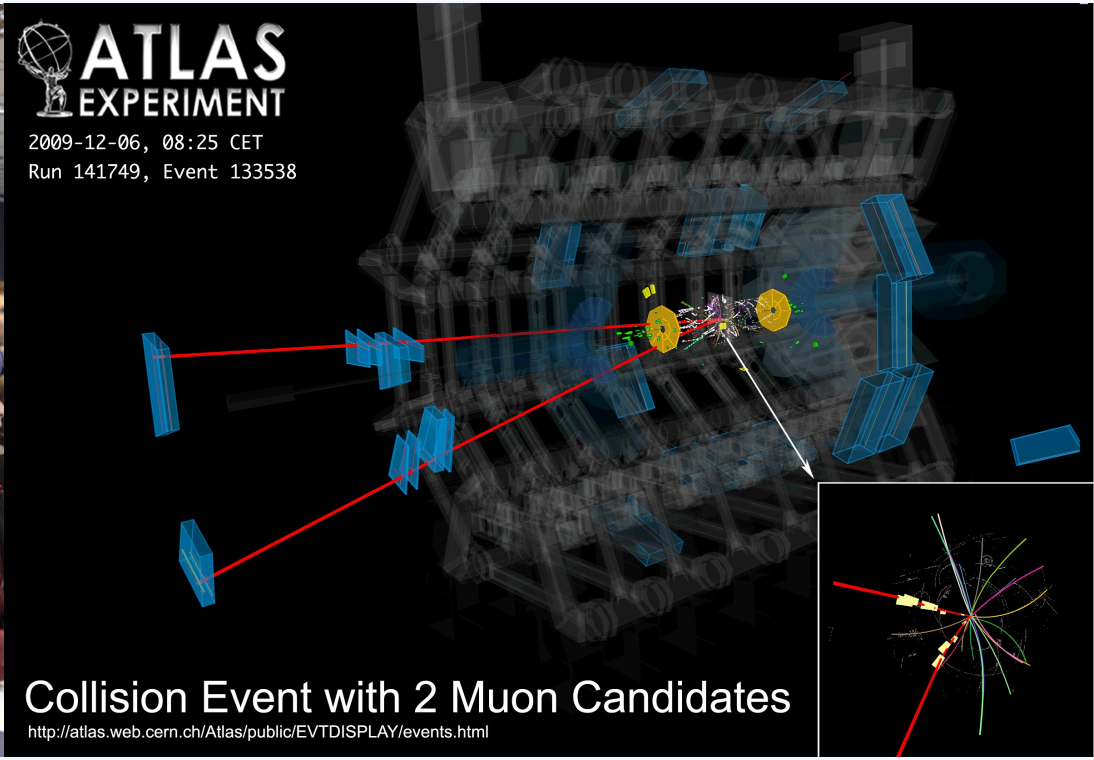
ATLAS Upgrades for High Luminosity

Physics Goals
LHC Development to sLHC
ATLAS Conditions at sLHC
ATLAS Detector Upgrades
- emphasis on Inner Tracker

LHC start-up 2009



The LHC had a very successful start-up at end of 2009

ATLAS ran very well, high efficiency for data taking, very high fraction of detector working

Opens the way to the main goals of ATLAS in the coming years

Introduction - LHC

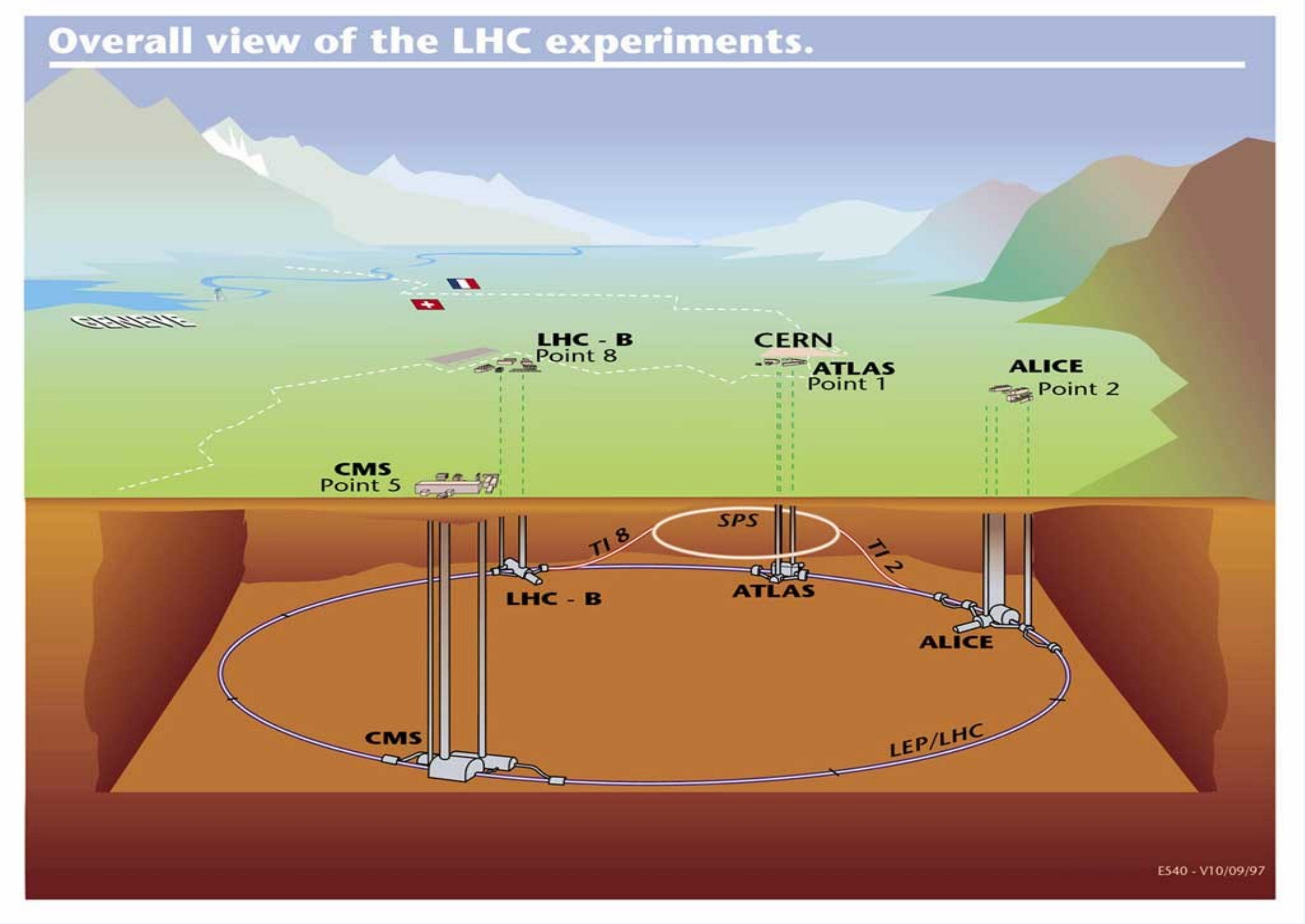
LHC

Designed for proton-proton collisions at 7 TeV per beam

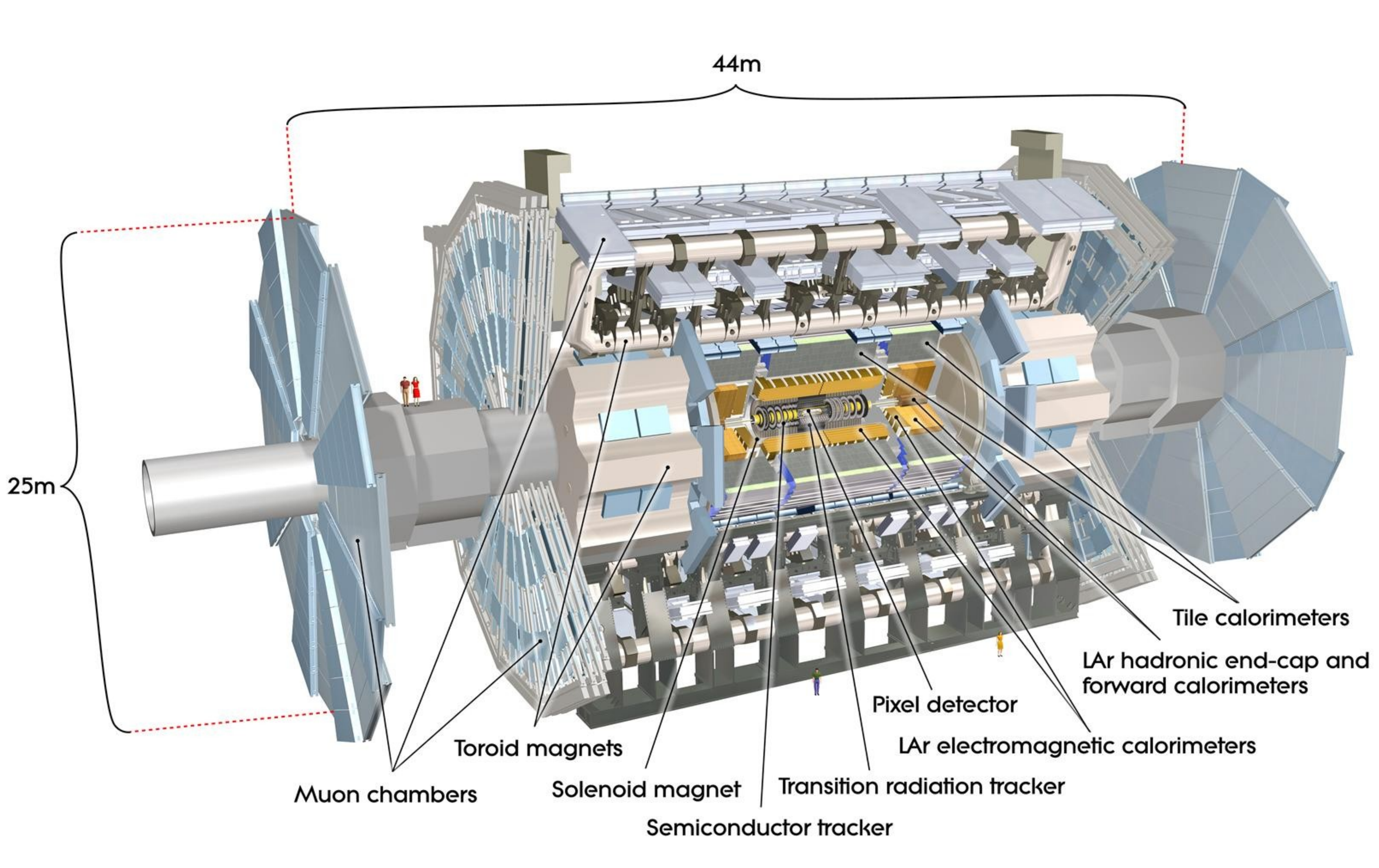
Luminosity 10^{34} $cm^{-2}s^{-1}$

Complicated machine; will take time to get there

Once there, it will deliver about 60 fb^{-1} per year



Introduction - ATLAS



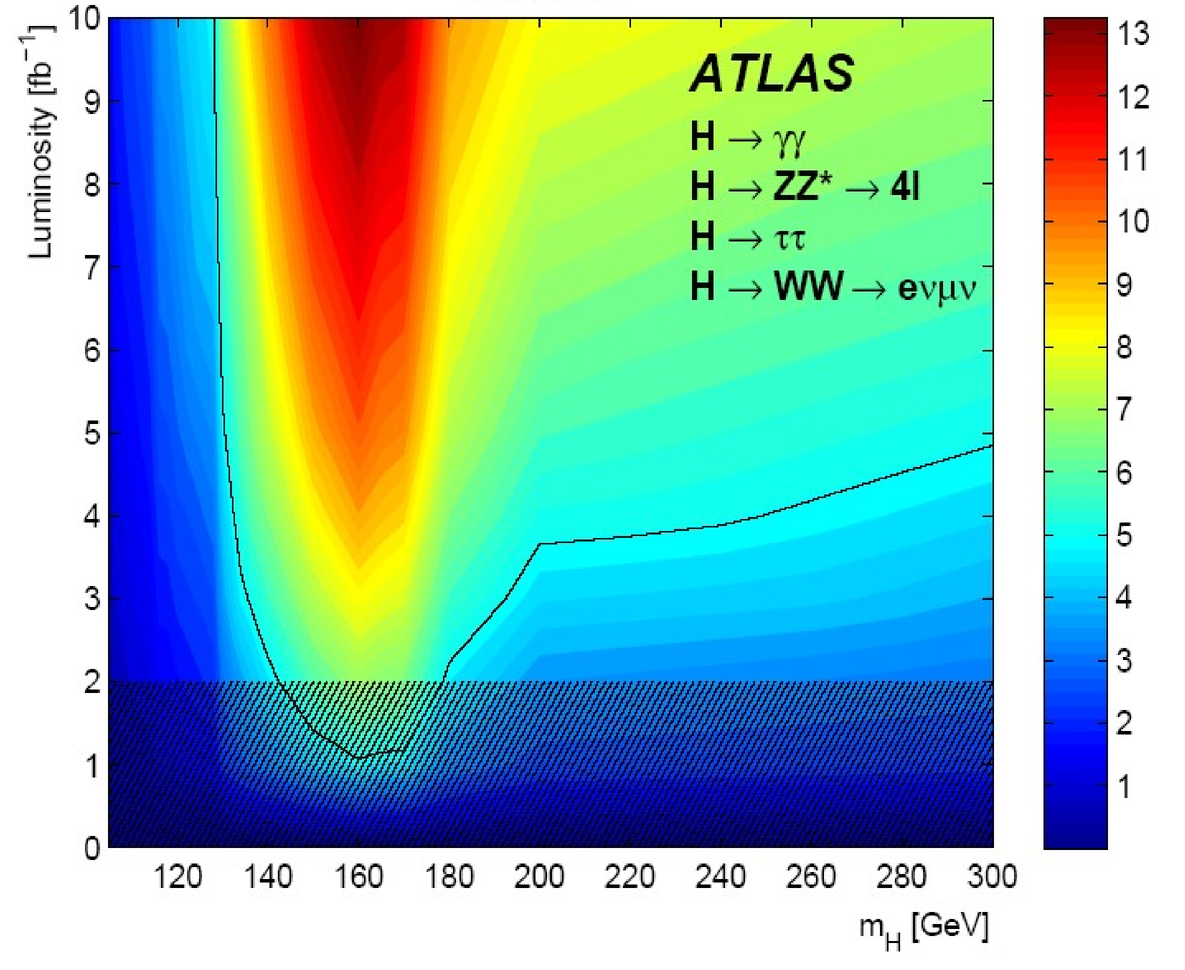
Main ATLAS Physics Goals

Mass and understanding electro-weak symmetry breaking; Higgs

Unification, gravity, SUSY, extra dimensions

New forces (W', Z')

Flavour: why 3 families, neutrino mass, dark matter



Need to see results of early LHC to know what will be important at the Upgrade, and finalise the physics case

With ~10 fb^{-1} (3 years from now?) a Standard Model Higgs will either be discovered or ruled out over a large mass range

Physics goals of sLHC

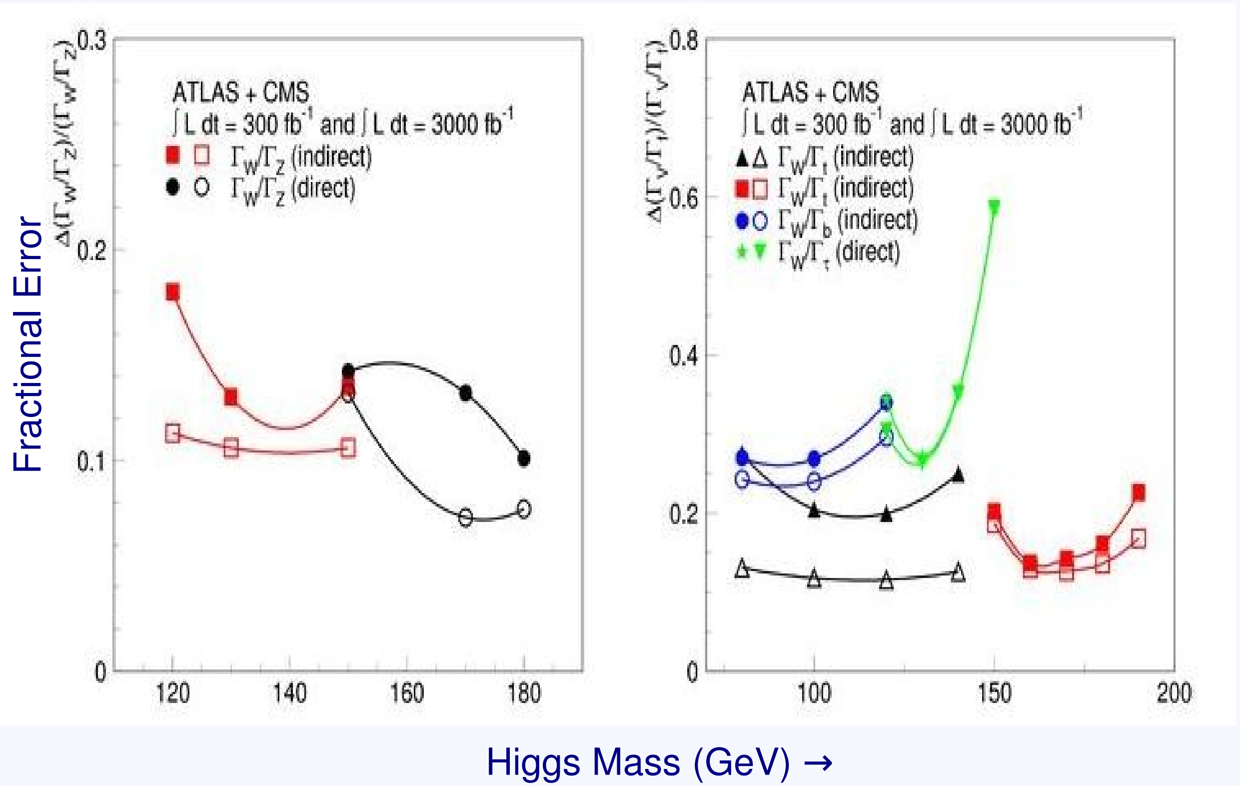
Whatever is discovered at the LHC will need a lot of data to understand just what has been discovered.
In addition, the sLHC can extend the discovery potential.
While the LHC aims at ~600 fb^{-1} per experiment, the sLHC aims for an extra 3000 fb^{-1}, opening up new possibilities for channels limited by statistics at the LHC

The main measurements where extending the LHC data set is important include:

1. Higgs couplings
2. Triple gauge couplings
3. Vector boson fusion at ~1 TeV
4. SUSY – discovery or spectroscopy
5. New forces: W', Z' to higher limits

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

Higgs couplings



Measure Higgs couplings to fermions and bosons and compare to SM predictions:

sLHC can significantly improve precision in some channels, e.g. Γ_{WW}/Γ_{ZZ} or Γ_{WW}/Γ_{tt}

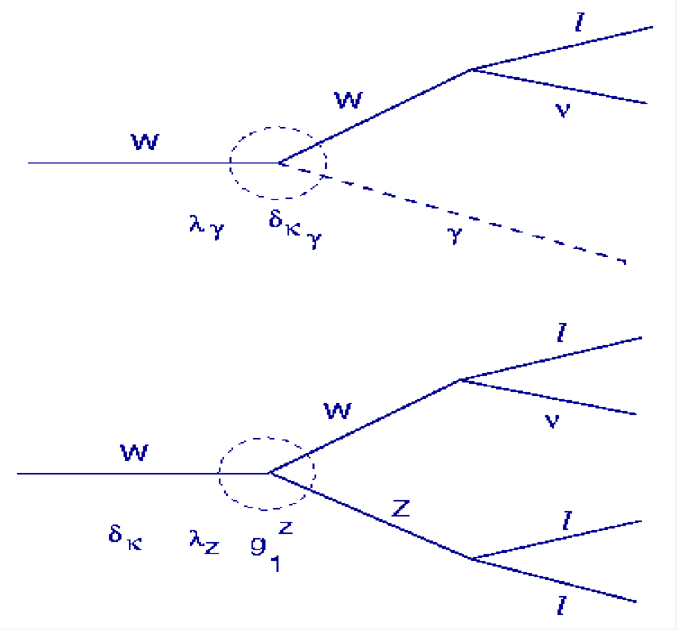
sLHC opens up some new channels:

- H-> $\mu\mu$ (5σ, 20% error for m_H < 140 GeV)
- H -> Zγ (11σ m_H ~ 140 GeV)

Triple Gauge Couplings

TGCs are fixed in the SM, but most general form can have 5 parameters.

sLHC can improve precision on these significantly in some cases.

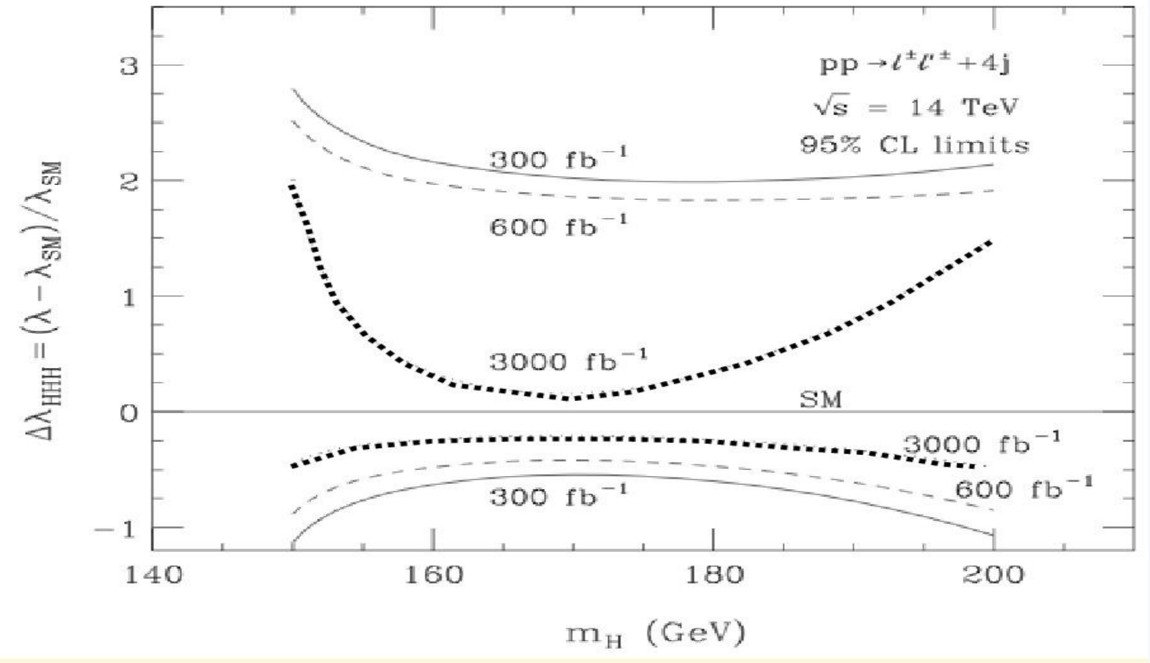


Coupling	100 fb-1	1000 fb-1
λ_{γ}	0.0014	0.0006
λ_{Z}	0.0028	0.0018
$\delta_{\kappa\gamma}$	0.0340	0.0200
$\delta_{\kappa Z}$	0.0400	0.0340
g_1^Z	0.0038	0.0024

An important test for the SM is the Higgs self coupling λ_{HHH}

Not possible at LHC; may be possible at sLHC (needs more studies of backgrounds)

Old study shown is probably optimistic

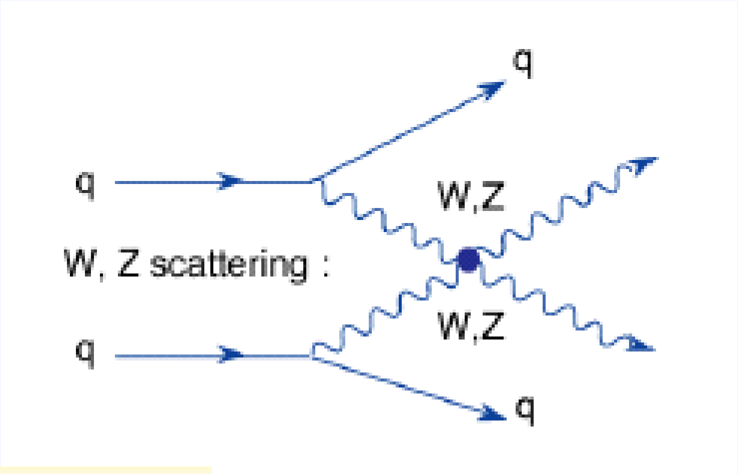


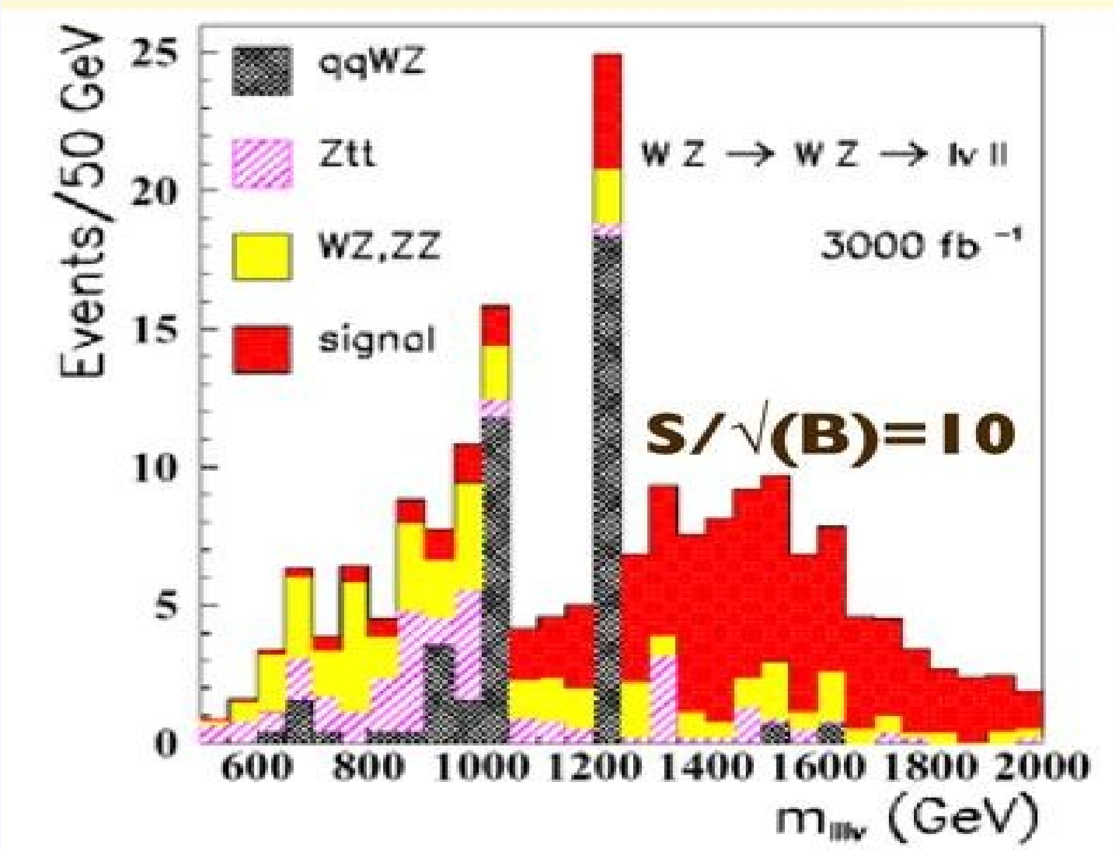
Vector boson fusion

If no Higgs is found, interest will focus on WW scattering at 1 TeV to find what mechanism maintains unitarity in boson boson scattering

Even if a Higgs is found, it may not be solely responsible for maintaining unitarity

The sLHC makes discovery of new resonances possible, e.g. 1.5 TeV WZ resonance



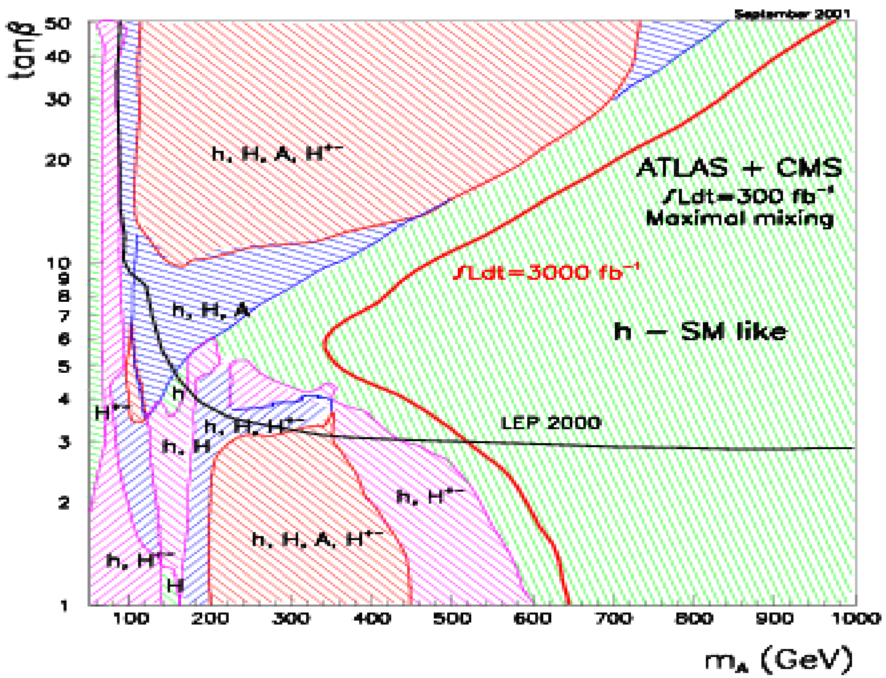


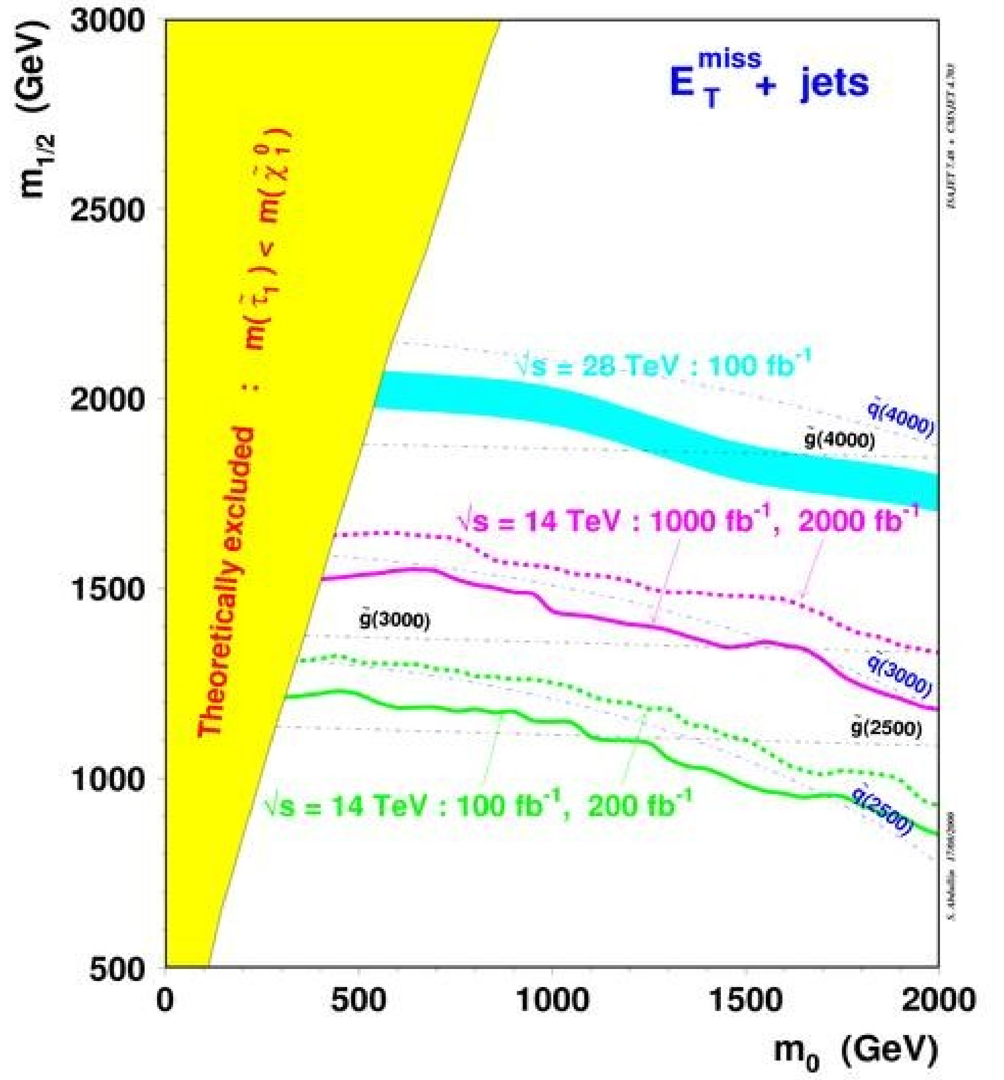
Super Symmetry

If supersymmetry is discovered at the LHC, then the sLHC can help understanding especially by finding more SUSY particles at higher masses (SUSY spectroscopy).

If not found, the sLHC can extend the search to higher masses

In SUSY models with more than one Higgs, sLHC can extend the region of discovery of multiple Higgs

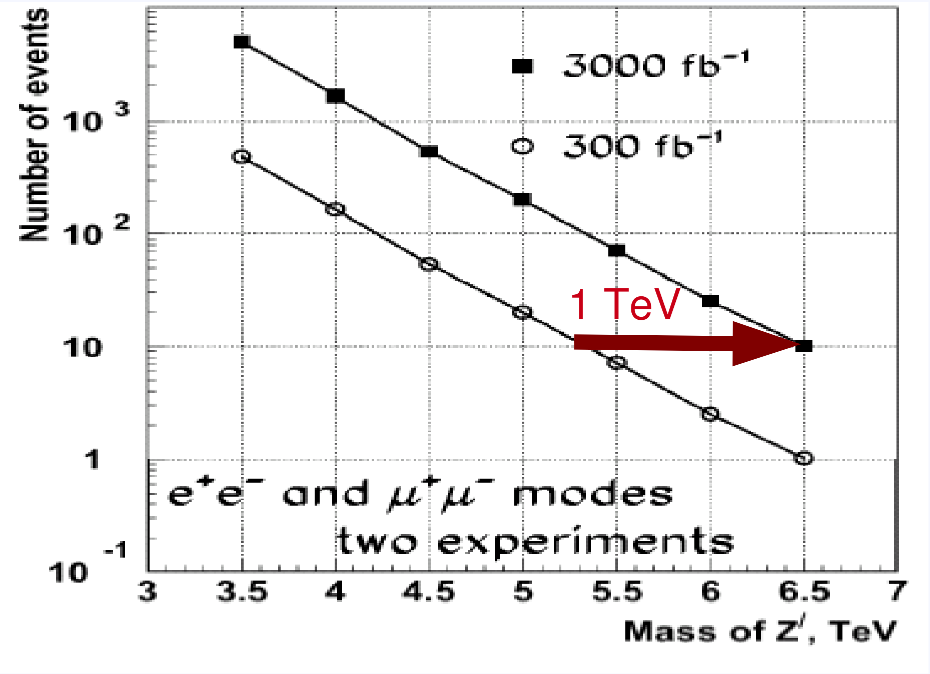




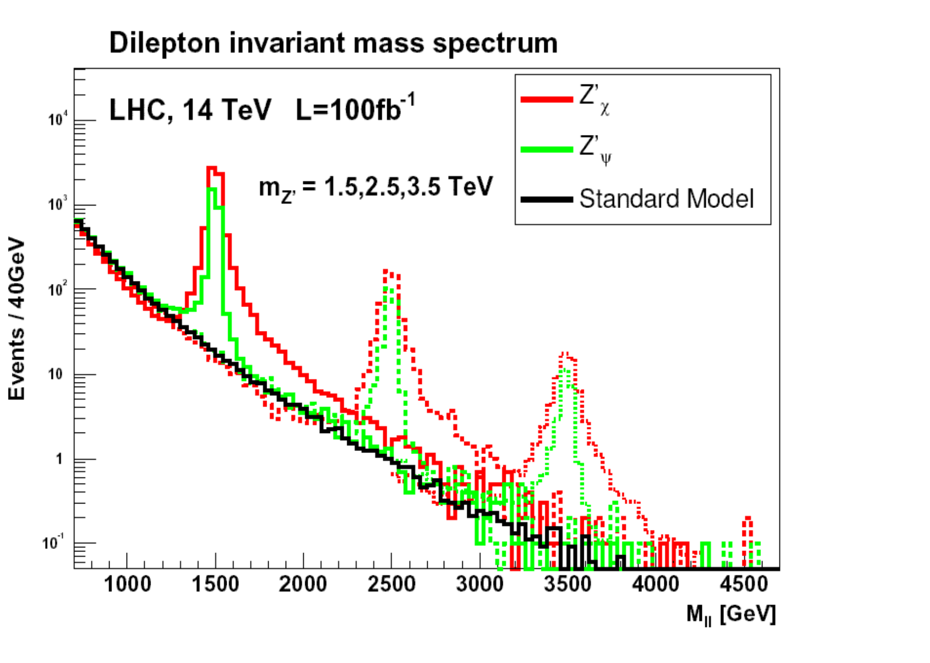
New forces (W', Z')

There are several models of new forces which would be mediated by bosons generically referred to as W' and Z'

The higher integrated luminosity at the sLHC allows an increase in the discovery region of about 1 TeV



With high statistics it will be possible to measure the widths sufficiently well to distinguish between forces



Physics Goals Summary

We need results from the LHC to better define the physics programme of the sLHC:

- Is there a Higgs? What is its mass?
- Discovery of SUSY, new forces?
- Several other things not mentioned here: gravity, black holes, compositeness

Whatever is discovered at the LHC will need more measurements to understand just what has been discovered

sLHC can:

- Measure many SM parameters significantly more precisely than LHC
- Improve precision of measurements in LHC discoveries
- Extend the mass range for discovery by 20 to 30 % in SUSY, new forces etc.

LHC Programme

- Currently many uncertainties; meeting in Chamonix this week to discuss the road to full energy and nominal luminosity, and upgrades above nominal luminosity
- Health warning: all predictions will be wrong
- LHC start-up was very successful at end of 2009.
  - Low energy (0.45 TeV and 1.18 TeV per beam) and low luminosity
- Several stages to higher energy and nominal luminosity:
  - New Quench Protection System to be completed by February 2010
    - Allow 3.5 TeV per beam end of February 2010
  - Experience, further tests
    - Allow ~4.5 TeV per beam, June 2010?
  - Shutdown at end of 2010 with ~200 pb^{-1}
  - Complete improved saftey in second half of machine, improve some (or all?) superconducting joints, train magnets to 6.5 TeV
    - Allow 6.5 TeV end of 2011
  - Improve collimation as needed for machine protection, tune and understand the machine
    - Allow higher luminosities, reaching nominal around 2014
- Since the accident in 2008, much more realism and caution at CERN
  - Slower luminosity profile; 600 fb^{-1} reached end 2019? Wait for Chamonix

Road to higher luminosities and sLHC

Several possible machine upgrades are being explored which may allow higher luminosities:

2014/15 Linac4

Final focus quadrupoles (NbTi)

2017? Crab cavities

2020? Final focus quadrupoles (NbSn)

Later still, further injector upgrades possible:

SPL to replace PSB

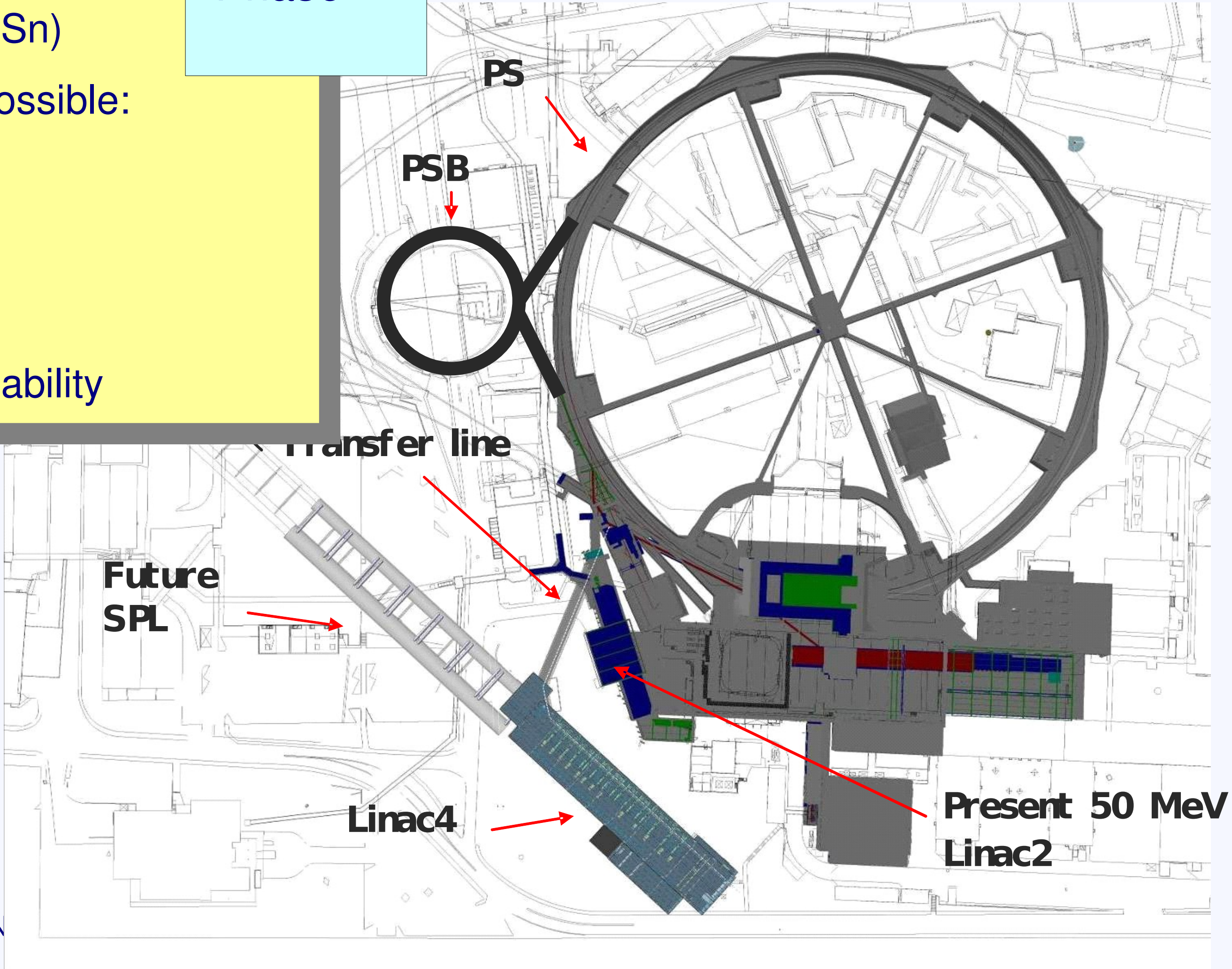
New PS2 to replace PS

Improved SPS

...Will allow brighter beams, more reliability

"Phase-I"

"Phase-II"



Linac4

Goal is to increase the injection energy to PS Booster 50 -> 160 MeV

Allows twice the brightness (machine current/emittance)

Also use H- (previously p) and strip before injection; allows higher current densities

Also will increase reliability

Linac4 construction well advanced (Aug 2009)

Expected to be ready and tested end 2014

Will need 8 month shutdown to integrate into transfer tunnel

Will take time to tune PS to benefit from higher brightness

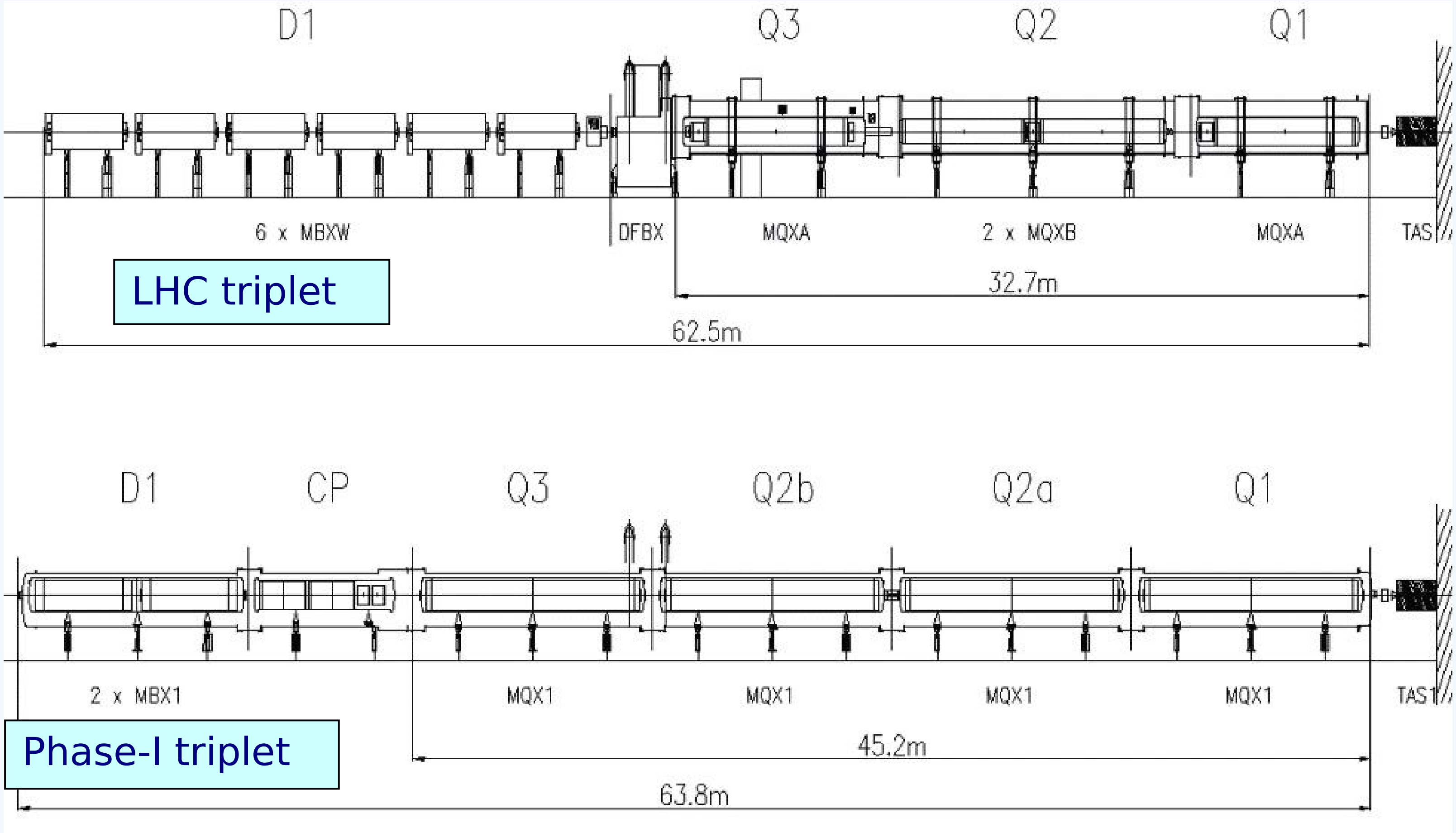
First Upgrade of final-focus quadrupoles

The new quadrupoles will use spare superconductor from the LHC programme (NbTi)

They will have wider aperture, allowing β^* to reduce from 55 cm to ~30 cm

The current quadrupoles can safely cope thermally with up to nominal luminosity; the new ones will cope with at least 3 times nominal

Schedule less certain; hopefully same time as Linac4

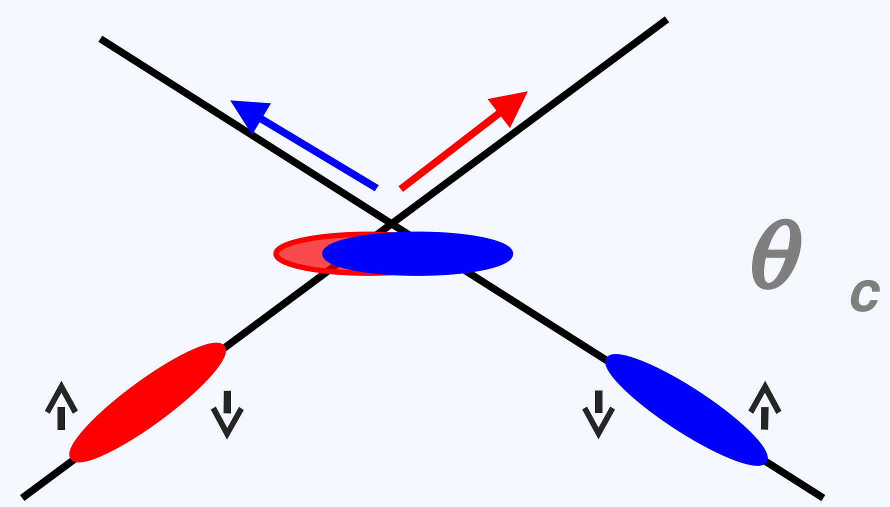


CRAB Cavities

Rotate the bunches so they move “sideways” (like a crab)

Allows a larger crossing angle, reducing beam-beam interactions, while ensuring each proton sees all those in the other bunch

First proposed in 1988, now used in KEK to achieve record luminosity

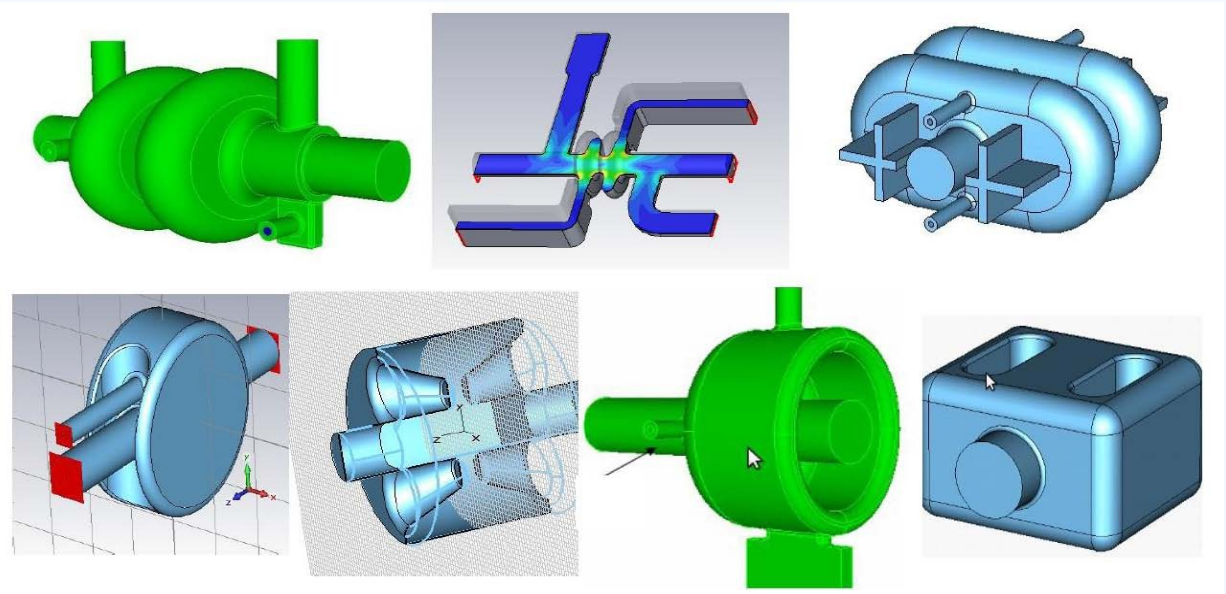


Many designs under study

Propose to test in interaction region 4 of LHC, installation 2014/15?

Timescale for deployment ~2018?

Working group set up Oct 2009



Luminosity Levelling

Both the machine and the experiments have major challenges to cope with very high instantaneous luminosities

For example, in the machine, the heat-load on the focussing quadrupoles can cause quenches

The beam life-time becomes very short (a few hours) while the fill time remains 5 – 10 hours, so efficiency drops

For the experiments, it can mean trying to cope with 360 – 480 pile-up events per bunch crossing, deteriorating calorimetry performance and requiring very high granularity and data rates in the inner trackers, which in turn lead to more material

Luminosity Levelling

Several options are available for starting collisions “detuned” giving lower peak luminosity, and changing during the spill to maintain that luminosity:

reduce β^* in steps; increase CRAB voltage; slowly reduce the bunch length

These scenarios are much preferred and will be investigated

They could lead to peak pile-up of minimum bias events in the range 80 – 150 for the experiments – much easier to handle

Levelling can lead to **higher** integrated luminosity if you can have a high machine fill and peak luminosity is limited (e.g. by interaction region quadrupoles)

Further developments...

NbSn Quadrupoles

NbSn can stand higher fields at higher temperatures: allows large aperture, high field gradient quadrupoles, giving a further reduction in β^* (~11 cm) and coping with higher heat loads

Difficult material to work with; Fermilab leading the development

Should allow significant increase above 3 x nominal

Injector Chain

Further improvements will be much more costly, such as a new SPL, PS (PS2), and upgrades to the SPS

Possibly targetted after 2020

Summary Possible ATLAS/LHC Upgrades Timeline

2009 Start of LHC (Confirmed!)

Ramp up luminosity to nominal (10^{34} cm^{-2} s^{-1}) and energy to 7 TeV per beam

2015 Bring in Linac4 and new quadrupoles – Phase-I Upgrade

Ramp up luminosity to 2.5 x nominal

2018 CRAB Cavities

Ramp up luminosity to peak 4.5 x nominal, and then start lumnosity levelling going to ~300 fb^{-1} per year

2020 Major ATLAS Upgrade: Phase-II with new inner tracker and forward calorimeter and muon chambers

Collect data until > 3000 fb^{-1}. New machine injectors PS2, SPL, ...

2030 ILC ?

ATLAS Changes for Phase-I LHC Upgrade

Conditions:

Peak luminosity 3 x 10^{34} cm^{-2} s^{-1}

Total integrated luminosity before Phase-II of 600 – 700 fb^{-1}

About 8 months shutdown for installation of new elements end of 2014

Detectors were designed to cope with nominal luminosity with a wide safety margin, so degradation to 3 x nominal is small, changes needed are small (but significant)

Trigger:

Beef up processors and links for extra data rate

Small increase in level-1 (L1) latency to near max. allowed (2.5 μs)

Bring in "topological" triggers – the ability to look at 2 or more trigger objects at L1

e.g. isolated muon = muon far from any jets

- requires new hardware element before L1 trigger processor to combine L1Calo and L1Muon, and faster L1Calo analysis hardware

Change beam-pipe material to reduce radiation levels and activation (SS --> AL or Be)

More radiation shielding on cavern walls to reduce radiation in rack areas

Changes to forward shielding to suit new quadrupoles

Complete some staged muon chambers in very forward region

New B-layer (IBL)

Current B-layer will become inefficient (max. bandwidth exceeded in front-end chips; radiation damage) at Phase-I

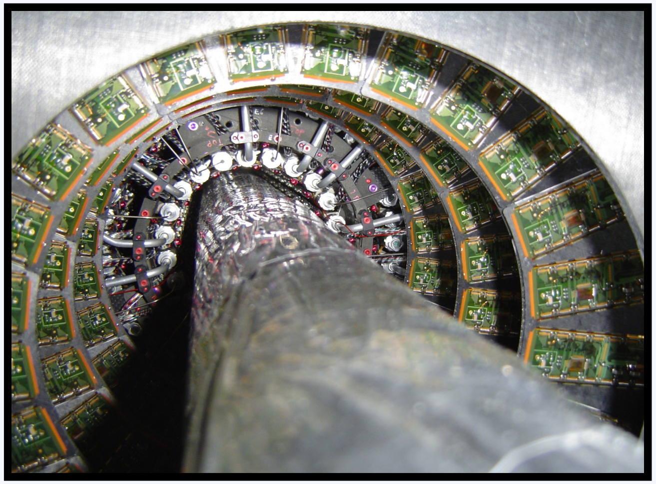
Cannot replace in a one-year shutdown; instead, insert a new layer inside the current one

Requires smaller beam-pipe to make space; agreed now with machine; 29 mm radius --> 25 mm.

Improves the vertexing performance because of proximity to beam

New FE-I4 chips allow higher rate (130 nm CMOS, per-pixel memory only read-out if L1 trigger)

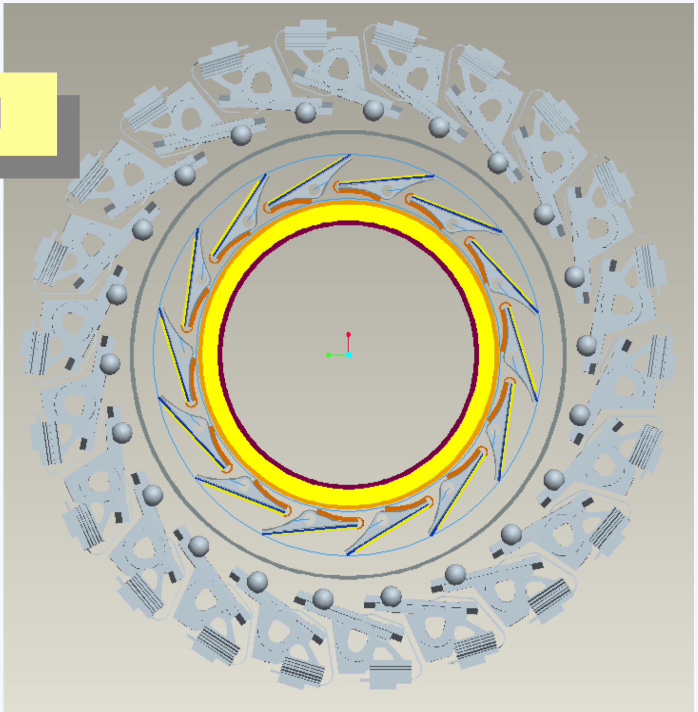
Submission of prototype chip very soon



Current beampipe and pixel detector; space is tight!

New layer inside the old

Several sensors considered: planar Si (thinned or not, n-in-n, n-in-p) 3D; diamond



Possible new warm calorimeter

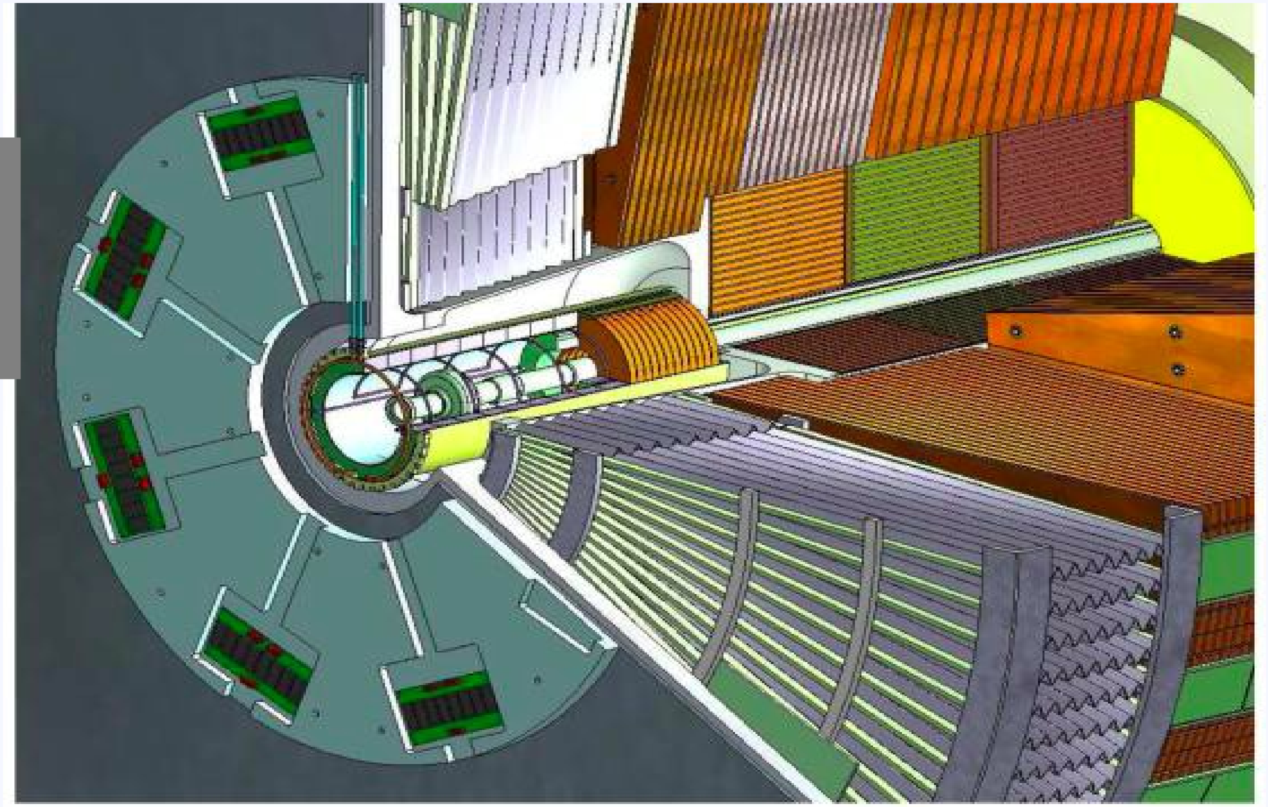
The LAr FCAL extends to pseudorapidity η = 4.9, with very high particle fluxes

Ar^{+} ion build up and (fluctuating) voltage drop across HV resistors will deteriorate performance; need studies to see how much.

If needed, we can insert a miniature warm calorimeter just in front of the current FCAL

It absorbs the e.m. jet component, halving the energy deposit in the FCAL

Cu absorbers, diamond sensors: very rad-hard, highly segmented readout. Placed in alcove around beam-pipe.



ATLAS Changes for Phase-II/sLHC

Conditions:

We have considered up to 10 x nominal, although now we do not expect above 5 x nominal.

- Still, very high instantaneous rates.

3000 fb^{-1} good data on tape: Very big increase in integrated luminosity --> radiation dose

We expect two winters and a summer for installation: 18 month shutdown

Allow for ATLAS down-time, uncertainty in 14 TeV pp cross section, particle multiplicities in pp collisions at 14 TeV: test prototypes for 6000 fb^{-1}

Most of ATLAS can remain:

Magnets, most of muon and calorimeter systems.

Changes summary:

New inner detector needed above 700 fb^{-1} (radiation damage) and > 3 x nominal (readout rates, occupancy, tracking inefficiency)
Several new muon chambers needed
New calorimeter readout
Changes in LAr End-cap calorimeter
Shielding, beam-pipes, ...
Trigger and DAQ: significant changes needed

Trigger at sLHC

Need to maintain low thresholds on leptons (20 – 30 GeV), missing ET, and forward jet trigger for the physics programme.

Events are ~5x bigger, storage and bandwidth limit us to same event rate to storage

(~200 events/s)

So must reject 5x as many events of 5x the size – challenging

Single particle rates at low PT are too high; raise single object thresholds but maintain low thresholds in combination with other features.

Main improvements:

Muon trigger – increase the sharpness of the threshold at higher PT (40 GeV/c)

Calorimetry: read out all data, full granularity, and build trigger off detector

- allows better particle ID at L1

Longer L1 latency (~6 μs), allowing more processing for combined objects

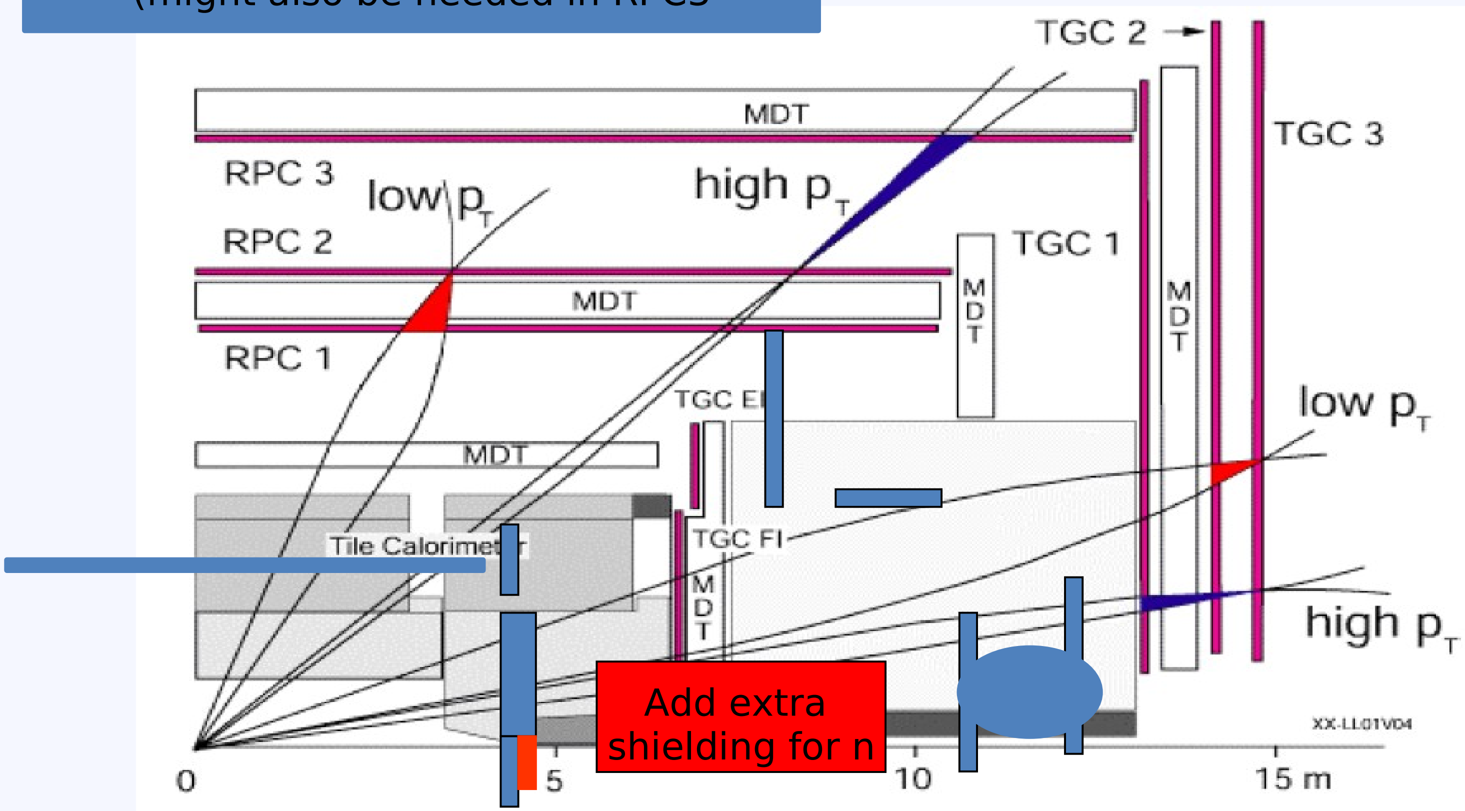
Possible track-trigger at L1

Fast track finder at L2 using big associative memory (like CDF)

MUON Upgrade for sLHC

Add extra doublet with mm resolution (might also be needed in RPC3

Might need to add a Doublet of Trigger ch. To improve L1 in low BdL region



Replace very forward chambers for higher resolution and rate capabilities

Replace Small-Wheel chambers for high rate tracking and triggering
Many R&D projects ongoing
Replacement extent depends on cavern background (large uncertainty)

Calorimeter Upgrades for sLHC

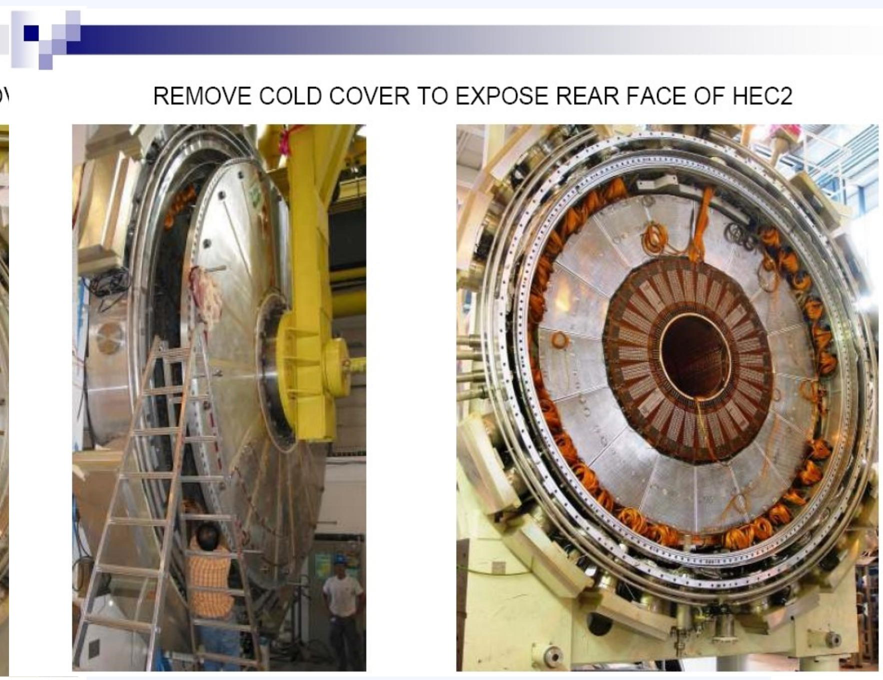
Barrel and Tiles will work well; no changes to detector

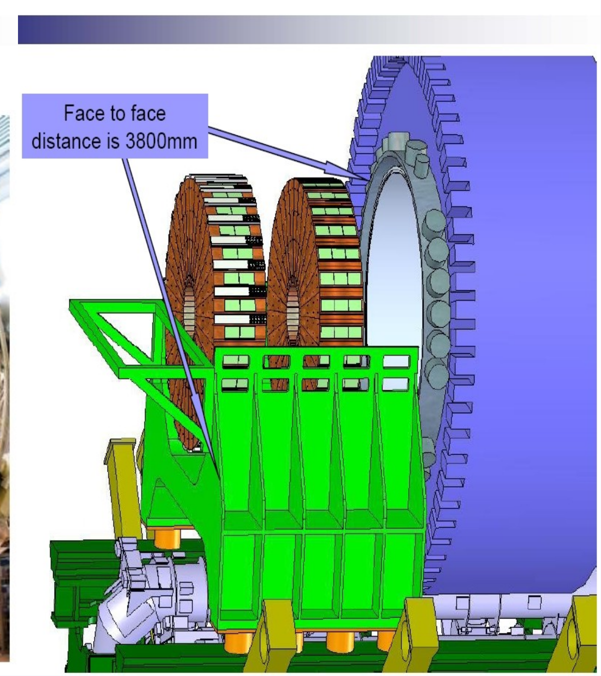
Replace all front end electronics – read all data out for better trigger

Cold electronics (pre-amps etc. inside end-cap cryostat): will they survive 3000 fb^{-1}? (Designed for 1000 fb^{-1}). If so, hopefully the miniature warm calorimeter in front of the FCAL at Phase-I is enough to fix HV drop, ion build up, and risk of boiling the Ar.

Otherwise, we need to open up the end-cap cryostats – very major task (can fit in 18 months if work is carried out in the pit)

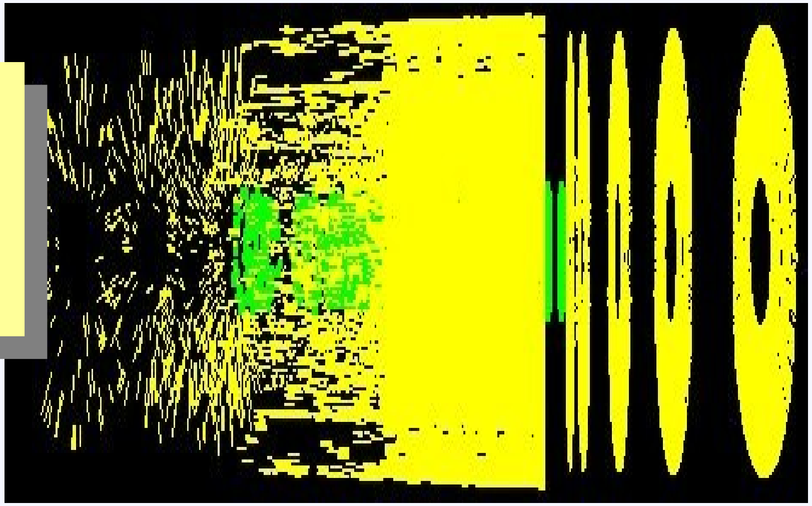
- Replace cold electronics and FCAL – smaller gaps (250 --> 100 μm).

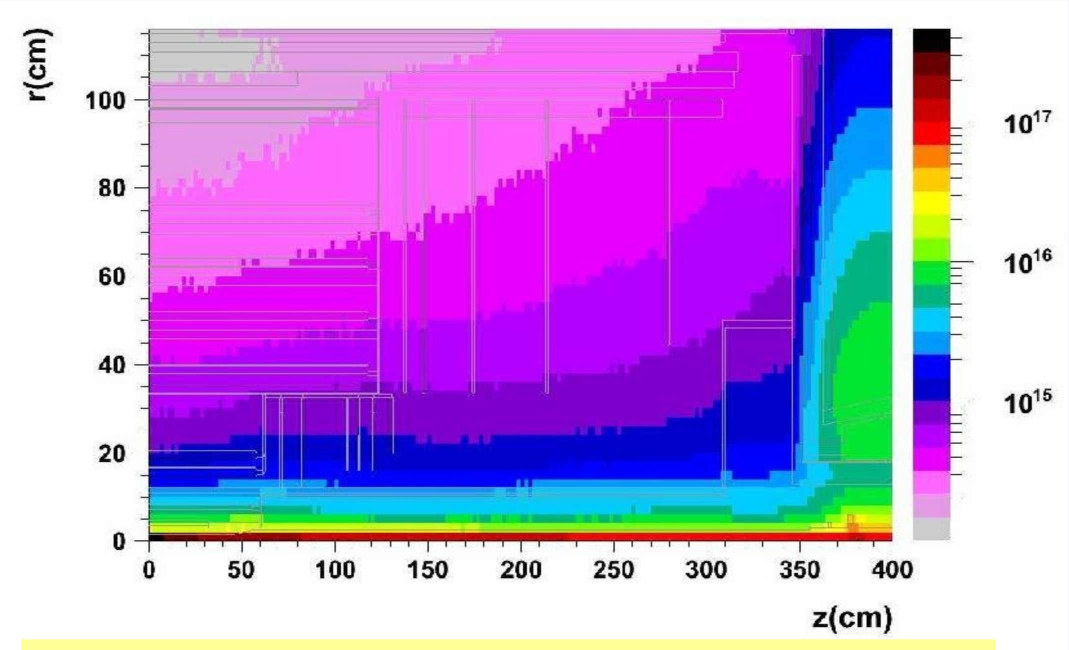




Inner Tracker

Picture shows hits in inner tracker from one bunch crossing with 400 pile up events; only tracks in forward half of detector were generated.





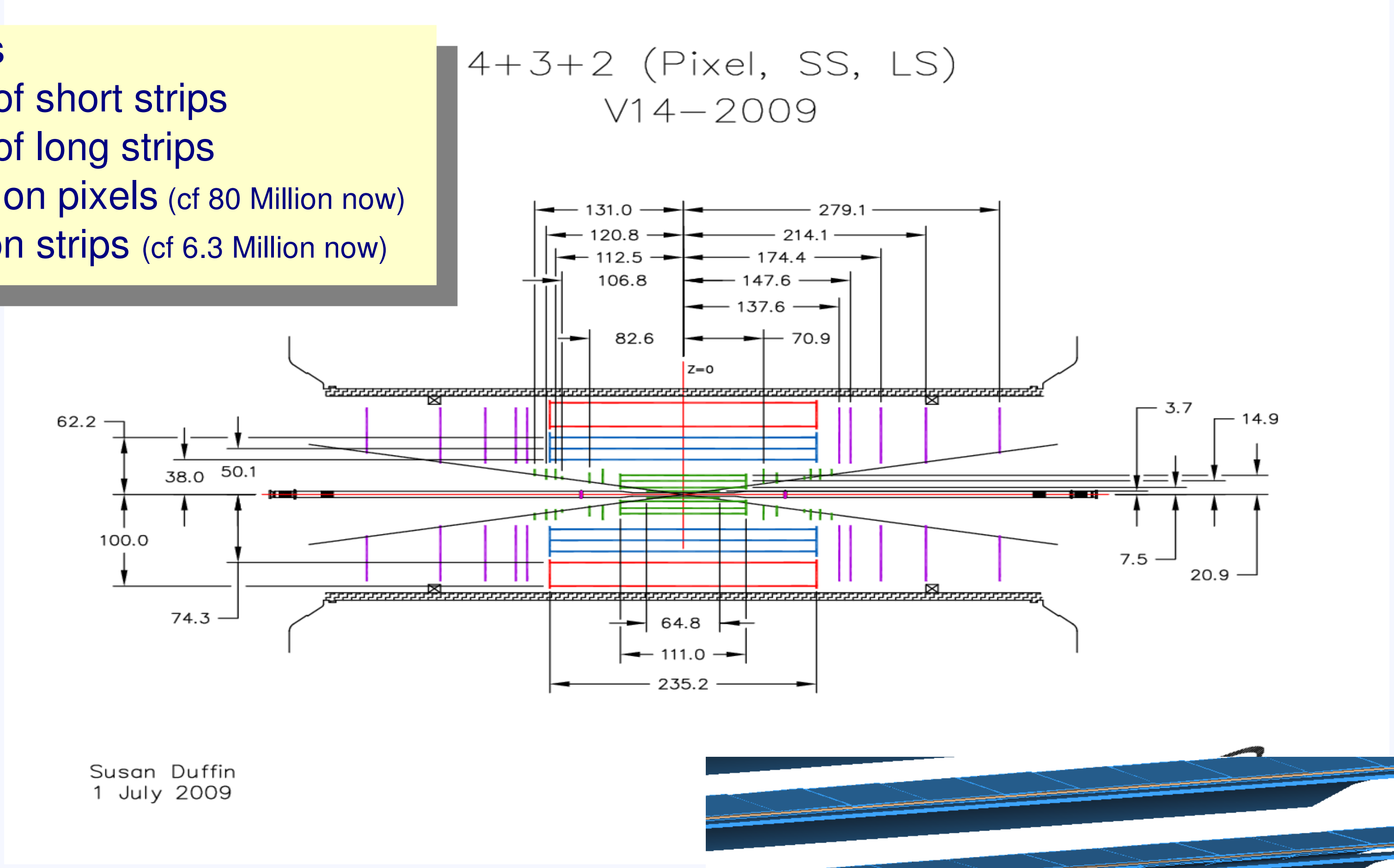
Inner tracker 1 MeV n_{eq} non-ionising doses after 3000 fb^{-1}

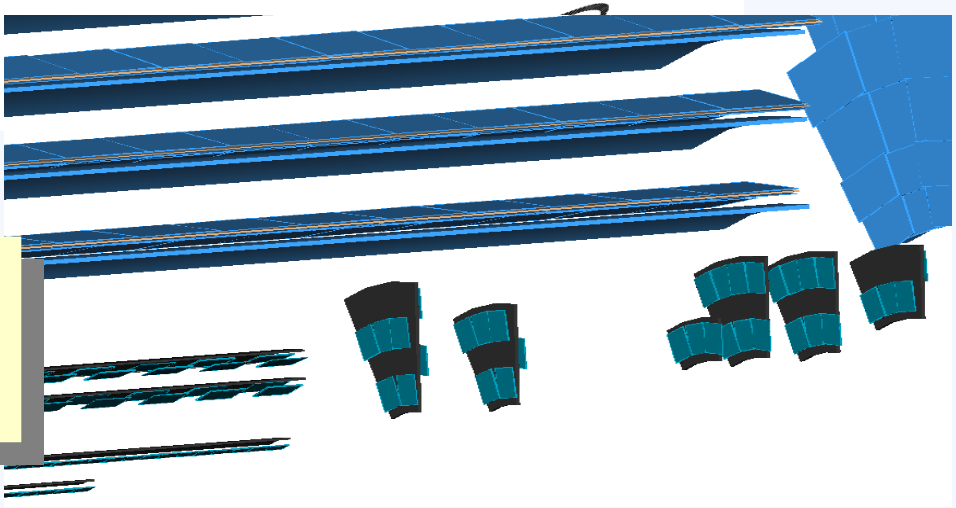
How to cope with up to 15,000 tracks per bunch crossing, 40 MGray ionising and few 10^{16} n_{eq}/cm^2 non-ionising dose in B-layer; 1.4 x 10^{15} n^{eq}/cm^2 in microstrips region? (including safety factors)

All new, all-silicon inner tracker

Strawman Layout of New ATLAS Inner Tracker

4 layers of pixels
3 double-layers of short strips
2 double-layers of long strips
Approx. 400 Million pixels (cf 80 Million now)
Approx. 45 Million strips (cf 6.3 Million now)

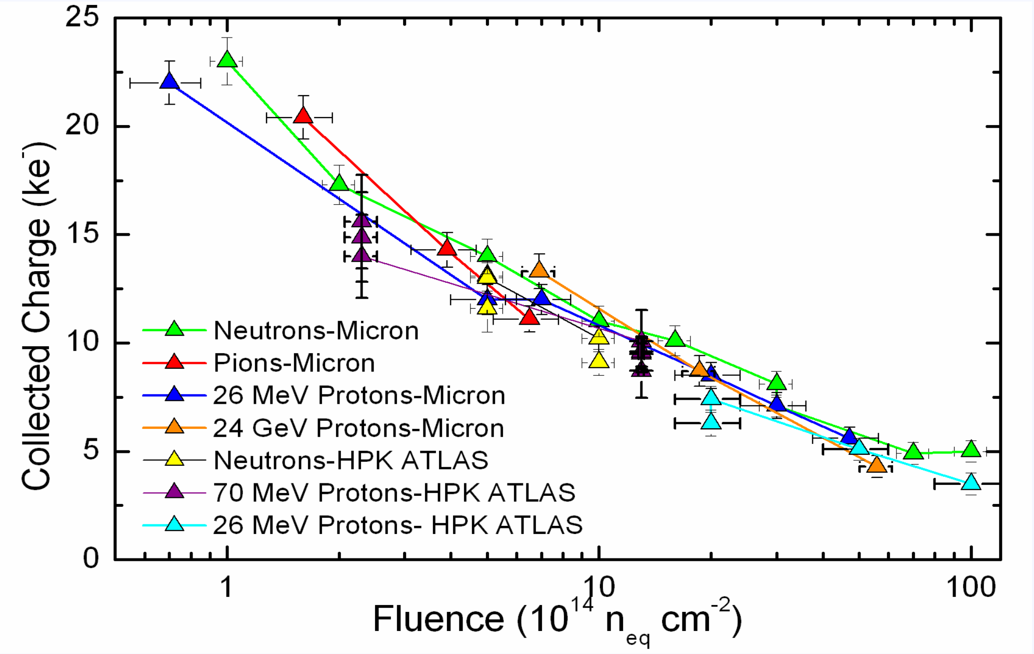




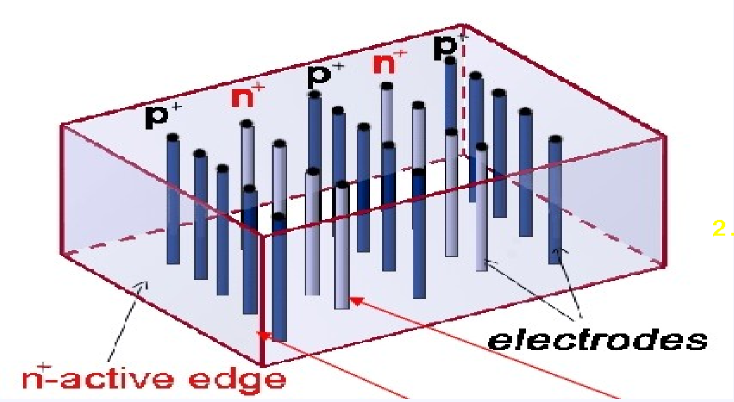
Being implemented in Geant, including realistic services, to study performance and look at optimisations

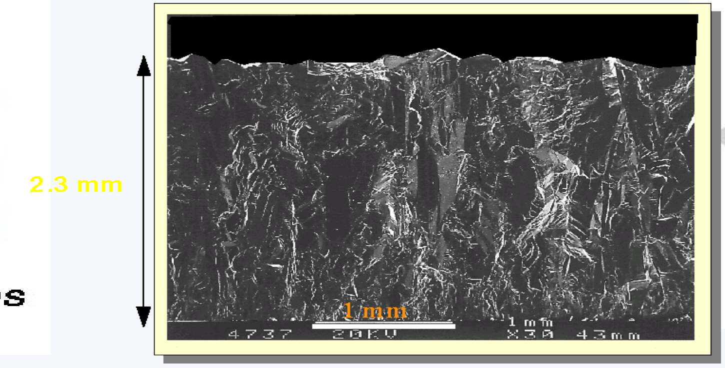
Pixel development and sensor options

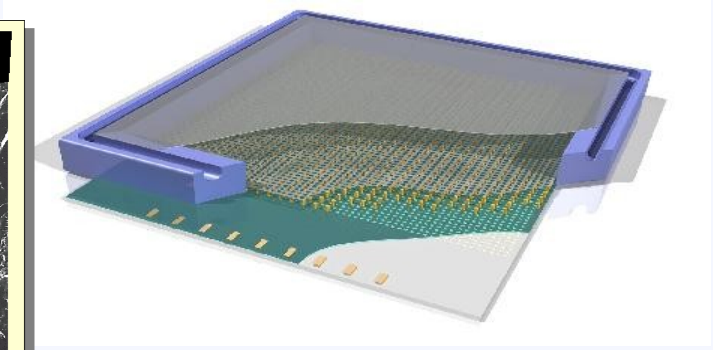
Several sensors investigated for radiation hardness
Sensors from several suppliers show same characteristics
With high enough bias give sufficient signal



3D, diamond, and Gossip also investigated for b-layer
– may be more rad-hard and other advantages



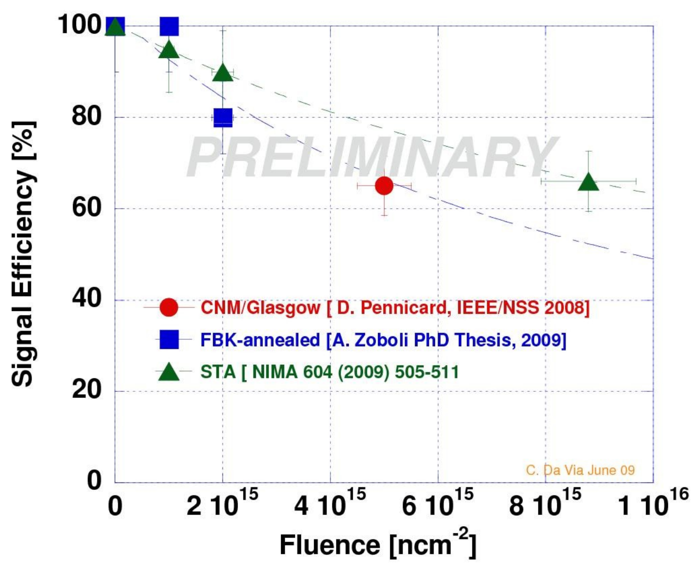


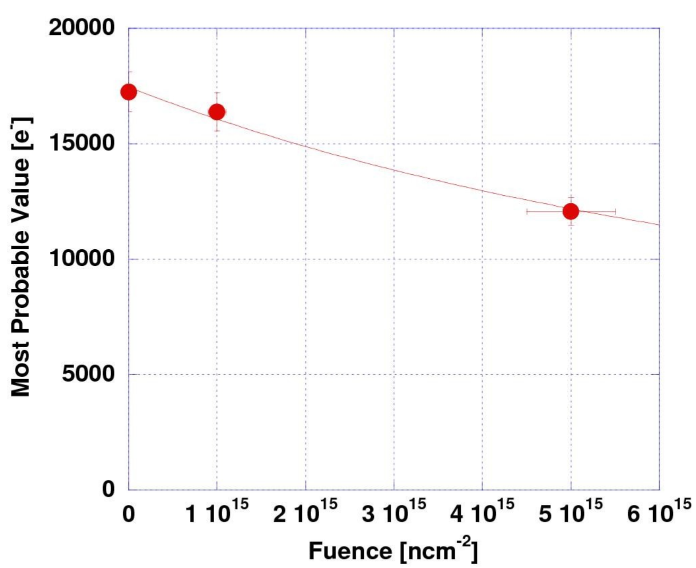


Most probable signal

MPS=230μm x 75e⁻ = 17 250

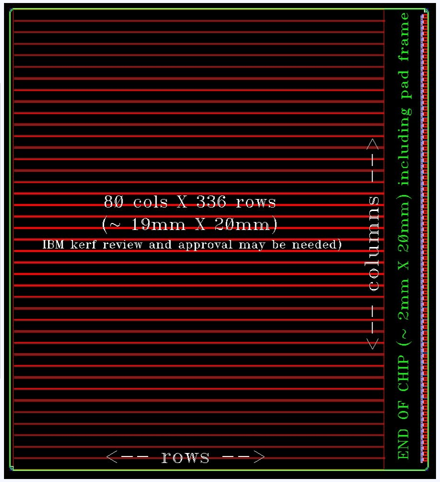
Fluence [ncm⁻²]	MPS [e⁻]
0	17250
$1x10^{15}$	16380
$5x10^{15}$	12075



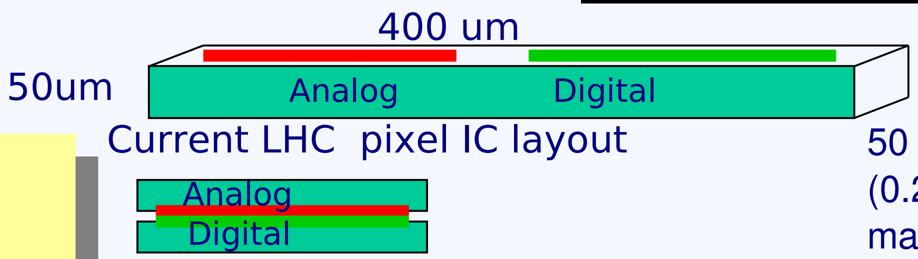


Pixel readout chip and mechanics

Pixel chip FE-I4 developed for Phase-I b-layer
Can be used for outer layers at Phase-II/sLHC
130 nm CMOS, largest pixel chip to date
Pixel 50 x 250 μm^2
Store data in each pixel, only move to end-of column if L1-Accept



B-layer at sLHC needs smaller pixels and more processing/bandwidth
-investigate 3D integration techniques



Current LHC pixel IC layout

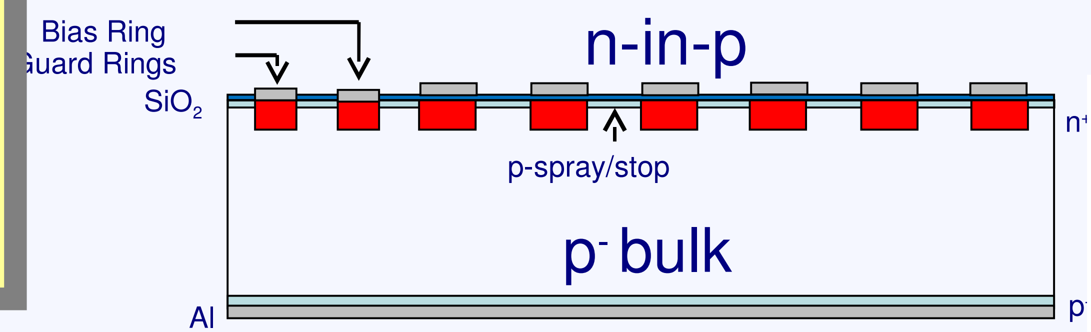
Possible future LHC pixel in 3D IC

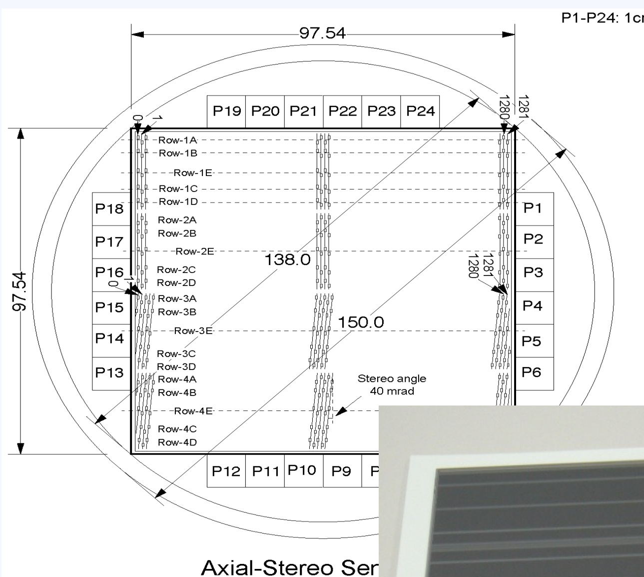
50 x 400 μm^2 (0.25 μm) may shrink to ~ 50 x 50 μm^2 (3D, 130 nm)

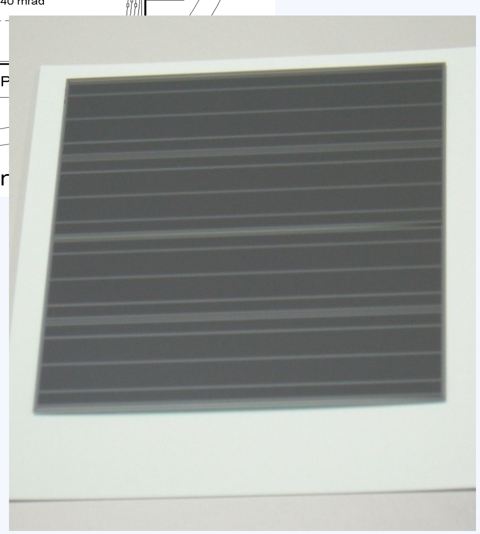
Investigate new materials for lightweight stable mechanics, with good thermal conduction
For IBL mechanics and cooling, factor two saving in material cf current pixel

Microstrips: sensors

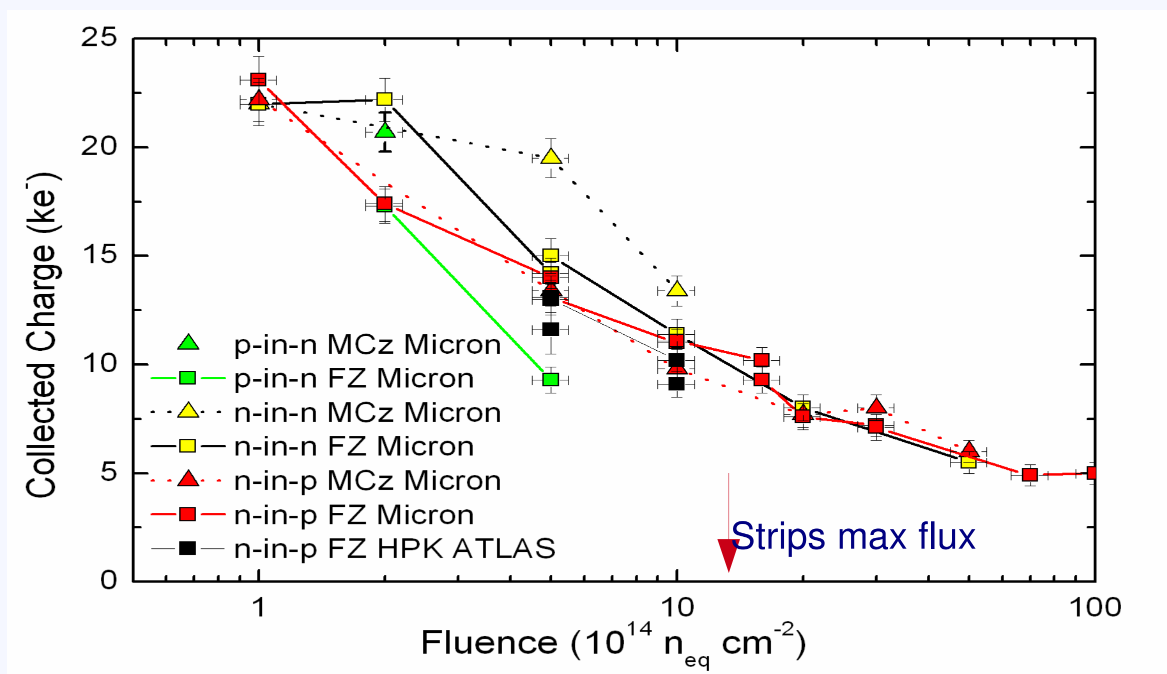
Choose n-in-p (cf p-in-n now)
Faster signal collection, cheaper production than n-in-n, does not need full depletion
Succesful production ATLAS07 sensors at Hamamatsu
- irradiation tests and prototyping





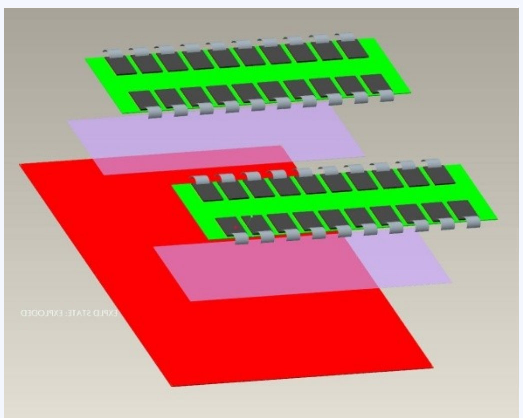


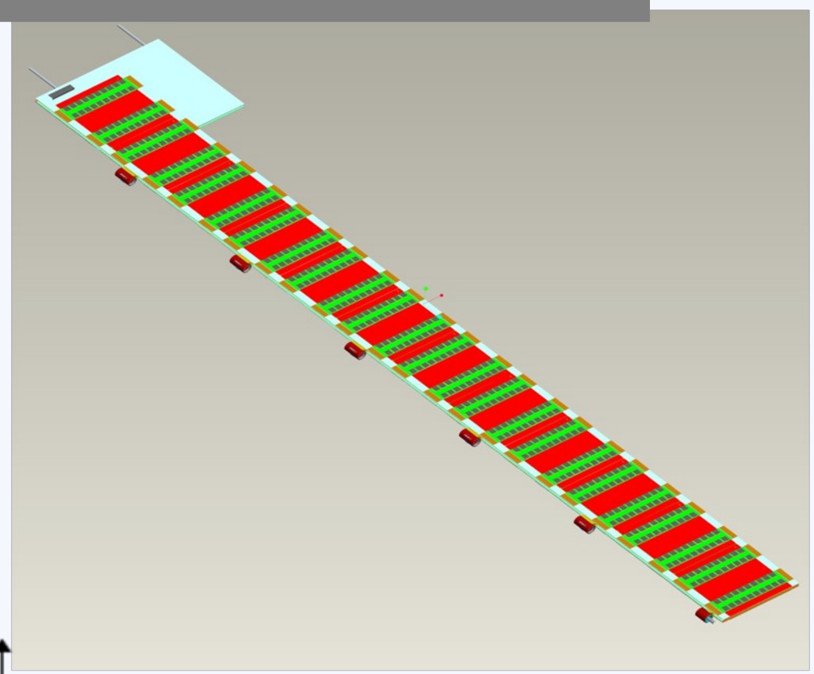
Neutron irradiation results
S/N worst case is 10:1

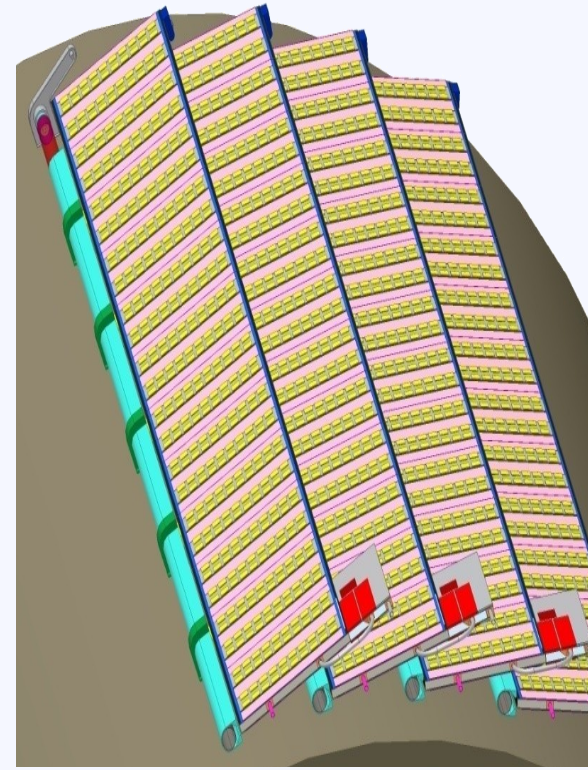


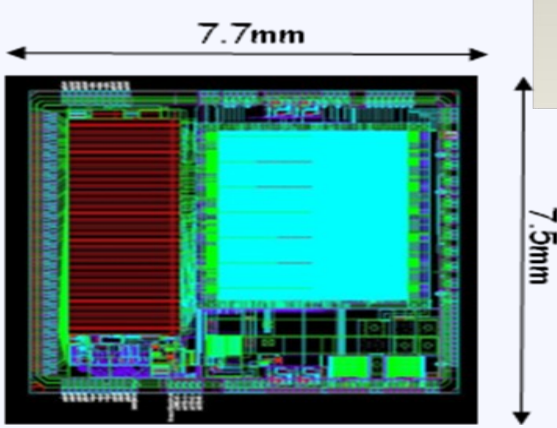
Microstrips: Modules

Hybrid with front-end chips glued directly to sensor
Sensor glued to cooled mechanical support - “Stave”
Staves arranged in cylinders
Stave can reduce material and helps assembly schedule
by avoiding bottle-neck at module mounting on cylinders





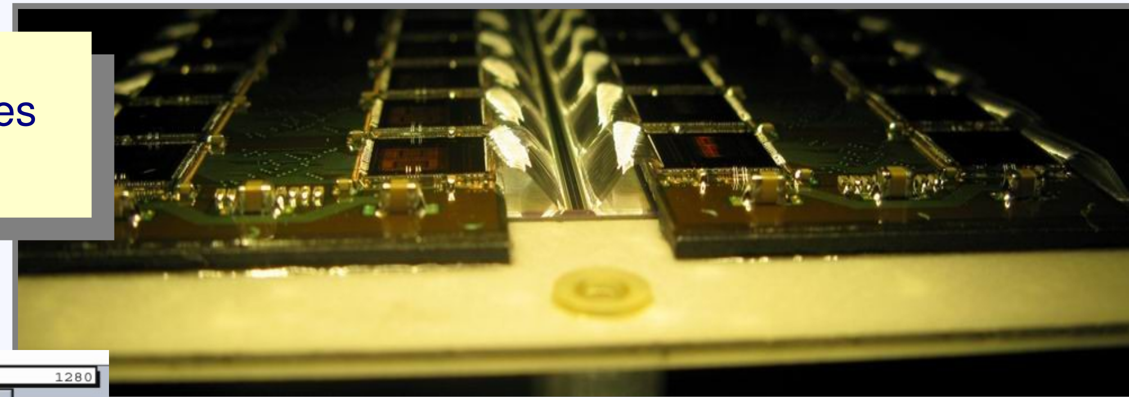


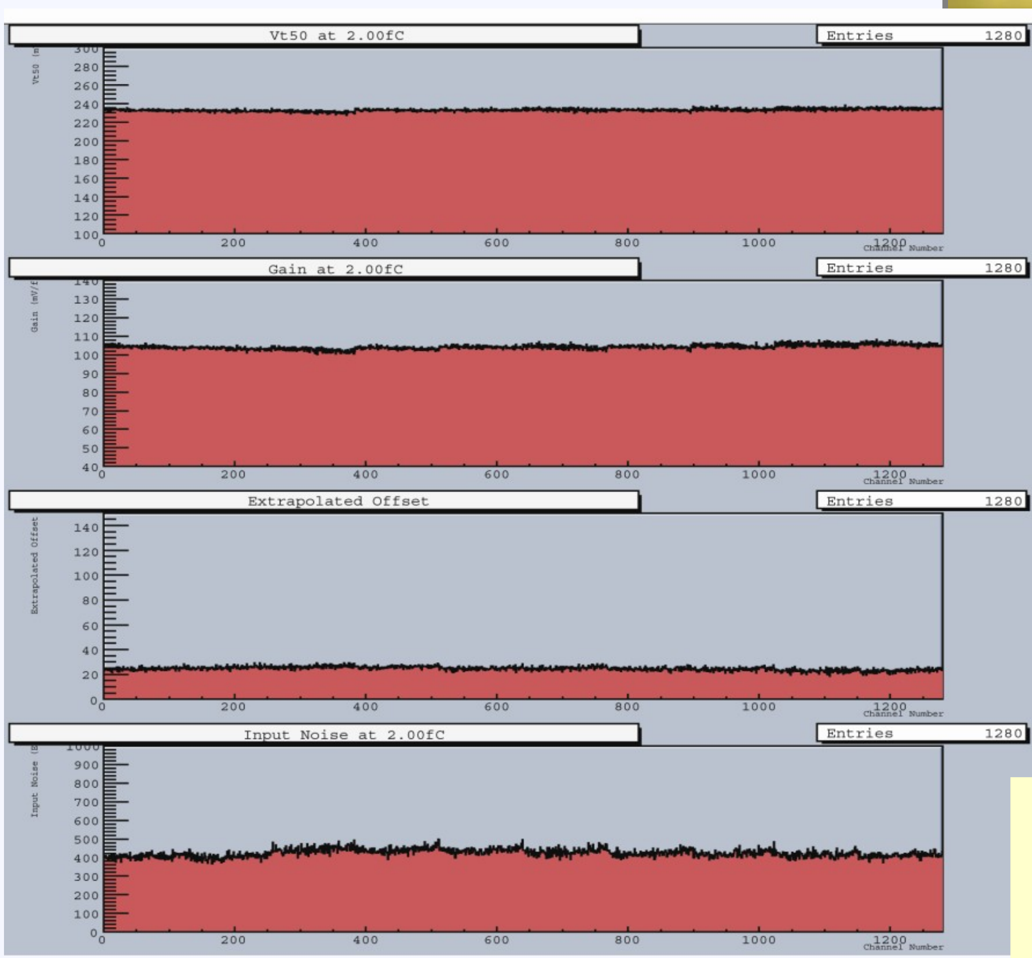


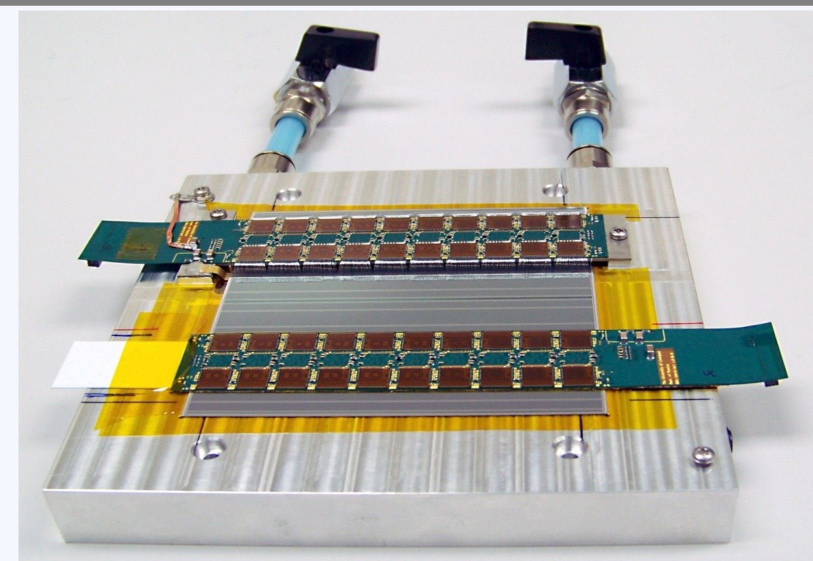
ABCNext prototype chip in 250 nm:
Delivered with very high yield and good performance
Allows early prototyping and try out many ideas on chip
Development of 130 nm version underway

Strip Modules R&D

Prototype strip sensors (ATLAS07), read-out chips (ABCNext) and hybrids built into modules with excellent performance







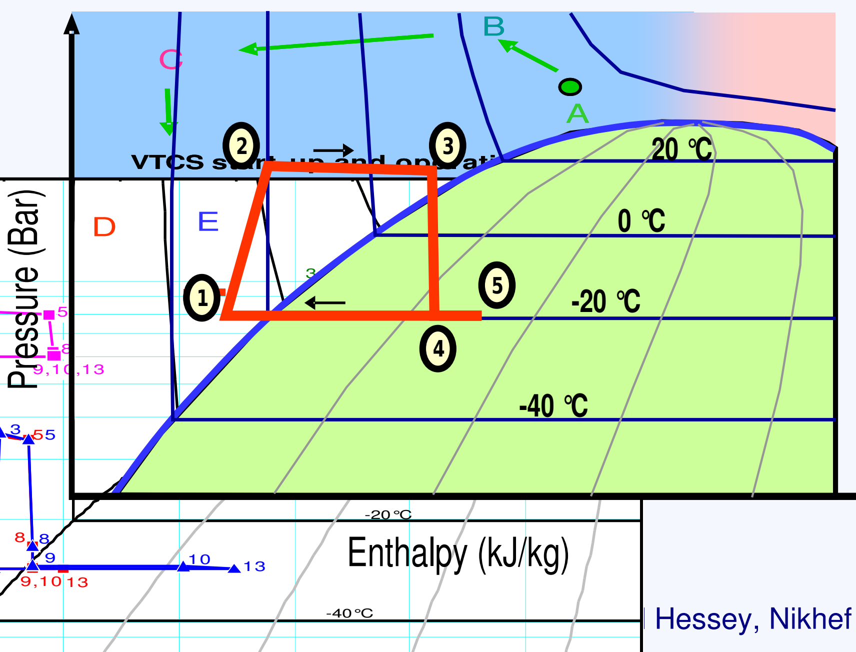
Very good and uniform front end performance (noise, gain, pedestal, threshold); low dead channel count – zero here

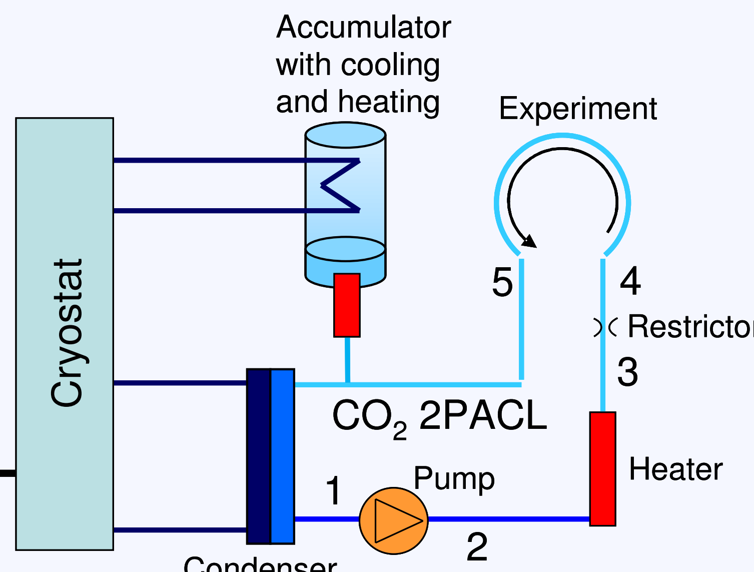
Tracker Power and Cooling – reducing material

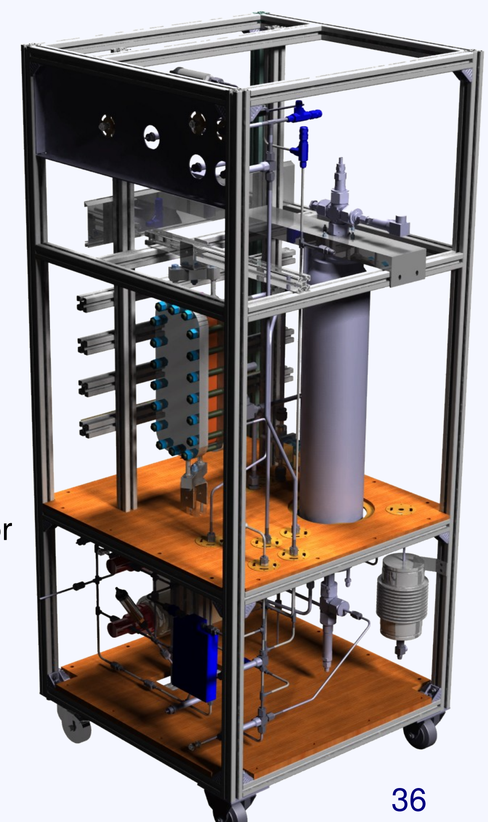
A stave needs > 100 A at 2.5 V – heavy cables not acceptable
Look into serial powering and DC-DC: Buck converters, piezo-electric ...
Many issues under investigation (coreless inductors, switching noise, high current capacity...)
Essential R&D

30-hybrid stave with serial powering successfully tested (UK+LBNL): same noise performance as individual powering

Bi-phase CO2 cooling can reduce mass of cooling system
Rad-hard and demonstrated in LHCb







Integration and Installation

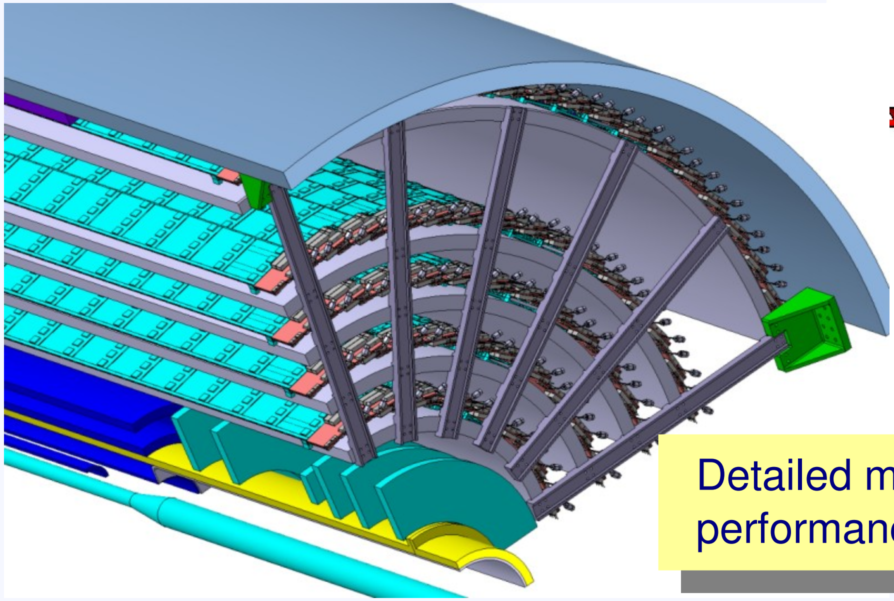
The present ID took much longer to install in the pit than the time we have available

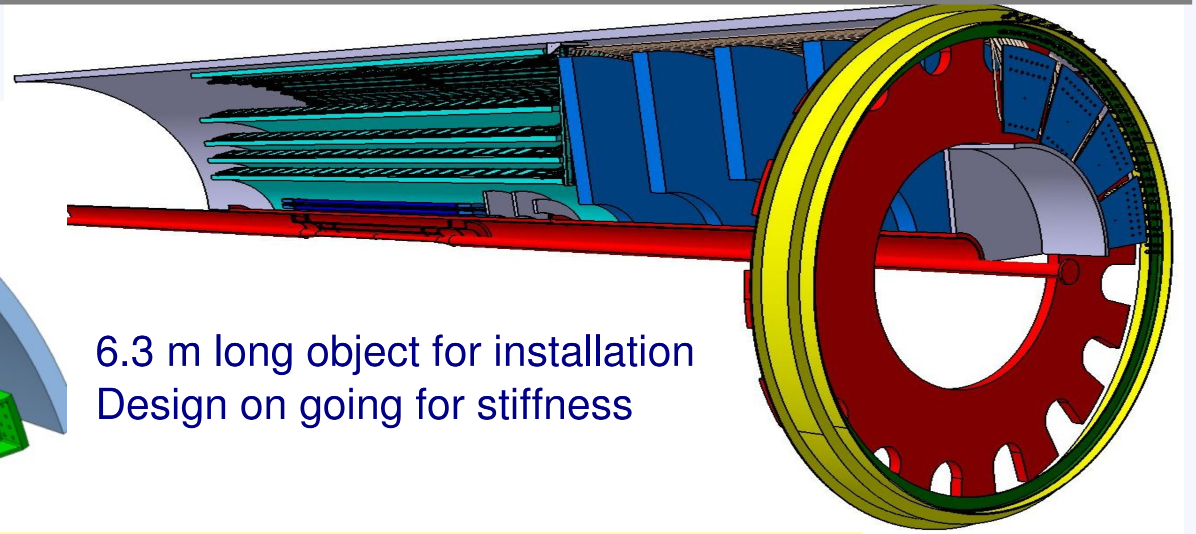
It will be installed in a radioactive environment

We propose to install it in one main piece (with the inner most pixel layers separate)

Assemble everything above ground, test

Solid connectors with high level of multiplexing (e.g. 5 Gb/s links – GBT and versatile link projects) for quick installation



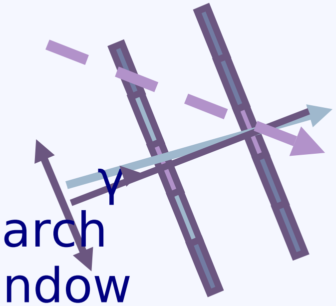


6.3 m long object for installation
Design on going for stiffness

Detailed modelling important for space, material, performance studies etc.

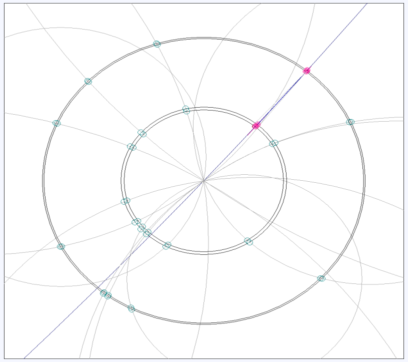
Despite many ideas to accelerate assembly and installation, it remains a challenge to be ready in time for ~2019

Track Trigger at L1



High momentum tracks are straighter so pixels line up

Pairs of stacked layers can give a P_T measurement



Several ideas for implementing a track trigger at L1. Wanted: high-PT (~20 GeV) leptons.

CMS need to identify electrons early so leans towards paired pixel planes

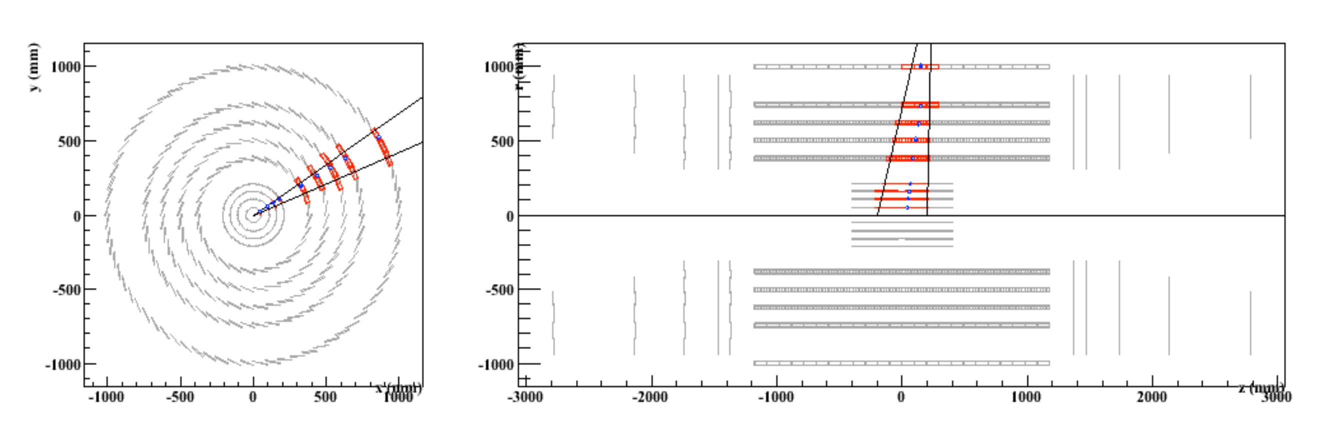
ATLAS EM calo has good identification, allowing another approach:

Calorimeter or muon system identifies a candidate high-PT lepton and gives region-of-interest

Inner tracker modules in that region are read-out, and hardware track finders confirm presence of track with matching momentum

RoI is a few % of modules so small increase in bandwidth needs --> very little increase in material

Needs additional data stream in FE chip and a lot more study, but encouraging so far



Summary

The LHC is expected to continue operation well beyond 2020 with upgrades to higher luminosity

ATLAS has several changes under development to extract as much benefit as possible from this

Rich variety of physics possibilities, with a mixture of SM verification and New Physics

- needs more studies of real performance with pile-up etc., and results from LHC for better understanding

Phase-I will see up to 3 times nominal luminosity, requiring a new B-layer, improved forward calorimeter, new trigger features, and several improvements elsewhere

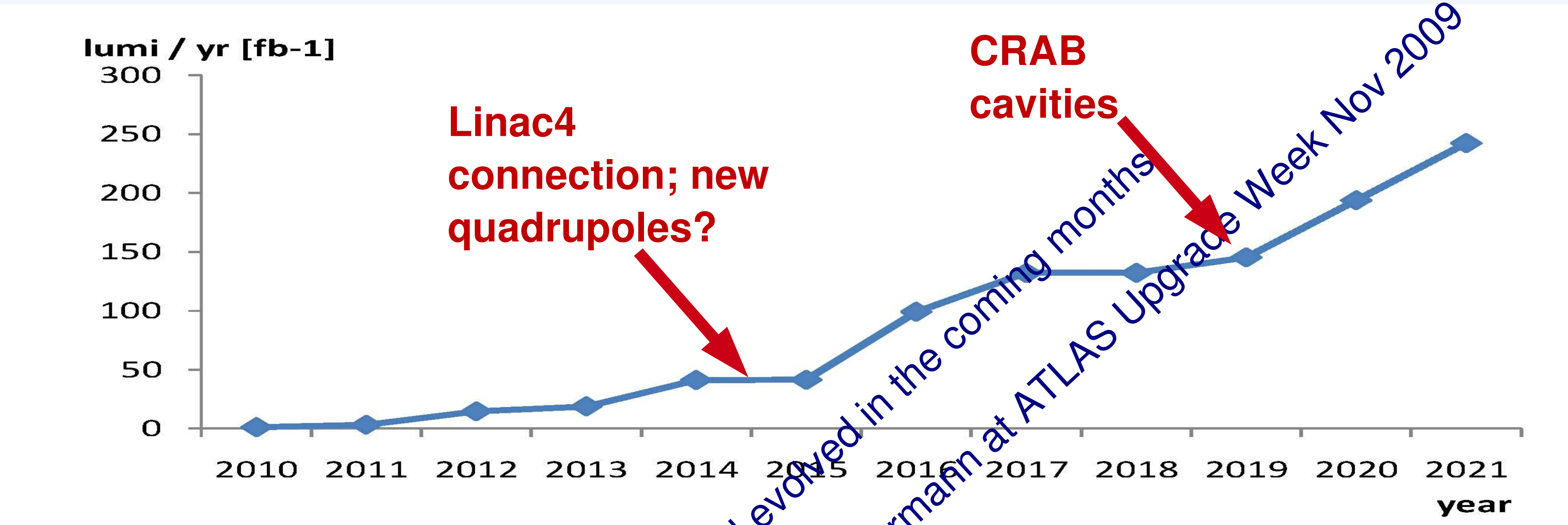
Phase-II will require a completely new Inner Tracker, some new muon chambers, major trigger and DAQ improvements and possibly a new FCAL.

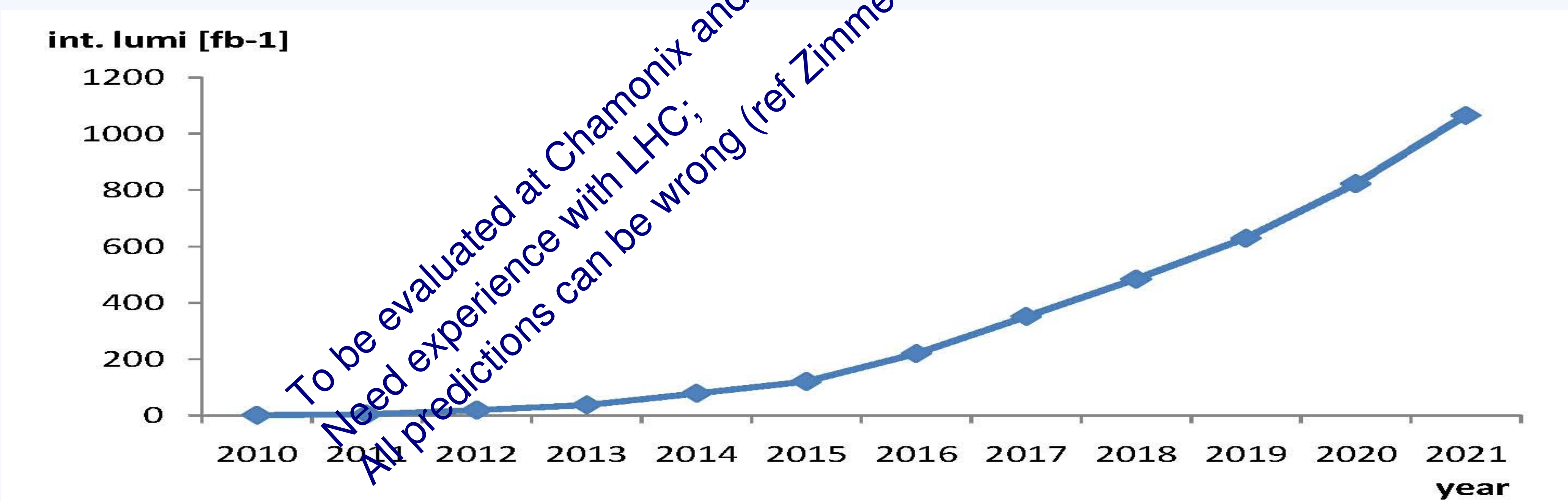
Work is well underway, despite pressures of starting up a new and very exciting initial ATLAS detector

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

Backup slides

An illustration of how things may (or may not) turn out





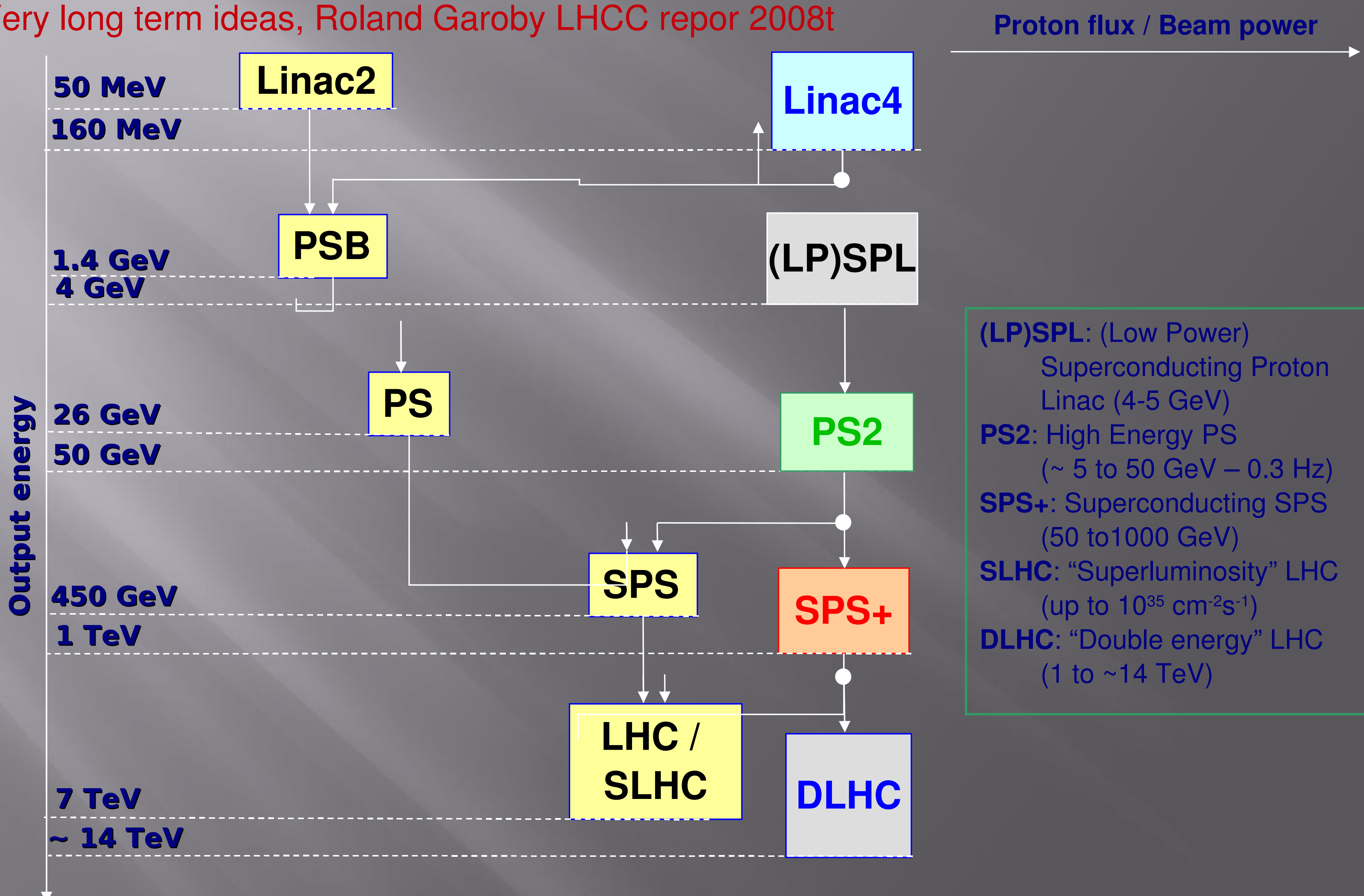
To be evaluated at Chamonix and evolved in the coming months

Need experience with LHC;

All predictions can be wrong (ref Zimmermann at ATLAS Upgrade Week Nov 2009

Present and future injectors

Very long term ideas, Roland Garoby LHCC repor 2008t



(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)