The SLHC Program and CMS Detector Upgrades

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ICPP Conference Istanbul*

* memorial for Engin Arik and her colleagues

- SLHC Upgrade
- Mature LHC $\rightarrow$ SLHC Discovery Physics examples
- CMS Detector Upgrades

Mature LHC Program

- If Higgs observed:
  - Measure parameters (mass, couplings), need up to 300 fb^{-1}
  - Self-coupling not accessible with LHC alone
- If we think we observe SUSY:
  - Try to measure mass (study cascades, end-points, …)
  - Try to determine the model: MSSM, NMSSM, …
  - Establish connection to cosmology (dark matter candidate?)
  - Understand impact on Higgs phenomenology
  - Try to determine the SUSY breaking mechanism
- If neither or something else:
  - Strong $W_L W_L$ scattering? Other EWSB mechanisms?
  - Extra dimensions, Little Higgs, Technicolor ?
  - Do we have to accept fine-tuning (e.g. Split Supersymmetry)
- Next: SLHC

Time Scale of LHC Upgrade

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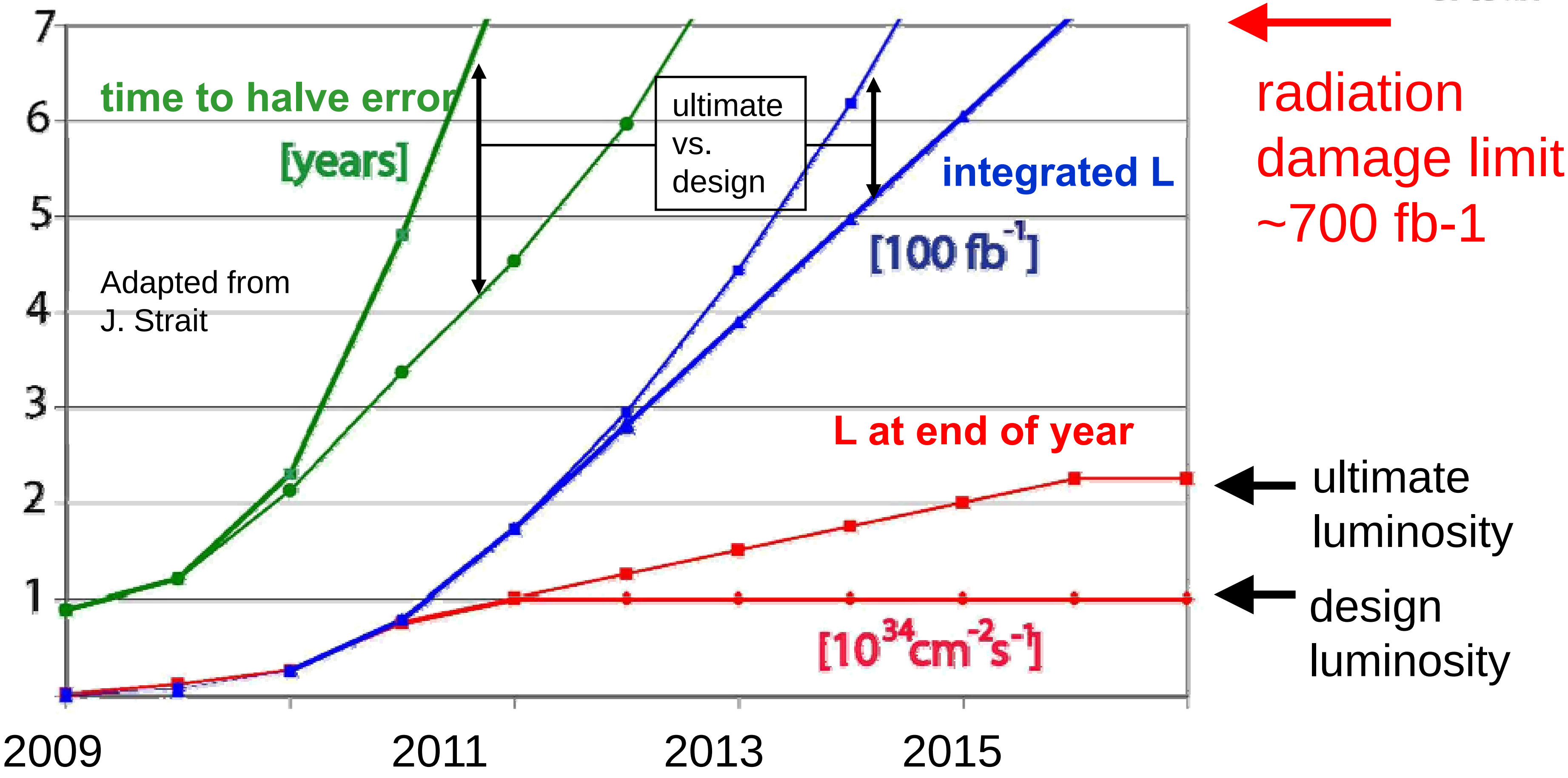


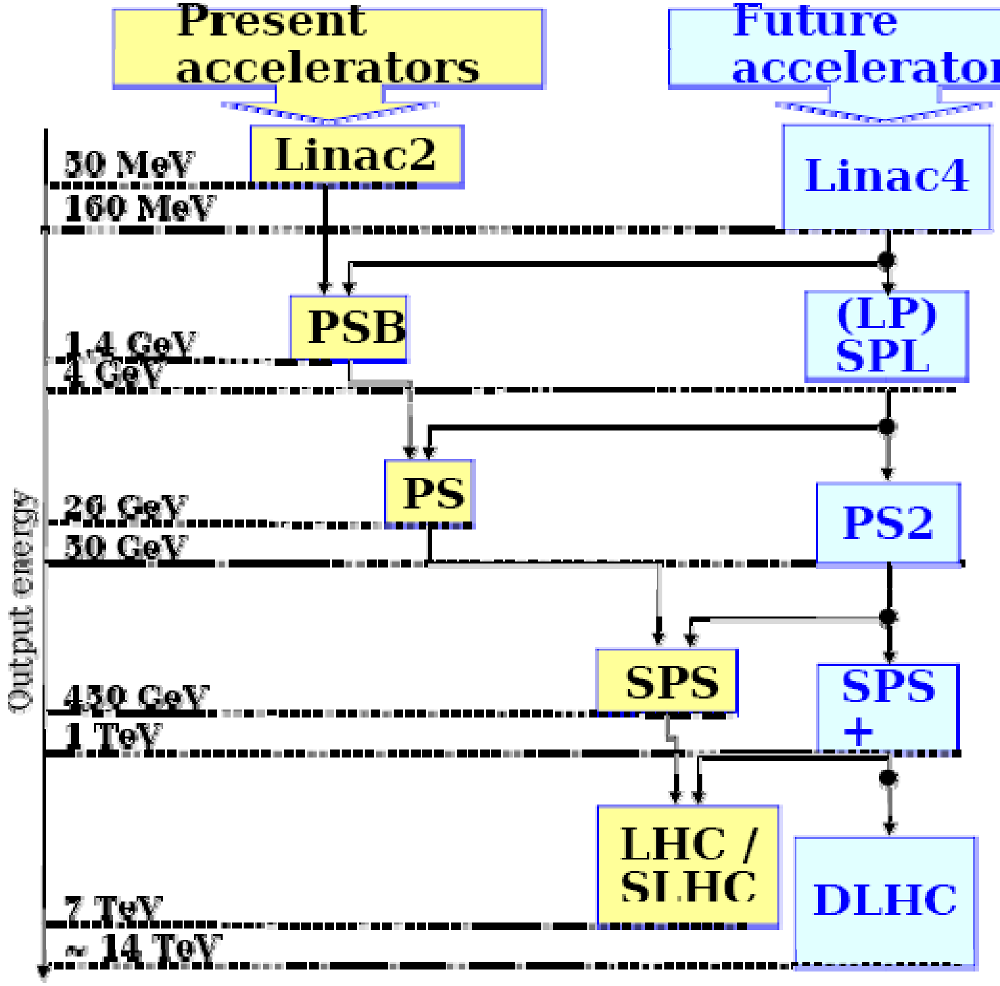
(1) ***LHC IR quads life expectancy*** estimated <10 years from radiation dose

(2) the ***statistical error halving time*** will exceed 5 years by 2013-2014

(3) therefore, it is reasonable to plan a ***machine luminosity upgrade based on new low-β IR magnets by ~2018***

LHC upgrade options

Themes 1 (2012) & 3 (2016)



"DONE" DEAL Linac4

THEME 1
NEAR TERM FOCUS ~2012
(LP)SPL (Low Power) Superconducting Proton Linac (4-5 GeV)
PS2 High Energy PS (~ 5 to 50 GeV – 0.3 Hz)

THEME 3
LUMI UPGRADE ~2016
SLHC "Superlumi" LHC (up to 10^{35} cm^{-2}s^{-1})

LONG TERM FANTASY
SPS+ Superconducting SPS
DLHC "Double energy" LHC

Not discussed →

SLHC Bunch Structure Options

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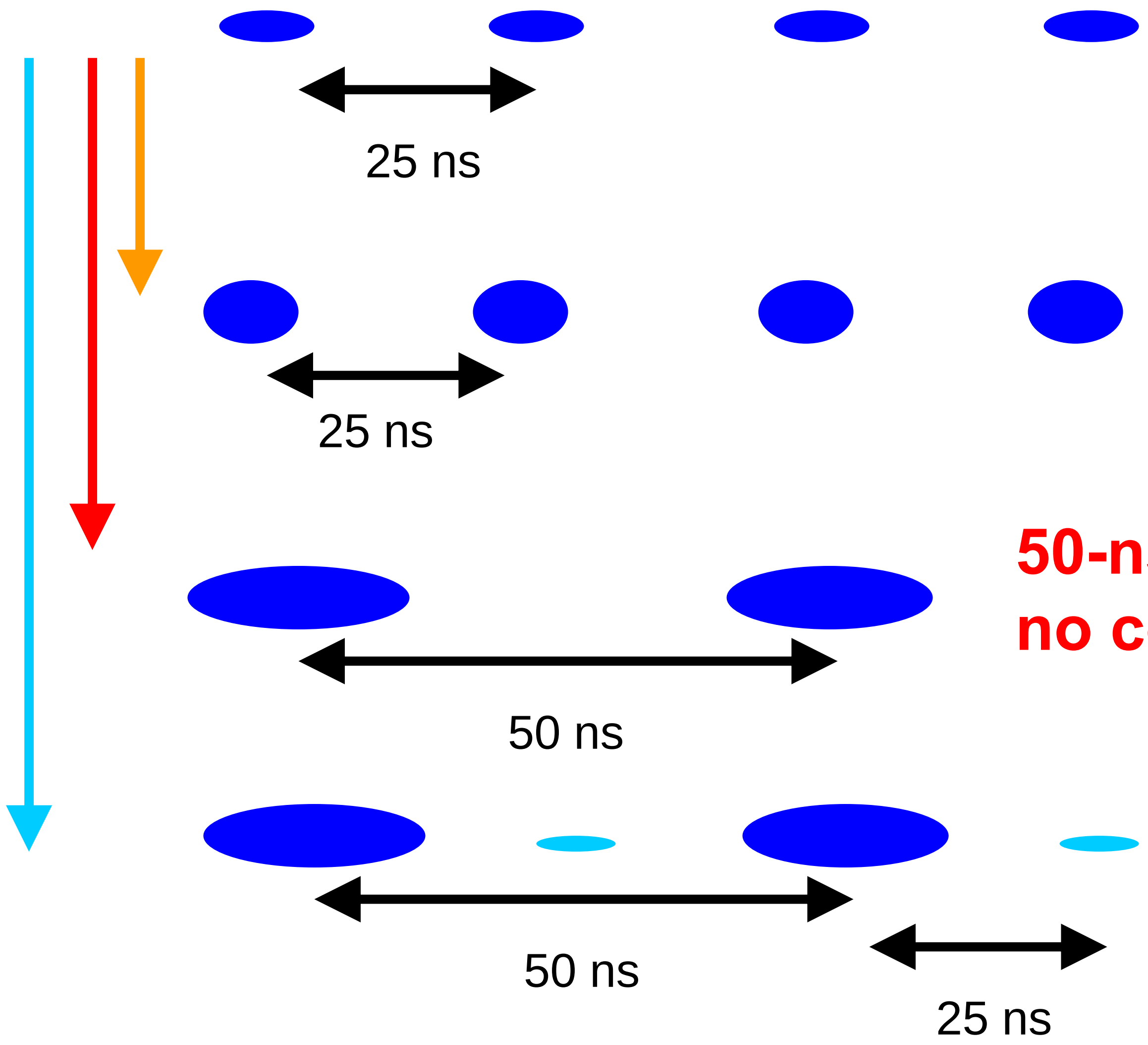


Nominal LHC

new alternative

ultimate
& 25-ns upgrade

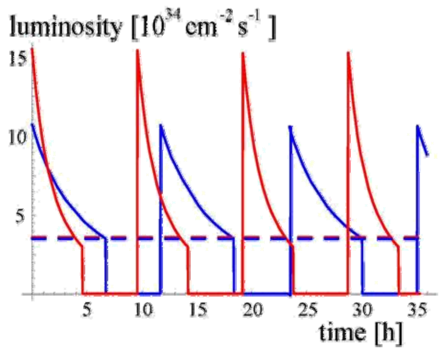
50-ns upgrade,
no collisions @S-LHCb

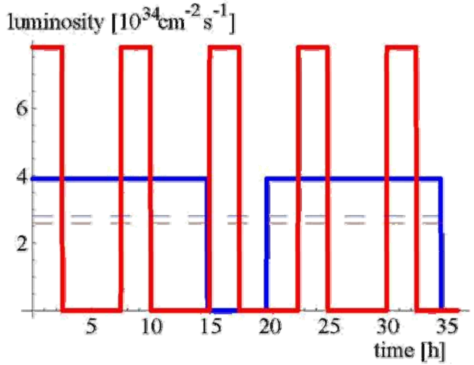
new baseline

50-ns upgrade
with 25-ns
collisions
in LHCb

LHC Upgrade Scenarios

- Two scenarios of L~10^{35} $cm^{-2}s^{-1}$ for which heat load and #events/crossing are acceptable
- 25-ns option: pushes β*; requires slim magnets inside detector, crab cavities, & Nb_3Sn quadrupoles and/or Q0 doublet; attractive if total beam current is limited; Peak events/crossing ~ 200.
- 50-ns option: has fewer longer bunches of higher charge ; can be realized with NbTi technology if needed ; compatible with LHCb ; open issues are SPS & beam-beam effects at large Piwinski angle; Peak events/crossing ~ 400
- Luminosity leveling may be done via bunch length and via β*, resulting in reduced number of events/crossing ~ 100.





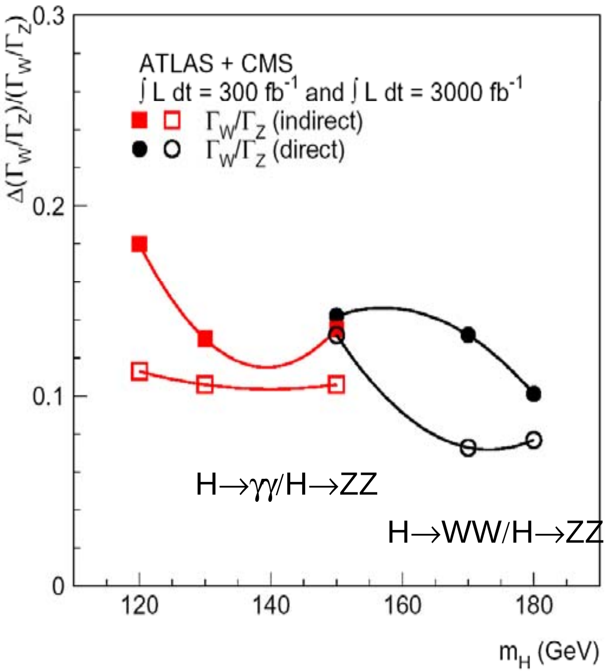
Two upgrade scenarios

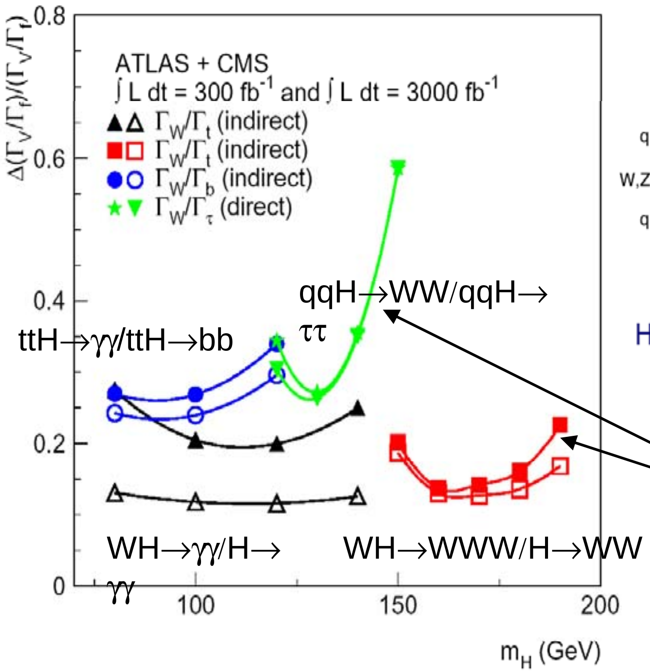
parameter	symbol	25 ns, small β*	50 ns, long
transverse emittance	ε [μm]	3.75	3.75
protons per bunch	N_b [10^{11}]	1.7	4.9
bunch spacing	Δt [ns]	25	50
beam current	I [A]	0.86	1.22
longitudinal profile		Gauss	Flat
rms bunch length	σ_z [cm]	7.55	11.8
beta* at IP1&5	β* [m]	0.08	0.25
full crossing angle	θ_c [μrad]	0	381
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0	2.0
hourglass reduction		0.86	0.99
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	15.5	10.7
peak events per crossing		294	403
initial lumi lifetime	τ_L [h]	2.2	4.5
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	2.4	2.5
	$T_{run,opt}$ [h]	6.6	9.5
effective luminosity ($T_{turnaround}$=5 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	3.6	3.5
	$T_{run,opt}$ [h]	4.6	6.7
e-c heat SEY=1.4(1.3)	P [W/m]	1.04 (0.59)	0.36 (0.1)
SR heat load 4.6-20 K	P_{SR} [W/m]	0.25	0.36
image current heat	P_{IC} [W/m]	0.33	0.78
gas-s. 100 h (10 h) τ_b	P_{gas} [W/m]	0.06 (0.56)	0.09 (0.9)
extent luminous region	σ_l [cm]	3.7	5.3
comment		D0 + crab (+ Q0)	wire comp.

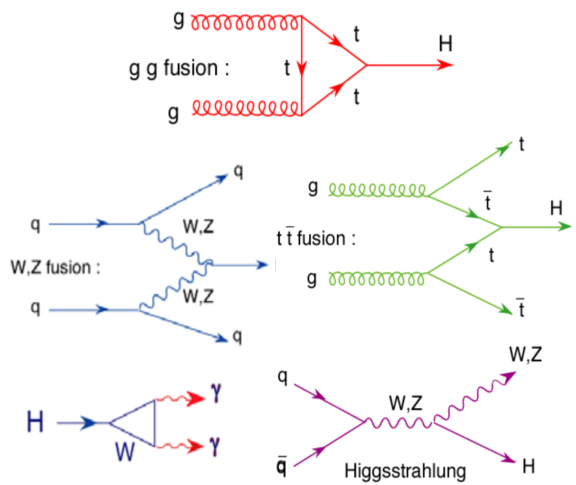
SM Higgs Couplings

- Combine different production & decay modes
  $\rightarrow$ ratios of Higgs couplings to bosons & fermions
  - Independent of uncertainties on σ^{tot}_{Higgs}, Γ_{H}, $\int L dt$ $\rightarrow$ stat. limited
  - Benefit from LHC $\rightarrow$ SLHC (assuming similar detector capabilities)

full symbols: LHC, 300 fb^{-1} per experiment
open symbols: SLHC, 3000 fb^{-1} per experiment





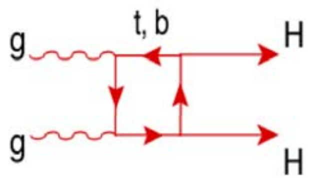


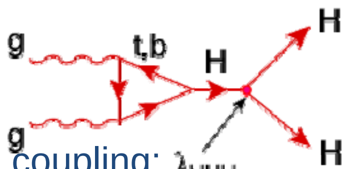
syst.- limited at LHC (σ_{th}),
~ no improvement at SLHC

➡ SLHC ratios of Higgs couplings should be measurable with a ~ 10% precision

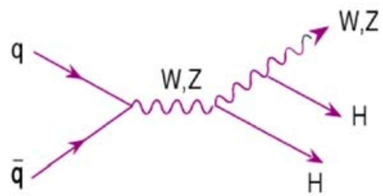
Higgs pair prod. & self coupling

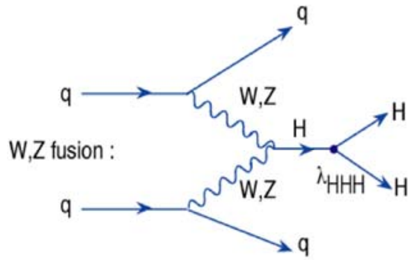
Higgs pair production through two Higgs bosons radiated independently (from VB, top) & from trilinear self-coupling terms proportional to λ_{HHH}^{SM}





triple H coupling: λ_{HHH}
$\lambda_{HHH}^{SM} = 3m_H^2/v$

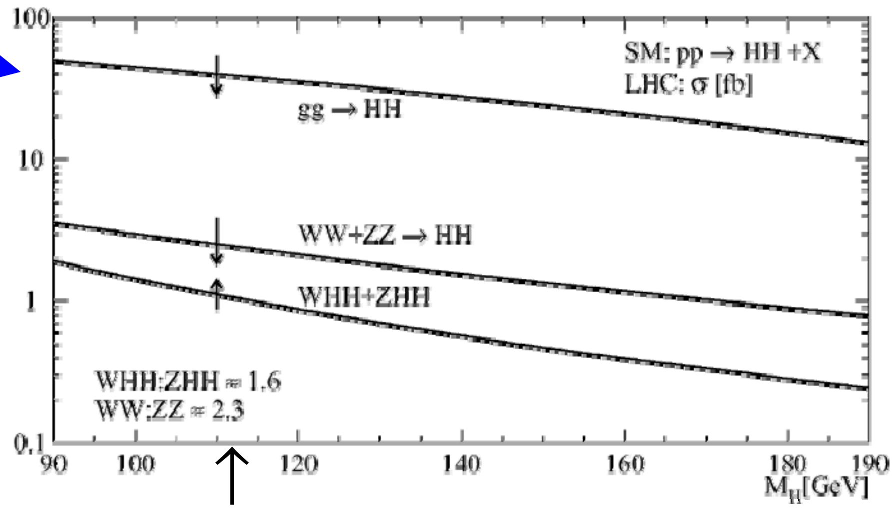




+….

$\sigma(pp \to HH) < 40$ fb, $M_H > 110$ GeV
Small BR for clean final states →no sensitivity at LHC (10^{34}),
but some hope at SLHC:
channel investigated:
$170 < m_H < 200$ GeV (ATLAS):
$gg \to HH \to W^+ W^- W^+ W^- \to l^\pm \nu jj \; l^\pm \nu jj$
with same-sign dileptons - difficult!

cross sections for Higgs boson pair production in various production mechanisms and sensitivity to λ_{HHH} variations



arrows correspond to variations of λ_{HHH} from 1/2 to 3/2 of its SM value

More optimistic study by Baur, Plehn, Rainwater:
$HH \to W^+ W^- W^+ W^- \to \lambda^\pm \nu jj \;\; \lambda^\pm \nu jj$
Limits @ 95% CL. for $\Delta\lambda = (\lambda - \lambda_{SM})/\lambda_{SM}$
LHC: $\lambda = 0$ can be excluded at 95% CL.
SLHC: λ can be determined to 20-30% (95% CL)

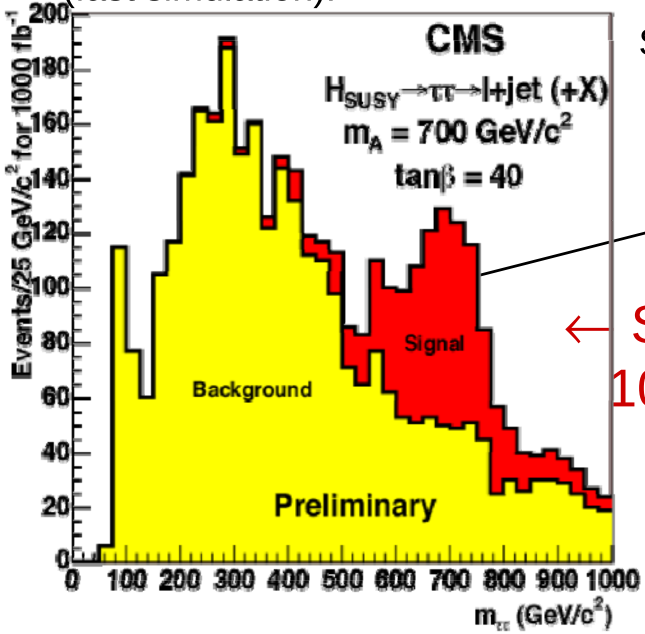
Improved reach for Heavy MSSM Higgs bosons

Order of magnitude increase in statistics with SLHC should allow

Extension of discovery domain for massive MSSM Higgs bosons A,H,$H^{\pm}$

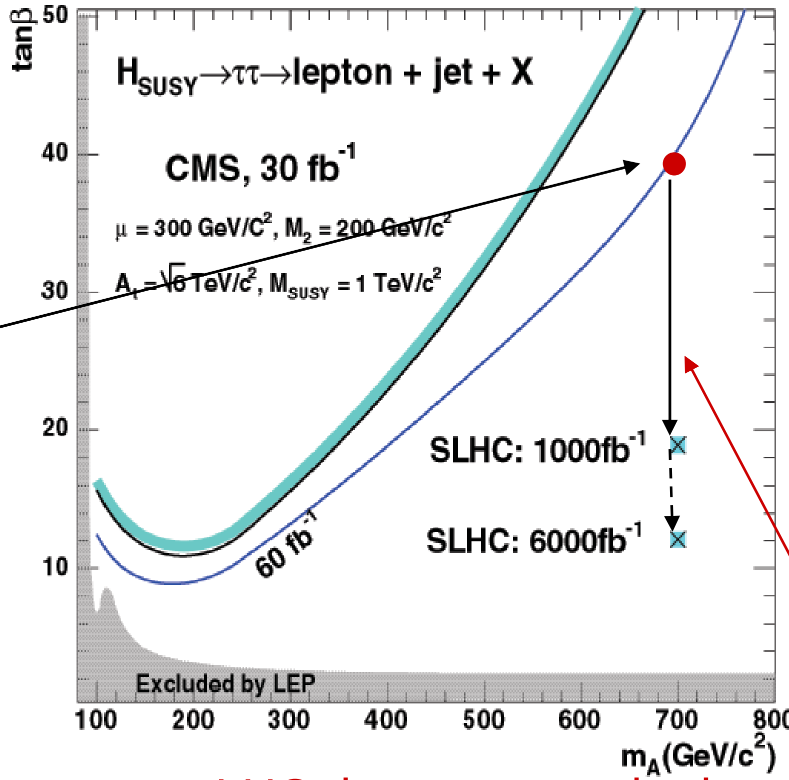
e.g.: A/H $\rightarrow \tau\tau \rightarrow$ lepton + τ-jet, produced in bbA/H

Peak at 5σ limit of observability at LHC greatly improves at SLHC, (fast simulation):



S. Lehti

← SLHC 1000 fb^{-1}



←LHC 60 fb^{-1}

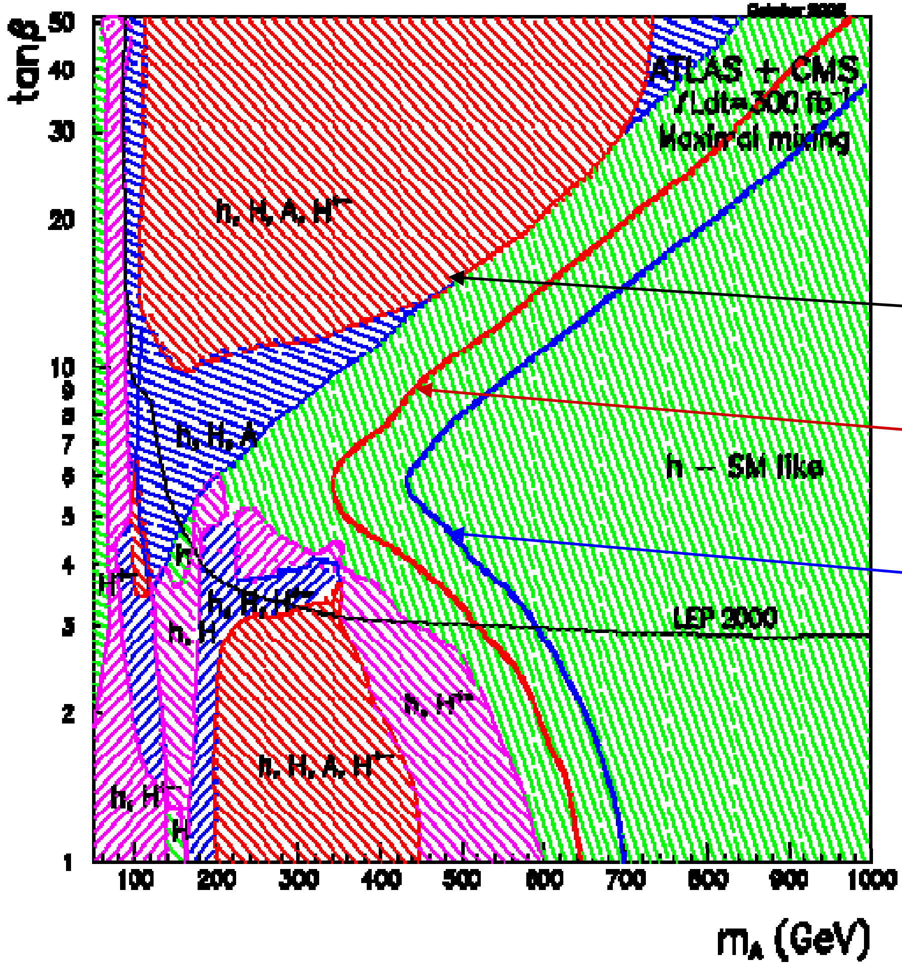
←SLHC 1000 fb^{-1}

gain in reach

b-tagging performance comparable to present LHC detectors required

Improved reach for MSSM Higgs bosons

MSSM parameter space regions for > 5σ discovery for the various Higgs bosons, 300 fb^{-1} (LHC), and expected improvement - at least two discoverable Higgs bosons - with 3000 fb^{-1} (SLHC) per experiment, ATLAS & CMS combined.



green area: region where only one (the h, ~ SM-like) among the 5 MSSM Higgs bosons can be found (assuming only SM decay modes)

LHC contour, 300 fb^{-1}/exp

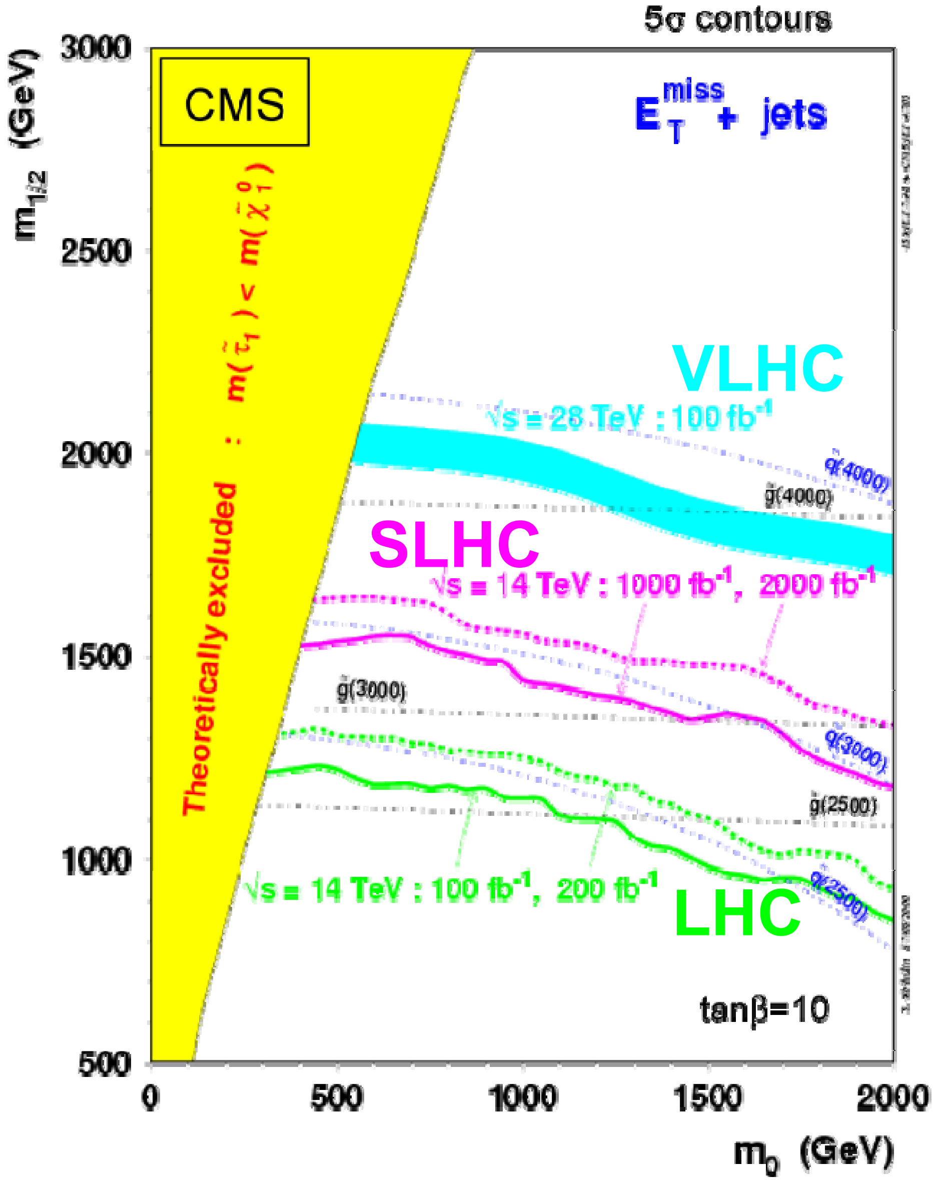
SLHC contour, 3000 fb^{-1}/exp
at least one heavy Higgs discoverable up to here

SLHC contour, 3000 fb^{-1}/exp
at least one heavy Higgs Excludable (95% CL) up to here

Heavy Higgs observable region increased by ~ 100 GeV

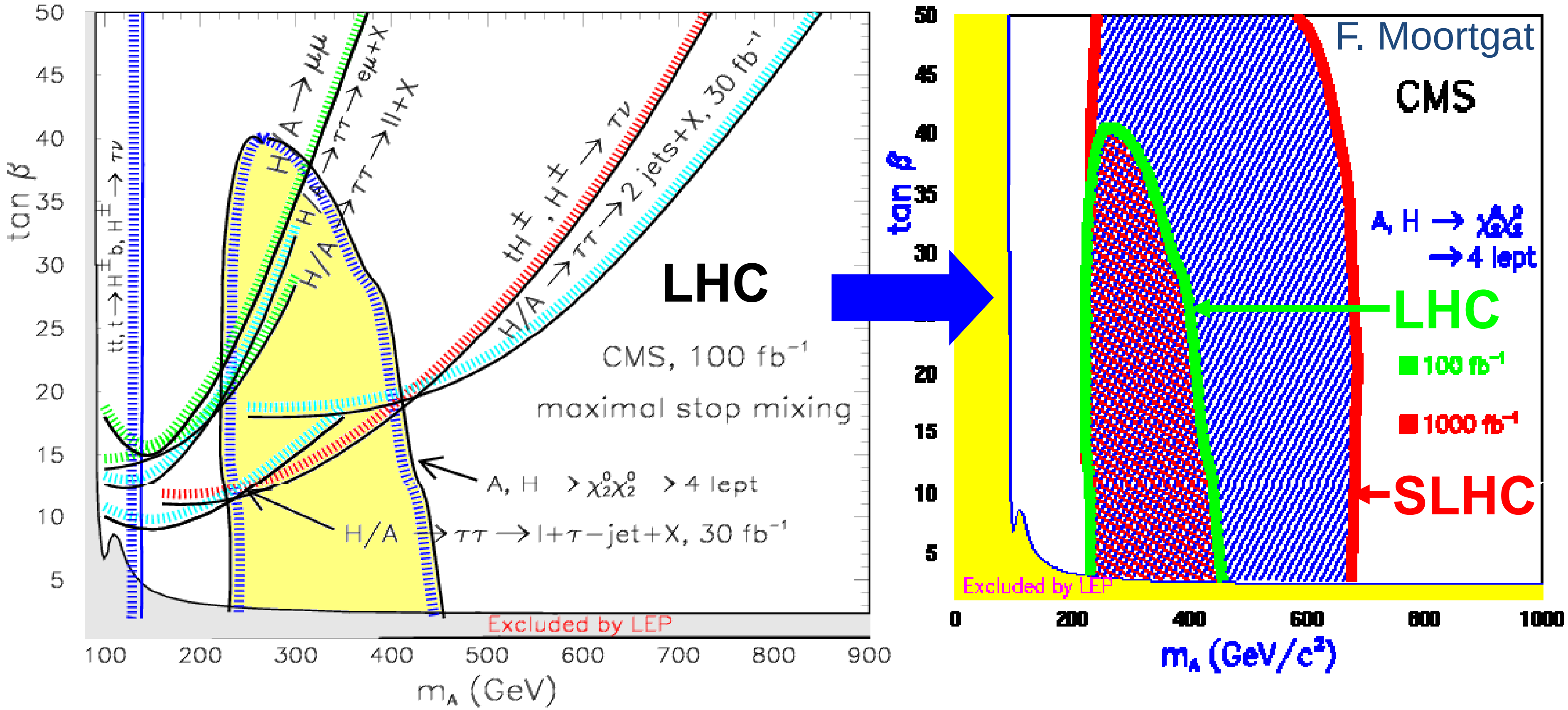
Supersymmetry

- Use high E_T jets, leptons & missing E_T
  - Not hurt by increased pile-up at SLHC
- Extends discovery region by ~ 0.5 TeV
  - ~ 2.5 TeV → 3 TeV
  - (4 TeV for VLHC)
  - Discovery means > 5σ excess of events over known (SM) backgrounds



Improved coverage of A/H decays to neutralinos, 4 isolated leptons

Use decays of H,A into SUSY particles, where kinematically allowed



A/H → χχ → 4 iso. leptons

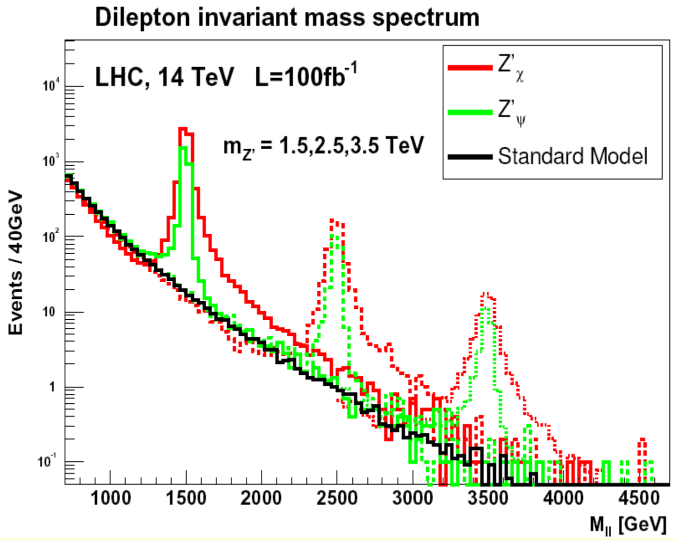
Strongly model/MSSM parameter dependent:
M_2 = 120 GeV, μ= -500 GeV,
$M_{sleptons}$ = 2500 GeV, $M_{squark, gluino}$ = 1TeV

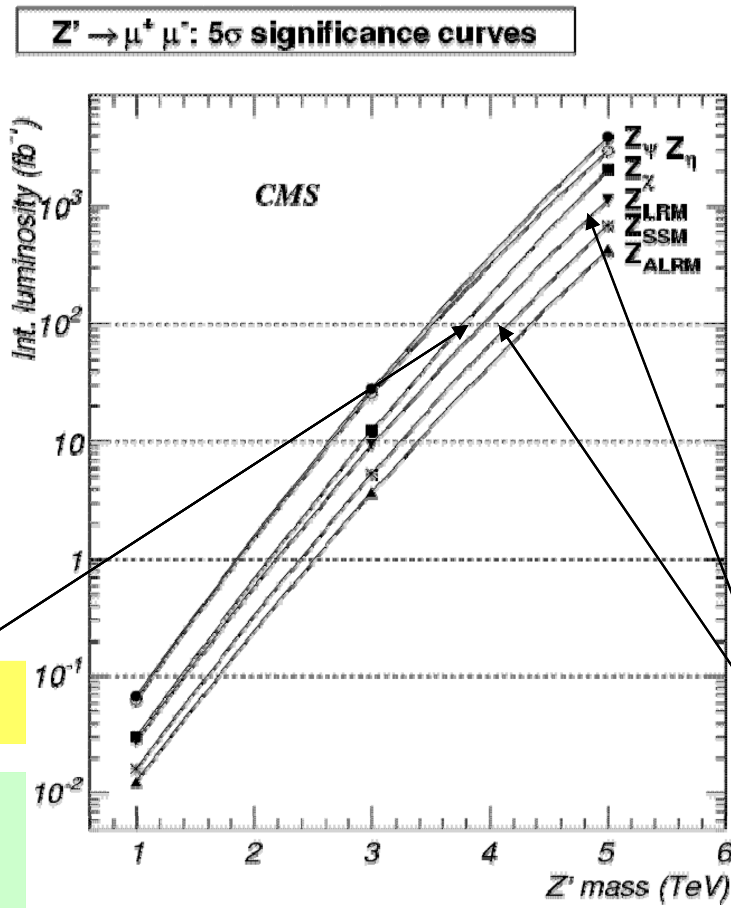
New gauge bosons

sequential Z' model, Z' production (assuming same BR as for SM Z) and Z' width:

Z' mass (TeV)	1	2	3	4	5	6
$\sigma(Z' \to e^+e^-)(fb)$	512	23.9	2.5	0.38	0.08	0.026
$\Gamma_{Z'}$ (GeV)	30.6	62.4	94.2	126.1	158.0	190.0

Acceptance, e/μ reconstruction eff., resolution, effects of pile-up noise at 10^{35}, ECAL saturation included. (CMS study)





← SLHC 1000 fb^{-1}

← LHC 100 fb^{-1}

~ 1.0 TeV

LHC reach ~ 4.0 TeV with 100 fb^{-1}

Gain in reach ~ 1.0 TeV i.e. 25-30% in going from LHC to SLHC

Extra Dimensions: Randall-Sundrum model

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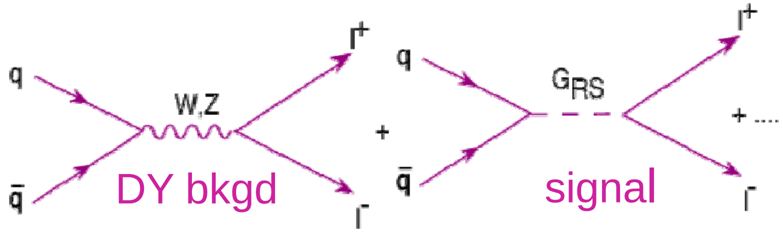
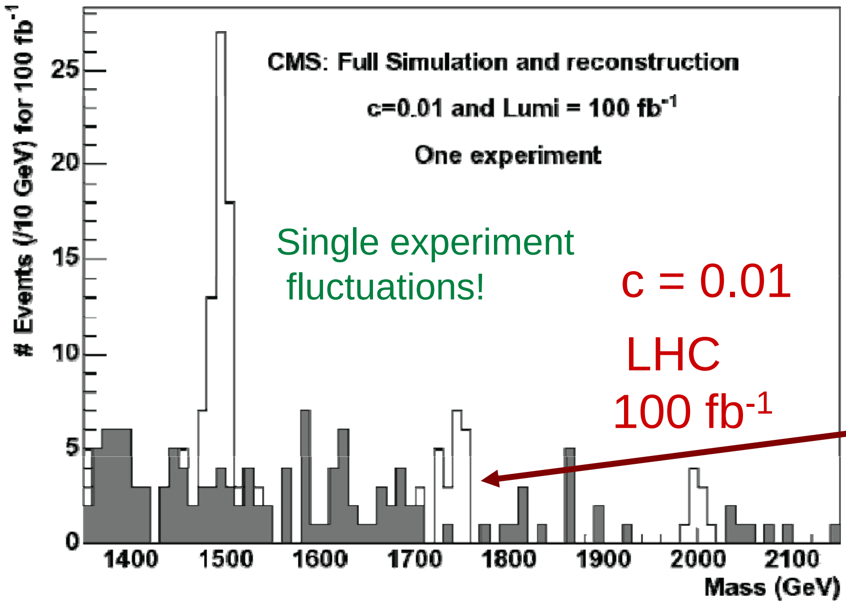
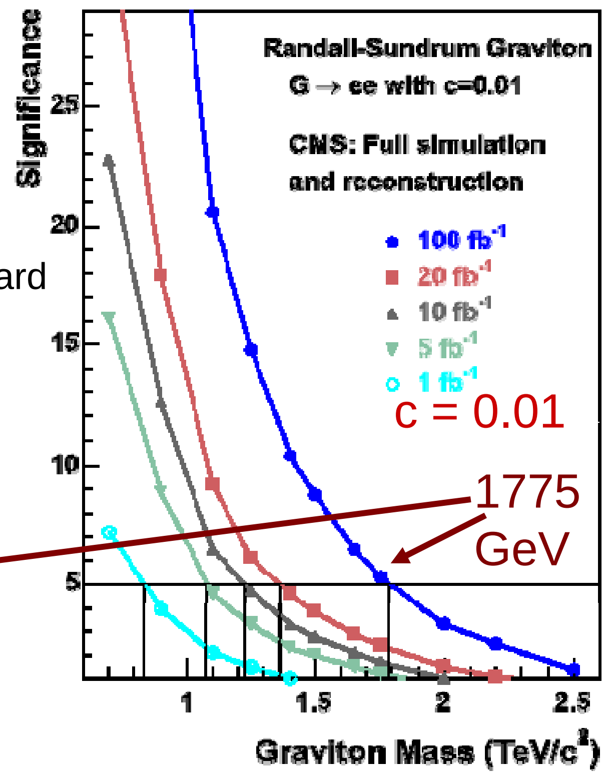
$pp \to G_{RS} \to ee$ full simulation and reconstruction chain in CMS,
2 electron clusters, p_t > 100 GeV, $|\eta| < 1.44$ and $1.56 < |\eta| < 2.5$, el. isolation, H/E < 0.1, corrected for saturation from ECAL electronics (big effect on high mass resonances!)



$$S = 2(\sqrt{N_S + N_B} - \sqrt{N_B}).$$



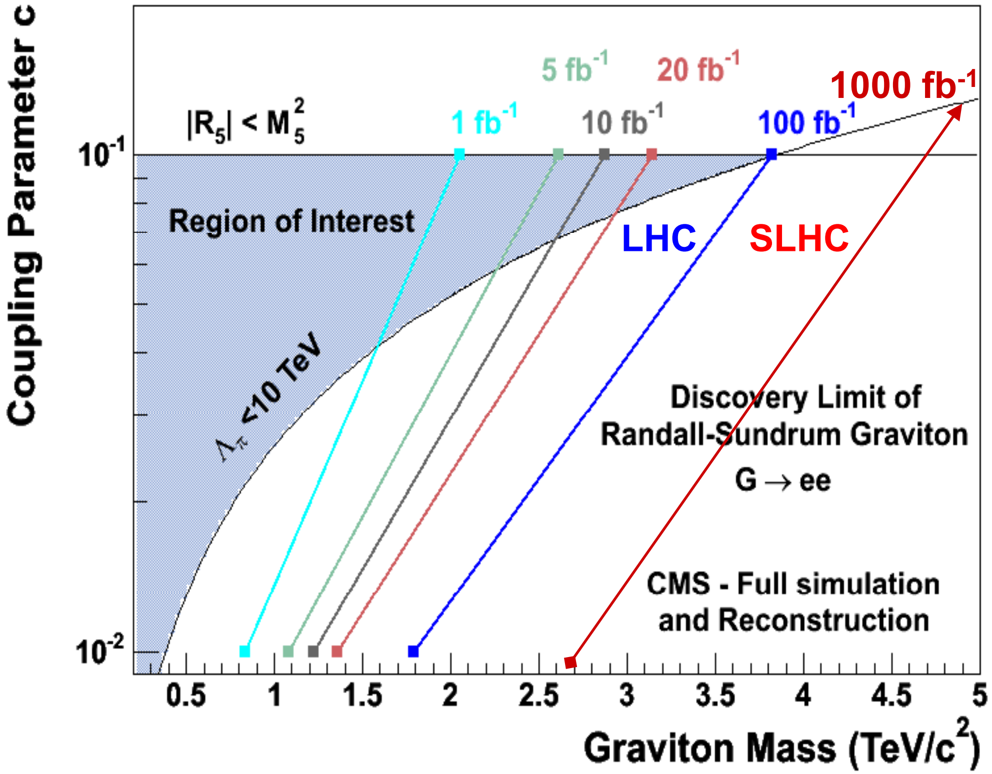
C. Collard



LHC: statistics limited. SLHC: ~ 10 increase in luminosity→ mass reach - increased by ~ 25% - & differentiate a Z' (spin = 1) from G_{RS} (spin = 2)

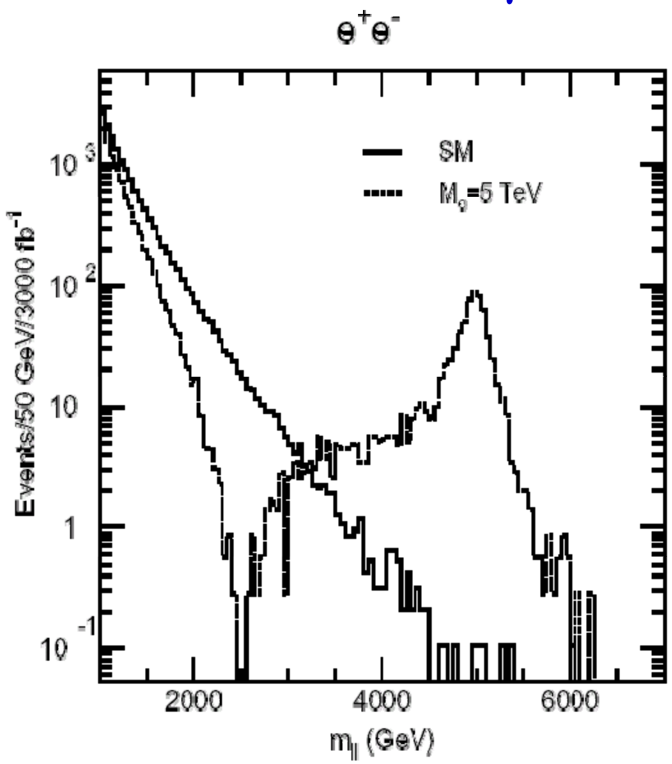
Gravitons

whole plane theoretically allowed, shaded part favored:



TeV scale Extra Dimensions

- KK excitations of the γ,Z

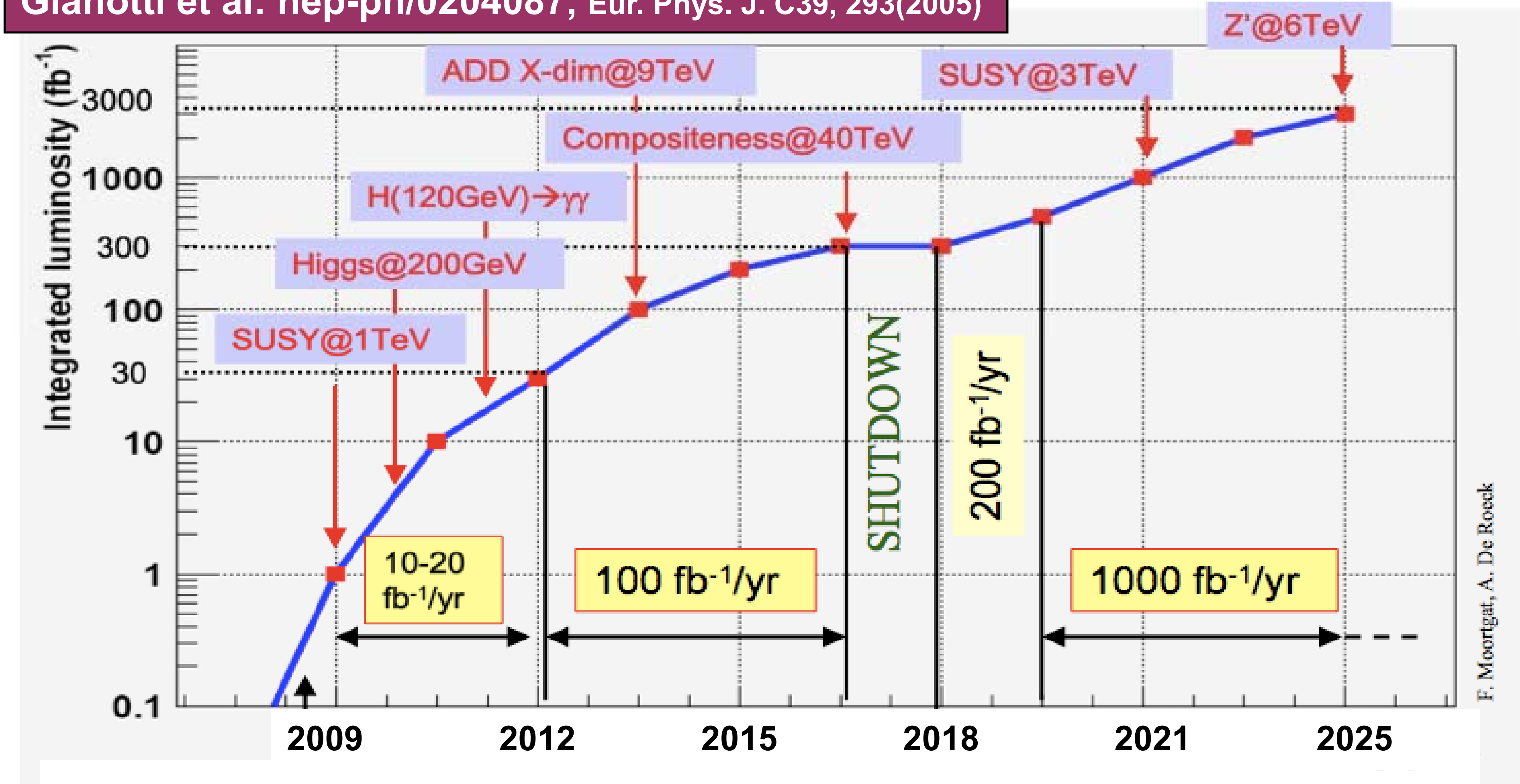


LHC→ SLHC: (100→1000 fb^{-1}): Increase in reach by ~ 1 TeV

Direct: LHC/600 fb^{-1} 6 TeV
SLHC/6000 fb^{-1} 7.7 TeV
Interf: SLHC/6000 fb^{-1} 20 TeV

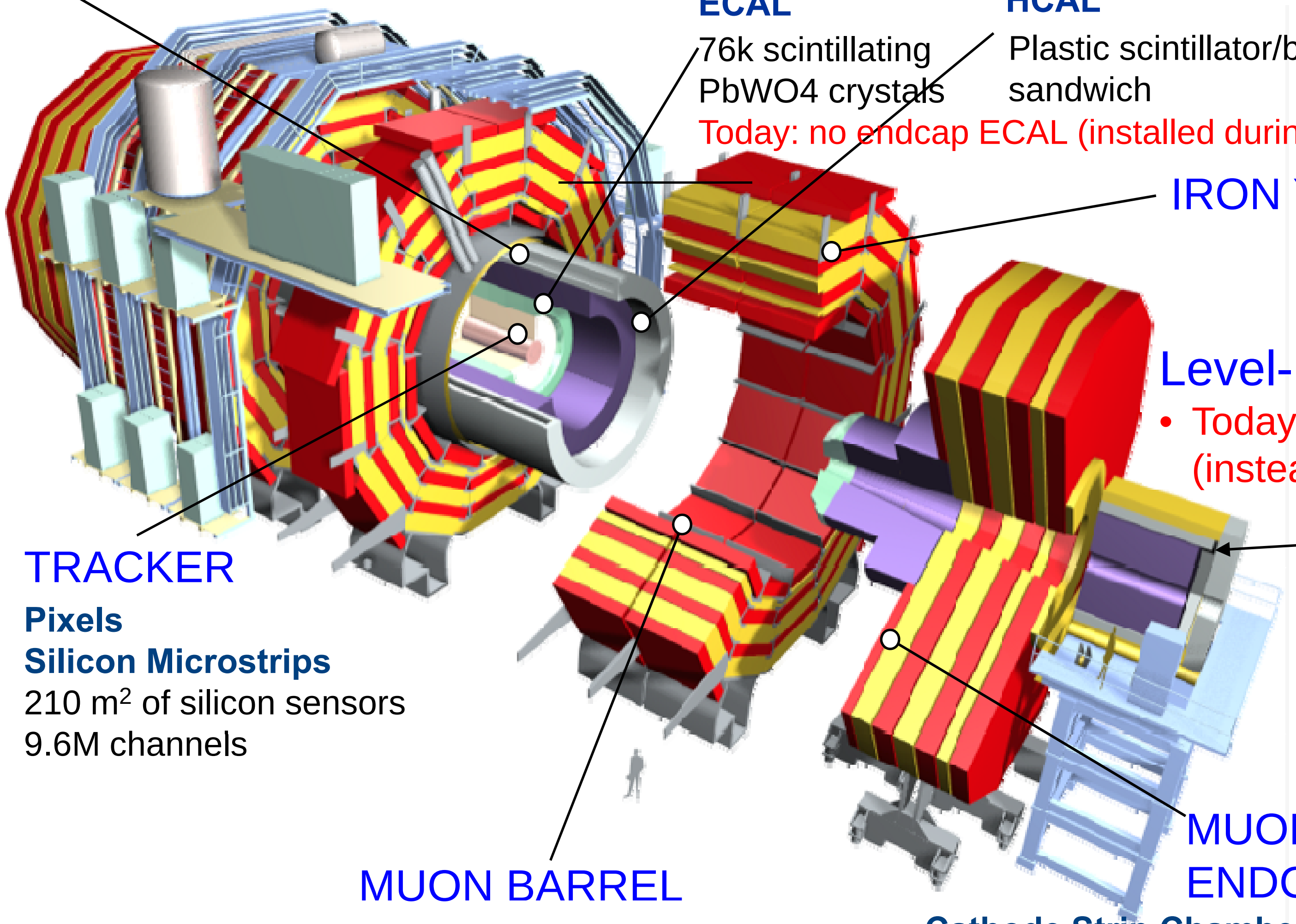
LHC → SLHC physics evolution

De Roeck, Ellis, Gianotti: hep-ph/0112004
Gianotti et al: hep-ph/0204087, Eur. Phys. J. C39, 293(2005)

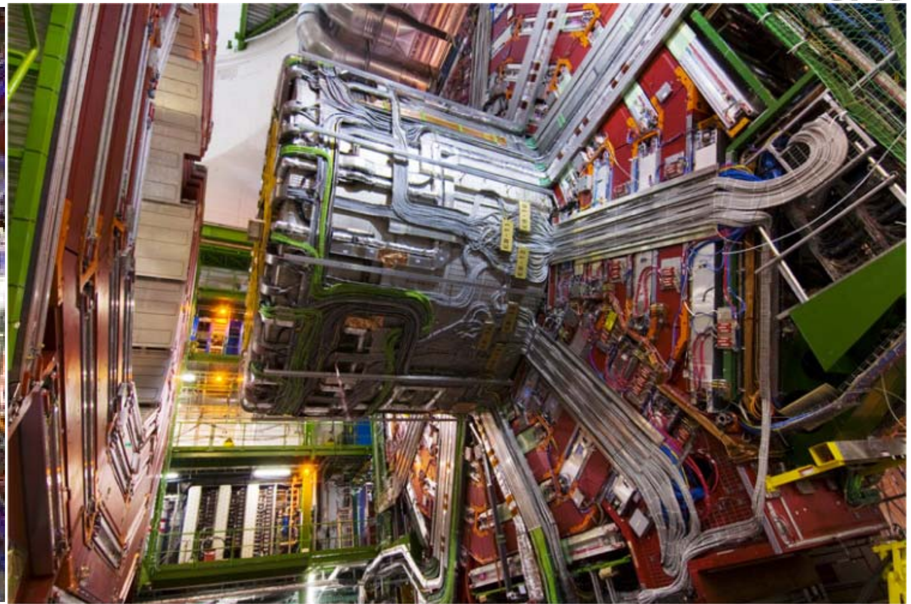


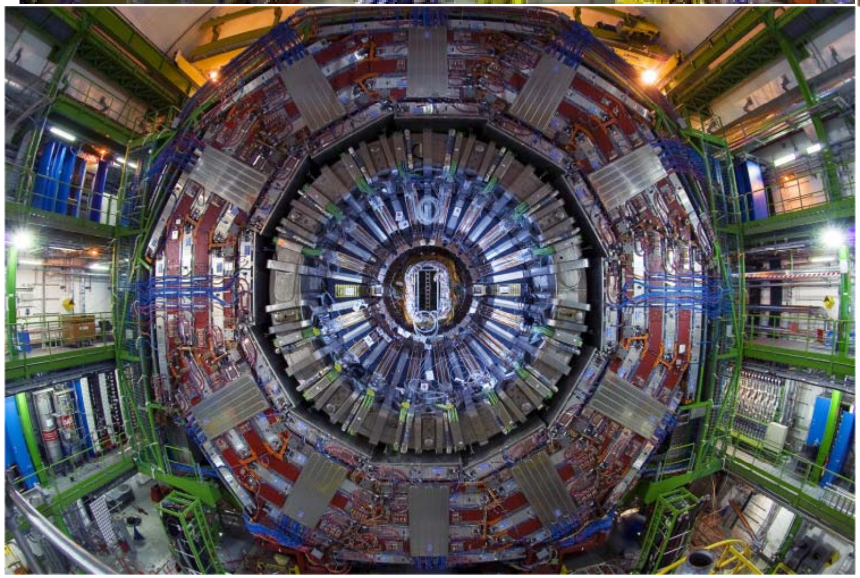
Timescale adjusted

CMS Detector Design

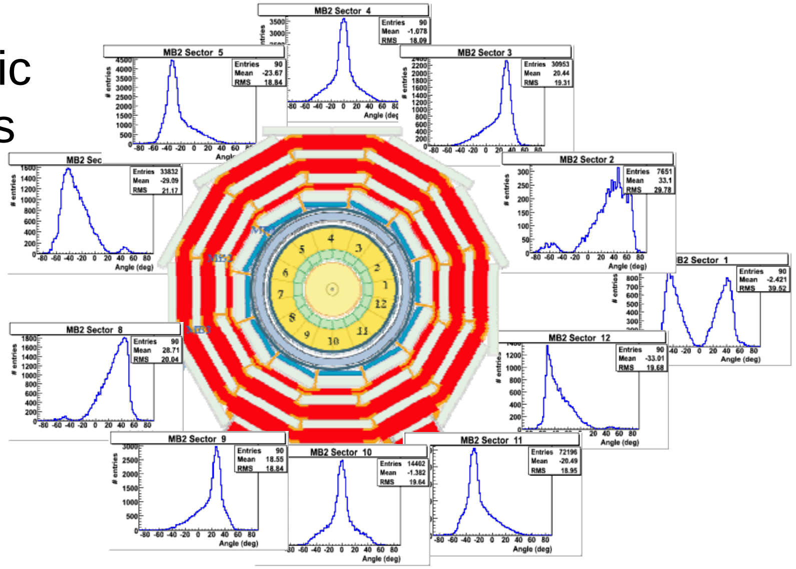


CMS Before Closing

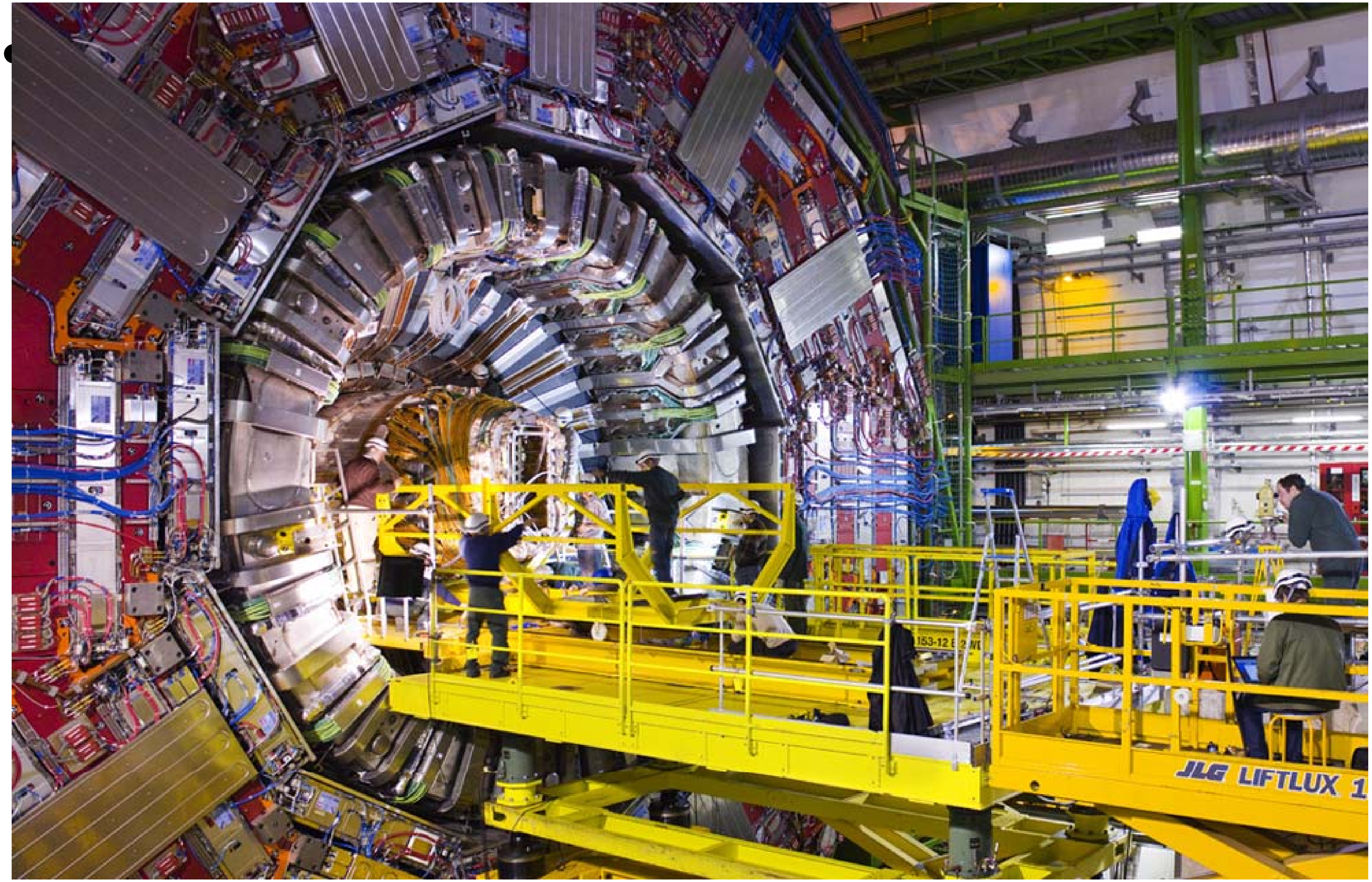




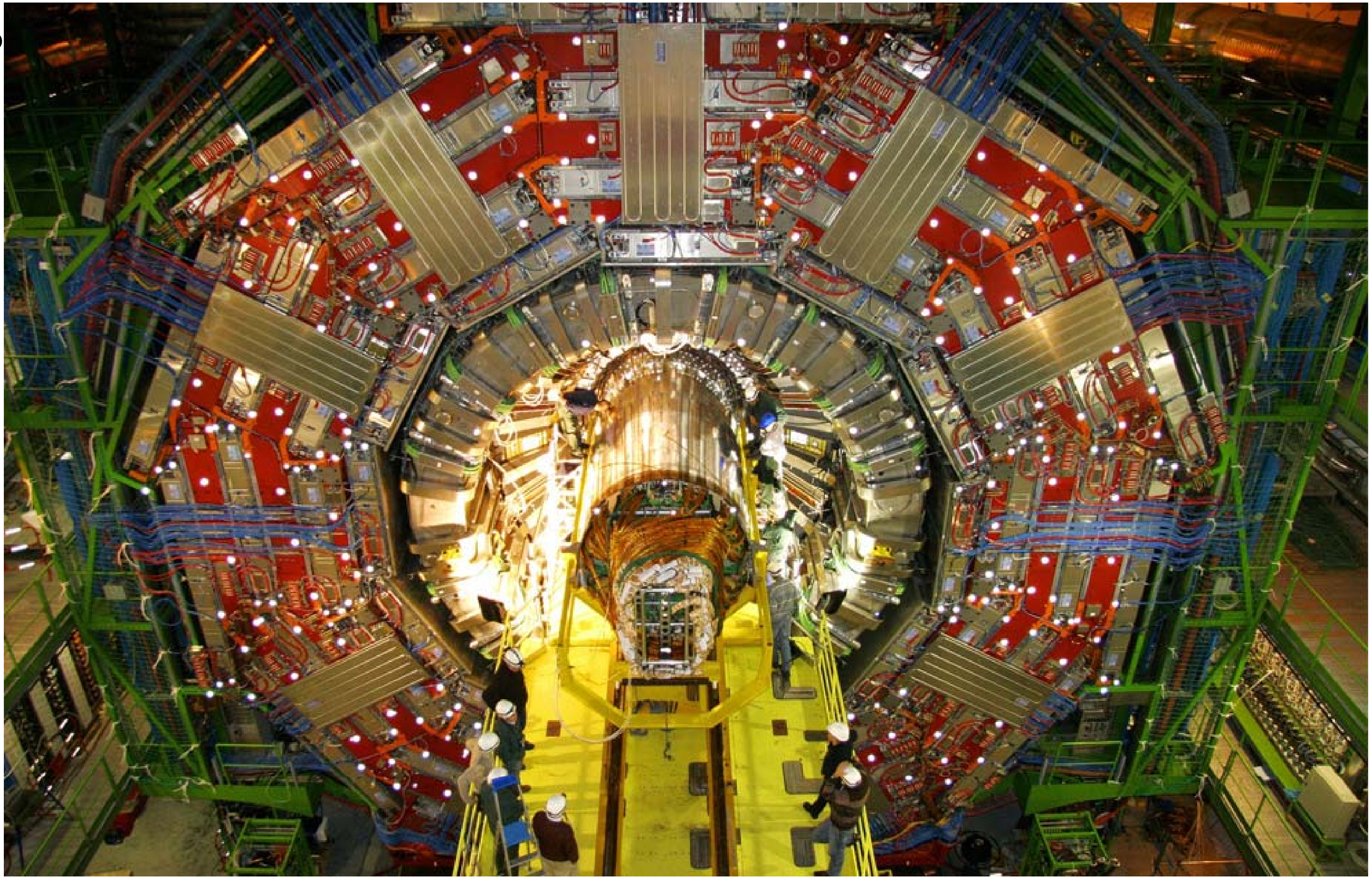
Cosmic
muons
thru
drift
tubes



CMS Before Closing



CMS Before Closing



CMS Before Closing

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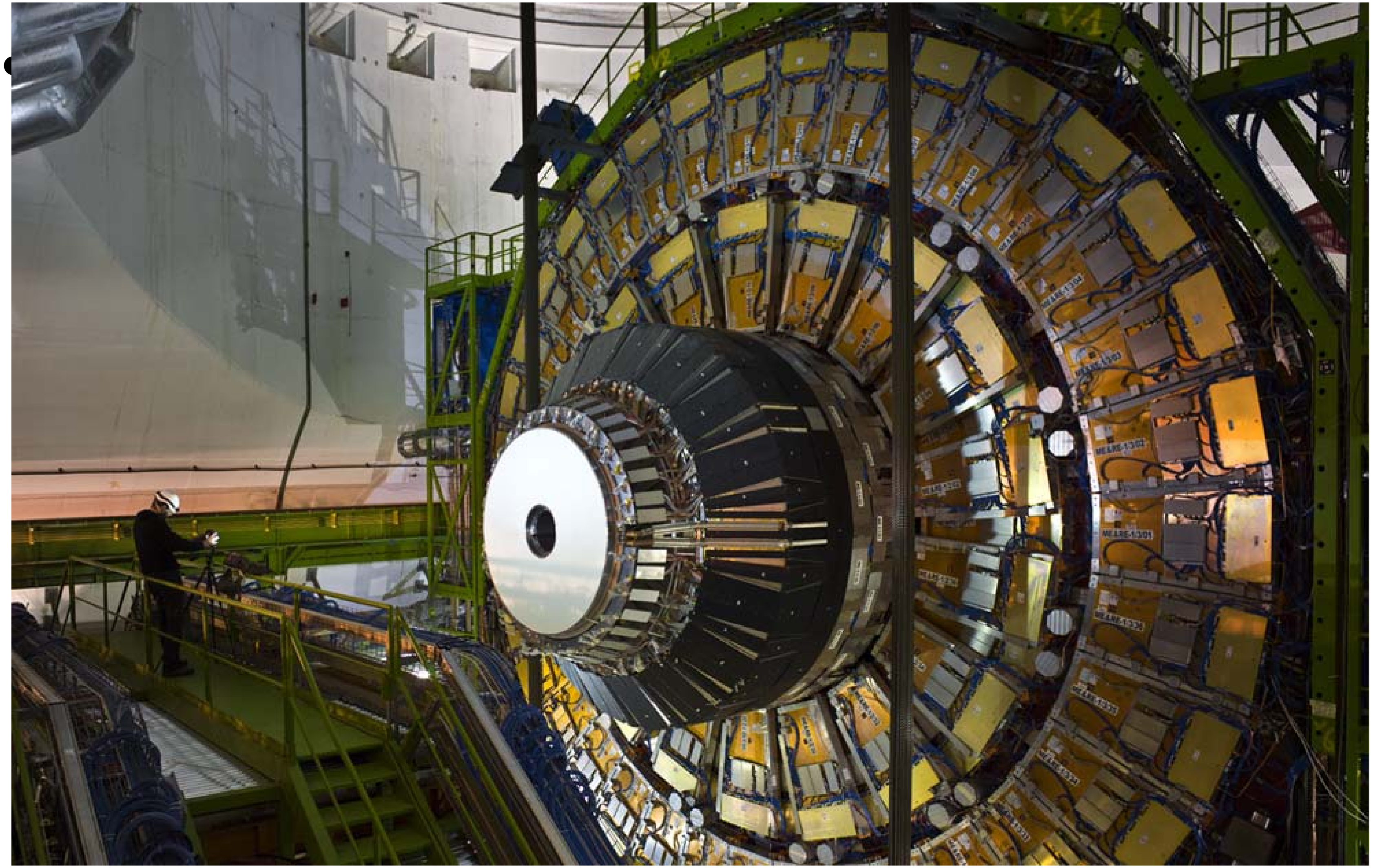
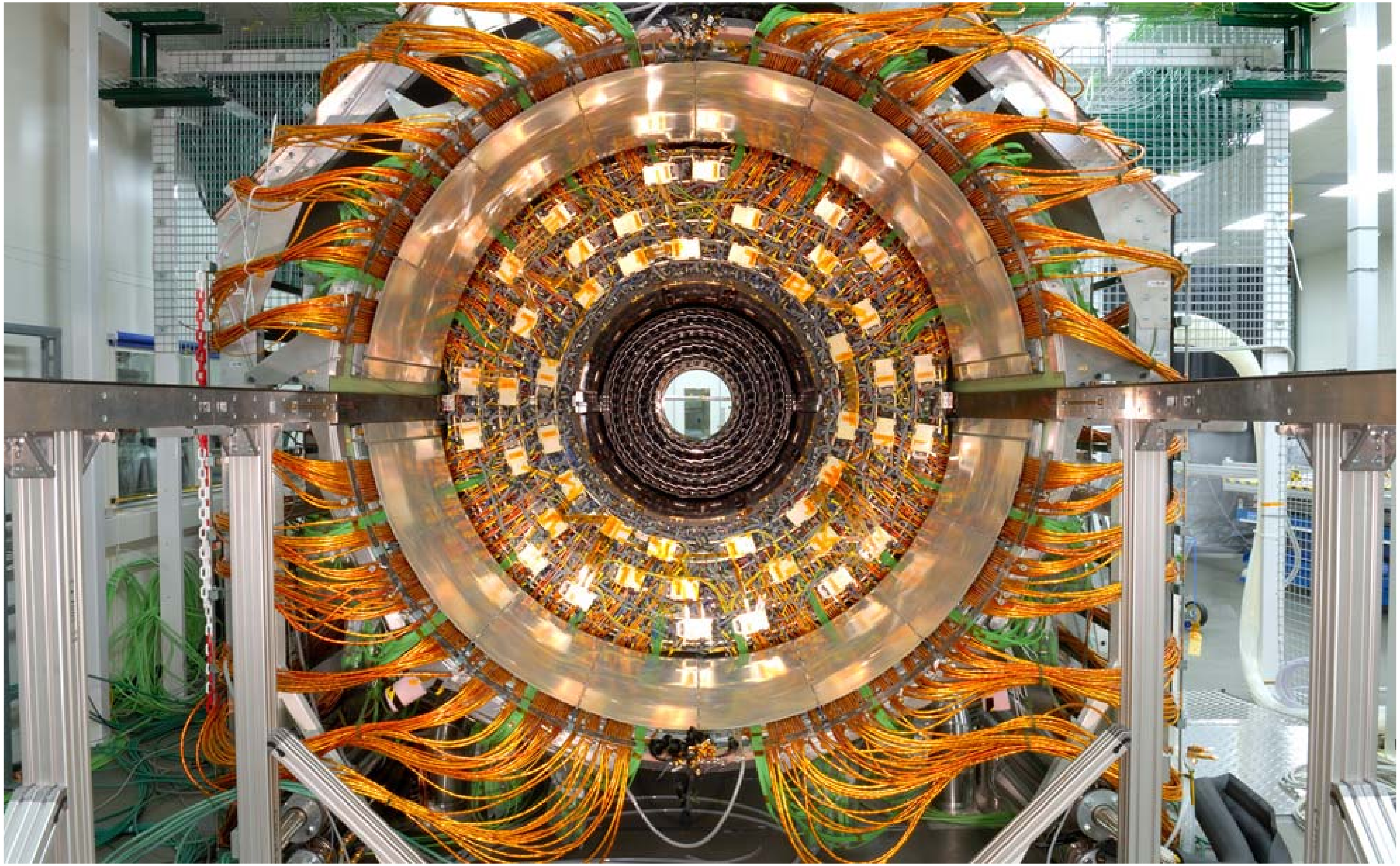
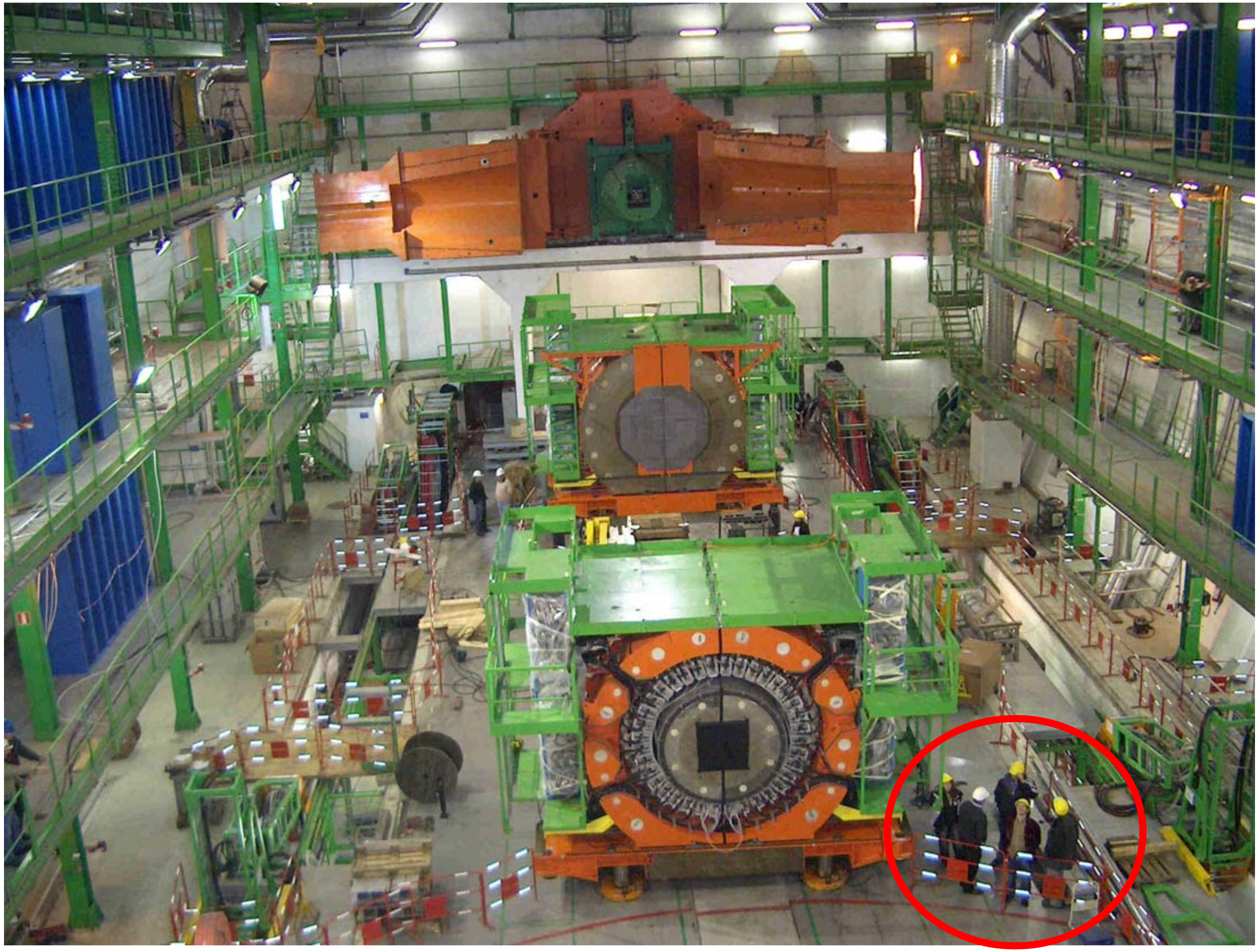


CMS Before Closing



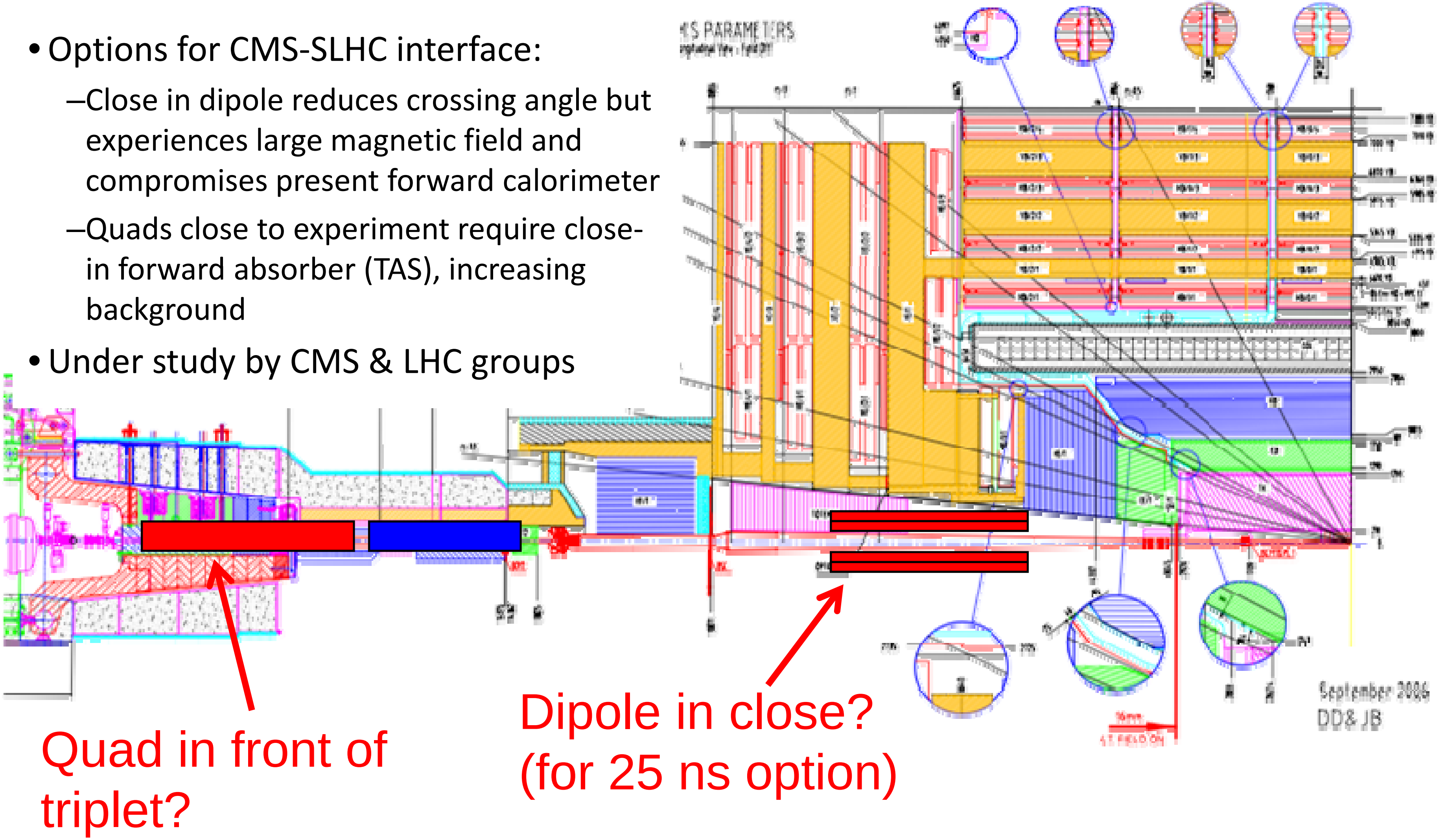
HF Lowering

Iowa Team at UX5



CMS at the SLHC

- Options for CMS-SLHC interface:
  - –Close in dipole reduces crossing angle but experiences large magnetic field and compromises present forward calorimeter
  - –Quads close to experiment require close-in forward absorber (TAS), increasing background
- Under study by CMS & LHC groups



Detector Luminosity Effects

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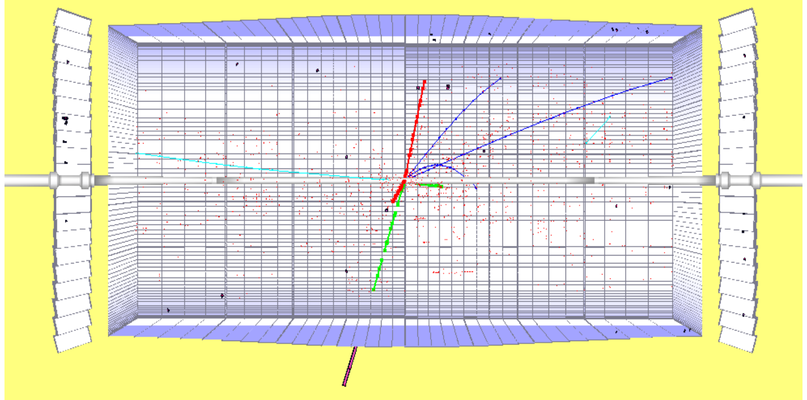
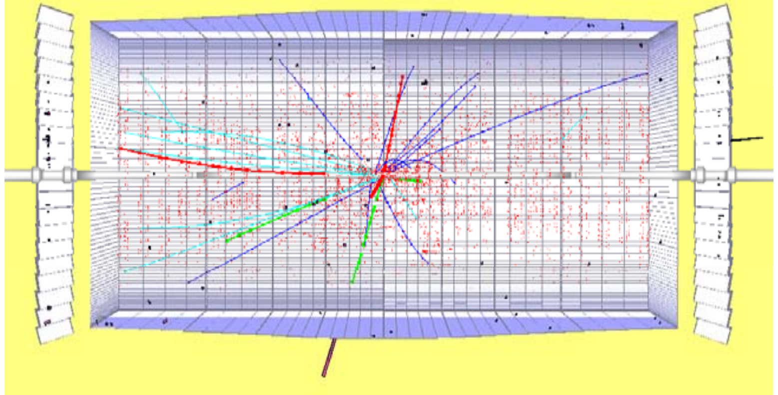
- $H \rightarrow ZZ \rightarrow \mu\mu ee$, M_H= 300 GeV for different luminosities in CMS

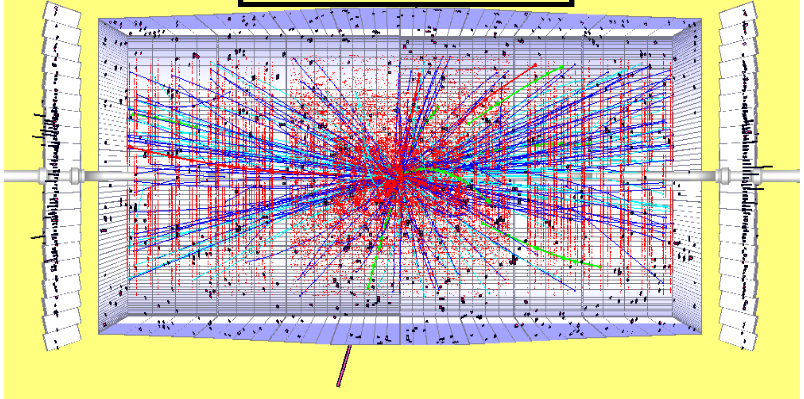
10^{32} cm^{-2}s^{-1}



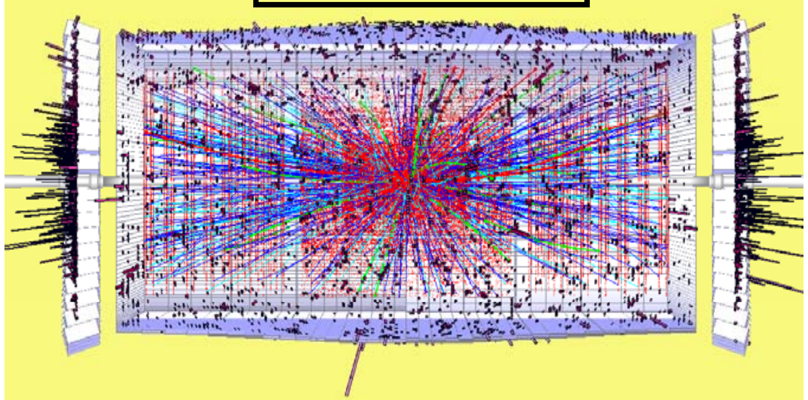
10^{33} cm^{-2}s^{-1}



10^{34} cm^{-2}s^{-1}

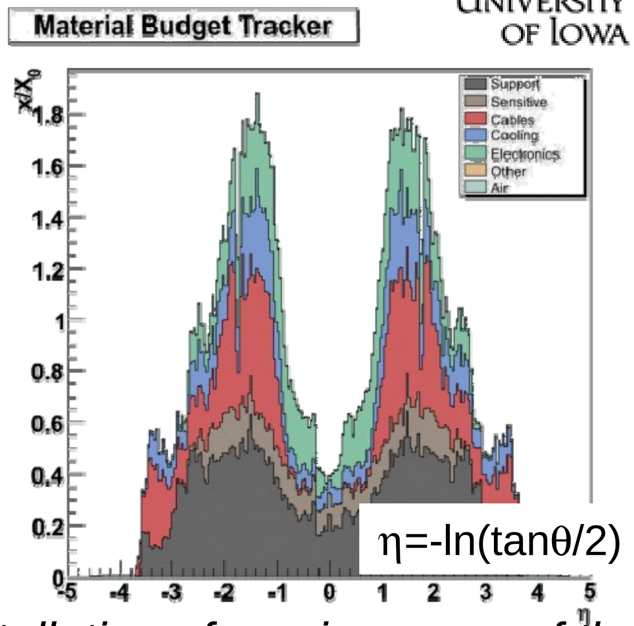


10^{35} cm^{-2}s^{-1}

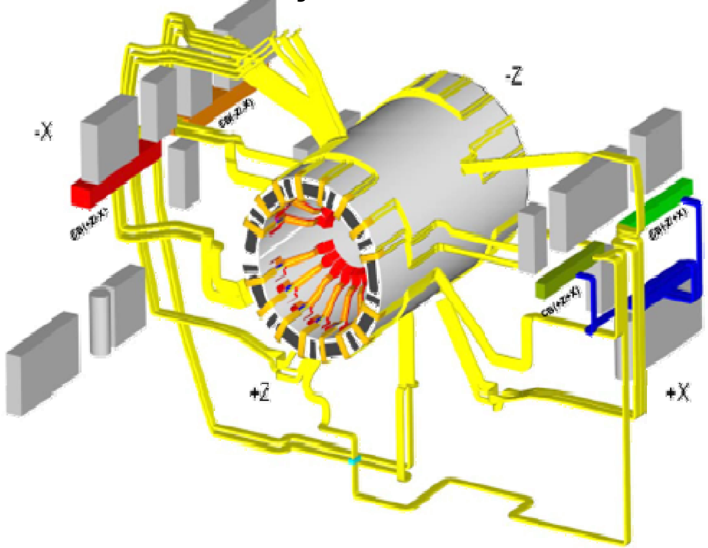


CMS Tracker Upgrade

- Challenge Facing CMS & ATLAS: Build a replacement tracker for L = 10^{35} $cm^{-2}s^{-1}$ with equal or better performance
- To do so, CMS & ATLAS need to solve several <u>very</u> difficult problems
  - deliver power - probably requiring greater currents
  - develop sensors to tolerate radiation fluences ~10x larger than LHC
  - reduce material in the tracker
  - *CMS needs to construct readout systems to contribute to the L1 trigger using tracker data - - next slides*
- It is probably <u>at least</u> as difficult a challenge as the original LHC detectors were in 1990



Installation of services one of the most difficult jobs to finish CMS

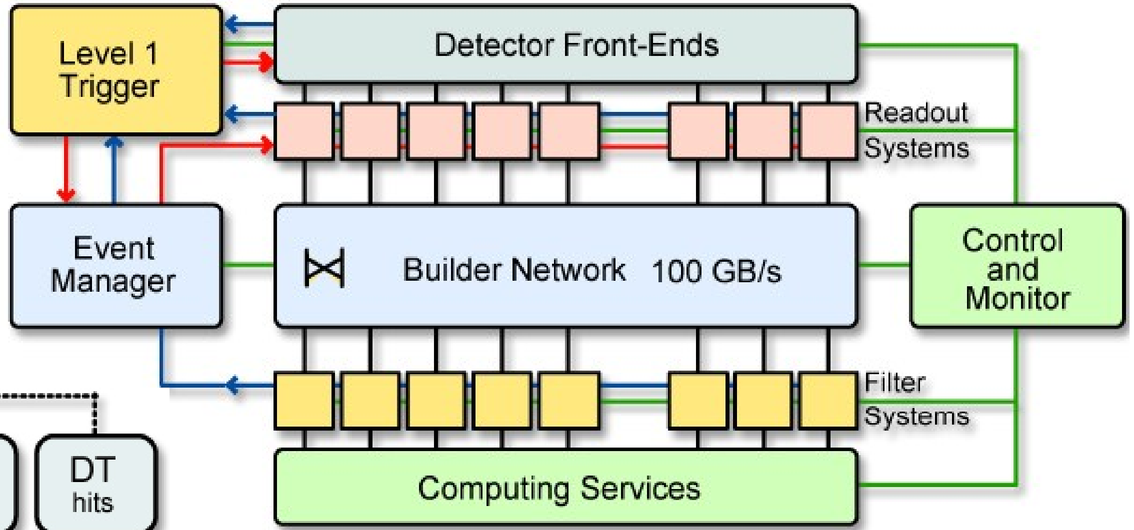


CMS SLHC Tracker R&D

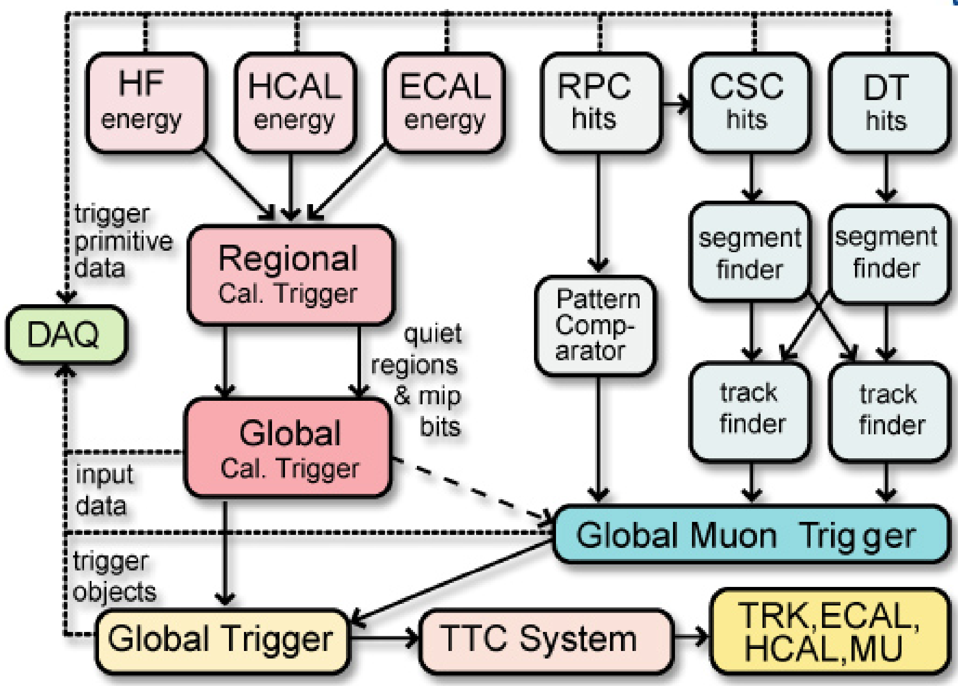
- Ultra Rad-hard sensors
  - Magnetic Czochralski (MCz) growth technology produces Si devices which are intrinsically highly oxygenated & high resistivity
  - Using p-type MCz Si wafers instead of n-type ones, has the further advantage of not encountering type inversion at high fluences
- Thin Sensors
  - For fluences > 10^{15} p/cm^2, sensors dissipate a lot of power
  - Thinner sensors $\rightarrow$ less volume $\rightarrow$ less current
- 3D or SOI Detectors
- Large area low cost interconnections
- Low mass components & cooling methods
- New Pixel Front End ASIC
  - Reduced power -- switch from 250 to 130 nm technology helps
  - Increased radiation tolerance

CMS Trig & DAQ for LHC

- Overall Trigger & DAQ Architecture: 2 Levels:



- Level-1 Trigger:



Interaction rate: 1 GHz

Bunch Crossing rate: 40 MHz

Level 1 Output: 100 kHz (50 initial)

Output to Storage: 100 Hz

Average Event Size: 1 MB

Data production 1 TB/day

SLHC Level-1 Trigger @ 10^{35}

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- Occupancy
  - Degraded performance of algorithms
    - Electrons: reduced rejection at fixed efficiency from isolation
    - Muons: increased background rates from accidental coincidences
  - Larger event size to be read out
    - New Tracker: higher channel count & occupancy → large factor
    - Reduces the max level-1 rate for fixed bandwidth readout.
- Trigger Rates
  - Try to hold max L1 rate at 100 kHz by increasing readout bandwidth
    - Avoid rebuilding front end electronics/readouts where possible
      - Limits: ⟨readout time⟩ (< 10 μs) and data size (total now 1 MB)
    - Use buffers for increased latency for processing, not post-L1A
    - May need to increase L1 rate even with all improvements
      - Greater burden on DAQ
  - Implies raising E_T thresholds on electrons, photons, muons, jets and use of multi-object triggers, unless we have new information ⇒Tracker at L1
    - Need to compensate for larger interaction rate & degradation in algorithm performance due to occupancy
- Radiation damage -- Increases for part of level-1 trigger located on detector

CMS Level-1 Latency

- Present CMS Latency of 3.2 μsec = 128 crossings @ 40MHz
  - Limitation from post-L1 buffer size of tracker & preshower
  - Assume rebuild of tracking & preshower electronics will store more than this number of samples
- Do we need more?
  - Not all crossings used for trigger processing (70/128)
    - It's the cables!
  - Parts of trigger already using higher frequency
- How much more? Justification?
  - Combination with tracking logic
  - Increased algorithm complexity
  - Asynchronous links or FPGA-integrated deserialization require more latency
  - Finer result granularity may require more processing time
  - ECAL digital pipeline memory is 256 40 MHz samples = 6.4 μsec
    - Propose this as CMS SLHC Level-1 Latency baseline

Use of CMS L1 Tracking Trigger

- Combine with L1 μ trigger as is now done at HLT:
  - Attach tracker hits to improve P_T assignment precision from 15% standalone muon measurement to 1.5% with the tracker
    - Improves sign determination & provides vertex constraints
  - Find pixel tracks within cone around muon track and compute sum P_T as an isolation criterion
    - Less sensitive to pile-up than calorimetric information *if* primary vertex of hard-scattering can be determined (~100 vertices total at SLHC!)
- To do this requires η–ϕ information on muons finer than the current 0.05–2.5°
  - No problem, since both are already available at 0.0125 and 0.015°

SLHC: CMS Calorimeter

- Forward Calorimeter: Quartz Fiber
  - –Radiation tolerant
  - –Very fast
  - –Modify logic to provide finer-grain information
    - Improves forward jet-tagging
- Hadron Barrel & Endcap Calorimeters
  - –Plastic scintillator tiles and wavelength shifting fiber is radiation hard up to 2.5 MRad while at SLHC, expect 25MRad in HE.
    - R&D new scintillators and waveshifters in liquids, paints, and solids, and Cerenkov radiation emitting materials e.g. Quartz
  - –Study silicon photomultipliers (SiPMs) to replace Hybrid Photodiodes (HPDs)
    - Less noise, more amplification, magnetic, radiation tolerance under study
- ECAL: PBWO4 Crystal: Stays
  - –Sufficiently radiation tolerant
  - –Exclude on-detector electronics modifications for now -- difficult:
    - Regroup crystals to reduce $\Delta\eta$ tower size -- minor improvement
    - Additional fine-grain analysis of individual crystal data -- minor improvement

HCAL Upgrades

The University of Iowa

- 1st Phase of R&D
- 2nd Phase of R&D
  - Light enhancement tools: ZnO, PTP
  - Radiation damage tests on Quartz and PTP
- 3rd Phase of R&D
  - Alternative readout options:
    - PIN Diode, APD, SiPMT,
    - Microchannel PMT, MPPC
  - Radiation Hard WLS Fiber options
    - Quartz core sputtered with ZnO
    - Sapphire fibers

First Phase of the R&D

1. Show that the proposed solution is feasible
2. Tests and simulations of QPCAL-1

The “Problem” and the “Solution”

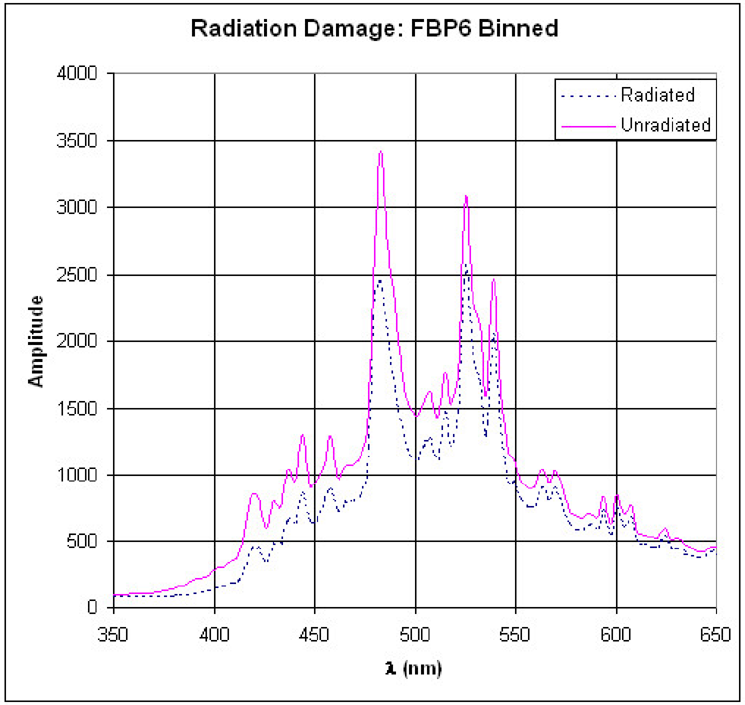
- As a solution to the radiation damage problem in SuperLHC conditions, quartz plates are proposed as a substitute for the scintillators at the Hadronic Endcap (HE) calorimeter.
- Quartz plates will not be affected by high radiation. But the number of generated cerenkov photons are at the level of 1% of the scintillators.

Rad-hard quartz

– Quartz in the form of fiber are irradiated in **Argonne IPNS** for 313 hours.

– The fibers were tested for optical degradation before and after 17.6 Mrad of neutron and 73.5 Mrad of gamma radiation.

– Polymicro manufactured a special radiation hard anti solarization quartz plate.



1st Paper : R&D Studies on Light Collection

- As a solution to the radiation damage problem in SuperLHC conditions, quartz plates are proposed as a substitute for the scintillators at the Hadronic Endcap (HE) calorimeter.

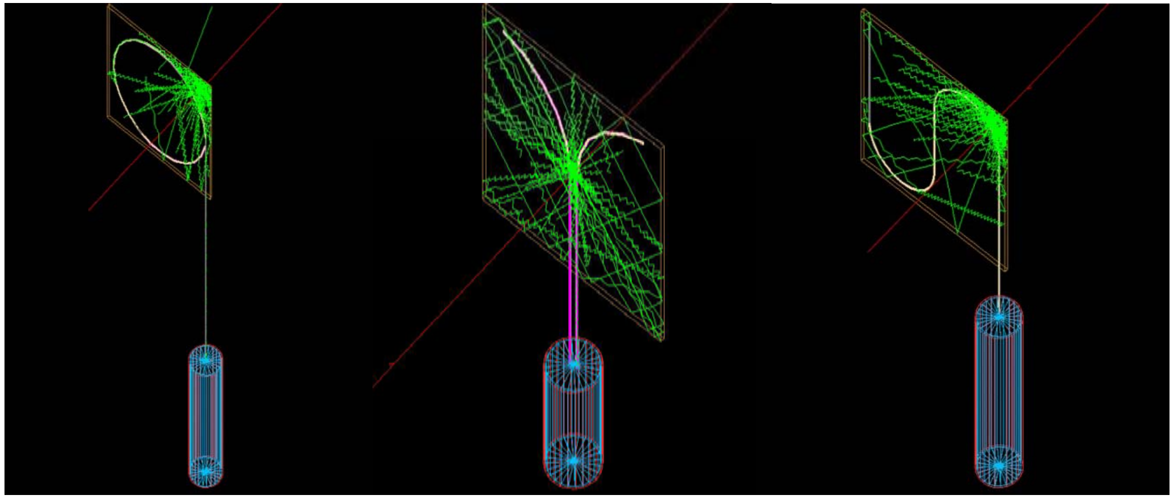
- The paper (CMS-NOTE 2007/019) summarizing the First Phase of the R&D studies has been published :

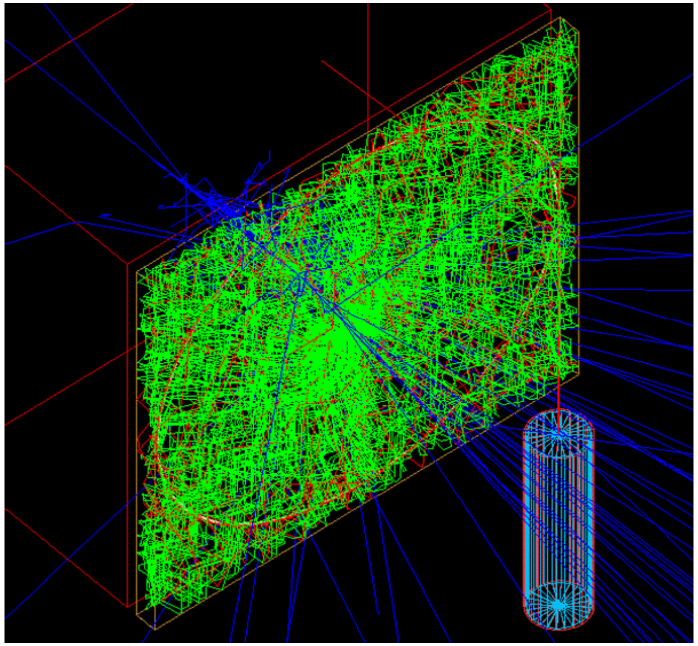
- *F. Duru et al*. "*CMS Hadronic EndCap Calorimeter Upgrade Studies for SLHC - Cerenkov Light Collection from Quartz Plates*" , *IEEE Transactions on Nuclear Science, Vol 55, Issue 2, 734-740, Apr 2008.*

- With these very nice comments from the editor and the refrees:

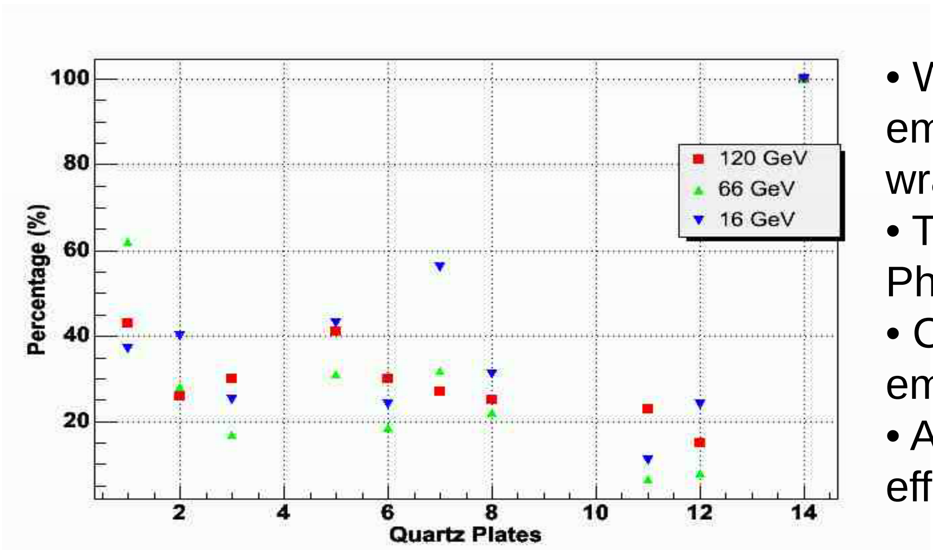
- *"The paper is very interesting and clearly proves that a solution exits for calorimeters in the SLHC era with similar light collection."*
- *"The authors are to be thanked for a very interesting piece of work"*

1st Paper : R&D Studies on Light Collection





• We have tested/simulated different fiber geometries in the quartz plates, for their light collection uniformity and efficiency.



• WaveLength Shifting (WLS) fiber, Bicron 91a, is embedded in the quartz plate. Quartz plates are wrapped with reflecting material of 95 % efficiency.

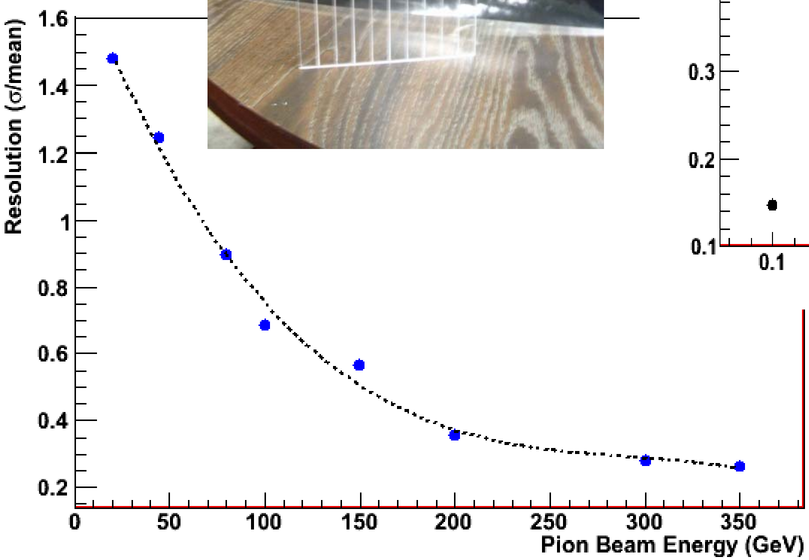
• The Cerenkov photons reaching the PhotoMultiplierTube (PMT) are counted.

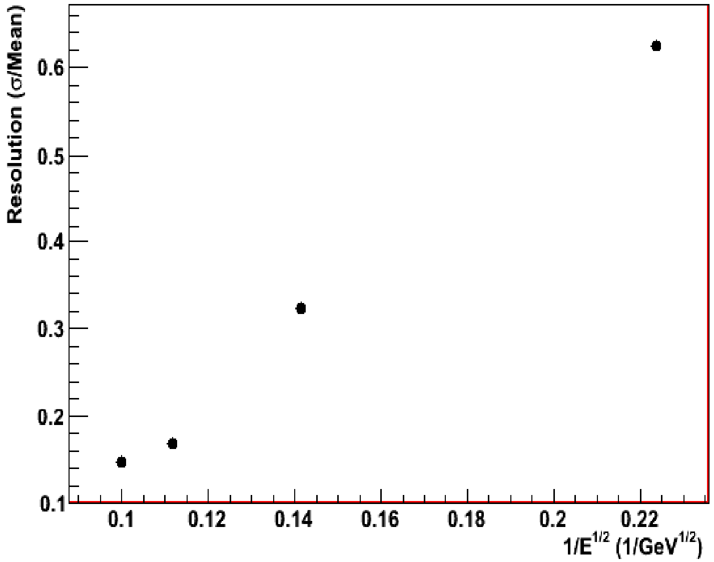
• Cerenkov Photons are shown in green. Photons emitted by WLS process are shown in red.

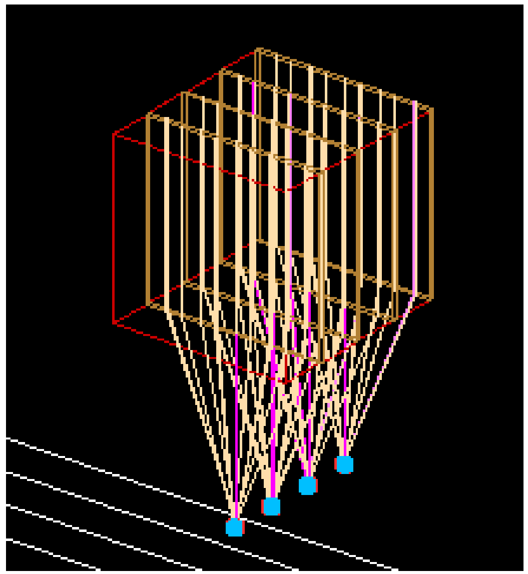
• At the test beams we compared the light collection efficiencies with that of original HE scintillators.

2nd Paper : Quartz Plate Calorimeter Prototype - I

The first quartz plate calorimeter prototype (QPCAL - I) was built with WLS fibers, and was tested at CERN and Fermilab test beams.





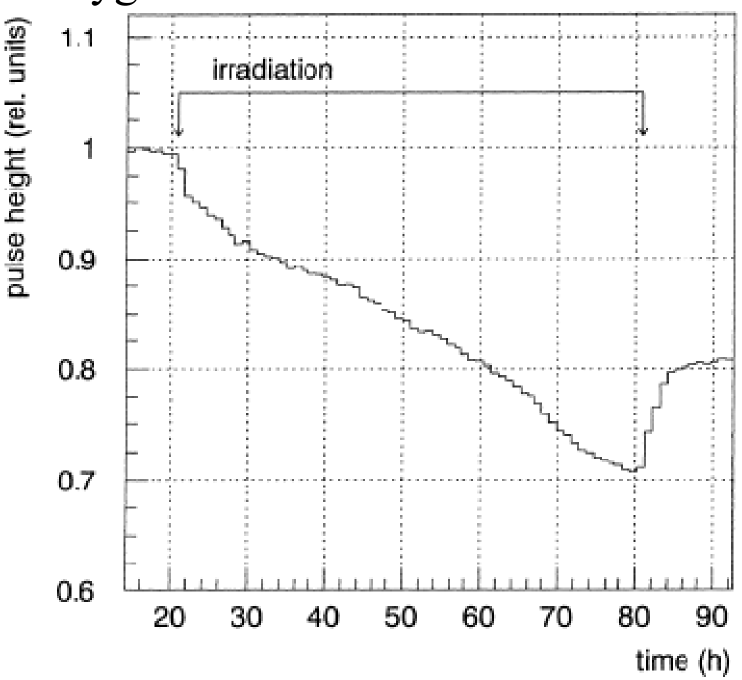


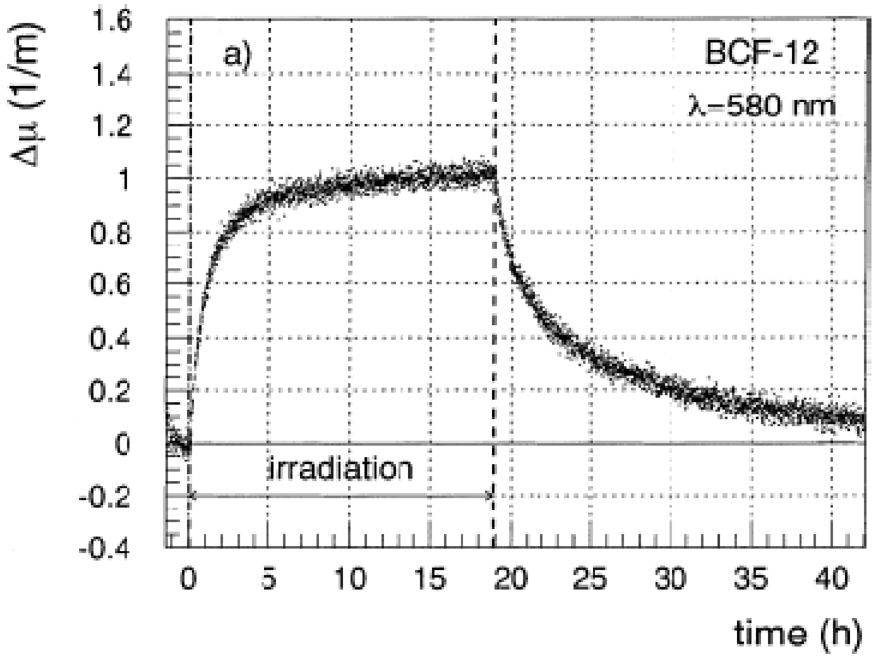
Hadronic Resolution

What is missing on the 1st Phase?

- The WLS fibers used in QPCAL are BCF-12 by Saint Gobain (old Bicron) are not radiation hard.
-The radiation hardness tests performed on BCF-12 shows that they are not very different than Kuraray 81 (current HE fibers).
-The studies shows that BCF-12 can be more radiation hard with the availability of oxygen.

W. Busjan et al. NIM B 152, 89-104





Second Phase of the R&D

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- 1. How can we solve the fiber radiation problem?
  a) Use engineering designs
  b) Light enhancement tools (ZnO, PTP, etc.)
- 2. Radiation Damage Tests
- a) On Quartz
- b) On PTP

Engineering Options

- Current BCF-12 WLS fiber is very radiation hard, but it can still be used

- *) We can engineer a system with fibers continuously fed thru a spool system. Iowa has
- built the source drivers for all HCAL (Paul Debbins), we also have expertise on site;
- Tom Schnell (University of Iowa Robotic Engineering).
- *We have shown that a set of straight (or a gentle bend) quartz plate grooves allow WLS fibers to be easily pulled out and replaced.*

- *) Different approach could be to use radiation hard quartz capillaries with pumped
- WLS liquid. We have the expertise; B. Webb (Texas A & M), E. Norbeck (Iowa) and
- D. Winn (Fairfield).
- *This has been studies at Fairfield. The liquid (benzyl alcohol + phenyl naphthalene) has an index of 1.6 but the attenuation length is still somewhat too short, possibly because of a too high WLS concentration.*

Light Enhancement Tools

THE UNIVERSITY OF IOWA

- Proposed Solution

- *) Eliminate the WLS fibers:
- Increase the light yield with radiation hard scintillating/WLS materials and use a direct readout from the plate.

- Questions… Questions …

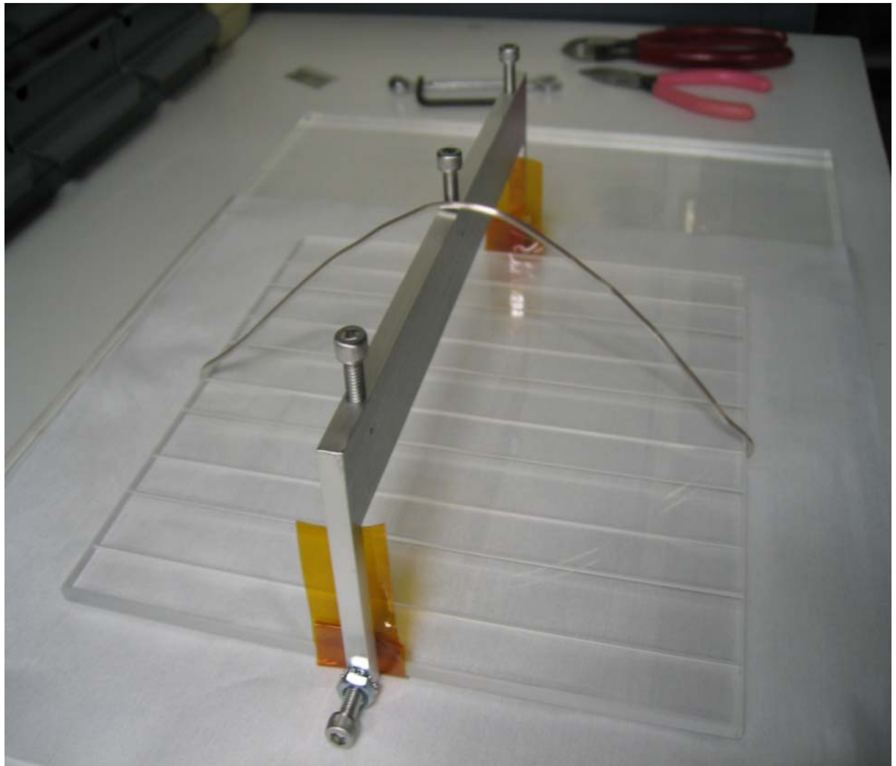
- *) What is out there to help us?
  PTP (oTP, mTP, pQP), and/or ZnO can be used to enhance the light production.
  - How to apply them to the plates? and what thickness?
  - Which one work better?
  - Which is more radiation hard?

Quartz Plates with PTP

•At Fermilab Lab7, we have covered quartz plates with PTP by evaporation. We deposited 1.5, 2, 2.5, and 3 micron thickness of PTP.

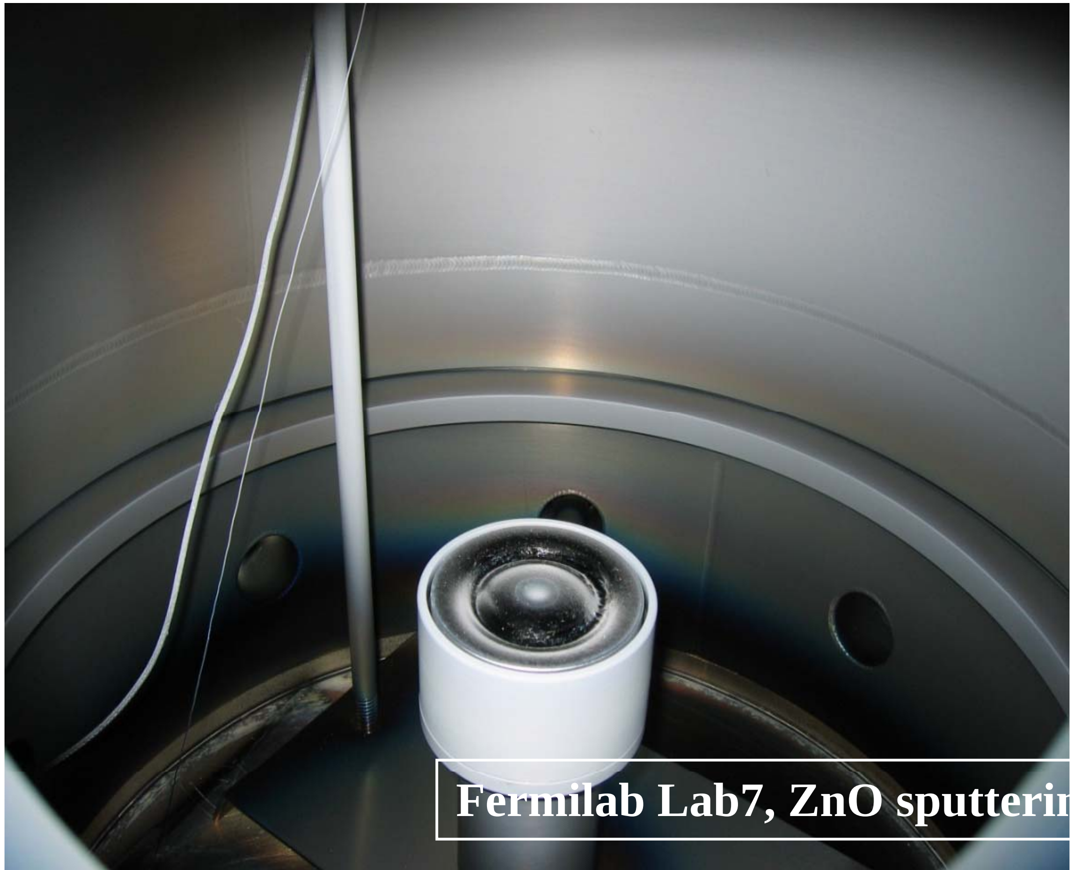
Quartz Plates with PTP

PTP evaporation setup, and quartz plate holder



Quartz Plates with ZnO

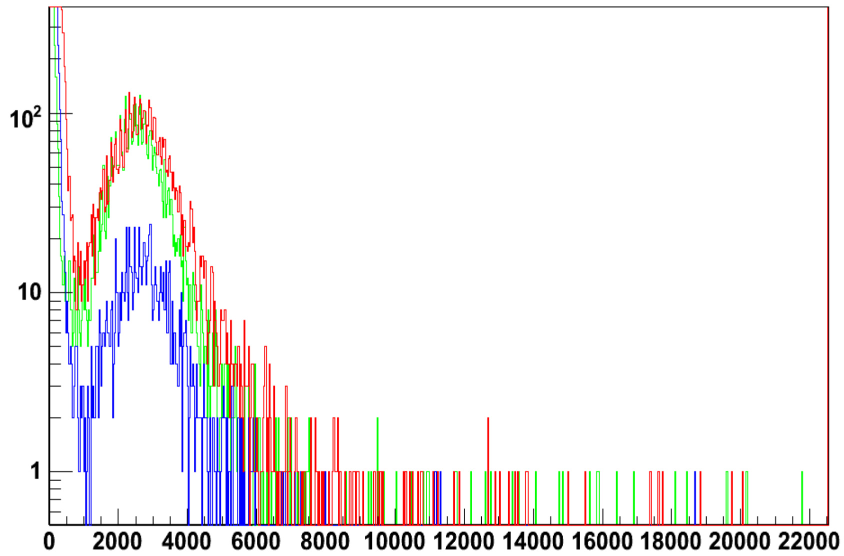
- We also cover quartz plates with ZnO (3% Ga doped), by RF sputtering. 0.3 micron and 1.5 micron.
- We are currently working on 100 micron thick quartz plates, we've deposited ZnO on each layer and bundle the plates together, for a radiation hard scintillating plate ☺



Fermilab Lab7, ZnO sputterin

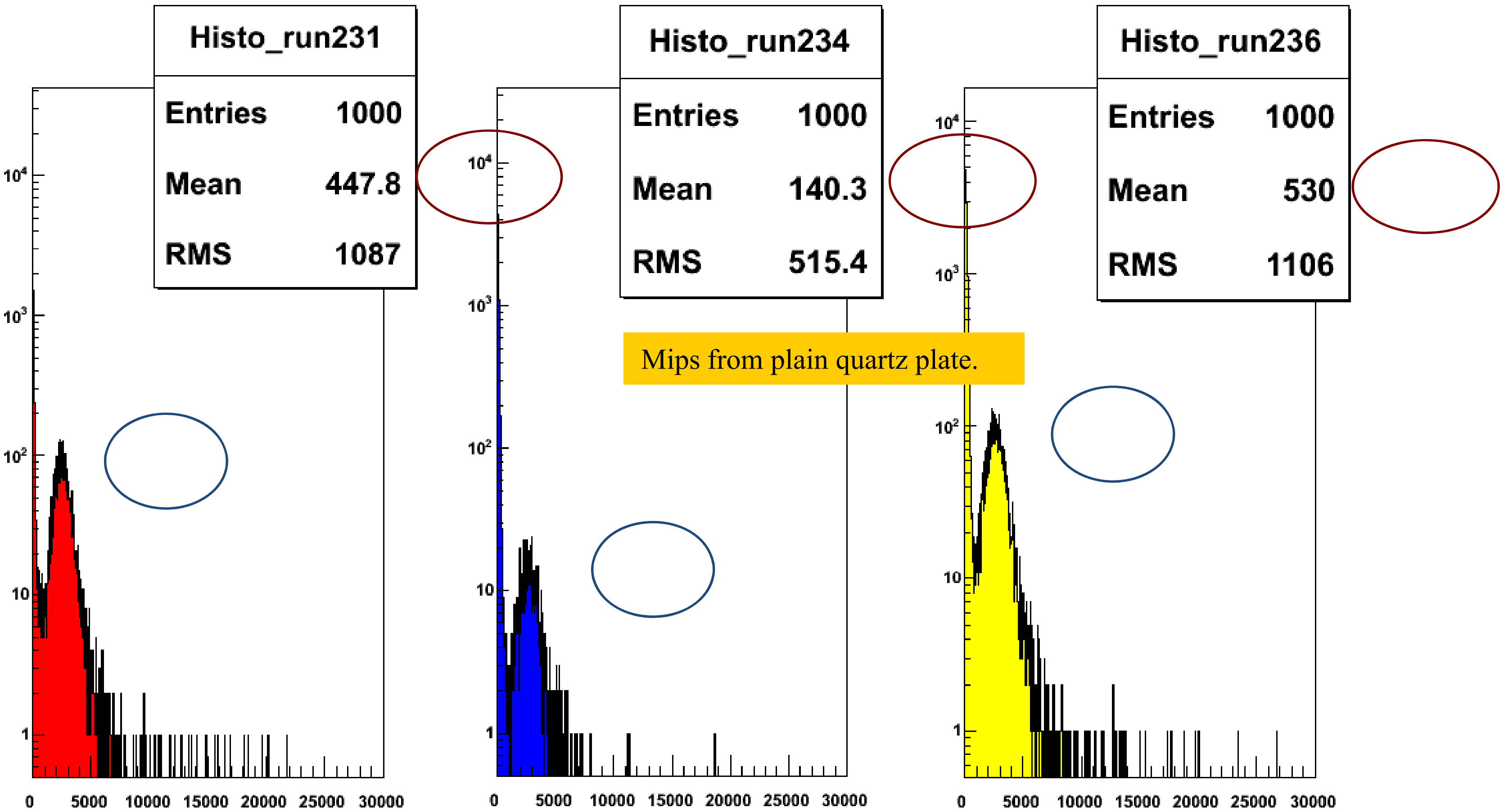
Test Beams for PTP and ZnO

We have opportunity to test our ZnO and PTP covered plates, at CERN (Aug07), and Fermilab MTest (Nov 07, and Feb 08).



Blue : Clean Quartz
Green : ZnO (0.3 micron)
Red : PTP (2 micron)

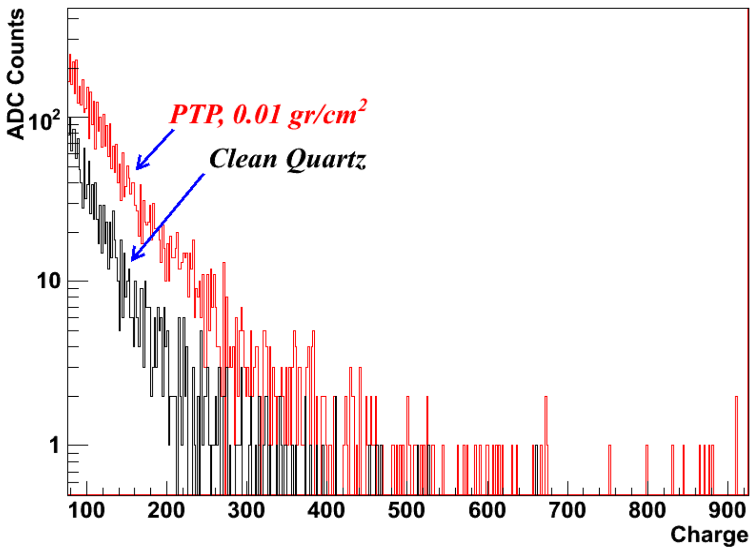
Test Beams for PTP and ZnO



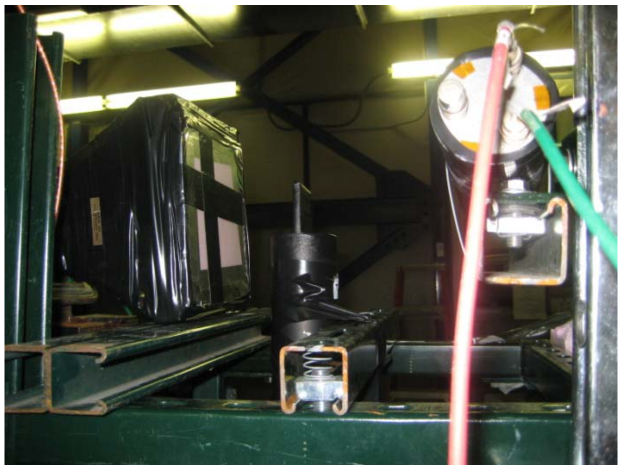
Mips from 0.3 micron thick ZnO (3% Ga) sputtered quartz plate.

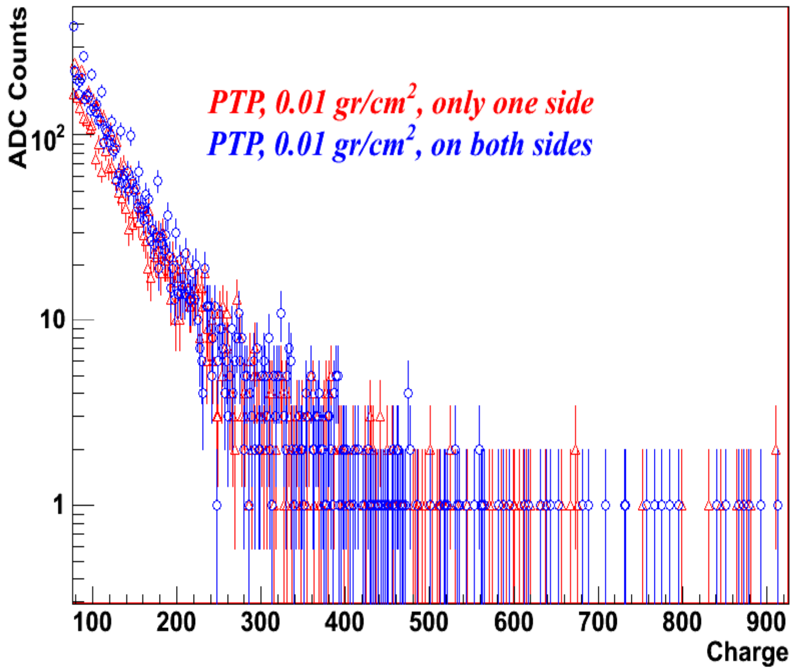
Mips from PTP evaporated quartz plate.

Test Beams for PTP and ZnO



We evaporated PTP on quartz plates in IOWA and tested them in MTest.
Different deposition amounts and variations Were tested.





Cern Test Beam – Summer 2008

- We built the QPCAL - V2, with PTP deposited quartz layers.
- The 20cm x 20cm x 5 mm, GE-124 quartz plates are used.
- 2 µm PTP is evaporated on quartz at Fermilab Lab 7.
- The readout was performed with Hamamatsu PMTs.
- We also tested different thickness of ZnO and PTP deposited plates for mips.
- The “new plate” with stack of seven 100 µm thick quartz plates, each sputtered ZnO on. This can give us a very radiation hard scintillating quartz plate. As a by product of our work ☺.

What is learned from Phase II ?

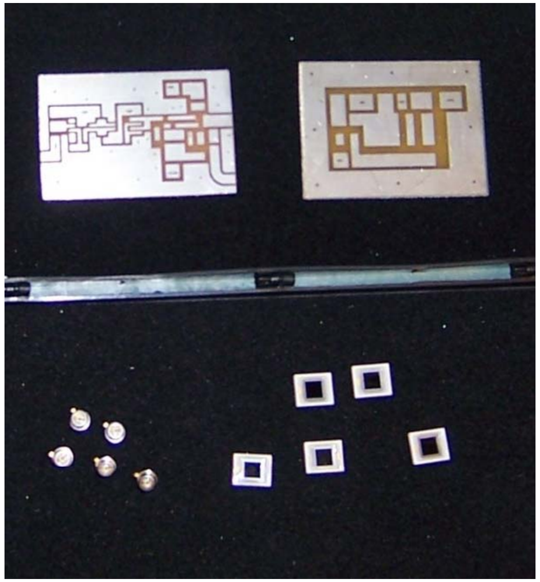
- The PTP and Ga:ZnO (4% Gallium doped) enhance the light production almost 4 times.
- OTP, MTP, and PQP did not perform as well as these.
- PTP is easier to apply on quartz, we have a functioning evaporation system in Iowa, works very well. We also had successful application with RTV. Uniform distribution is critical!!
- ZnO can be applied by RF sputtering, we did this at Fermilab- LAB7. We got 0.3 micron, and 1.5 micron deposition samples. 0.3 micron yields better light output.

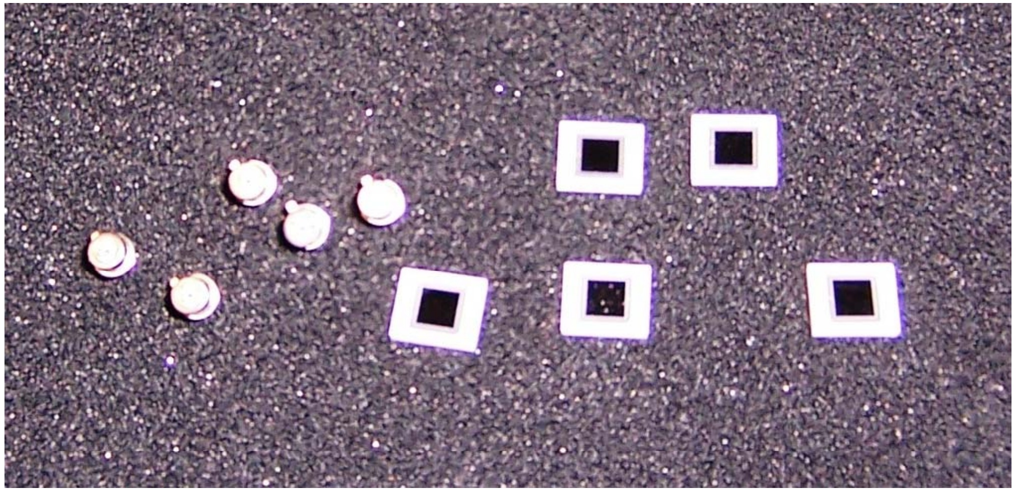
Third Phase of the R&D

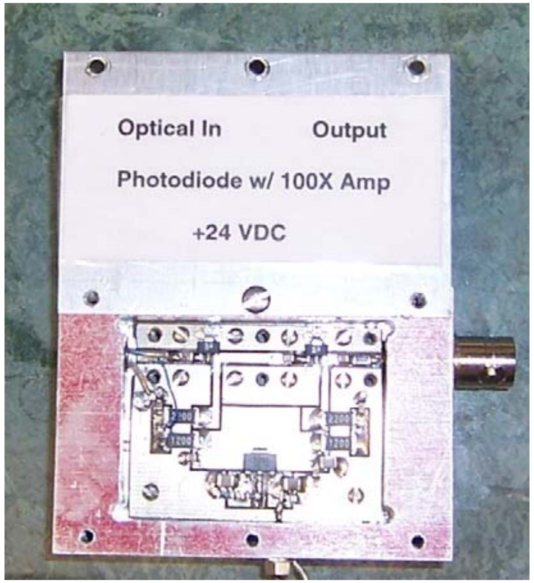
- Alternative Readout Options : APD, SiPMT, PIN diode.
- Which one is better? Wavelength response? Surface area?
- Are they radiation hard?

- Developing Radiation Hard Wavelength Shifing Fibers
- Quartz fibers with ZnO covered core.
- Sapphire fibers

New Readout Options





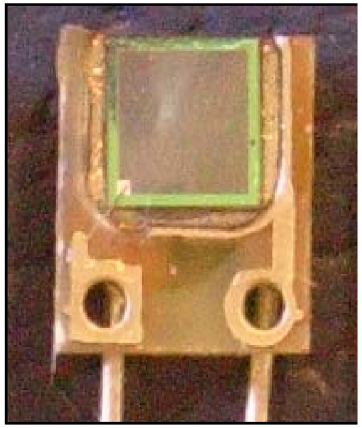


We tested;
*) Hamamatsu S8141 APDs (CMS ECAL APDs).
The circuits have been build at Iowa. These APDs are known to be radiation hard; *NIM A504, 44-47 (2003)*

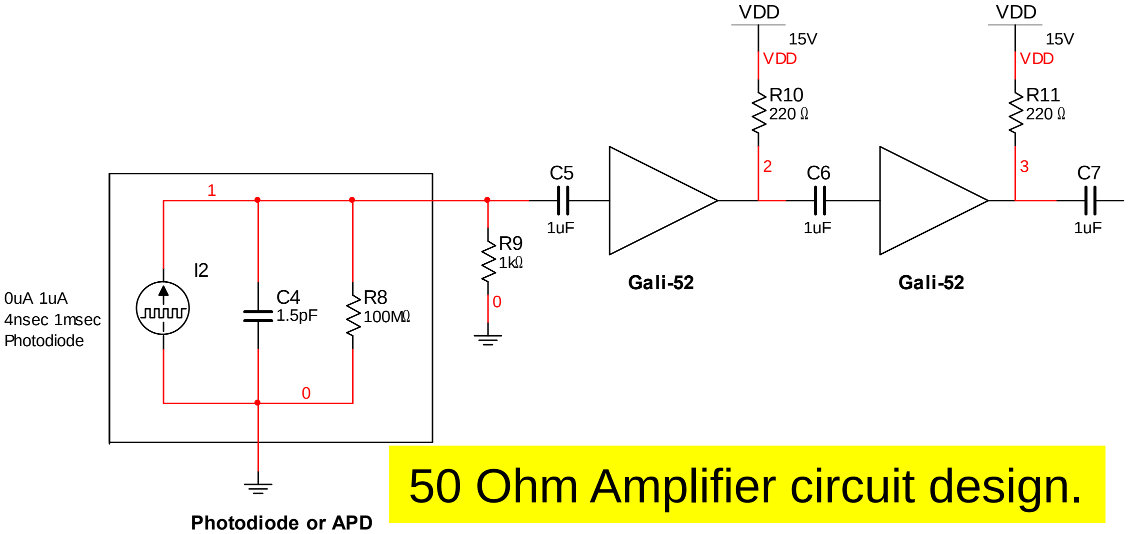
*) Hamamatsu APDs: S5343, and S8664-10K
*) PIN diodes; Hamamatsu S5973 and S5973-02
*) Si PMTs

New Readout Options

- SiPMT has lower noise level.



- For all of these readout options we designed different amplifier approaches:
  - 50 Ohm amplifier.
  - Transimpedance amplifier.
  - Charge amplifier.



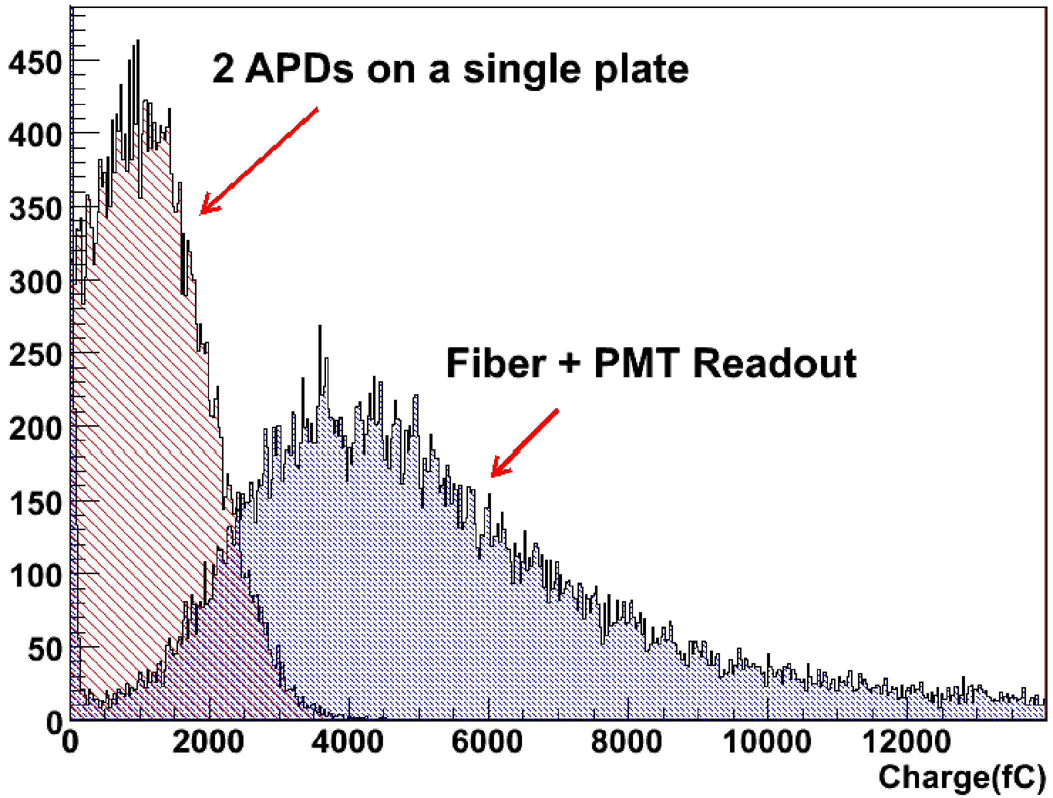
50 Ohm Amplifier circuit design.

New Readout Options

The speed of the readout is essential. The pulse width of the optical pulses from the scintillator limits the selection of photodiode or APD used. A bandwidth of 175 MHz is equivalent to a rise and fall time of 1.75 nsec.

Topology	Price	Speed (Rise time)	Input Equiv. Noise	Comments
Photodiode with 50 Ohm amplifier	Low	Fast (< 1 nsec)	~ 50 pW/√Hz	Simple circuitry
Photodiode with fast transimpedance amplifier	Low	Moderate (< 3 nsec)	~ 10 pW/√Hz	Simple circuitry
APD with 50 Ohm amplifier	Moderate	Fast	~ 250 fW/√Hz (Gain of 50)	Drift with temperature High voltage Moderate complexity for HV APD gain from 25 to 150
APD with 50 Ohm amplifier	Moderate	Moderate (<3 nsec)	~ 50 fW/√Hz	Drift with temperature High voltage Moderate complexity for HV APD gain from 25 to 150
Silicon PMT	Moderate	Fast	~.1 fW/√Hz	Simple to moderate complexity

New Readout Options



We have tested ECAL APDs as a readout option. 2 APD connected to plain quartz Plate yields almost 4 times less light than fiber+PMT combination.

What is learned from Phase III ?

- Single APD or SiPMT is not enough to readout a plate. But 3-4 APD or SiPMT can do the job.
- SiPMTs have less noise, higher gains, better match to PTP and ZnO emission λ.
- As the surface area get bigger APDs get slower, we cannot go above 5mm x 5mm.
- The PIN diodes are simply not good enough.
- The APD and SiPMTs are not radiation hard. The ECAL APDs are claimed to be radiation hard, there is no rad-hard readout technology option;
    - Feed the linear arrays of SiPMT or APD to the system, arranged as a strip of 5mm x 20-50 cm long… engineering !!…
    - A cylindrical HPD, 5-6 mm in diameter, with a sequence of coaxial target diodes anodes on the axis, 20-50 cm long, and a cylindrical photocathode.

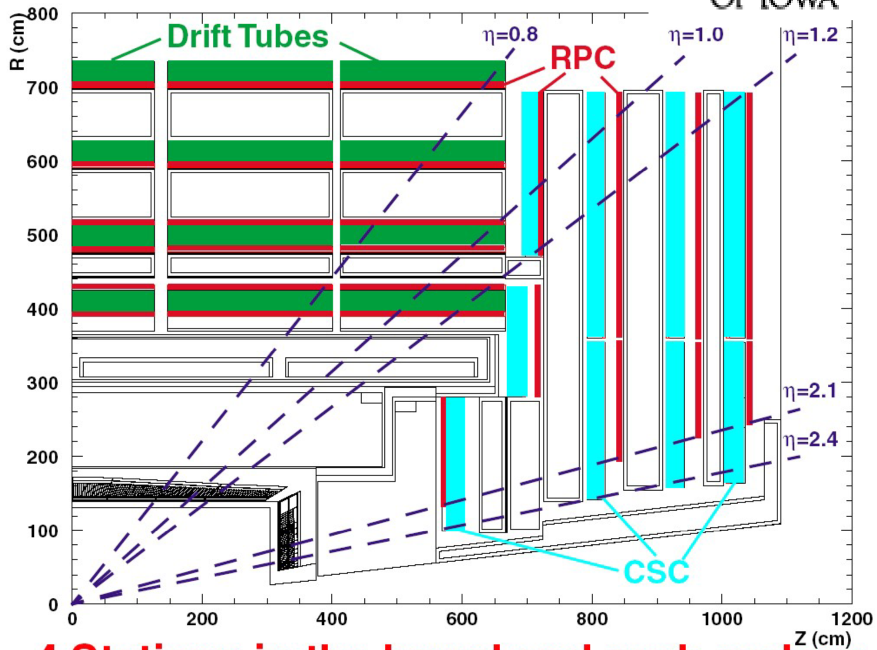
Developing new technologies

- We propose to develop a radiation hard readout option.
  - Microchannel PMT.
  - MPPC (Multi Pixel Photon Counter)

- We also propose to develop a radiation hard WLS fiber option.
  - Doped sapphire fibers.
  - Quartz fibers with ZnO sputtered on core.

CMS SLHC Muon

- Drift Tubes (barrel):
  - –Electronics might sustain rad. damage
  - –Increase x 10 in muon rates will cause dead time & errors in BTI algorithm, due to long drift times.
  - –# two tracks per station/bx could limit due to ghosts.
- RPC (barrel & endcap):
  - –Operate in low η region with same FE
  - –Detector & FE upgrade is needed for $\eta > 1.6$ region
  - –Trigger Electronics can operate with some modifications
  - –Some front-end electronics may not be sufficiently radiation tolerant
- CSCs (endcap):
  - –CSCs in endcaps have demonstrated required radiation tolerance
  - –Need ME4/2 layer recovered
  - –Parts of trigger & DAQ may need replacement to cope with high rates
  - –Some front-end electronics may not be sufficiently radiation tolerant



4 Stations in the barrel and each endcap

- **Initial coverage of RPC is staged to $\eta<1.6$ and 3 disks**
- **Initial trigger coverage of CSC 1st station is staged to $\eta<2.1$**
- **Fourth CSC disk staged to $\eta<1.8$**

Conclusions

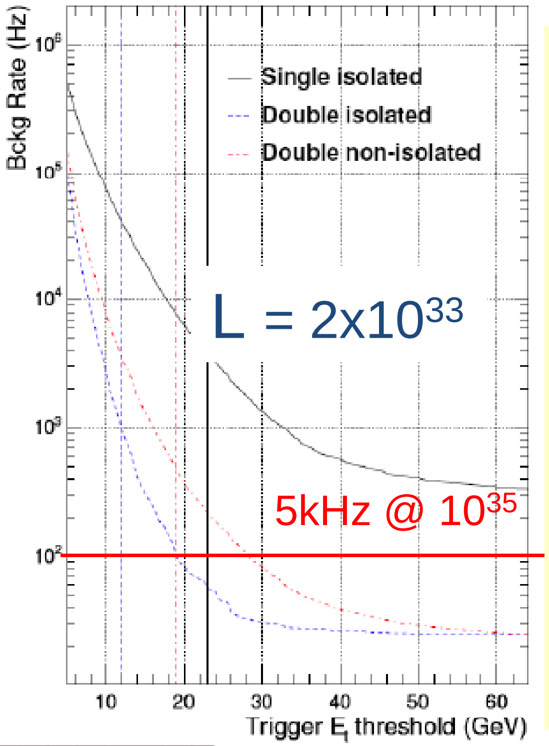
- The LHC will initiate a new era in colliders, detectors & physics.
  - Searches for Higgs, SUSY, ED, Z' will commence
    - Exploring the TeV scale
  - Serious challenges for the machine, experiments & theorists will commence
- The SLHC will extend the program of the LHC
  - Extend the discovery mass/scale range by 25-30%
  - Could provide first measurement of Higgs self-coupling
  - Reasonable upgrade of LHC IR optics
  - Rebuilding of experiment tracking & trigger systems and parts of calorimetry, muon systems
  - Need to start now on R&D to prepare

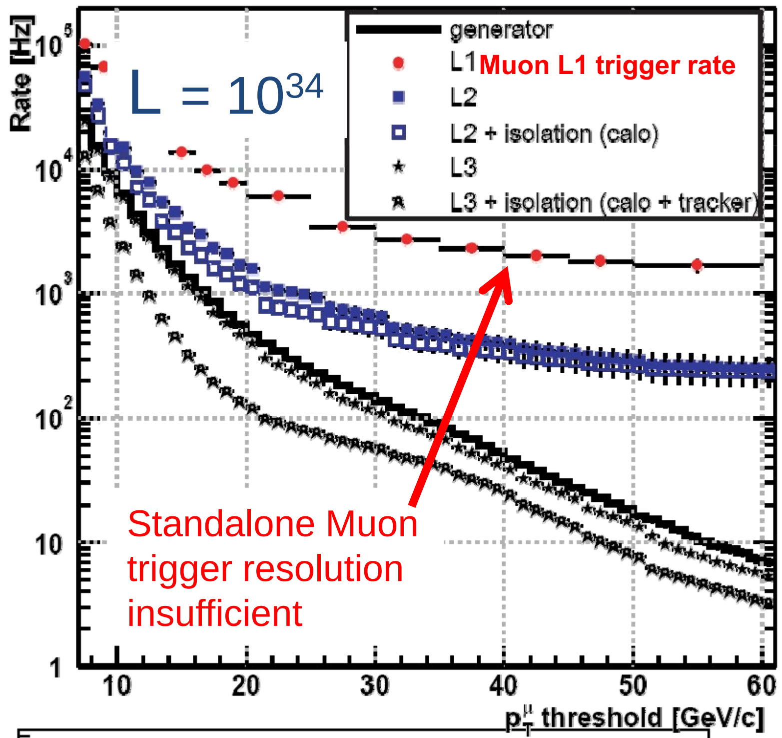
BACKUP

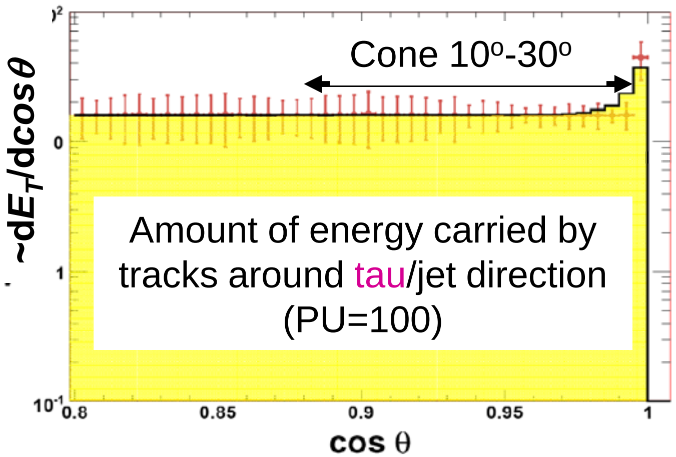
Tracking needed for L1 trigger

Single electron trigger rate

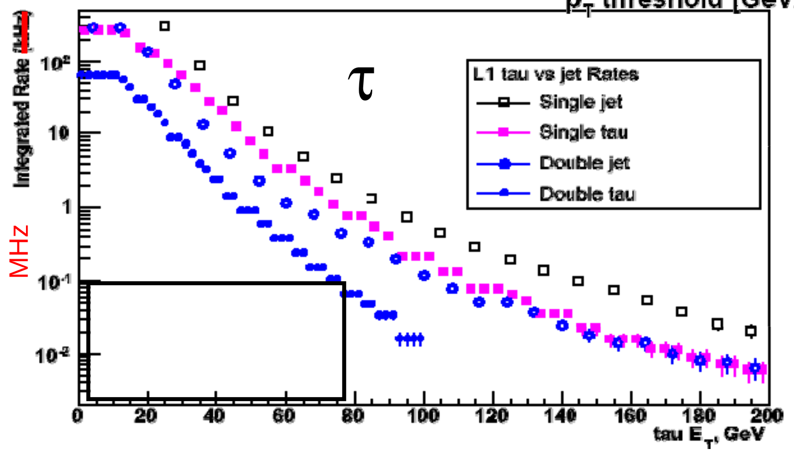
Isolation criteria are insufficient to reduce rate at L = *10^{35} cm^{-2}.s^{-1}*





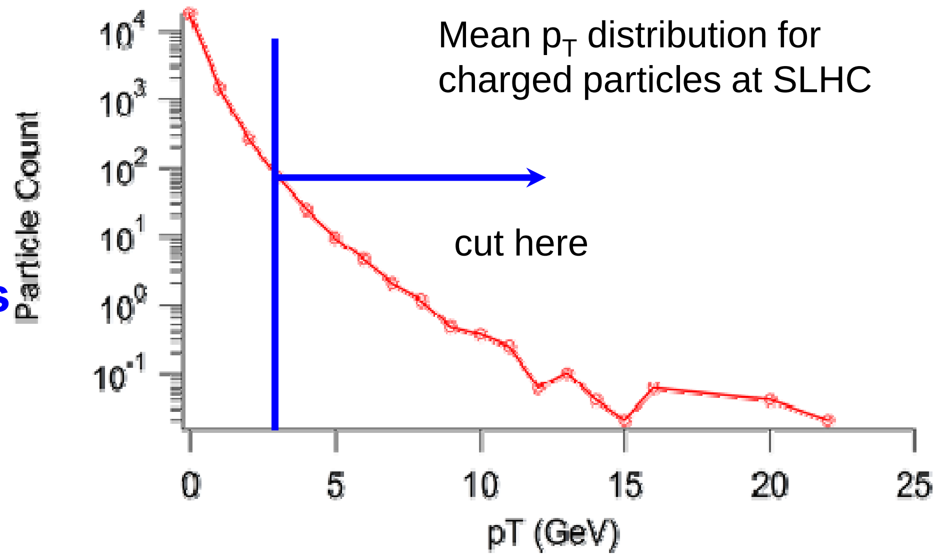


We need to get another x200 (x20) reduction for single (double) tau rate!



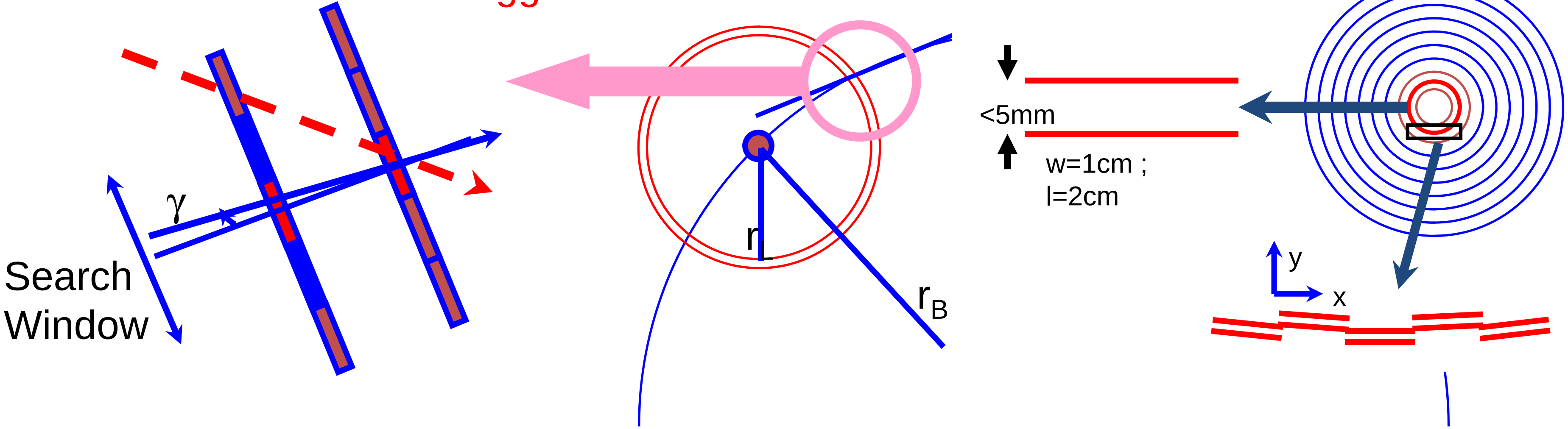
CMS ideas for trigger-capable tracker modules -- very preliminary

- **Use close spaced stacked pixel layers**
- **Geometrical p_T cut on data (e.g. ~ GeV):**
- **Angle (γ) of track bisecting sensor layers defines p_T ($\Rightarrow$ window)**
- **For a stacked system (sepn. ~1mm), this is ~1 pixel**
- **Use simple coincidence in stacked sensor pair to find tracklets**



-- C. Foudas & J. Jones

A track like this wouldn't trigger:



p_T Cuts in a Stacked Tracker – p_T Cut Probabilities

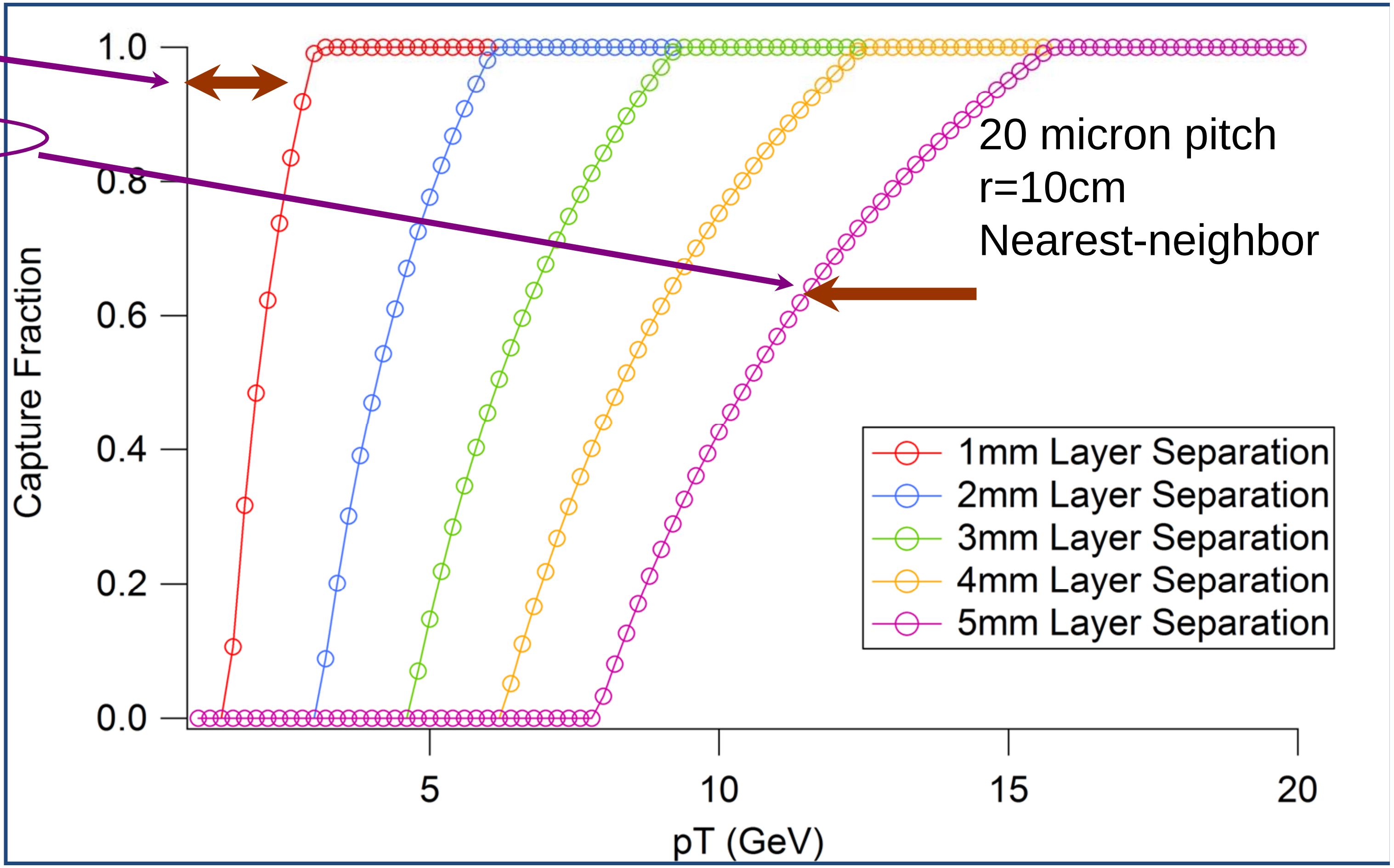
- J. Jones

•Depends on:

Layer Sepn. & Radius

Pixel Size

Search Window



There is an additional ‘blurring’ caused by charge sharing…

Alternative Tracking Trigger: Associative Memories (from CDF SVX)

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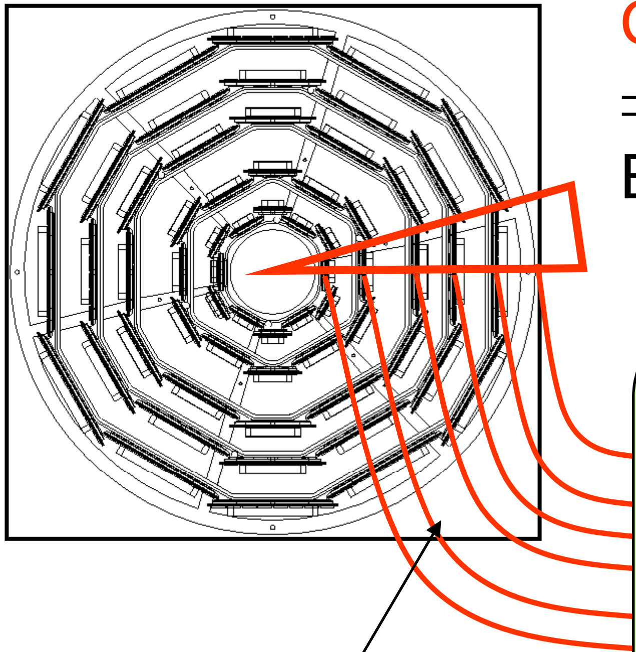


Data links

-- F. Palla, A. Annovi, *et al.*

Challenge: input Bandwidth

⇒divide the detector in thin ϕ sectors.

Each AM searches in a small $\Delta\phi$

OFF DETECTOR

1 AM for each enough-small $\Delta\phi$

Patterns

Hits: position+time stamp

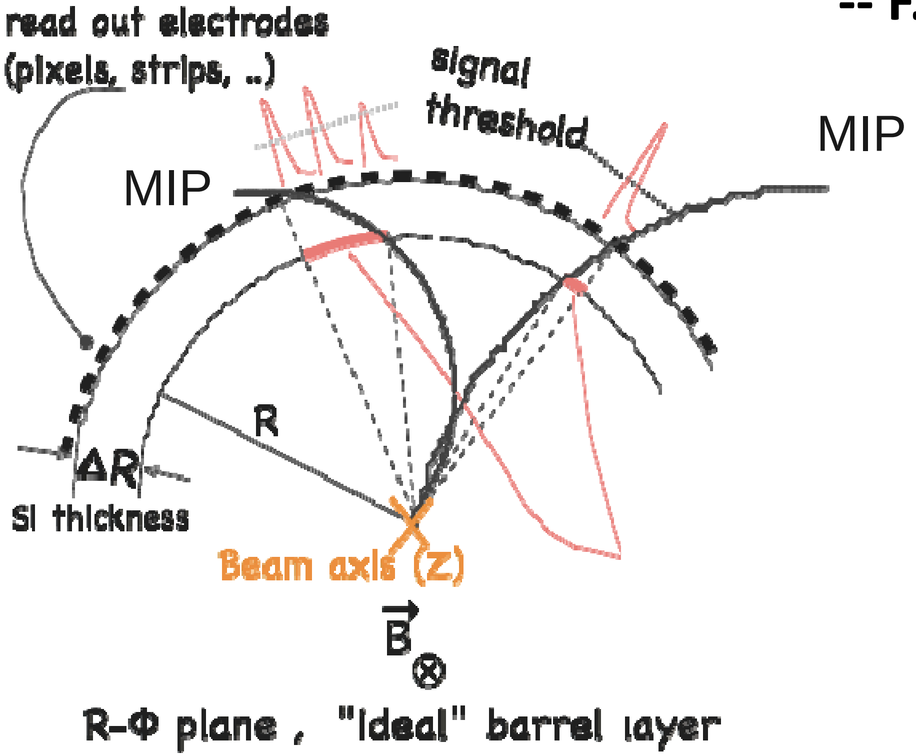
All patterns inside a single chip

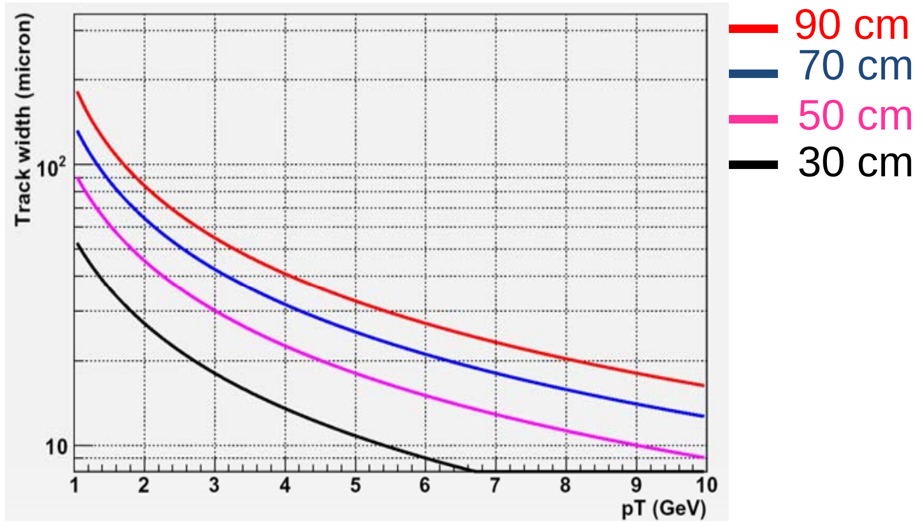
N chips for N overlapping events identified by the time stamp

Event1 AMchip1	Event2 AMchip2	Event3 AMchip3	• • • • •	EventN AMchipN

Cluster width discrimination

-- F. Palla





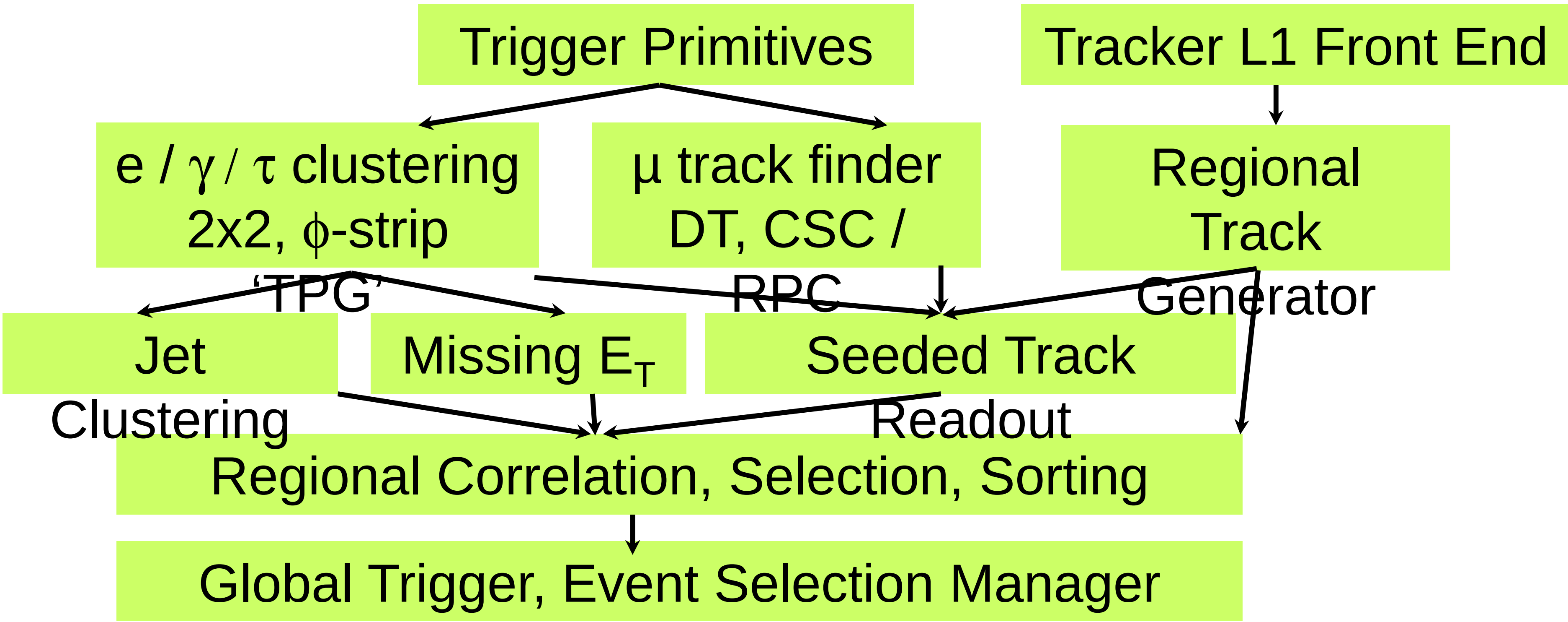
Discrimination of low p_T tracks made directly on the strip detector by choosing suitable pitch values in the usual range for strip sensors.

(Needed because 25M channels x 4% occupancy would require 6000 2.8 Gbps links at 100 kHz.)

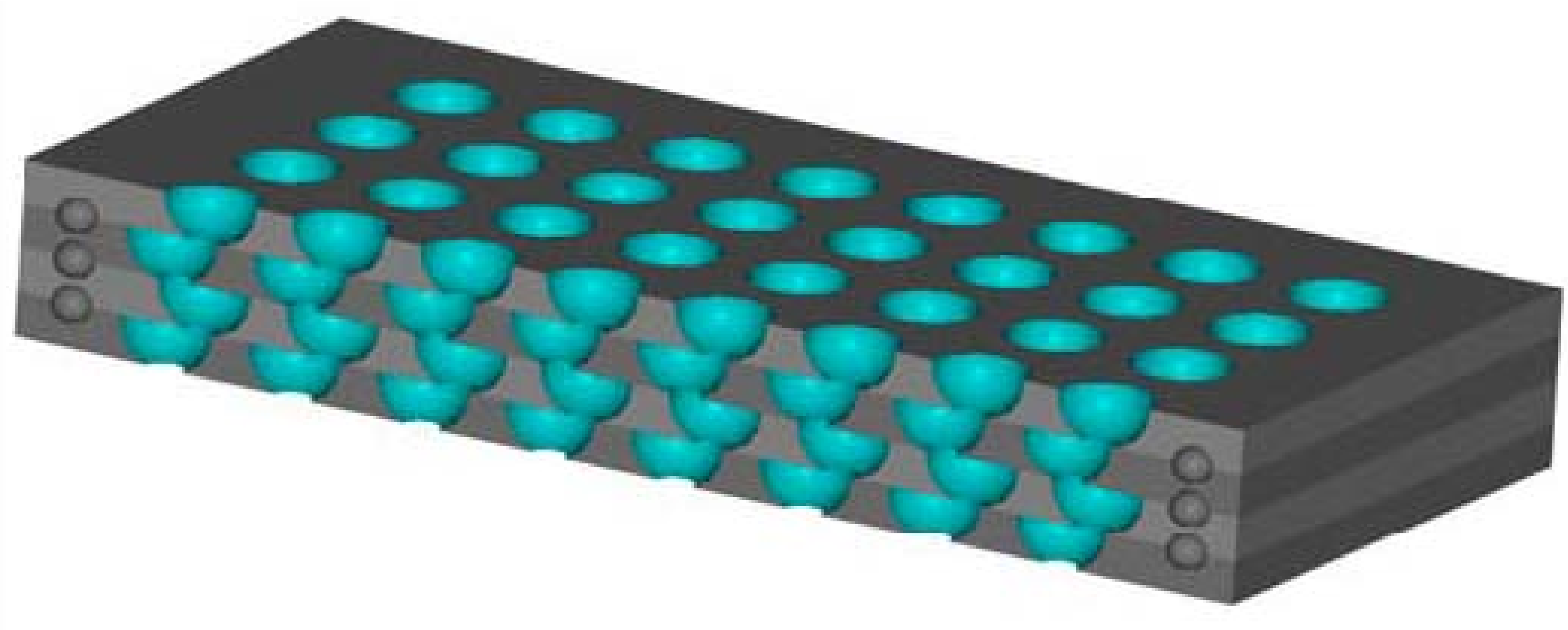
- In the region above 50 cm, using 50µm pitch, about 5% of the total particles leave cluster sizes with ≤2 strips
  - No. of links (2.5Gbps) ~300 for whole tracker (assuming 95% hit rejection)
- Once reduced to ~100 KHz, it would only need few fast readout links to readout the entire Tracker

CMS L1 Trigger Stages

- Current for LHC:
  TPG ⇒ RCT ⇒ GCT ⇒ GT
- Proposed for SLHC (with tracking added):
  TPG ⇒ Clustering ⇒ Correlator ⇒ Selector

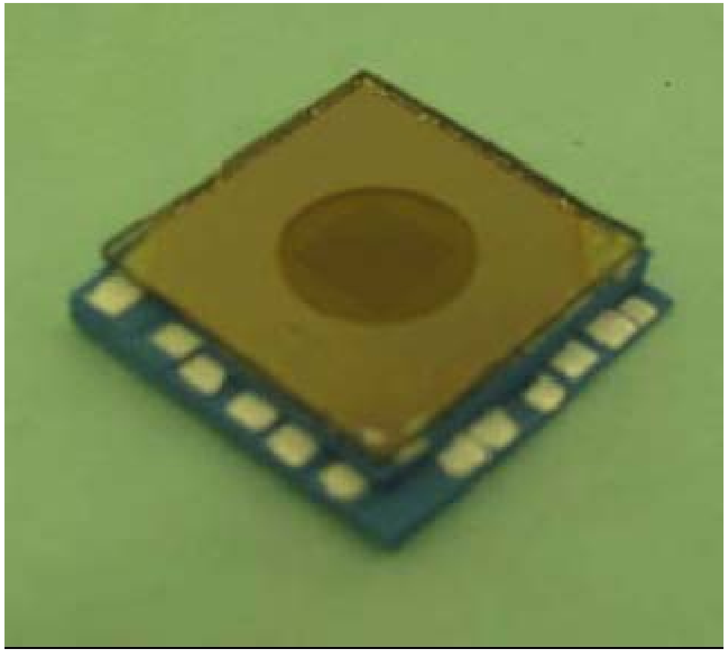


Radiation hard readout option
"Microchannel PMT"



*) Fairfield and Iowa have focused on revolutionizing photomultiplier technology through miniaturization coupled with the introduction of new materials technologies for more efficient photocathodes and high gain dynode structures.
*) Miniaturization enables photomultipliers to be directly mounted on circuit boards or silicon for interfacing directly with readout circuits.
*) Fast response time, high gain, small size, robust construction, power efficiency, wide bandwidth, **radiation hardness**, and low cost.

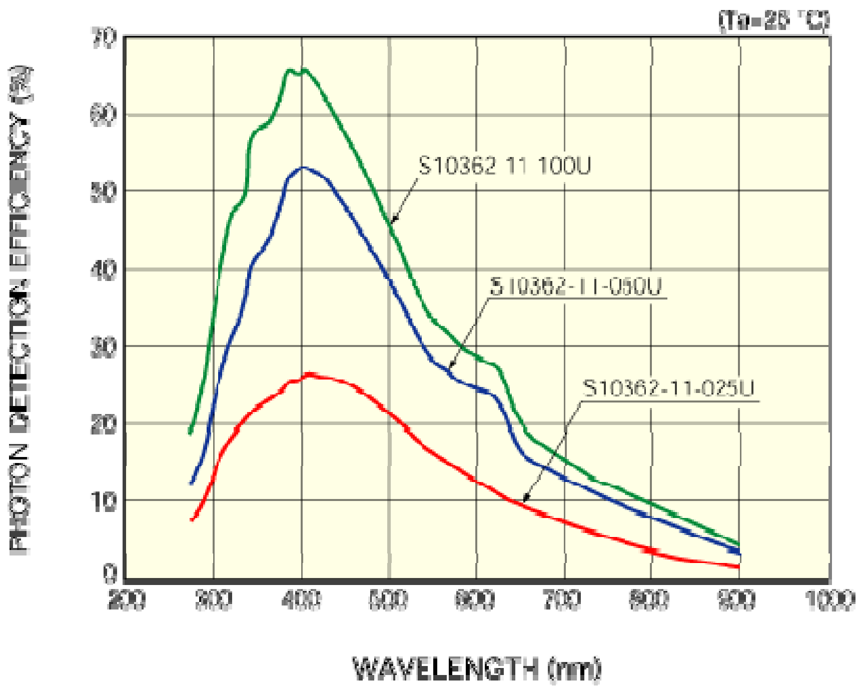
Radiation hard readout option
“Microchannel PMT”

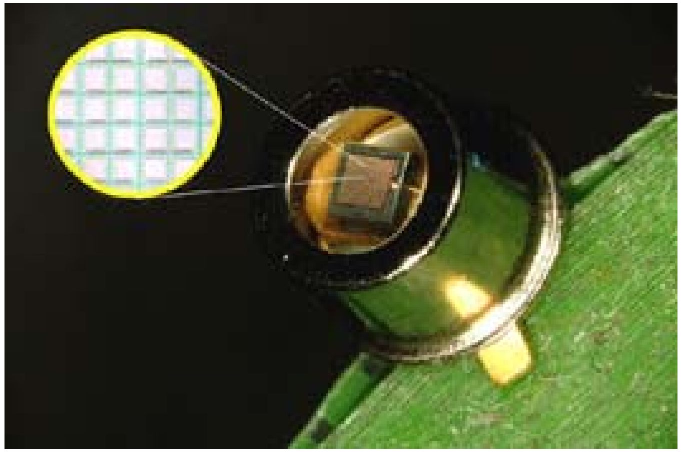


*) Photograph of a micromachined PMT in engineering prototype form.
*) The metal tabs for the dynode and focusing voltages, signal, cathode.
*) 8 stage device is assembled from micromachined dynodes which exhibits a gain of up to 2-4 per stage onsingle stage.
*) The total thickness < 5 mm.
*) 8x4 pixel micro-dynode array is shown
*) The layers are offset relative to each other to maximize secondary electron emission collisions.

Hamamatsu MPPCs

Hamamatsu released a new product. Multi Pixel Photon Counter, MPPC.
We purchased this unit, working on tests, but it is simply an array of APDs. It is not the same thing with our proposed "microchannel PMT".

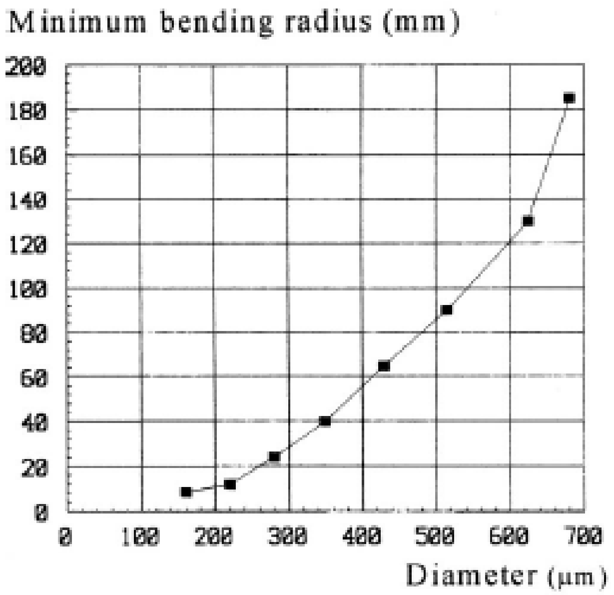




Radiation Hard WLS fibers: Sapphire Fibers

Sapphire is a very radiation hard material and it can be brought into fiber form. But by itself It has very little absorption and florescence.

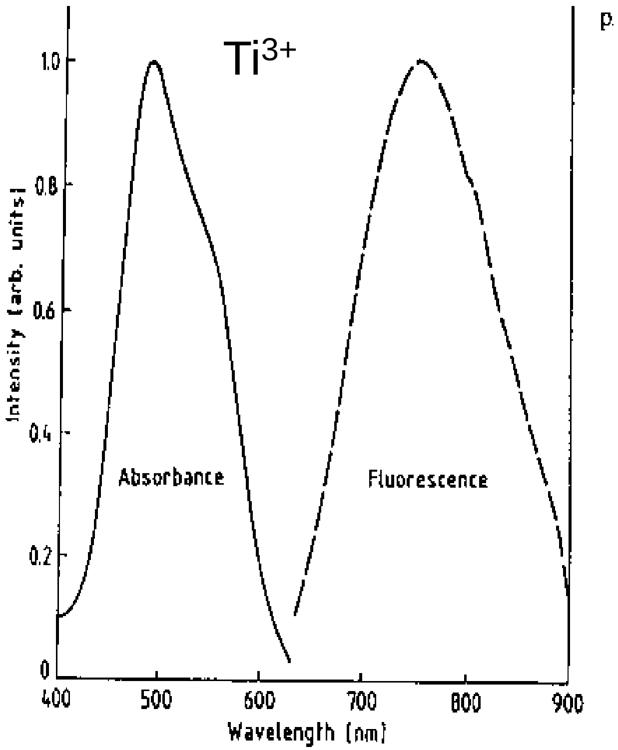
Tong et.al., Applied Optics, 39, 4, 495

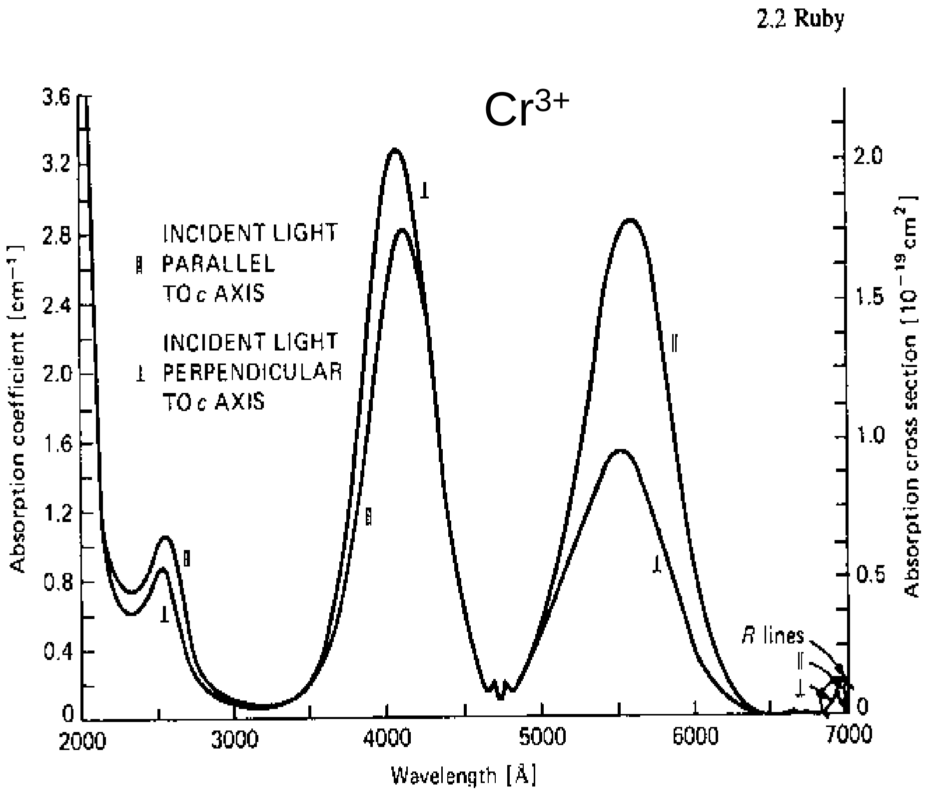


- Absorption in Sapphire can be provided by;
  - conduction to valence band in UV
  - multiphonon in mid-IR
  - native defects
    - vacancies, antisites, interstitials,
  - **Impurities !!!!**
    - e.g. transition metals: Cr, Ti, Fe, …

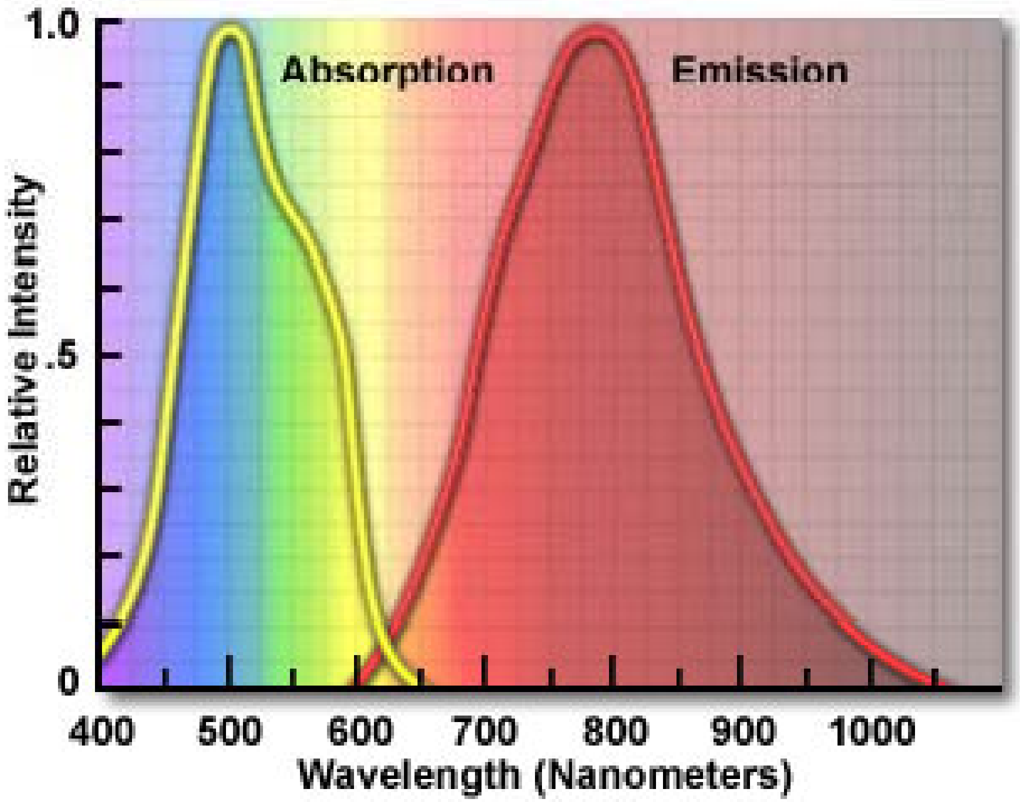
Doped Sapphire !!

A. Alexandrovski et al.





Ti:Sapphire looks promising



What about treating quartz fibers?

- Heterogenous nanomaterials: Scintillating glass doped with nanocrystalline scintillators has also been shown to be a good shifter.
- (i) We propose testing radiation hardness and
- (ii) to investigate doping quartz cores with nanocrystalline scintillators (ZnO:Ga and CdS:Cu). The temperatures involved are very reasonable.
- Thin film fluorescent coatings on quartz cores 250-300 nm.
- UV has been shown to cause 5-10 ns fluorescence in MgF2, BaF2, ZnO:Ga. We propose coating rad-hard quartz fibers with a thin film, and then caldding with plastic or fluoride doped quartz. CVD deposition of Doped ZnO is now a commercial process, as it is used to make visible transparent conducting optical films as an alternative to indium tin oxide, as used in flat panel displays and solar cells.

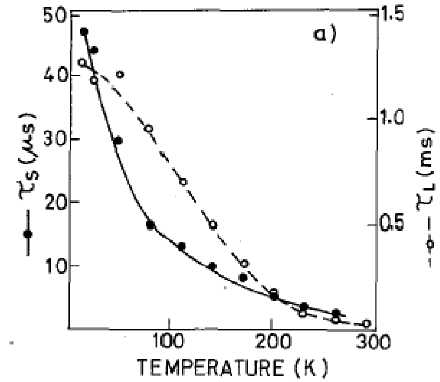
CMS Level-1 Latency

- Present CMS Latency of 3.2 μsec = 128 crossings @ 40MHz
  - Limitation from post-L1 buffer size of tracker & preshower
  - Assume rebuild of tracking & preshower electronics will store more than this number of samples
- Do we need more?
  - Not all crossings used for trigger processing (70/128)
    - It's the cables!
  - Parts of trigger already using higher frequency
- How much more? Justification?
  - Combination with tracking logic
  - Increased algorithm complexity
  - Asynchronous links or FPGA-integrated deserialization require more latency
  - Finer result granularity may require more processing time
  - ECAL digital pipeline memory is 256 40 MHz samples = 6.4 μsec
    - Propose this as CMS SLHC Level-1 Latency baseline

Problems with Ti:Sapphire

- There are some crystals used for lasers, but no fiber, yet.

- The Ti:Sapphire has a luminescence lifetime of 3.2 microsec!! And looks like this is temperature dependent (*Macalik et. al. Appl. Physc. B55, 144-147*) .



- off "resonant" absorption significant

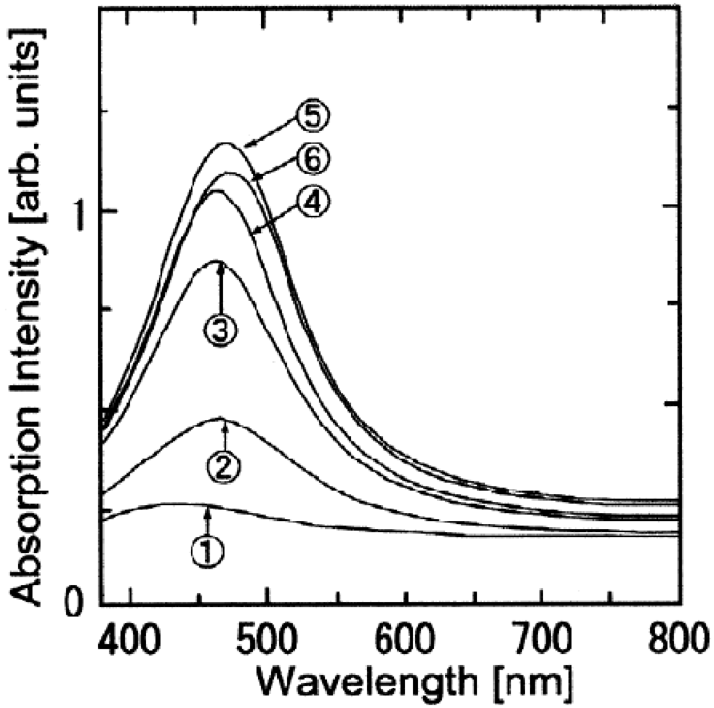
- sum of several species can contribute to absorption at given λ

- Redox state important
  - e.g. $a[Ti^{3+}] \neq a[Ti^{4+}]$
  - annealing alters absorption without altering impurity concentrations

- Impurities do not necessarily act independently
  - Al : Al :Ti^{3+} : Ti^{4+} : Al : Al $\neq$ Al : Ti^{3+} : Al : Al : Ti^{4+} : Al
  - absorption spectra at high concentrations not always same as low

Ag-Sapphire ??

A recent study shows that the Ag ions can be implanted into sapphire in the keV and MeV energy regimes. The samples implanted at 3MeV shows a large absorption peak at the wavelengths ranging from 390 to 450 nm when heated to temperatures higher than 800◦C.
Y. Imamura et al.
Jpn. J. Appl. Phys. Vol. 41 (2002) Pt. 2, No. 2B



What can be done with sapphire?

- Sapphire optical fibers are commercially available in standard lengths of 200 cm x 200 micron diameter. Cheaper stock fibners are 125 micron diameter x 125 cm long. These fibers are of use in Ti:sapphire fiber lasers, and sensors.
- A large variety of dopants are possible in sapphire, covering a large wavelength interval.
- Under the right conditions, the Ti+4 ion (40 ppm) in heat treated sapphire absorbs in the UV and emits in the blue, with a time constant 5-7 ns. it is reasonably (50%-90% or more) efficient. At 1ppm the shift is at 415 nm - even at 1 ppm the fluorescnece is visible to the human eye. At 40 ppm it shifts to 480 nm. Fe2+ and Mg2+. Other Ti charge states and other dopants absorb in the UV-Blue and emit in the yellow and red.
- We propose to investigate these and similar inorganic fibers, grown mainly for fiber lasers, but with dopants adjusted for fast fluorescence (rather than forbidden transistion population inversions), and to test the rad hardness.