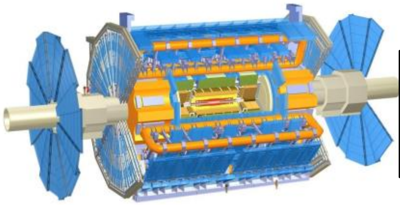
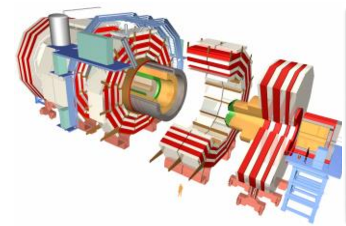
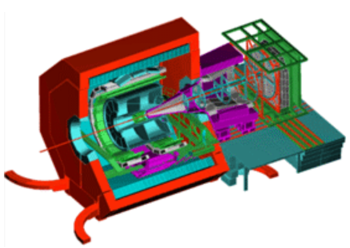




Detector Challenges for the LHC Upgrade Program

TIPP 2014

Werner Riegler, CERN



LHC Schedule

The long term schedule for the LHC was established during the fall of 2013, following two important workshops of the LHC experiments and LHC machine.

The ECFA High Luminosity LHC workshop in Aix-les-Bains at the beginning of October 2013 discussed the long term plans of the LHC experiments including many details on physics motivations, detector technologies and shutdown needs.

The RLIUP (Review of LHC Injector Upgrade Projects) workshop at the end of October discussed the strategy for the LHC machine that should lead to an integrated pp luminosity of $3000\,fb^{-1}$ and Heavy Ion luminosity of $10\,nb^{-1}$ by the end of the HL-LHC programme.

Based on this input, the long term LHC schedule was established in December of 2013.

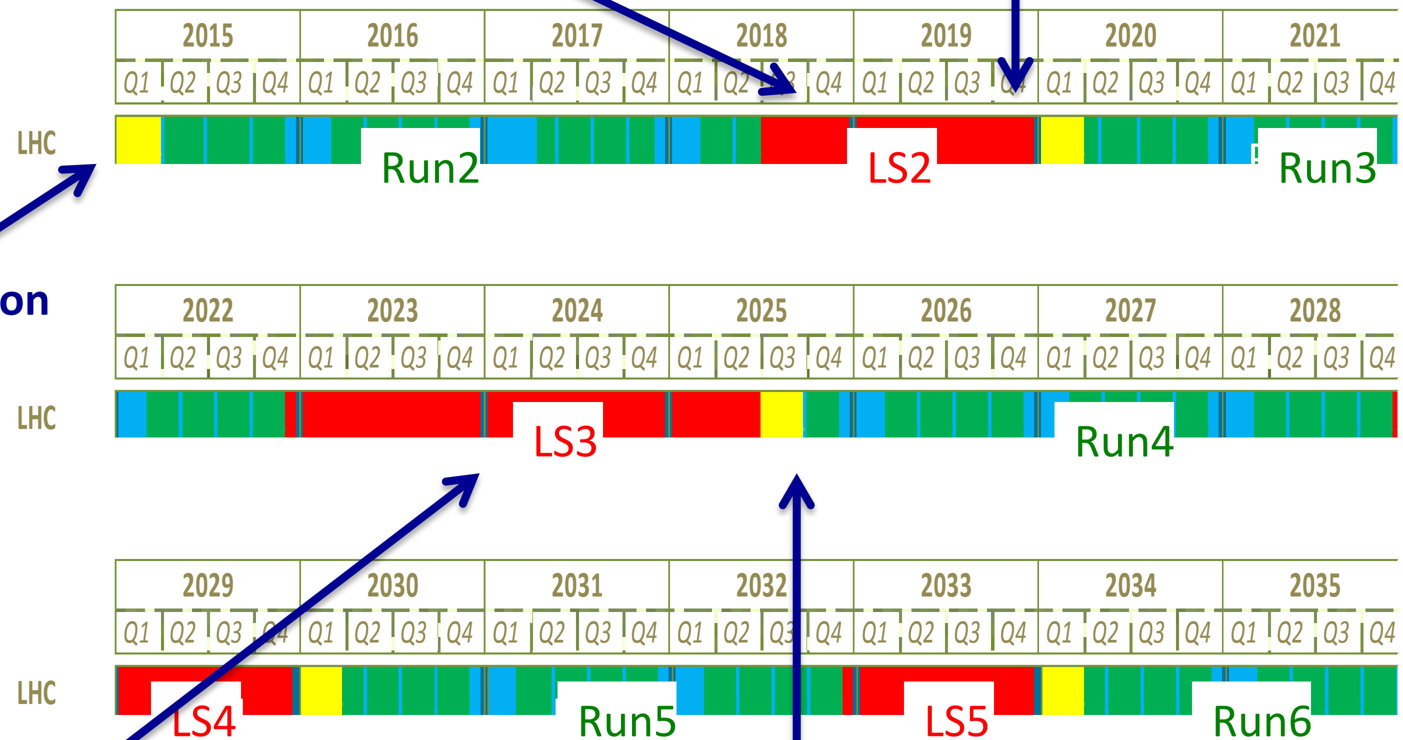
http://indico.cern.ch/event/252045/

Long Term Schedule

PHASE I Upgrade
ALICE, LHCb major upgrade
ATLAS, CMS ‚minor' upgrade
Linac4, LHC collimation upgrade etc.

Heavy Ion Luminosity from 10^{27} to 7×10^{27}

14TeV operation

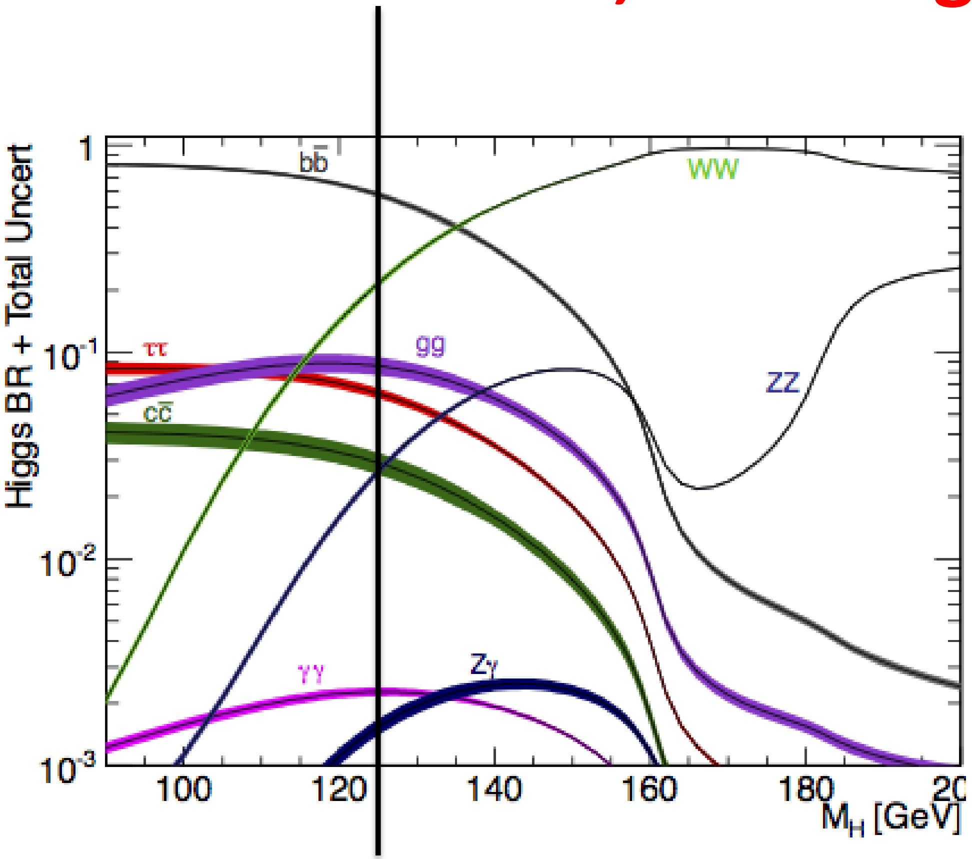


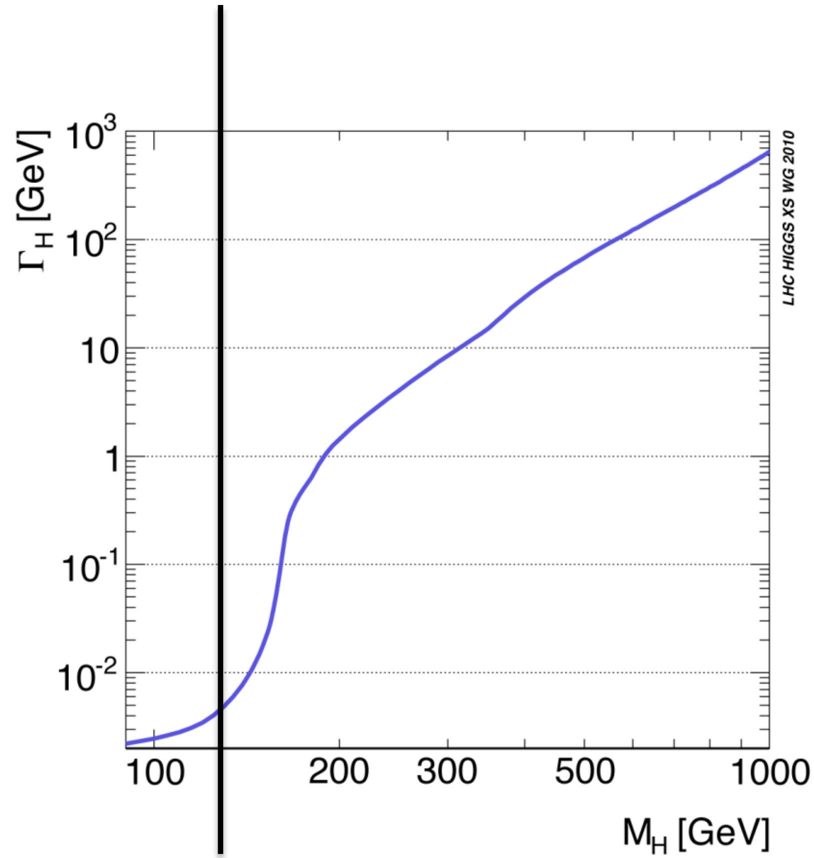
PHASE II Upgrade
ATLAS, CMS major upgrade

HL-LHC, pp luminosity from $(1\text{-}2)\times 10^{34}$ (peak) to 5×10^{34} (levelled)

A few physics highlights and HL-LHC motivations

ATLAS, CMS: Higgs at 125GeV





Wonderful mass !

- **Higgs decays into many channels that are accessible**

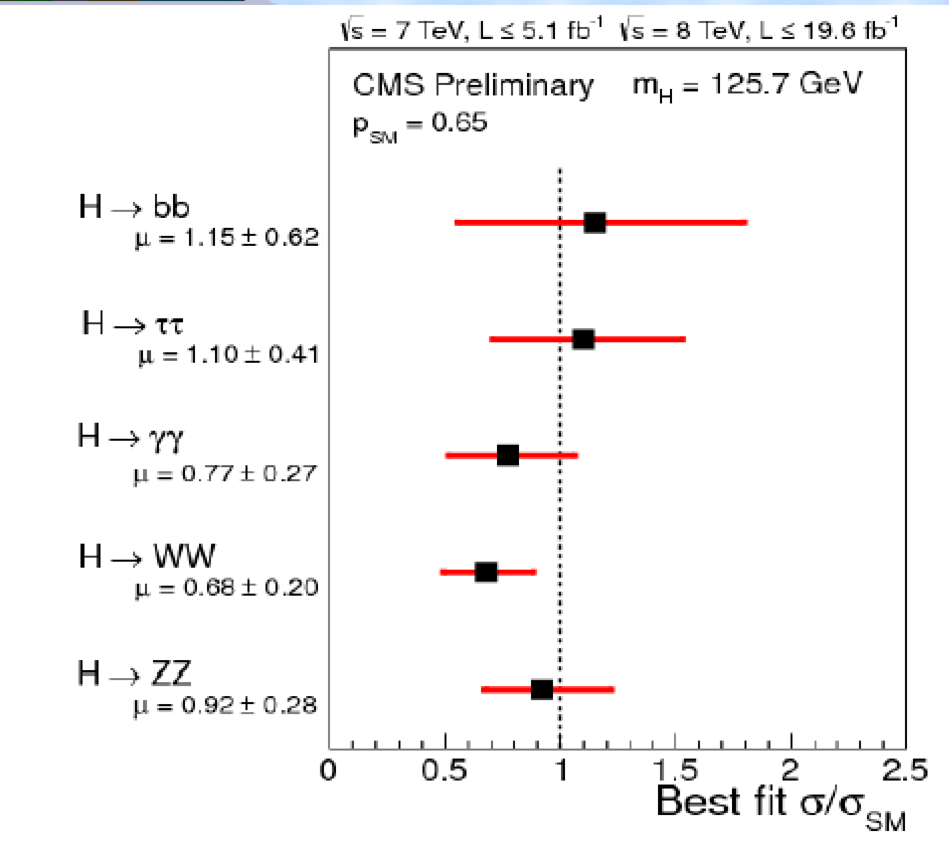
→ **Check predictions on couplings**

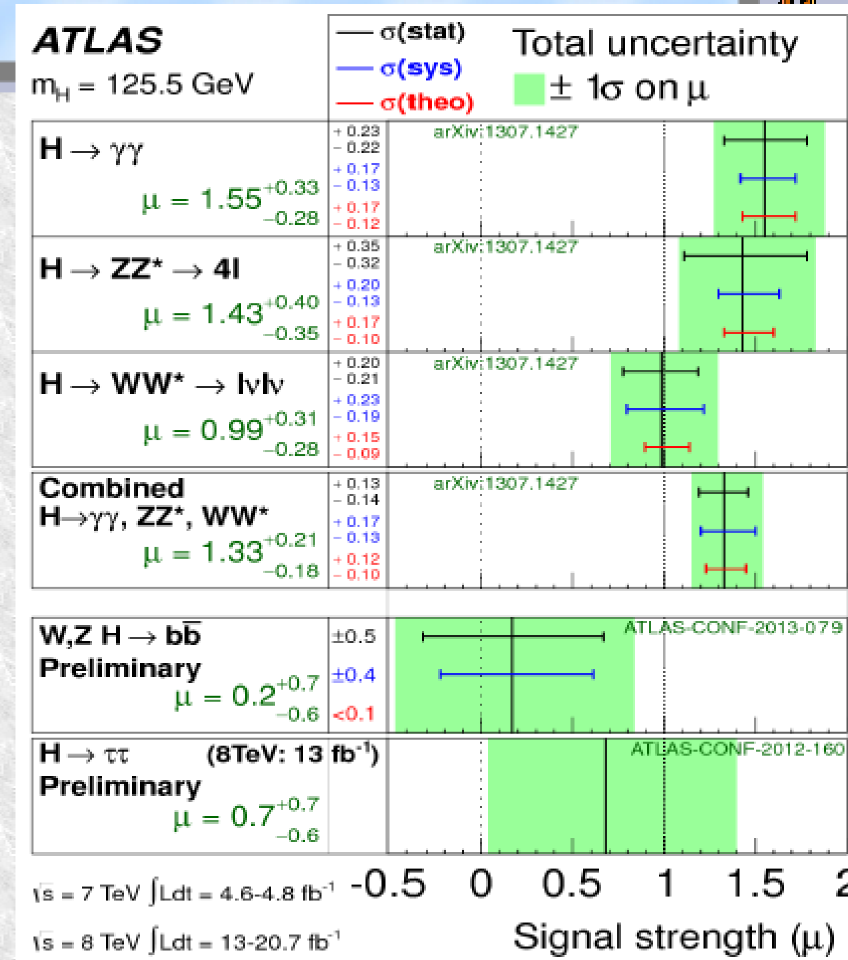
- **Width is only a few MeV**

→ **Width of peak determined by the detector performance**

The Big Five

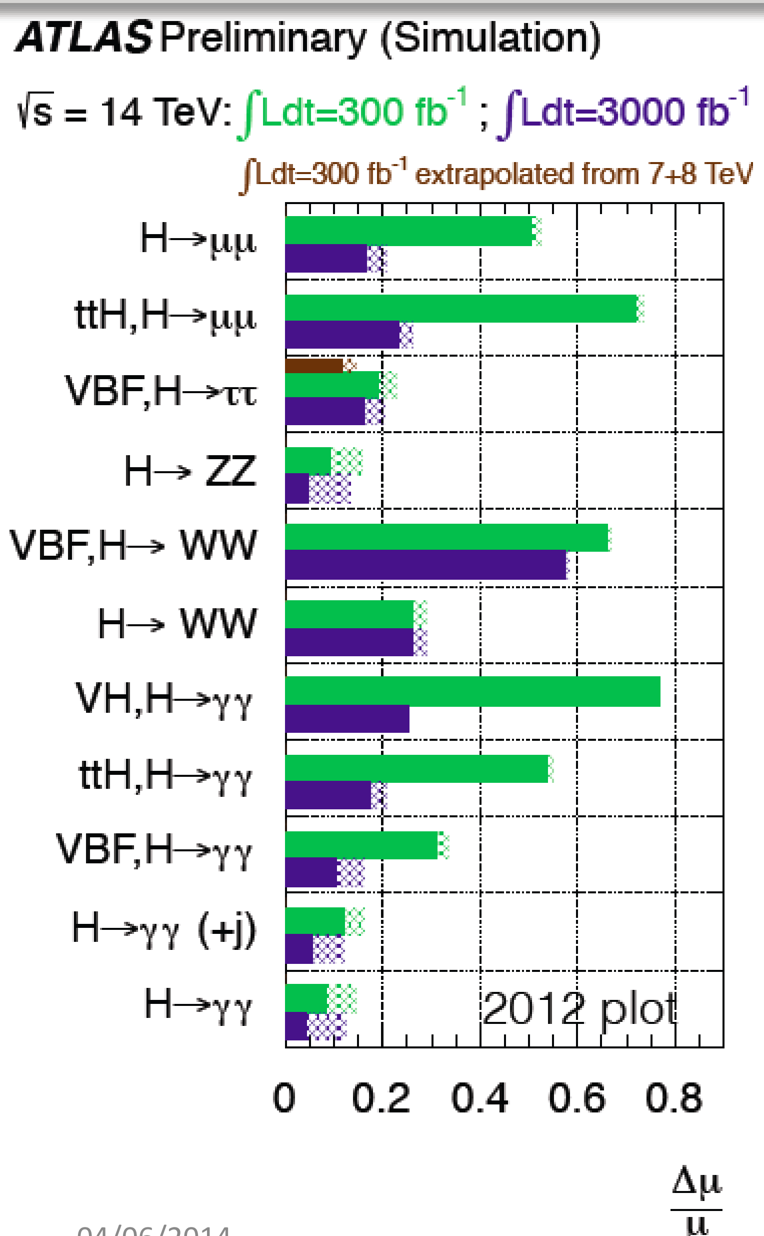
Higgs results so far





- Sensitivity of 'big 5' differs only by about a factor 3
- There is a rich programme

What does 14 TeV @3000fb^{-1} bring?

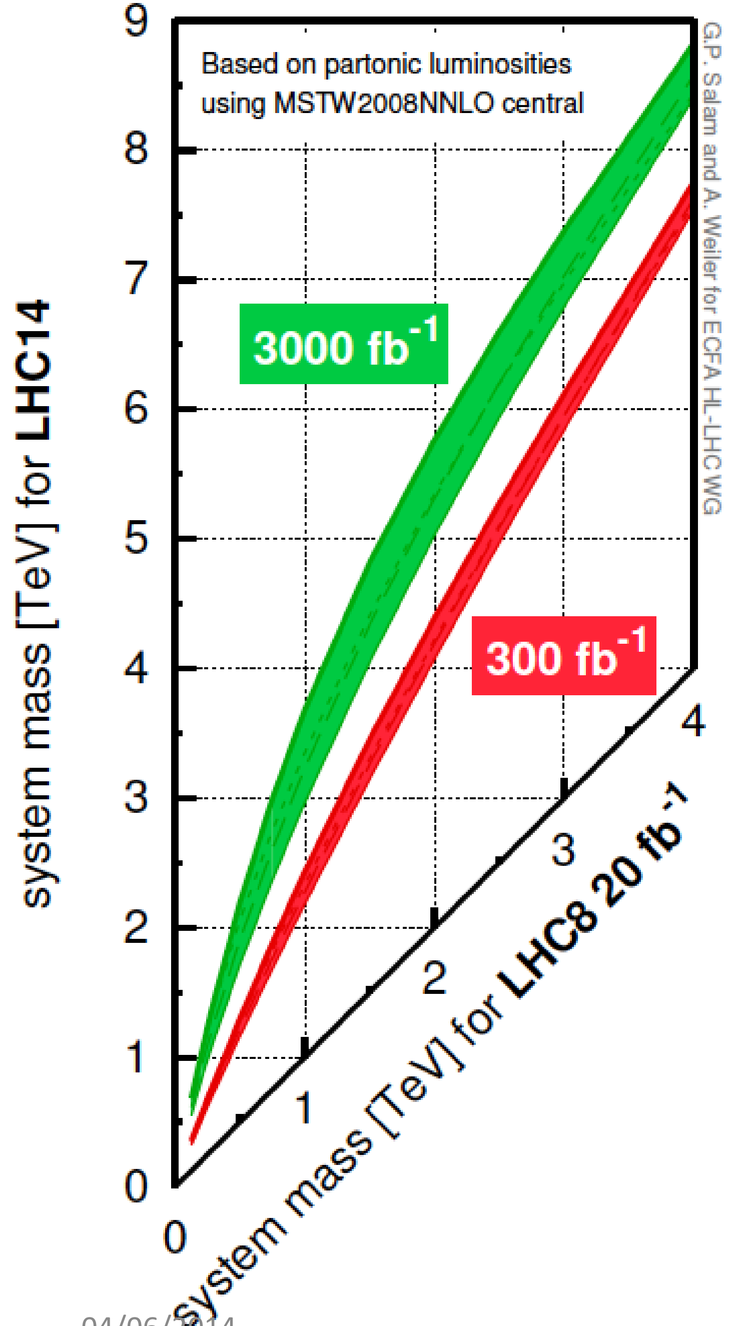


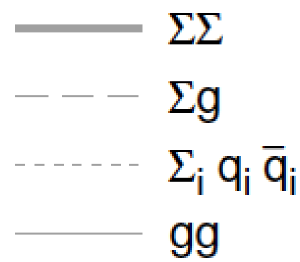
arXiv:1307.7135

Table 2: Precision on the measurements of the signal strength for a SM-like Higgs boson. These values are obtained at $\sqrt{s}$ = 14 TeV using an integrated dataset of 300 and 3000 fb^{-1}. Numbers in brackets are % uncertainties on the measurements estimated under [Scenario2, Scenario1], as described in the text. For the direct search for invisible Higgs decays the 95% CL on the branching fraction is given.

L (fb^{-1})	$H \to \gamma\gamma$	$H \to WW$	$H \to ZZ$	$H \to bb$
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]

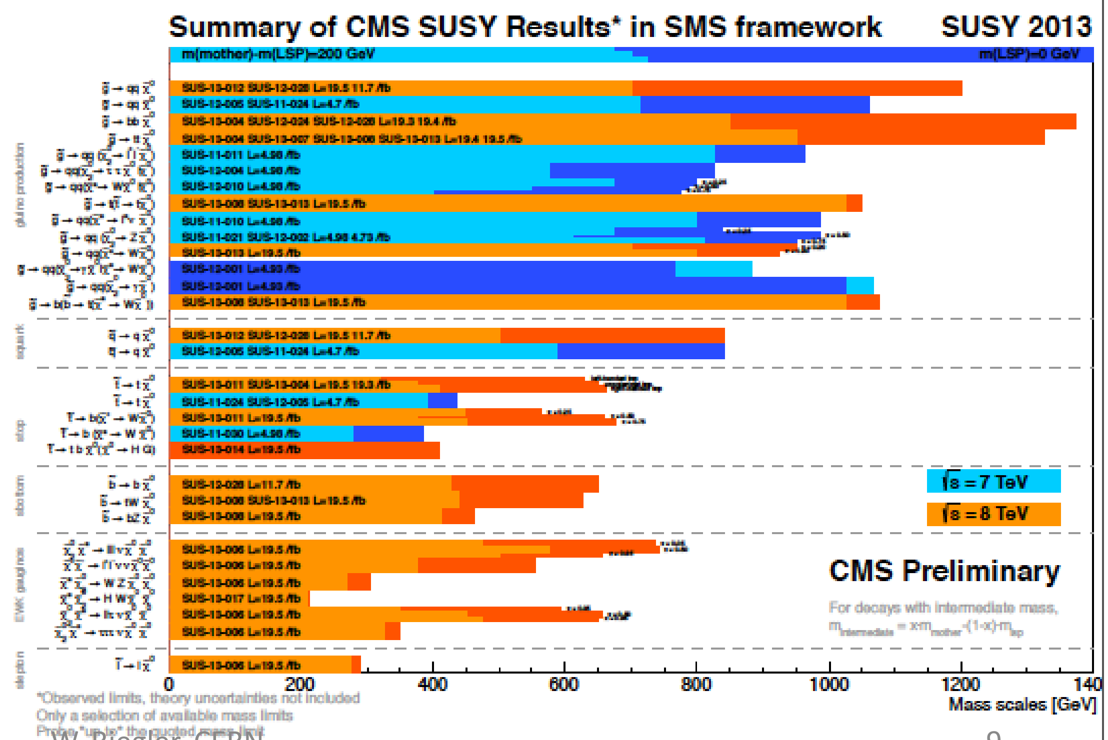
$H \to \tau\tau$	$H \to Z\gamma$	$H \to inv.$
[8, 14]	[62, 62]	[17, 28]
[5, 8]	[20, 24]	[6, 17]





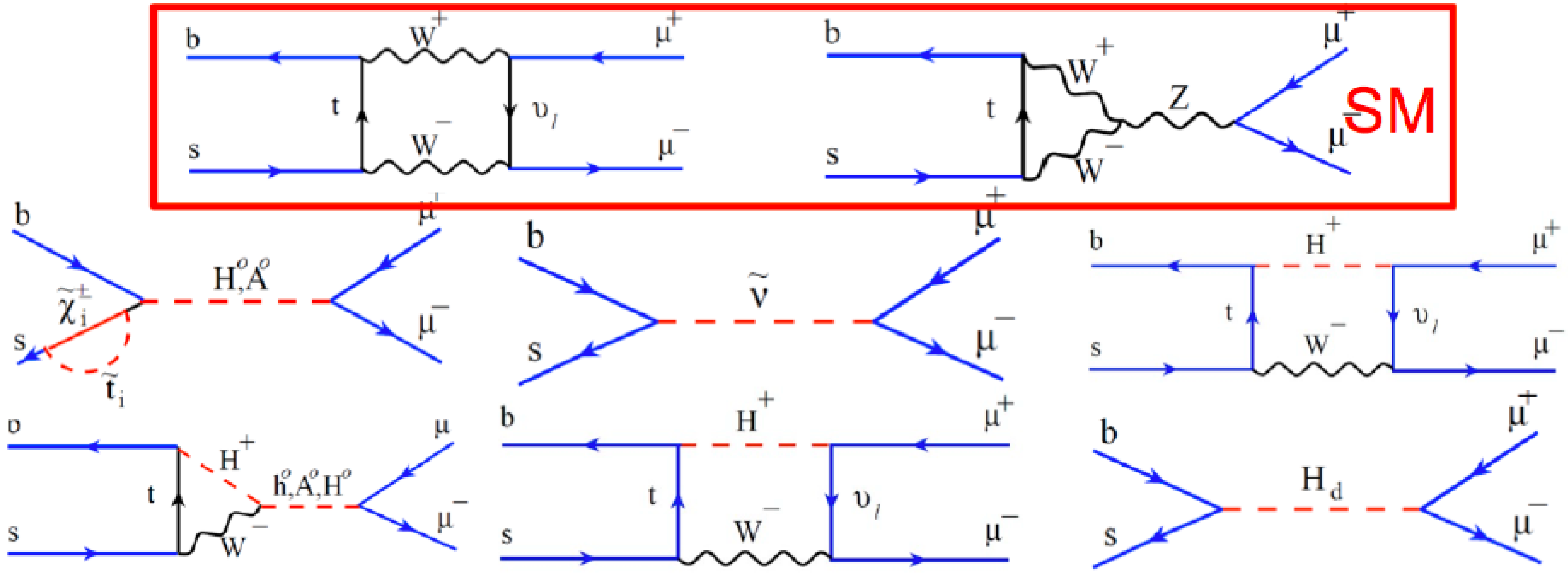
Take existing searches and figure out reach at 14 TeV, for different lumis

Doubling the reach from now to LS3.



B-physics, LHCb & others

$B_{d,s} \longrightarrow \mu^+\mu^-$



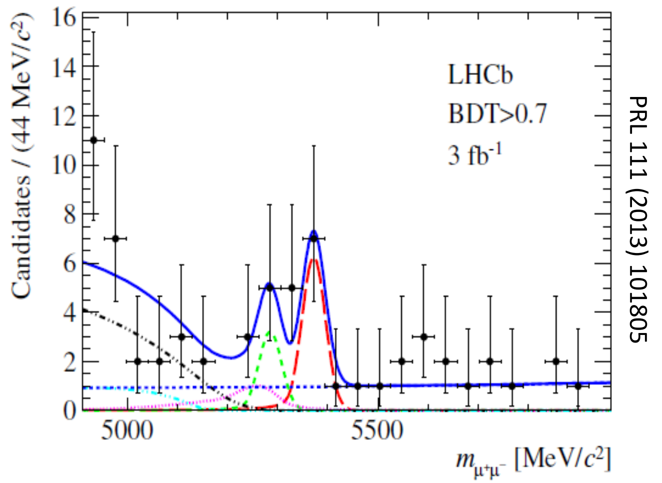
SM : very rare (V_{tq}, helicity suppression)

Large sensitivity to NP, eg : $\mathrm{Br}_{\mathrm{MSSM}}(B_q \to \ell^+\ell^-) \propto \frac{M_b^2 M_\ell^2 \tan^6\beta}{M_A^4}$

NP: New Physics

B-physics, LHCb & others

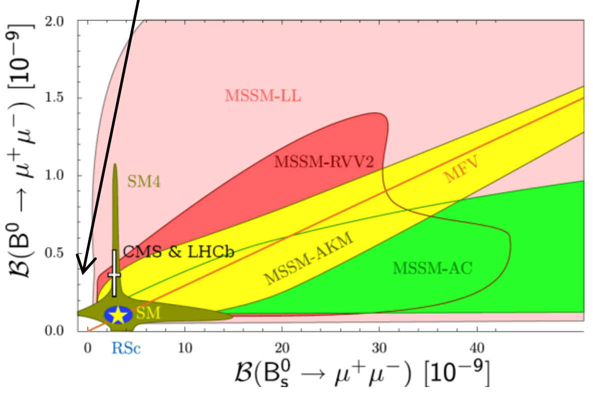
Very strong constraints on supersymmetry and other ‚beyond the standard model' physics.



$$BR(B_S^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)) \times 10^{-9}$$

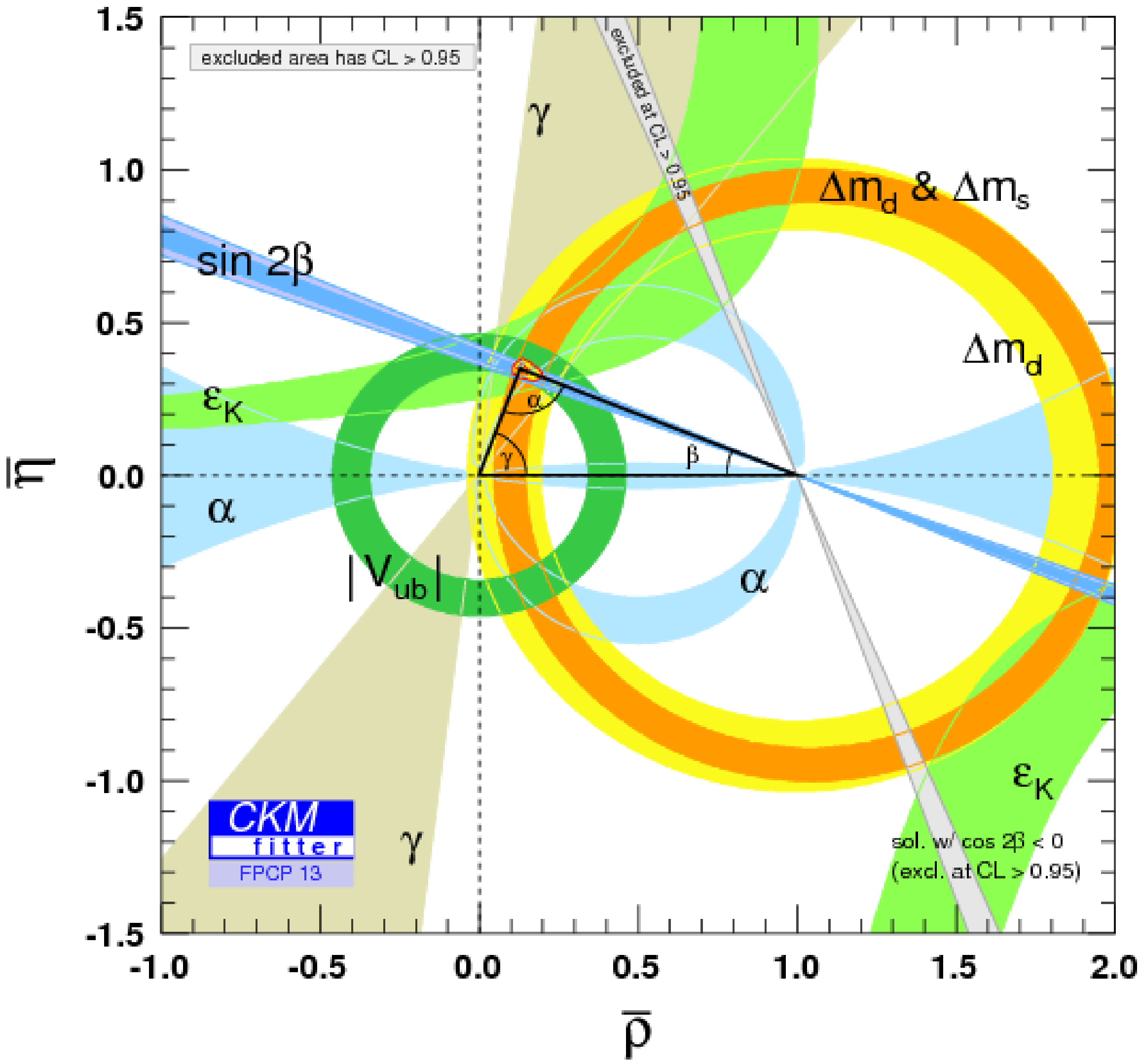
combining CMS & LHCb →

$$BR(B^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$
$$BR(B_S^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$



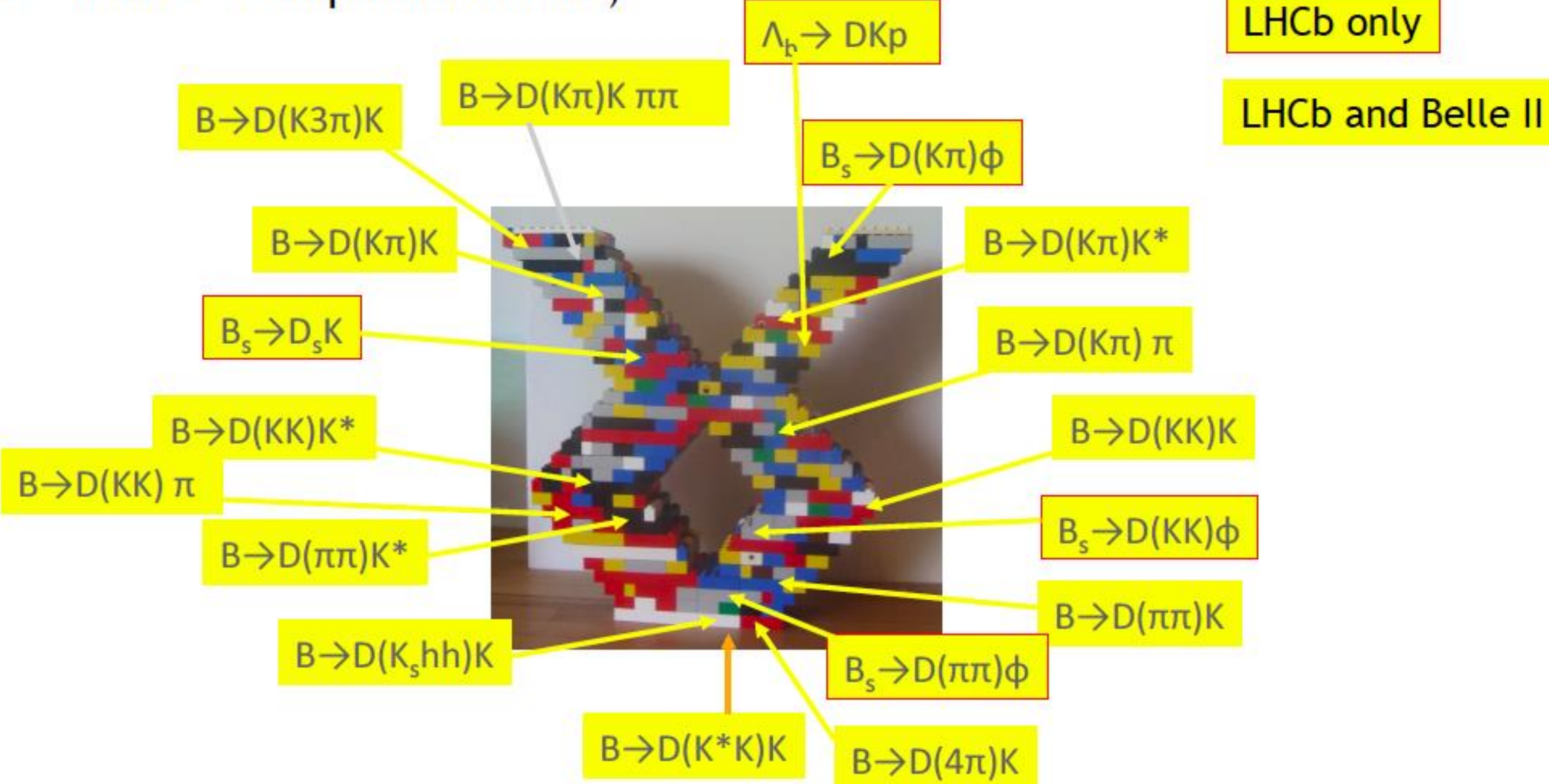
Similar sensitivities to direct searches.

B-physics, CKM



B-physics, CKM

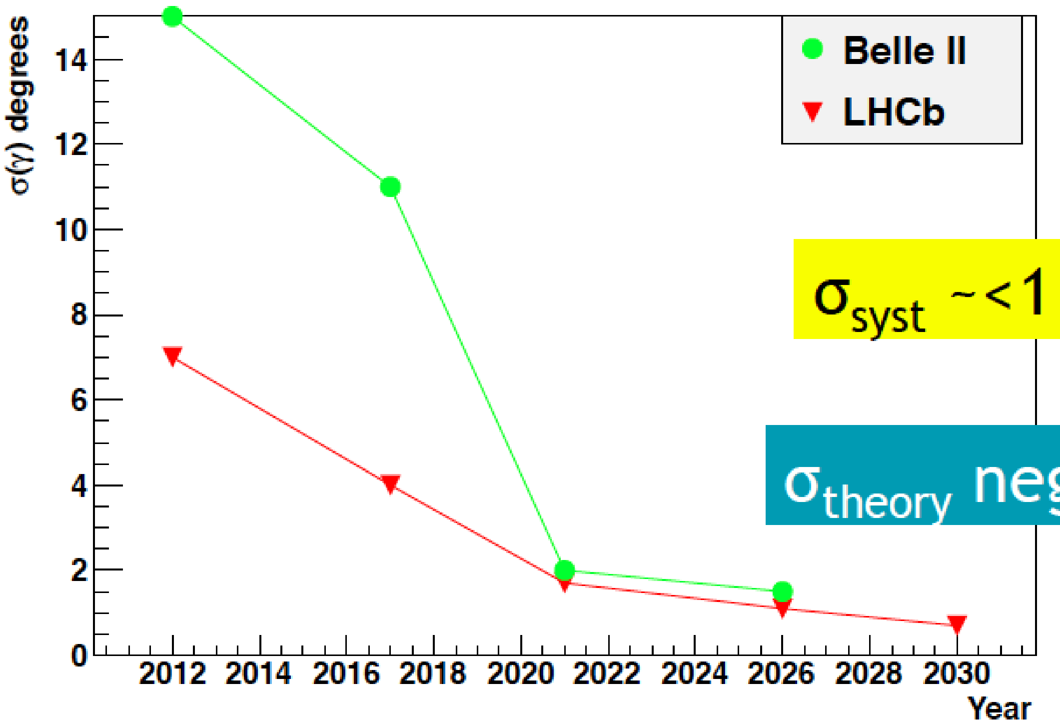
The “ultimate” γ-from tree-decays precision will be reached through many individual measurements, with very different sensitivities (due to different *b→u to b→c* amplitudes ratio)



Some of them are challenging at the LHC (many tracks, low p_T, hadronic trigger)

B-physics, LHCb

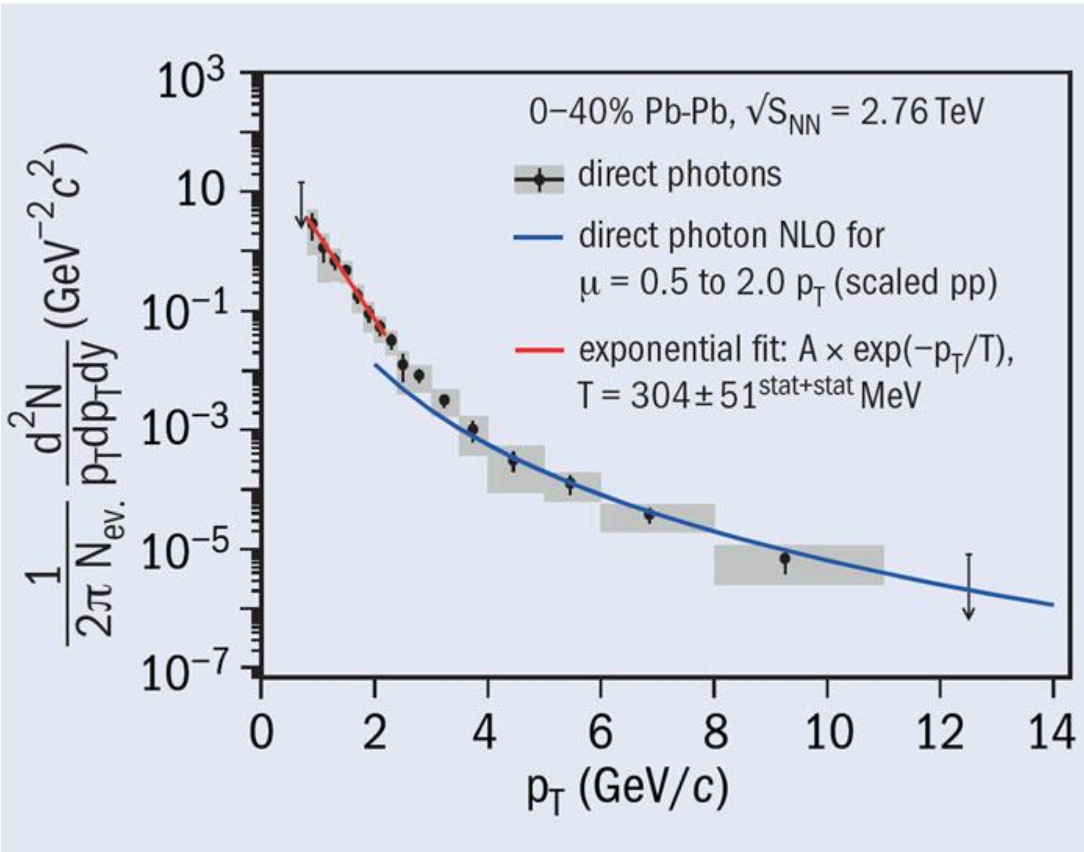
Expected precision on γ from tree decays



σ_{syst} ~<1 °

σ_{theory} negligible

Heavy Ion Physivs, ALICE & others



Direct photons from PbPb collisions.

Thermal radiation from the Quark Gluon Plasma !

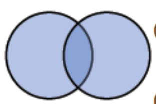
Many sophisticated ways to study this QGP phase of matter by comparing PbPb collisions to pp and pPb collisions.

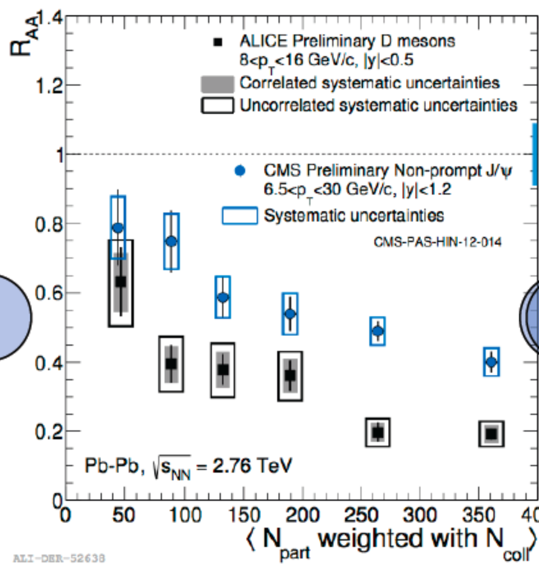
Heavy Ion Physivs, ALICE & others

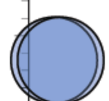
Heavy quark probes of the medium

- Energy loss expected to depend on parton mass
- First indication at LHC:

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

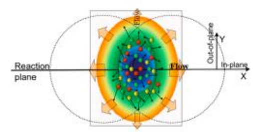


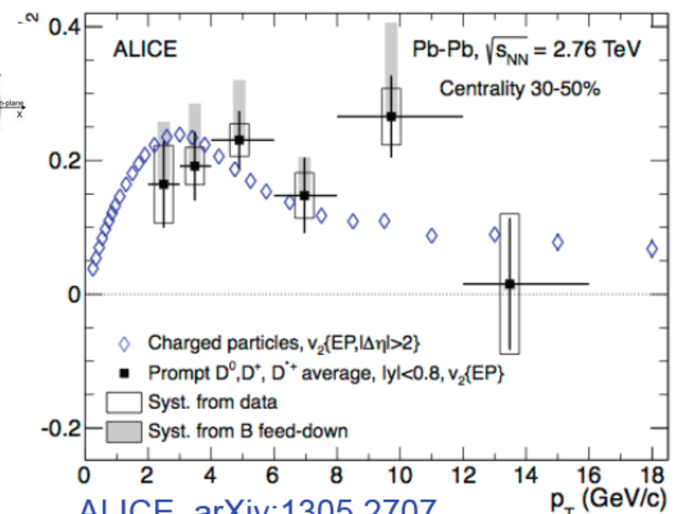




R_{AA}^{B} (CMS) > R_{AA}^{D} (ALICE)

- Azimuthal anisotropy v_2
  - strength of collectivity
  - mean free path of partons
- Charm hadrons have $v_2>0$, comparable to light hadrons





ALICE, arXiv:1305.2707

- Heavy quark collective flow?

How will LHC manage to deliver 3000fb^{-1} of pp and 10nb^{-1} of PbPb collisions

https://espace.cern.ch/HiLumi/PLC/default.aspx

$$L = \gamma \frac{f_{rev}\, n_b\, N_b^{\;2}}{4\pi \varepsilon_n \beta^*} R$$

Factor = 1.9^2 x 3.7 x 1.5 = 20

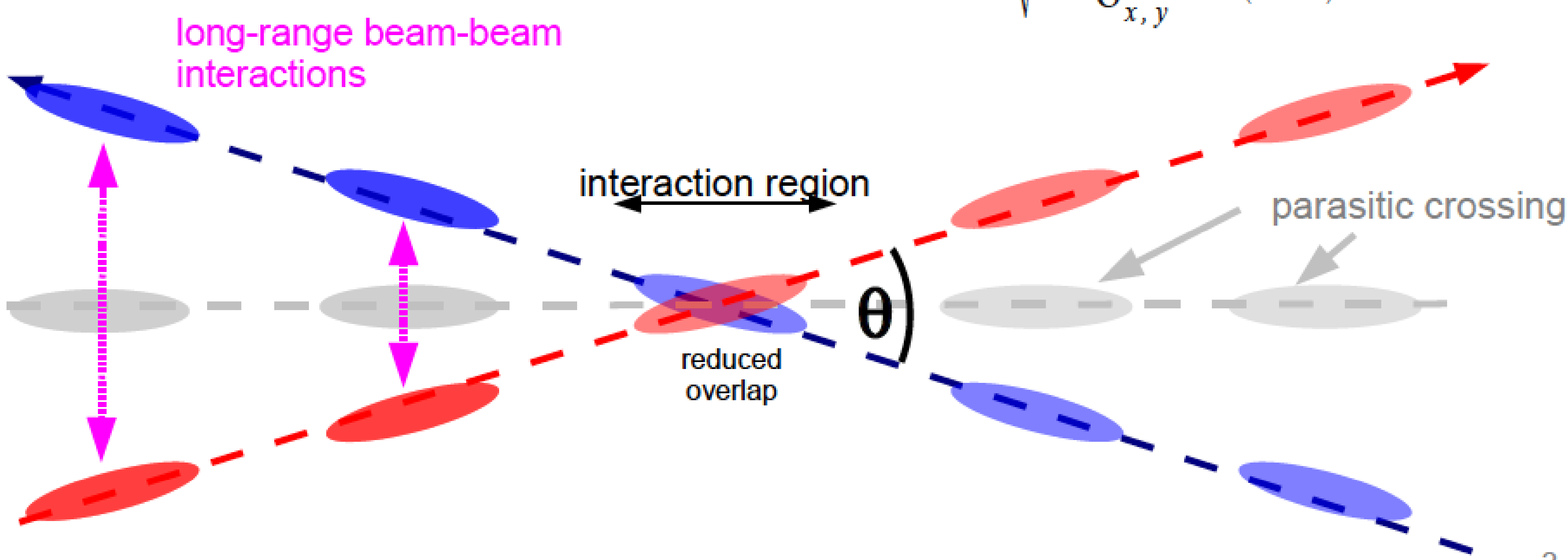
Parameter	LHC nominal	HL-LHC 25ns	factor
N_b	1.15E+11	2.2E+11	1.9
n_b	2808	**2808**	
N_{tot}	3.2E+14	6.2E+14	
beam current [A]	0.58	**1.11**	
x-ing angle [μrad]	300	↔ 590	
beam separation [σ]	9.9	12.5	
β^* [m]	0.55	**0.15**	3.7 new quads
ε_n [μm]	3.75	2.50	1.5
ε_L [eVs]	2.51	2.51	
energy spread	1.20E-04	1.20E-04	
bunch length [m]	7.50E-02	7.50E-02	
IBS horizontal [h]	80 -> 106	18.5	
IBS longitudinal [h]	61 -> 60	20.4	
Piwinski parameter	0.68	3.12	
Reduction factor 'R1*H1' at full crossing angle (no crabbing)	0.828	↔ 0.306	
Reduction factor 'H0' at zero crossing angle (full crabbing)	0.991	↔ **0.905**	crab cavities
beam-beam / IP without Crab Cavity	3.1E-03	3.3E-03	
beam-beam / IP with Crab cavity	3.8E-03	1.1E-02	
Peak Luminosity without levelling [$cm^{-2}\ s^{-1}$]	1.0E+34	7.4E+34	
Virtual Luminosity: Lpeak*H0/R1/H1 [$cm^{-2}\ s^{-1}$]	1.2E+34	**21.9E+34**	
Events / crossing without levelling	19 -> 28	210	
Levelled Luminosity [$cm^{-2}\ s^{-1}$]	-	5E+34	
Events / crossing (with leveling for HL-LHC)	*19 -> 28	140	
Leveling time [h] (assuming no emittance growth)	-	9.0	

High Luminosity LHC

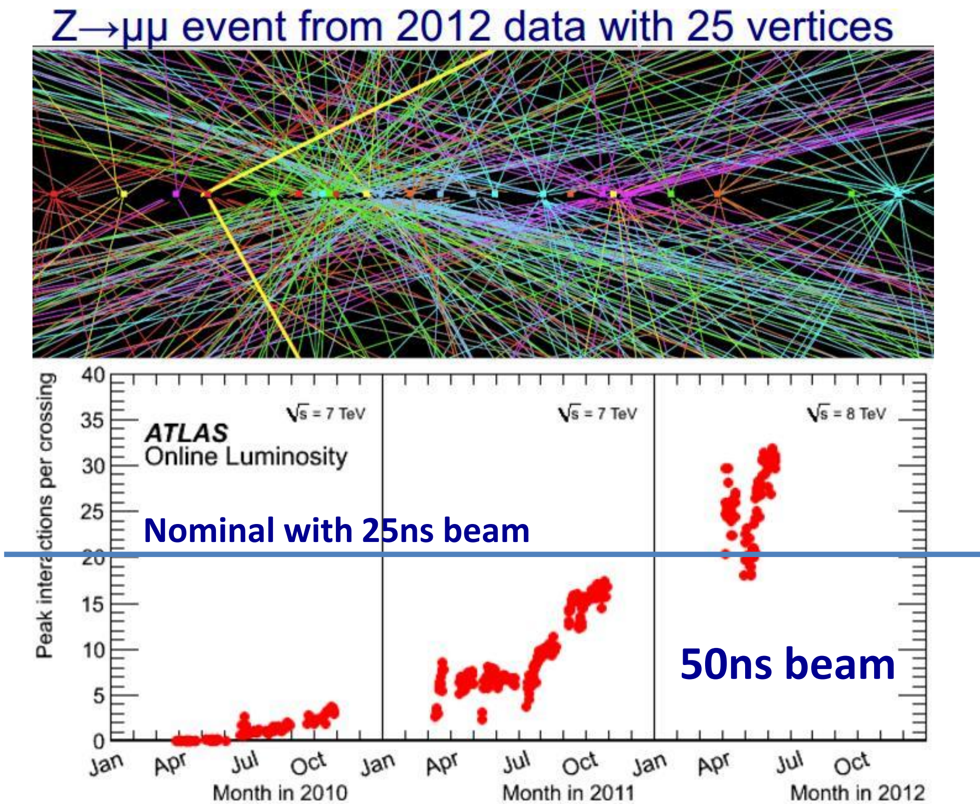
Beam-Beam Interactions in a Nutshell

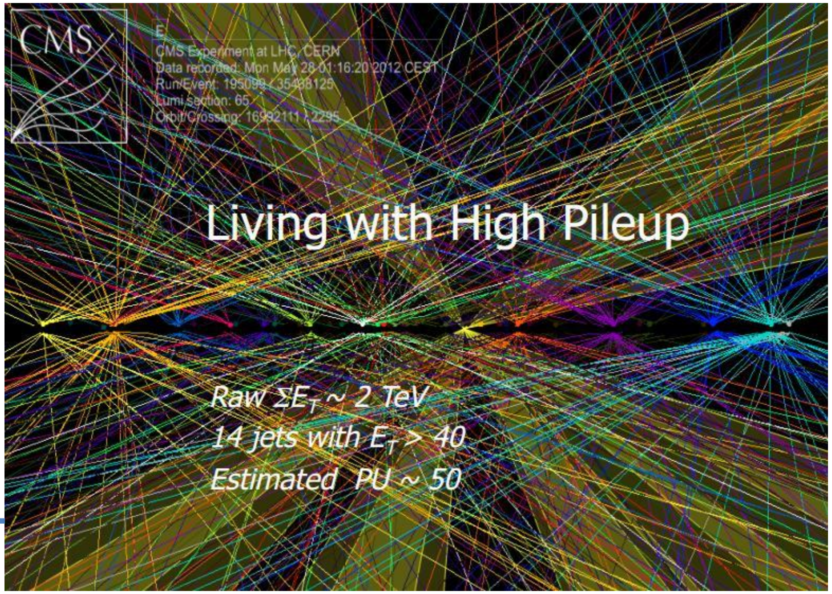
- Need crossing angle θ to avoid parasitic crossings
  → reduces bunch overlap & luminosity
- Two mitigations:
  - “crab cavities” rotating the bunches before and after the IR
  - beam-beam compensator (BBC) mitigating effect of long-range interactions
  - present LHC: $F_{crossing} \approx 0.7 \rightarrow$ HL-LHC ~ 0.2

$$L = L_0 \cdot F_{crossing} \cdot \ldots \qquad F_{crossing} = \frac{1}{\sqrt{1 + \frac{\sigma_s}{\sigma_{x,y}} \tan(\theta/2)}}$$



Pileup = Numer of pp interactions per bunchcrossing





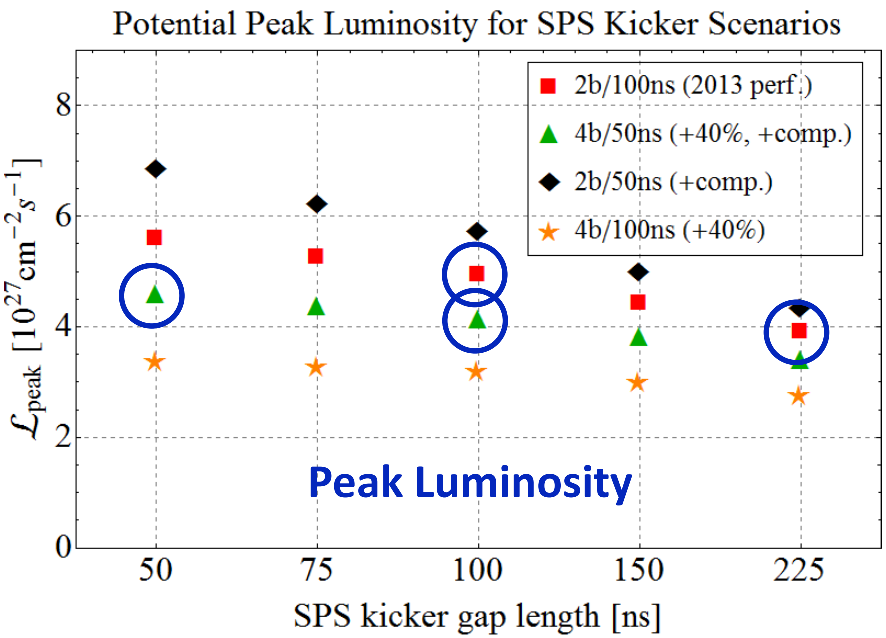
From nominal LHC (25ns) to HL-LHC: Number of bunches stays the same i.e. increase in Luminosity from 10^{34} to 5×10^{34} will increase the pilup by a factor of 5 → change from 20 to 100 pp collisions/crossing on average globally.

Bunch charge varies from bunch to bunch i.e. one assumes a maximum average pileup per bunch crossing of 140 for HL-LHC.

Different schemes so lower the pileup density (number of vertices per mm) are investigated.

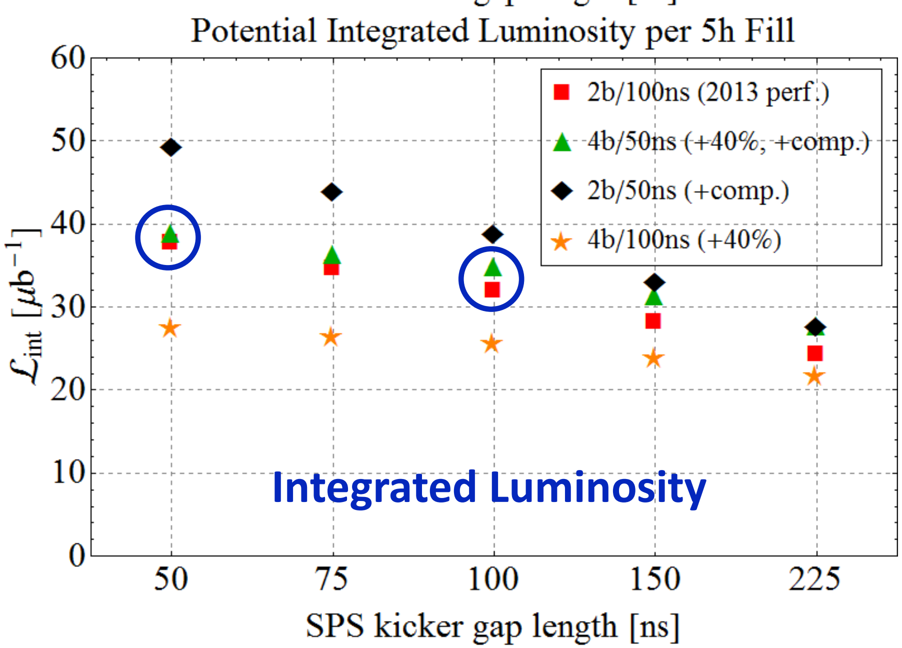
Change shape of the beam from gaussian to square (800MHz cavities), collide at an angle (Crab Kissing)

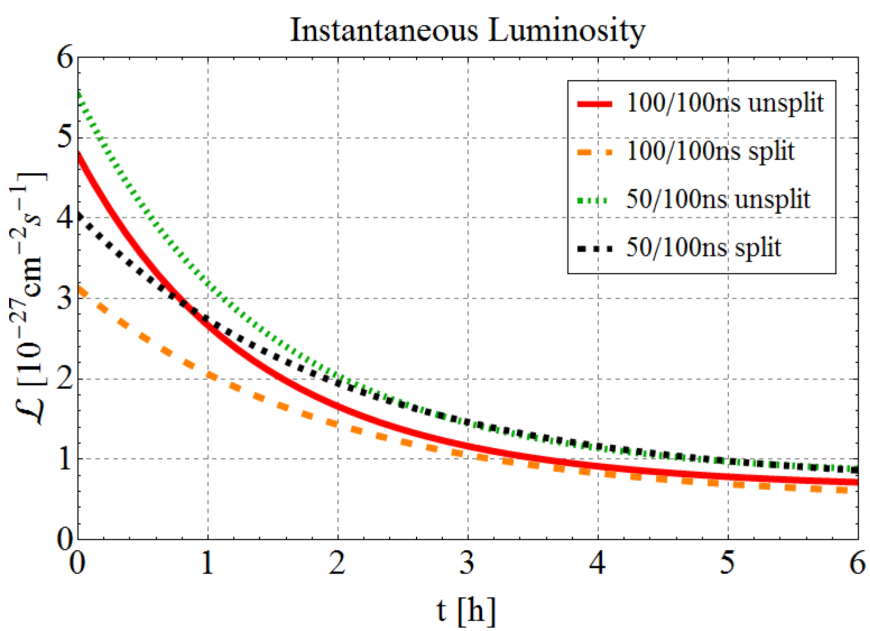
PbPb Estimates for after LS2



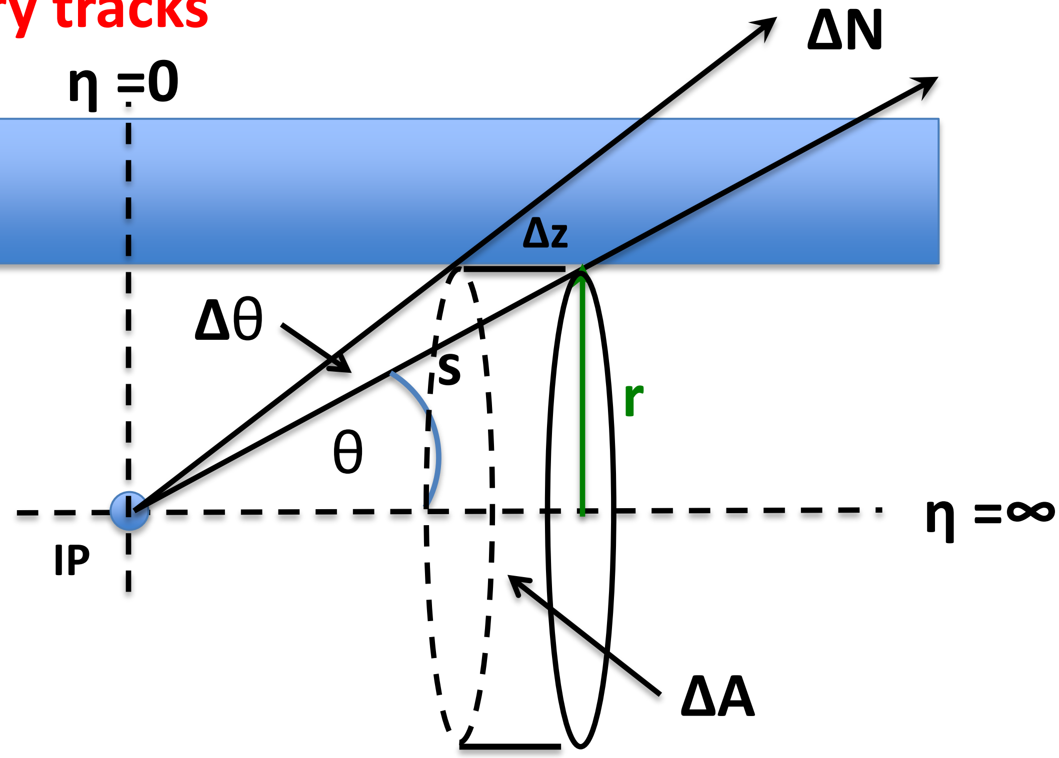
Peak luminosity higher for 100ns PS spacing with unsplit bunches.
→ Higher brightness bunches decay faster.
→ Higher integrated luminosity for 50ns PS spacing with split bunches.

50/100ns split → ~1000 bunches/beam
100/100ns unsplit → ~600 bunches/beam





Fluence and Dose from primary tracks



$$\eta = -\ln\tan\frac{\theta}{2}$$

$$\frac{dN}{d\eta} \approx const. = N_0$$

$$\frac{dN}{d\theta} = \frac{dN}{d\eta}\frac{d\eta}{d\theta} = \frac{dN}{d\eta}\frac{1}{\sin\theta} \approx \frac{N_0}{\sin\theta}$$

$$\Delta N = \frac{dN}{d\theta}\Delta\theta$$

$$\Delta A = 2r\pi\Delta z = 2r\pi\frac{s\Delta\theta}{\sin\theta} = \frac{2r^2\pi}{\sin^2\theta}\Delta\theta$$

$$\frac{\Delta N}{\Delta A} = \frac{dN}{d\theta}\frac{\sin^2\theta}{2r^2\pi}$$

$$\text{Fluence} = \frac{\Delta N}{\Delta A}\frac{w}{w\sin\theta} = \frac{dN}{d\theta}\frac{\sin\theta}{2r^2\pi} \approx \frac{N_0}{2r^2\pi}$$

Fluence = number of particles traversing a detector elements weighted by the track length in the material.

→ **The hadron fluence due to primary particles is just a function of the distance from the beamline !**

→ **Eqi-fluence and equi-dose lines are parallels to the beamline !**

Crosscheck with ATLAS Phase II LOI

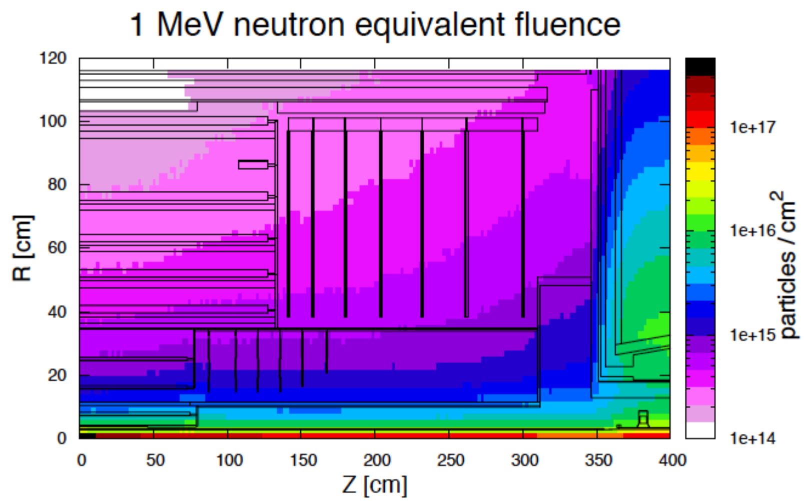


Figure 6.2: *RZ*-map of the 1 MeV neutron equivalent fluence in the Inner Tracker region, normalised to 3000 fb^{-1} of 14 TeV minimum bias events generated using PYTHIA8.

Layer	Occupancy with 200 pile-up events (%)				
	Radius mm	Barrel (z = 0 mm)		Z mm	Endcap
Pixel: layer 0	37	0.57	Disk 0	710	0.022– 0.076

3000 fb^{-1}
80mb inelastic pp crossection
$2.4 * 10^{17}$ events
dN/dη = N0=5.4 at 14 TeV
Pixel layer1 at r=3.7cm

1MeVneq Fluence =
$2.4*10^{17}*5.4/(2*\pi*3.7^2)$ =
$1.5*10^{16}$ cm^{-2}

Dose = $3.2x10^{-8}*1.5*1016$ =
4.8MGy

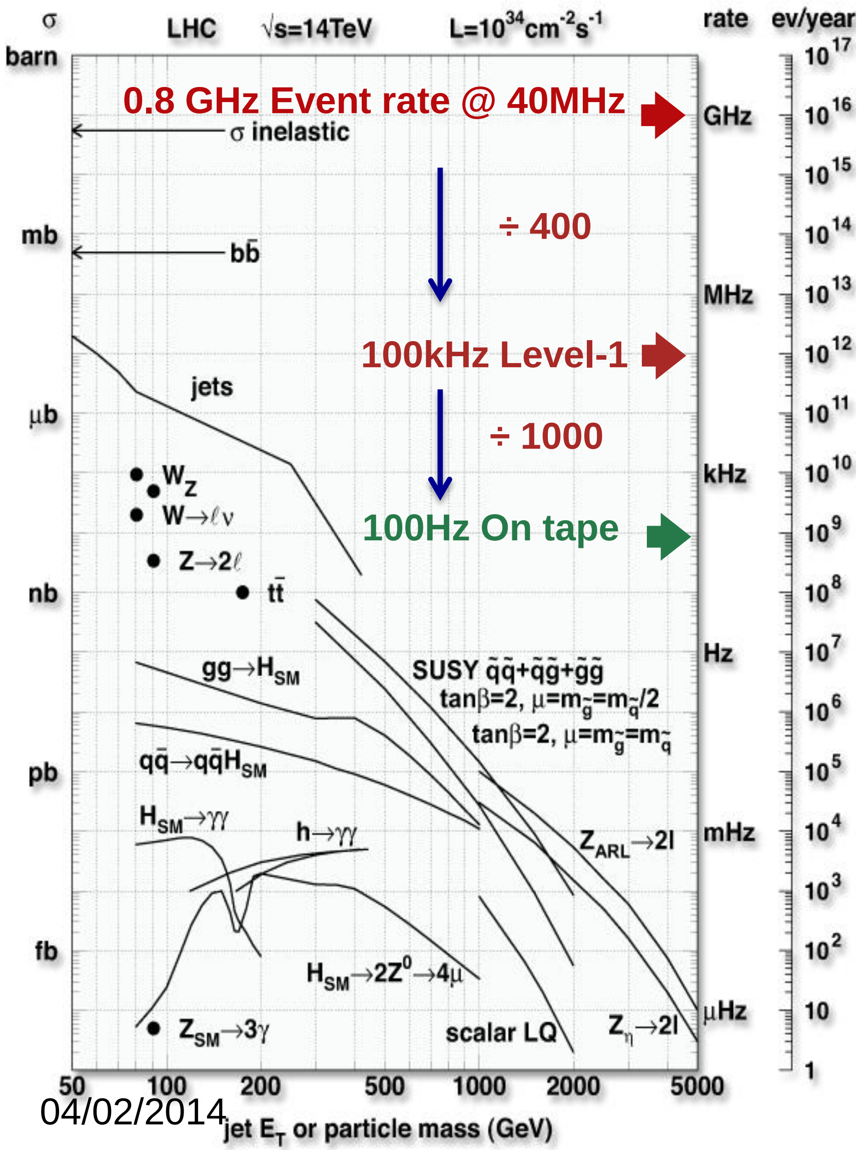
The predictions for the maximum 1MeV-neq fluence and ionising dose for 3000fb^{-1} in the pixel system is $1.4 \times 10^{16}$$cm^{-2}$ and 7.7 MGy at the centre of the innermost barrel layer. For the

Key Sensor Issues for the Upgrades

- **Radiation damage** will increase to several 10^{16} n_{eq} cm^{-2} for the inner regions in ATLAS and CMS
  - Example of common activities to develop radiation harder sensors within the RD50 collaboration
  - Operational requirements more demanding (low temperature and all related system aspects)
- **Increased performance:**
  - Higher granularity
  - Lower material budget
- **Control and minimize cost**
  - Large areas
  - Stable and timely production

Upgrades	Area	Baseline sensor type
ALICE ITS	10.3 m^2	CMOS
ATLAS Pixel	8.2 m^2	*tbd*
ATLAS Strips	193 m^2	n-in-p
CMS Pixel	4.6 m^2	*tbd*
CMS Strips	218 m^2	n-in-p
LHCb VELO	0.15 m^2	*tbd*
LHCb UT	5 m^2	n-in-p

LHC to HL-HLC



ATLAS/CMS plans for $L=5\times10^{34}$

4 GHz Event Rate @ 40MHz

÷ 40

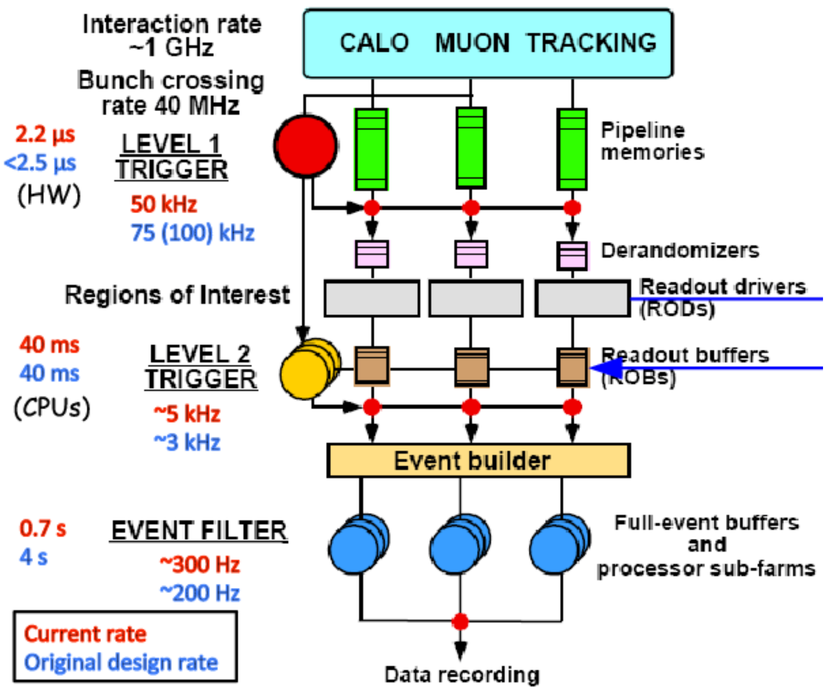
0.5-1 MHz Level-1 Rate

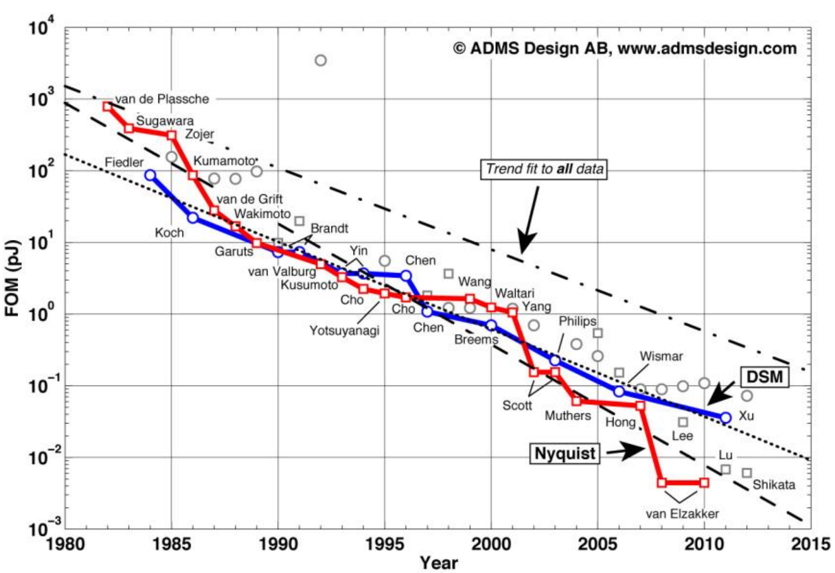
÷ 100

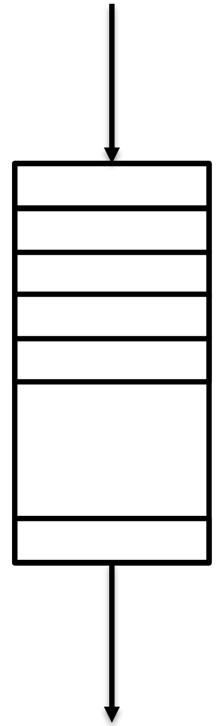
5-10kHz Rate to Tape

Increase in computing power, according to Moores Law doubling every 2 years, and related increase in storage capacity, makes it possible !

Pipelines &Triggering







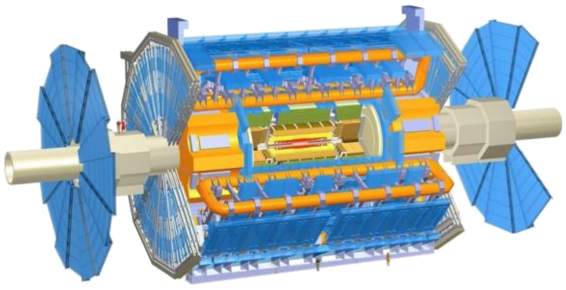
Pipeline Memories, e.g. ATLAS Liquid Argon Calorimeter:

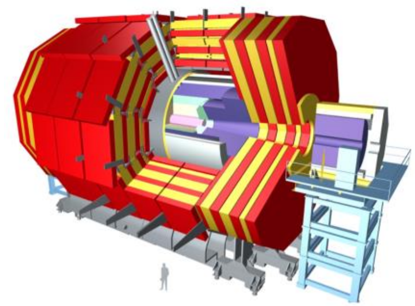
Analog pipeline i.e. Switch Capacitor Array (SCA)

Up to now, full Digitization was not possible at 40MHz 10bit in 2005 due to excessive power consumption.

The power consumption of ADCs has however desreased dramatically over the last years i.e. for the LHC experiment upgrades, 40MHz digitization will be possible !

ATLAS & CMS @ Run 4





40 MHz

Level 1 | Level 1

0.5-1 MHz

HLT | HLT

5-10 kHz (2MB/event) | 10 kHz (4MB/event)

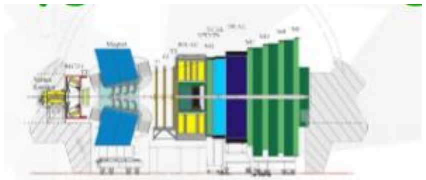
Storage | Storage

10-20 GB/s ← PEAK OUTPUT → 40 GB/s

LHCb & ALICE @ Run 3

4 TByte/s

All events into HLT



40 MHz

DAQ

40 MHz

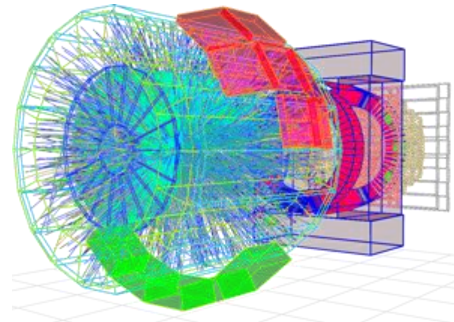
LLT: μ,e/γ, hadrons

5-40 MHz

HLT: event recon.

20 kHz (0.1 MB/event)

Storage



50 kHz

1 TByte/s

Reconstruction + Compression

After compression, all events to disk

50 kHz (1.5 MB/event)

Storage

2 GB/s ← PEAK OUTPUT → 75 GB/s

Moore‘s Law

http://www.livescience.com/23074-future-computers.html

If the doubling of computing power every two years continues to hold, "then by 2030 whatever technology we're using will be sufficiently small that we can fit all the computing power that's in a human brain into a physical volume the size of a brain,"

explained Peter Denning, distinguished professor of computer science at the Naval Postgraduate School and an expert on innovation in computing.

"Futurists believe that's what you need for artificial intelligence. At that point, the computer starts thinking for itself.“

→ Computers will anyway by themselves figure out what to do with the data very soon.

How to improve the performance?

- **Clock frequency**
- **Vectors**
- **Instruction Pipelining**
- **Instruction Level Parallelism (ILP)**
- **Hardware threading**
- **Multi-core**
- **Multi-socket**
- **Multi-node**

Very little gain to be expected and no action to be taken

Potential gain in throughput and in time-to-finish

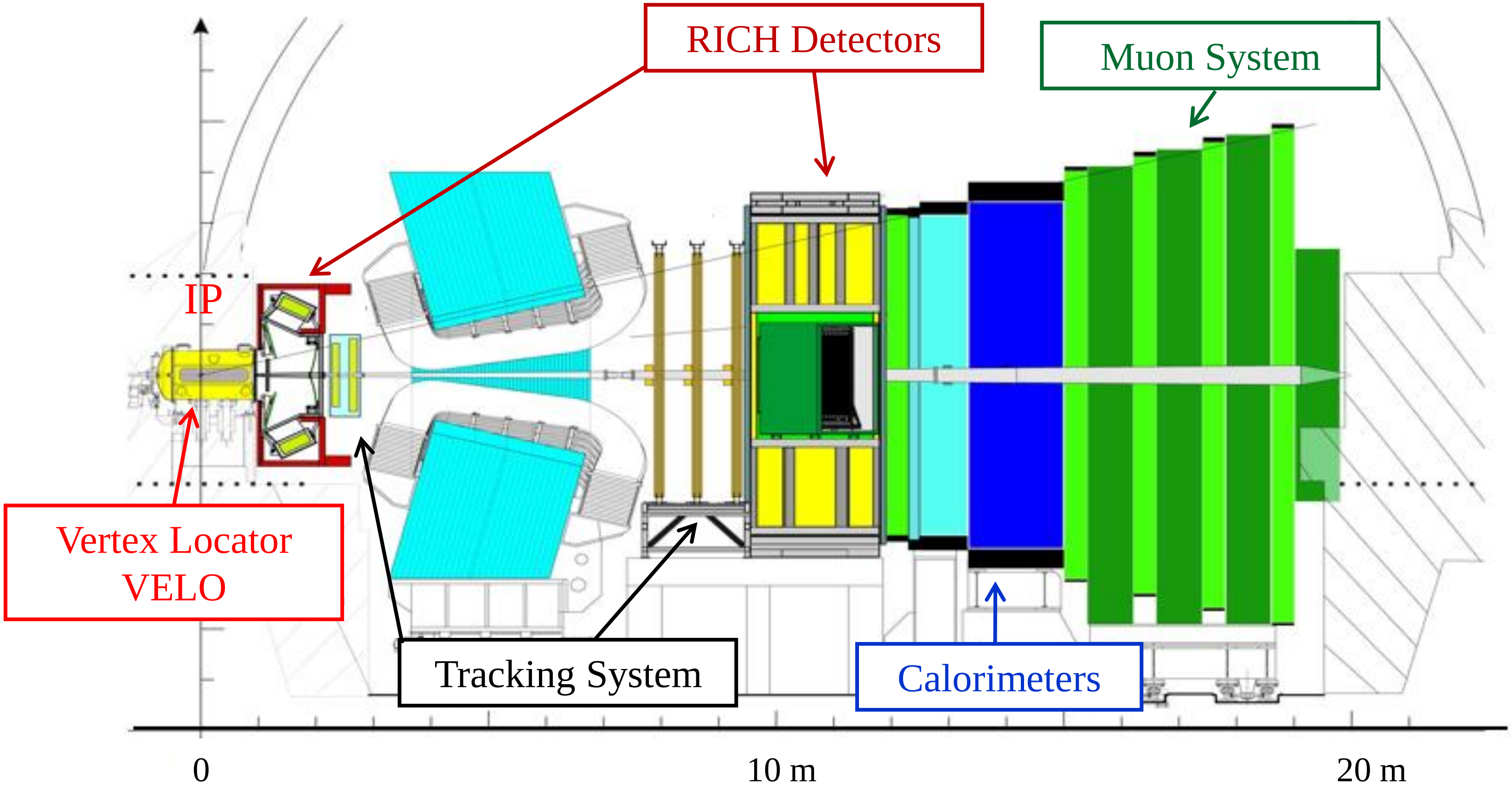
Gain in memory footprint and time-to-finish but not in throughput

Running independent jobs per core (as we do now) is optimal solution for High Throughput Computing applications

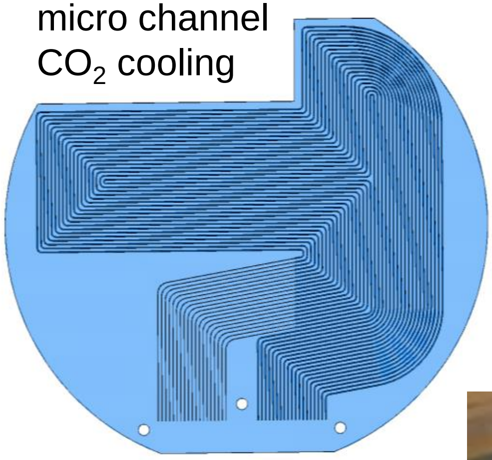
Improving the algorithms is the only way to reclaim factors in performance!

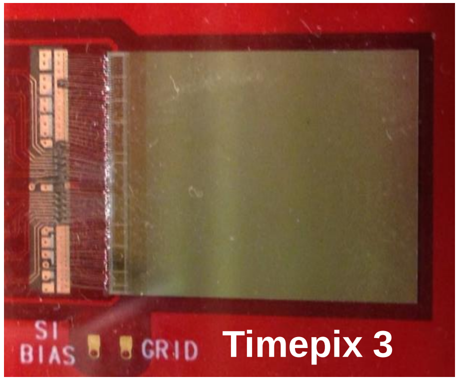
LHCb detector upgrade to 40 MHz readout

- ✓ upgrade ALL sub-systems to 40 MHz Front-End (FE) electronics
- ✓ replace complete sub-systems with embedded FE electronics
- ✓ adapt sub-systems to increased occupancies due to higher luminosity $4x10^{32}$ – $1\text{-}2x10^{33}$
- ➢ keep excellent performance of sub-systems with 5 times higher luminosity and 40 MHz R/O



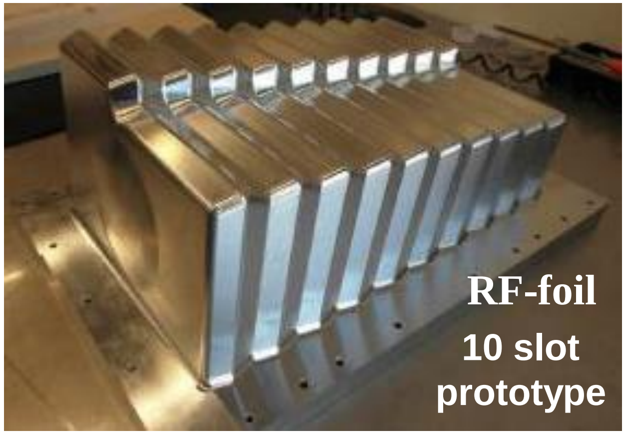
VELO upgrade





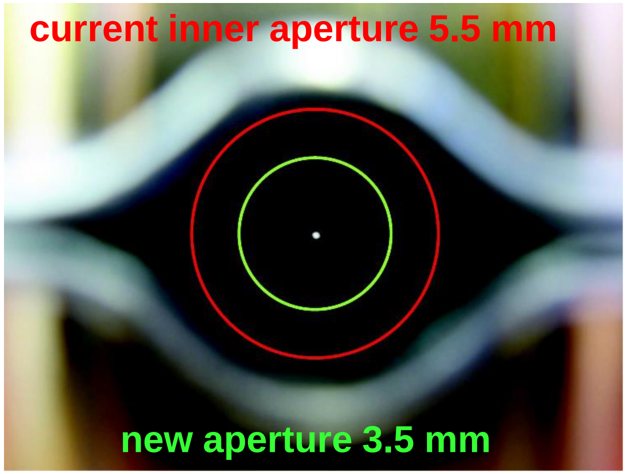
Upgrade challenge:

- ✓ withstand increased radiation
  (highly non-uniform radiation of up to $8 \cdot 10^{15}$ n_{eq}/cm^2 for 50 fb^{-1})
- ✓ handle high data volume
- ✓ keep (improve) current performance
  - ➢ lower materiel budget
  - ➢ enlarge acceptance



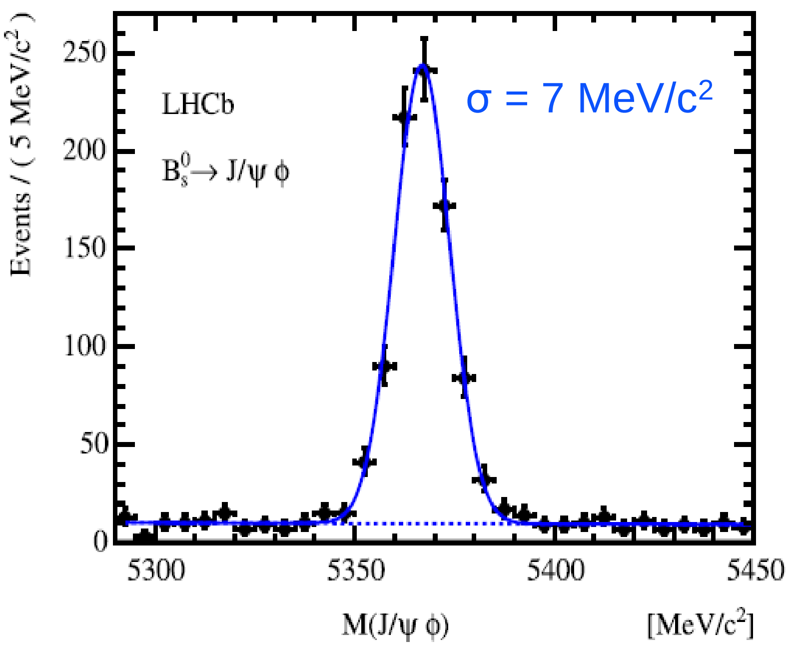
Technical choice :

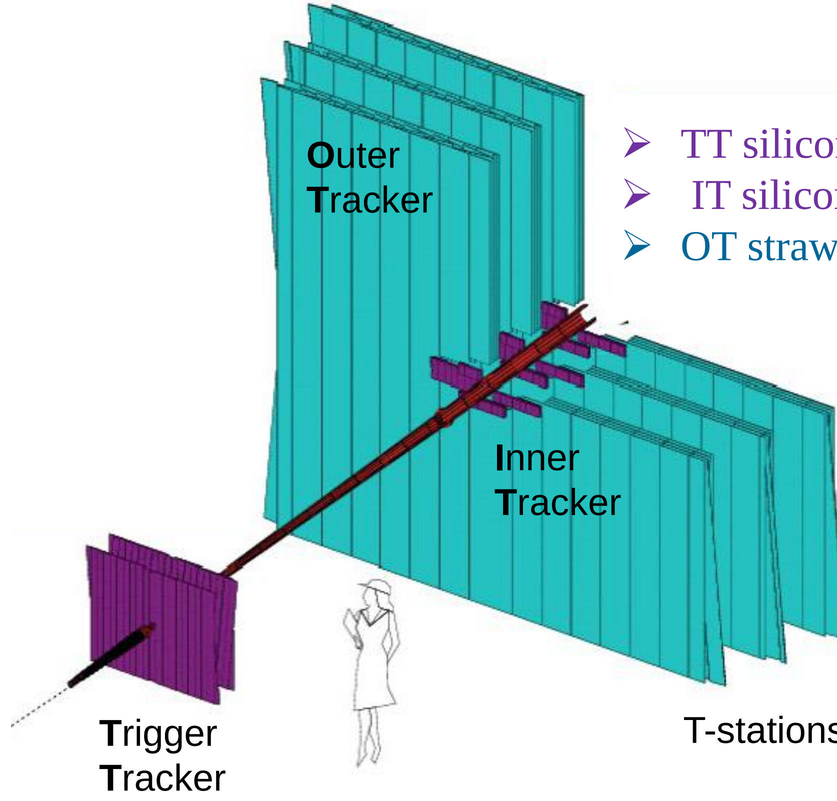
- ✓ 55x55 μm^2 pixel sensors with micro channel CO_2 cooling
- ✓ 40 MHz VELOPIX (evolution of TIMEPIX 3, Medipix)
  - ➢ 130 nm technology to sustain ~400 MRad in 10 years
  - ➢ VELOPIX hit-rate = ~8 x TIMEPIX 3 rate
- ✓ replace RF-foil between detector and beam vacuum
  - ➢ reduce thickness from 300 μm → ~150 μm
- ✓ move closer to the beam
  - ➢ reduce inner aperture from 5.5 mm → 3.5 mm



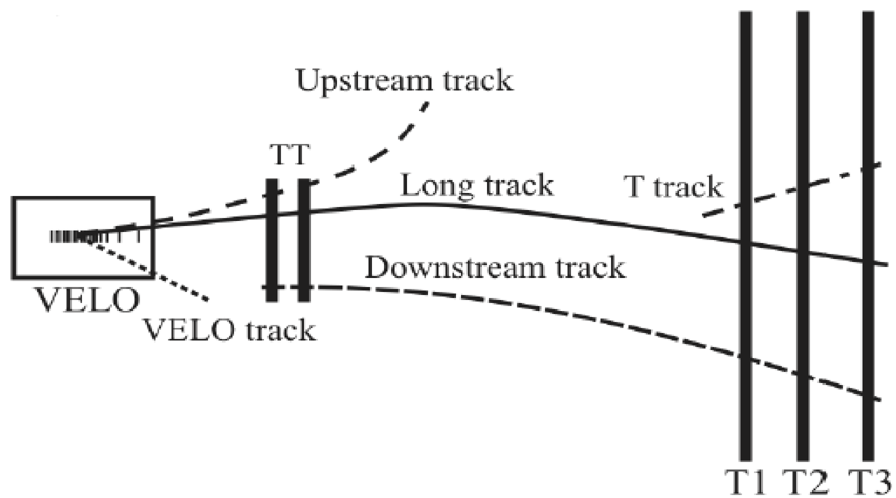
Tracking System

- excellent mass resolution
- very low background, comparable to e^+e^- machines
- worlds best mass measurements [PLB 708 (2012) 241]





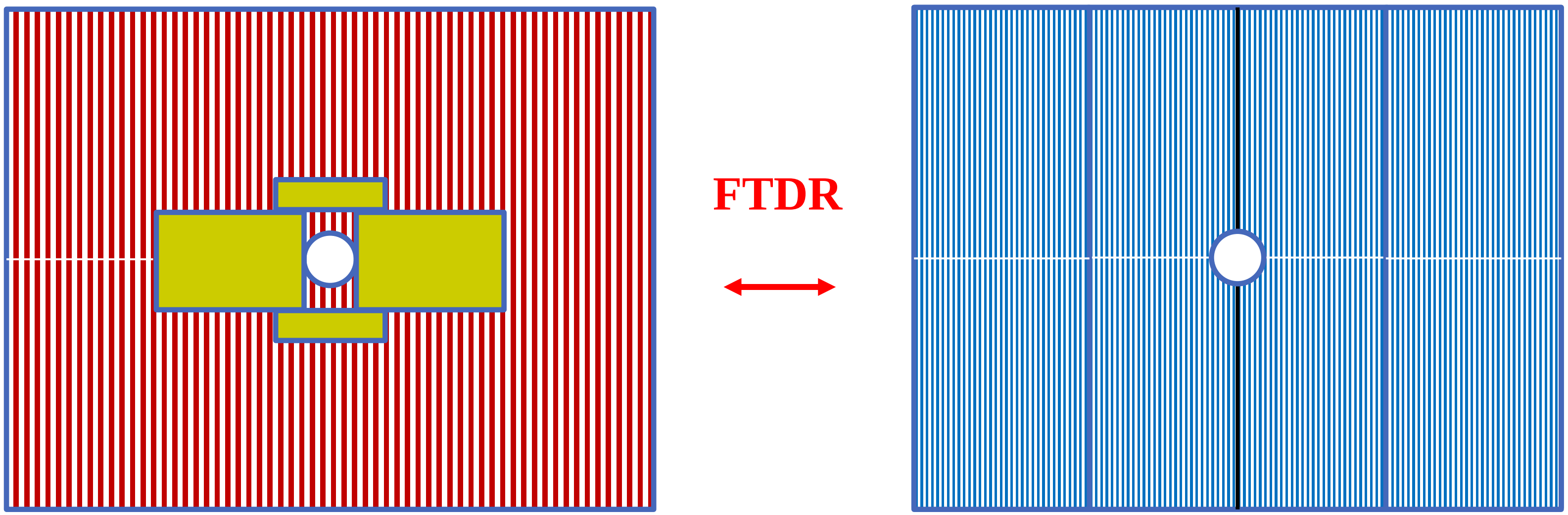
- TT silicon
- IT silicon
- OT straw tubes



T-stations upgrade

Inner Tracker & Outer Tracker

Full Fibre Tracker

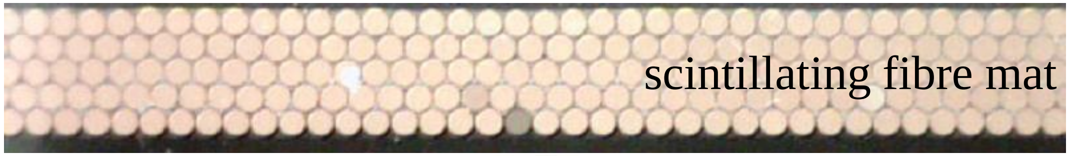


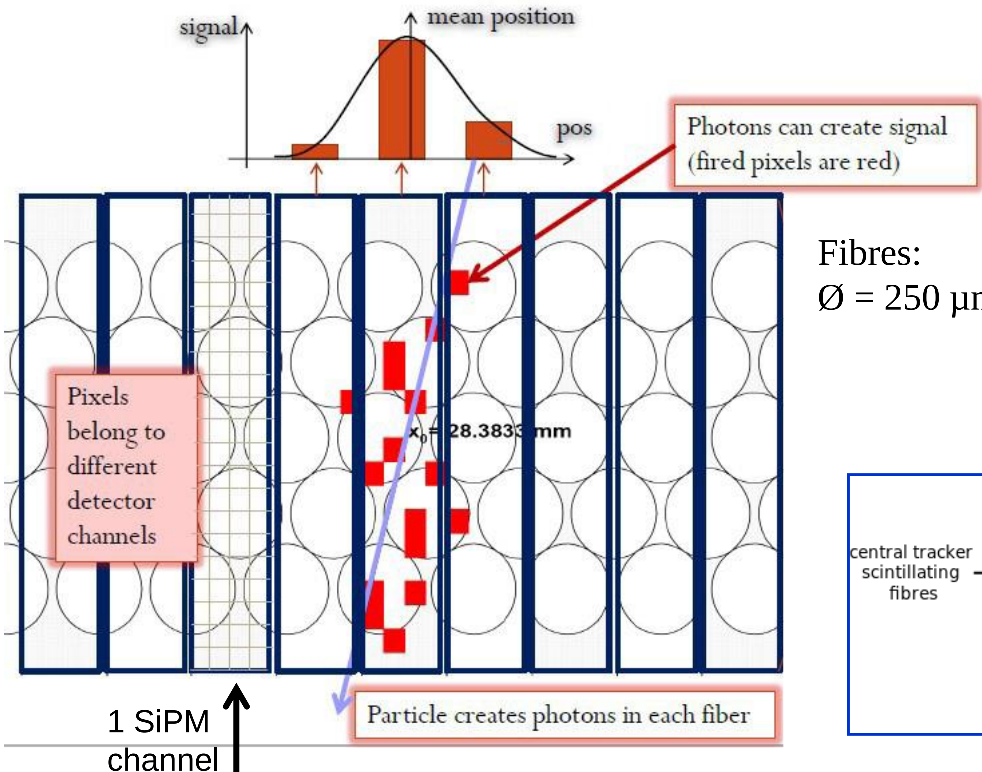
Outer Tracker with straw tube technology

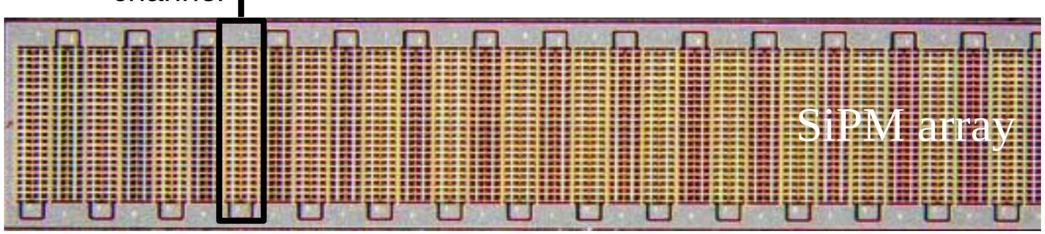
Inner Tracker with silicon strip technology

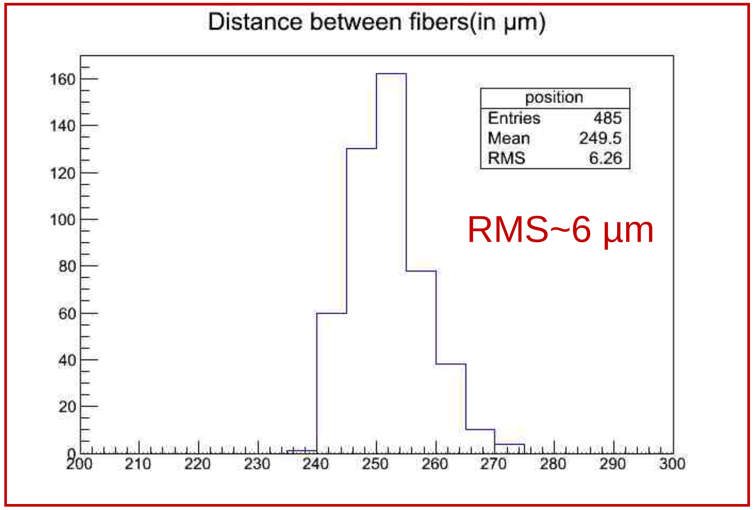
Tracker with scintillating fibre technology

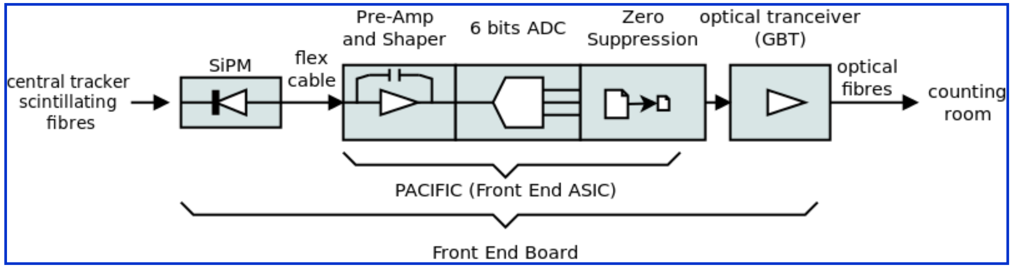
T-stations upgrade: Fibre Tracker (FT), SiPMs









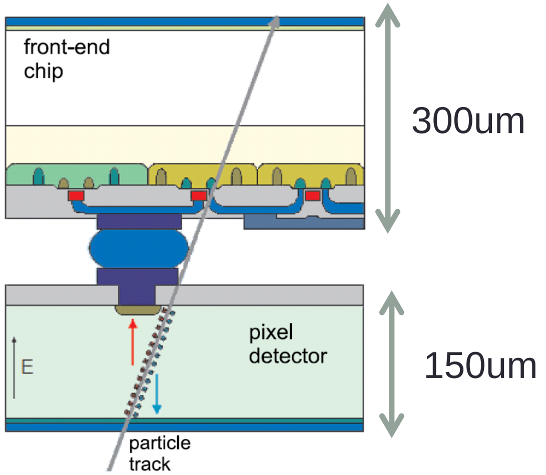


analog readout by dedicated
40 MHz PACIFIC chip

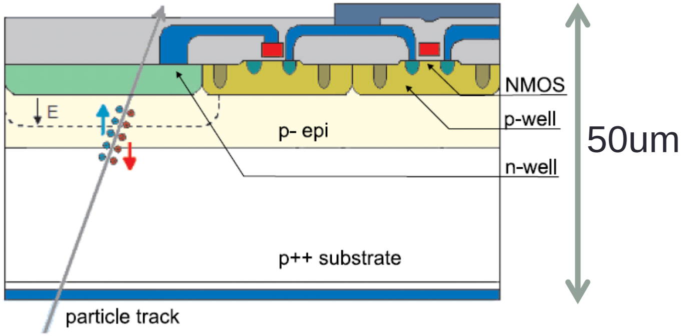
CMOS Sensors

- CMOS sensors **contain sensor and electronics combined in one chip**
  - No interconnection between sensor and chip needed
- Standard CMOS processing
  - Wafer diameter (8”)
  - Many foundries available
  - Lower cost per area
  - Small cell size – high granularity
  - Possibility of stitching (combining reticles to larger areas)
- Very low material budget
- Baseline for ALICE ITS upgrade

Hybrid Pixel Detector



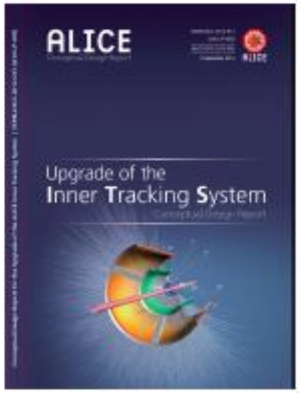
CMOS (Pixel) Detector



ALICE ITS Upgrade

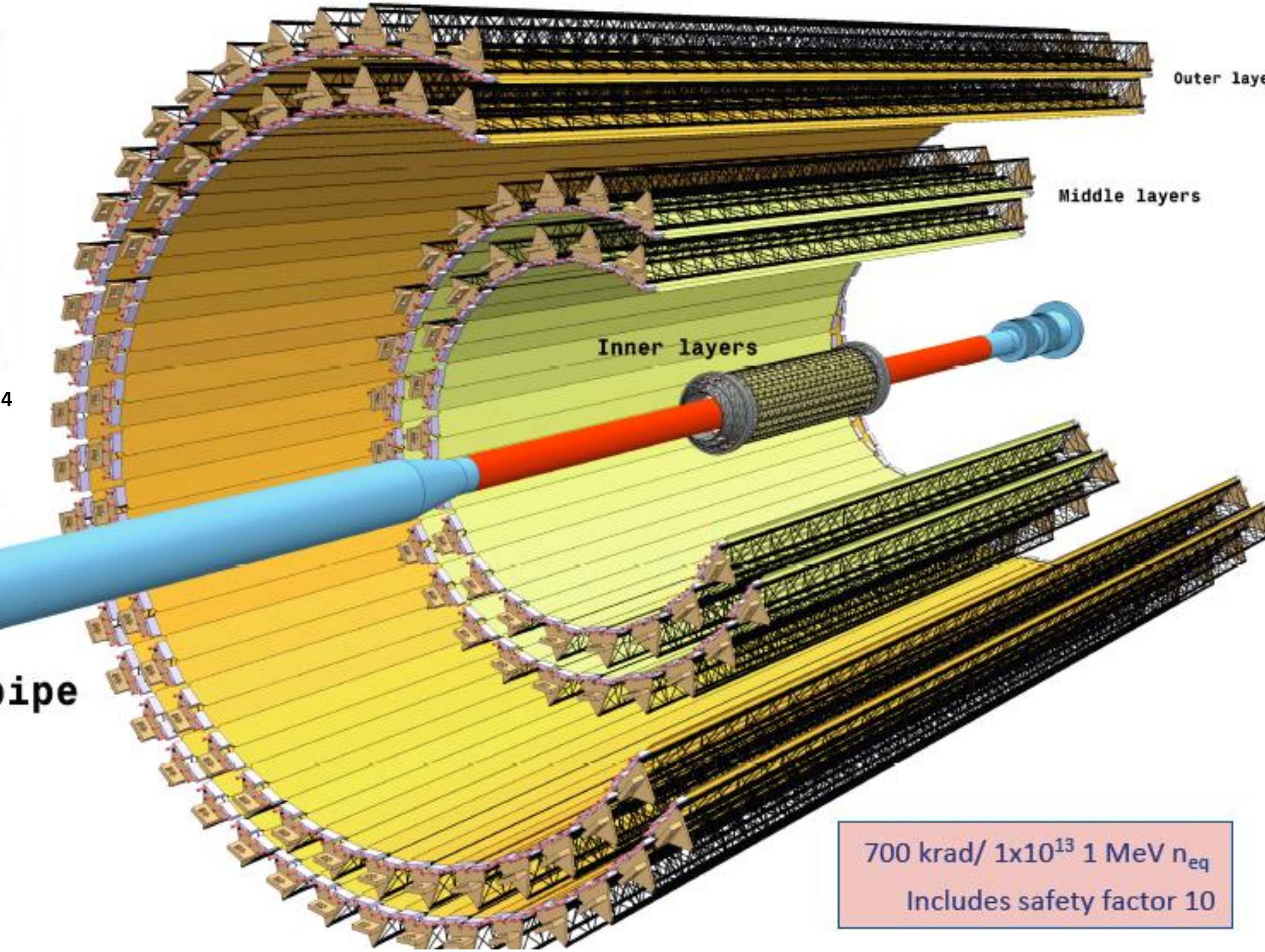
New ITS Layout

25 G-pixel camera
(10.3 m^2)



ITS TDR CERN-LHCC-2013-024

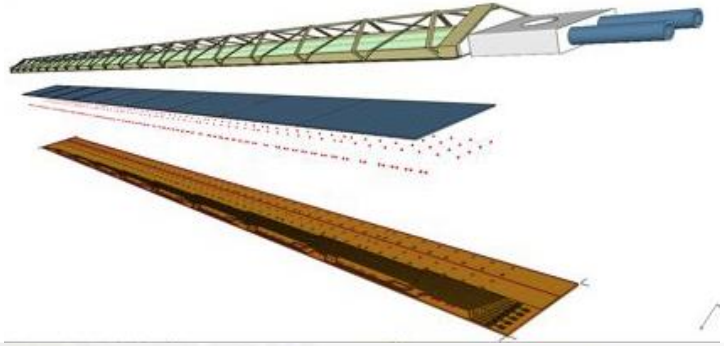
7 layers of MAPS

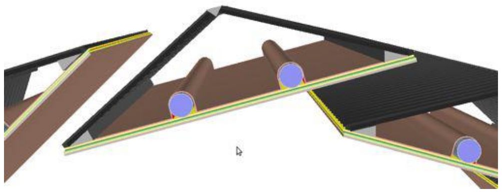


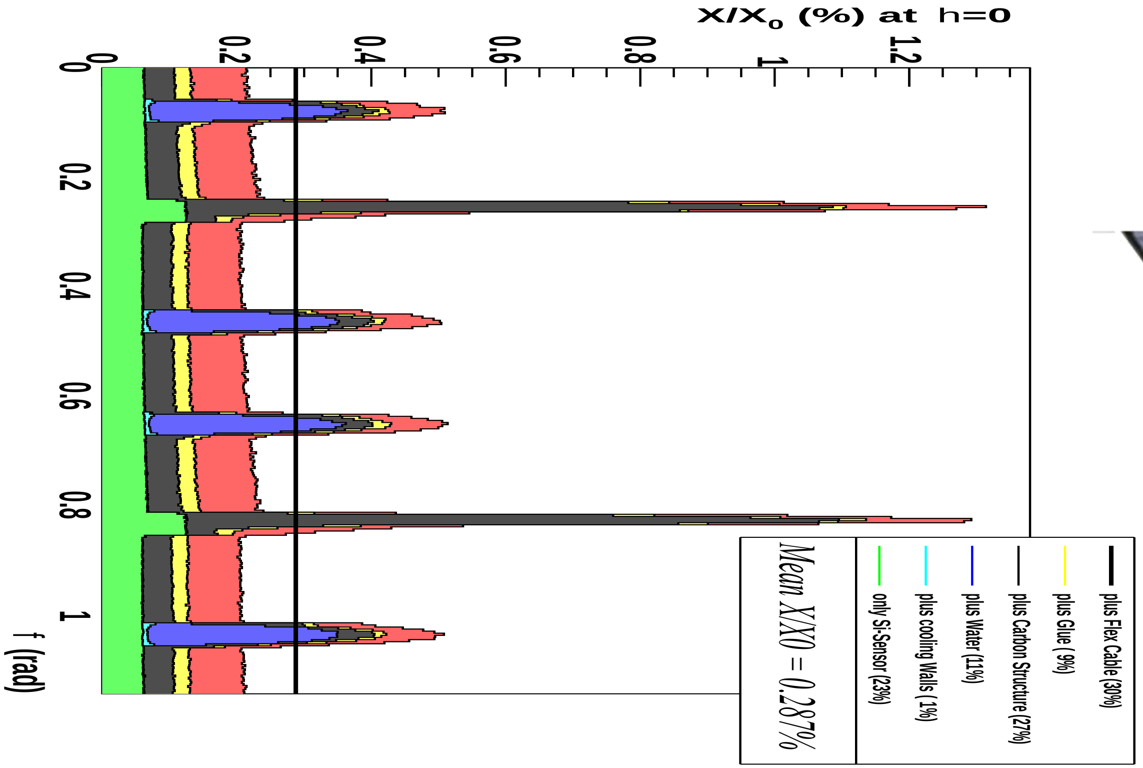
Radial coverage
22 – 406 mm

700 krad/ 1×10^{13} 1 MeV n_{eq}
Includes safety factor 10

Inner Barrel Detector Stave

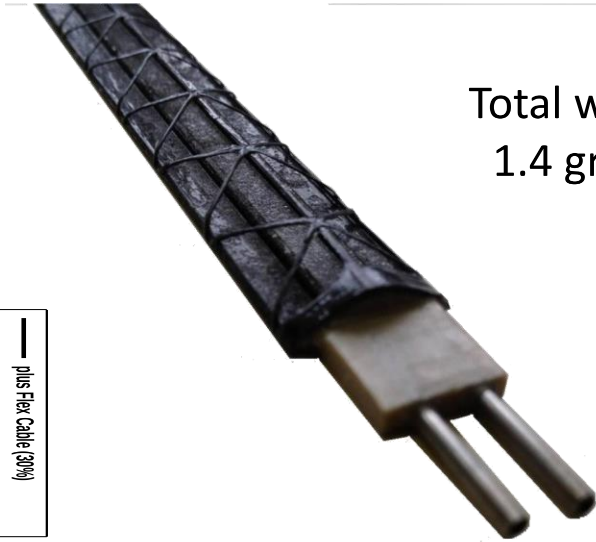






MECHANICS &COOLING

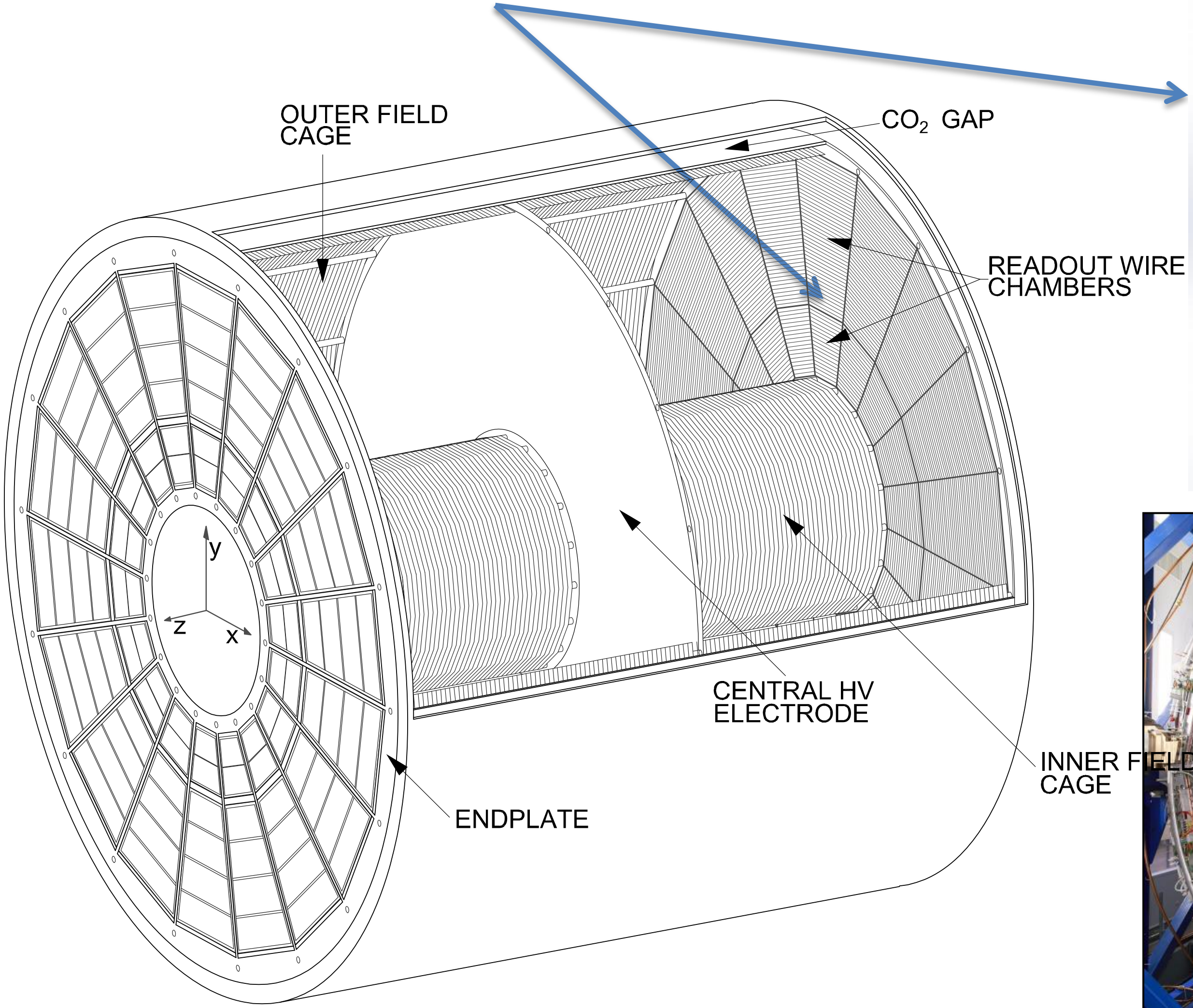
- ✓ Design optimization for material budget reduction

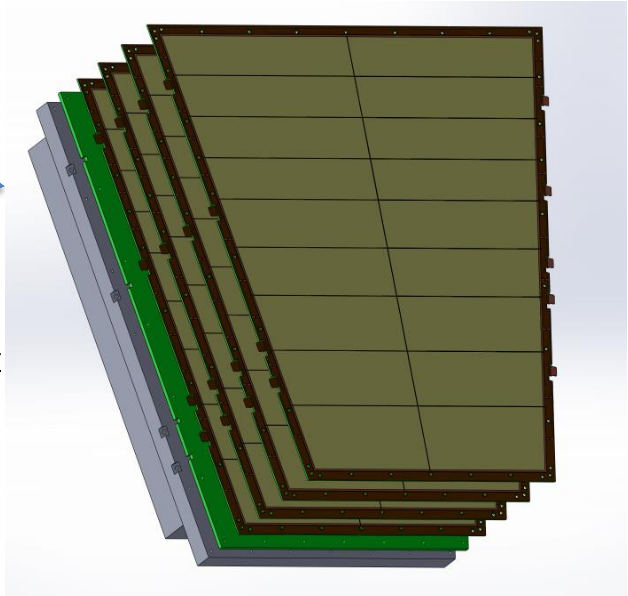


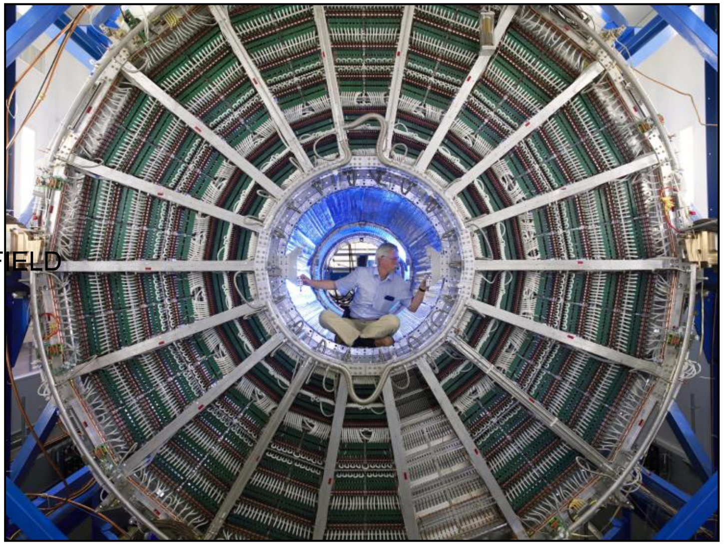
Total weight
1.4 grams

ALICE TPC Upgrade with Micropattern Detectors

Replace wire chambers
With quadruple-GEM chambers



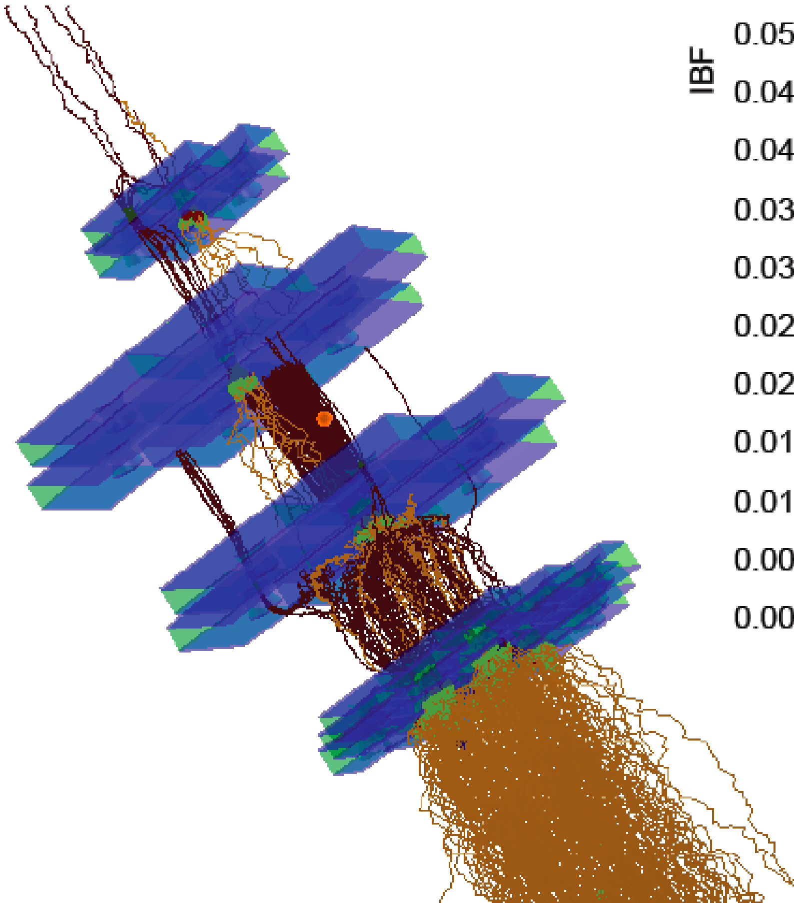


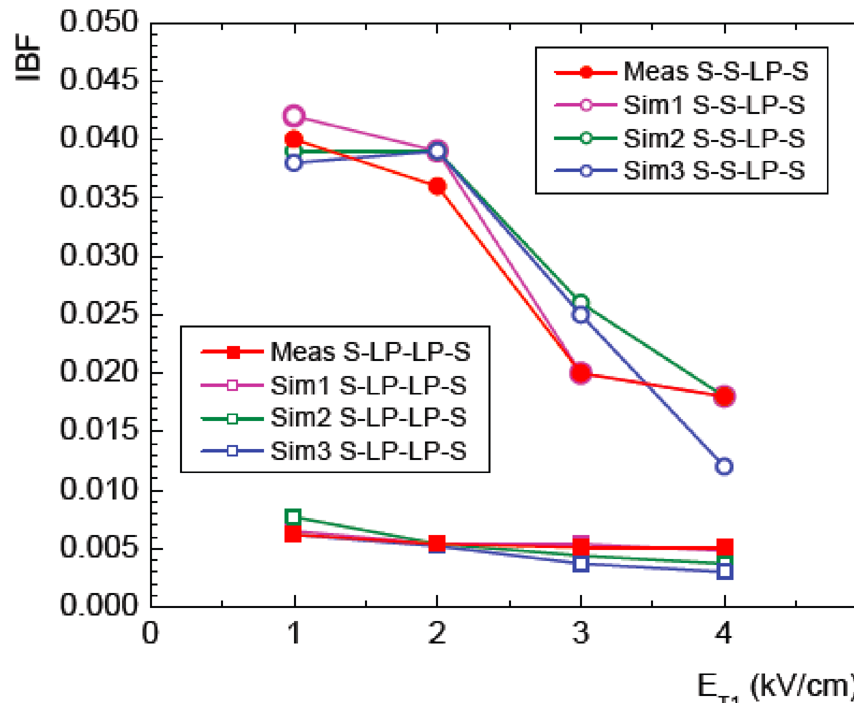


Minimizing the Ion Feedback is the big Challenge

simulation: IBF in 4-GEM systems

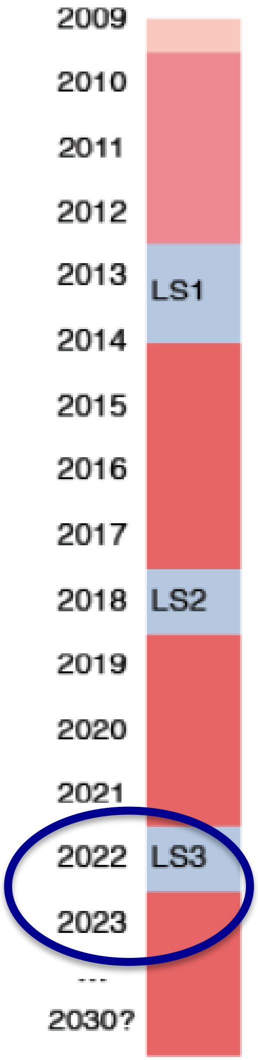
ALICE





- IBF quantitatively well described by simulation based on Garfield++

ATLAS Upgrade Plan



$L_{inst} \simeq 5 \times 10^{34}\ cm^{-2}s^{-1}$ ($\mu \simeq 140$) w. level.
$\simeq 6\text{-}7 \times 10^{34}\ cm^{-2}s^{-1}$ ($\mu \simeq 192$) no level.
$\int L_{inst} \simeq 3000\ fb^{-1}$

- All new Tracking Detector
- Calorimeter electronics upgrades
- Upgrade muon trigger system
- Possible Level-1 track trigger
- Possible changes to the forward calorimeters

Phase-2

Prepare for <μ>=200
Replace Inner Tracker
New L0/L1 trigger scheme
Upgrade muon/calorimeter electronics

CMS Upgrade program

LS1
2013-14

LS2
2018

LS3
2022-23

LS1 consolidation: Complete detector & consolidate operation for nominal LHC beam conditions ~13 TeV, 1 x Hz/cm^2 , <PU> ~25

- Complete Muon system (4th endcap station), improve RO of CSC ME1/1 & DTs
- Replace HCAL HF and HO photo-detectors and HF backend electronics
- Tracker operation at -20◦C
- Prepare and install slices of Phase 1 upgrades

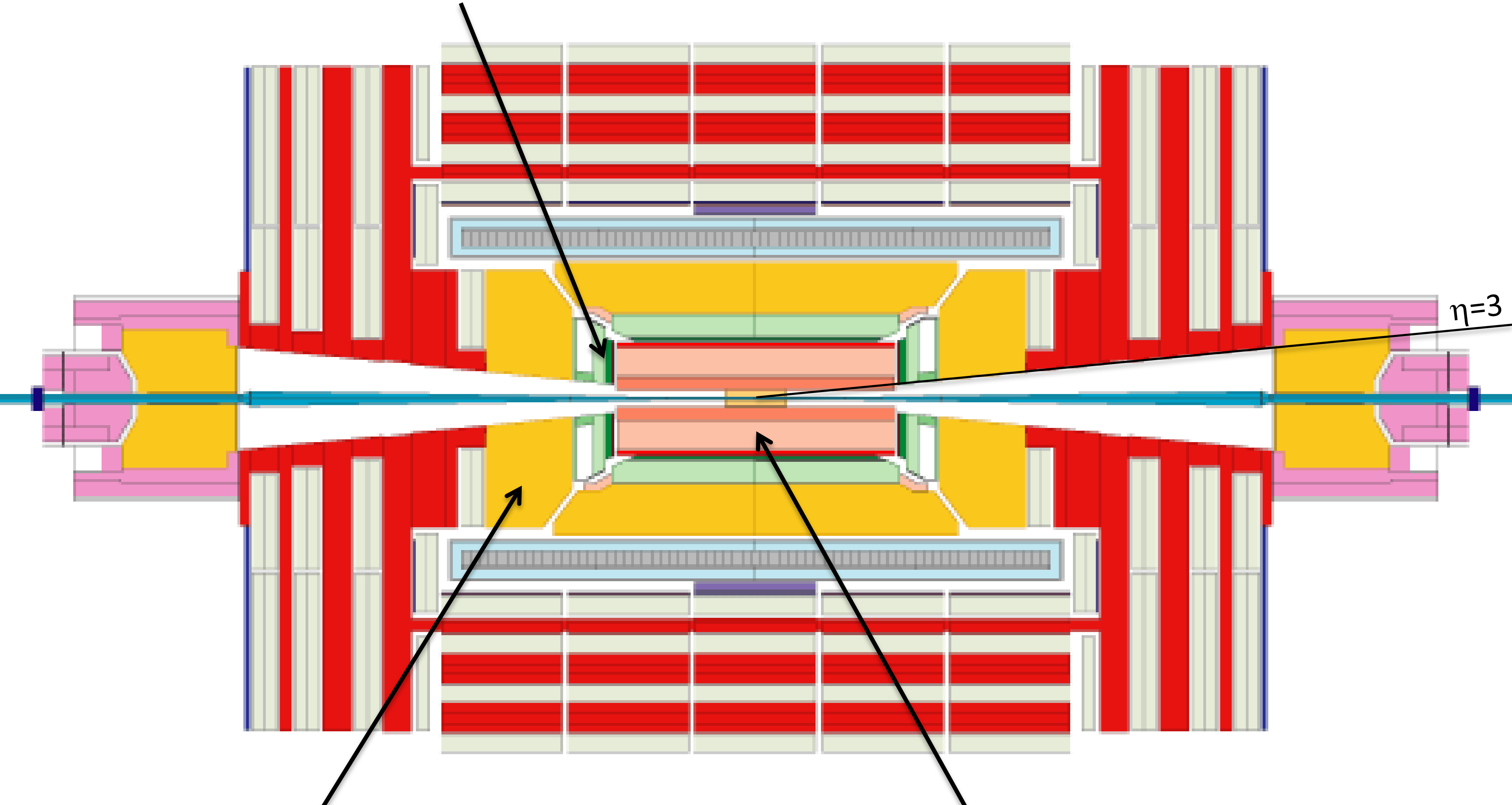
Phase 1 upgrades: Prepare detector for 1.6 x 10^{34} Hz/cm^2 , <PU> ~40, and up to 200 fb^{-1} by LS2, and 2.5 x 10^{34} Hz/cm^2, <PU> ~ 60, up to 500 fb^{-1} by LS3

- New L1-trigger systems (Calorimeter - Muons - Global) (ready for 2016 data taking)
- New Pixel detector (ready for installation in 2016/17 Year End Technical Stop)
- HCAL upgrade: photodetectors and electronics (HF 2015/16 YETS, HB/HE LS2)

Phase 2 upgrades: $\gtrsim$ 5 x 10^{34} Hz/cm^2 luminosity leveled, <PU> ~128 (simulate 140), reach total of 3000 fb^{-1} in ~10 yrs operation

- Replace detector systems whose performance is significantly degrading due to radiation damage
- Maintain physics performance at this very high PU

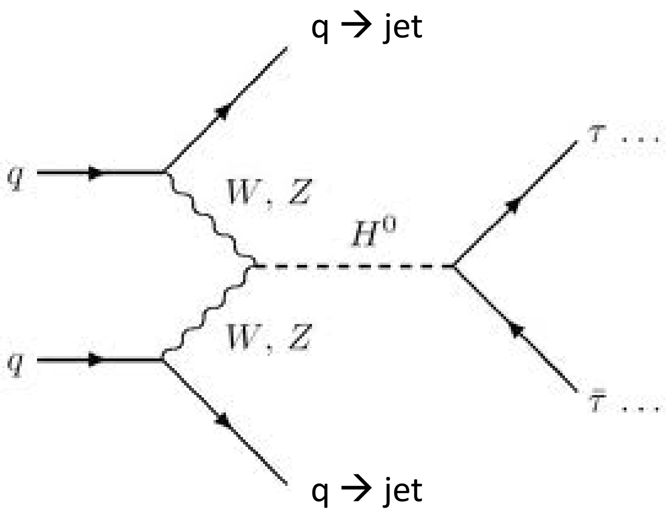
Electromagnetic Endcap Calorimeter ($PbWO_4$ Crystals), light output will become too small due to radiation damage

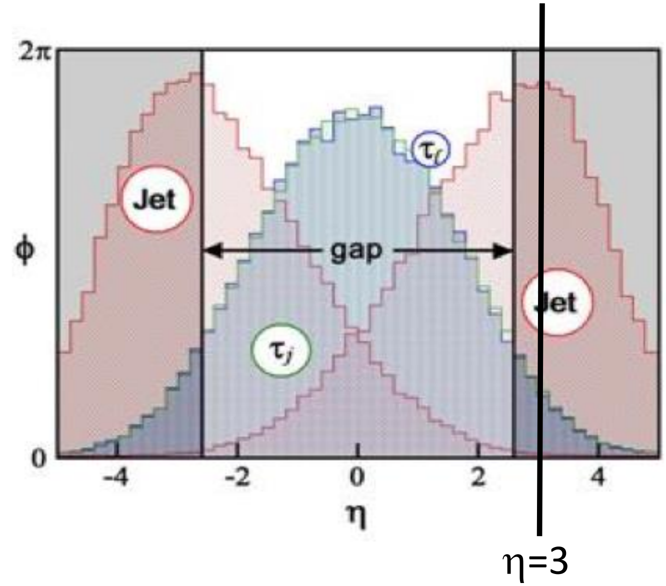


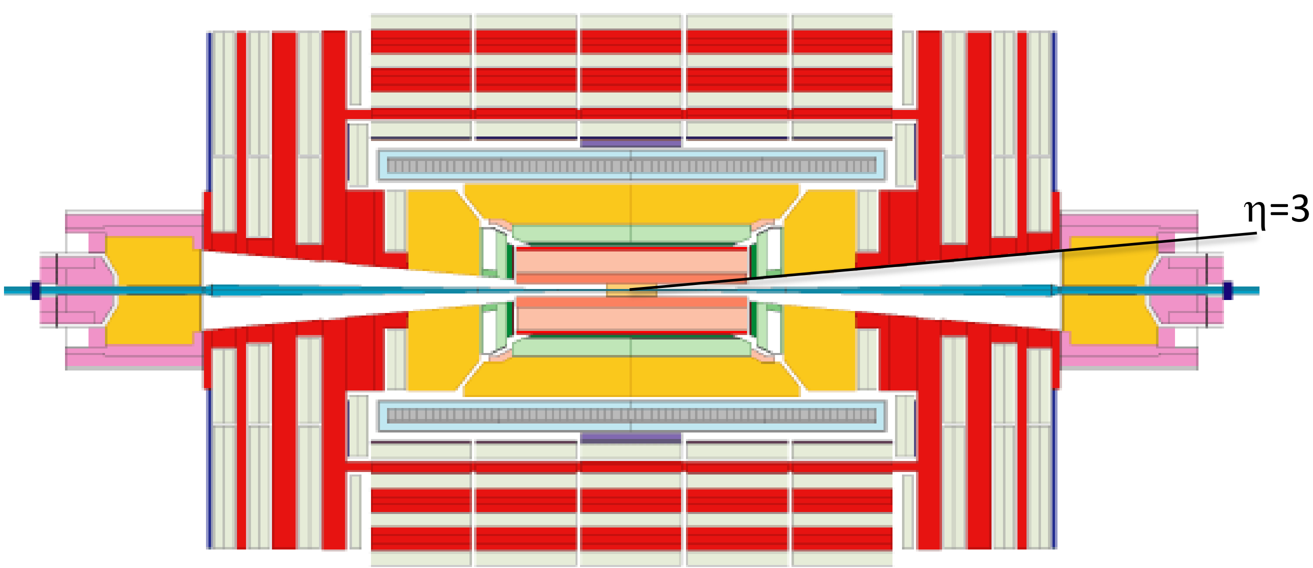
Hadron Endcap Calorimeter (Brass Scintillator) has to be replaced. Plastic Scintillators and WLS fibers will broken by radiation.

Entire Silicon Tracker has to be replaced → radiation hardness and readout (track triggering)

Vector Boson Fusion (VBF) -Jets







Very important channel to measure.

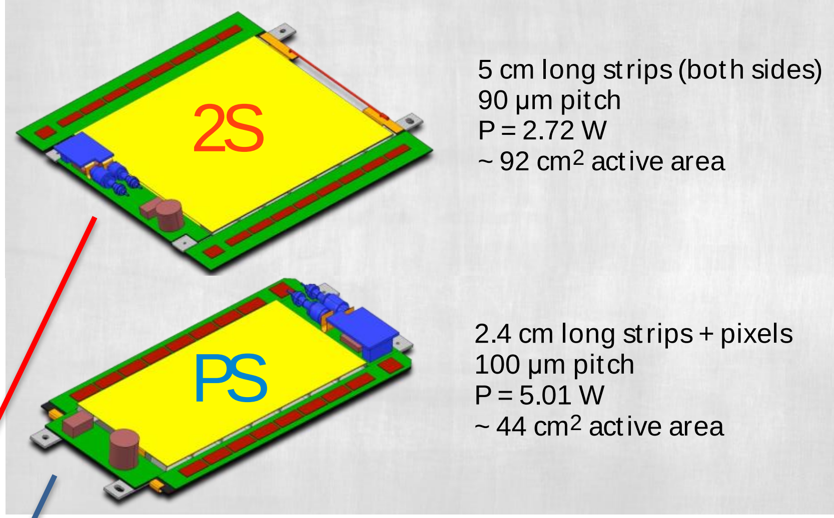
Quarks do not interact through color exchange i.e. the jets are peaked in forward direction at η=3.

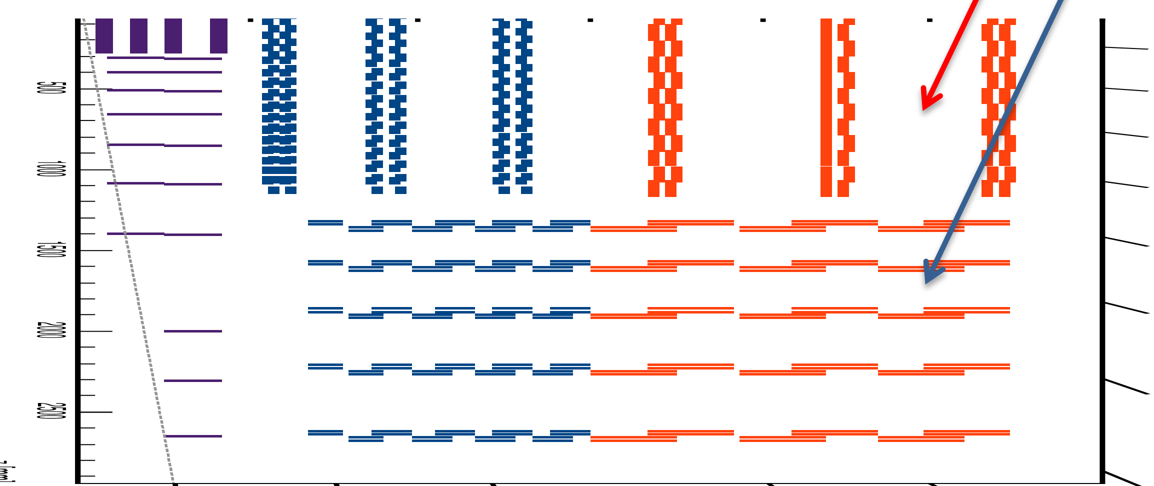
Signature: high jet activity in forward region, little hadronic activity in the barrel.

η = 3 is exactly in the transition region of the endcap calorimeters !

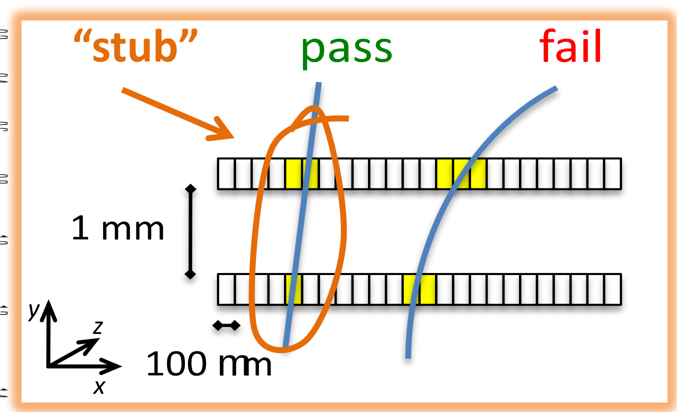
CMS Phase 2 Tracker: conceptual design

- Outer tracker
  - High granularity for efficient track reconstruction beyond 140 PU
  - Two sensor "Pt-modules" to provide trigger information at 40 MHz for tracks with Pt≥2GeV
  - Improved material budget
- Pixel detector
  - Similar configuration as Phase 1 with 4 layers and 10 disks to cover up to |η|= 4
  - Thin sensors 100 µm; smaller pixels 30 x 100 µm
- R&D activities
  - In progress for all components - prototyping of 2S modules ongoing
  - BE track-trigger with Associative Memories





Trigger track selection in FE



Challenges for LHC Detector Upgrades

Fluence of >1.5×10^{16} Hadrons/cm^2 and Ionizing Dose of almost 1GGy for the first pixel layers.

Up to 140 pp collisions in a single bunch crossing.

Data rates in excess of 5TB/s between detector and Online System.

Improvement of algorithms in order to make use of the available computing power.

Track triggering at L1.

Bring Monolithic Silicon Sensors and Silicon Photo Multipliers to maturity in large scale applications

→ these novel technologies will heavily impact on our future particle detectors !

Expected Integrated Luminosities

ATLAS/CMS p-p:		
Run1	(2010 to 2012)	≈ 30 fb^{-1}
Run2 + Run3	(2015 to 2022)	≈ 300 fb^{-1}
Run4 + ...	(2025 to ∞)	≈ 3000 fb^{-1}
ALICE/ATLAS/CMS Pb-Pb:		
Run1	(2010 to 2012)	≈ 0.15 nb^{-1}
Run2	(2015 to 2018)	≈ 1 nb^{-1}
Run3 + ...	(2020 to ∞)	≈ 10 nb^{-1}
LHCb p-p:		
Run1	(2010 to 2012)	≈ 3.36 fb^{-1}
Run2	(2015 to 2018)	≈ 7 fb^{-1}
Run3 + ...	(2020 to ∞)	≈ 50 fb^{-1}
All experiments p-Pb:		
Run1	(2010 to 2012)	≈ 30 nb^{-1}
Run2	(2015 to 2018)	≈ 30-100nb^{-1}
Run3 +...	(2015 to 2018)	> 50 nb^{-1}