CMS Upgrades Workshop –

- FNAL Nov 2008

Outline

- Current Machine plans for the upgrade
- Brief review of CMS upgrade plans
- Workshop goals

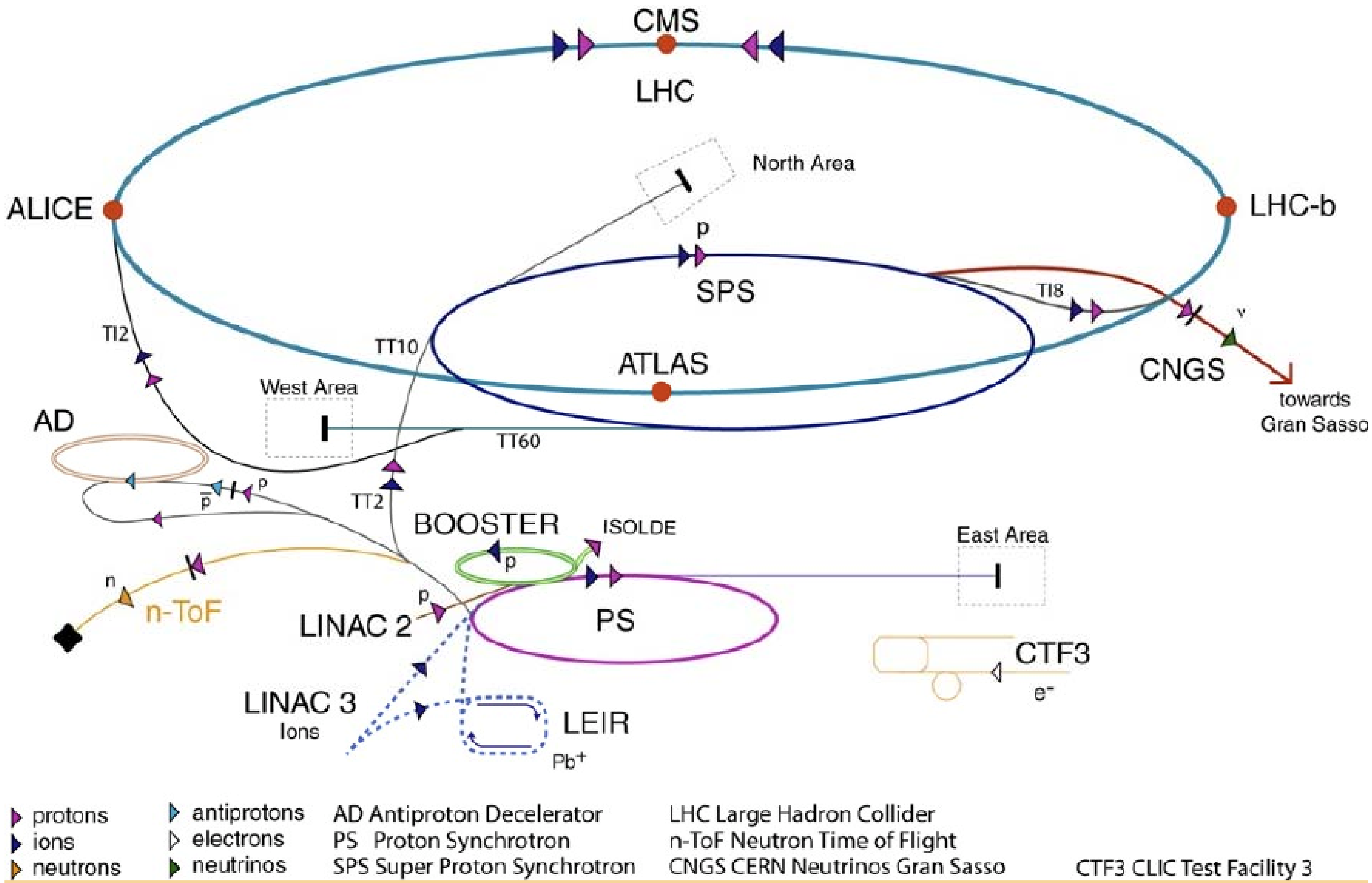
Peak Luminosity

$$L = \frac{N_b^2 n_b f_r \gamma}{4\pi\varepsilon_n \beta^*} F$$

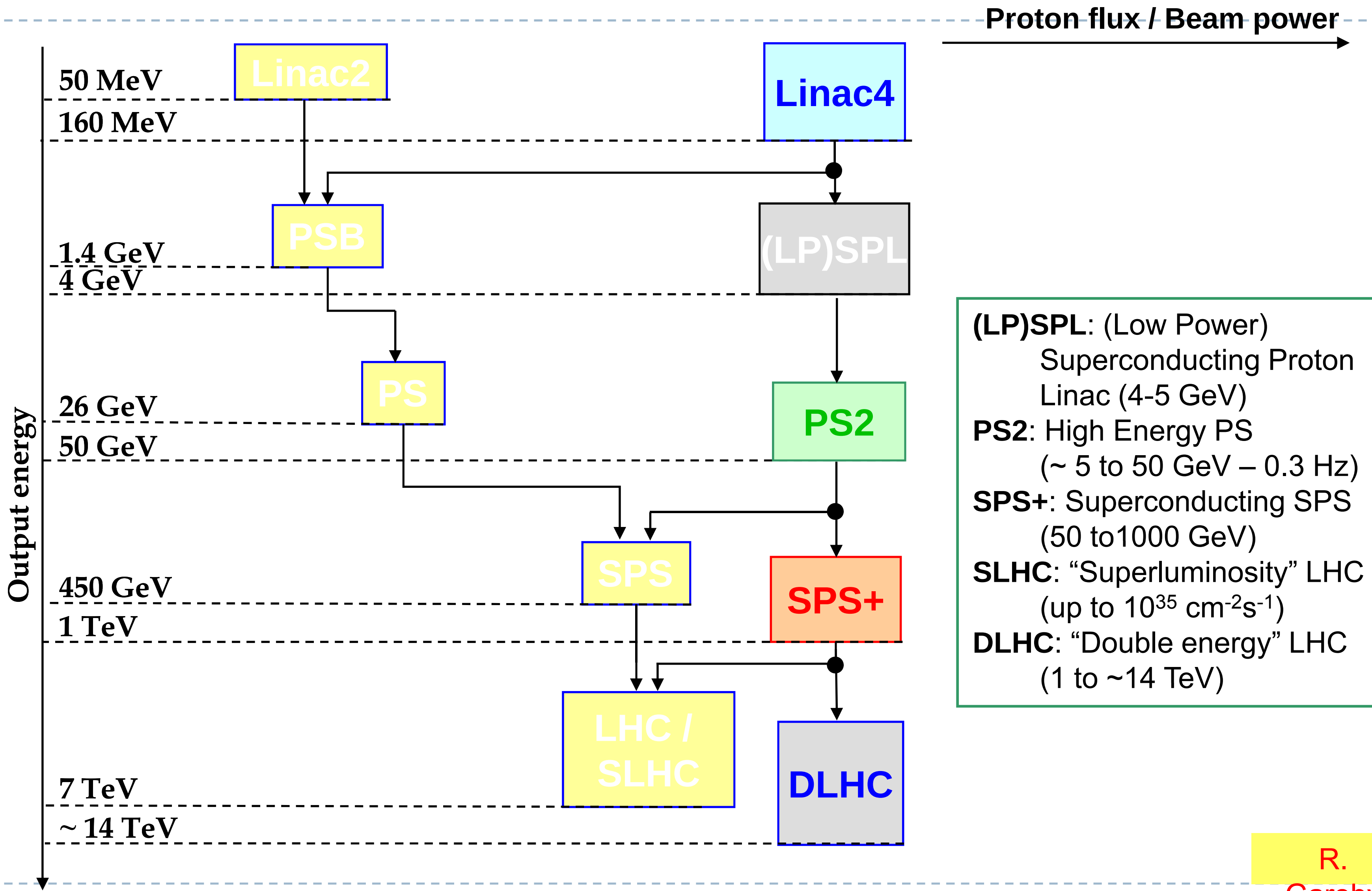
- N_b number of particles per bunch
- n_b number of bunches
- f_r revolution frequency
- ε_n normalised emittance
- β^* beta value at Ip
- F reduction factor due to crossing angle

- N_b, ε_n → injector chain
- β^* → LHC insertion
- F → beam separation schemes
- n_b → electron cloud effect

Cern Injector Complex



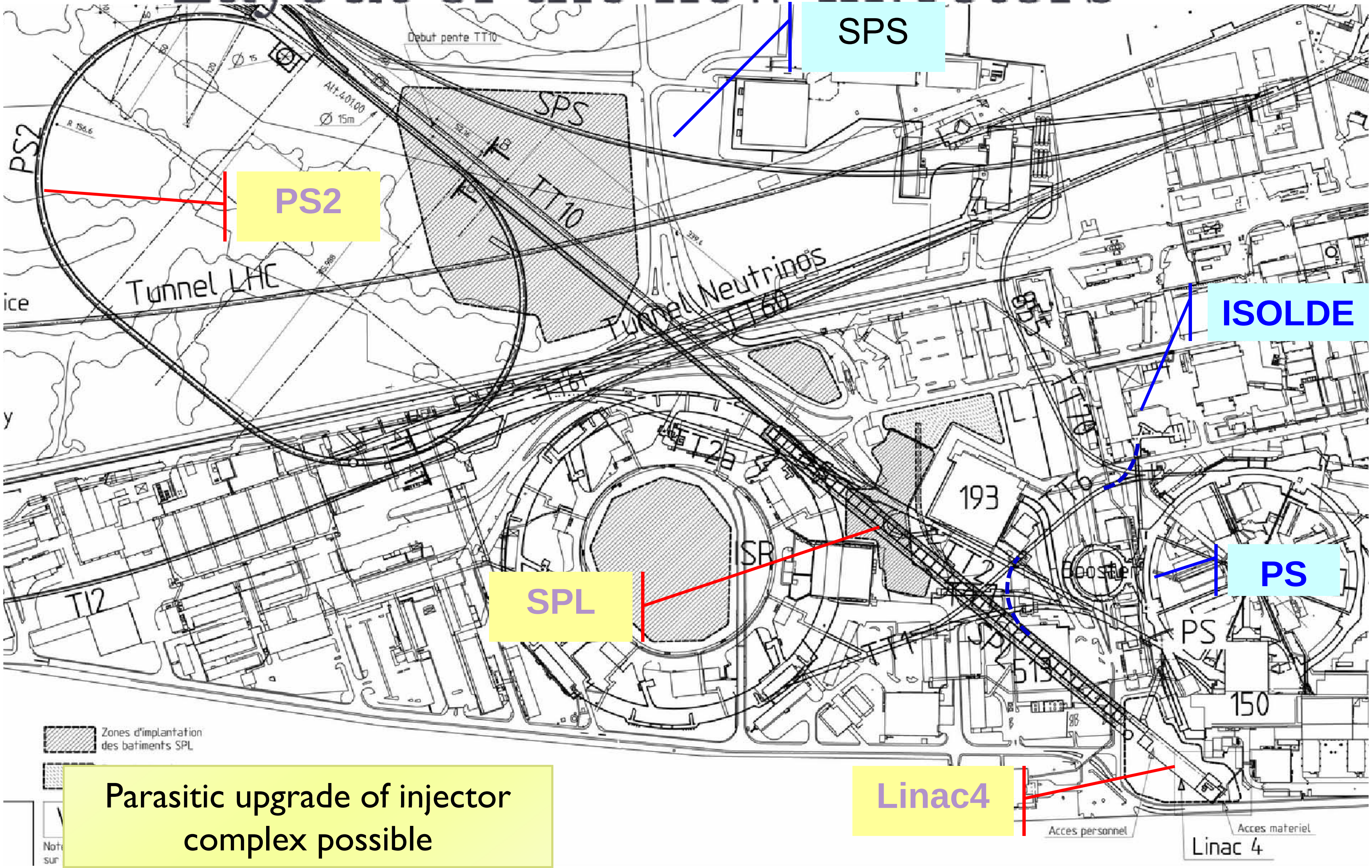
Present and future injectors



(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)

R. Garoby

Layout of the new injectors



Parasitic upgrade of injector complex possible

Preliminary improvements

IR upgrade phase 1

- **Goal: Enable focusing of the beams to β*=0.25 m in IP1 and IP5, and reliable operation of the LHC at**

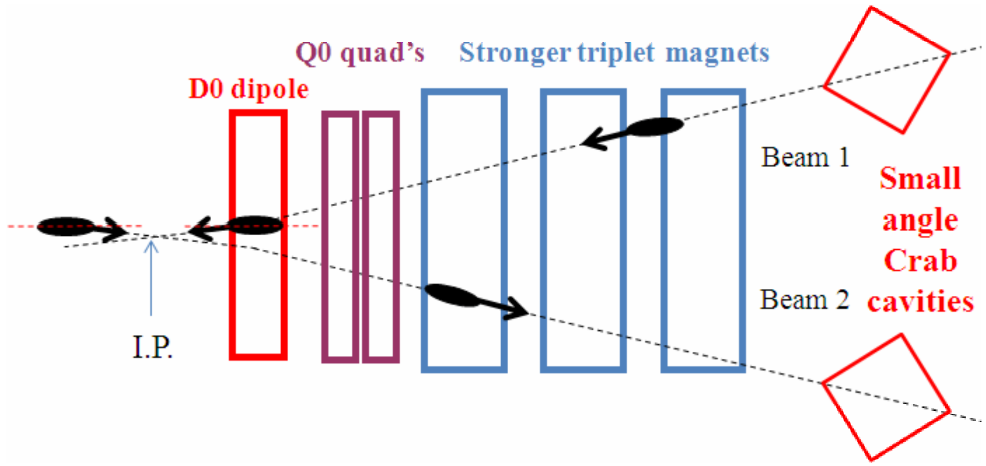
  2 - 3 ´ 10^{34} $cm^{-2}s^{-1}$.
- **Scope:**
  - **Upgrade of ATLAS and CMS IRs.**
  - **Replace present triplets with wide aperture quadrupoles based on LHC dipole cables (Nb-Ti) cooled at 1.9 K.**
  - **Upgrade D1 separation dipole, TAS and other beam-line equipment so as to be compatible with the inner triplet aperture.**
  - **Modify matching sections (D2-Q4, Q5, Q6) to improve optics flexibility. Introduction of other equipment to the extent of available resources.**
- **Planning: operational for physics in 2013**

“Early Separation” scheme

Factor wrt ultimate

Main ingredients:

Ultimate beam	1
D0 dipole close to IP ⇒ bunches quasi-aligned at collision ($\phi \sim 0$) ⇒ larger ΔQ_{bb}	1.3
Very small β*(8 cm)	6
Hour-glass effect	0.86
Total	**6.7**



→ hardware inside ATLAS & CMS detectors, first hadron crab cavities; off-δ β

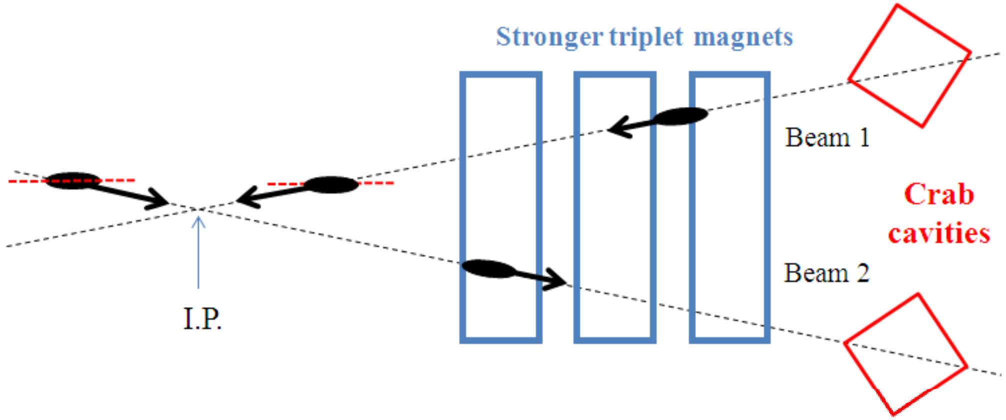
"Full Crab Crossing" scheme

Factor wrt ultimate

Main ingredients:

- **Ultimate beam** — 1
- **Crab cavities ⇒ bunches quasi-aligned at collision ($\phi \sim 0$) ⇒ larger ΔQ_{bb}** — 1.3
- **Very small β*(8 cm)** — 6
- **Hour-glass effect** — 0.86

Total — **6.7**



→ first hadron crab cavities, off-δ β-beat

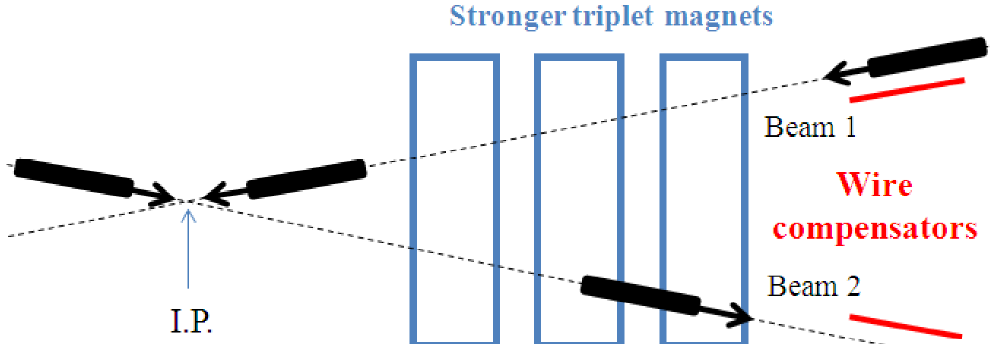
"Large Piwinski angle" scheme

Factor wrt ultimate

Main ingredients:

- **Larger beam current** 1.45
- **Large Piwinski angle and 3´ intensity per bunch(ϕ ~ 2) $\Rightarrow$ larger ΔQ_{bb}** 1.3
- **Reduced β*(25 cm)** 2
- **Longit. profile** 1.4

Total 5.3



→ novel operating regime for hadron colliders

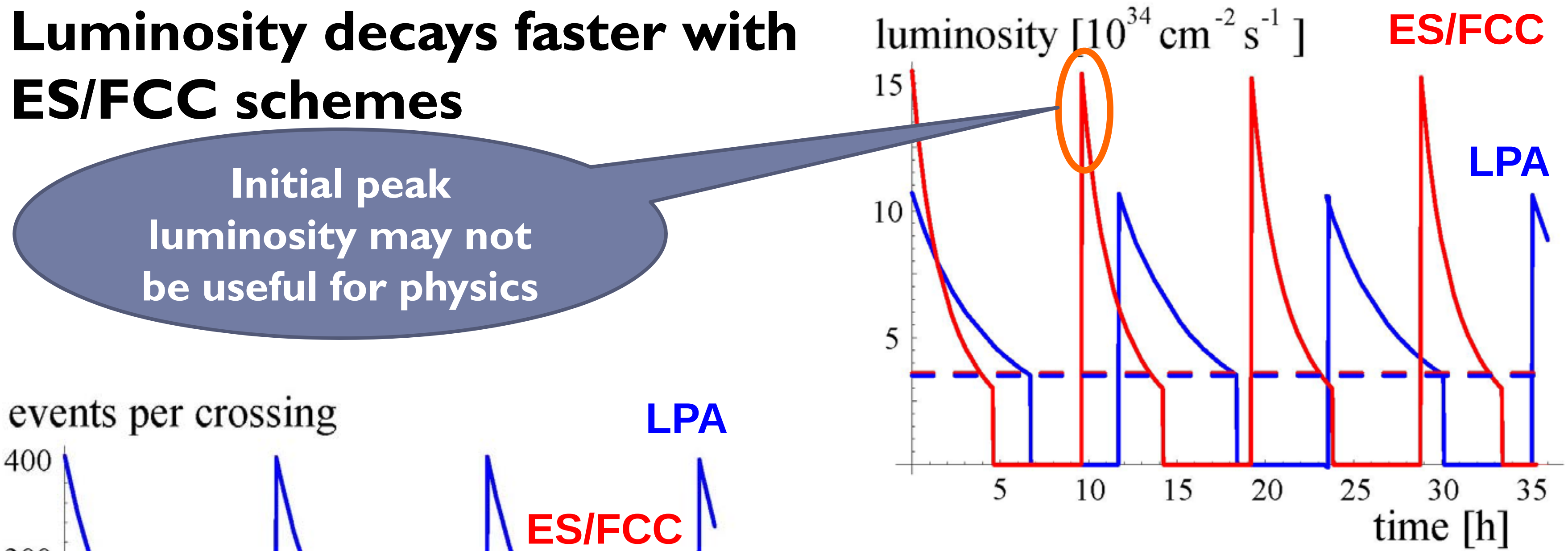
Schemes comparison

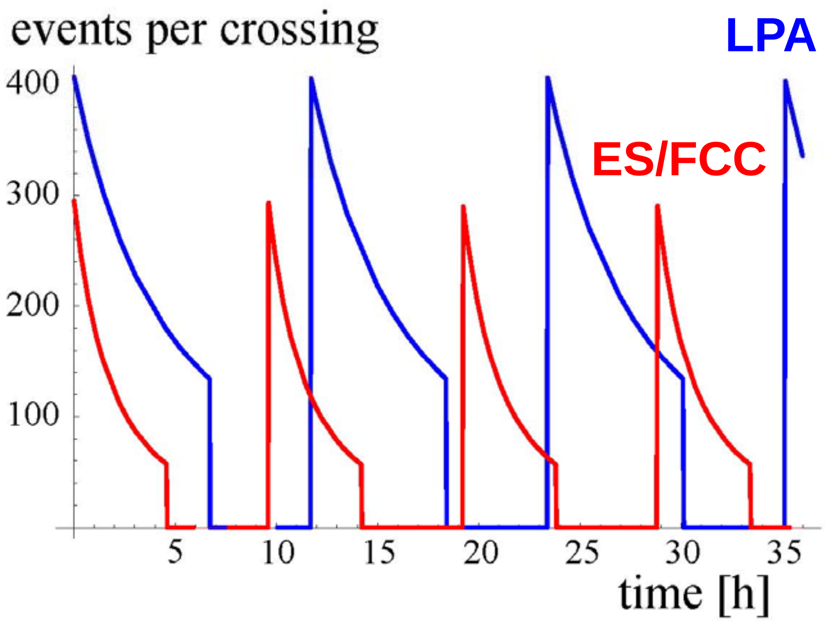
© F. Zimmermann

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

Luminosity evolution

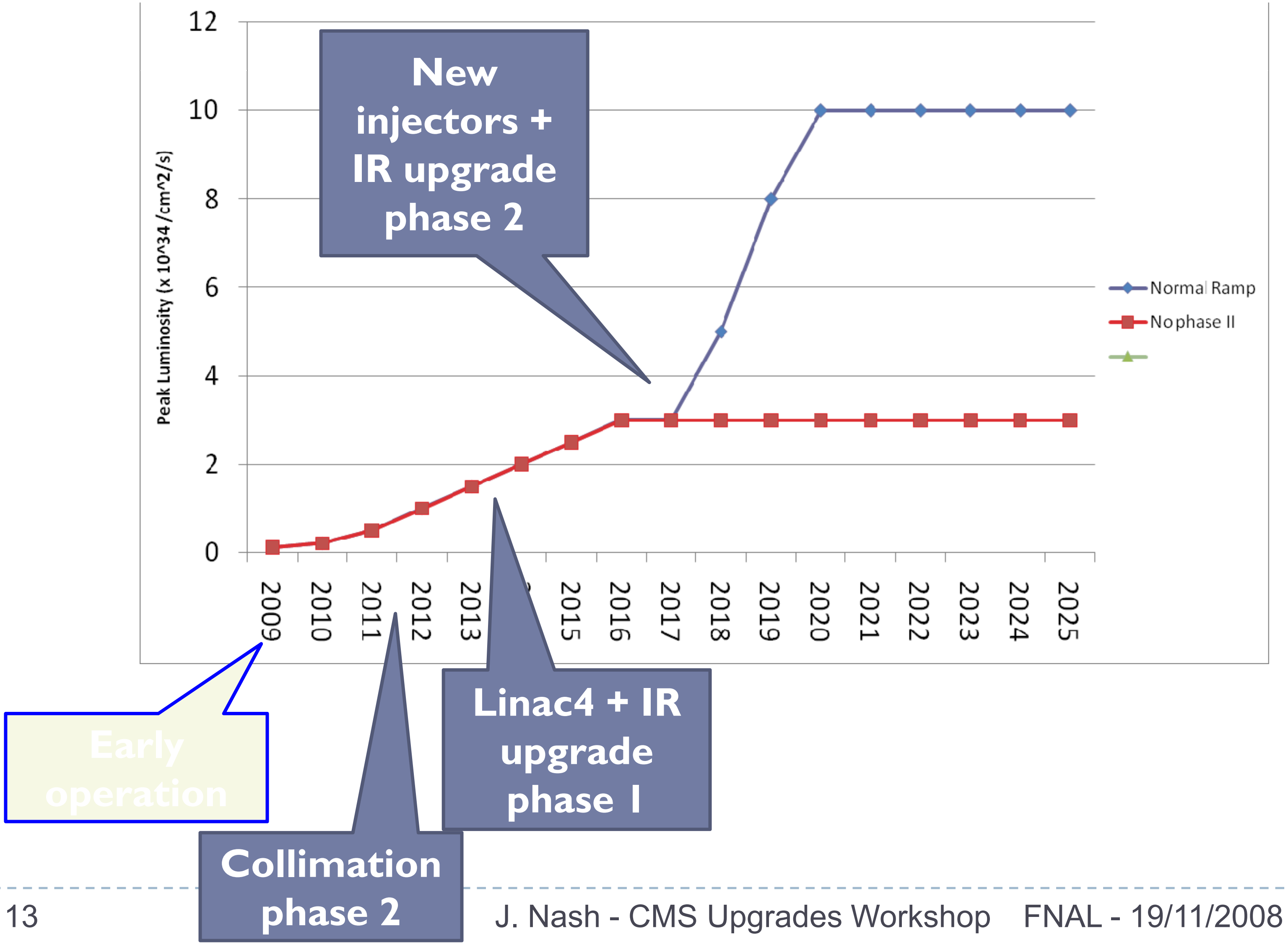
- **Luminosity decays faster with ES/FCC schemes**



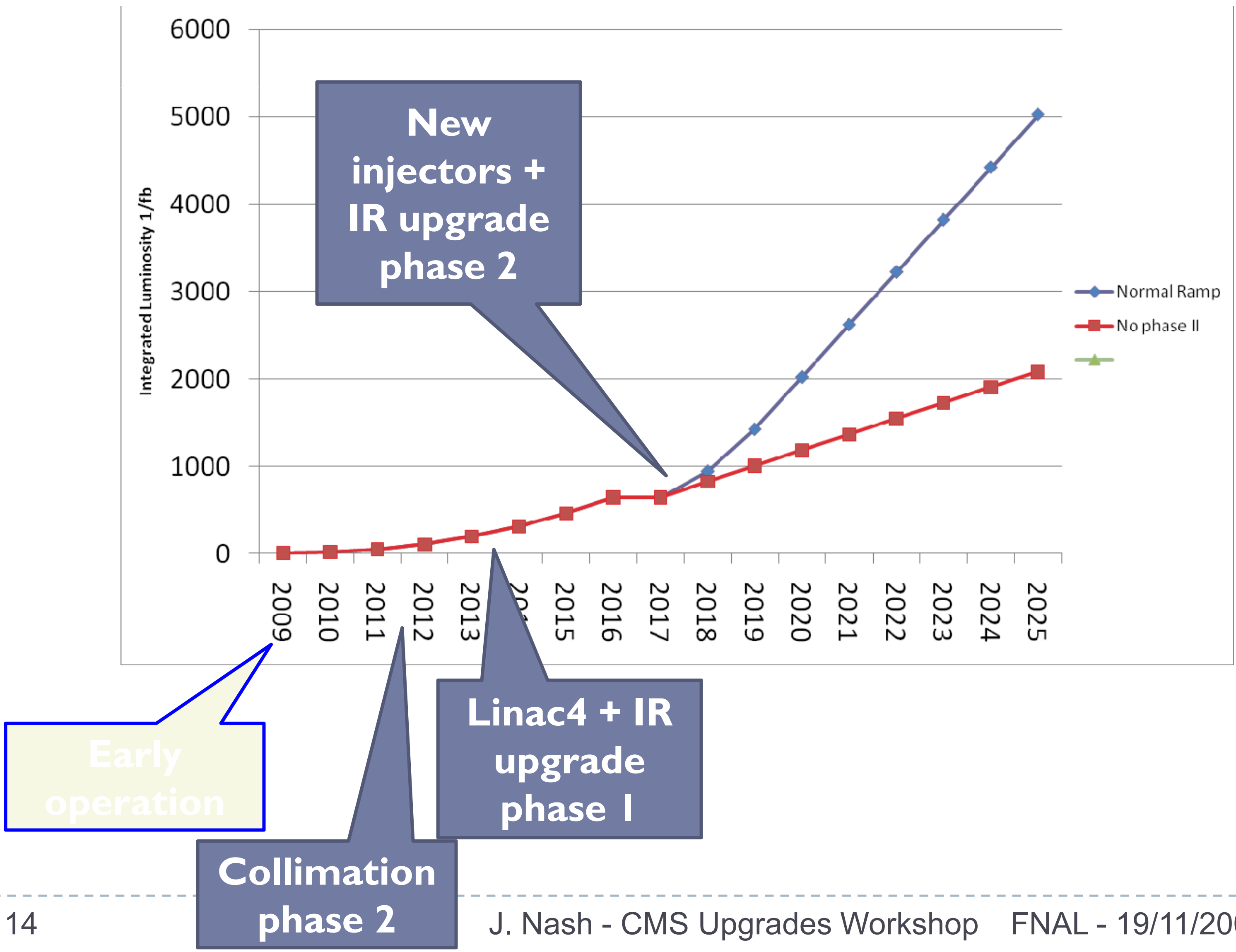


- **But LPA always gives more events per crossing…**

Scenario for Peak luminosity…



Integrated luminosity…



For CMS: What are the key timescales/issues?

- Phase 1
  - How well do detector components handle the increasing luminosity?
    - Both instantaneous and integrated effects
  - What detector elements will need replacement/modification to cope?
    - Detectors will record >500 fb^{-1}, can they withstand this?
- Phase 2
  - What detector elements will need replacement?
  - What do machine plans imply for interaction regions
  - Is there a requirement for a long shutdown?
    - How long – 18 Months? (1 Full calendar year without beam +)
    - When – sometime after the middle of the next decade
      - Developing and building new tracking detectors will take many years
      - We have to plan this now in order to have any chance of running detectors with high luminosity
    - ATLAS and CMS now agree on the dates
      - No sense in having two long shutdowns
      - Reach 700 fb^{-1} (potential limit)
        - Likely 2017

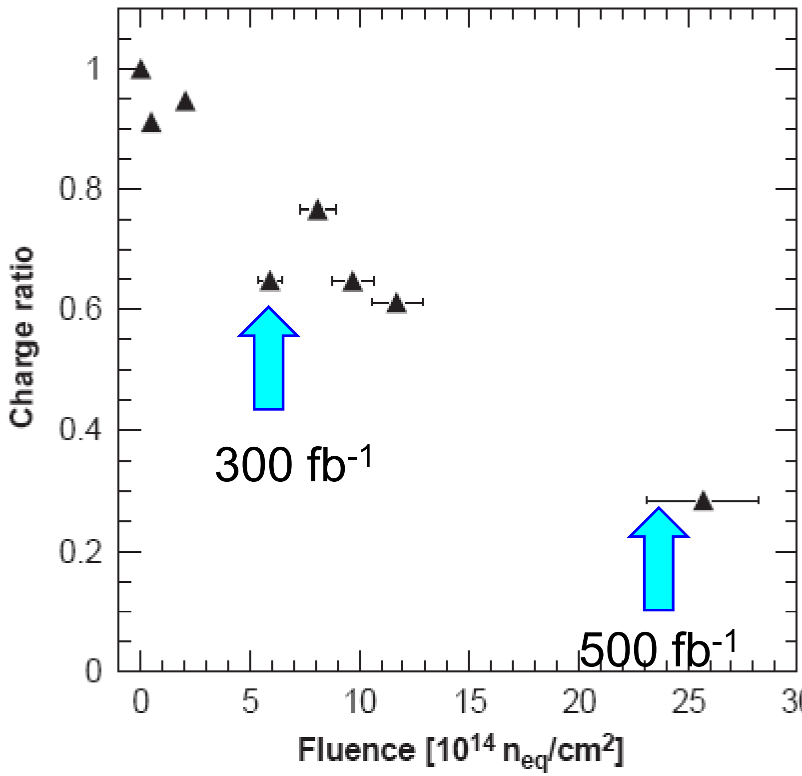
Phase I issues for tracking

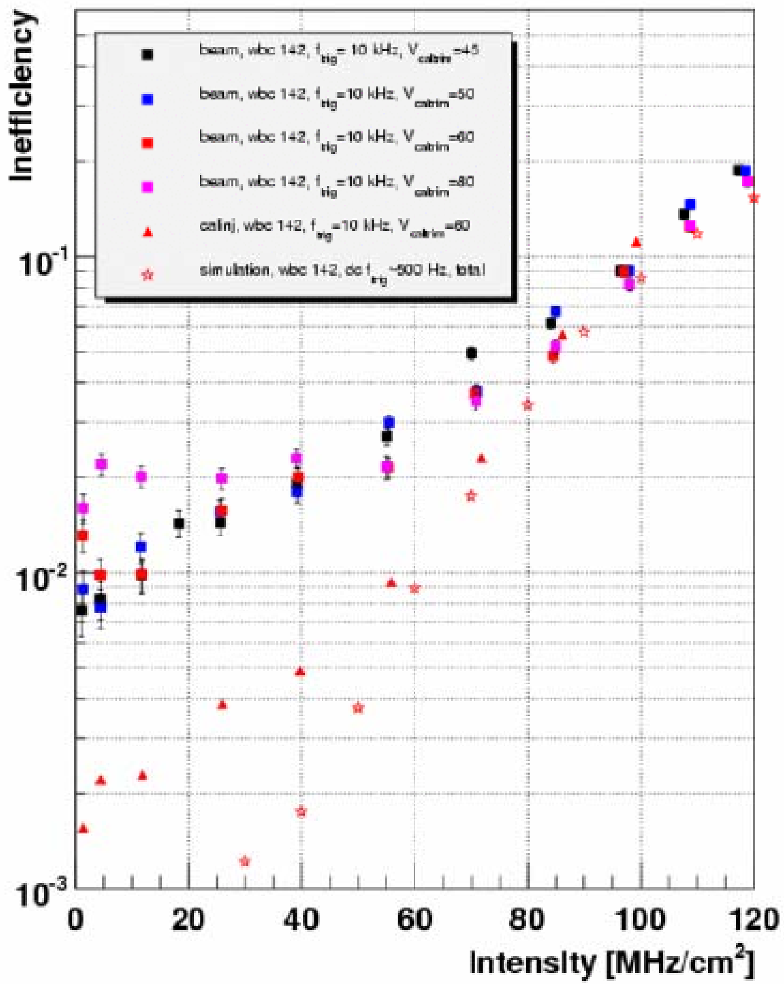
- Rough estimate of pixel layer lifetimes

  4cm layer should survive a minimum of 200fb^{-1}
- Will have to replace the pixel detector during phase I
  - How often?
  - How much to replace?
  - New features
- Looking at reducing the material in the replacement pixel detector, and potentially adding a fourth layer
- Outer tracker looks robust to survive Phase I

Limitations in Phase 1

- Radiation damage due to integrated luminosity.
  - Sensors designed to survive $6\times10^{14} n_{eq}/cm^2$ (~ 300 fb^{-1}).
  - n-on-n sensors degrade gradually at large fluences

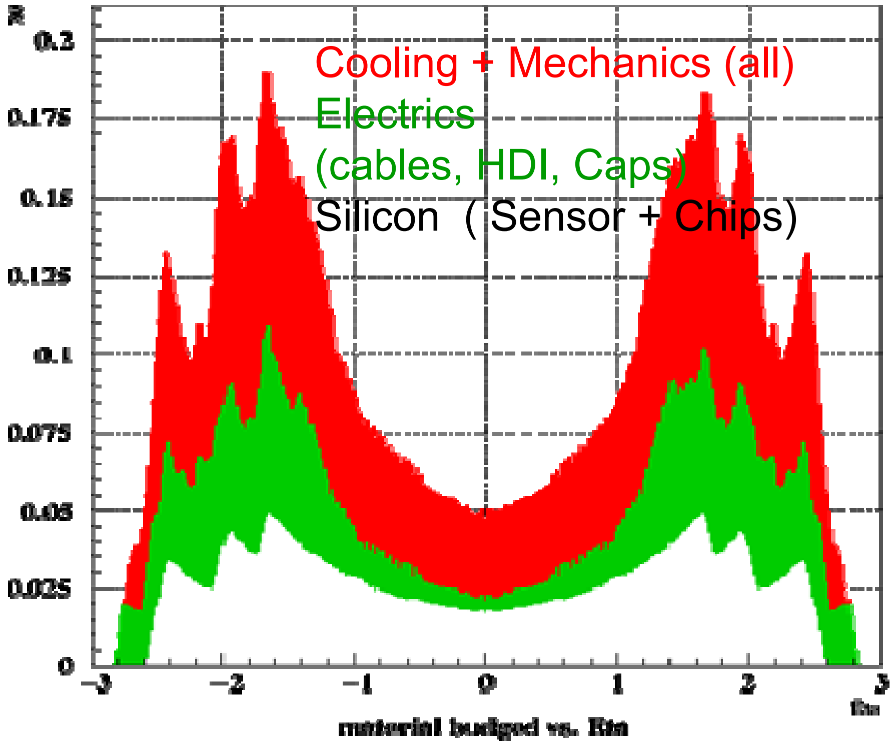




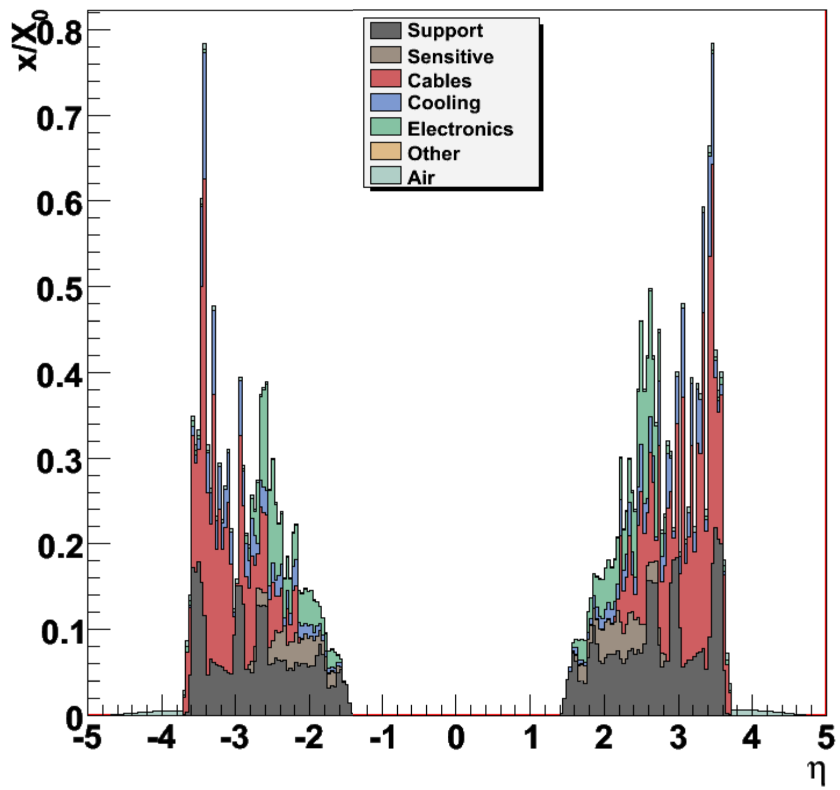
Dead time will rise to ~12% due to increase in peak luminosity

Limitations in Phase 1

BARREL PIXELS



ENDCAP PIXELS



- Material budget both in endcap and barrel
  - Significant contribution from mechanical supports, cables

BPIX Options for 2013 replacement/upgrade – R. Horisberger

Option	Layer/Radii	Modules	Cooling	Pixel ROC	Readout	Power
0 (as 2008)	4, 7, 11cm	768	C_6F_{14}	PS46 as now	analog 40MHz	as now
1	4, 7, 11cm	768	C_6F_{14}	2x buffers	analog 40MHz	as now
2	4, 7, 11cm	768	CO_2	2x buffers	analog 40MHz	as now
3	4, 7, 11cm	768	CO_2	2x buffers	analog 40MHz μ-tw-pairs	as now
4	4, 7, 11cm	768	CO_2	2xbuffer, ADC 160MHz serial	digital 320MHz μ-tw-pairs	as now
5	4, 7, 11, 16cm	1428	CO_2	2xbuffer, ADC 160MHz serial	digital 640 MHz μ-tw-pairs	DC-DC new PS

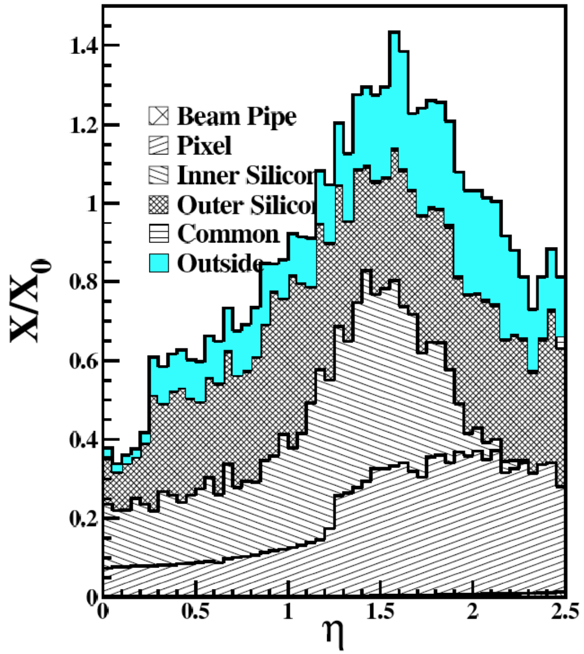
Upgrade Plans

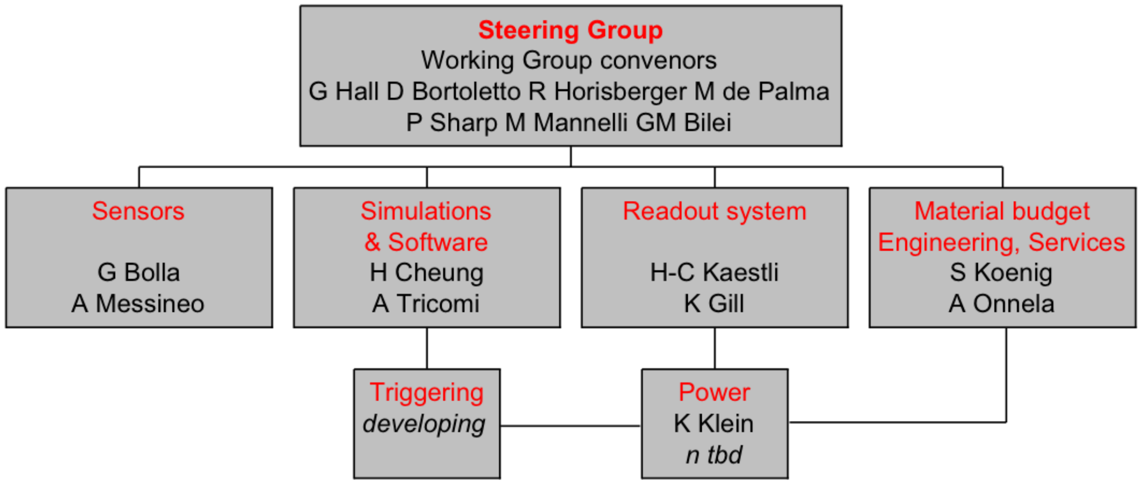
D. Bortoletto

- Baseline: 3 layers (4 layer option) 3 disk in each endcap
  - Detector technology
- Single sided n-on-p sensors (more rad-hard) instead of n-on-n (fallback)
- Evaluating 3D sensors industrialization for innermost layer at 4 cm.
  - Readout Chip
- Double buffer size (in 250 nm CMOS extra 0.8 mm needed for chip periphery)
  - Minimal R&D. Design, verification, testing at high beam rates 8-10 months
  - Mechanical changes
- Further gains possible with 130 nm CMOS but R&D needed
  - Layout, mechanical assembly, and cooling (aim at material reduction of about a factor of 3 in barrel and 2 in forward)
- $C0_2$ cooling (as in VELO for LHCb)
- Low mass module construction and simplified thermal interfaces
- Further material reduction can be acheived with on module digitization:
  - R&D needed: It requires new ADC and Token Bit Manager changes

Key issues for tracker Phase II upgrades (Not just more channels!)

- Power
  - How to get current needed to the electronics
  - More complicated front ends, more channels may want more power
    - DC-DC converters, Serial powering
- Material Budget
  - Can we build a better/lighter tracker?



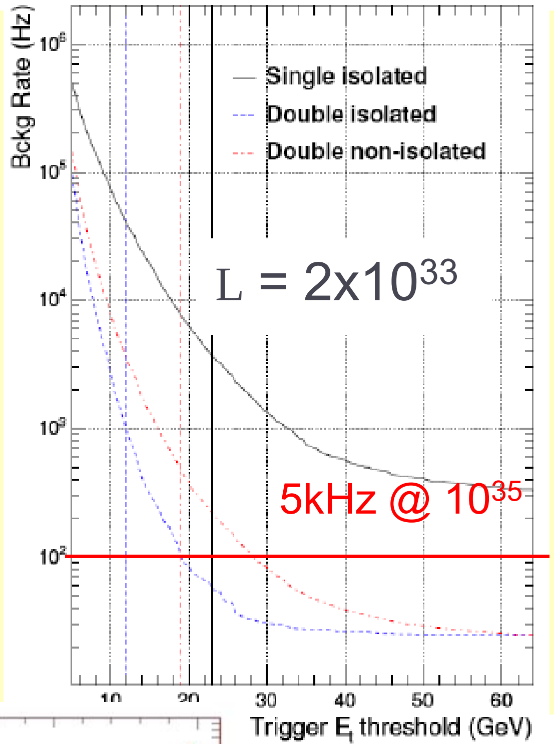


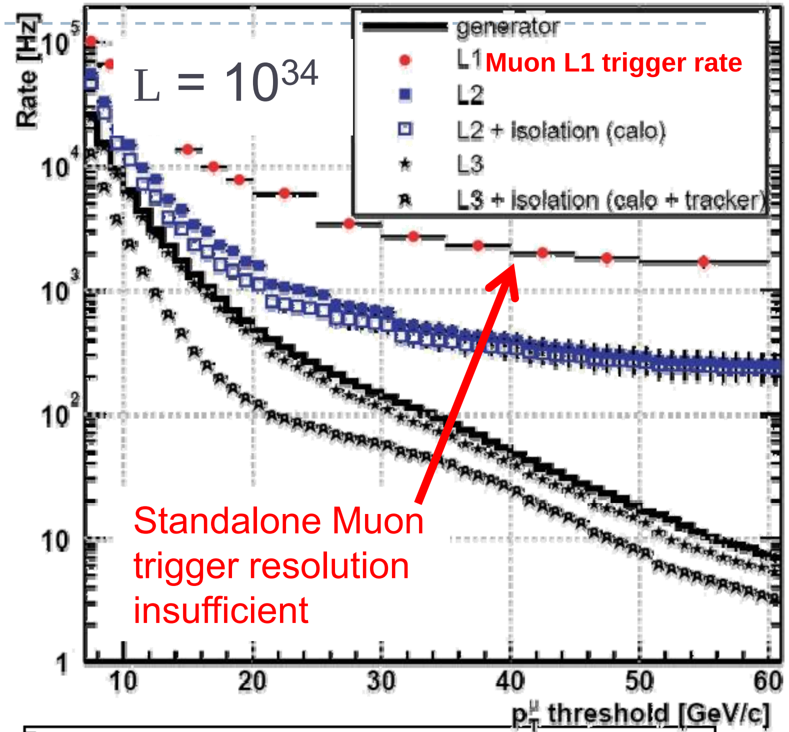
From Physics TDR Vol 1 (LHCC 2006-001)

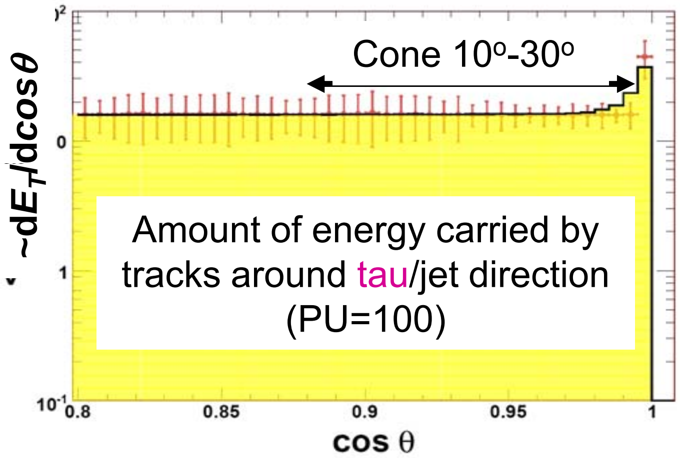
Tracking needed for L1 trigger @ 10^{35}

Single electron trigger rate

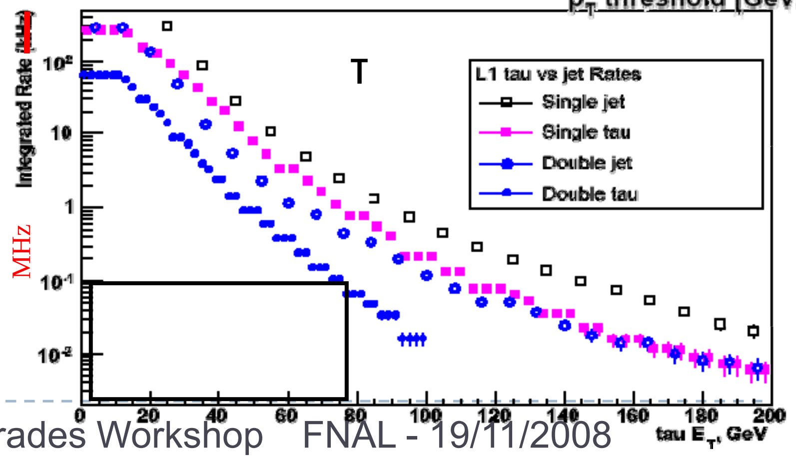
Isolation criteria are insufficient to reduce rate at L = 10^{35} $cm^{-2}.s^{-1}$



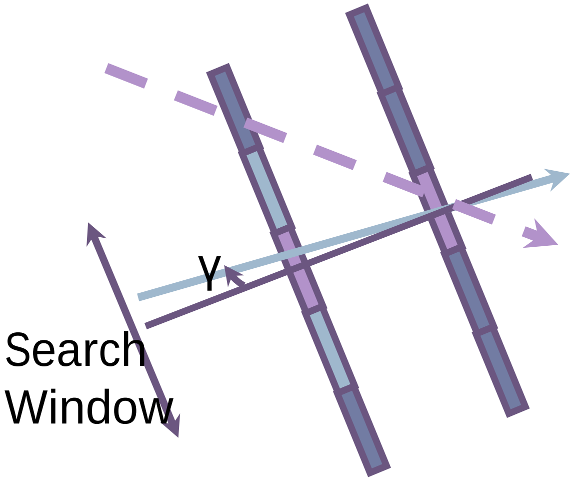




We need to get another x200 (x20) reduction for single (double) tau rate!

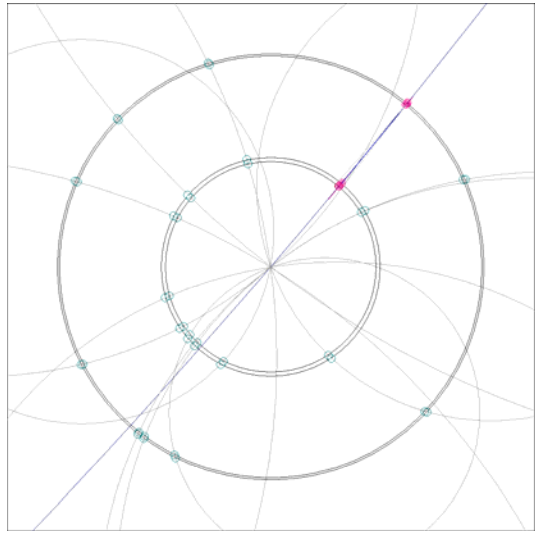


Concepts:Tracking Trigger



High momentum tracks are straighter so pixels line up

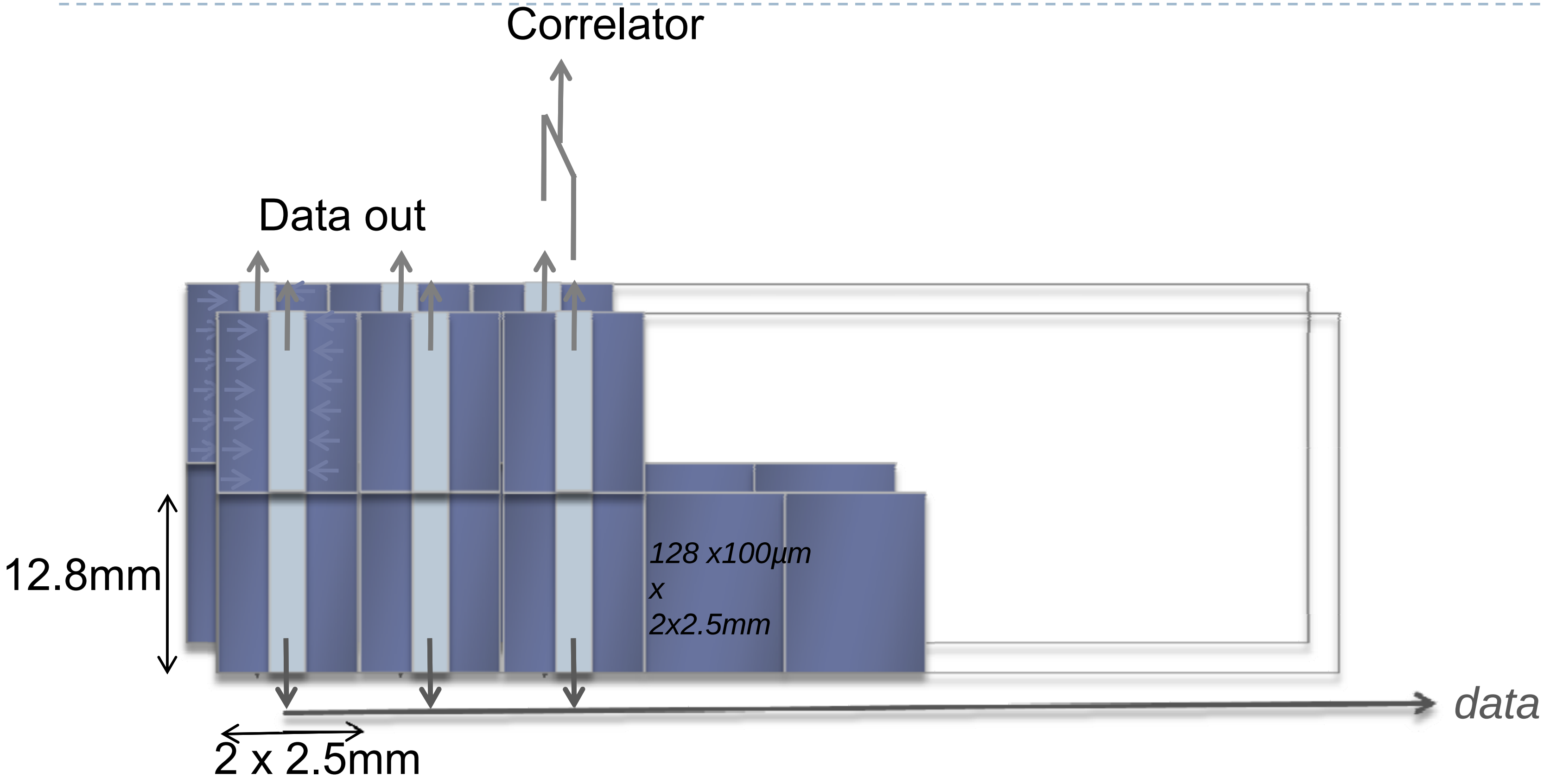
Pairs of stacked layers can give a P_T measurement



Geometrical p_T-cut - J. Jones, A. Rose, C. Foudas LECC 2005

- Why not use the inner tracking devices in the trigger?
  - Number of hits in tracking devices on each trigger is enormous
  - Impossible to get all the data out in order to form a trigger
  - How to correlate information internally in order to form segments?
- Topic requiring substantial R&D
  - "Stacked" layers which can measure p_T of track segments locally
    - Two layers about 1mm apart that could communicate
  - Cluster width may also be a handle

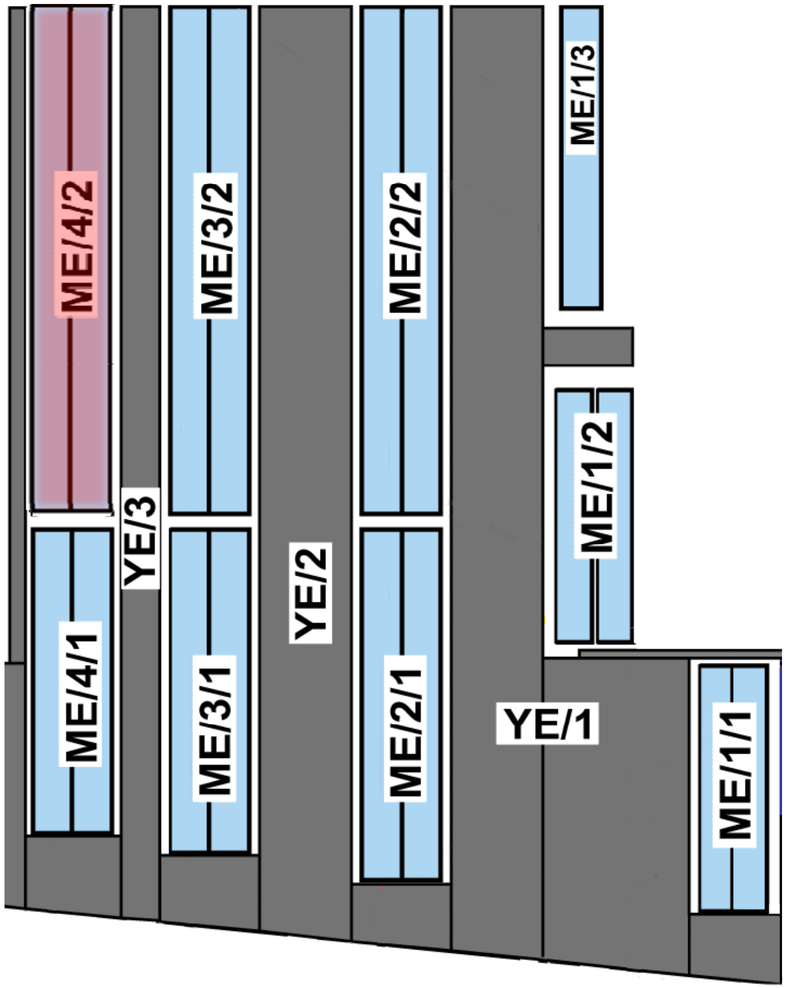
Example PT module

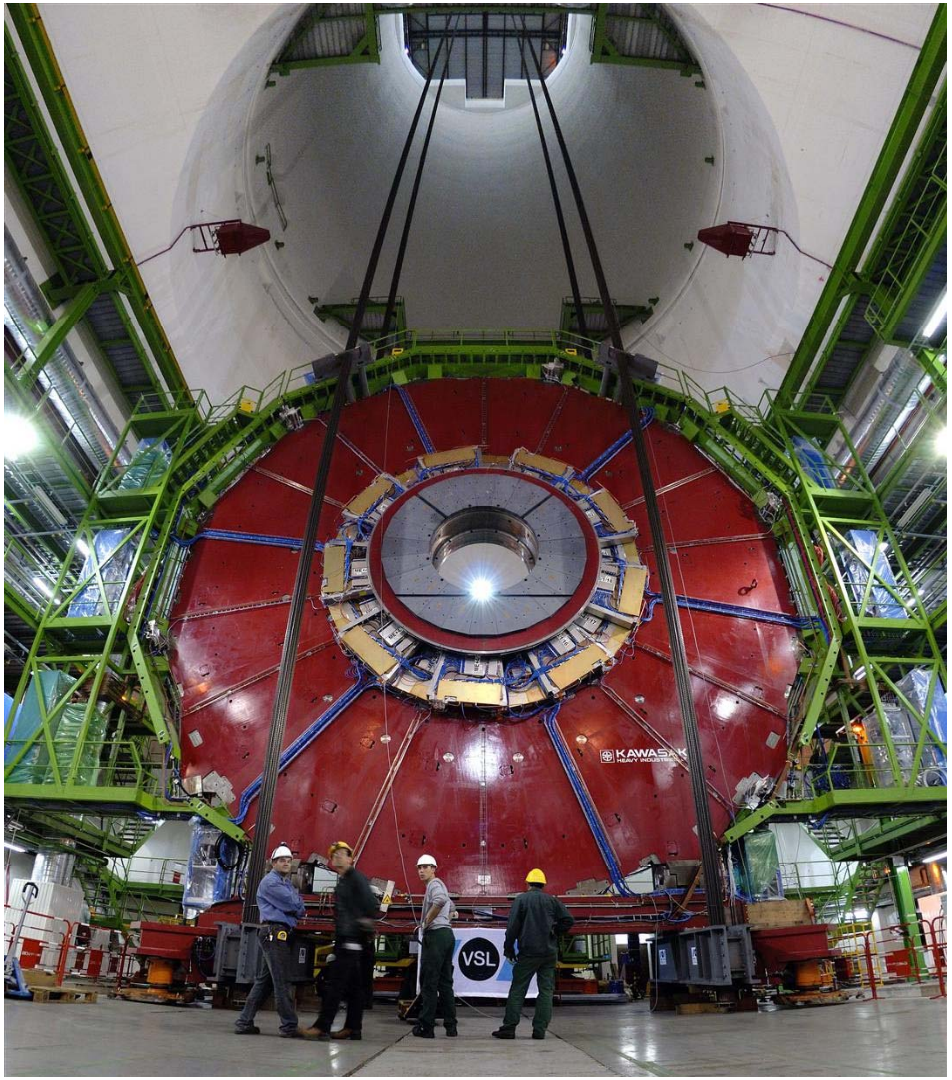


Such a design has potential for inexpensive assembly, using wire bonding, with low risk and easy prototyping

Endcap CSC Muon Phase 1 Upgrade (ME4/2)

R-Z cross-section

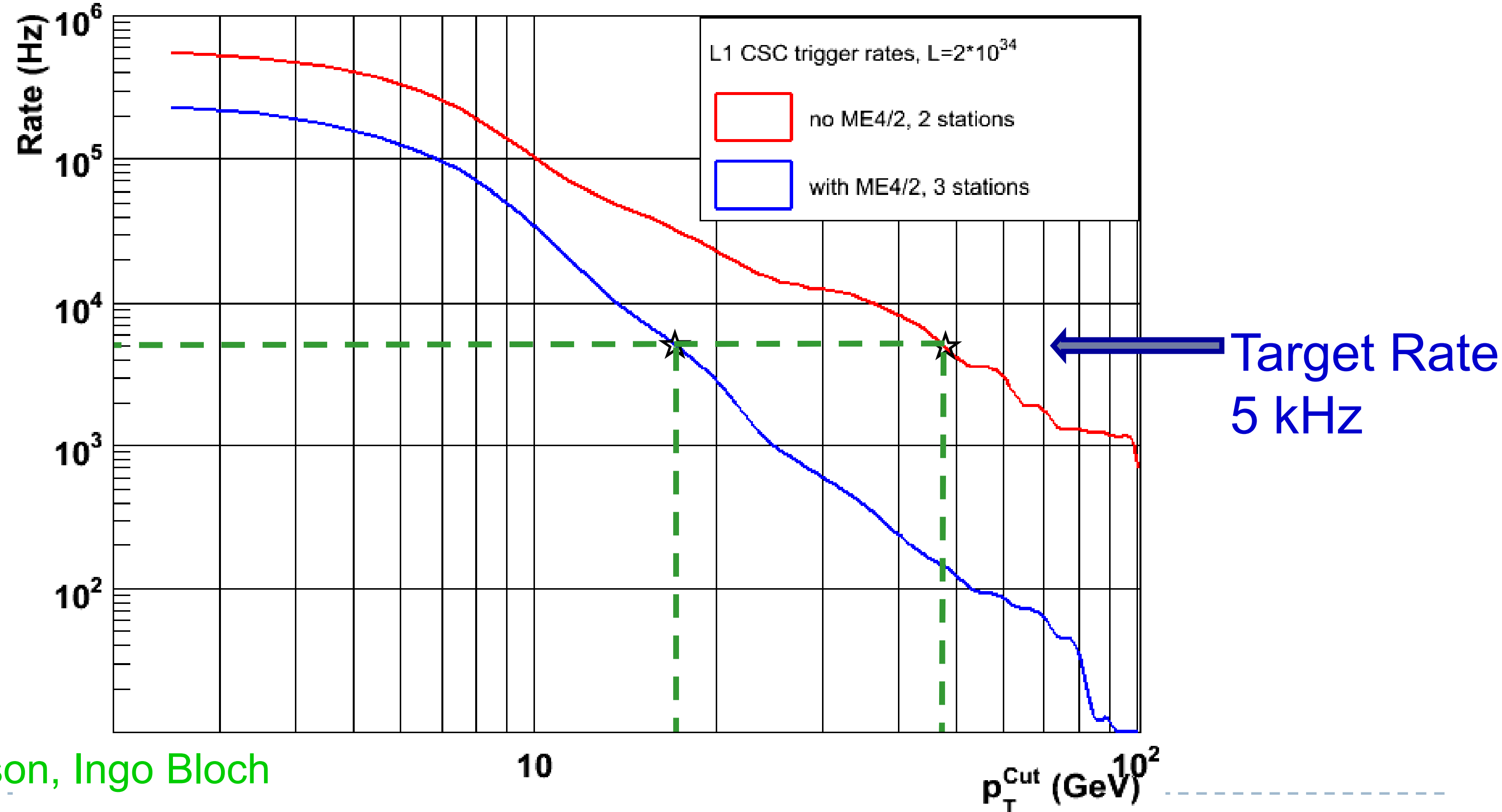




"Empty" YE3 ready for ME4/2

Phase 1 : Muons ME4/2 upgrade motivation

- Compare 3/4 vs. 2/3 stations:
  - (Triggering on *n* out of *n* stations is inefficient and uncertain)
- Recent simulation with & without the ME4/2 upgrade:
  - The high-luminosity Level 1 trigger threshold is reduced from 48 → 18 GeV/c



Rick Wilkinson, Ingo Bloch

HCAL Front-end enhancement

D. Baden

- Increase longitudinal segmentation in HB and HE
  - Add redundancy, survive high luminosities, and surpass current HCAL capabilities
  - Self-imposed constraint, keep present digital fiber plant
- Replace HPDs (HB/HE) and PMTs (HF) with better technology
  - Array’s of APDs
    - They call these “Silicon Photo Multipliers”, or SiPMs
    - Were not available ~10 years ago when choice of HPDs had to be made
    - They are rad hard, cheap, small, flexible, higher gain, quieter
    - Will allow us to increase segmentation, add timing, avoid HPD noise issues
  - Used in commercial PET scanners, laser range finders, long distance fiber optic communications
- SiPMs allow longitudinal segmentation and timing capability to FE
  - Improves ability to reject backgrounds, reduce out-of-time pileup
    - At SLHC luminosities will have 400 events per crossing, way beyond original CMS specs

Upgrade Scope

System	Phase 1	Phase 2
Pixel	New Pixel Detector (1 or 2 iterations?)	
Tracker	FEDs?	New Tracking System (incl Pixel)
HCAL	Electronics + PD replacement	HF/HE?
ECAL	TP (Off Detector Electronics) ?	EE?
Muons	ME4/2, ME1/1 ,RPC endcap, Minicrate spares, some CSC Electronics	Electronics replacement
Trigger	HCAL/RCT/GCT to μTCA	Complete replacement

Documents

Phase I Upgrades

Concept → LOI/TP → TDR

- Concept: mid 2008
- LOI/TP: mid 2009
- TDR: Early 2010

Phase 2 Upgrades

Strawman → TP/LOI → TDR

- Strawman: Mid 2009
- TP/LOI: Mid 2010
- TDR: 2012

Workshop – Working Groups

- Five main working groups
  - Tracking
  - Trigger
  - HCAL
  - ECAL
  - Muons
- Plenary discussions on
  - Simulation
  - Power/Cooling
  - Electronics Issues

Tracking Working Group

- Sensors
  - Radiation issues
  - Progress on R/D
- Simulation and Layout
  - Discussion of potential geometries which may be candidates for strawman, and tools for evaluating layouts
- Power
  - Progress on DC-DC convertors for SLHC
  - Prospects for Serial Power distribution

Trigger

- Technologies for Phase I upgrades
  - Micro TCA implementations
  - The hope is to develop a common infrastructure for use in trigger upgrades
    - Reduce the large number of standards currently in use in the trigger system
    - Increase reliability/flexibility
- Tracking Trigger discussions
  - Possible candidate architectures
  - Simulations
  - Key R/D for phase II
    - Need to establish which ideas most likely to be successful and dedicate sufficient resources to determine viability
      - Can it be implemented
      - How well does it work
      - Power/Material implications

Calorimeters

- HCAL
  - Progress on using Silicon PMs
  - New off detector electronics
  - Upgrade strategies
- ECAL
  - Data on radiation damage to crystals and VPTs in the EE
    - Establish what will be the performance at SLHC
  - Simulations of SLHC and EE
    - How well will the EE perform given any performance degradation
  - ECAL/HCAL joint electronics issues
    - e.g. Trigger electronics

Muons

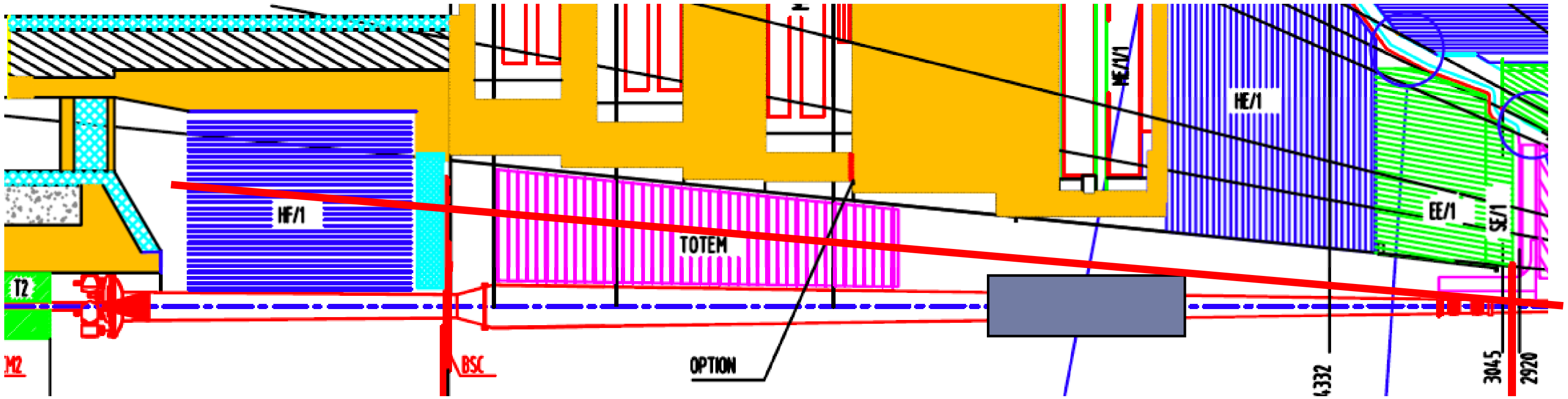
- Planning for Phase I upgrades
  - CSC production
  - RPC production
- Planning for installation
- Concepts for using the Muon system in a tracking trigger

Conclusions

- CMS upgrades making progress towards 2009 milestones
- This Meeting
  - follow progress,
  - establish the workplan for the coming 6 months
    - This is the key output for this workshop. We want to see a plan which helps us arrive at a planning for the Phase I upgrades.

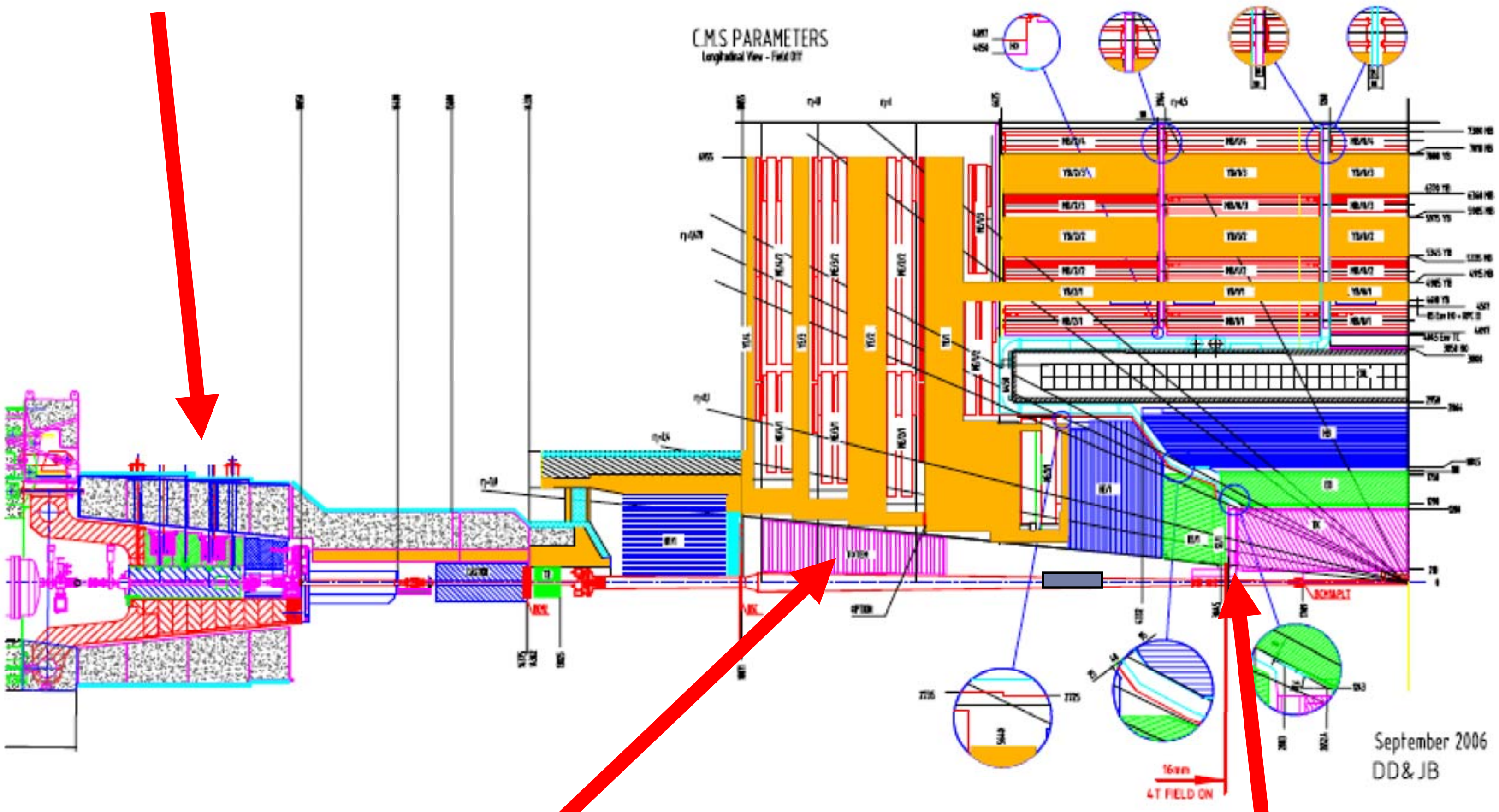
Implications of Early Separation

- Could we do this without replacing HF?
  - No way without obscuring part of the detector
  - But perhaps lower eta region still usable
- Will the HF still be useful at SLHC



What about maintenance?

Triplet moves closer to IP



These wheels move for maintenance

Either D0 has to clear the EE, or it has to move for maintenance

Current performance limitation

Incoherent space charge tune spreads ΔQ_{SC} at injection in the PSB (50 MeV) and PS (1.4 GeV) because of the required beam brightness N/ε^*.

$$\Delta Q_{SC} \propto \frac{N_b}{\varepsilon_{X,Y}} \cdot \frac{R}{\beta\gamma^2}$$

$\Rightarrow$ need to increase the injection energy in the synchrotrons

- Increase injection energy in the PSB from 50 to 160 MeV kinetic
- Increase injection energy in the SPS from 25 to 50 GeV kinetic
- Design the PS successor (PS2) with an acceptable space charge effect for the maximum beam envisaged for SLHC: => injection energy of 4 GeV

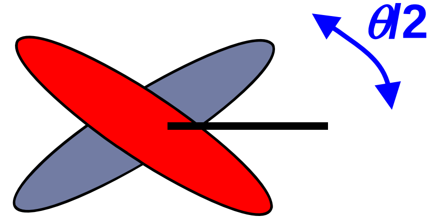
Longer Term: Instantaneous luminosity

For operation at the beam-beam limit with alternating planes of crossing <u>at two IPs:</u>

$$L = \frac{f_{rev}\gamma}{2r_p} n_b \frac{1}{\beta^*} N_b \Delta Q_{bb} F_{profile} F_{hg}$$

where (ΔQ_{bb}) = total beam-beam tune shift

$$\Delta Q_{bb} \cong -\frac{N_b}{\varepsilon_N} \frac{r_p}{2\pi\sqrt{1+\phi^2}}$$



effective beam emittance

with ϕ = Piwinski angle

$$\phi = \theta\sigma_Z /(2\sigma^*)$$

Luminosity lifetime

$$\tau = \frac{1}{2}\frac{N_b}{\dot{N}_b} = \frac{n_b N_b}{L\sigma}$$

Increased luminosity ⇒ reduced life time

- **Compensation measures ⇒ increased total intensity:**
  - **either more bunches (*n_b* ↑) : abandoned because of heat load to the beam screen and electron clouds effects**
  - **or higher intensity per bunch (*N_b* ↑): "soft" limit used in the LPA scheme**
- **Possible additional action: luminosity leveling**