Searches with Taus: Experimental Challenges

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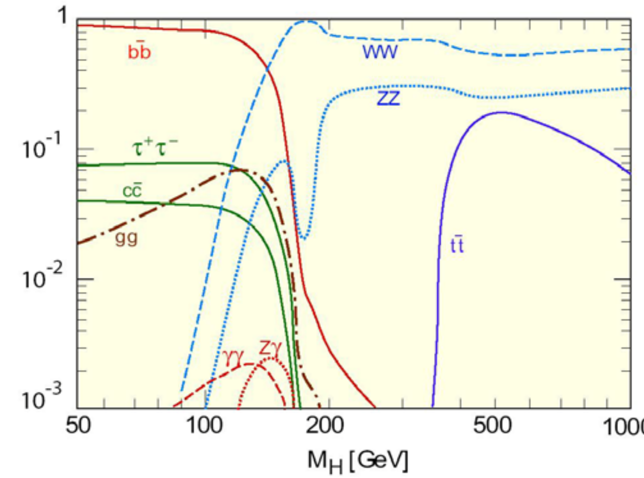
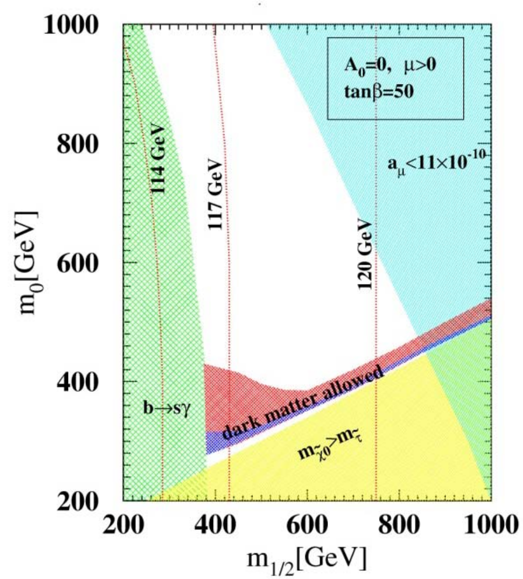
Motivation for Taus

- Light SM higgs discovery:
  - Second highest BR after b's
    - Cleaner signatures
  - Understanding higgs:
    - Verifying fundamental $V_{hff} \sim m_f$ prediction requires two channels:
    - $h \rightarrow \gamma\gamma$ and $h \rightarrow \tau t$
- If nature chose SUSY, taus even more important:
  - Co-annihilation region: SUSY cascades contain taus
    - Easy to confuse with jets
  - Higgs: enhancement in cross-sections, additional heavy higgs bosons can be directly observed
    - H, H+, LR H++, NMSSM a_1





Hadronically Decaying Taus

- Tau branching fractions:
  - BR($\tau \rightarrow \mu\nu\nu$)=BR($\tau \rightarrow e\nu\nu$)≈18%
  - BR($\tau \rightarrow$hadrons+ν)≈64%
- Many potentially interesting signatures have 2-4 tau leptons in the final state leading to some variety in possible combinations

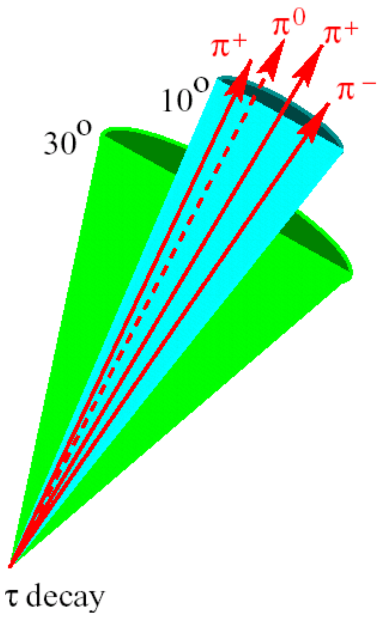
$\tau\tau$ Channel	BR
ee	3%
$\mu\mu$	3%
$e\mu$	6%
$e\tau_h$	23%
$\mu\tau_h$	23%
$\tau_h\tau_h$	42%

- Lepton-only channels may be cleaner, but hadronically decaying tau's share is too large to ignore
- For channels with more taus, fraction of purely leptonic decays will be much less

Reconstruction and identification Techniques

Experimental Challenge

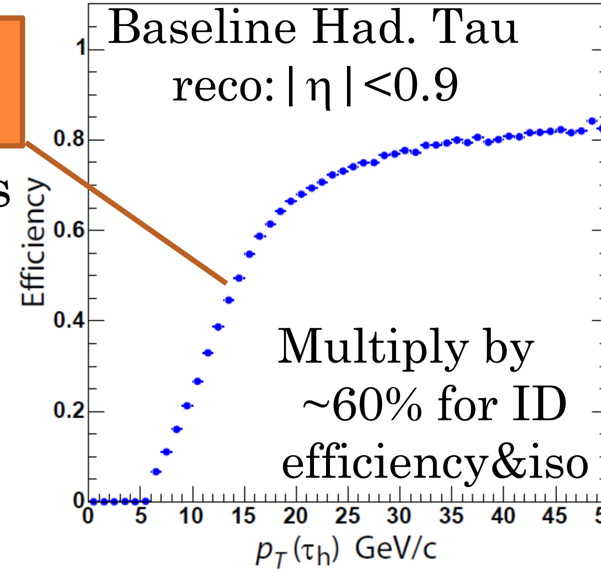
- Visible decay products of taus are soft due to escaping neutrinos:
  - Requires low thresholds to preserve acceptance
  - True for both light higgs and SUSY searches and also for important calibrations samples (Z's, W's)
- Multi-jet background for hadronic taus is high:
  - Fake rate is at least 1-2 orders of magnitude higher than for e or μ
- Typical hadronic tau ID strategy:
  - Look for narrow energetic isolated jets
    - At least one relatively high p_T particle (track), isolation, low multiplicity and narrow shape of the jet core
    - Implementations can vary

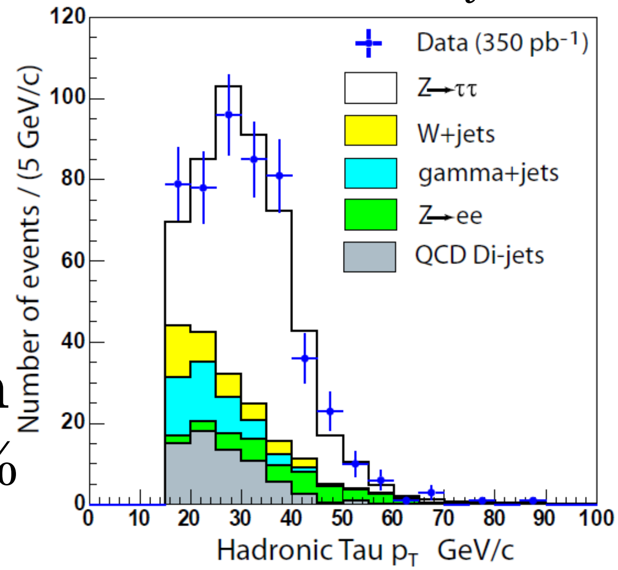


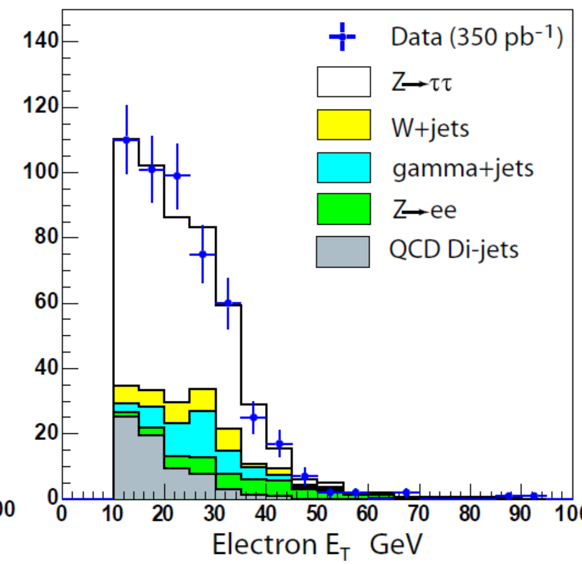
An Illustration from CDF: Z→ττ Cross-Section

Seed track p_T>5 GeV

- Channel with e+τ_{had}
  - Having electron reduces backgrounds by ~x10 compared to $\tau_{had}\tau_{had}$
- Fairly harsh isolations on electron and tau to lower backgrounds:
  - Electron ID ~70% due to isolations
    - Typically ~90% in electroweak analyses
- Despite all, background contamination is large: ~40%
- Signal selection efficiency ~1.6%





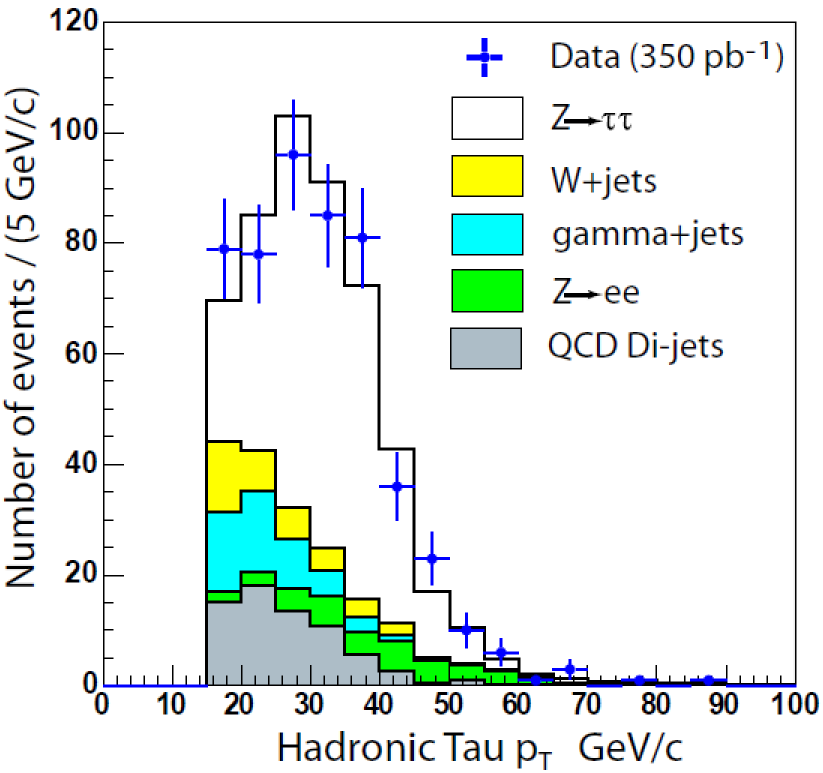


Tau Reconstruction and ID: Wishes and Lessons

Desires	Constraints
Low p_T thresholds to keep acceptance high as escaping neutrinos soften the spectrum	Jet backgrounds exponentially increase towards low p_T
Keep reconstruction seed thresholds low to maintain high efficiency at low p_T •Important for Higgs, could be critical for SUSY	Jet backgrounds grow fast with lower seed requirements
Decrease inefficiency of ID (dominated by isolations)	Jet backgrounds grow x5-10 faster than signal efficiency
Decrease backgrounds	Efficiency is already low, need new handles on backgrounds •Does not have to be just tau ID, e.g. event topology cuts can help just as well

Tau Energy Measurement

- Jet backgrounds generally fall steeper than signal
  - See plot on the right
- Accurate measurement of tau jet energy aids in discriminating from jets
  - It keeps shapes different and prevents large backgrounds on the left from entering the picture
- Can benefit from Particle Flow like algorithms

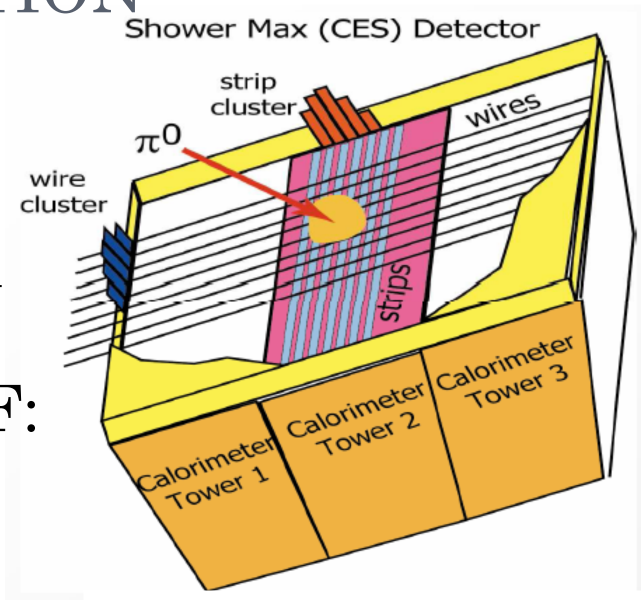


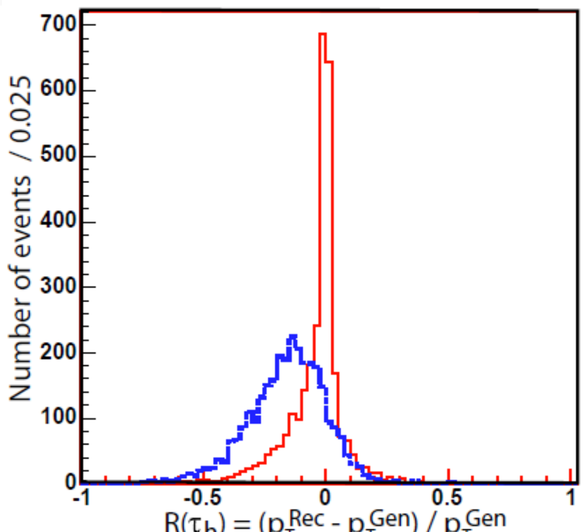
Particle Flow

- Particle Flow idea is based on reconstructing individual particles by combining best available measurements from across the detector
  - Standard jet reconstruction often rely on calorimeters only, yet the momentum of a charged pion in a jet can be much better measured in the tracker
- Three steps: break complex objects and energy deposits into particles, measure momentum of each particle, then put things back together
  - The challenge is to correctly divide energy deposits and make all pieces work together
- CMS is blessed with a beautiful and powerful PF algorithm
  - Not many realize that e.g. CDF has been using a PF tau reconstruction for already well over a decade

CDF PF Tau Reconstruction

- Tau decay products consist mainly of $\pi^{\pm}$'s and π^{o}'s
  - Need to separate their deposits in ECAL to measure photon E
- CDF is highly not optimal for PF:
  - Too large calorimeter towers ($\Delta\eta\times\Delta\varphi\approx0.1\times0.25$)
  - Cf. typical tau size $\Delta R\sim0.07$
  - ECAL deposits can't be separated
- Poor man's solution:
  - Count photons in Shower Max detector and subtract expected charged pion contribution on average + "ad hoc corrections"

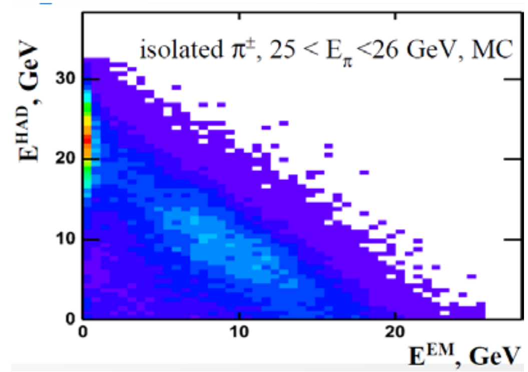


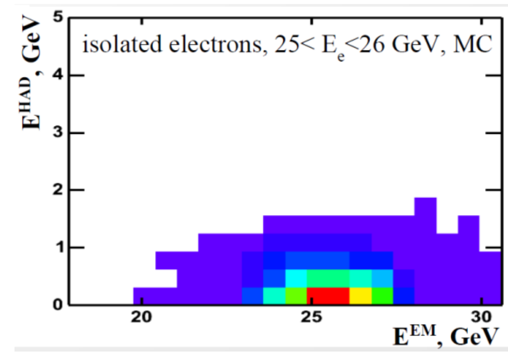


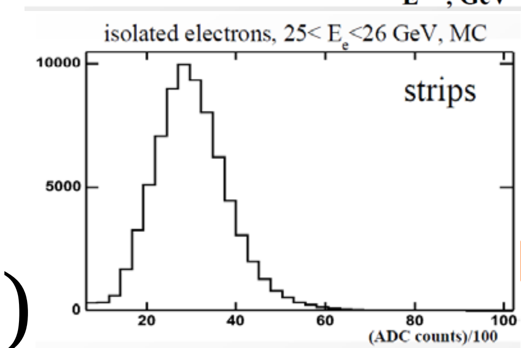
CDF Likelihood Based Tau PF

- A better approach is to build a consistent framework for statistical separation of the deposits
- Build Probability Density Functions (PDF) for calorimeter responses for pions and electrons vs true p_T:
  - 2D ECAL vs HCAL (they are correlated)
  - 1D ShowerMax(turns out it can measure energy w/ $\Delta E/E \sim 30\%$ if well calibrated)
- Next, for a given hypothesis of tau particle content and momenta build likelihood of the observed detector responses:

$$L(\vec{p}_i) = PDF(\vec{p}_i \mid E_j^{dep})$$

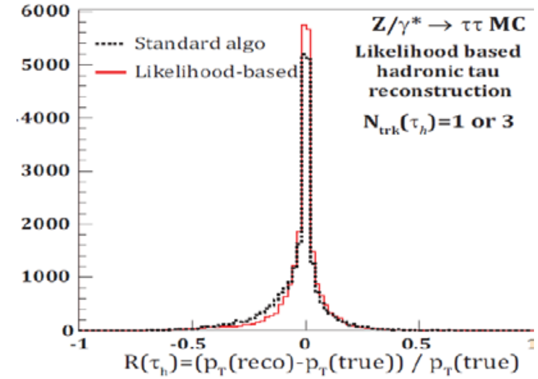


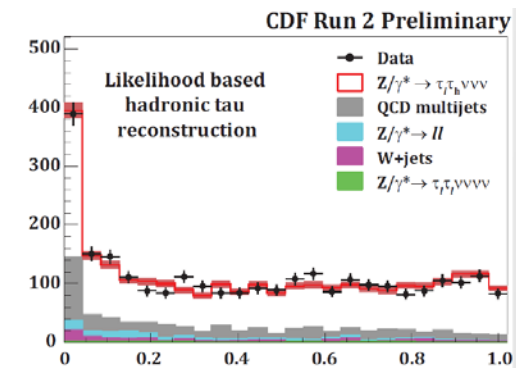


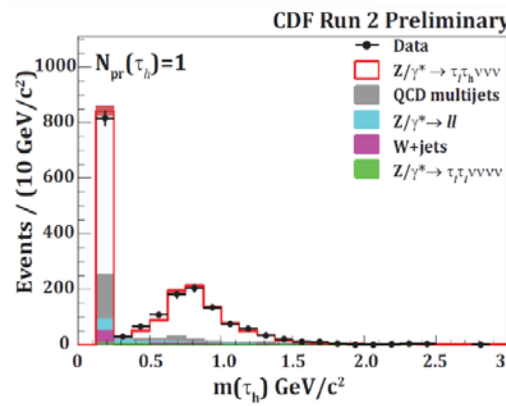


CDF Likelihood-Based Tau

- Improved tau energy resolution
- Not even the best part
  - Several new Tau ID knobs
  - Energy dependent p-value, improved energy profile, tau invariant mass
  - Estimator for energy uncertainty (separate golden taus from ok taus)
  - Steeper falling jet backgrounds (due to better resolution)
- As a bi-product, found CDF HCAL energy scale to be off by ~15%
  - For at least 10 years, maybe 20
- All this will go into the new CDF high luminosity Higgs search

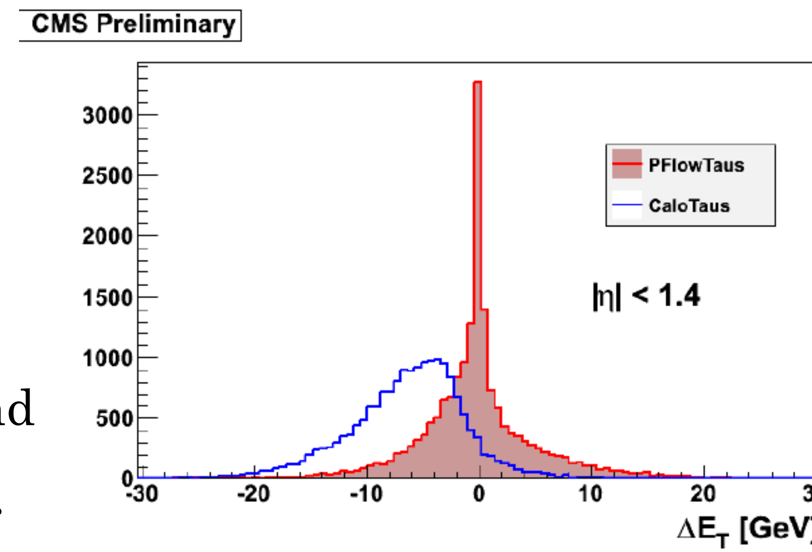


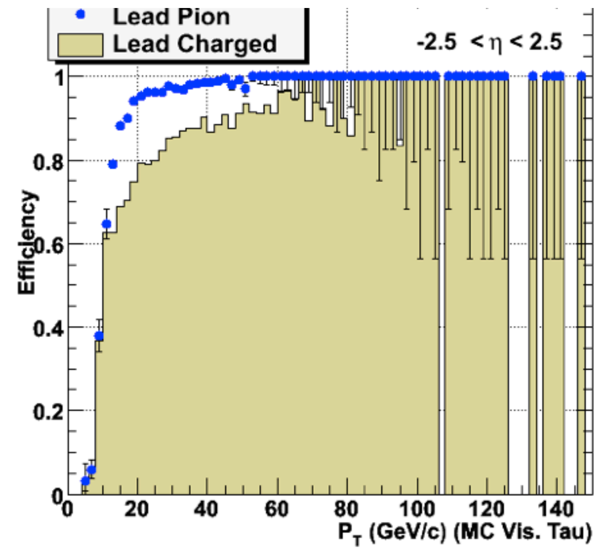




CMS PF Based Tau Reconstruction

- Seeded by generic PF jets
  - Inherits excellent energy resolution
  - CMS is almost as if it was built for PF
- Followed by Clustering
  - Particles assigned to the tau and isolation regions
    - Some variations – will talk later
- One improvement is adding photon based seeding
  - Appreciable improvement in low momentum efficiency
    - Low p_T taus are important in SUSY
  - Came with surprisingly little overhead in background rates



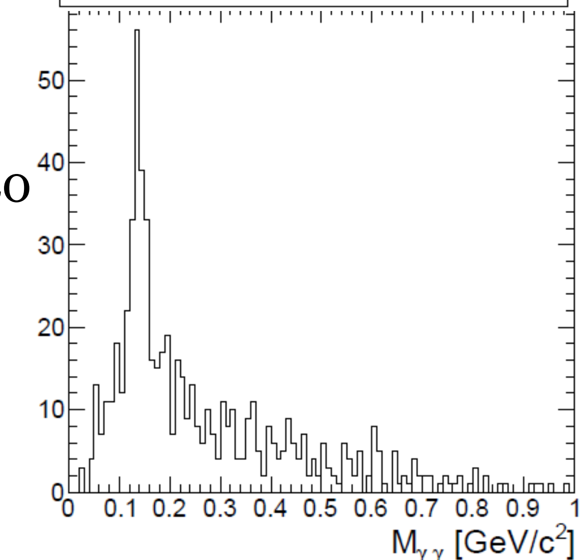


S. Gennai

CMS PF Tau: Decay Mode Classification

- Classify candidates according to known tau decay modes
  - A clever idea b/c different modes have different levels of background
  - More knobs to optimize efficiency versus backgrounds
- A couple of methods now combined into a single common scheme
  - One has an additional recovery for conversion electrons from photons bending in the magnetic field

Decay Mode	Branching ratio(%)
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	17.4
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	17.9
$\tau^- \to h^- \nu_\tau$	11.6
$\tau^- \to h^- \pi^0 \nu_\tau$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	10.8
$\tau^- \to h^- h^+ h^- \nu_\tau$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$	4.8
other	1.7

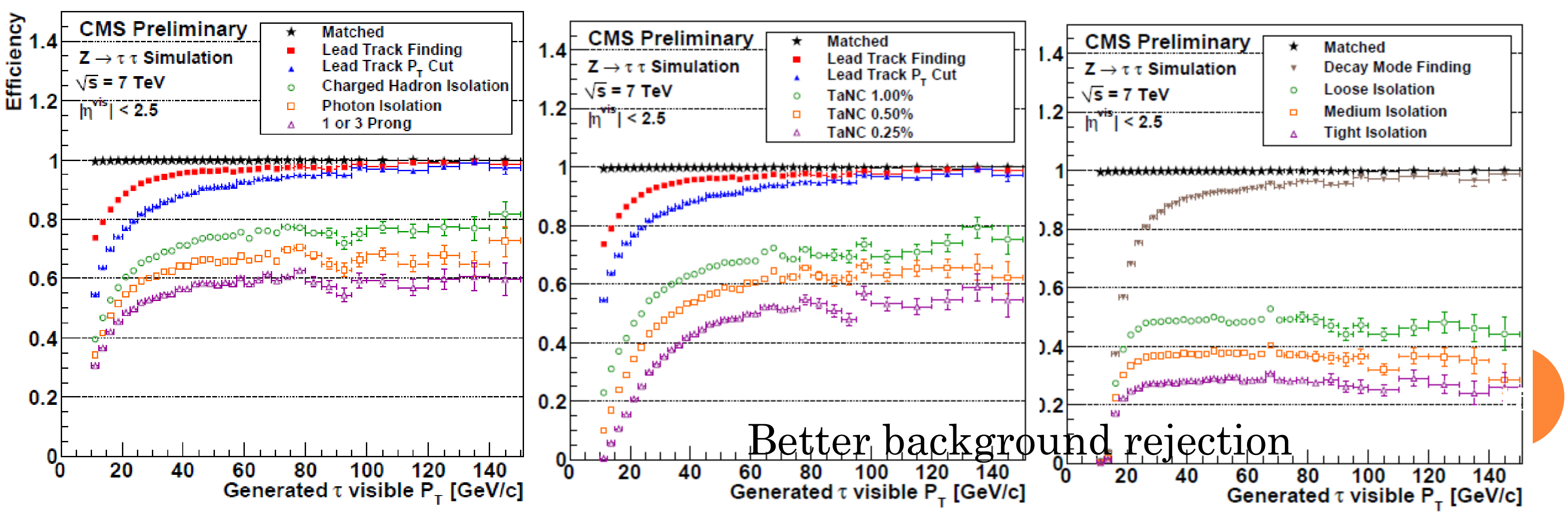


M. Bachtis, E. Friis et al

True decay mode	Reconstructed Decay Mode					
	$\pi^- \nu_\tau$	$\pi^- \pi^0 \nu_\tau$	$\pi^- \pi^0 \pi^0 \nu_\tau$	$\pi^- \pi^+ \pi^- \nu_\tau$	$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$	Other
$\pi^- \nu_\tau$	16.2%	1.0%	0.1%	0.1%	0.0%	0.3%
$\pi^- \pi^0 \nu_\tau$	10.7%	21.4%	3.6%	0.2%	0.1%	1.9%
$\pi^- \pi^0 \pi^0 \nu_\tau$	1.8%	7.1%	4.4%	0.1%	0.0%	1.5%
$\pi^- \pi^+ \pi^- \nu_\tau$	0.9%	0.2%	0.0%	11.5%	0.6%	5.4%
$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$	0.1%	0.3%	0.0%	3.2%	2.9%	2.7%

CMS PF Tau: Identification Methods

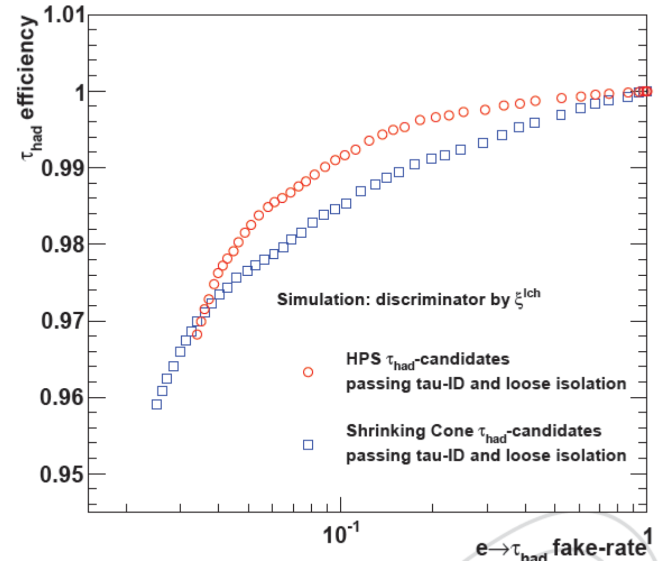
- Two and a half methods:
  - Traditional cone based algorithm – more of a base for further more advanced methods
  - TaNC: NN-based algorithm built on top of cone based
  - HPS: inside-out tau reconstruction, more cut-based
- Performance:

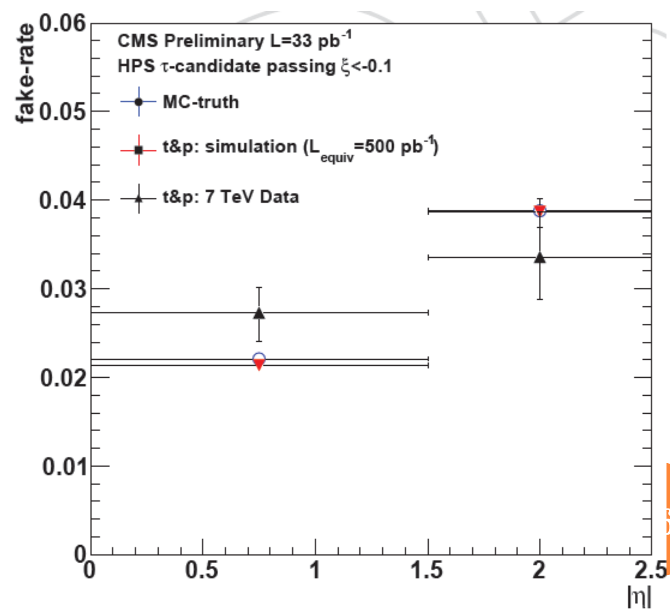


Better background rejection

CMS PF Tau: Electron Rejection

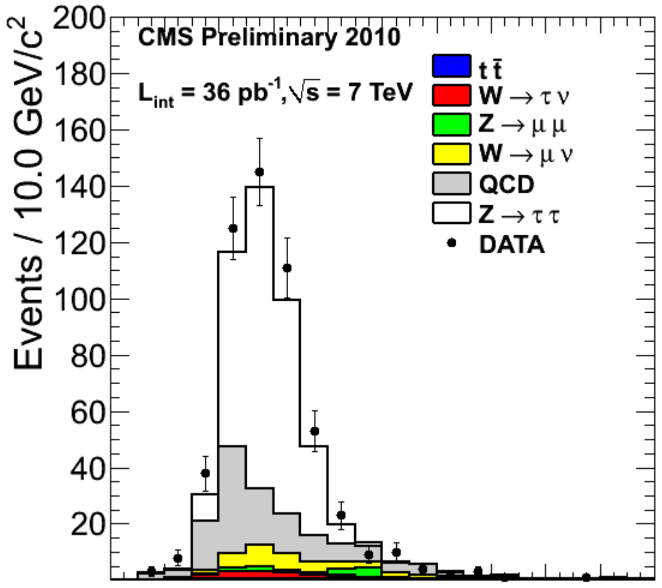
- After you are done fighting jet backgrounds, an unpleasant surprise:
  - Electrons are "perfect taus"
  - Some are easy to remove, but there is a stubborn component when an electron undergoes strong brem
- Multivariate discriminator to distinguish
  - Rejection power in data is in reasonable agreement with simulation
    - Z→ee data w/ tag&probe

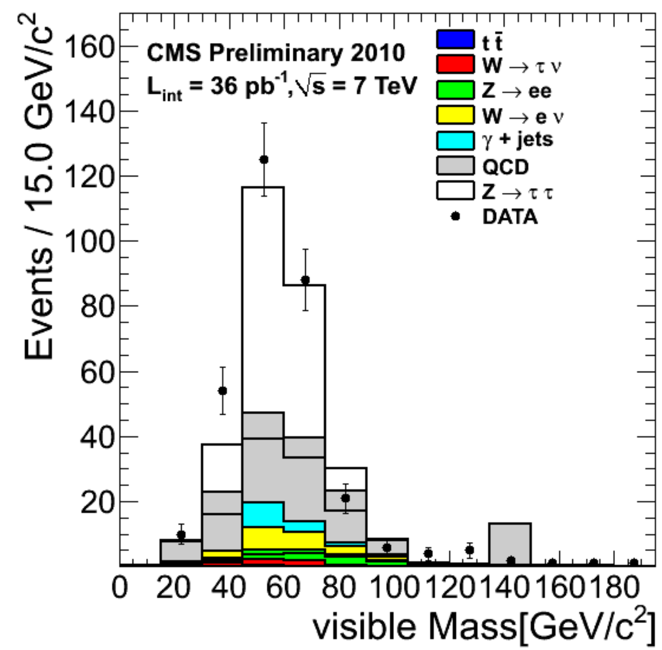


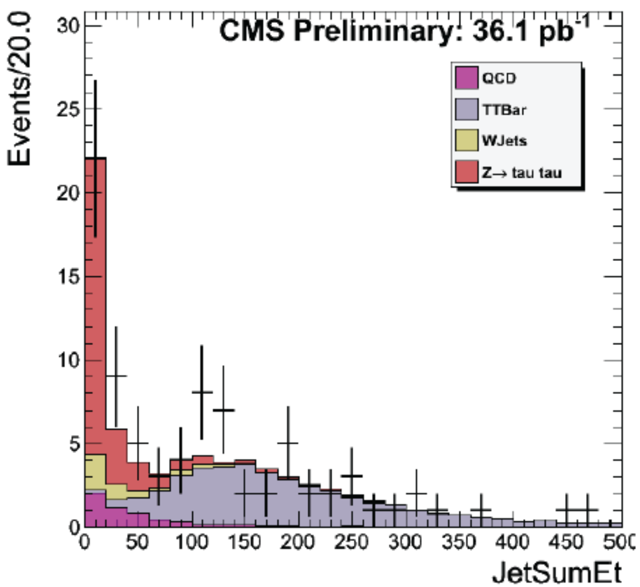


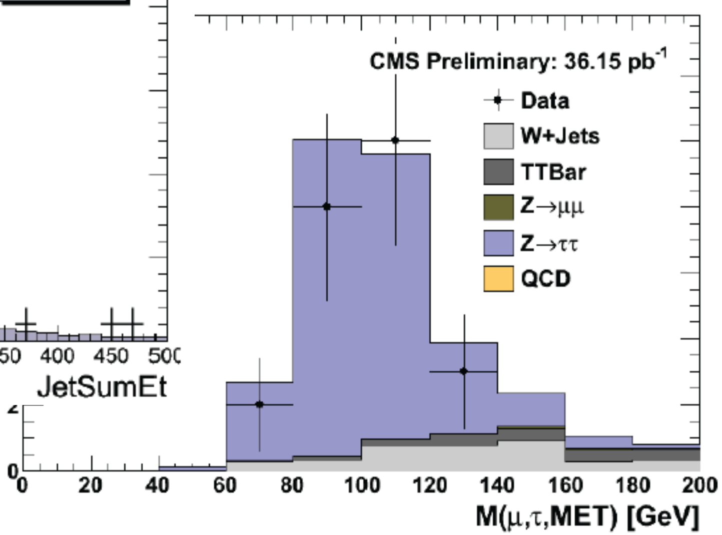
CMS PF Tau Performance in Data

- Multiple results came out
- Good agreement of data and simulation
  - Even jet backgrounds look not too bad





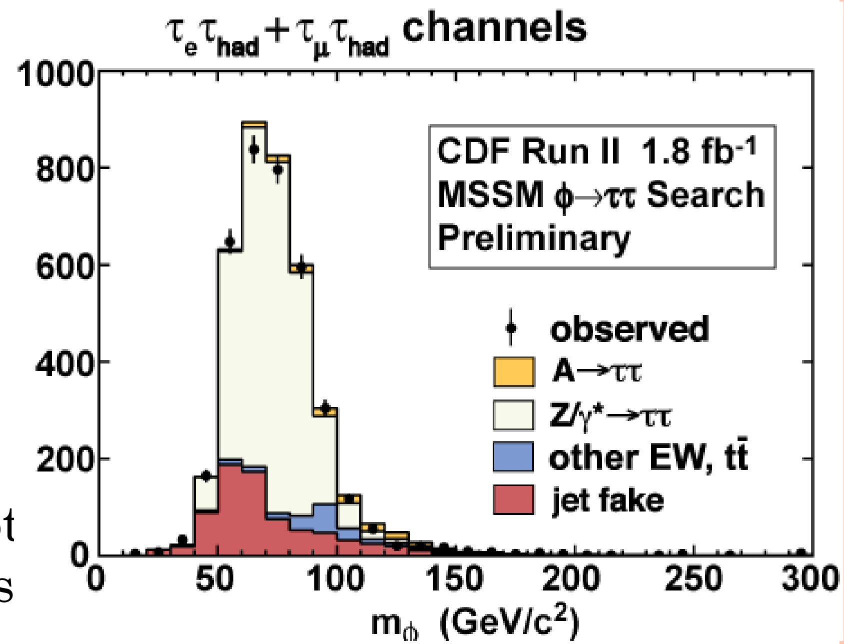




Di-Tau Mass Reconstruction

Di-Tau Invariant Mass Reconstruction

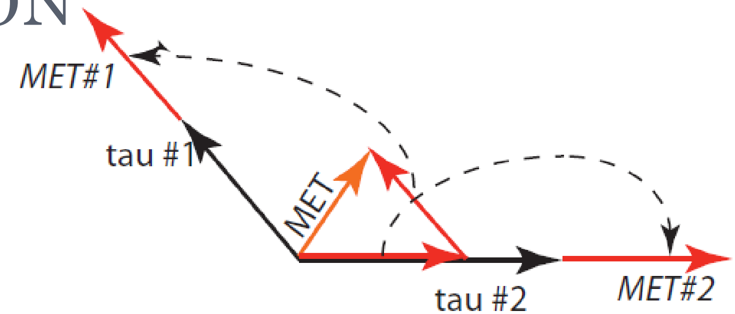
- Strictly speaking, mass is not reconstructable due to cancellation of missing energy from neutrinos
  - Consider a back-to-back Higgs decay: adding 1 TeV of neutrino energy in each direction does not change any measured quantities
- Critical item for Higgs search
  - Large $Z \rightarrow \tau\tau$ is just a step away
- Use estimators:
  - E.g., invariant mass of two visible tau decay products and measured MET

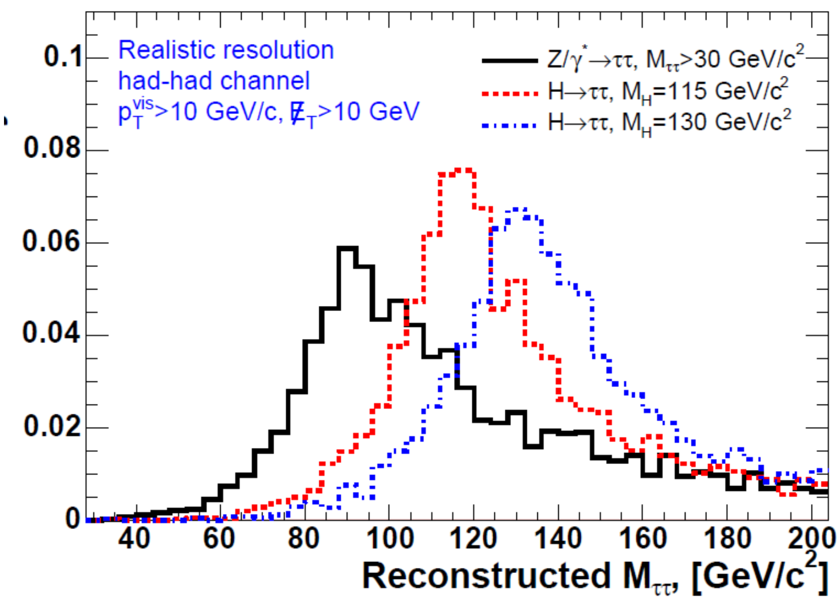


- Separating Z and h is a key challenge in searching for Higgs
  - Any improvement will be a big help

Collinear Approximation

- High p_T taus are collimated:
  - Small angle between neutrinos and visible decay particles
- Un-project 2D MET onto the visible tau 3D directions
- Now can measure mass as peak position is about right
- But major shortcomings:
  - Only works for substantially not back-to-back topologies
    - ~30% of events?
  - A long tail (Z tail!)





R.K. Ellis, I. Hinchliffe, M. Soldate and J.J. Van der Bij, Nucl. Phys. B297, 221 (1988).

Missing Mass Calculator Algorithm

- Start with both hadronic decays. 4 equations

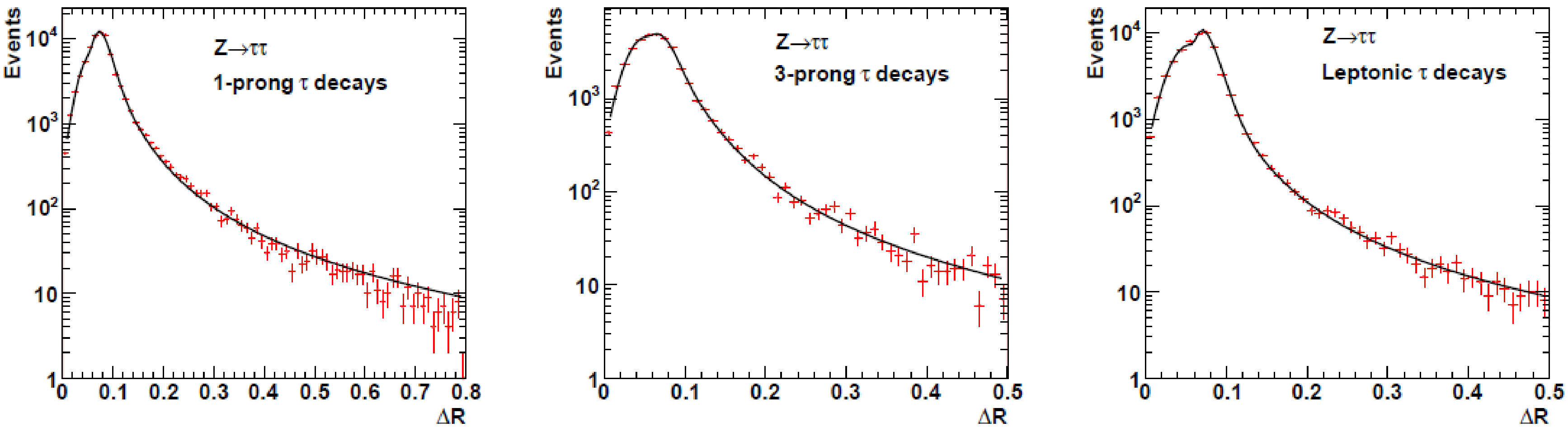
$$\not{E}_{T_x} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \cos\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \cos\phi_{\text{mis}_2}$$
$$\not{E}_{T_y} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \sin\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \sin\phi_{\text{mis}_2}$$
$$M_{\tau_1}^2 = m_{\text{mis}_1}^2 + m_{\text{vis}_1}^2 + 2\sqrt{p_{\text{vis}_1}^2 + m_{\text{vis}_1}^2}\sqrt{p_{\text{mis}_1}^2 + m_{\text{mis}_1}^2} - 2p_{\text{vis}_1} p_{\text{mis}_1} \cos\Delta\theta_{vm_1}$$
$$M_{\tau_2}^2 = m_{\text{mis}_2}^2 + m_{\text{vis}_2}^2 + 2\sqrt{p_{\text{vis}_2}^2 + m_{\text{vis}_2}^2}\sqrt{p_{\text{mis}_2}^2 + m_{\text{mis}_2}^2} - 2p_{\text{vis}_2} p_{\text{mis}_2} \cos\Delta\theta_{vm_2}$$

- … and 6 unknowns (m_{mis}=0 as only one neutrino)
- Can solve for given pairs of (ϕ_{mis1},ϕ_{mis2})
  - Each (ϕ_{mis1},ϕ_{mis2}) corresponds to a certain orientation (angle) of neutrino wrt to the visible tau direction
  - But not all of them are equally likely
    - e.g. a soft neutrino with large angle can satisfy mass constraints but how often does that happen?

* *The idea and a lion share of credit belongs to Sasha Pronko (FNAL/LBNL)*

Missing Mass Calculator Algorithm

- Check MC for the angle between the tau direction and neutrinos:

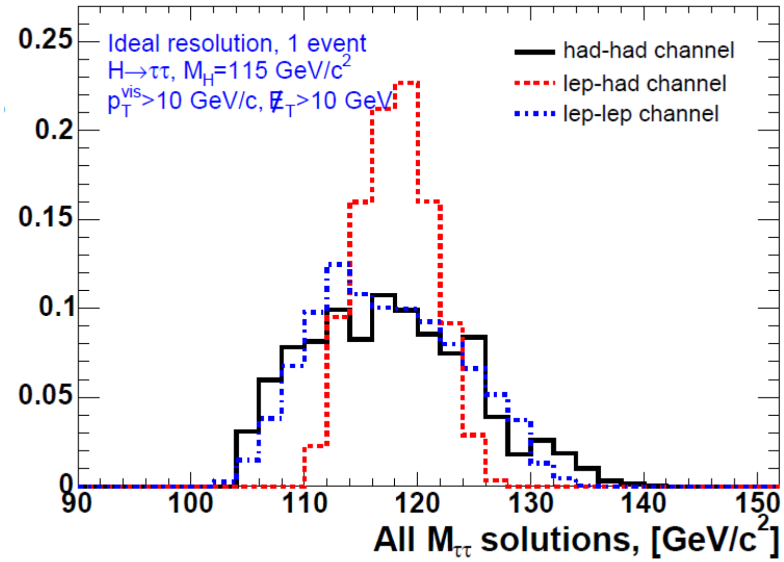


- Use these distributions to classify likelihood of each topology (= a solution for a point in (ϕ_{mis1},ϕ_{mis2}) grid) and therefore each value of mass

$$L(m\,|\,\phi_1,\phi_2) = L(\Delta R_1\,|\,\phi_1)\times L(\Delta R_2\,|\,\phi_2)$$

Missing Mass Calculator Algorithm

- Now fill a distribution of invariant masses from scanned points weighing each by L:
  - And use maximum as an estimator
- In real life need to account for MET resolution
  - Add MET is an additional scan parameter constrained by the actual measurement

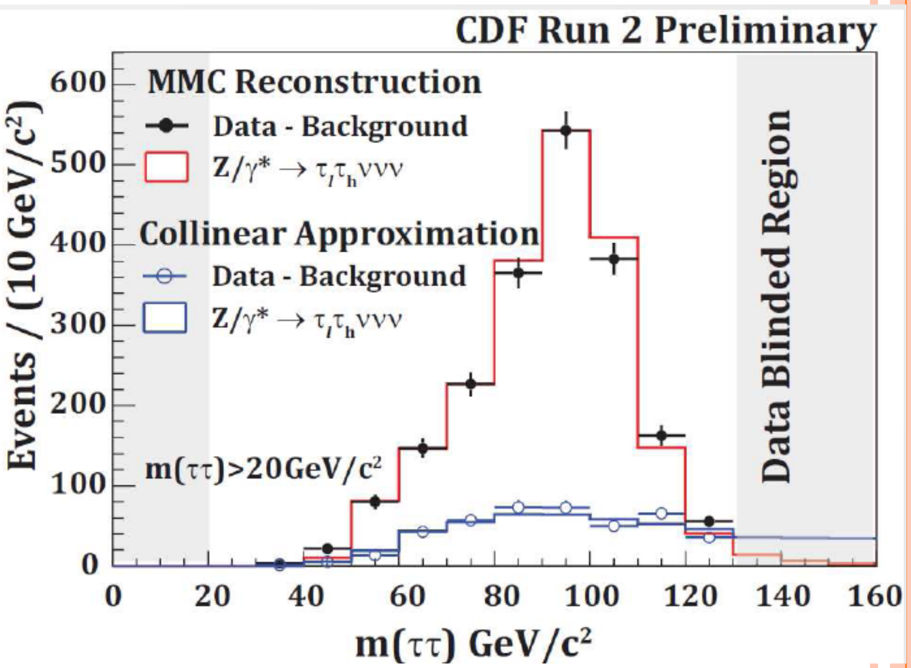


Details in A. Elagin, P. Murat, A.Pronko, A.S., arXiv:1012.4686

$$L(m) = L(m \mid \phi_1, \phi_2, \not{E}_T) \times PDF(\not{E}_T)$$

MMC: Test with Data

- Fantastic improvement:
  - The peak is in the right place
  - Much superior resolution
  - No high mass tail
  - No loss of efficiency for back-to-back topology
    - The lower integral for the Collinear Approximation is due to its inefficiency for the back-to-back topology



- Note that this is the lepton+tau channel, not the best performing
  - Two hadronic tau one

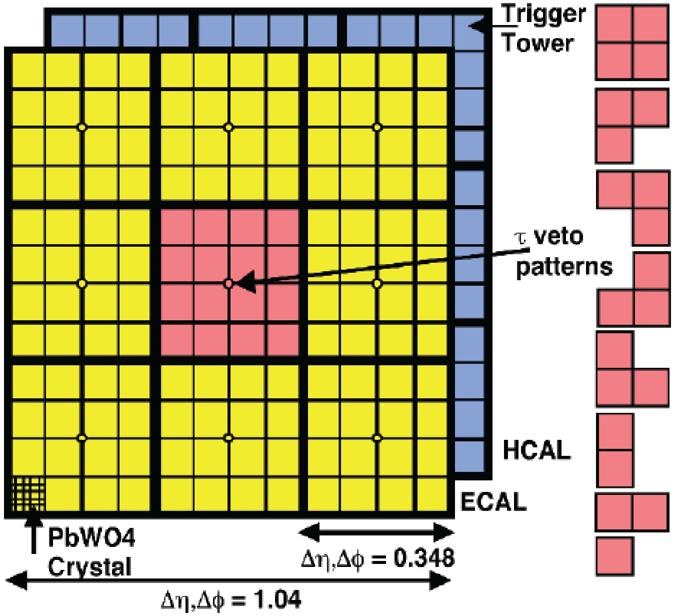
Triggering for Taus

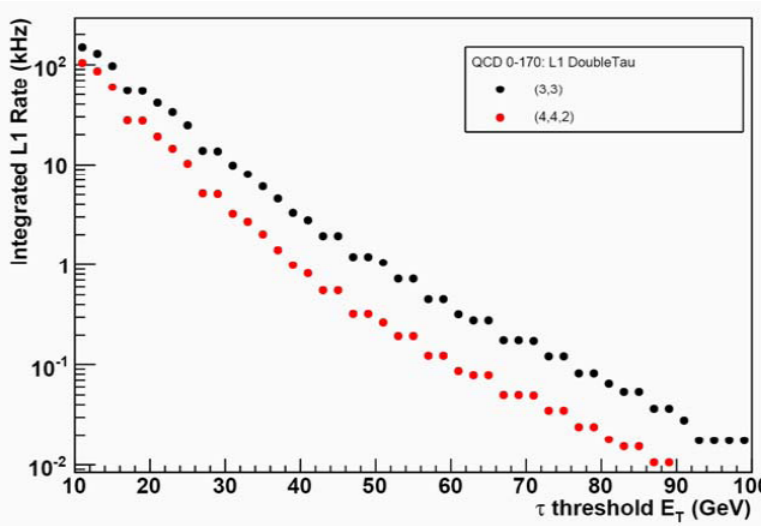
Tau Triggering

- When triggering, you want to repeat the reconstruction steps but real fast
  - So simplified algorithms
- To get fast background rejection, recast the most powerful tools you have in offline:
  - Seeding (e.g. ask a stiff track, spatially compact energy deposit)
  - Isolation (no stuff around)
- The trick is to do it as early as possible (Level-1)
  - The more you cut early, the more time you have to do more through clean-up later
- CDF has been an excellent place for it and it paid off:
  - Tracking at Level-1, flexible calorimeter trigger

TAU TRIGGERS AT CMS

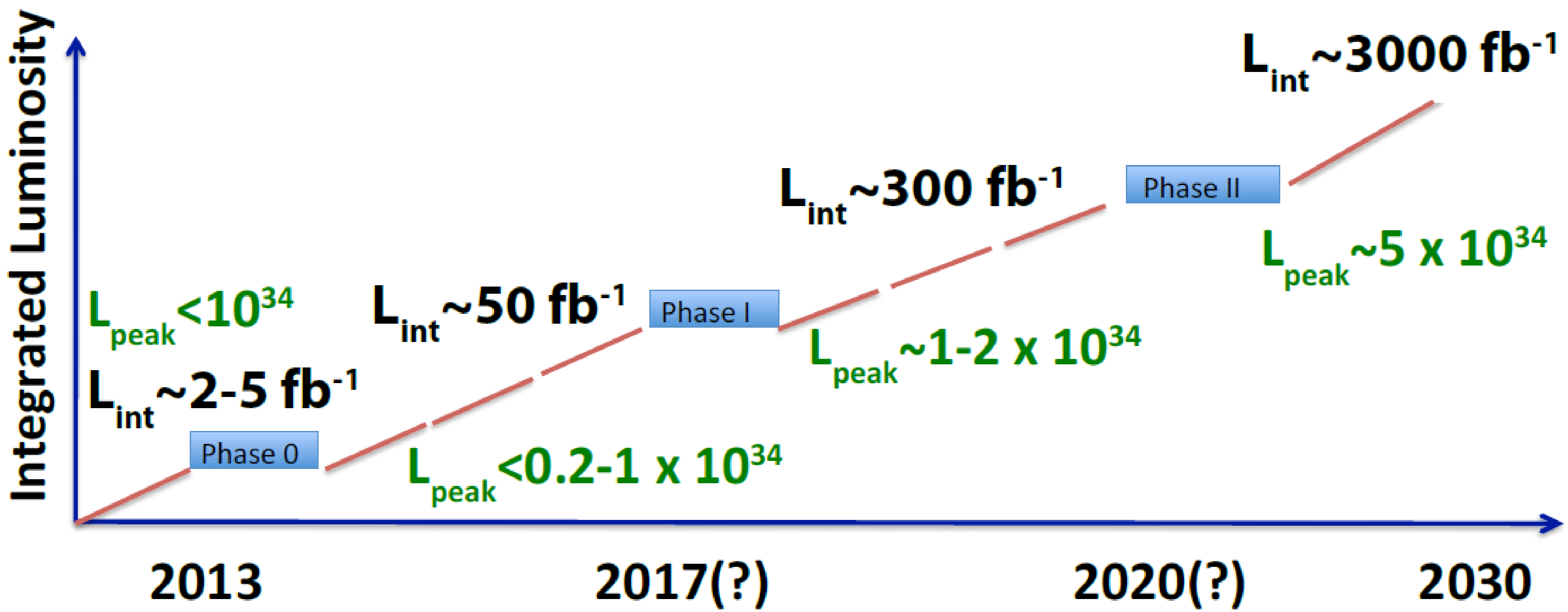
- The weakest point in the CMS tau program:
  - L1 has no tracking and the Calorimeter trigger was just not designed well for taus
    - The wide cone (shared with regular jets) prevents background control and poor energy resolution
    - Some remedies applied, but this is remains a problem
    - May have to use variety of trigger paths to increase acceptance if rate gets high and thresholds move up
  - Expect enormous improvement with the trigger upgrade in 2017(?)





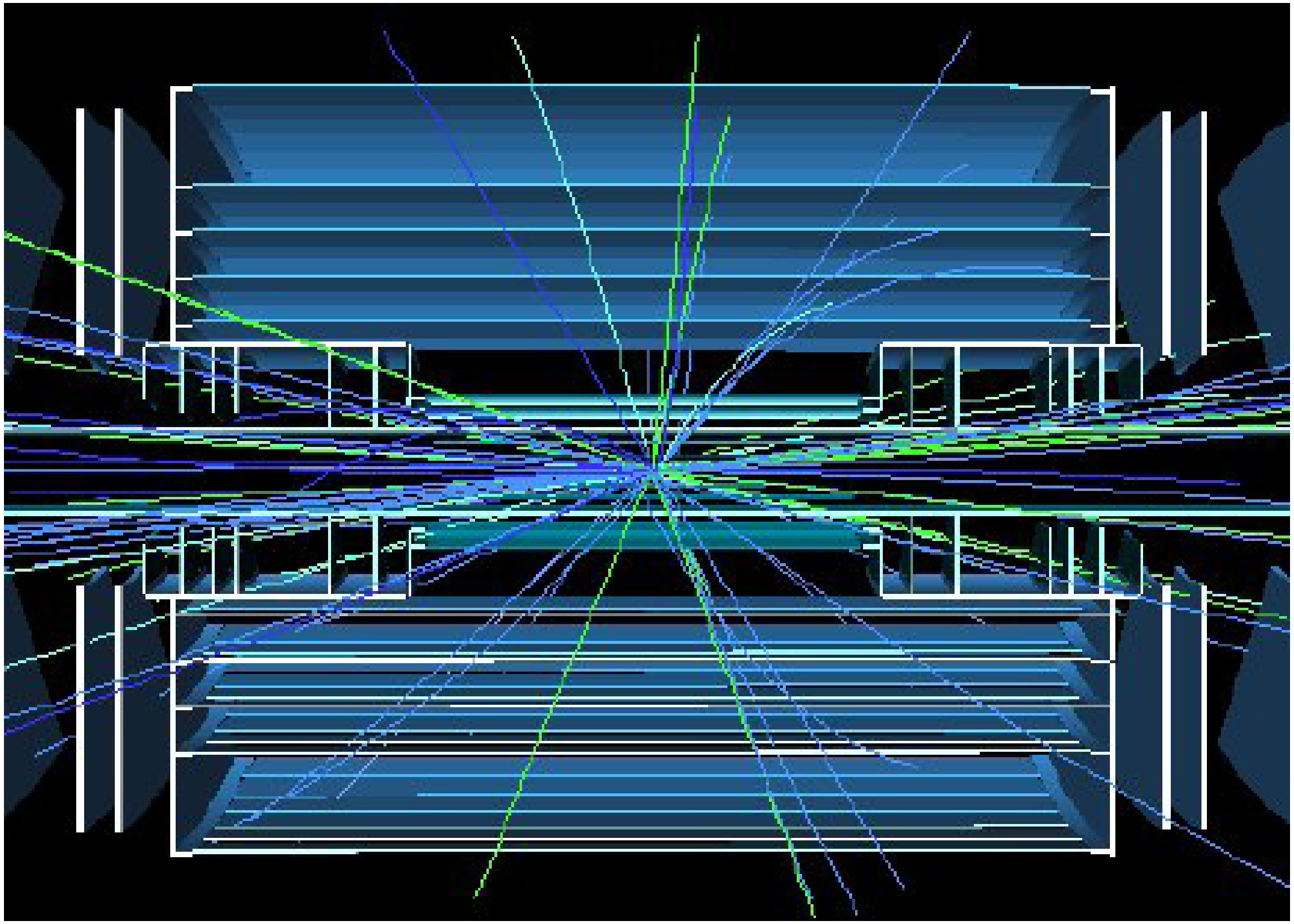
Not So Distant Future: HL-LHC

LHC→HL-LHC Luminosity Profile



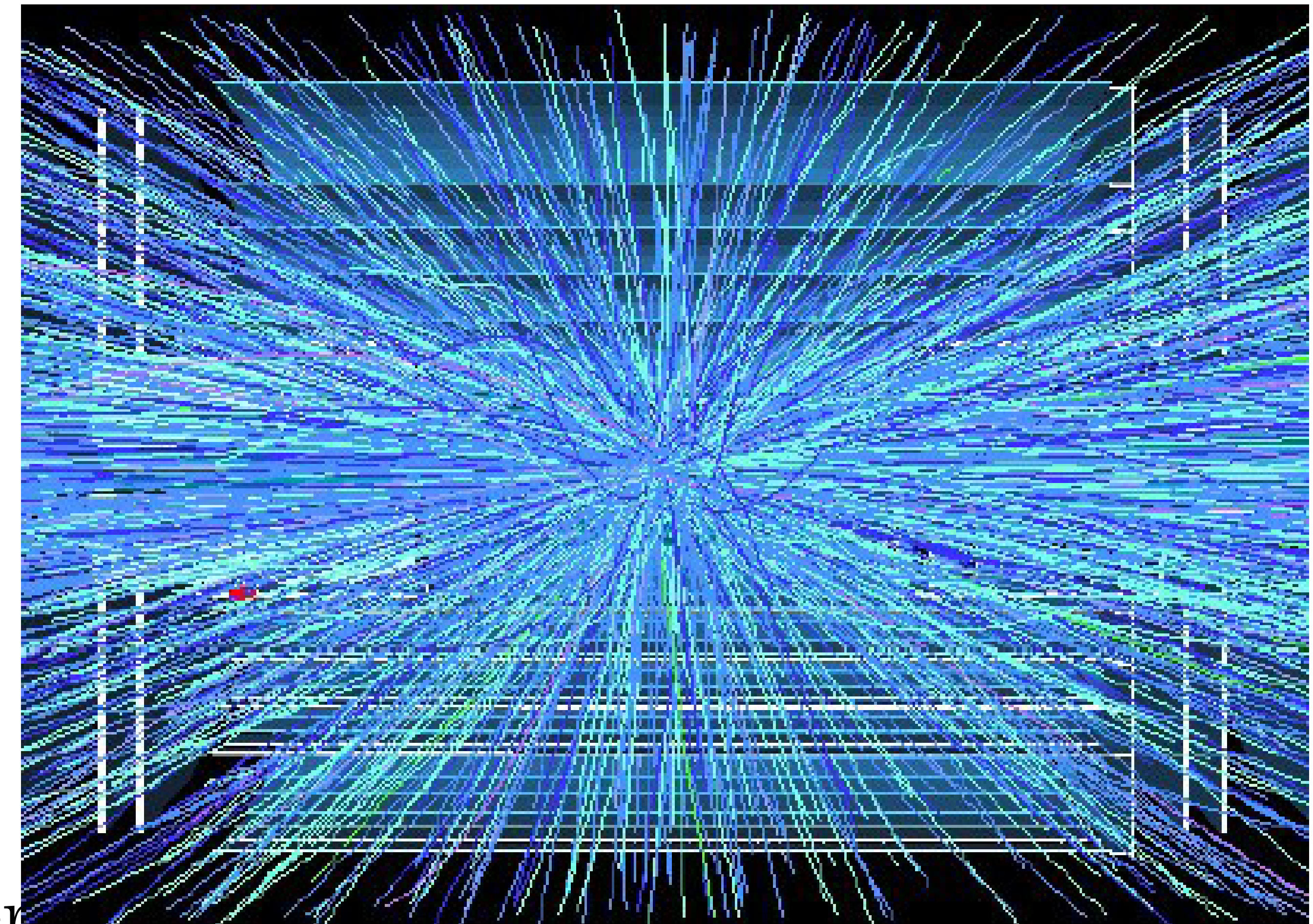
- Disclaimer: above is a mix of official provisional projections and my own guesses
- Luminosity leveling

HI-LHC: Future in Graphic Details



- Every experimentalist's ultimate nightmare!

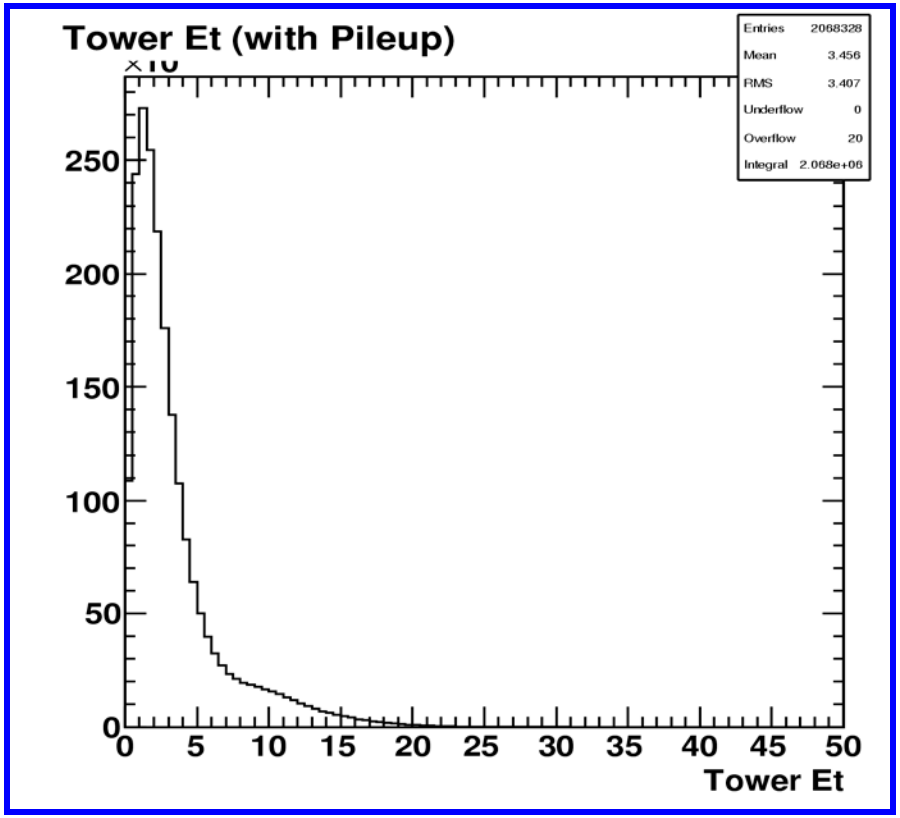
HI-LHC: Future in Graphic Details



- Ever

SLHC: Finding Jets is a Daunting Task

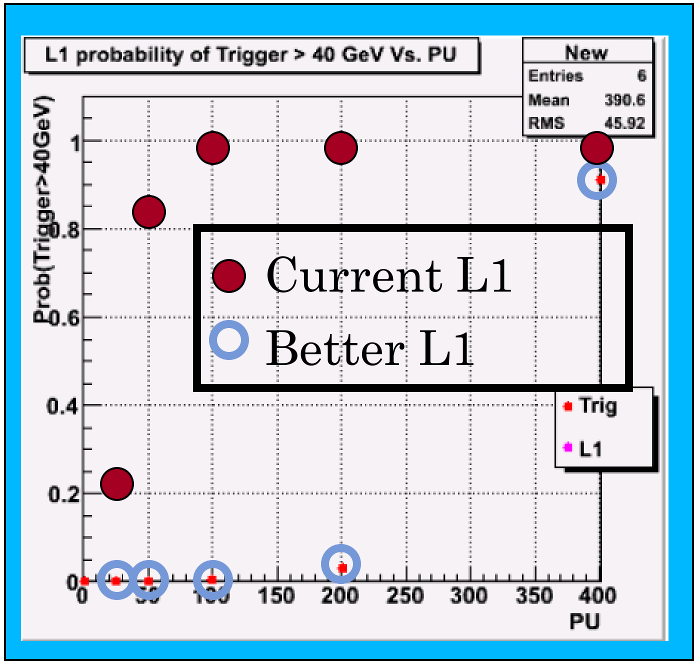
- With 200 pile-up interactions, expect ~3 GeV of random energy per calorimeter tower
  - C.f. a typical jet cone of $\Delta R \sim 0.5$ is 144 towers
- If you look for a 200 GeV jet, there will be one in any random direction in the CMS
  - Heavy implications for taus



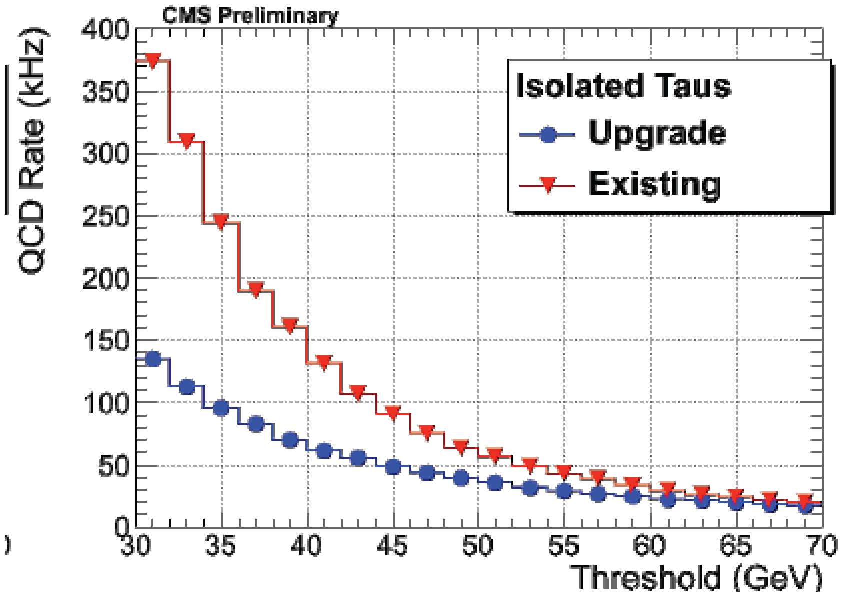
Energy per tower at 200 pile-up interactions at LHC

Tau Triggering at SLHC

- Fortunately, current CMS calo trigger has flaws
  - Fortunately b/c it leaves room for large improvements
- Can do a lot better by going to tower level



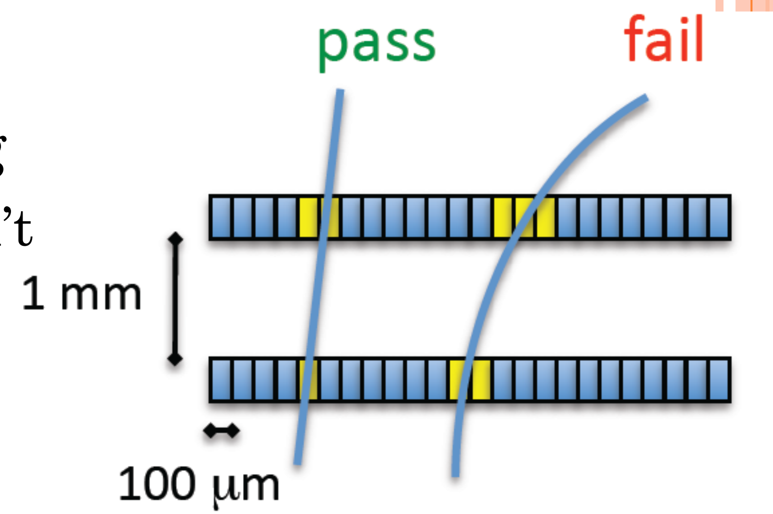
Probability of triggering for a 40 GeV tau in a crossing with i_{PU} PU events vs i_{PU}.

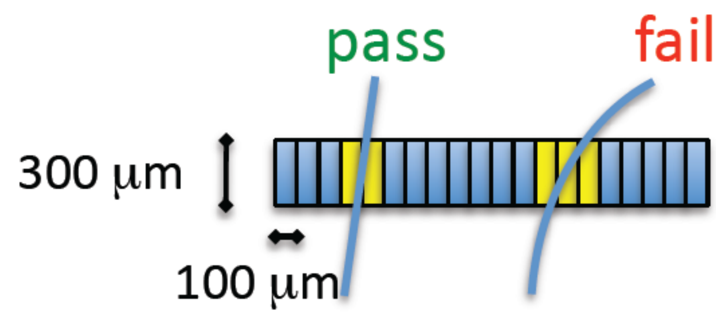


New trigger design: improves rate for ~50 pile-up interactions

Is Phase II Tracking Possible?

- Critically important for taus
- Even more critical for triggering
  - Amounts of data are enormous, can't move it off the detector in real time
- A couple of ideas:
  - New "stacked layers" with built-in fixed threshold triggering
    - Allows reduction in the amount of data to be moved from the detector
    - Possibly regional tracking seeded by muon detectors or calorimeters
  - Thick sensors, look at the cluster size
    - Sort of similar idea





SUMMARY

- There is plenty of motivation for using tau leptons in searches for new physics at the energy frontier
- Low acceptances and high background rates make tau identification challenging
- Despite that, there has been a steady improvement in tau reconstruction and identification techniques
  - Some matured at the Tevatron
  - A lot more coming from the LHC active deployment of multivariate techniques
  - Some are very new, like the MMC mass calculation
- The discovery can be around the corner and we have the tools to make that discovery