Challenges of LHC: Trigger

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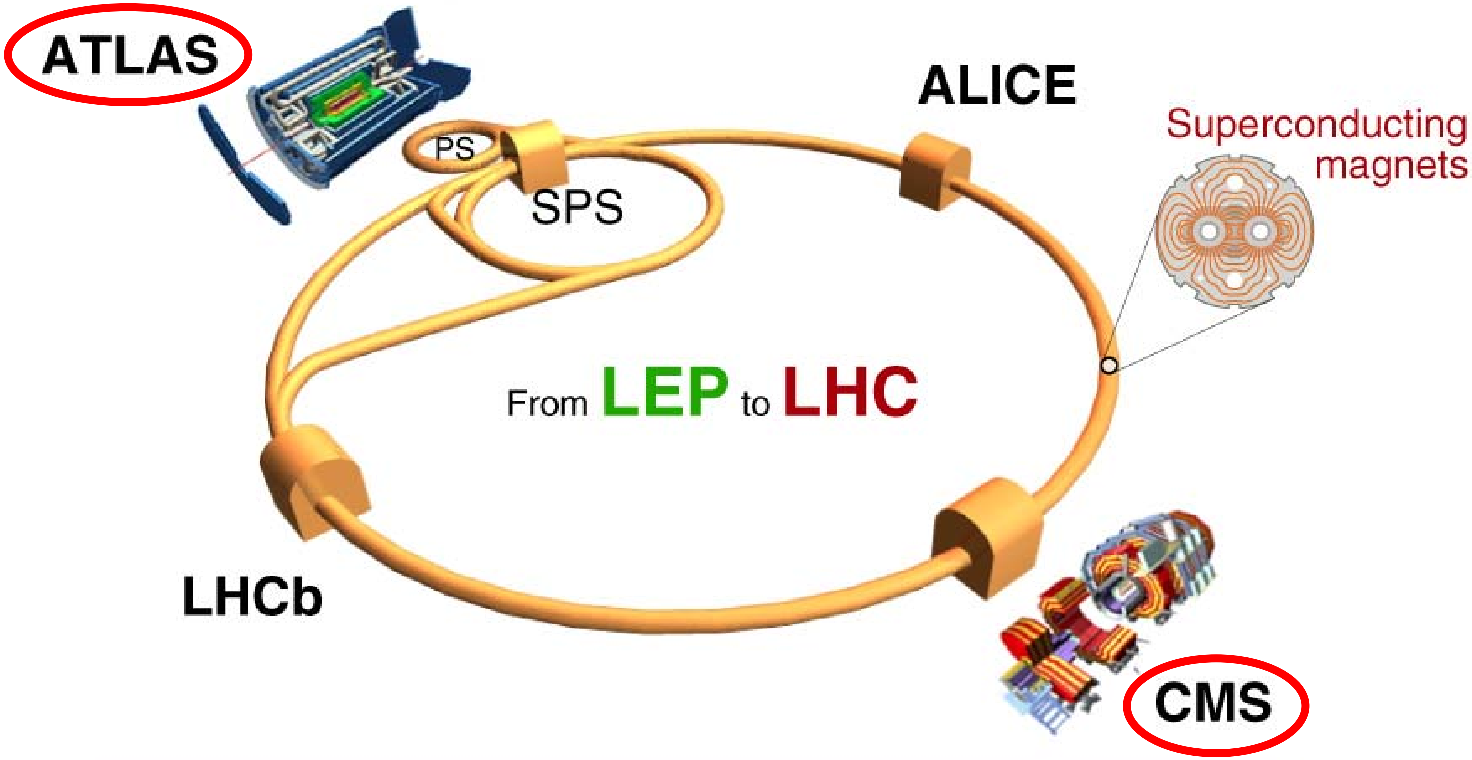
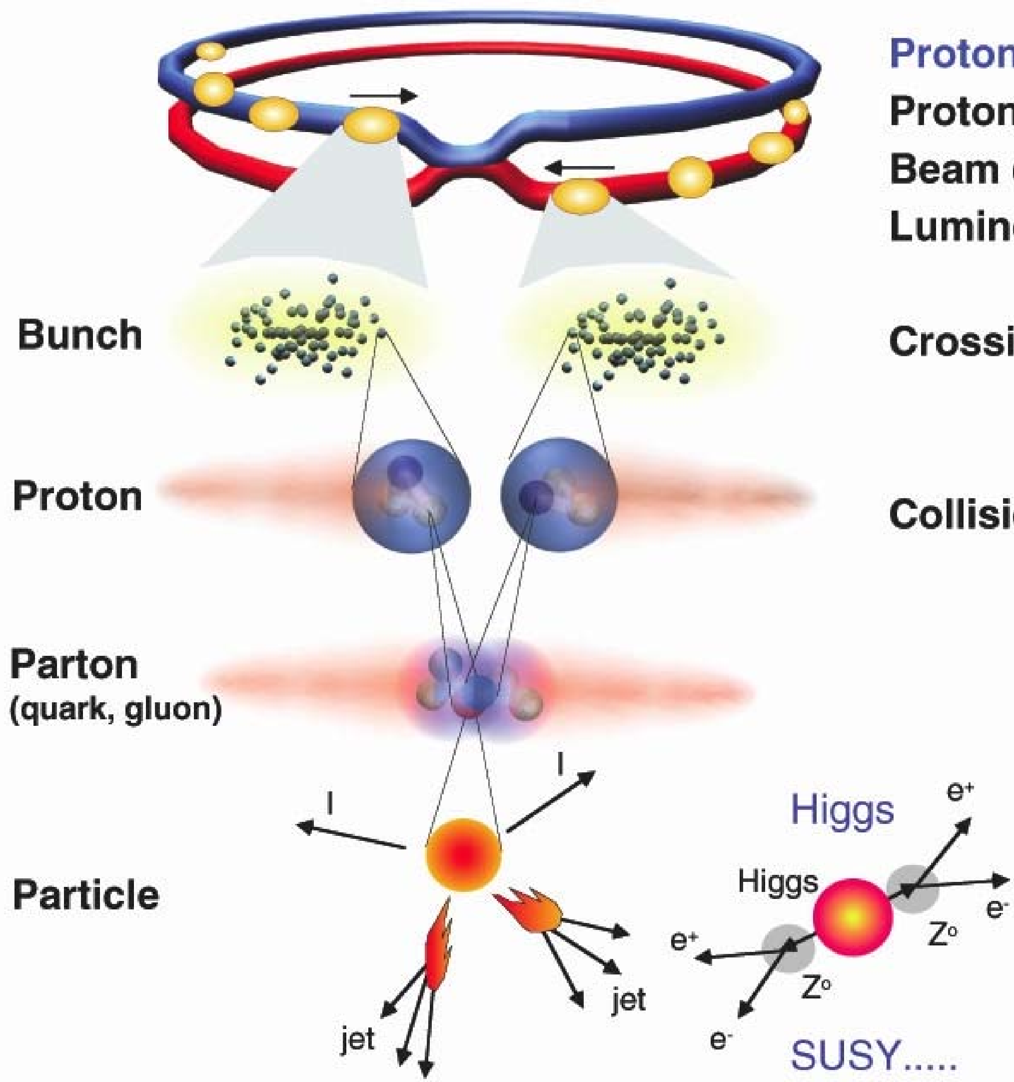


	Beams	Energy		Luminosity
LEP	e^+ e^-	200	GeV	10^{32} cm^{-2}s^{-1}
LHC	p p	14	TeV	10^{34}

The Large Hadron Collider



Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz

Selection of 1 in 10,000,000,000,000

Physics in LHC Era

Trigger Challenge

- Electroweak Symmetry Breaking Scale
  - Higgs discovery and higgs sector characterization ← Low P_T γ, e, μ
  - Quark, lepton Yukawa couplings to higgs ← Low P_T B, τ jets
- New physics at TeV scale to stabilize higgs sector
  - Spectroscopy of new resonances (SUSY or otherwise) ← Multiple low P_T objects
  - Find dark matter candidate ← Missing E_T
- GUT scale physics (loop effects)
  - Indirect effects on flavor physics (mixing, FCNC, etc.)
    - B_s mixing and rare B decays ← ~ give up to dedicated experiment, LHCB
  - Lepton flavor violation
    - Rare Z and higgs decays ← Low P_T leptons
- Planck scale physics
  - Large extra dimensions to bring it closer to experiment
  - New heavy bosons
  - Blackhole production

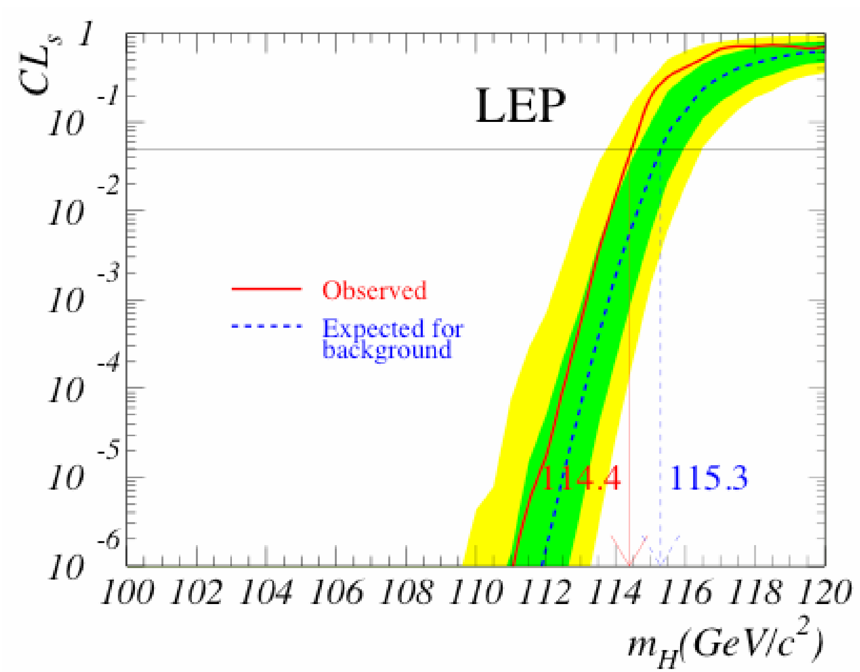
← High P_T leptons and photons

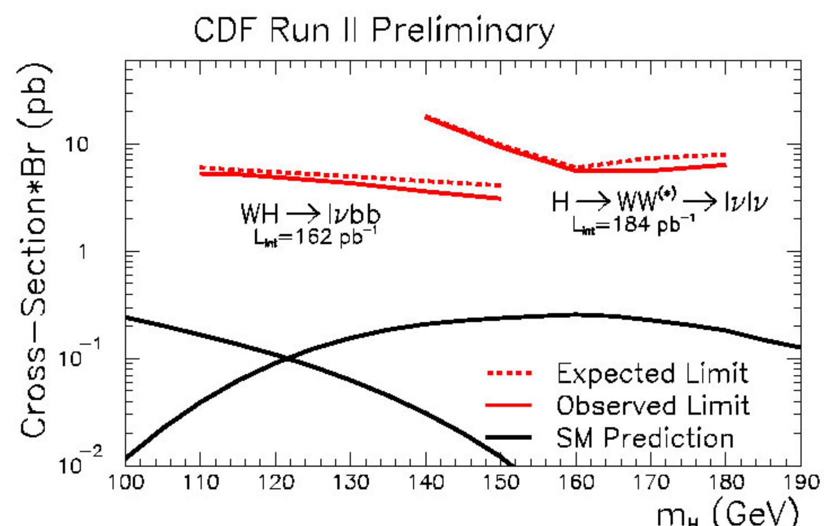
Multi particle and jet events

Low ≅ 40 GeV

Low Mass Higgs dominates the Trigger Challenge

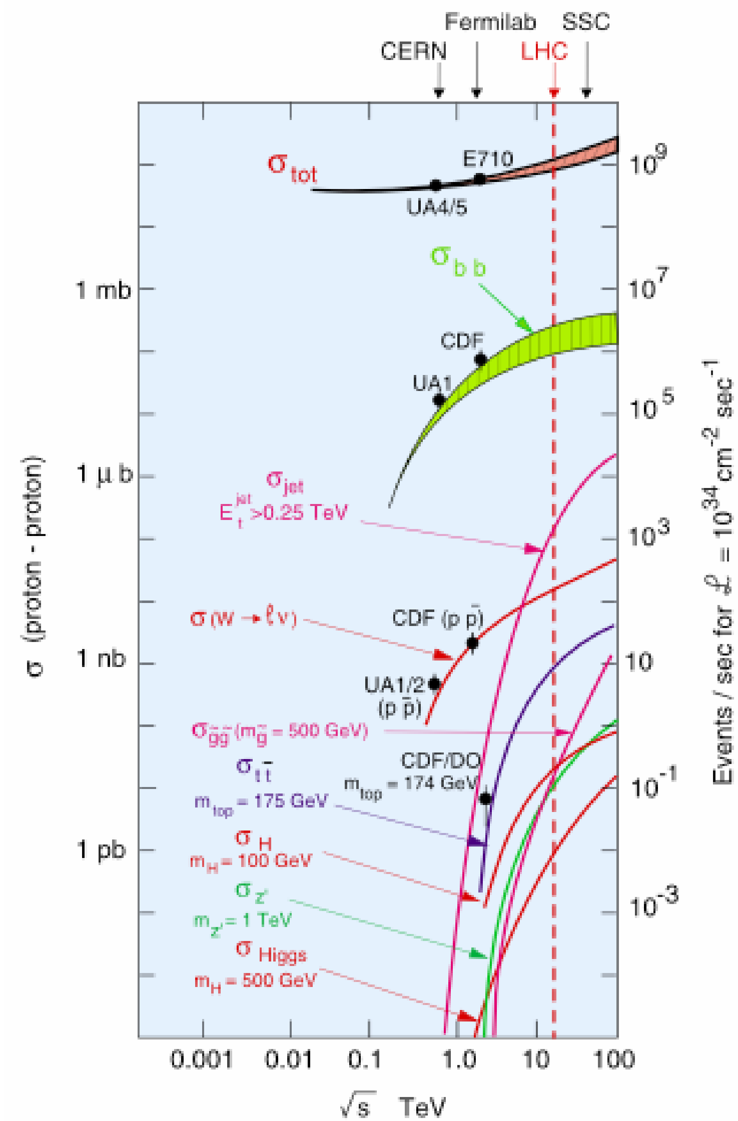
- LEP direct search limit
  - $M_H > 114.4$ GeV (95% C.L.)
  - MSSM Higgses, $M_h > 91.0$ GeV, $M_A > 91.9$ GeV, $M_H+ > 78.6$ GeV (95% C.L.)
- Tevatron with current projection of luminosity (8 fb^{-1}) may leave the low mass higgs region still open
  - However, other new particle searches go to kinematic limit, ~450 GeV





Must be able to trigger on ~40 GeV higgs decay remnants, or leptons from associated Ws.

The LHC Trigger Challenge



Physics at EWSB scale

- $115 < M_{higgs} < 250$ GeV
- Decays to $\gamma\gamma$, WW*, ZZ*
  - 2-γ P_T~20 GeV, Lepton P_T ~ 40 GeV

TeV scale supersymmetry

- Multiple leptons, jets and LSPs (missing P_T), H_T ~ 300 GeV

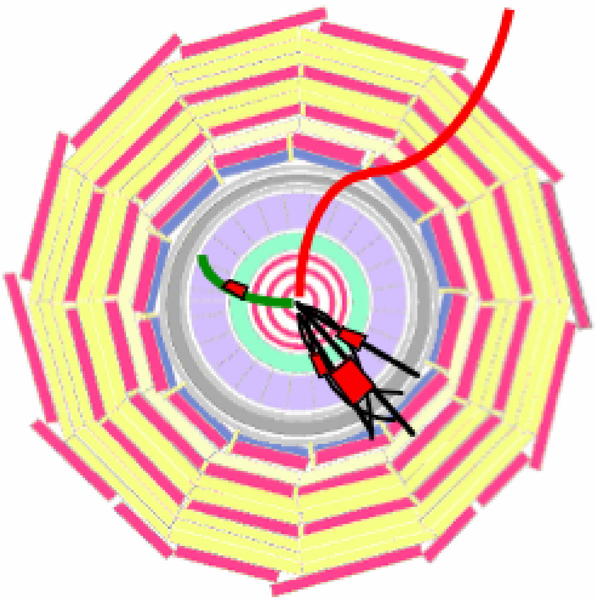
QCD Background

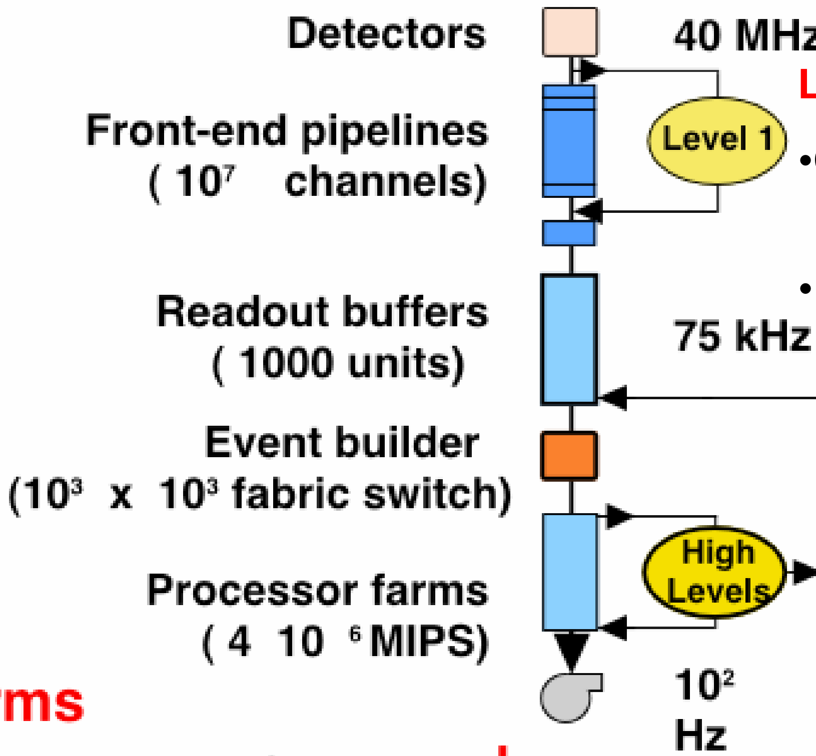
- Jet E_T ~ 250 GeV, rate = 1 kHz
- Jet fluctuations ⇒ electron BG
- Decays of π, k, B ⇒ muon BG

Technical challenges

- 40 MHz input ⇒ fast processing
- 100 Hz output ⇒ physics selection
- 10^9 events per year ⇒ ≤10^2 higgs events

Multi Level Trigger Strategy





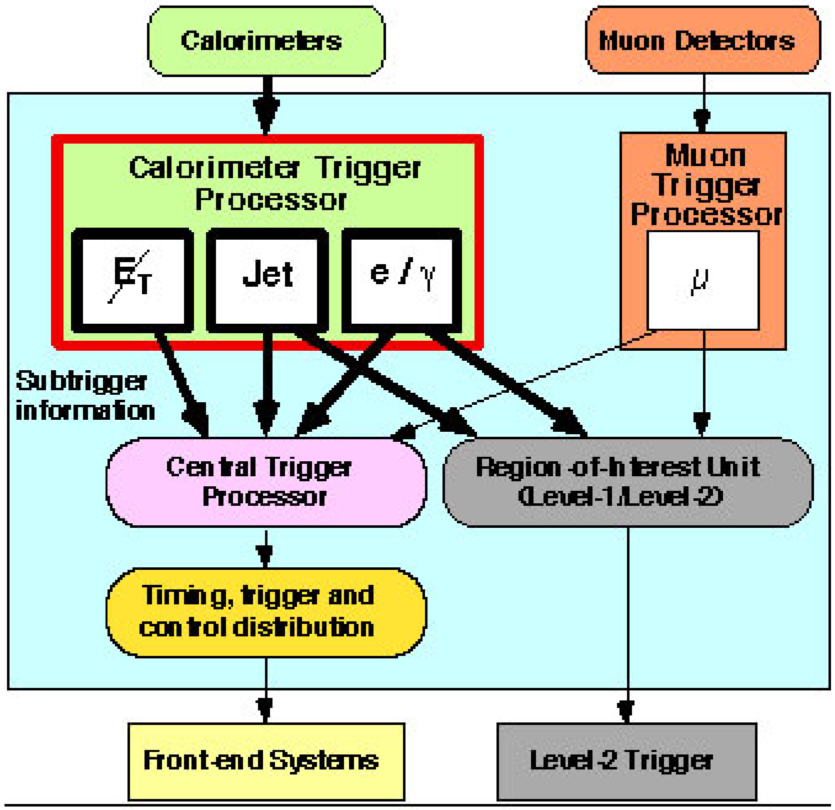
Level 1
- Coarse object identification
- Limited isolation

High level triggers. CPU farms

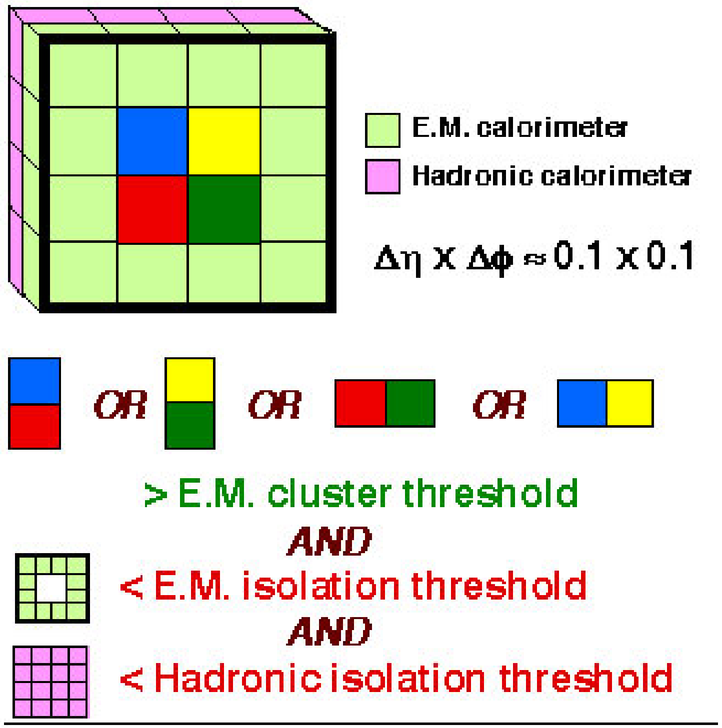
- Finer granularity precise measurement
- Clean particle signature (π^0-γ, isolation, ...)
- Kinematics. Effective mass cuts and topology
- Track reco and matching, b,τ-jet tagging
- Full event reconstruction and analysis

Successive improvements : background event filtering, physics selection

ATLAS L1 Trigger



em cluster trigger algorithm



CMS Electron/Photon Algorithm

Trigger Primitive Generator

Fine grain Flag Max of (, , ,) & Sum ET

Regional Calorimeter Trigger

E_T cut + Max ( ) > Threshold

AND

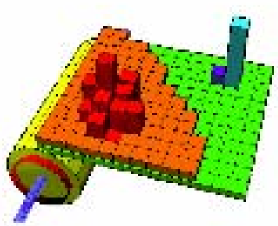
Longitudinal cut (H/E) / < 0.05

AND

Isolation, Hadronic & EM < 2 GeV

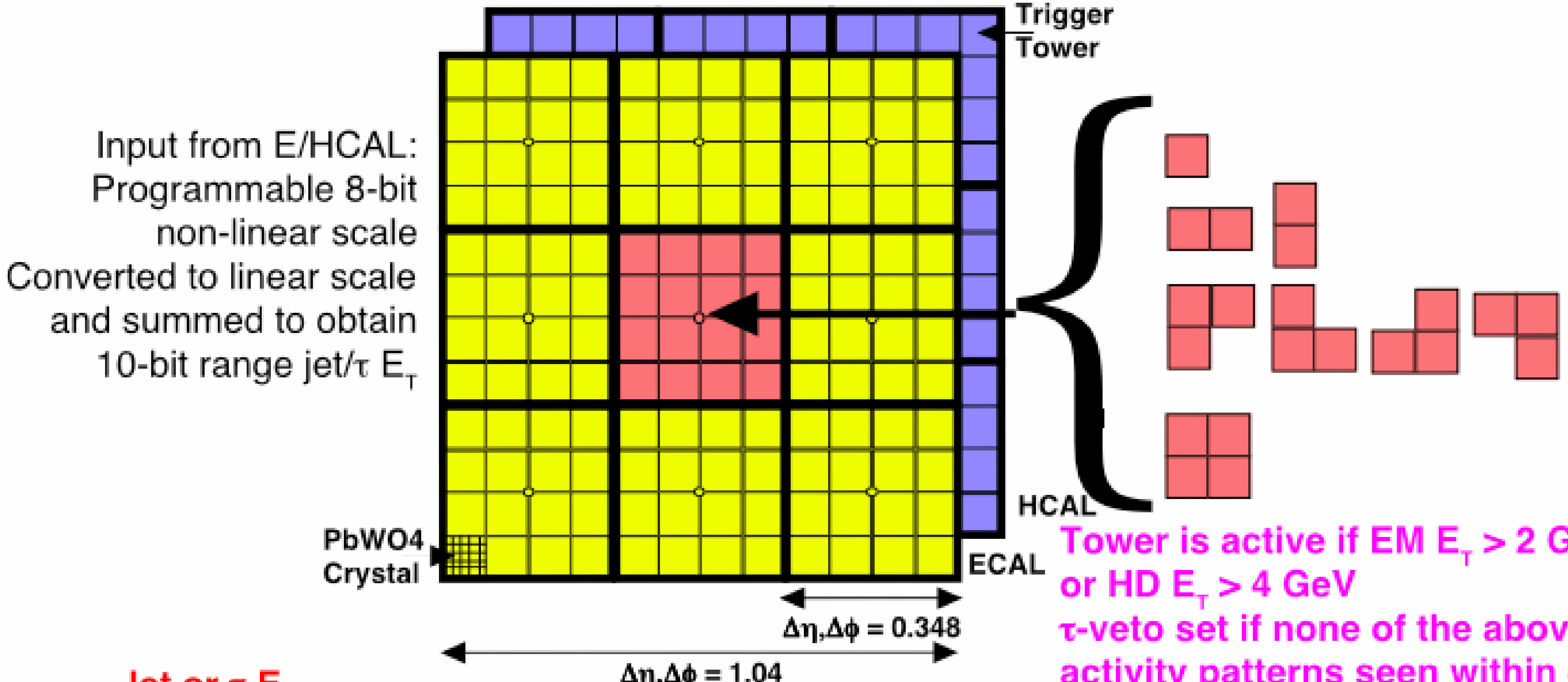
AND

One of (, , ,) < 1 GeV



ELECTRON or PHOTON

CMS τ / Jet Algorithm



Tower is active if EM E_T > 2 GeV or HD E_T > 4 GeV
τ-veto set if none of the above activity patterns seen within 4x4

Jet or τ E_T

- 12x12 trigger tower E_T sums in 4x4 region steps with central region > others
- Larger trigger towers in HF but ~ same jet region size, 1.5 η x 1.0 ϕ

τ algorithm (isolated narrow energy deposits), within -2.5 < η < 2.5

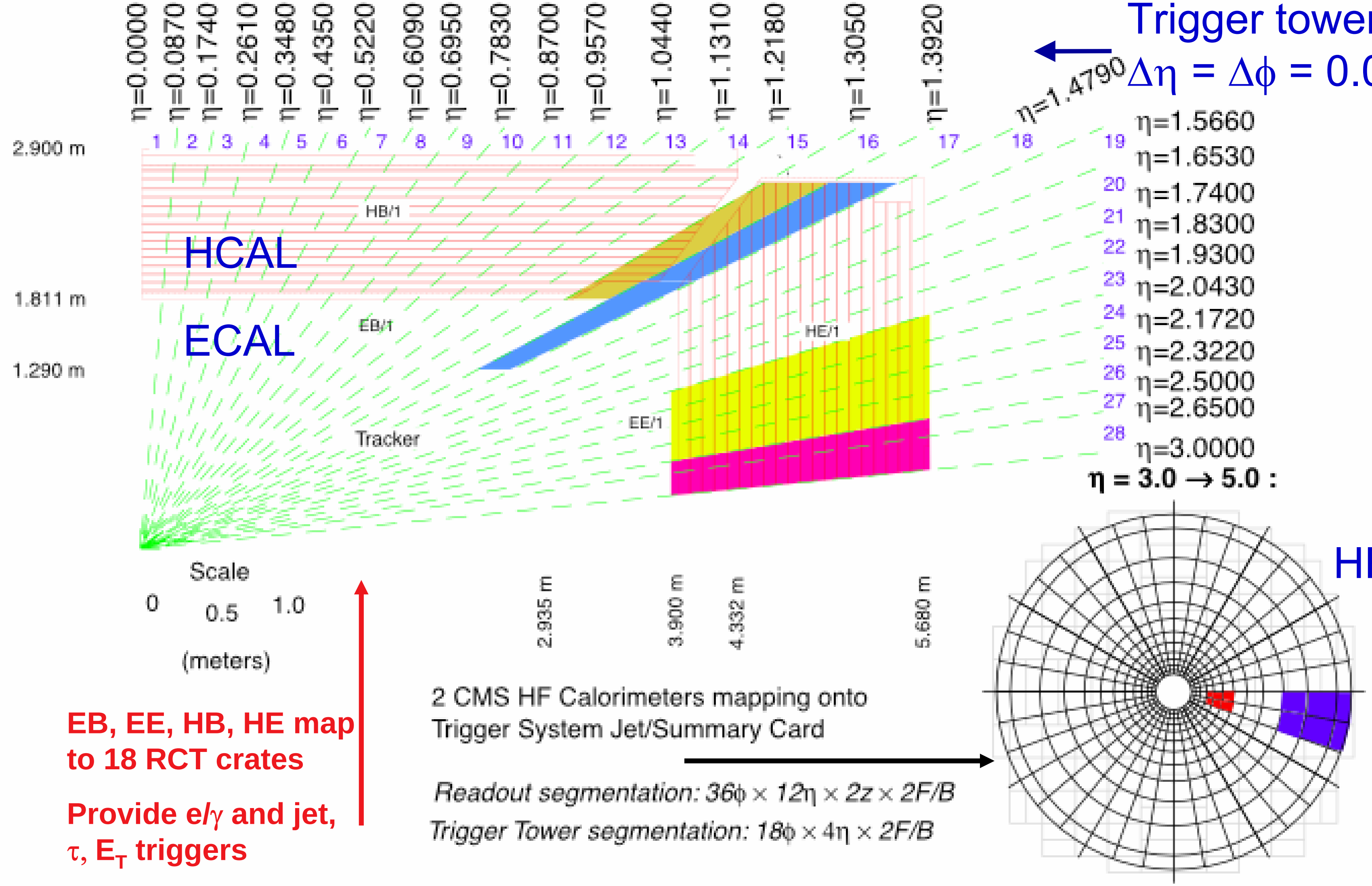
- Redefine jet as τ jet if none of the nine 4x4 region τ-veto bits are on

Output

- Top 4 τ-jets and top 4 jets in central rapidity, and top 4 jets in forward rapidity

Calorimeter Trigger Geometry

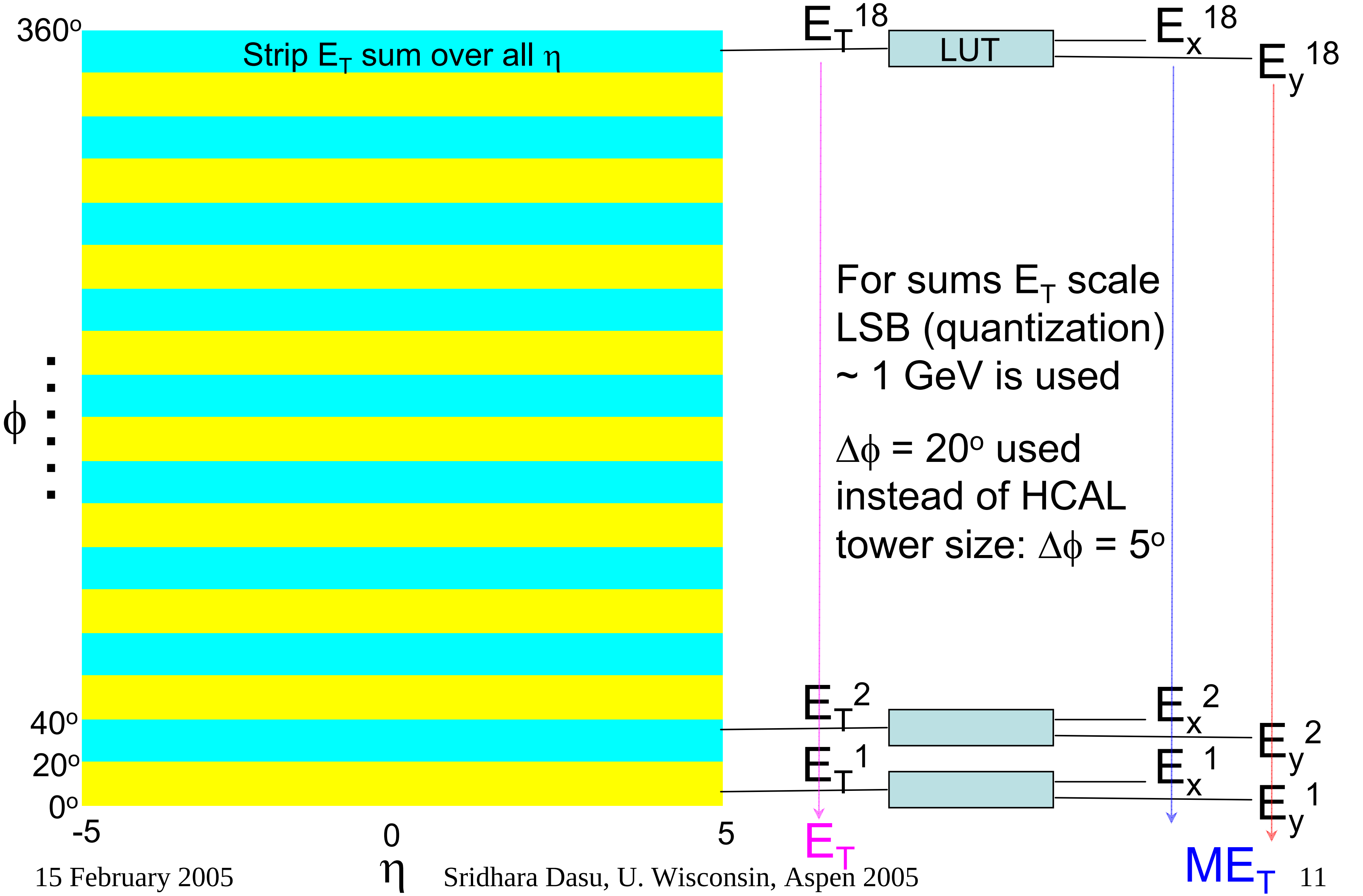
Trigger towers:
$\Delta\eta = \Delta\phi = 0.087$



EB, EE, HB, HE map to 18 RCT crates

Provide e/γ and jet, τ, E_T triggers

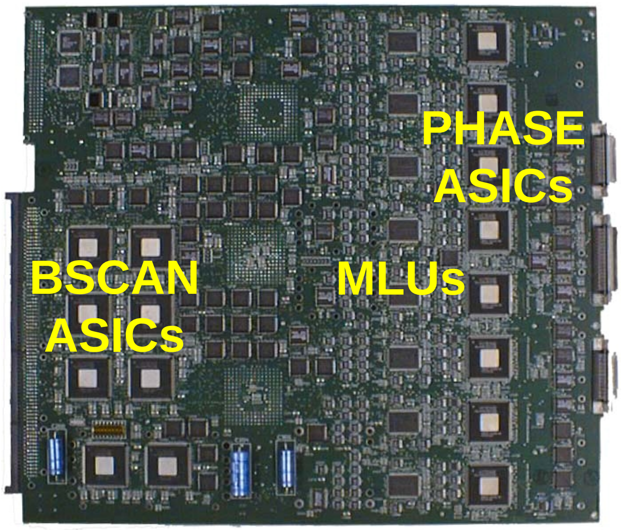
Missing / Total E_T Algorithm



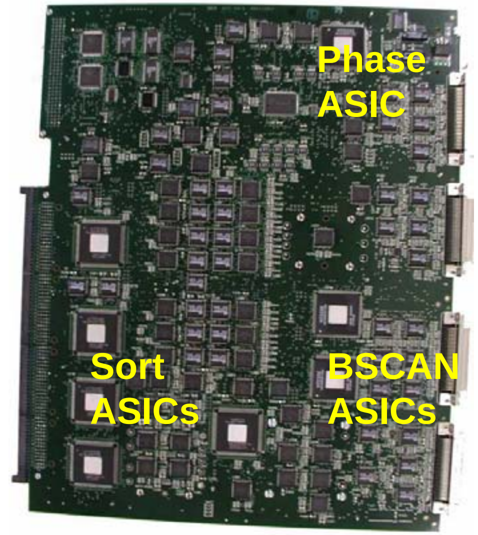
For sums E_T scale LSB (quantization) ~ 1 GeV is used

$\Delta\phi = 20^o$ used instead of HCAL tower size: $\Delta\phi = 5^o$

L1 Trigger System Production

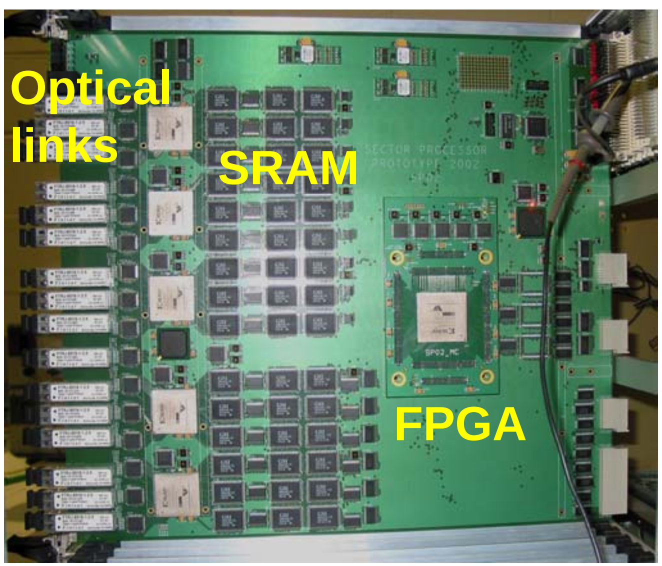


RCT Receiver card



RCT Jet/Summary card

RCT Electron isolation card



CSC
Track-Finder

- **Custom ASICs**
- **Large FPGAs**
- **SRAM**
- **Gbit/s Optical links**
- **Dense boards**

Simulation: Importance & Scale

- Detailed simulations necessary
  - Large QCD backgrounds at 30-50 GeV lepton and photon thresholds needed for EWSB physics
  - Dominated by fluctuations of tails
    - Isolation cuts, Shower profile cuts, etc.
    - Cannot perform analytical calculations of efficiencies and rates
- Computation scale
  - QCD background every crossing - 40 MHz
    - Up to 10 minutes on a 1 GHz CPU to simulate full event
    - 2 x 10^9 s CPU time to simulate 1 s of LHC operation
    - Requires 1000 CPUs running for 1 month
  - ATLAS/CMS have large number of detector channels, 10^8
    - Each event requires 1-10 MB storage space
    - 32-320 TB needed for 1 s of LHC operation
  - Optimizing CPU and data storage
    - Simulate in bins of P_T and event reuse for minimum bias events

Example Level-1 Trigger Table (L=2 x 10^{33})

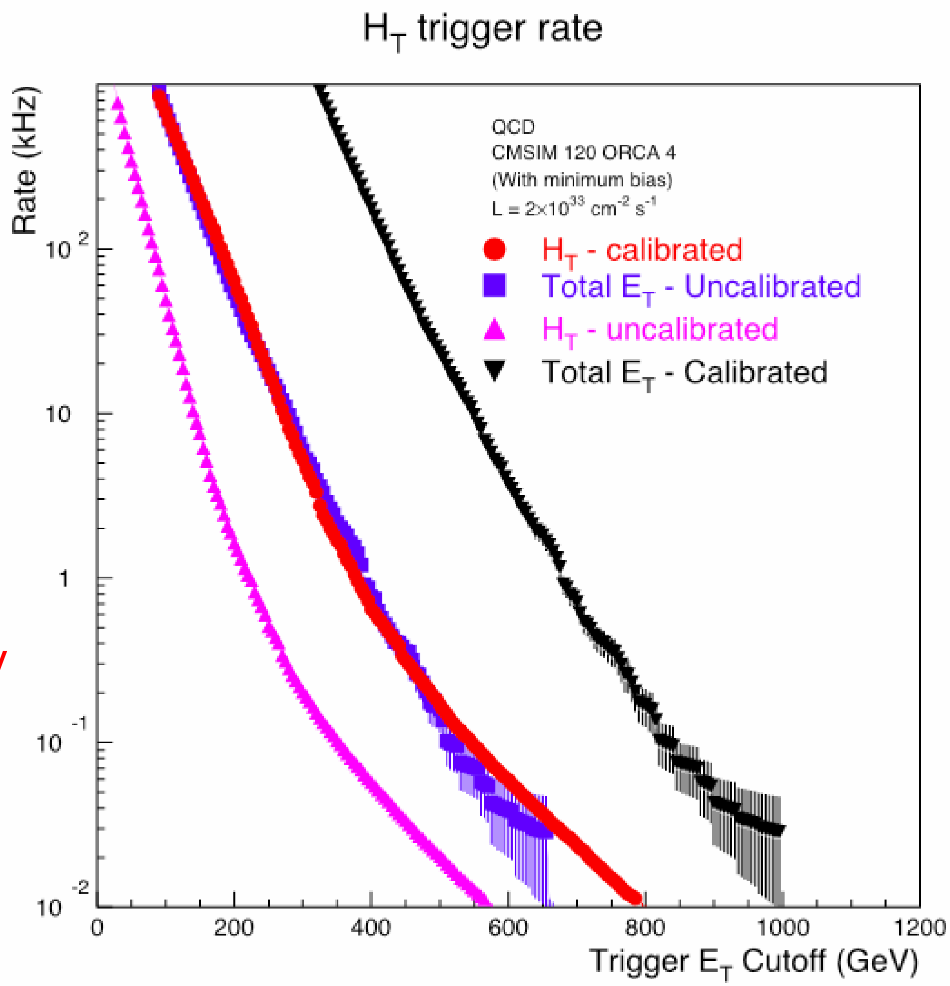
Trigger	*Threshold (GeV or GeV/c)*	*Rate (kHz)*	*Cumulative Rate (kHz)*
Isolated e/γ	29	3.3	3.3
Di-e/γ	17	1.3	4.3
Isolated muon	14	2.7	7.0
Di-muon	3	0.9	7.9
Single tau-jet	86	2.2	10.1
Di-tau-jet	59	1.0	10.9
1-jet, 3-jet, 4-jet	177, 86, 70	3.0	12.5
Jet*E_T^{miss}	88*46	2.3	14.3
Electron*jet	21*45	0.8	15.1
Min-bias		0.9	16.0
TOTAL			**16.0**

$\times$ 3 safety factor $\Rightarrow$ 50 kHz (expected start-up DAQ bandwidth)

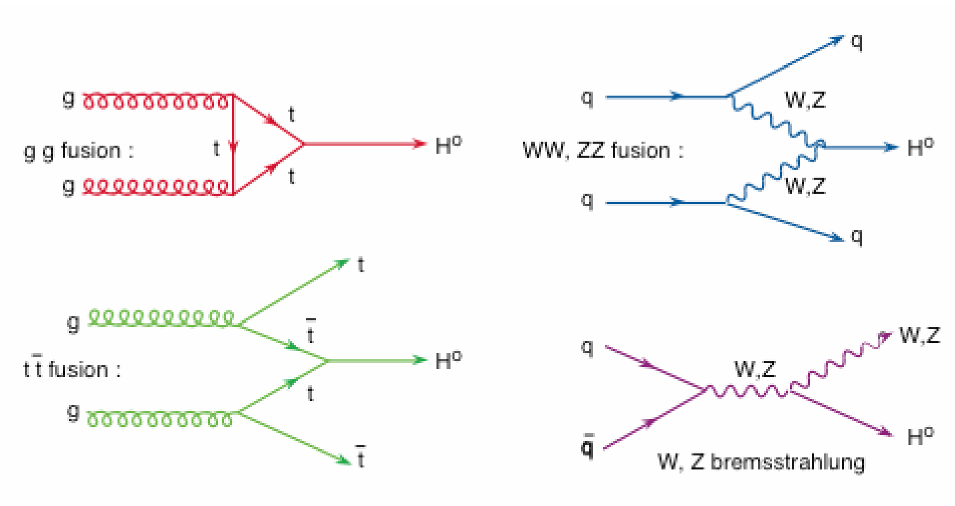
Only muon trigger has low enough threshold for B-physics (aka $B_s \rightarrow \mu\mu$)

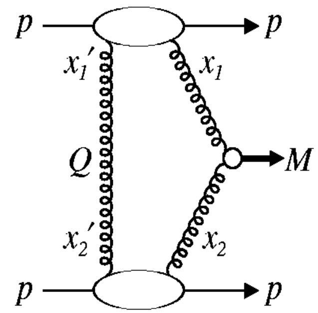
H_T Trigger

- Total scalar E_T integrates too much noise and is not easily calibrated
  - At L1 tower-by-tower E_T calibration is not available
- However, jet calibration is available as function of (E_T, η, ϕ)
- Therefore, H_T which is the sum of scalar E_T of all high E_T objects in the event is more useful for heavy particle discovery/study
  - SUSY sparticles
  - Top



Higgs Production at LHC



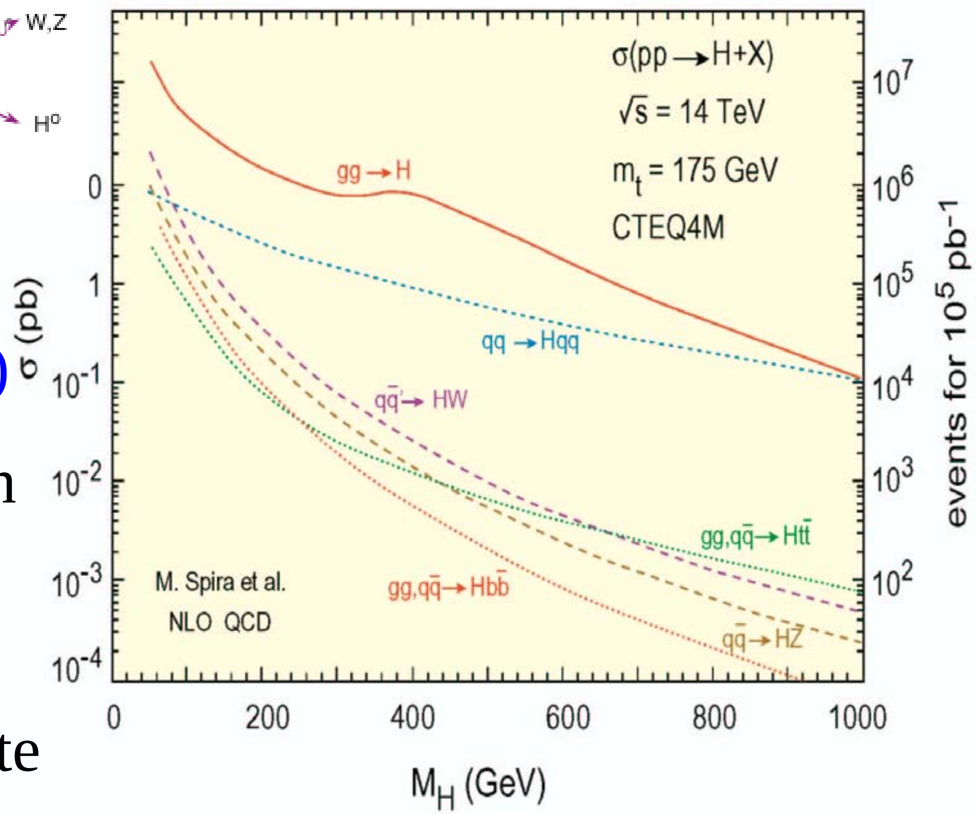


Dominated by gg→H

qq →qqH is cleaner (not quite e^+e^-)

Top and W,Z associated production
have reduced backgrounds

Diffractive case is very clean (e^+e^-)
But, we have ~no idea about rate



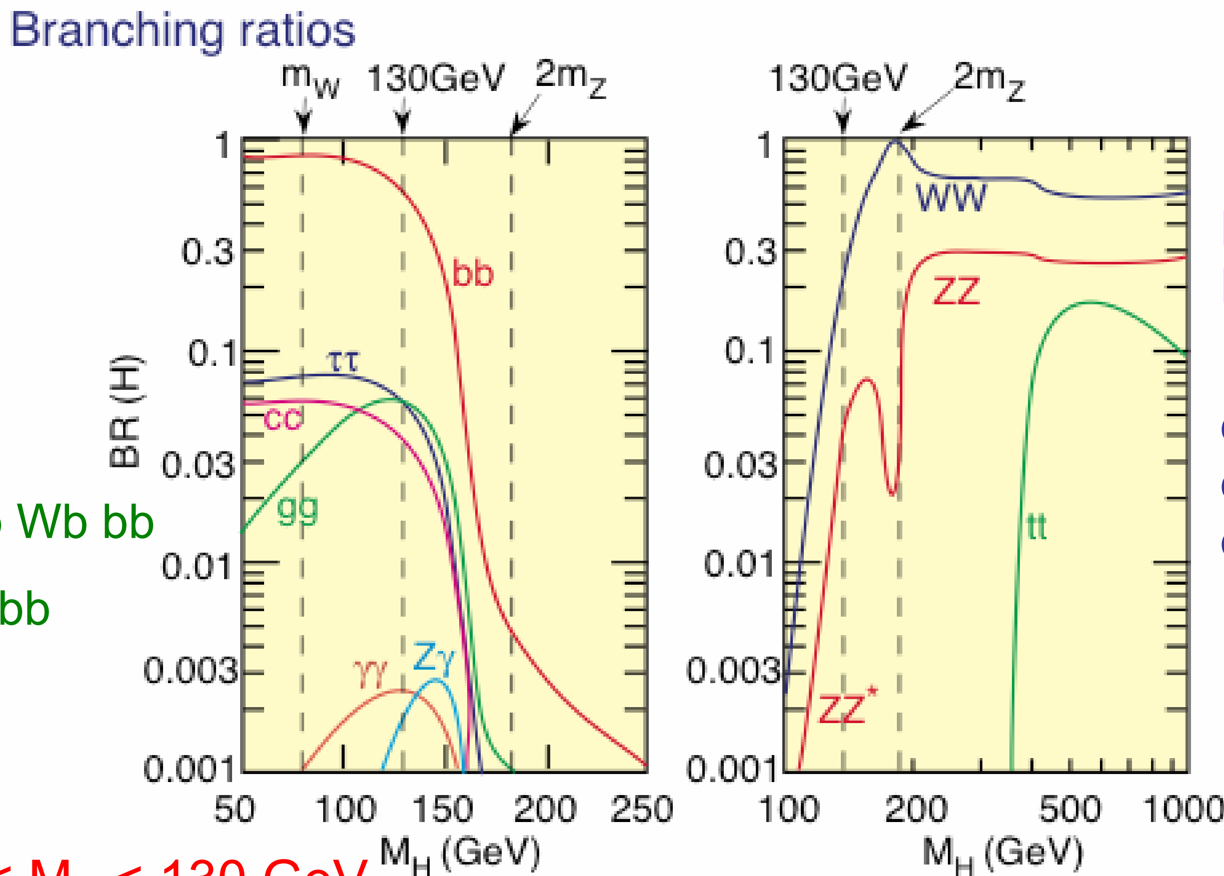
Standard Model Higgs Decay

$H \rightarrow \gamma\gamma$

$qqH \rightarrow \tau\tau$

$ttH \rightarrow Wb\ Wb\ bb$

$WH \rightarrow l\nu\ bb$

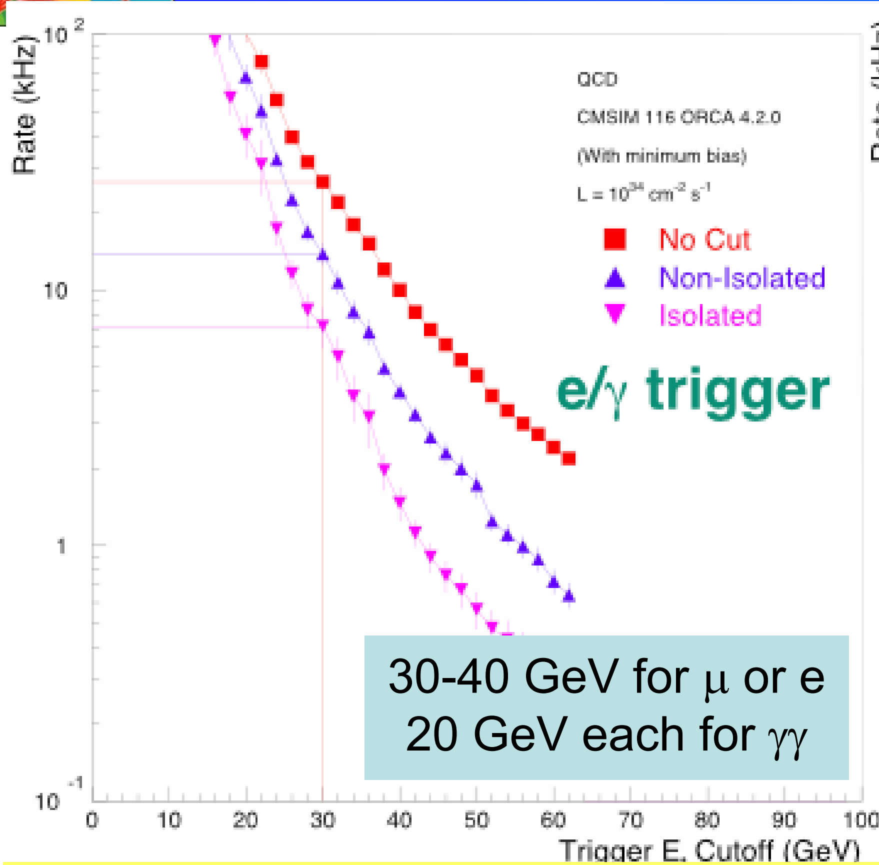


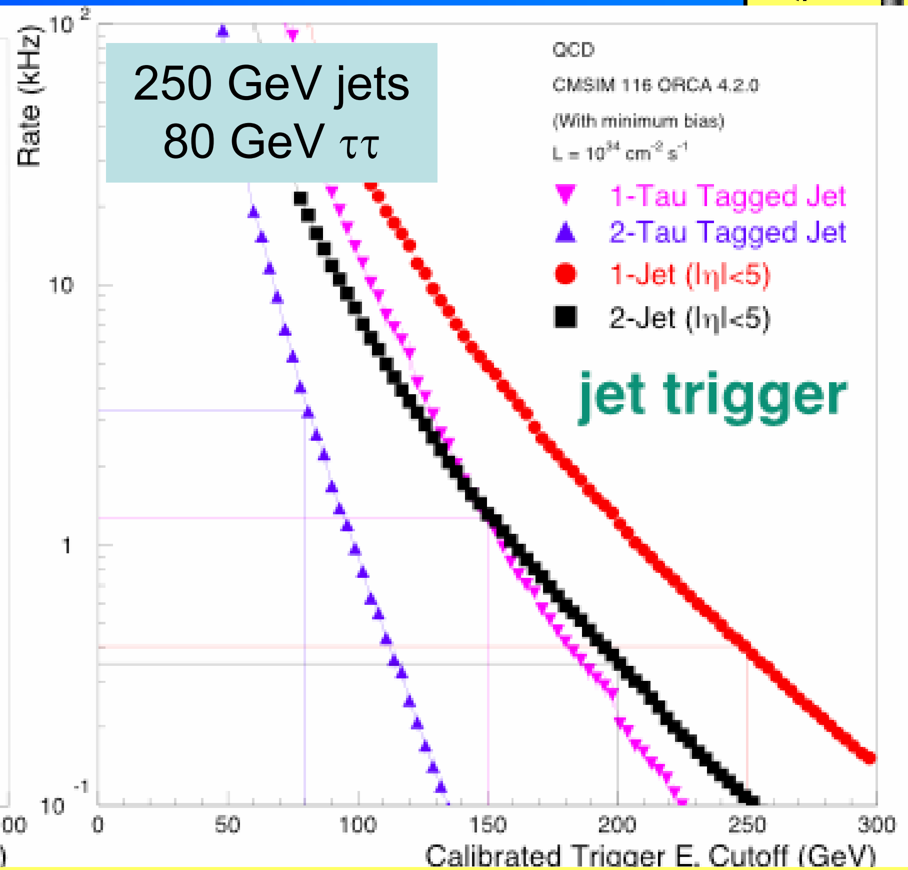
$H \rightarrow WW^{(*)} \rightarrow l\nu\ l\nu$
$H \rightarrow ZZ^{(*)} \rightarrow 4$ leptons

$qqH \rightarrow WW \rightarrow l\nu\ jj$
$qqH \rightarrow ZZ \rightarrow ll\ \nu\nu$
$qqH \rightarrow ZZ \rightarrow ll\ jj$

- $115 < M_H < 130$ GeV
  - $H \rightarrow bb$ dominates - however, to avoid backgrounds, use $H \rightarrow \gamma\gamma$
- $M_H > 130$ GeV
  - $H \rightarrow WW^*$, $H \rightarrow ZZ^*$, $H \rightarrow WW$, $H \rightarrow ZZ$ (at least one lepton to avoid backgrounds)

Level-1 Trigger Rates



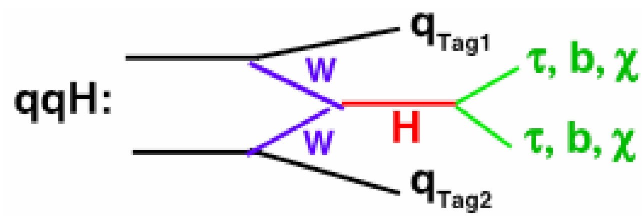


Trigger cuts determine physics reach!

- Efficiency for $H \to \gamma\gamma$ and $H \to 4$ leptons = >90% (in fiducial volume of detector)
- Efficiency for WH and ttH production with $W \to l\nu$ = ~85%
- Efficiency for qqH with $H \to \tau\tau$ ($\tau \to 1/3$ prong hadronic) = ~75%
- Efficiency for qqH with $H \to$ invisible or $H \to bb$ = ~40-50%

qqH - Low mass H challenges

- Higgs production in weak boson fusion
  - Accompanied by jets in the forward direction
- Forward jet characteristics
  - Lower jet E_T (underlying event + pileup problem)
- Challenge for trigger (level-1 and higher levels)
  - Trigger on higgs decay products
    - Decays to Z (ee, $\mu\mu$) or photons (OK)
      - Low threshold electron/photon algorithm
    - Decays to τ
      - Narrow jet tag - dedicated τ algorithm (~OK)
  - Tag jets with location information (Can do this at Level-1)
    - Additional reduction in background
      - Require two forward tag jets
      - Require $\Delta\eta$ between the jets
    - Decays to b jets (dominant but dirty mode)
      - Four jet trigger including forward tag jets
      - Require $\Delta\eta$ between jets
      - Require two jets to be central (b tagging)



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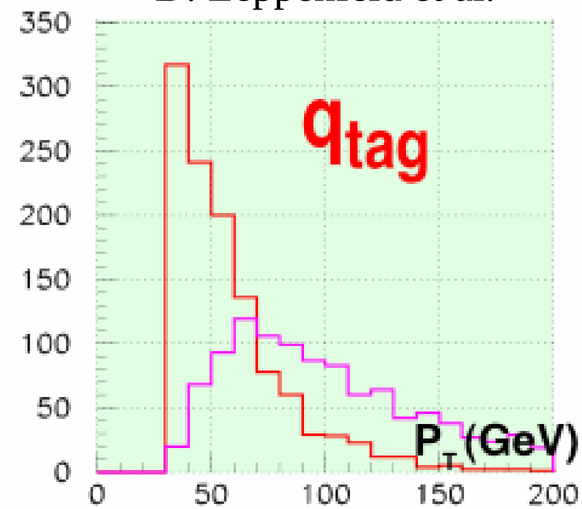
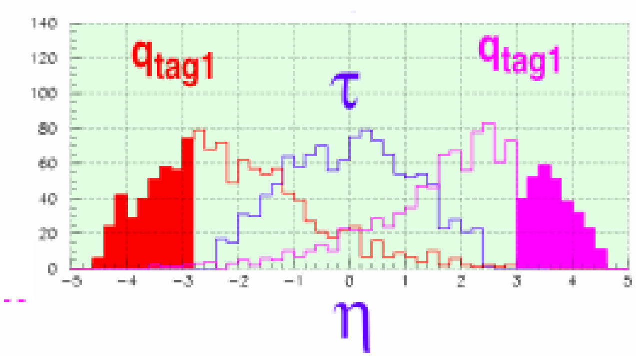
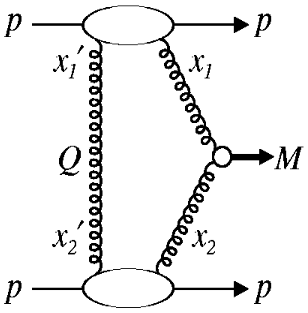




Diffractive Higgs Trigger



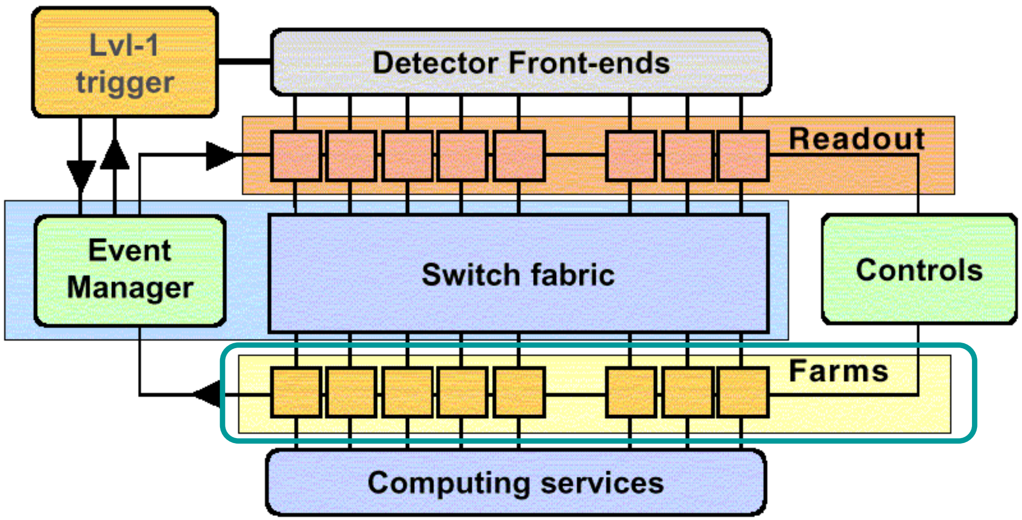
- Rewarding if there is sufficient production
  - Tagged protons give good M_H measurement
  - Since expected σ is small, need all H decays
- Central detector
  - Two Low P_T jets from low mass Higgs decay
    - Must tag as b-jets at HLT
    - $|\eta|<2.5$
  - Essentially nothing else in the detector
    - Require small H_T - E_T^{jet1} - E_T^{jet2}
    - Pileup persists
- Proton taggers
  - Too far to be part of trigger
  - Trying to get around speed of light problem

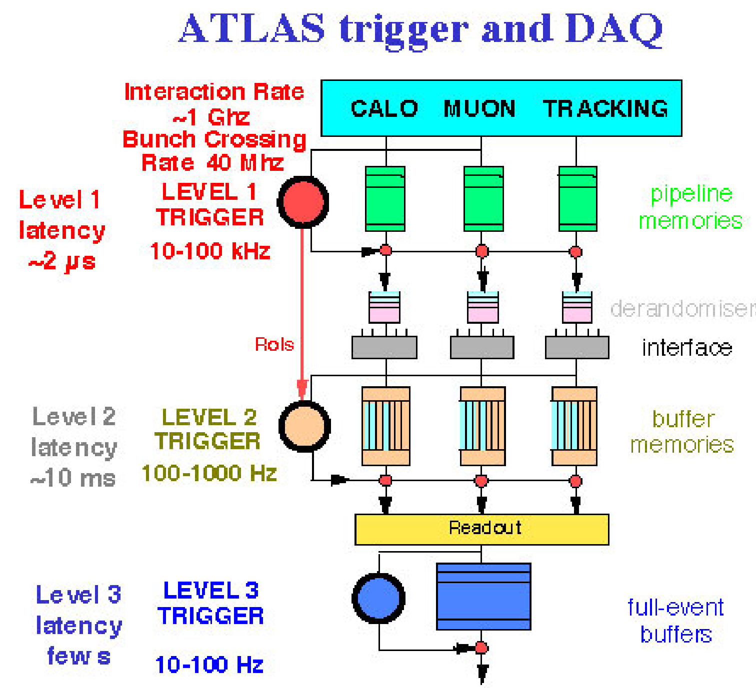
Ground Reality at L1 Trigger

- No tracker in level-1 trigger
  - Electron, photon and π^0 looks the same
  - Trigger level muon P_T is poorly measured
- Jet trigger limitations
  - Limited capability to get low P_T jets
    - Limited calorimeter resolution: $100\% / \sqrt{E}$
    - Calibration to take out η,ϕ variation in response
- Poor measurement of missing E_T
  - At best the resolution can be: $100\% g \sqrt{\sum E_T}$
  - Calibration not possible
  - Underlying event and pileup contribution
  - Additional limitations due to trigger calculations

Most of L1 output are mistags - Another factor of 1000 rejection at HLT

The High-Level Triggers





CMS has no Level-2 trigger in hardware

Everything beyond Level-1 performed in the Filter Farm

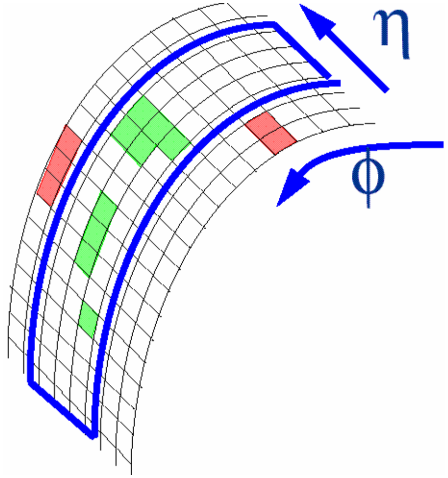
ATLAS does have separate switch & farm for L2

L2 does partial event reconstruction “on demand” using full detector resolution

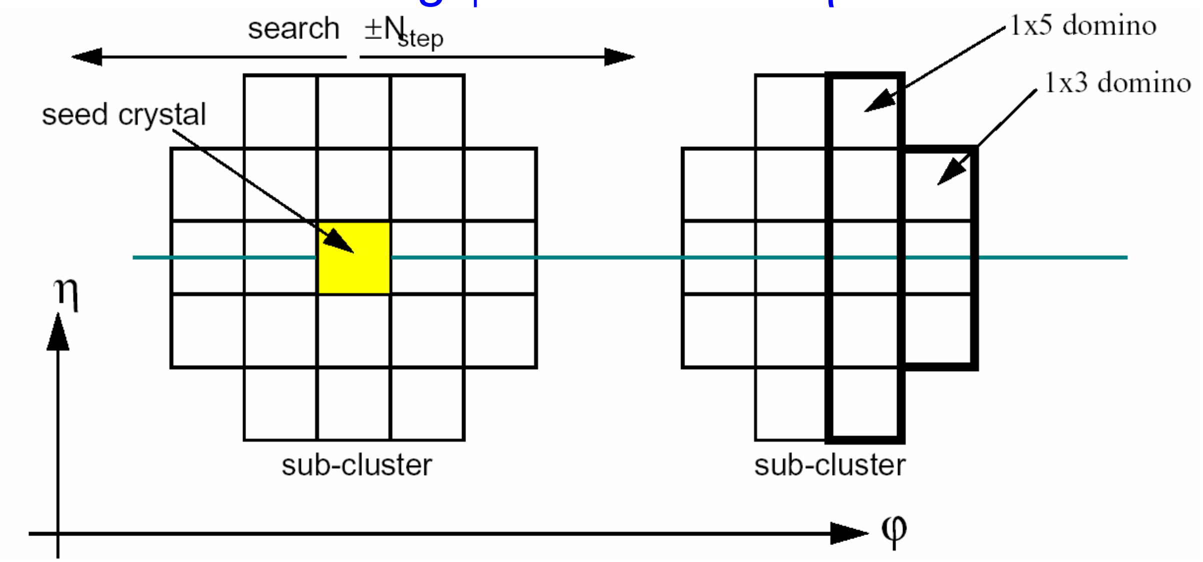
ATLAS drives Level-2 processors using L1 regions of interest

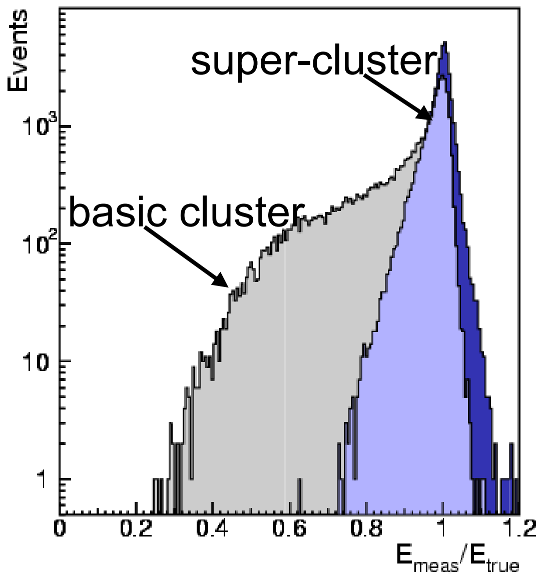
Electron selection: Level-2

- "Level-2" electron:
  - Search for match to Level-1 trigger
    - Use 1-tower margin around 4x4-tower trigger region
  - Bremsstrahlung recovery "super-clustering"
  - Select highest E_T cluster



- Bremsstrahlung recovery:
  - Road along ϕ — in narrow η-window around





MSSM Higgs

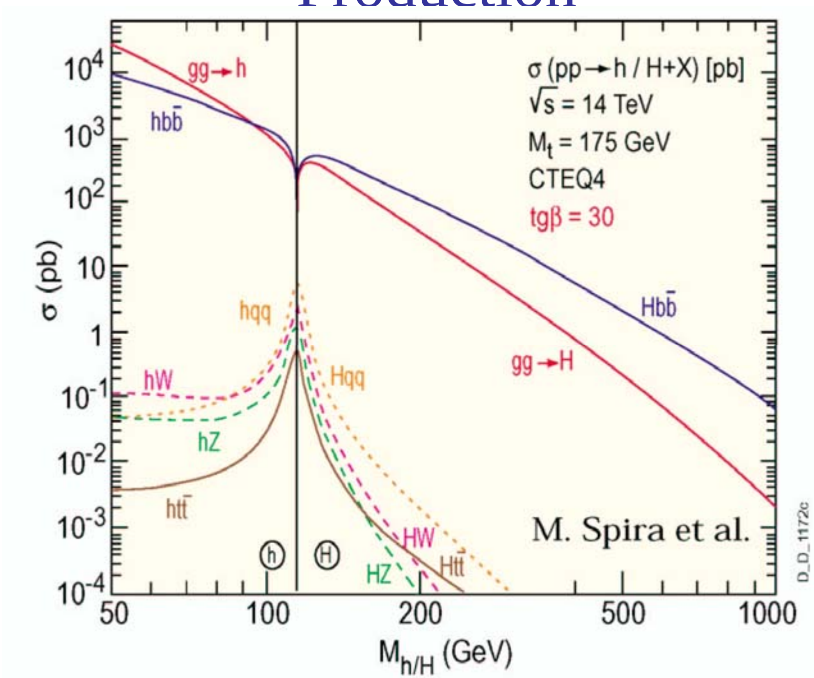
Higgs sector: h^0, H^0, A^0, $H^\pm$

– Light higgs h^0 - standard model like

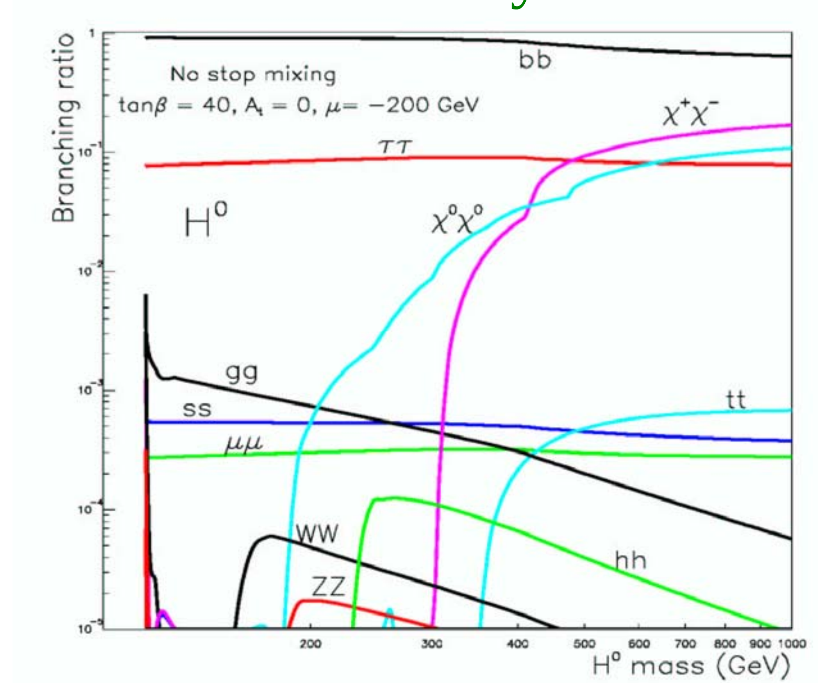
Challenges
Trigger, b and τ tagging

At high $\tan\beta$, $H\rightarrow bb$, $H\rightarrow\tau\tau$ and $H\rightarrow\chi\chi$ dominate

Production



H[0] Decay



qq→bbH large and well understood

Measure decay to bb and $\tau\tau$

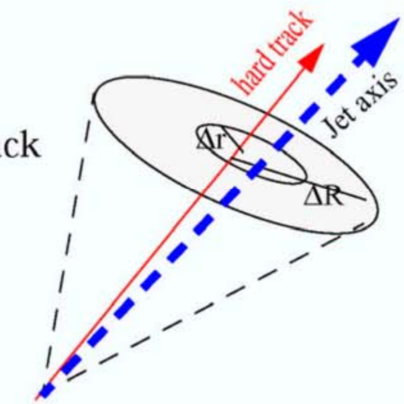
CMS

τ-jet tagging at HLT

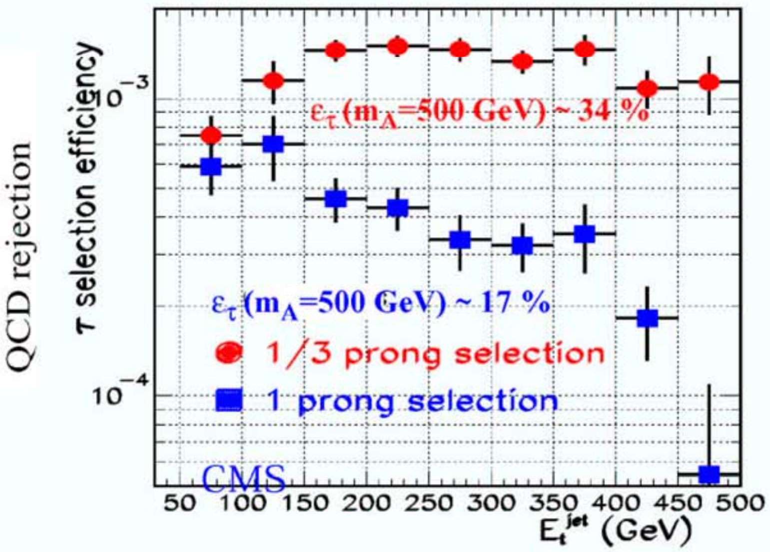
ATLAS

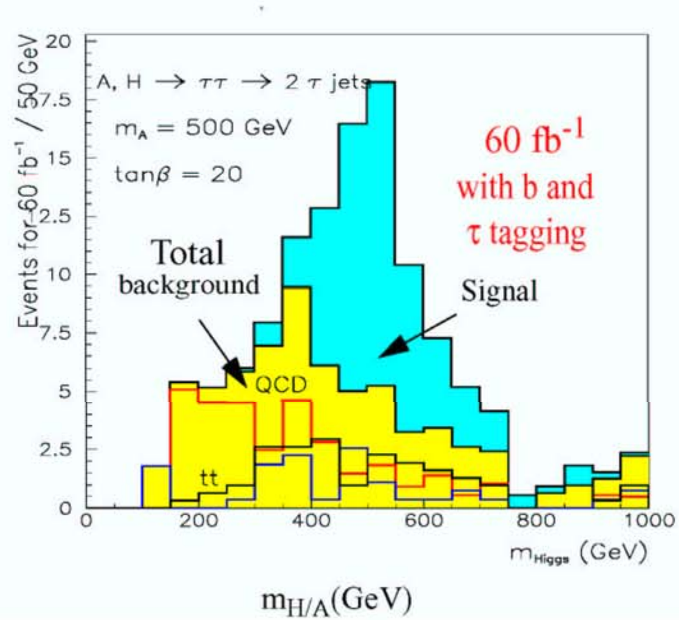
τ-jet ($E_t^{\tau\text{-jet}} > 60$ GeV) identification (mainly) in the tracker:

- Hard track, $p_t^{max} > 40$ GeV, within $\Delta R < 0.1$ around calorimeter jet axis
- Isolation: no tracks, $p_t > 1$GeV, within $0.03 < \Delta R < 0.4$ around the hard track
- For 3-prong selection 2 more tracks in the signal cone $\Delta r < 0.03$



QCD jet rejection from isolation and hard track cuts





Further reduction by ~ 5 expected for 3-prong QCD jets from τ vertex reconstruction (CMS full simulation)

Example HLT Trigger Menu (L=2x10^{33})

Trigger	Threshold (GeV or GeV/c)	Rate (Hz)	Cumulative Rate (Hz)
Inclusive electron	29	33	33
Di-electrons	17	1	34
Inclusive photons	80	4	38
Di-photons	40, 25	5	43
Inclusive muon	19	25	68
Di-muons	7	4	72
Inclusive τ-jets	86	3	75
Di-τ-jets	59	1	76
1-jet * E_T^{miss}	180 * 123	5	81
1-jet OR 3-jets OR 4-jets	657, 247, 113	9	89
Electron * Jet	19 * 45	2	90
Inclusive *b*-jets	237	5	95
Calibration and other events (10%)		10	105
TOTAL			**105**

SUSY Efficiencies

$m(\tilde{g})$ (GeV/c²)	$m(\tilde{u}_L)$ (GeV/c²)	$m(\tilde{\chi}_1^0)$ (GeV/c²)
466	410	70
447	415	66
349	406	45

	Level-1 Trigger		High-Level Trigger	
SUSY point	1 Jet >79 GeV+ E_T^{miss}>46 GeV	3 jets, E_T>86 GeV	1 Jet >180GeV+ E_T^{miss}>123 GeV	4 jets, E_T>113 GeV
	efficiency (%)	efficiency (%) (cumulative efficiency)	efficiency (%)	efficiency (%) (cumulative efficiency)
4	88	60 (92)	67	11 (69)
5	87	64 (92)	65	14 (68)
6	71	68 (85)	37	16 (44)
4R	67	89 (94)	27	28 (46)
5R	58	90 (93)	17	30 (41)
6R	47	84 (87)	9	20 (26)
Background	rate (kHz)	rate (kHz) (cumulative rate)	rate (Hz)	rate (Hz) (cumulative rate)
	2.3	**0.98 (3.1)**	**5.1 Hz**	**6.8 (11.8)**

MSUGRA provides a benchmark

ATLAS Trigger Selection (HLT)

Object	Examples of physics coverage	Low Luminosity $2*10^{33}\ cm^{-2}s^{-1}$	Rates (Hz)
Electrons	Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W, top	e25i, 2e15i	~40
Photons	Higgs (SM, MSSM), extra dimensions, SUSY	γ60, 2γ20i	~40
Muons	Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W, top	μ20i, 2μ10	~40
	Rare b-decays ($B \rightarrow \mu\mu X$, $B \rightarrow J\Psi(\Psi')X$)	2μ6 + $\mu^+ \mu^-$ + mass cut	~25
Jets	SUSY, compositeness, resonances	j400, 3j165, 4j110	~20
Jet+missing E_T	SUSY, leptoquarks	j70 + xE70	~5
Tau+missing E_T	Extended Higgs models (e.g. MSSM), SUSY	τ35i + xE45	~10
Others	Prescaled, calibration, monitoring		~20
Total HLT Output Rate			~200

Trigger menus will evolve continuously with time to reflect our best knowledge of the physics and the detector

Favorite Questions

- How do you trigger on long-lived staus?
  - Missing E_T
- How do you trigger on invisible higgs?
  - Missing E_T
- How do you trigger …?
  - Missing E_T
- How do you debug the detector?
  - Missing E_T

Summary

LHC Trigger is Challenging

- The choice of physics studied is already made at level-1 trigger
  - Choices made with calorimeter and muon systems only
- Complete object reconstruction at higher level trigger
  - Optimum resolution online with calibration and alignment
  - Includes b/τ tagging in high level trigger farms
- Both CMS and ATLAS have designed trigger systems for golden discovery modes (lepton, diphoton, muti-jets…)
  - Exploit qqH, WH, ttH production to cover difficult regions
  - Definitive exploration of higgs sector is assured
  - Pickup searches for new particles where left off by Tevatron
- Innovative designs may allow more measurements
  - Topological selection starting from level-1
  - Low mass higgs & some MSSM higgs decays to $\tau\tau$
  - Measurement of Yukawa couplings
  - Invisible higgs decays