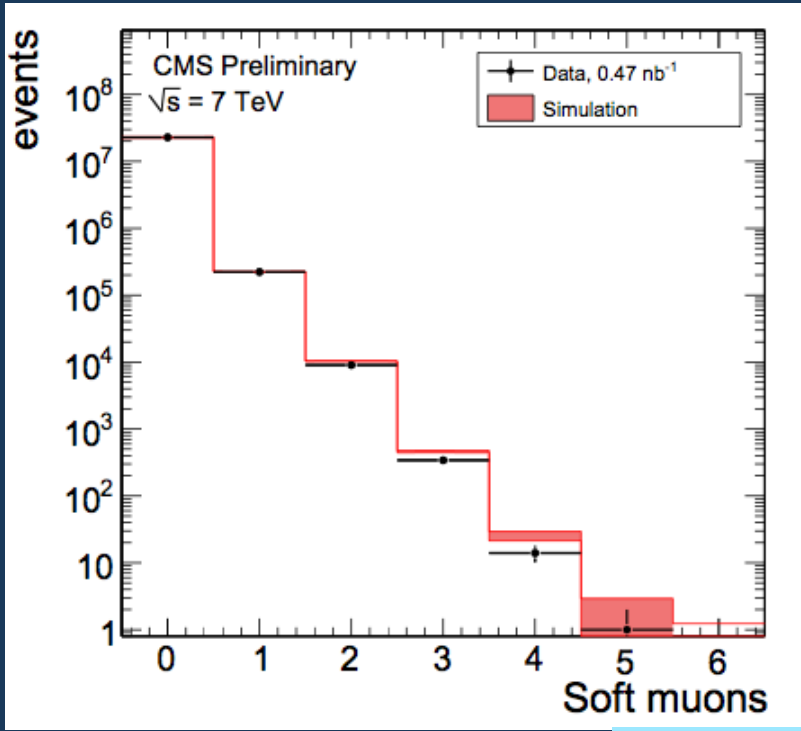
Muon ID

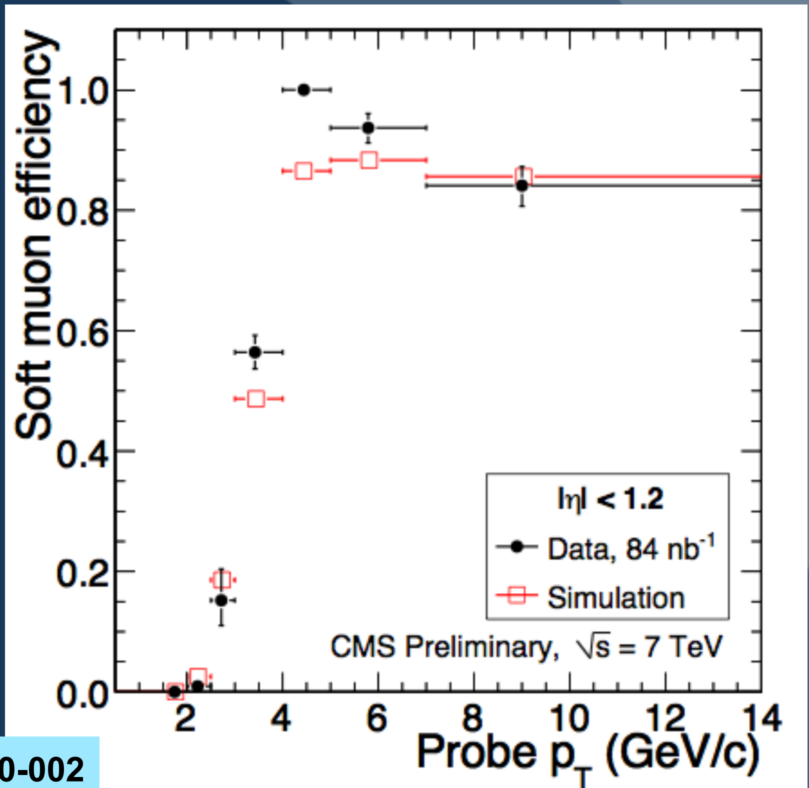
Soft Muon defined as:

- ✓ Global Muon with good quality global and tracker tracks
- ✓ Primary Vertex match within 200 μm transversely and 1 cm longitudinally
- ✓ Isolation defined by asking PF ISO:

$$\mu_{Iso} = \frac{\sum_{trk}^{\Delta R=0.3} p_T^{chargedhadron} + \sum_{ecal}^{\Delta R=0.3} e_T^{neutralhadron} + \sum_{hcal}^{\Delta R=0.3} e_T^{photons}}{p_T} < 0.2$$

Muon Performance





CMS-PAS-MUO-10-002

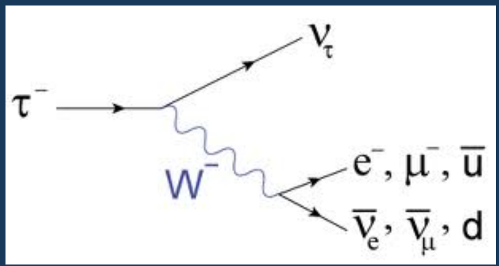
Soft muon multiplicity in MinBias events

Soft muon efficiency using Data Driven Tag & Probe Method using J/χ(μμ)

$\sigma_{pT/pT}$ <1% at 10 GeV/c, ~8% at 500 GeV/c

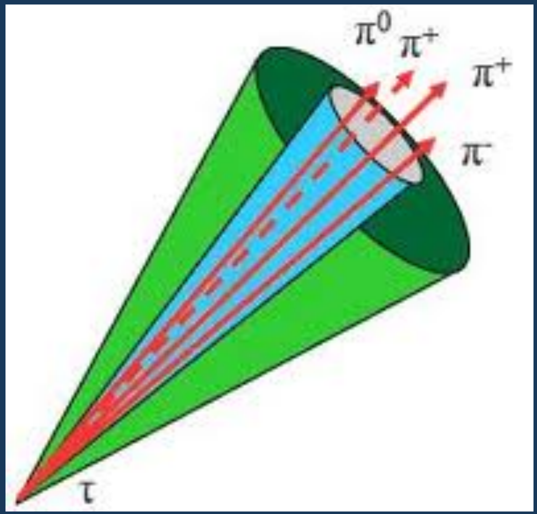
arXiv:0911.4994

Tau Reconstruction & ID



Large mass (1.77 GeV) as compared to μ (106 MeV) and electron (0.5 MeV)

- Hadronic decay, τ_{had}, 2/3 of times
- Leptonic decay, remaining branching ratio

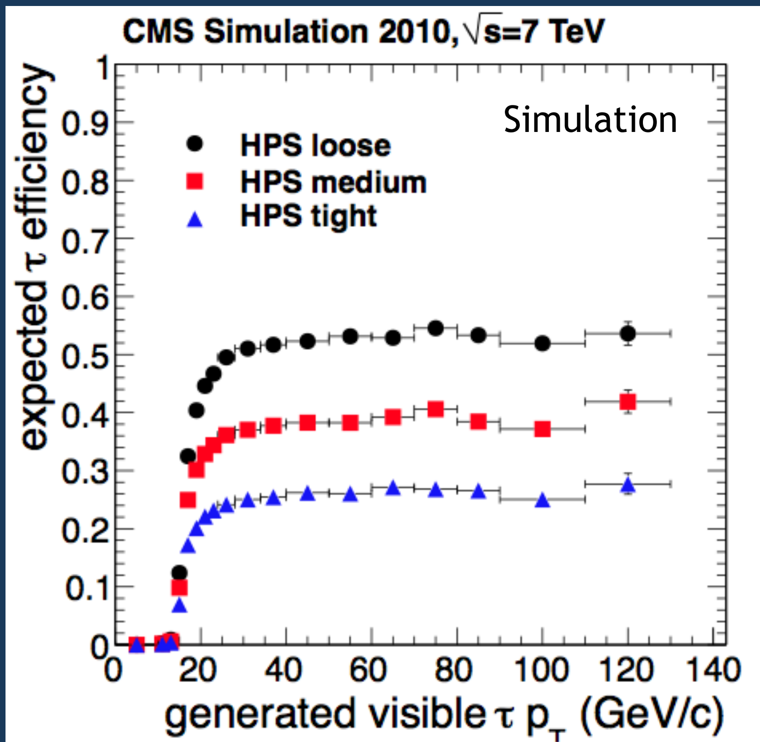


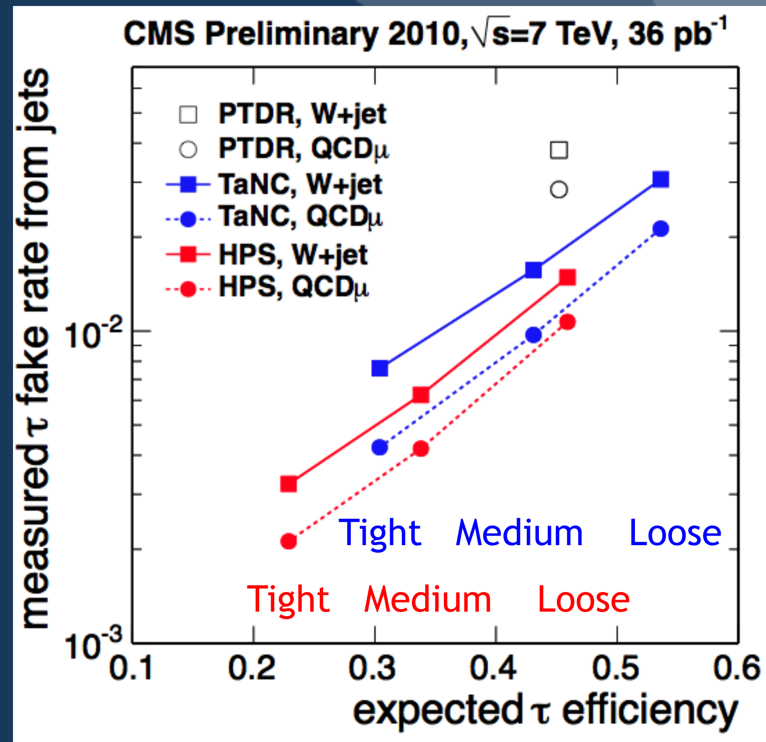
Hadronic τ decay

- Typically one or three charged mesons (π^+,π^-), up to 2 neutral mesons (π^0), and a ν_τ, with π^0 decaying to two γ
- Collimated jet similar to QCD jet of q/g

Reconstruction based on Pflow reco & ID of individual particles

Tau Reconstruction & ID





τ reco efficiency using "tag & probe" from Z->$\tau\tau$ with $\tau\tau$->$\mu\tau_{had}$

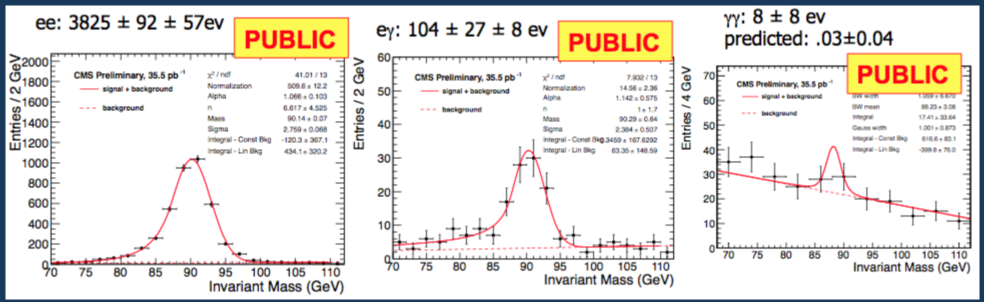
τ fake rate from jets versus efficiency for tight, medium, loose operating points

The Tag & Probe Method

Concept

Data driven method to measure efficiencies and fake rates:

- Example: e->γ fake rate
  - ✓ Start with ee, eγ, $\gamma\gamma$ samples (e is tag object, γ is probe object)
  - ✓ After background subtraction, all events in peak are Z->ee
  - ✓ $f_{e\text{-}\gamma} = (N_{e\gamma}+2N_{\gamma\gamma})/2N_{total}$



- Example: tau reco & ID efficiency
  - ✓ Select sample of Z->$\tau\tau$ with $\tau\tau$->$\mu\tau_{had}$ using cuts to suppress background but not the τ ID cuts
  - ✓ $f_{jet\text{-}\tau}=N_{pass}/(N_{pass}+N_{fail})$

b-Jet Reconstruction

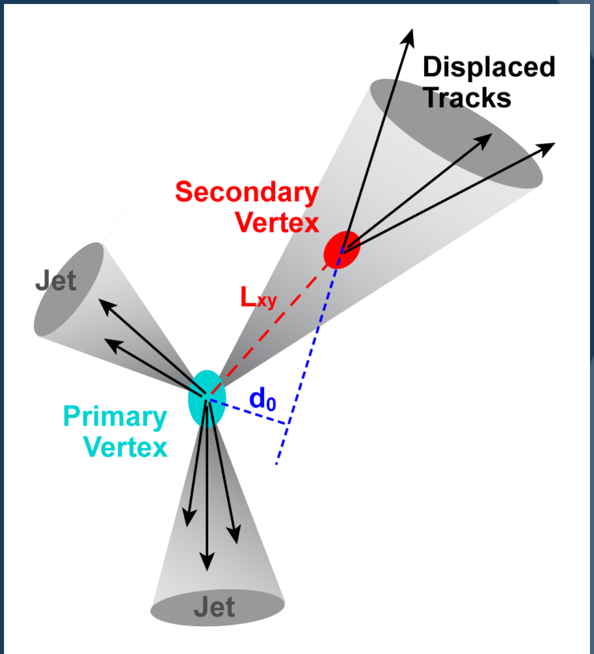
Hadron Colliders: outgoing b-partons evolve into jets

- M_b = 4.2 GeV
- Lifetime ~1.5 psec, 1.8 mm
- Weak decay into $\mu\nu_\mu$ + c-quarks ->μ (20%)

} Displaced decay vertex

Look for displaced tracks & vertices in jets:

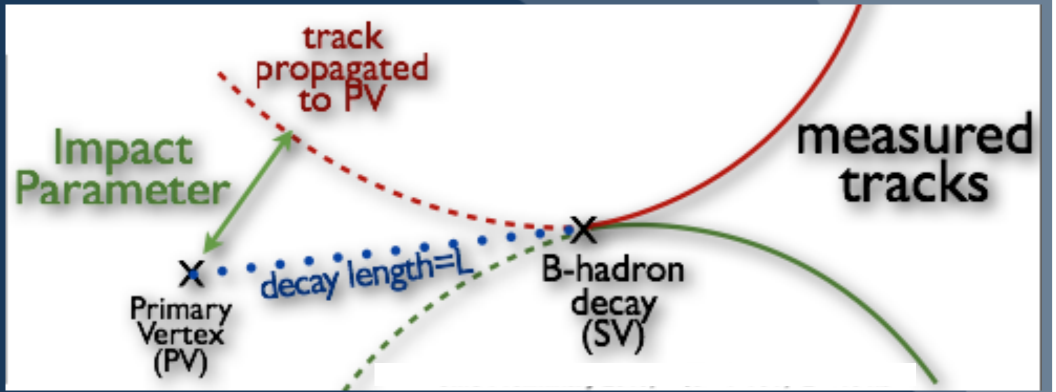
b-jet tagging



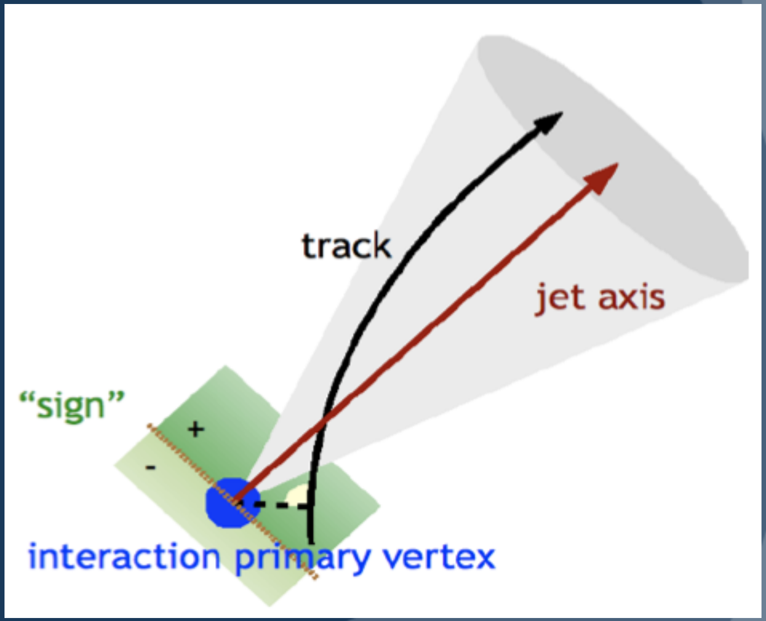
b-tagging: Impact Parameter

Impact Parameter

Closest distance of a track w.r.t. the primary vertex (PV)



- IP sign reflects the lifetime of the particle at PV
  - +: long lived hadron
  - - : detector resolution effect
- IP Significance = IP/σ_{IP}



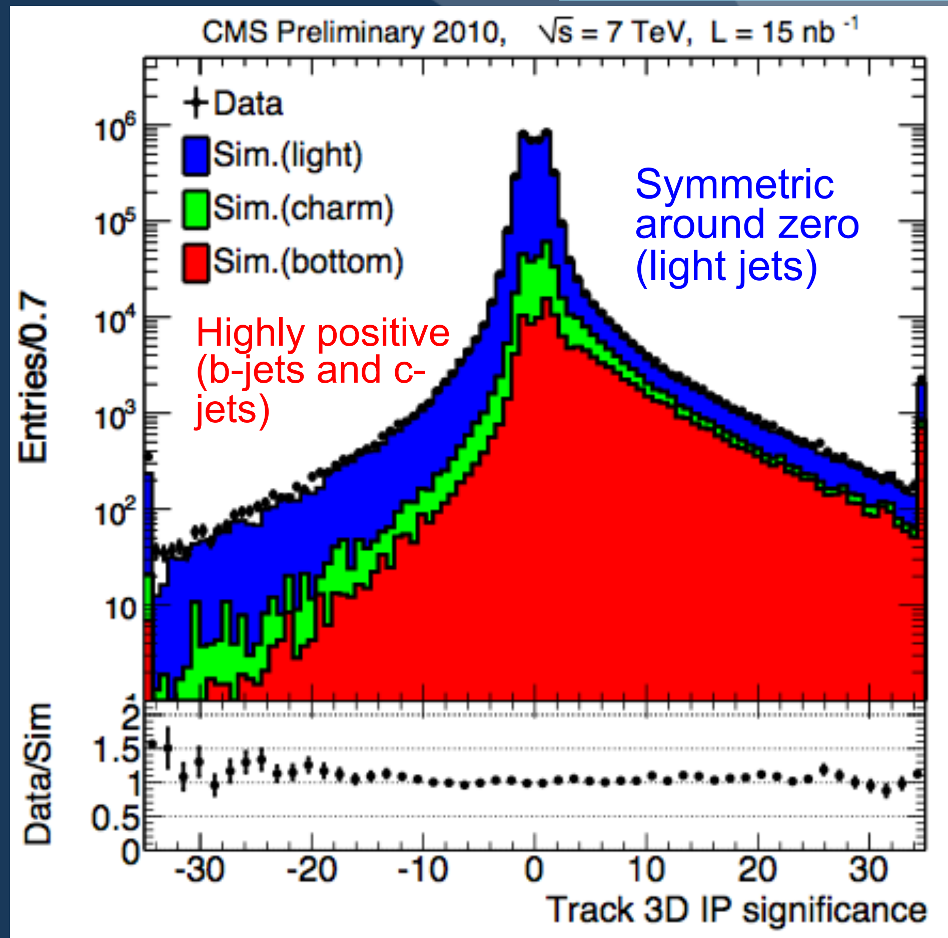
b-tagging: Track Counting

CMS-PAS-BTV-10-001

Track Counting
discriminator (TC)

- #tracks with IP significance > a value "S"
  - 2 for high efficiency (TCHE)
  - 3 for high purity (TCHP)
- Three operating points. "S" selected for acceptance of light jets:
  - 10% (loose)
  - 1% (medium)
  - 0.1% (tight)

  (TCHEL/M/T or TCHPL/M/T)



Excellent Monte Carlo modeling of data

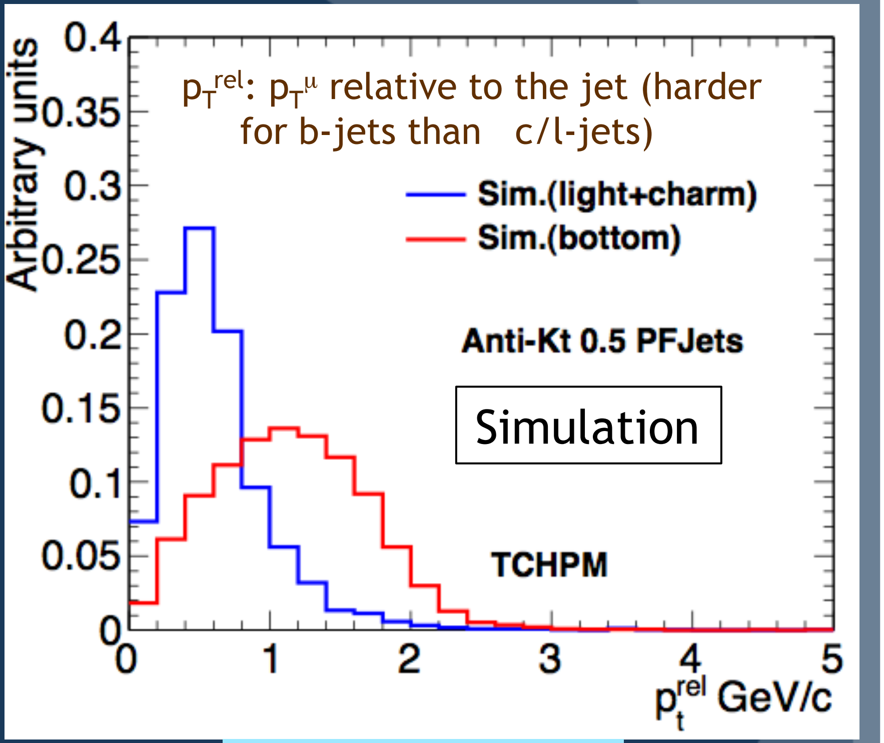
b-tagging: efficiency, fake rate

p_T^{rel} template method on a data sample of μ+jets

- Shapes (templates) for b and non-b jets from MC
- Max. likelihood fit of p_T^{rel} from muon data to a linear combination of *b* and non-*b* jet templates before and after b-tagging

"Data Driven" (DD) technique

$$\epsilon_b^{\text{data}} = \frac{f_b^{\text{tag}} \cdot N_{data}^{\text{tag}}}{f_b^{\text{tag}} \cdot N_{data}^{\text{tag}} + f_b^{\text{untag}} \cdot N_{data}^{\text{untag}}}$$



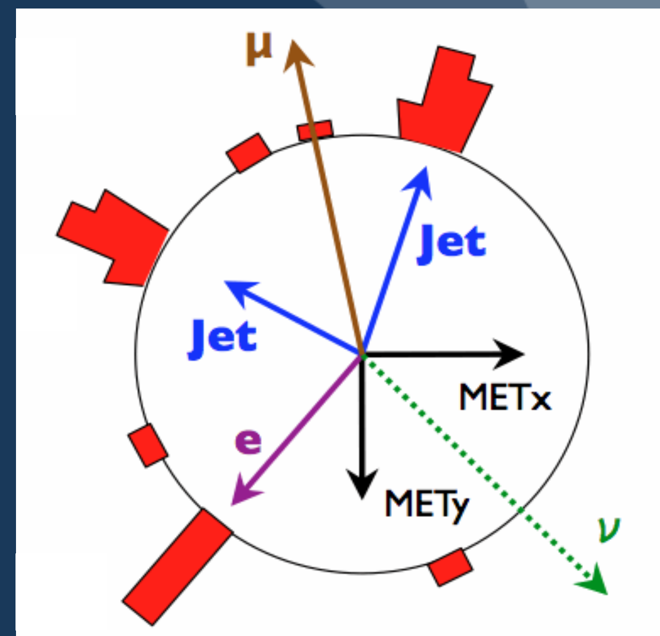
CMS-PAS-BTV-10-001

Efficiencies in the 0.15-0.55 range depending on discriminator and operating point

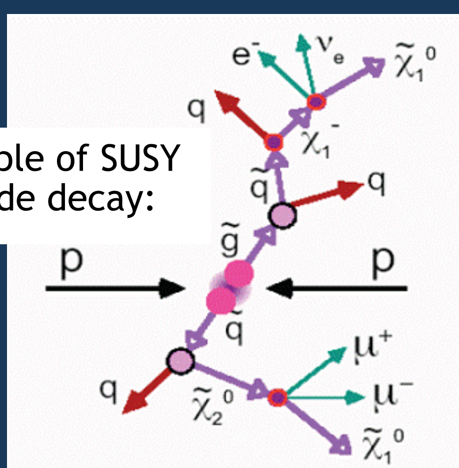
Missing Transverse Energy (MET)

MET indicates non-uniform detector response or the presence of particles that have escaped detection (weak interactions, cracks). MET is a signature for:

- SM particles decaying into neutrinos: Small MET
  - top, W leptonic decays.
- New physics: Large MET
  - Weakly interacting exotic particles in models with extra dimensions: monojets + MET.
  - Production of Lightest SUSY Particles (LSP) in cascade decays, which would go undetected.



Example of SUSY cascade decay:



Experimental Challenges:
- Good low MET resolution.
- Understand high MET tails

Missing Transverse Energy (MET)

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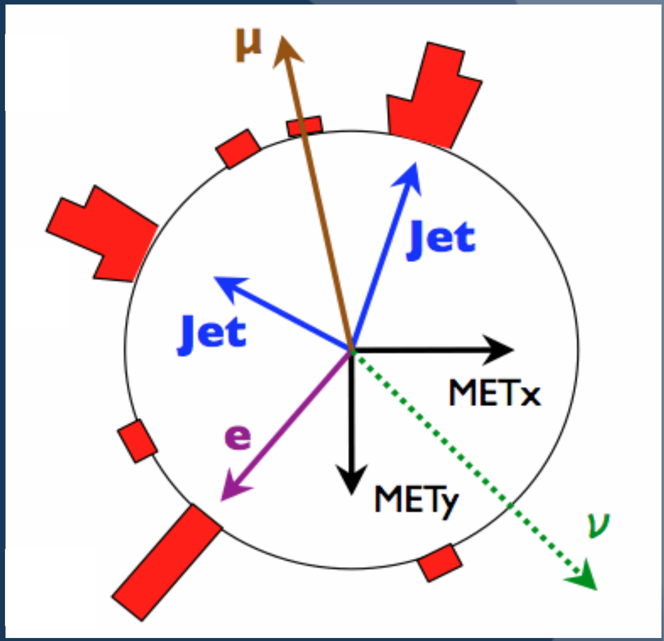
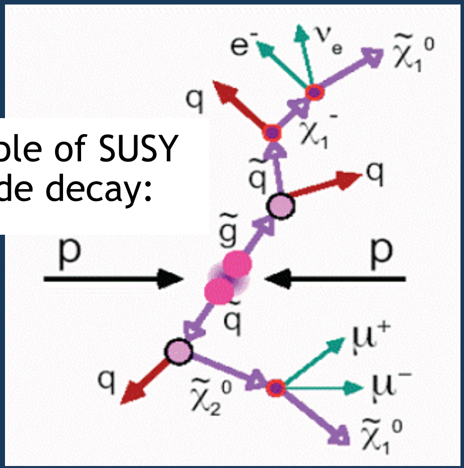


Example of SUSY cascade decay:



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- Good low MET resolution.
- Understand high MET tails
- Is E.T. missing?.

Calorimeter MET (CaloMET)

$$\vec{\not{E}}_T = -\sum_{n:\,\text{CaloTowers}} (E_n \sin\theta_n \cos\phi_n \hat{\mathbf{i}} + E_n \sin\theta_n \sin\phi_n \hat{\mathbf{j}}) = \not{E}_x \hat{\mathbf{i}} + \not{E}_y \hat{\mathbf{j}}$$

- Jet Energy Corrections

$$\vec{\not{E}}_T^{\text{corr}} = \vec{\not{E}}_T - \sum_{i=1}^{\text{N}_{\text{jets}}} \left[\vec{p}_{T_i}^{\,\text{corr}} - \vec{p}_{T_i}^{\,\text{raw}}\right]$$

- Muon Corrections

$$\vec{\not{E}}_T = -\sum_{i=1}^{\text{towers}} \vec{E}_T^{\,i} - \sum^{\text{muons}} \vec{p}_T^{\,\mu} + \sum_{i=1}^{\substack{\text{deposit}\\\text{towers}}} \vec{E}_T^{\,i}$$

- Tau Corrections account for difference in energy scale between hadronic taus and light jets.

- Unclustered energy correction.

Track Corrected CaloMET (tcMET)

- Step 1: Calculate muon corrected Calo MET:

$$
\begin{aligned}
\not{E}_T^{\mu} &= \not{E}_T^{\mathrm{calo}} + \delta \not{E}_T^{\mu}, \\
&= -\sum_{\mathrm{towers}} \vec{E}_T - \sum_{\substack{\mathrm{good} \\ \mathrm{muons}}} \vec{p}_T + \sum_{\substack{\mathrm{good} \\ \mathrm{muons}}} \vec{E}_T^{\mathrm{MIP}}
\end{aligned}
$$

Tracker muon p_T

Calo E deposit (~2 GeV)

- Step 2: Calculate tcMET using hadron tracks:

$$
\begin{aligned}
\not{E}_T^{\mathrm{tc}} &= \not{E}_T^{\mu} + \delta \not{E}_T^{\mathrm{tc}}, \\
&= \not{E}_T^{\mu} + \sum_{\substack{\mathrm{good} \\ \mathrm{tracks}}} \langle \vec{E}_T \rangle - \sum_{\substack{\mathrm{good} \\ \mathrm{tracks}}} \vec{p}_T
\end{aligned}
$$

Expected energy deposited (RF)

Track momentum at vertex

Single pion gun → **track/calo** → **Filter** (• Quality Cuts • Kinematic Cuts) → **(η,p_T)** → **⟨E/p⟩ table**

The pion response function (RF) is measured from data.

Particle Flow MET

- `pfMET` is the transverse momentum vector sum over all reconstructed particles:

$$\vec{\not{E}}_T = - \sum_{\mathbf{particles}} (p_x \hat{\mathbf{i}} + p_y \hat{\mathbf{j}})$$

- The list of reconstructed particles form a global event description, provided by the PF Algorithm:

  $\mu^{\pm}$, $e^{\pm}$, γ, charged hadrons, neutral hadrons, pile-up particles.

- The PF Algorithm exploits full ensemble & redundancy of all CMS detector.

  tracker, ECAL, HCAL, muon system.

MET Performance: Cleaning

Anomalous detector signals causing spurious high MET events

- Beam halo events
- Particles hit Calo photo-multipliers
- Ecal: Particles hit avalanche photo-diodes
- HF: scintillator light in HF light guides, Cherenkov light in PMT windows
- Ecal masked cells (noise or dead)
  - ✓Jet energy artificially low (high MET)

Cleaning procedure based on timing, energy pattern (shape)

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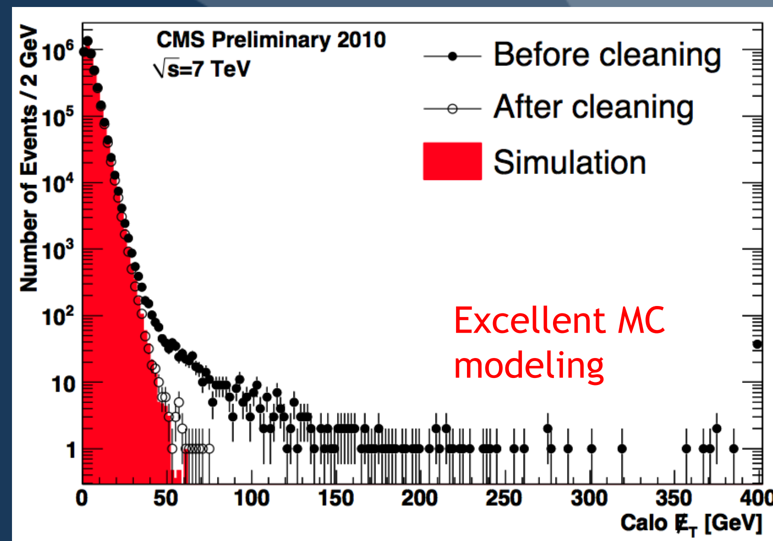
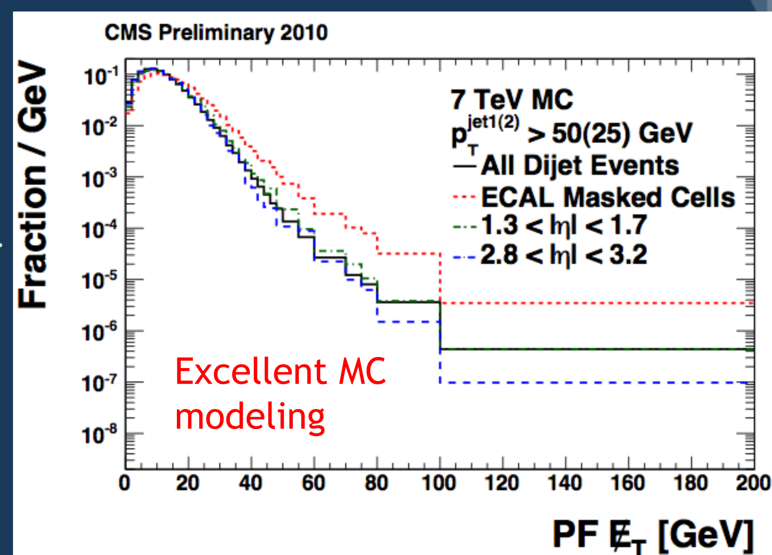




MET Performance: γ/Z+jets

Recoil p_T measured as:

$$\vec{u}_T = \vec{\not{E}}_T + \vec{q}_T$$

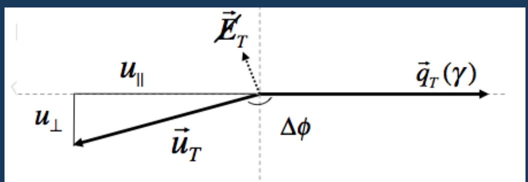
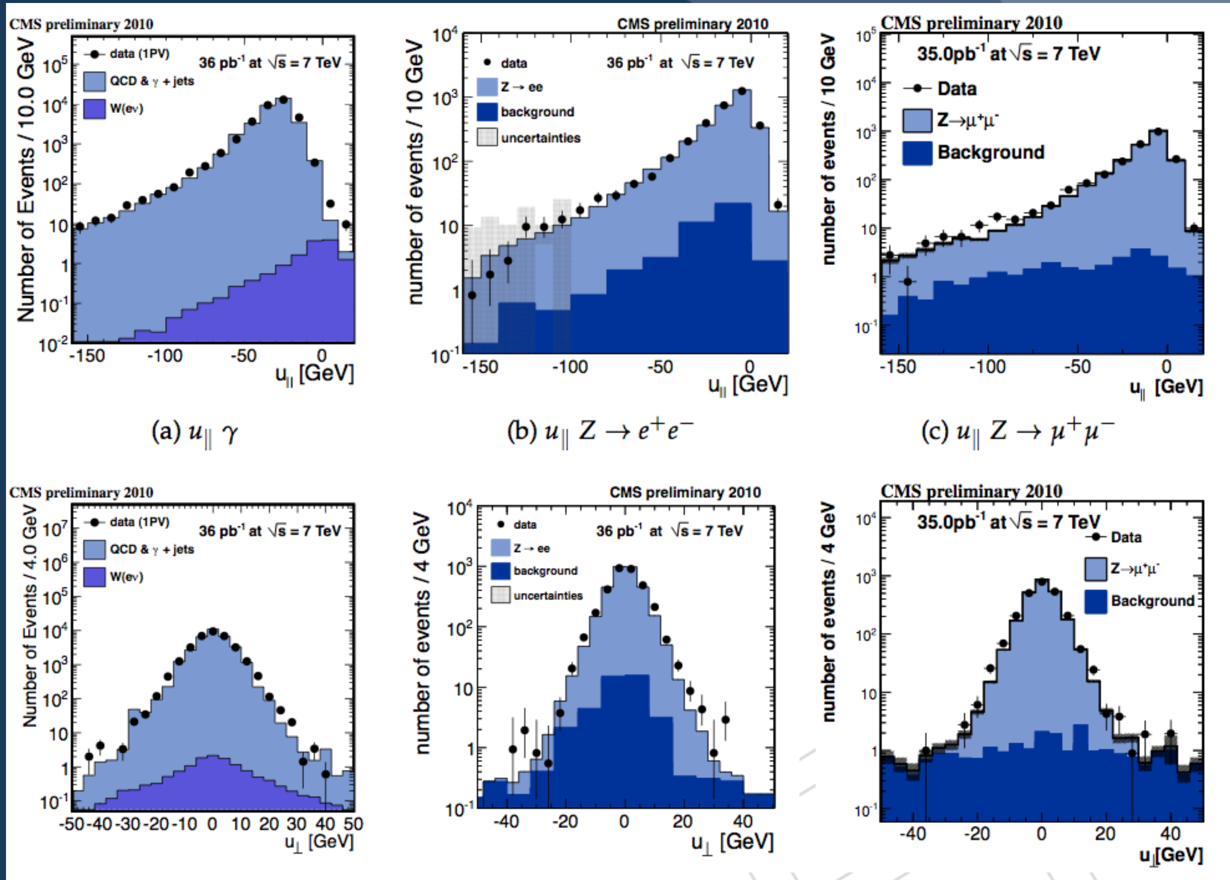


Figure 9: Kinematic definitions for Photon-Jet or Z events

Excellent Monte Carlo modeling of data



(a) $u_{\parallel}$ γ
(b) $u_{\parallel}$ $Z \to e^+e^-$
(c) $u_{\parallel}$ $Z \to \mu^+\mu^-$
(d) $u_{\perp}$ γ
(e) $u_{\perp}$ $Z \to e^+e^-$
(f) $u_{\perp}$ $Z \to \mu^+\mu^-$

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MET Performance: W+jets

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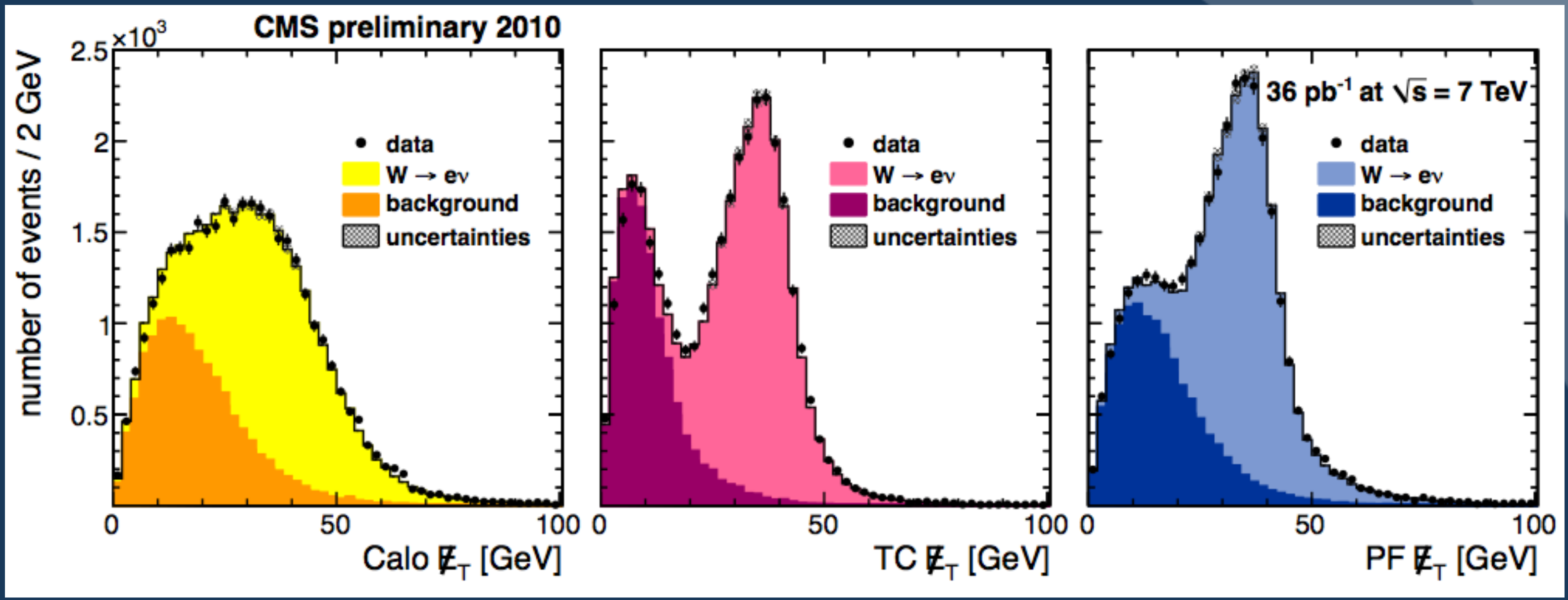
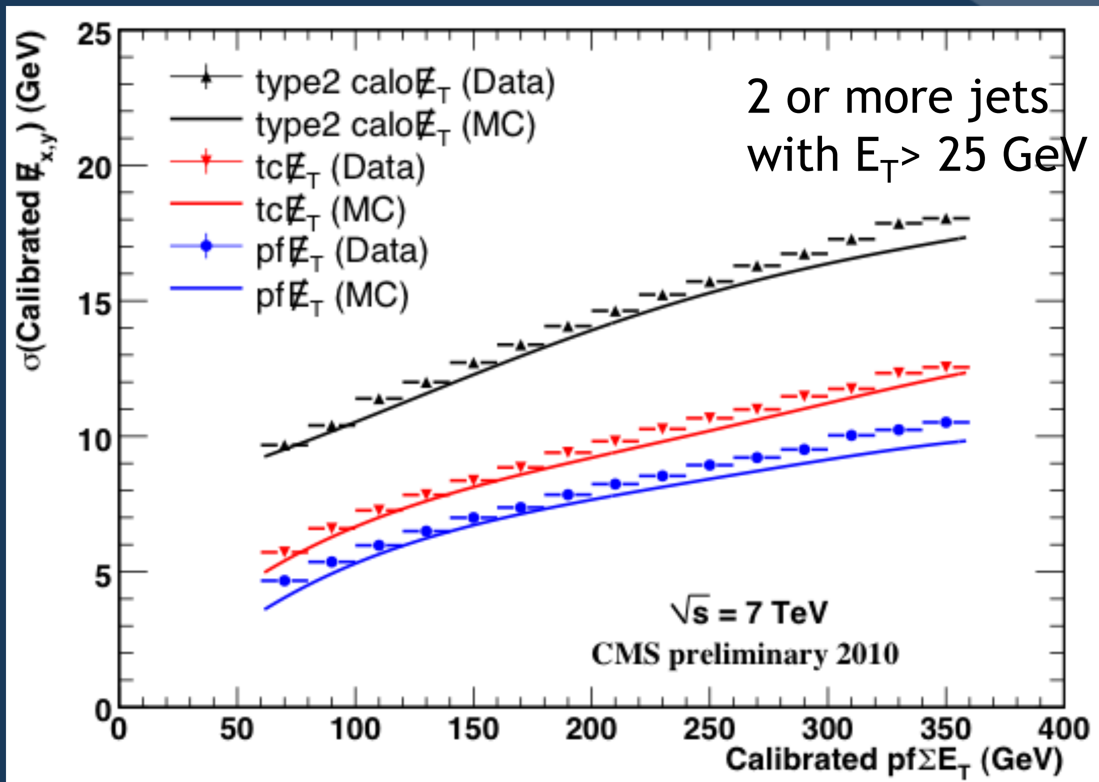


tcMET and pfMET provide better resolution and signal/ background separation

Excellent agreement of simulation with data
Impressive description of SM signal and backgrounds

MET Performance: Multijets



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- Resolution defined as σ of Gaussian fit to $MET_{x,y}$
- tcMET, PF MET improves resolutions significantly: important for SUSY
- PF MET gives the best resolution

MET-like Variables

$$HT = \sum_{i=1}^{Njets} p_T^{jet\,i}$$

HT is the scalar sum of the p_T of the jets in the event. It is the "scale" of the interaction in a fully hadronic event

$$MHT = \sum_{i=1}^{Njets} \vec{p}_T^{\,jet\,i}$$

MHT is exactly an object based MET in a fully hadronic event. Less sensitive noise than CaloMET

$$M_{EFF} = MET + \sum_{i=1}^{Njets} p_T^{jet\,i} + \sum_{i=1}^{Nleptons} p_T^{lepton\,i}$$

Effective Mass representing the scale (invariant mass) of the primarily produced SUSY pair

$$m_{T2}(\vec{p}_T^{(1)}, \vec{p}_T^{(2)}, \not{\vec{p}}_T) \equiv \min_{\vec{q}_T^{(1)} + \vec{q}_T^{(2)} = E_T^{miss}} \{\max(m_T(\vec{p}_T^{(1)}, \vec{q}_T^{(1)}), m_T(\vec{p}_T^{(2)}, \vec{q}_T^{(2)}))\}$$

MT2 represents the scale of the SUSY particle

SUSY searches are based on different variables defined to enhance signal and reduce backgrounds

In addition to MET, MHT, MEFF, MT2, we will define more complex variables such as α_T, Razor at a later stage