SEARCH FOR HEAVY RESONANCES DECAYING TO τ'S IN 7 TEV PROTON-PROTON COLLISIONS AT THE LARGE HADRON COLLIDER

A Dissertation

by

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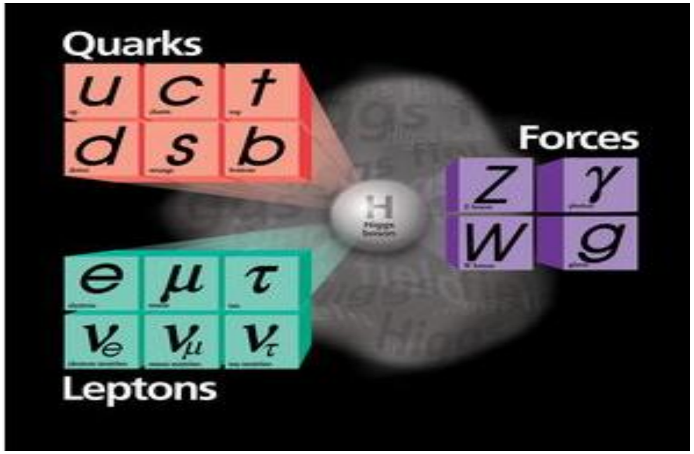
Major Subject: Physics

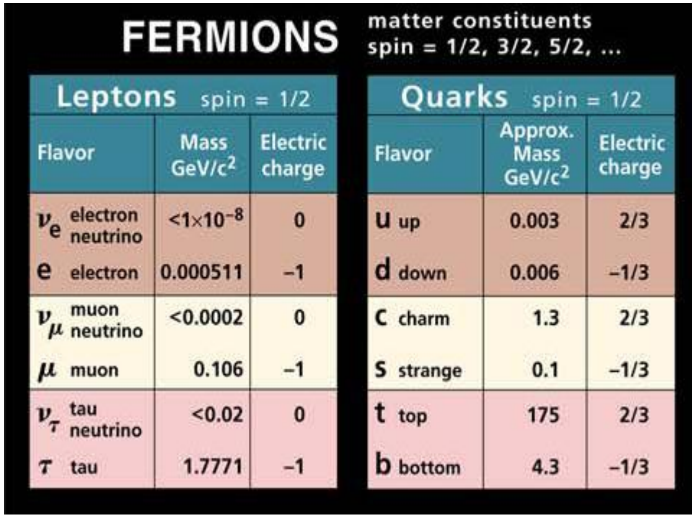
Outline

- The Standard Model
- Importance of Taus
- Electroweak Symmetry Breaking
- Heavy Resonances Decaying to Taus
- The Large Hadron Collider and CMS Detector
- Taus and Hadronic Jets
- Tau Reconstruction and Identification
- Muon Reconstruction and Identification
- DiTau Mass Reconstruction and MET
- Topological Selections
- Background Extraction
- Results
- Summary

Basics of the Standard Model (SM)

- Matter is composed of fermions
  - Spin ½ particles
  - Leptons
    - Electric charge (electroweak interactions)
  - Quarks
    - Electric & color charge (strong interactions)
- Bosons – mediate forces
  - Integer spin particles
  - γ – electromagnetic interactions
  - Z/W – weak interactions
  - Gluon (g) – strong interactions
- Other particles are made up of these fundamental particles
- Higgs boson
  - $\longrightarrow$ massive gauge bosons (next slides)



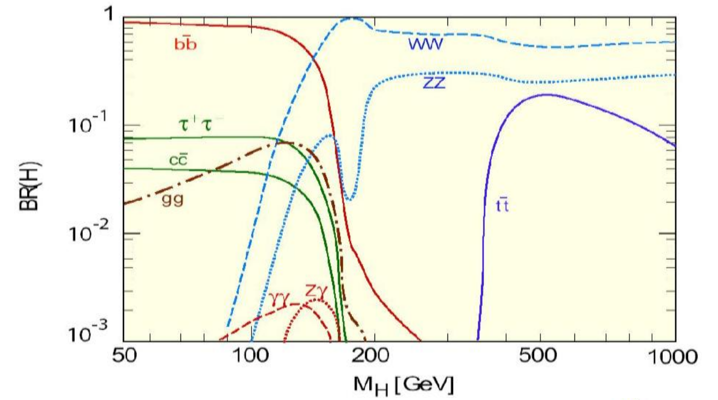


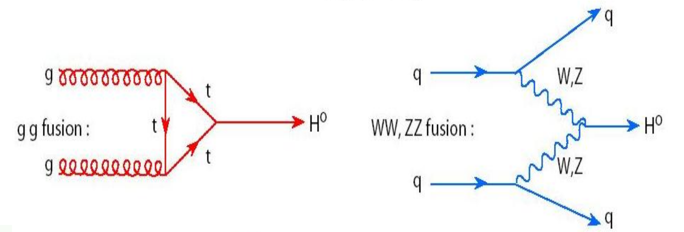
FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

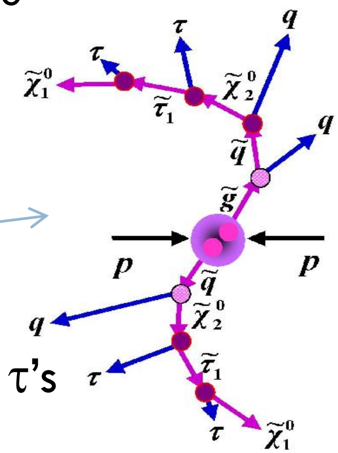
Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_e electron neutrino	<1×10^{-8}	0	u up	0.003	2/3
e electron	0.000511	−1	d down	0.006	−1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	−1	s strange	0.1	−1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	−1	b bottom	4.3	−1/3

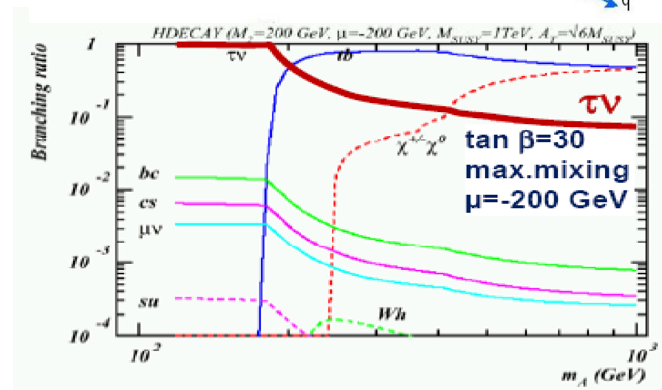
The Importance of Taus (Motivation)

- SM Higgs decaying τ's become extremely important for light Higgs (mass < 150 GeV)
  - Final states w/ b-jets can become difficult
    - large multi-jet background & low mass resolution of the b-jet system
  - It becomes important to search for the Higgs in final states w/ τ's
- MSSM charged Higgs
  - Decays to τ's dominate for large range of masses
- Dark Matter Searches
  - Several BSM theories naturally give rise to cold dark matter candidates
  - Example: mSUGRA (high tanβ)
  - More to follow
- Heavy Gauge Bosons decaying to τ's
  - More later









Electroweak Symmetry Breaking

- The Standard Model is a theory based on *local gauge invariance*
  - Fields and interactions are invariant under certain transformations
  - e.g. invariance under phase transformations, invariance under rotations
- $U(1)_{EM}$ gauge group describes the electromagnetic interaction
- SU(2) gauge group describes the weak interaction
  - The symmetry alone dictates three massless gauge bosons
  - Problem: W/Z are massive!
    - ***Broken Symmetry***
- Weinberg et al. unify the weak and electromagnetic interactions: SU(2)xU(1)
- Higgs field is introduced to account for the broken symmetry

Electroweak Symmetry Breaking

- Broken symmetry occurs in the vacuum state, not the interaction

$$l = \left(\partial_\mu \phi\right)^+ \left(\partial^\mu \phi\right) - \mu^2 \phi^+ \phi - \lambda\left(\phi^+ \phi\right)^2$$

- Minimizing the Lagrangian, one gets $\phi^+ \phi = -\frac{\mu^2}{2\lambda} = \frac{\nu^2}{2}$
- Two stable minimums (scale of the symmetry breaking): $+\nu, -\nu$
- Break the symmetry by choosing a specific direction for the field

$$\phi^0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu \end{pmatrix}$$

- Expand around the minimum to find the excited states (particles):

$$\phi^0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + H(x) \end{pmatrix} \Rightarrow \text{e.g.} M_W = \frac{\nu}{2} g$$

- What happens if we include additional gauge groups?
  - ***New gauge bosons predicted in many extensions of the SM designed to answer many open physics questions!***

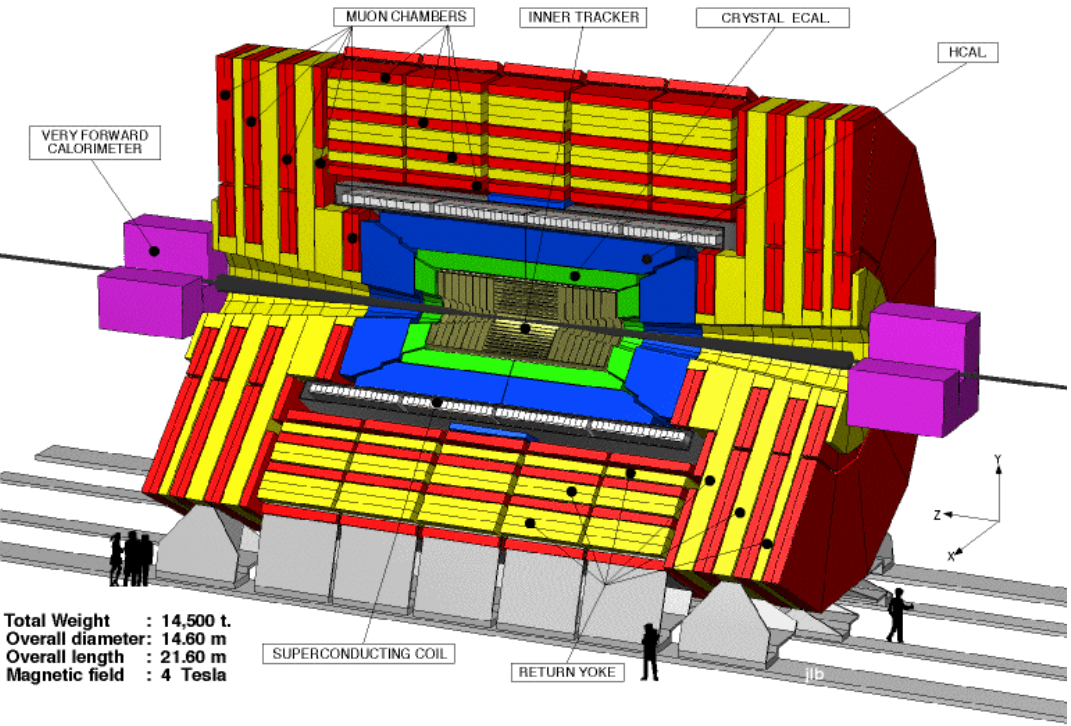
Heavy Resonances Decaying to τ's

- Standard Model Higgs *H* is one of the most interesting heavy gauge bosons that can be discovered in $\tau\tau$ final states
- Pseudoscalar Higgs *A* in minimal supersymmetric extensions of the SM (MSSM) most likely to be discovered via $\tau\tau$ decay modes
- *Z'* bosons refer to hypothetical new gauge bosons that arise from extensions of the Standard Model
  - e.g. U(1) extensions with SM couplings are the simplest
  - CDF excluded a sequential Z' with SM couplings having a mass < 399 GeV/c^2
- Perform a direct search for new hypothetical massive particles decaying to a pair of τ leptons $X \rightarrow \tau\tau$
  - Use sequential Z' as a benchmark
  - Models where new heavy gauge bosons X have enhanced couplings to taus present the opportunity for discovery
  - Models where X has SM like couplings more likely to be first discovered in ee or $\mu\mu$, but $\tau\tau$ mode search remains important universality of the couplings.

The Large Hadron Collider

- ❑ Protons are accelerated to velocites close to the speed of light!
  - ❑ Designed to collide particles to center of mass energy of 14 TeV (7/beam)
- ❑ *The LHC is expected "re-discover" the SM, Symmetry Breaking, and probe physics BSM*

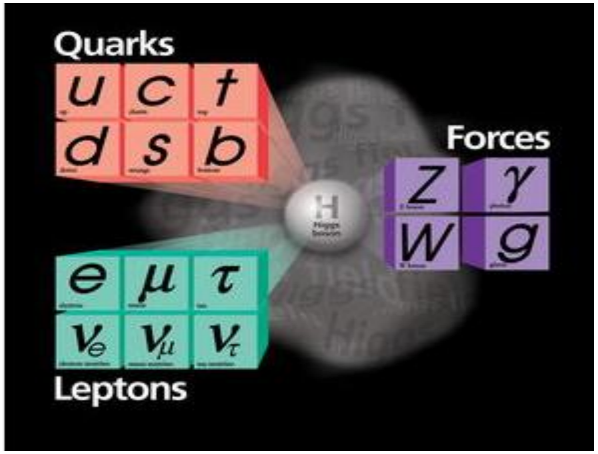
Compact Muon Solenoid Detector



- Solenoid Magnet
  - 4 T strength for the precise measurement of particle momentum
- Inner Tracker System
  - Pixel detector starts at ~ 4cm
  - Outer silicon tracker ends at ~ 1m
  - Tracks the trajectory of charged particles
- Electromagnetic Calorimeter (Ecal)
  - Lead Tungstate chrystals
  - Designed to detect e's and γ's
- Hadron Calorimeter (Hcal)
  - Brass and steel material sampled in with scintillators
  - Designed to detect hadrons
- Muon System
  - Gas detectors

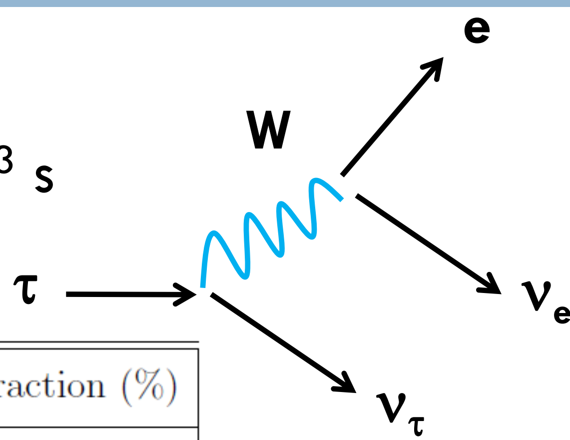
Goals of CMS

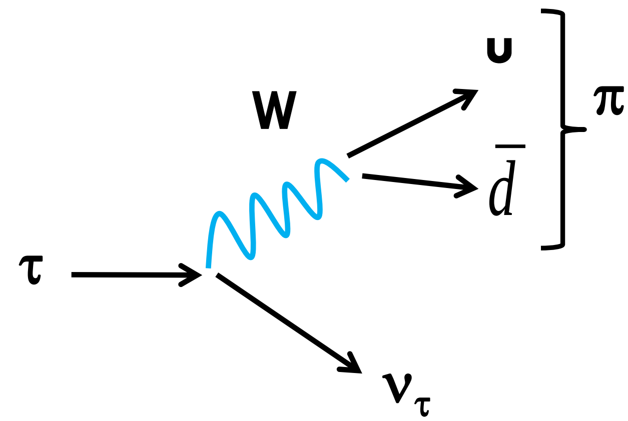
- "Rediscover" the Standard Model (SM)
  - Confirm the "old" and set precise benchmarks for determining whether new phenomena is indeed new
- Electroweak Symmetry Breaking (ESB)
  - γ's have zero mass while the Z/W have non-zero mass (need something to account for the broken "symmetry")
  - Searching for the Higgs Boson
- Physics Beyond the Standard Model (BSM)
  - Is the SM incomplete?
  - Are there undiscovered forces of nature?
  - Do more particles exist? Why?
  - What is dark matter?
  - Is there a "theory of everything"?



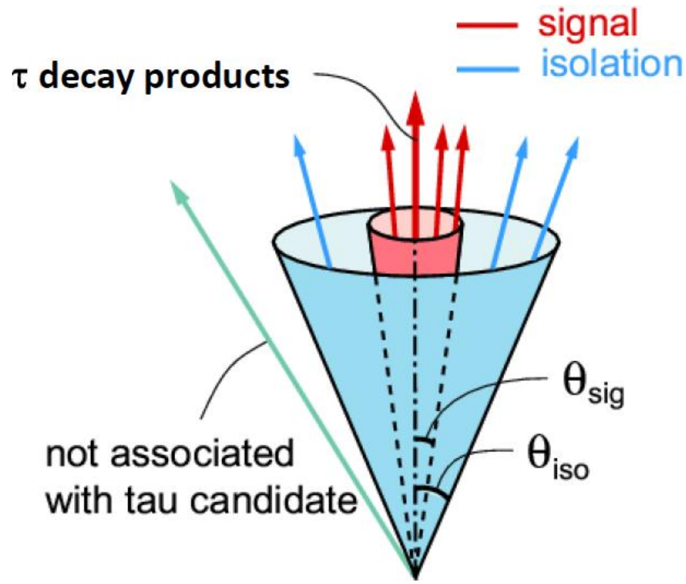
Basic Properties of the Tau

- Mass ~ 1.8 GeV/c^2
- Lifetime = 2.9 x 10^{-13} s
  - cτ ~ 87 μm



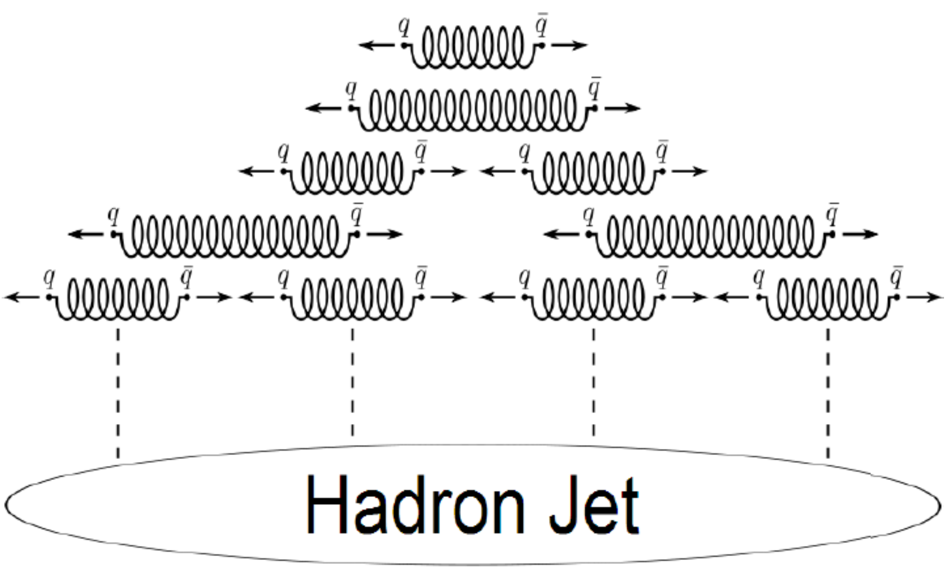


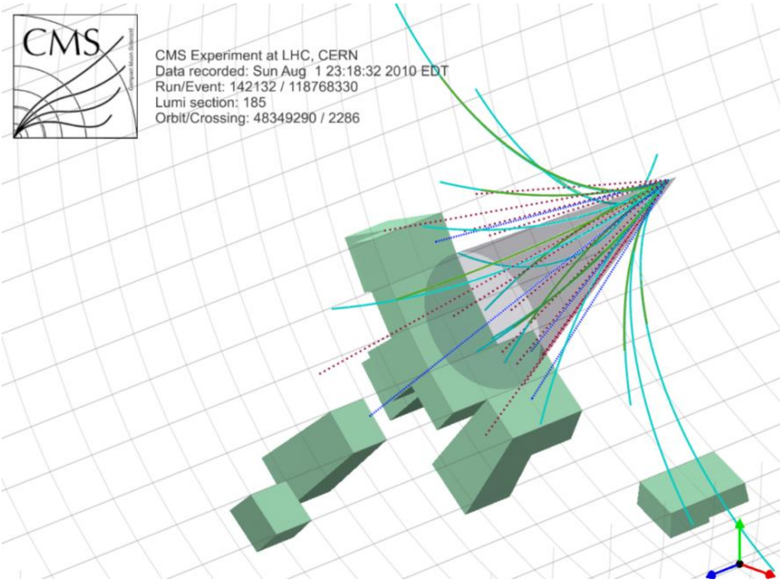
Decay Mode	Branching Fraction (%)
$\tau^\pm \to e^\pm \nu_e \nu_\tau$	17.8
$\tau^\pm \to \mu^\pm \nu_\mu \nu_\tau$	17.4
$\tau^\pm \to \pi^\pm \nu_\tau$	11.1
$\tau^\pm \to \pi^\pm \pi^0 \nu_\tau$	25.4
$\tau^\pm \to \pi^\pm \pi^0 \pi^0 \nu_\tau$	9.2
$\tau^\pm \to \pi^\pm \pi^0 \pi^0 \pi^0 \nu_\tau$	1.1
$\tau^\pm \to \pi^\pm \pi^\pm \pi^\mp \nu_\tau$	9.5
$\tau^\pm \to \pi^\pm \pi^\pm \pi^\mp \pi^0 \nu_\tau$	4.4



Hadronic Jets

- Strong force – no asymptotic freedom → quarks can't exist as free particles
- Strength varies as ~ r → as quarks are pulled apart, becomes preferable to create quark-antiquark pairs until color field no longer has sufficient energy
  - Collimated "spray" of hadrons

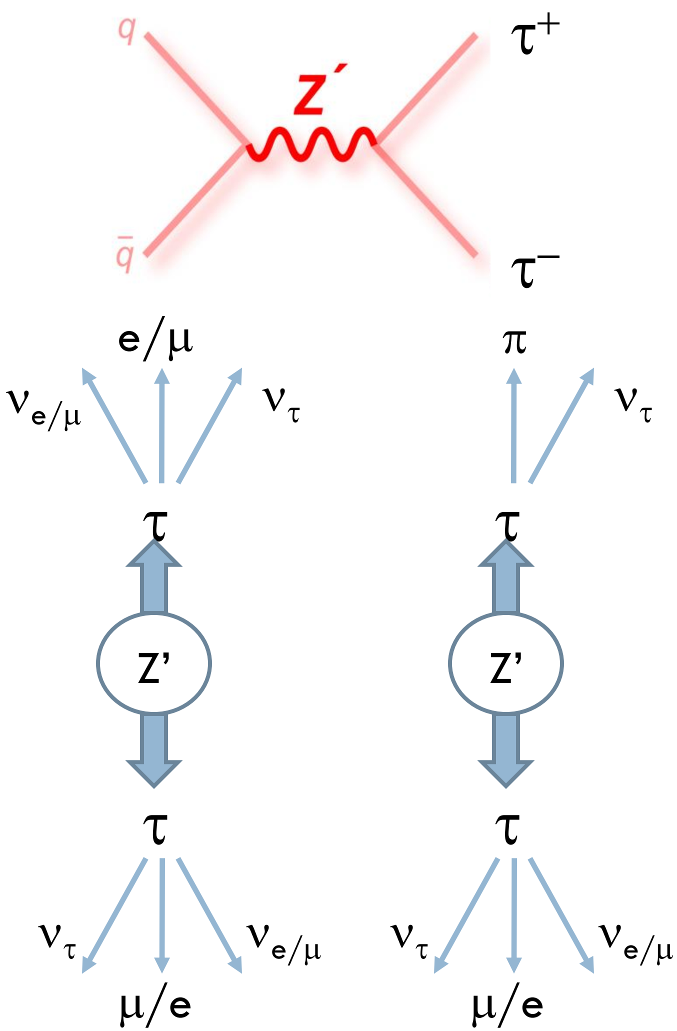




Experimental Challenges for Taus

- Resolution for primary vertex construction ~ 10-100 μm
  - Tau lifetime $c\tau$ ~ 87μm → can't distinguish leptonic tau decays from direct production of electrons and muons.
  - Tau identification limited to the identification of hadronic decays
    - Lose ~ 35% of phase space
- Hadronically decaying taus lose ½ of their energy to neutrinos
  - Reduces the possibility of successful discrimination against jets
  - Cannot produce narrow $\tau\tau$ mass peak
- Difficult to discriminate against hadronic jets
  - Similar composition – hadrons
  - Produced with cross-sections ~ 10^6 larger
- In general, physics with taus among the most difficult

A Look at the $X \to \tau\tau$ Final State

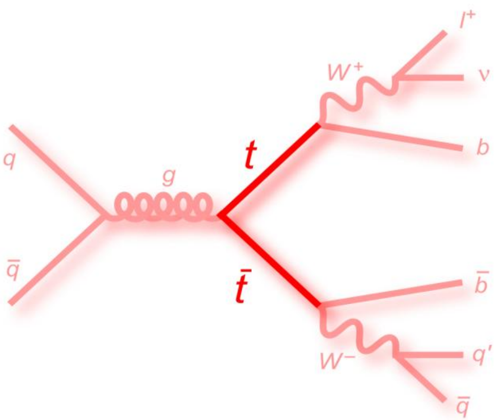


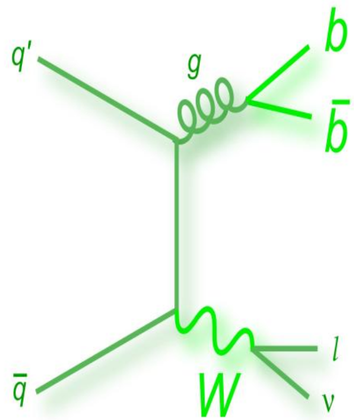
- Properties
  - $\tau\tau$ are nearly back-to-back in ϕ
  - $\tau\tau$ pairs are oppositely charged
  - $j \to \mu \sim 10^{-4}$–10^{-3}, $j \to e \sim 10^{-3}$–10^{-2}, $j \to \tau \sim 10^{-2}$–10^{-1}
  - $\tau\tau$ mass does not have a narrow mass resonance
  - Large momentum imbalance due to the mass of the Z'
    - M(Z') ~ 500 $\longrightarrow$ E_ν ~ 100 GeV

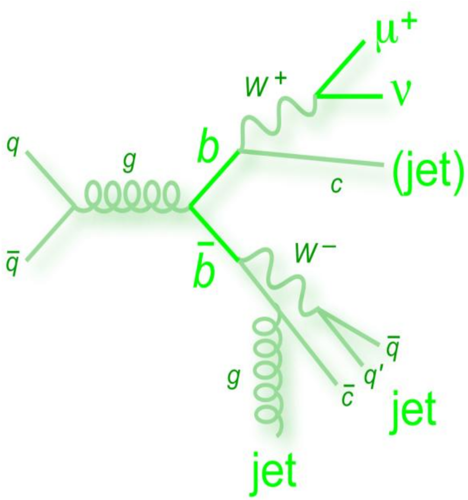
Final State	Branching Ratio (%)
$\tau\tau \to \mu\mu$	3.1
$\tau\tau \to ee$	3.1
$\tau\tau \to e\mu$	6.2
$\tau\tau \to e\tau_h$	23.1
$\tau\tau \to \mu\tau_h$	22.5
$\tau\tau \to \tau_h\tau_h$	42.0

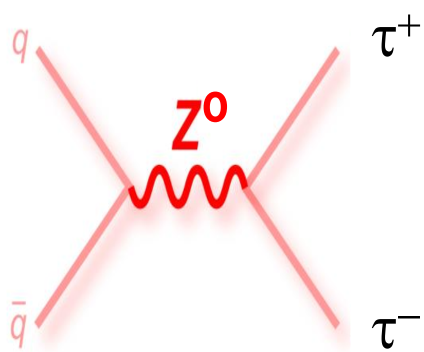
This analysis makes use of the $\mu\tau_h$ final state!

Possible Backgrounds





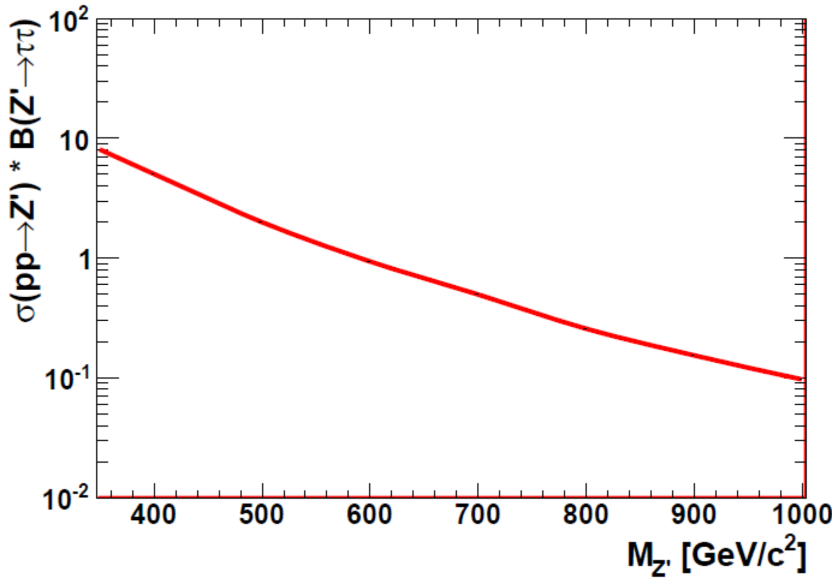




- Properties
  - $Z \to \tau\tau$: negligible in high mass region
    - Similar to our Z' final state
    - Serves as our control region since we want to show we can identify taus
  - W+jets : isolated lepton combined with a non-isolated lepton or jet
    - Clean muon from W
    - Jet fakes the tau
  - TTBar : isolated leptons combined with high multiplicity of jets
    - Clean muon and/or tau from W's
    - jets from W fakes tau
  - QCD : non-isolated jets
    - Non-prompt muon from b jet
    - Jet fakes tau

Rates and Cross-Sections

Sample	σ x Filter Efficiency
$Z'(500) \to \tau\tau$	1.94 pb
$Z \to \tau\tau$	1653 pb
$Z \to \mu\mu$	1653 pb
W + Jets	29349 pb
Incl. $\mu(10)$	349988 pb
$t\bar{t}$	149.6 pb



$$N_{QCD} \sim \sigma_{QCD} \times L \sim 10^7$$

$$N_{W+jets} \sim \sigma_{W+jets} \times L \sim 10^6$$

$$N_{Z^0\to\tau\tau} \sim \sigma_{Z^0\to\tau\tau} \times L \sim 10^4 - 10^5$$

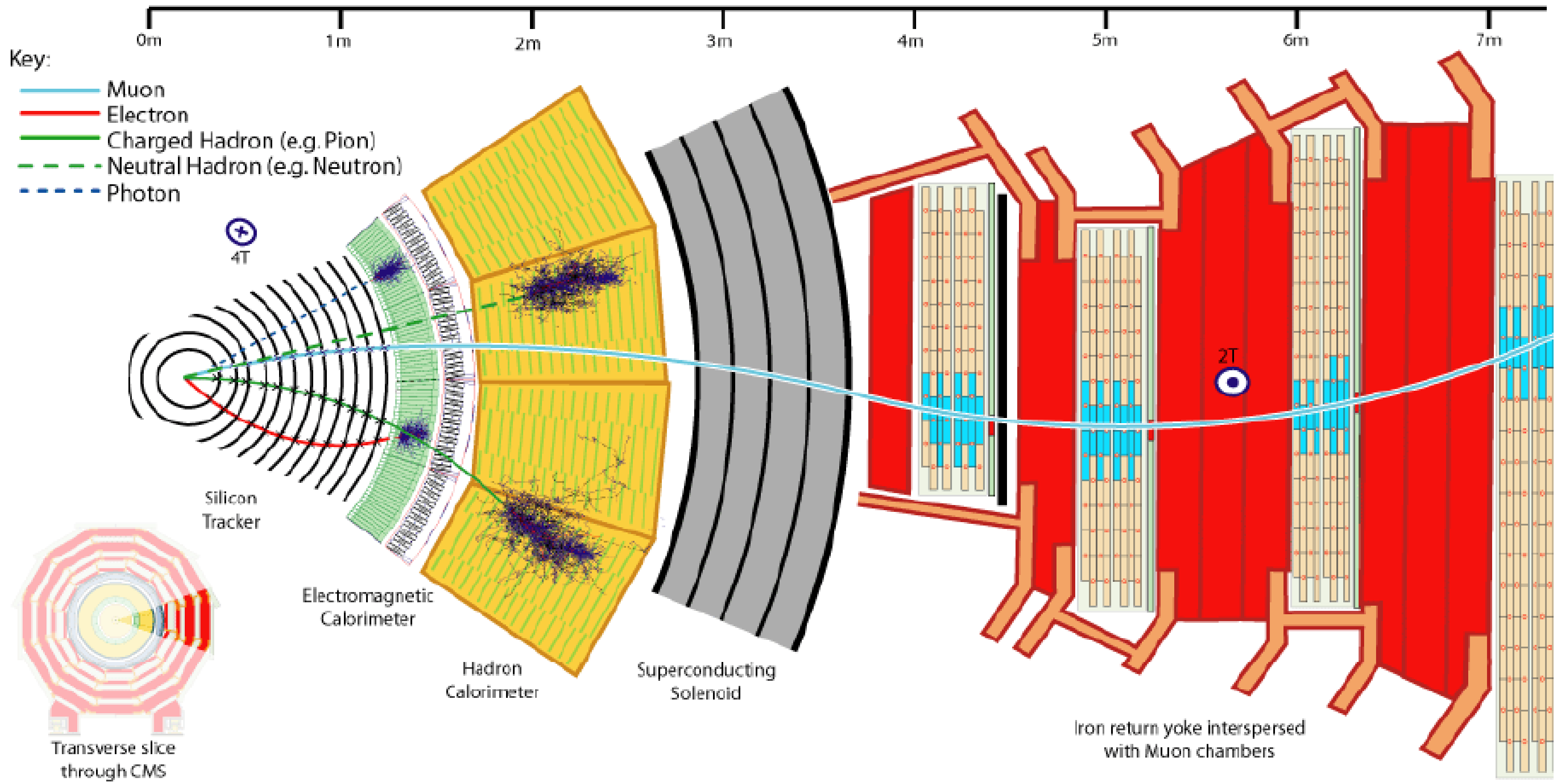
$$\boxed{N_{Z'\to\tau\tau} \sim \sigma_{Z'\to\tau\tau} \times L \sim 10^2}$$

Backgrounds need to be reduced by ~ 10^{-6}-10^{-7} while maintaining a signal efficiency of ~ 10%

Search Strategy

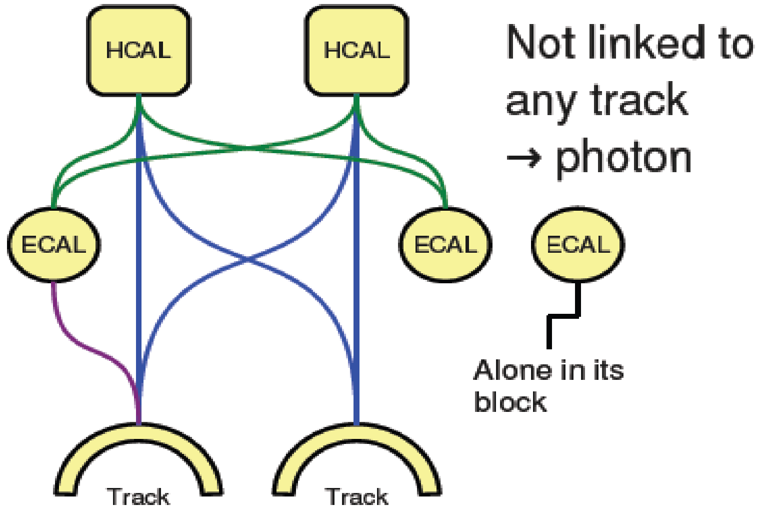
- Search $X \rightarrow \tau\tau$ in $\mu\tau_h$ final state: ~10^2 larger QCD reduction than $\tau_h\tau_h$
- Select *isolated objects*: define some tau/muon region and then require minimal energy surrounding it (exact definitions later)
- Select $\mu\tau_h$ pairs that are nearly back-to-back and oppositely charged
- Heavy gauge bosons → large momentum imbalance: require MET
- Use the measurement of MET to improve $\tau\tau$ mass reconstruction
- Cuts need to be chosen to preserve the $Z \rightarrow \tau\tau$ control region.
  - Ideal scenario: look in the high mass region (e.g. $M > 250$) to find mostly Z'/H/A/X events and look in the low mass region (e.g. $M < 150$) to find mostly Z
  - Ensures robustness of the analysis and confidence in ability to identify taus
- Choose the selections so that we obtain a relatively clean signal, while minimizing the systematic effects

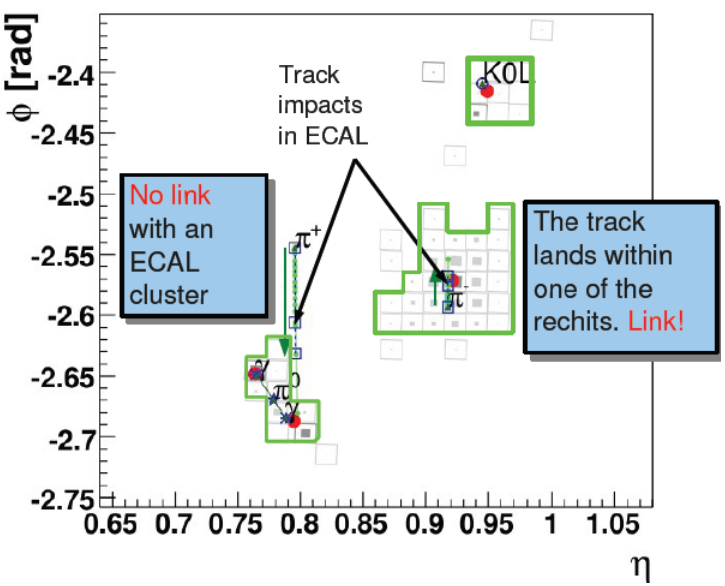
Particle Flow Algorithm



Particle Flow reconstruction takes advantage of all subdetectors to reconstruct particles.

Particle Flow Algorithm





- **For each hcal:**
  - if calorimeter energy is bigger than the track momentum:
    - create a charged hadron and one additional photon or neutral hadron
  - if not:
    - simply consider the calorimeter deposit as derived from the energy deposition of the charged hadron

- if the excess is bigger than the Ecal only energy:
  - both a photon (taking all the Ecal energy) and a neutral hadron (with the remaining excess) are created
    - each of them with the proper calibration applied
- if the excess is less than the Ecal only energy:
  - only a photon is created

Tau Reconstruction

- Taus decay immediately after being produced → taus must be inferred from particle signatures in the detector (use particle flow objects as starting point for tau reconstruction).
- Taus are very collimated … but how do we quantify it?
  - First need to choose a proper metric.
  - Need to consider both the ***ability to identify taus with high efficiency*** while also achieving significant ***rejection against hadronic jets***.
  - How does the level of collimation evolve with increasing energies?
- Region used to define the tau constituents needs to be large enough to contain all tau decay products, but small enough to reject a large fraction of QCD jets.

Tau Reconstruction

Consider a particle under boost b along z. The 4-momentum transforms as

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \gamma & \beta\gamma \\ 0 & 0 & \beta\gamma & \gamma \end{pmatrix} \begin{pmatrix} \mathrm{p}_x \\ \mathrm{p}_y \\ \mathrm{p}_z \\ \mathrm{E} \end{pmatrix} = \begin{pmatrix} \mathrm{p}_x \\ \mathrm{p}_y \\ \gamma(p_z + \beta E) \\ \gamma(\beta p_z + E) \end{pmatrix}$$

The rapidity of the particle can be defined as $y = \frac{1}{2} ln \frac{E + p_z}{E - p_z}$

and transforms as $y \rightarrow y + \tanh^{-1}\beta$

For p >> m, then $p_z/E \sim p_z/p = \cos\theta$. This implies that $y \sim \eta$

$$\Delta\phi = \phi_1 - \phi_2 \rightarrow \phi_1 - \phi_2 = \Delta\phi$$

$$\Delta\eta = \eta_1 - \eta_2 \rightarrow (\eta_1 + \tanh^{-1}\beta_1) - (\eta_2 + \tanh^{-1}\beta_2) \sim \Delta\eta$$

Given the E_T of a jet, the boost factor along the z direction plays a negligible affect on the determination of jet shape variables.

Tau Reconstruction

Problem: Don't know the energy of the tau unless we have defined the tau region!

How do we define the tau region? Consider a pure kinematic argument for the decay of a tau to a neutrino and a charged hadron ($\tau \rightarrow \nu\pi$). The momenta of the tau decay products in the tau rest frame are given by

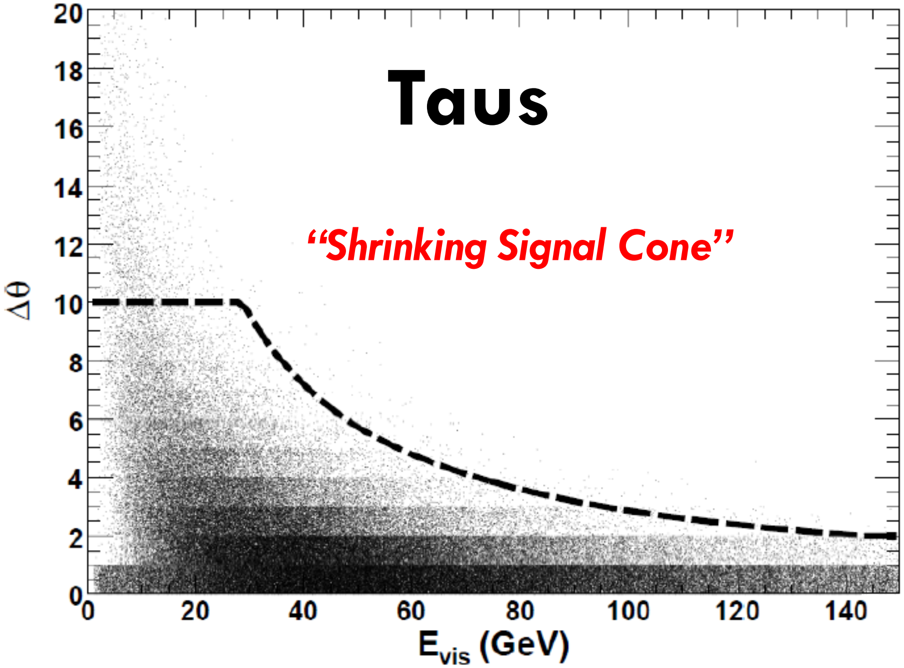
$$P_{\nu_\tau} = \frac{m_\tau}{2}(0, \sin\theta^*, \cos\theta^*, 1)$$
$$P_{\pi^-} = \frac{m_\tau}{2}(0, \text{-}\sin\theta^*, \text{-}\cos\theta^*, 1)$$

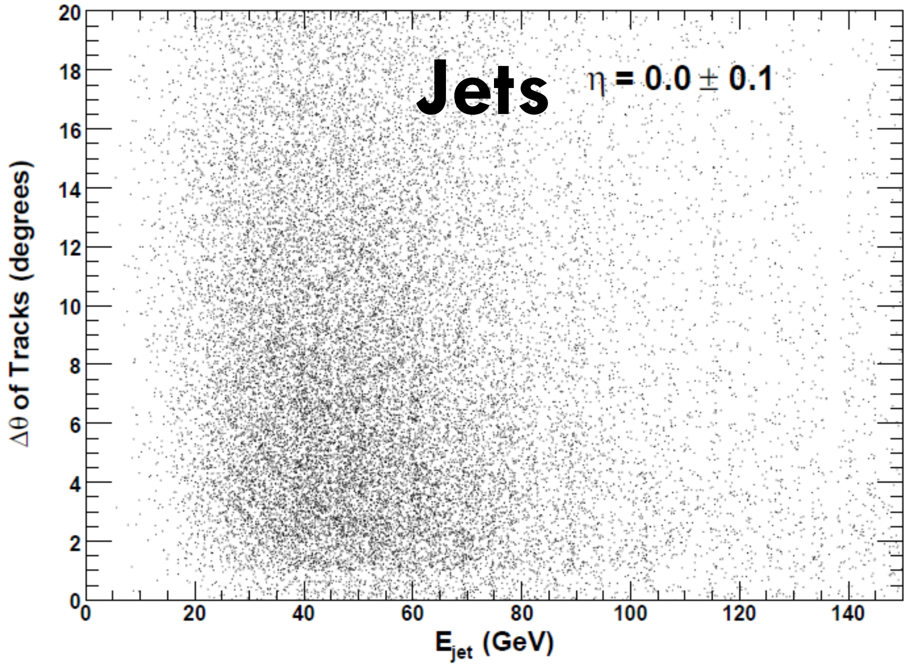
Transforming to lab frame yields $\alpha = \arccos\left(\frac{p_\tau^2 \sin^2\theta^* - m_\tau^2}{p_\tau^2 \sin^2\theta^* + m_\tau^2}\right)$

for the angle between the decay products

The decay angles between tau constituents are energy dependent

Tau Reconstruction



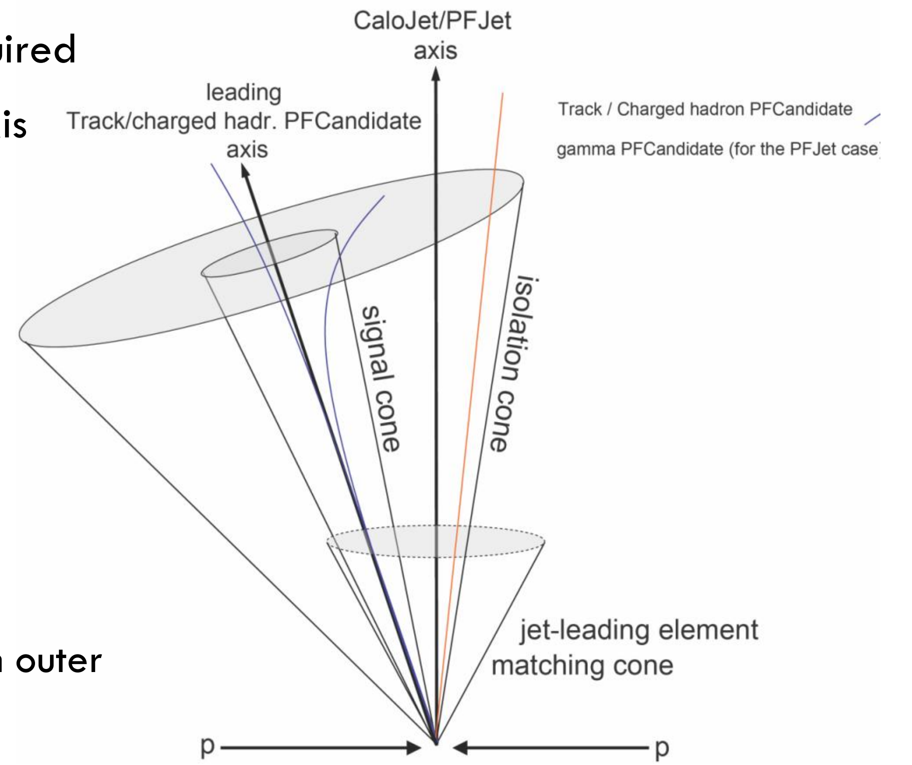


Tau constituents are defined by using an energy dependent "shrinking cone" in order to maintain the tau region as small as possible for all values of energy.

Any jet rejection variables are obtained by defining enclosing "jet constituents" using a fixed region in η–ϕ space.

Standard Tau Identification Cones

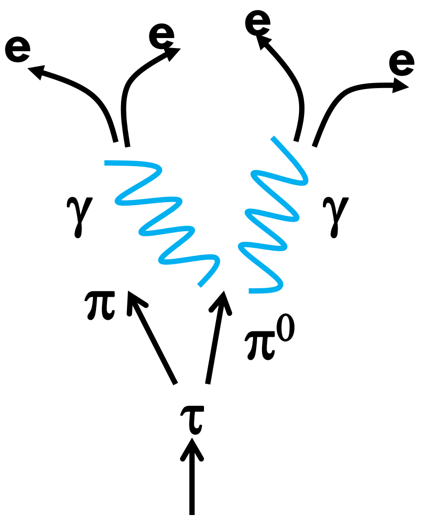
- Definition: Seed track – highest P_T track
  - For τ jets, a seed track (w/ P_T > X) is required within some matching cone from the jet axis
- Track signal cone
  - Defined relative to the seed track
  - Signal cone/annulus
    - ΔR = "5.0/ET" with max ΔR=0.15 and min ΔR=0.07
- Track isolation annulus
  - Region between the track signal cone and an outer isolation cone
  - Tracker isolation cones: ΔR=0.5

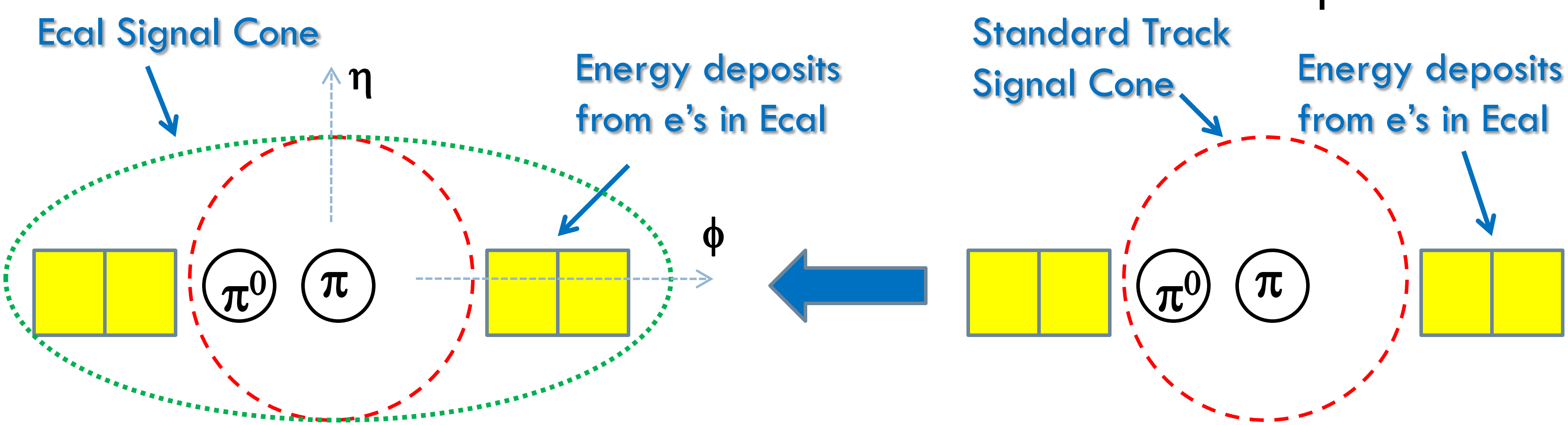


Standard Tau Identification Cones

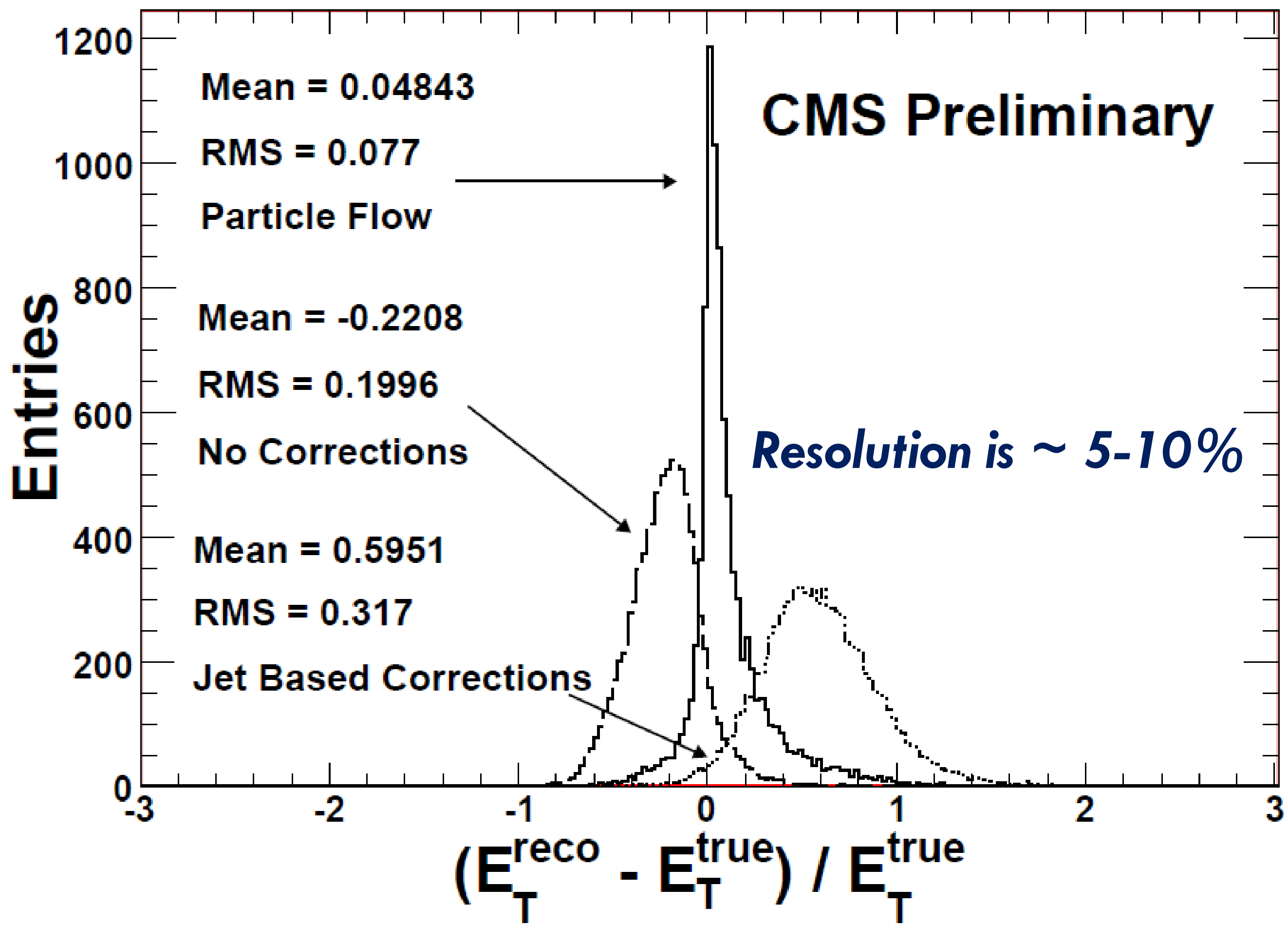
- Neutral pions from the tau will decay to γ's
- γ's will decay to electrons that bend in the B field
- Define the Ecal signal cone as an elliptical region in $\eta - \phi$ space
  - $R_\phi = 2R_\eta$
  - Ecal isolation cone: $\Delta R = 0.5$

$$\left(\frac{\Delta\phi}{R_\phi}\right)^2 + \left(\frac{\Delta\eta}{R_\eta}\right)^2 < 1$$



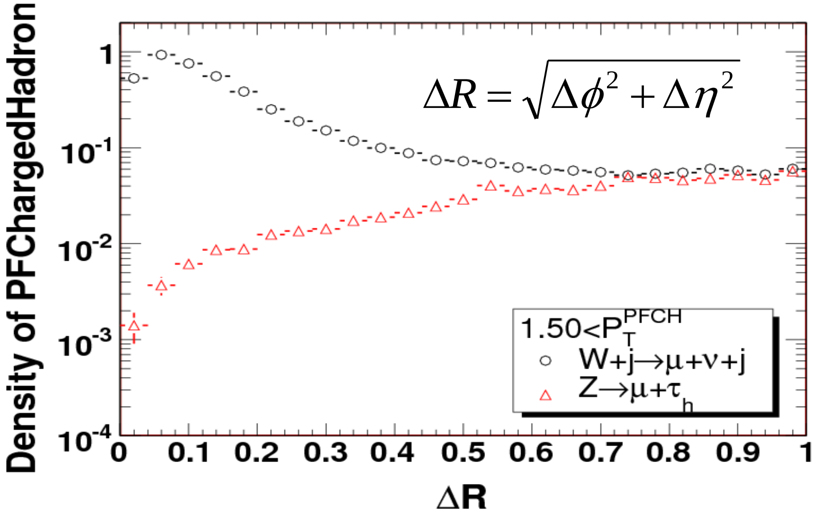


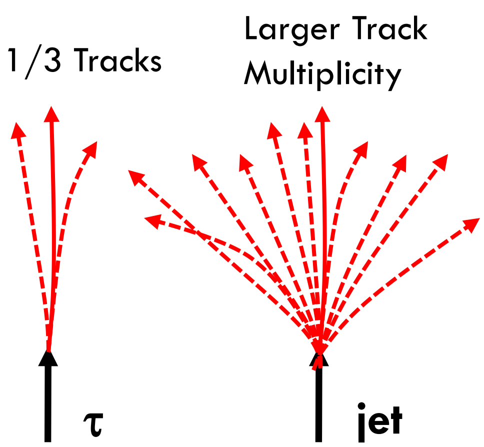
Tau Reconstruction

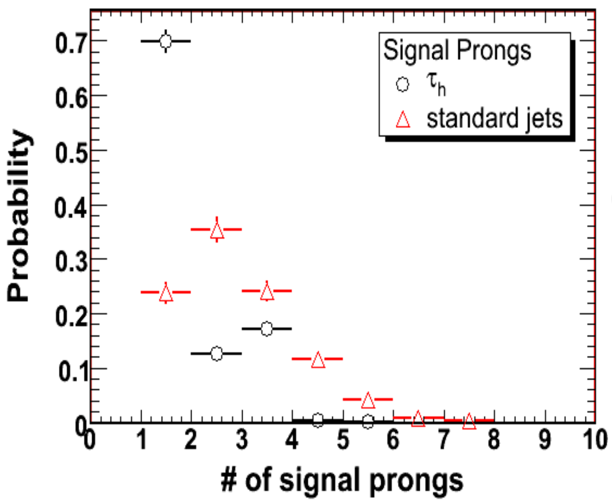


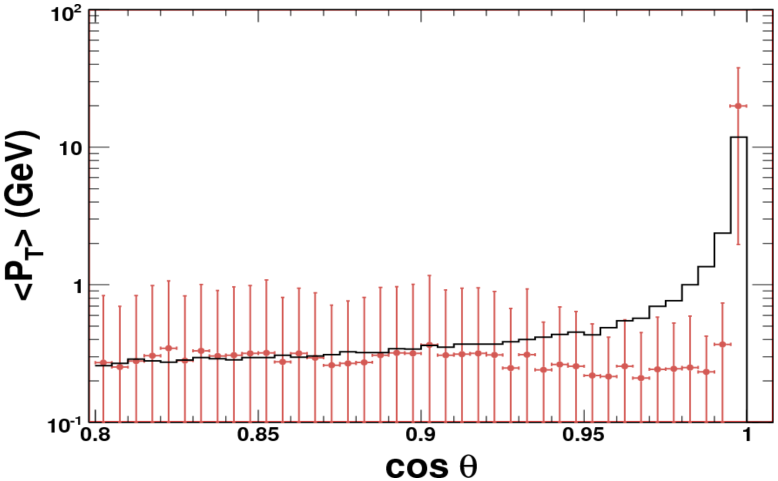
Hadronic Tau Identification (τ jets)

- Tau Jets vs. Standard Jets
  - Main differences:
    - On average, standard jets have higher density of tracks
    - Taus have narrow energy profiles
    - Taus have fewer tracks (prongs) within a narrow cone (signal cone) around the jet axis

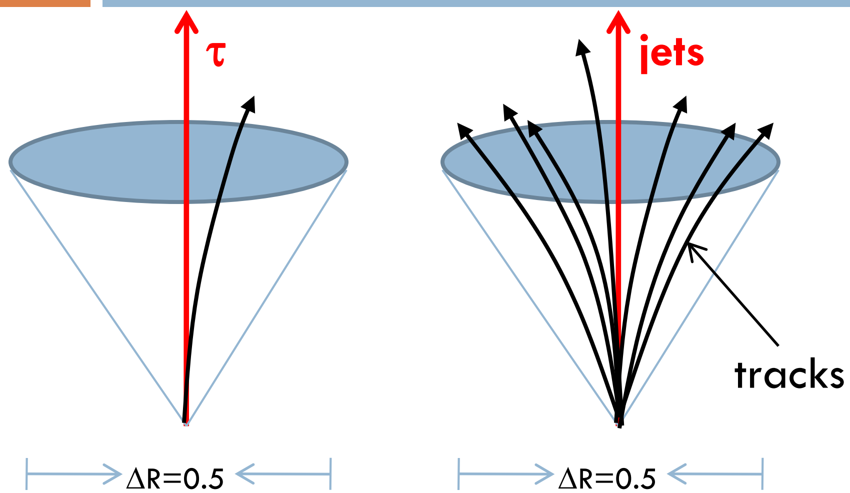


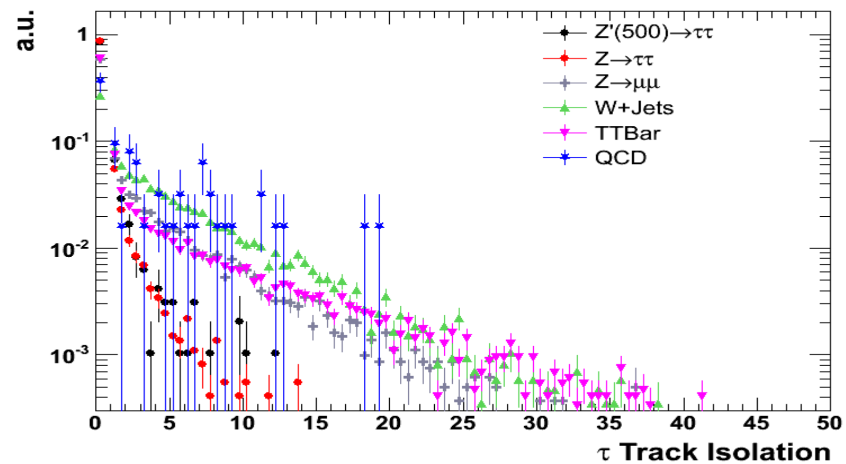


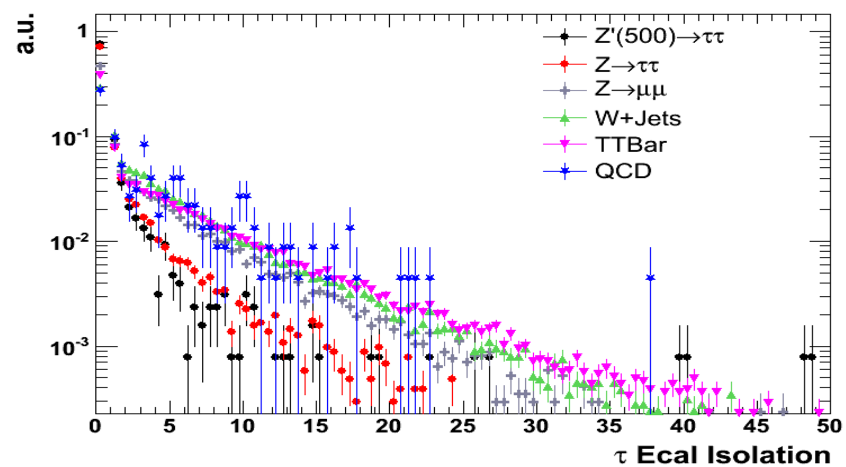




Tau Isolation

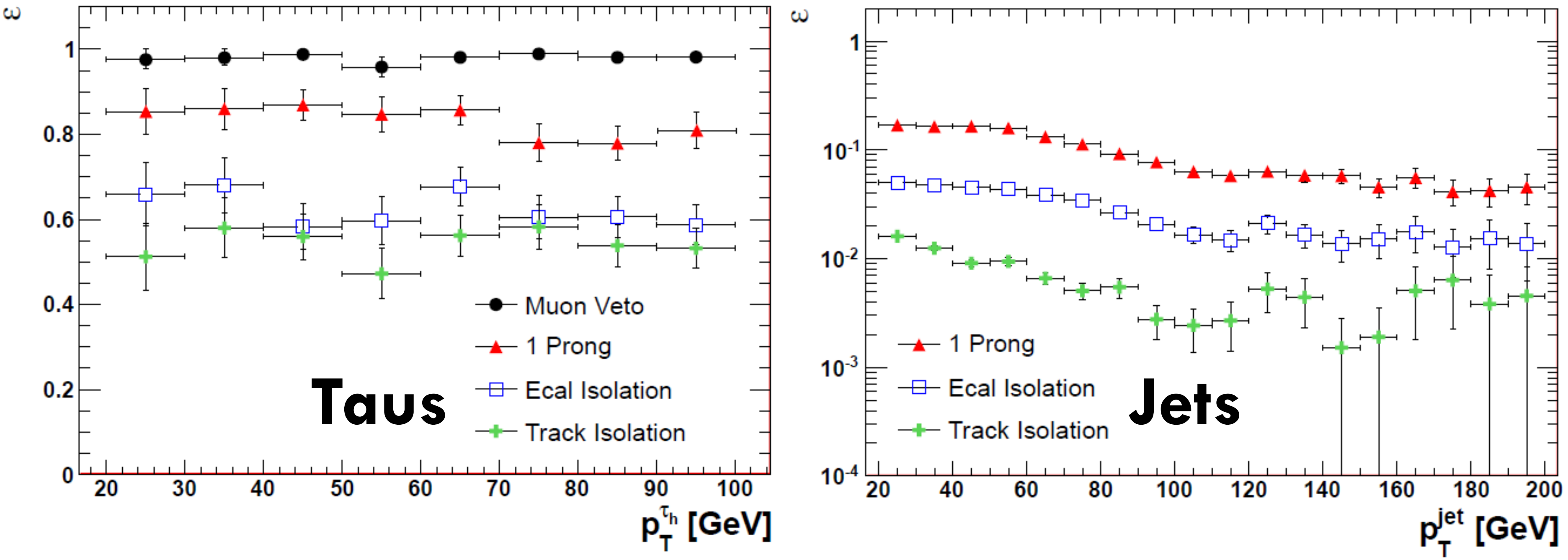






- Isolation definition: $I = \sum_{tracks/gammas} P_T$
- Thresholds on tracks and gammas:
  - P_T of tracks and gammas > 1 GeV
- Define our selection: $I = \sum_{tracks/gammas} P_T < 1$

Tau ID Efficiencies and Fake Rates

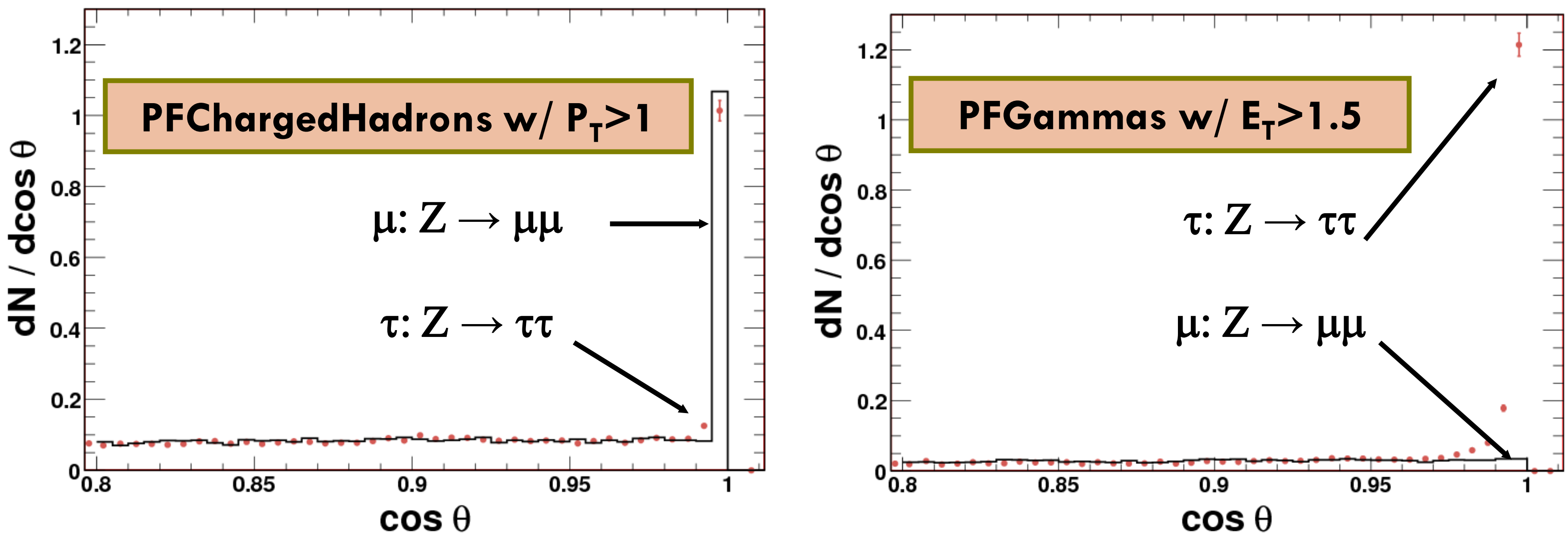


Tau identification efficiency ~ 55% for all p_T. The "flat" dependence on pT ensures the robustness of the tau identification criteria. Furthermore, if we are able to validate $Z \rightarrow \tau\tau$ in the low mass/ p_T regions, then that gives us confidence that the tau identification works at high p_T .

Probability for a jet to fake a tau is ~ 1%.

Measuring Tau ID Efficiencies

- Standard τ iso. requirements: 0 tracks/PFChargedHadrons/γ's in the isolation annulus
- Density of tracks and gammas around the μ & τ :



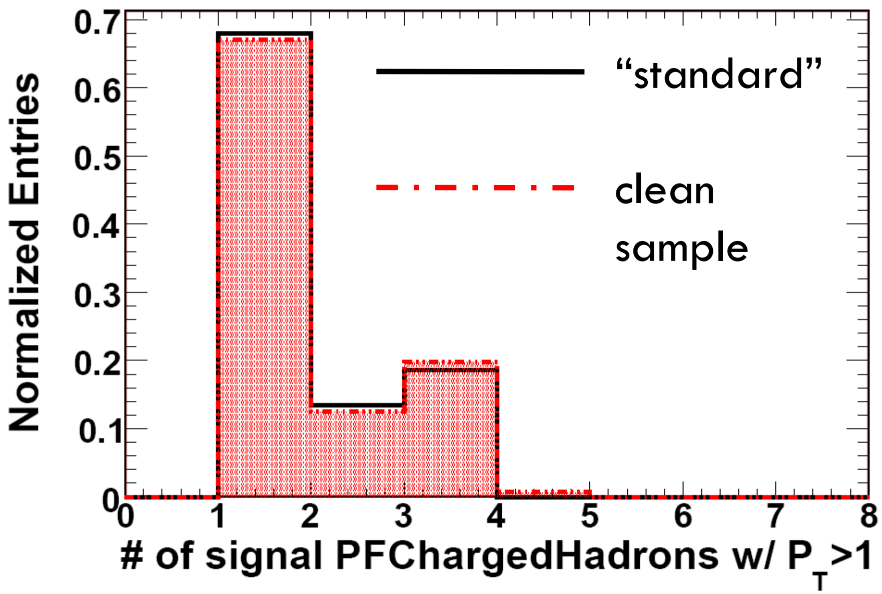
- Efficiencies in Z → $\tau\tau$ and Z → $\mu\mu$ are similar, thus Z → $\mu\mu$ events can be used to obtain a scale factor which can then be applied on top of isolation efficiencies from our Z → $\tau\mu$ MC sample. $S_{iso}^{\mu} = \varepsilon_{iso}^{\mu-data} / \varepsilon_{iso}^{\mu-MC}$, $\varepsilon_{iso}^{\tau-DATA} = S_{iso}^{\mu} \times \varepsilon_{iso}^{\tau-MC}$

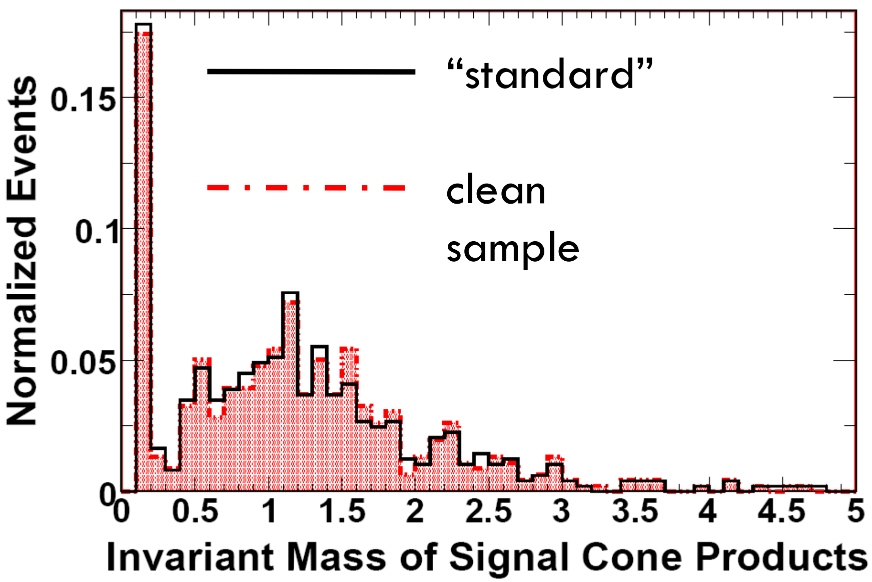
Measuring τ ID Efficiencies

- How will we measure the τ ID efficiencies?

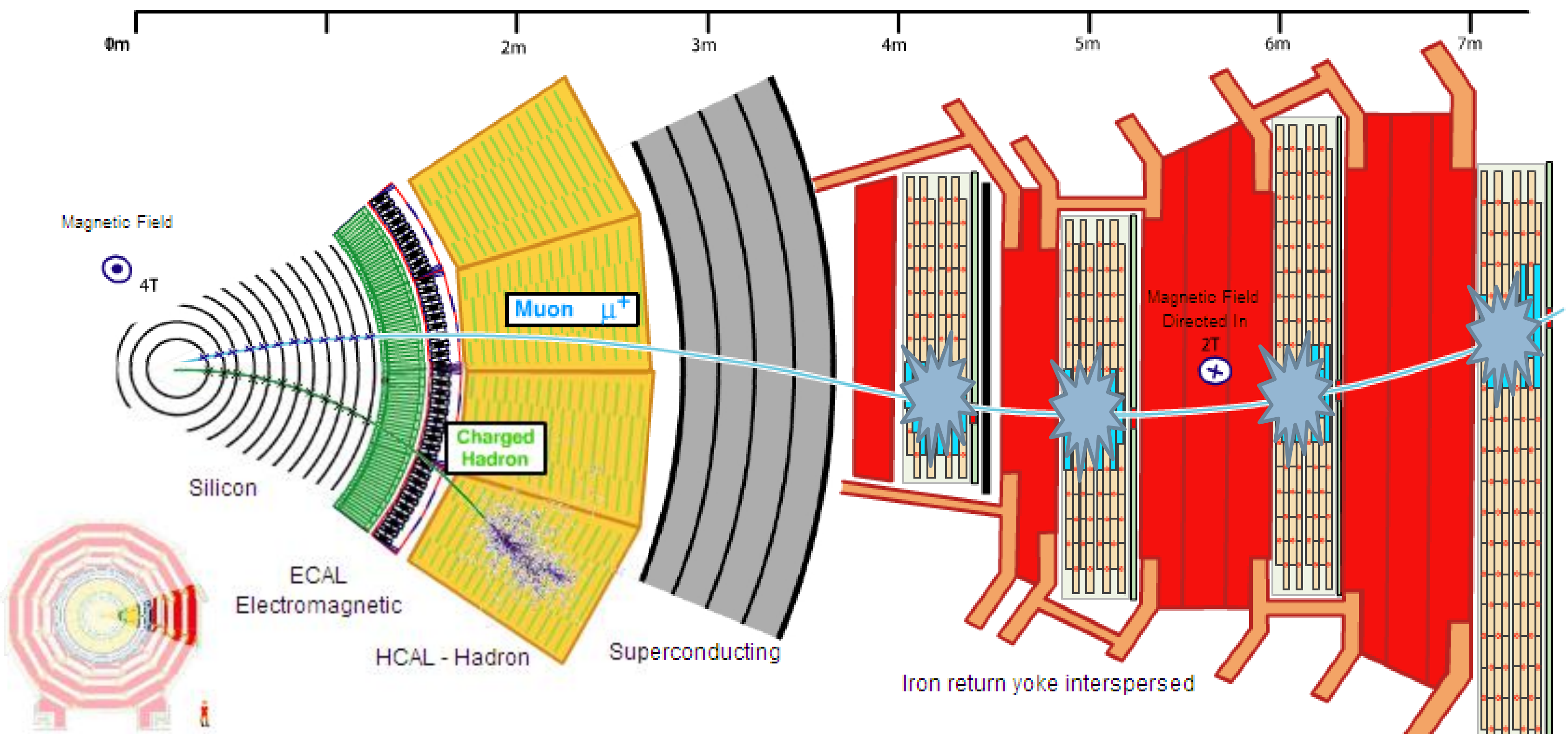
$$S^{\tau}_{selection} = \varepsilon^{\tau-data}_{selection} / \varepsilon^{\tau-MC}_{selection}$$

  - We can measure the efficiencies of each τ ID selection using our clean sample & then compare it with MC to obtain a scale factor per selection
- We want to make sure that our methodology doesn't cause biases
  - "Standard" selections: Isolation cone of 0.5, P_T(track)>1, $E_T(\gamma)$>1, MC hadronic tau from Z matched to a reconstructed tau using a $Z \rightarrow \tau\tau$ sample



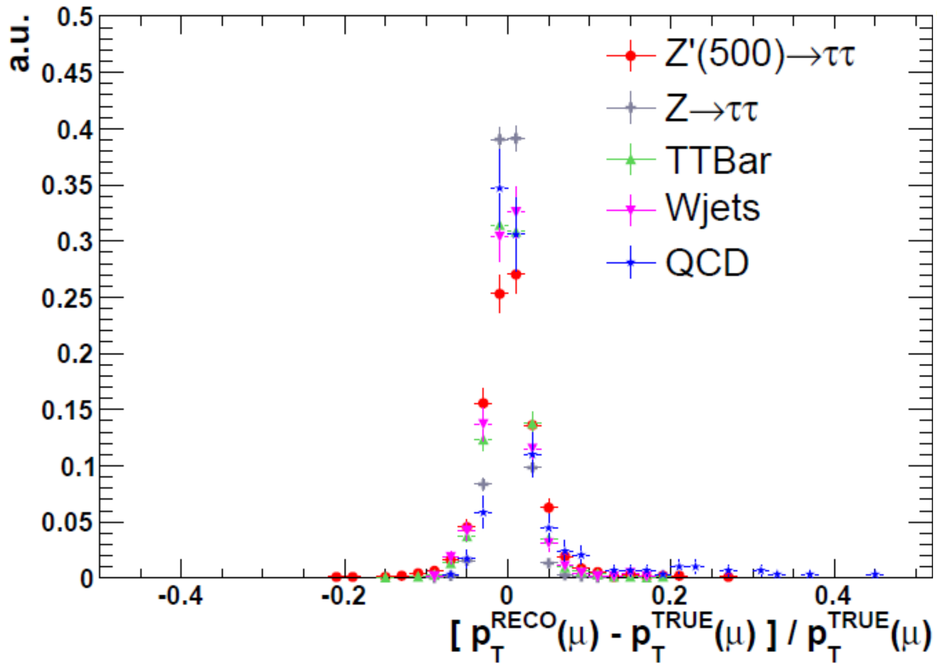


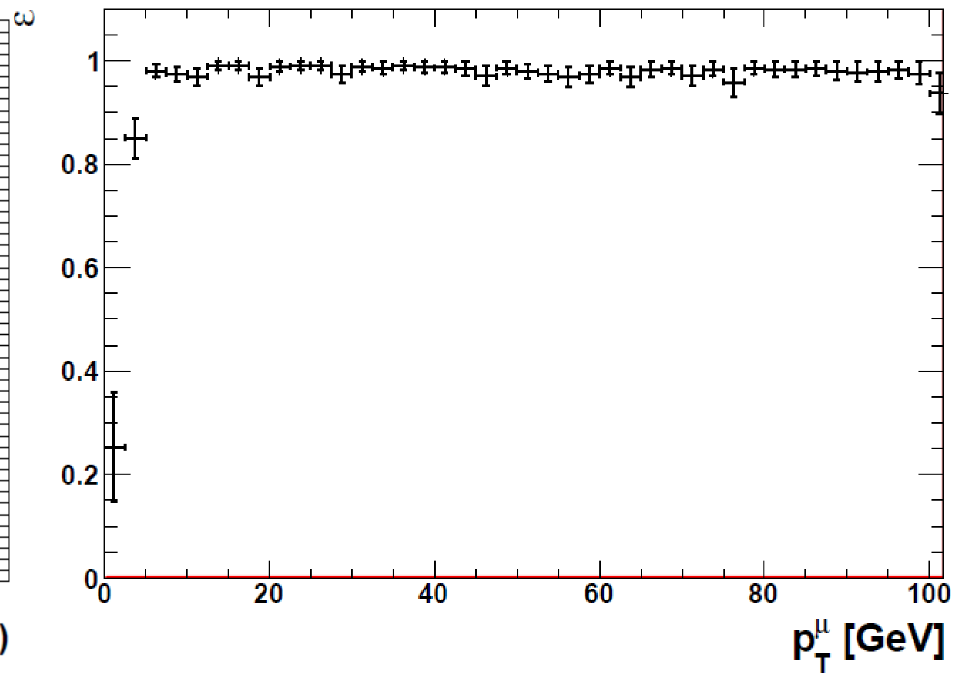
Muon Reconstruction & Identification



Much simpler than taus: "Hits" in the μ chambers + ""'Hits" in the inner silicon tracker + minimal energy in the calorimeters → global muon

Muon Reco. Resolution & Efficiency

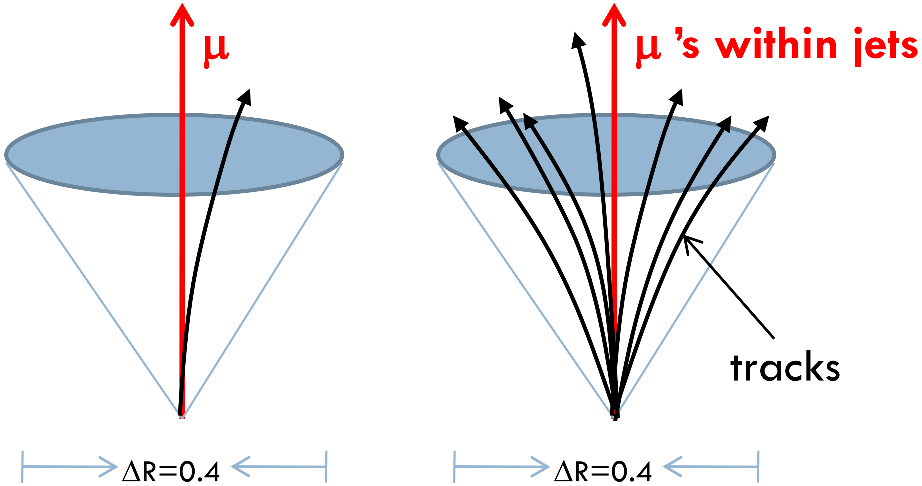


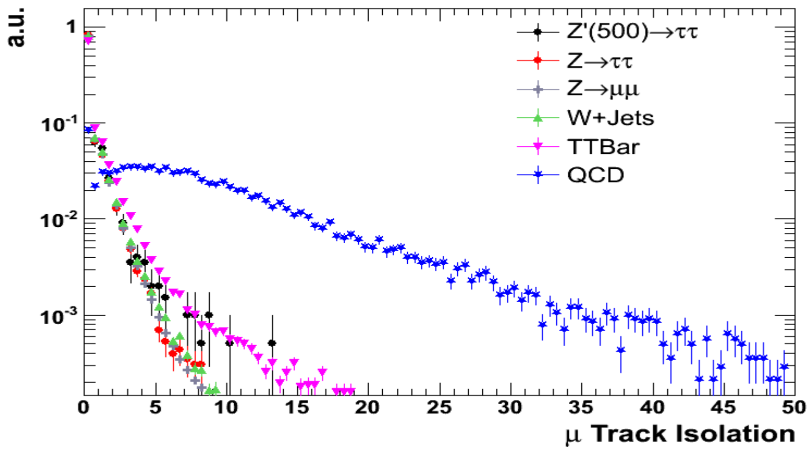


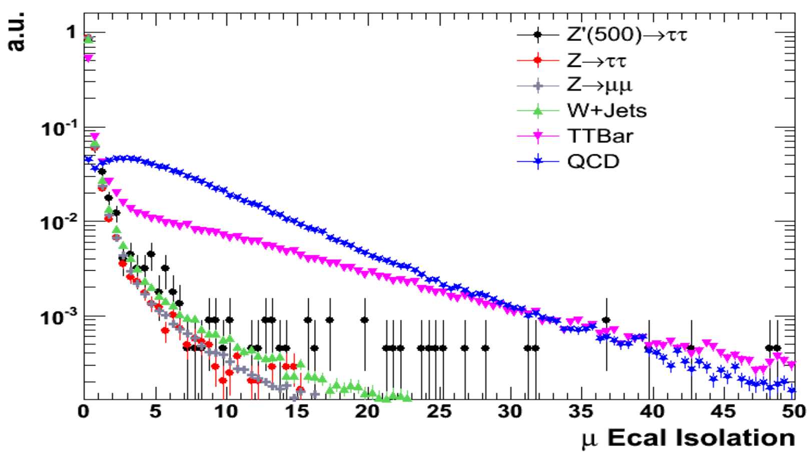
Muon p_T resolution is ~ 1% even for high p_T muons.

Global muon reconstruction efficiency is ~ 99% for p_T > 10 GeV/c. Analysis selections require p_T > 20 GeV/c in order to stay away from the rising slope below 10 GeV, where differences between MC and data are likely.

Muon Isolation







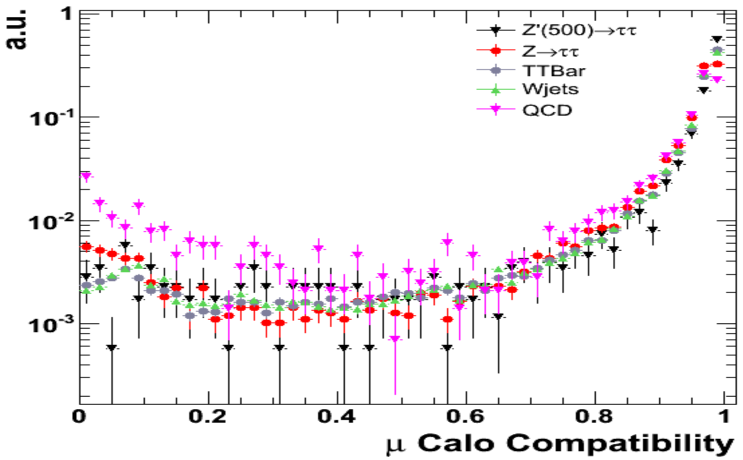
- Isolation definition: $I = \sum_{tracks/gammas} P_T$
- Thresholds on tracks and Ecal RecHits:
  - Track $P_T > 0.7$, P_T of Ecal RecHits > 0.3
- Define our selection: $I = \sum_{tracks/gammas} P_T < 1$

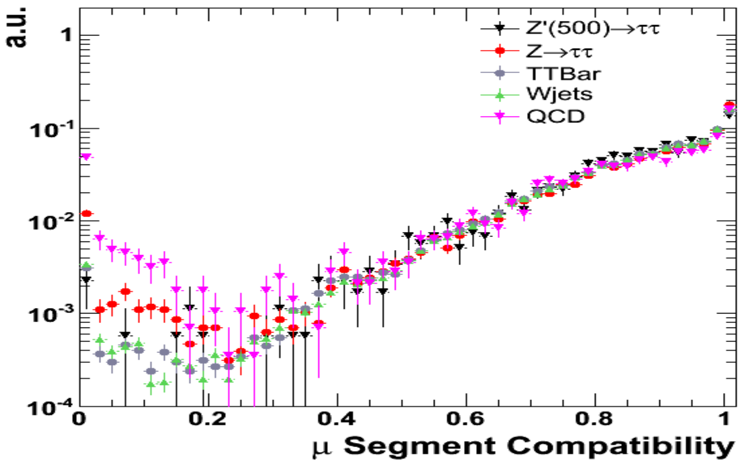
Muon Identification

- Calo/Segment Compatibility:
  - Looks at calorimeter energies and/or muon segments along the extrapolated muon direction
  - Likelihood variable is created - determines how consistent these energies /segments are with respect to what is expected for a muon.

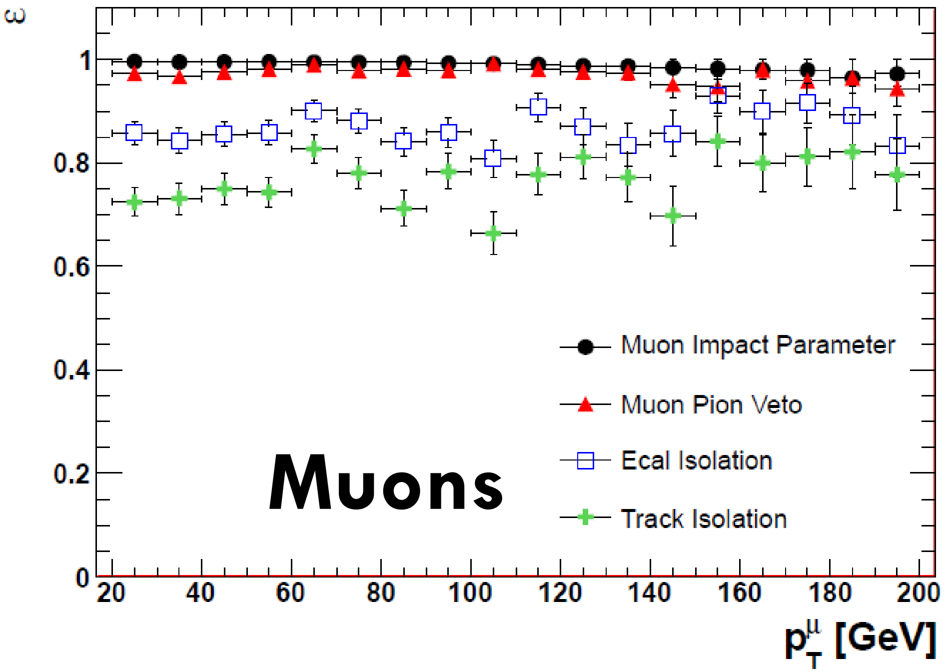
$$\frac{P_S(x)\cdot P_S(y)\cdot P_S(z)}{P_S(x)\cdot P_S(y)\cdot P_S(z)+P_B(x)\cdot P_B(y)\cdot P_B(z)}$$

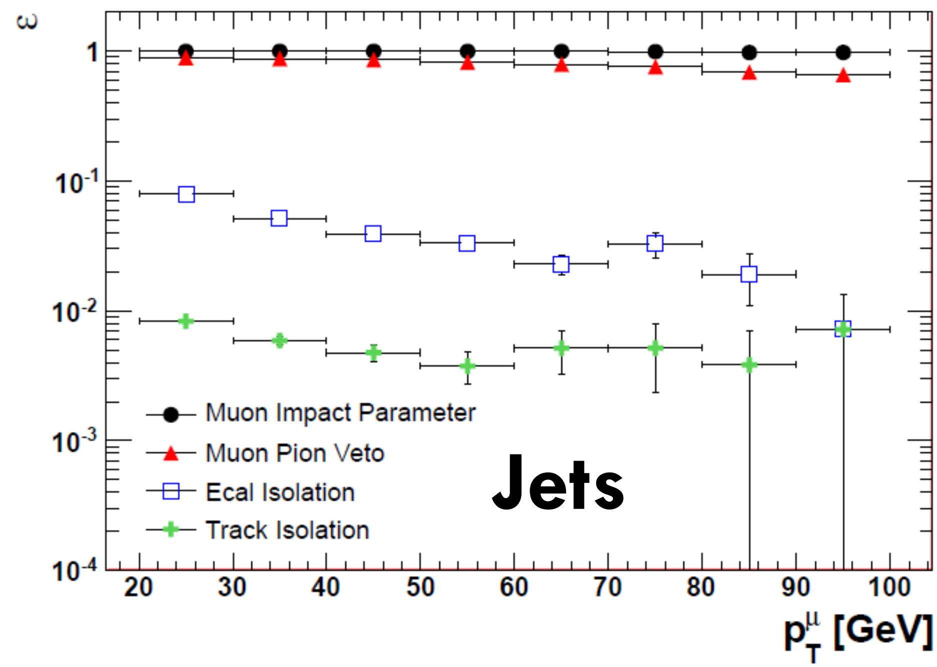
- Define the pion veto X:
  - X = (0.8 * CaloComp) + (1.2 * SegComp) > 1





Muon ID Efficiencies & Fake Rates



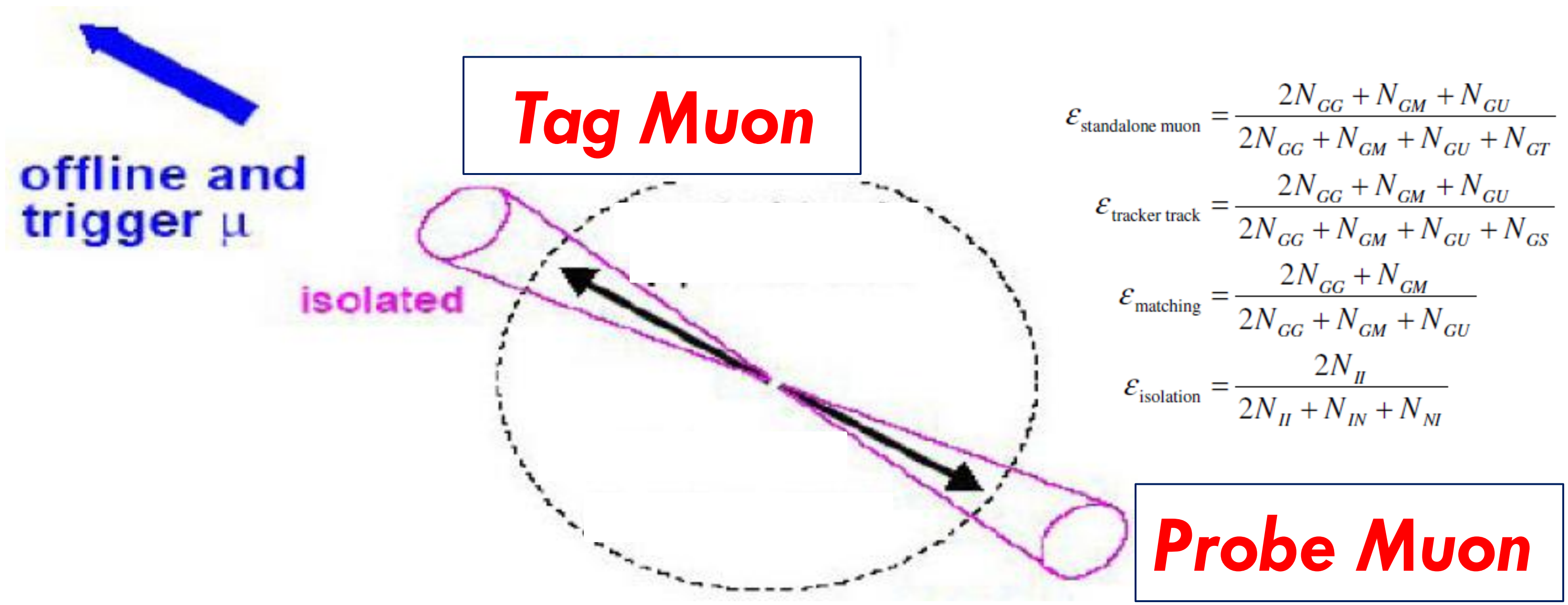


Muon identification efficiency ~ 80% for all p_T. The "flat" dependence on p_T ensures the robustness of the muon identification criteria. Furthermore, if we are able to validate $Z \to \mu\mu$ in the low mass/p_T regions, then that gives us confidence that the muon identification works at high p_T .

Probability for a jet (heavy flavour and decays in flight) to fake a muon is < 1%.

Measurement of Muon ID Efficiencies

- <u>Tag and Probe Method</u>:
  - Dimuon pair around Z mass gives a clean sample of muons
  - Apply all selections on one muon (Tag muon) and use the second muon (Probe muon) to measure efficiencies



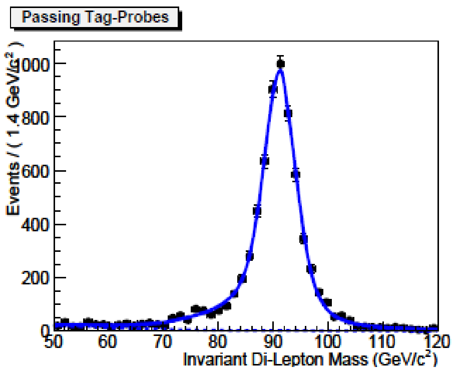
$$\varepsilon_{\text{standalone muon}} = \frac{2N_{GG} + N_{GM} + N_{GU}}{2N_{GG} + N_{GM} + N_{GU} + N_{GT}}$$

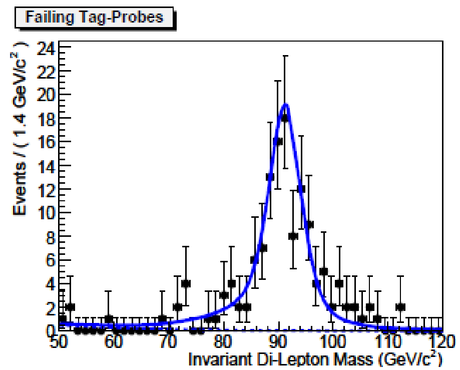
$$\varepsilon_{\text{tracker track}} = \frac{2N_{GG} + N_{GM} + N_{GU}}{2N_{GG} + N_{GM} + N_{GU} + N_{GS}}$$

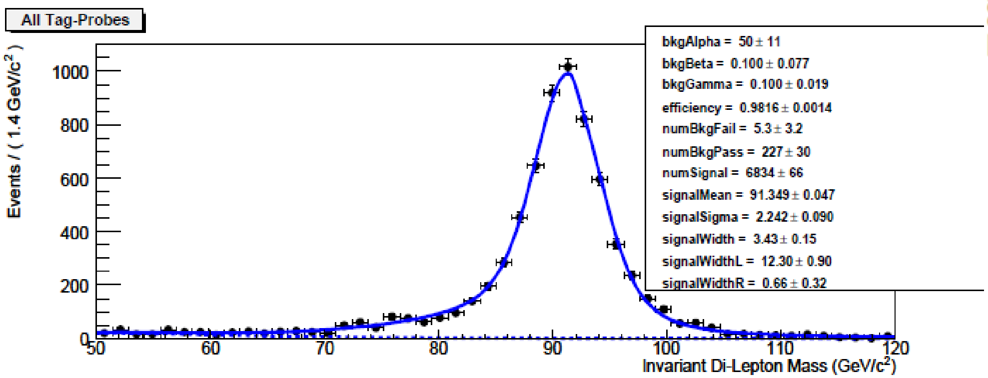
$$\varepsilon_{\text{matching}} = \frac{2N_{GG} + N_{GM}}{2N_{GG} + N_{GM} + N_{GU}}$$

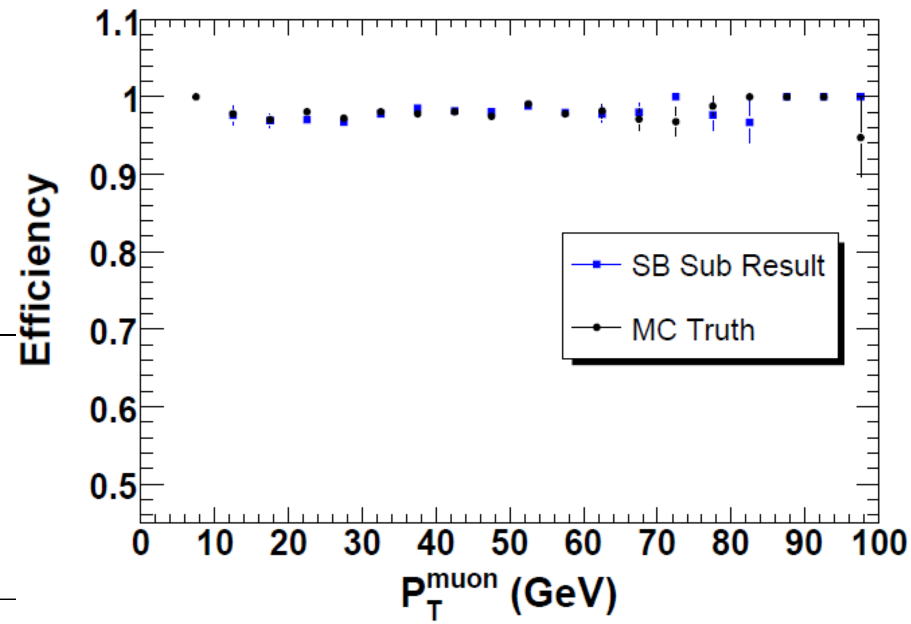
$$\varepsilon_{\text{isolation}} = \frac{2N_{II}}{2N_{II} + N_{IN} + N_{NI}}$$

Measurement of Muon ID Efficiencies









μ ID efficiencies used for 2010 data taking (with $p_T > 20$)

	Scale Factors		
Total	0.9951 ± 0.0049	0.9944 ± 0.0060	1.0003 ± 0.0025

Di-Tau Mass Reconstruction

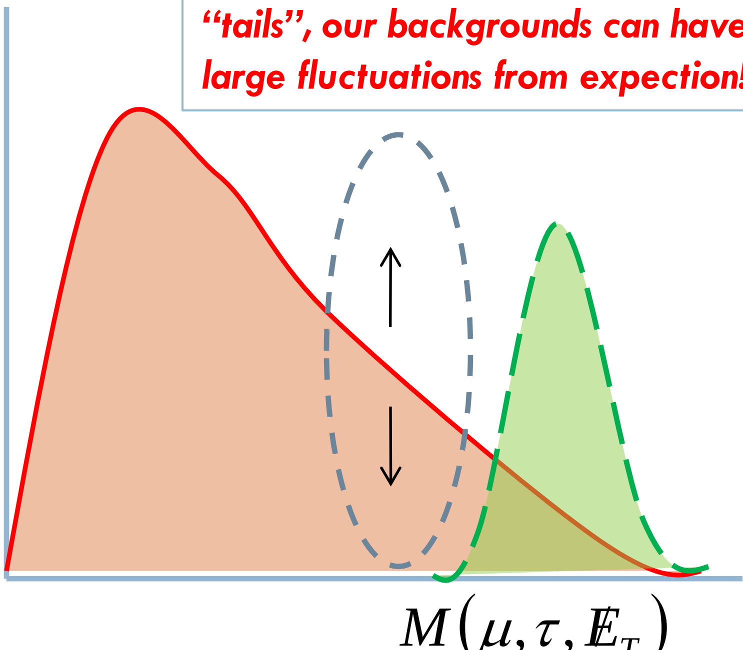
- Neutrinos from taus do not allow the full reconstruction of the Z' mass resonance
  - We can use the measurement of the momentum imbalance

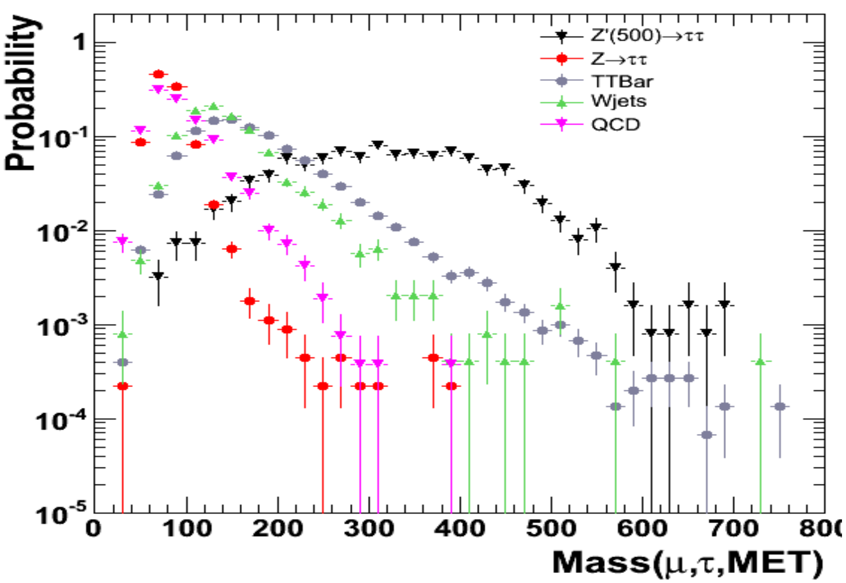
$$M(\mu,\tau,\not{E}_T)=\sqrt{\left(E_1^{\mu}+E_2^{\tau}+\not{E}_T\right)^2-\left(\vec{p}_1^{\,\mu}+\vec{p}_2^{\,\tau}+\vec{\not{E}}\right)^2}$$

$$\sum_{\upsilon_i's}\vec{p}_{\upsilon_i's}+\sum_{Visible}\vec{p}=\vec{0}\Rightarrow\vec{\not{E}}\approx-\sum_{Detected}\vec{p}$$

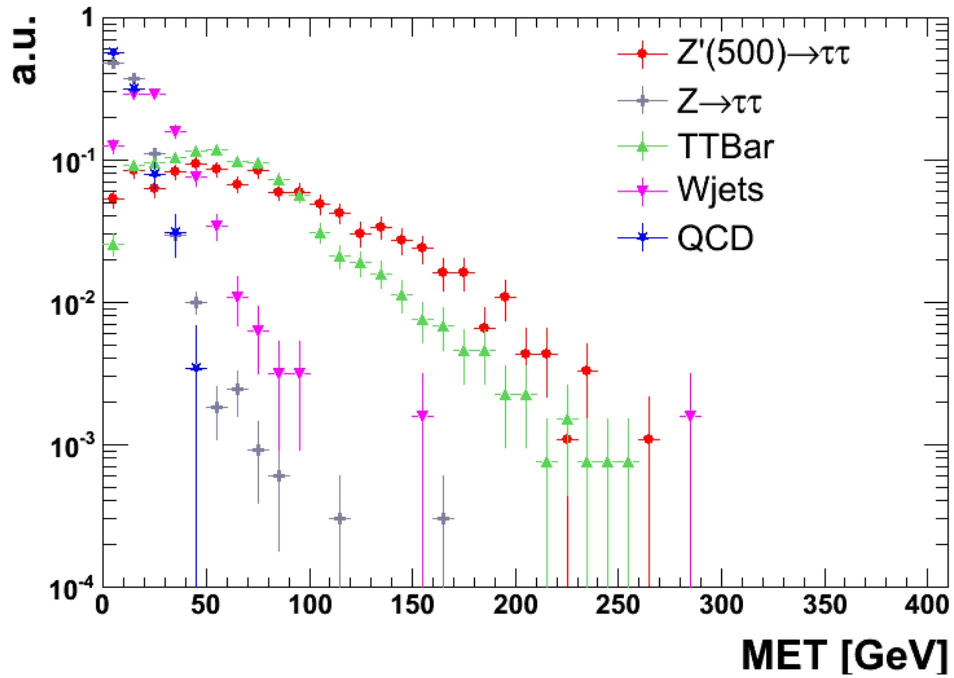
Momentum imbalance in each event is a sign of neutrinos or other weakly interacting particles. We call this "Missing Transverse Energy" (MET).

If we don't understand the MET "tails", our backgrounds can have large fluctuations from expection!!!





Missing Transverse Energy



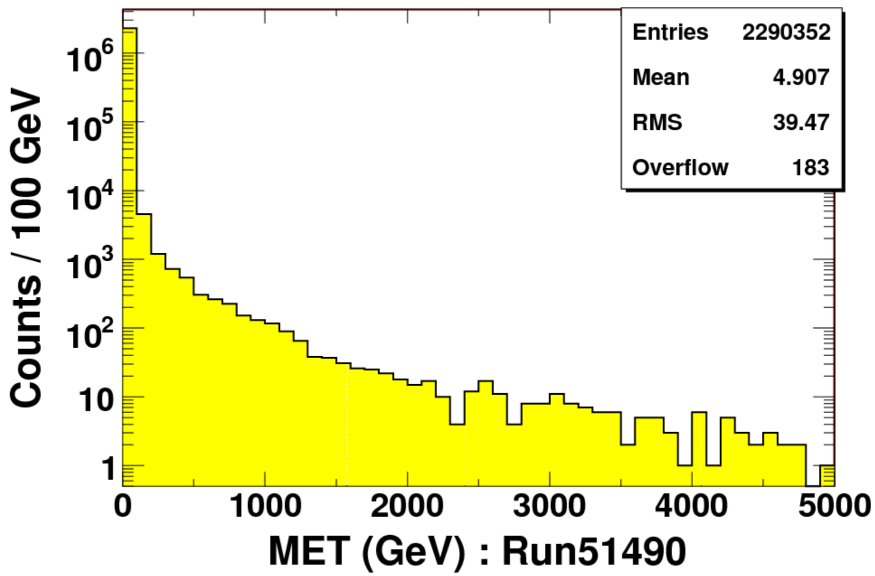
MET is sensitive to:

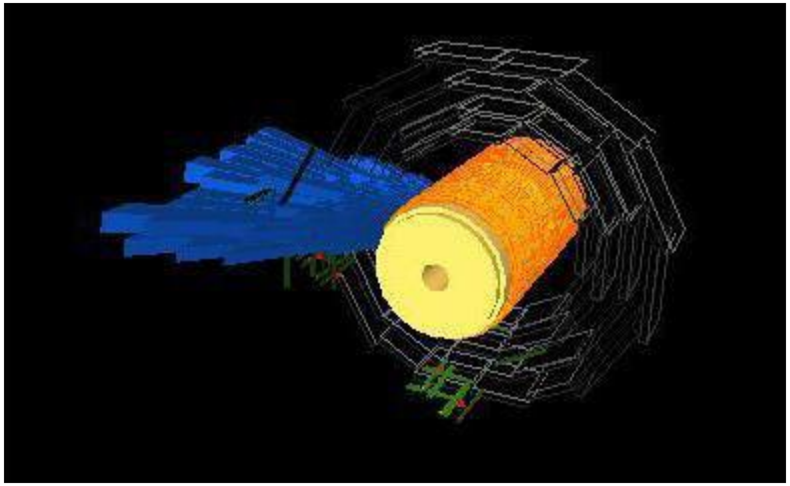
- Detector noise
- Dead material
- Cracks in the detector
- Pile-up
- Jet mismeasurements
- …
- …

Detector noise and pile-up are the most significant contributions for this analysis and are not well modeled by simulation!

Understanding MET at CMS

- Beginning in 2008, we observe large MET events at CMS



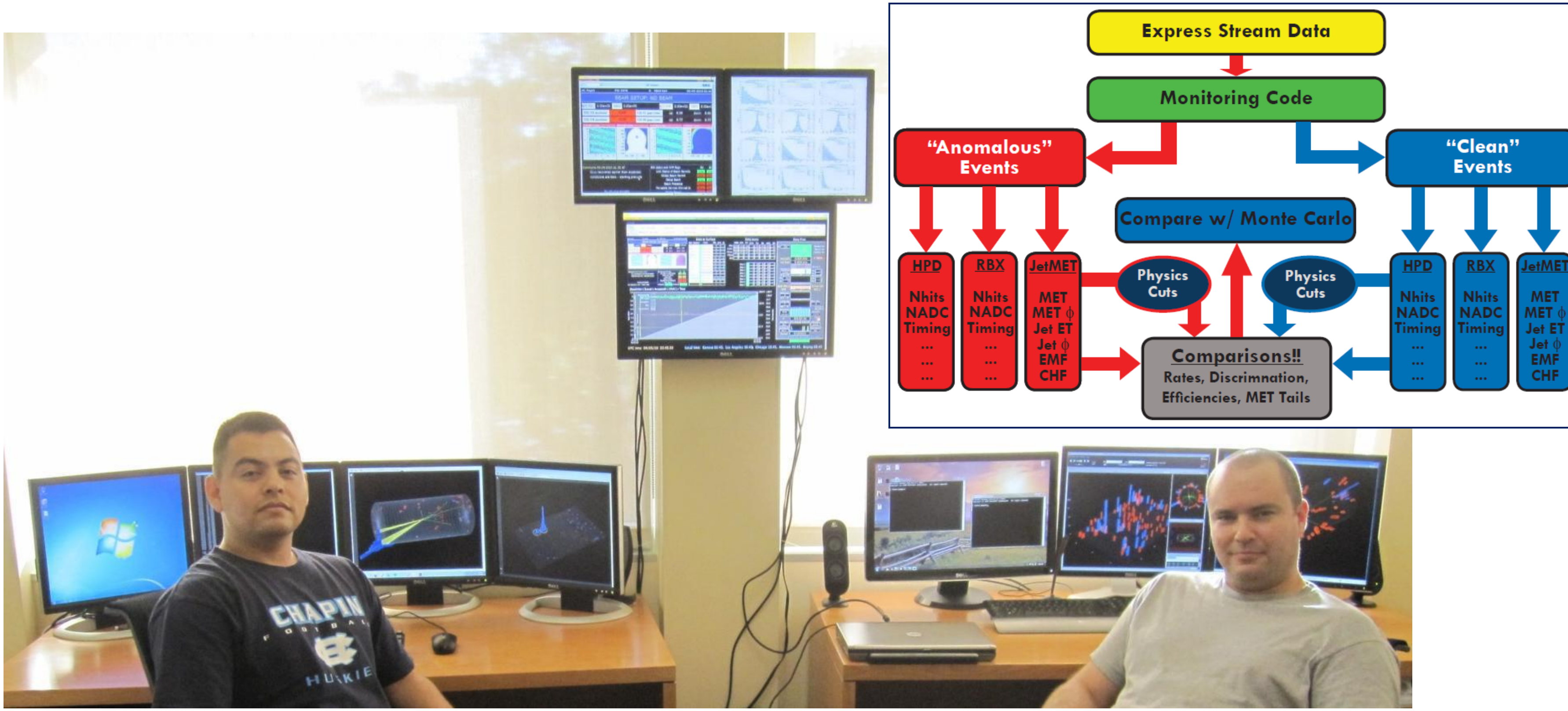


- Raised concerns over the possible effect on physics analyses

What are the sources of large MET?

- Large values of MET due to anomalous sources such as:
  - Hcal anomalies
    - HPD ion feedback: thermal emission of electrons ionize the acceleration gap of the hybrid photodiodes (HPDs).
    - HPD discharge: electrical from the wall of the HPD due to mis-alignment with the magnetic field
    - RBX noise: don't really understand the source, but noise is observed in all four HPDs within a readout box (RBX).
  - Ecal anomalies
    - Large energy readouts from a single lead tungstate chrystal
  - HF anomalies
    - Particles traverse the photomultiplier windows and generate Cerenkov radiation which results in large "fake" energy readouts.

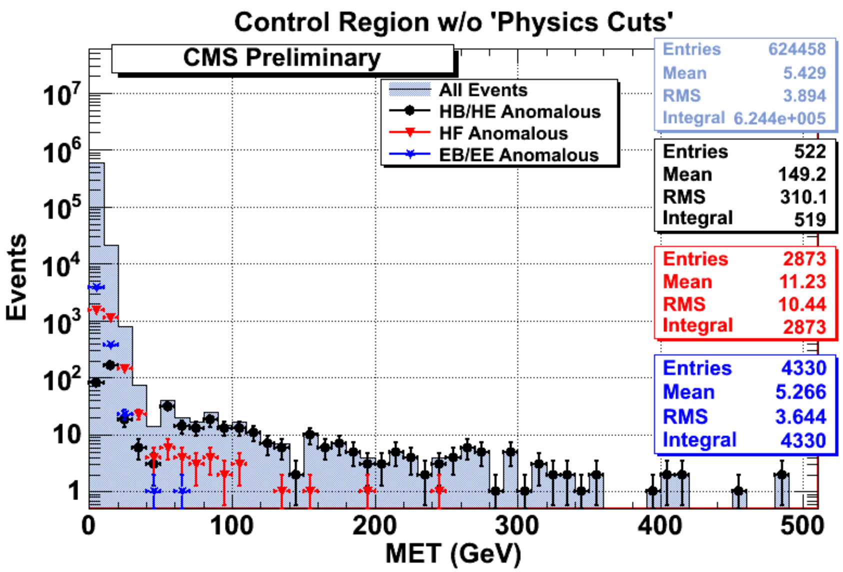
MET Monitoring Methodology

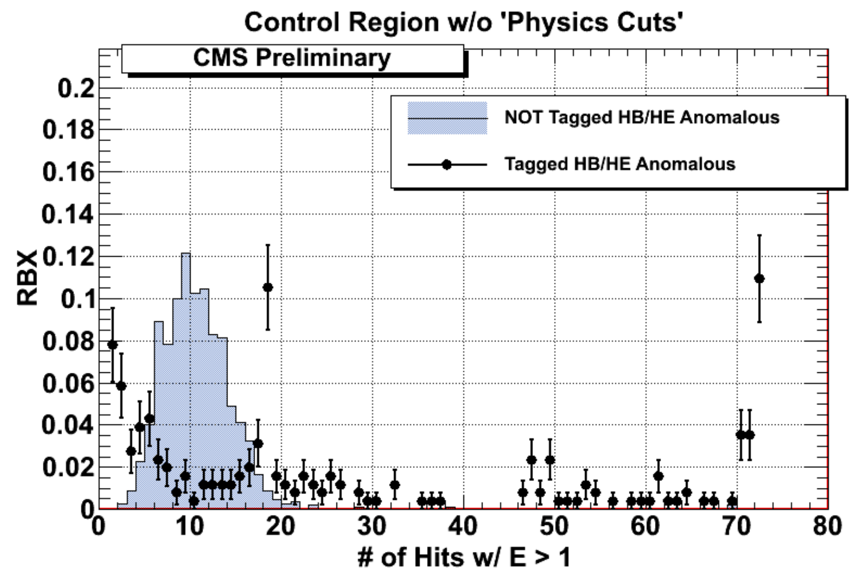


We developed a MET monitoring scheme to try to understand MET as quickly as possible

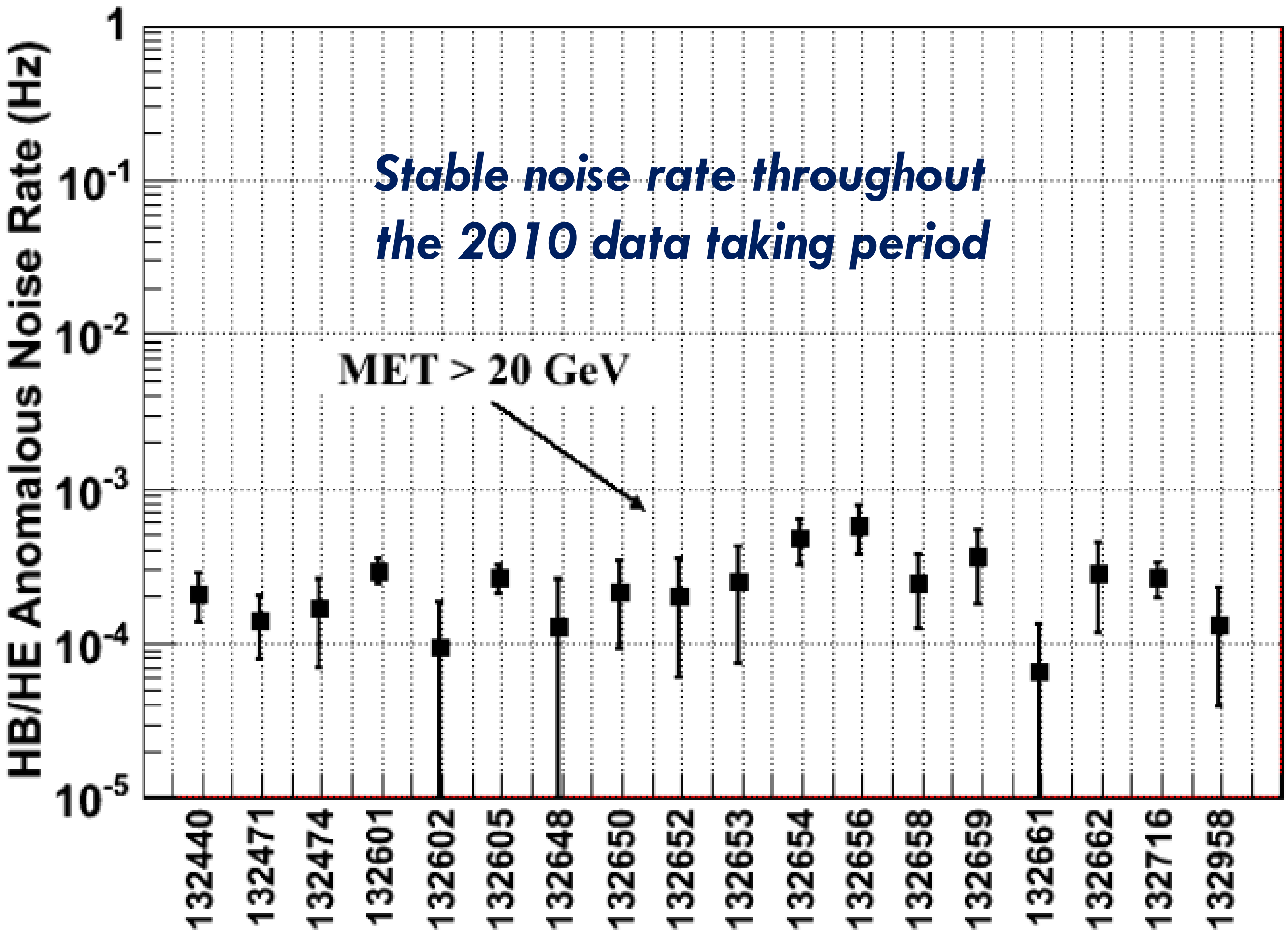
MET from Noise

- We were able to identify the noise and develop methods to clean up our event or throw away unwanted events

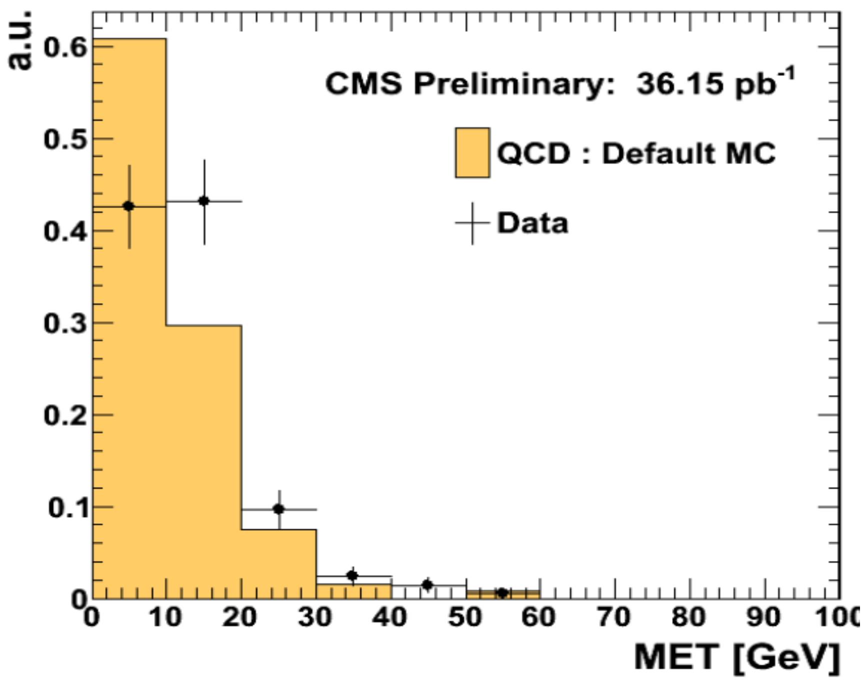


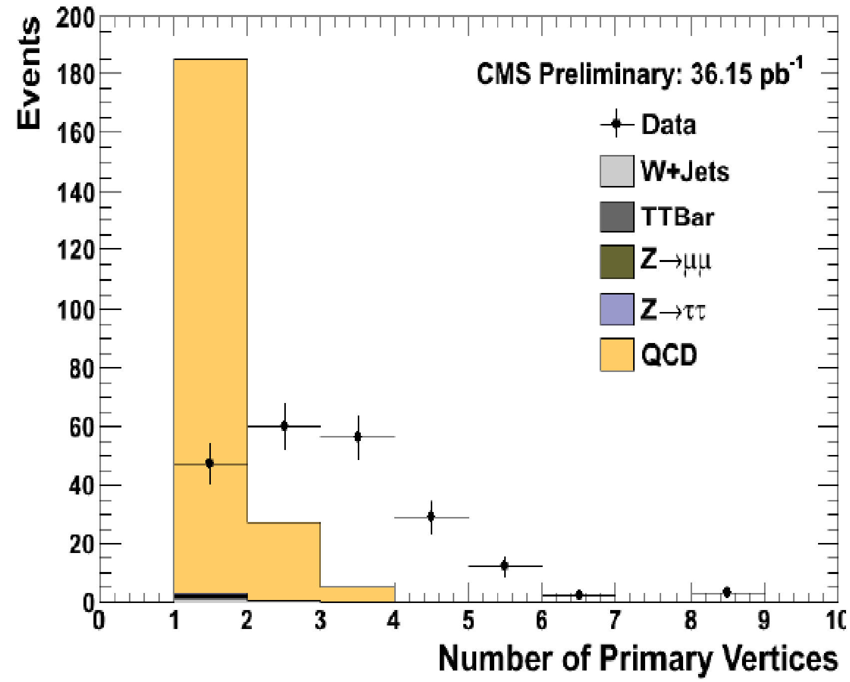


Stability of Noise Rate



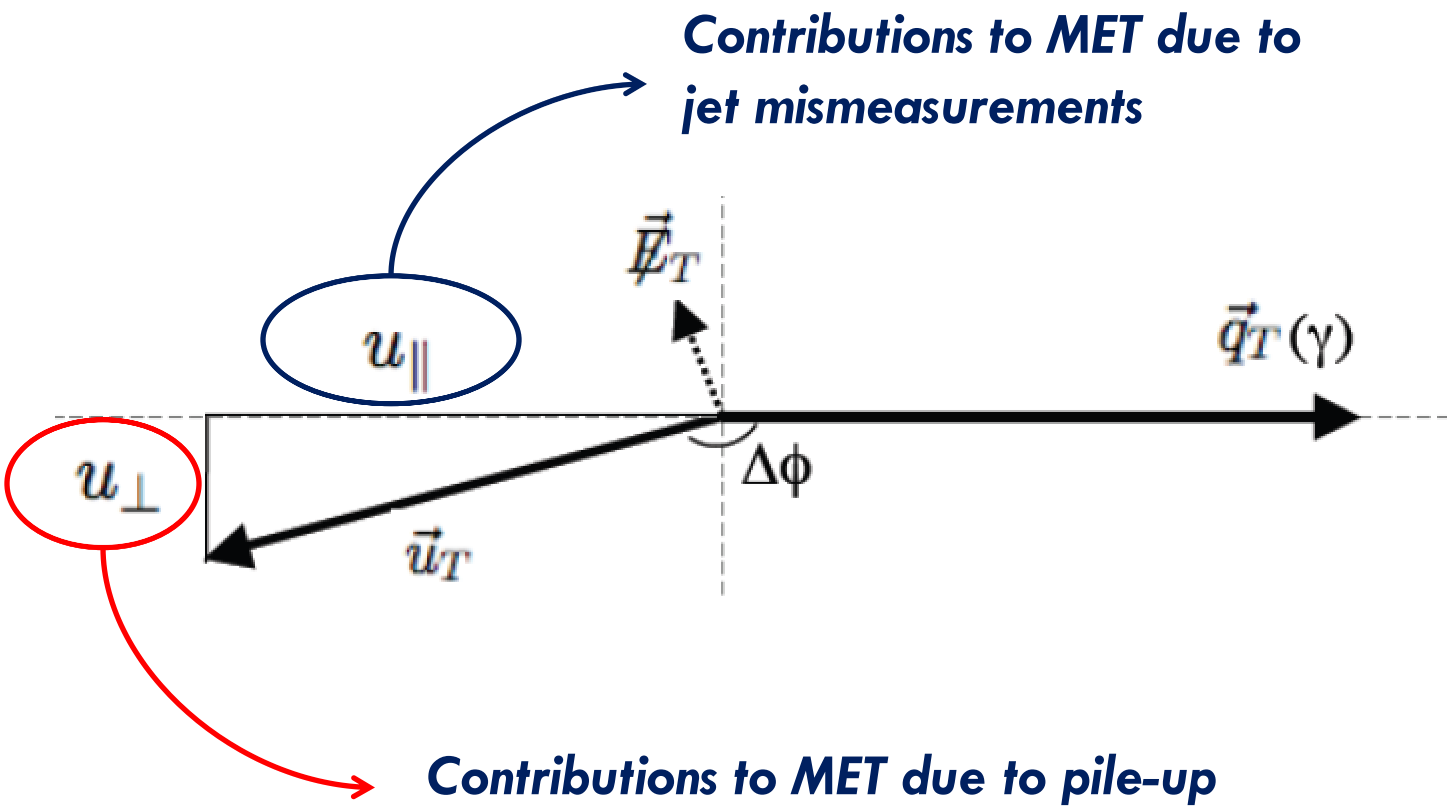
Pile-Up Contributions To MET



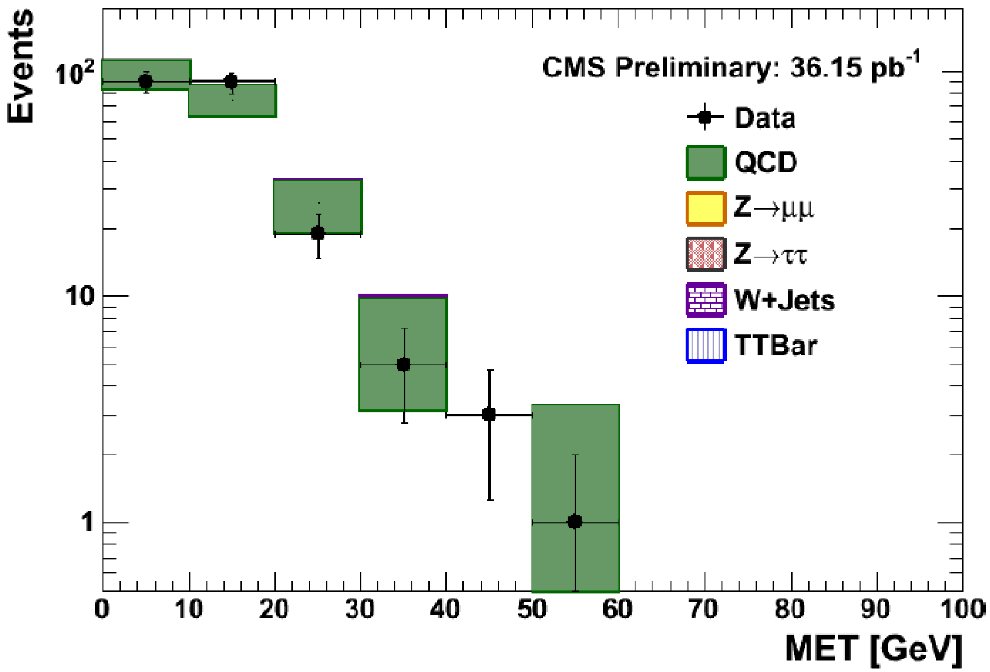


First signs of discrepancy between data and simulation were found in MET because simulation did not include proper consideration of pile-up.

Pile-Up Contributions To MET



Pile-Up Contributions To MET



$$\overrightarrow{\not{E}_{\mathrm{T}}}^{Corrected} = \overrightarrow{\not{E}_{\mathrm{T}}}^{Raw} + \overrightarrow{\Delta\not{E}_{\mathrm{T}}}^{PU}$$

$$\delta\not{E}_{\mathrm{T}} = \sqrt{n} \cdot \sigma_{PU} \cdot F_{scale}(\not{E}_{\mathrm{T}})$$

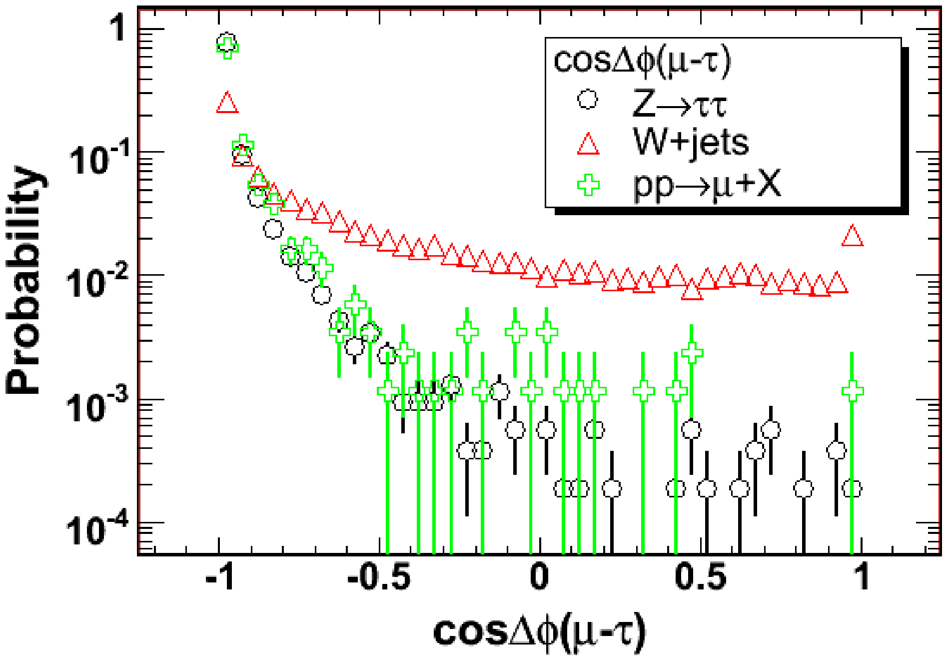
$\not{E}_T$ Algorithm	σ_{PU} $(u_{\parallel})$	σ_{PU} $(u_{\perp})$
Calo$\not{E}_T$ raw	2.84±0.06	3.03±0.04
Calo$\not{E}_T$ Type II	6.47±0.08	6.67±0.07
tc$\not{E}_T$	3.05±0.05	3.23±0.03
pf$\not{E}_T$ raw	3.53 ±0.04	3.48±0.03
pf$\not{E}_T$ Type I	3.85±0.05	3.86±0.03
pf$\not{E}_T$ Type II	4.63±0.05	4.56±0.04

CMS AN-10-432

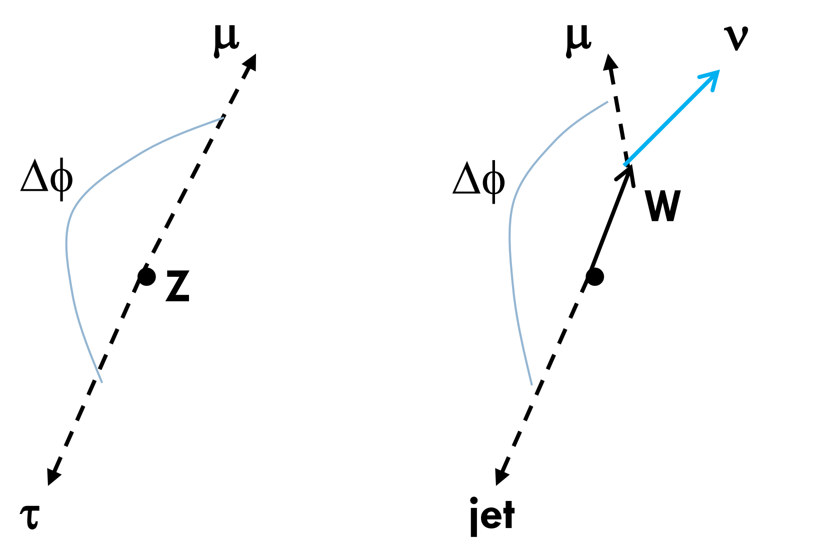
Great agreement between simulation and data after proper PU corrections are made!

Rejection of Events with W's

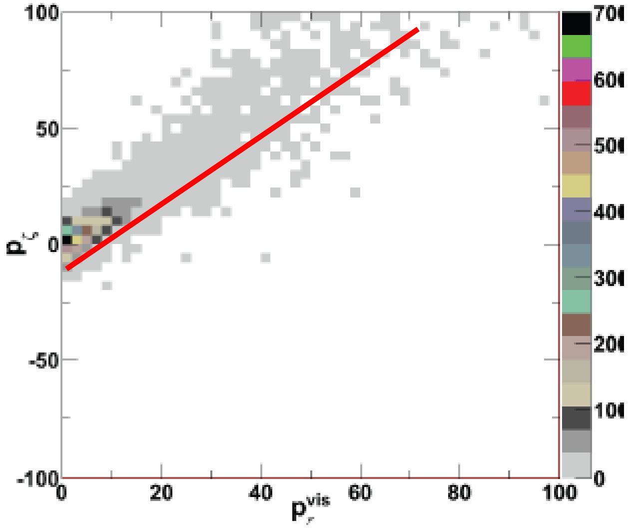
- Can use the topological characteristics of our signal & background samples for further background reduction
- Define the selection: $\cos\Delta\phi < -0.95$

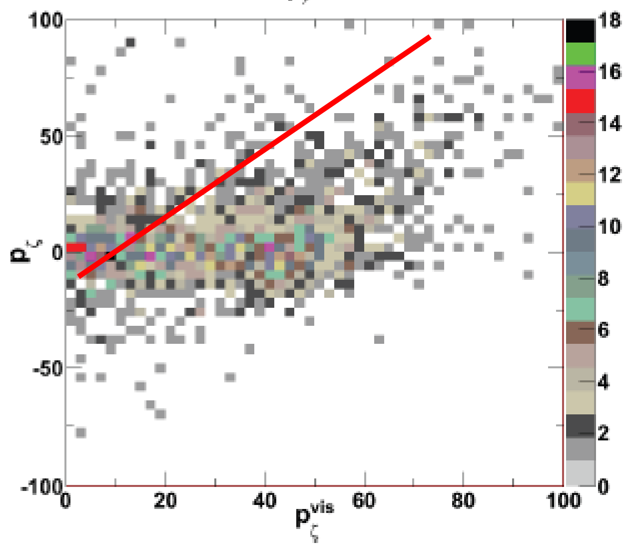


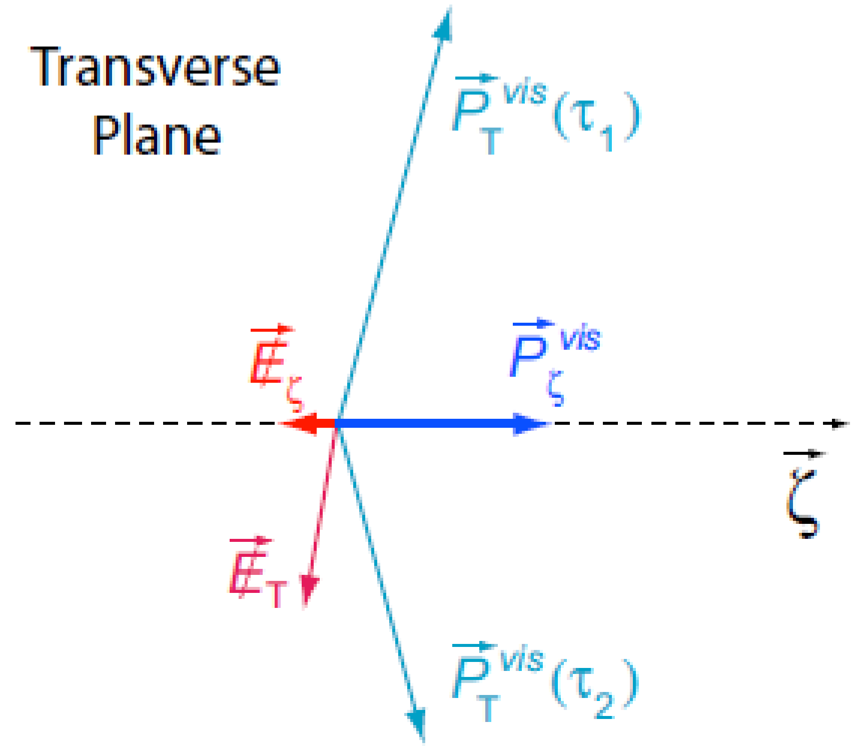
Cross-sectional view of the detector (x-y plane)



Rejection of Events with W's





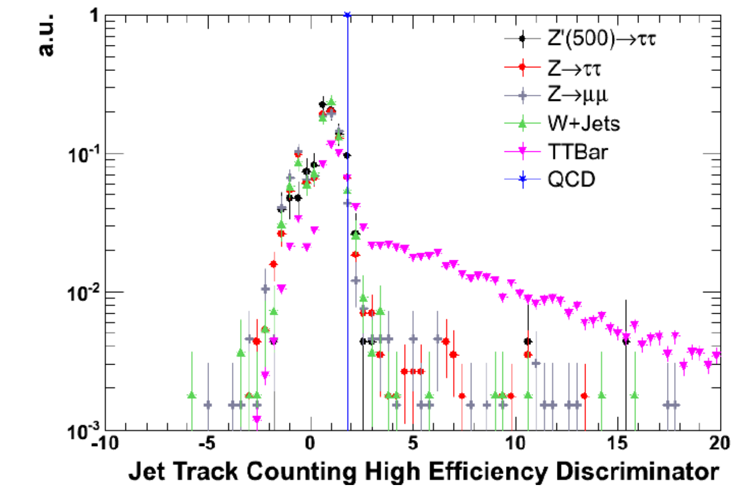


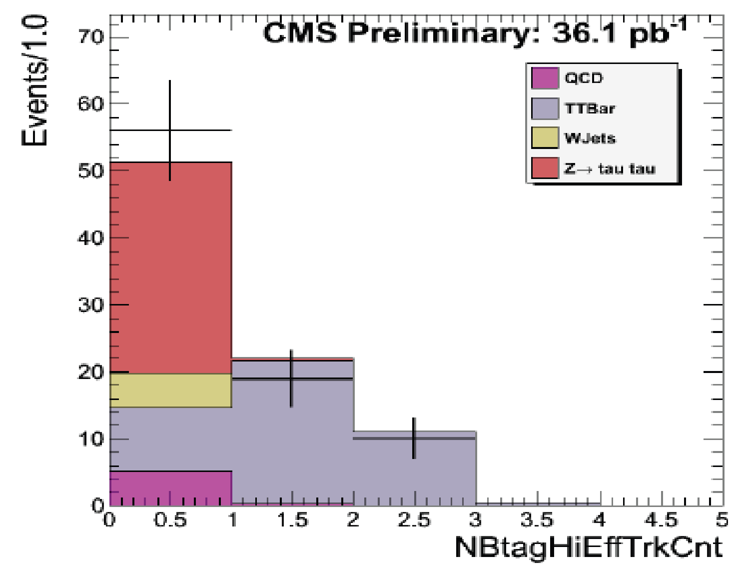
$$p_\zeta^{vis} = \vec{p}^{\,vis}_{\tau_1} \cdot \hat{\zeta} + \vec{p}^{\,vis}_{\tau_2} \cdot \hat{\zeta}$$

$$p_\zeta = p_\zeta^{vis} + \not{E}_{\mathrm{T}} \cdot \hat{\zeta}$$

Rejection of Events with Top Quarks

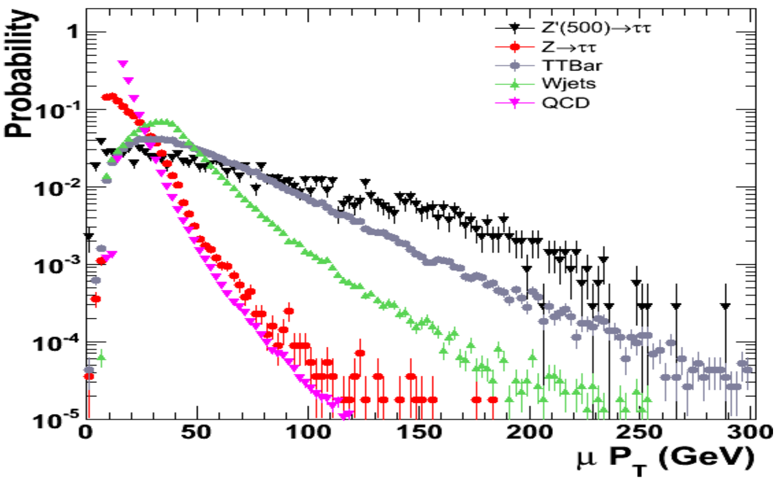
- Events with top quarks contain *b* jets, whereas signal events do not
- *b* jet identification …
  - Look for a jet containing tracks that have a vertex not consistent with the primary interaction vertex
- Events are required to have 0 jets tagged as b-jets
  - ~ 100% efficient for signal
  - ~ 20-30 % efficient for TTBar

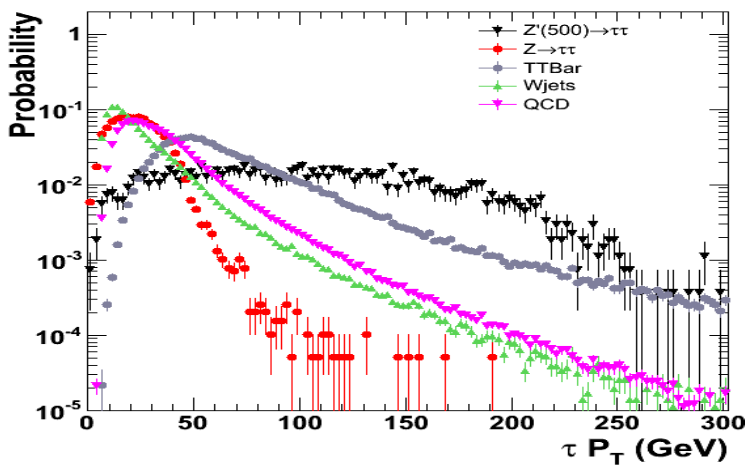




Summary of Selections

- Acceptance
  - $\Delta R(\mu,\tau)>0.7$
  - Global μ with $P_T>20$ & $|\eta|<2.1$
  - τ with $P_T>20$, $|\eta|<2.1$, and seed track $P_T>5$
- Muon ID
  - Pion Veto
  - Track & Ecal Isolation
- Tau ID
  - Muon Veto
  - Exactly 1 signal charged hadron
  - Track & Ecal Isolation
- Topology
  - $\cos\Delta\phi(\mu,\tau)<-0.95$
  - $Q(\mu)*Q(\tau) < 0$
  - MET > 30
  - 2D Zeta Cut
  - 0 b-tagged jets





Final Selection Efficiencies

Cut/Selection	$Z \to \tau\tau$	$Z \to \mu\mu$	W+Jets	QCD	$t\bar{t}$
$\mu\ p_T > 20$	39.57 ± 0.14	73.30 ± 0.04	80.49 ± 0.05	11.67 ± 0.02	63.07 ± 0.08
$\mu\ \lvert\eta\rvert < 2.1$	91.17 ± 0.13	95.66 ± 0.02	89.33 ± 0.04	94.00 ± 0.04	96.91 ± 0.03
$\tau\ p_T > 20$	64.50 ± 0.22	86.27 ± 0.04	49.73 ± 0.07	73.99 ± 0.07	98.91 ± 0.02
$\tau\ \lvert\eta\rvert < 2.1$	90.60 ± 0.17	85.81 ± 0.04	89.89 ± 0.06	84.62 ± 0.07	98.78 ± 0.02
τ Seed $p_T > 5$	90.83 ± 0.18	97.06 ± 0.02	88.62 ± 0.06	85.82 ± 0.07	96.07 ± 0.04
$\mu\ \lvert d_0\rvert < 0.2$	99.98 ± 0.01	100.00 ± 0.00	99.98 ± 0.01	99.86 ± 0.01	99.91 ± 0.01
$\mu\ \pi$ veto	95.69 ± 0.13	99.80 ± 0.01	97.96 ± 0.03	88.71 ± 0.07	93.95 ± 0.05
μ ECAL Iso. $\sum p_T < 1$	94.22 ± 0.15	98.11 ± 0.02	91.50 ± 0.06	8.09 ± 0.07	62.51 ± 0.10
μ Track Iso. $\sum p_T < 1$	89.82 ± 0.20	95.95 ± 0.03	88.08 ± 0.07	10.64 ± 0.26	81.60 ± 0.11
$\tau\ \mu$ veto	94.21 ± 0.17	15.00 ± 0.05	99.22 ± 0.02	98.22 ± 0.34	97.32 ± 0.05
τ 1 prong	55.23 ± 0.36	21.75 ± 0.15	17.12 ± 0.09	15.53 ± 0.94	36.46 ± 0.15
τ ECAL Iso. $\sum p_T < 1$	71.29 ± 0.45	47.03 ± 0.38	29.33 ± 0.27	27.71 ± 2.95	38.11 ± 0.25
τ Track Iso. $\sum p_T < 1$	87.06 ± 0.39	58.31 ± 0.55	26.93 ± 0.48	36.51 ± 6.07	59.80 ± 0.40
$\cos\Delta\phi(\mu,\tau) < -0.95$	69.51 ± 0.58	60.77 ± 0.71	21.29 ± 0.85	56.52 ± 10.34	15.55 ± 0.39
$Q(\mu) * Q(\tau jet) < 0$	99.45 ± 0.11	92.99 ± 0.48	86.10 ± 1.65	76.92 ± 11.69	97.16 ± 0.45
$\not{E}_T > 30$	3.97 ± 0.29	0.6785 ± 0.16	28.19 ± 2.21	20.00 ± 12.65	83.60 ± 1.01
$P_\zeta - 0.875 P_\zeta^{vis} > -7$	89.14 ± 2.35	55.56 ± 11.71	48.72 ± 4.62	50.00 ± 35.36	54.03 ± 1.49
0 b-tagged jets	98.72 ± 0.90	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	25.87 ± 1.78

Final Selection Efficiencies

Cut/Selection	Z'(500)$\rightarrow \tau\tau$	Z'(600)$\rightarrow \tau\tau$	Z'(700)$\rightarrow \tau\tau$
$\mu\ p_T > 20$	81.76 ± 0.63	84.48 ± 0.58	86.19 ± 0.55
$\mu\ \lvert\eta\rvert < 2.1$	94.78 ± 0.40	95.37 ± 0.37	96.66 ± 0.31
$\tau\ p_T > 20$	96.53 ± 0.34	97.67 ± 0.27	97.93 ± 0.25
$\tau\ \lvert\eta\rvert < 2.1$	87.24 ± 0.63	88.49 ± 0.58	90.04 ± 0.53
τ Seed $p_T > 5$	92.77 ± 0.52	92.50 ± 0.51	93.31 ± 0.47
$\mu\ \lvert d_0\rvert < 0.2$	100.0 ± 0.00	100.0 ± 0.00	100.0 ± 0.00
$\mu\ \pi$ veto	98.35 ± 0.27	98.88 ± 0.21	99.14 ± 0.18
μ ECAL Iso. $\sum p_T < 1$	88.53 ± 0.67	88.28 ± 0.65	87.89 ± 0.63
μ Track Iso. $\sum p_T < 1$	87.55 ± 0.74	88.28 ± 0.69	87.73 ± 0.68
$\tau\ \mu$ veto	98.63 ± 0.28	98.13 ± 0.31	97.74 ± 0.33
τ 1 prong	74.64 ± 1.05	75.58 ± 0.99	76.24 ± 0.95
τ ECAL Iso. $\sum p_T < 1$	75.33 ± 1.20	76.43 ± 1.12	74.18 ± 1.12
τ Track Iso. $\sum p_T < 1$	85.17 ± 1.14	85.64 ± 1.06	84.90 ± 1.07
$\cos\Delta\phi(\mu,\tau) < -0.95$	91.17 ± 0.99	93.27 ± 0.82	94.67 ± 0.73
$Q(\mu) * Q(\tau jet) < 0$	97.21 ± 0.60	98.17 ± 0.45	96.69 ± 0.60
$\not{E}_T > 30$	75.03 ± 1.60	78.76 ± 1.40	82.51 ± 1.28
$P_\zeta - 0.875 P_\zeta^{vis} > -7$	92.18 ± 1.15	91.56 ± 1.07	92.80 ± 0.96
0 b-tagged jets	100.0 ± 0.00	99.51 ± 0.28	99.25 ± 0.33

Z' Mass (GeV/c^2)	Acceptance
350	0.0813 ± 0.0041
400	0.1025 ± 0.0047
500	0.1154 ± 0.0050
600	0.1418 ± 0.0054
700	0.1595 ± 0.0058
800	0.1673 ± 0.0059
900	0.1690 ± 0.0060
1000	0.1785 ± 0.0067

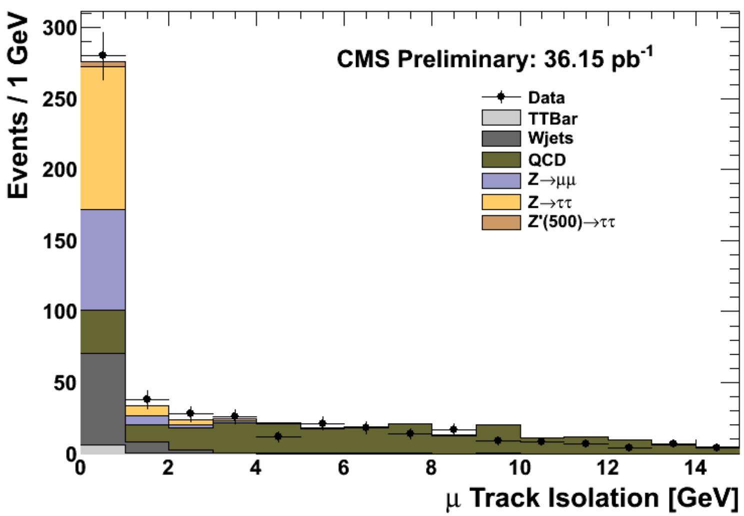
Blind Analysis & Background Estimation

- Blind analysis
  - Do not want to look at data satisfying the final selection criteria until the background contributions in the signal region have been estimated using data-driven methods
- Background Estimation
  - Do not expect MC simulation to properly model our backgrounds
  - In all cases, data-driven background estimation methods are employed by modifying the final signal selections slightly in order to obtain background enhanced regions where selection efficiencies can be measured and used to determine the expected contribution in the signal region.

QCD Extraction From Data

- Take the cuts/selections defined previously and make the following modifications:
  1) Loose μ track iso cut: iso sum $P_T < 15$
  2) Loose τ track iso cut: iso sum $P_T < 15$
  3) Remove OS requirement on μ–τ pairs
  4) Remove MET requirement
  5) Remove ζ requirement

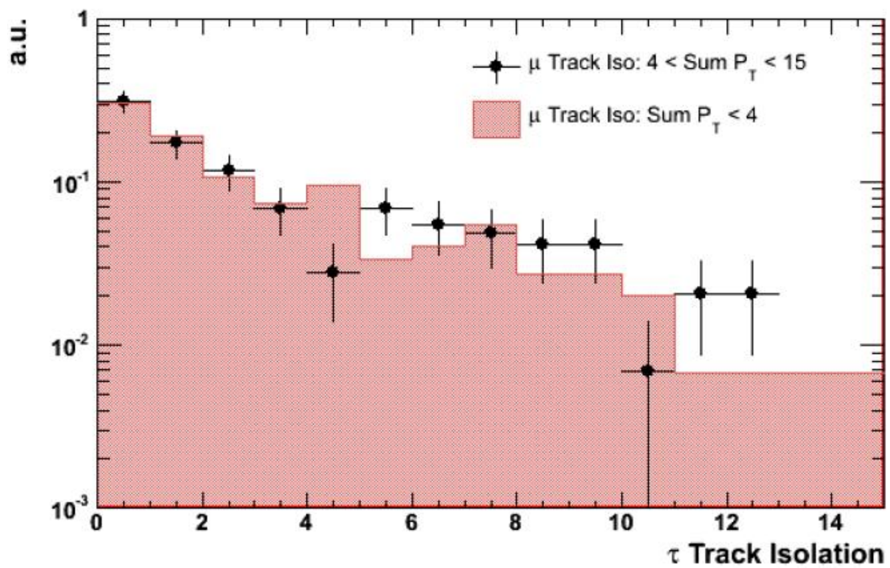
Sample	Events
Data	208
QCD	194.3 ± 17.52
$W + Jets$	0.98 ± 0.26
$t\bar{t}$	0.12 ± 0.02
$Z \rightarrow \tau\tau$	1.10 ± 0.18
$Z \rightarrow \mu\mu$	0.68 ± 0.13

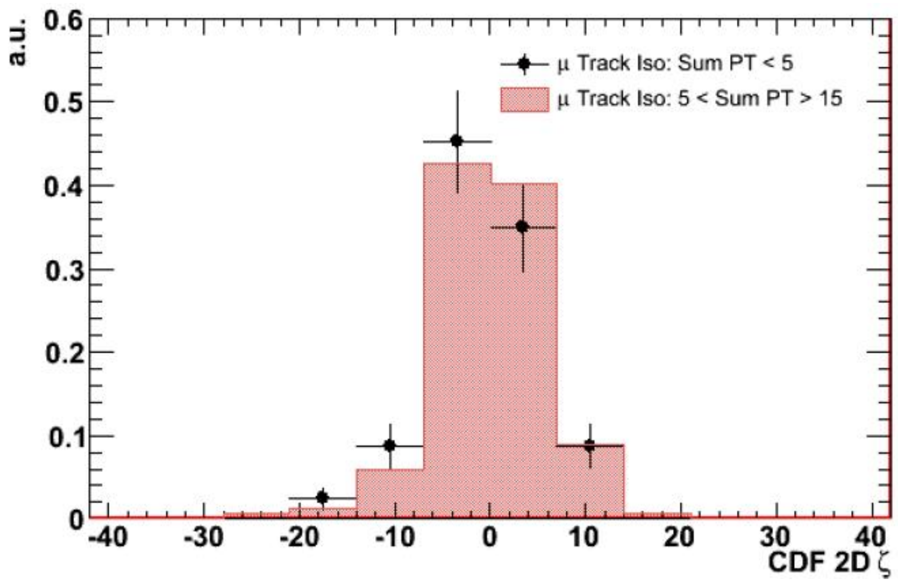


- As expected, the tail of the distribution is dominated by QCD
- How to select a pure sample of QCD?
  - μ track iso cut: $4 < \text{sum } P_T < 15$
- *Once we have obtained our pure sample of QCD events, we can extract our scale factors & QCD contribution in the signal*

QCD Extraction From Data

- Method will only work if selecting non-isolated muons does not bias the efficiencies and shapes.

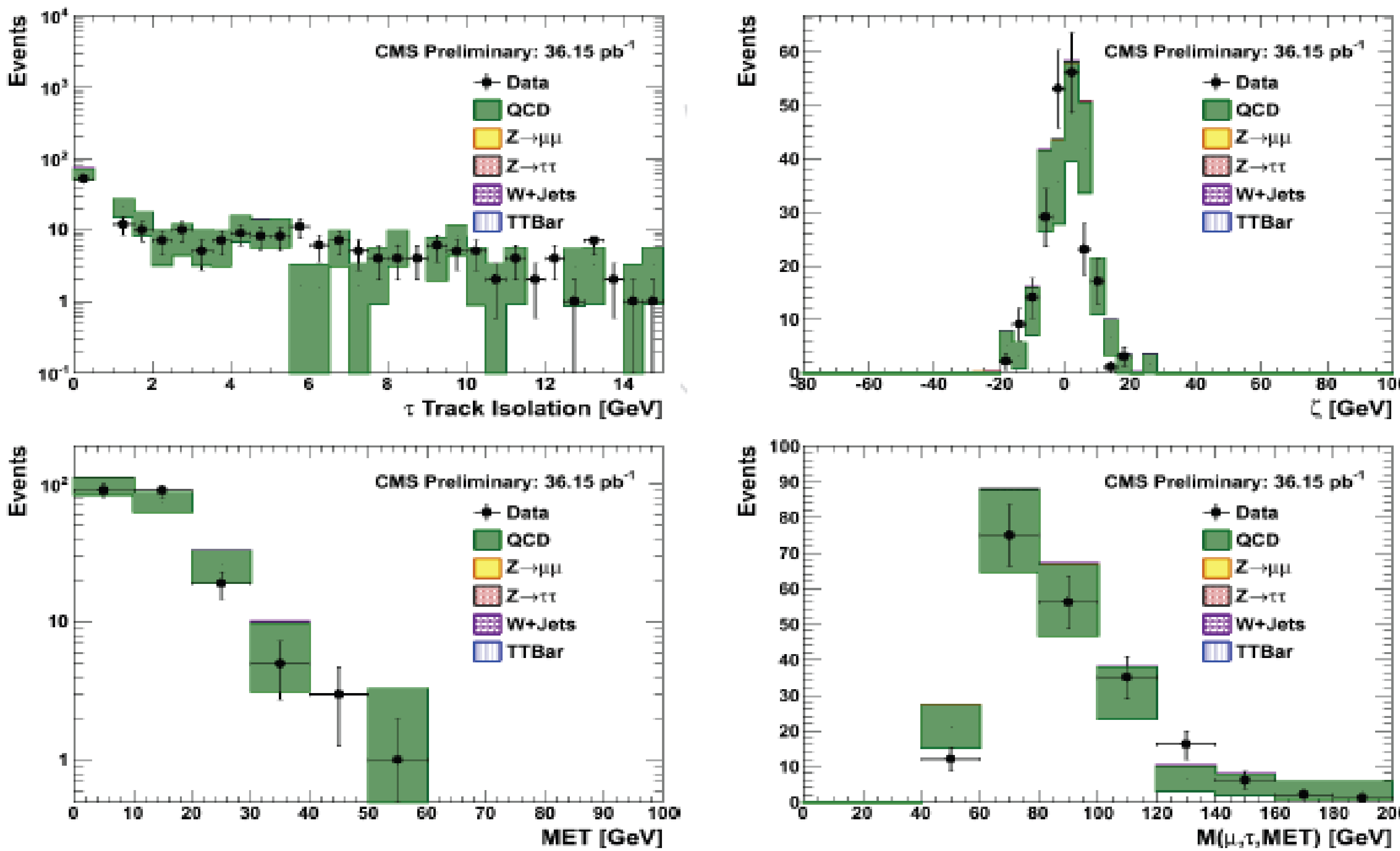




Plots shown are based on simulation. Efficiencies and shapes are not biased by the requirement of a non-isolated muon

QCD Control Region

- Let’s take a look at MC-Data comparisons in our control region



QCD in the Signal Region

- Calculate efficiencies in the control regions:

$$\varepsilon_{QCD}^{\tau \text{ Trk Iso}} = \frac{Events\ w/\ \tau\ Trk\ Iso\ Sum\ P_T < 1}{N_{QCD}^{Pure\ Sample}}$$

$$\varepsilon_{QCD}^{Met\ \&\ \varsigma} = \frac{Events\ w/\ Met > 30\ \&\ \varsigma > -7}{N_{QCD}^{Pure\ Sample}}$$

$$\varepsilon_{QCD}^{OS} = \frac{Events\ w/\ Q(\mu) * Q(\tau) < 0}{N_{QCD}^{Pure\ Sample}}$$

Cut	Data	MC
ε^{τ} Track Iso	0.245 ± 0.030	0.267 ± 0.041
$\varepsilon^{\zeta} + \not{E}_T$	0.029 ± 0.012	0.031 ± 0.016
$\varepsilon^{Q(\mu)*Q(\tau_{seed})<0}$	0.457 ± 0.035	0.527 ± 0.045
ε^{μ} Track Iso	0.177 ± 0.043	0.153 ± 0.025
$N^{[0,1]}_{\mu \text{ Track Iso}} / N^{[4,15]}_{\mu \text{ Track Iso}}$	0.304 ± 0.068	0.260 ± 0.040
Expected Number of Events	0.205 ± 0.101	1.579 ± 1.579

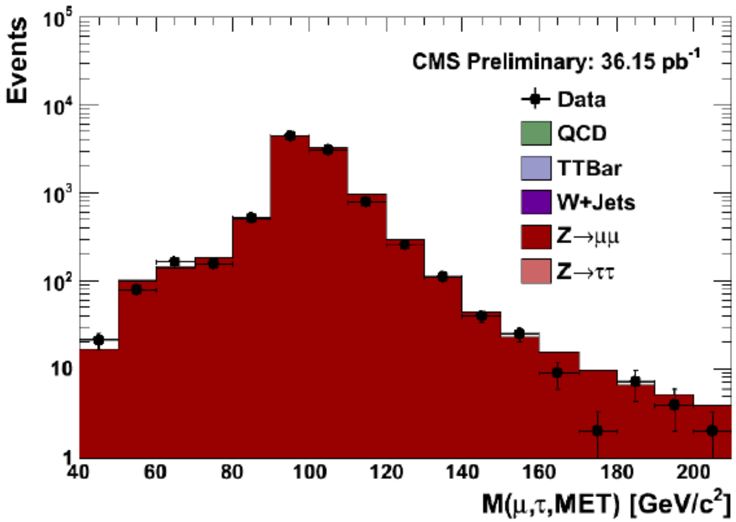
- The expected number of events in the signal region:

$$N_{QCD}^{Signal} = N_{QCD}^{Pure\ Sample} * \varepsilon_{QCD}^{Met\ \&\ \varsigma} * \varepsilon_{QCD}^{OS} * \varepsilon_{QCD}^{\tau\ Trk\ Iso} * \frac{N_{QCD}^{0 < \mu\ Trk\ Iso < 1}}{N_{QCD}^{4 < \mu\ Trk\ Iso < 15}}$$

Z→ μμ Extraction From Data

- **Take the cuts/selections defined previously and make the following modifications:**
  1) **Remove MET requirement**
  2) **Remove the muon veto on the tau leg and instead apply an anti-muon veto requirement**

Sample	Events
Data	5898
QCD	0.00 ± 1.57
$W + Jets$	0.28 ± 0.14
$t\bar{t}$	0.50 ± 0.05
$Z \to \tau\tau$	16.8 ± 0.70
$Z \to \mu\mu$	5765 ± 11.0



$$N^{signal}_{Z\mu\mu} = N^{pure}_{Z\mu\mu}\, \varepsilon_{\not{E}_T > 30}\, \varepsilon_{\mu\ \mathrm{veto}}$$

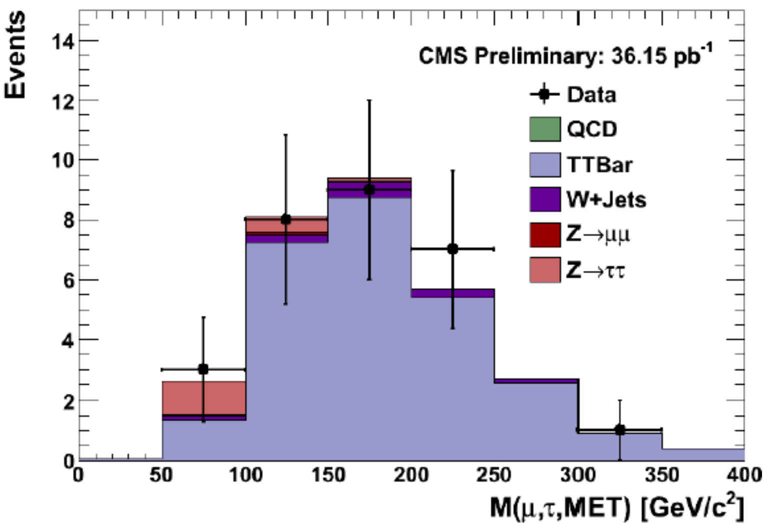
Cut	Data
$\varepsilon^{\not{E}_T}$	0.0029 ± 0.0007
ε^{μ} Veto	0.013 ± 0.0001
Expected Number of Events	0.225 ± 0.054

Not only does this region allow us to estimate the Z→$\mu\mu$ contribution, but it also validates the robustness of the muon selections and scale factors!

TTBar Extraction From Data

- **Take the cuts/selections defined previously and make the following modifications:**
  1) **Remove requirement: cosΔϕ<-0.95**
  2) **Require > 0 b-tagged jets**
  3) **Remove ζ requirement**

Sample	Events
Data	19
QCD	0.00 ± 1.57
$W + Jets$	0.28 ± 0.14
$t\bar{t}$	23.7 ± 0.34
$Z \rightarrow \tau\tau$	0.52 ± 0.12
$Z \rightarrow \mu\mu$	0.08 ± 0.05



$$P(1\ b\text{-jet}) = 2 * (1 - \varepsilon^{b\text{-tag}}) * \varepsilon^{b\text{-tag}}$$

$$P(0\ b\text{-jets}) = 1 - P(2\ b\text{-jets}) - P(1\ b\text{-jet})$$

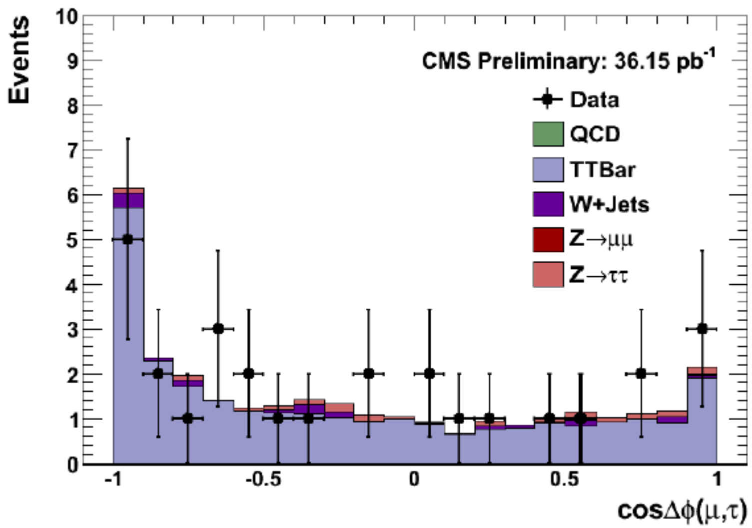
$$N_{t\bar{t}}^{Signal} = N_{t\bar{t}}^{pure} \frac{P(0\ b\text{-jets})}{P(1\ b\text{-jet}) + P(2\ b\text{-jets})} \varepsilon^{cos\Delta\phi(\mu,\tau)}, \text{ and } \zeta$$

Cut	Data	MC
$P_\zeta - 0.875 P_\zeta^{vis} > -7$ AND $cos\Delta\phi <= -0.95$	0.053 ± 0.053	0.086 ± 0.004
$\varepsilon^{b-Tagging}$	0.455 ± 0.016	0.494 ± 0.003
Probability to tag $\geq 1\ b - jets$	0.703 ± 0.025	0.744 ± 0.005
Probability to tag $0\ b - jets$	1 - (0.703 ± 0.025)	1 - (0.744 ± 0.005)
Expected Number of Events	0.425 ± 0.427	0.718 ± 0.059

TTBar Extraction From Data

- Take the cuts/selections defined previously and make the following modifications:
  1) Remove requirement: cosΔϕ<-0.95
  2) Require > 0 b-tagged jets
  3) Remove ζ requirement

Sample	Events
Data	19
QCD	0.00 ± 1.57
$W + Jets$	0.28 ± 0.14
$t\bar{t}$	23.7 ± 0.34
$Z \to \tau\tau$	0.52 ± 0.12
$Z \to \mu\mu$	0.08 ± 0.05



$$P(1\ b\text{-jet}) = 2 * (1 - \varepsilon^{b\text{-tag}}) * \varepsilon^{b\text{-tag}}$$

$$P(0\ b\text{-jets}) = 1 - P(2\ b\text{-jets}) - P(1\ b\text{-jet})$$

$$N_{t\bar{t}}^{Signal} = N_{t\bar{t}}^{pure} \frac{P(0\ b\text{-jets})}{P(1\ b\text{-jet}) + P(2\ b\text{-jets})} \varepsilon^{\cos\Delta\phi(\mu,\tau)}, \text{ and } \zeta$$

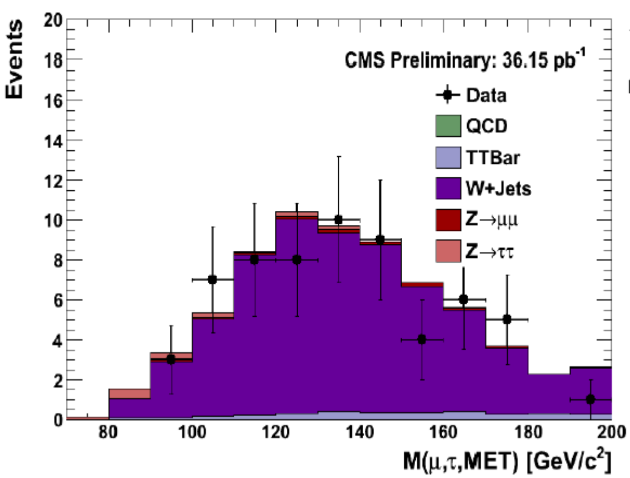
Cut	Data	MC
$P_\zeta - 0.875 P_\zeta^{vis} > -7$ AND $\cos\Delta\phi <= -0.95$	0.053 ± 0.053	0.086 ± 0.004
$\varepsilon^{b-Tagging}$	0.455 ± 0.016	0.494 ± 0.003
Probability to tag $\geq 1\ b-jets$	0.703 ± 0.025	0.744 ± 0.005
Probability to tag $0\ b-jets$	$1 - (0.703 \pm 0.025)$	$1 - (0.744 \pm 0.005)$
Expected Number of Events	0.425 ± 0.427	0.718 ± 0.059

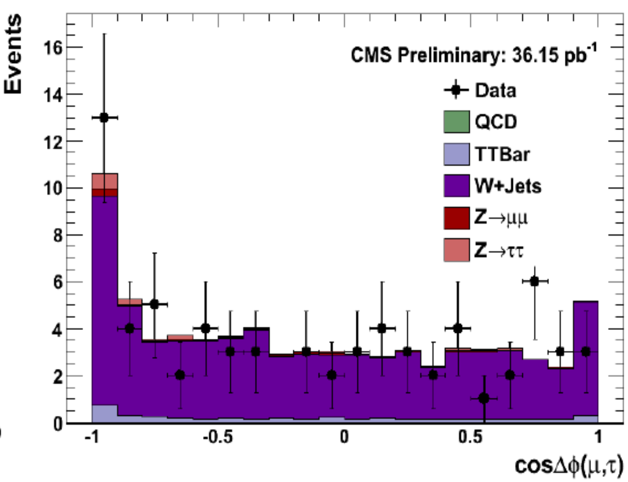
W+Jets Extraction From Data

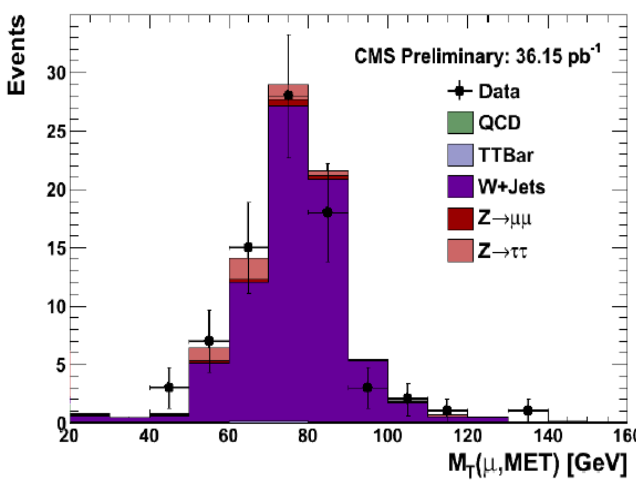
- Take the cuts/selections defined previously and make the following modifications:
  1) Remove requirement: $\cos\Delta\phi<-0.95$
  2) Remove ζ requirement
  3) Transverse mass of μ+MET : $50 < M_T < 100$

Cut	Data	MC
$P_\zeta - 0.875P_\zeta^{vis} > -7$ AND $\cos\Delta\phi <= -0.95$	0.057 ± 0.028	0.043 ± 0.006
$50 < M_T(\mu, \not{E}_T) < 100$	0.899 ± 0.034	0.898 ± 0.009
Expected Number of Events	4.44 ± 2.19	3.58 ± 0.50

Sample	Events
Data	70
QCD	0.00 ± 1.57
$W + Jets$	67.2 ± 2.17
$t\bar{t}$	4.08 ± 0.14
$Z \to \tau\tau$	1.68 ± 0.22
$Z \to \mu\mu$	1.21 ± 0.18

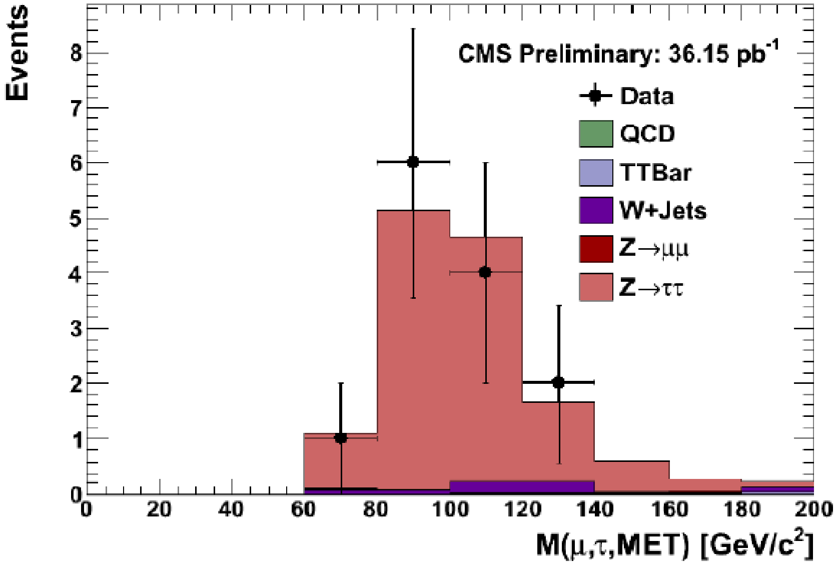






Do We See Taus?

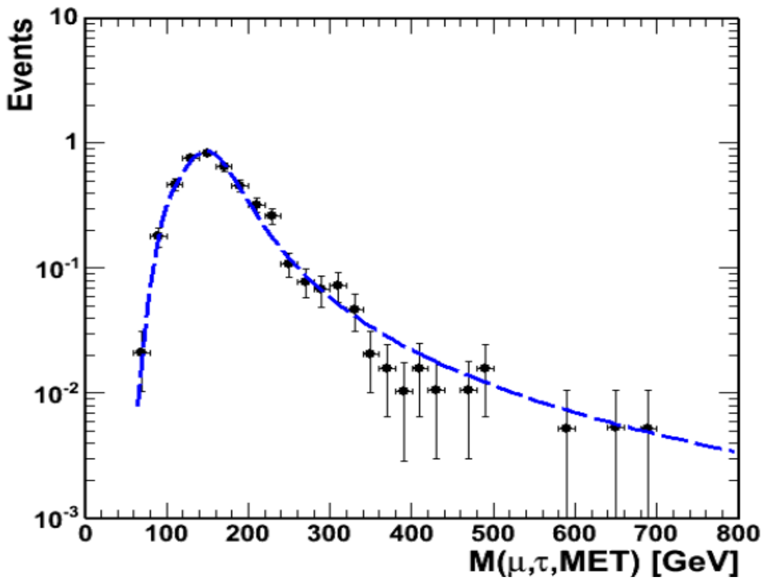
- Start with the standard signal selections and make the following modifications:
  - Loosen the muon P_T cut: μ P_T>15
  - Transverse mass cut: M_T<40

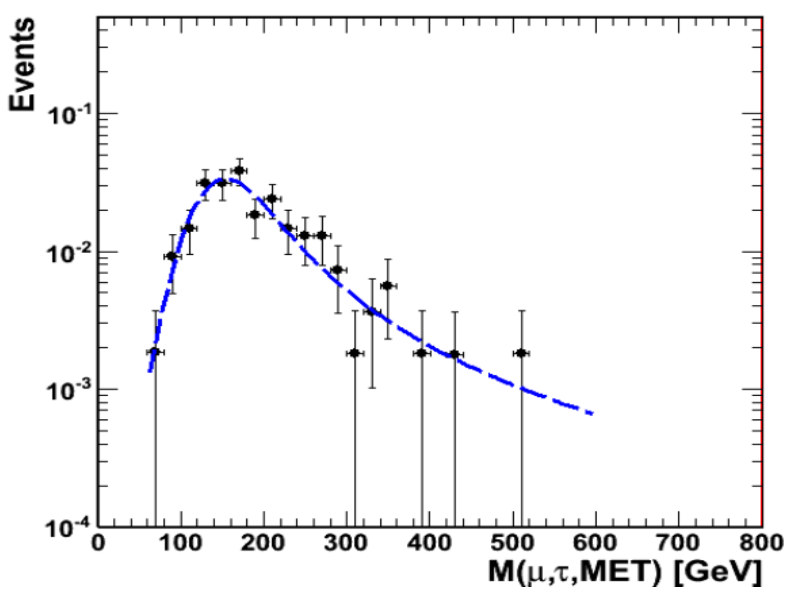


Sample	Events
Data	13
QCD	0.00 ± 1.57
$W + Jets$	0.63 ± 0.19
$t\bar{t}$	0.07 ± 0.01
$Z \rightarrow \tau\tau$	12.81 ± 0.49
$Z \rightarrow \mu\mu$	0.13 ± 0.06

Extracting the Mass Shapes

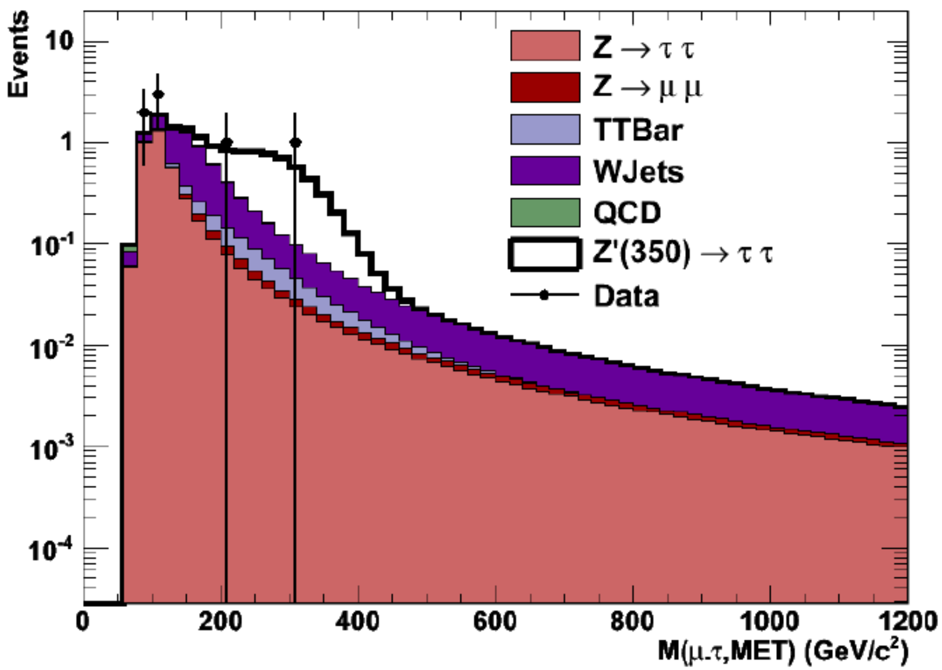
- The data-driven extraction of the mass shapes is not possible with only 36.15 pb^{-1} of data.
- However, cross-checks are made in all control regions to ensure that shapes in MC and data agree.
- Shapes are taken from MC and fit to obtain smooth trends in the high mass regions.





Open the Box

- No observed excess in the high mass region …



Sample	Events
QCD	0.205 ± 0.101
$W + Jets$	4.44 ± 2.19
$t\bar{t}$	0.512 ± 0.30
$Z \to \tau\tau$	3.978 ± 0.34
$Z \to \mu\mu$	0.225 ± 0.054
Total	9.36 ± 2.985
Observed	7

Extracting the Limits

- Likelihood is based on the Poisson probability of observing n events given an expection of m events:

$$\mathcal{L} = \prod_{i=1}^{N_{ch}} \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}$$

- The expected number of events : $\mu_i = L_i \sigma_{\mathrm{sig}} \epsilon_i + b_i$
- Systematics are incorporated as nuissance parameters :

$$\mu_i' = (1 + g_L) L \sigma_{\mathrm{sig}} (1 + f_{\epsilon i})(1 + g_\epsilon)\epsilon_i + (1 + f_{bi})(1 + g_b) b_i$$

where f and g are the correlated and uncorrelated relative errors

- The 95% confidence limit is extracted via

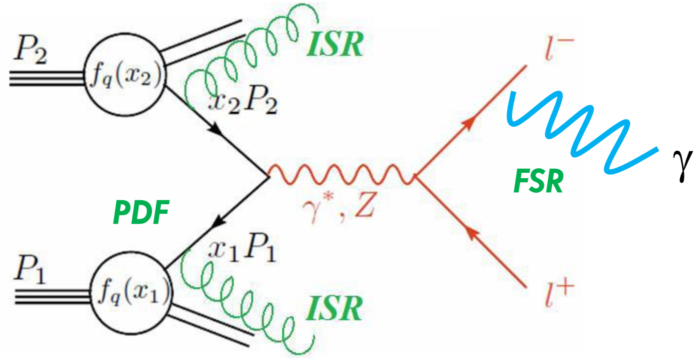
$$0.95 = \frac{\int_0^{\sigma_{95}} \mathcal{L}(\sigma) d\sigma}{\int_0^{\infty} \mathcal{L}(\sigma) d\sigma}$$

Systematics (1)

- Background estimation – major source of systematic; completely driven by the statistics in the control samples used to measure efficiencies.
- Muon momentum scale and resolution – at low p_T, it is mostly due to mis-alignment; at high p_T mostly due to the magnetic field; can be obtained using tag and probe methods and comparing the mass fits with those expected under e.g. ideal conditions.
- Tau energy scale and resolution – for particle flow taus, uncertainty in the energy scale due to mis-calibrated single particle response needed to assign extra photons or neutral hadrons when linking tracks to clusters; non-linear response of the calorimeter; double counting of energy in cases when bad matching of tracks to clusters exist; leakage of converted photons; can be measured several ways … can measure jet scale and resolution using photon+jets.

Systematics (2)

- Parton Distribution Functions (PDF) - How is the proton momentum is distributed amongst the constituent partons?
  - Affects the cross-section (goes in to theory band)
  - Affects the signal acceptance (goes in to bayesian fit)
- Initial & Final State Radiation - QCD or QED radiation is only incorporated in simulation to first order.
  - Affects the number of jets in an event
  - More jets ⟶ more likely to find a jet that passes the signal selections
  - p_T spectra of jets, leptons, …
  - Calculation of MET



$$\sum_{\sigma\lambda\lambda_\nu\lambda_l} |M^{\sigma}_{\lambda,\lambda_\nu,\lambda_l}(k,Q,p_\nu,p_l)^{(a)} + M^{\sigma}_{\lambda,\lambda_\nu,\lambda_l}(k,Q,p_\nu,p_l)^{(b)}|^2\,(1+\delta)$$

- How are systematic effects determined?
  - CTEQ PDF's are compared to default PDF's and parameterizations within
  - Events are weighted based on theoretical calculations
  - Use the samples created with "more" or "less" ISR/FSR

Systematics (3)

- Tau Identification – most significant effects:
  - Probability to reconstruct a single isolated charged hadron
  - Probability to reconstruct charged hadrons for high pT three pronged taus when tracks can be collinear.
  - Probability for charged pions or neutral pions to "leak" out of the tau signal cone and in to the isolation annulus
  - Probability for UE/PU to spoil isolation
  - Probability for UE/PU particles to fall in to the signal region and spoil the one or three prong requirements
  - Probability for a three prong tau to become a one prong tau
    - Tracks are not reconstructed
    - Some tracks fall in to the isolation region

Systematics (3)

- Tau Identification – most significant effects:
  - Probability to reconstruct a single isolated charged hadron – measured by determining the ratio of neutral charm meson decays to two or four charged particles (4%).
  - Probability for neutral pions to "leak" out of the tau signal cone and in to the isolation annulus – minimized by the use of Ecal signal ellipse
  - Probability for UE/PU to spoil isolation – obtained using dimuon events (1.8%)
  - Probability for UE/PU particles to fall in to the signal region and spoil the one or requirement (similar to isolation, but smaller due to smaller size of signal cone vs. isolation region)
  - Probability for a three prong tau to become a one prong tau (0.74%)
    - Studied with MC by matching generator level taus to reconstructed taus and determining the number of generator level three prong taus that became one prong reco taus.

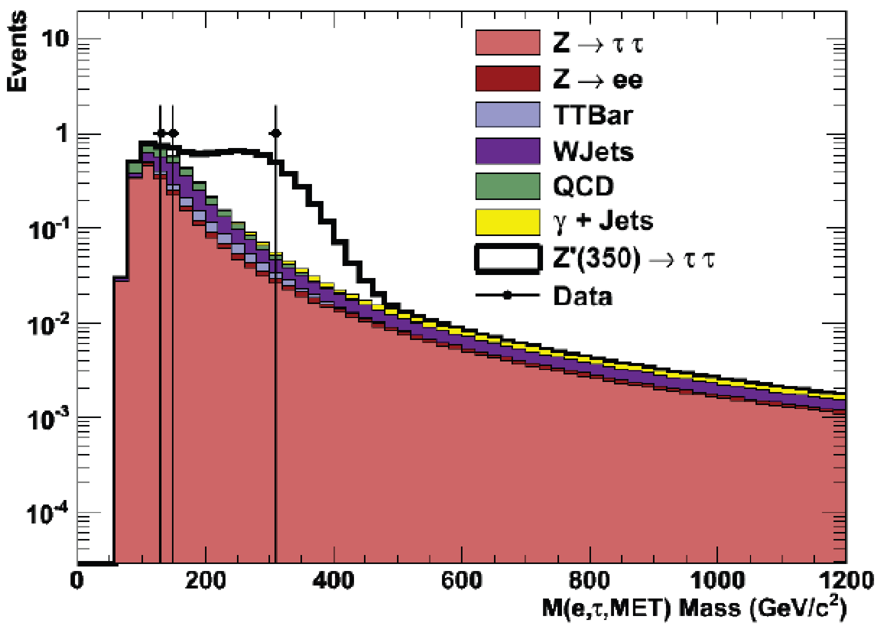
Tau ID systematics expected to be ~ 5%. However, to be conservative, we use a value of 7% obtained using a clean sample of $Z \rightarrow \tau\tau \rightarrow \mu\tau$ events, fixing the cross-section to the $Z \rightarrow ee/\mu\mu$ measured cross-section, and fitting the tau ID efficiency.

Summary of Systematics

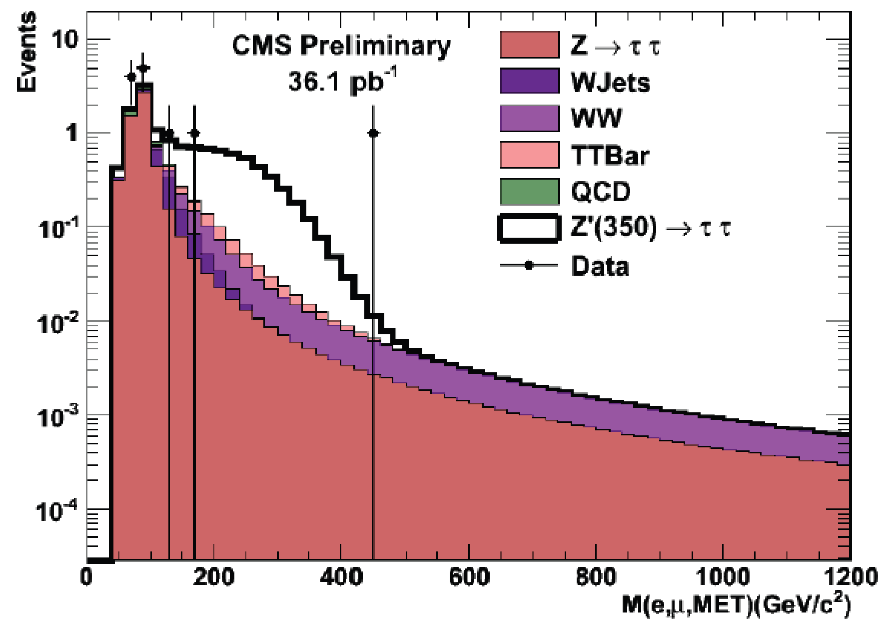
Source of Systematic	$\mu\tau_h$	$e\tau_h$	$e\mu$	$\tau_h\tau_h$
Luminosity	4%	4%	4%	4%
Muon Trigger	0.55%	—	0.55%	—
Electron Trigger	—	0.39%	—	—
Tau Trigger	—	—	—	4%
Muon ID	0.59%	—	0.59%	—
Electron ID	—	1.37%	—	—
Tau ID	7.0%	7.0%	—	7.0%
Parton Distribution Functions	3.96%	3.96%	3.96%	3.96%
Initial State Radiation	2.14%	2.14%	2.14%	2.14%
Final State Radiation	1.7%	1.7%	1.7%	1.7%
Tau Energy Scale (3%)	2.1%	2.1%	—	2.1%
Electron Energy Scale (1%)	—	1.8%	1.8%	—
Muon Momentum Scale (1%)	1%	—	1%	—
Tau Energy Resolution	Negligible	Negligible	Negligible	Negligible
Electron Energy Resolution	Negligible	Negligible	Negligible	Negligible
Muon Momentum Resolution	Negligible	Negligible	Negligible	Negligible
Background Estimation	33%	45%	14%	28%

Additional Final States

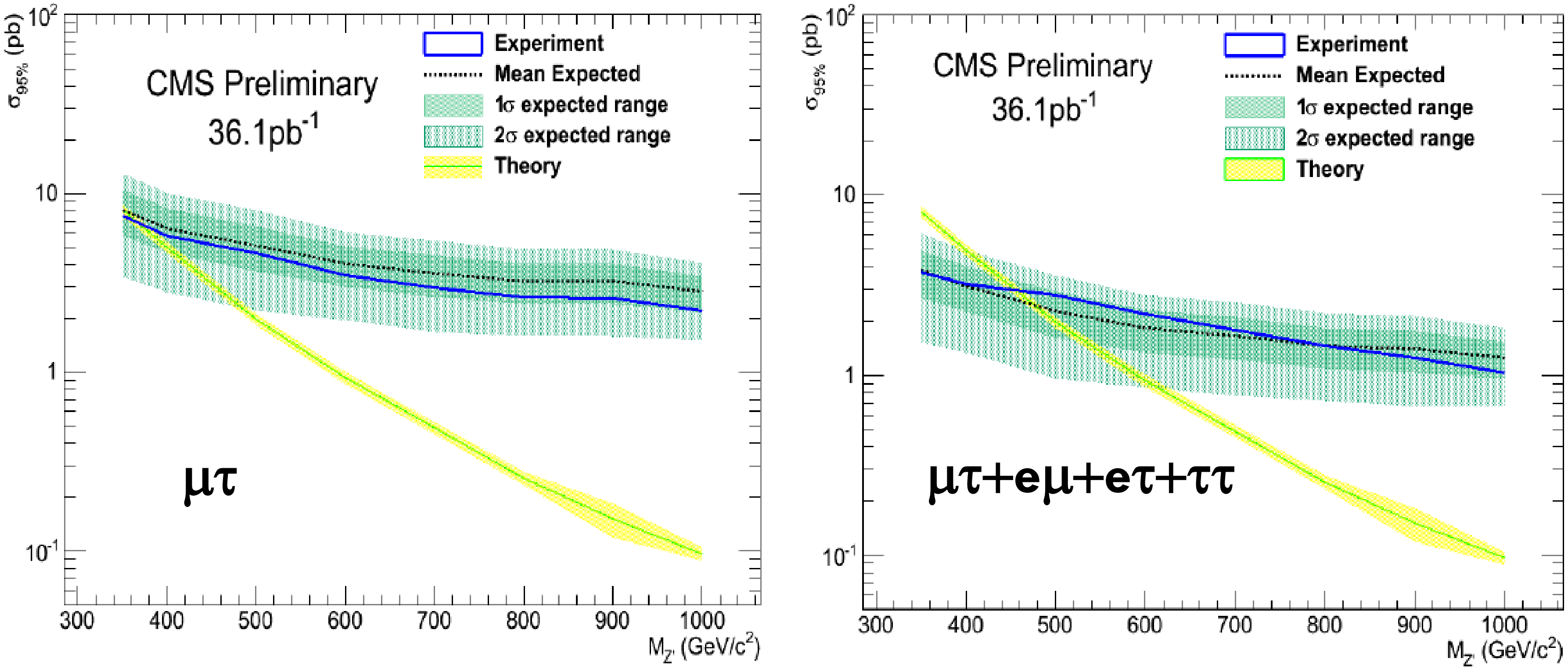
Andres Florez (Vanderbilt)



Eduardo Luiggi (Colorado)



Results



A sequential Z' with mass less than 468 GeV/c² can be excluded at 95% C.L.

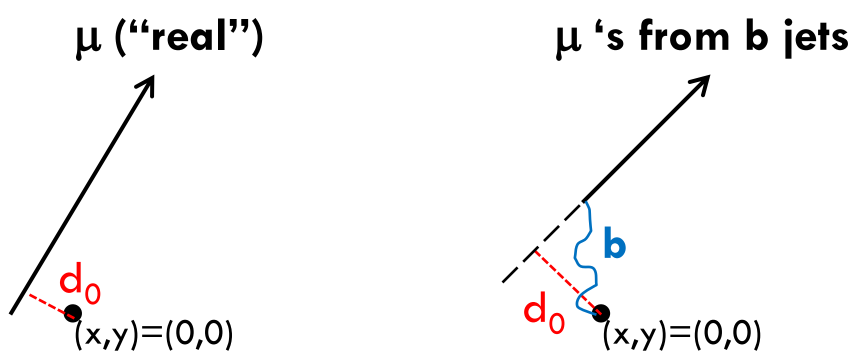
Summary

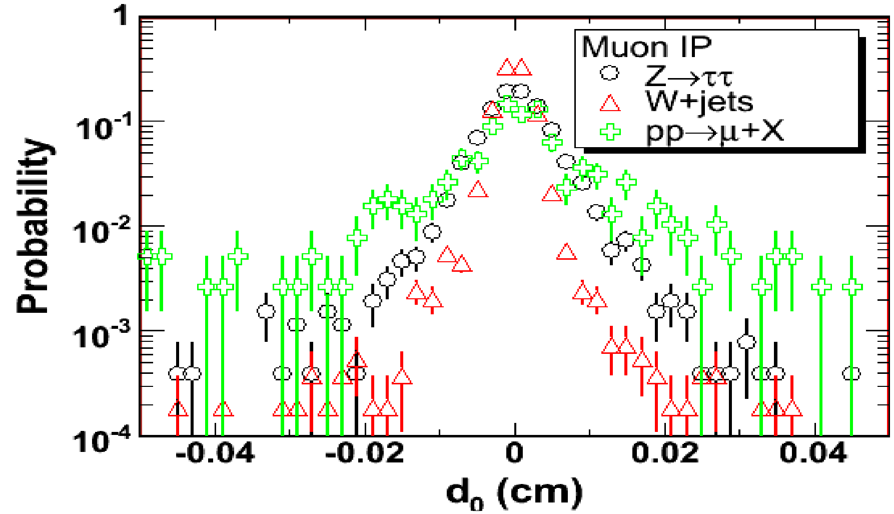
- Have provided a general search for new heavy resonances decaying to a pair of tau leptons using 36.15 pb^{-1} of CMS data collected in 2010.
- No excess has been observed ….
- Have used a sequential Z’ as a benchmark
- Have exclude a sequential Z’ with mass less than 468 GeV/c^2 , exceeding the sensitivity achieved by CDF in 2005.

BACKUP SLIDES

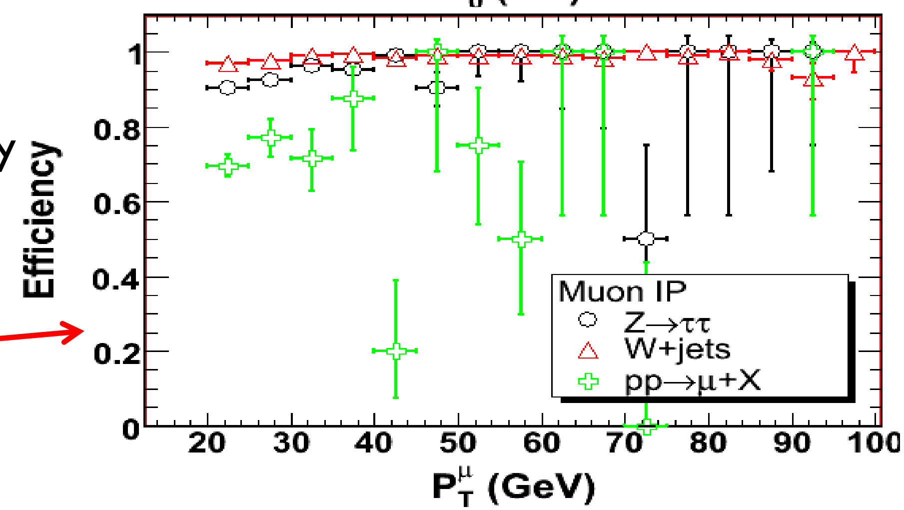
Muon Impact Parameter

Cross-sectional view of the detector (x-y plane)





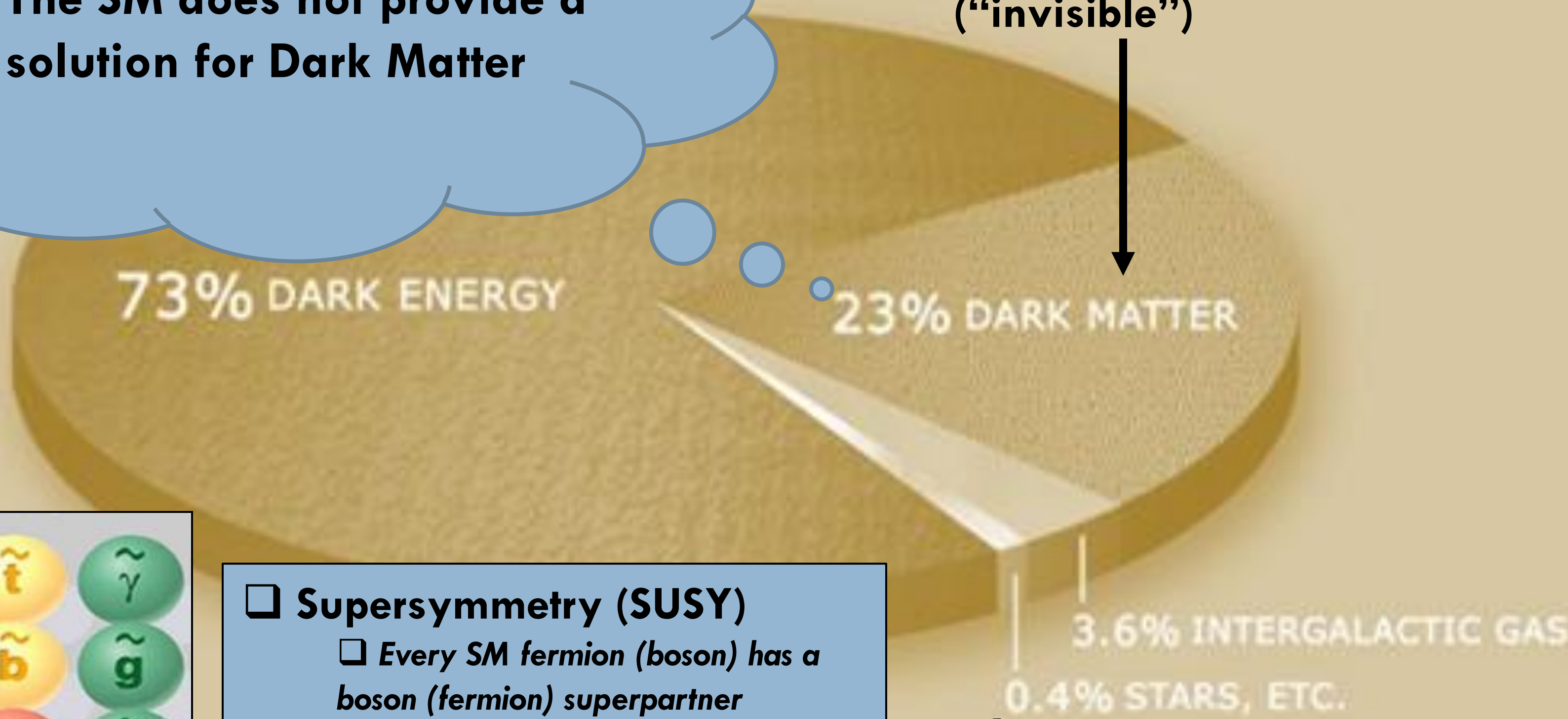
- Large contributions from QCD $b\bar{b}$ pairs
- Can we remove QCD events w/ b jets by looking at the μ impact parameter (IP)?
- Define our selection:
  - $|d_0| < 0.01$ cm



Signs of Physics Beyond the SM

The SM does not provide a solution for Dark Matter

Does not interact with light ("invisible")

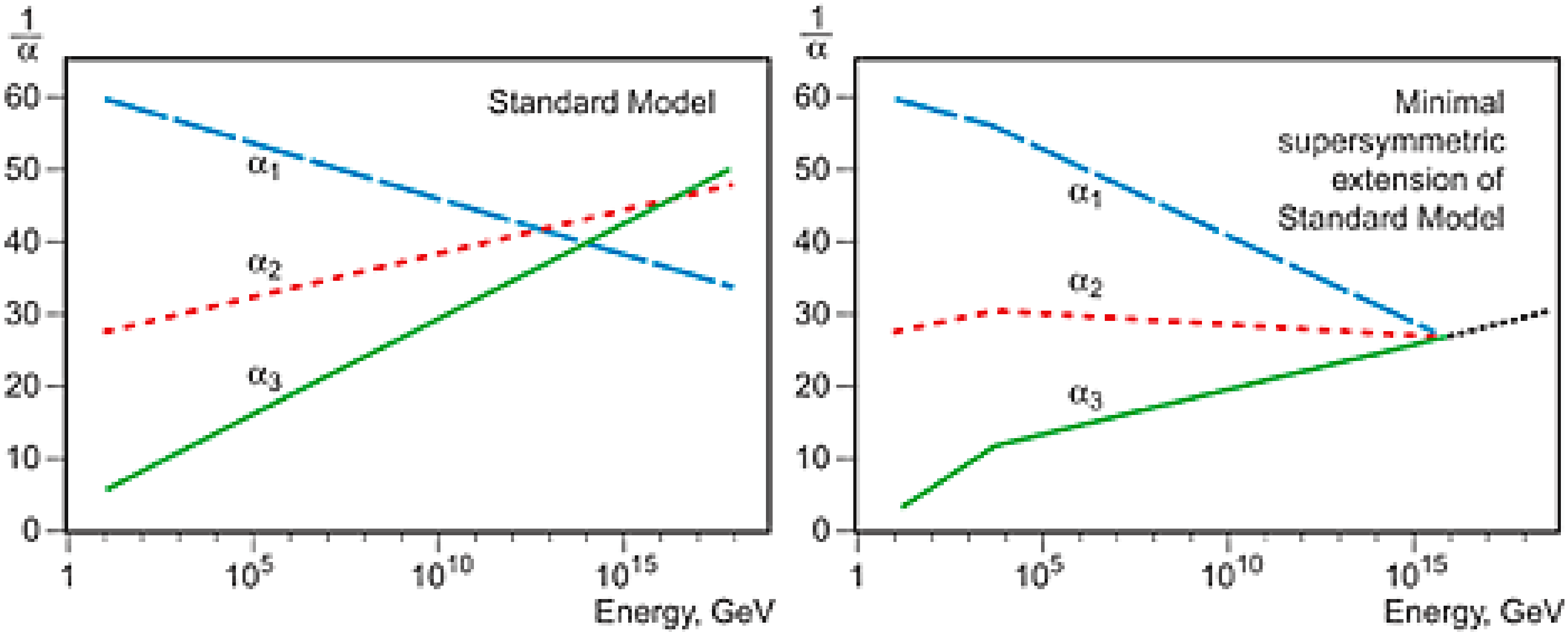


"Normal" Matter

- **Supersymmetry (SUSY)**
  - ***Every SM fermion (boson) has a boson (fermion) superpartner***
- **SUSY extensions of the SM**
  - ***Lightest Supersymmetric Particle (LSP) is a natural CDM candidate***

Signs of Physics Beyond the SM

- Mathematical extensions of the SM lead to the unification of the coupling constants (forces) at energies characteristic of the Big Bang
- These so called Grand Unified Theories (GUT) give rise to new phenomena



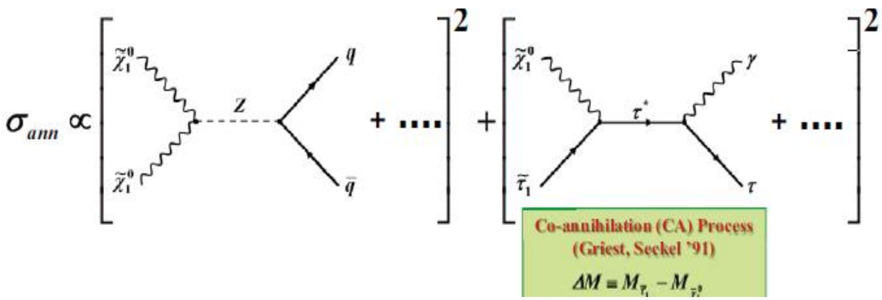
Dark Matter Relic Density

❖ ***We wanted to design techniques and methods to extract the dark matter relic density using events with final states containing taus.***

❖ Relic density calculation depends on the particular case of interest:

Standard Cosmology

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right)$$



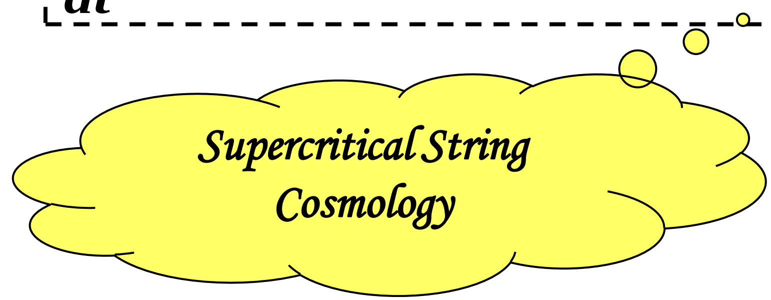
[Case 1] "Coannihilation (CA)" Region

Arnowitt, Dutta, Gurrola, Kamon, Krislock, Toback, **PRL100 (2008) 231802**

For earlier studies, see Arnowitt *et al.*, PLB 649 (2007) 73; Arnowitt *et al.*, PLB 639 (2006) 46

Non-Standard Cosmology

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right) + S(\dot{\phi})$$



e.g., Rolling dilation in Q-cosmology

[Case 2] "Over-dense" Region

Dutta, Gurrola, Kamon, Krislock, Lahanas, Mavromatos, Nanopoulos

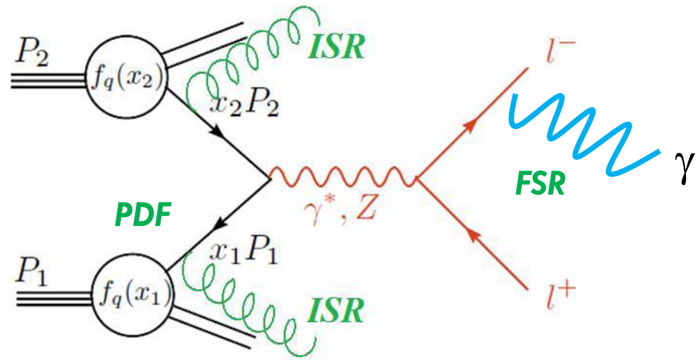
PRD 79 (2009) 055002

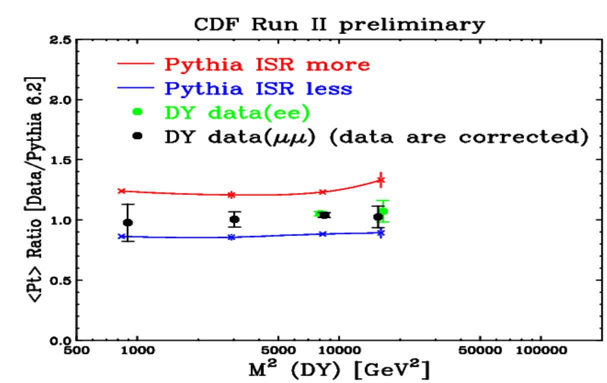
Systematics

- Due to our imperfect knowledge of some part of the analysis, we must allow measurements to fluctuate in a manner dictated by experiment.
- Some examples:
  - Parton Distribution Functions (PDF):
    - How is the proton momentum is distributed amongst the constituent partons.
  - Initial/Final State Radiation (ISR and FSR):
    - QCD or QED radiation is only incorporated in simulation to first order
- Ways to study/incorporate them:
  - Can be completely theoretically driven

$$\sum_{\sigma\lambda\lambda_\nu\lambda_l} |M^{\sigma}_{\lambda,\lambda_\nu,\lambda_l}(k,Q,p_\nu,p_l)^{(a)} + M^{\sigma}_{\lambda,\lambda_\nu,\lambda_l}(k,Q,p_\nu,p_l)^{(b)}|^2\,(1+\delta)$$

  - Drell-Yan events: $\mu+\mu$ mass vs. $P_T(\mu\mu)$





Y. Kim & U. Yang, *CDFR6804, April 12, 2004Kyoko*