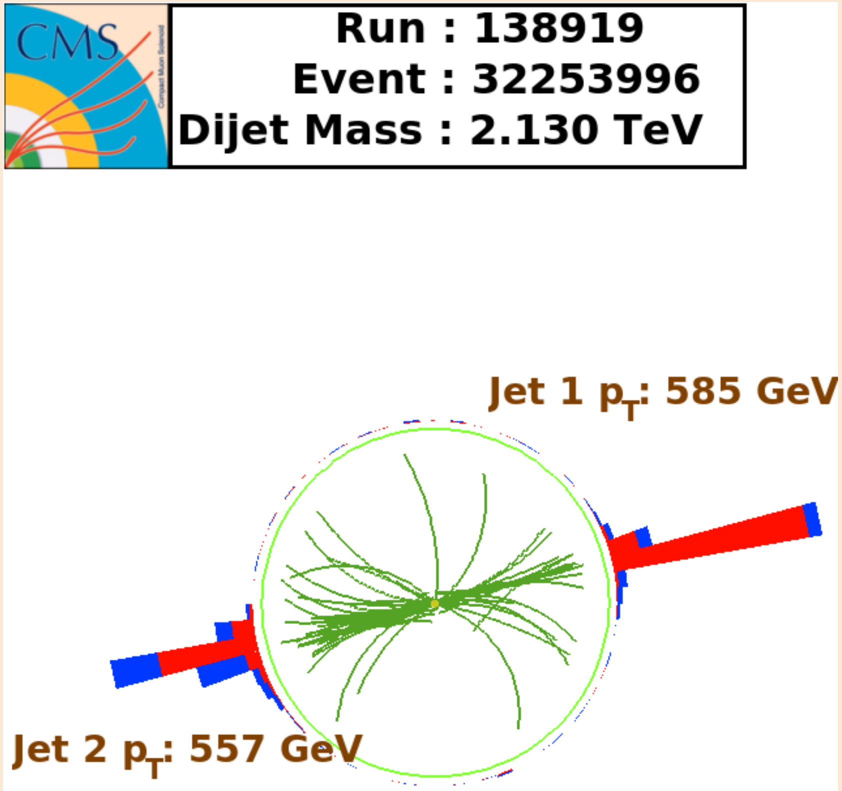


US ATLAS Hadronic Final State Forum

CMS Overview

Salvatore Rappoccio
(Johns Hopkins University)

For the CMS Collaboration

Outrun a bear?

Outrun a bear?

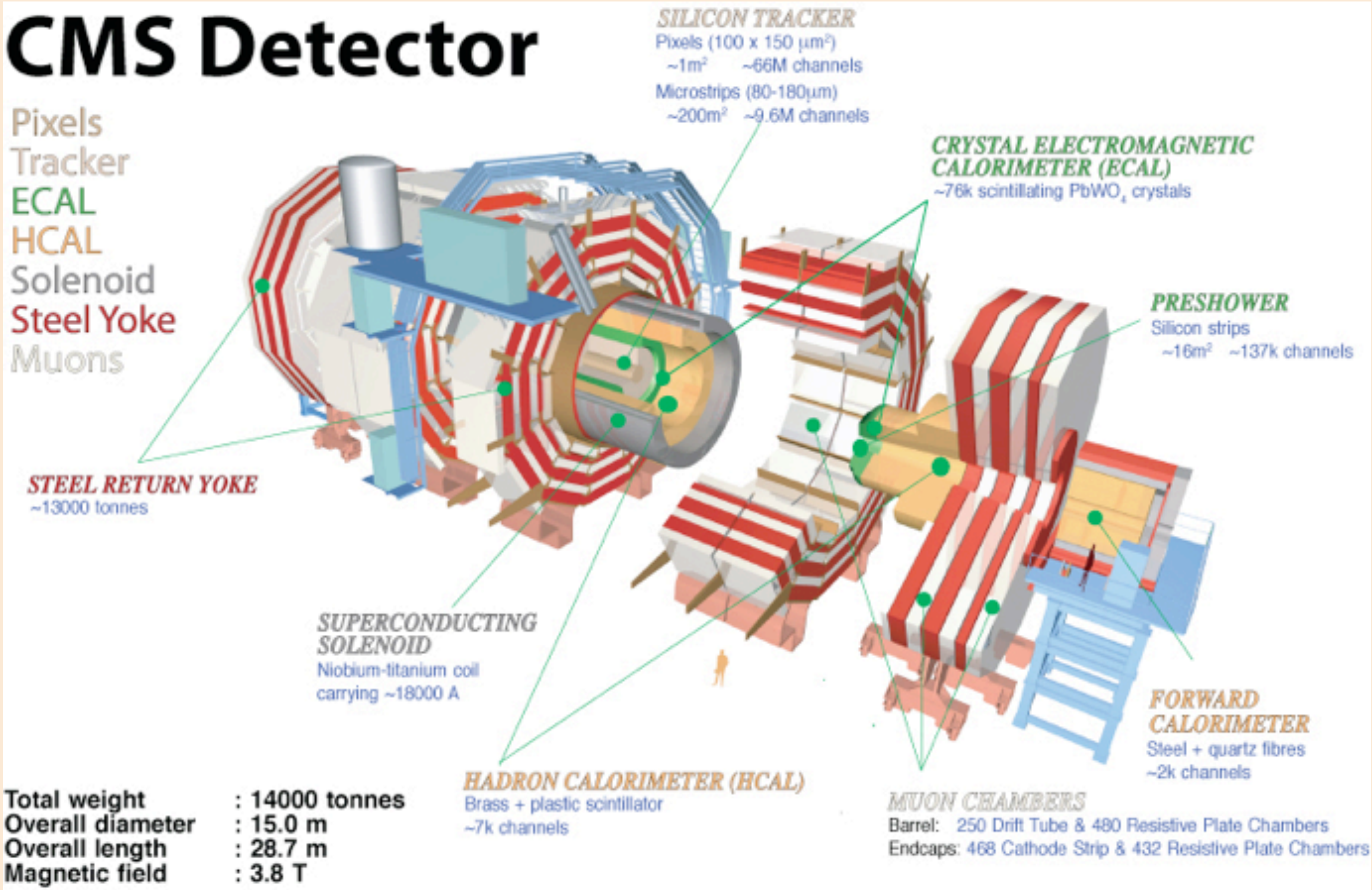
We don’t actually want to find something the competition doesn’t.

We just want to find it first!

Fine Print

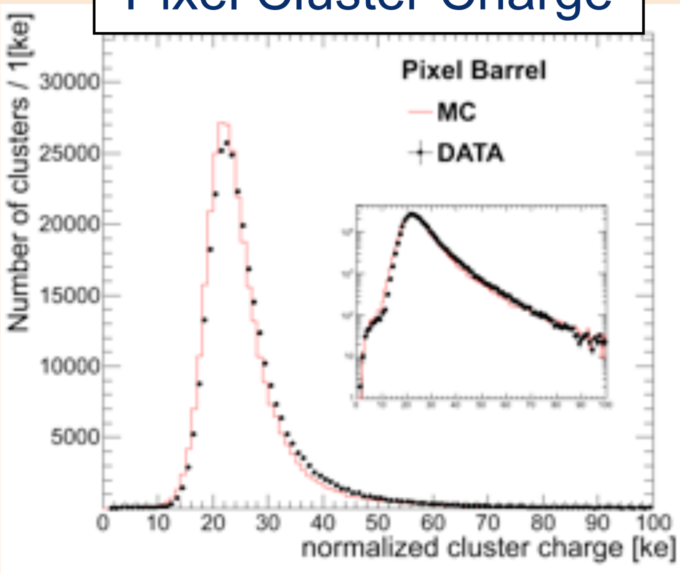
- I'll spend most of my time describing aspects of CMS related to the hadronic final state
  - Jets, MET, b-tagging
    - Not really enough taus to be very quantitative yet
  - Lots of other material presented (eg at ICHEP)
- This is also the combination of two talks
  - CMS Overview
  - Jet Substructure
    - Jet substructure will get more "weight" than other topics due to this construction!

Detector Overview



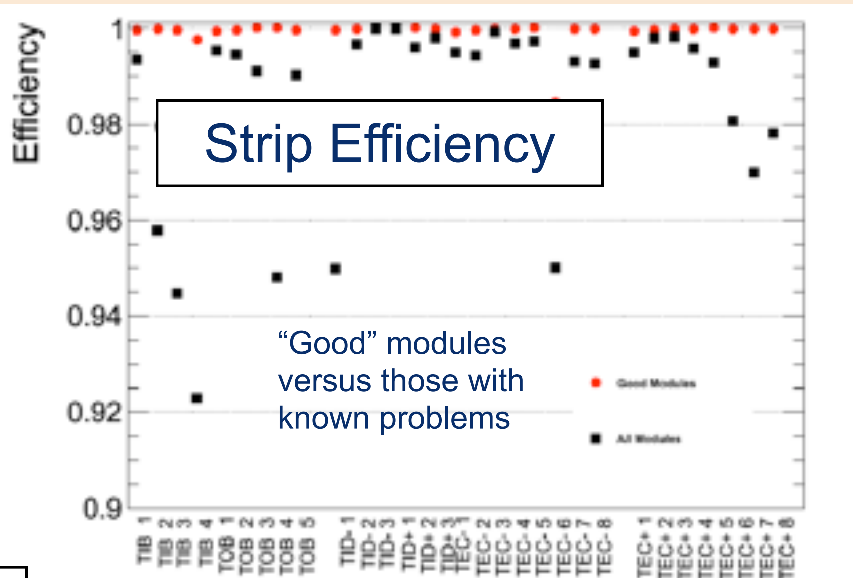
Tracker

Pixel Cluster Charge

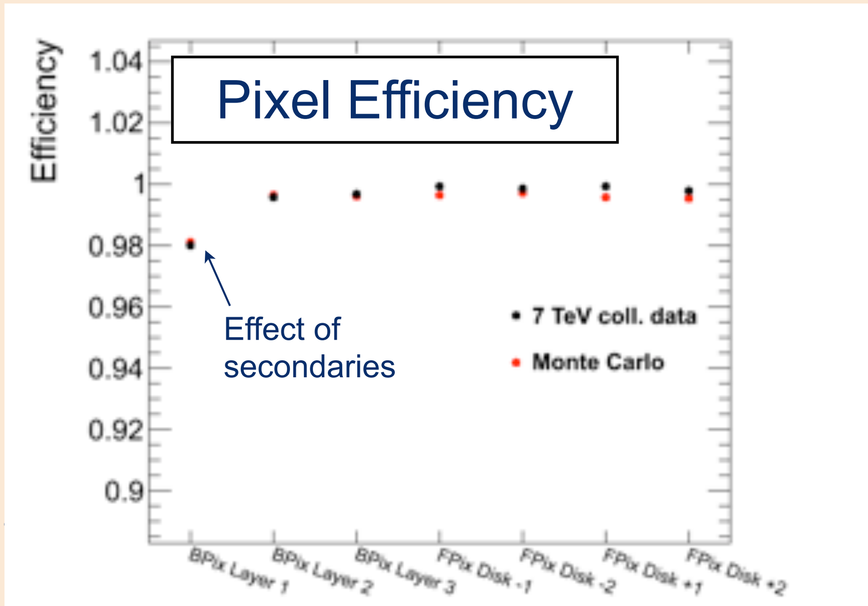


σ_x = 12.7 ± 2.3 μm (MC: 14.1 ± 0.5 μm)

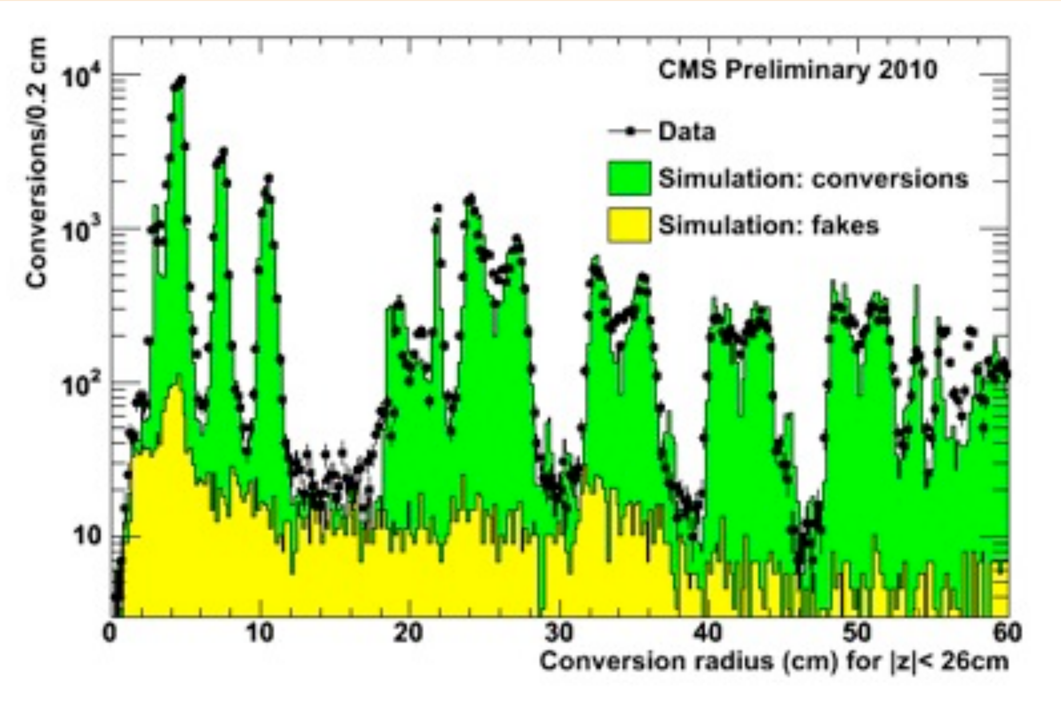
σ_y = 28.2 ± 1.9 μm (MC: 24.1 ± 0.5 μm)



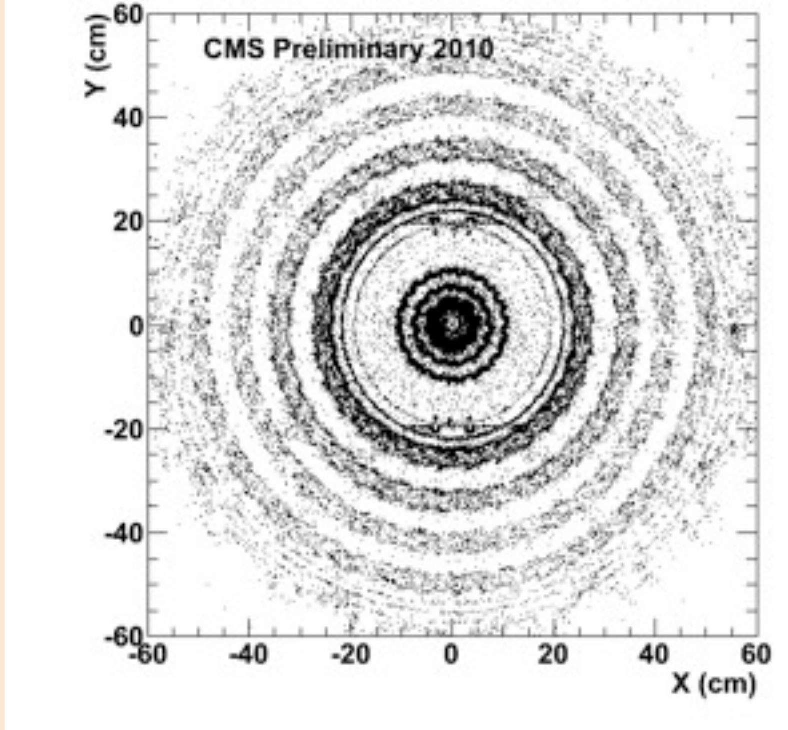
H



Material Budget



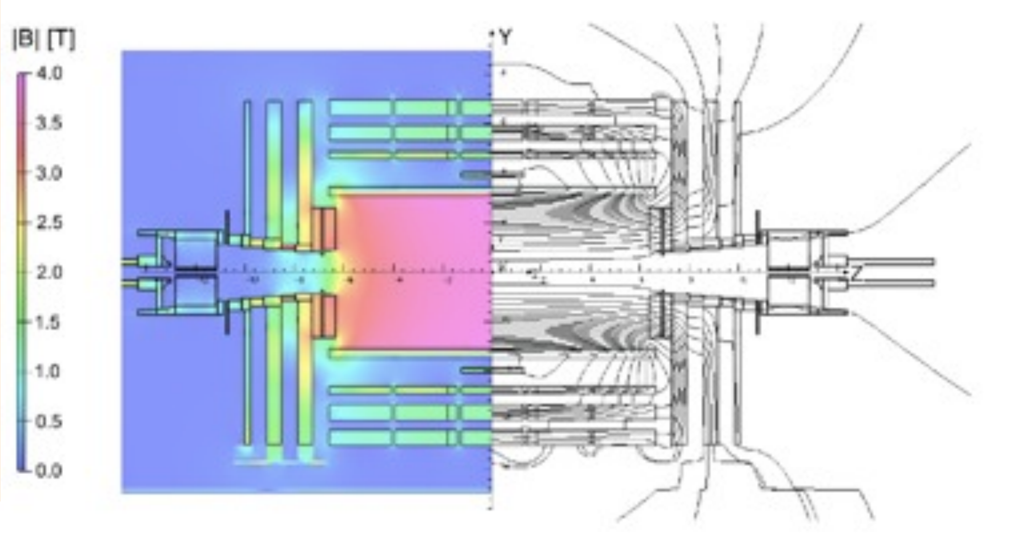
Conversion vertex



- Material budget very well understood
- Some discrepancies still, actively working on it

Magnetic Field

- Understanding of B-field at the per-mil level!



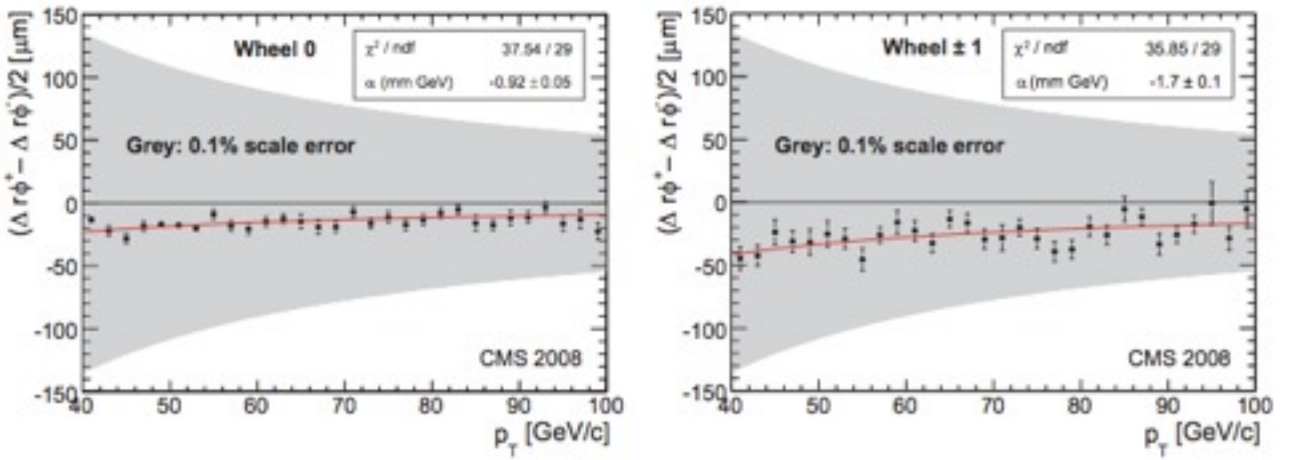


Figure 2. Residual distances, in the bending plane, between the extrapolation of the tracker tracks and the measurements in the first muon station, for the CRAFT cosmic muon data set, as a function of the transverse momentum. Left: wheel 0. Right: wheels ±1. The shaded area shows the expected effect of a 0.1% distortion of the field map in the region between the inner tracker and the coil. The solid line represents a fit

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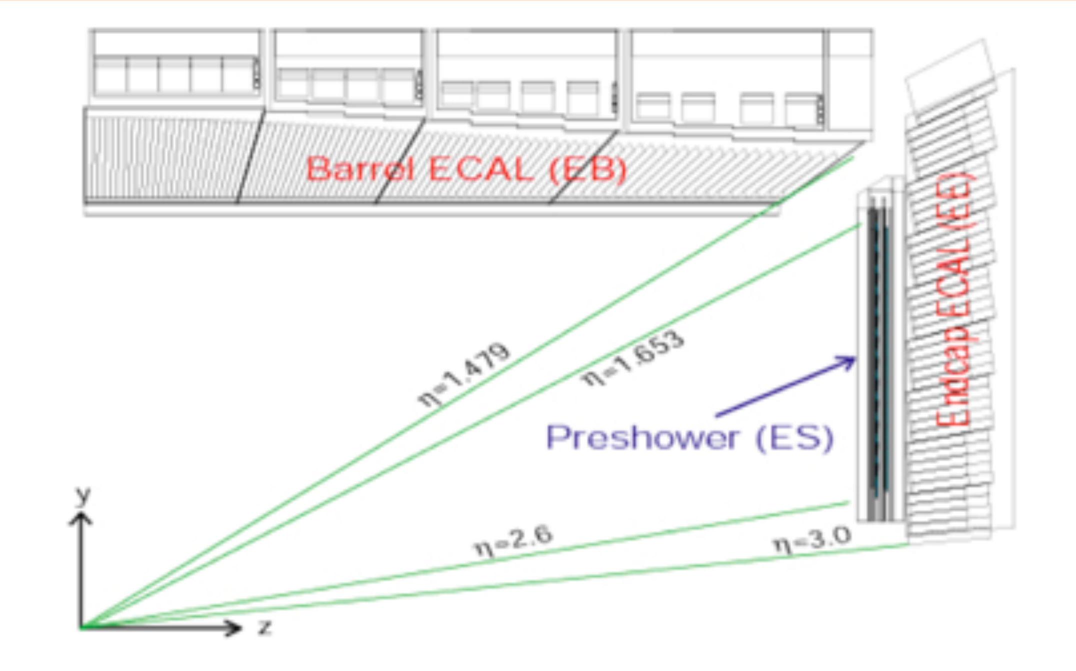
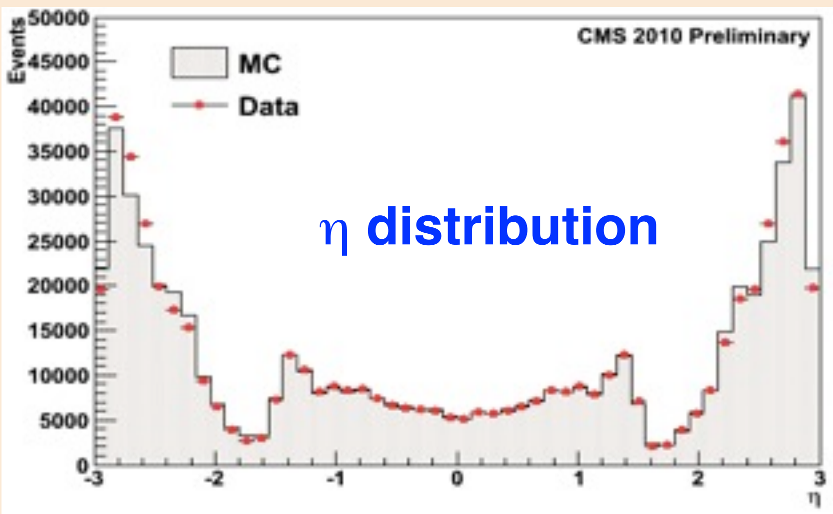
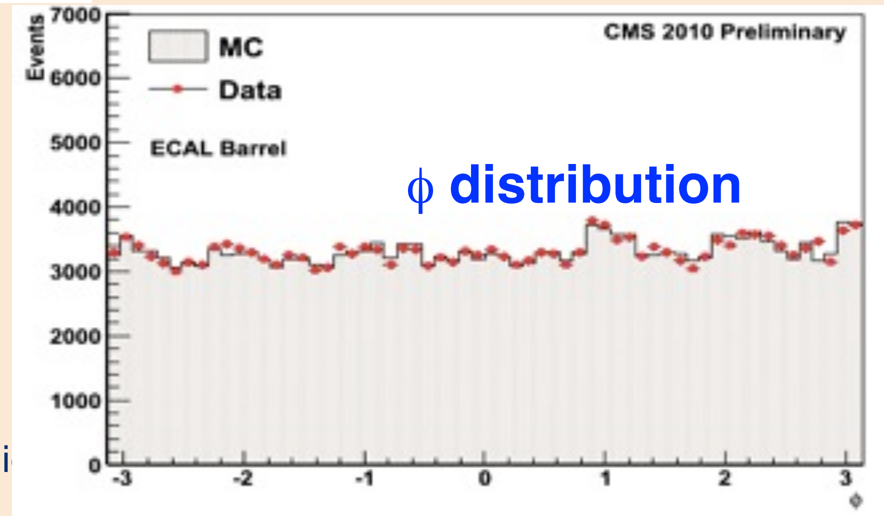
ECAL



- Pb-WO4 crystals throughout
- Extremely well reproduced in MC



S Hadroni



HCAL

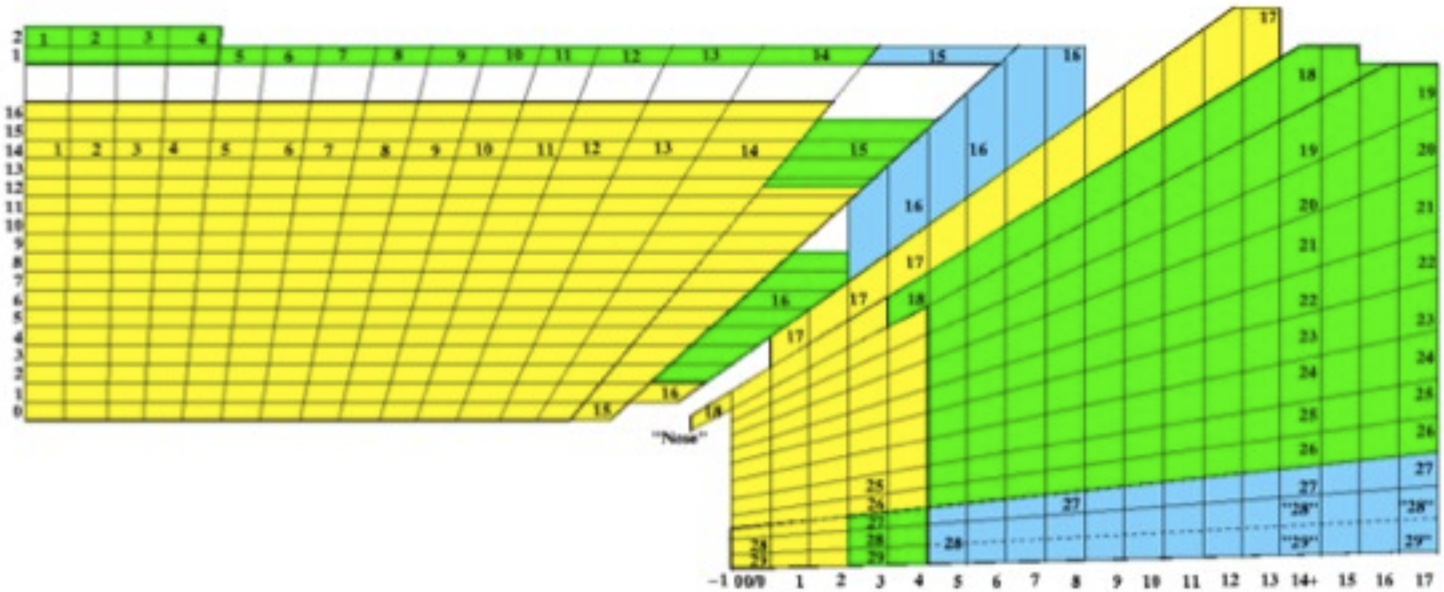


Figure 5.1: A schematic view of the tower mapping in r-z of the HCAL barrel and endcap regions.

- HB and HE
  - Brass/scintillator sampling
- HO
  - Scintillator sampling
- HF (not shown)
  - Steel/quartz fiber sampling

HCAL

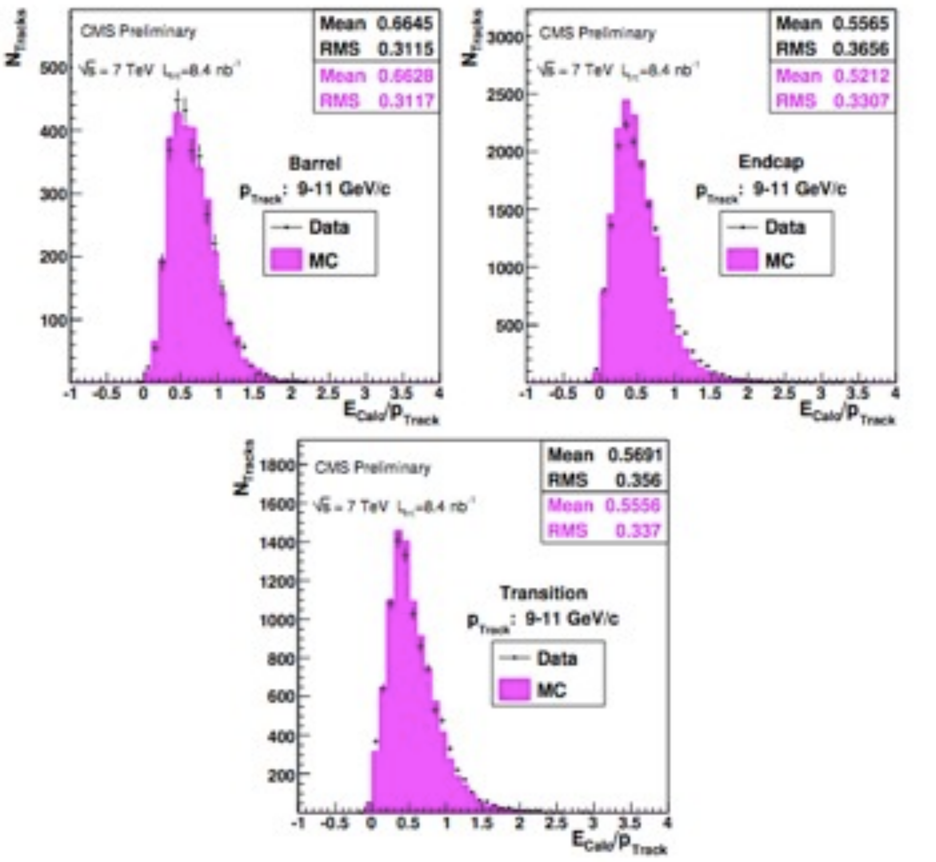


Figure 2: Response measurements as a function of the track momentum in the three different regions of the CMS calorimeter system. Data distributions for tracks with momentum between 9 and 11 GeV/c are compared with the results from the GEANT4-based simulation of minimum-bias events.

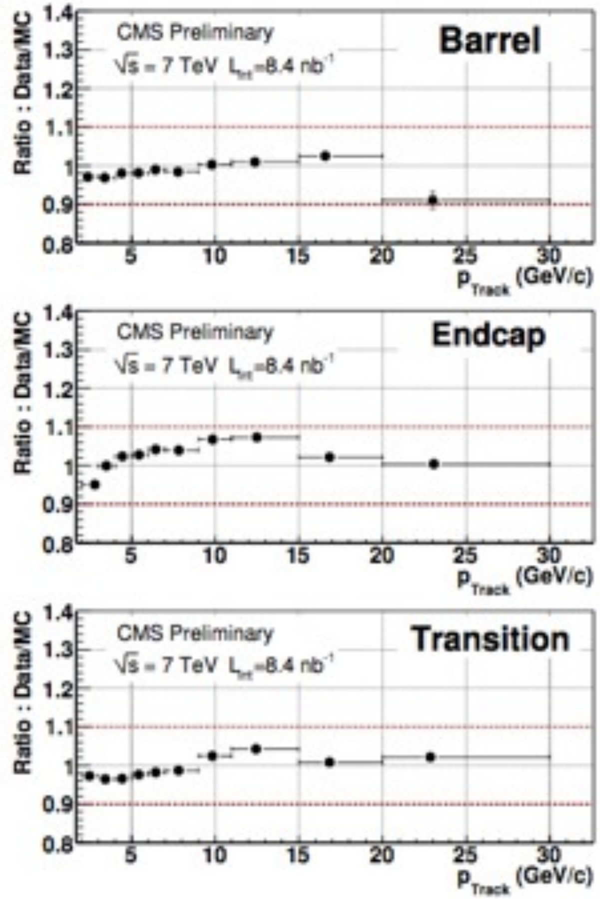
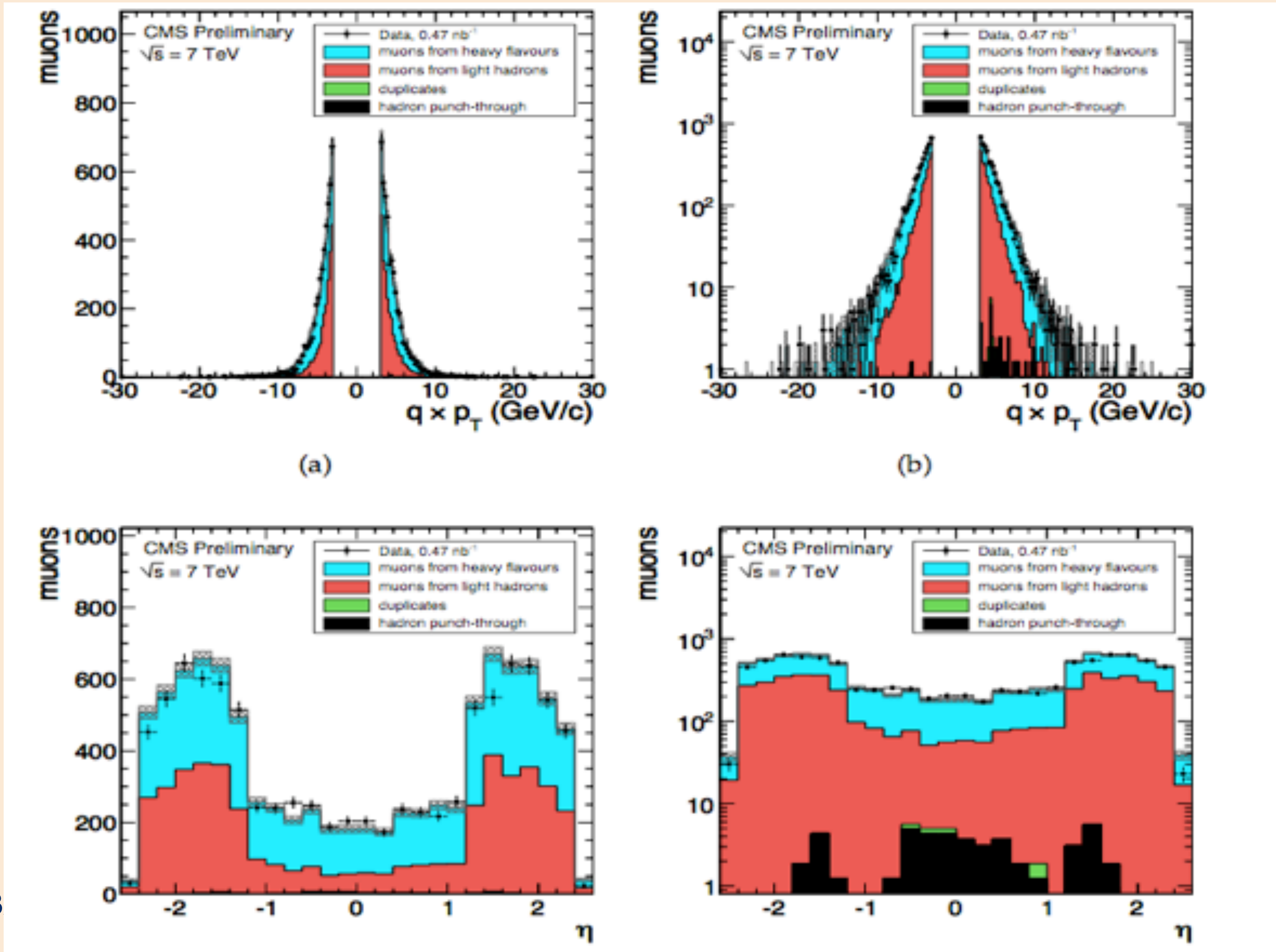


Figure 4: The ratio of the mean response measurements between the data and Monte Carlo as a function of the track momentum in the three different regions of the calorimeter. The three columns refer to the barrel (top), the endcap (middle) and the transition (bottom) regions.

- Single particle response well-modeled in MC

Muons


CMS Preliminary
$\sqrt{s}$ = 7 TeV
Data, 0.47 nb^{-1}
muons from heavy flavours
muons from light hadrons
duplicates
hadron punch-through
muons
$q \times p_T$ (GeV/c)
(a)
(b)
η

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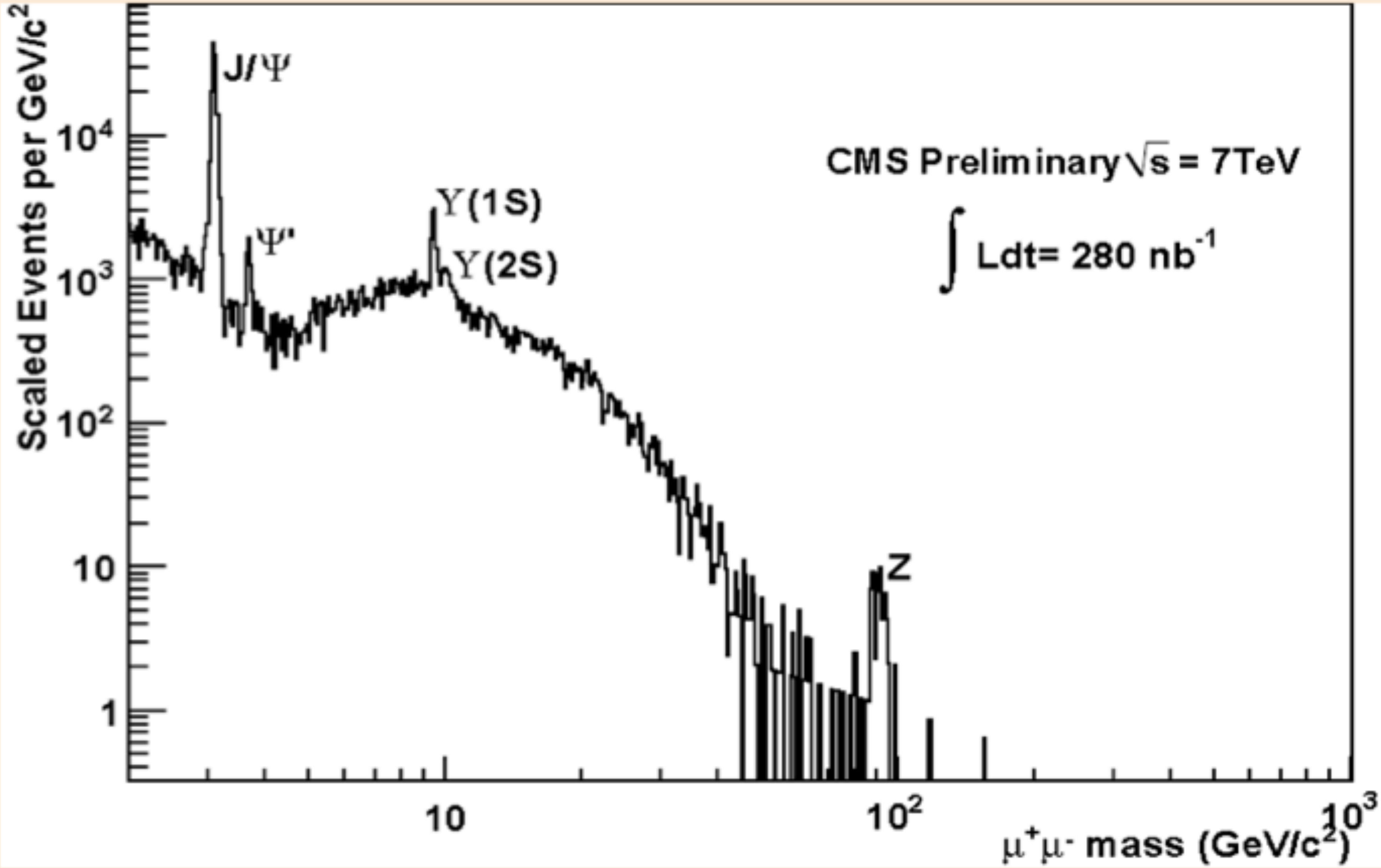
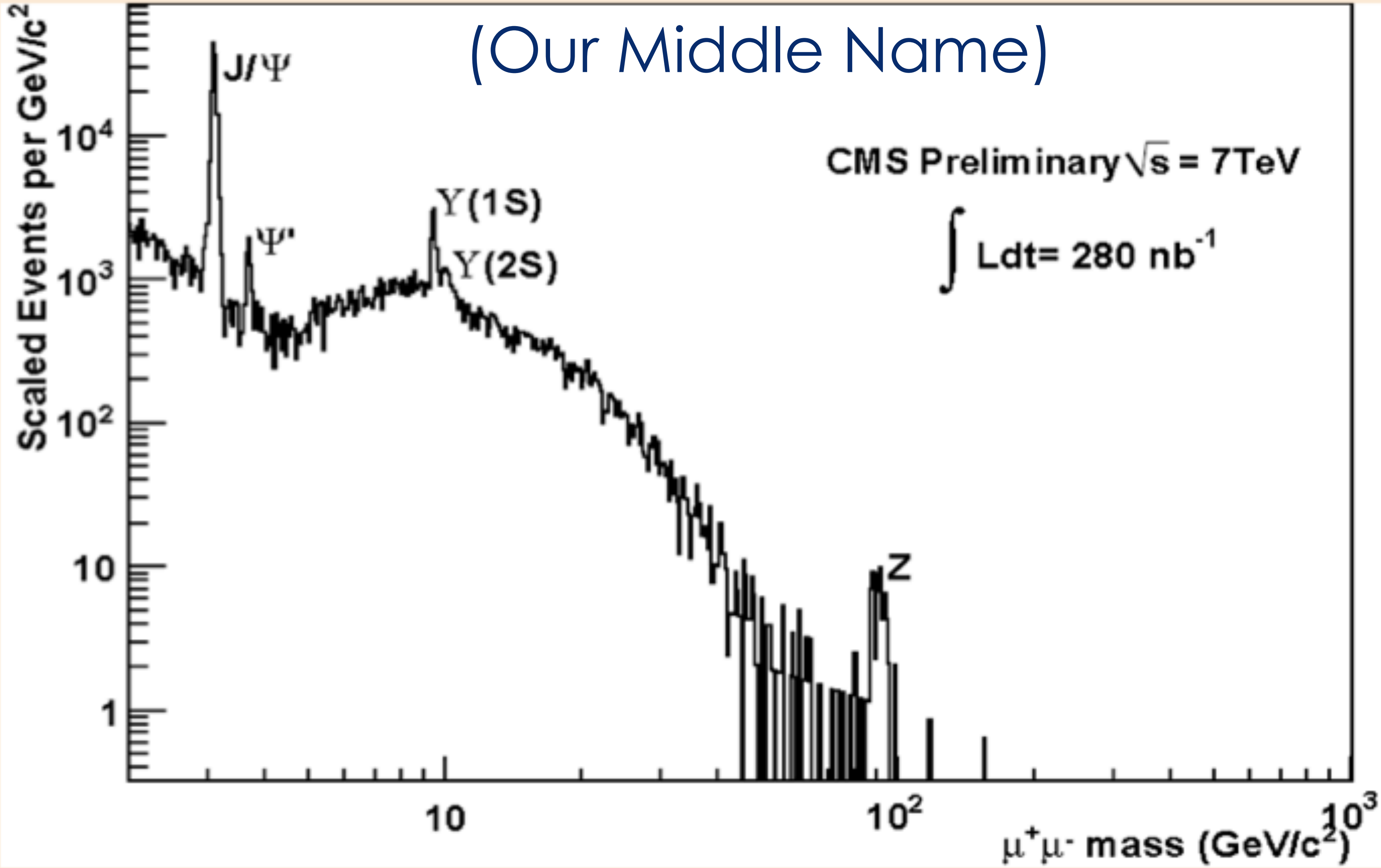
Muons



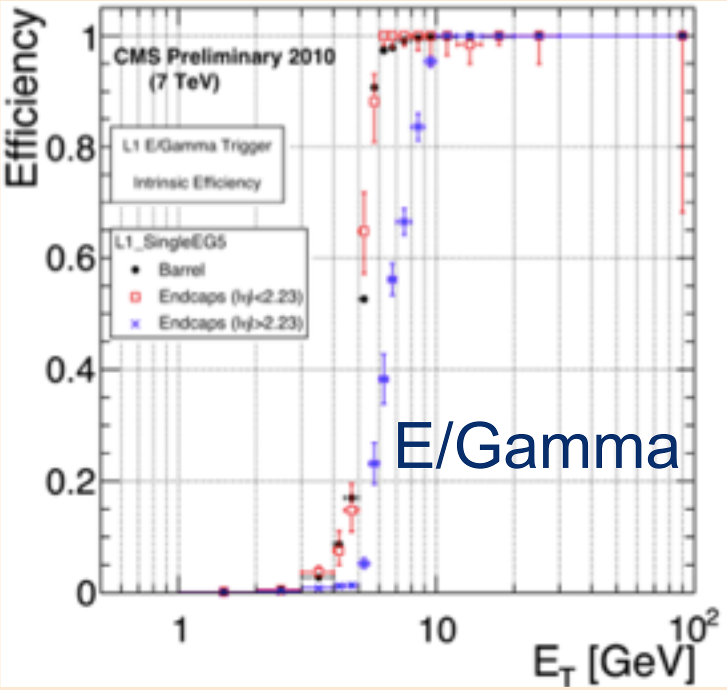
Scaled Events per GeV/c²
J/Ψ
Ψ'
Υ(1S)
Υ(2S)
Z
CMS Preliminary √s = 7TeV
∫ Ldt= 280 nb⁻¹
μ⁺μ⁻ mass (GeV/c²)

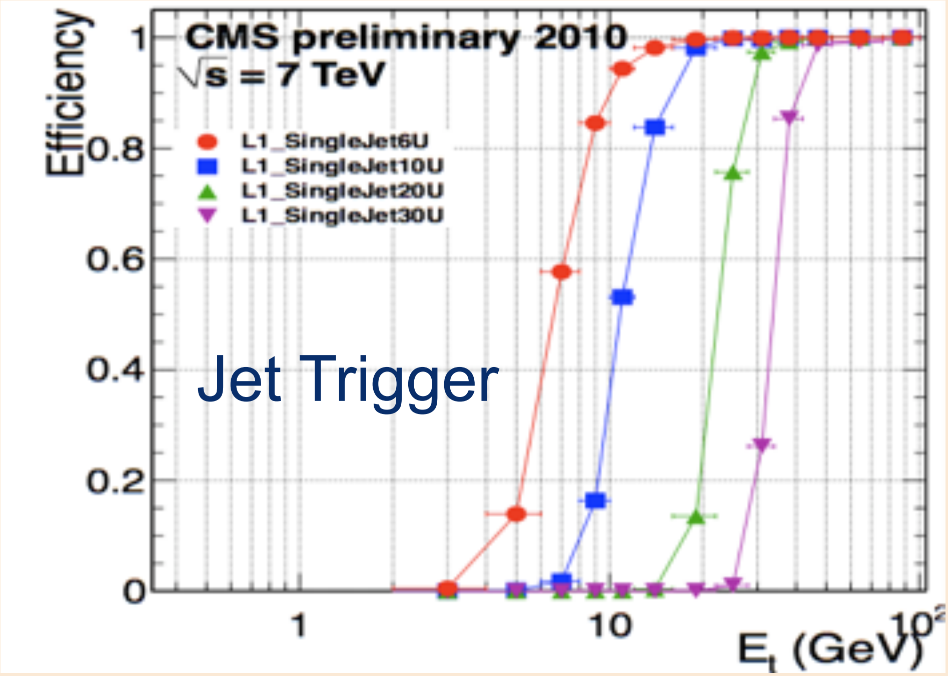
Muons

(Our Middle Name)



Trigger





- Efficiencies measured in data
- "Ratchet up" after prescaled due to lumi increase

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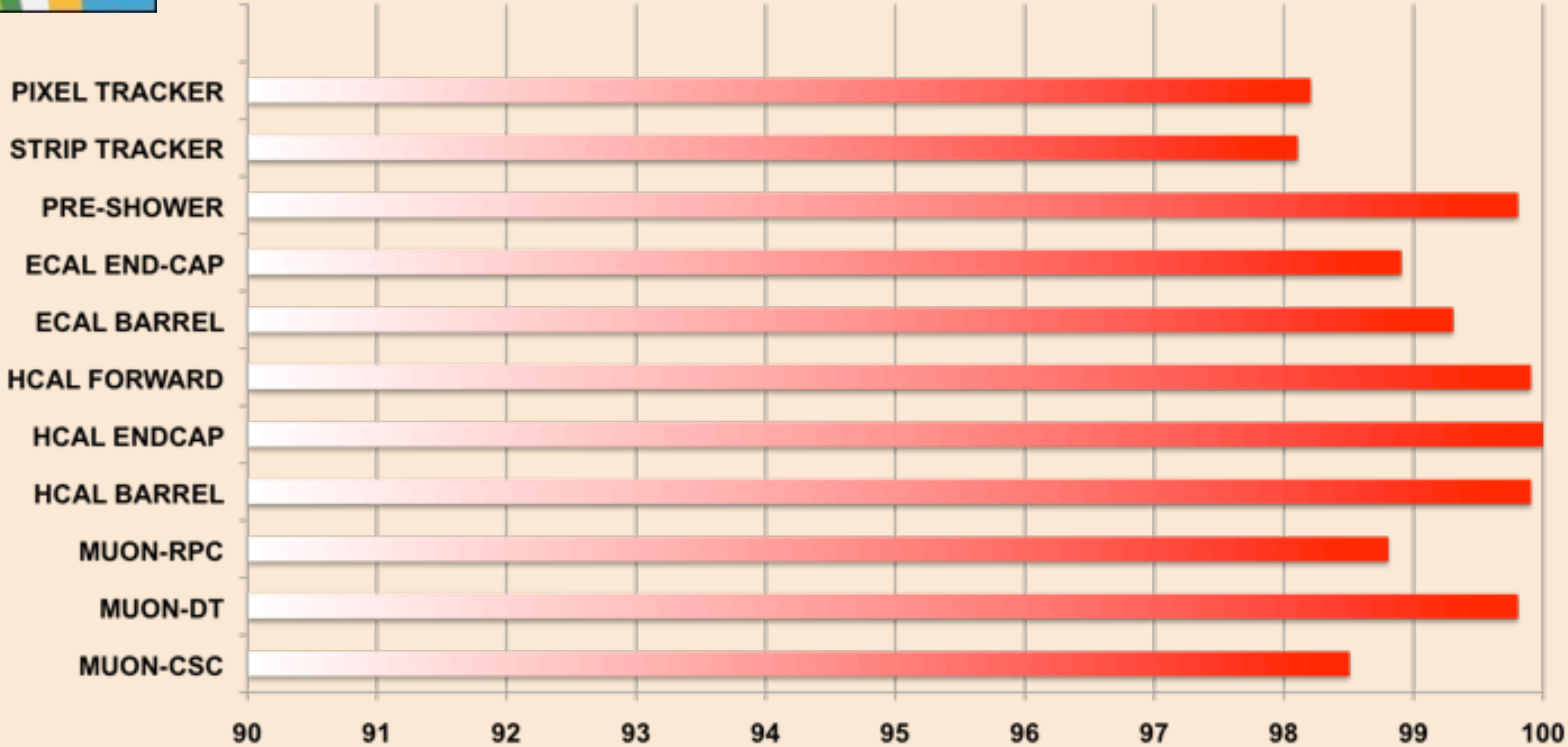
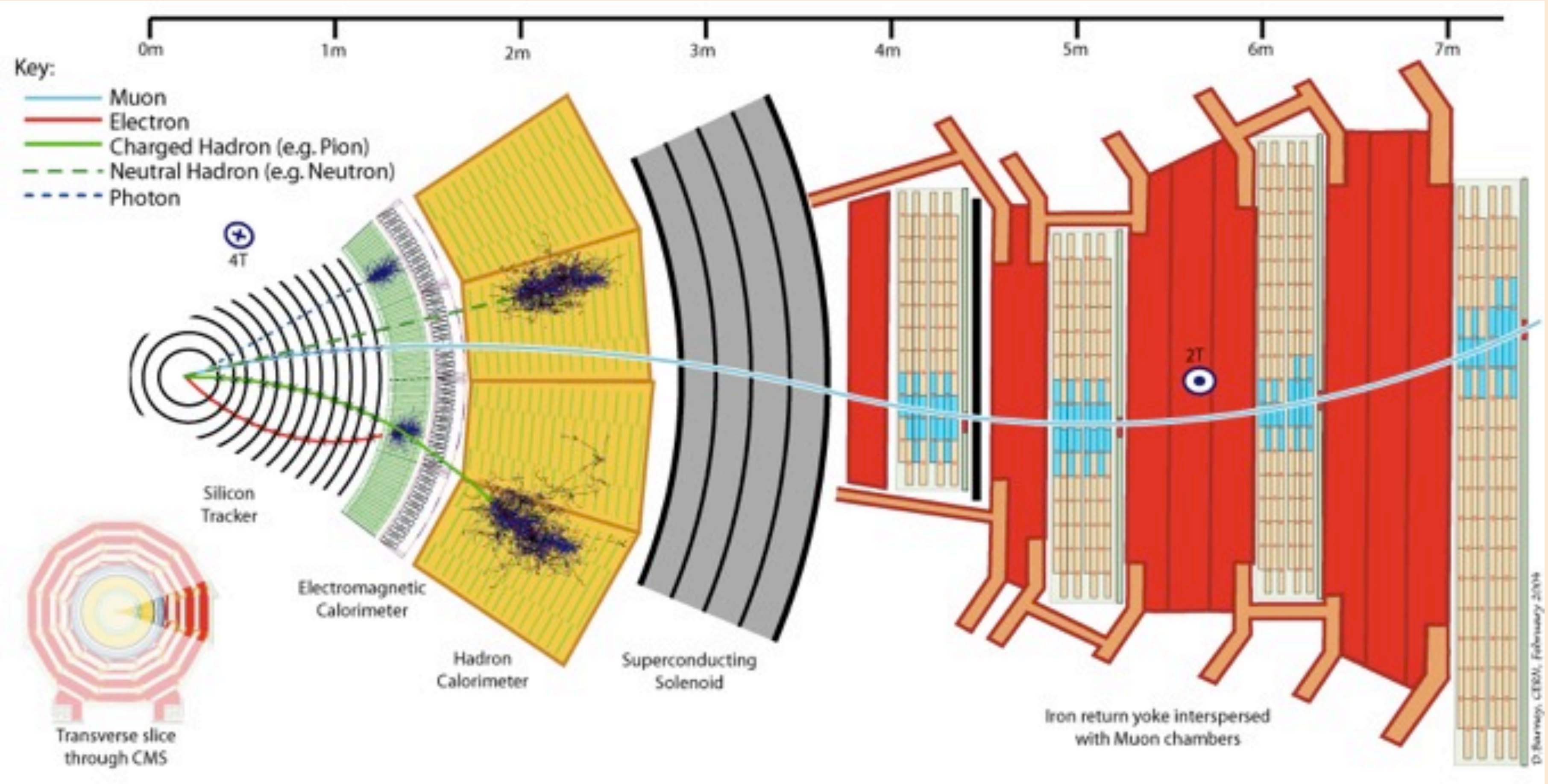
Operational Status

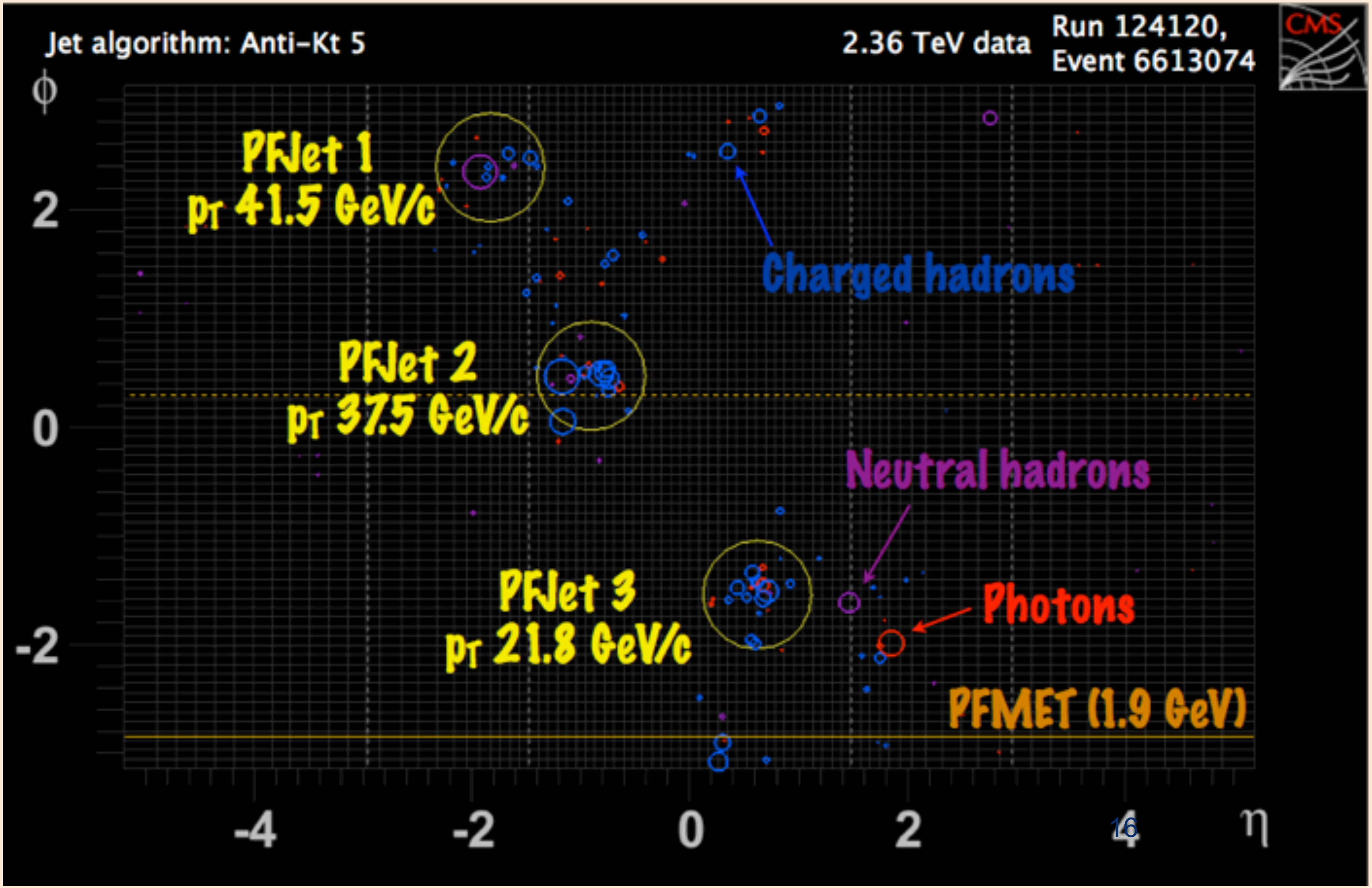


	MUON-CSC	MUON-DT	MUON-RPC	HCAL BARREL	HCAL ENDCAP	HCAL FORWARD	ECAL BARREL	ECAL END-CAP	PRE-SHOWER	STRIP TRACKER	PIXEL TRACKER	
Series1	98.5	99.8	98.8	99.9	100	99.9	99.3	98.9	99.8	98.1	98.2	

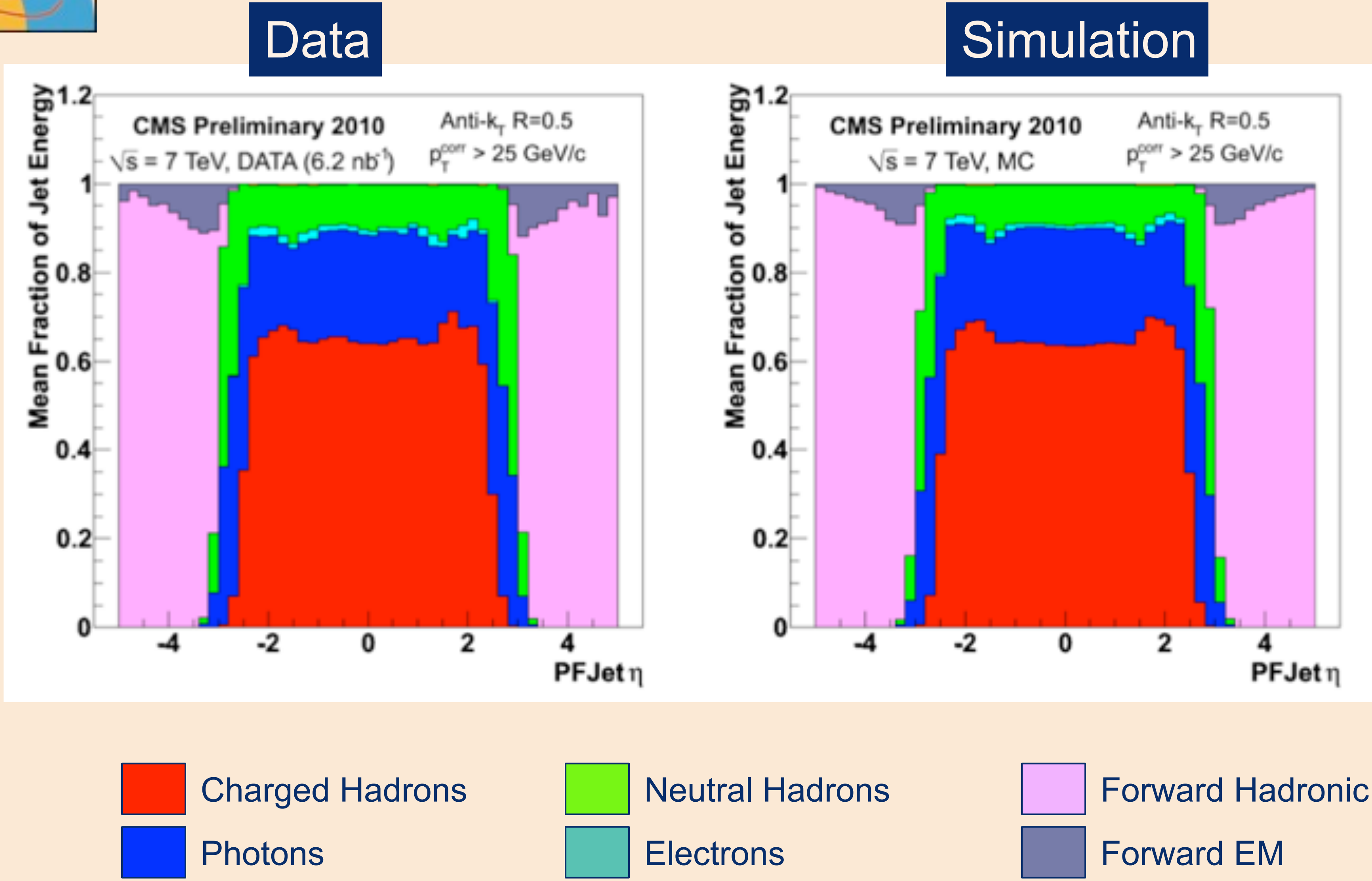
Reconstruction



Using the Full Event : Particle Flow

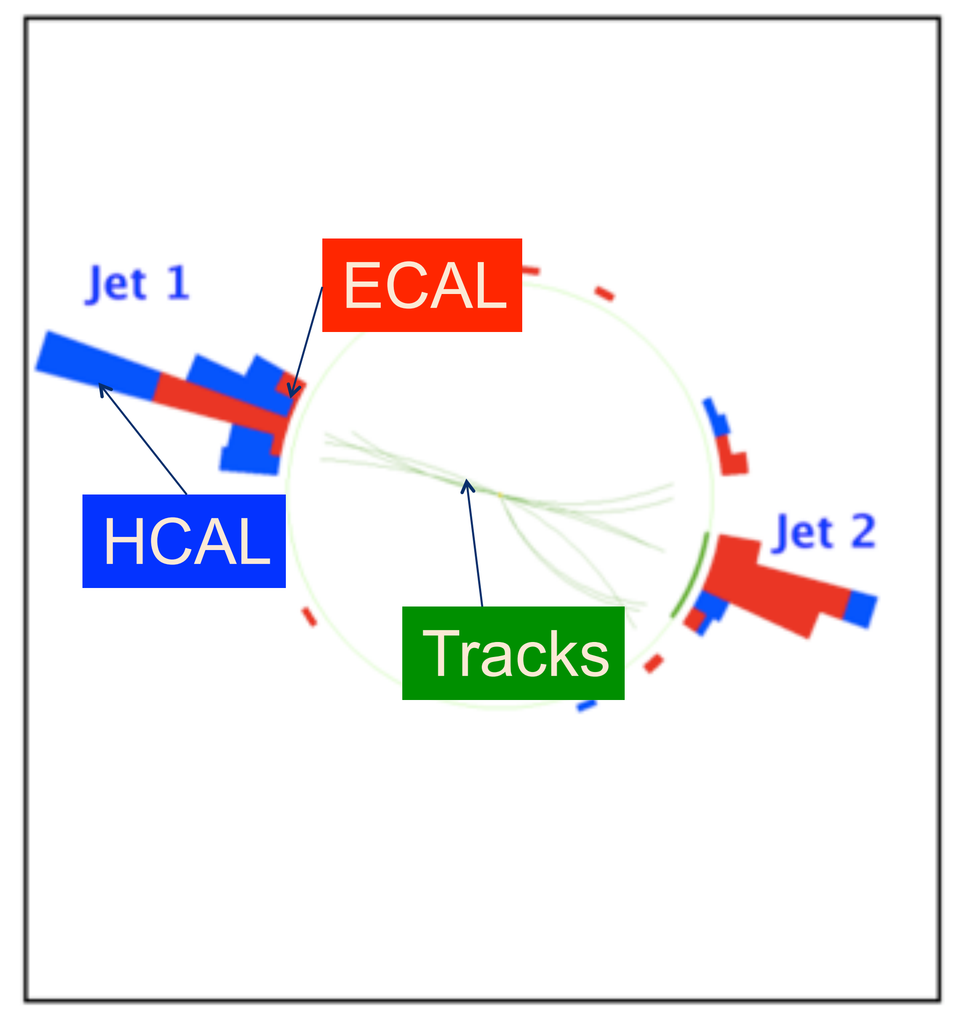


Using the Full Event : Particle Flow



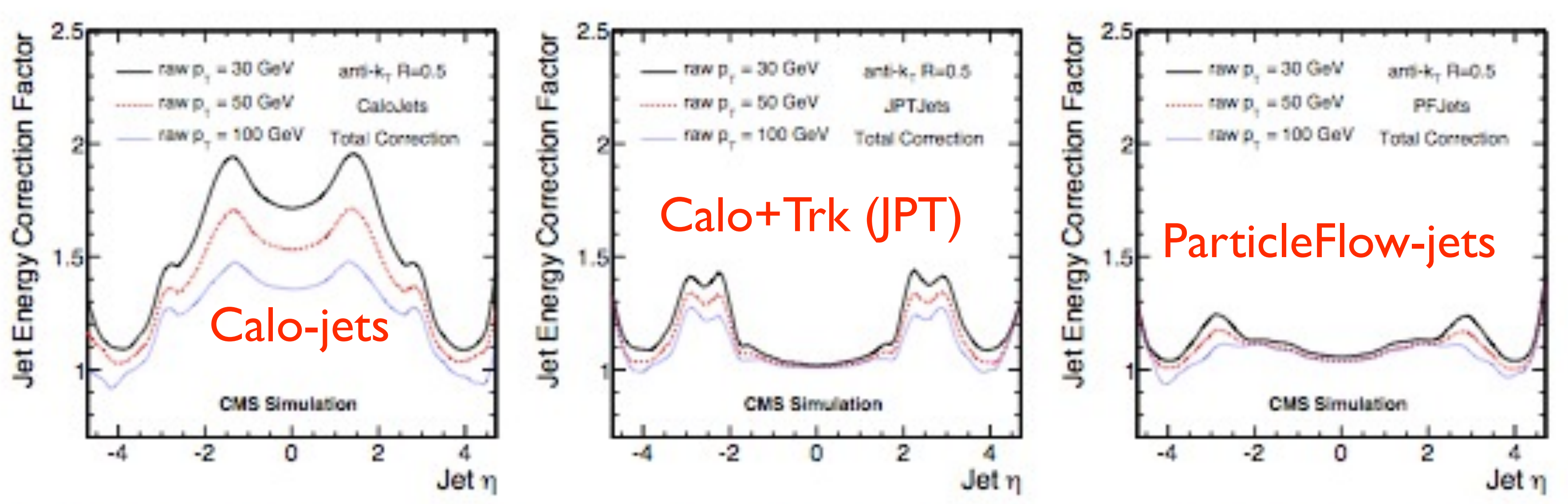
Jets at CMS

- Calorimeter jets
- Track Jets
- Track-corrected calorimeter jets
  - aka "jet-plus-tracks"
  - Replace calorimeter single-particle response with tracker response
- Particle Flow jets
  - Use all detector elements in an integrated way
  - Reconstruct particles, then cluster to jets
- Default jet algorithm: anti-kT, D = 0.5*
  - Others available, focus initially on AK5



*JHEP 0804:063,2008

Jet Corrections at CMS

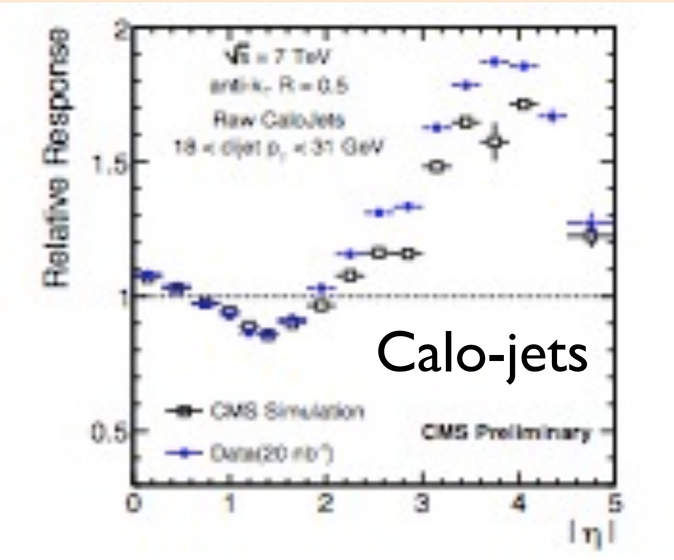


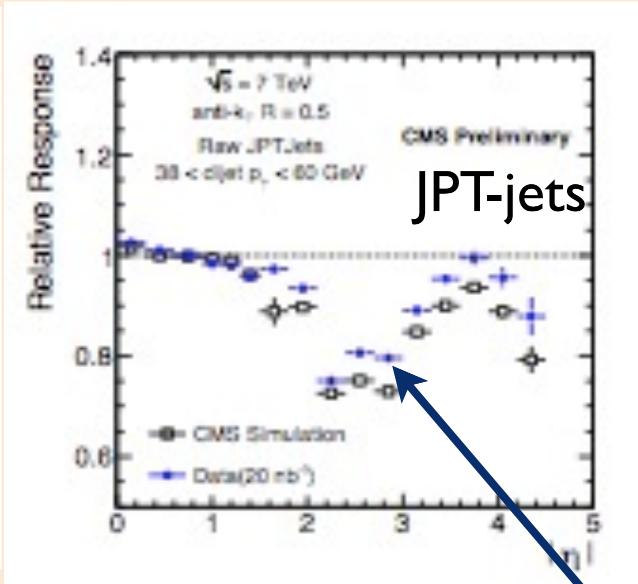
$$E_{Corrected} = (E_{Uncorrected} - E_{offset}) \times C_{Rel}(\eta, p_T'') \times C_{Abs}(p_T')$$

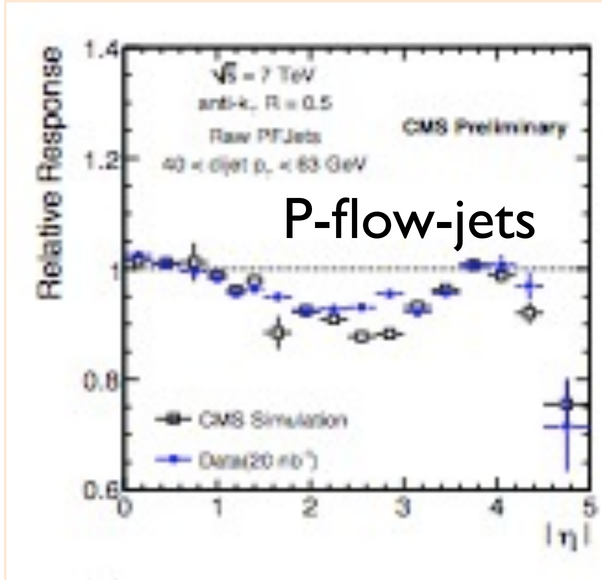
- Jet corrections applied to Calo, JPT + PF jets
- Still insufficient data to do full JEC from data
- Corrected to equal the Pt of AK5 jets made from MC particles

Jet Corrections at CMS

$$E_{Corrected} = (E_{Uncorrected} - E_{offset}) \times C_{Rel}(\eta, p''_{T}) \times C_{Abs}(p'_{T})$$



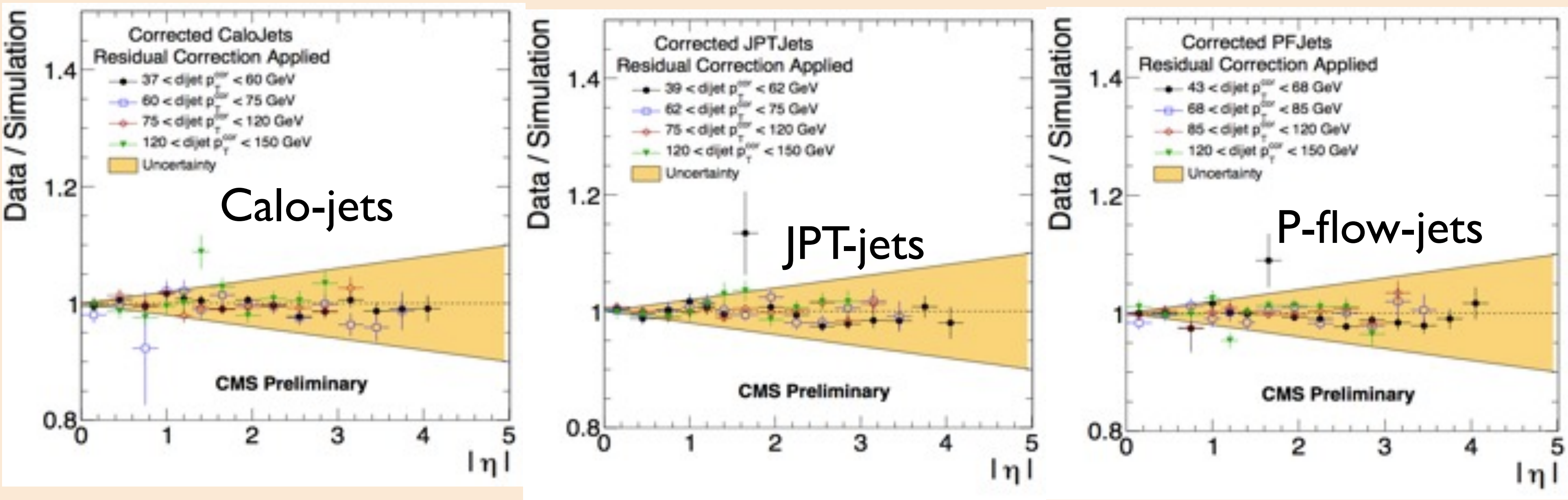




- Have enough dijet data for residual relative correction
  - For ICHEP-analysis only
  - Will update to full data-driven JEC ASAP

Jet Corrections at CMS

$$E_{Corrected} = (E_{Uncorrected} - E_{offset}) \times \boxed{C_{Rel}(\eta, p''_{T})} \times C_{Abs}(p'_{T})$$

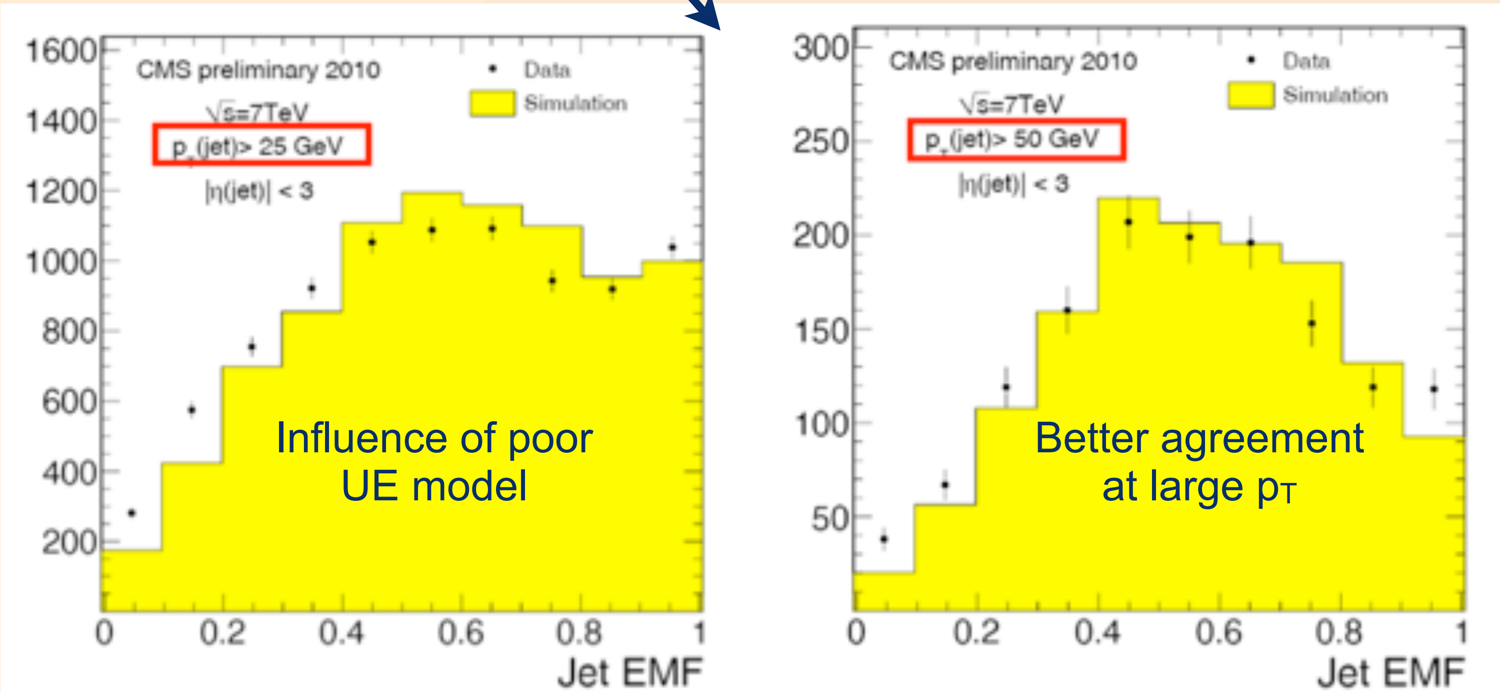


- Use data to derive residual correction

Jet ID At CMS

- Calo / JPT Jets

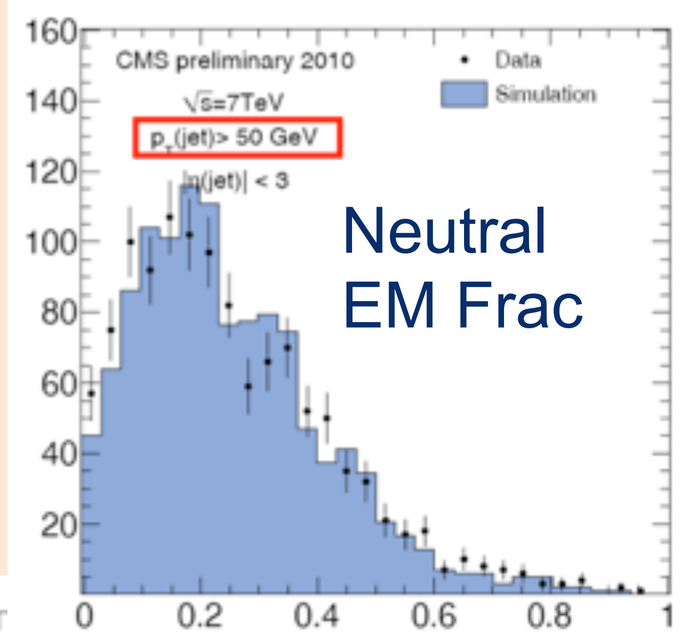
variable	$\|\eta\|$	loose	tight
EMF	< 2.6	> 0.01	> 0.01
n_{hits}^{90}	-	> 1	> 4
f_{HPD}	-	< 0.98	< 0.98
f_{RBX}	-	-	< 0.98
σ_η	-	-	> 0.01
σ_φ	-	-	> 0.01

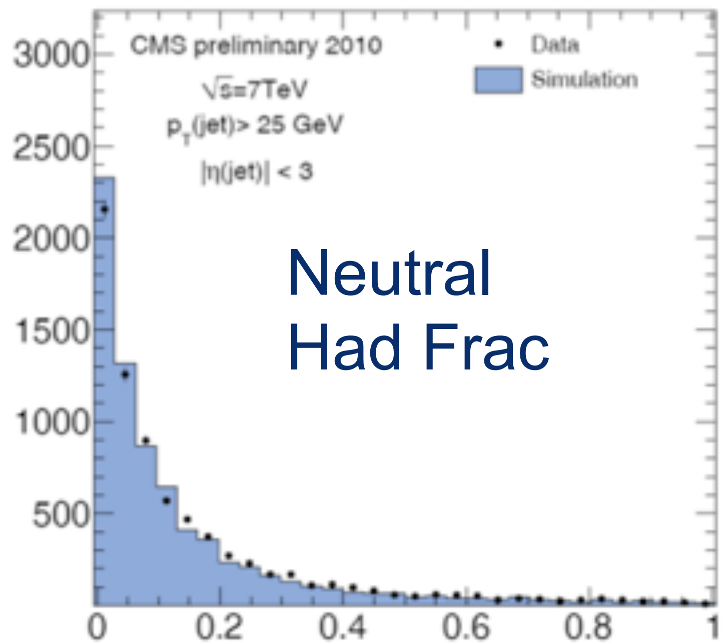


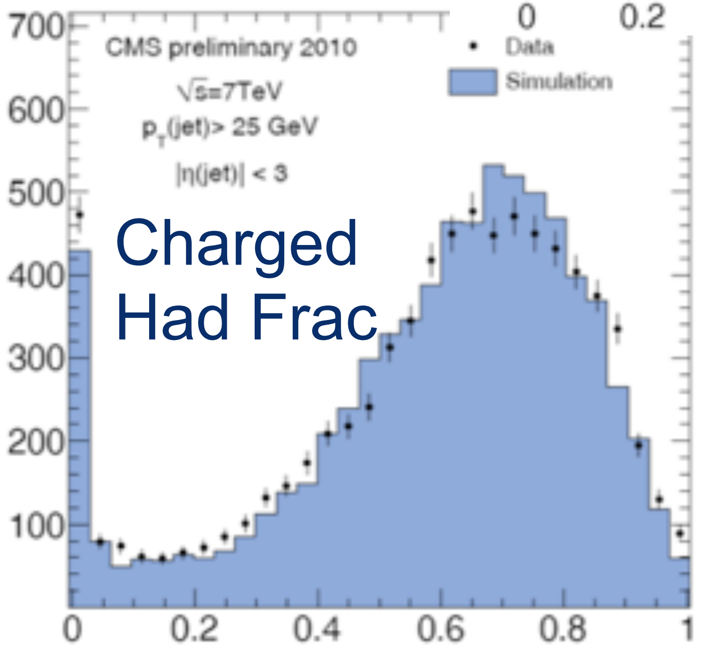
Jet ID At CMS

- PF Jets

variable	$\|\eta\|$	loose	tight
CHF	< 2.4	> 0.0	> 0.0
NHF	-	< 1.0	< 0.9
CEF	-	< 1.0	< 1.0
NEF	-	< 1.0	< 0.9







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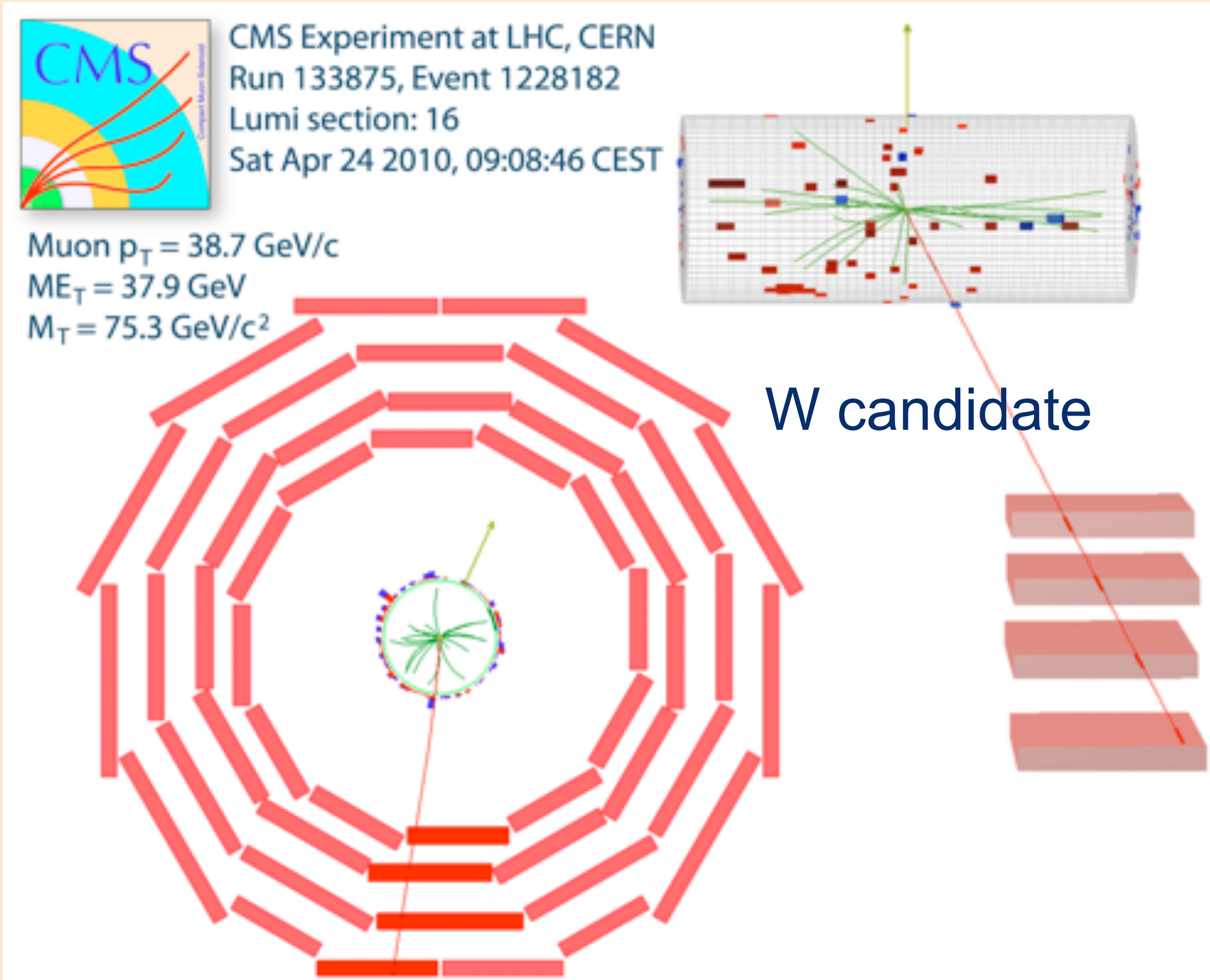
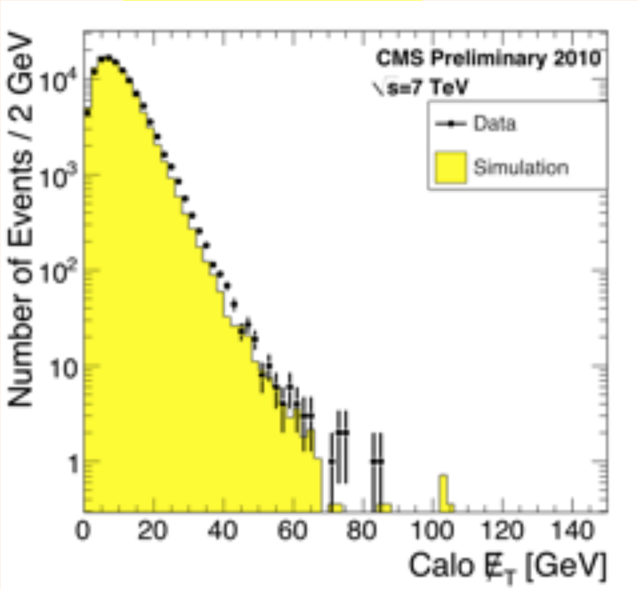
MET at CMS

- Calorimeter MET
- Track-Corrected MET
- Particle Flow MET

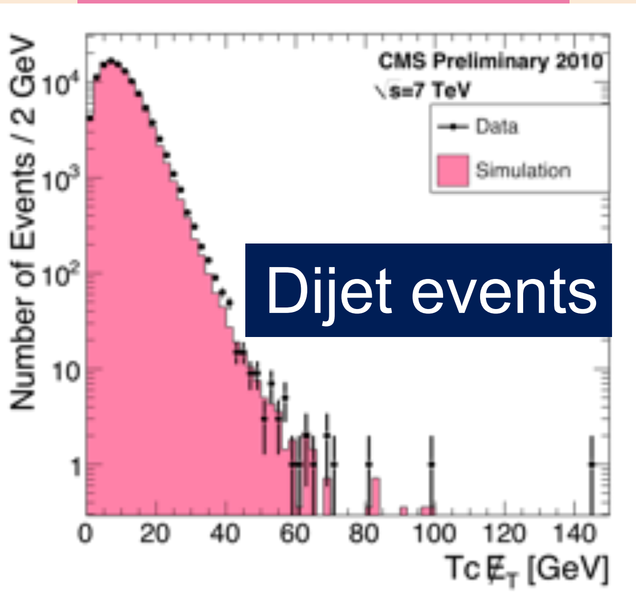


MET at CMS

Calo only

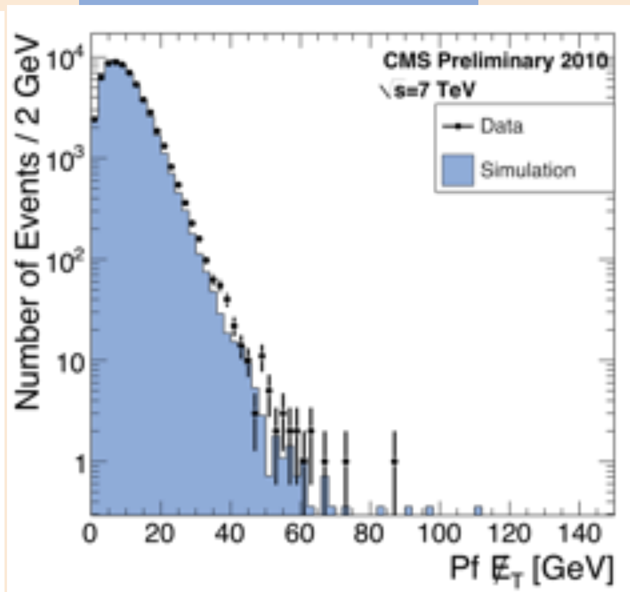


Track-Corrected



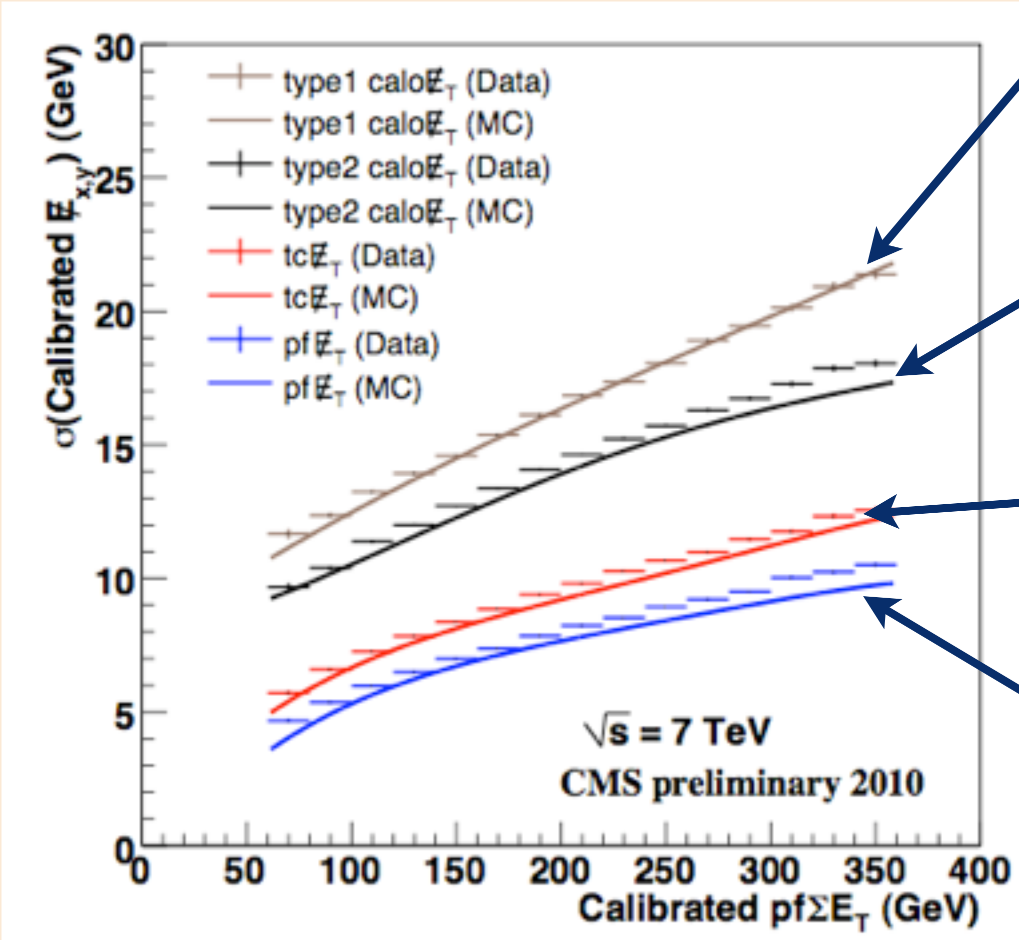
Dijet events

Particle Flow



The simulation reproduces the data after cleanup

MET Resolution at CMS



Corrected for JES

Corrected for nonlinearity in unclustered towers

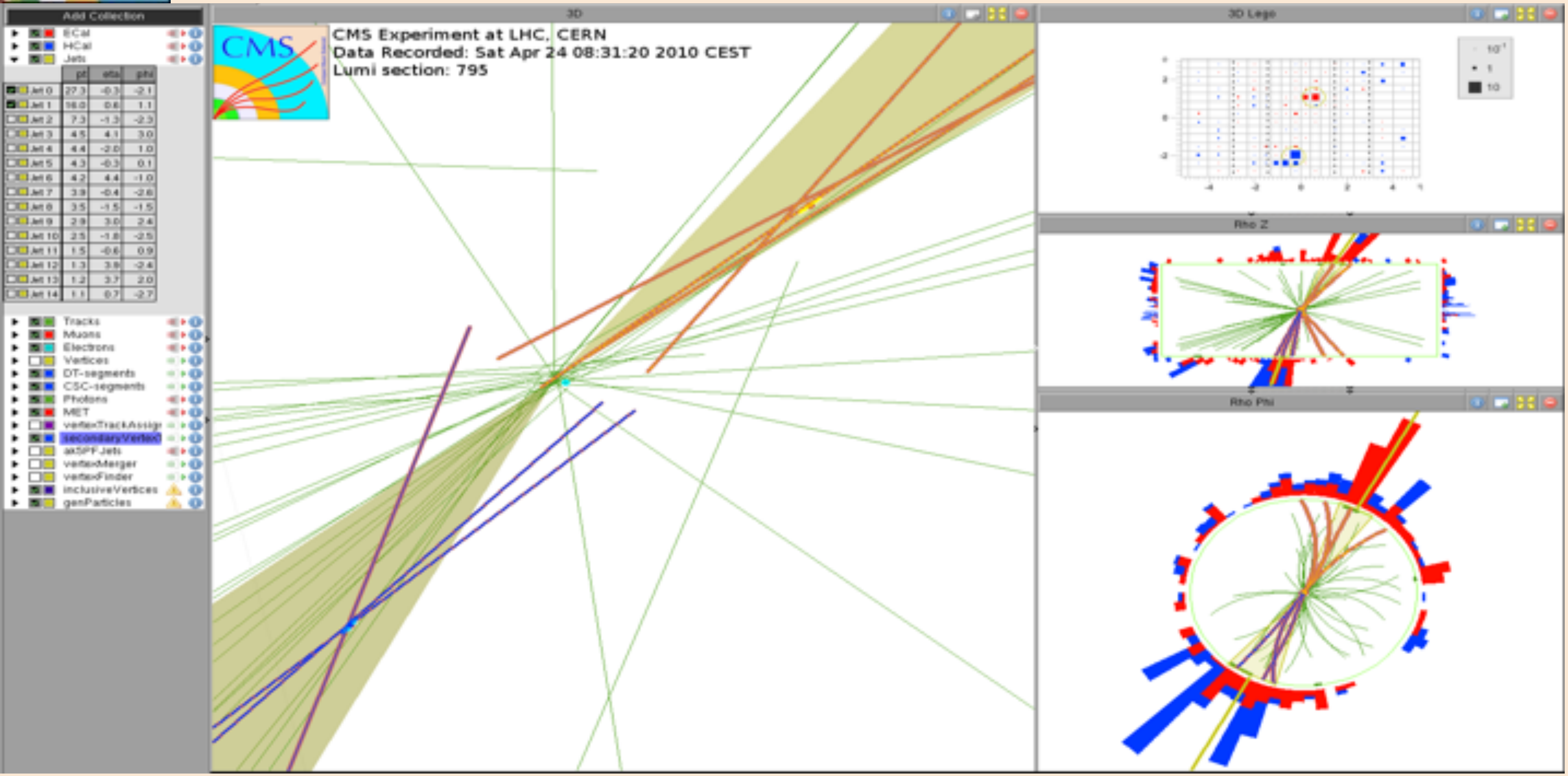
Corrected with track p_T

Using full detector in integrated way with particle flow

MET resolution in simulation reproduces the data reasonably well

23Aug2010

B-Tagging



- Primary vertex resolution < 200 μm (x,y), < 300 μm(z)
  - Includes beamline

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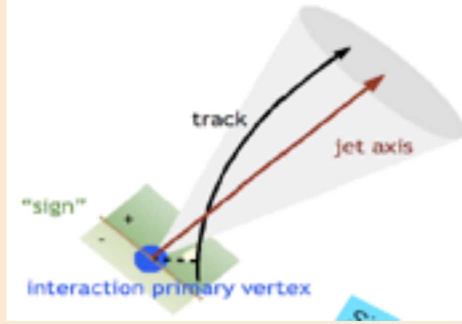
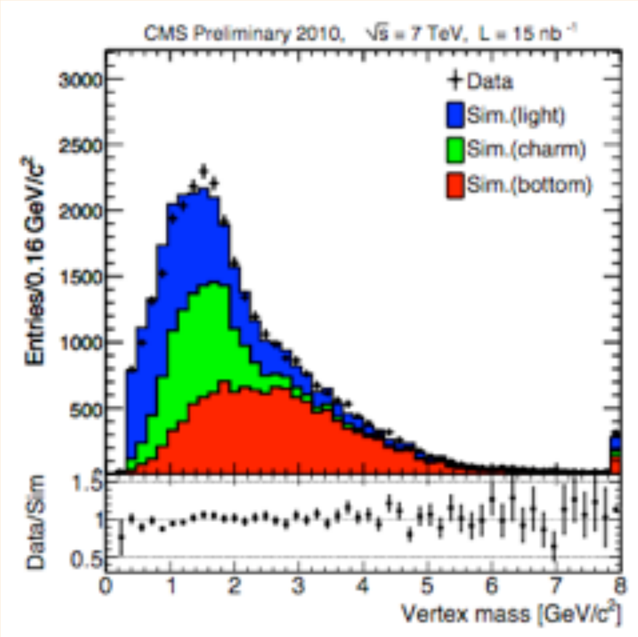
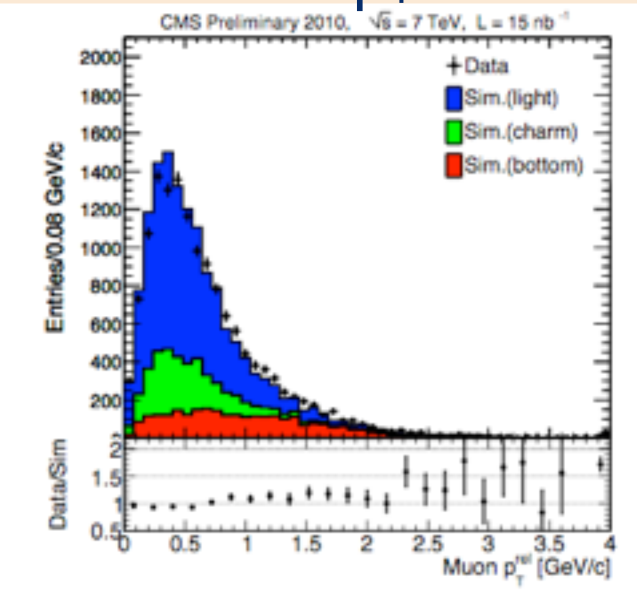
B-Tagging



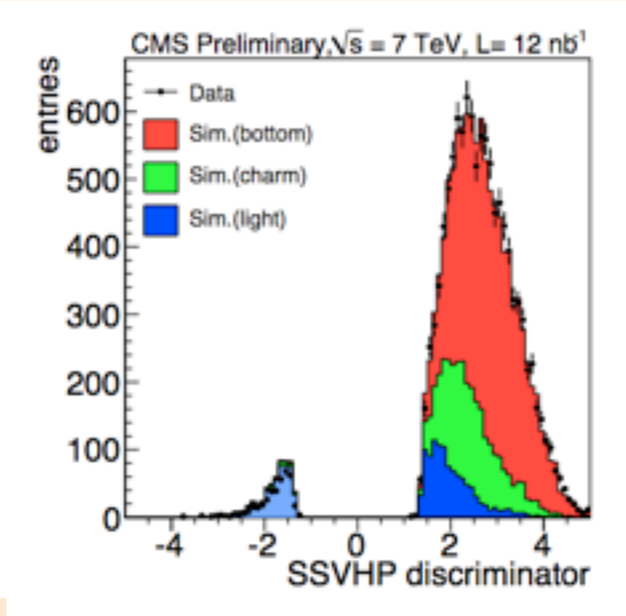
Vertex Mass



Muon p_T^{Rel}



Discriminator



- All very well modeled by MC!
  - Extract purity from vertex mass
  - Extract efficiency from p_T^{Rel}
  - Extract mistag rate from negative tags

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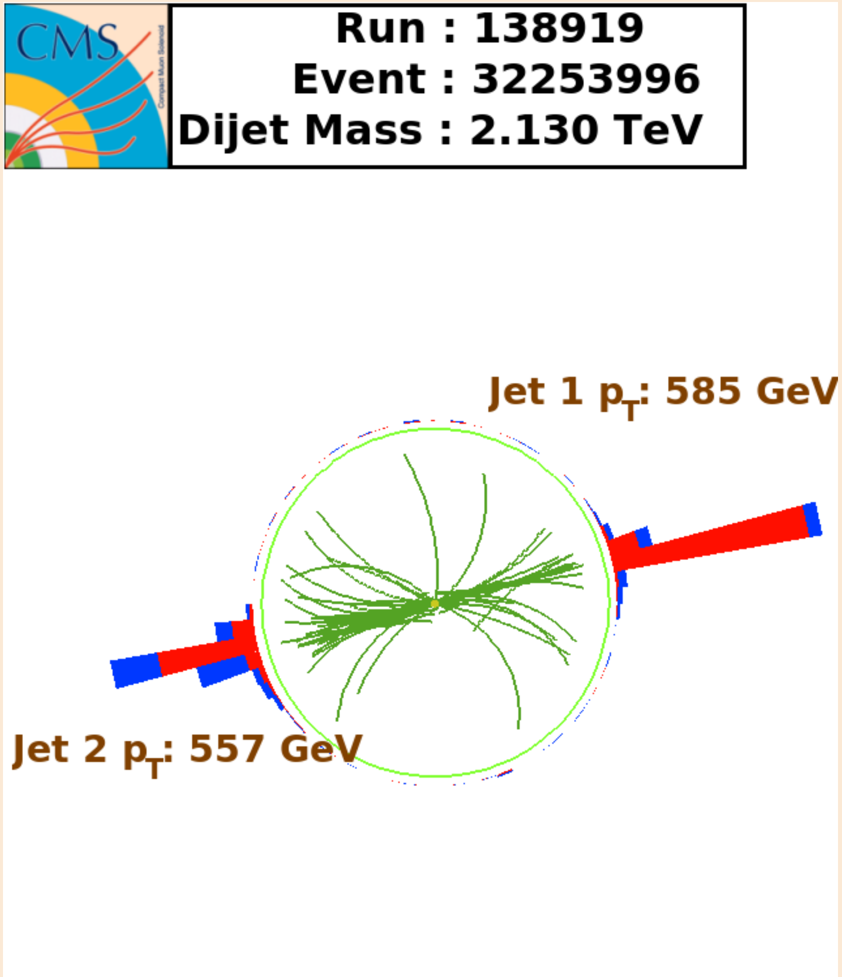
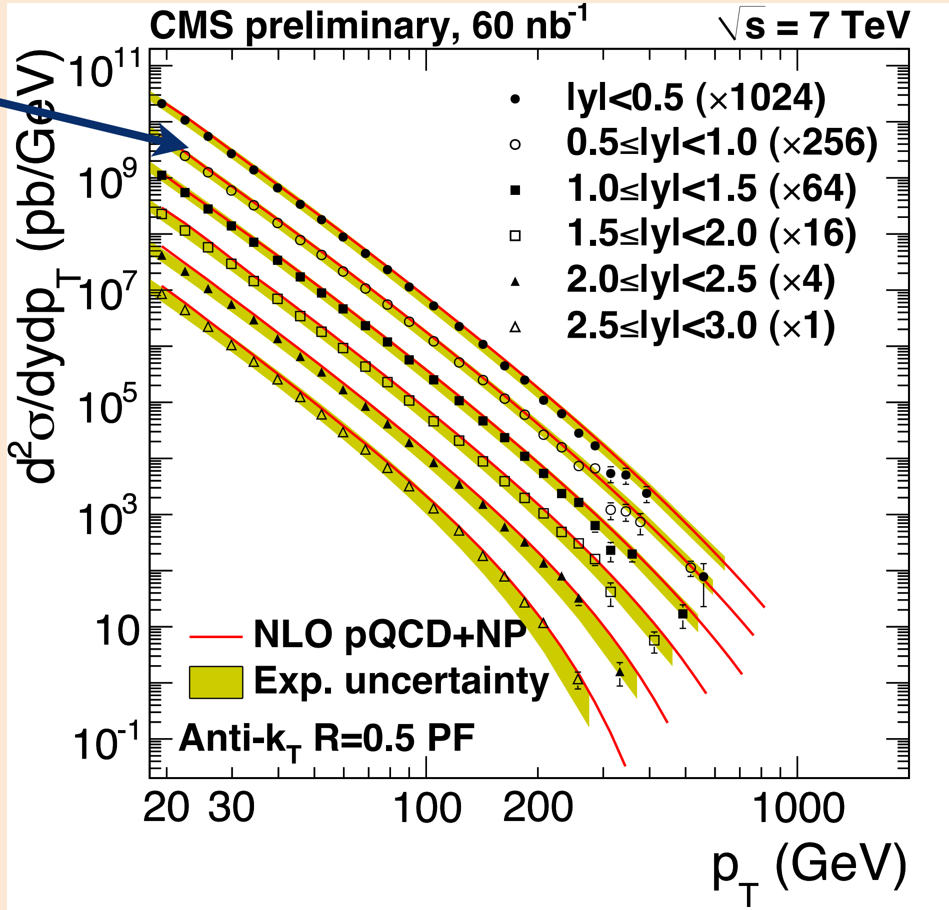
First Physics with Jets and MET



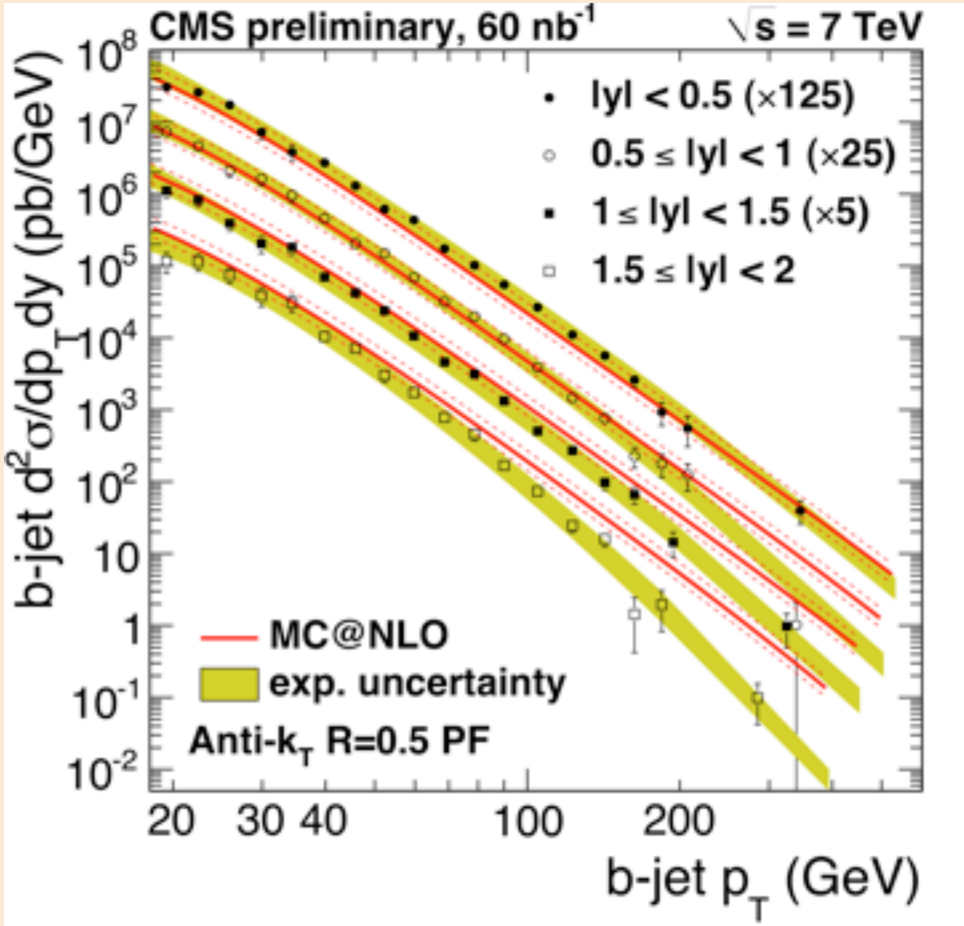
Inclusive Jet p_T Spectrum

- Use AK5 PF jets to get down to low p_T
- Extremely good agreement with NLO (with corrections for nonperturbative effects)
  - N.P. calculation largest sys. at low p_T
  - PDF uncertainty largest sys. at high p_T



Inclusive b-jet p_T Spectrum

- AK5 PF Jets
- Extract purity, efficiency, and mistag rate as described above
- Reasonable agreement with MC after corrections, still has some discrepancies to work on



3-Jet to 2-jet Ratio

- AK5 Calo jets
- Compute cross section for 2 and 3 jets:

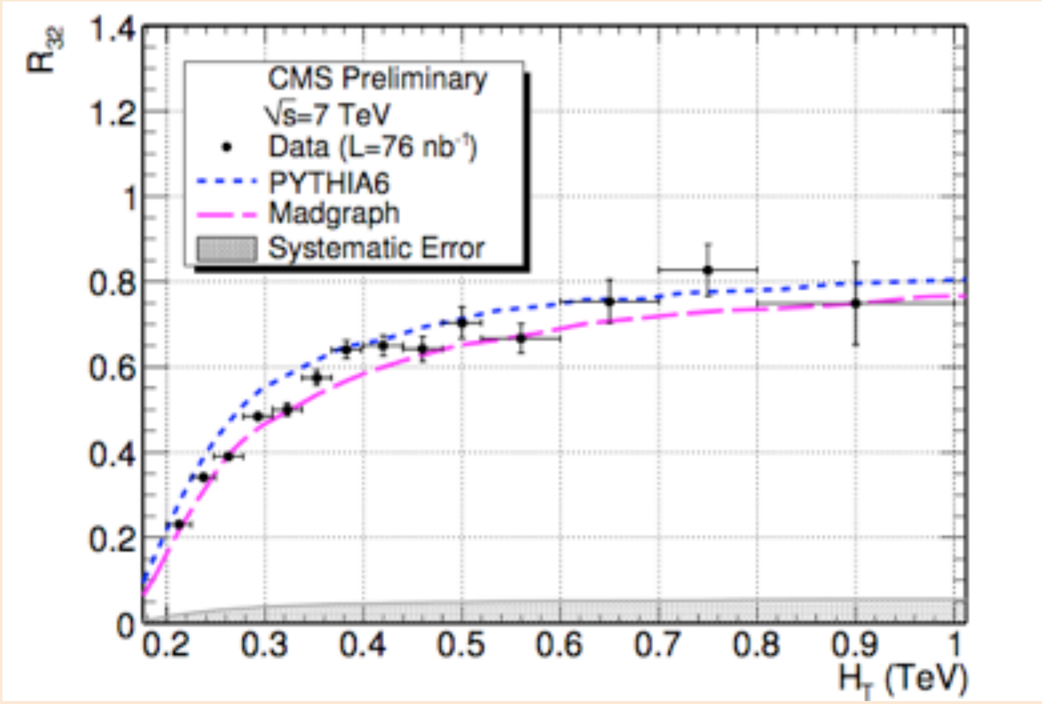
Smearing factor

$$\frac{d\sigma_i}{dH_T} = \frac{C_i}{L \cdot \varepsilon_i} \cdot \frac{N_i}{\Delta H_T}$$

Efficiency

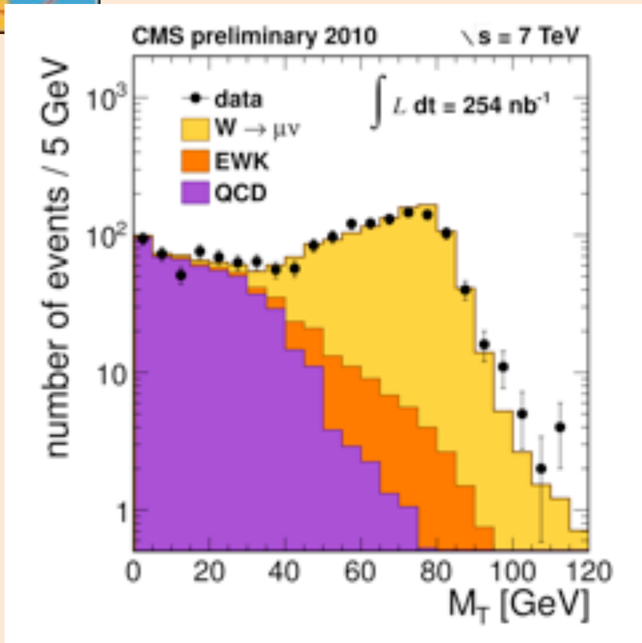
- Calculate ratio:

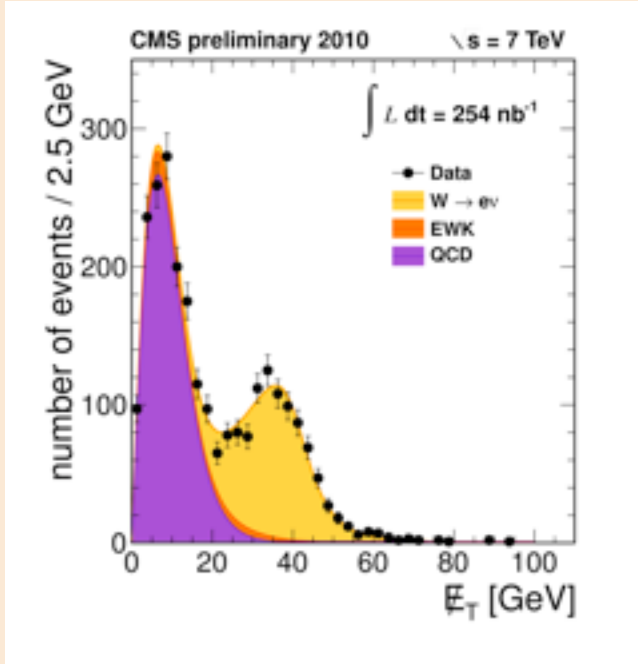
$$R_{32} = \frac{d\sigma_3/dH_T}{d\sigma_2/dH_T}.$$



Good agreement with PYTHIA and MADGRAPH, no discernment yet

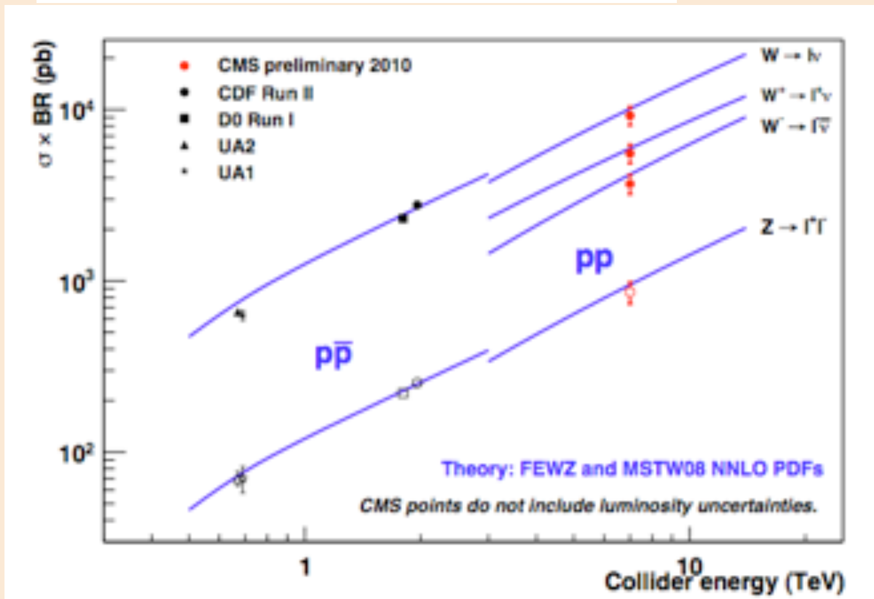
Electroweak Measurements



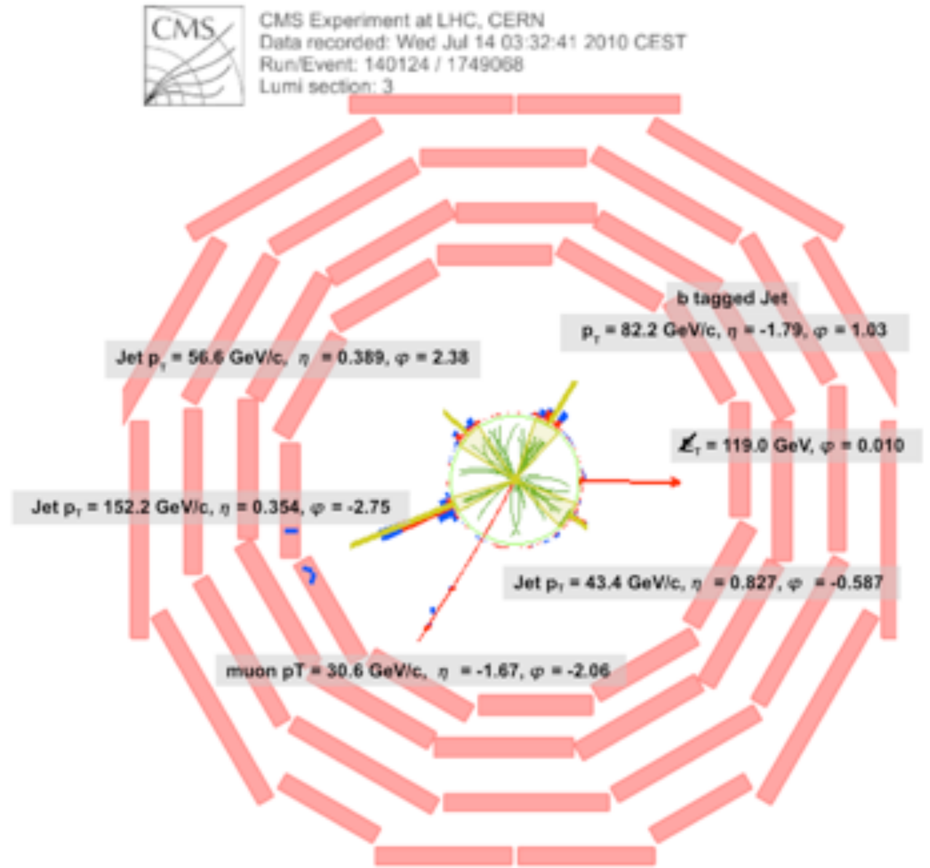


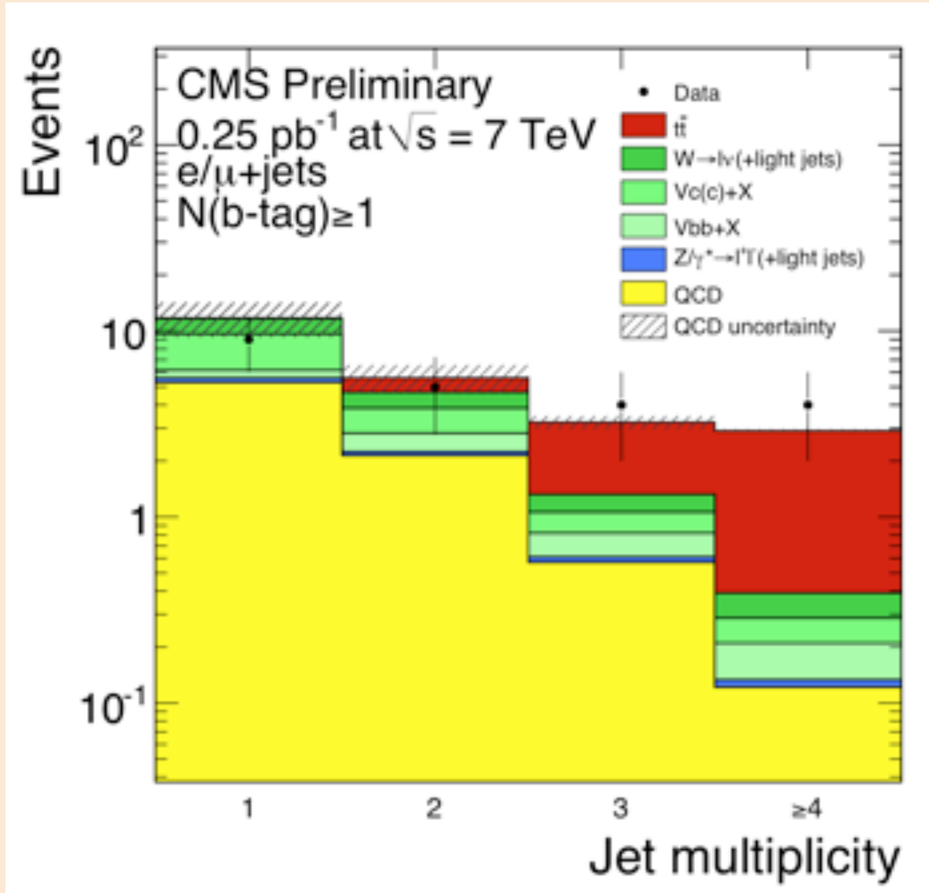
- Using MET to extract W in electron and muon channels

- MET at CMS is ready for physics!



Top Quark





- Combines all information in detector!
- So far so good
- Expect updates for PIC this week!

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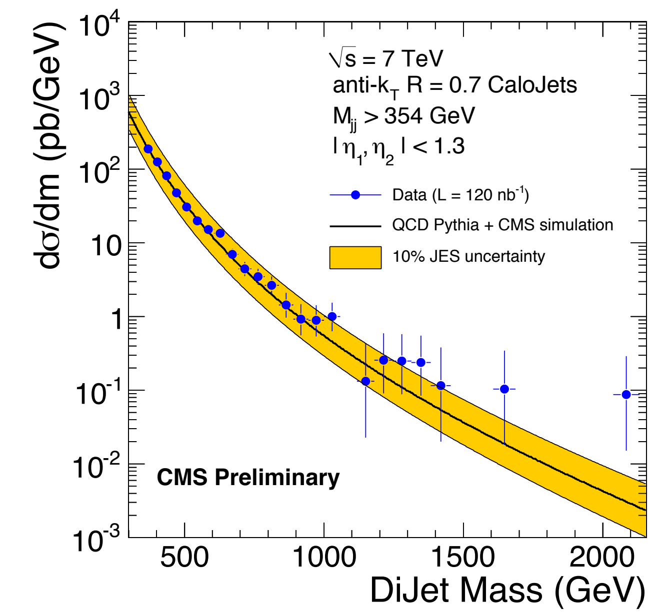
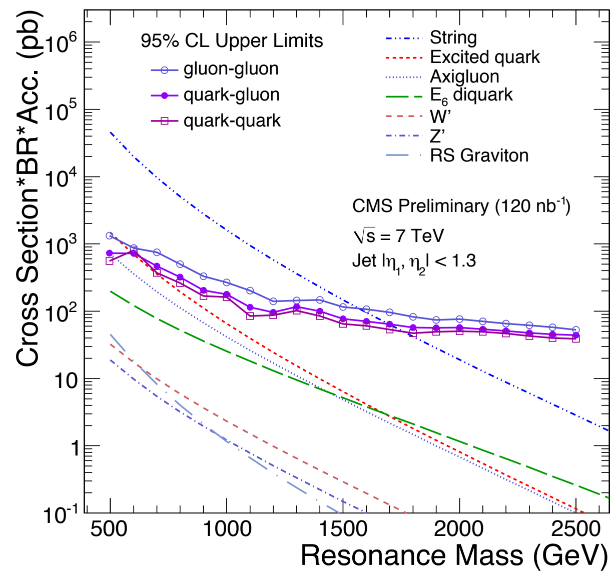
Dijet Resonances

- AK7 Calo Jets, search for narrow resonaces
- Fit to falling spectrum

$$\frac{d\sigma}{dm} = \frac{P_0 \cdot (1 - m/\sqrt{s})^{P_1}}{m^{P_2}}$$

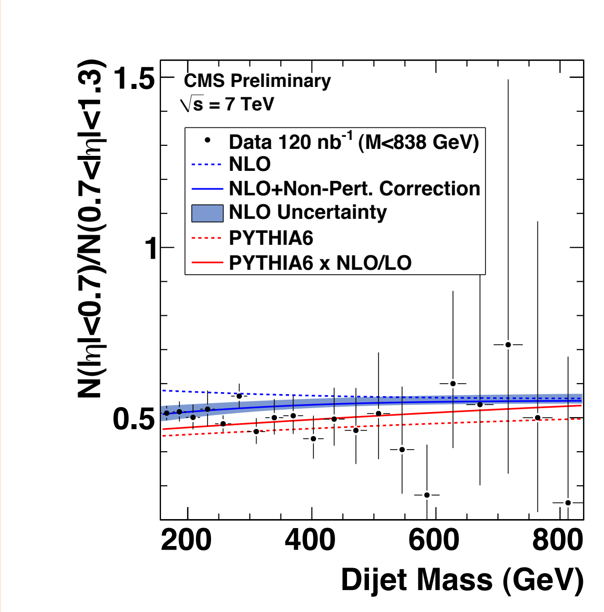
- Search for excess
- Hybrid Bayesian technique for limit setting
  - Convolute likelihood with a Gaussian for uncertainty
- Uncertainties:
  - Jet energy scale
  - Jet energy resolution
  - Background parameterization
  - Luminosity
- No new physics signatures

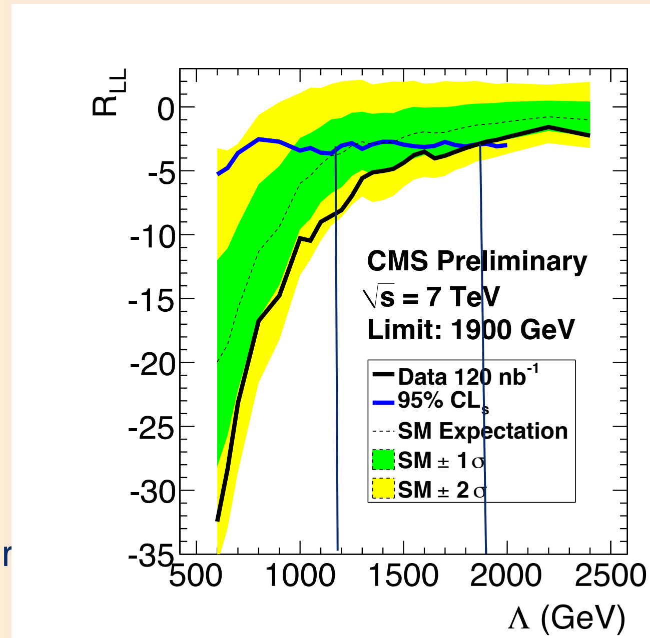




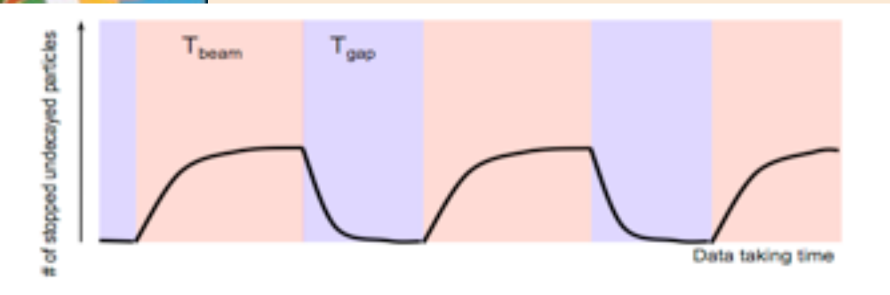
Dijet Centrality

- Examine ratio of dijet events from "inner" versus "outer" regions
  - Inner : |η| = 0 - 0.7
  - Outer : |η| = 0.7 - 1.3
  - Nearly flat in the Standard Model case
- Complimentary analysis to the dijet resonance search
- Event selection is the same
- Uses lower pt mass bins (and triggers) also
- Expected limit:
  - 1.2 TeV
- Observed limit:
  - 1.8 TeV



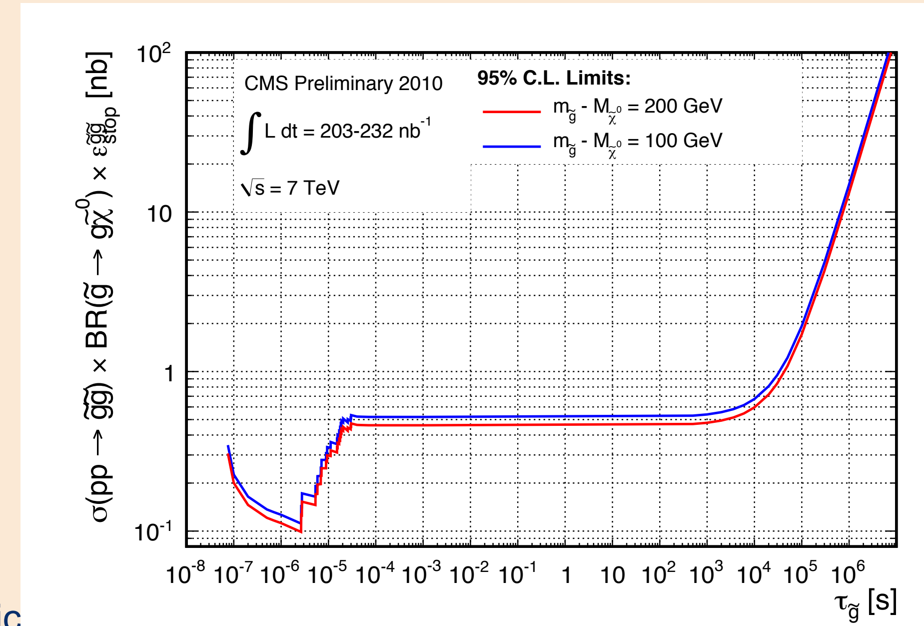


Stopped Gluinos

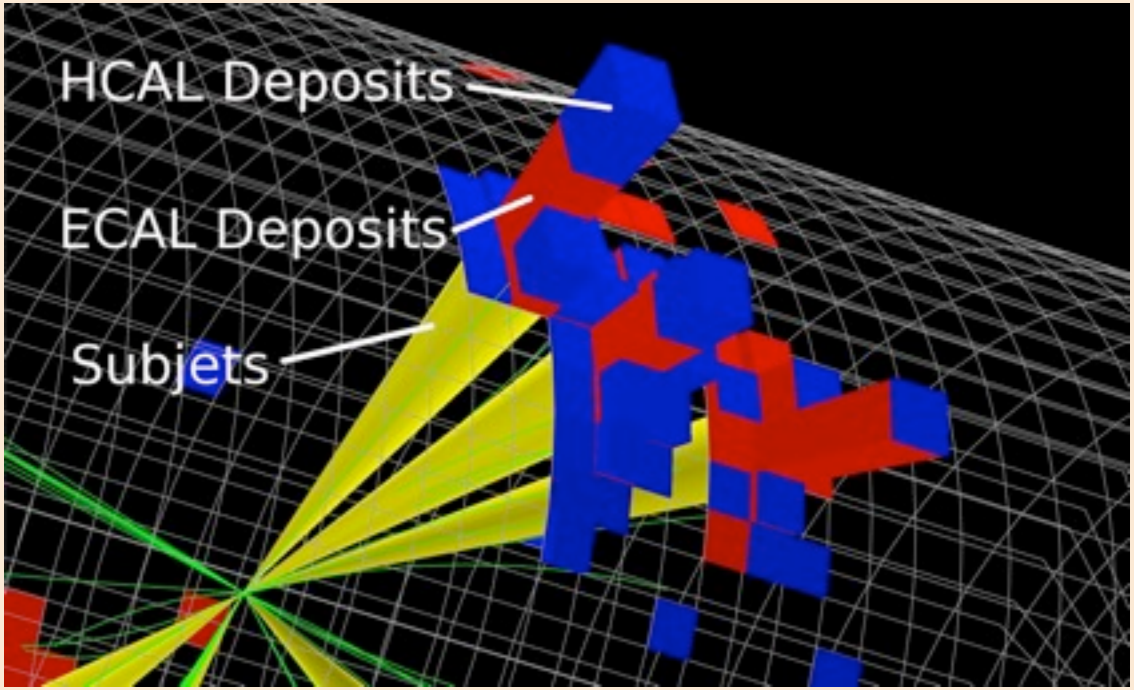


Selection Criteria	Background Rate (Hz)	Signal Efficiency %
L1+HLT (HB+HE)	3.27	30.5
Calorimeter noise filters	1.12	29.9
BPTX/BX veto	1.11	29.9
muon veto	6.6×10^{-1}	26.4
$E_{jet} > 50$ GeV, $\lvert\eta_{jet}\rvert < 1.3$	7.6×10^{-2}	20.5
$n_{60} < 6$	7.6×10^{-2}	20.2
$n_{90} > 3$	3.1×10^{-3}	18.6
$n_{phi} < 5$	1.3×10^{-4}	18.5
$R_1 > 0.15$	1.1×10^{-4}	18.5
$0.1 < R_2 < 0.5$	8.5×10^{-5}	17.5
$0.4 < R_{peak} < 0.7$	7.9×10^{-5}	17.3
$R_{outer} < 0.1$	6.9×10^{-5}	17.2

- Stopped R-hadrons (like gluinos) produced during collisions, but decay at any time!
  - Can look during "gap" periods!
- Event selection is conservative, mostly removes beam and noise backgrounds
  - Noise and cosmics backgrounds are measured from data during cosmic data taking
  - Beam-related backgrounds are reduced by looking far from triggered bunch crossings
- No new physics seen



Jet Substructure at CMS

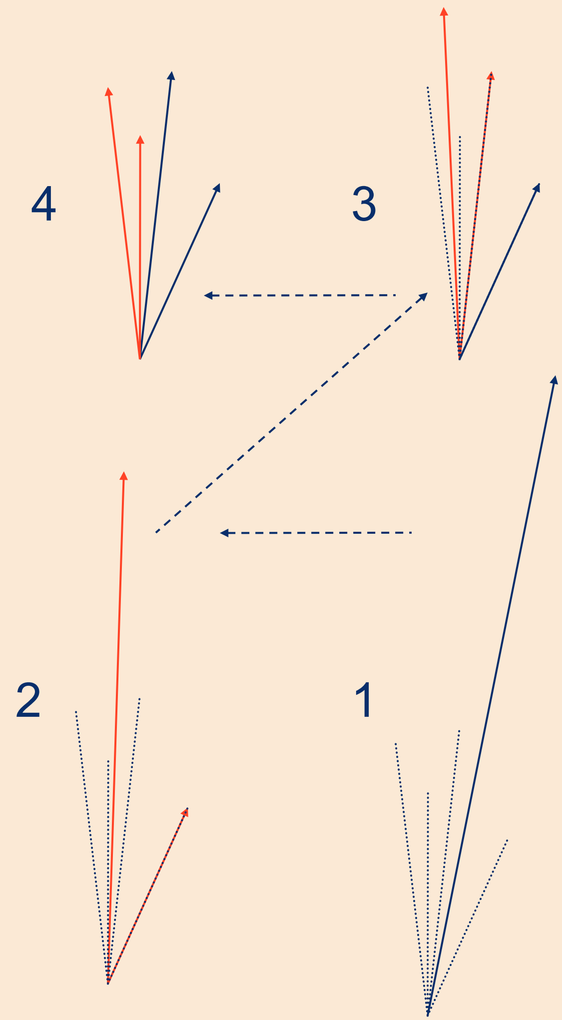


Fine Print

- No new 7 TeV results approved
  - Long saga, many familiar
- Previous work done with Calo Jets, switching now to PF
- Working on first data measurements, more later!
- Will focus on CMS strategies for substructure
  - Preliminarily focused on top tagging, branching out now

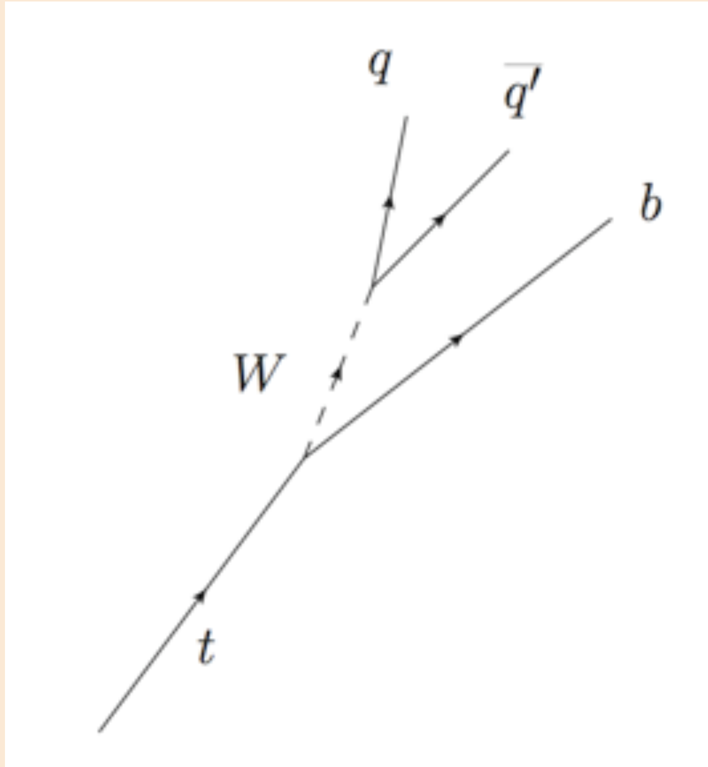
Top Tagging

- Based on JHU tagging algorithm from Kaplan et al (http://arxiv.org/abs/0806.0848, Phys.Rev.Lett. 101:142001,2008)
- **“Hard jets”:** Cluster jets with C-A
  - R = 0.8
  - p_T > 250 GeV
  - |y| < 2.5
- Reverse cluster sequence
  - Throw out soft clusters
    - Fraction of hard jet pt < 0.05
- Repeat on clusters until either
  - Have 3 or 4 hard clusters **(PASS)**
  - There are all soft clusters **(FAIL)**
- These are called **“subjets”**



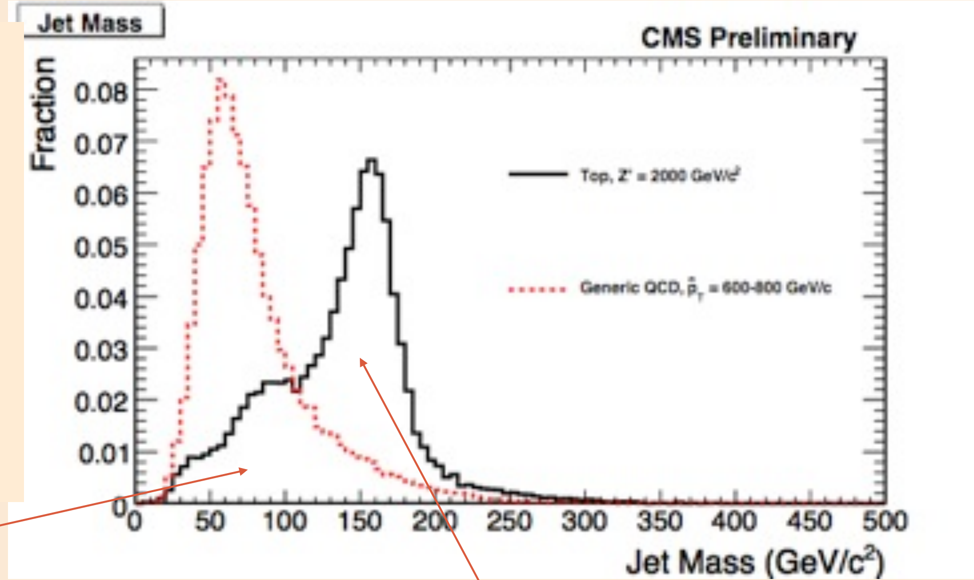
Top Tagging

- Discriminate **top jets** against **non-top jets**
  - Top mass
  - W mass
  - b-tagging



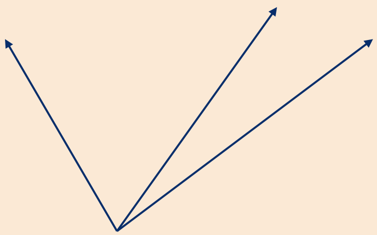
Top Tagging

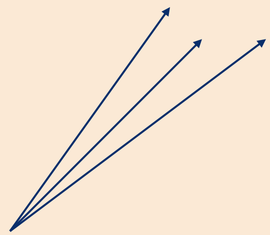
- Discriminate **top jets** against **non-top jets**
  - **Top mass ~ jet mass**
  - W mass



Partially merged jets

Fully Merged jets

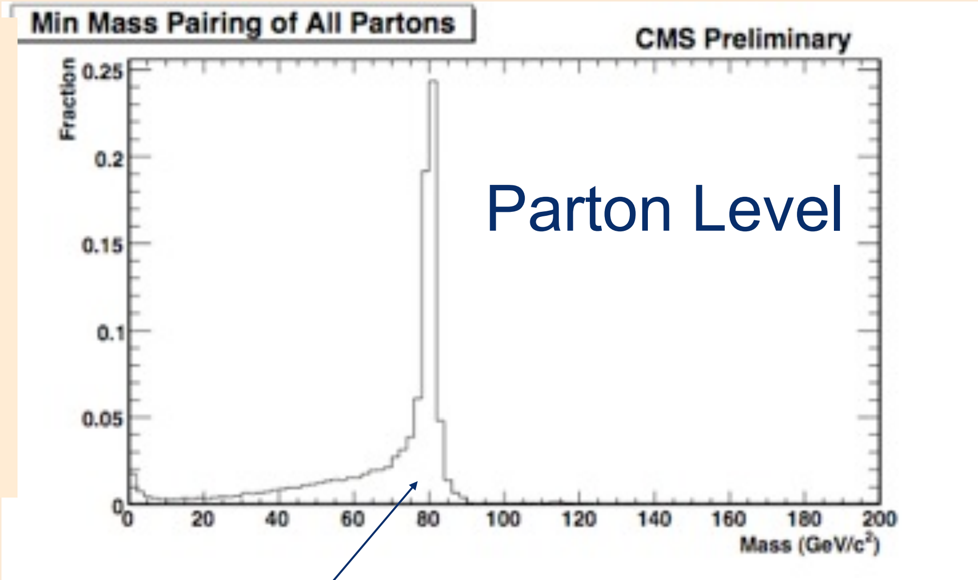




Jet mass good approximation for top mass

Top Tagging

- Discriminate **top jets** against **non-top jets**
  - Top mass
  - **W mass ~ min di-subjet mass**



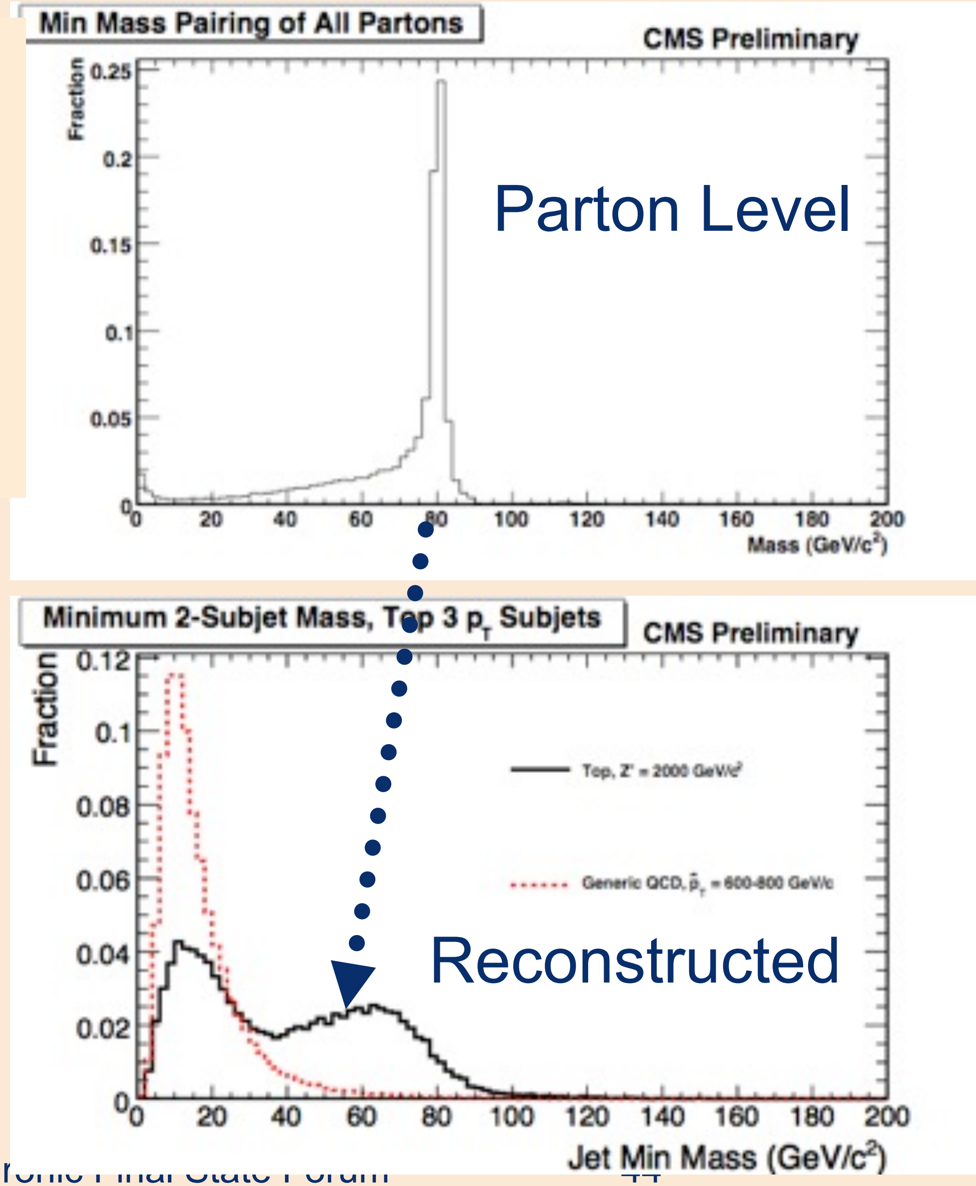
bq
bq'
qq'

Take minimum mass pairing

Top Tagging

- Discriminate **top jets** against **non-top jets**
  - Top mass
  - **W mass ~ min di-subjet mass**

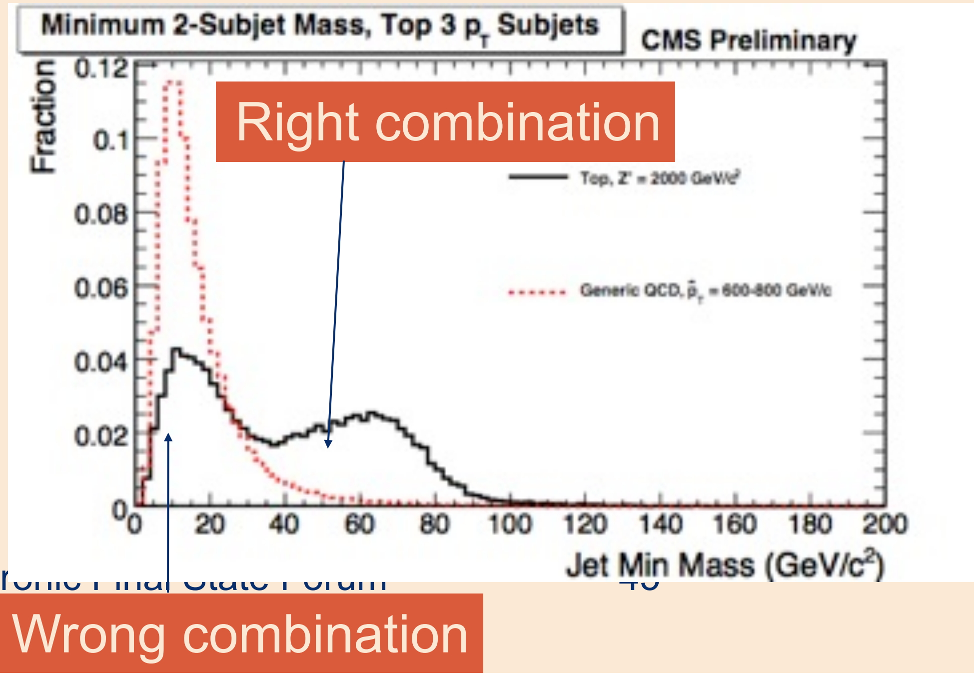
bq → j1+j2
bq' •••••• → j1+j3
qq' → j1+j3



Top Tagging

- Discriminate **top jets** against **non-top jets**
  - Top mass
  - **W mass ~ min di-subjet mass**

After reconstruction, still often gets W mass



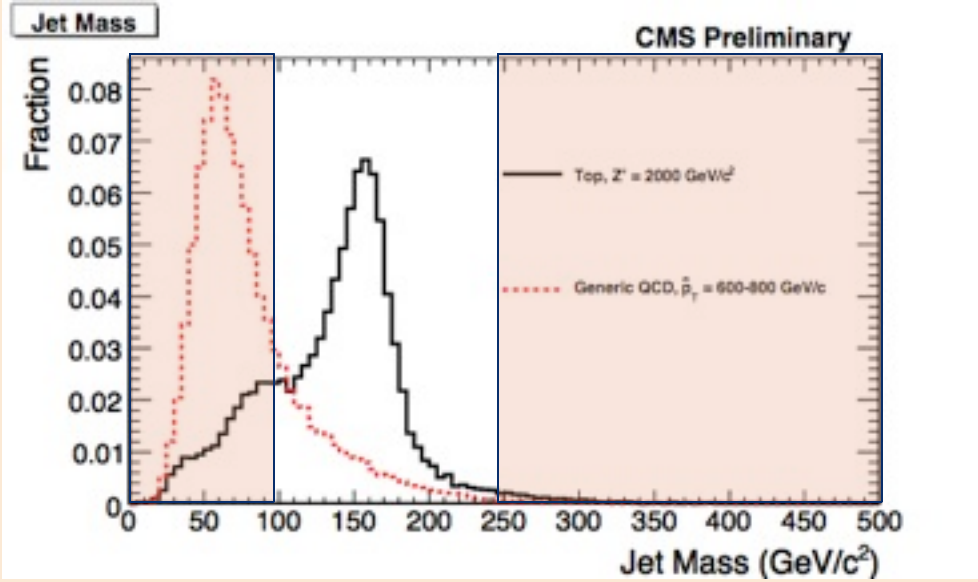
Top Tagging

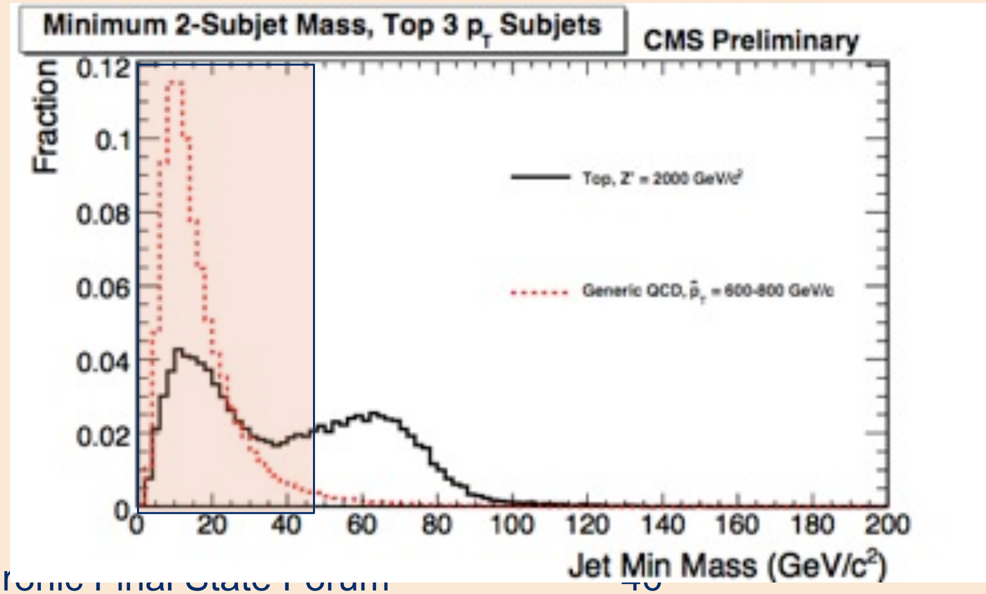
- Discriminate **top jets** against **non-top jets**
  - Top mass
  - W mass

Require

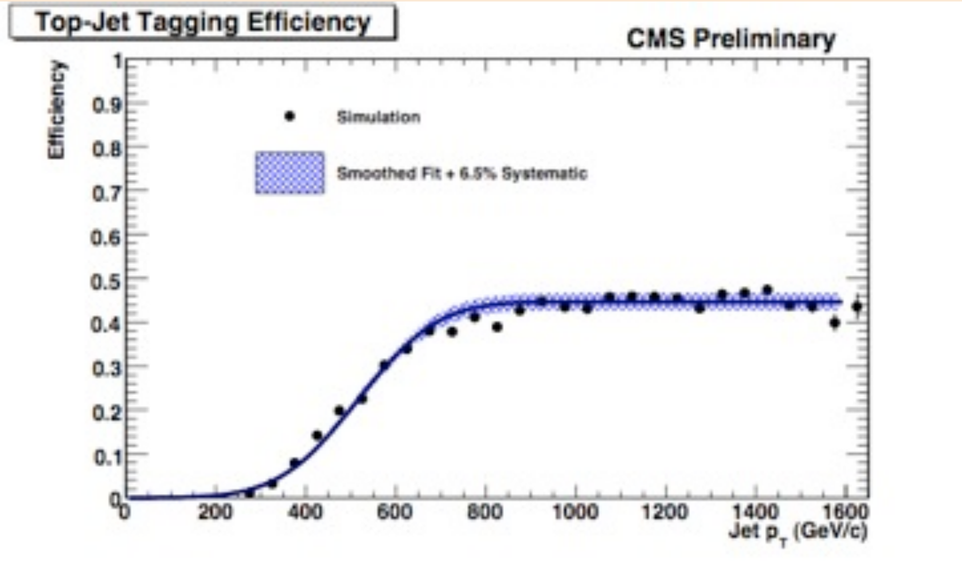
$100 < m_{jet} < 250$ GeV/c^2

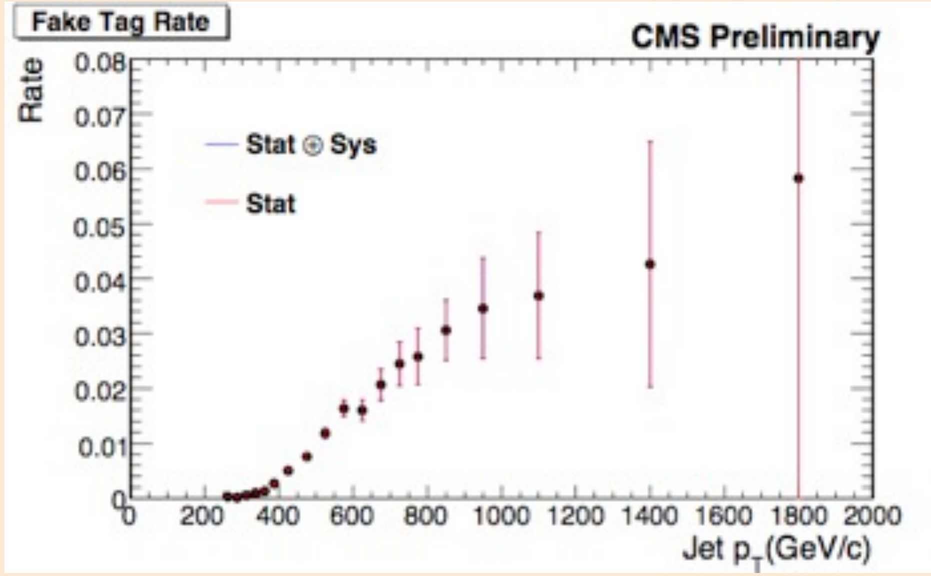
50 GeV/c^2 $< m_{min}$





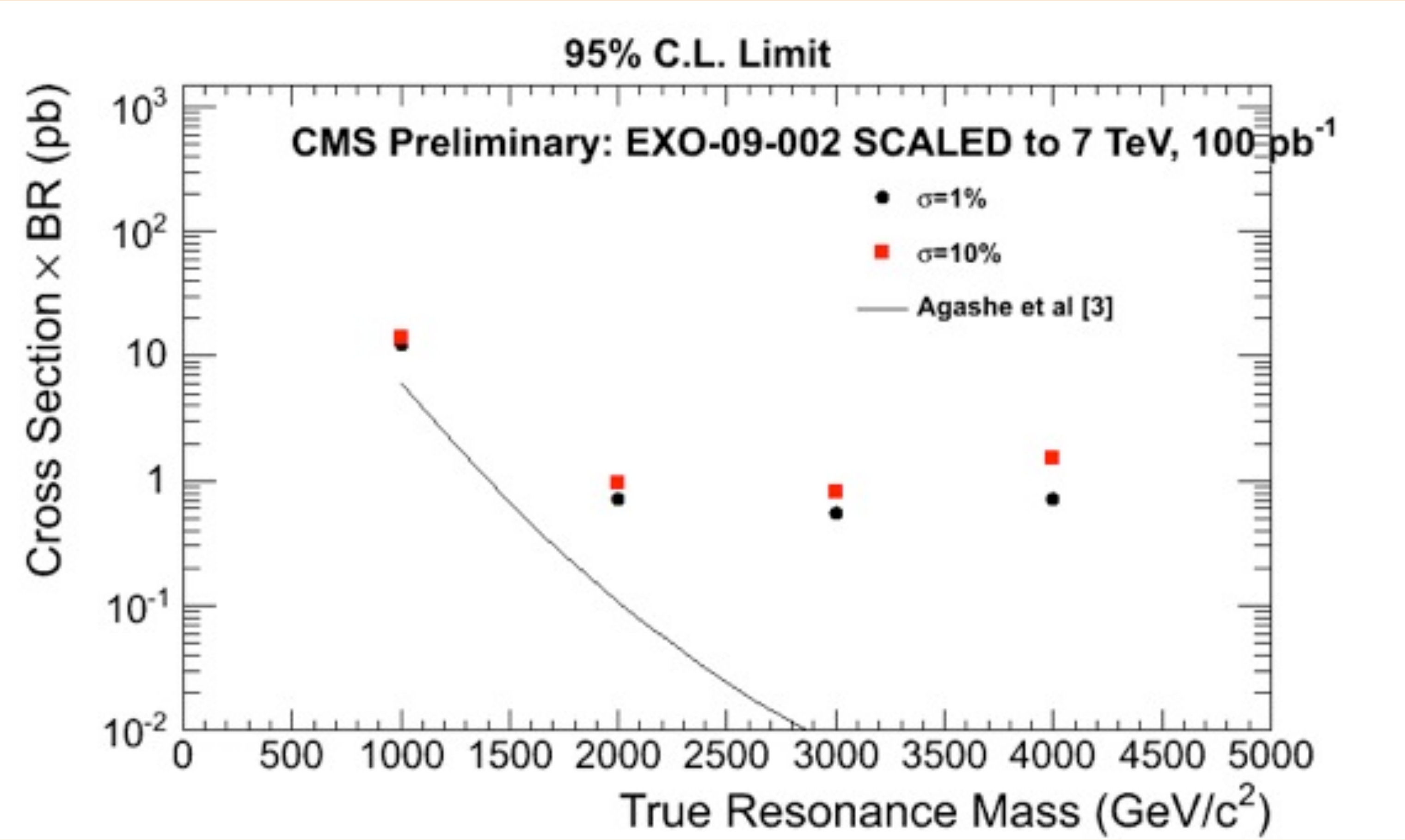
Performance





- Efficiency derived from MC
- Fake rate derived from data-driven method in dijets

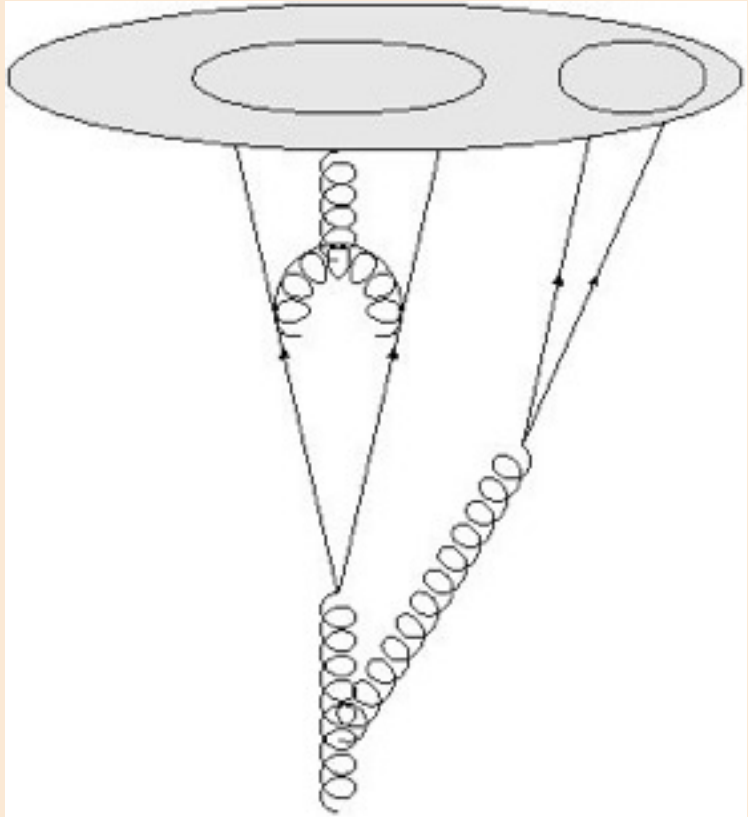
All-Hadronic Sensitivity



Other Jet Substructure Plans

- QCD Measurement : Quark/gluon fraction
  - Proof of principle
    - Usage of jet substructure in data
  - Examine MC agreement
    - S. Mrenna active on the analysis
  - Separate out quark and gluon fake rates for top and W taggers

- Jet Pruning:
  - Ellis et al, aka U of Washington algorithm (arXiv:0903.5081v4)
  - Cluster jets, in addition to kT-like sequence, require:
    - 2-Subjet configurations
    - $\min(p_{T1}, p_{T2})/p_T > 0.1$
    - $\Delta R_{12} < 0.5 * M_{jet} / p_T$

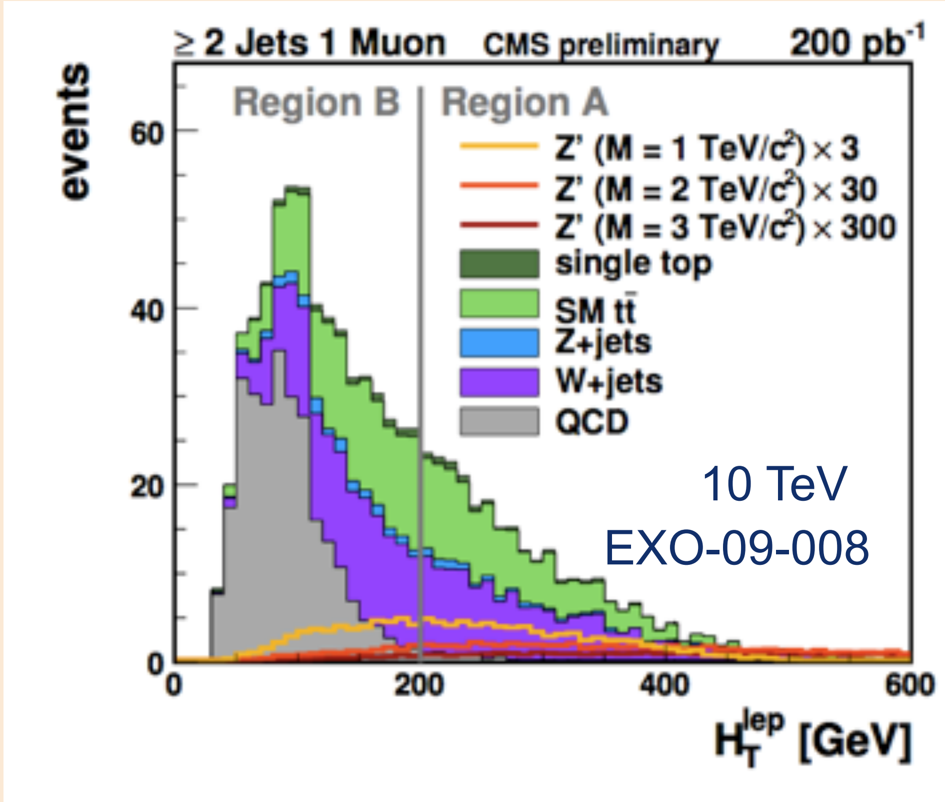


Expect sometime in fall!

Other Jet Substructure Plans

- Large uncertainties in semileptonic channels due to W-background uncertainty

- Reduce using jet substructure to tag W jets? Top jets?



Other Jet Substructure Plans

- Work by ATLAS is more advanced in Higgs substructure studies
- CMS has reproduced similar analyses, nothing approved for public yet

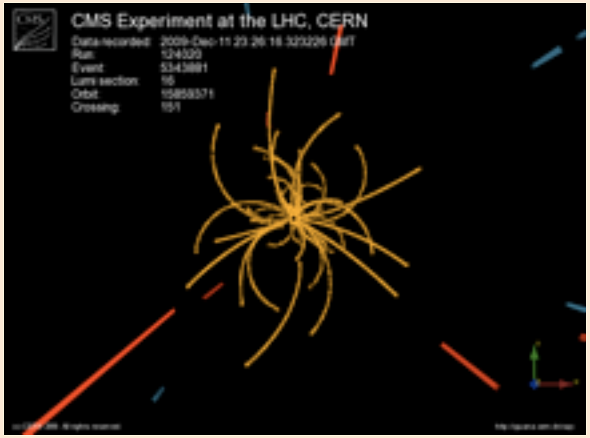
Conclusions

- CMS detector, trigger, reconstruction, simulation, etc are performing well
- Hadronic final state is already being widely exploited, both for "baseline" measurements and for new physics measurements
- Expect an excellent hadronic physics program in 2010/2011!

Backups

Anomalous Signals in Calorimeters

In collision data we observe some anomalous signals in ECAL and HCAL
Now ECAL ed in simulation.



- Appear mostly in a single crystal
- In time with collisions but with wider time-spread (also occur in cosmics at a much lower rate)
- Caused mostly by deposits in APDs by highly ionising secondary particles.

Anomalous Signals in Calorimeters

In collision data we observe some anomalous signals in ECAL and HCAL
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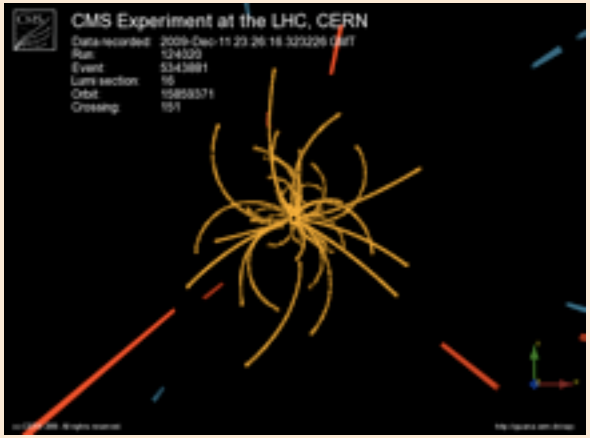
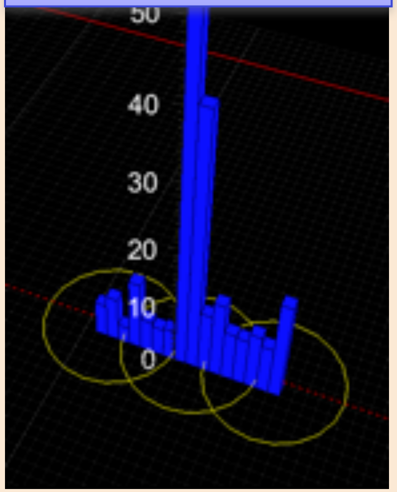
HCAL:
HB,HE





- Appear mostly in a single crystal
- In time with collisions but with wider time-spread (also occur in cosmics at a much lower rate)
- Caused mostly by deposits in APDs by highly ionising secondary particles.

- Appear in 1-72 channels
- Random, low rate,
~ 10-20 Hz (E>20 GeV)
- Caused by ion feedback, noise & discharges in HPDs

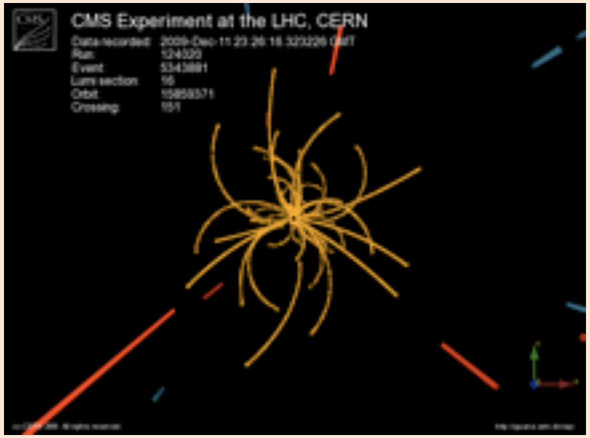
Anomalous Signals in Calorimeters

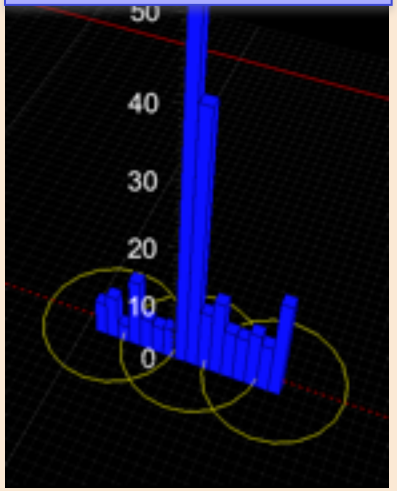
In collision data we observe some anomalous signals in ECAL and HCAL

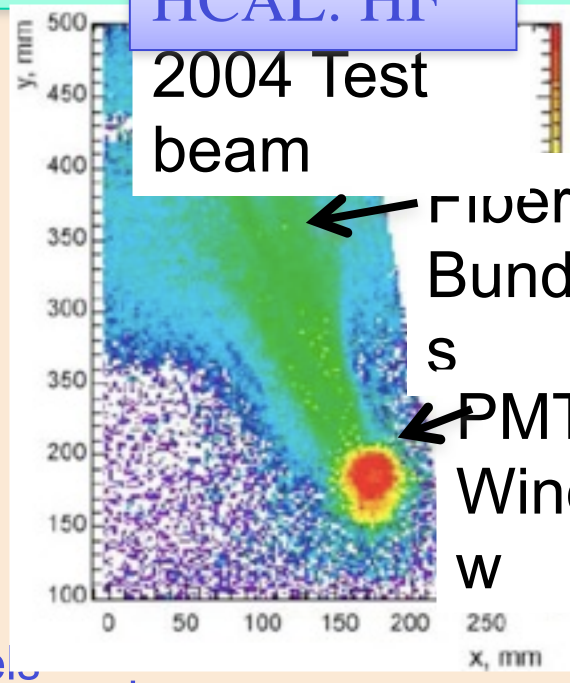
Now ECAL ed in simulati

HCAL: HB,HE

HCAL: HF







2004 Test beam

Fiber Bundles

PMT Window

- Appear mostly in a single crystal
- In time with collisions but with wider time-spread (also occur in cosmics at a much lower rate)
- Caused mostly by deposits in APDs by highly ionising secondary particles.

- Appear in 1-72 channel
- Random, low rate, ~ 10-20 Hz (E>20 GeV)
- Caused by ion feedback, noise & discharges in HPDs

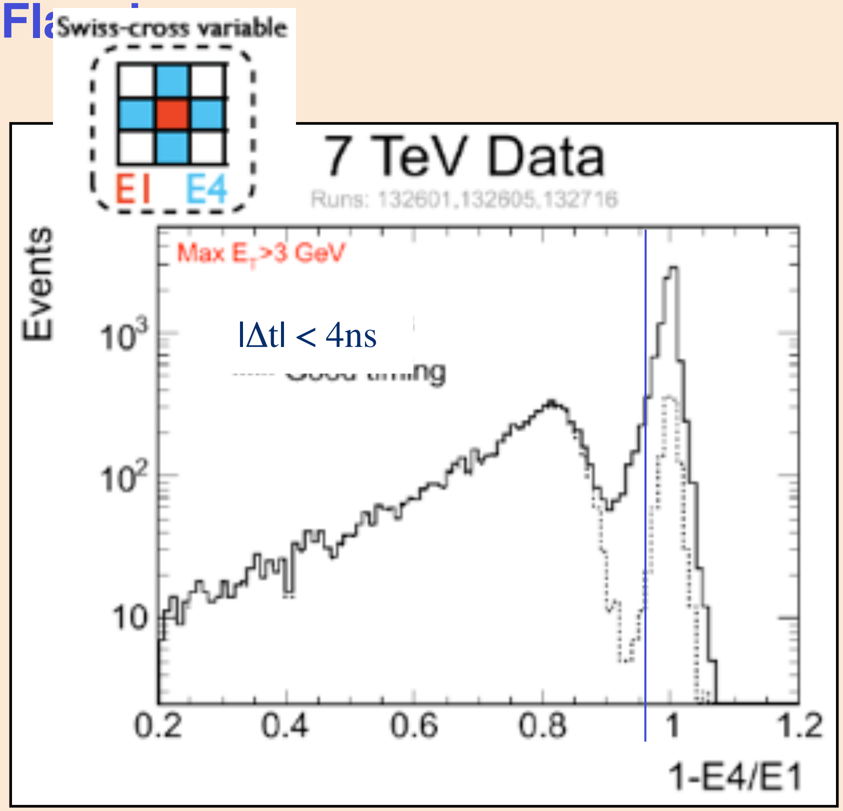
ch.
- In time with collisions
- Caused by C^{v} light by particles going through PMT glass

Identification of EB Anomalous Deposits

Tagging by topology:

At the cluster level the anomalous deposits tend to be in a single isolated crystal, while for good deposits energy is typically shared between neighbouring crystals.

Fl



ICHEP10

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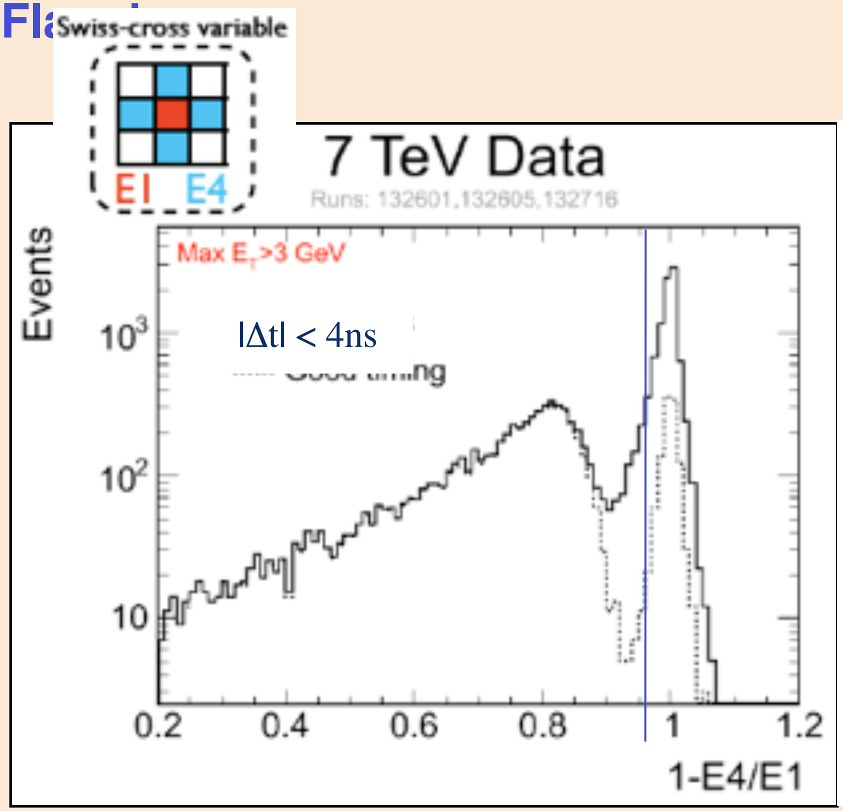
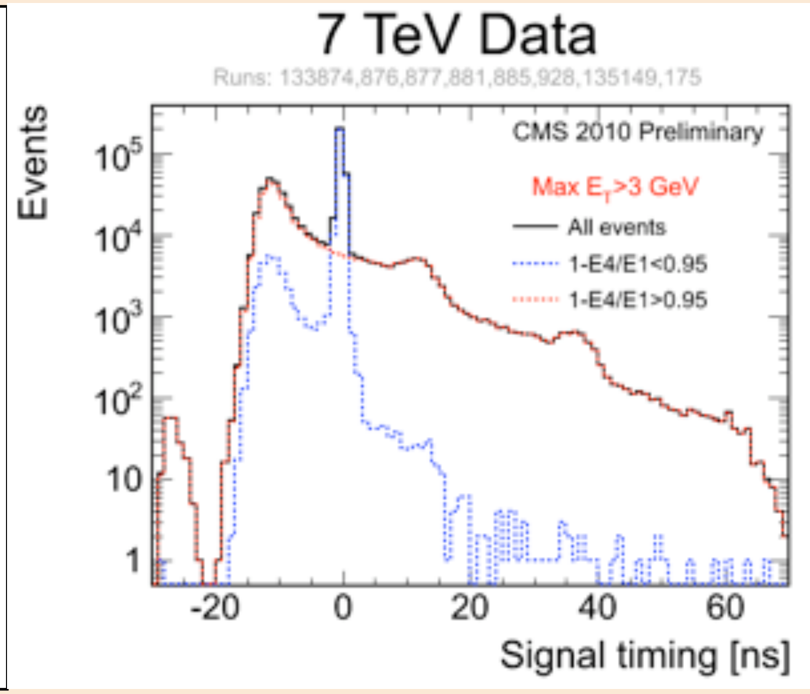


Tagging using timing:.

1) The anomalous signals tend to be out of time and have a much wider spread around the good timing.

2) The anomalous signal's rise time is faster

Flags: $k_{out\ of\ time}$, χ^2

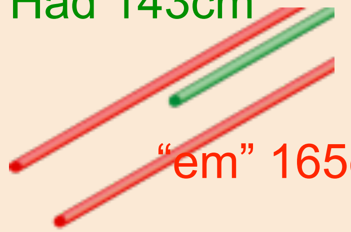


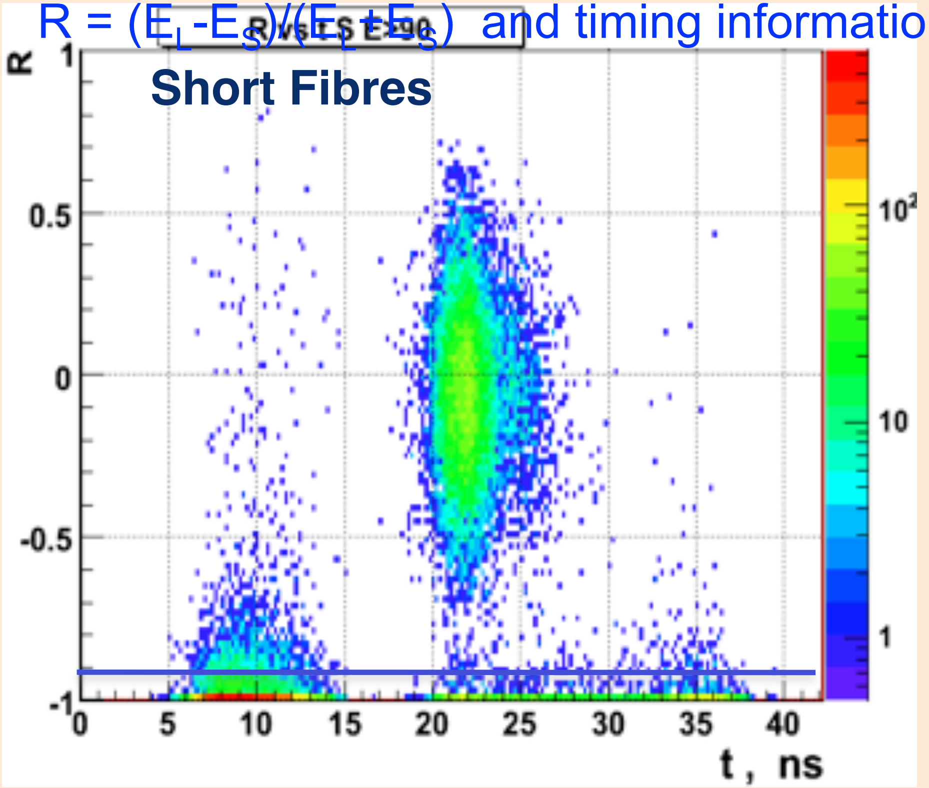
HF: Topological Criterion V/s Timing

Long fibers: extend for the full length of HF

Short fibers: start at a depth of 22cm from the front of HF

HF PMT hits can be identified based on the energy sharing between the Long and Short fibers using a cut on $R = (E_L - E_S)/(E_L + E_S)$ and timing information.





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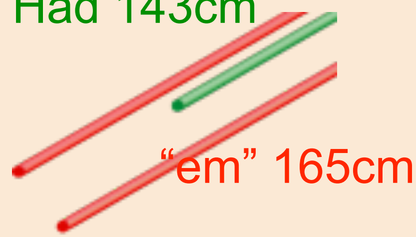
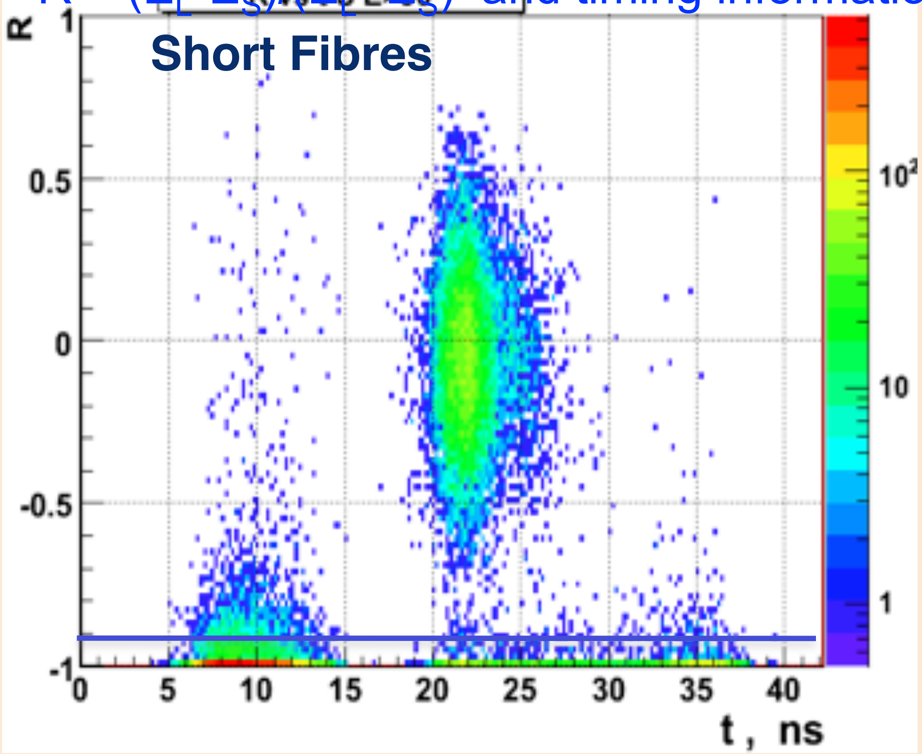
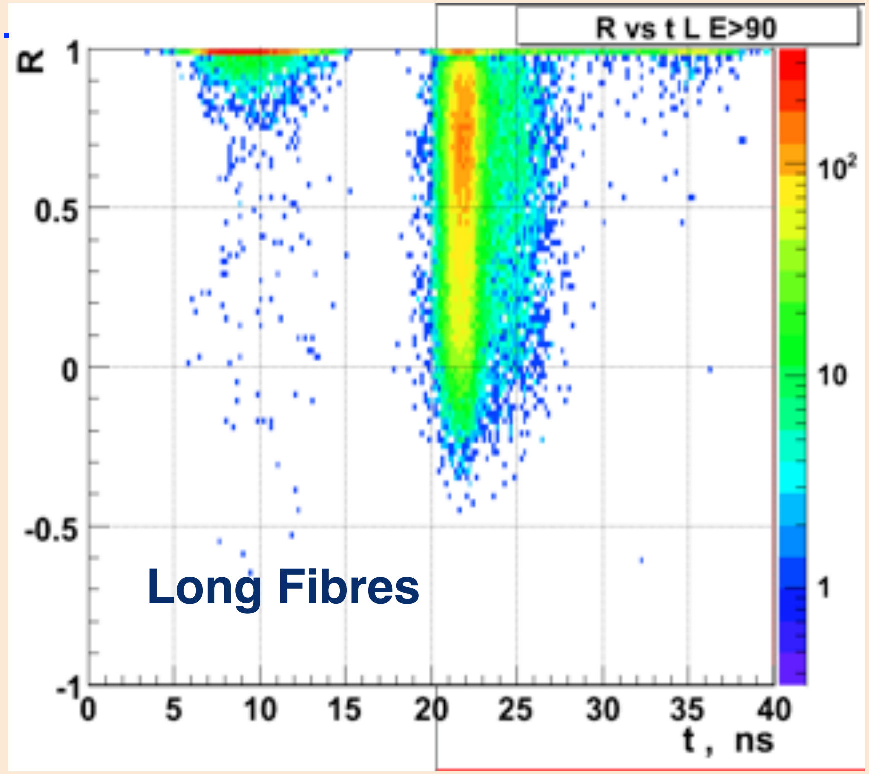
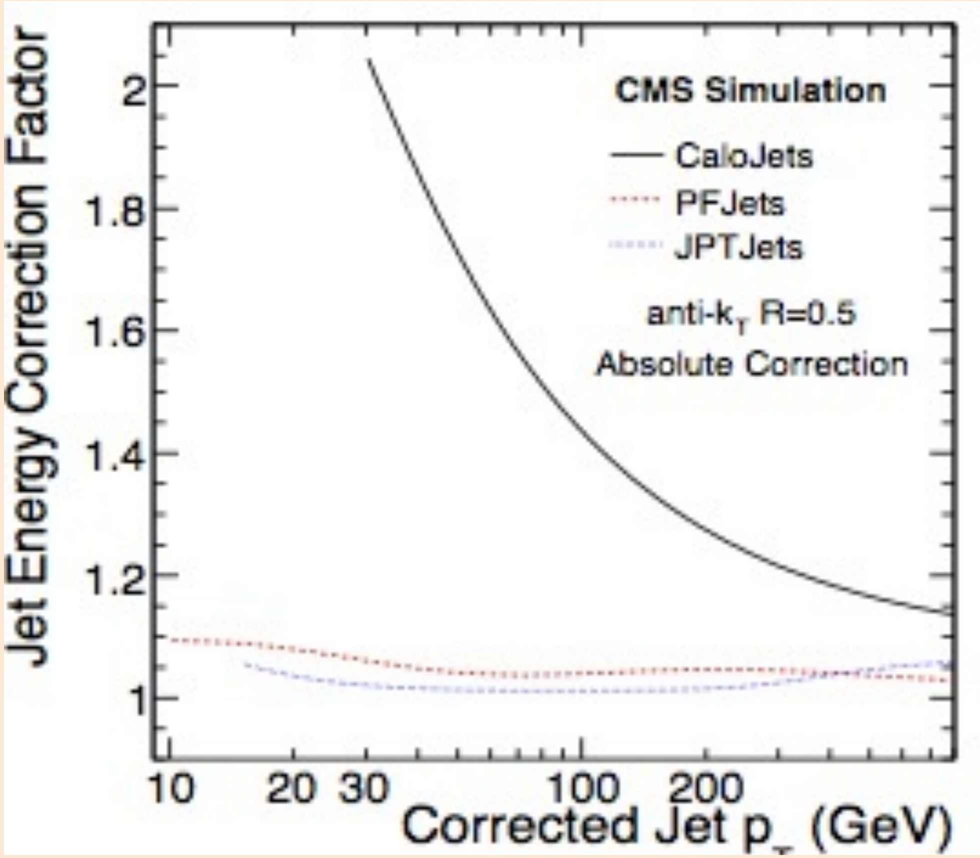






Jet Corrections at CMS



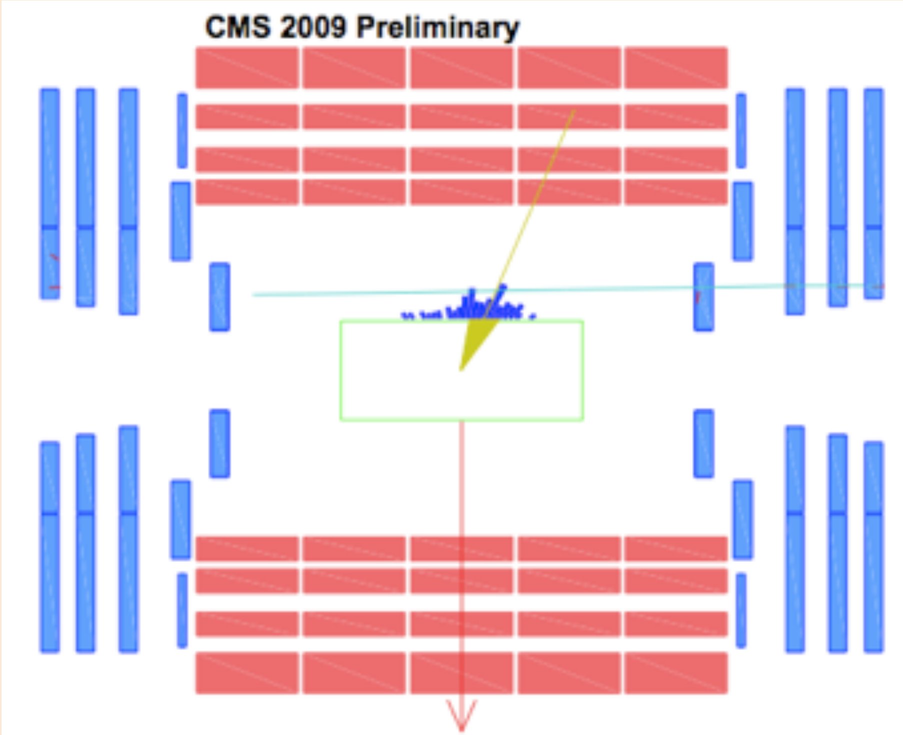
- Calo jets: Require p_T > 30 GeV/c
- PF and JPT jets : Require p_T > 15-20 GeV/c

MET at CMS

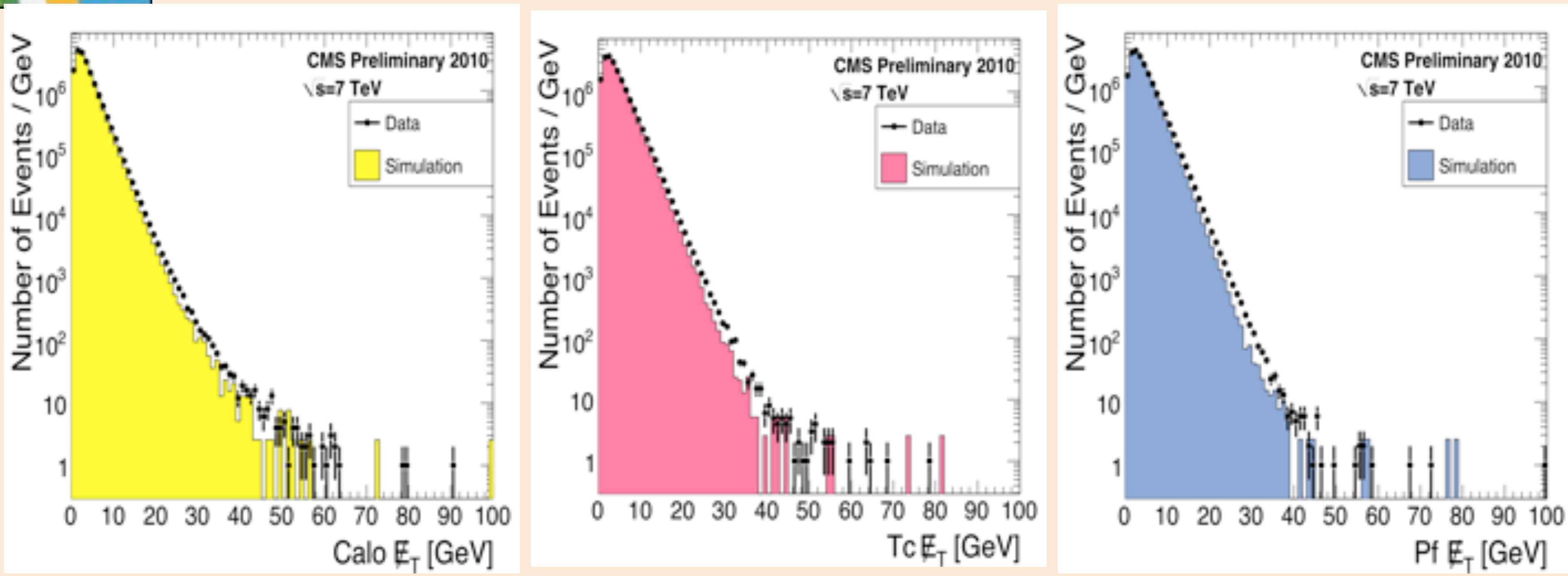
- Correcting Instrumental Noise
  - Spikes in the HF
    - Charged particles striking the PMT window
    - Removed by energy distribution in fibers
  - Spikes in the ECAL
    - Examine energy sharing with neighboring crystals and timing information
    - Spikes are isolated
  - RBX + HPD: rate low, but will need correction later

- Beam Halo
  - Charged particles surrounding beam
  - Removed by trigger coincidence vetos

onic



Current Status of MET Cleaning



Distributions exponential over 5-6 orders of magnitude

Scan of events in the high tail show no entries from potential ECAL anomalous deposits. There are a few HF ones, look to be easily identifiable and algorithms against these are being developed.

Though more work is still needed

Sequential Jet Algorithms

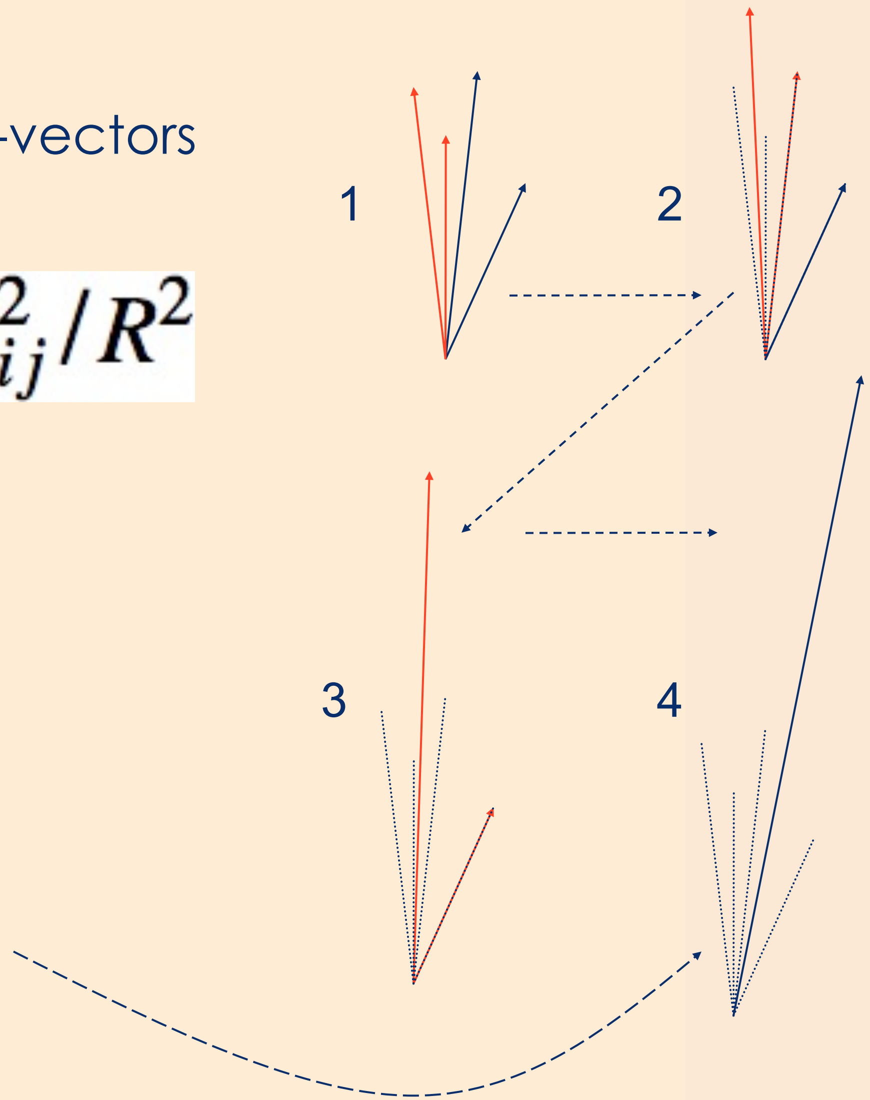
- Pairwise examination of input 4-vectors
- Calculate d_{ij}

$$d_{ij} = min(k_{ti}^{n}, k_{tj}^{n})\Delta R_{ij}^{2}/R^{2}$$

  - N = 2: k_T
  - N = 0: Cambridge Aachen
  - N = -2: anti-k_T
- Also find the "beam distance"

$$d_{iB} = k_{T,i}^{n}$$

- Find min of all d_{ij} and d_{iB}
- If min is a d_{ij}, merge and iterate



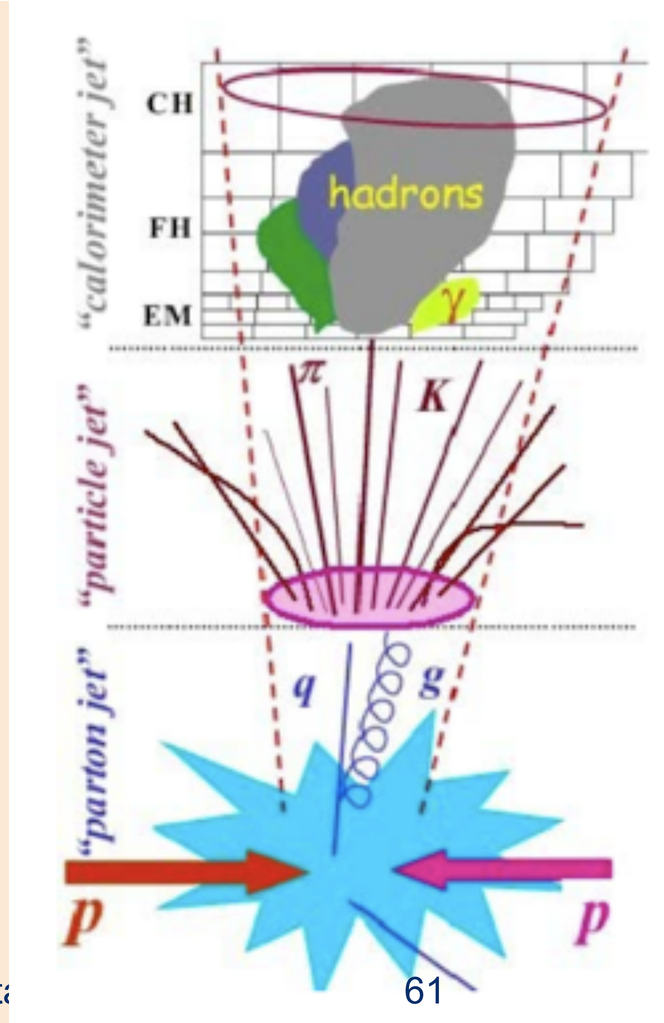
[1]: arXiv:hep-ph/9707323

Jets Corrections at CMS

$$E_{Corrected} = (E_{Uncorrected} - E_{offset}) \times C_{Rel}(\eta, p''_T) \times C_{Abs}(p'_T)$$

Jet corrections:

- *Relative scale*
  - Makes response flat versus eta
  - Use central jet/forward jet balancing
- *Absolute scale*
  - Makes response flat versus pT
  - Use Z/gamma + jet balancing
- *EMF corrections*
  - Makes response flat versus EM fraction
- *Flavor corrections*
  - Residual correction for uds, c, b, and gluon jets
- *Parton-jet corrections*
  - Makes response equal to parton energy



Efficiency Estimate

- Efficiency derived from MC
- Systematic uncertainties will include:
  - Theoretical uncertainties
  - Smearing detector-based resolutions

Efficiency Estimate

Theory

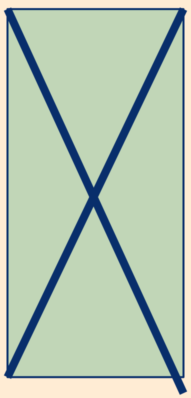
- Heavy quark fragmentation
- Light quark fragmentation
- ISR/FSR
- Λ_{QCD}

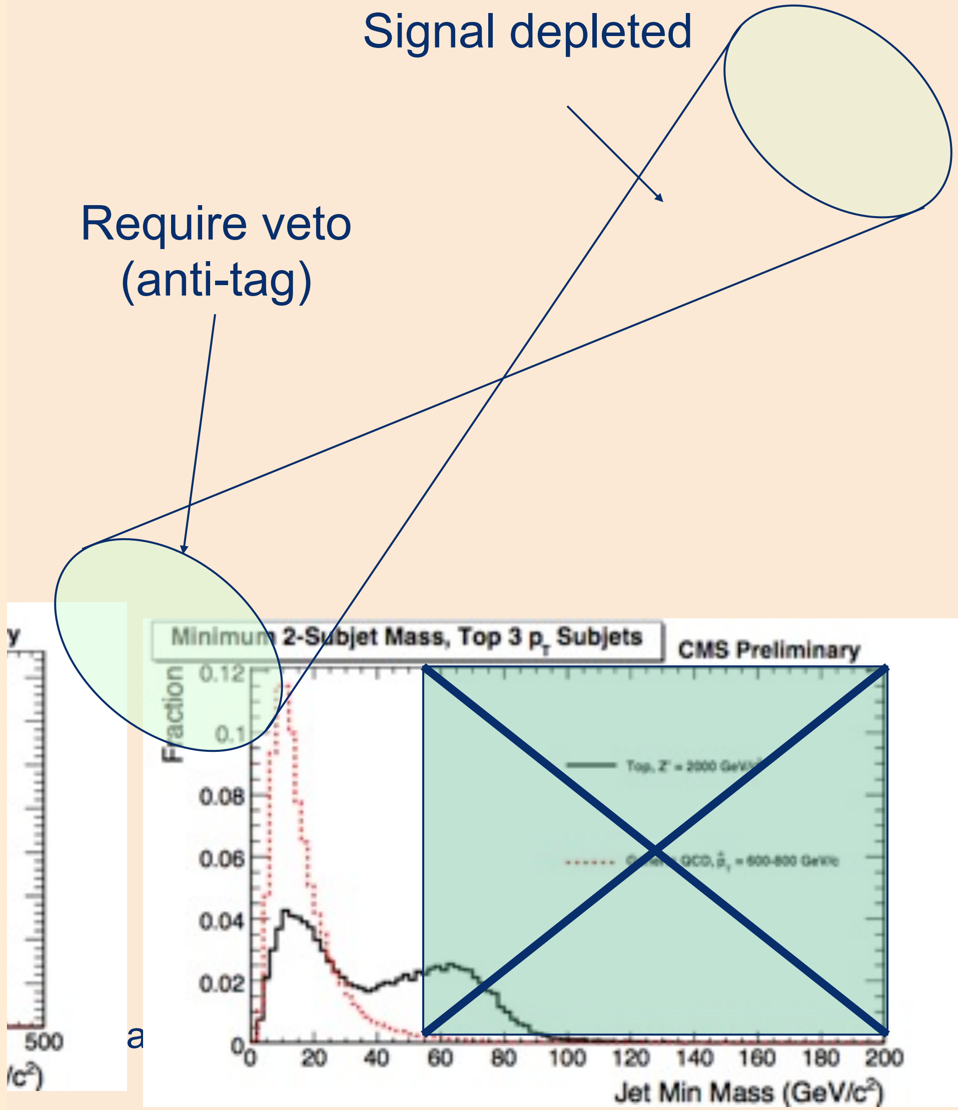
Detector

- Select partons from t->Wb decay
  - b, q, q’
- Compare true value to response in subjet
- Parameterize resolutions with parton p_T
- Smear p_T by 10%
- Smear Y, phi by 50%

Mistag Parameterization

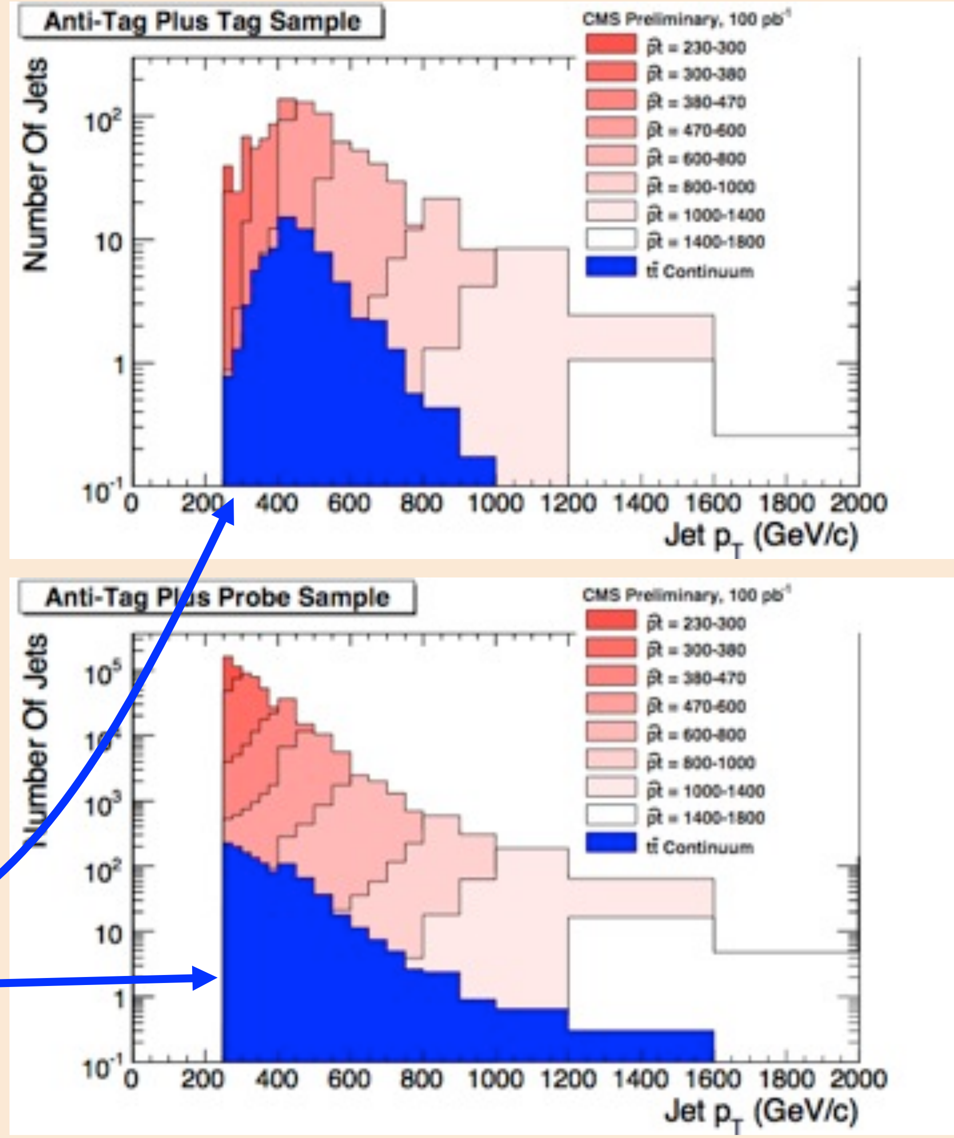
- **“Anti-tag-and-probe”**
  - Look at “anti-tagged” sample collected from dijet triggers
  - Have a signal-depleted sample on the “away” side





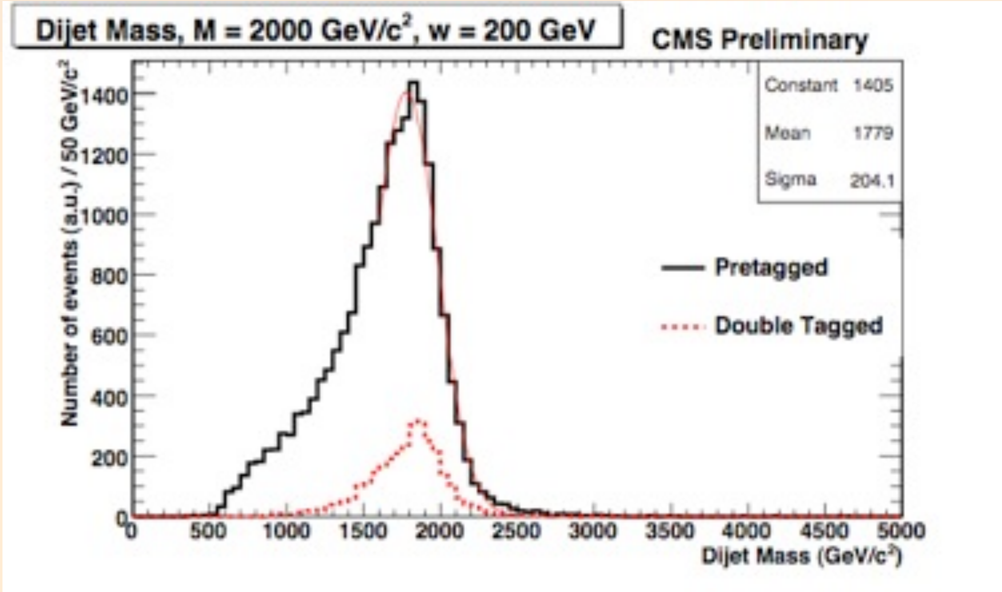
Mistag Parameterization

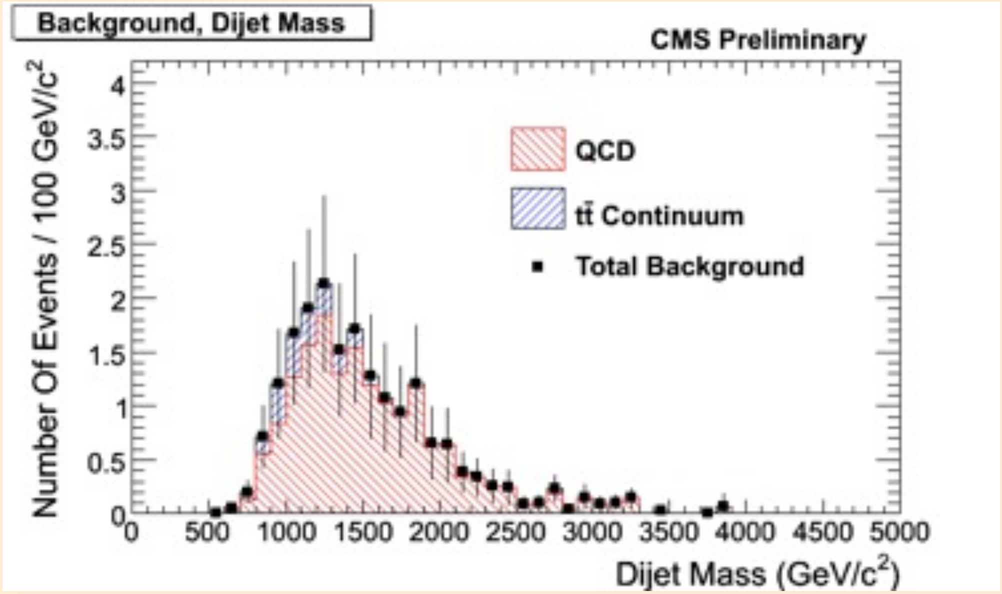
- **Data-based background estimate**
- Parameterize the background rate with jet p_T
- Numerator: Anti-tag Plus Tag
- Denominator: Anti-tag Plus Probe
- For simulation: scale to 100 pb^{-1}



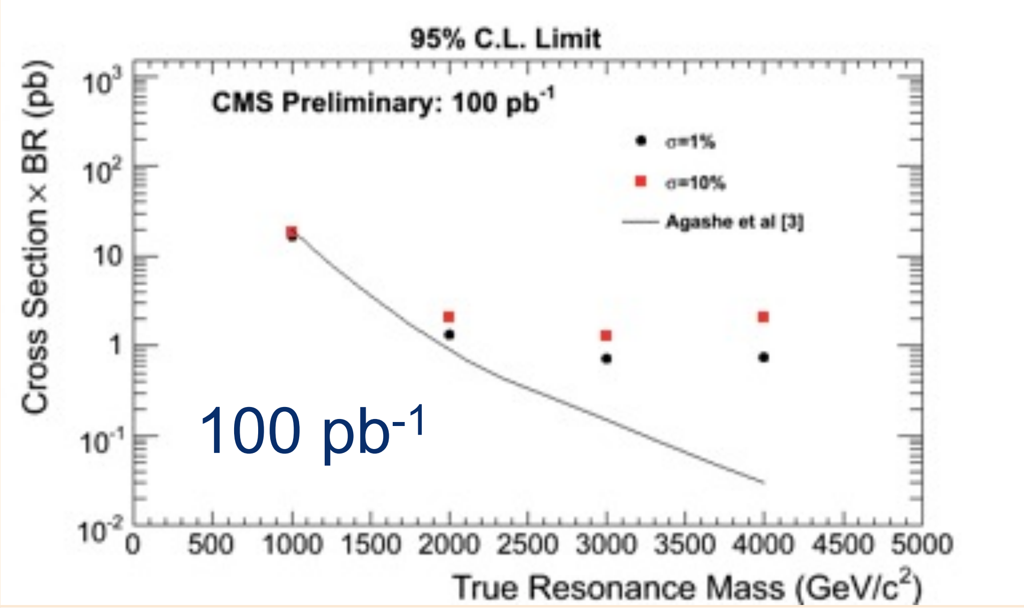
Application: Dijet Search

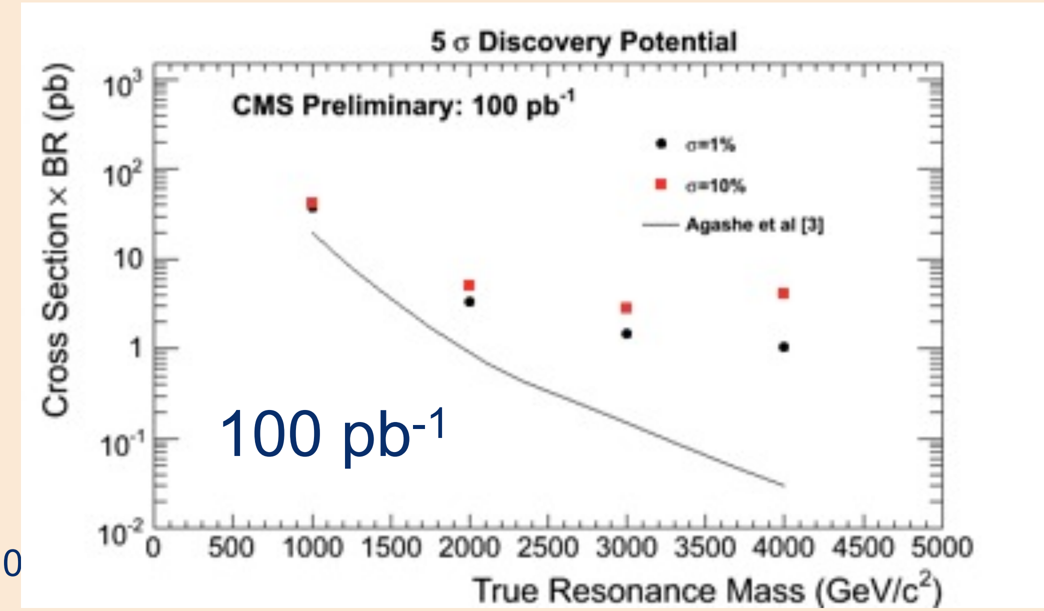
- CMS PAS EXO-09-002
- Examine dijet search for resonances decaying to ttbar in hadronic channel
- Simple bump-hunt
- Signal from MC
- Background:
  - QCD dijets **(red)** : data-driven.
  - Ttbar **(blue)** : from MC





Application: Dijet Search





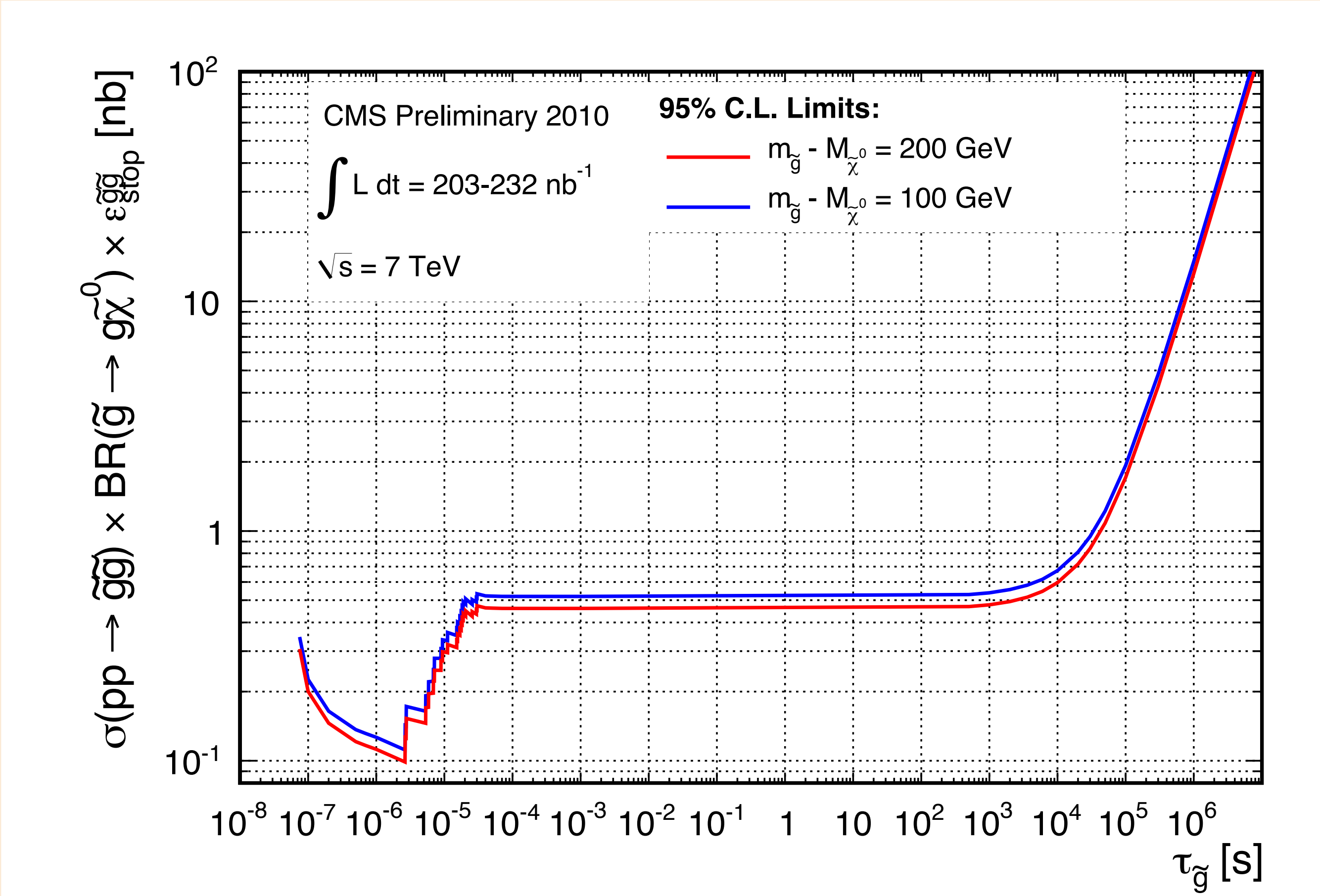
With ~200 pb^{-1} can begin to probe realistic new physics scenarios giving boosted top

Stopped Gluinos

Lifetime [s]	Expected Background ($\pm$ stat $\pm$ syst)	Observed
1e-07	$0.15 \pm 0.04 \pm 0.05$	0
1e-06	$1.8 \pm 0.5 \pm 0.5$	0
1e-05	$11.7 \pm 3.2 \pm 3.5$	8
1e-04	$28.3 \pm 7.8 \pm 8.5$	19
1e-03	$28.3 \pm 7.8 \pm 8.5$	19
1e+03	$28.3 \pm 7.8 \pm 8.5$	19
1e+04	$28.3 \pm 7.8 \pm 8.5$	19
1e+05	$28.3 \pm 7.8 \pm 8.5$	19
1e+06	$28.3 \pm 7.8 \pm 8.5$	19

- Perform simple counting experiment in "off" cycles
- Results consistent with null hypothesis

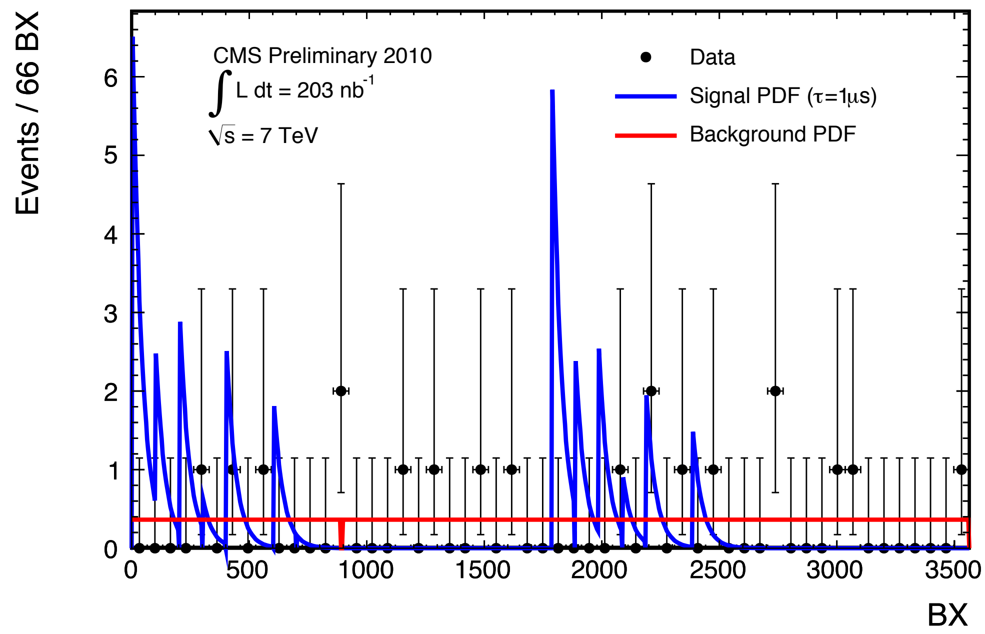
Stopped Gluinos

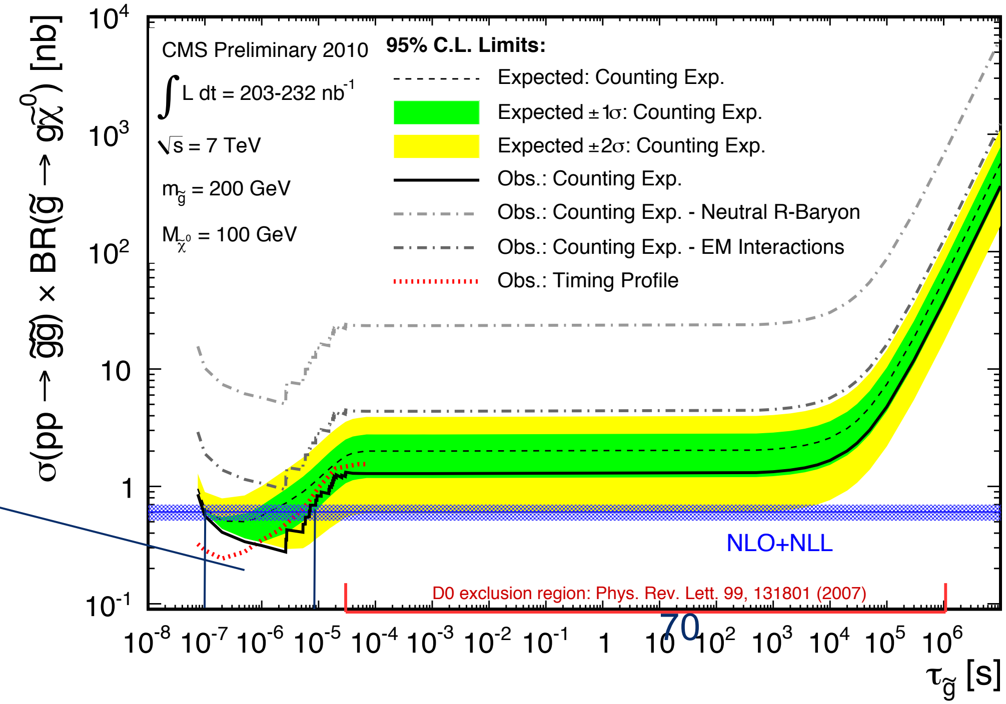


- Model independent limit
- Structure seen due to different time windows in analysis, based on hypothesized gluino lifetime

Stopped Gluinos

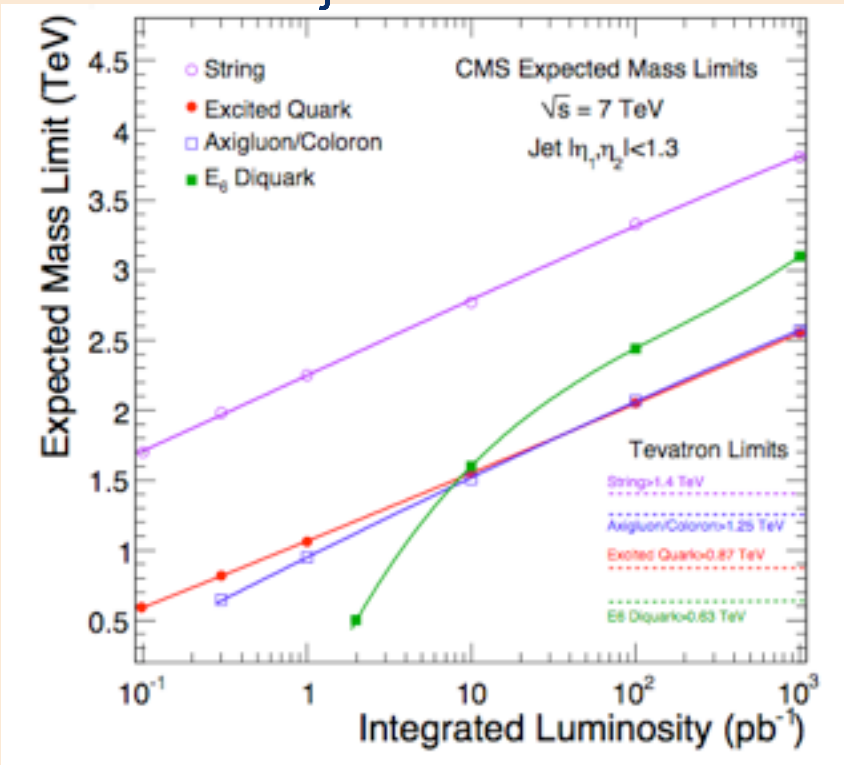
- Time profile analysis
  - Signal PDF based on beam profile
  - Background PDF is flat
- Model-dependent exclusion
  - Consistent with null hypothesis
- Extends current Tevatron limits!
  - 120 ns < t < 6 μs



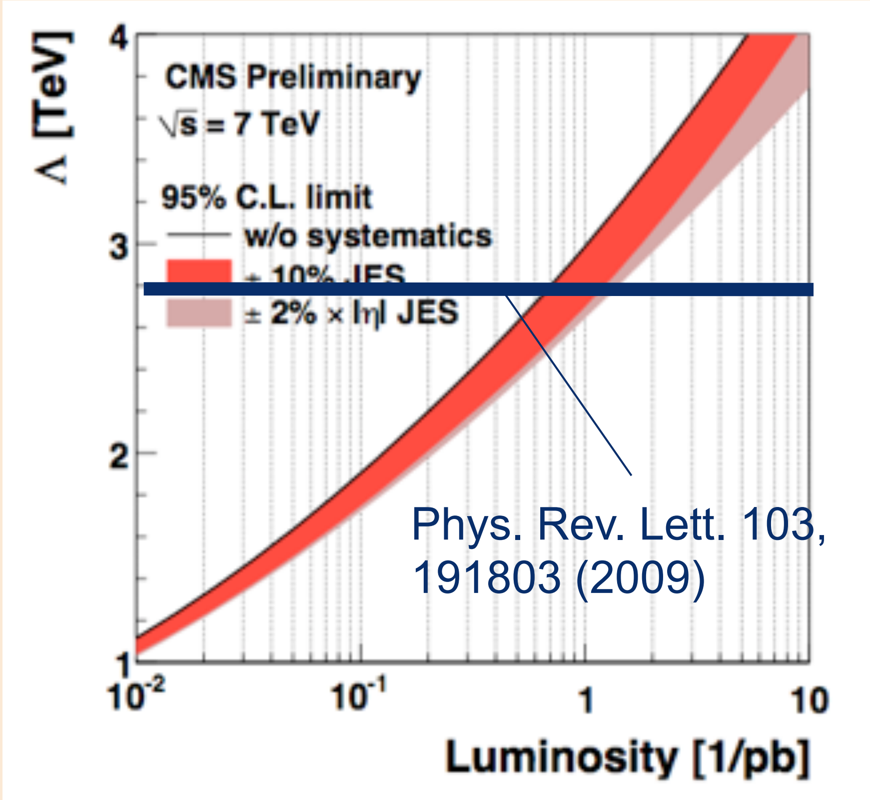


Expected Limits

Dijet resonances



Compositeness with angular analysis



- Expect to exceed Tevatron limits with ~ 10 pb-1!
  - In a few cases, already have!

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