CMS Trigger Simulation

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Outline:

- **Calorimeter Level-1**
  - Trigger Algorithms
  - Rates and Efficiencies
- **Muon Level-1**
  - Trigger Algorithms
  - Rates and Efficiencies
- **Combined Rates**
- **Physics Performance**

Present algorithms that capture the CMS physics within the constraints of the data acquisition bandwidth.

Hardware implementation issues - W.H. Smith and J. Hauser talks

CMS/LHC Trigger Physics

Standard model Higgs (high luminosity)

- H (80 GeV) $\rightarrow \gamma\gamma$
- H (120 GeV) $\rightarrow$ Z Z* (4 leptons)
- H (>500 GeV) $\rightarrow$ leptons (+ ν's)
- H (< $2M_w$ Associated t or W or Z) $\rightarrow$ b b (lepton + X)

SUSY Higgs (low luminosity)

- (standard model Higgs like channels)
- h, H, A $\rightarrow \tau\,\tau$ (lepton + X) or $\rightarrow \mu\mu$
- A $\rightarrow$ Z h ; h $\rightarrow$ bb (lepton + X)
- p p $\rightarrow$ t t X; t $\rightarrow$ H^+ b; $H^+ \rightarrow \tau\,\nu$; t $\rightarrow$ lepton + X; $\tau \rightarrow$ X

SUSY sparticle searches (low luminosity)

- MSSM sparticle $\rightarrow$ LSP (Missing E_t) + n jets
- MSSM sparticle $\rightarrow$ Same sign dileptons + X

Other new particles

- Z' $\rightarrow$ dileptons
- Leptoquarks: dileptons

Top physics (low luminosity)

- t $\rightarrow$ lepton + X
- t $\rightarrow$ multijets

Bottom physics (low luminosity)

- b $\rightarrow$ lepton + X
- b $\rightarrow \psi k_s$ (leptons + X)

QCD

- Low luminosity 100 GeV jets
- High luminosity 200 GeV jets

$\Rightarrow$ Trigger candidate requirements:

- High luminosity: lepton/γ (30 GeV), dileptons/$\gamma\gamma$ (15 GeV)
  missing E_t (100 GeV), jets (200 GeV)
- Low luminosity: lepton/γ (15 GeV), dileptons/$\gamma\gamma$ (10 GeV)
  missing E_t (50 GeV), jets (100 GeV)

Calorimeter requirements

Input

- ECAL trigger towers, 0.087ϕ x 0.087η
- Matching HCAL towers
- Data every 25ns - including any corrections for time development of calorimeter signal
  - 8 bit transverse energy
  - 1 bit finegrain charecterization of energy deposit
- Data presynchronized across all channels, ECAL and HCAL

Output

- Top 4 nonisolated electrons/photons (E_t and location)
- Top 4 isolated electrons/photons (E_t and location)
- Top 4 jets (E_t and location)
- Top 4 isolated hadrons (E_t and location)
- Total and missing transverse energy (E_t, E_x, E_y)
- Minimimum ionization ID and isolation bits for use with muon trigger

Outut rate

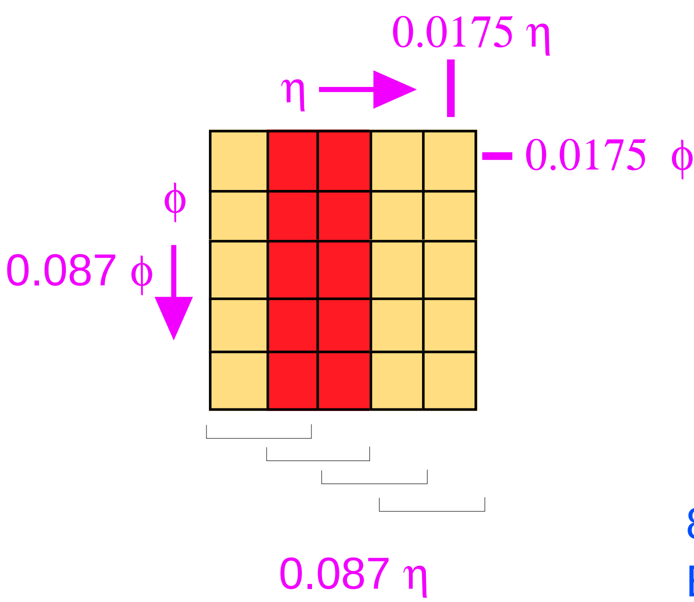
- 75/2=37.5 kHz maximum for calorimeter trigger
- Simulations should indicate significant safety margin - i.e., ~15 kHz rate from calorimeter trigger simulation

Efficiency

- Trigger should contribute no more than a few percent inefficiency for any physics channel compared to other offline analysis cuts.
- Trigger efficiencies should be measurable

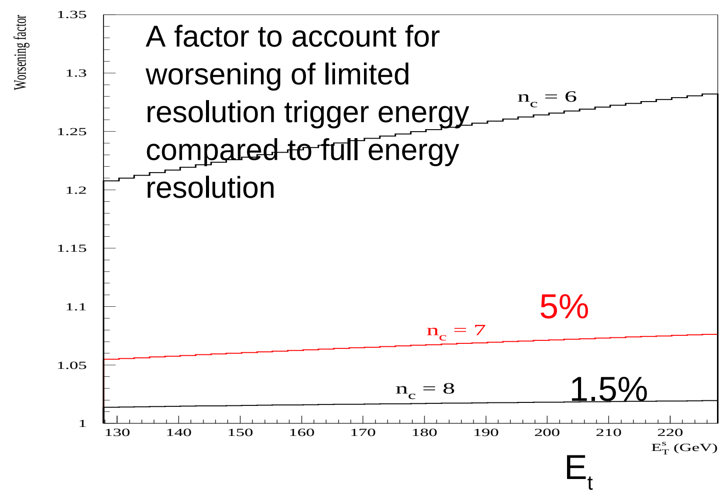
Cal Regional Trigger Input

ECAL Crystals in Trigger Tower



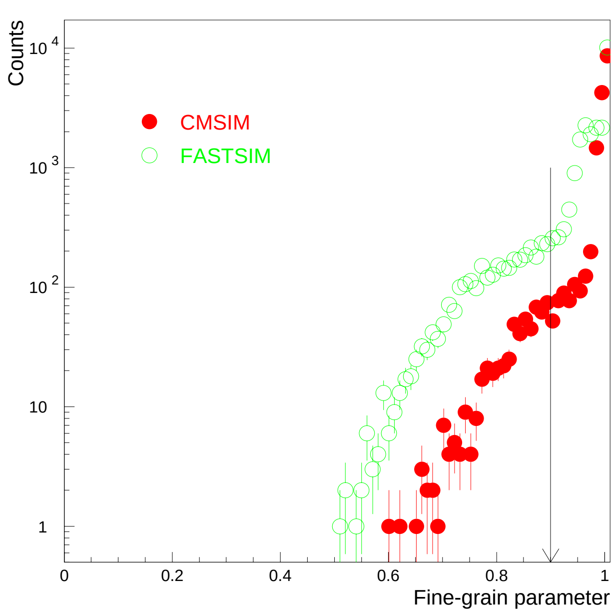
Used 6x6 for simulation

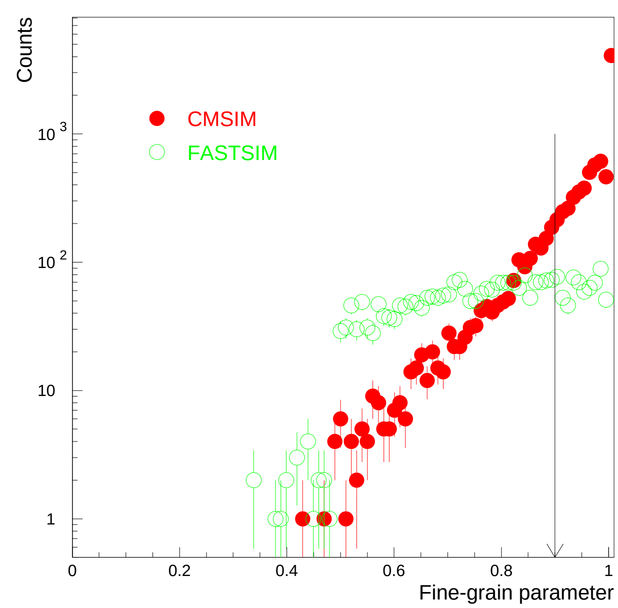
Transverse Energy in Trigger Tower



8 bit transverse energy output from both ECAL and HCAL trigger towers

Shower Profile in Trigger Tower



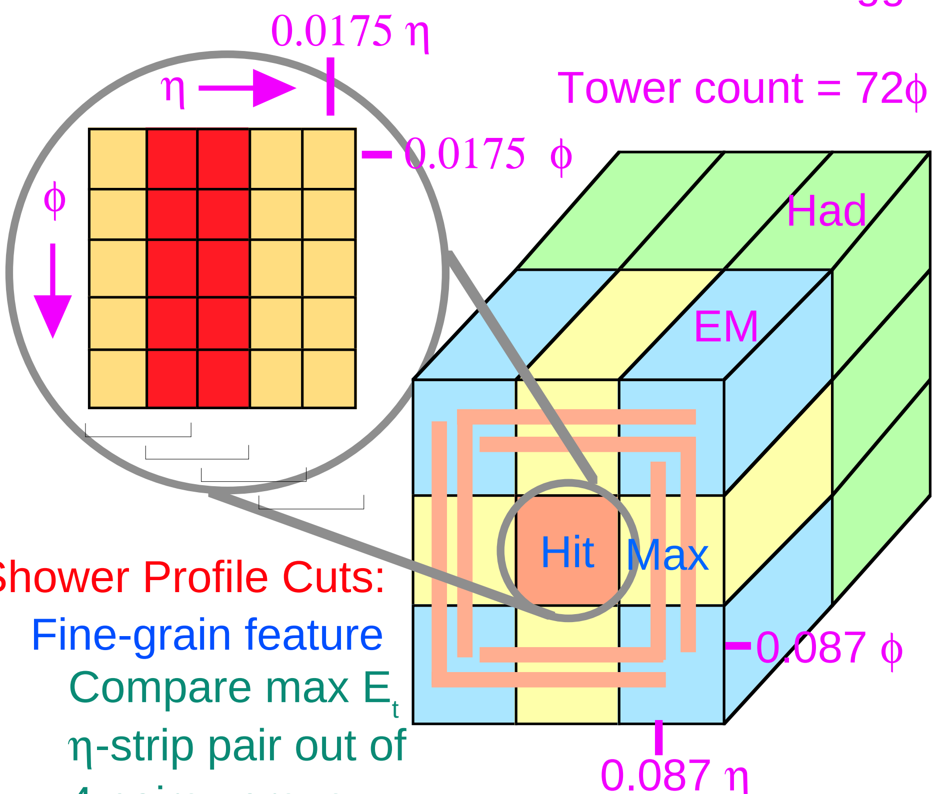


Single bit to indicate electron like shower profile within the trigger tower - Comparison of the maximum strip pair energy sum to the total energy sum in the trigger tower.

Electron/photon algorithm

Sliding window centered on all ECAL/HCAL trigger tower pairs

Tower count = 72φ x 54η x 2 = 7776



Candidate Energy:

- Max: Max E_t of 4 Neighbors
- Hit: Hit + Max E_t > Threshold

Shower Profile Cuts:

Fine-grain feature

Compare max E_t η-strip pair out of 4 pairs versus total E_t in trigger tower, e.g., require 90% energy in a pair.

HAC Veto

Compare HCAL versus ECAL E_t in Memory Lookup to veto non-EM deposits, e.g., H/E<5% when E is significant.

Isolation Cuts:

Neighbor HAC Veto

HAC Veto passes on all eight neighbors also.

New E_t isolation: Quiet Neighborhood

At least one of four corners has all five quiet towers, i.e, (E_t<1.5 GeV)

Summary:

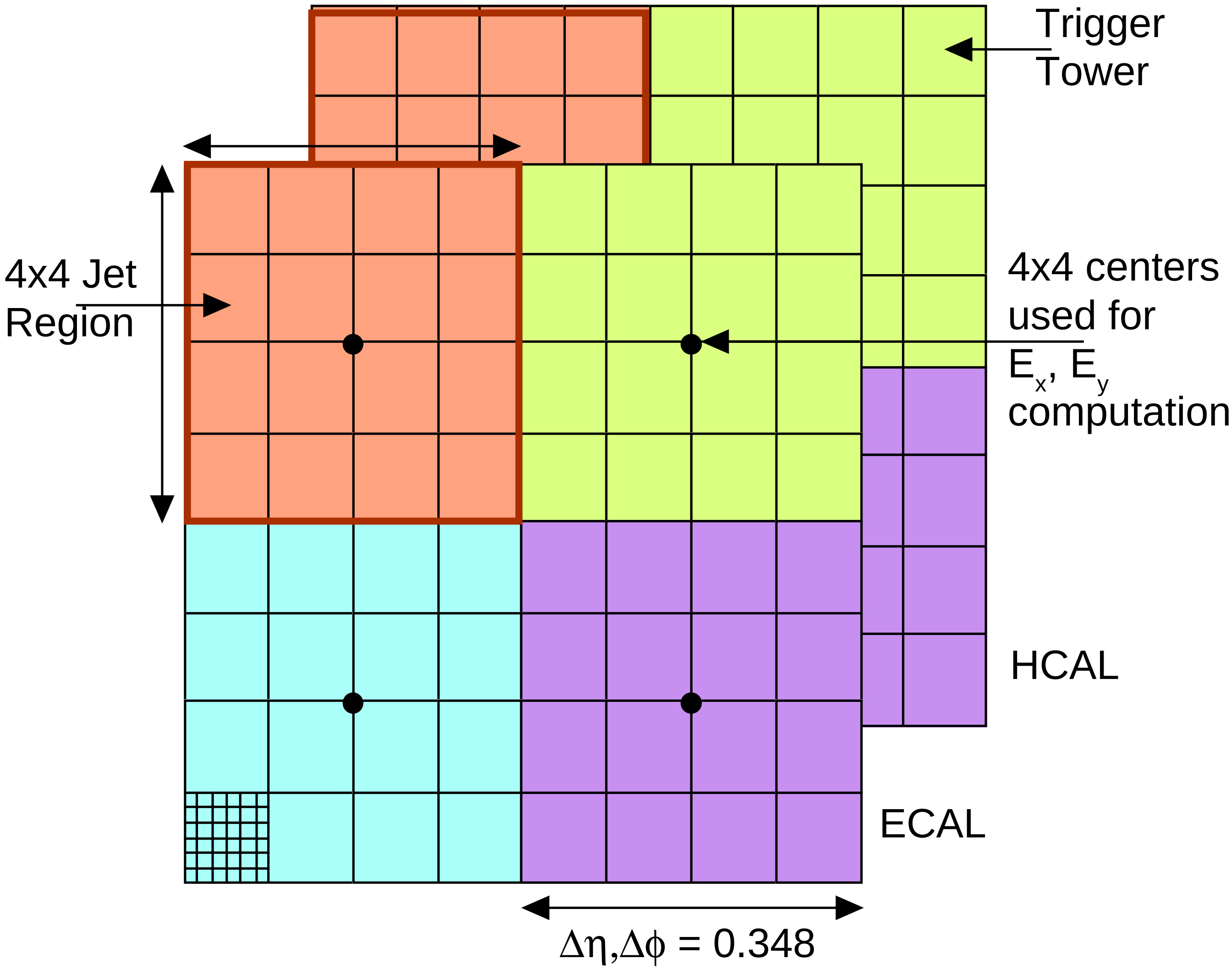
Regional

Pick highest energy candidate in 4x4 trigger tower region.

Global

Sort to find top-4 isolated and non-isolated candidates separately.

Jet, Missing E_t algorithms



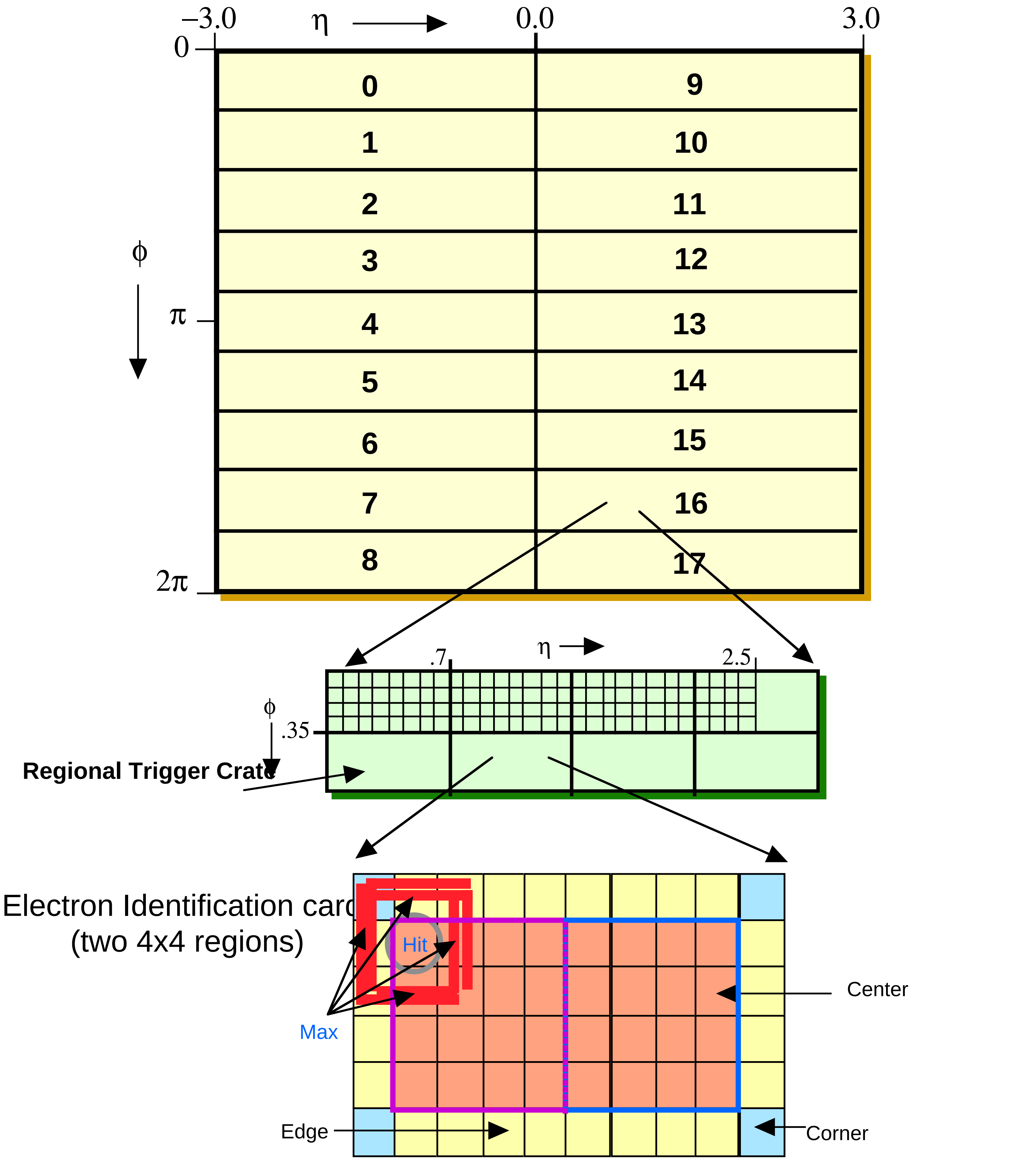
Jet E_t is given by the sum of ECAL and HCAL trigger tower E_t in a non-overlapping 4x4 region

Jet candidates are sorted to find highest energy jets

Jet trigger is caused by core of the physical jet. This allows for jet counting without the problems of dealing with multiple jets overlapping in large (0.1ηx0.1φ) regions

E_x and E_y are obtained by a memory lookup using 4x4 E_t
Signed E_x and E_y sums over the entire calorimeter are made to calculate missing E_t

Trigger/Calorimeter Map



Simulation programs

FASTSIM - Fast simulation of event response

- Simplified CMS geometry, uniform tracking medium, decays of mesons, and parameterized calorimeter showers (independent of CMSIM) are implemented.

CMSIM - Version 111

- CMS standard GEANT based detector simulation
- Detailed geometry for calorimeter, average response for tracker but no preshower.

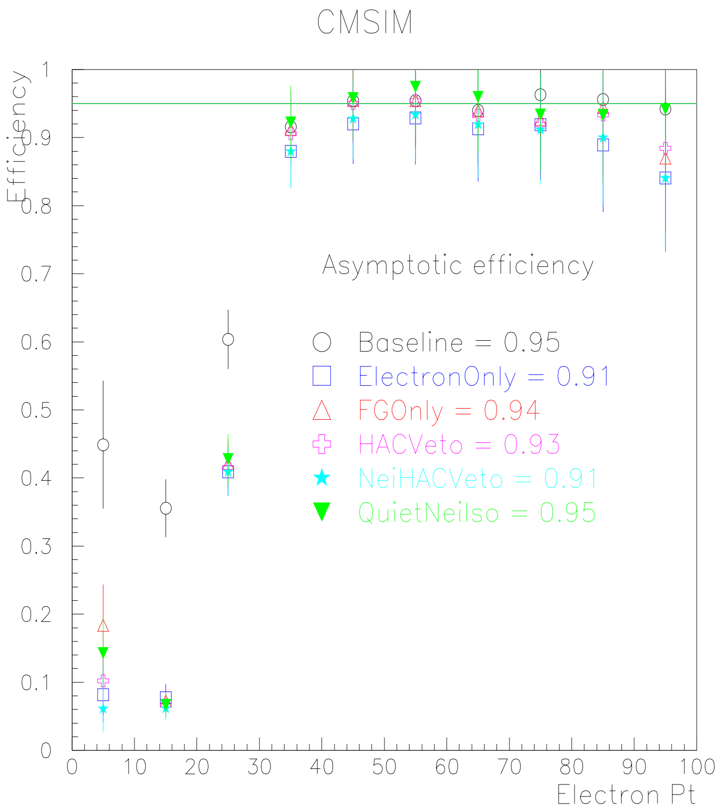
PYTHIA - common for FASTSIM/CMSIM

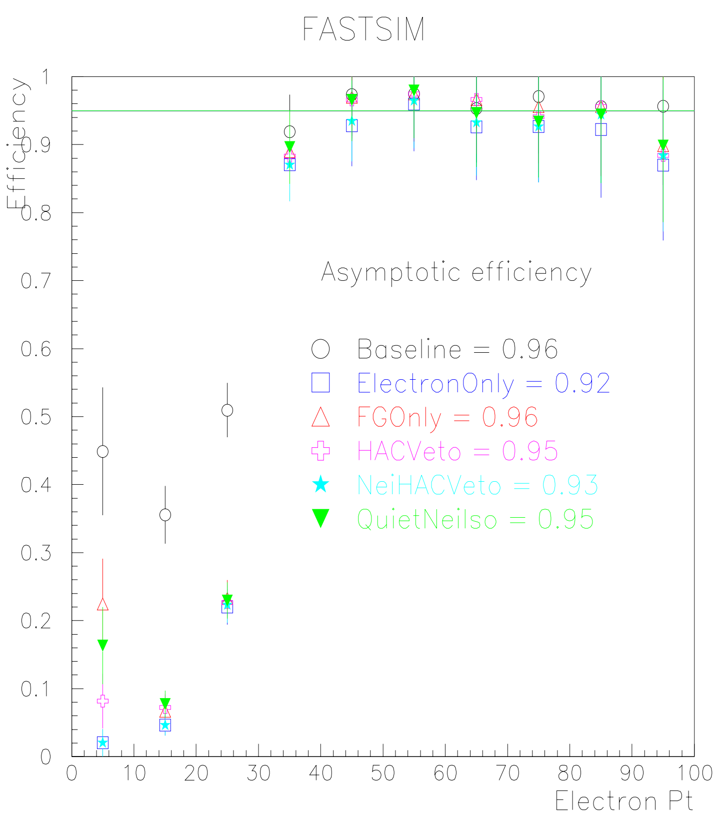
- QCD background events are used for rate studies.
- High P_t signal events, e.g., top, Higgs and SUSY particle decays, are used for efficiency studies.
- Noise hits are superposed with high P_t events.
- Minimum bias included - FASTSIM minbias is added for both CMSIM and FASTSIM high P_t events.

Trigger simulation - common for FASTSIM/CMSIM

- Various digital scales with limited resolution and dynamic range involved in the trigger system are fully implemented.
- Algorithms are performed in integer arithmetic using memory lookup tables when needed.

Electron/photon Efficiency



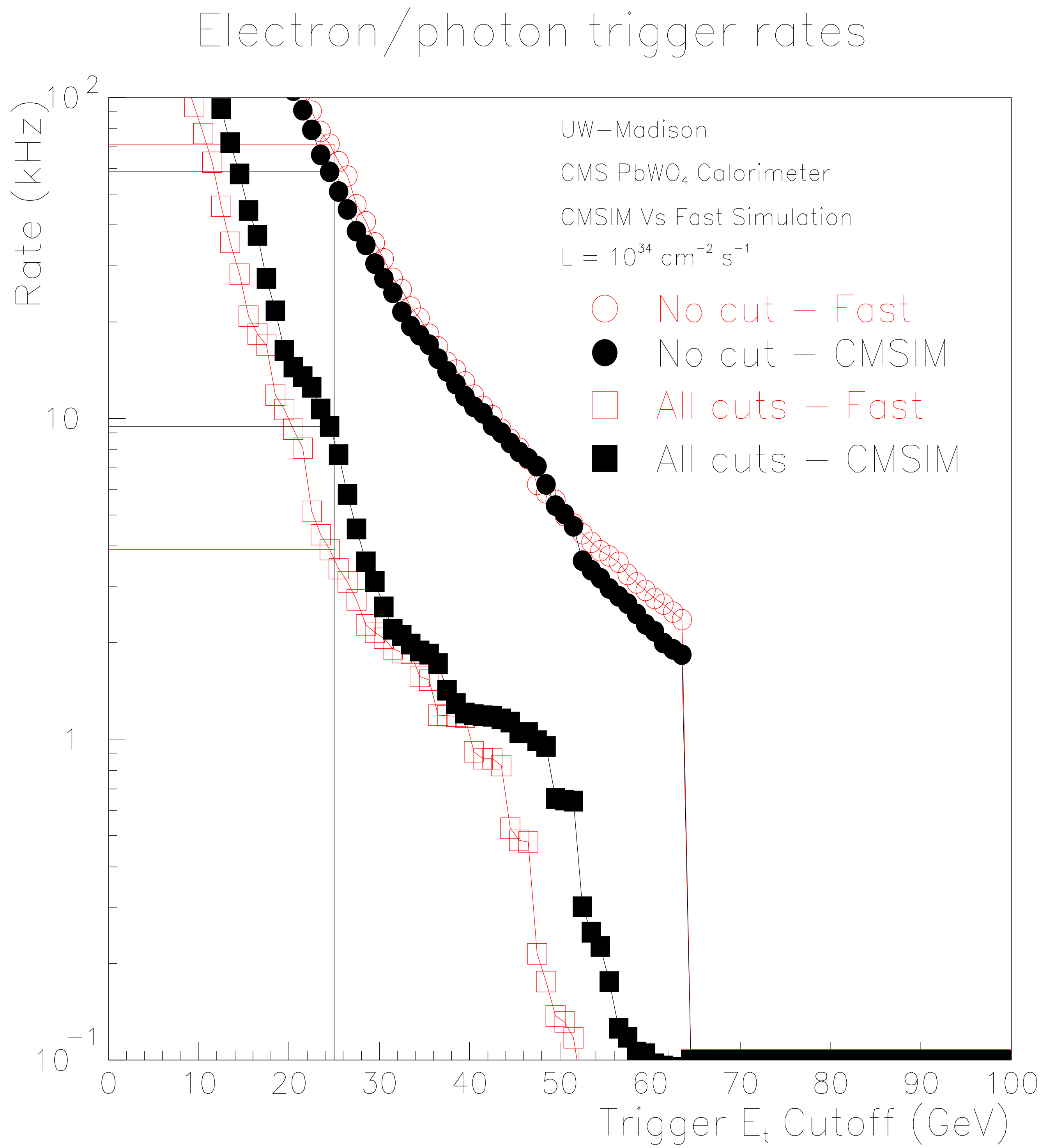


Efficiency for triggering top to electron decay events is plotted versus the P_t of the electron for various cuts.

Identical values for the four cut parameters yield similar efficiencies - custom tuning was not necessary.

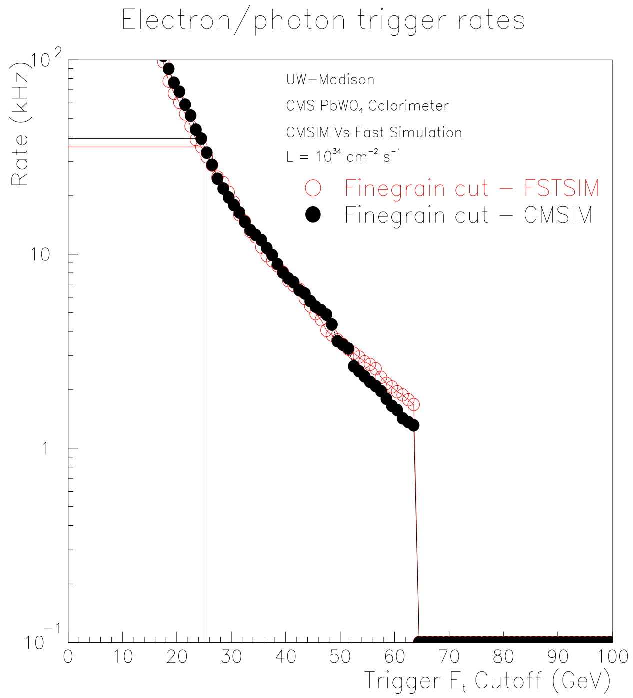
All efficiencies are over 90%.

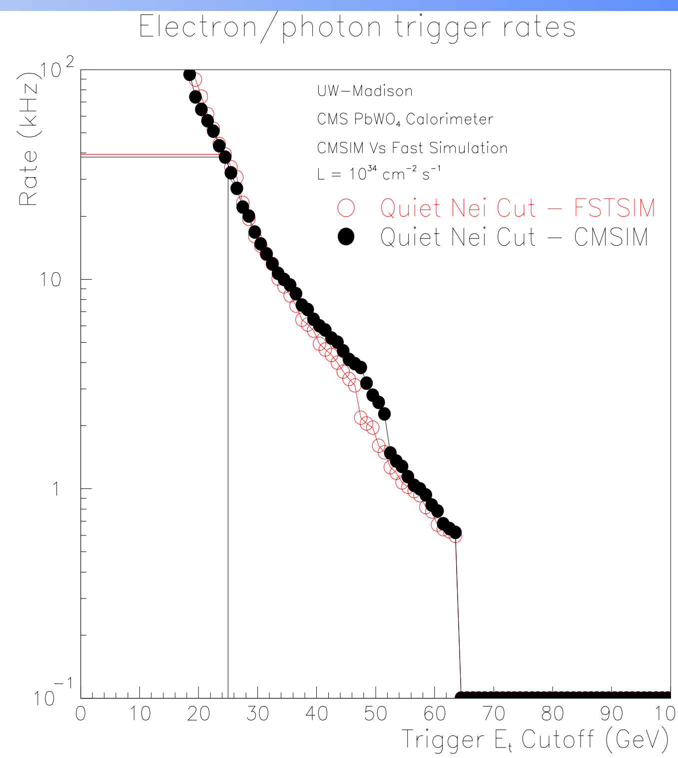
Electron/Photon Rates

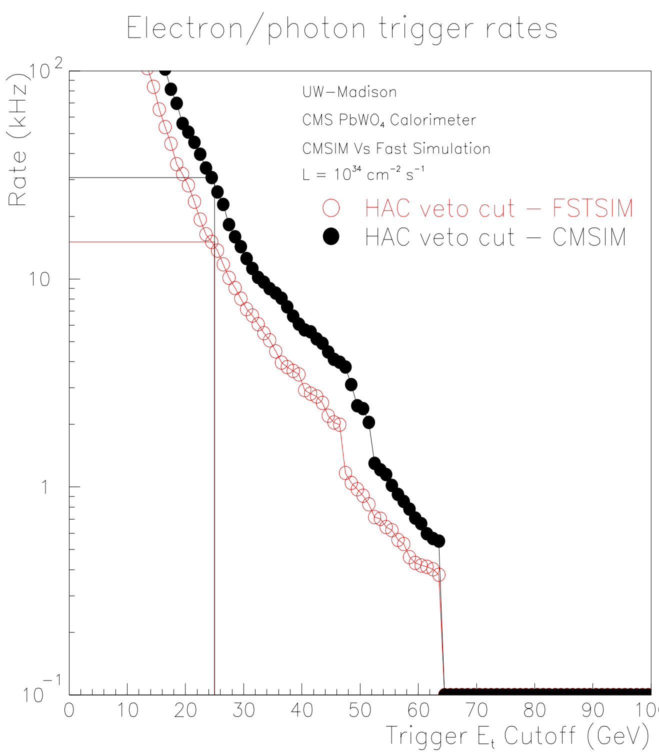


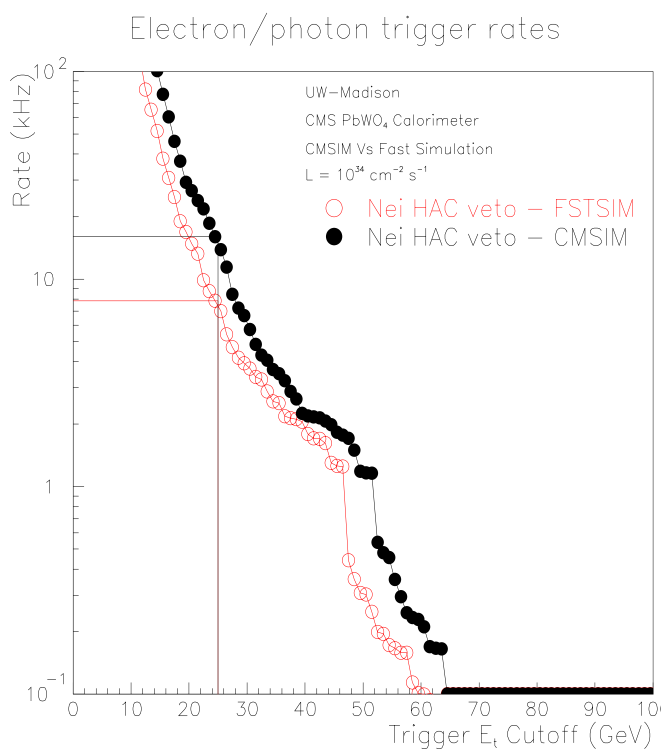
Integrated rate above E_t cut is plotted versus E_t cut.
All four, i.e., finegrain, HAC veto, neighbor HAC veto and quiet neighborhood, cuts are included.
For 25 GeV E_t cut, CMSIM rate is 9 kHz versus to 4 kHz in FASTSIM.

EM Rate Breakdown





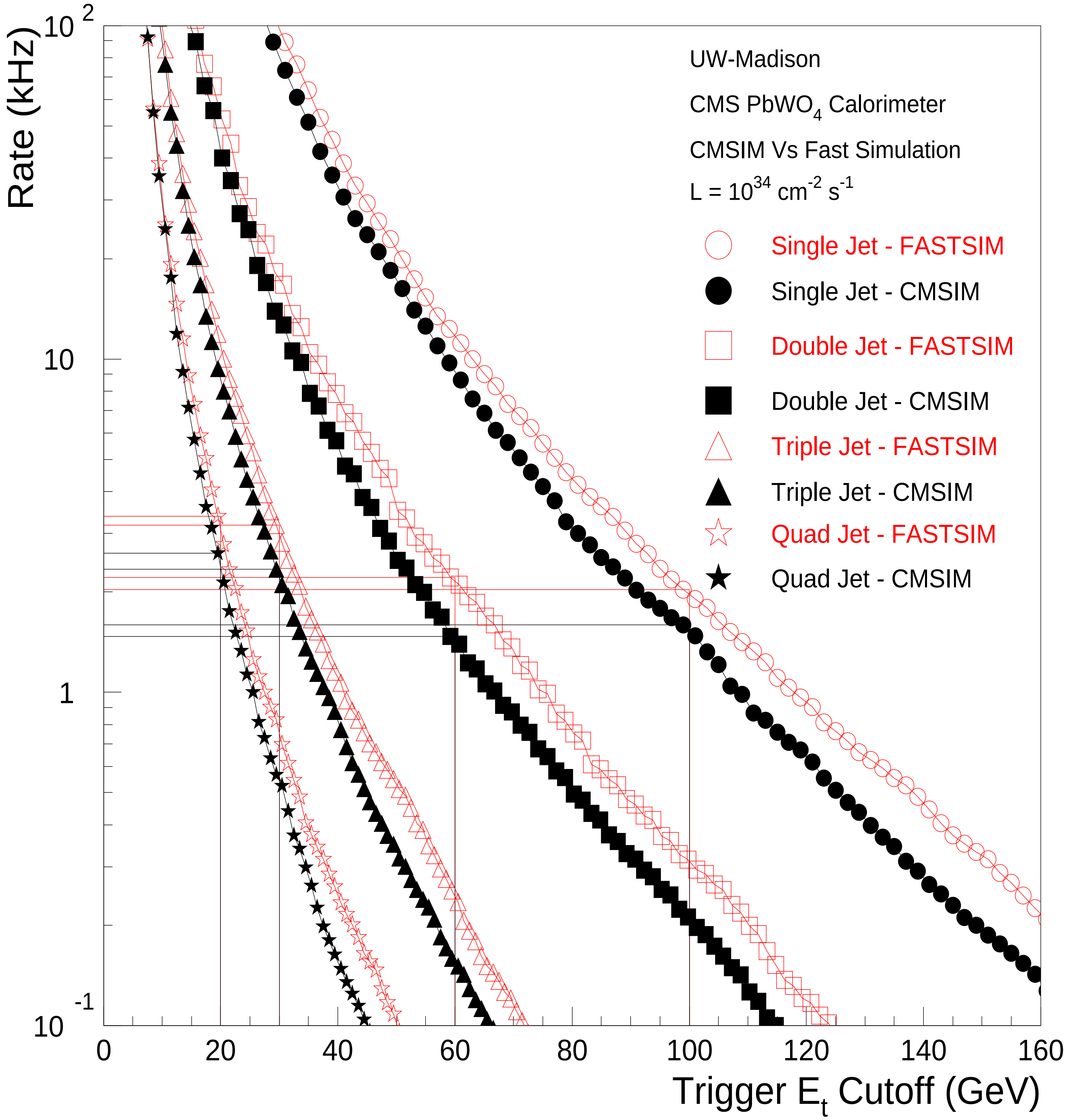




Rates after finegrain and quiet neighborhood cuts match but those after HAC veto and neighbor HAC veto cuts do not because of differences in the simulation of hadron response.

Jet rates

Jet trigger rates

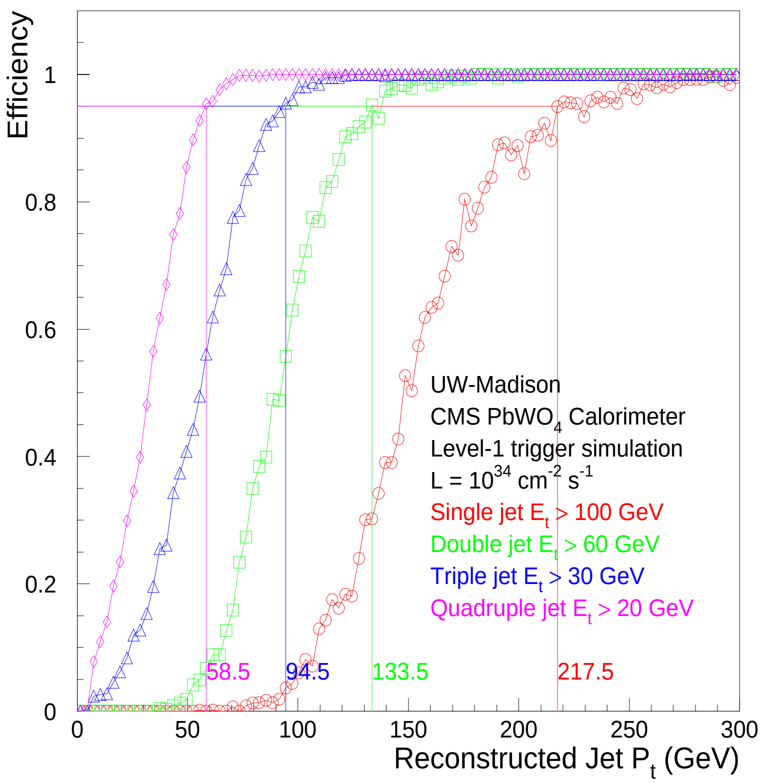


Integrated rates above trigger E_t cutoff are plotted versus the E_t cutoff for single, double, triple and quad jet events.

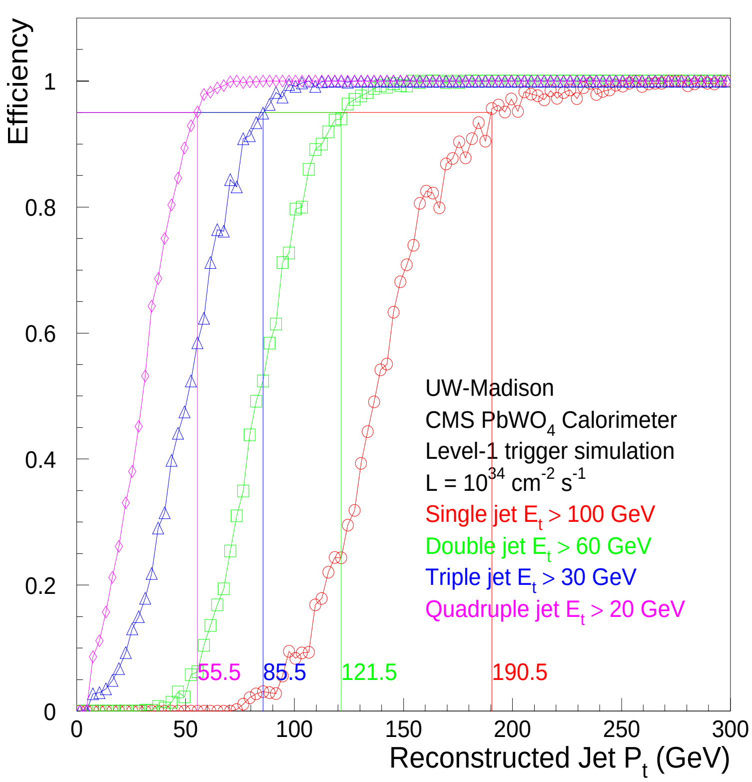
Rates are in reasonable agreement

Jet efficiency

QCD jet efficiency - 4x4 algorithm



QCD jet efficiency - 4x4 algorithm



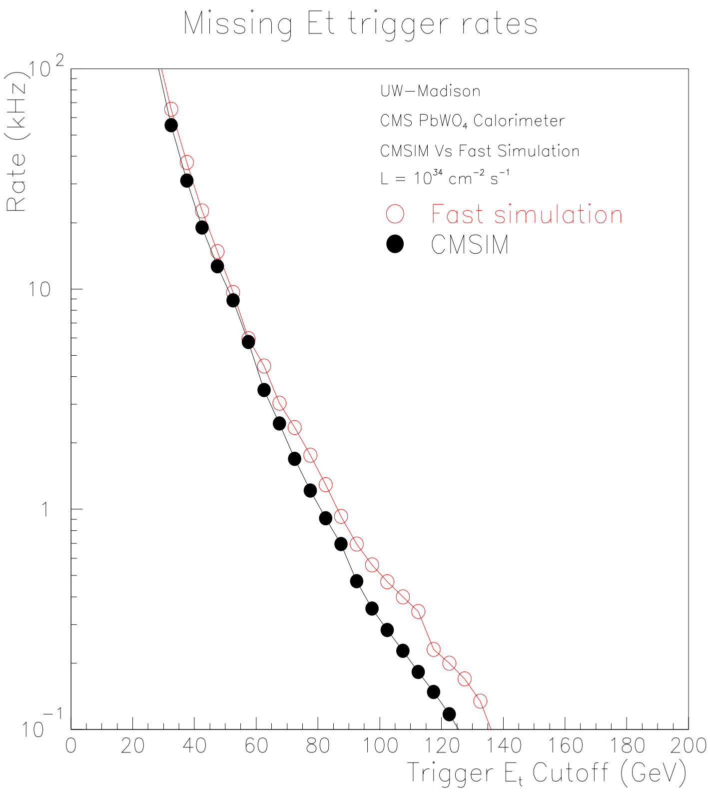
Efficiency for triggering on single, double, triple and quad jet events is plotted versus the reconstructed jet Pt of the lowest energy jet.

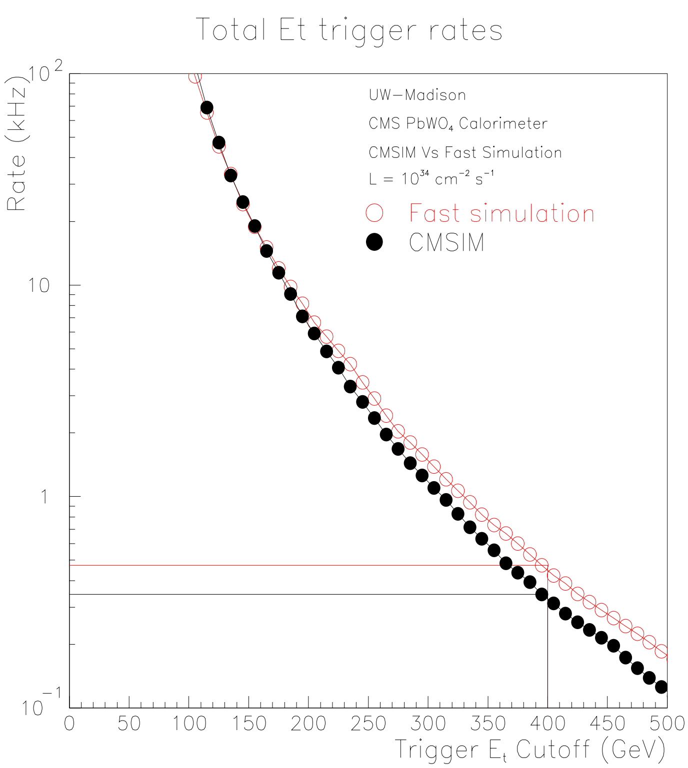
N-jet efficiency is cumulative of all jet cuts 1-N.

CMSIM efficiency turn-on is somewhat slower than FASTSIM.

This can be explained by the lower energy deposition for the hadrons in the events.

Missing and total E_t Rates



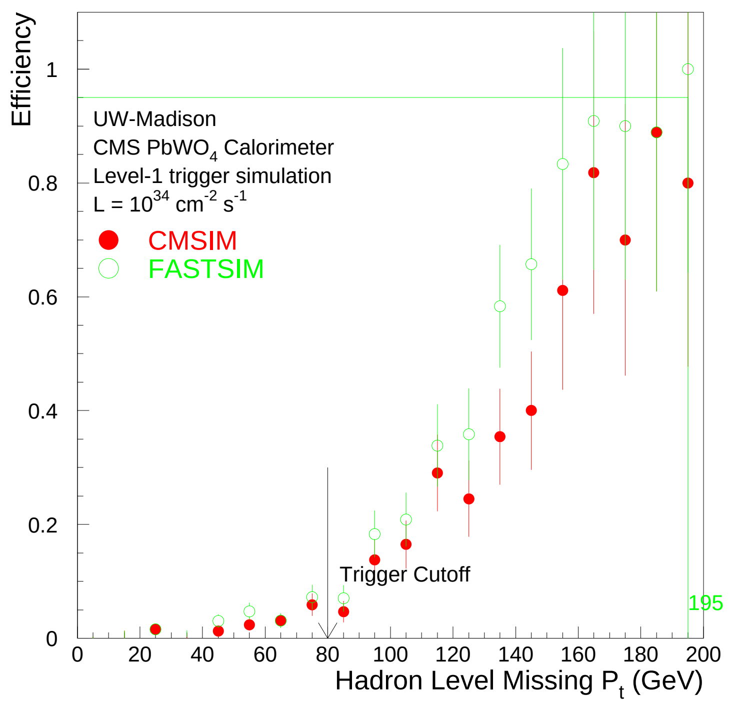


Integrated rates above missing and total E_t trigger cutoffs are plotted versus the missing and total E_t cutoff respectively.

The agreement between CMSIM and FASTSIM is quite good.

Missing E_t Efficiency

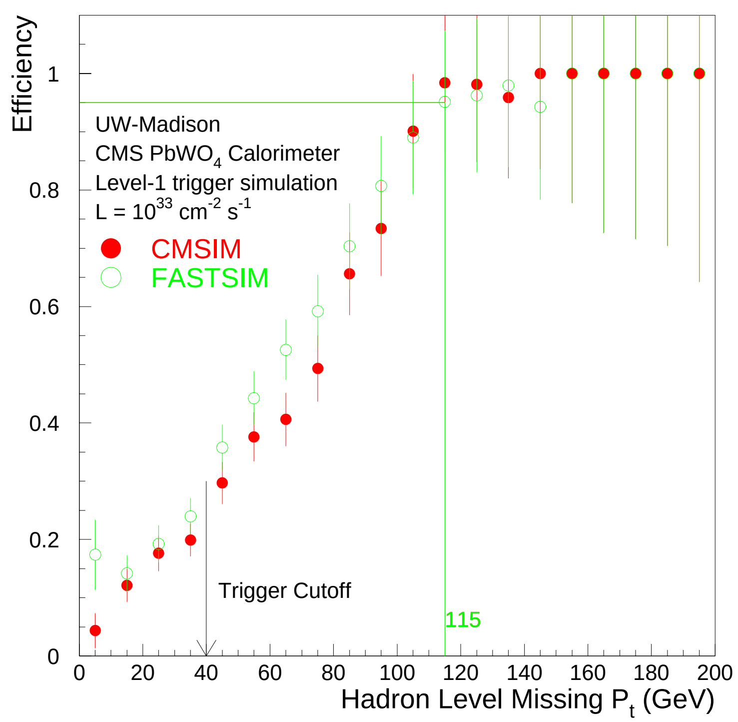
Missing E_T Trigger at L = 10^{34} cm^{-2} s^{-1}



Missing E_T Efficiency is plotted versus the ISAJET hadron level missing P_T for SUSY sparticle production.

Both CMSIM and FASTSIM efficiency turn-on is somewhat slower than desirable.

Missing E_T Trigger at L = 10^{33} cm^{-2} s^{-1}



Trigger factors are responsible for only half the worsening of resolution compared to the ISAJET hadron level values .

However, SUSY events efficiency is supplemented by the total and multijet triggers.

Cal Physics at high lumi

Trigger Type	Trigger Et Cutoff (GeV)	Rate (kHz)			
		CMSIM		FASTSIM	
		Individual	Incremental	Individual	Incremental
Sum Et	400	0.3	0.3	0.4	0.4
Missing Et	80	1.2	0.9	1.7	1.3
Electron	25	11.4	9.3	4.5	3.9
DiElectron	12	2.1	1.8	1.0	1.0
Single jet	100	1.5	1.0	2.0	1.3
Dijet	60	1.2	0.7	1.9	1.1
Trijet	30	2.3	1.3	3.1	1.8
Quadjet	20	2.6	1.1	3.3	1.4
Jet+Elctrn	50 & 12	1.3	0.3	0.7	0.2
Cumulative Rate		16.7		12.4	

Process	Efficiency (%)		
	CMS-TN-95/183	FASTSIM	CMSIM
H (80 GeV) → γ γ	97	92	94
H (120 GeV) → Z Z → e e μ μ	76*	76*	74*
H (200 GeV) → Z Z → e e j j	99	96	95
p p → t t → e X	88	82	82
p p → t t → H+ X → t X	82	76	76

*Inclusion of muon trigger provides full efficiency

Luminosity = 10^{34} cm^{-2} s

QCD Background

The sum and missing E_t cutoff are chosen to provide a 2 kHz rate.
Electron/photon triggers are emphasized, with about 8 kHz rate out of total available 15 kHz.
The remaining 5 kHz is availal for jet triggers.

Signal Efficiency

High efficiency for all channels with electrons and photons.

The difficult-to-trigger top decay events have high efficiency, enabling studies of associated Higgs production.
Unfortunately, no eta cut on trigger particle in new FAST and CMSIM studies!

Cal Physics at low lumi

Trigger Type	Trigger Et Cutoff (GeV)	Rate (kHz)			
		CMSIM		FASTSIM	
		Individual	Incremental	Individual	Incremental
Sum Et	150	1.0	1.0	1.2	1.2
Missing Et	40	2.7	1.7	3.1	2.0
Electron	12	11.4	9.1	5.4	4.4
DiElectron	7	1.2	1.9	0.4	1.0
Single jet	50	1.5	0.3	1.8	0.6
Dijet	30	1.3	0.3	1.7	0.4
Trijet	20	0.8	0.1	1.1	0.1
Quad jet	15	0.6	0.04	0.8	0.1
Jet+Elctrn	15 & 9	11.2	3.4	5.6	2.0
Cumulative Rate		17.8		11.8	

Luminosity = 10^{33} cm^{-2} s^{-1}

QCD Background

CMSIM and FASTSIM rates are compared for the low luminosity E_t cutoffs selected in CMS-TN-95/183

Electron trigger rate is twice as high in CMSIM results

Process	Efficiency (%)		
	CMS-TN-95/183	FASTSIM	CMSIM
p p $\rightarrow$ t t $\rightarrow$ e X	99	97	97
p p $\rightarrow$ t t $\rightarrow$ H+ X $\rightarrow$ t X	99	94	94
p p $\rightarrow$ b b (hadronize), B $\rightarrow$ e X	0.2 (But 400Hz)	-	-
SUSY CMS TP Scenario A (M_{LSP} = 45, M_{spart} ~ 300 GeV)	98	83	81
SUSY Neutral Higgs (Range of tan β and M_H values)	45 - 98	30 - 96	39 - 96

Signal efficiency

High efficiency is realized for the benchmark processes involving top decays and SUSY sparticles.
A dedicated tau trigger is under study to improve efficiency for low mass range of SUSY Higgs.
There is also high rate of B signal in level-1 sample.

Low rate trigger - High lumi

Background rate Luminosity = 10^{34} cm^{-2} s^{-1}

Trigger Type	Nominal		Descoped	
	Trigger Et Cutoff (GeV)	Incremental Rate (kHz)	Trigger Et Cutoff (GeV)	Incremental Rate (kHz)
Sum Et	400	0.3	400	0.3
Missing Et	80	0.9	80	0.9
Electron	25	9.3	30	2.5
DiElectron	12	1.8	15	1.2
Single jet	100	1.0	100	1.0
Dijet	60	0.7	65	0.4
Trijet	30	1.3	45	0.1
Quadjet	20	1.1	25	0.5
Jet+Elctrn	50 & 12	0.3	50 & 10	0.5
Cumulative Rate (kHz)	16.7		7.4	

Trigger scope studie

CMSIM results

Total calorimeter trigger rate limited tc 7.5 kHz

Signal efficiency

Process	Efficiency (%)	
	Nominal Et Cutoffs	Descoped Et Cutoffs
H (80 GeV) $\rightarrow \gamma\gamma$	93	88
H (120 GeV) $\rightarrow$ Z Z $\rightarrow$ e e $\mu\mu$	76*	70*
H (200 GeV) $\rightarrow$ Z Z $\rightarrow$ e e j j	95	94
p p $\rightarrow$ t t $\rightarrow$ e X	82	77
p p $\rightarrow$ t t $\rightarrow$ H^+ X $\rightarrow$ t X	76	72

*Inclusion of muon trigger provides full efficiency

Low rate trigger - Low lumi

Background rate Luminosity = 10^{33} cm^{-2} s^{-1}

Trigger Type	Nominal		Descoped	
	Trigger Et Cutoff (GeV)	Incremental Rate (kHz)	Trigger Et Cutoff (GeV)	Incremental Rate (kHz)
Sum Et	150	1.0	150	1.0
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Trijet	20	0.1	20	0.2
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Cumulative Rate (kHz)	17.8		7.6	

Trigger scope studie

CMSIM results

Total calorimeter trigger rate limited tc 7.5 kHz

Signal efficiency

Process	Efficiency (%)	
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p p $\rightarrow$ t t $\rightarrow$ e X	98	97
p p $\rightarrow$ t t $\rightarrow$ H+ X $\rightarrow$ t X	94	94
SUSY CMS TP Scenario A (M_{LSP} = 45, M_{spart} ~ 300 GeV)	82	77
SUSY Neutral Higgs (Range of tan β and M_H values)	40 - 96	30 - 95

Muon System Requirements

MUON IDENTIFICATION

At least 16 λ of material is present up to $|\eta|=2.4$ with no acceptance losses.

STANDALONE MOMENTUM RESOLUTION

From 8-15% dp_T/p_T at 10 GeV and 20-40% at 1 TeV.

GLOBAL MOMENTUM RESOLUTION

After matching with the Central Tracker:
from 1.0-1.5% at 10 GeV, and from 6-17% at 1 TeV.

Momentum-dependent spatial position matching
at 1 TeV less than 1 mm in the bending plane
and less than 10 mm in the non-bending plane.

CHARGE ASSIGNMENT

Correct to 99% conf. up to the kinematic limit of 7 TeV.

MUON TRIGGER

The combination of precise muon chambers and fast dedicated trigger detectors provide unambiguous beam crossing identification and trigger on single and multimuon events with well defined p_T thresholds from a few GeV to 100 GeV up to $|\eta|=2.1$.

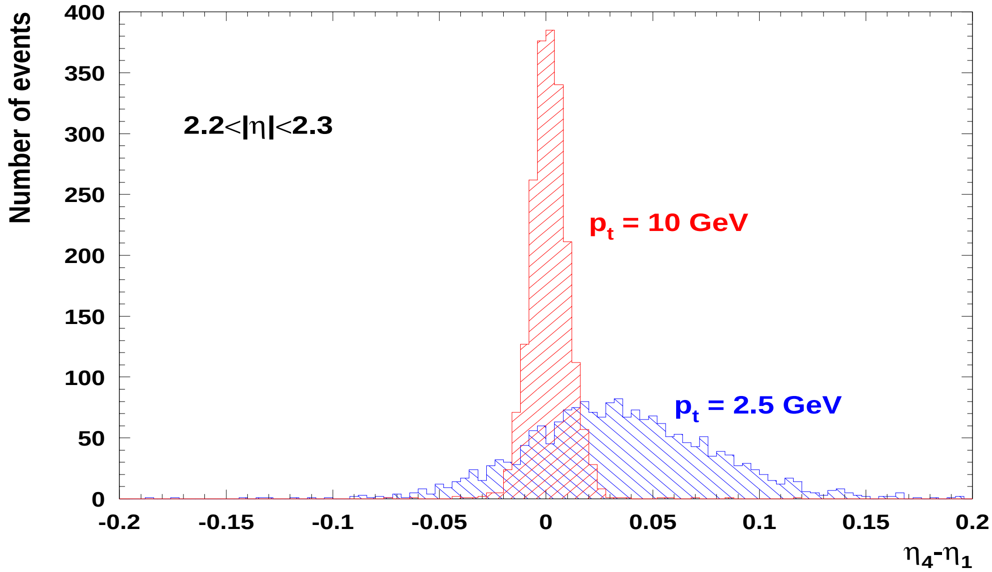
Muon Trigger

Solenoidal fields of CMS bends tracks in Rφ plane.

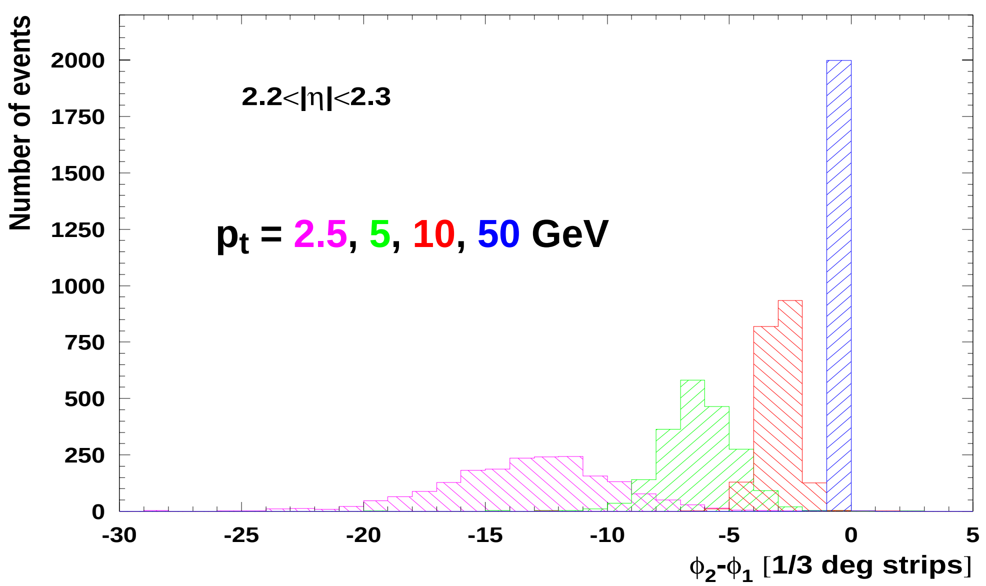
Thus tracks keep almost constant η.

$$\Delta\varphi \propto \int B \times dl \qquad \Delta\eta \approx 0$$

Even for the softest forward tracks $\Delta\eta<0.15$.

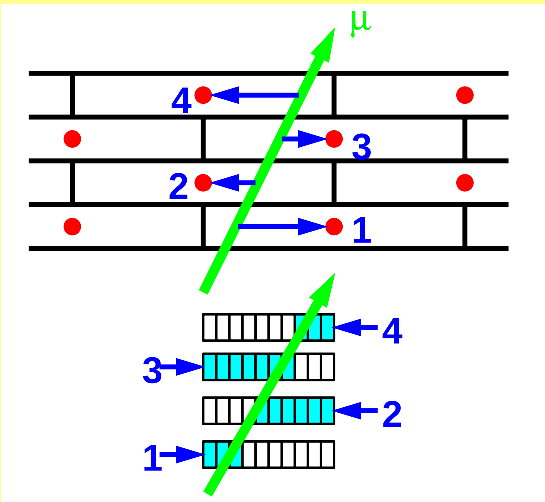


For $|\eta|<2.5$ the $\int B\times dl$ is enough to provide a p_t cut.
Strips of $\Delta\varphi=1/3°$ are narrow enough.

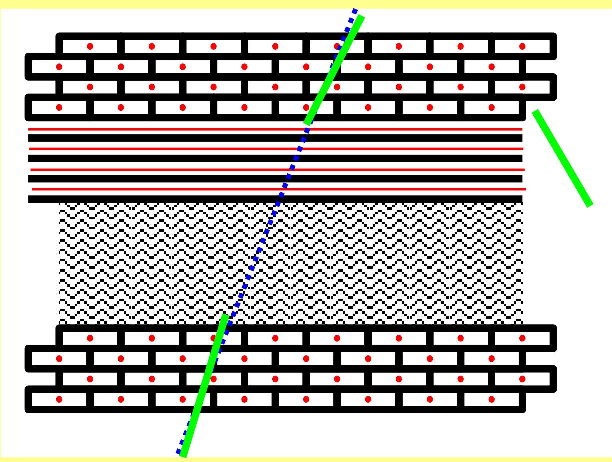


Muon Chamber Trigger Logic

Drift Tubes

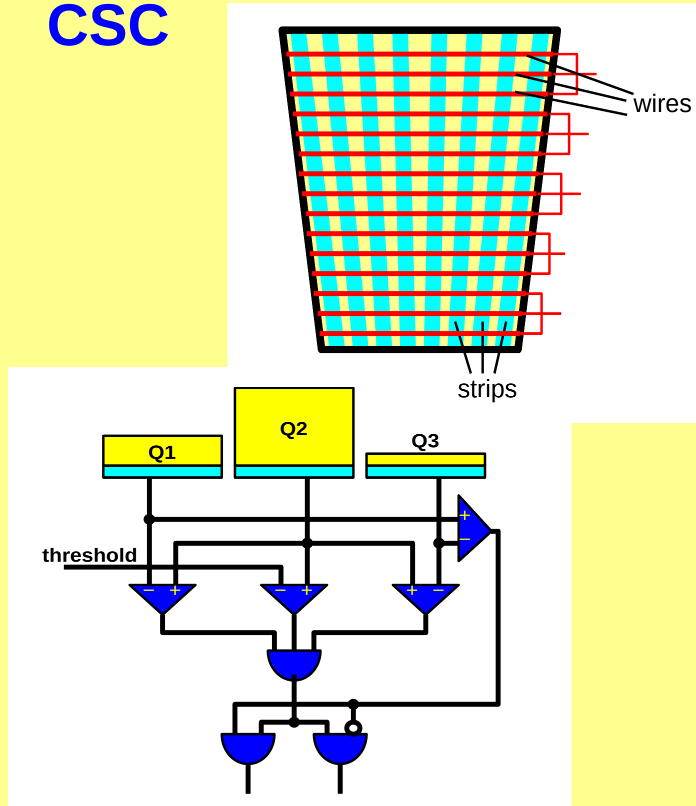


Meantimers recognize tracks and form vector / quartet.

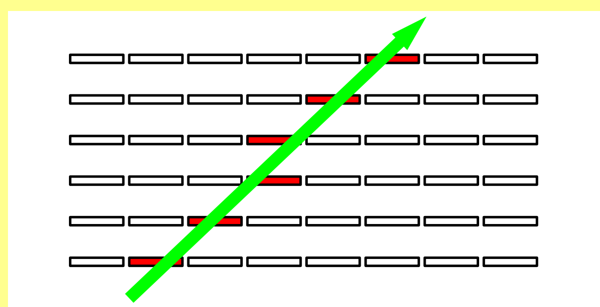


Correlator combines them into one vector / station.

CSC

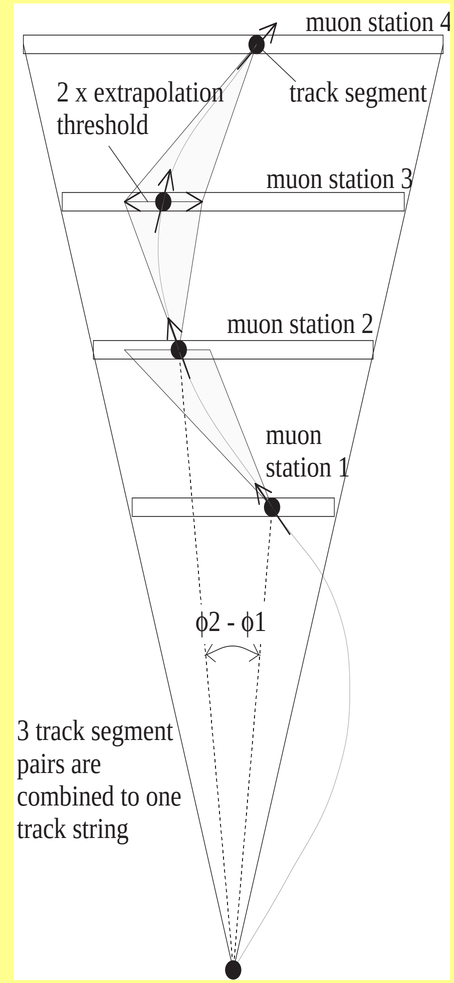


Comparators give 1/2−strip resol.



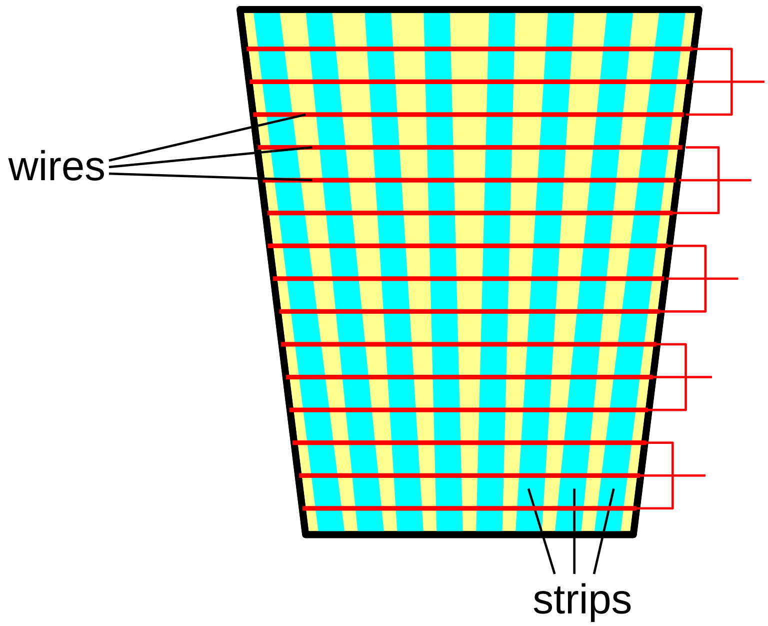
Hit strips of 6 layers form a vector.

Track Finder



- combines vectors,
- forms a track,
- assigns p_t value.

Cathode Strip Chambers



TIME:

OR of 6 planes of wires

first pulse gives t_0 but $\geq$4 planes out of 6 must be fired

$$t_{drift}^{max} = 40\ ns \quad \Rightarrow \quad \sigma(t_0) < 3\ ns$$

POSITION:

cluster center in every plane of strips

$$\Delta x = 1/2 \text{ strip width}$$

ANGLE:

local charged track (LCT) determined by

pattern of fired halfstrips in a gi ven station

MOMENTUM:

combination of LCT's from all stations

Muon Trigger Simulation

Trigger Primitives

- **Formed from hits generated in GEANT based CMSIM**
- **Detailed simulation used to check resolutions, background, ghosts**
- **Discussed by J. Hauser**

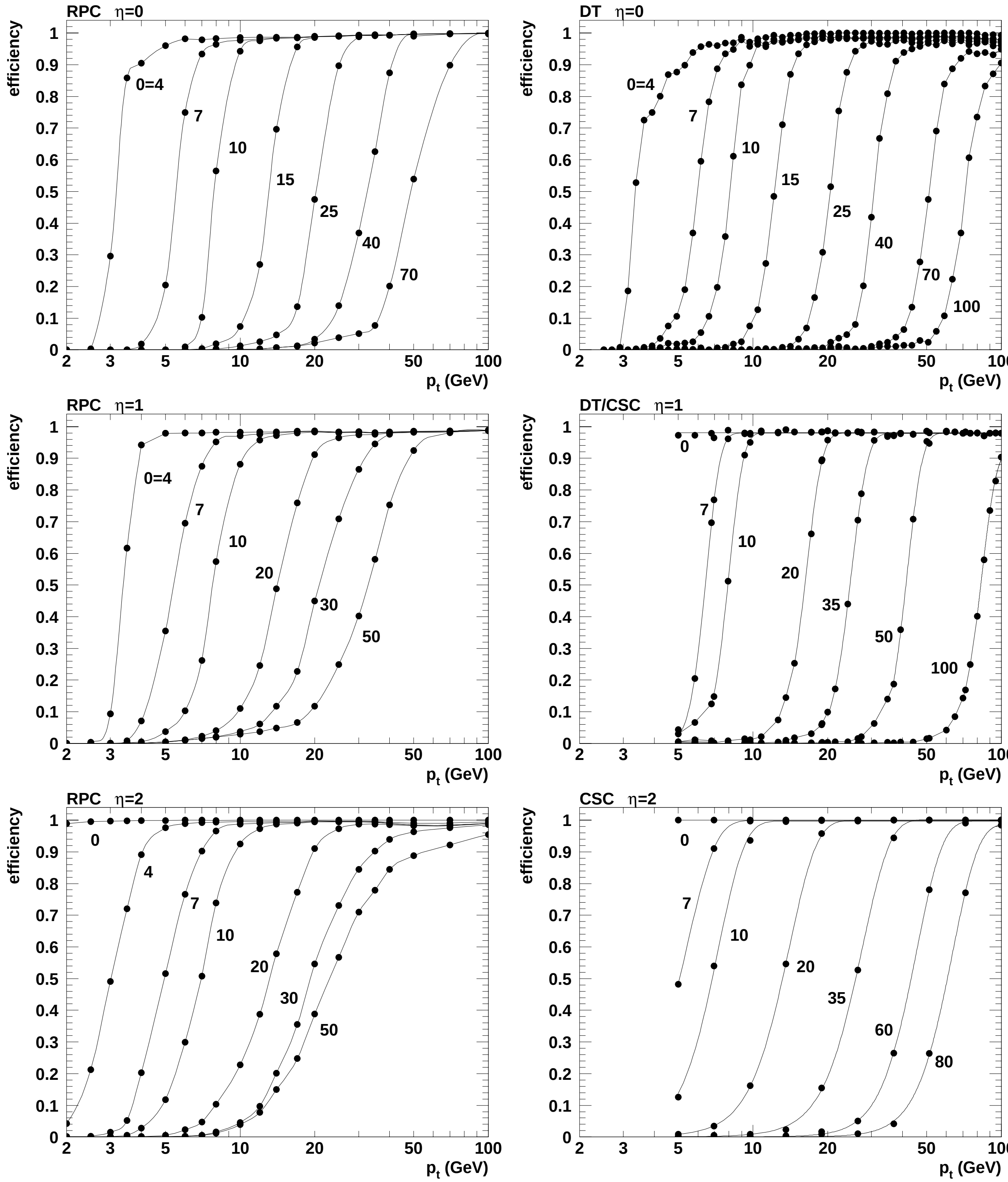
Track finder

- **DTBX input 2 track segments per chamber**
  - Detailed trigger primitives used
- **CSC input 3 track segments per logical 30 degree chamber**
  - Parameterized trigger primitives
    - Azimuthal angle resolution = 1.4 mrad
    - Bend angle resolution (slope measured by the strips) 30 mrad
    - Efficiency - 97%

Trigger processor simulation

- **Track finding**
  - Track recognized if 2 out of 4 muon stations find track segments
    - Pairwise matching with extrapolation
  - Track should extrapolate to the interaction region
  - 1 track segment should belong to no more than 1 track
- **Assignment**
  - Transverse momentum including charge
    - Uses bend angle only
  - Location (η,ϕ)
  - Quality
    - Number of stations contributing to track
    - Qualities of contributing track segments
- **Removal of ghosts**
- **Track sorting using P_T and quality**

Muon Trigger Efficiency



Single muon events simulated in CMSIM framework- but with CSC trigger primitives parameterized.

Muon Trigger Physics

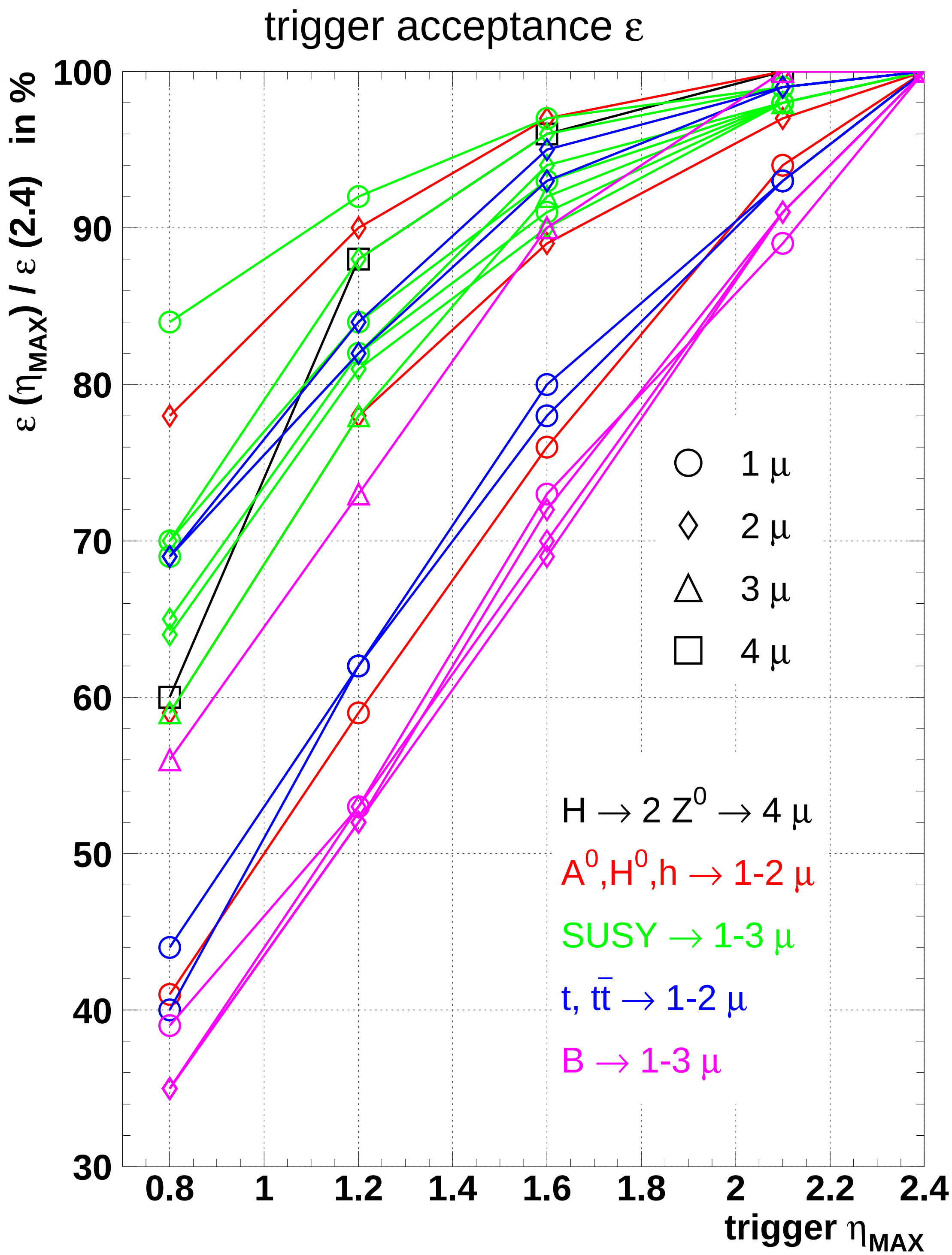
Single muon efficiency curves folded with various physics processes

Rate studies

- Pythia QCD jet events generated
- Muons from long lived π and k meson decays within the CMS and b,c decays are considered
- Separately, W, Z, top, J/ψ and Drell-Yan muons also considered
- Total and partial muon rates for these processes are obtained by folding them with the expected single muon event efficiency curves.

Thresholds can be set at 7 GeV for single muon trigger and 2-4 GeV for dimuon trigger within the allocated muon trigger bandwidth of 15 kHz, ensuring better than 95% efficiency for the high P_T processes of interest to CMS.

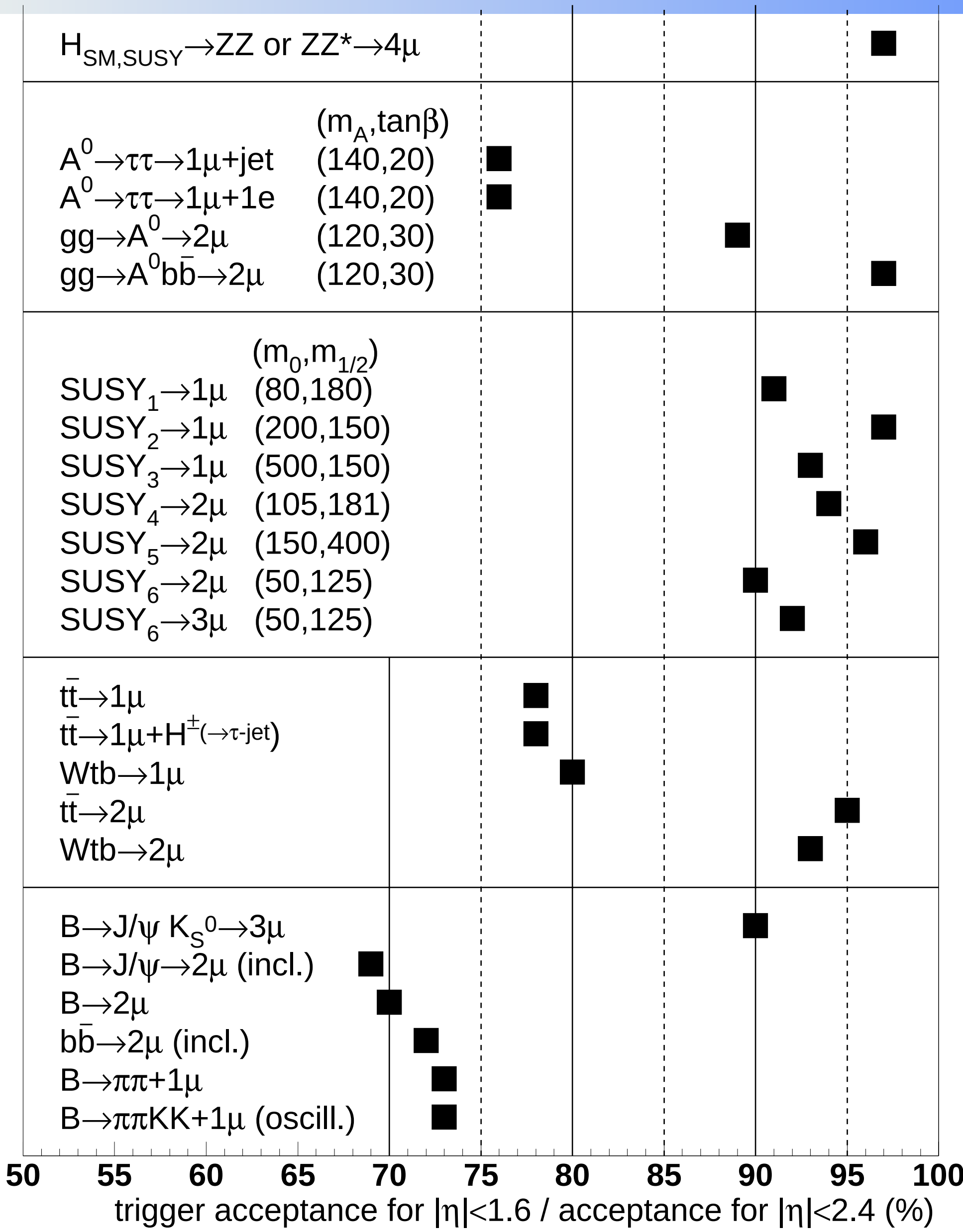
Muon Trigger Efficiency vs η



low lumi. trigger thresholds - $p_t^{1\mu}$ = 7 GeV, $p_t^{2\mu}$ = 4 GeV

Study by S.Abdulin, C.Albajar, D.Denegri, I.Iashvili, A.Kharchilava, R.Kinnunen, A.Nikitenko, L.Rurua, G.Wrochna

Acceptance η=1.6 vs 2.4

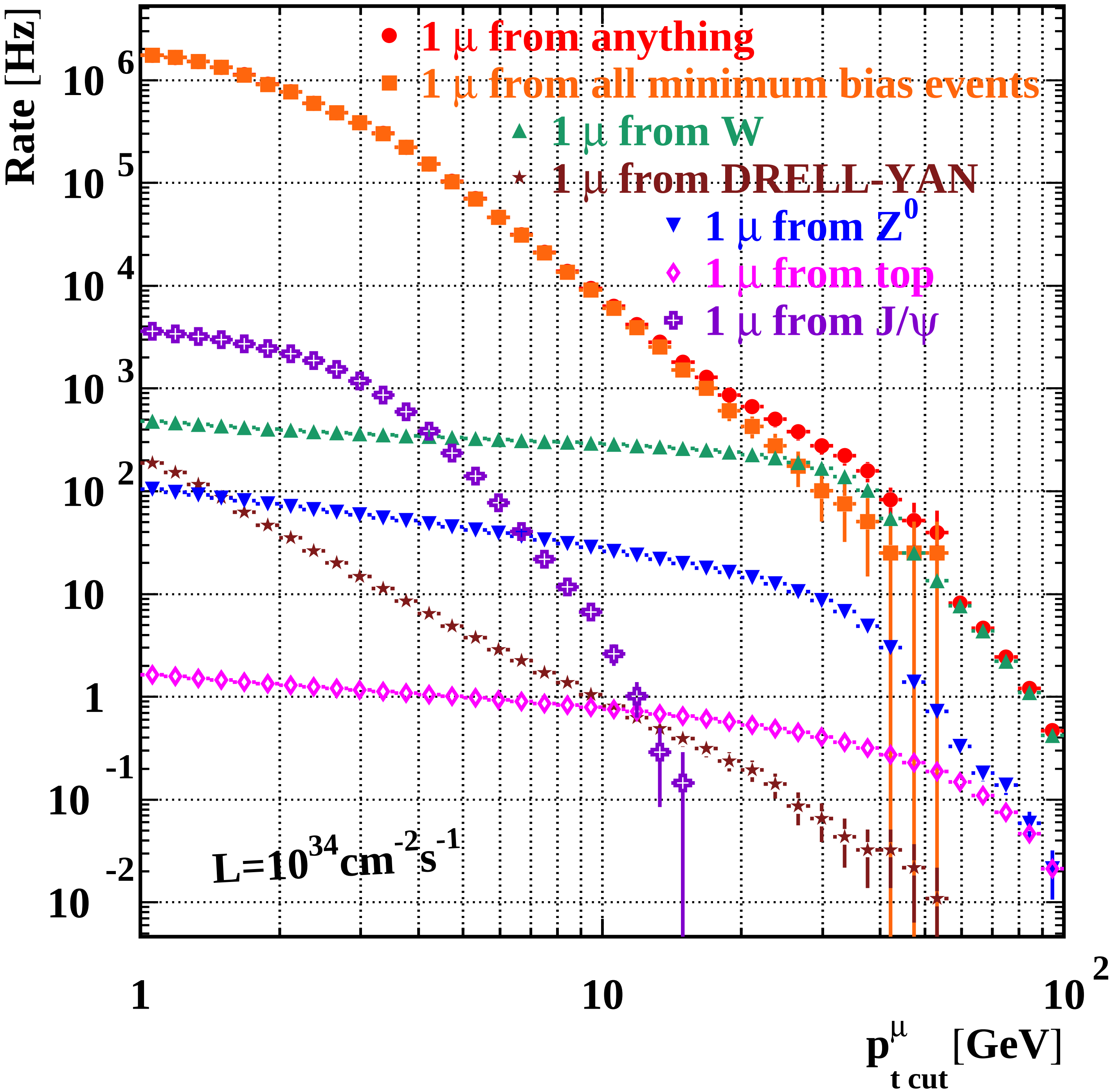


low lumi. trigger thresholds - $p_t^{1\mu}$ = 7 GeV, $p_t^{2\mu}$ = 4 GeV

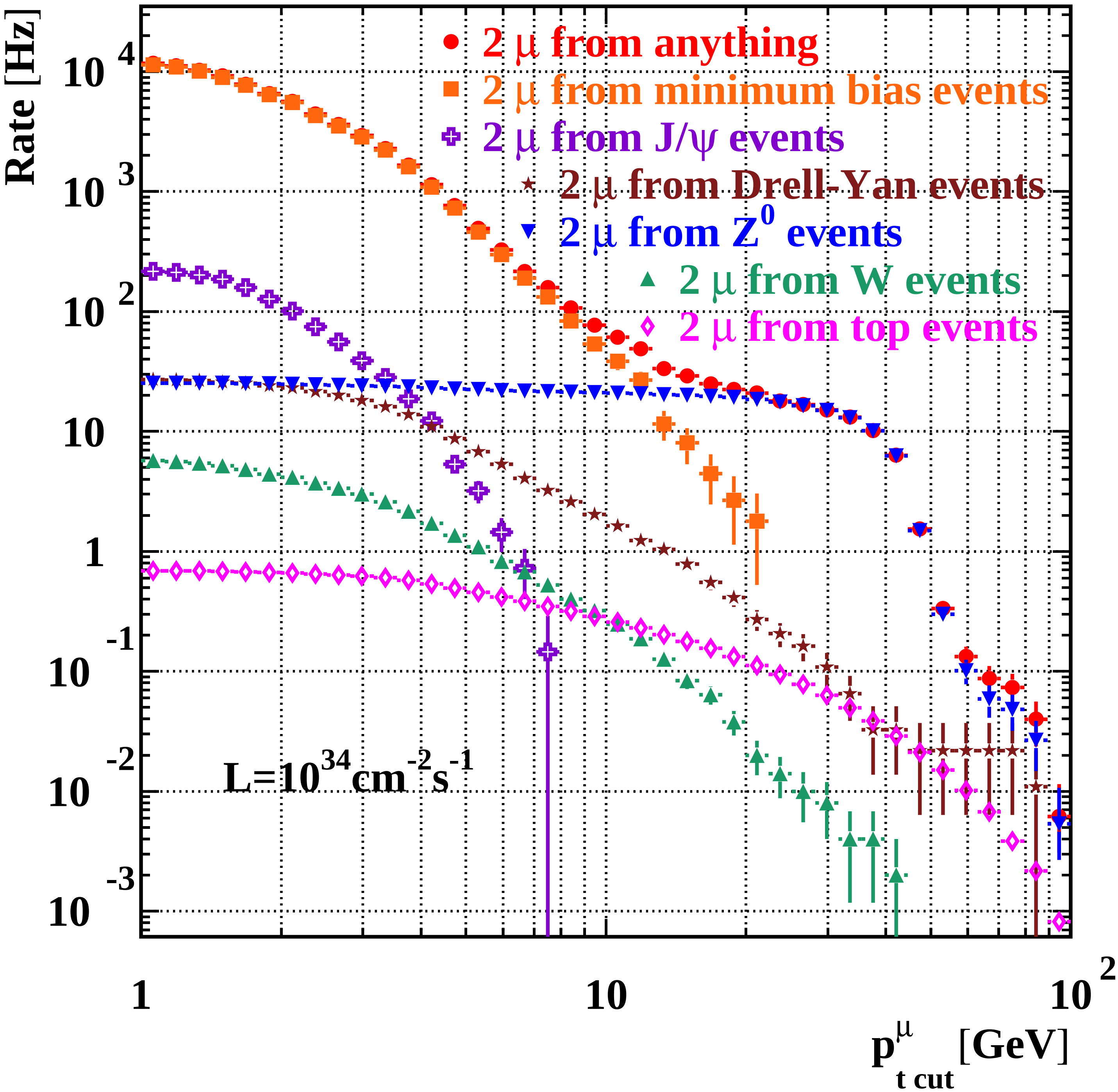
Study by S.Abdulin, C.Albajar, D.Denegri, I.Iashvili, A.Kharchilava, R.Kinnunen, A.Nikitenko, L.Rurua, G.Wrochna

CSC trigger is necessary to provide full acceptance for important CMS physics. Efficiency with nominal coverage at η=2.4 is >95%

Single Muon Rates



Dimuon Rates



Cal/Muon Combined Rates

	$L = 10^{33} cm^{-2} s^{-1}$			$L = 10^{34} cm^{-2} s^{-1}$		
trigger type	**threshold [GeV]**	**rate [kHz]**	**cumulative rate [kHz]**	**threshold [GeV]**	**rate [kHz]**	**cumulative rate [kHz]**
μ	7	9.8	9.5	20	7.8	7.8
$\mu\ \mu$	2-4	0.5	10.1	4	1.6	9.2
μ e/γ	2-4, 6	2.5	12.2	4, 8	5.5	14.4
$\mu\ e_b$	2-4, 5	3.5	13.4	—	—	—
μ j	2-4, 12	2.2	14.5	4, 40	0.3	14.4
$\mu\ E_t^{miss}$	2-4, 40	0.8	14.7	4, 60	1.0	15.3
$\mu\ \Sigma E_t$	2-4, 150	0.8	14.7	4, 250	0.2	15.3

threshold = 2-4 GeV means: 4 GeV in the barrel, 2 GeV in the endcaps

muon threshold = transverse momentum threshold
calorimeter threshold = transverse energy threshold

e/γ — electron/photon trigger, e_b — trigger on electron from b-quark decay

Summary

Calorimeter Trigger

- Detailed GEANT based calorimeter shower simulation and the trigger system algorithms simulation, including bit resolutions and lookup tables, has been carried out.
- The rate and efficiency results are in reasonable agreement with our independent parameterized fast simulation effort.

Muon Trigger

- Detailed GEANT simulation is used to understand trigger primitive resolutions, backgrounds, etc.
- Parameterized simulation of the trigger primitives with detailed simulation of the muon track finder logic is used to determine the rates and efficiency.

Performance

- The calorimeter and muon trigger simulations enabled the design of algorithms which can be implemented in electronics.
- The rate requirements of the data acquisition system can be met by these algorithms with a reasonable safety factor of about three while providing good efficiencies for high E_T physics processes of interest to CMS.
- Hardware that implements these algorithms is discussed in the talks of W.H. Smith and J. Hauser.

Future Simulation Program

Calorimeter

- **Latest CMSIM (version 114)**
  - ECAL segmentation: 5x5 vs. 6x6 granularity
  - Endcap/barrel interface
  - HCAL geometry update
  - Hadronic energy deposition problem
  - Obtain new rates/efficiency/Improve statistics
- **Higher Level Triggers**
  - Incremental data access scheme validation
  - Algorithms design and complexity study
  - Study rate reduction without tracker data

Muon

- **CMSIM**
  - Trigger primitives for DT/CSC/RPC
  - Optimize track finder algorithms
  - Ghosts in realistic events with jets/minbias
  - Punchthrough rate
  - Calorimeter isolation
- **Higher Level Triggers**
  - Design algorithms (without tracker data?!)