# Preparing for the Future:
# Upgrades of the LHC Experiments

**521. Wilhelm und Else Heraeus-Seminar**
***First Results from the Large Hadron Collider***
**Bad Honnef, December 9–12, 2012**


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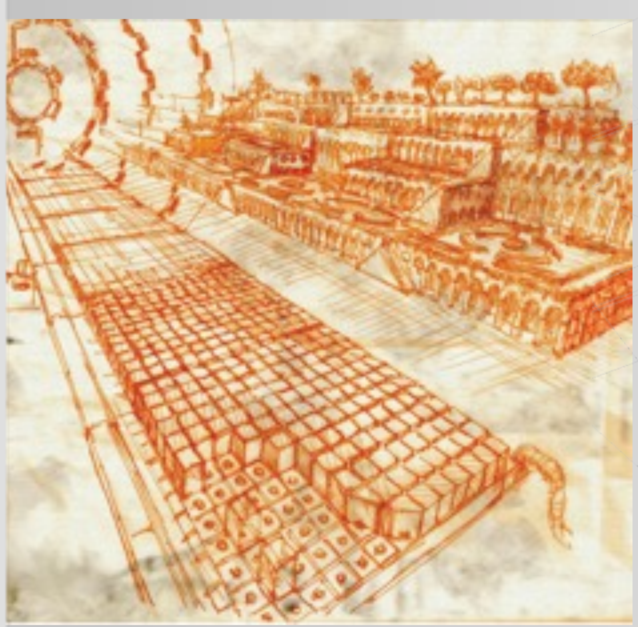
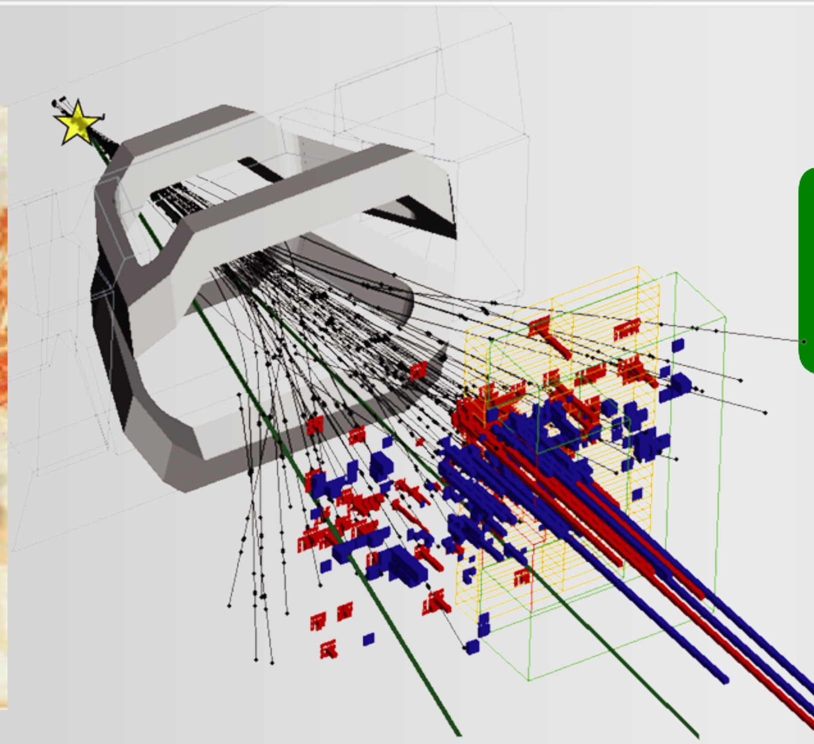
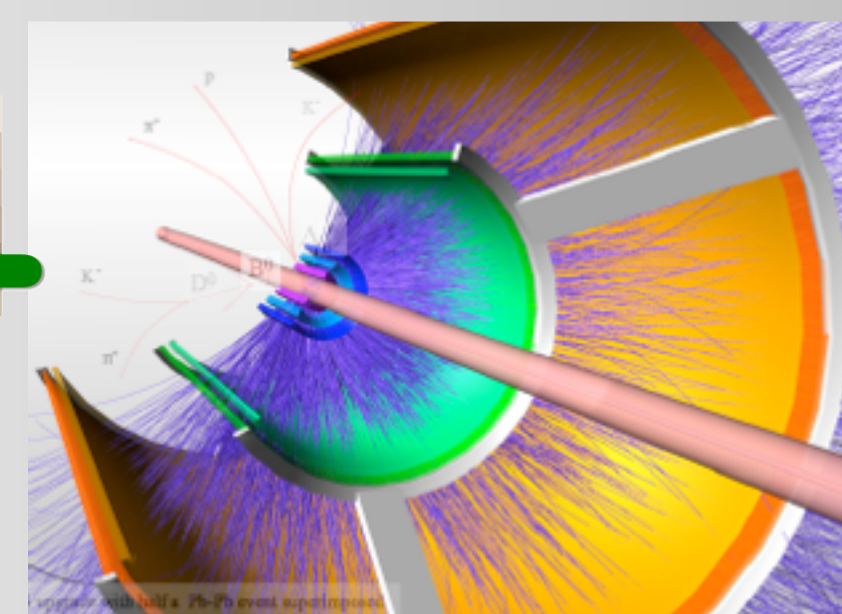




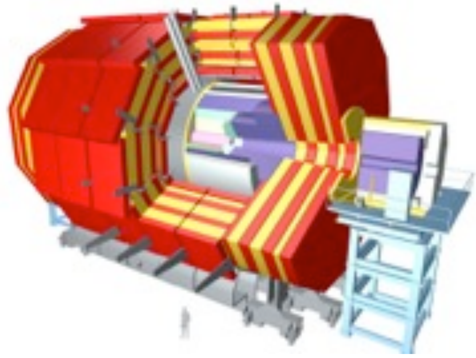



## LHC – the Large Hadr

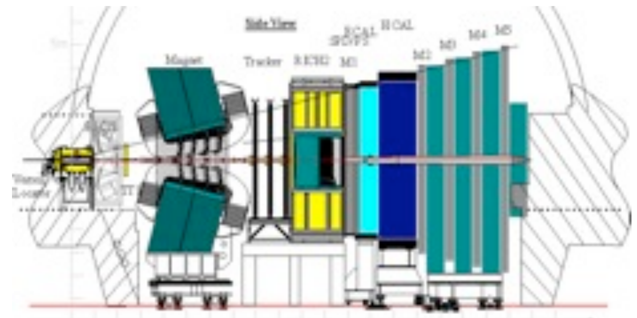
Lake Geneva

### LHC Accelerator:
proton-proton and
lead-lead collisions

### CMS Experiment:
multi-purpose experiment



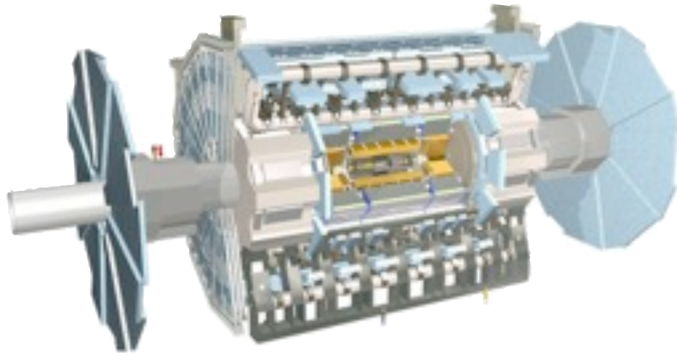
### LHCb Experiment:
CP violation and B physics



CERN accelerator complex,
about 100 m under ground
LHC circumference: ~27 km

### ALICE Experiment:
heavy ion physics

### ATLAS Experiment:
multi-purpose experiment



# Upgrades: Why, How, and When


- **Why**:
  - Physics: the best is yet to come (cf. Tevatron: $B_S$ mixing and single top after ~20 years of operation)
  - Detectors: replace aging components, update obsolete technologies
- **How**:
  - Upgrades of the LHC (including injection chain)
  - Upgrades of detectors, trigger, data acquisition
  - Goal: keep comparable performance in increasingly challenging environment
- **When**:
  - Three phases: 2013 – 2018 – 2022

# Outline

- The Case for LHC Upgrades
- ATLAS and CMS Upgrades
- ALICE and LHCb Upgrades
- The Far Future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# The Case for LHC Upgrades


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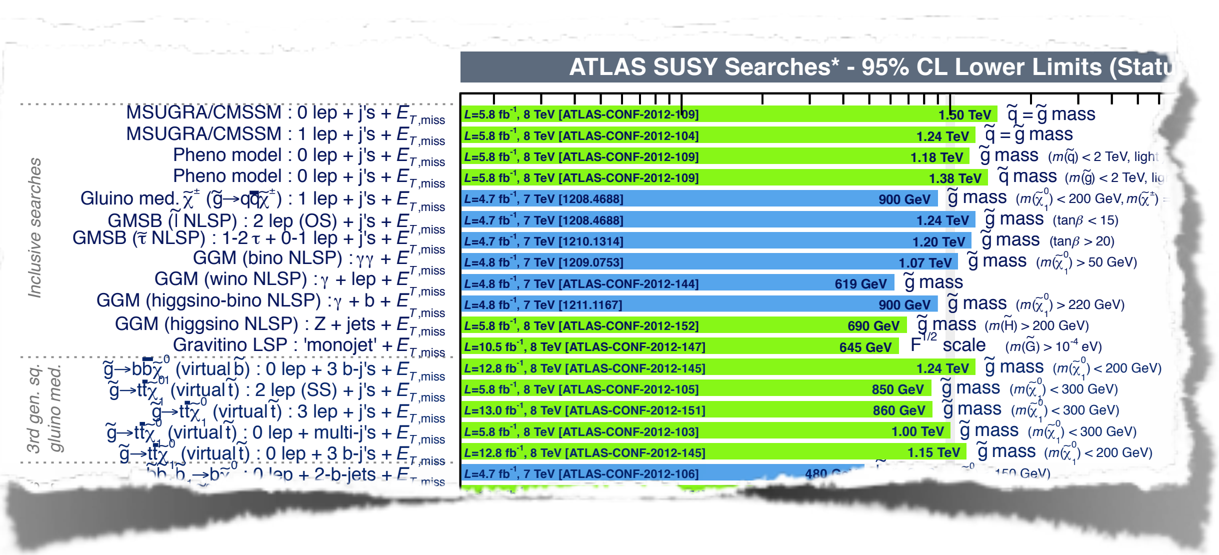
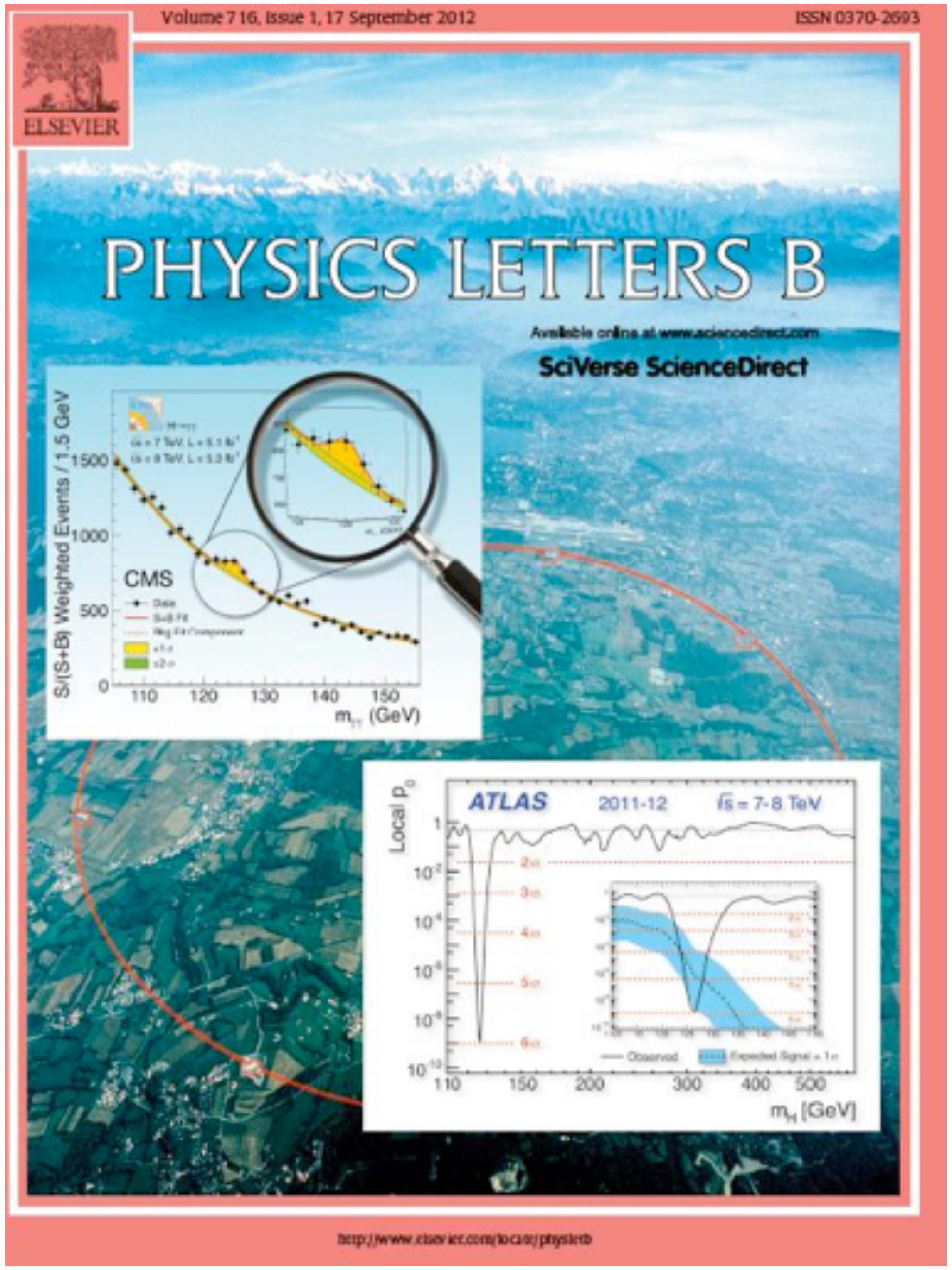
# Status December 2012

- Discovery of Higgs-like boson
- LHC = factory of standard model (SM) particles (W, Z, top, …)
- No signs of beyond-SM physics yet (SUSY, new strong dynamics, 4th generation, extra dimensions, …)




[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots]




[elsevierconnect.com]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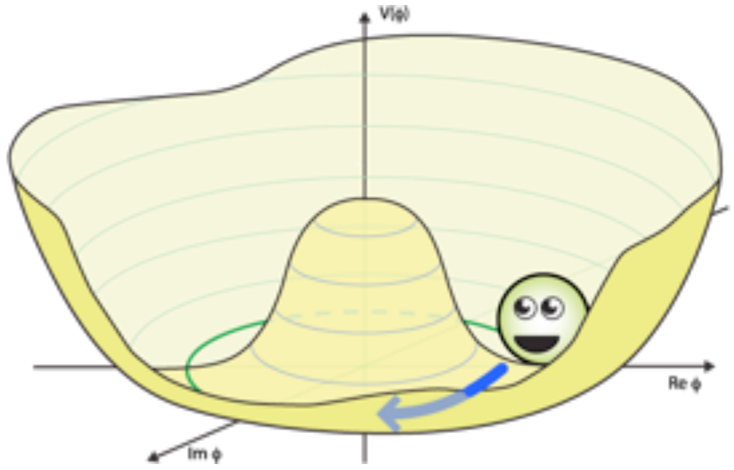
# Implications for Future Physics Programm

- Comprehensive Higgs properties program
  - Relatively low energy processes (<100 GeV) stay relevant
  - Experiments: keep trigger and detection thresholds low

- Tests of electroweak symmetry breaking (ESWB)
  - Question: is (only) the Higgs responsible for EWSB
  - Access to EWSB mechanism: longitudinal WW scattering
  - Experiments: forward instrumentation important



[quantumdiaries.org]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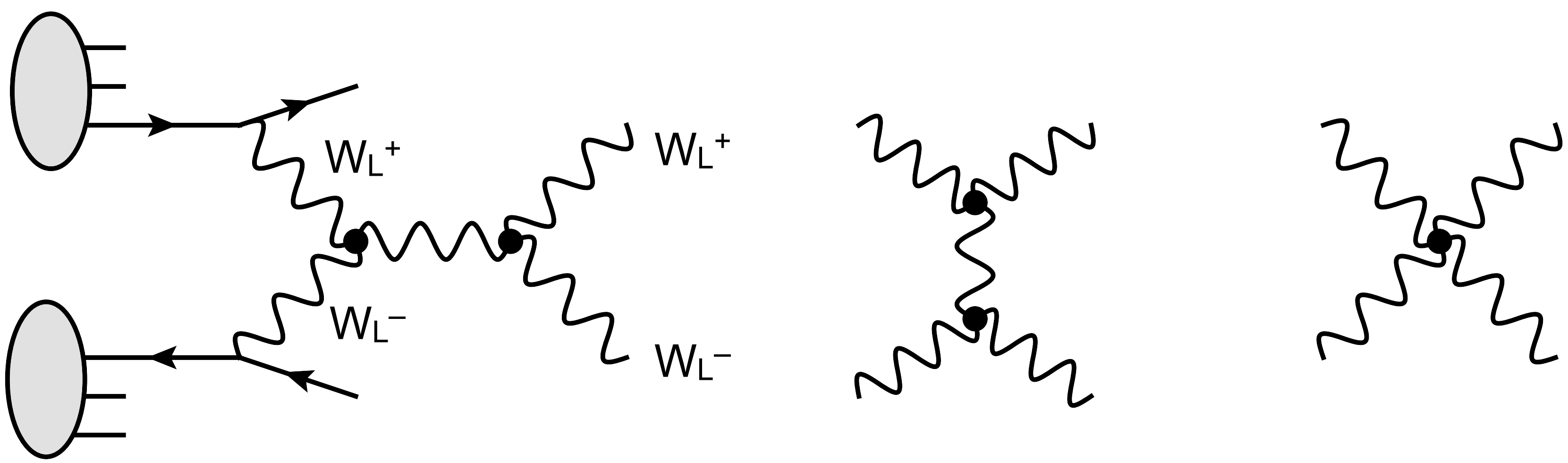
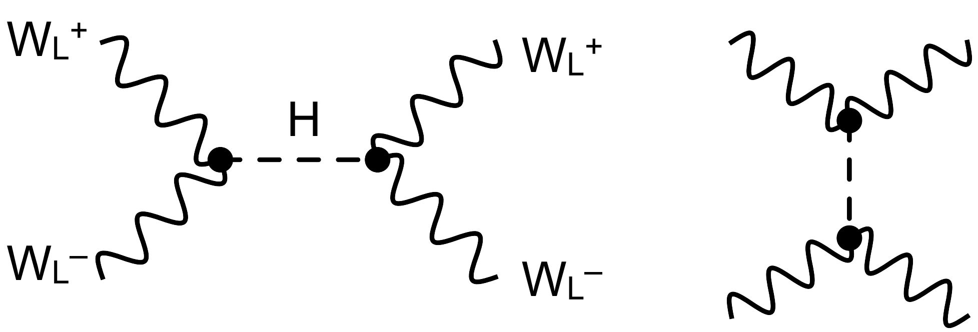
# Longitudinal WW Scattering

- Question: is SM Higgs mechanism at work or something else?
- Scattering of longitudinally polarized gauge bosons $W_L^+ W_L^- \rightarrow W_L^+ W_L^-$
  - Without Higgs boson: cross section diverges for large CM energies ($\gtrsim$ 1.2 TeV)




  - No color exchange between initial state partons → expect forward jets
  - Standard model: Higgs boson with $m_H \lesssim$ 850 GeV regularizes divergence



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- Tests of electroweak symmetry breaking (ESWB)
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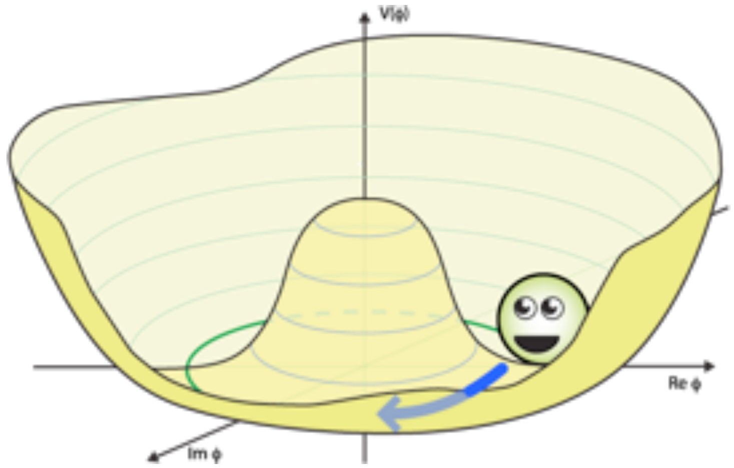
  - Access to EWSB mechanism: longitudinal WW scattering
  - Experiments: forward instrumentation important
- Search for physics beyond the SM
  - New physics scale likely above 1 TeV
  - Accessible with higher center-of-mass (CM) energy and/or lots of luminosity



[quantumdiaries.org]


[C. Grupen]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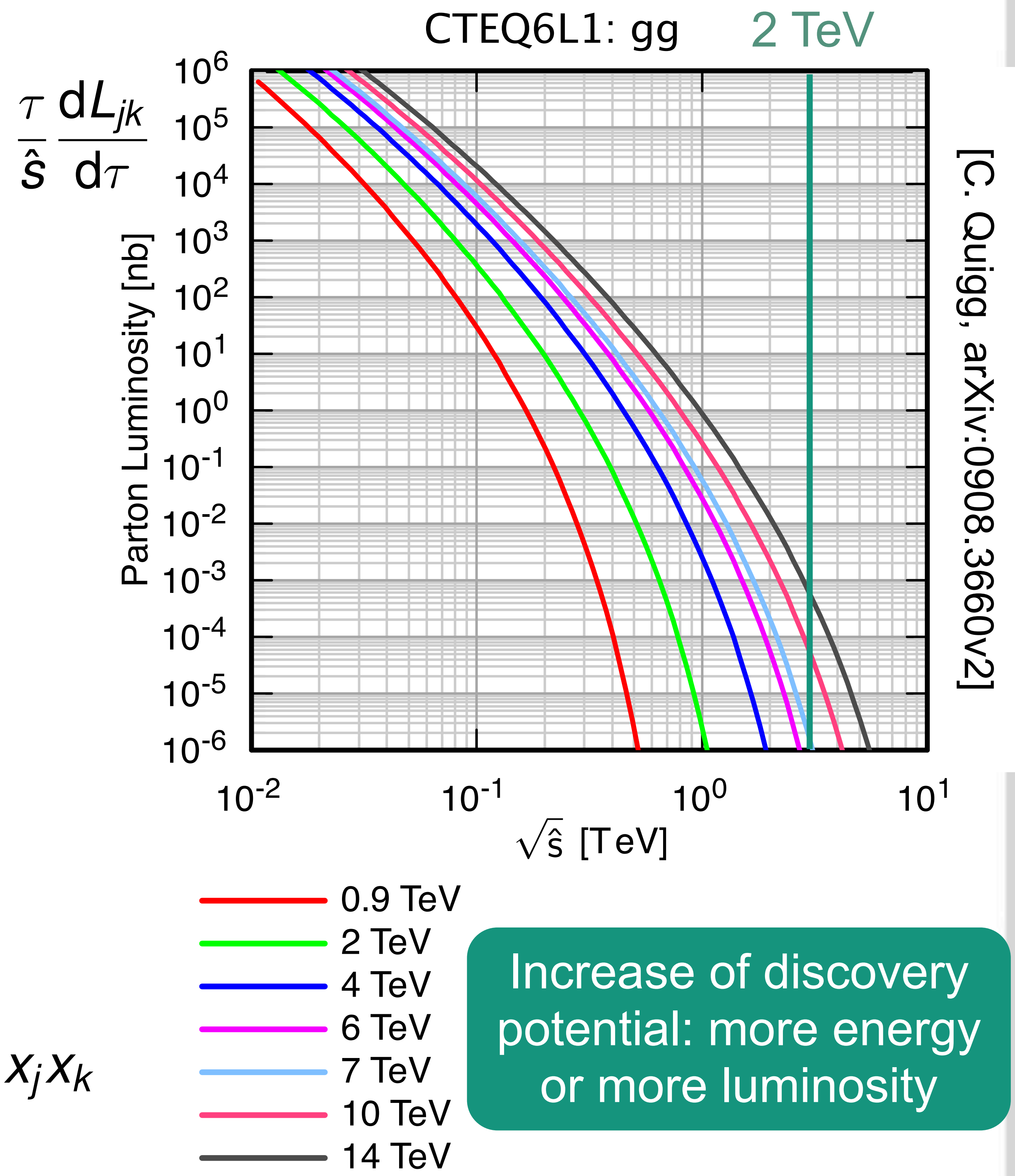
# Parton Luminosity

- Proton-proton collisions are really parton-parton collisions with broad spread in momentum
- Discovery potential for new heavy particles (e.g. SUSY) depends available luminosity at a given partonic center of mass energy
- Convenient notation: parton luminosity (derived from QCD factorization)

$$\frac{dL_{jk}}{d\tau} = \int_{\tau}^{1} \frac{dx}{x} f_j(x, \mu_F^2)\, f_k\left(\frac{\tau}{x}, \mu_F^2\right)$$

with j, k parton flavors and $\tau \equiv \frac{\hat{s}}{s} = x_j x_k$




Increase of discovery potential: more energy or more luminosity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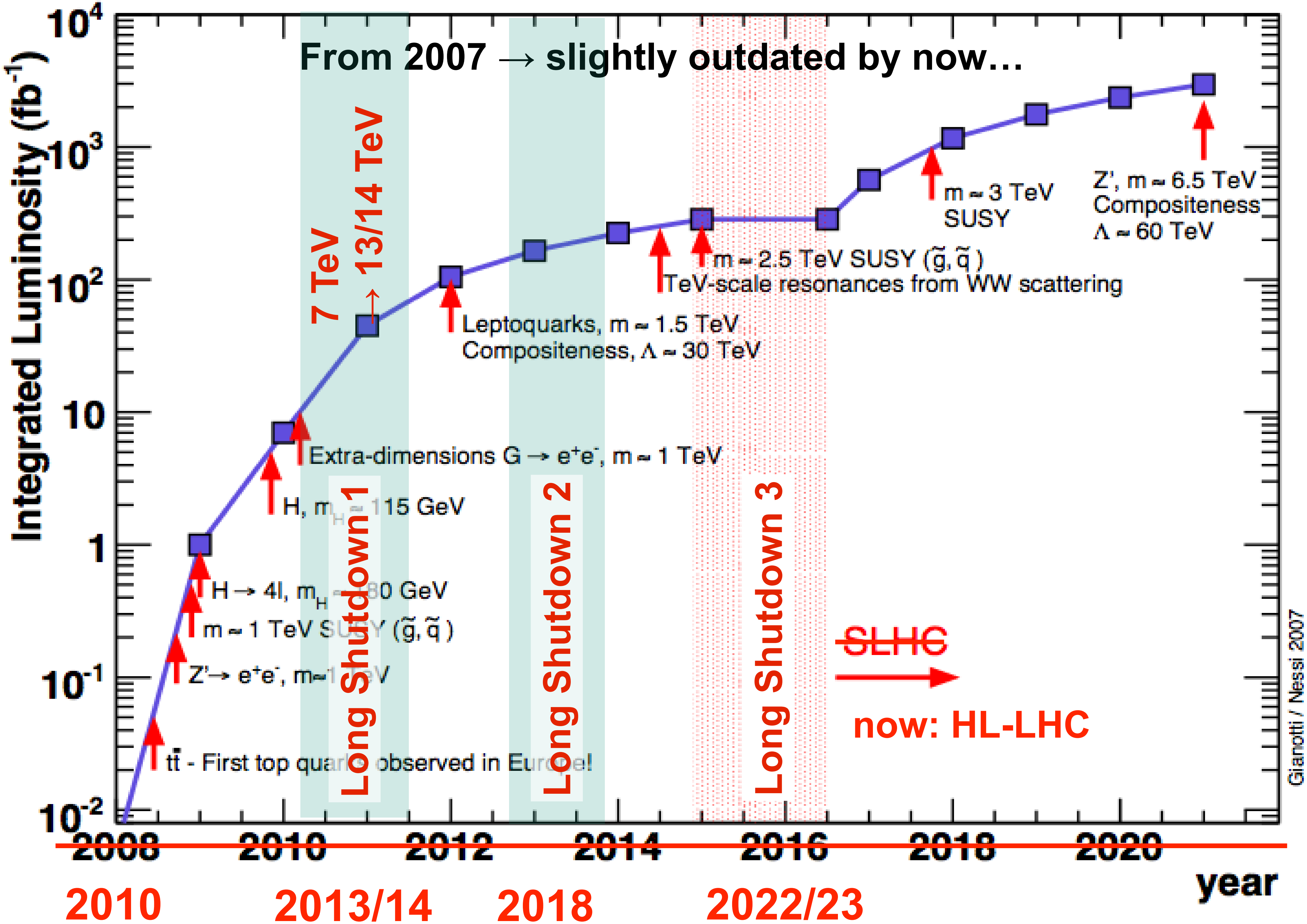
# LHC High Luminosity Upgrade: Physics Case





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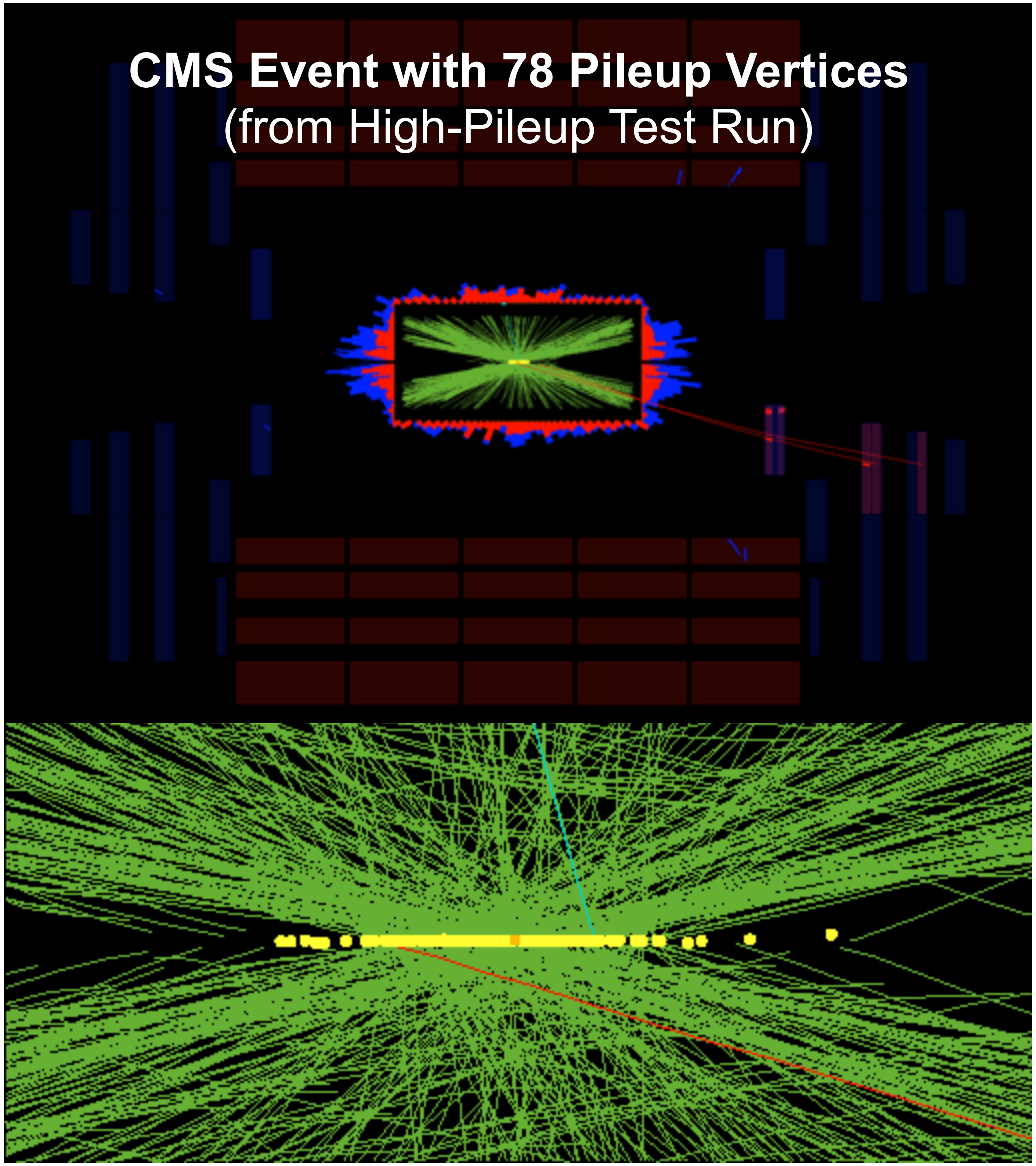
# Pileup

- High luminosity comes at a price: pileup
- LHC design luminosity: 2808 proton bunches/ beam, 25 ns spacing → 25 pileup vertices
- Pileup 2012: 1380 bunches/beam, 50 ns spacing → 30+ pileup vertices
- Upgrade: expect 100–200 pileup vertices





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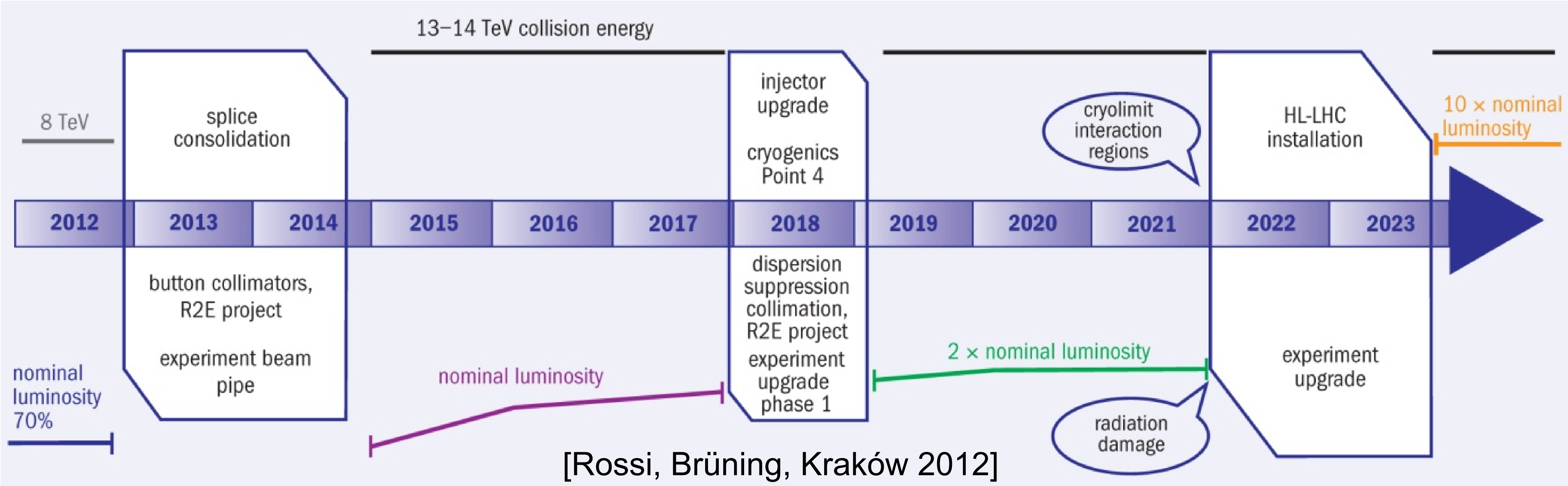
# High Luminosity LHC

- Goal: integrated luminosity 3000 $fb^{-1}$ at 14 TeV CM energy in 10–12 years
  - Peak luminosity: $5\times10^{34}$ $cm^{-2}$ $s^{-1}$ → 5× LHC design
  - 25 ns bunch spacing → 140 pileup vertices
- Successful upgrade of accelerator chain: many projects
  - Consolidation: magnets, cryogenics, collimation, electronics, machine protection
  - Modifications: injector, new (quadrupole) magnets, collimators, crab cavities



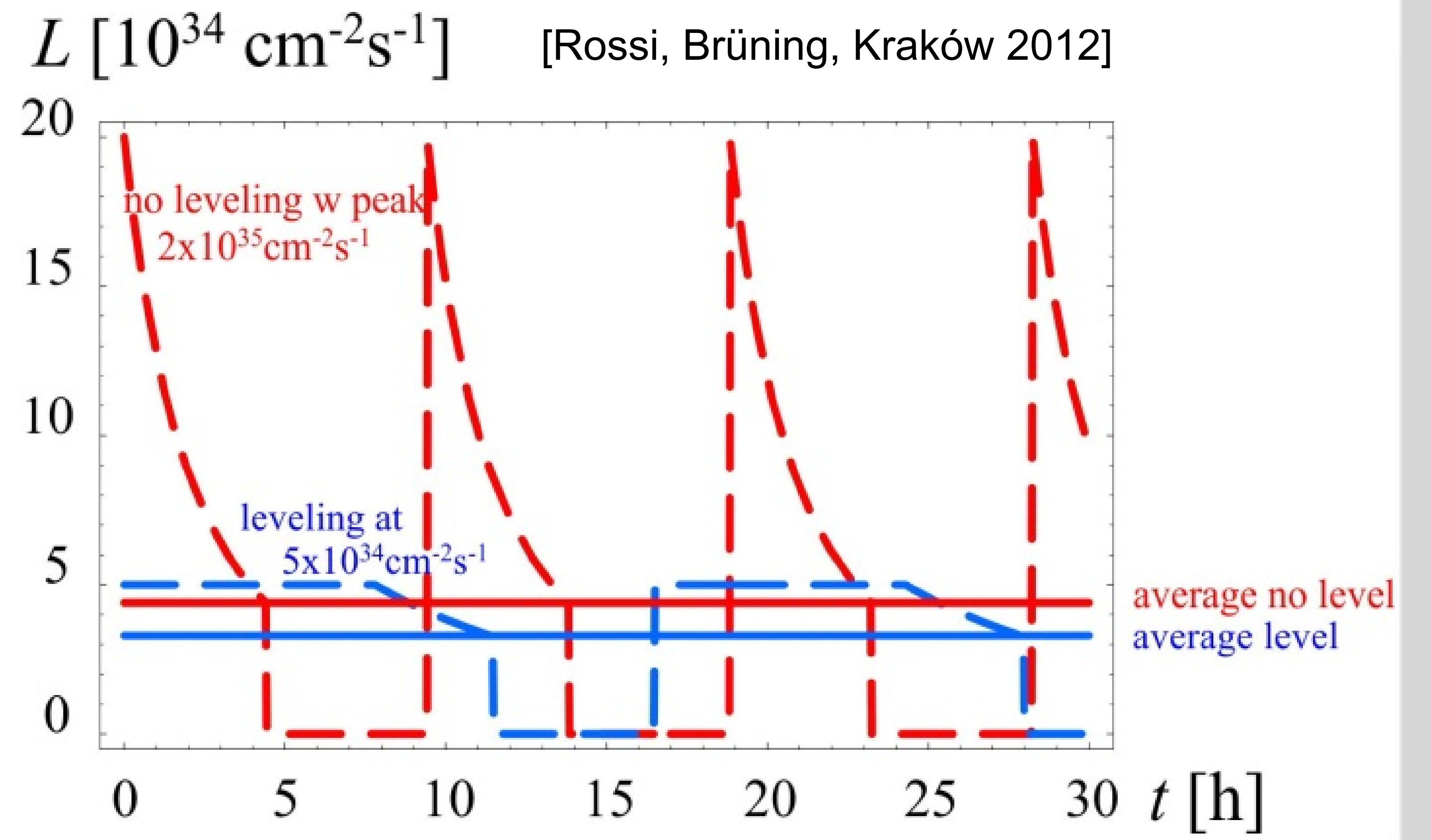

[Rossi, Brüning, Kraków 2012]

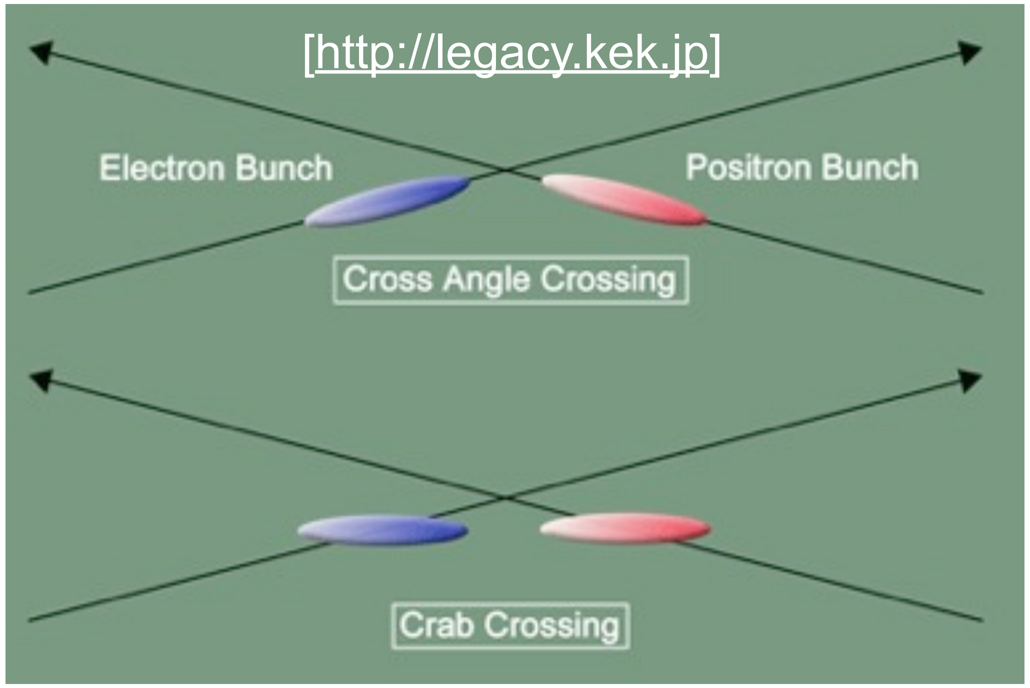
"Phase 0" "Phase 1" "Phase 2"

# Accelerator Upgrade: Some Examples

- Luminosity leveling
  - Very high luminosities: high pileup, short beam lifetime
  - Solution: keep luminosity at approx. constant level during fill (already done today at ALICE and LHCb)
- Higher luminosity achievable by crab crossing of bunches
  - RF cavities “turn” bunches sideways → bunches collide head-on
  - Successfully used in $e^+e^-$ (KEKB), not yet in pp

[Rossi, Brüning, Kraków 2012]

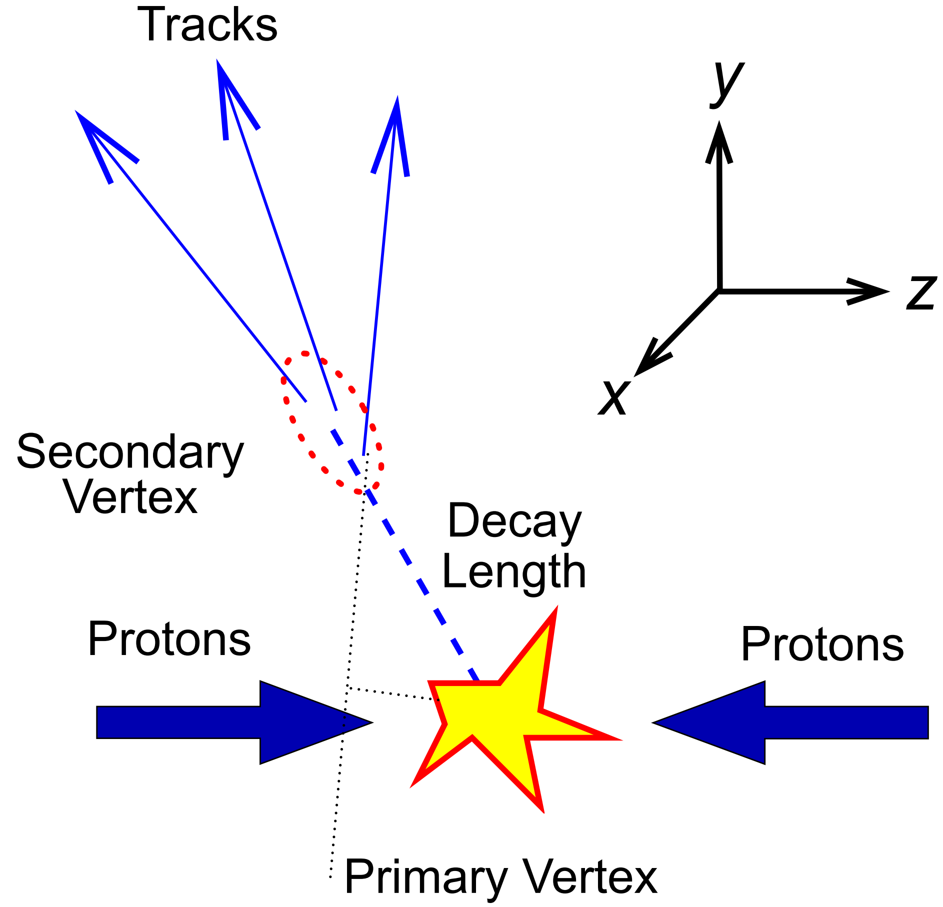


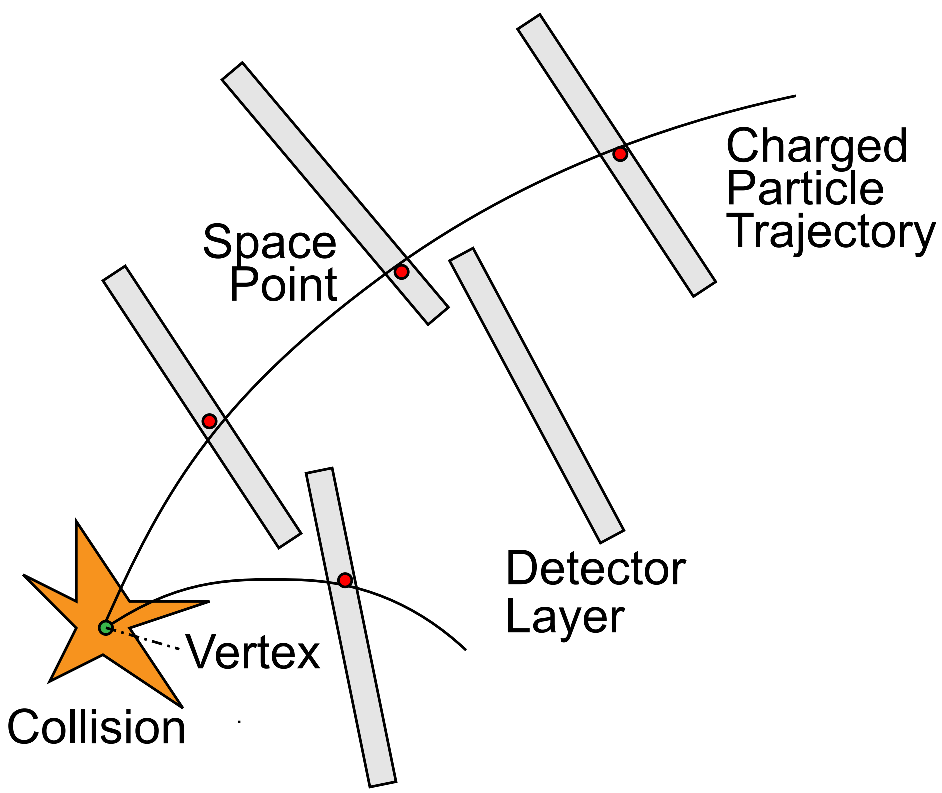



# ATLAS and CMS Upgrades

# Tracking, Vertexing, and B-Tagging

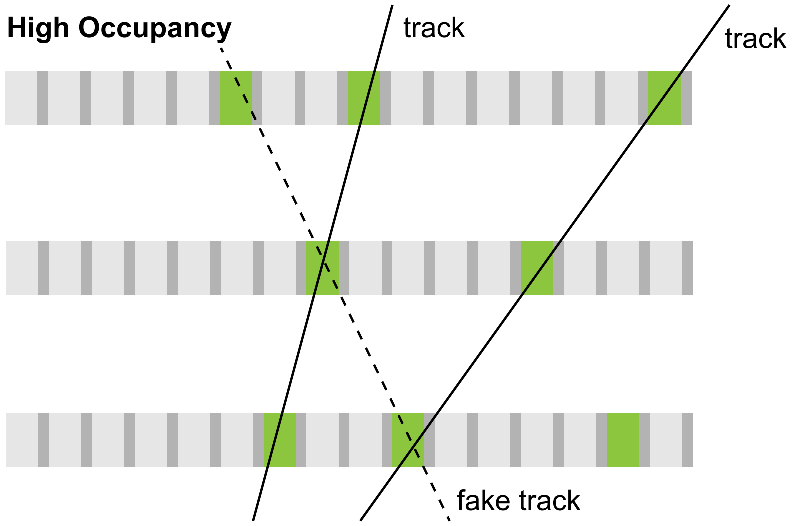
- Tracking & vertexing
  - Charged particle tracking at small distances (~5 cm) from collision point: precise reconstruction of vertices
  - Charged particle tracking at large distances (~1 m): precise momentum measurement

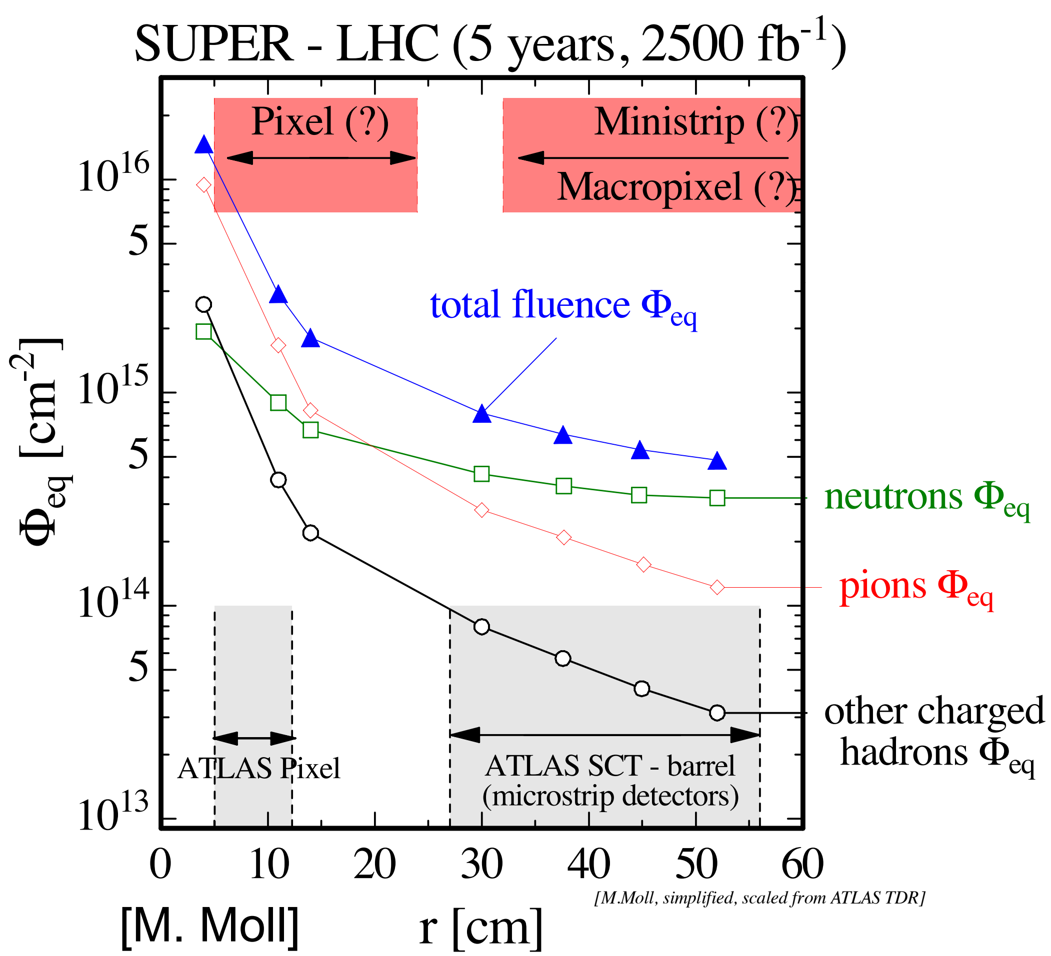



- B-tagging:
  - Identify hadrons with b-quarks via their long lifetimes (picoseconds)
  - Parts of the tracks from B hadron decays: large impact parameters and/or displaced secondary vertex
  - Low particle momenta important

# High-Luminosity Challenges I: Radiation



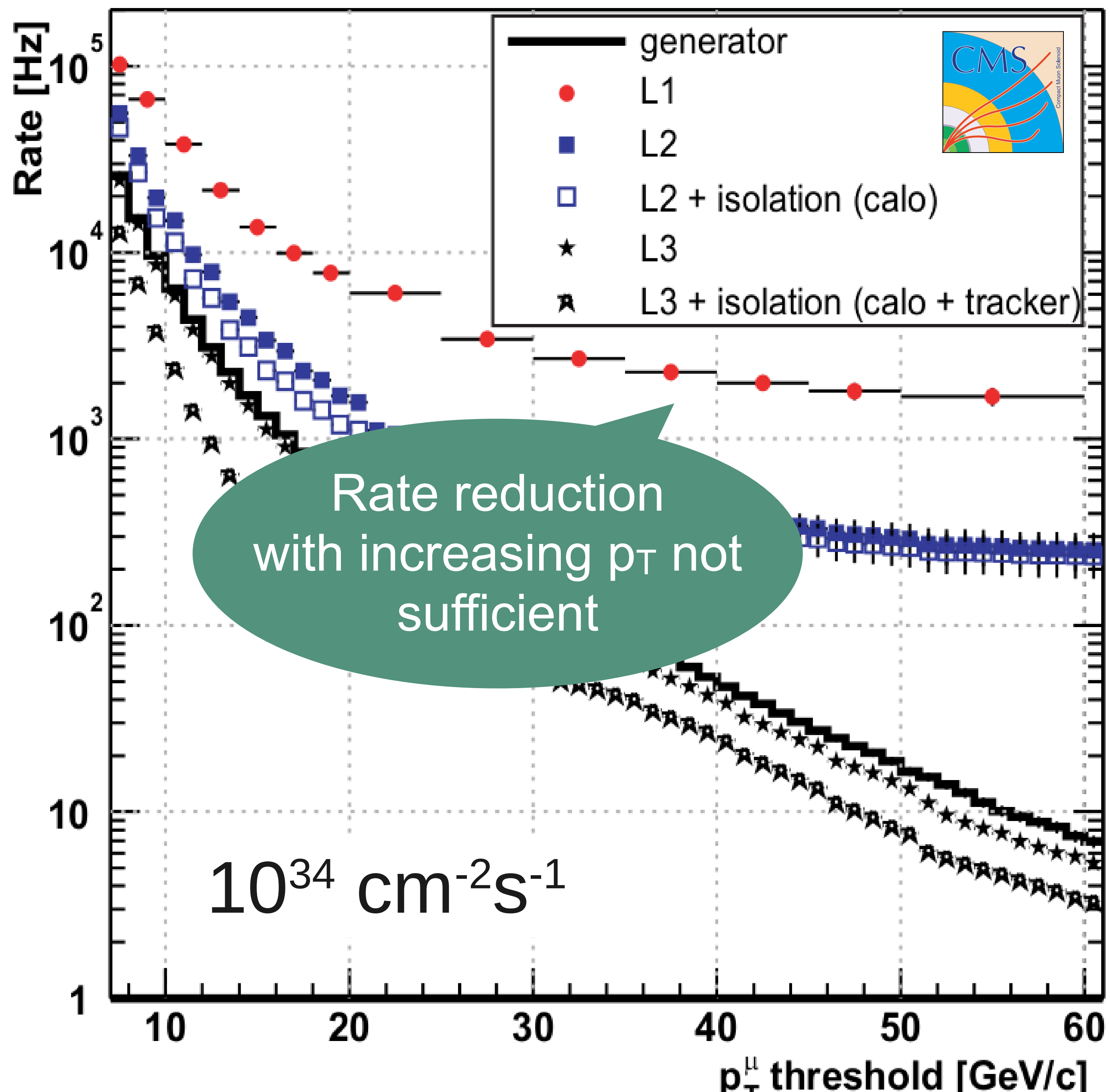

[M. Moll]

- At high luminosity:
  - High channel occupancy (= fraction of bunch crossings in which given channel fires)
  - Rule of thumb: tracking works up to occupancies of 1%
  - Solution: increase detector granularity
  - Constraints: material budget, power consumption, data transfer rates
- Radiation damage:
  - Aging of components closest to interacting point → limited lifetime
  - Solution: design radiation-hard detectors and electronics
  - Constraints: availability, cost

# High-Luminosity Challenges II: Trigger Rate

- Physics requirement: keep trigger thresholds for key objects low at high luminosity
- Simulations show: insufficient reduction of single lepton trigger rate with $p_T$ threshold
- Way outs:
  - Make existing triggers more granular
  - Use tracking information in trigger
- Challenge: process many more channels within same trigger latency

**Simulated μ Trigger Rates vs. $p_T$ Threshold**



# ATLAS Upgrade Matrix

| Subsystem | Phase 0 | Phase 1 | Phase 2 |
| --- | --- | --- | --- |
| **Silicon Pixel** | New Beam Pipe, Insertable B-Layer | – | New Tracker |
| **Silicon Strips** | – | – | New Tracker |
| **Electromagnetic Calorimeter** | Consolidation | Finer Granularity in Trigger | New Electronics, Forward Cal |
| **Hadronic Calorimeter** | – | – | New Electronics, Forward Cal |
| **Muon System** | Endcap Extension | Small Wheels (Forward) | – |
| **Trigger** | – | Topological Triggers, Fast Track Trigger | Complete Replacement |

+ several smaller projects

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# CMS Upgrade Matrix

| Subsystem | Phase 0 | Phase 1 | Phase 2 |
|---|---|---|---|
| **Silicon Pixel** | New Beam Pipe | New Pixel Detector | New Tracker |
| **Silicon Strips** | Consolidation | – | New Tracker |
| **Electromagnetic Calorimeter** | – | Improved Trigger Primitives | ? |
| **Hadronic Calorimeter** | New Photon Detection | New Electronics & Photon Detection | ? |
| **Muon System** | Complete Coverage | Improve Trigger, Prepare Electronics | New Electronics |
| **Trigger** | – | New L1 Trigger | Complete Replacement |

+ several smaller projects

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| --- | --- | --- | --- |
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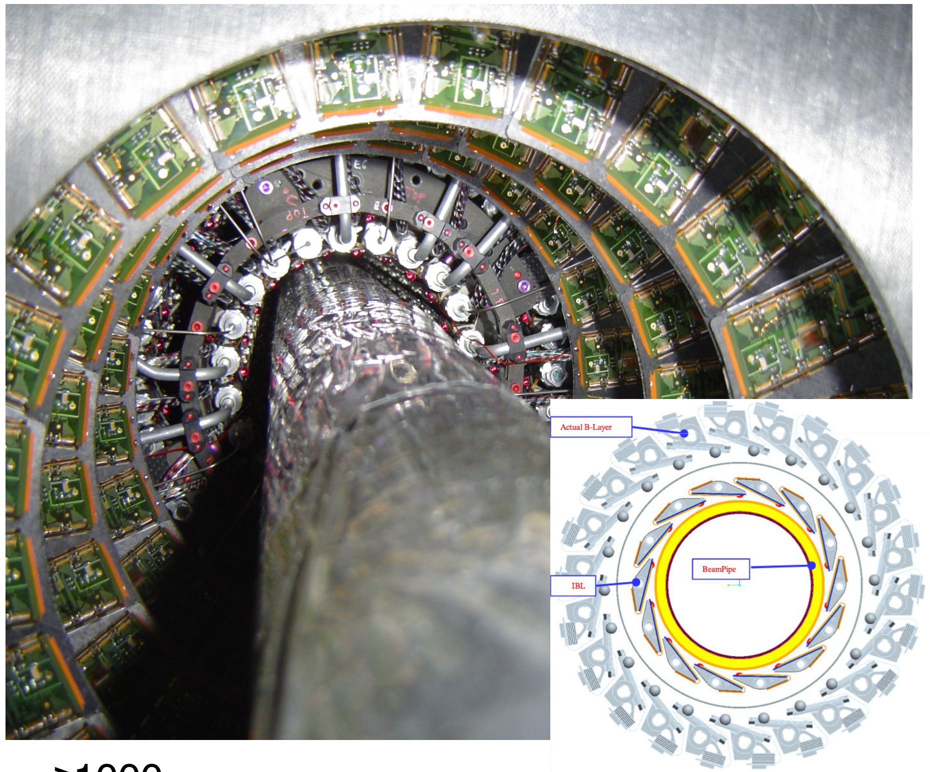
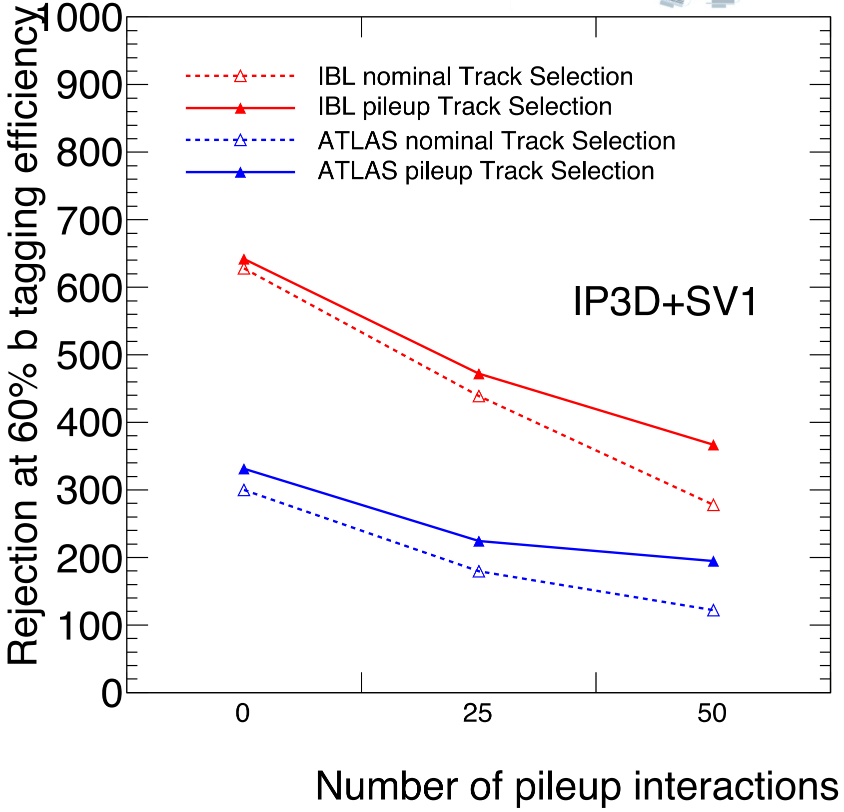
| **Hadronic Calorimeter** | New Photon Detection | New Electronics & Photon Detection | ? |
| **Muon System** | Complete Coverage | Improve Trigger, Prepare Electronics | New Electronics |
| **Trigger** | – | New L1 Trigger | Complete Replacement |

+ several smaller projects

# ATLAS Insertable B-Layer (IBL)

- Goals:
  - Add redundancy to current pixel detector
  - Improve tracking, vertexing, b-tagging for high pileup
  - Establish new technology for HL-LHC
- Solution: Insertable B-Layer
  - 4th pixel detector layer, sensors at r = 33 mm
  - New readout chip, advanced planar and 3D pixel sensors
  - Very low material budget: 0.015 $X_0$
- Installation: LS1 (2013/2014)




[CERN-LHCC-2010-013]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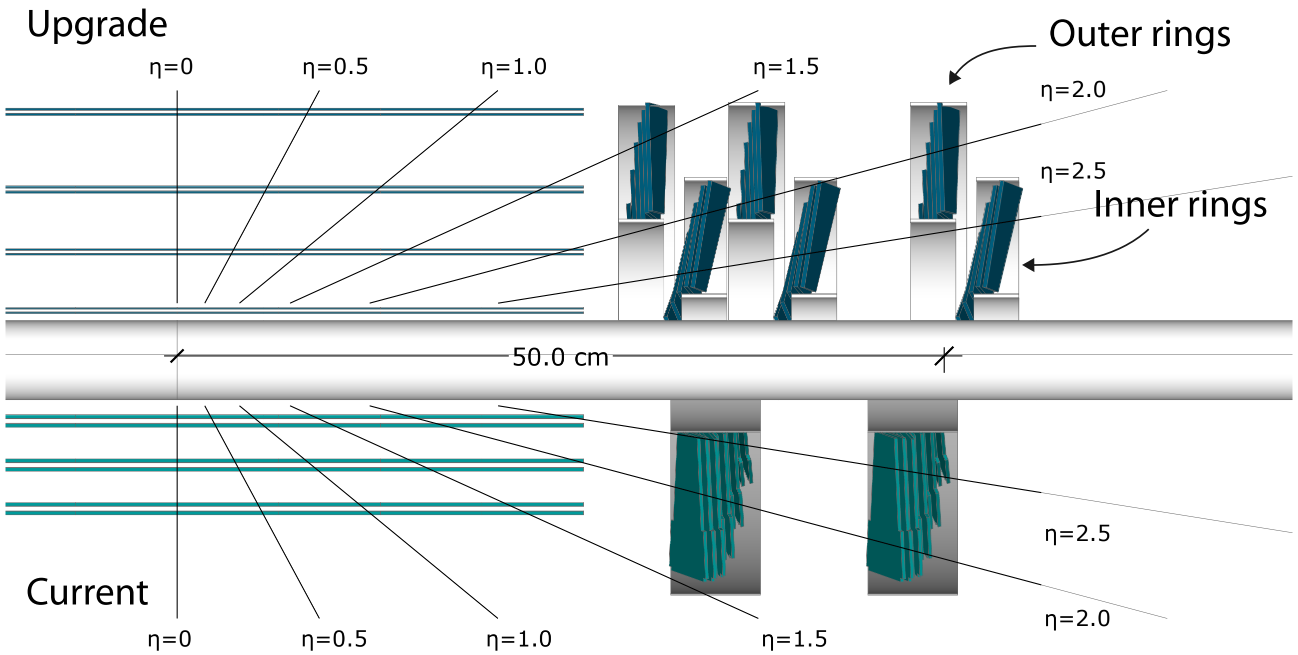
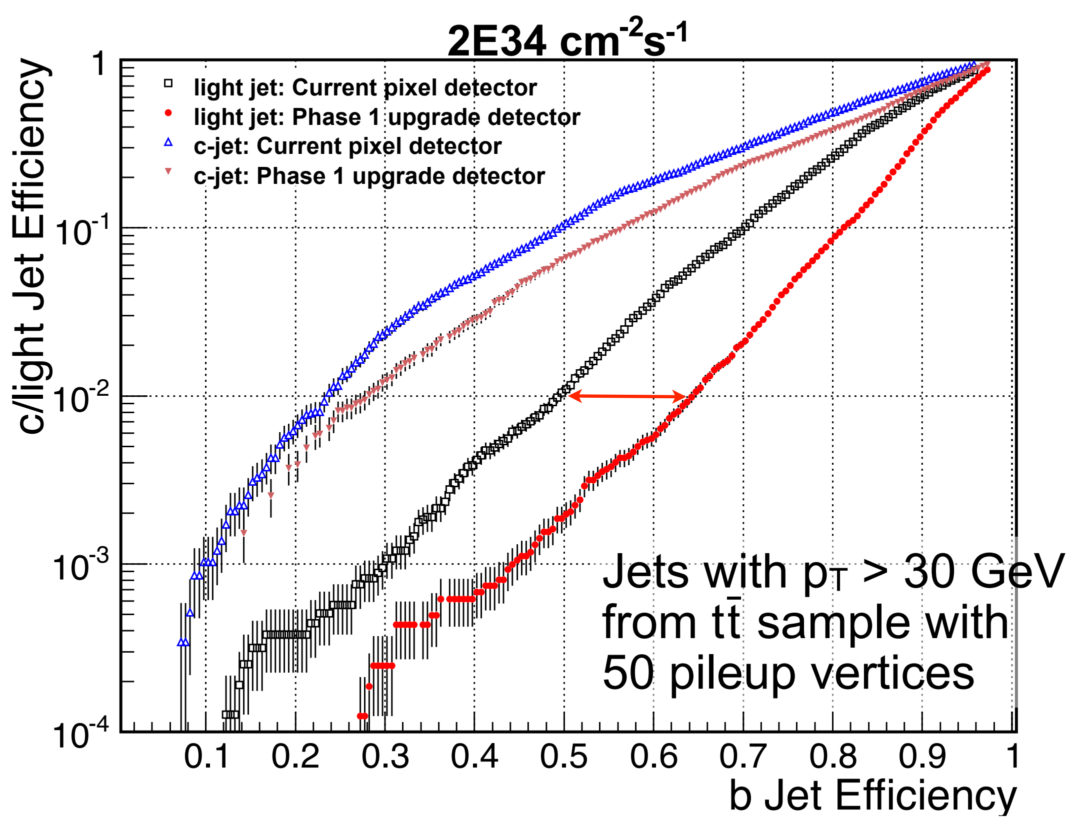
# Upgrade of CMS Silicon Pixel Detector




[CERN-LHCC-2012-016]

- Goal: similar performance in much harsher environment
  → tracking, vertexing, b-tagging, …
- Solution: four-layer pixel detector
  - Innermost radius: 29 mm
  - New digital readout chip
  - Ultra-lightweight mechanics, $CO_2$ cooling → reduced material budget: 0.015 $X_0$ per layer
- Installation
  - LS1: new beampipe
  - Modular design: Installation during year-end technical stop (planned for 2016/2017)



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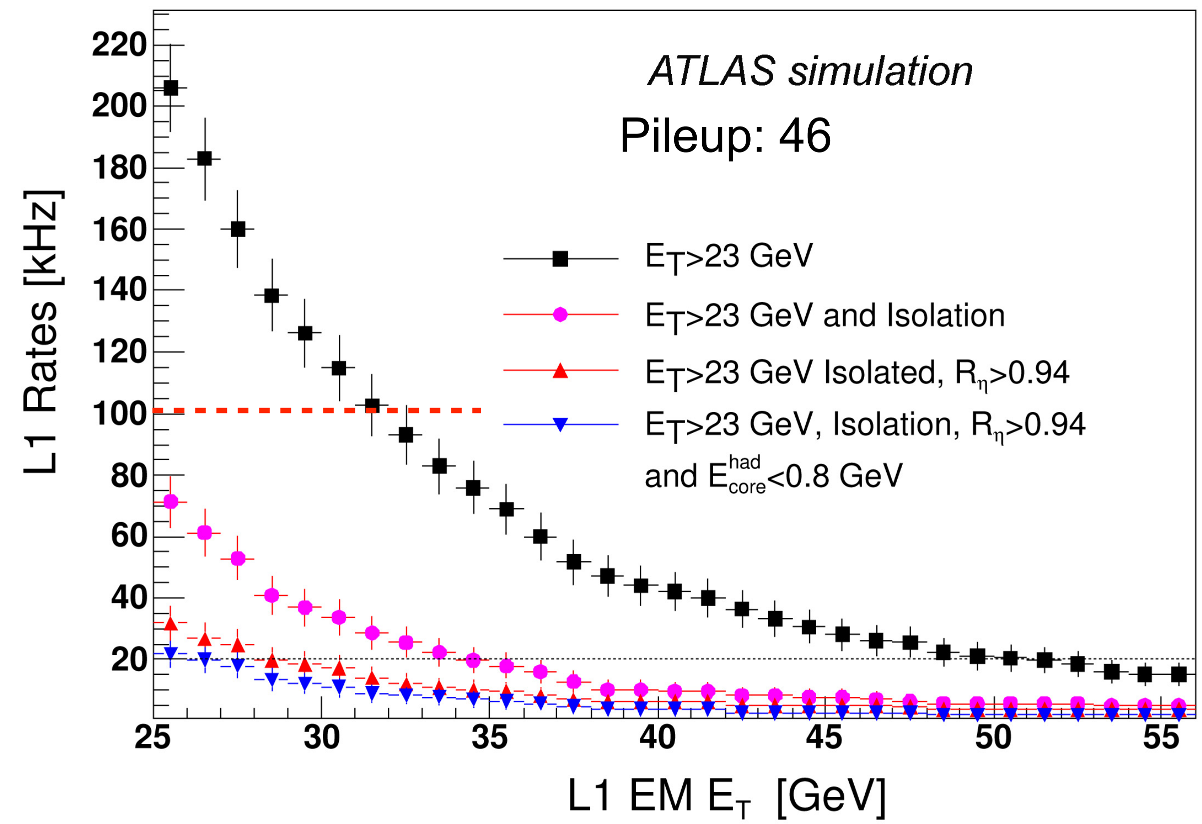
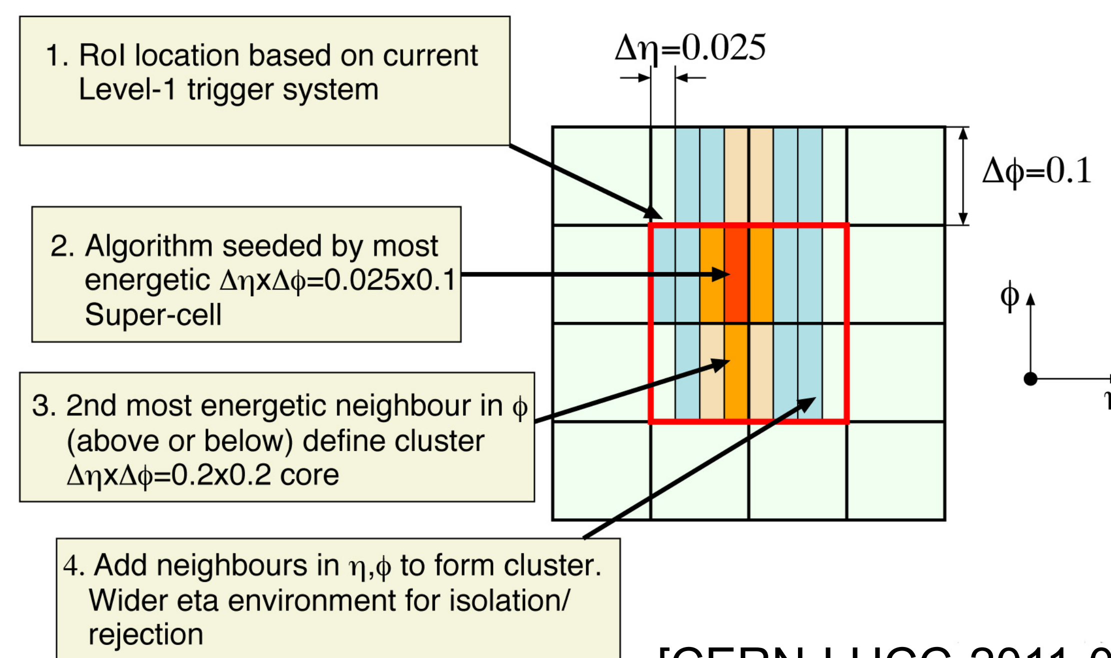
# ATLAS Calorimeter Trigger

- Goal: keep electron trigger thresholds low
- Solution: improve electron-jet discrimination
  - Improved L1 calorimeter trigger granularity (currently: $\Delta\eta\times\Delta\varphi = 0.1\times0.1$)
  - Better discrimination via shower shape algorithms already at L1
  - New "tower builder board"
  - New digital processing (replacing analog sums) to prepare for HL-LHC
- Installation:
  - LS1: slice of new system for tests
  - LS2: full installation




[CERN-LHCC-2011-012]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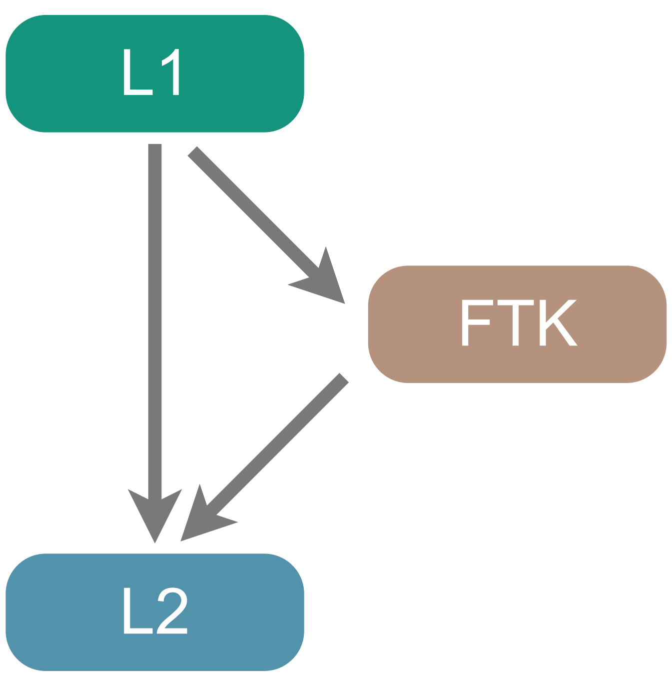
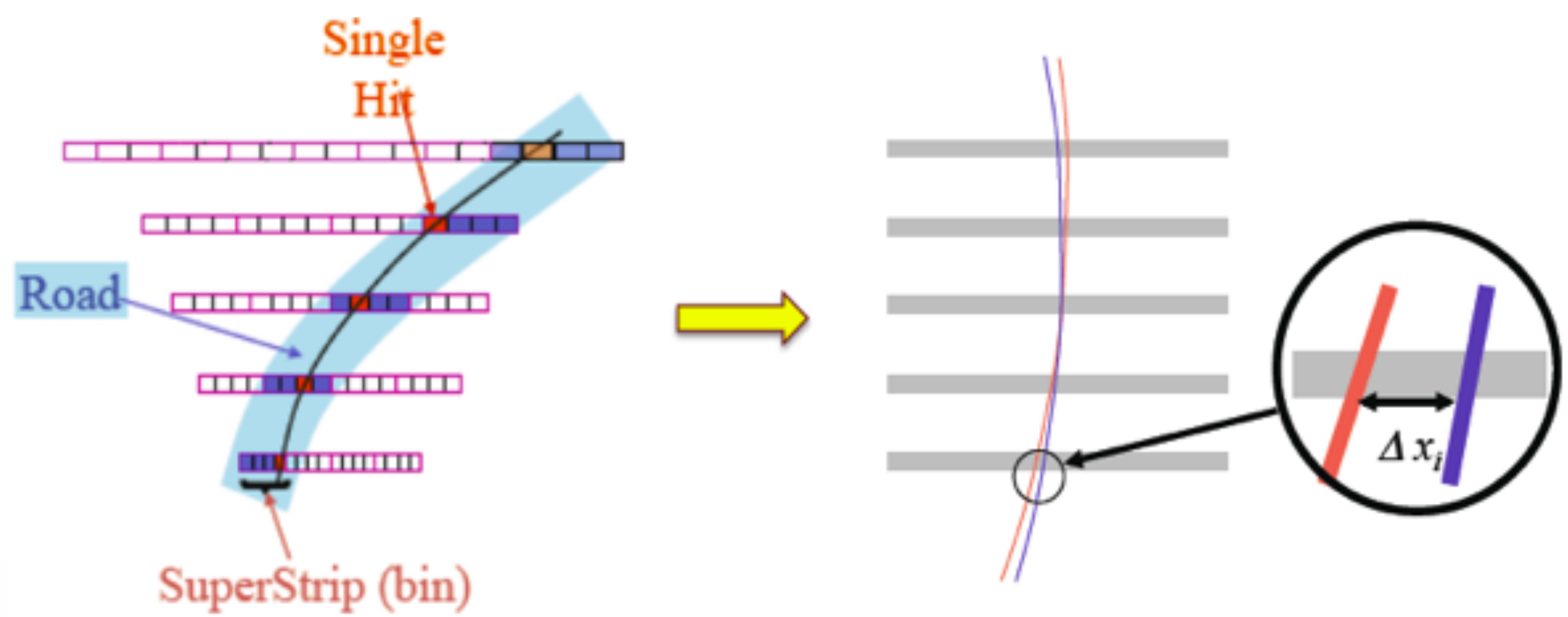
# ATLAS Fast TracKer (FTK)

- Goal: improve triggering at high luminosity (esp. track-based triggers)
- Solution: "level-1.5" trigger
  - After L1 trigger accept: send silicon pixel & strip data to fast processors for pattern recognition and tracking → provide tracking information for L2 procesors
  - Key technology: associative memory




**Pattern recognition in coarse resolution (superstrip→road)**

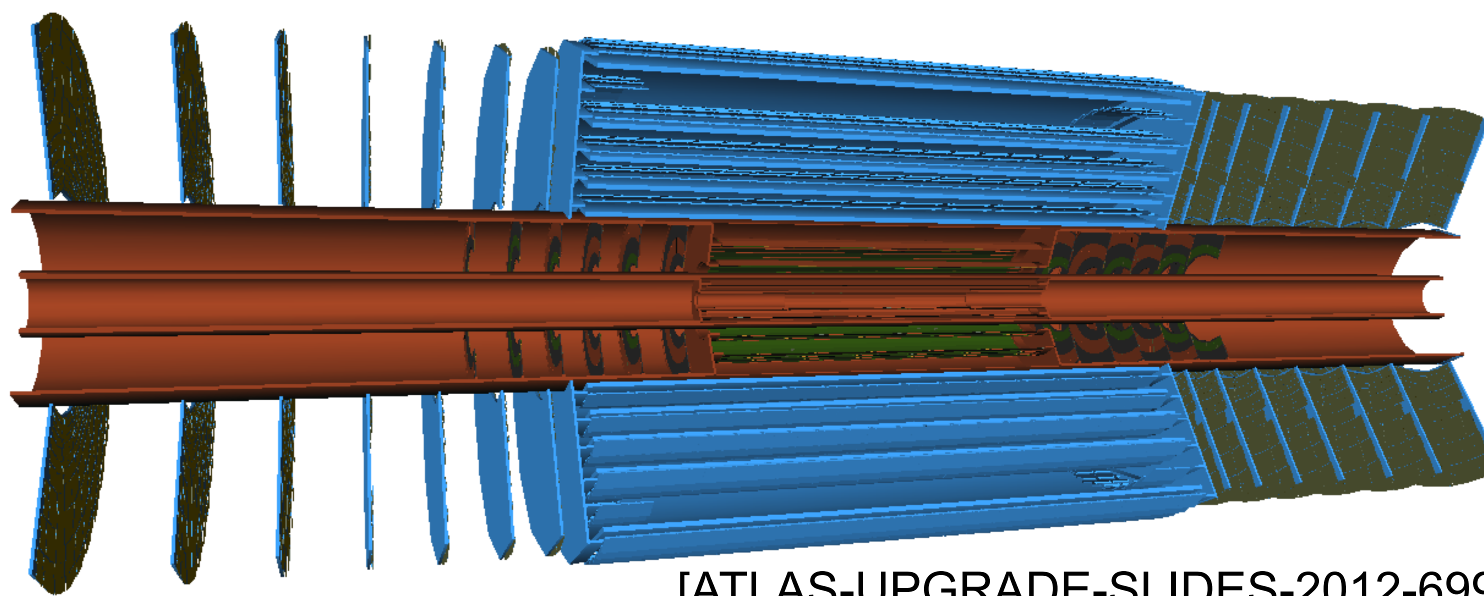
**Track fit in full resolution (hits in a road)**

$$F(x_1, x_2, x_3, \ldots) \sim a_0 + a_1\Delta x_1 + a_2\Delta x_2 + a_3\Delta x_3 + \ldots = 0$$

# ATLAS & CMS Trackers for HL-LHC

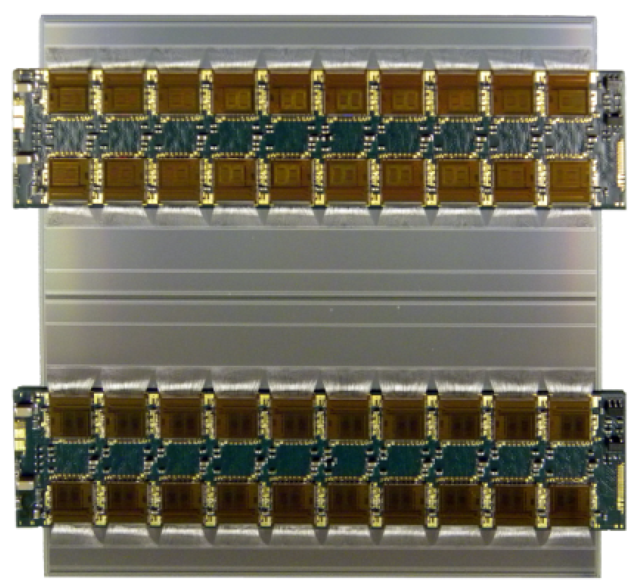
- ATLAS & CMS: replacement of entire tracker
  - End of lifetime for current trackers
  - Increase granularity, e.g. shorter silicon strips
  - New readout chips
  - New services: cooling ($CO_2$), powering (DC-DC or serial), …
- Extensive R&D programs ongoing
  - Robust light-weight detector designs (ATLAS)
  - Radiation hard silicon sensors (“HPK Campaign”, CMS)

**Current ATLAS Design: 4 Pixel + 5 Strip Layers (Barrel)**

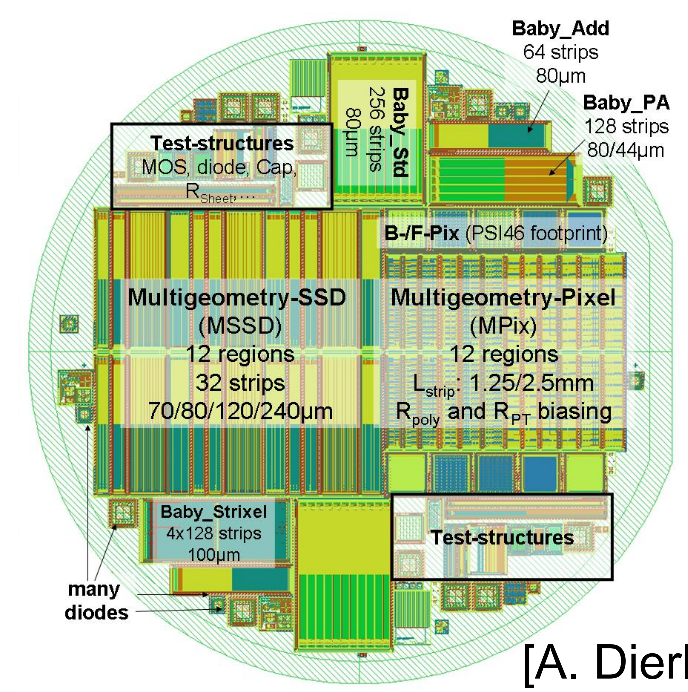


[ATLAS-UPGRADE-SLIDES-2012-699]

**ATLAS Prototype Module**



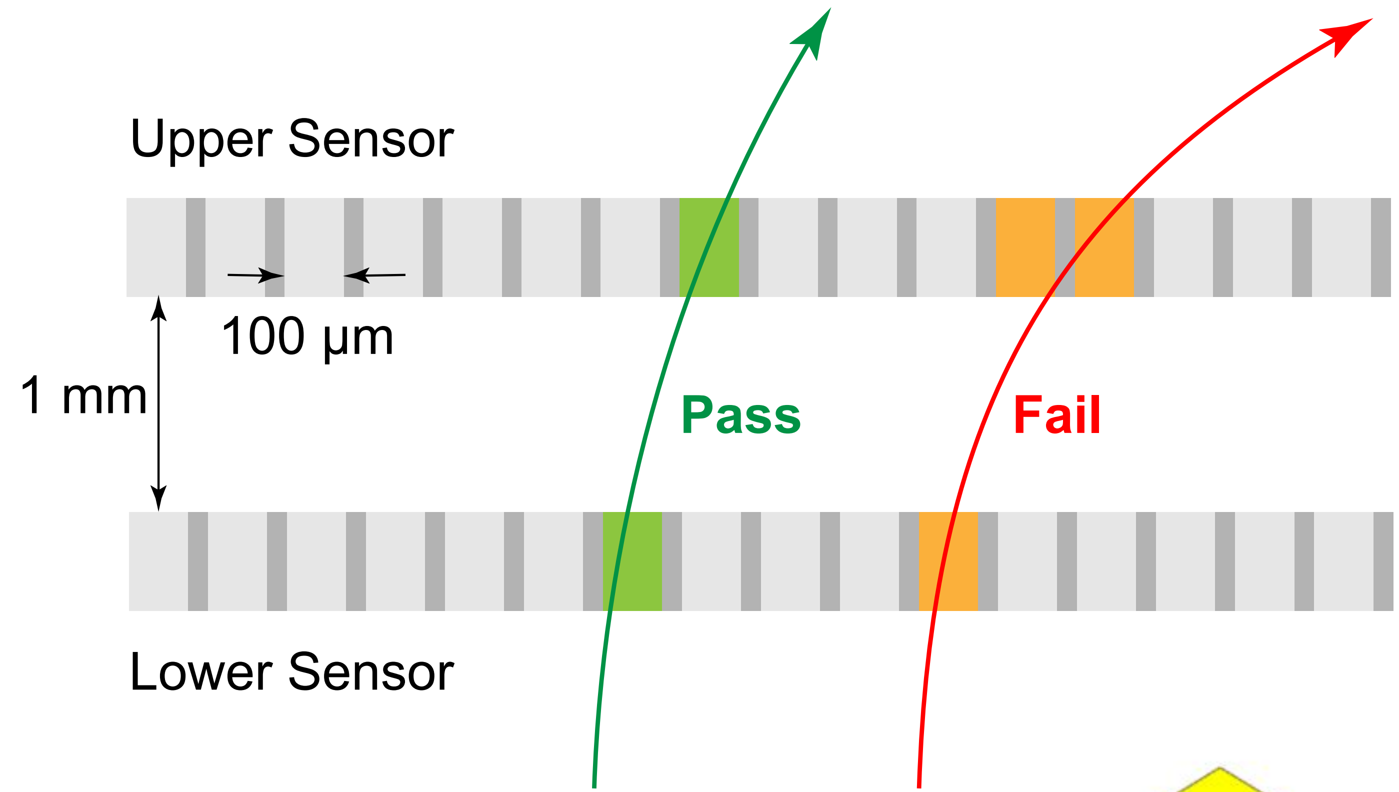
**CMS HKP Campaign Wafer**

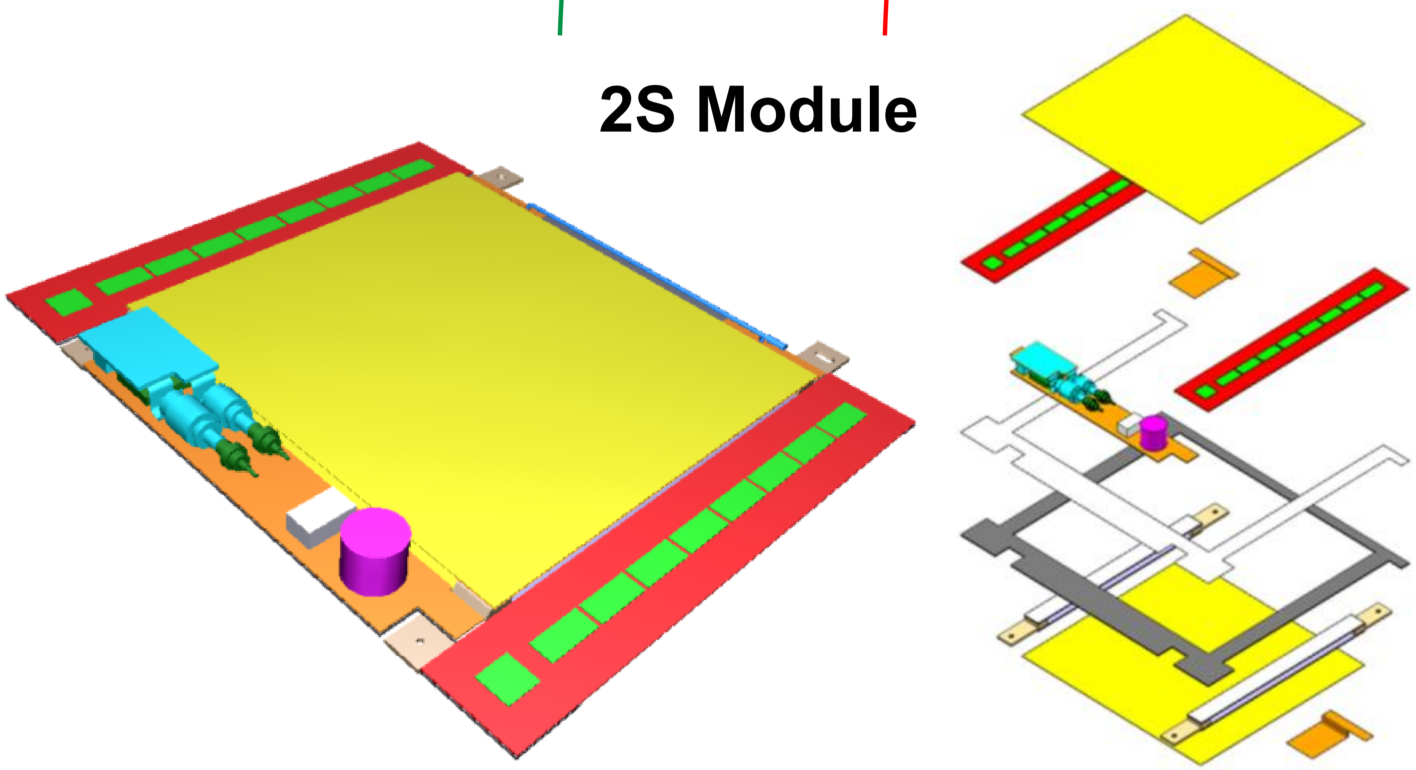



[A. Dierlamm]

# CMS Tracker Upgrade: $p_T$ Modules

- Goal: keep trigger thresholds for single lepton triggers low
- Idea: exploit tracking information in early trigger stages (L1)
- Novel concept: $p_T$ modules
  - Goal: suppression of low-$p_T$ tracks (< 1–2 GeV) for trigger
  - Idea: local coincidence of two sandwiched silicon detector layers
  - 2S modules (strips + strips) and/or PS modules (pixels + strips)





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# ALICE and LHCb Upgrades


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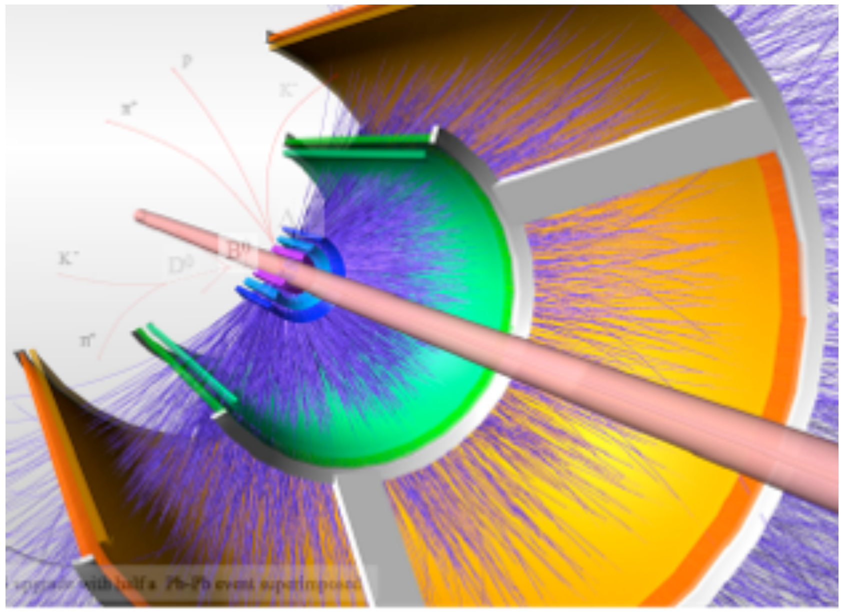
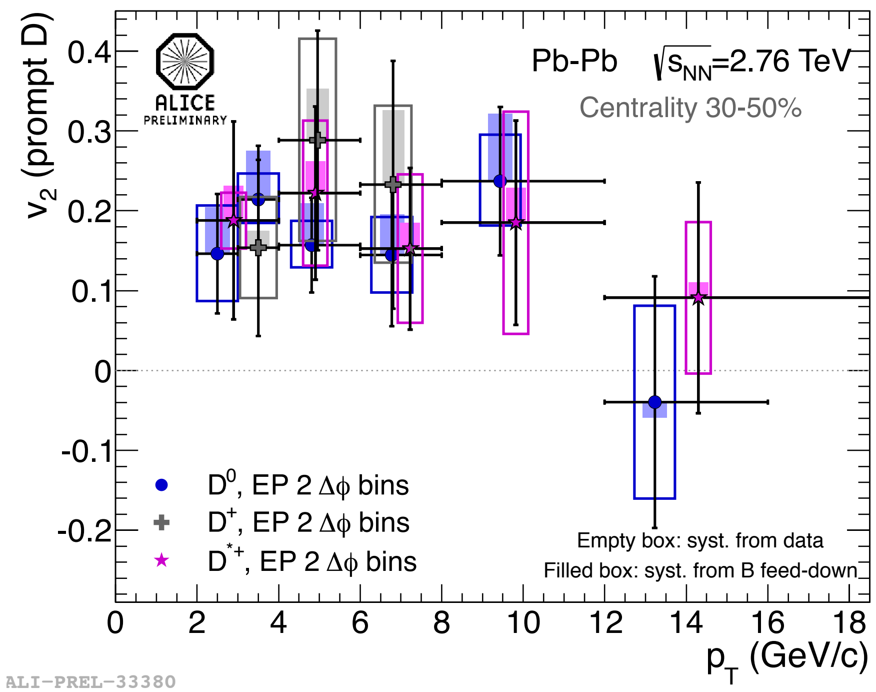
# The Case for ALICE Upgrades



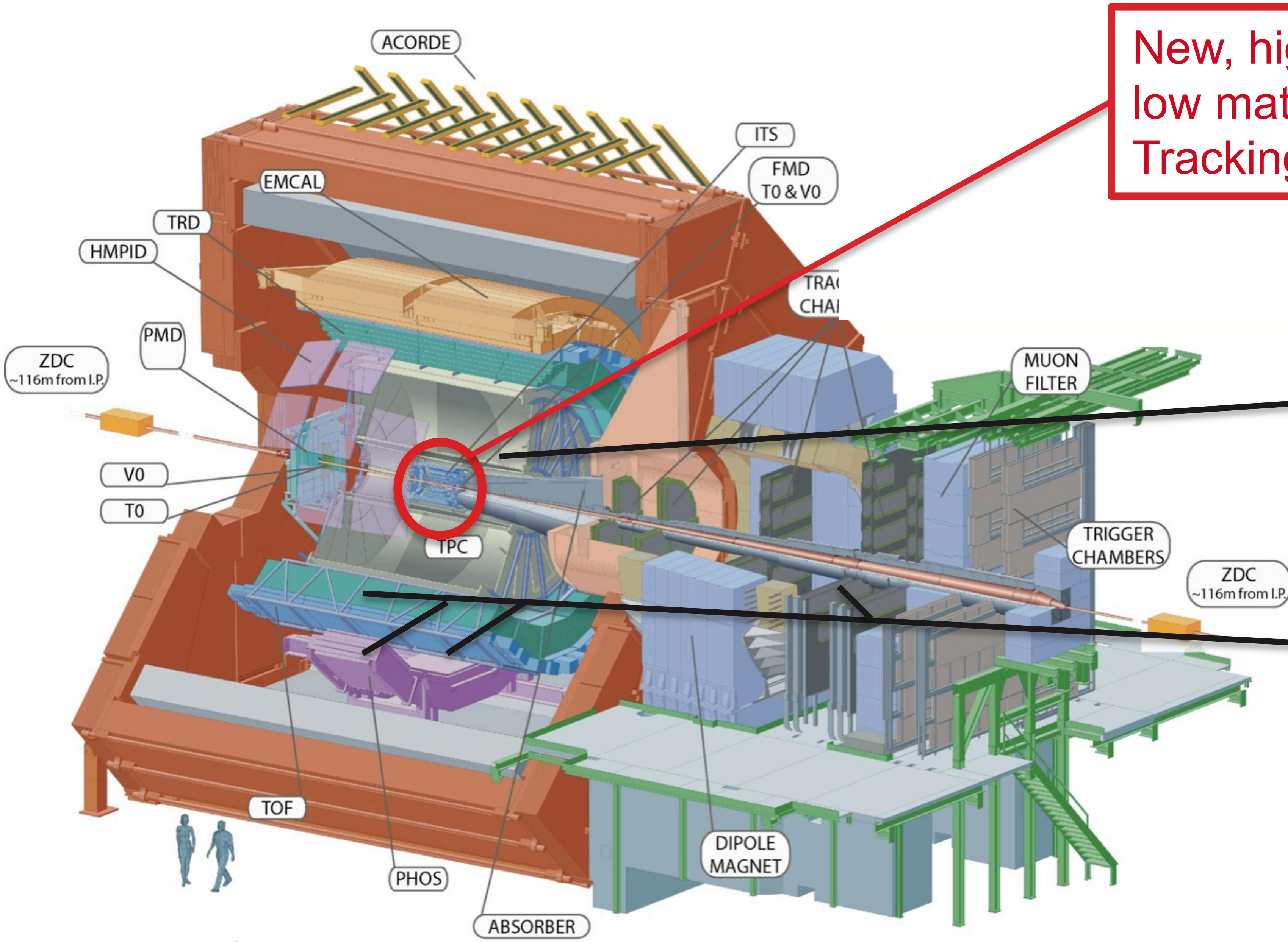
**Elliptic Flow of D Mesons**




[CERN-LHCC-2012-013]

- Upgrade: exploit physics topics uniquely accessible to ALICE
- Strongly coupled probes: heavy flavor hadrons and quarkonia
  - Physics: properties of quark-gluon plasma
  - Detector: tracking down to very low transverse momenta ($p_T$), excellent secondary vertex reconstruction
- Loosely coupled probes: low-mass dileptons
  - Physics: generation of hadron masses via chiral symmetry breaking
  - Detector: low material budget, low-$p_T$ tracking, lepton identification

# ALICE Upgrade Plans




[P. Riedler, CERN]

New, high-resolution and low material Inner Tracking System (ITS)

TPC upgrade: replace MPWCs with GEMs and new piplelined readout

Upgrade of readout electronics (TRD, TOF, PHOS, MUON)

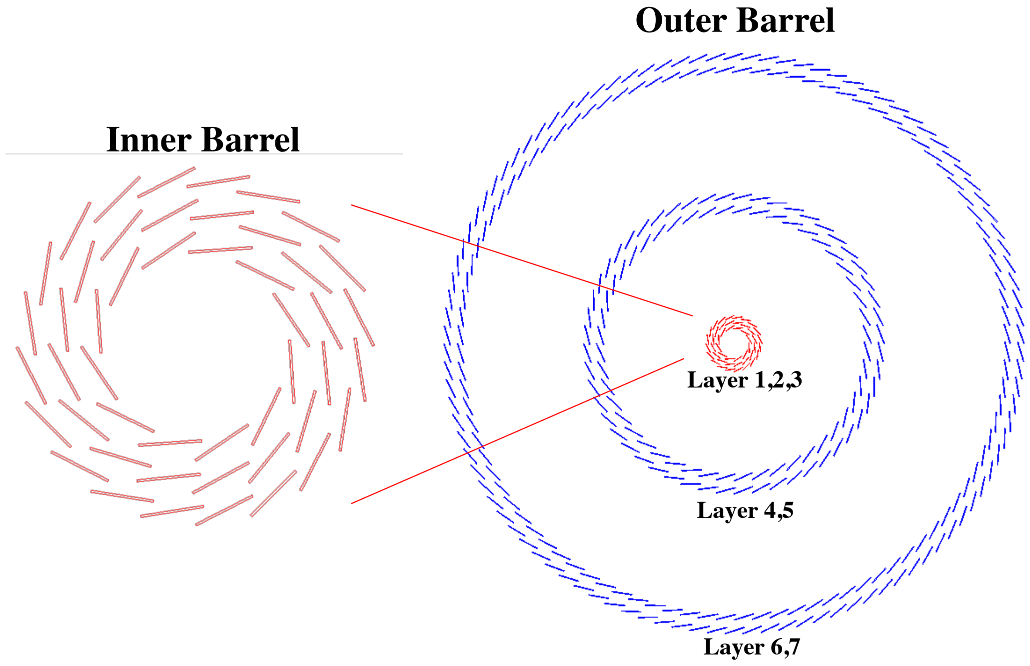
Upgrade of the forward trigger detectors

Upgrade of online systems and of offline reconstruction and analysis framework and code

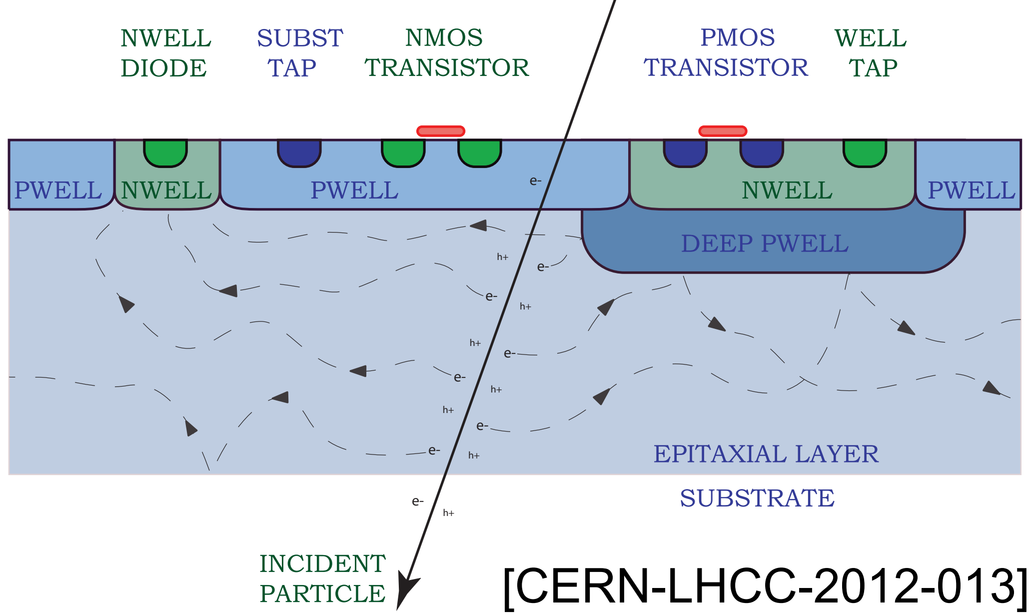
# Example: ALICE Tracking Upgrade

- Goal: improve impact parameter resolution and tracking efficiency
- Solution:
  - Move closer to interaction point: 22 mm
  - Reduce material budget: 0.003 $X_0$/layer
  - Increase granularity: 7 layers, smaller pixels
  - Fast readout (50 kHz), fast insertion/ removal
- Technology choices:
  - 7 pixel layers or 3 pixel + 4 strip layers
  - Option 1: hybrid pixels (current LHC pixel technology)
  - Option 2: monolithic pixels (sensing layer integrated into CMOS chip)

**Schematic Layout**




**Monolithic Pixels (0.18 µm CMOS)**




[CERN-LHCC-2012-013]



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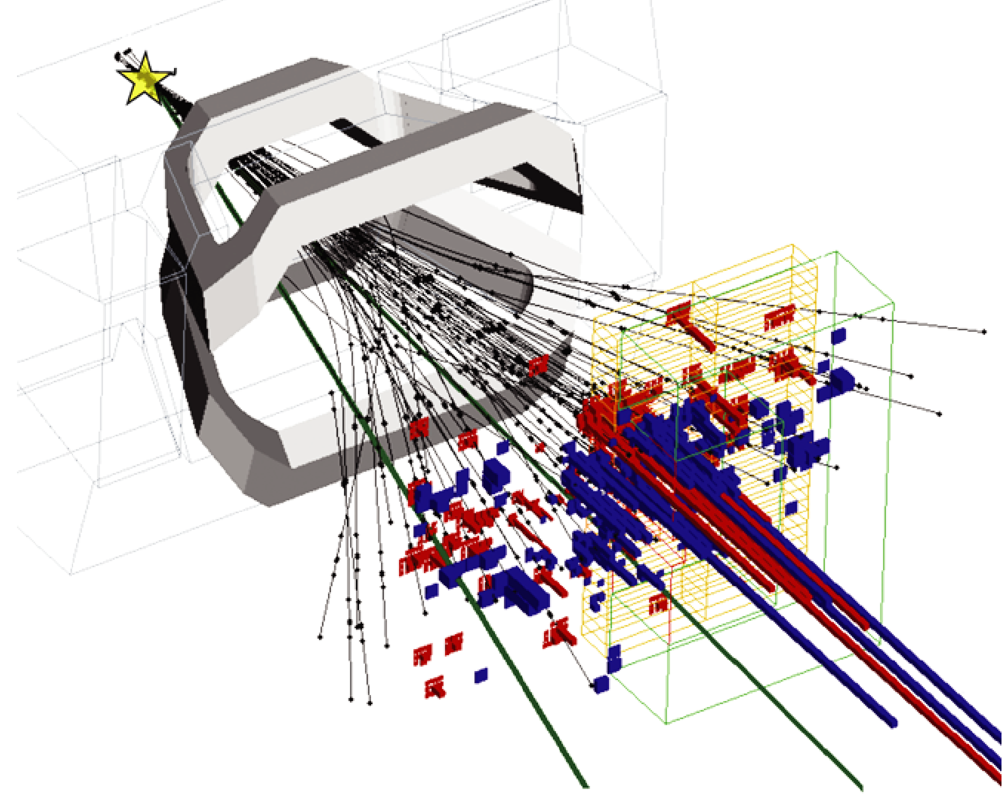
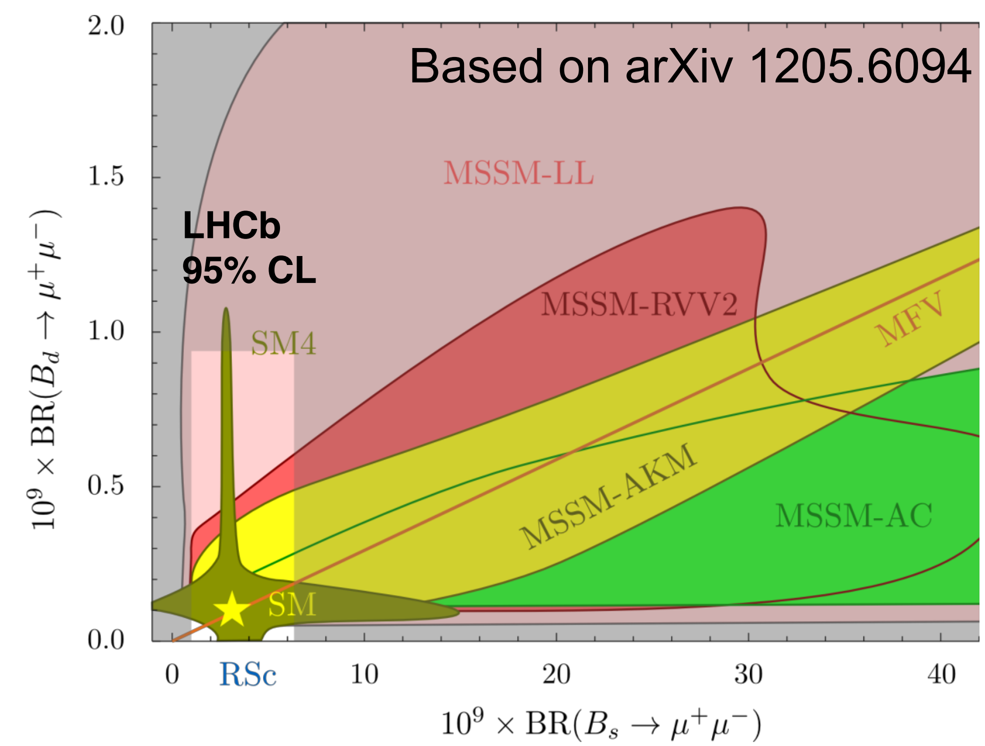
# The Case for LHCb Upgrades

- LHCb rates:
  - Rate limitation: 1 $fb^{-1}$ per year
  - Upgrade: running at $10^{33}$ $cm^{-2}$ $s^{-1}$ with 40 MHz readout → 5 $fb^{-1}$ per year
- Many extensions to physics program
  - Complementary to Belle II: $B_s$, B baryons
  - Mixing-induced CPV in $B_s \to J/\psi\ \varphi$
  - Charmless hadronic B decays
    $B_s \to K^{*0} K^{*0}$
    → CP angle γ at tree level to 1°
  - Rare decays: $B/B_s \to \mu\mu$, $B \to K^* \mu\mu$
  - Charm physics, lepton flavor physics, weak mixing angle, …
- Upgrades not tied to LHC upgrades



[CERN-LHCC-2011-001]




[M. Perrin-Terrin]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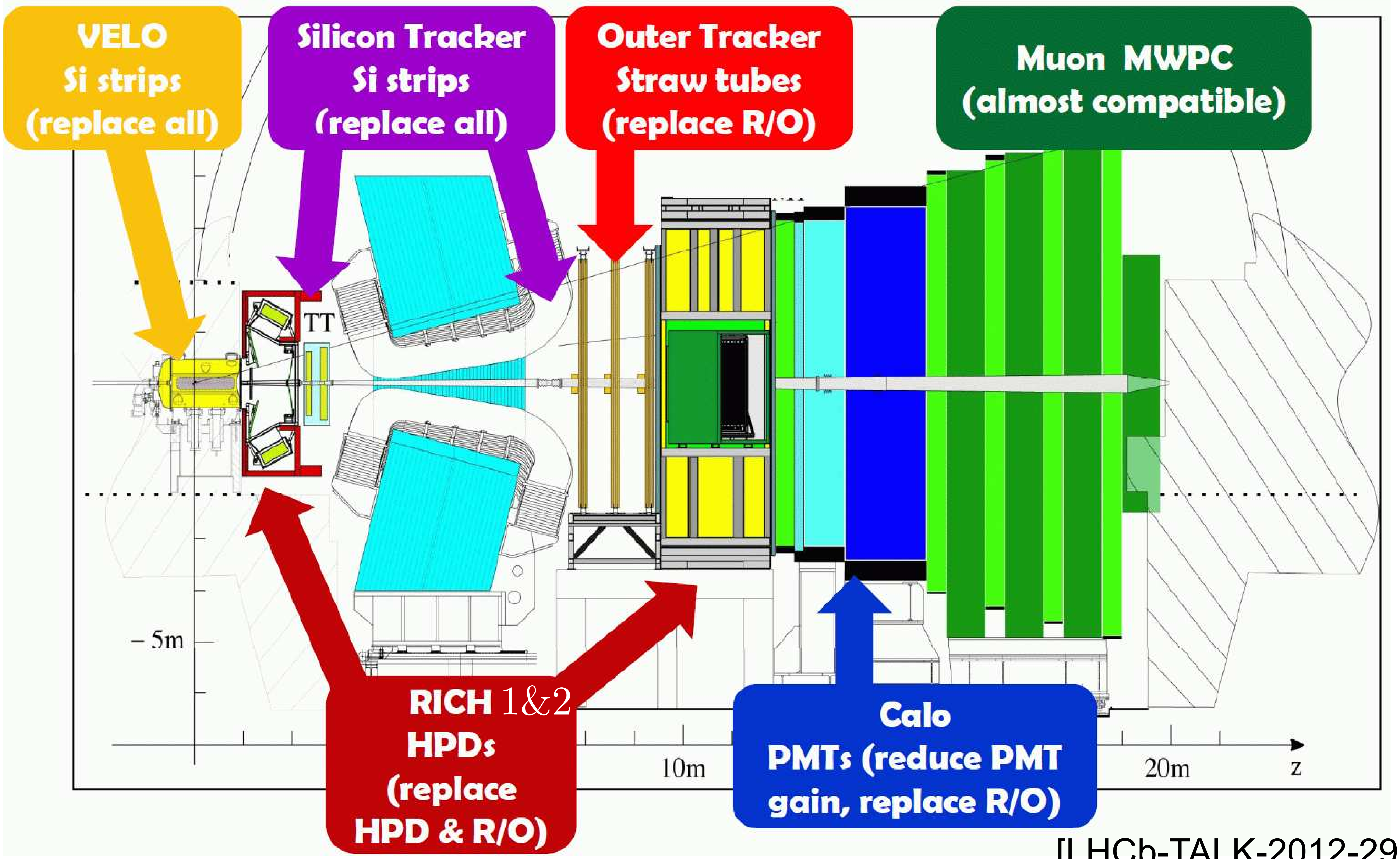
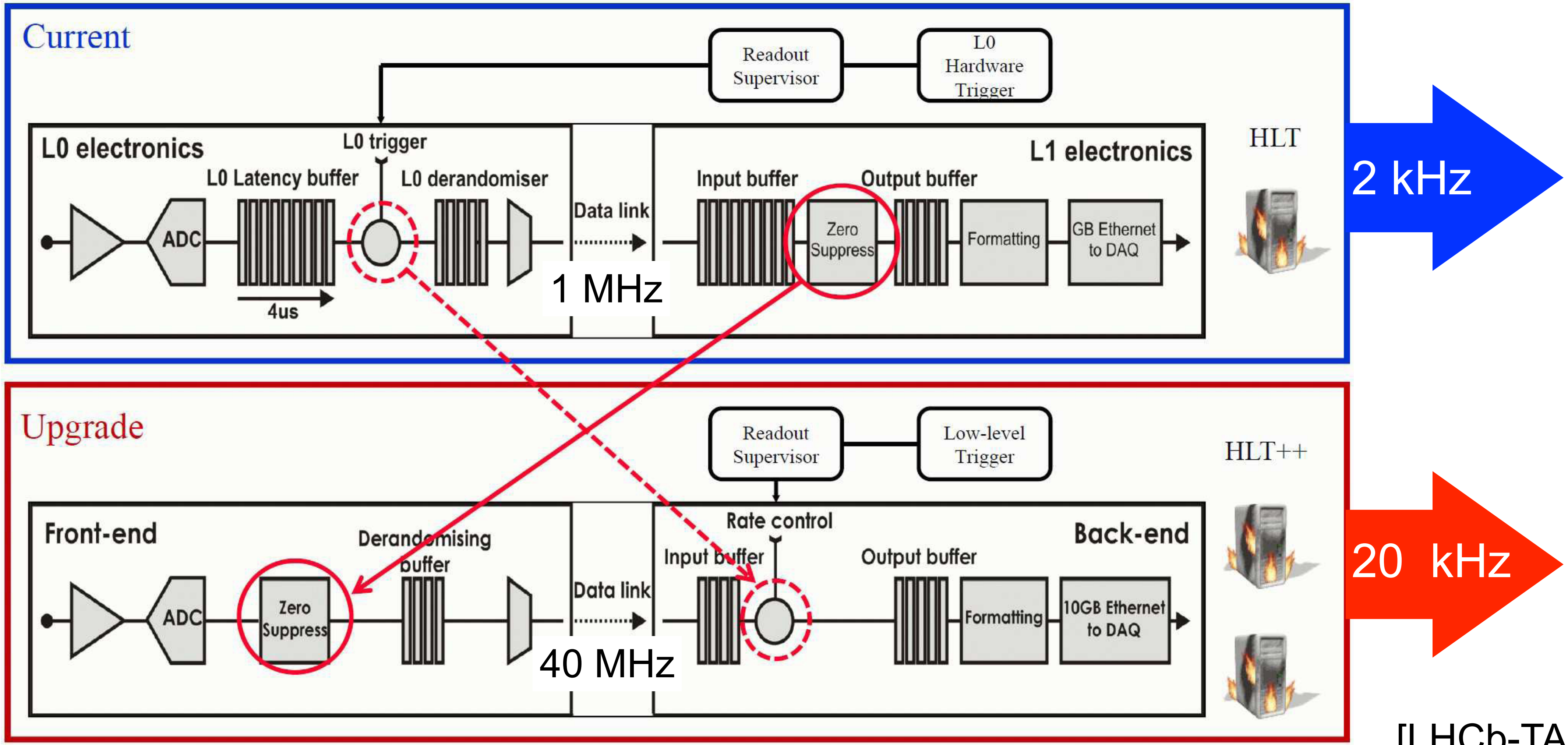
# LHCb Upgrade Plans




[LHCb-TALK-2012-299]

# Example: LHCb DAQ/Trigger Upgrade

- L0 hardware trigger upgraded to low-level trigger (LLT)
  - 1–40 MHz trigger-less readout to high-level trigger (HLT)
  - Replace all front-end electronics (except muon system)
- HLT: full event selection in software → 20 kHz output rate




[LHCb-TALK-2012-299]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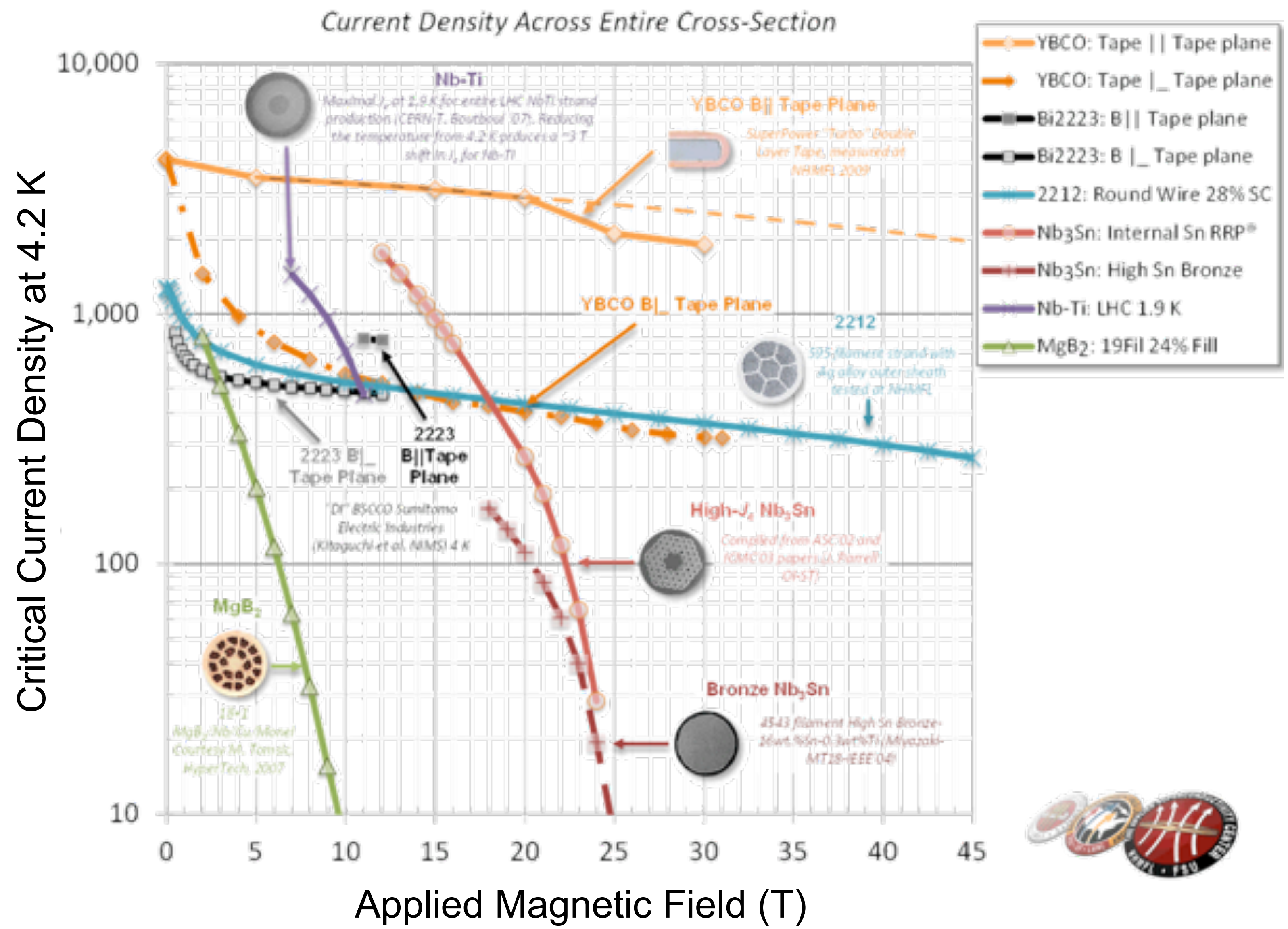
# ALICE & LHCb Upgrade Schedules

| | ALICE | LHCb |
|---|---|---|
| **Proposals** | Upgrade LoI and CDR for Inner Tracking submitted (Sep 2012), TDRs 2013 | Framework TDR submitted (May 2012), subsystem TDRs to follow in 2013 |
| **Installation/ Commissioning** | LS2 (2018) | Cables/Fibers: LS1<br>Detectors: LS2 (2018) |
| **Luminosity Goals** | >10 $nb^{-1}$ of PbPb data<br>>6 $pb^{-1}$ of pp data | > 50 $fb^{-1}$ of pp data |
| **Running Scenario 2019** | PbPb interactions at 50 kHz ($6\times10^{27}$ $cm^{-2}$ $s^{-1}$) $\rightarrow$ 2.85 $nb^{-1}$ per year | pp interactions at 20 kHz ($1–2\times10^{33}$ $cm^{-2}$ $s^{-1}$) $\rightarrow$ 5 $fb^{-1}$ per year |

# The Far Future

# High Energy LHC

- HE-LHC: around 2035?
  - Increase of LHC center-of-mass energy to 26–33 TeV
  - New machine in LHC tunnel: replace dipole magnets
  - Physics: “final word” on electroweak symmetry breaking, discoveries?
- Challenges
  - Novel materials for high-field superconducting magnets
  - New injection chain (SPS at 1–1.3 TeV)
  - Collimation, beam dump, synchrotron radiation, …

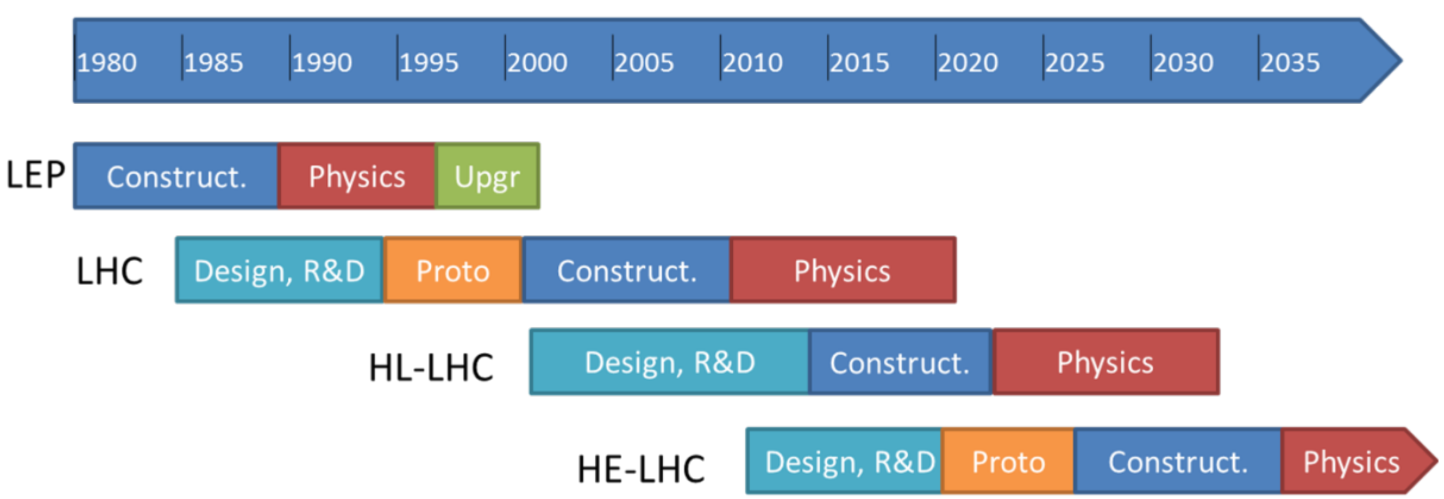



[http://fs.magnet.fsu.edu/~lee/plot/plot.htm]

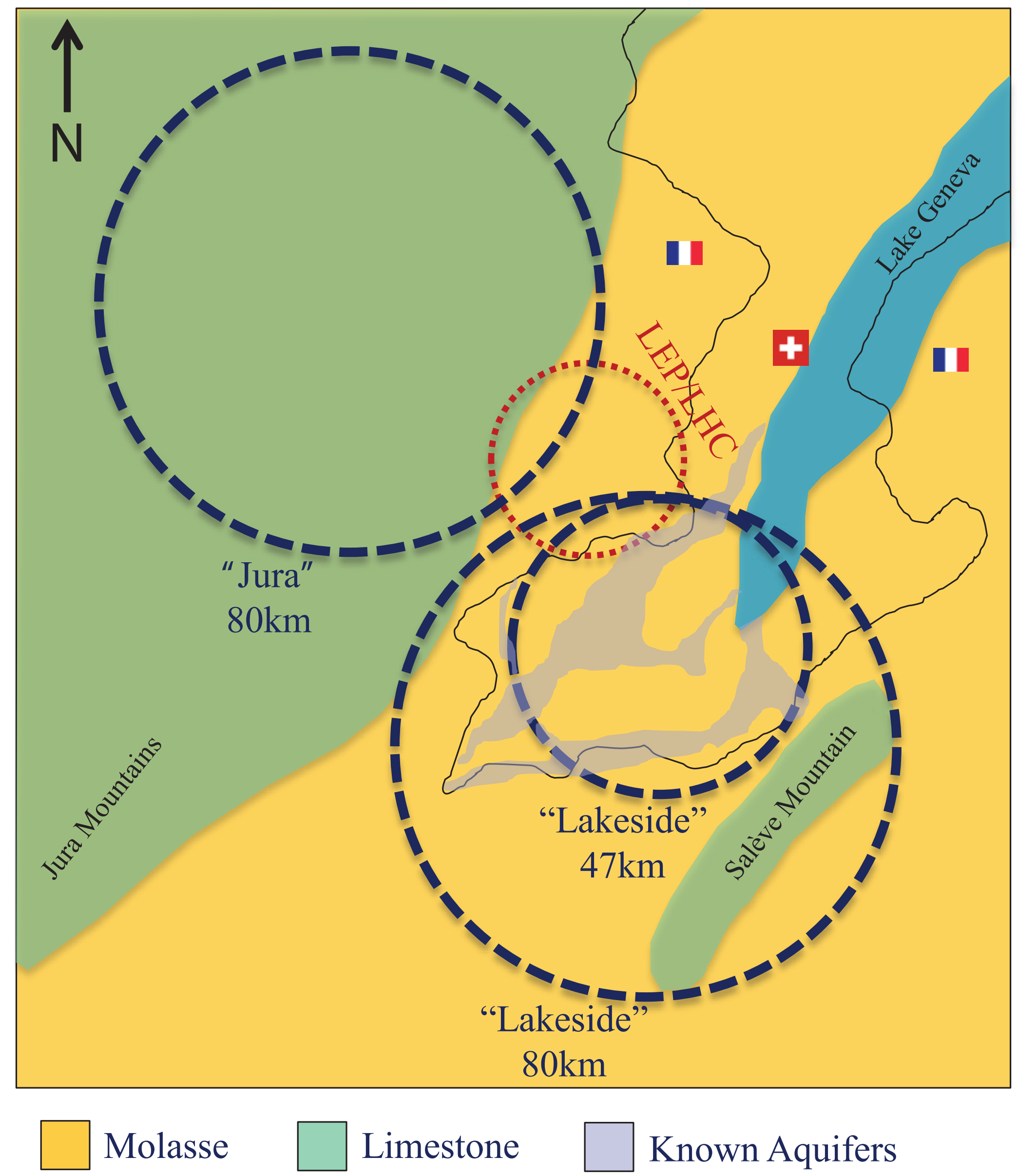
# Super High Energy LHC

- Alternative: new tunnel in Geneva area
  - 47 or 80 km circumference
  - 42 TeV center-of-mass energy with present LHC dipoles
  - 80–100 TeV with novel high-field magnets
  - Price tag?

The super-exploitation of the CERN complex:
Injectors, LEP/LHC tunnel, infrastructures




[CERN-ATS-2012-237, Kraków 2012]




[CERN GS, Kraków 2012]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# Summary & Conclusions

- CERN's goal: exploit full LHC physics potential until ~2030
- Multi-phase upgrade program of accelerator chain and experiments
  - Projects grouped around three long shutdowns: LS1 (2013/2014), LS2 (2018), LS3 (2022/2023)
  - ATLAS/CMS: keep comparable performance at highest luminosities
  - ALICE/LHCb: optimize detector and readout for highest rates
- Far future: (super) high energy LHC?