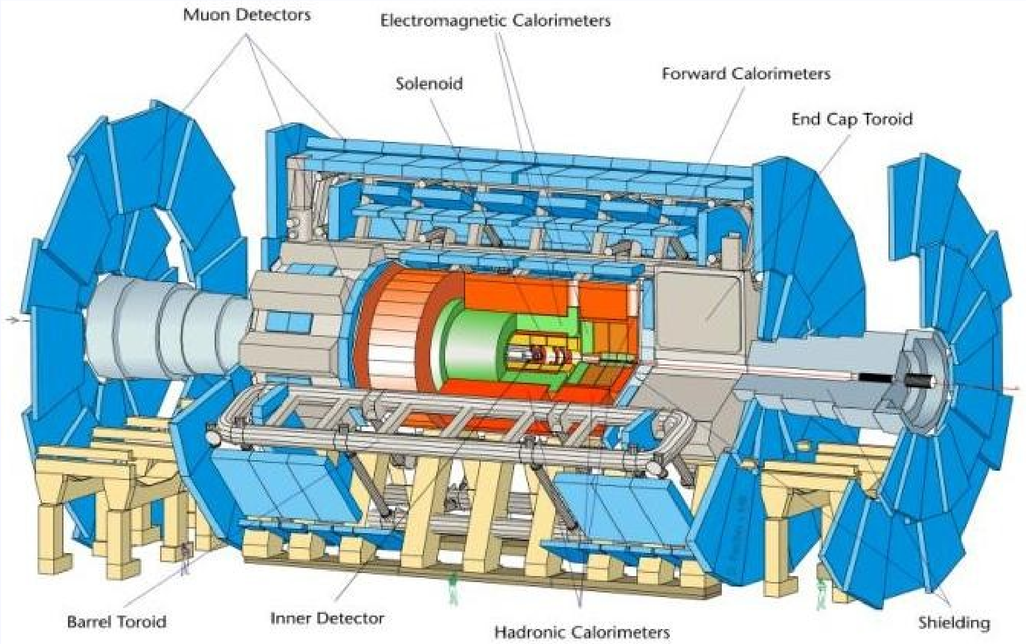
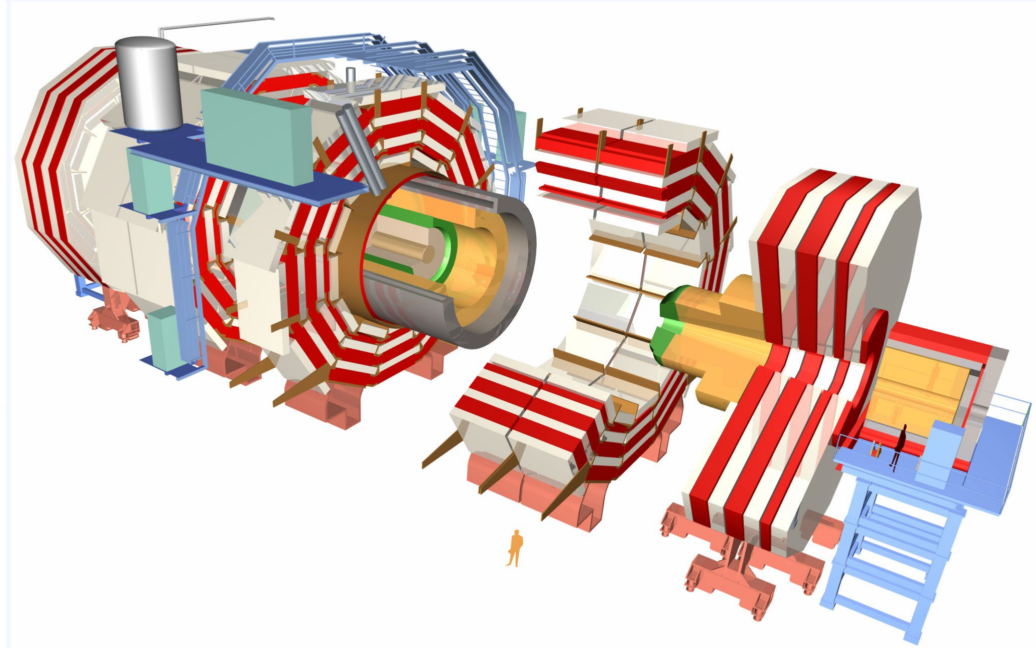
Overview and Electronics Needs of ATLAS and CMS High Luminosity Upgrades



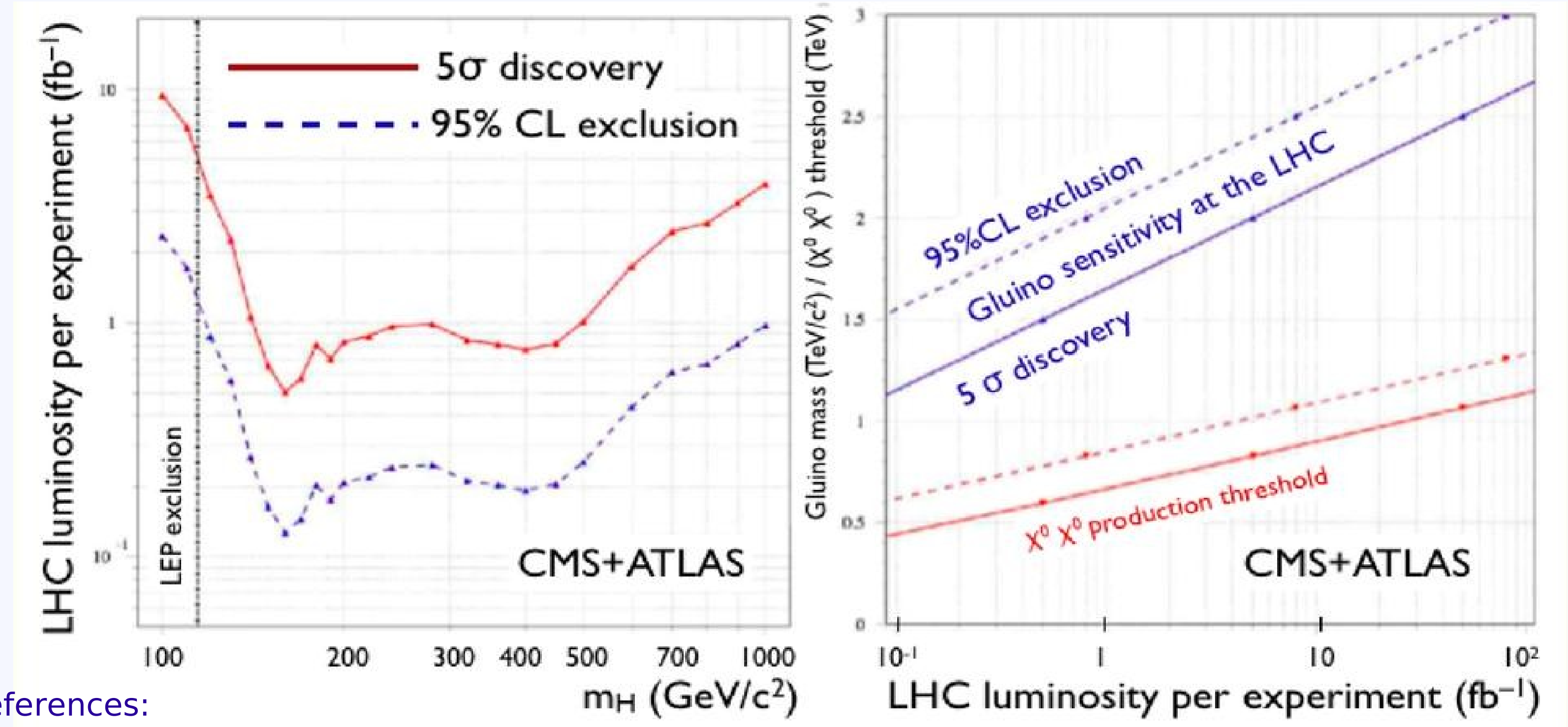


Physics Goals
LHC Machine Plans and Conditions
ATLAS and CMS Changes Needed
Electronics needs

Nigel Hessey, Nikhef

Initial Physics Goals

- LHC collisions at 5 TeV imminent
- Will ramp up to “nominal” luminosity 1 x 10^{34} cm^{-2} s^{-1} over 2 – 3 years
- Next year already should take ~1 fb^{-1}
  - Quite soon a lot will be known about TeV scale



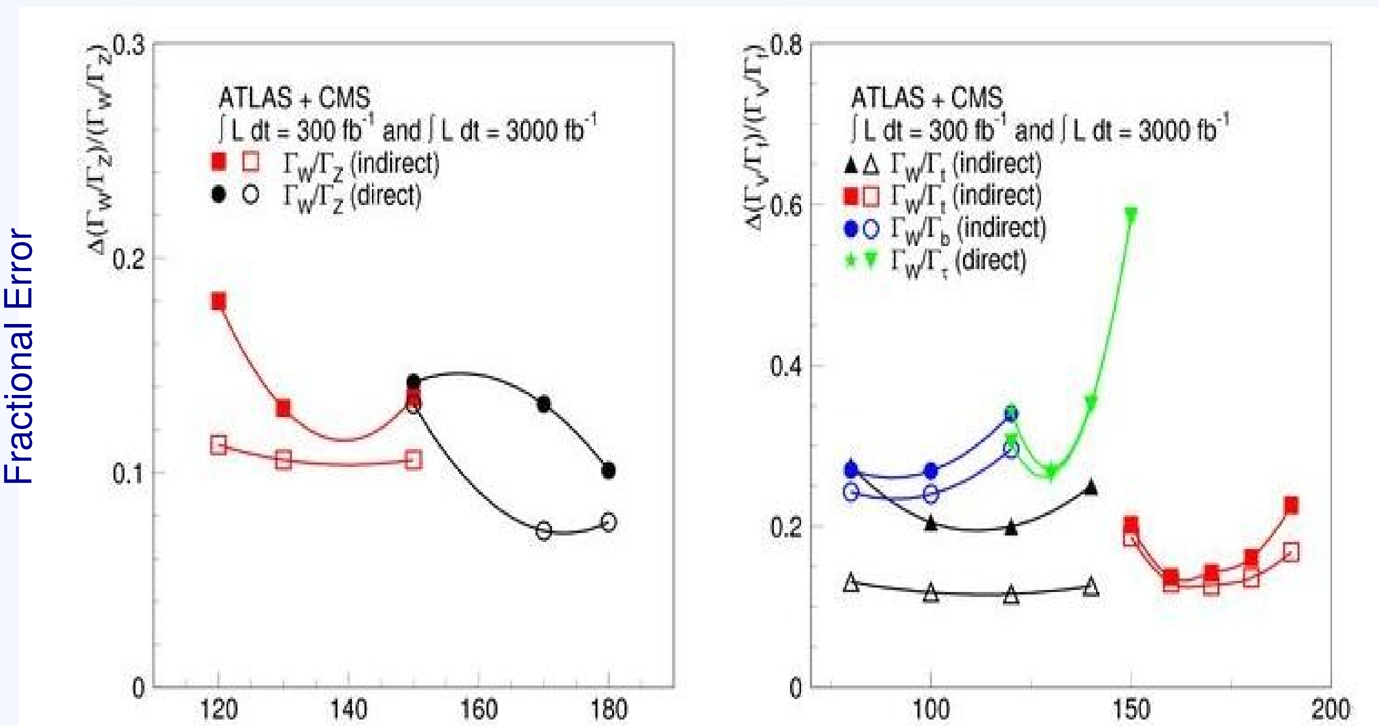
- References:
  - Michelangelo Mangano at SLHC Kick-off Meeting
  - F. Gianotti et al, Eur.Phys.J.C39:293-333,2005

Reach of original LHC

- Expect 700 fb-1 per experiment before sLHC
- Either Higgs found or strong boson scattering at ~TeV
- W', Z' limits or discovery up to ~5 TeV mass
- SUSY limits or discovery up to ~2.5 TeV mass
- But just what has been found? What is the Lagrangian?
  - Needs much more study
    - Precise measurement of parameters
    - Deviation from SM values ==> New physics; need precision
  - Search for partners – SUSY spectroscopy
    - Extend the discovery range to higher masses
- These will require much more data

If Higgs Found

- Measure (ratios of) BR to less common states
- Deviations from SM → new physics
- Some are sytematics limited already at LHC, but significant improvement in others

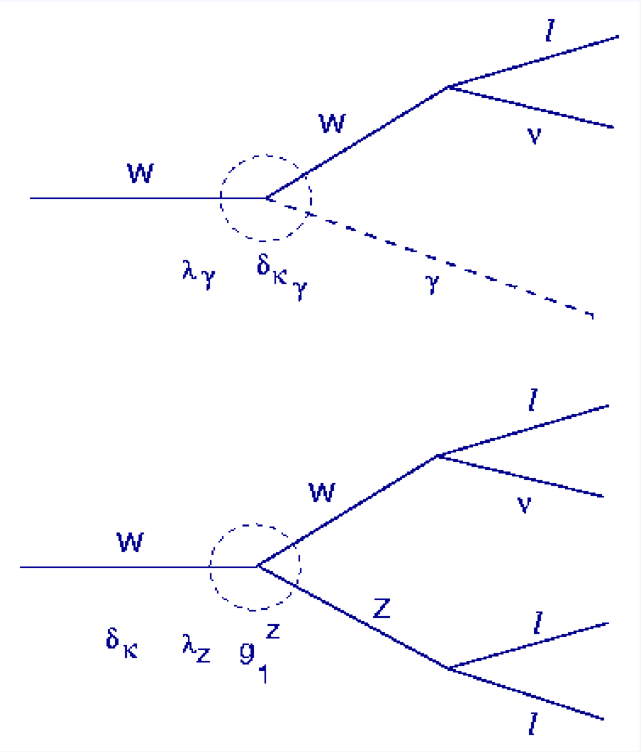


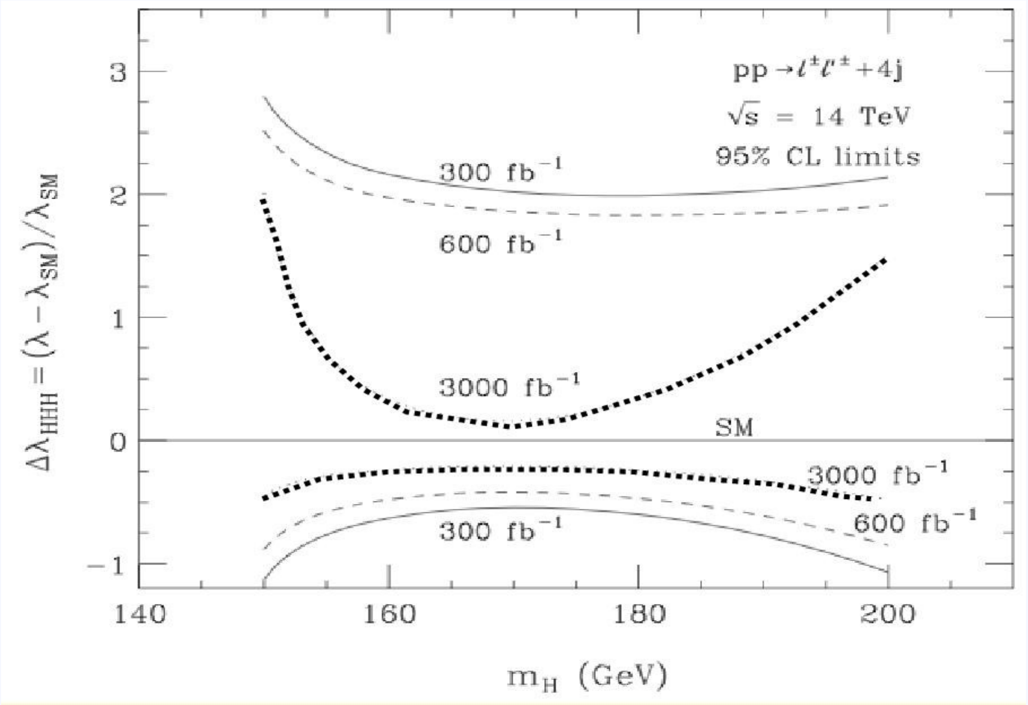
Fractional Error

Higgs Mass (GeV) →

Triple Gauge Couplings

- SM fixes couplings; most general forms have 5 extra parameters possible. (The 4 shown are 0 in SM).
  - sLHC can significantly reduce error bars on most.
- Higgs self-coupling also much better measured at sLHC

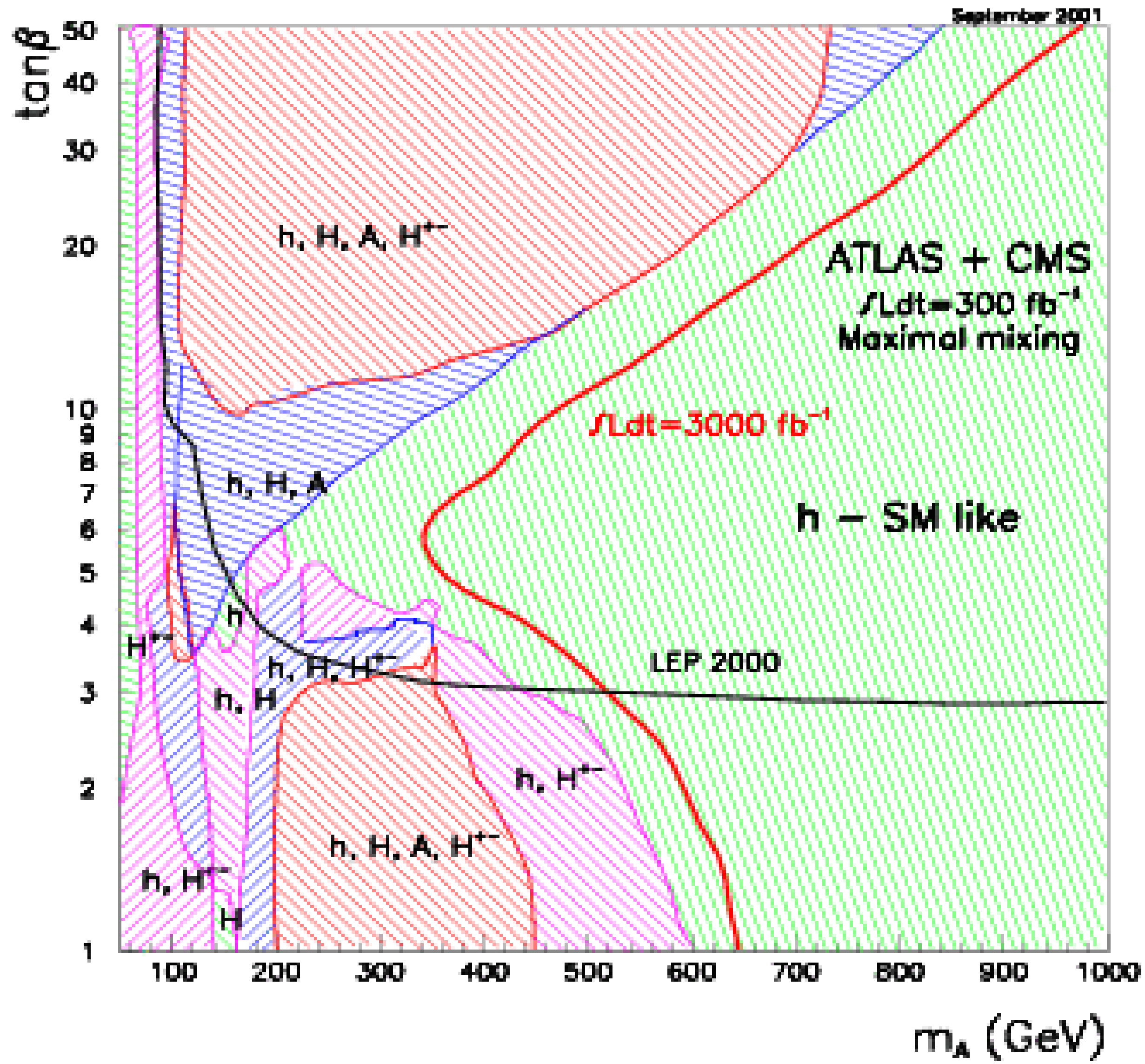




Coupling	100 fb-1	1000 fb-1
$\lambda\gamma$	0.0014	0.0006
λz	0.0028	0.0018
$\Delta\kappa\gamma$	0.0340	0.0200
$\delta\kappa z$	0.0400	0.0340

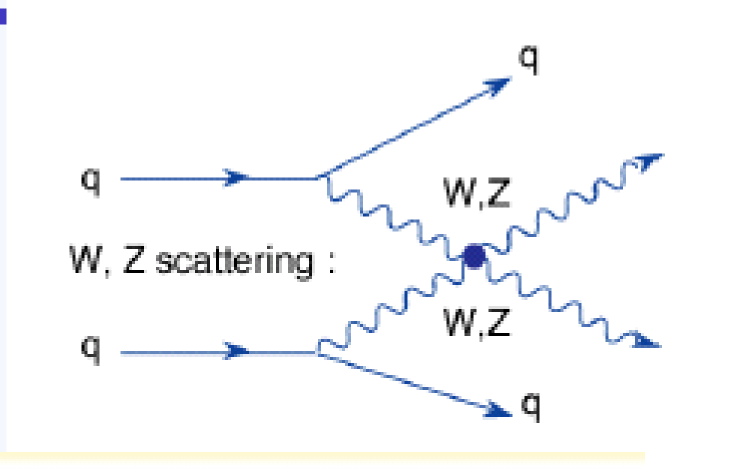
How many Higgs's?

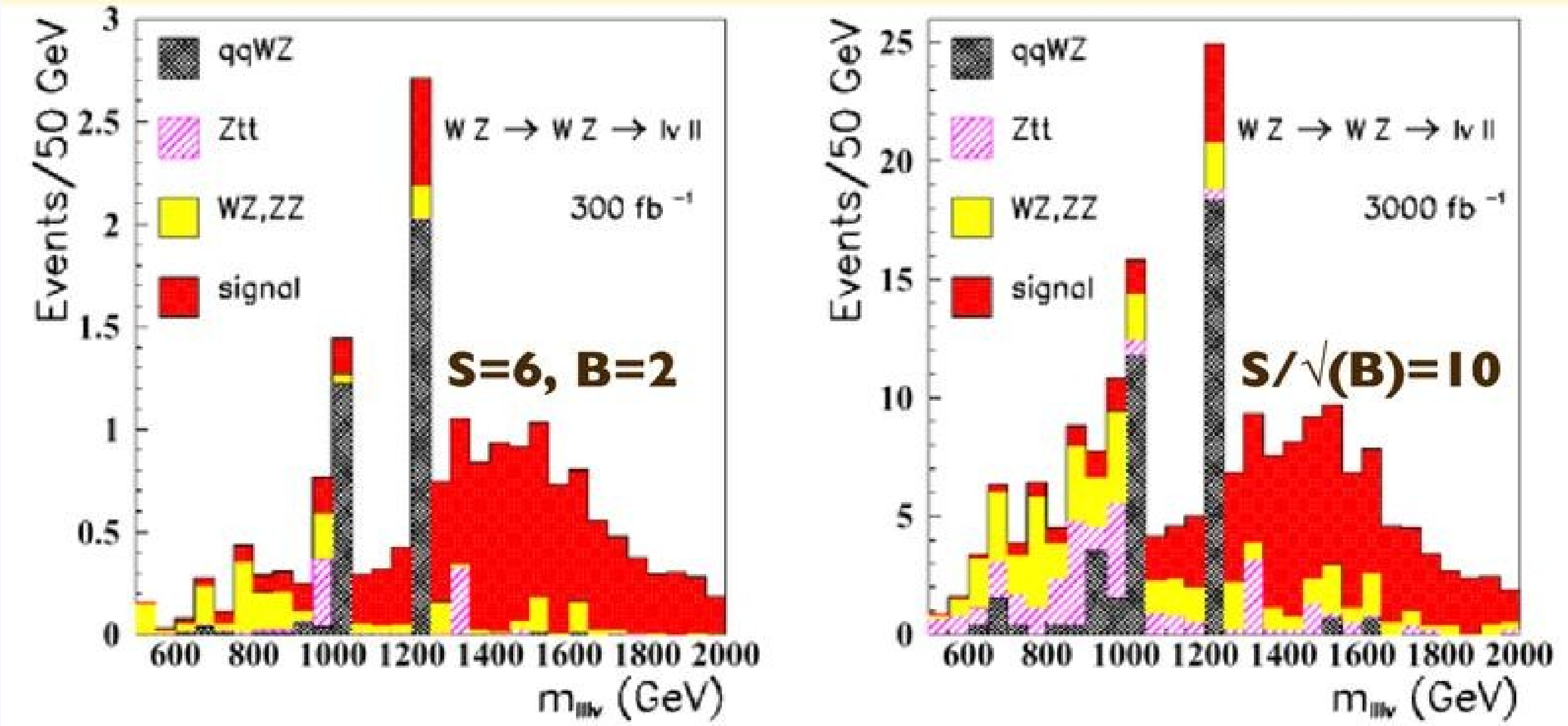
- Some models have more than one Higgs. Finding 2 or more clearly very exciting. sLHC boosts the region in which more than one can be observed. E.g. MSSM model:



No Higgs?

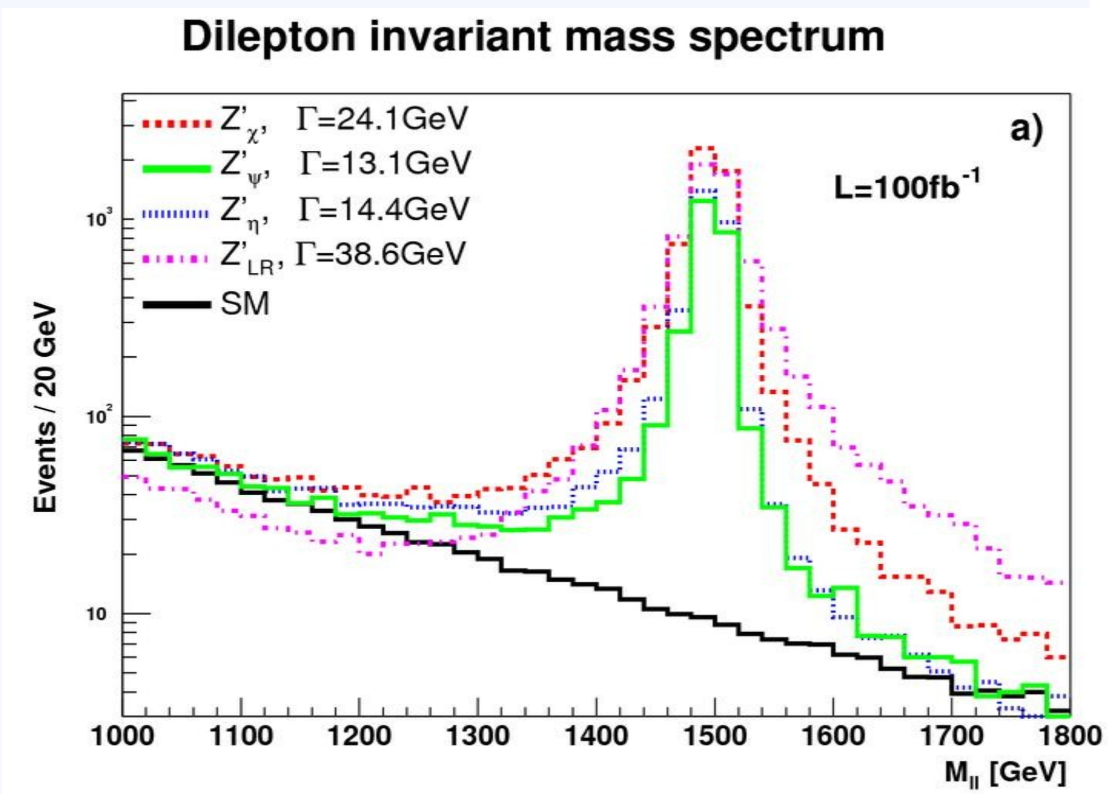
- Then strong vector boson scattering needed ~1 TeV
- Low statistics at LHC (few events); clear signal at sLHC even for 1.5 TeV WZ or ZZ resonance

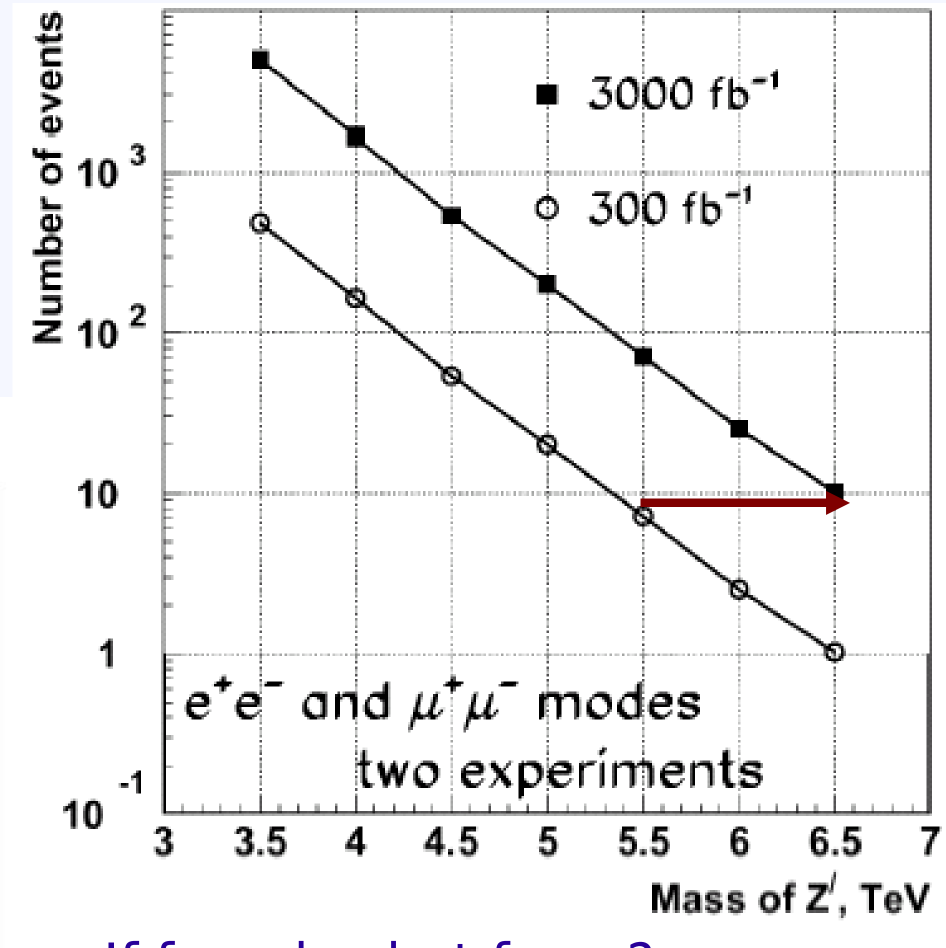




New Forces; W' and Z'

- Increased mass reach from higher statistics and tails of PDF
- 5 TeV reach at LHC --> 6 TeV at sLHC

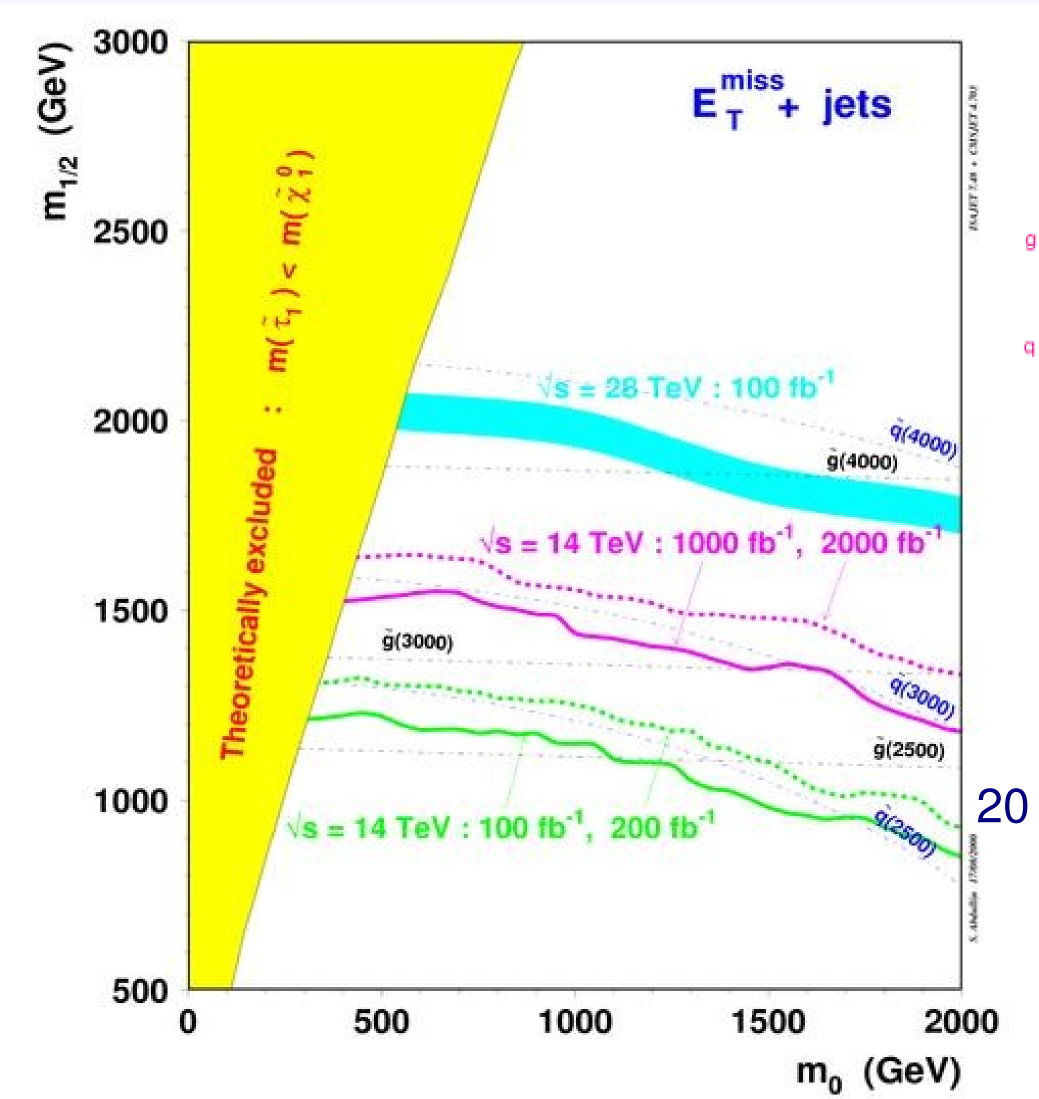




- If found, what force?
- Peak shape and asymmetries (Dittmar et al) with high statistics can distinguish between models

SUSY

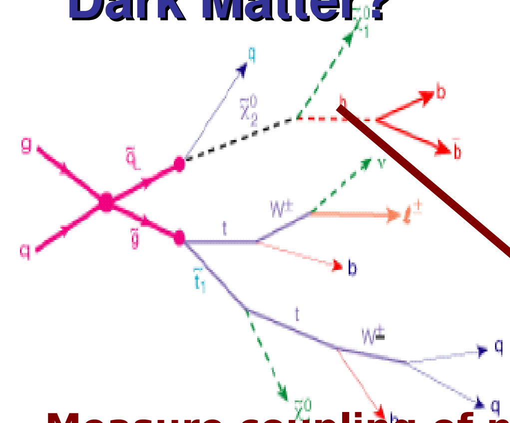
- Either already found at LHC; sLHC allows heavier partners to be found
- Or not found: sLHC allows higher mass reach for discovery

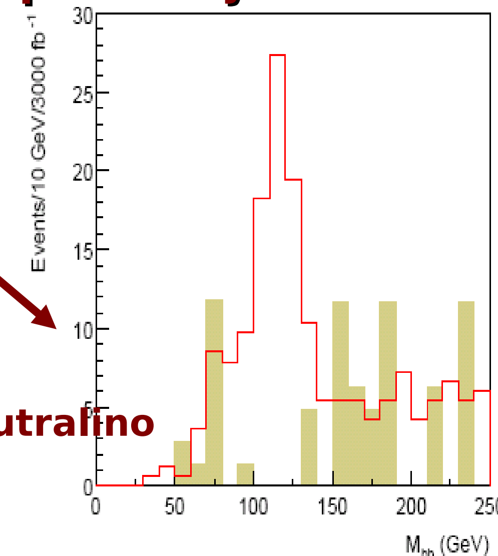


Require two b-tagged jets and reconstruct peak from $h \to bb$ decay

Dark Matter?

Requires 5 years of SLH





Measure coupling of neutralino to Higgs. Determine its higgsino component.

Plot assumes $\epsilon_b = 60\%$ for light jet rejection of 100

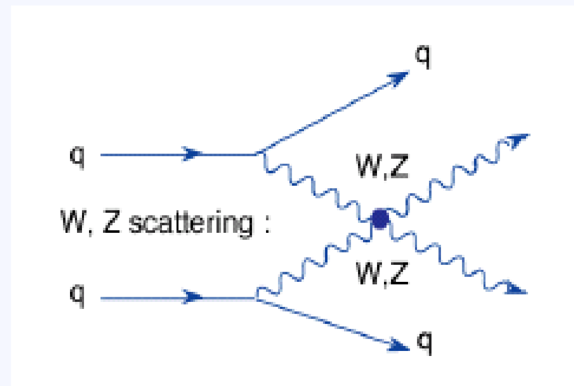
20 % increase in mass reach

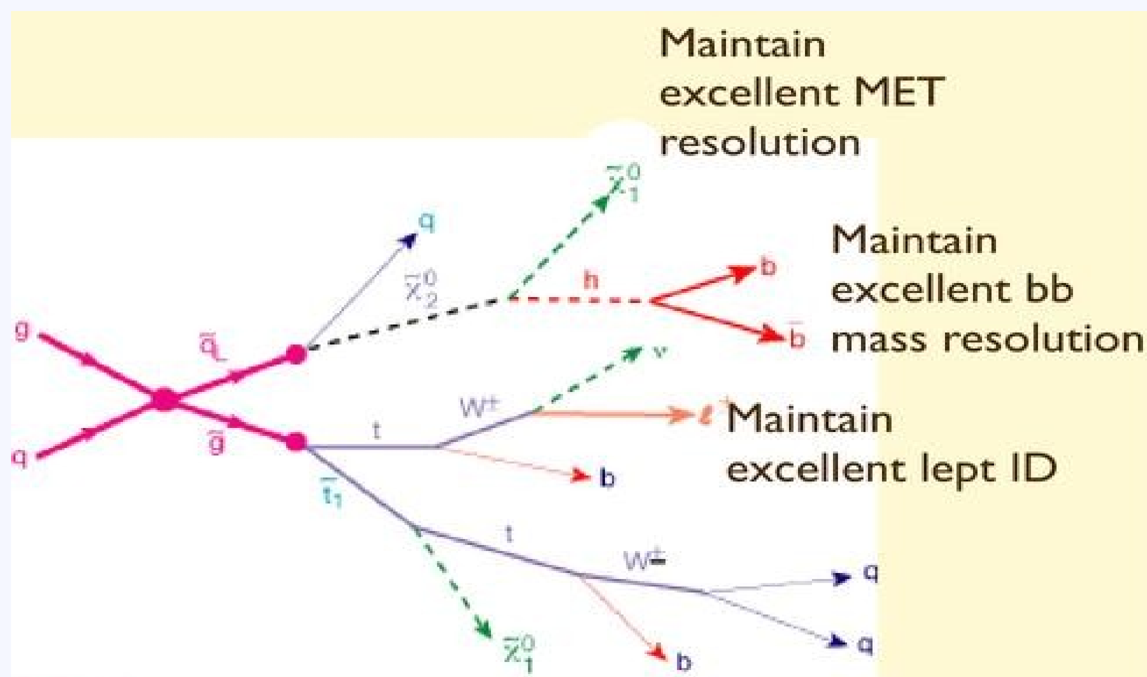
sLHC Physics Goals Summary

- We will soon know a lot more, and we need to wait to find out before the sLHC goals are fixed
- But whatever is found, understanding the early results will require many years of study, with many inputs
- sLHC has the potential to deliver large data sets, making new measurements accessible
- Mangano, SLHC-PP kickoff meeting:
  - Demands for a ten-fold increase in luminosity will likely be fully justified a few years from now

Detector Needs at sLHC

- Detector performance needs to be maintained despite the pile-up!
  - High-mass (~TeV) can tolerate some degradation; low back grounds
  - But WW scattering (Higgs couplings or vector boson fusion) needs forward jet trigger and central jet veto
  - Vertex, missing Et, pt resolution remain important, and efficiencies, for many channels of interest
  - Electron ID and muons for W/Z, W'/Z', and SUSY





b-tag eff

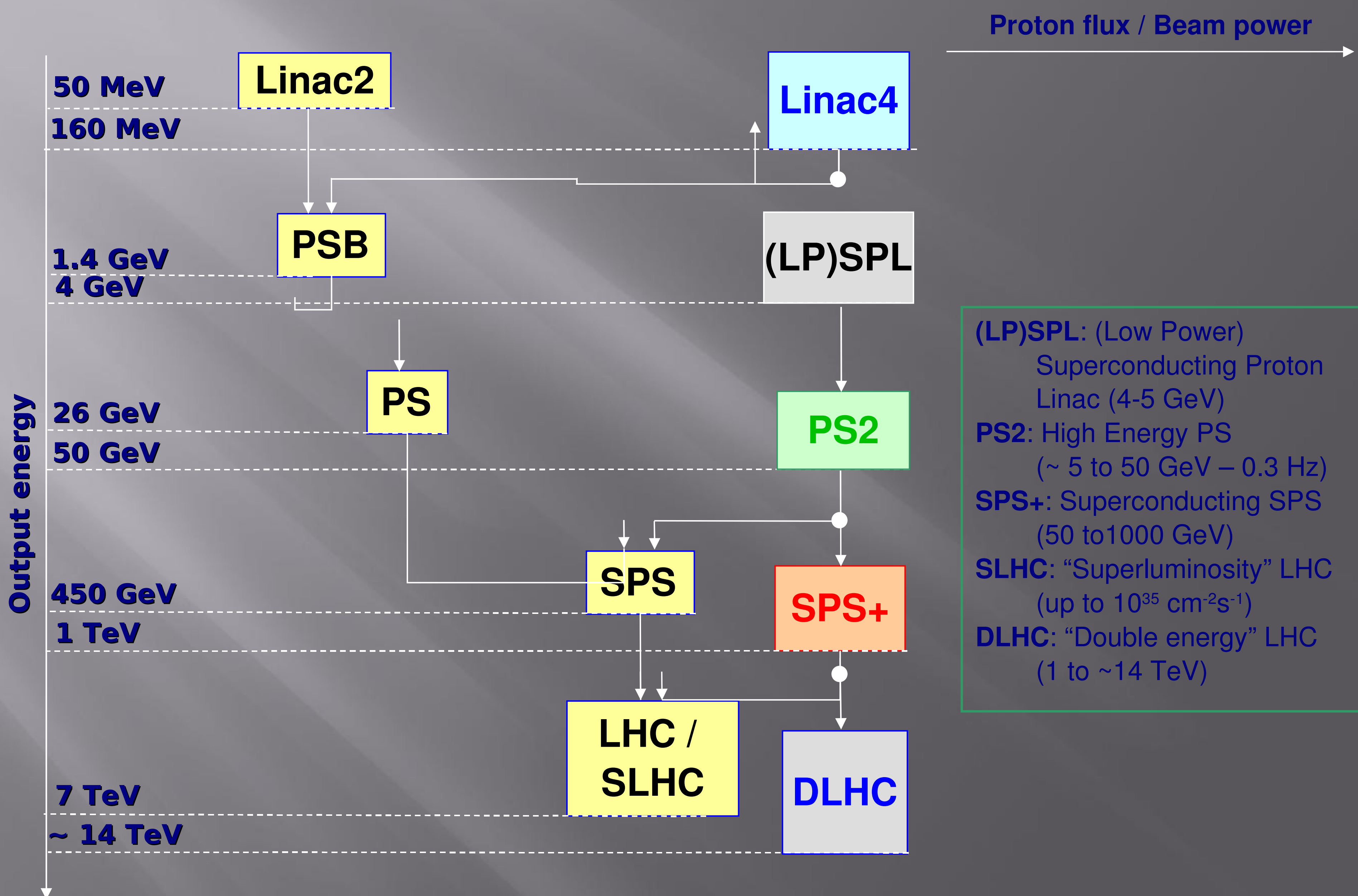
LHC Evolution – Phase 1

- LHC is complete apart from full collimation
  - Limited to 40 % of nominal for protection until collimators installed
  - Collimators to be completed in 2010/11 shutdown, allowing rise to ~nominal luminosity of 10^{34} cm^{-2} s^{-1}
  - Best current estimate is that one nominal year will deliver 60 fb^{-1}
- Phase-1: 2013-2016
  - Linac-4
    - Approved and work has started; higher brightness
      - Allows higher LHC current, to “Ultimate” which is 2.3 times nominal
    - Ready to run in 2013
  - New Inner Triplet focussing magnets
    - Use spare super-conductor from LHC magnets
    - Larger aperture, allows β* of 0.25 m instead of 0.55 m
    - Install in 2012/13 shutdown
    - In principle also gives factor 2 on nominal
  - Expectation is that these two improvements will allow a ramp-up to 3 x nominal; Conditions: 70 minimum bias events per BC; ~700 fb^{-1} before phase 2

LHC Evolution – Phase 2

- Several ideas being explored to see the best way to achieve 10 x nominal in 2017
- Injector improvements – higher current, higher reliability, shorter fill time
- New machine elements and ideas:
  - Magnets inside the experiments for “Early Separation” schemes
  - Crab cavities
  - Wire correctors
  - Luminosity Levelling

Present and future injectors

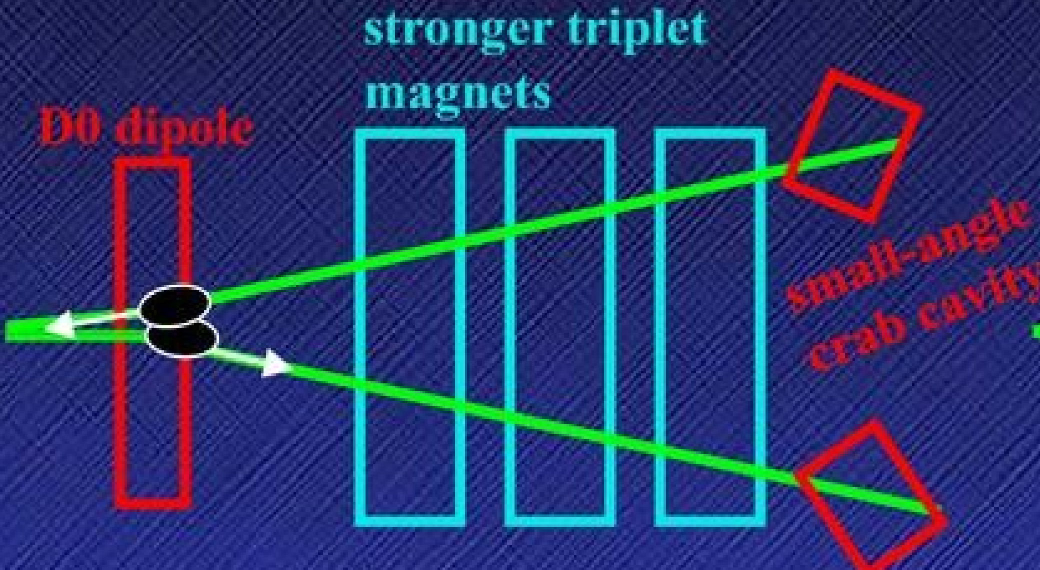


(LP)SPL: (Low Power) Superconducting Proton Linac (4-5 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
SLHC: "Superluminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)
DLHC: "Double energy" LHC (1 to ~14 TeV)

Reminder: LHC upgrade paths

early separation (ES)

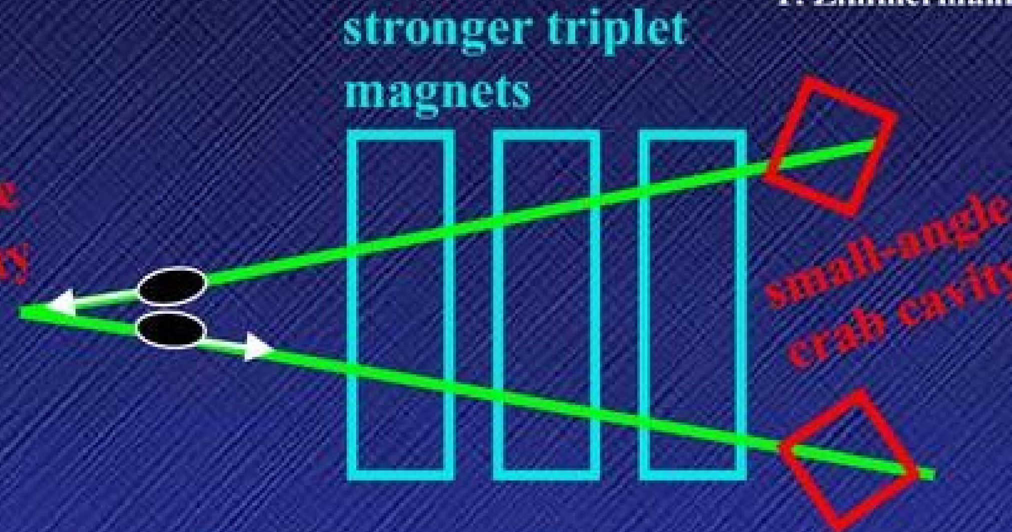
J.-P. Koutchouk



- ultimate beam (1.7×10^{11} protons/bunch, 25 spacing), β^* ~10 cm
- early-separation dipoles in side detectors , crab cavities
  → hardware inside ATLAS & CMS detectors,
  first hadron crab cavities; off-δ β

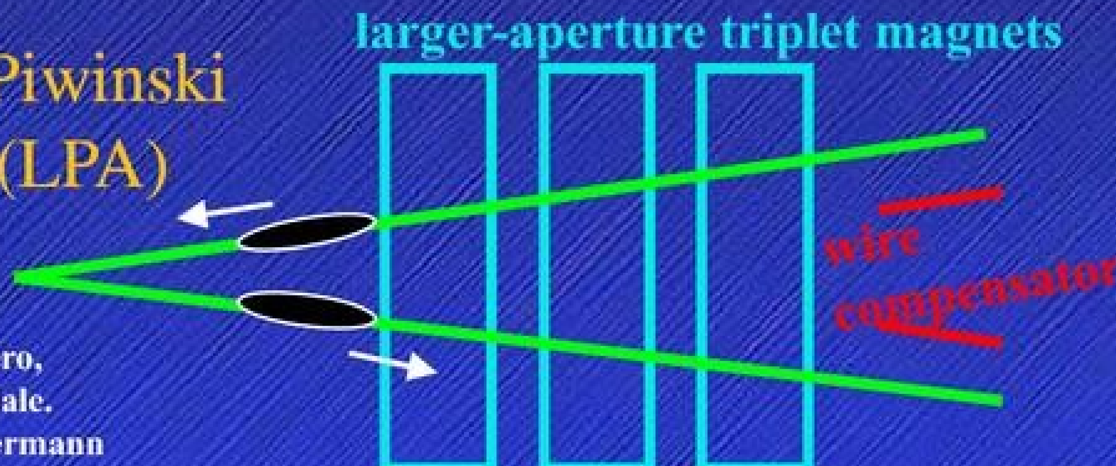
full crab crossing (FCC)

L. Evans,
W. Scandale,
F. Zimmermann



- ultimate LHC beam (1.7×10^{11} protons/bunch, 25 spacing)
- β^* ~10 cm
- crab cavities with 60% higher voltage
  → first hadron crab cavities, off-δ β-beat

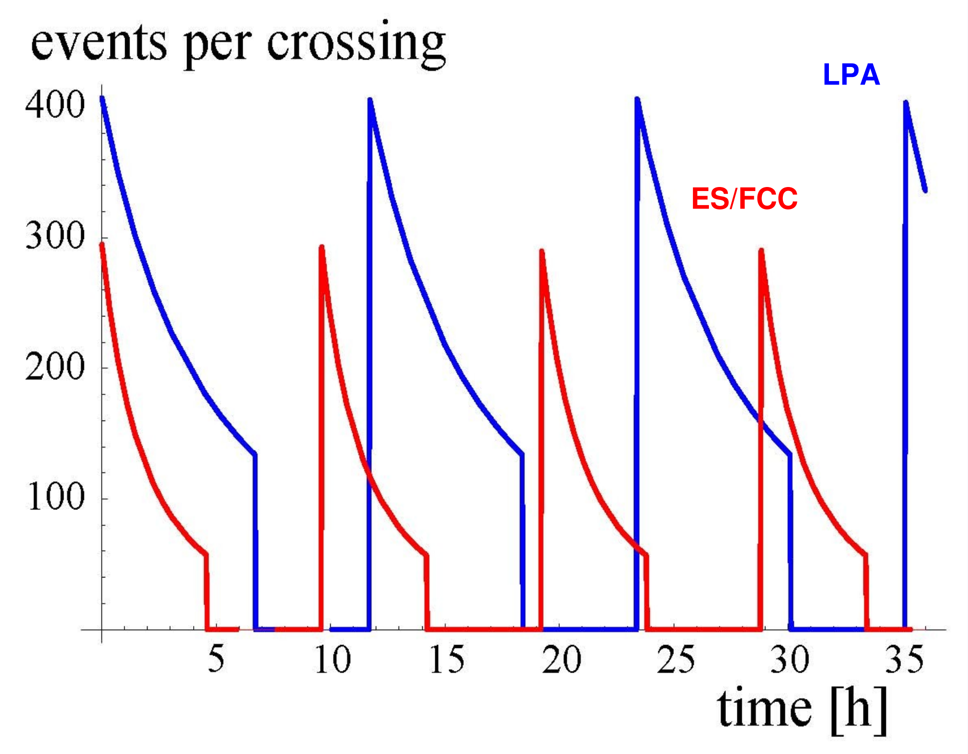
large Piwinski angle (LPA)



F. Ruggiero,
W. Scandale.
F. Zimmermann

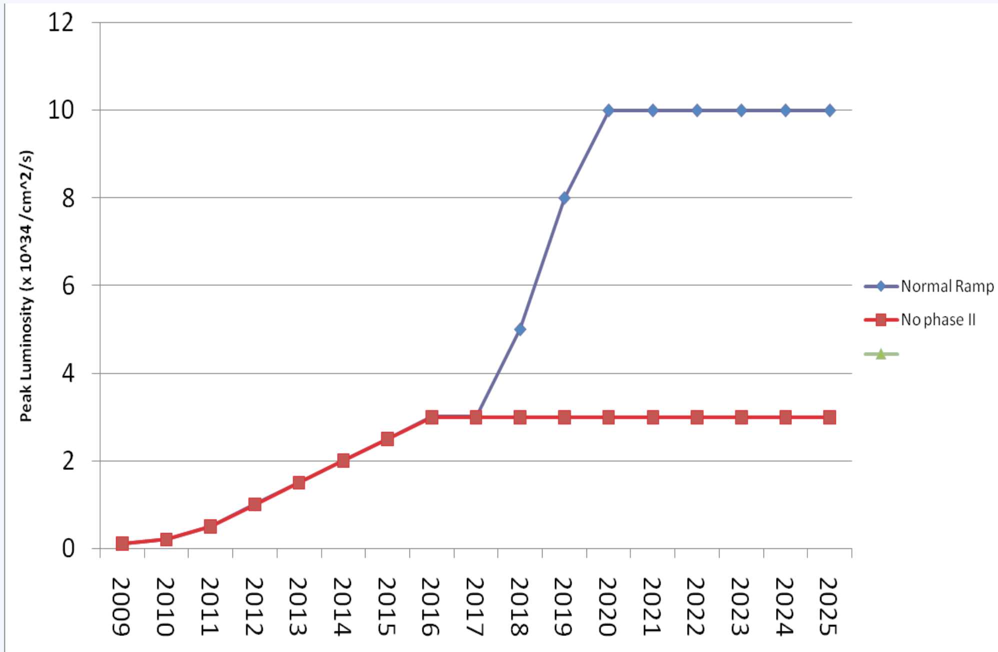
- 50 ns spacing, longer & more intense bunches (5×10^{11} protons/bunch)
- β^*~25 cm, no elements inside detectors
- long-range beam-beam wire compensation
  → novel operating regime for hadron colliders,
  beam generation

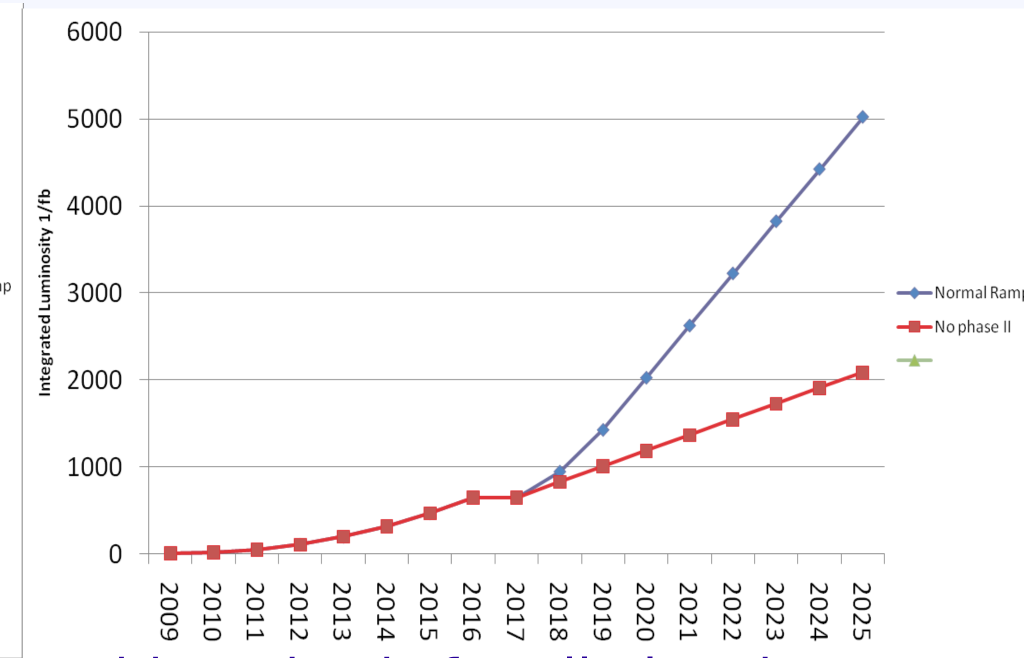
Luminosity Levelling



- 50 ns scheme is always more events per crossing – high pileup
- 25 ns also high despite 25 ns bunch crossing:
  - low machine fill means short spill; fill time the same. So needs very high peak luminosity (15 x nominal) for same integrated luminosity as 50 ns
- Investigate (de-)tuning β^*, vary crabbing, or bunch length to have fixed intensity throughout spill
- Win-win: it turns out these schemes can allow a higher machine fill
  - Higher! Integrated luminosity than without levelling
  - Very interesting to the experiments

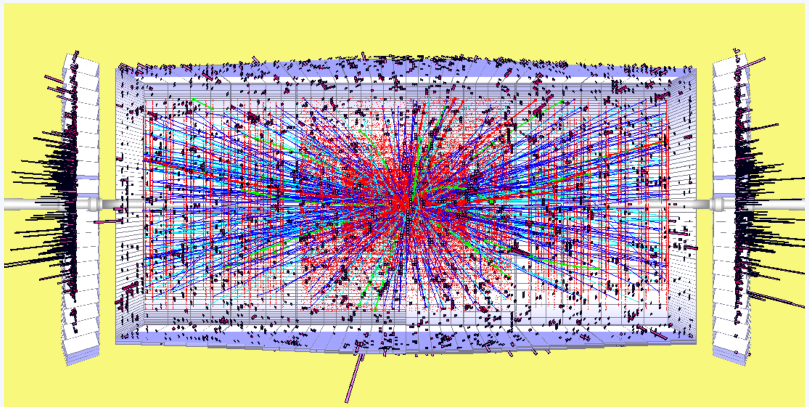
Anticipated Peak and Integrated Luminosity



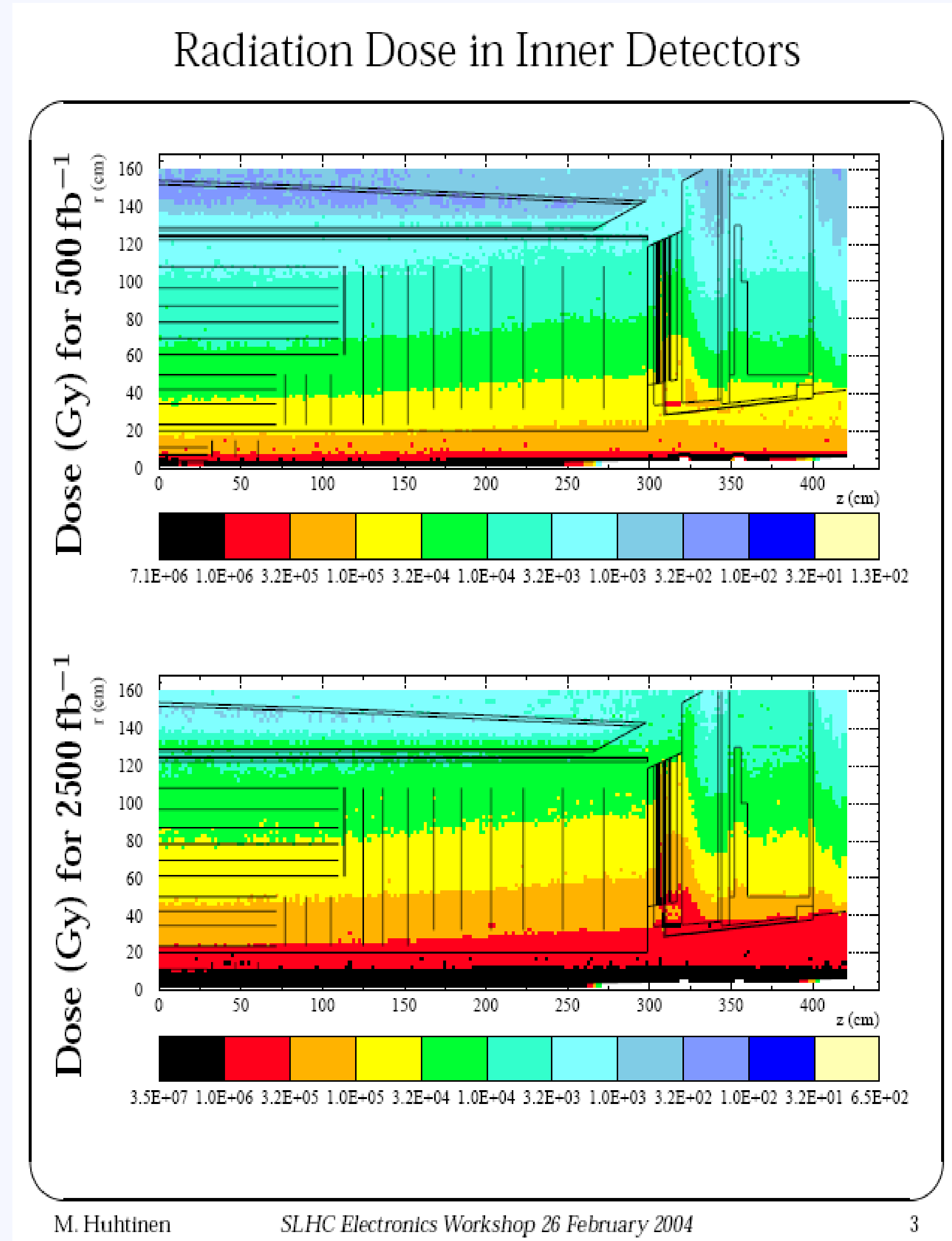


- LHC, ATLAS and CMS agreed to use this as basis for all planning
- Approved at LHCC meeting 1 July 2008
- Sets the conditions and timescale
  - Phase 1 starts with 6 – 8 month shutdown end 2012
    - Peak luminosity 3 x 10^{-34} cm^{-2} s^{-1} at end of phase 1
  - Phase 2 will start with an 18 month shutdown at end of 2016
    - Peak 10 x 10^{-34} cm^{-2} s^{-1} in phase 2
  - 3000 fb^{-1} integrated luminosity lifetime of detectors minimum in phase 2

What are the conditions at sLHC?

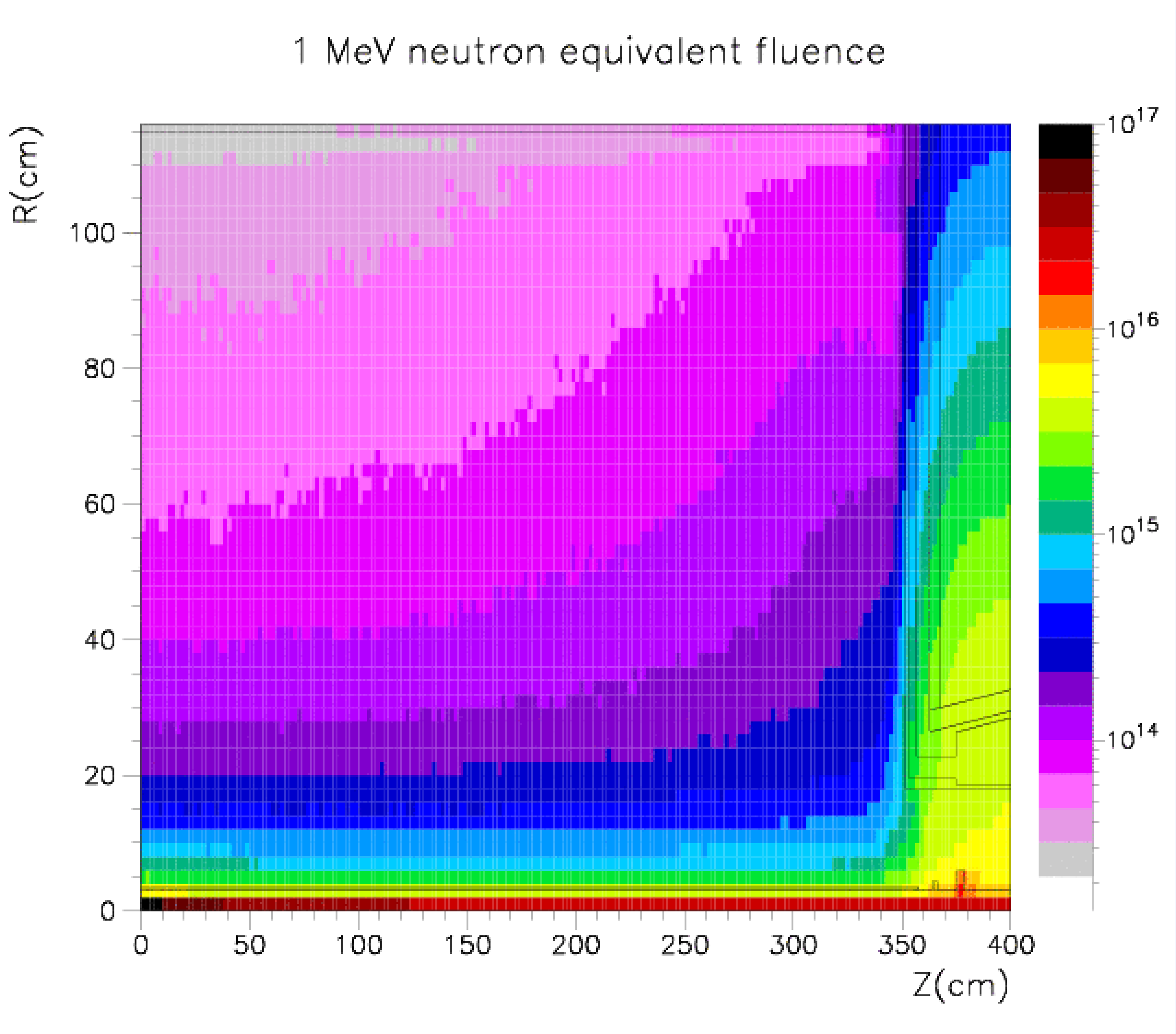


- 300 – 400 pile-up events at start of spill (unless luminosity levelling)
- Want to survive at least 3000 fb^{-1} data taking
- B-layer at 37 mm:
  - ~30 tracks per cm^{-2} per bunch crossing
  - $>10^{16}$ 1 MeV n-equivalent non-ionising
  - Few 10s of MGray



Non-ionising fluence

- ATLAS 1 MeV n_{eq} cm^{-2} fluence at 1000 fb^{-1} (Ian Dawson)



Detector Plans – Phase 1

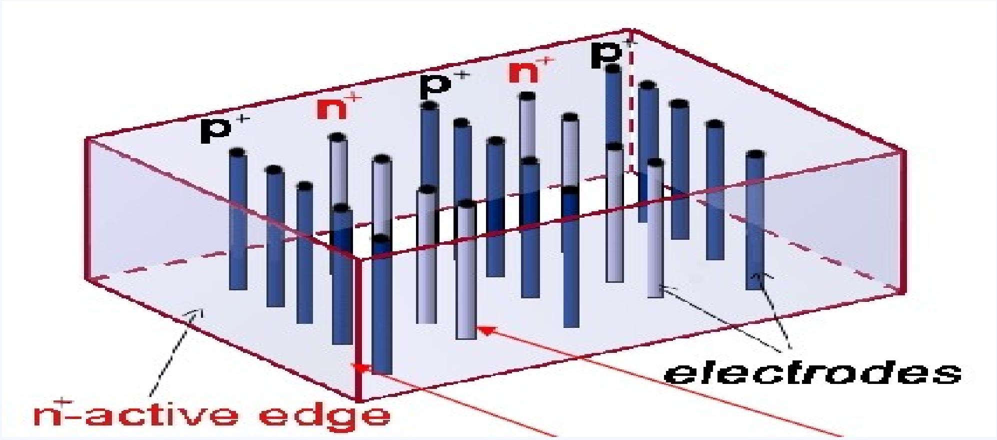
- Limited time for installation – 6 to 8 months in 2012/13 shutdown
- Small increase in peak rate above previous estimates (2 --> 3 x 10^{34})
- Total integrated luminosity similar to previous expectations ~700 fb^{-1}
  - Limited changes needed; some completion of staged items e.g. CMS muons
- CMS pixel detector is fast to replace
  - Will replace at least the B-layer, and investigating more ambitious plans to replace the whole pixel detector
- ATLAS pixel takes ~ 1 year to replace B-layer
  - ATLAS will insert a new B-layer inside the current detector, along with a new smaller diameter beam pipe, in 2012/13 shutdown
- TDAQ
  - Both experiments will continuously upgrade TDAQ to cope with rates and take advantage of new processing power
  - CMS investigate track triggers at Level-1 with new pixel
  - ATLAS look at topological triggers – combining different trigger elements, e.g. muon with no jet and fast track finding (associative memory) at LVL2

Detector Changes for Phase 2

- Most of ATLAS and CMS will cope well at sLHC
  - Keep magnet systems, muon systems, calorimeters
  - But inner trackers in both experiments need complete replacement
    - Radiation damage limit will have been reached
      - Need to replace them even if no sLHC!
    - Higher rates cause dead time (e.g. ATLAS TRT)
    - Need finer granularity detectors for good pattern recognition
  - And parts of all systems need upgrading, even if most of the basic detector parts remain

Inner detectors - B-layers

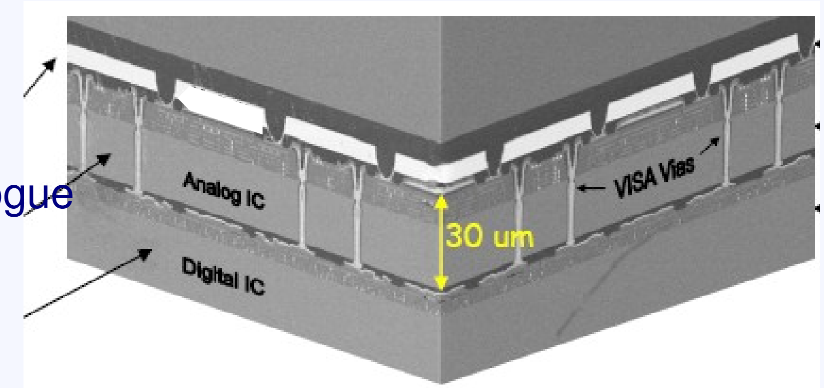
- Most challenging for track density, radiation damage, SEU
- Highest requirements: efficiency, coverage, position resolution
- Sensors: current planar-Si sensor technology is not rad-hard enough to survive to end of sLHC. Either new sensors, or replace every few years
  - 3D silicon, thin silicon, diamond, MPGD (Gossip) as alternatives
- Smaller beampipes --> b-layer closer to beam

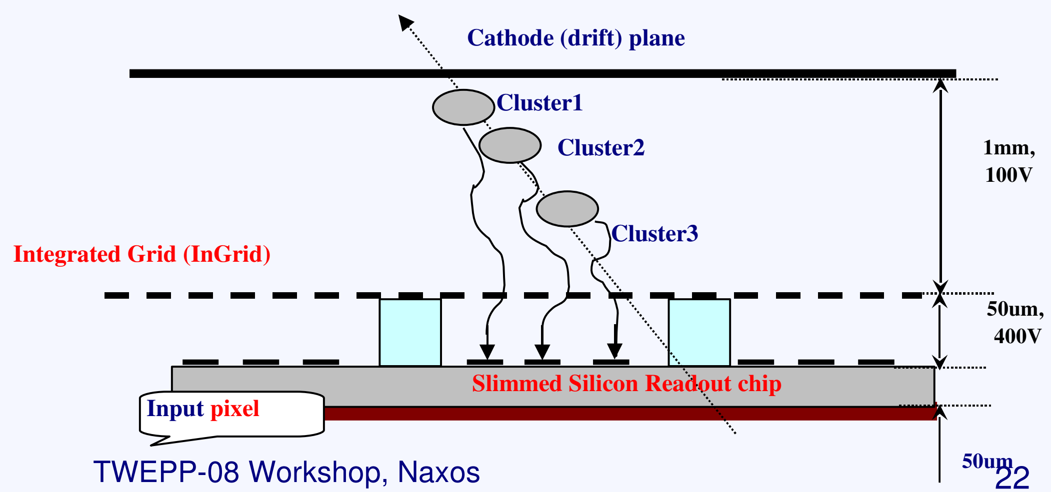


Si pixel sensor

BiCMOS analogue

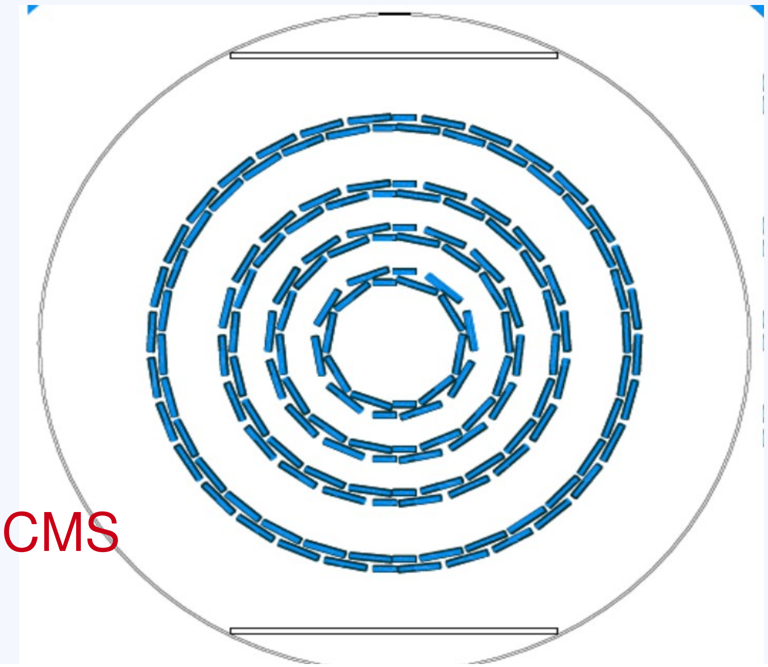
CMOS digital

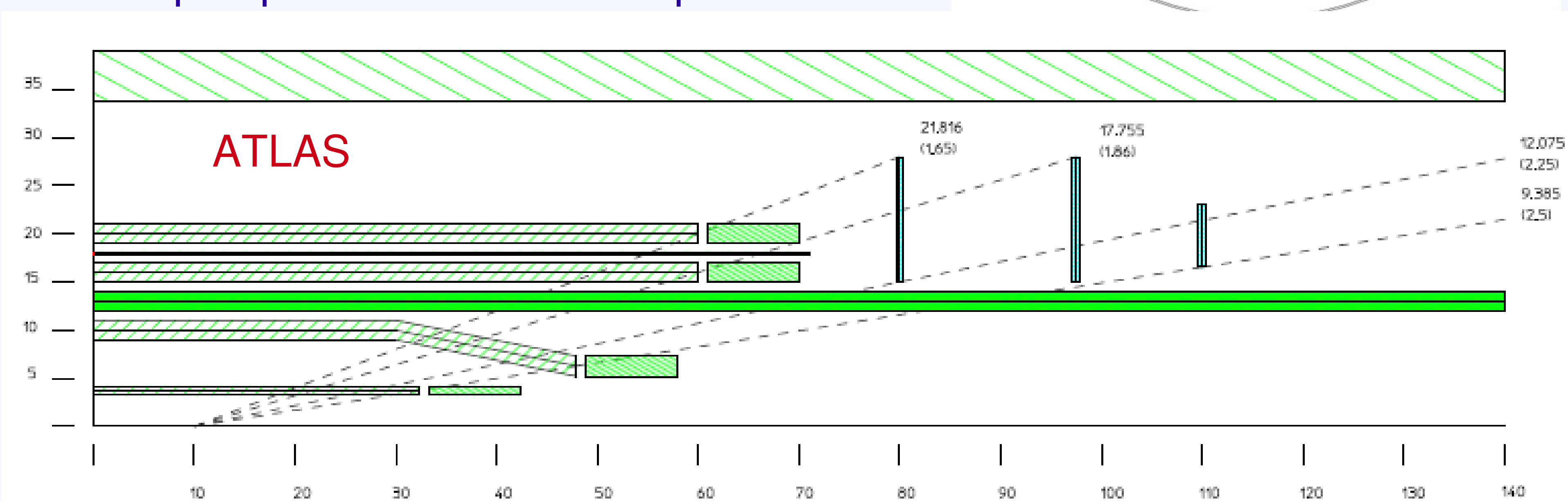




Pixel Detectors

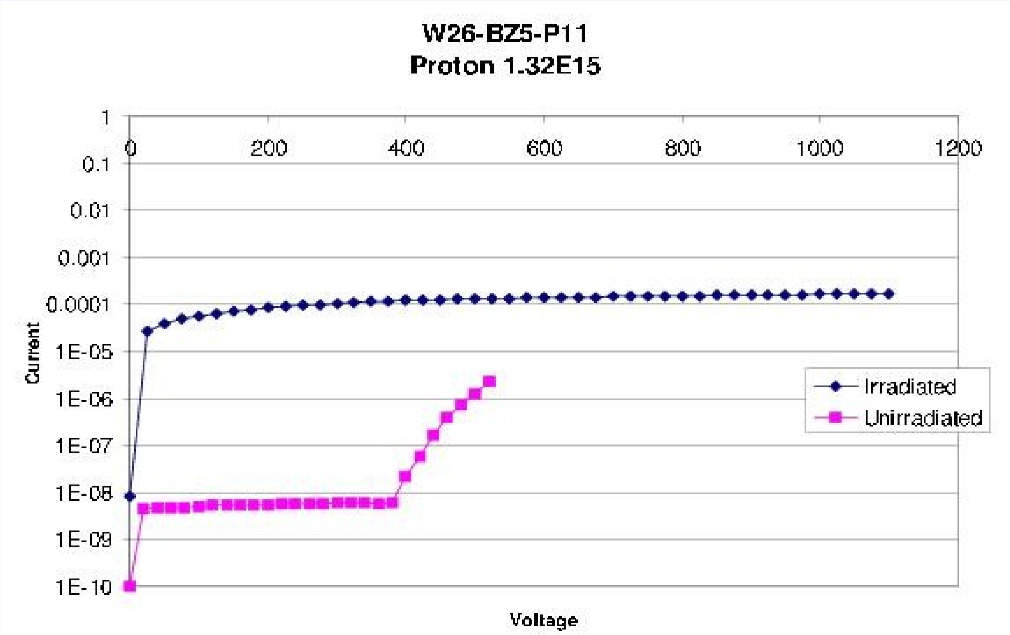
- Read-out architecture and front-end chips under development
  - 130 nm; low power; minimum pixel length; high data rates
- High power levels -> look at new cooling, including CO2
- Lighter mass supports and services?
- Cheaper production – more pixels?

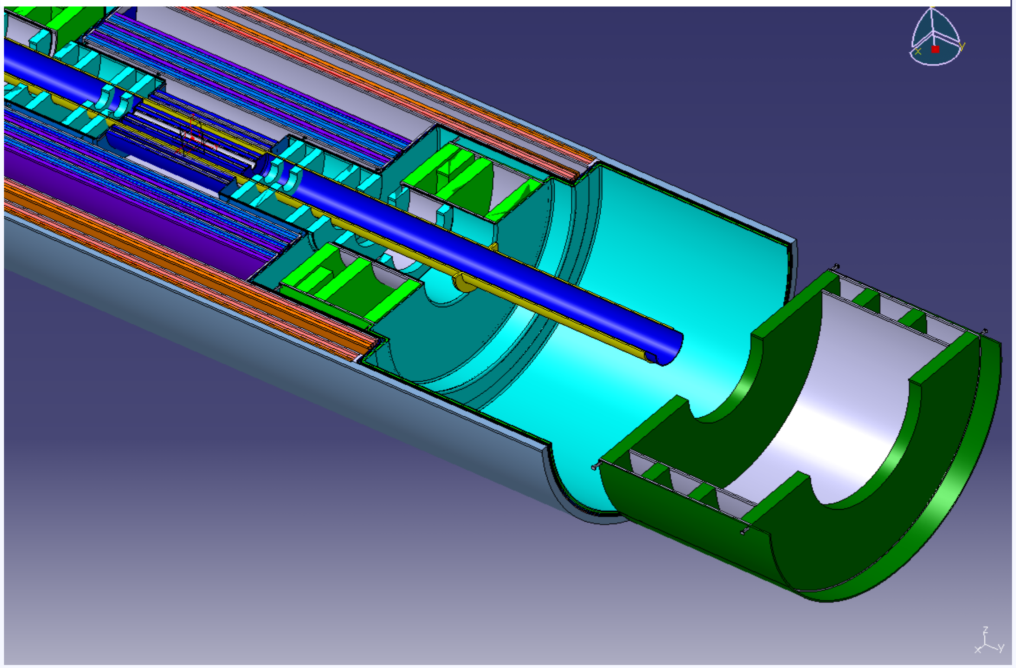




New Strips Detectors

- Switch to n-in-p sensors
  - At high dose, may not achieve full depletion
  - Still have readout junction in the depleted region, no big signal loss
  - Prototype sensors reach 1000 V after irradiation -> good charge collection efficiency
- Short strips (~25 mm) at inner region for lower occupancy
- Mechanics and assembly
  - Take into account need for low radiation length and rapid installation in a short shutdown
  - Both experiments insert complete ID's



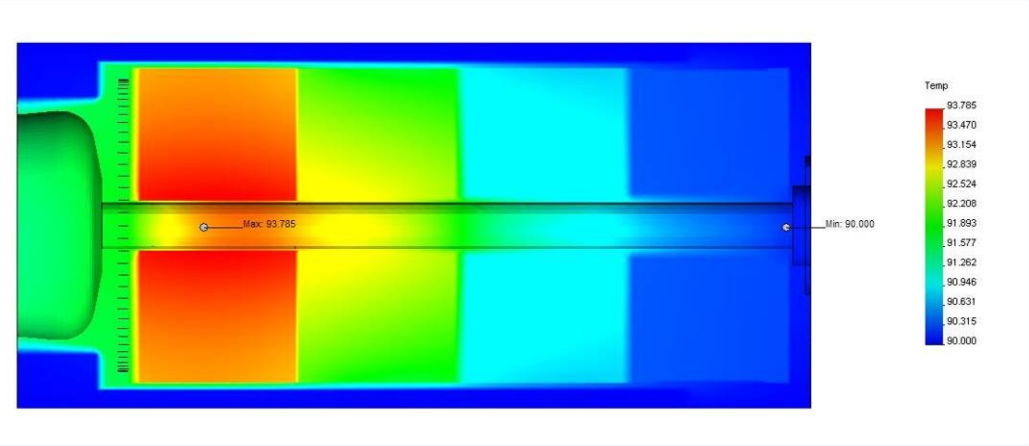


Electromagnetic Calorimeters

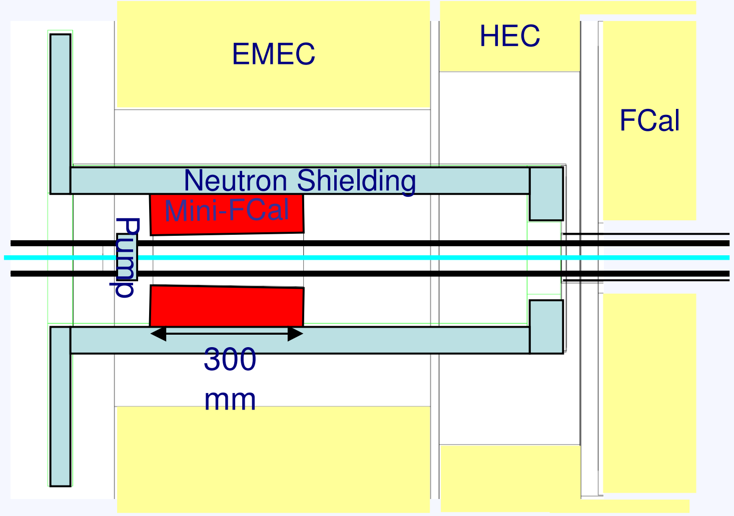
- Both ATLAS and CMS EM calorimeters should perform well at sLHC
- Pileup worsens the resolution a little, partially compensated by optimising the sampling
- New electronics can allow more flexibility in trigger; all data read out
- Worst affected region is forward
  - Remains important for WW-scattering triggers
- CMS forward VPT may darken; very dificult to access/replace

Electromagnetic Calorimeters: Atlas LAr

- ATLAS forward calorimeter may (being investigated) suffer a number of problems:
  - Boiling of LAr, ion build up between electrodes, voltage drop over HV resistor
  - Studies underway; If these show action is needed, two solutions considered:
    - Warm calorimeter in front of current calorimeter
    - Open cryostat, insert complete new FCAL with smaller gaps and more cooling

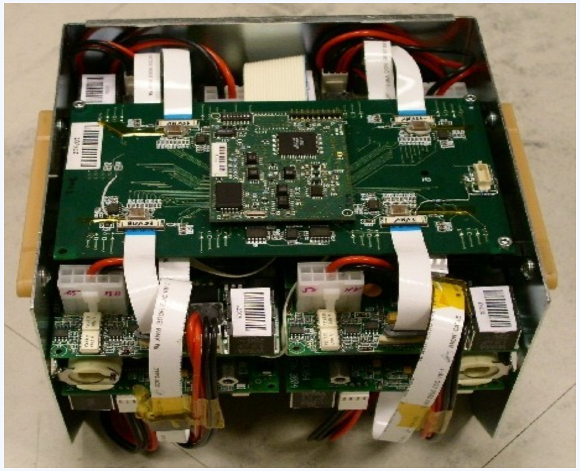


Mini-FCal (Front)



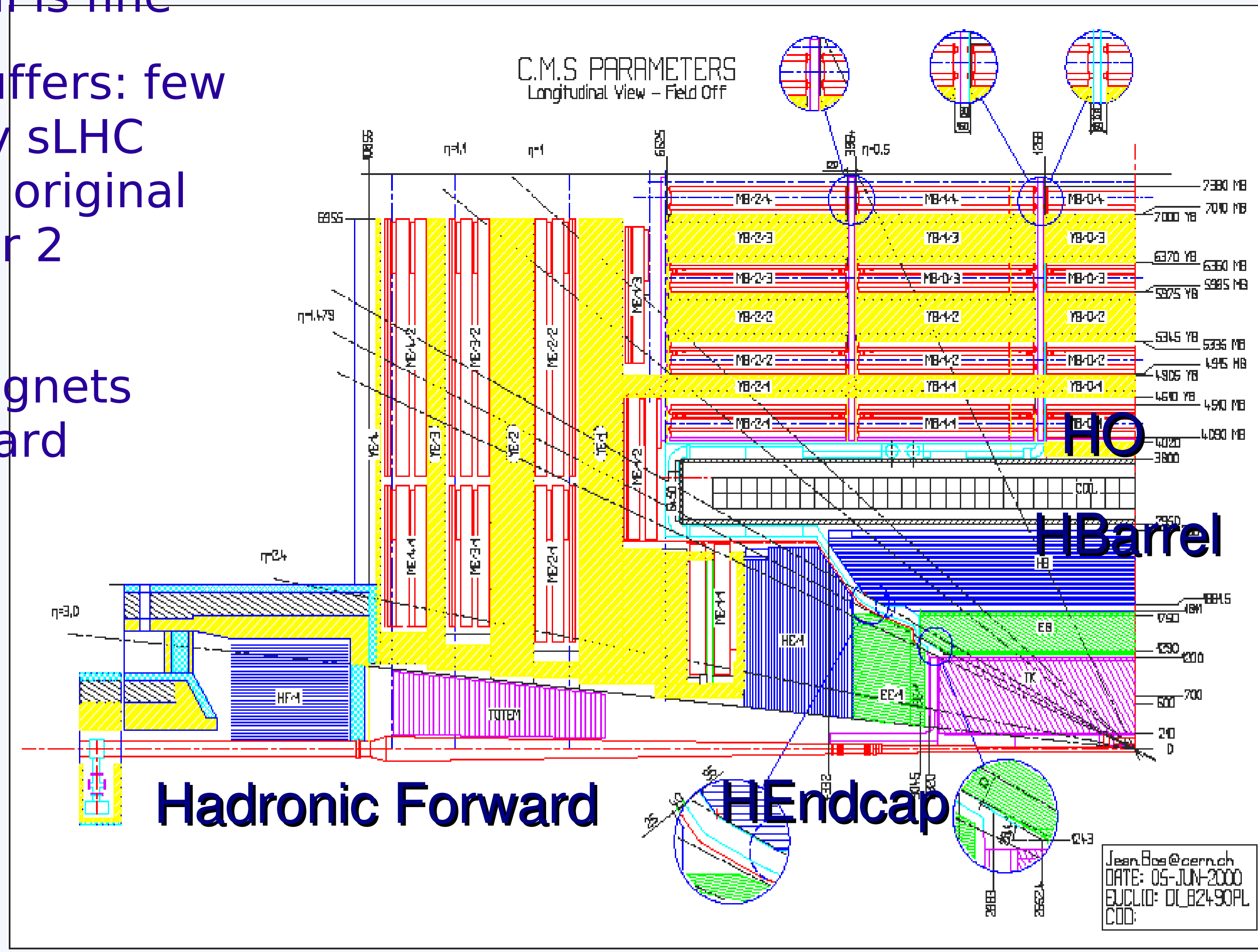
Hadronic Calorimeters - Atlas

- Atlas tiles, fibres, PM: expected to survive
  - Small decrease in performance after 7 years LHC running
  - Even at the end of sLHC running they will be working fine - though worst regions may have significantly less light
  - So do not expect major detector parts to be changed
- ATLAS Readout Electronics: rad hardness, maintainance, trigger needs - all benefit from new readout
- Power supplies – rad hardness and repairability issues so replacement plans



Hadronic Calorimeters - CMS

- Most of hadron cal is fine
- Forward region suffers: few towers blacked by sLHC (tower 1 ~ 4 % of original light output; tower 2 ~23%)
- Also, machine magnets (“D0”) block forward calorimetry

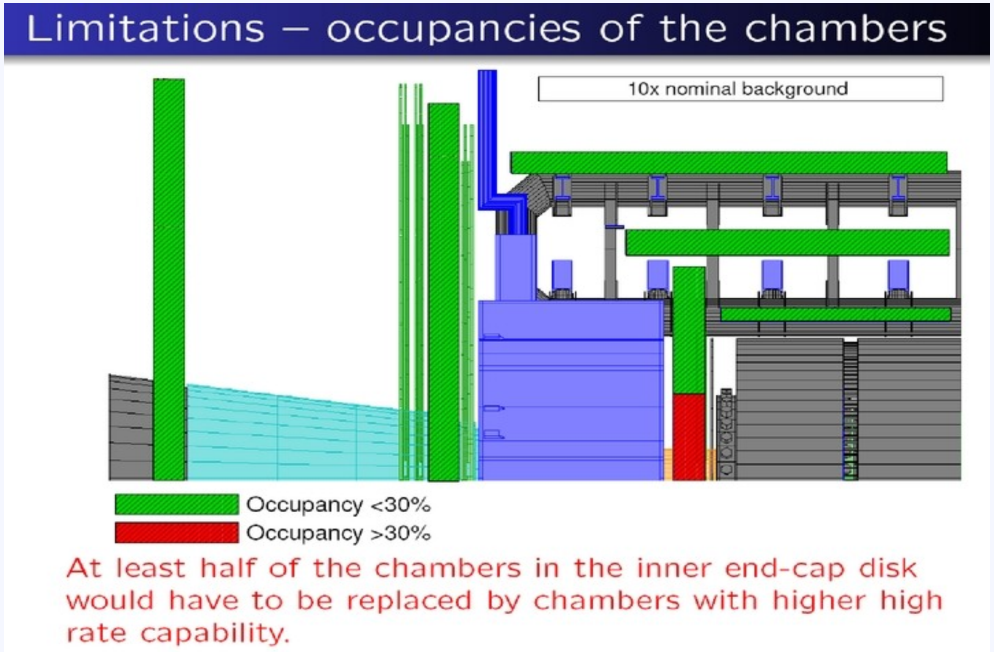


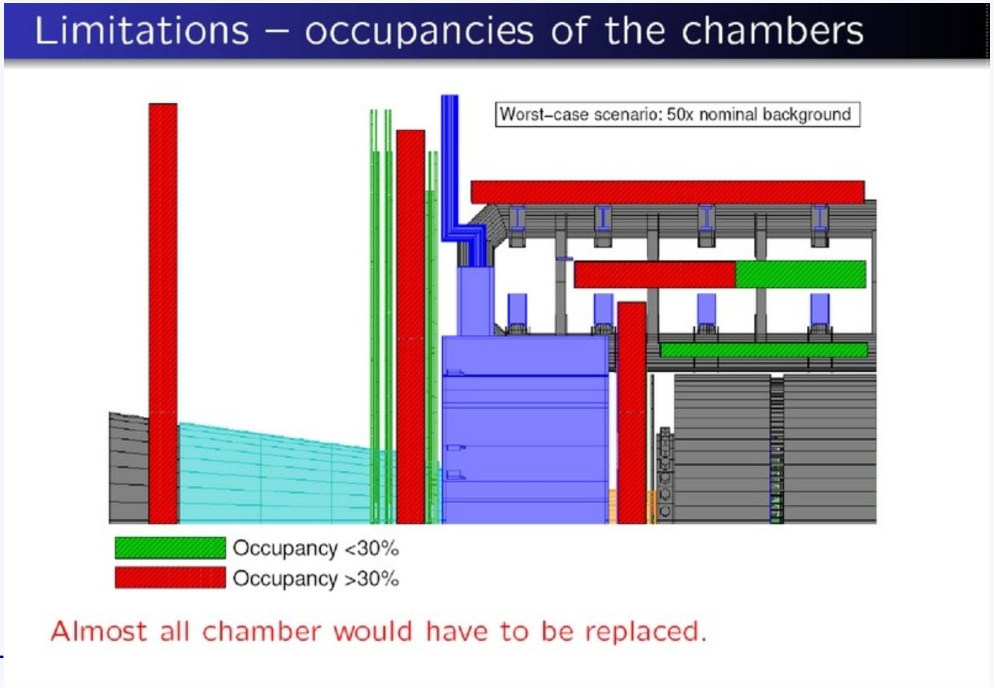
Muon Systems

- CMS has a lot of shielding, rate probably OK for current chambers
  - Need to see backgrounds to confirm; possibly $\eta > 2$ need changing, or limit trigger region to this
  - New readout electronics? FPGA not rad hard enough
- ATLAS air core toroids have higher backgrounds; need to replace forward chambers (CSCs mainly) at nominal background.
  - Very important to measure actual background to see how much of “safety factor 5” is used up to see if significantly more needs replacing
- Both experiments are looking into improved shielding
  - Difficult : current design is highly optimised
  - Other possibility is to develop single chambers to do both triggering and precision read-out: thinner chambers leave more space for shielding – see talk later on

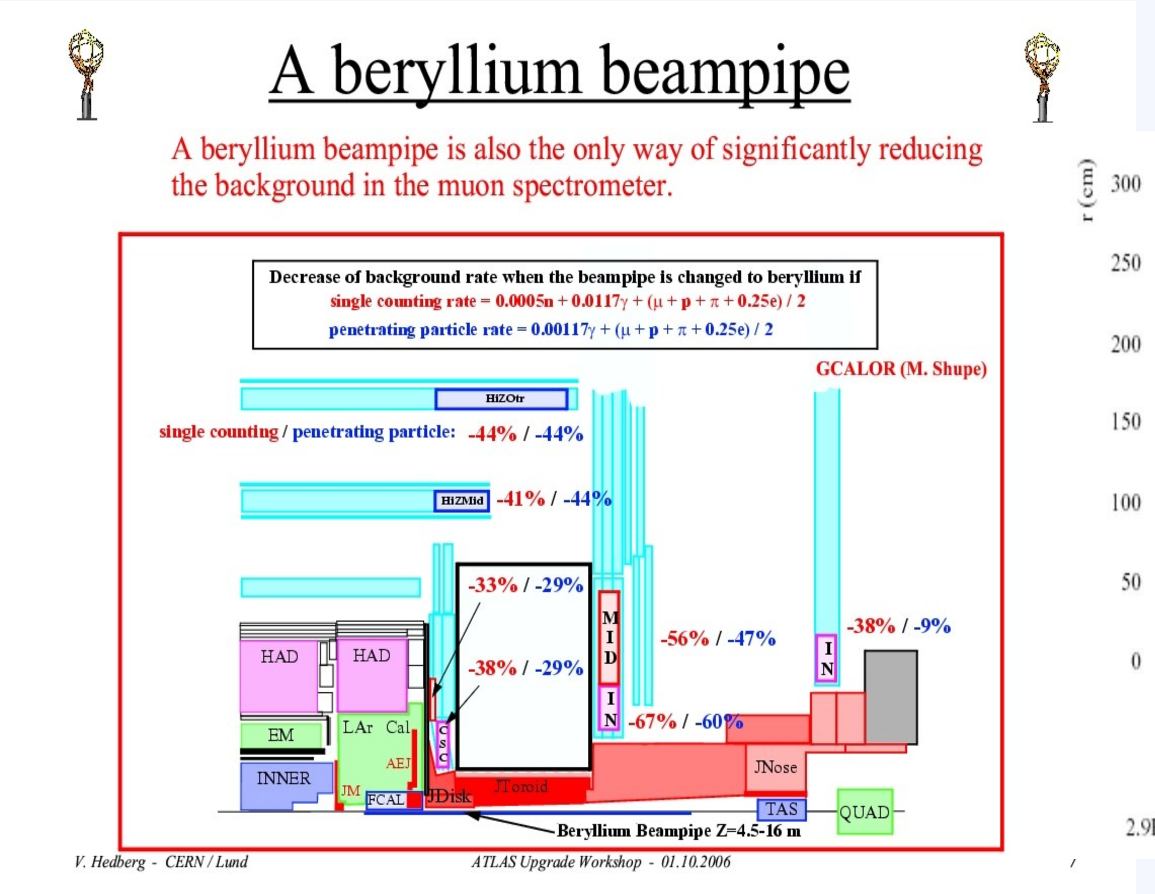
ATLAS Muon Chamber Replacement Range

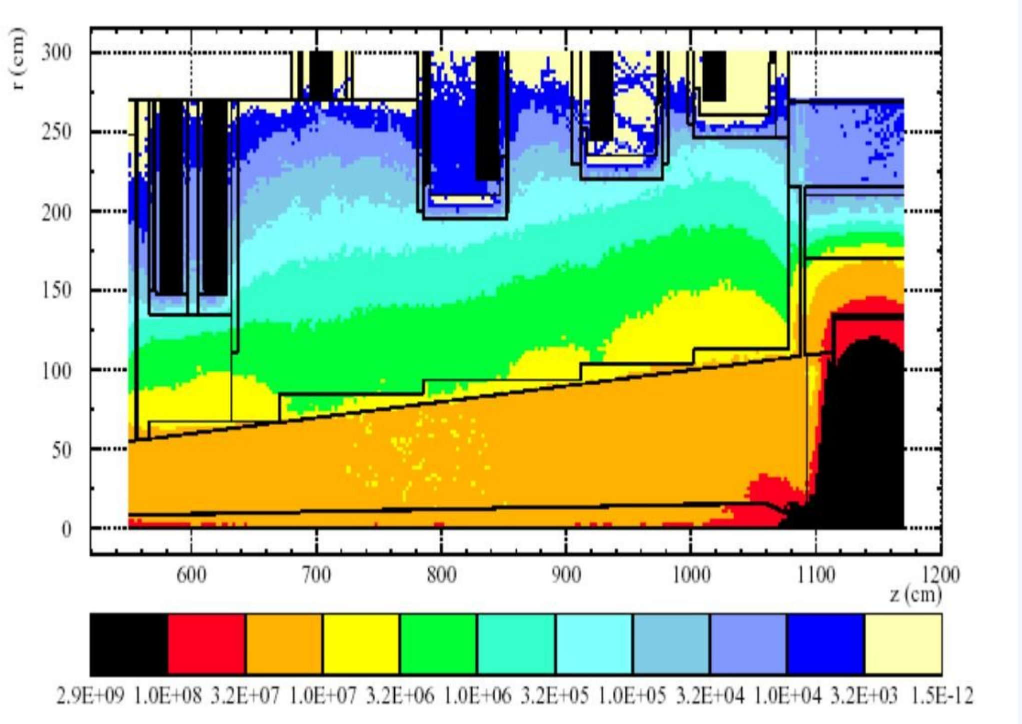
- Depending on backgrounds, either minimal or very large fraction of Atlas muon system needs replacing, unless backgrounds can be reduced (in relation to luminosity)
- Both Atlas and CMS have to wait for data





Beam-pipe and shielding





- All-Be beam pipe reduces muon BG considerably
  - Expensive beampipe, but **much** cheaper than new muon chambers
- CMS consider more shielding to $\eta = 2$
  - Add borated polythene; better shielding of PMTs

Triggers

- In both experiments the goal is to maintain trigger rates.
  - Still challenging! You have to reject 10 times more events at LVL1, and process much more data at LVL2 (pile-up --> bigger events)
- Continuos process of replacing and increasing processor hardware
- Also look at “topological” cuts: e.g. isolated muon as a muon trigger with no jet trigger in the vicinity
- Consider increasing level-1 latency: the time available to actually run the trigger increases rapidly
- Atlas considers a “Fast Track Trigger” which snoops on Inner Tracker LVL1 data as it passes to LVL2. It uses massive associative memory to recognise hit patterns as tracks, and passes LVL2 rather precise helix parameters.
- Track triggers at LVL1 – see later

Main Electronics Needs – Readout chips

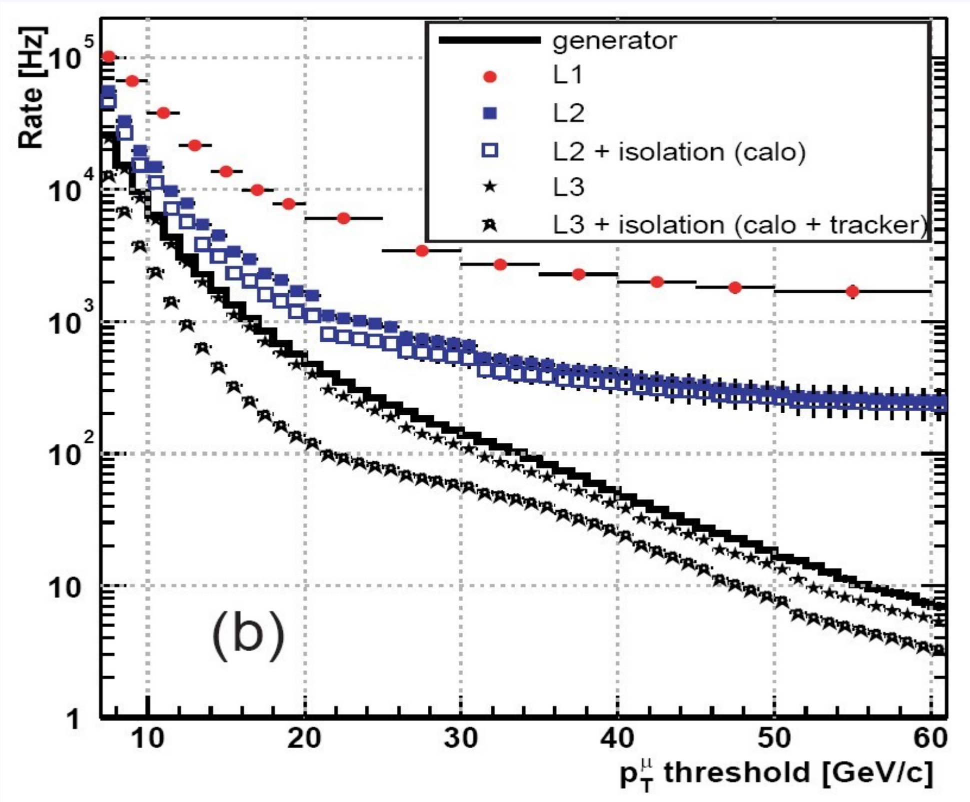
- The ATLAS and CMS Upgrades need new electronics throughout the detector: power supplies of calorimeters, data transfer and handling for all detectors; some cases highlighted below
- Read-out chips for pixels and strips
  - Under development for ATLAS and CMS; ABCNext, FE-I4, Timepix-2, CMS – see following talks
  - Controller chips
  - High speed data links
  - Requirements
    - Very challenging: rad hard, SEU tolerant, low analogue noise.
    - Low power: number of channels increases by large factors between current and upgraded detectors. Bringing power in and removing it are major contributors to the material budget
    - High data rates: e.g. develop per-pixel storage, read pixel to end of column only at level-1 trigger

Powering and data transfer

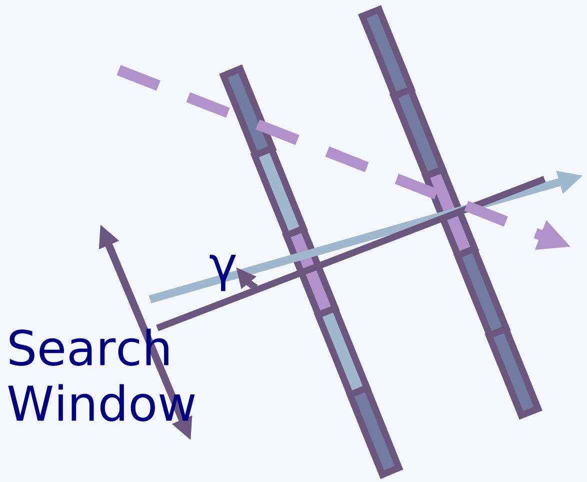
- Powering scheme
  - Cannot have individual module LV – no space, too much material
  - DC/DC or serial very important; many possible schemes
  - Look beyond the basic requirements of high power efficiency and low noise
    - Safety: overcurrent, overvoltage, overtemperature
    - Monitoring
      - Can we avoid copper sense lines, e.g. local safety; local ADC; send DCS information along with data on fibre optics
- Data transfer
  - High-speed electrical and optical links
    - Calorimeters may want to read out all data to RODs: a lot of data
      - better triggering capability
  - How rad hard can we get optical links? Affects where we make the optical-electronic transition in the ID
  - Multiplexing and redundancy schemes
  - Error correction schemes (SEU tolerance)

Track trigger

- Inner Tracker Triggers at Level-1
  - Muon trigger rate ~constant above ~20-30 GeV/C; both ATLAS and CMS
  - Current understanding is this is due to multiple scattering at CMS and width of RPC strips at ATLAS
  - Cannot improve muon situation at CMS; difficult at ATLAS (new muon trigger chamber layer with higher resolution?)
  - Several ideas to investigate inner tracker triggers
    - both P_t and vertex displacement triggers

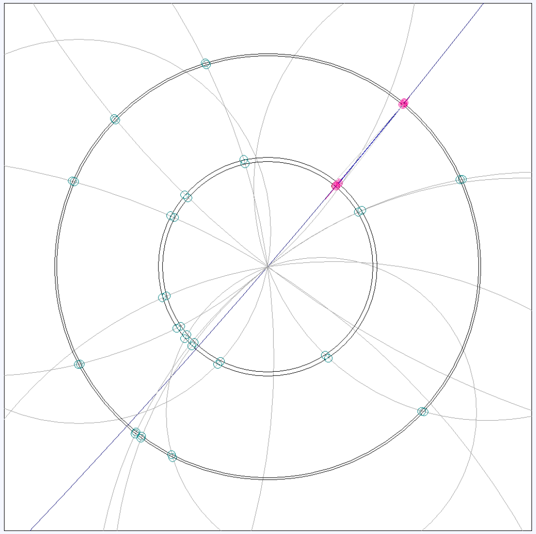


Track trigger (Cont)



High momentum tracks are straighter so pixels line up

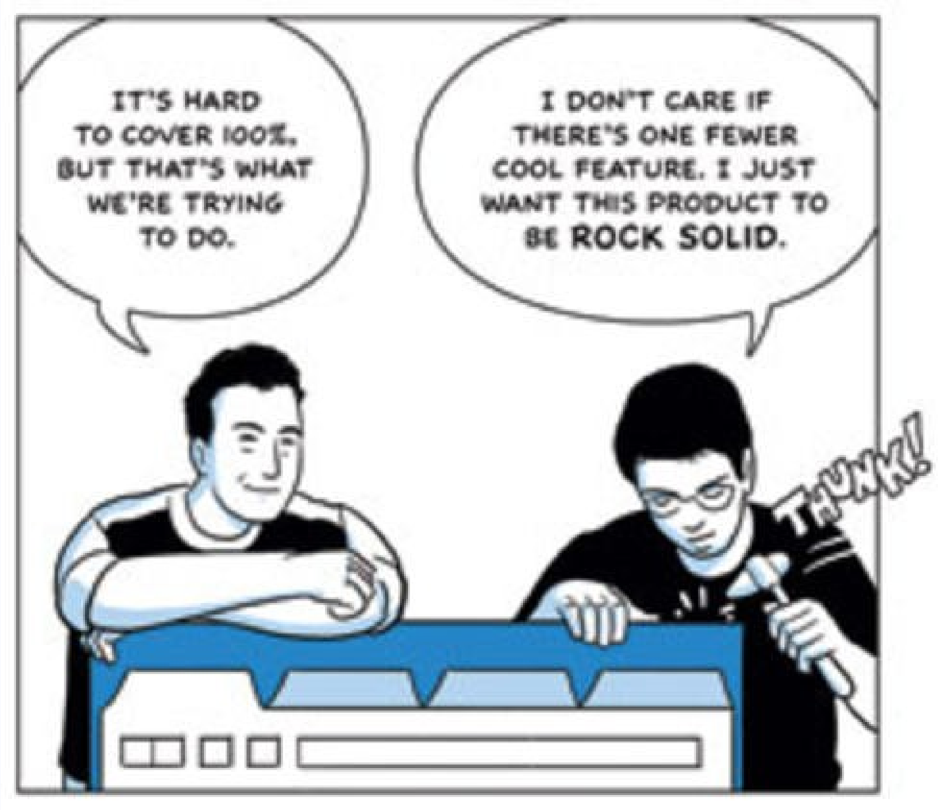
Pairs of stacked layers can give a P_T measurement



- Several ideas to investigate inner tracker triggers
  - both P_t and vertex displacement triggers
- E.g. local coincidences separated by >~ 1 mm in pixels read to end-of-stave
  - then check for pairs of these in different layers
- Micropattern gas detectors also interesting – collect the “coincidence” over ~17 mm gap onto one chip
  - Requires a lot of processing on the chip
- Challenge is to develop new chips in time, without increasing the material budget too much (power as well as chip material)

Summary

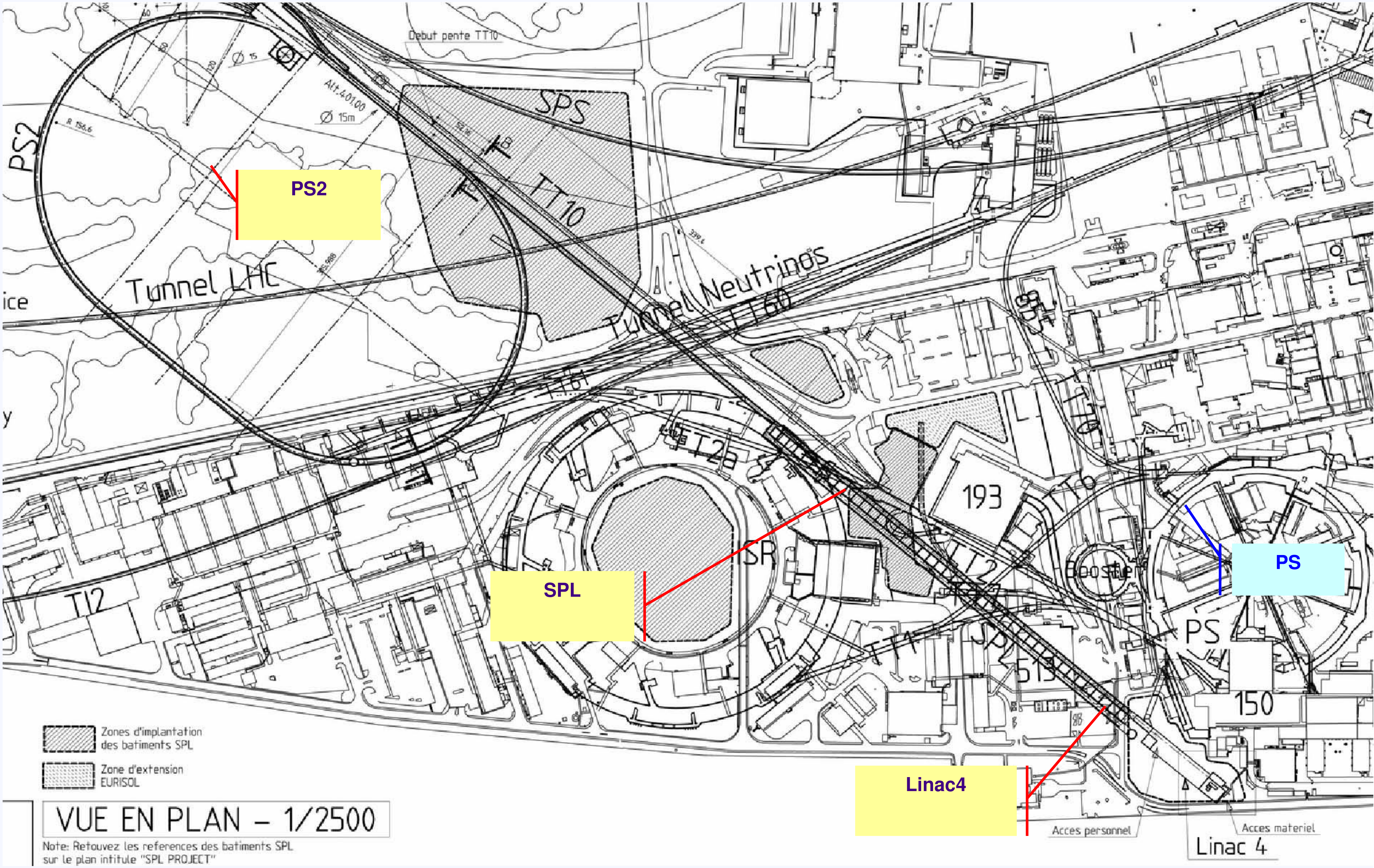
- There is every hope there will be a rich field of physics to explore at the LHC into the 20's
- The LHC expects
  - Phase-1 upgrade 2012 leading to 3 x 10^{34} cm^{-2} s^{-1} peak luminosity
  - Phase-2 upgrade starts end 2016 leading to 10 x 10^{34} cm^{-2} s^{-1} peak luminosity
- Atlas and CMS require major upgrades (even without Phase-2) installed in long shutdown 2017
- Electronics performance is at the core of the upgrades



This project has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under the Grant Agreement nº212114

Backup slides

Injector Chain Plans



Comparison of the different schemes (F. Zimmerman)

Parameter	Symbol	Nominal	Ultimate	EA	FCC	LPA
transverse emittance	ε [μm]	3.75	3.75	**3.75**	**3.75**	**3.75**
protons per bunch	N_b [10^{11}]	1.15	1.7	**1.7**	**1.7**	**4.9**
bunch spacing	Δt [ns]	25	25	**25**	**25**	**50**
beam current	I [A]	0.58	0.86	**0.86**	**0.86**	**1.22**
longitudinal profile		Gauss	Gauss	**Gauss**	**Gauss**	**Flat**
rms bunch length	σ_z [cm]	7.55	7.55	**7.55**	**7.55**	**11.8**
beta* at IP1&5	β^* [m]	0.55	0.5	**0.08**	**0.08**	**0.25**
full crossing angle	θ_c [μrad]	285	315	**0**	**673**	**381**
Piwinski parameter	$\phi = \theta_c \sigma_z/(2*\sigma_x^*)$	0.64	0.75	**0**	**0**	**2.0**
hourglass reduction		1	1	**0.86**	**0.86**	**0.99**
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	2.3	**15.5**	**15.5**	**10.7**
peak events per #ing		19	44	**294**	**294**	**403**
initial lumi lifetime	τ_L [h]	22	14	**2.2**	**2.2**	**4.5**
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.46	0.91	**2.4**	**2.4**	**2.5**
	$T_{run,opt}$ [h]	21.2	17.0	**6.6**	**6.6**	**9.5**
effective luminosity ($T_{turnaround}$=5 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.56	1.15	**3.6**	**3.6**	**3.5**
	$T_{run,opt}$ [h]	15.0	12.0	**4.6**	**4.6**	**6.7**
e-c heat SEY=1.4(1.3)	P [W/m]	1.07 (0.44)	1.04 (0.59)	**1.04 (0.59)**	**1.04 (0.59)**	**0.36 (0.1)**
SR heat load 4.6-20 K	P_{SR} [W/m]	0.17	0.25	**0.25**	**0.25**	**0.36**
image current heat	P_{IC} [W/m]	0.15	0.33	**0.33**	**0.33**	**0.78**

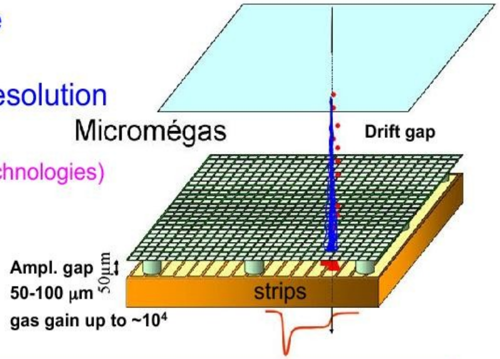
Pixel replacements for Phase 1

- Challenge here is production of new modules to work at higher rates and survive higher dose – in a short time (< 4 years)
- Copying the previous B-layers is unattractive: old technology would last about two years and be inefficient
- Use as a stepping stone to phase 2:
  - New sensors, e.g. 3D detectors or more rad hard planar silicon
  - New readout chips: higher hit rate, 130 nm, single event upset (SEU) tolerant
- Less material
  - Reduce power, powering schemes, cooling e.g. CO_2
  - Lower $\%X_0$ in mechanics and services

Muons - example of chamber R&D

Micromegas for tracking + trigger

- Very high rate tolerance
  measured in kHz/mm²
- Good spatial and time resolution
- Low cost (potentially)
  Bulk MicroMegas (industrial technologies)
  - use of wire mesh
  - PC board technology

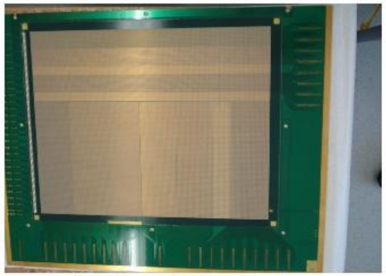


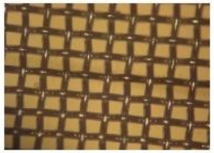
Goal:
$\sigma_x < 100\ \mu m$
$\sigma_t < 5$ ns
size ~ 1x2 m^2

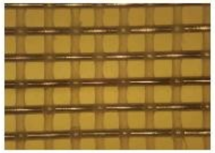
For EI (+ inner EM) region,
with tracking + trigger in a single detector unit.
(good, because of the limited space).

12.02.2008 T. Kawamoto 9

Prototype chambers 45 x 35 cm^2 (2 of the biggest MMs ever made)

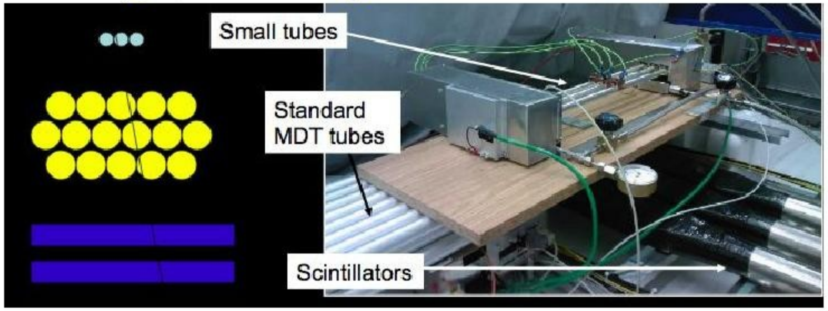


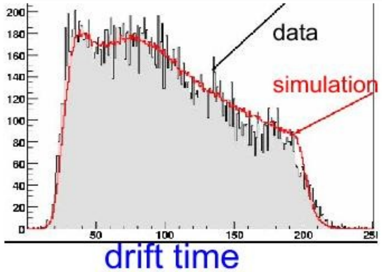




Thin tube MDT

Prototype, cosmic-ray tests 15 mm tube



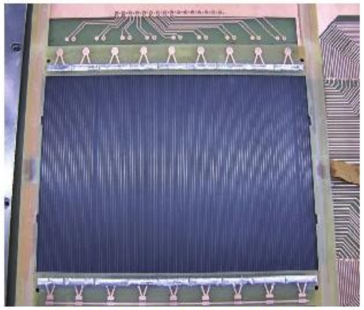


Outlook

- 15 mm tube : x10 higher limit
- Cosmic ray test results promising
- Further tests at GIF planned in 2008

TGC for tracking + trigger

Prototype chambers tested at T9 (Oct/Nov. 2007)



1.5mm and 2 mm strip
Charge readout