# ICFA Seminar on "Future Perspectives in High Energy Physics"

## LHC Detector Upgrade - Oct. 9

**Dan Green**

**Fermilab**

# Outline

- **Physics Basics**
  - **Z’ vs $\sqrt{s}$**
  - **Rapidity Range**
  - **Minbias**
  - **Pileup and Jets**
- **Occupancy and Radiation Dose**
- **Tracker Upgrade**
- **Calorimetry**
- **Muons**
- **Trigger and DAQ**

**CERN-TH/2002-078 “Physics Potential and Experimental Challenges of the LHC Luminosity Upgrade”**

**10x will be challenging!**

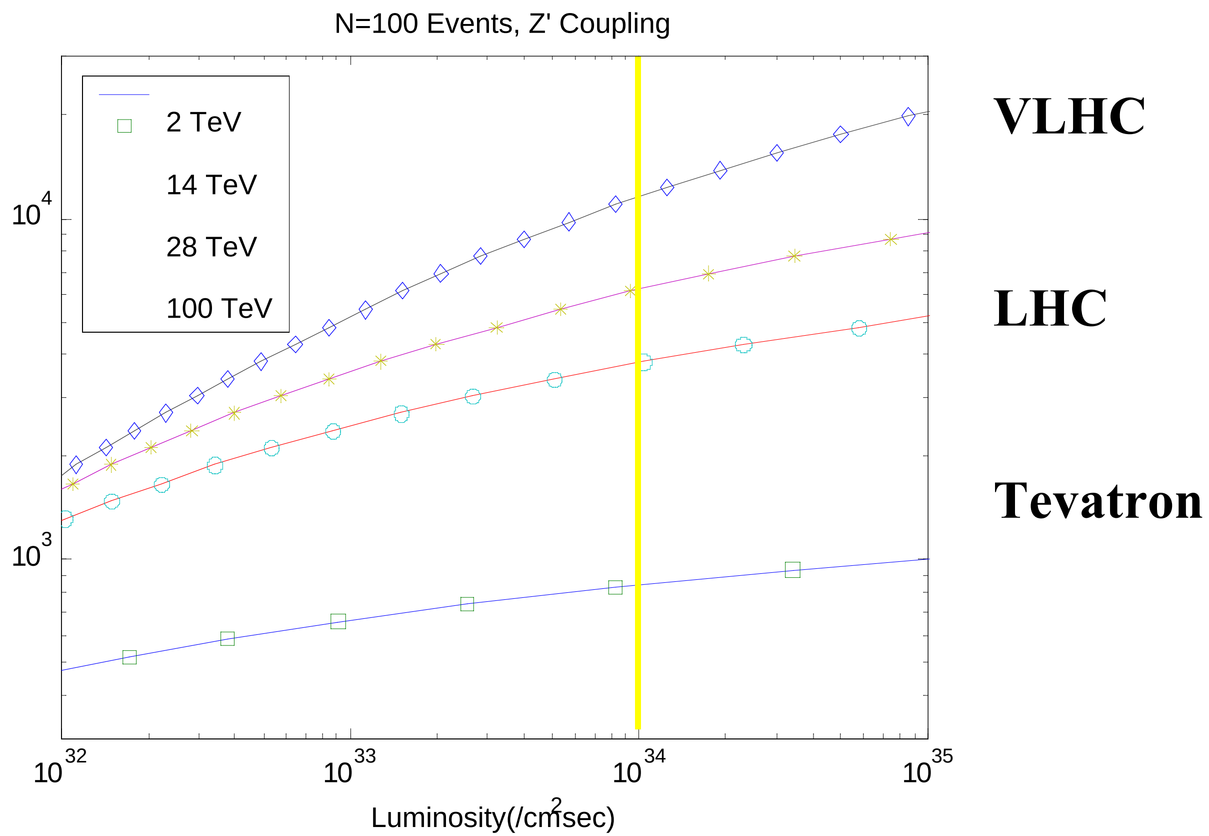
# Mass "Reach" and L

- **The number of Z' detected in leptonic decays is:**

  $xM$ — √

- **For** [()()]0.36(1) — √ **, if N = 100 is discovery level then M ~ 5.3 TeV is ~ the mass "reach" in 1 year (M=4 -> 5.3 TeV).**
- **The leptons will be sharply limited to low y or large angles ("barrel") which helps.**

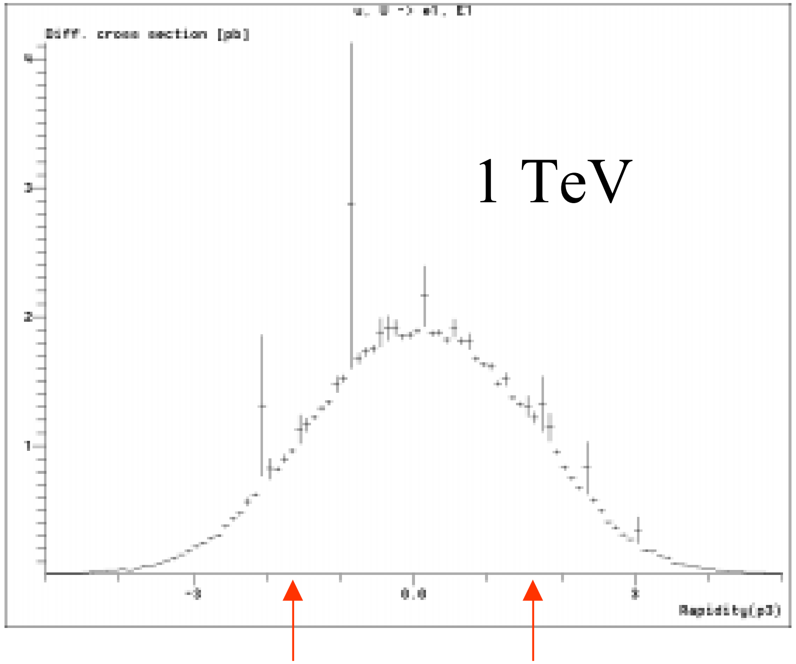
# Mass Reach vs L

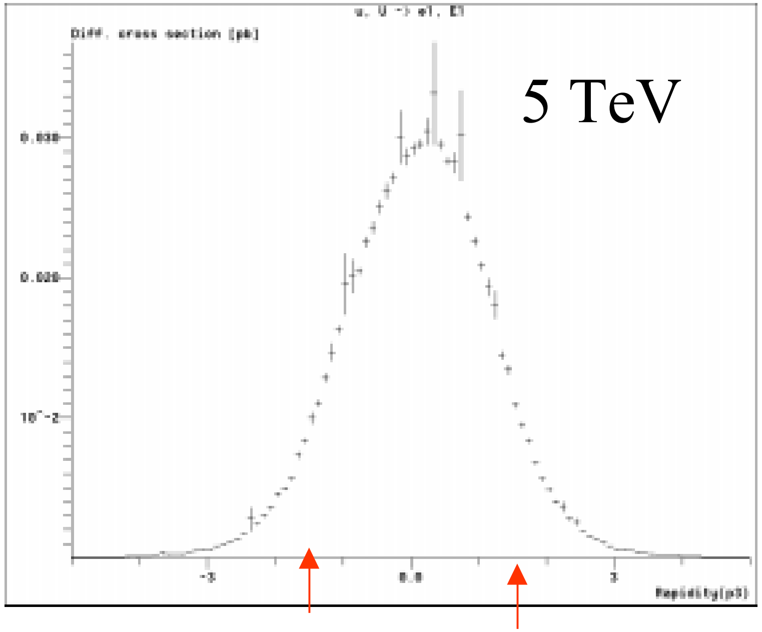



**In general mass reach is increased by ~ 1.5 TeV for Z', heavy SUSY squarks or gluinos or extra dimension mass scales. A ~ 20% measurement of the HHH coupling is possible for Higgs masses < 200 GeV. However, to realize these improvements we need to maintain the capabilities of the LHC detectors.**

# Kinematics

$d\sigma/dy$




**Heavy States decay at wide angles. For example Z' of 1 and 5 TeV decaying into light pairs. Therefore, we need to concentrate on wide angle detectors.**

# Inclusive Interactions

- The inclusive p-p interaction has an inelastic cross section $\sigma$ ~ 50 mb.
- It produces ~ equal numbers of $\pi^+, \pi^-, \pi^0$ which are distributed ~ uniform in rapidity, y, with a "density" $\rho = dN/dy$ ~ 9 pions per unit of y.
- The pions have a distribution in transverse momentum with a mean, $\langle p_T \rangle$ ~ 0.6 GeV.

# Pileup and Luminosity

- For $\sigma$ ~ 50 mb, and $\rho$ [illegible] 6 charged pions/unit of y with a luminosity

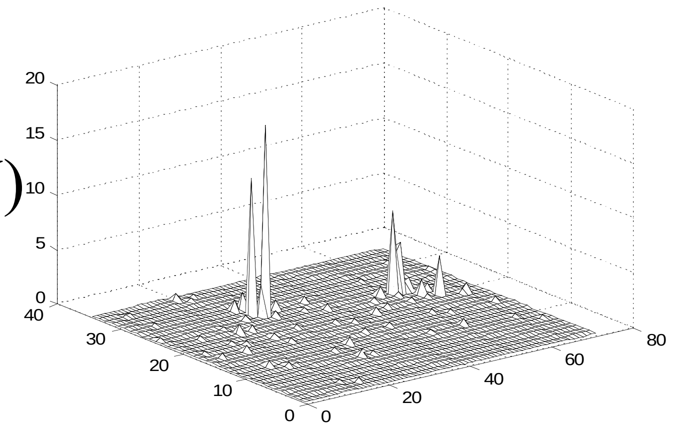
and a crossing time of 25 nsec (12.5 nsec ?):

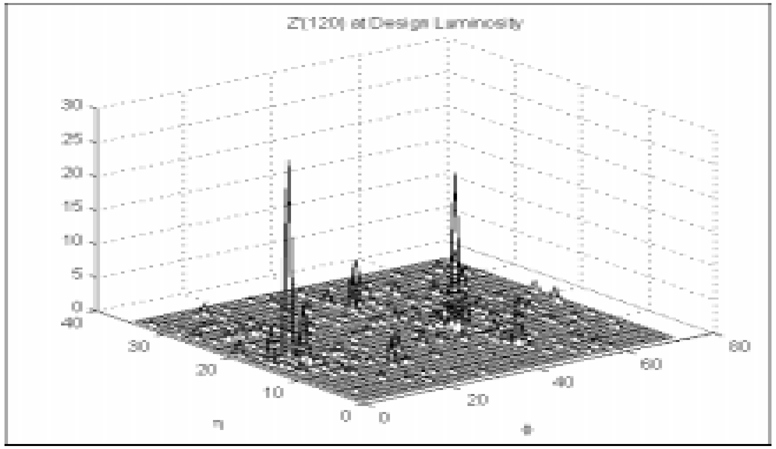
[illegible]

- In a cone of radius = 0.5 there are ~ 141 pions, or ~ 84 GeV of transverse momentum. This makes low $E_t$ jet triggering and reconstruction difficult.

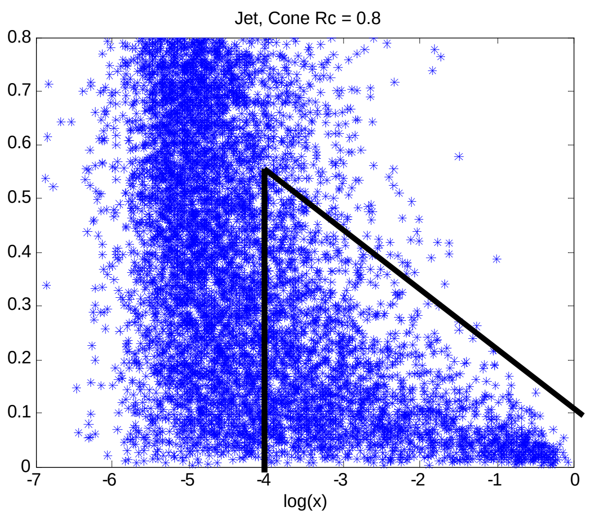
# Z’(120) at L/5 and L

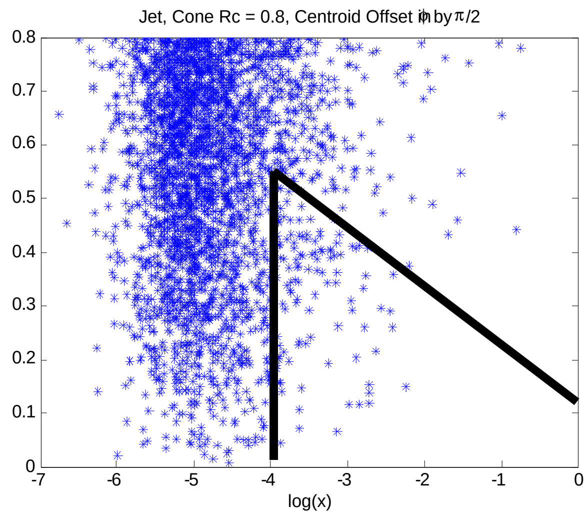
Et(GeV)





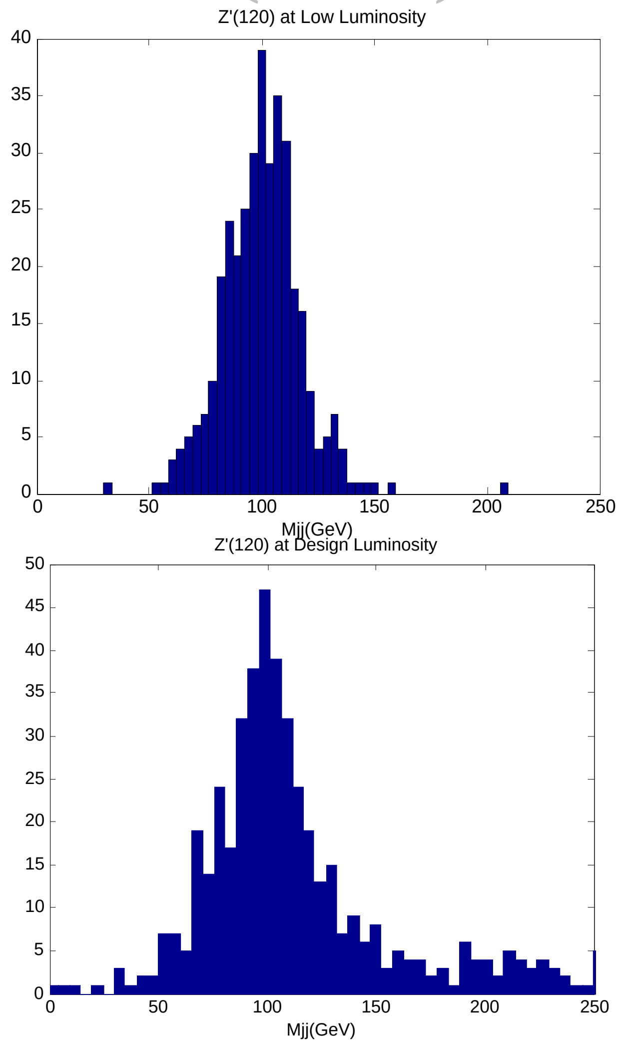

dR




**Log(x)**

# Z'(120) Mass Resolution



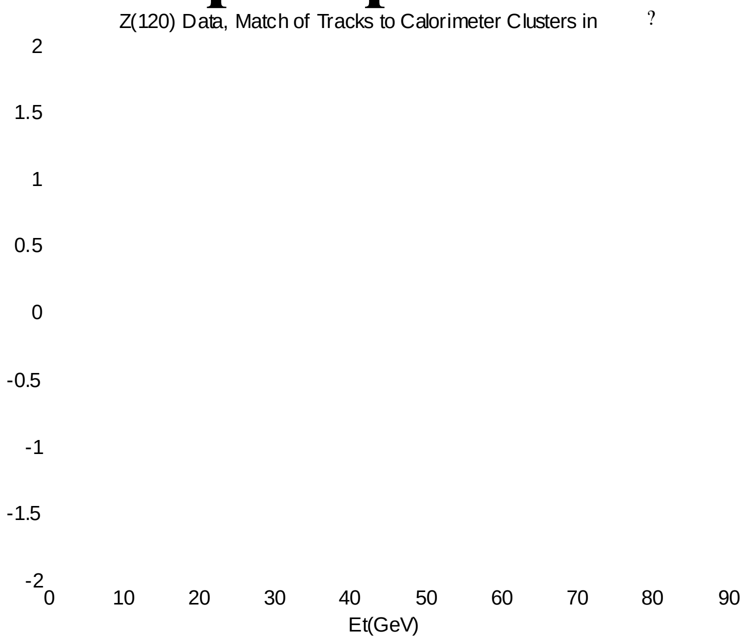

M(GeV)

**Note that the calorimeter cells are still fairly sparsely populated (granularity $(\Delta\eta = 0.087)$ ) at $10^{34}$ . With the cuts shown, the dM/M with Gaussian fits is the same at L/5 and at L. Use the fact that QCD implies that there is a core of the jet at small dR and large x. Extend to 10x L using tracker and energy flow inside the jet?**

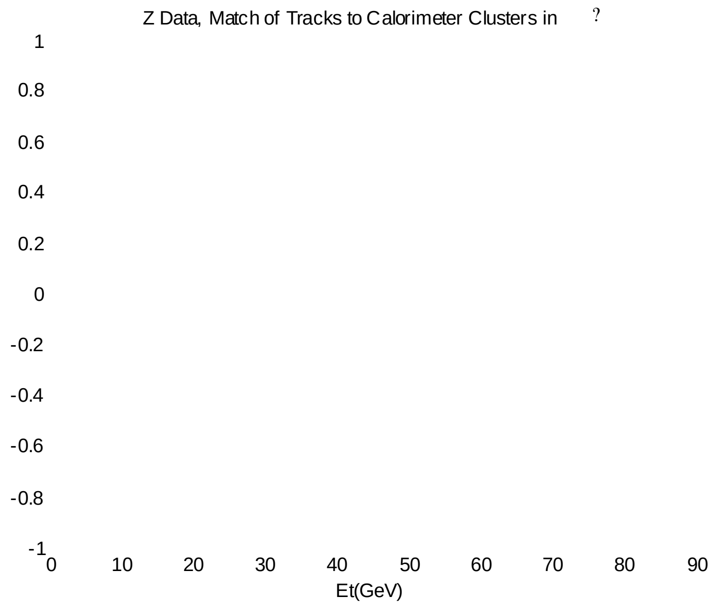
# Tracker and Energy Flow

- **For 120 GeV Z’ match tracks in η and ϕ to “hadronic” clusters within the jet. Improves dijet mass resolution. Units are HCAL tower sizes. Also use track match to remove deposits from pileup vertices ?**

dϕ

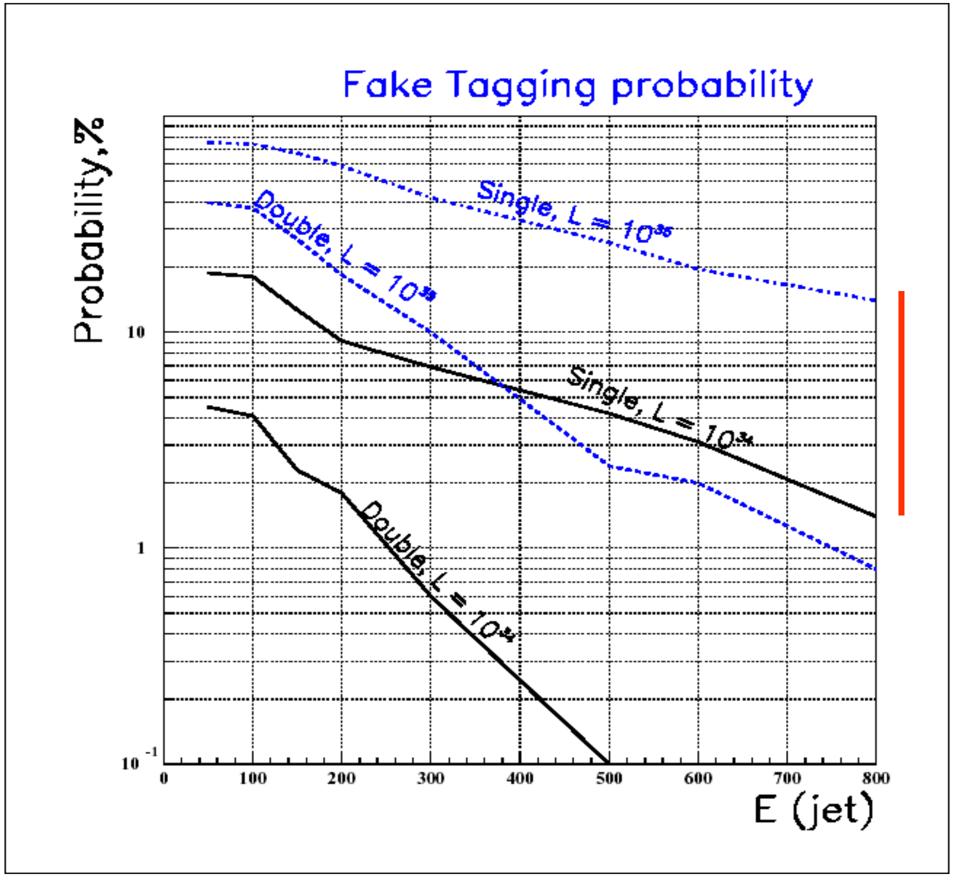


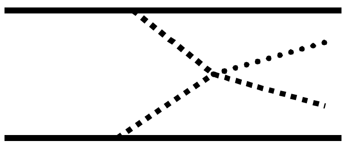

dη




**$E_T$(GeV)**

# WW Fusion and "Tag Jets"



WW
fusion

These jets have

and <y> ~ 3. Lose 10x in fakes. We must use the energy flow inside a jet cone to further reduce the fake jets due to pileup. We can also use the tracker to remove charged energy from pileup vertices (in principle)

# Tracking Detectors

- Clearly, the tracker is crucial for much of the LHC physics [e.g. e, μ, jets (pileup, E flow)].

- The existing trackers will not be capable of utilizing the increased luminosity as they will be near the end of their useful life.

- It is necessary to completely rebuild the LHC tracking detectors.

# Tracker - Occupancy

- **The occupancy, O, for a detector of area dA exposed for time dt at (r,z) is**

$$O = \rho\,[dA\,dt]$$

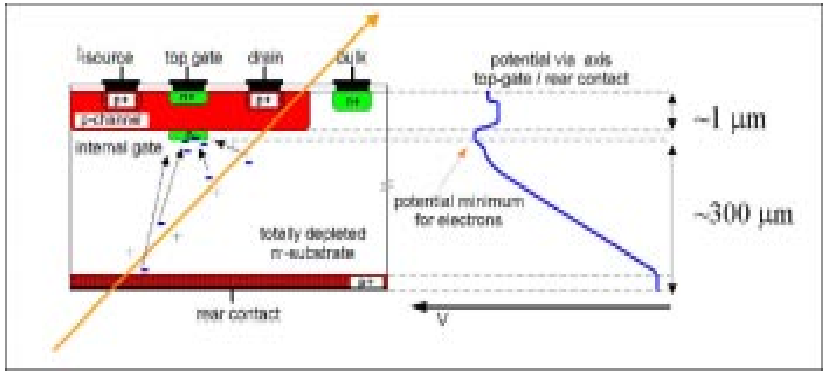
- **e.g. Si strip 10 cm x 100 μm in a 25 nsec crossing at r = 30 cm is 1.3 %**
- **For higher luminosity, decrease dA, or decrease dt or increase r – smaller, faster or further away.**

# Tracker Occupancy

- Preserve the performance using $1/r^2$ :
  - Push Si strips out to ~ 60 cm. – development
  - Push pixels out to 20 cm. – development
  - For r < 20 cm. Need new technologies – basic research
- Shrink dAdt 10x at fixed r to preserve b tagging?
- Possibilities
  - 3-d detectors – electrodes in bulk columns
  - Diamond (RD42) - radhard
  - Cryogenic (RD39) – fast, radhard
  - Monolithic – reduced source capacity.

# Monolithic Pixel - DEPFET

**Combine the detector and the readout for pixels?**



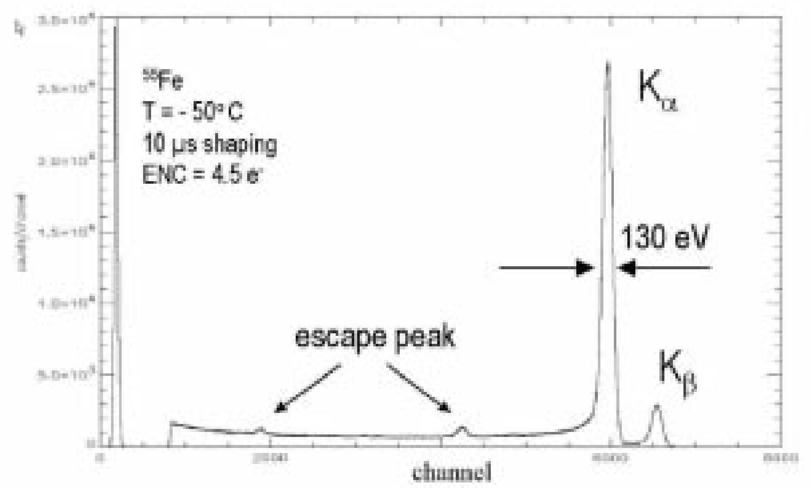




Fig. 10. Response of a DEPFET pixel detector to an $^{55}$Fe 6keV X-ray source obtained using a single pixel device operated at $-50^{\circ}$C with a shaping time of 10$\mu$s.

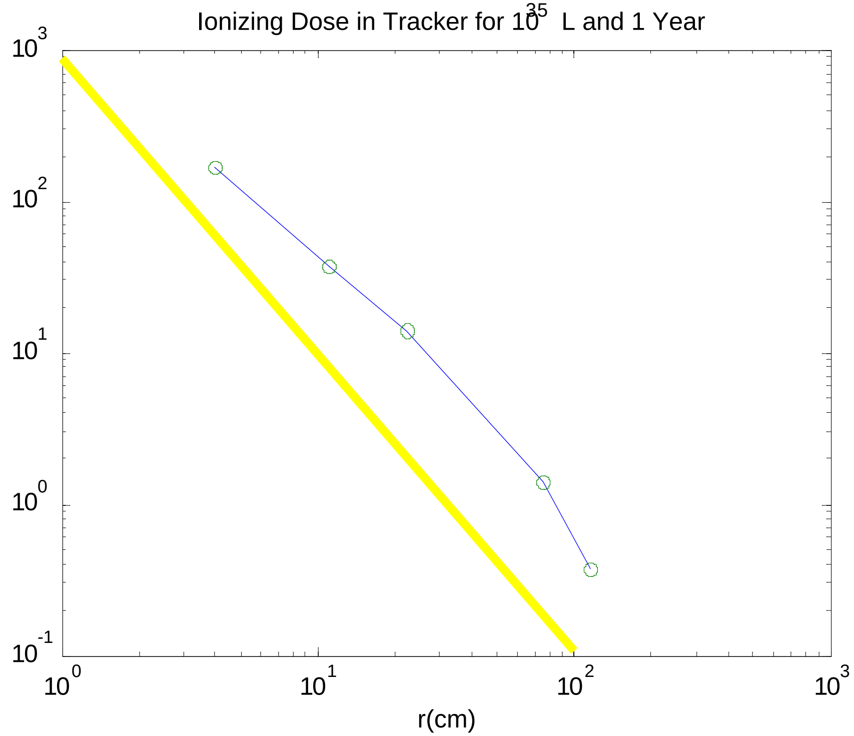
# Tracker – Ionizing Dose

- **The ionizing dose due to charged particles is:** $dE\,dx$

- **The dose depends only on luminosity, r, and exposure time dt.**

- **For example, at r = 30 cm, the dose is 1.3 Mrad/yr – ignoring loopers, interactions, ….**

# Tracker ID vs. Radius




- **DSM is radiation hard in 0.25 um**
- **0.13 um is available – use Moore's "law"**
- **Development needed – track and adapt commercial processes**
- **Optical links – development needed**

# ECAL – Shower Dose

- **The dose in ECAL is due to photon showers and is:**

  *dEdxpE*

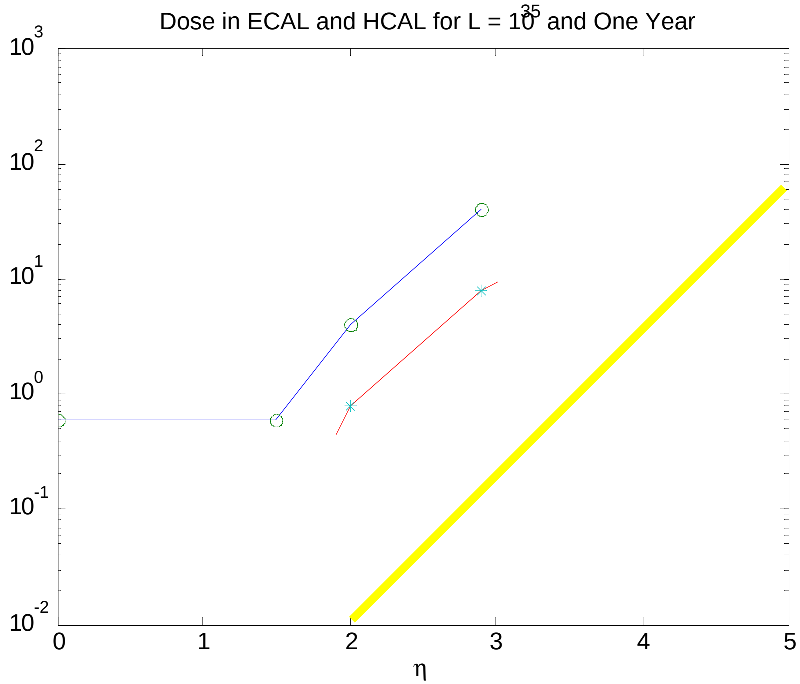
  [sin]

- **In the barrel, SD is ~ . In the endcap, SD ~**

  *(r)*

- **At r = 1.2 m, for Pb with Ec = 7.4 MeV, the dose at y=0 is 3.3 Mrad/yr, at |y|=1.5 it is 7.8 Mrad/yr.**

# HCAL and ECAL Dose




**The dose ratio is ~ Barrel doses are not a problem. For the endcaps a technology change may be needed for 2 < |y| < 3. For CMS endcap switch to quartz fiber?**

# ECAL

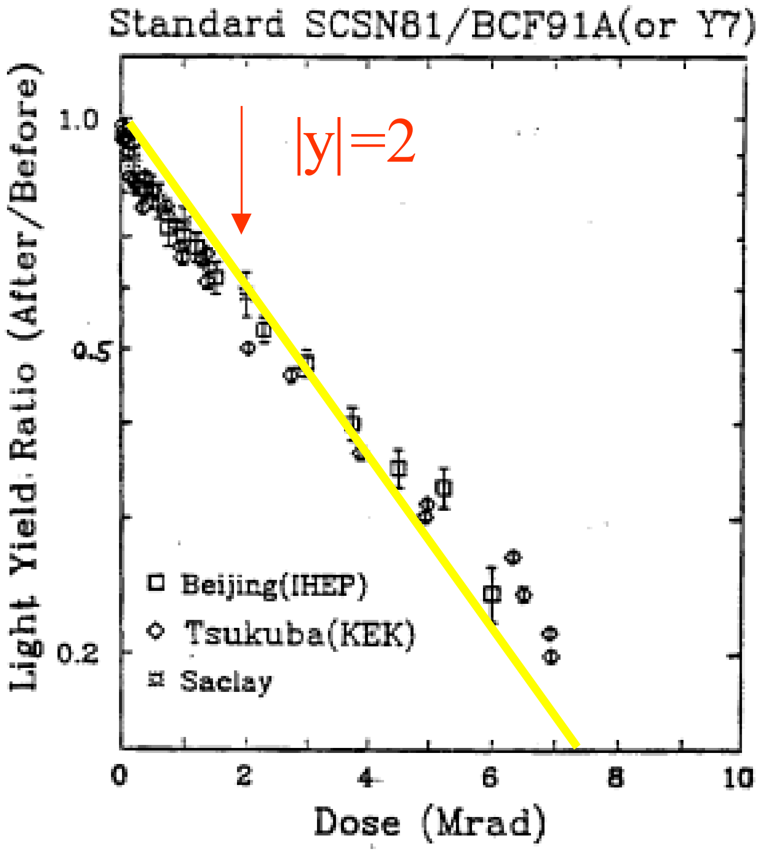
- **For both ATLAS and CMS the barrel will probably tolerate the increased dose. There are issues of ~ 3x increased pileup noise and poorer isolation for electrons.**

- **ATLAS LA has space charge and current draw issues. CMS has APD leakage current noise issues in the barrel. The CMS endcap needs development.**

# HCAL

- **Both ATLAS and CMS will function in the barrel region.**
- **In the 3<|y|<5 region, a reduction to y < 4.2 keeps the dose constant. The loss of efficiency is not terrible (peak "tag"rate at |y|=3). Or replace quartz fibers with high pressure gas? Better tower granularity might be needed due to pileup and "fake" jets.**
- **At |y| ~ 3 the CMS scintillator needs development – better longitudinal segmentation and/or improved scintillator**.

# Scintillator - Dose/Damage




Scintillator under irradiation forms
Color centers which reduce the
Collected light output (transmission loss).

LY ~ exp[-D/Do], Do ~ 4 Mrad

**This technology will not survive gracefully at |y| ~ 3 without development of improved scintillator.**

# Muons and Shielding

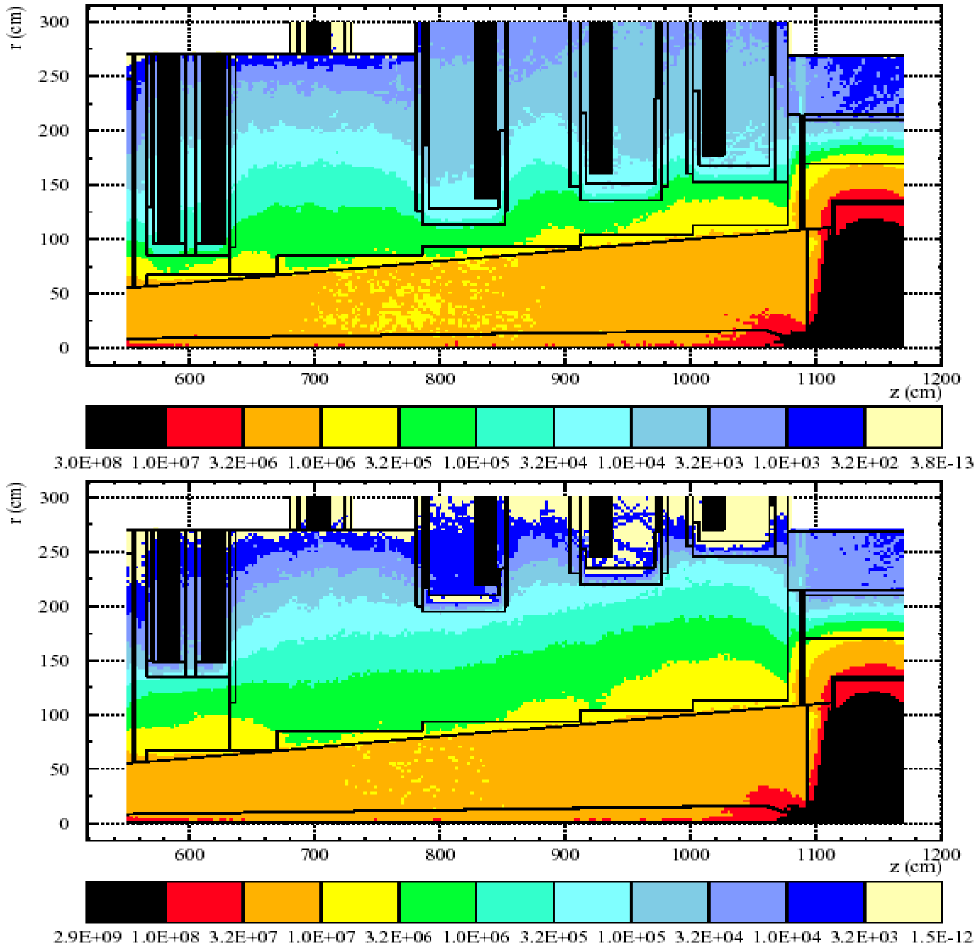



Fig. 24: Upper: the neutron fluxes in the low radius, high $\eta$-region of the CMS endcap muon detector for $\eta < 2.4$ and present LHC shielding $10^{34}$ cm$^{-2}$s$^{-1}$. Lower: same, for for $\eta < 2$ and possible shielding for SLHC $10^{35}$ cm$^{-2}$s$^{-1}$.

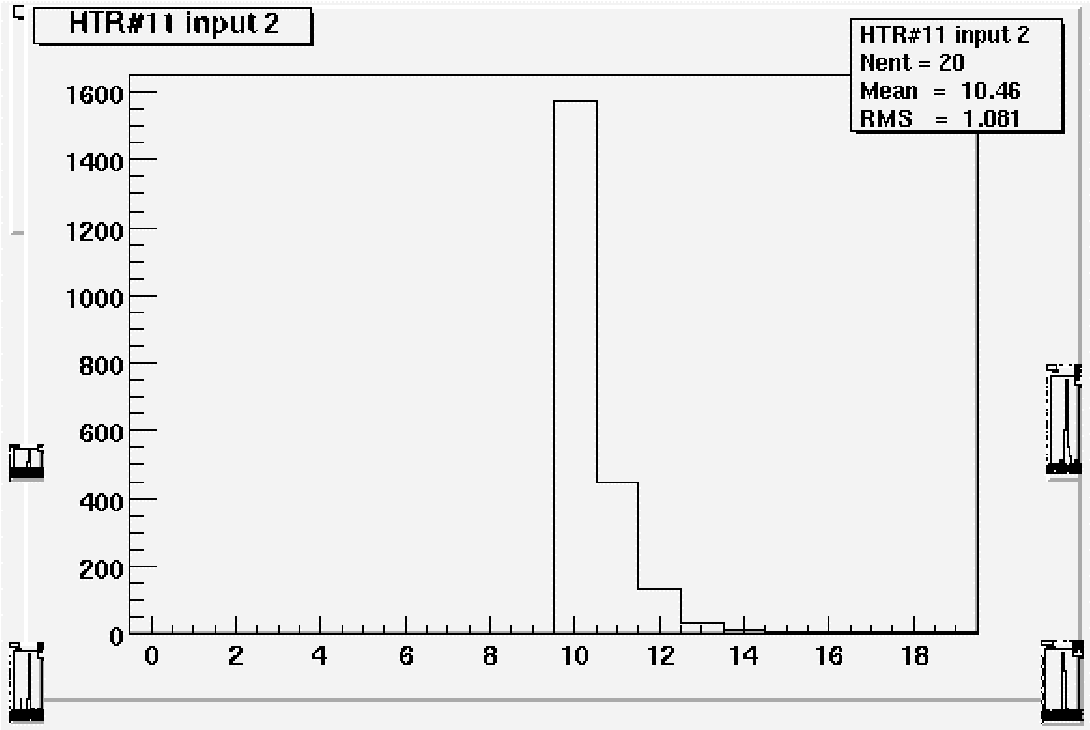
**With added shielding, dose rates can be kept constant if angular coverage goes from |y|<2.4 to |y|<2. CSC migrate into barrel?**

# Trigger and DAQ

- **Assuming LHC initial program is successful, raise the trigger thresholds.**
- **Rebuild trigger system to run at 80 MHz. Utilize those detectors which are fast enough to give a BCID within 12.5 nsec.**
- **Examine algorithms to alleviate e.g. degraded e isolation.**
- **Design for the increased event size (pileup) with reduced L1 rate and/or data compression.**
- **For DAQ track the evolution of communication technologies, e.g. 10 Gb/sec Ethernet.**

# 300 GeV Pion – H2 test Beam

E




**HTR - Bunch crossing number**

**The shape of the pulse in time is ~ as expected – due to scint flours and HPD drift. Bunch crossing ID can be extended to 12.5 nsec ( 80 MHz) ?**

# Summary

- The LHC Physics reach will be substantially increased by higher luminosity.
- To realize that improvement, the LHC detectors must preserve performance.
- The trackers must be rebuilt – with new technology at r < 20 cm.
- The calorimeters, muon systems, triggers and DAQ will need development.
- The upgrades are likely to take ~ (6-10) years. The time to start is now, and the people to do the job are those who did it for the present detectors.

# HH Study

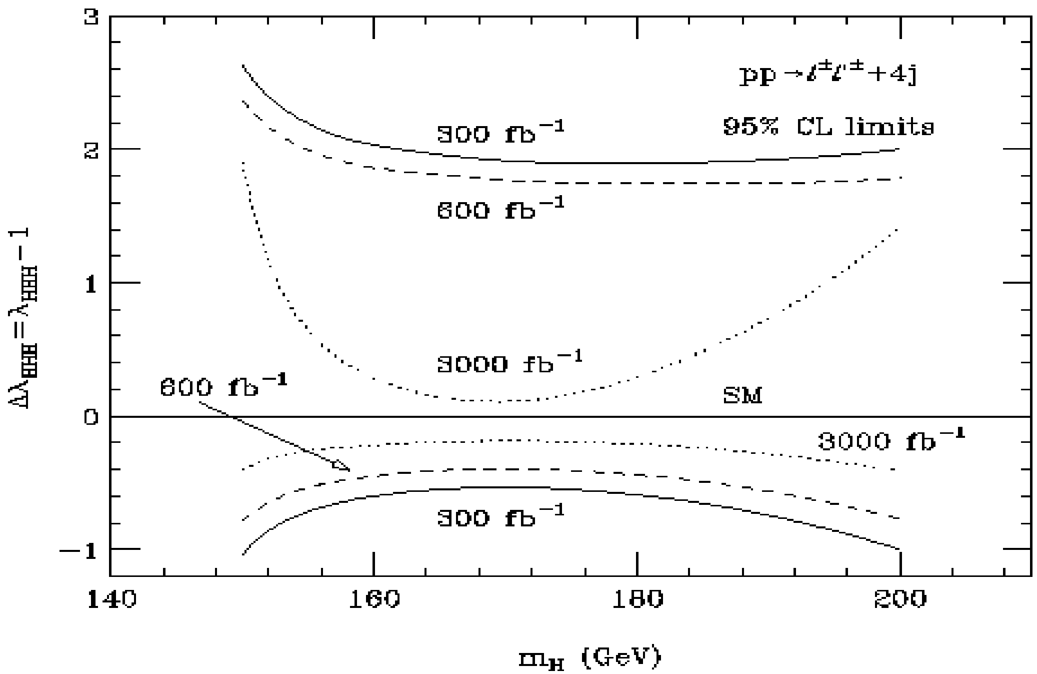



Figure 4. Limits achievable at 95% CL for $\Delta\lambda_{HHH} = \lambda_{HHH} - 1$ ($\lambda_{HHH} = \lambda/\lambda_{SM}$) in $pp \to \ell^{\pm}\ell'^{\pm} + 4j$ at the LHC. Bounds are shown for integrated luminosities of 300 fb$^{-1}$ (solid lines), 600 fb$^{-1}$ (dashed lines) and 3000 fb$^{-1}$ (dotted lines). The allowed region is between the two lines of equal texture. The Higgs boson self-coupling vanishes for $\Delta\lambda_{HHH} = -1$.

# Higgs Self-Coupling

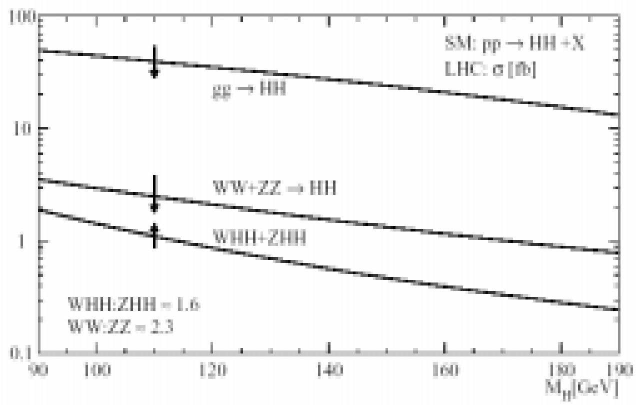



*Figure 4: The cross sections for gluon fusion, $WW/ZZ$ fusion and double Higgs-strahlung $WHH$, $ZHH$ in the SM. The vertical arrows correspond to a variation of the trilinear Higgs coupling from 1/2 to 3/2 of the SM value.*

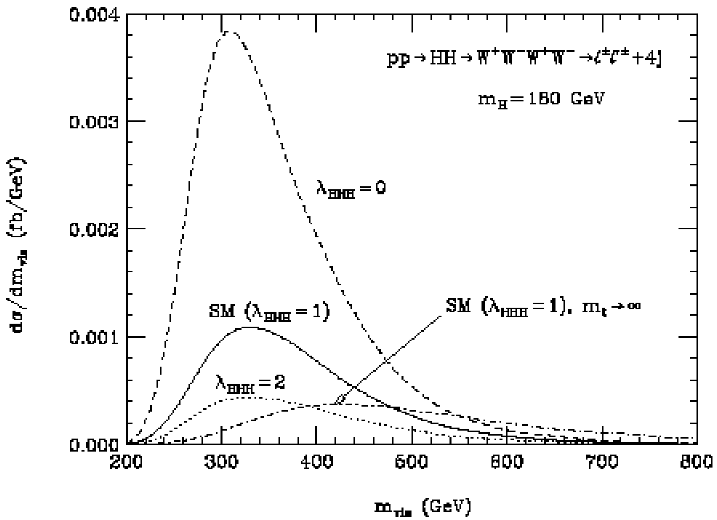
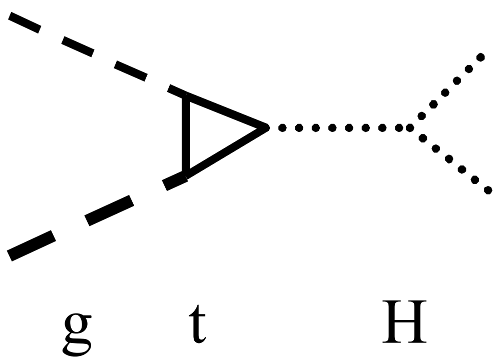



Figure 3. The $m_{vis}$ distribution of the signal for $M_H = 180$ GeV in the SM (solid curve), for $\lambda_{HHH} = \lambda/\lambda_{SM} = 0$ (dashed line) and for $\lambda_{HHH} = 2$ (dotted line). The dot-dashed line shows the SM cross section in the large $m_t$ limit. Qualitatively similar results are obtained for other values of $M_H$.




**Get a first indication of HHH coupling before the LC?**

# Higgs Self Coupling

Table 8: Expected numbers of signal and background events after all cuts for the $gg \to HH \to 4W \to \ell^{+}\ell'^{+}4j$ final state, for $\int \mathcal{L} = 6000\ \mathrm{fb}^{-1}$.

| $m_H$ | Signal | $t\bar{t}$ | $W^{\pm}Z$ | $W^{\pm}W^{+}W^{-}$ | $t\bar{t}W^{\pm}$ | $t\bar{t}t\bar{t}$ | $S/\sqrt{B}$ |
|---|---|---|---|---|---|---|---|
| 170 GeV | 350 | 90 | 60 | 2400 | 1600 | 30 | 5.4 |
| 200 GeV | 220 | 90 | 60 | 1500 | 1600 | 30 | 3.8 |

**A ~ 20% measurement of the HHH coupling is possible for Higgs masses < 200 GeV. However, to realize these improvements we need to maintain the capabilities of the LHC detectors.**

# Kinematics

- A particle of mass M produced by $x_1, x_2$ partons of momentum fraction $x_1 x_2 = x^2 = M^2/s$ has the kinematic relations where s = C.M. energy squared. Thus, on average $x \sim M/\sqrt{s}$

- The rapidity y is , $y \sim \sinh^{-1}(p/M)$ . It is related to pseudorapidity, $\eta = -\log(\tan\theta/2)$ $\eta$ ~ y.

# Tracker Front Ends, Links

Table 17: Hadron fluence and radiation dose in different radial layers of the CMS Tracker (barrel part) for an integrated luminosity of 2500 $fb^{-1}$.

| Radius (cm) | Fluence of fast hadrons ($10^{14}cm^{-2}$) | Dose (kGy) | Charged Particle Flux ($cm^{-2}s^{-1}$) |
|---|---|---|---|
| 4 | 160 | 4200 | $5 \times 10^8$ |
| 11 | 23 | 940 | $10^8$ |
| 22 | 8 | 350 | $3 \times 10^7$ |
| 75 | 1.5 | 35 | $3.5 \times 10^6$ |
| 115 | 1 | 9.3 | $1.5 \times 10^6$ |

- **DSM is radiation hard in 0.25 um**
- **0.13 um is available – use Moore's "law"**
- **Development needed – track and adapt commercial processes**
- **Optical links – development needed**

# Dose for ECAL and HCAL

Table 18: The neutron fluence and radiation dose at shower maximum at different pseudorapidities for an integrated luminosity of 2500 $fb^{-1}$.

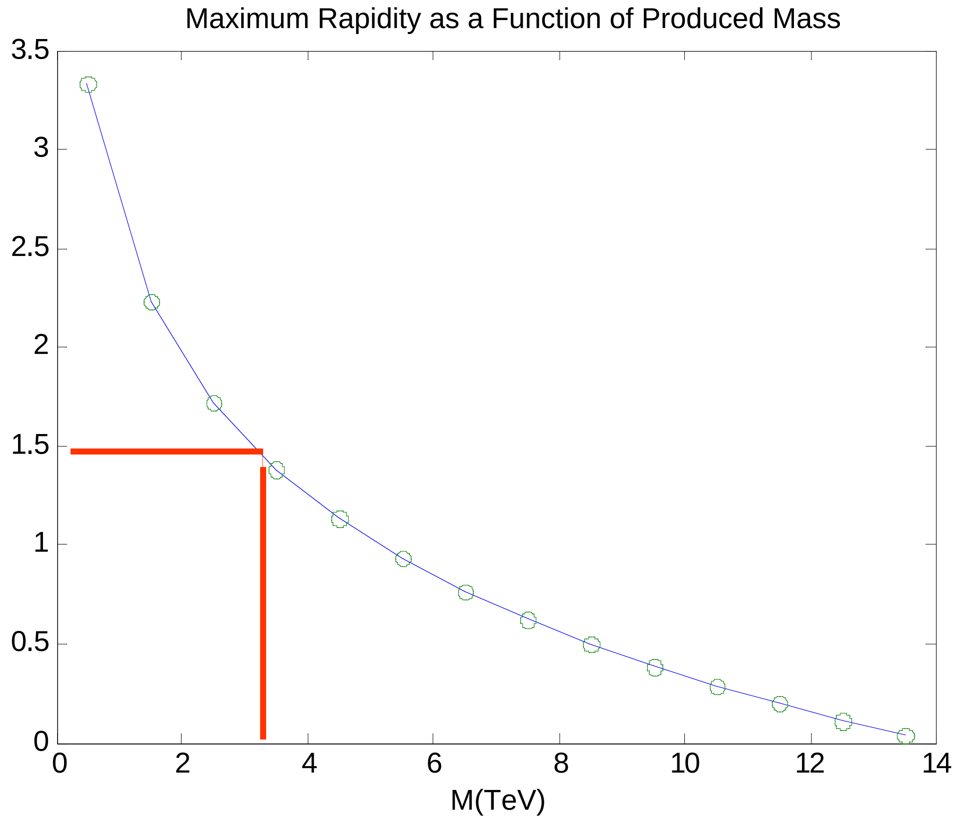
| Pseudorapidity $\eta$ | ECAL Dose (kGy) | HCAL Dose (kGy) | ECAL Dose Rate (Gy/h) |
|---|---|---|---|
| 0 - 1.5 | 15 | 1 | 2.5 |
| 2.0 | 100 | 20 | 14 |
| 2.9 | 1000 | 200 | 140 |
| 3.5 | - | 500 | - |
| 5 | - | 5000 | - |

**Barrel doses are not a problem. For the endcaps a technology change may be needed for 2 < |y| < 3. For CMS endcap switch to quartz fiber?**

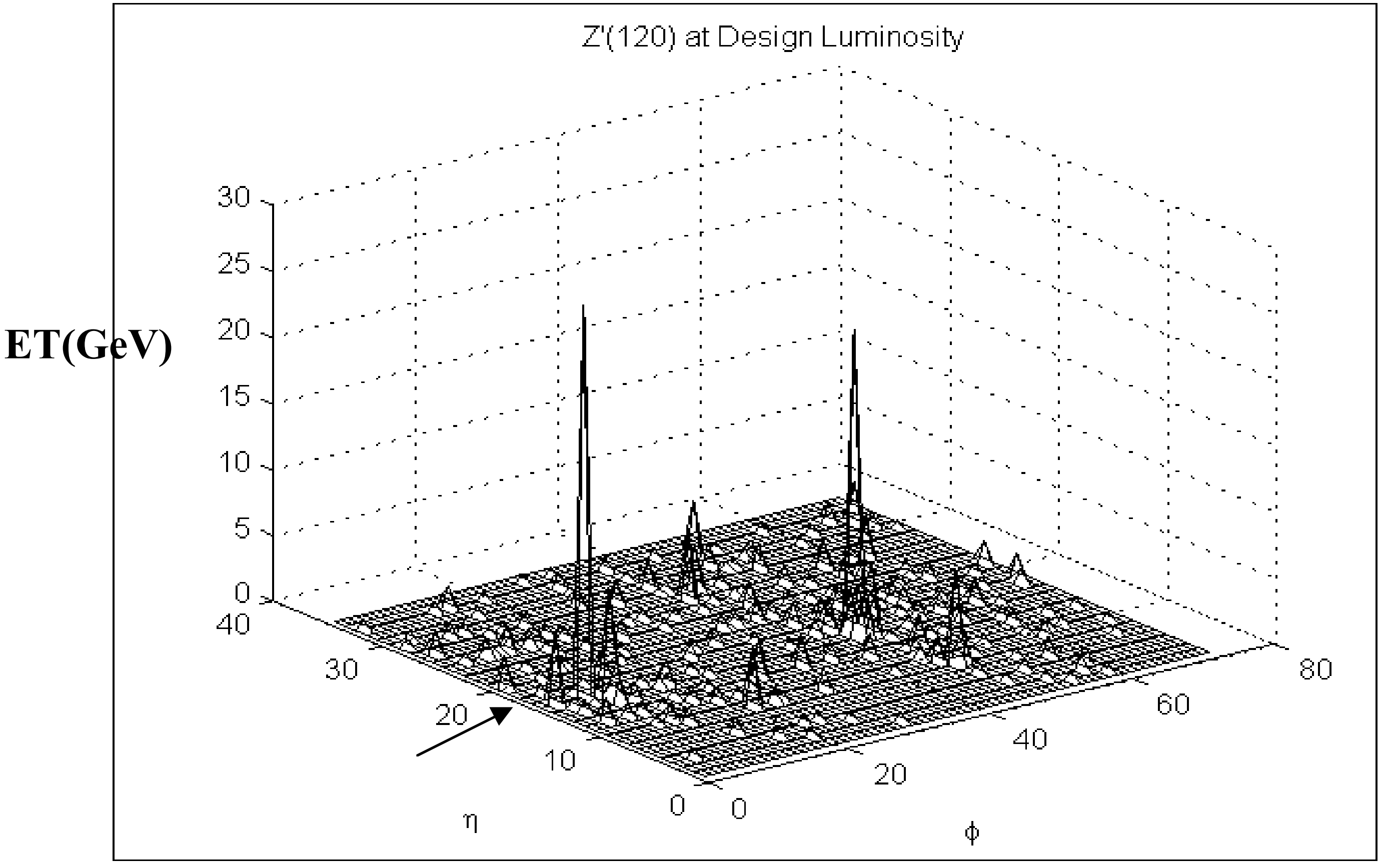
# Produced Mass and y

- Heavy states are produced at wide angle to the beams and strike the "barrel".

$y_{max} \sim \log(/)$ $M$ $\sqrt{\ }$

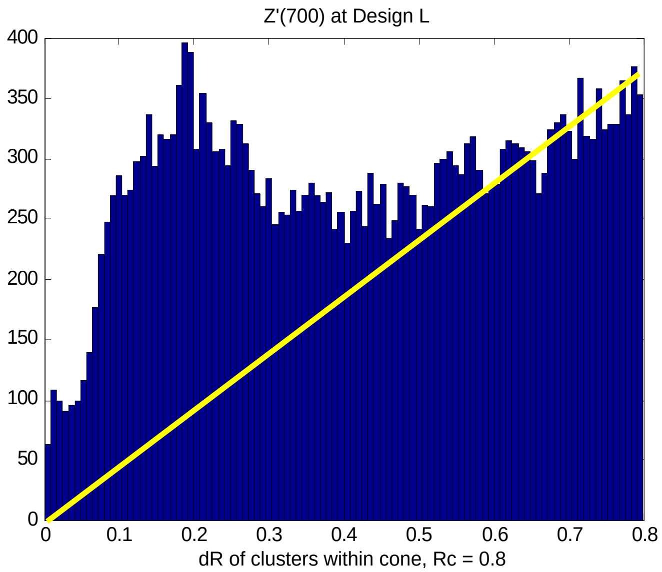


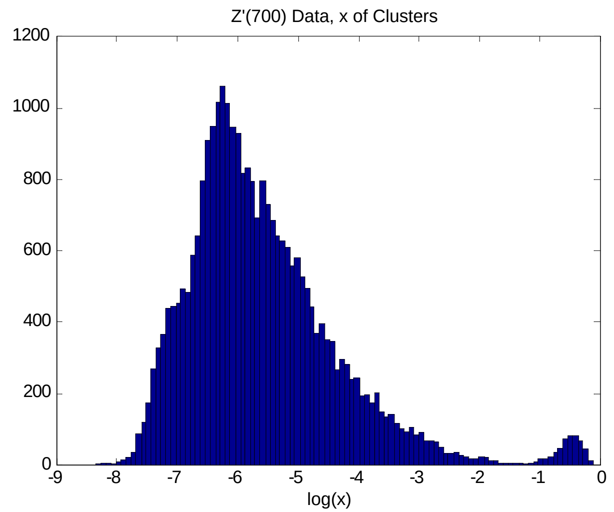
# Z'(120) at Design L



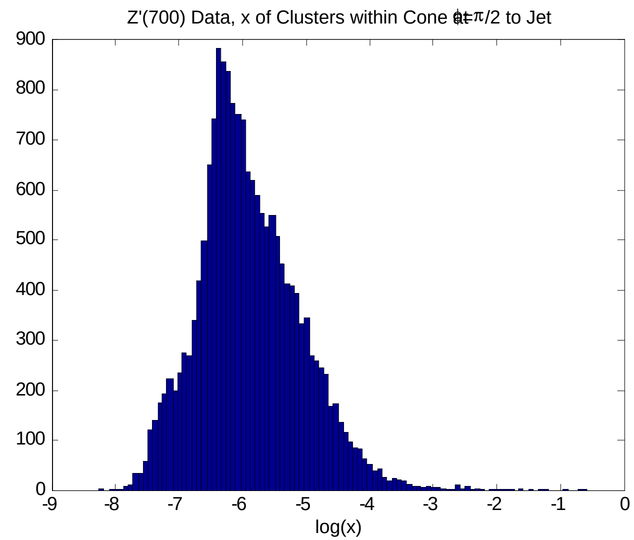

**Note that the calorimeter cells are still fairly sparsely populated (granularity $(\Delta\eta \sim 0.087)$ )**

# dR and log(x) for Z'(700)

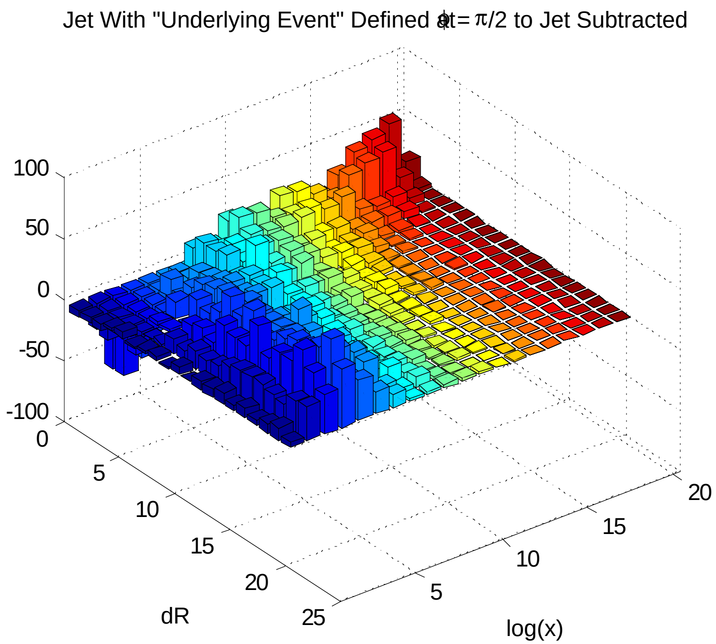


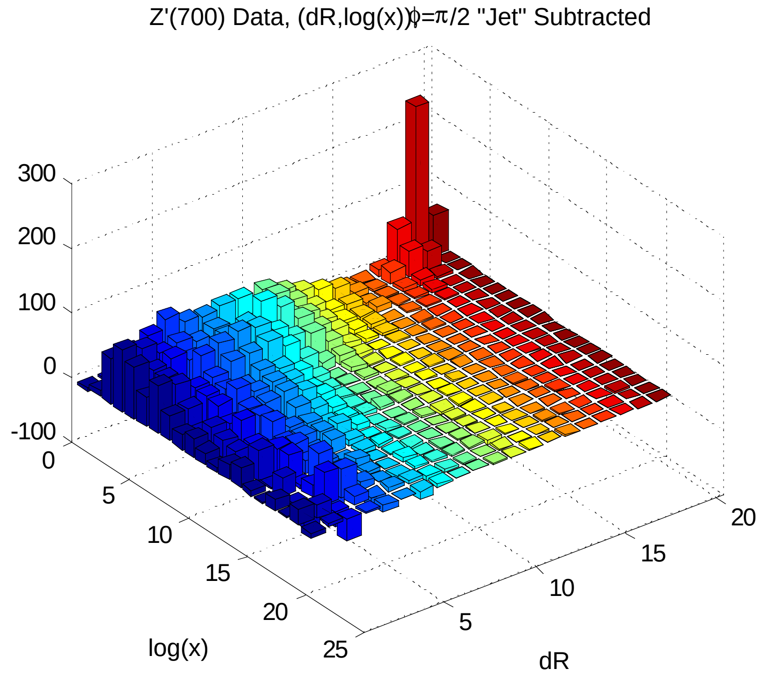




Clearly the pileup has dNdR~R (area), while the jet shows a peak at R ~ 0.2. The pileup is at low x, while there is a jet "core" at high x. Use tracker to subtract charged pileup? Reduce pileup by 3x.



# Pileup Subtracted (logx, dR) Jet Contours




**For both Z′(120) at low L and for Z′(700) at design L there is a core of the jet at small dR and large x. Extend to 10x L using tracker and energy flow inside the jet?**