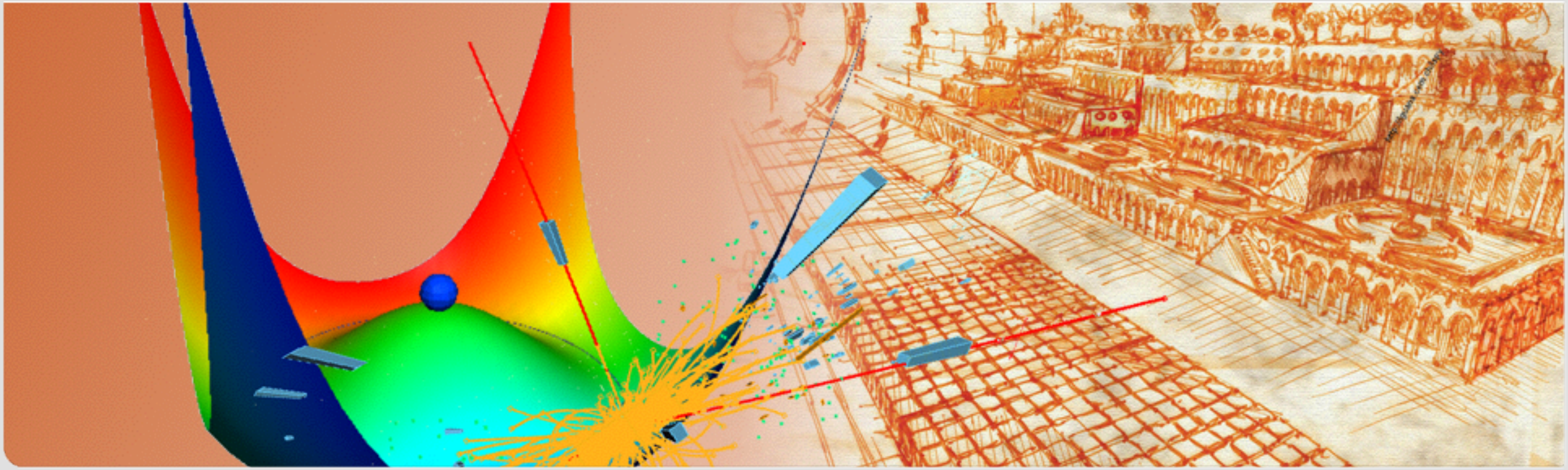
Karlsruhe Institute of Technology

Preparing for the Future: Upgrades of the LHC Experiments

European Summer Campus
From the Mystery of Mass to Nobel Prizes – The Physics of the Higgs Boson
Strasbourg, France, July 6–12, 2014

Ulrich Husemann
Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology

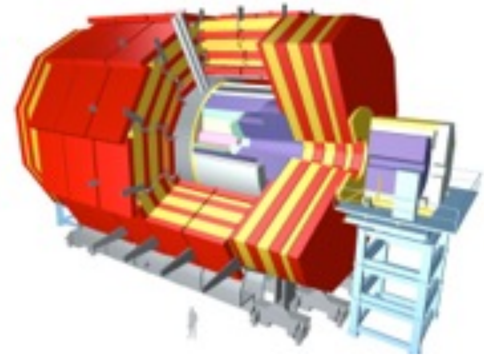


LHC – the Large Hadr

Lake Geneva

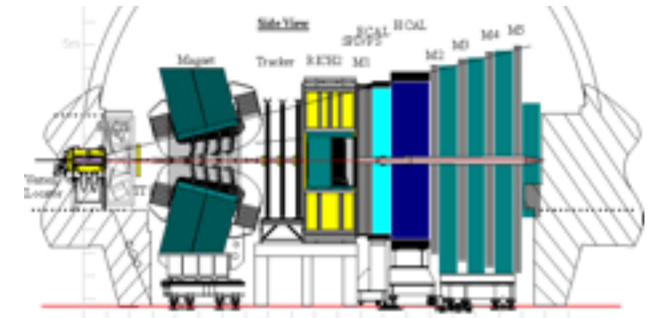
LHC Accelerator:
proton-proton and
lead-lead collisions

CMS Experiment:
multi-purpose experiment



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

LHCb Experiment:
CP violation and B physics



ALICE Experiment:
heavy ion physics

ATLAS Experiment:
multi-purpose experiment

LHC 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, triggers, data acquisition systems
  - Goal: keep **comparable performance** in increasingly challenging environment
- **When**:
  - Three upgrade periods: 2013/4 – 2018/9 – 2023/4

Outline

The Case for LHC Upgrades

ATLAS and CMS Upgrades

ALICE and LHCb Upgrades

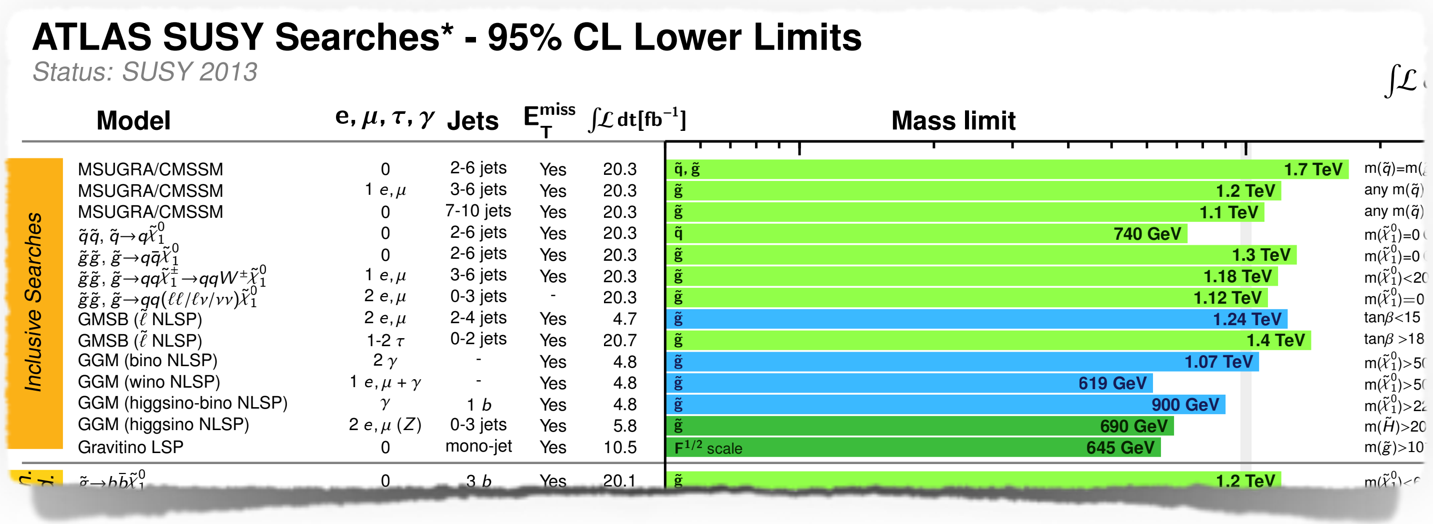
Beyond LHC

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

The Case for LHC Upgrades

Status July 2014

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

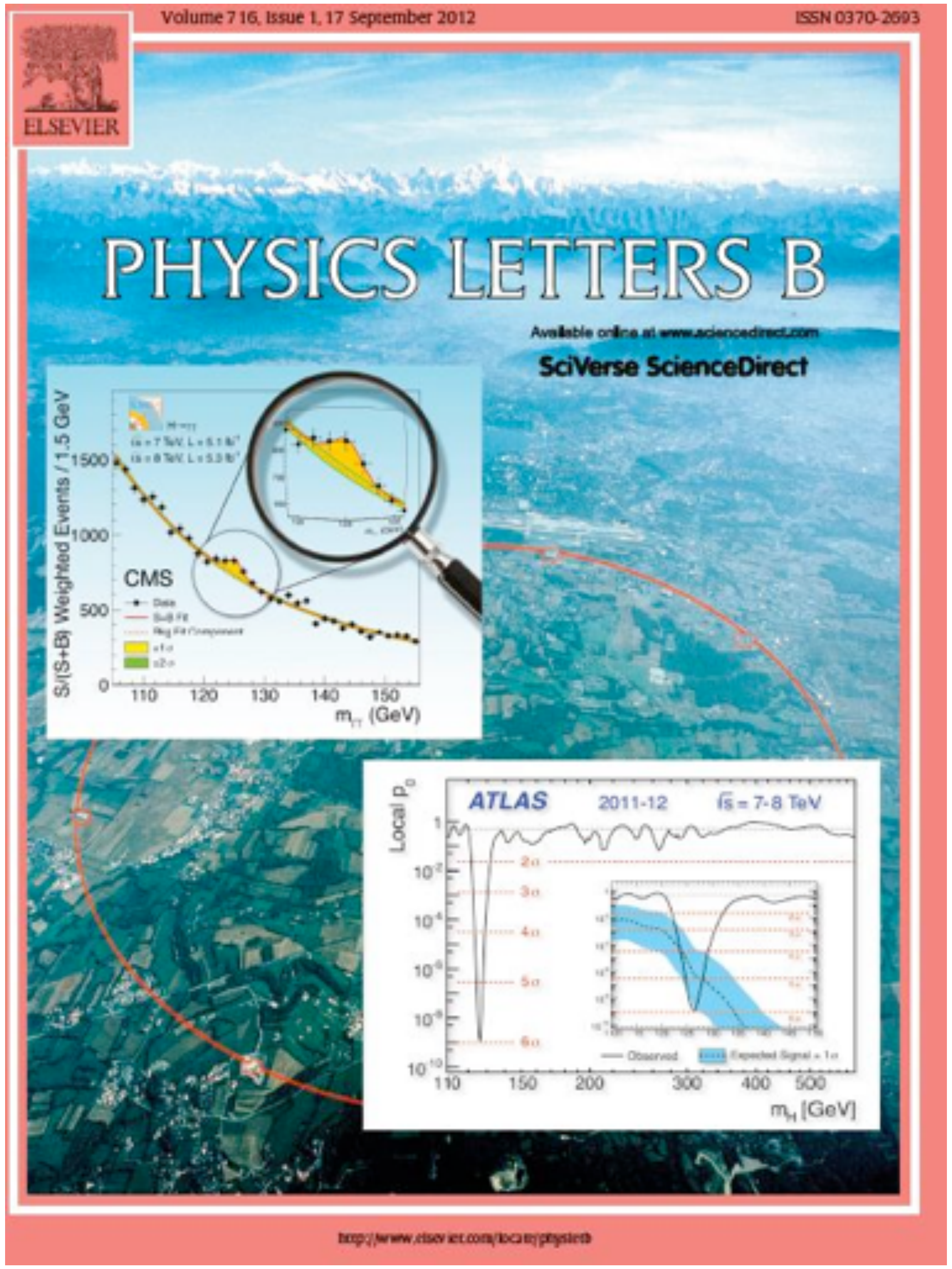


ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[fb^{-1}]$	Mass limit	
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m($
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}_1^0)=0$
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)=0$
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)<20$
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)=0$
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta<15$
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta>18$
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}_1^0)>50$
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)>50$
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)>22$
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\tilde{H})>20$
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{g})>10$
	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)<$

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



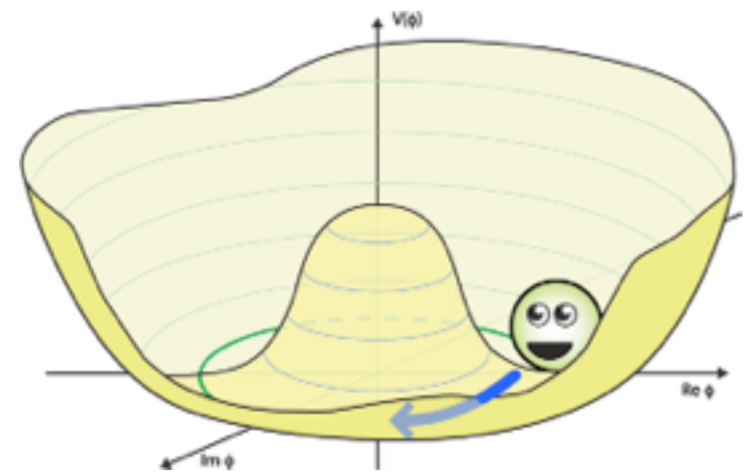
[elsevierconnect.com]

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

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

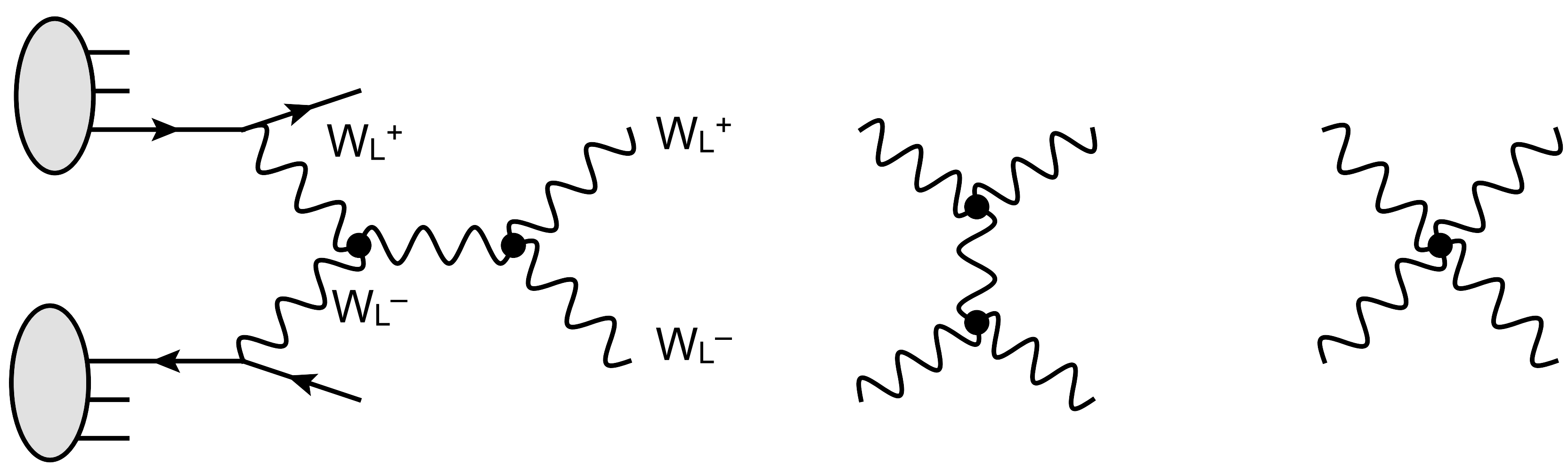


[quantumdiaries.org]

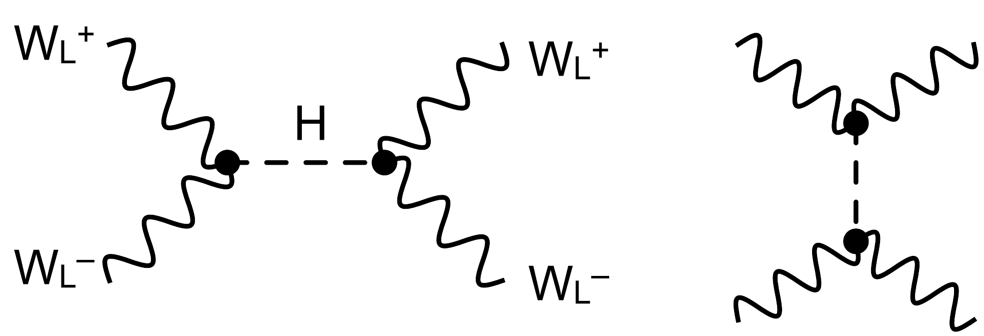
Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

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)



  - Standard model: Higgs boson with $m_H \lesssim$ 850 GeV **regularizes** divergence

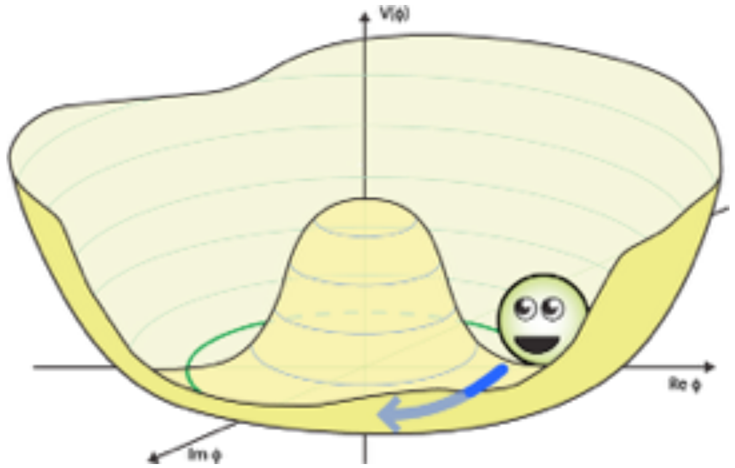


  - No color exchange between initial state partons → expect **forward** jets

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]

- Search for **physics beyond the SM**
  - New physics scale likely well above 1 TeV
  - Accessible with higher center-of-mass (CM) energy and/or lots of luminosity

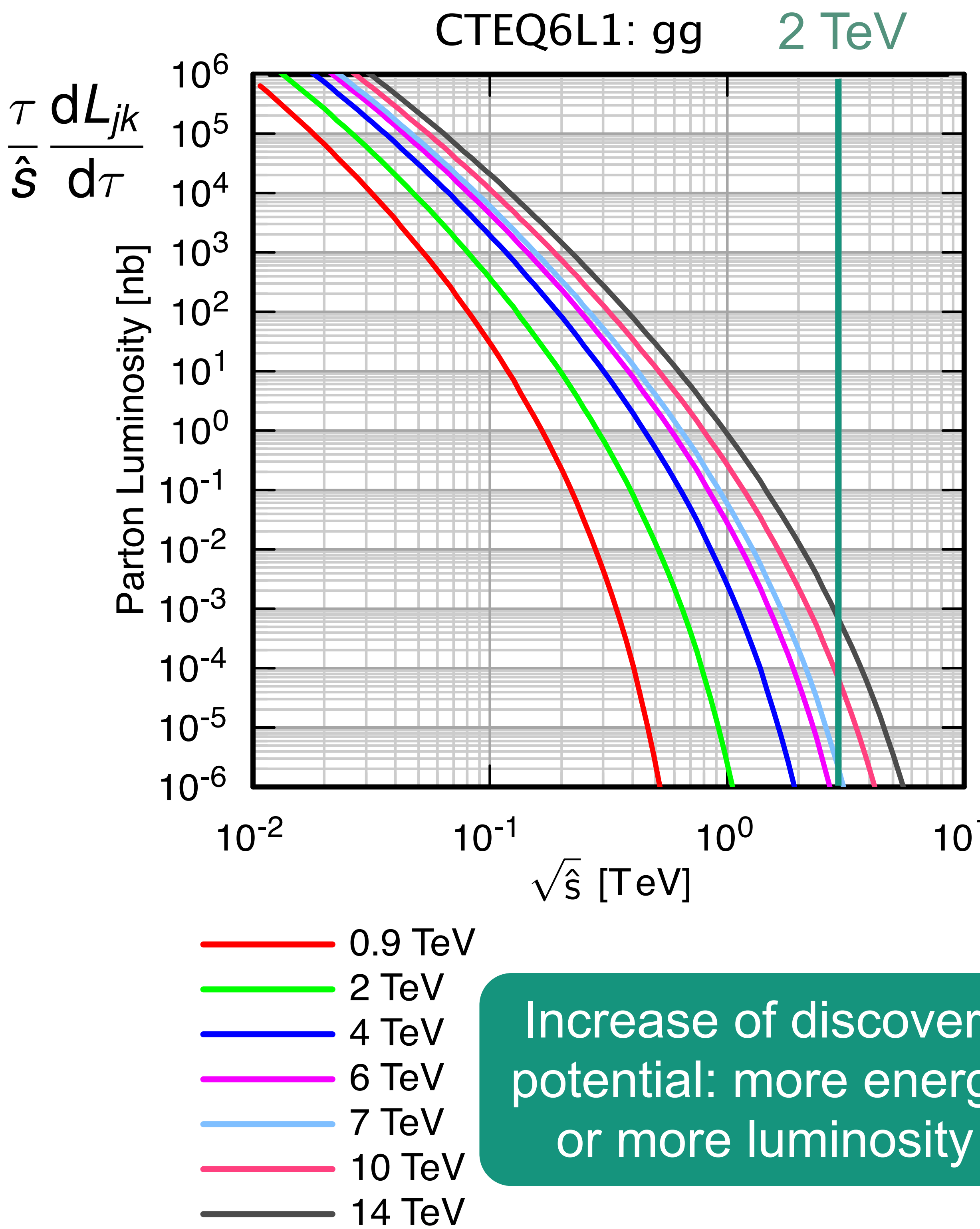
[C. Grupen]

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)

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

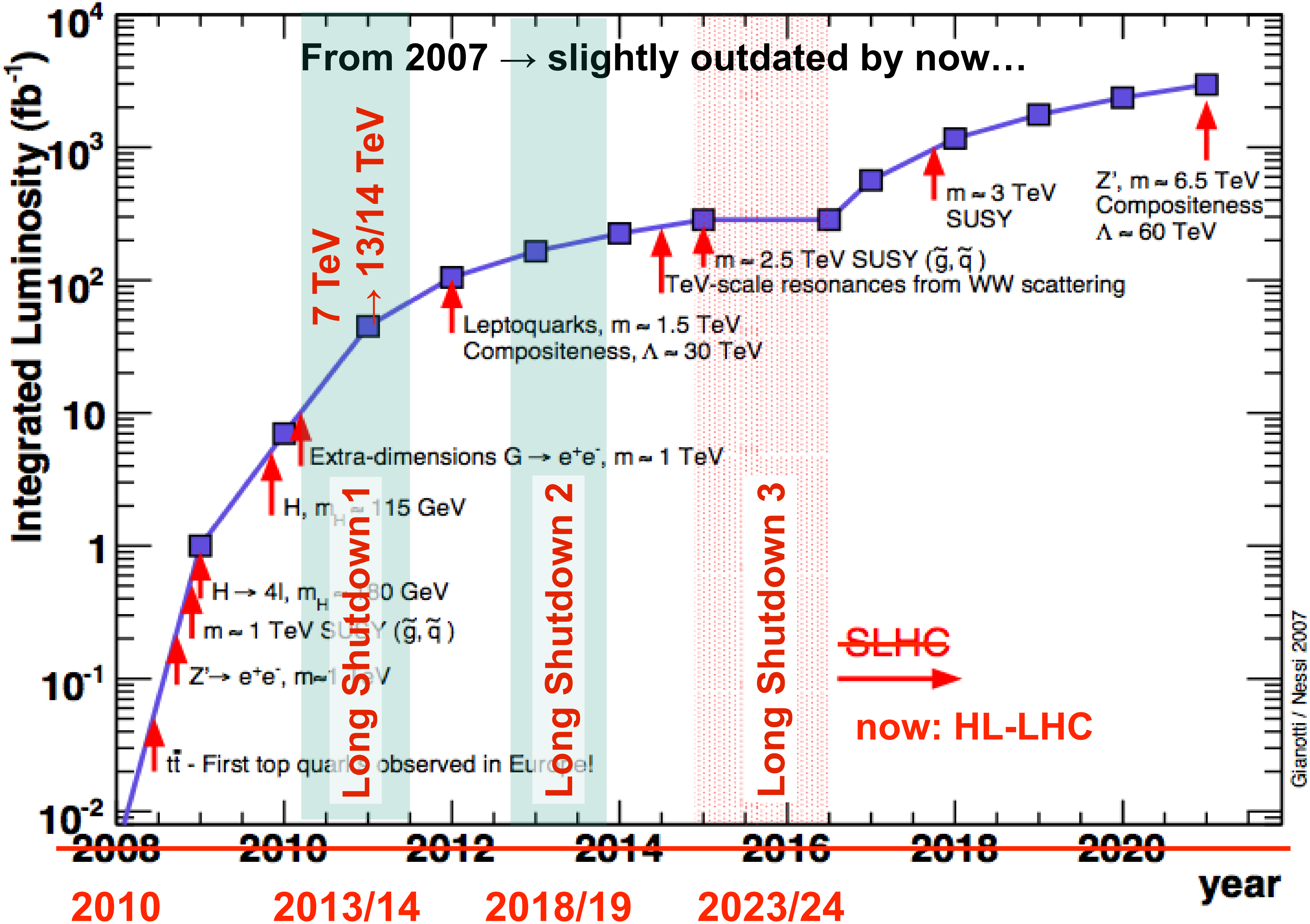
with f_j, f_k PDFs for parton flavors j, k and $\tau \equiv \hat{s}/s = x_j x_k$



[C. Quigg, arXiv:0908.3660v2]

Increase of discovery potential: more energy or more luminosity

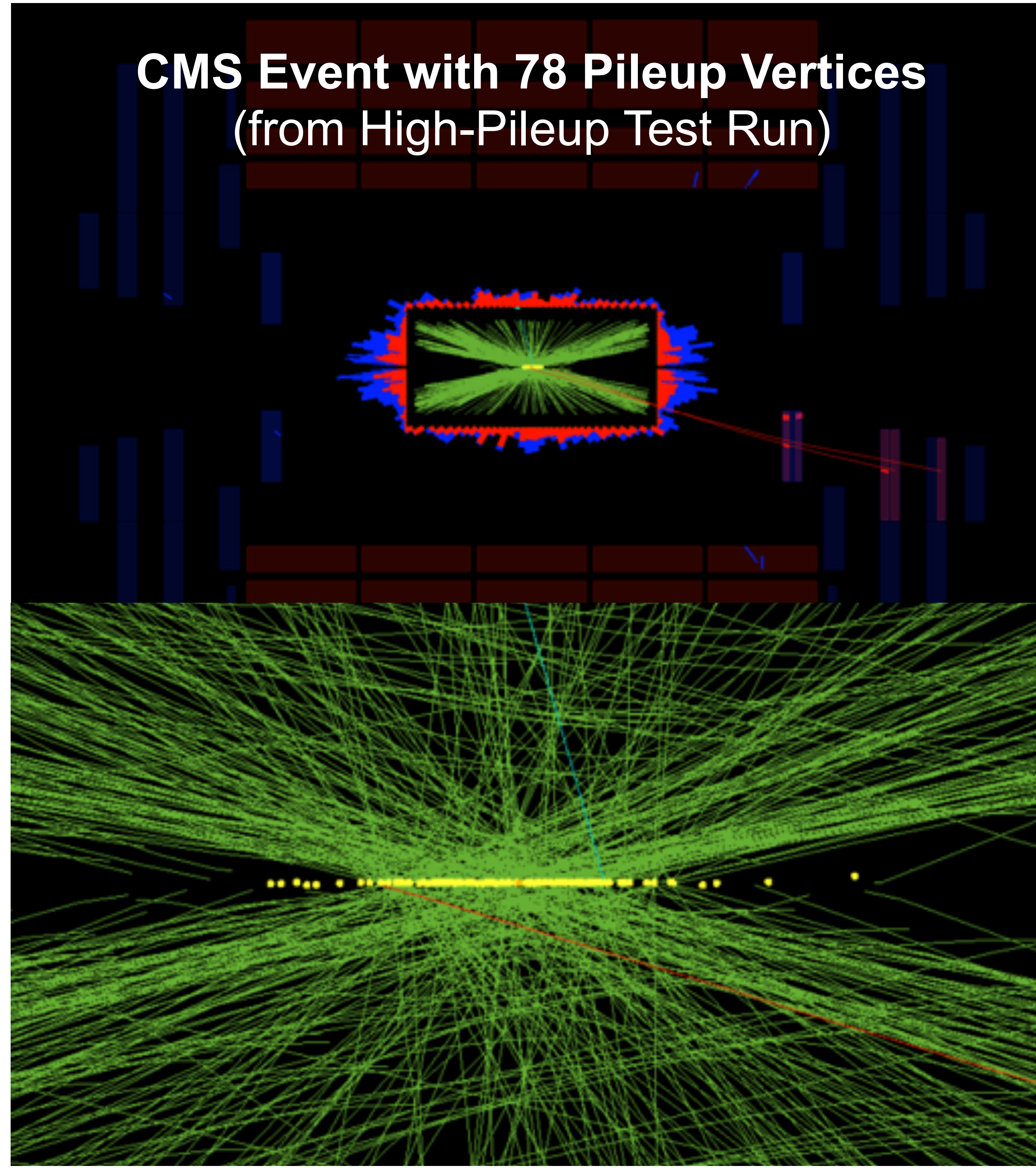
LHC High Luminosity Upgrade: Physics Case



Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Pileup

- High luminosity comes at a price: **pileup** (= simultaneous pp interactions in the same bunch crossing)
- LHC design luminosity: 2808 proton bunches/beam, 25 ns spacing → 25 pileup vertices
- Pileup 2012: 1380 bunches/beam, **50 ns** spacing → 30+ pileup vertices
- LHC upgrade: expect **100–200 pileup vertices**



Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

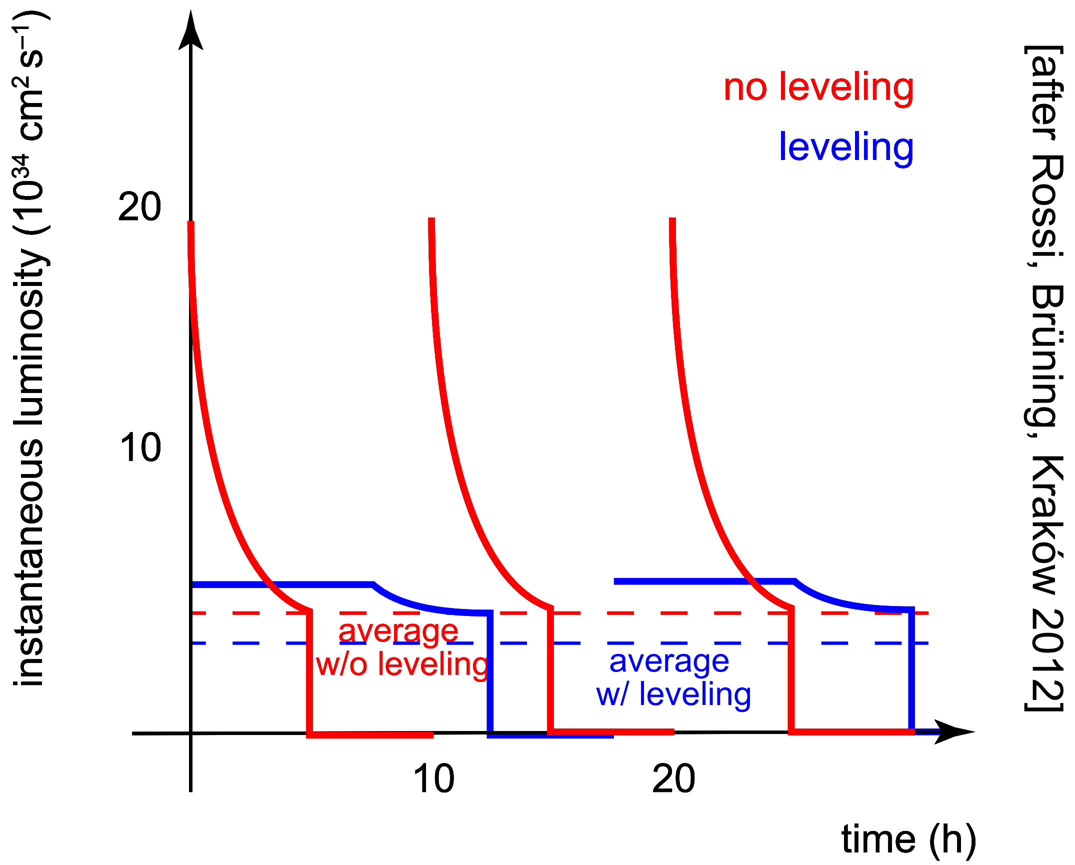
High Luminosity LHC

- Goal: integrated luminosity of **3 ab^{-1} = 3000 fb^{-1}** at 14 TeV CM energy in 10–12 years of LHC operation
  - Peak luminosity: 5×10^{34} cm^{-2} s^{-1} → 5× LHC design
  - 25 ns bunch spacing → 140 pileup vertices
- Upgrade of accelerator chain: **many** projects have to **succeed together**
  - **Consolidation**: magnets, cryogenics, collimation, electronics, machine protection
  - **Modifications**: injectors, new (quadrupole) magnets, collimators, crab cavities

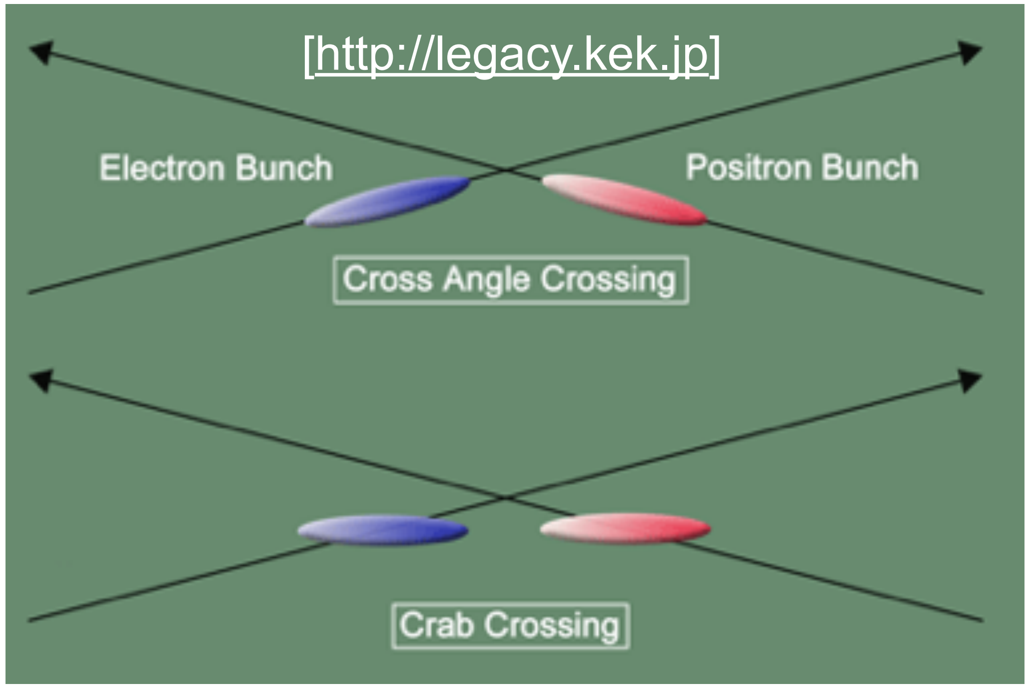
[F. Bordry, Dec. 2013]

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 in LHC Run 1 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



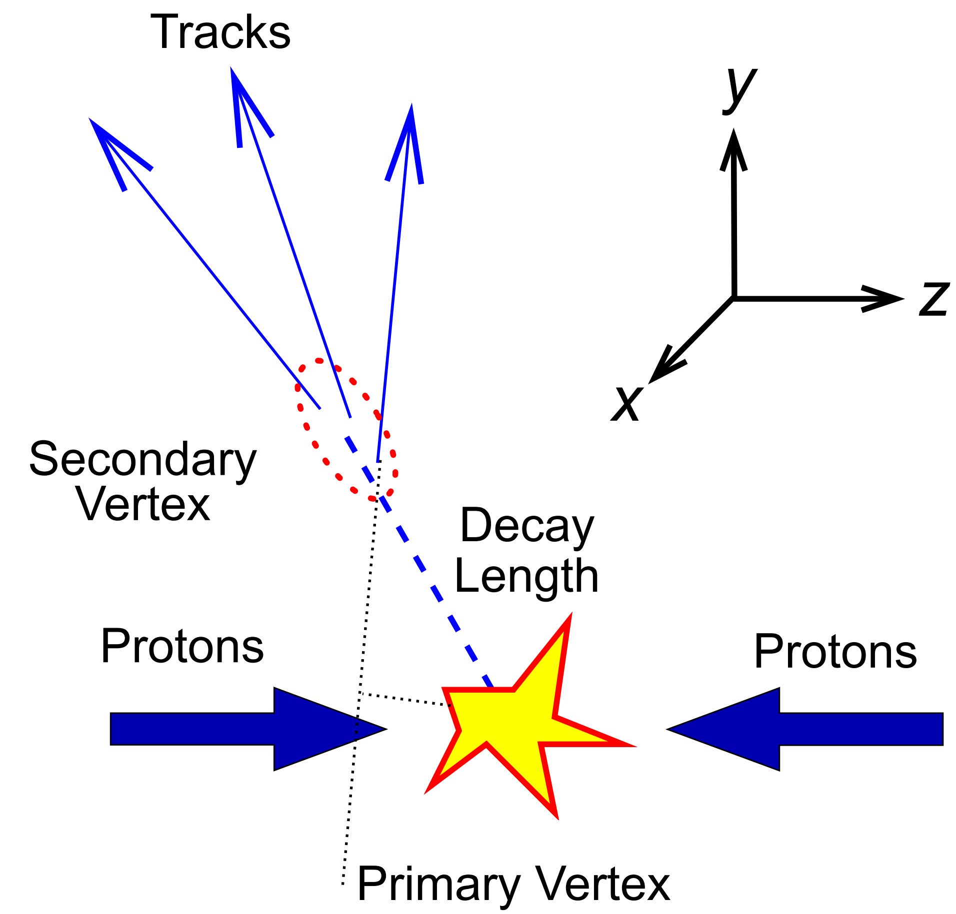
Short Summary

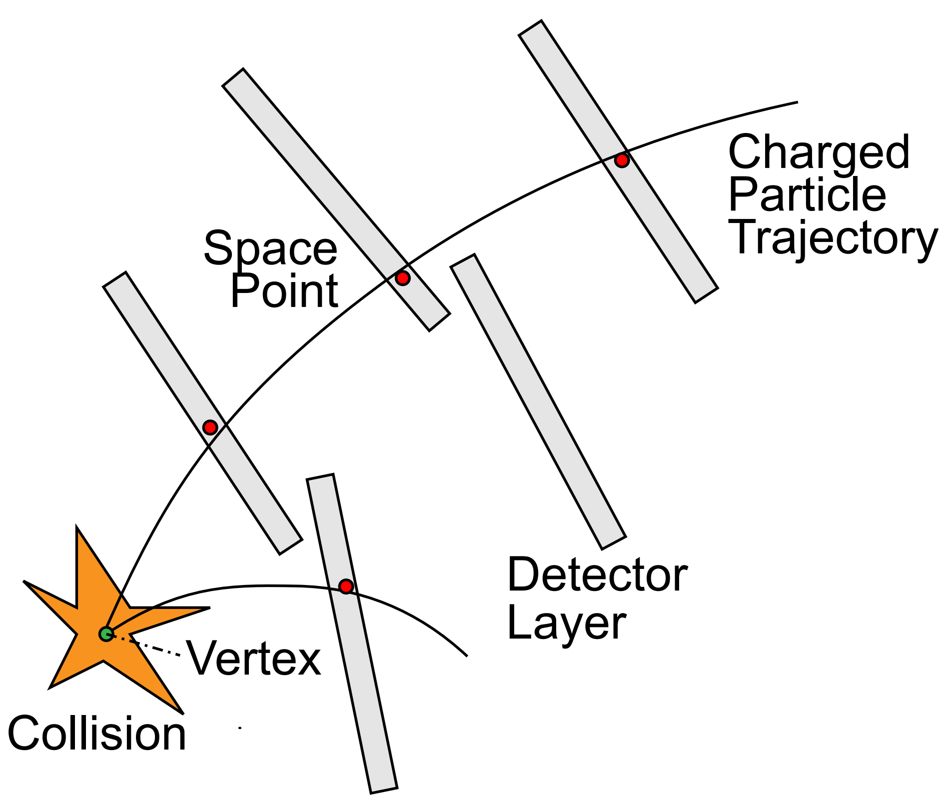
- Physics motivation for LHC upgrades
  - **Precision physics**: Higgs properties and other SM measurements
  - **Electroweak symmetry breaking**: is the Higgs mechanism really at work?
  - Search for **new physics** at the highest energies and luminosities
- Many **challenges** for accelerators and experiments
  - High luminosity: challenging experimental environment, e.g. **pileup**
  - **Consolidation** and **modification** of accelerator chain, e.g. crab crossing
- LHC upgrade **schedule** (as of 2014)
  - 2013/2014: consolidation, upgrade to 13(14) TeV
  - 2018/19: injector upgrade
  - 2023/24: final preparation for HL-LHC

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

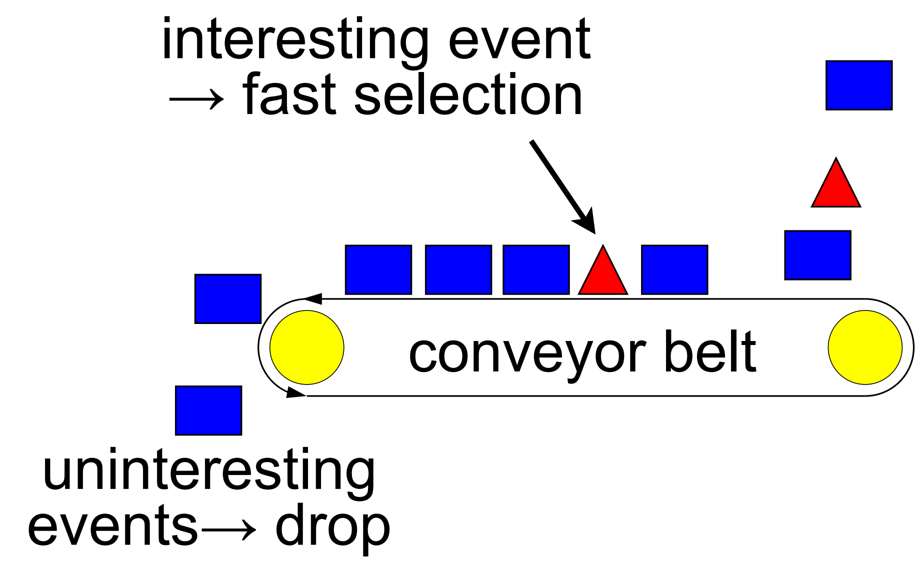


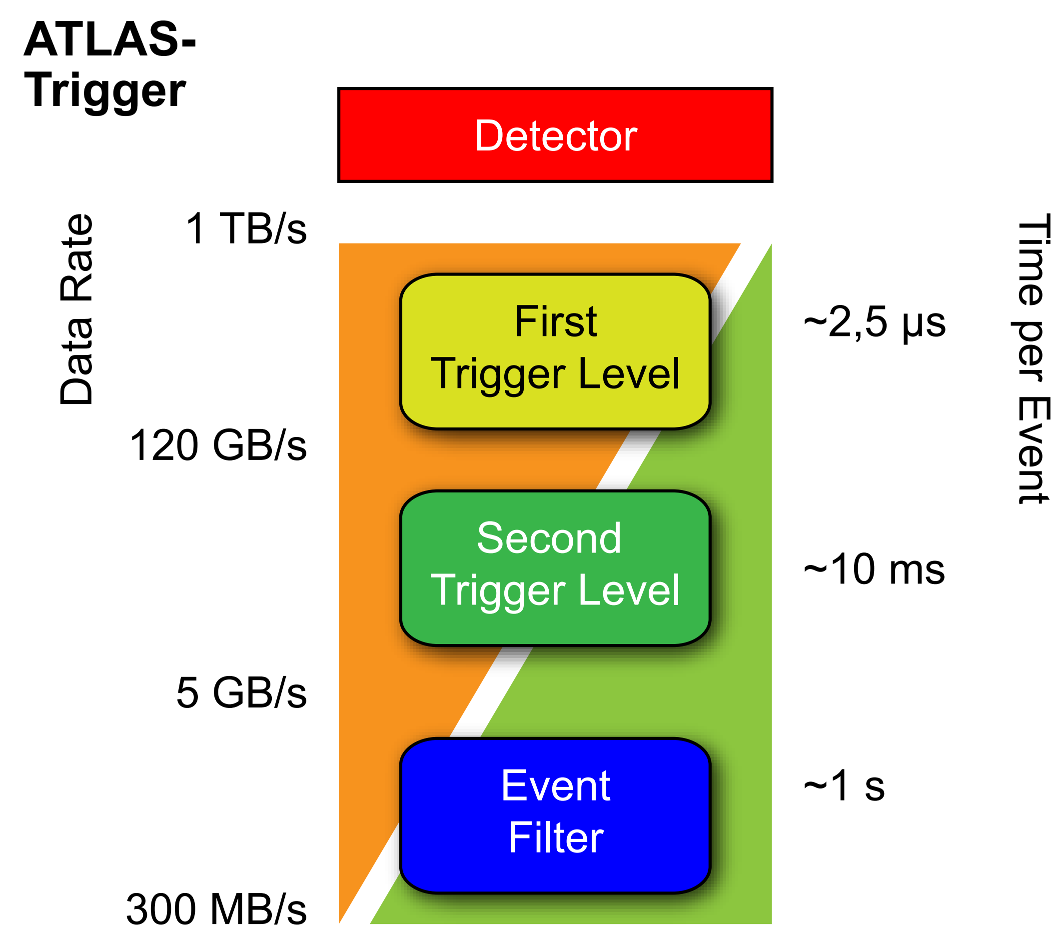


- B-tagging:
  - Identify hadrons with b-quarks mainly via their long lifetimes (picoseconds)
  - Parts of the tracks from B hadron decays: large **impact parameters** and/or **displaced secondary vertex**
  - Low particle momenta important

Triggering at the LHC

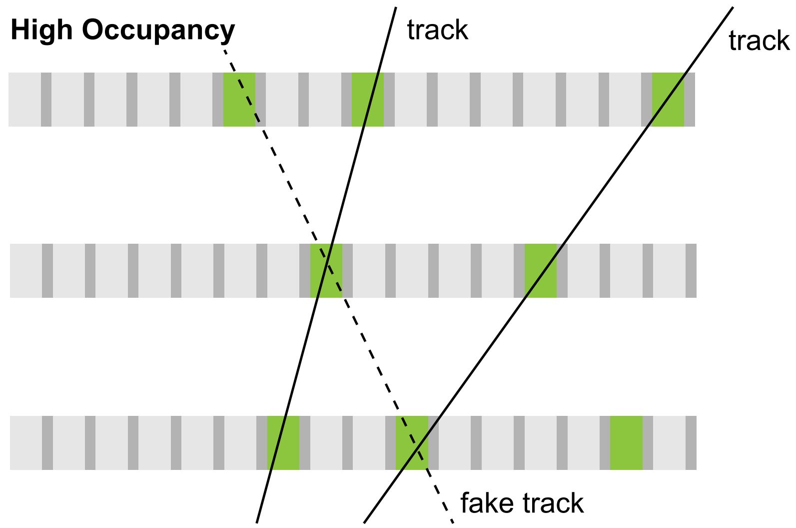
- Challenge: **data rate (“needle in the haystack” problem)**
  - Processing of **up to 1 billion pp collisions** per second (40M bunch crossings, 25 simultaneous pp collisions each)
  - Only a **few 100** of these collisions contain **interesting** physics
- Solution: Trigger = multi-level **online data filter**
  - Level 1: **simple** and **fast**, in hardware
  - Level 2 and event filter: enough time for computer **farm**

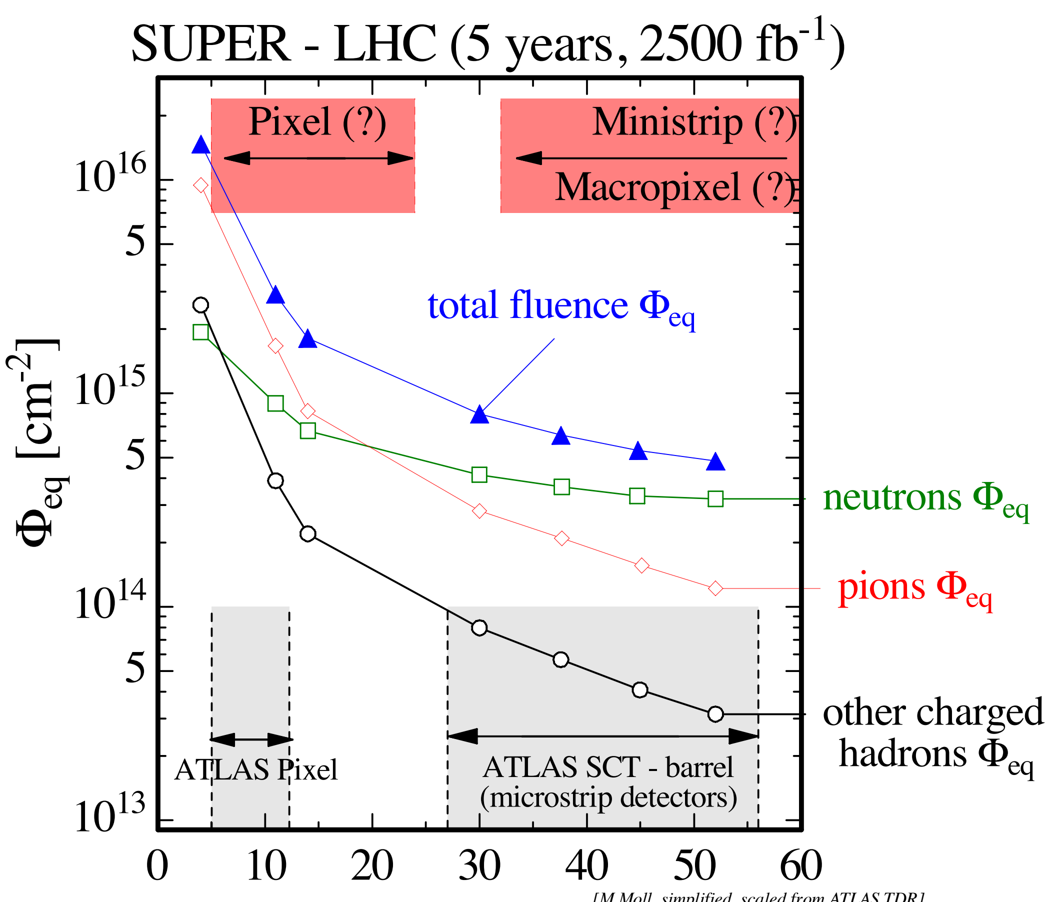




Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

High-Luminosity Challenges I: Radiation





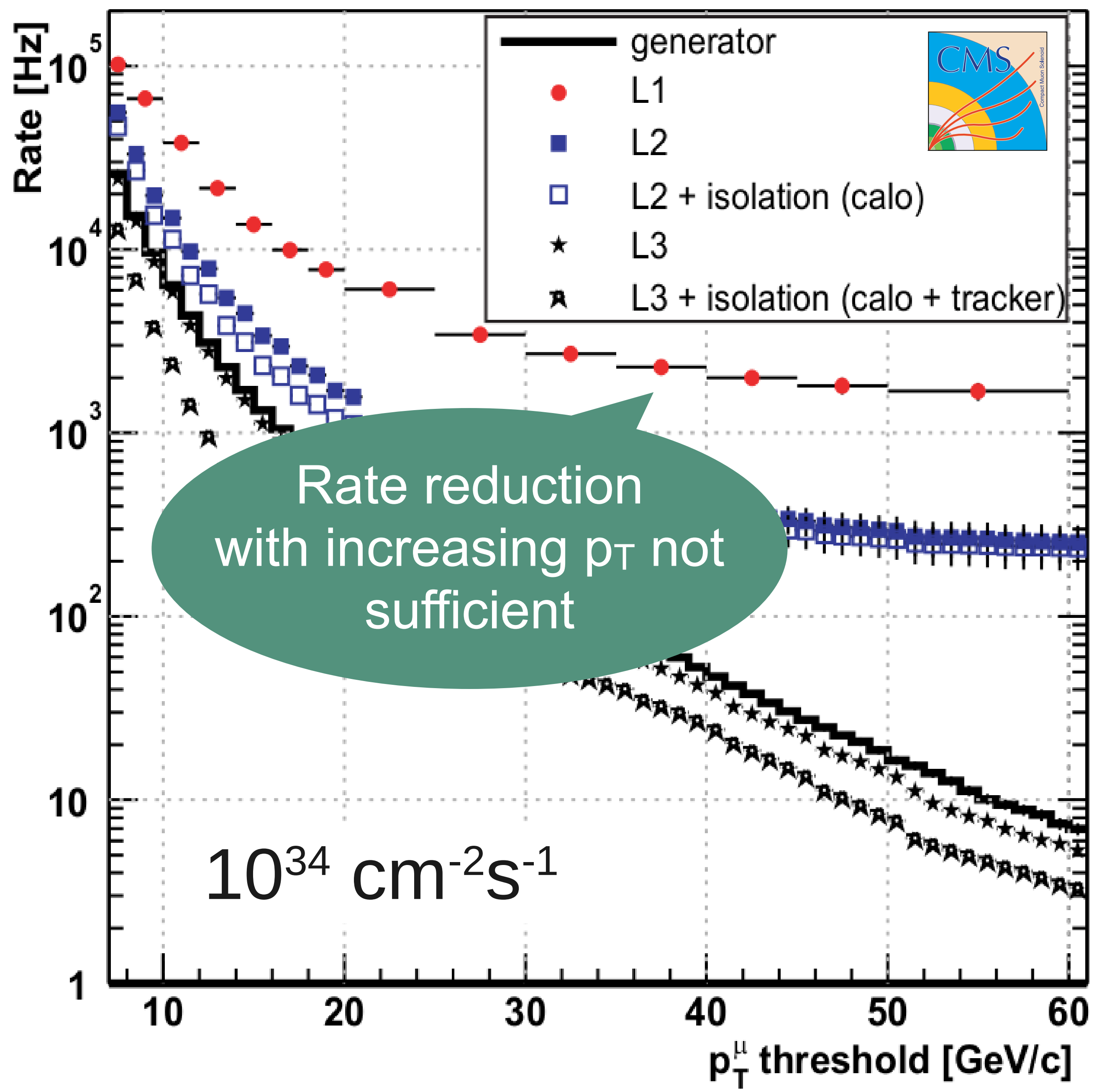
[M. Moll]

- 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: reduce occupancy by increasing 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
- Possible way outs:
  - Make existing triggers **more granular**
  - Use **tracking** information in trigger
- Challenge: trigger must process **many more channels** within **same trigger latency**

Simulated μ Trigger Rates vs. p_T



ATLAS Upgrade Matrix

Subsystem	From 2013/2014	From 2018	From 2023
Silicon Pixel	New Beam Pipe, Insertable B-Layer	–	New Tracker
Silicon Strips	–	–	New Tracker
Electromagnetic Calorimeter	Consolidation	Finer Granularity in Trigger	New Electronics, Forward Calo
Hadronic Calorimeter	–	–	New Electronics, Forward Calo
Muon System	Endcap Extension	New Small Wheels (Forward)	New Electronics
Trigger	–	New e/Jet Triggers, Fast Tracker (2015)	Complete Replacement

+ several smaller projects

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

ATLAS Upgrade Matrix

Subsystem	From 2013/2014	From 2018	From 2023
Silicon Pixel	New Beam Pipe, Insertable B-Layer	–	New Tracker
Silicon Strips	–	–	New Tracker
Electromagnetic Calorimeter	Consolidation	Finer Granularity in Trigger	New Electronics, Forward Calo
Hadronic Calorimeter	–	–	New Electronics, Forward Calo
Muon System	Endcap Extension	New Small Wheels (Forward)	New Electronics
Trigger	–	New e/Jet Triggers, Fast Tracker (2015)	Complete Replacement

+ several smaller projects

CMS Upgrade Matrix

Subsystem	From 2013/2014	From 2018	From 2023
Silicon Pixel	New Beam Pipe	New Pixel Detector (ready for 2017)	New Tracker Forward Coverage?
Silicon Strips	Consolidation	–	New Tracker
Electromagnetic Calorimeter	–	Improved Trigger Primitives	Endcap Replacement
Hadronic Calorimeter	New Photon Detection	New Electronics & Photon Detection	Endcap Replacement
Muon System	Complete Coverage	Improve Trigger, Prepare Electronics	New Electronics, Forward Coverage?
Trigger	New L1 Trigger (ready for 2016)	–	Complete Replacement

+ several smaller projects

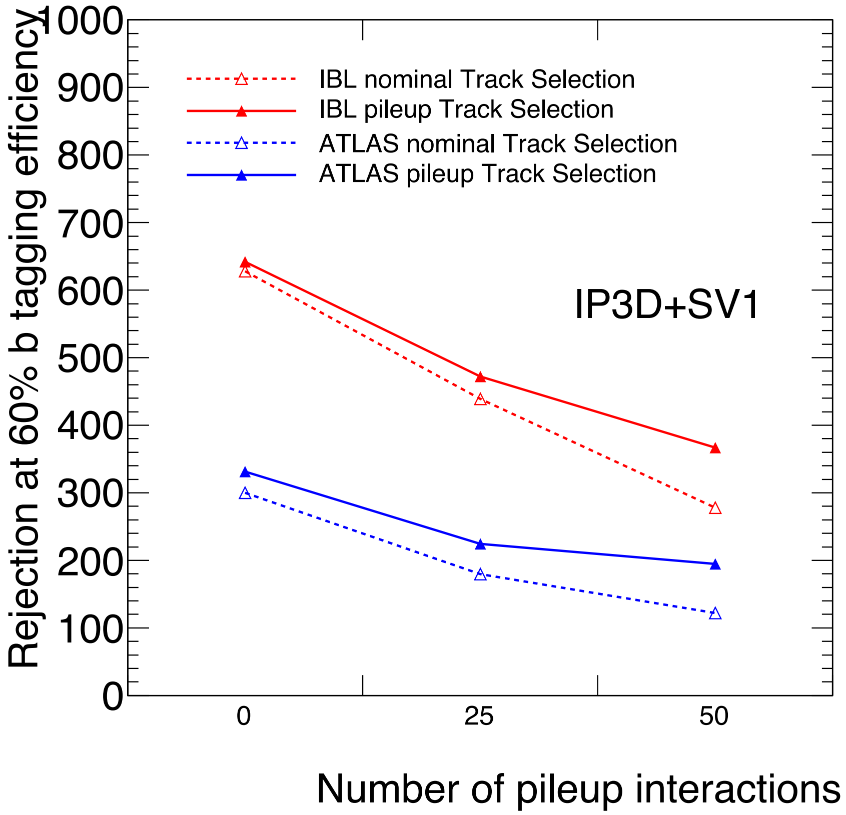
CMS Upgrade Matrix

Subsystem	From 2013/2014	From 2018	From 2023
Silicon Pixel	New Beam Pipe	New Pixel Detector (ready for 2017)	New Tracker Forward Coverage?
Silicon Strips	Consolidation	–	New Tracker
Electromagnetic Calorimeter	–	Improved Trigger Primitives	Endcap Replacement
Hadronic Calorimeter	New Photon Detection	New Electronics & Photon Detection	Endcap Replacement
Muon System	Complete Coverage	Improve Trigger, Prepare Electronics	New Electronics, Forward Coverage?
Trigger	New L1 Trigger (ready for 2016)	–	Complete Replacement

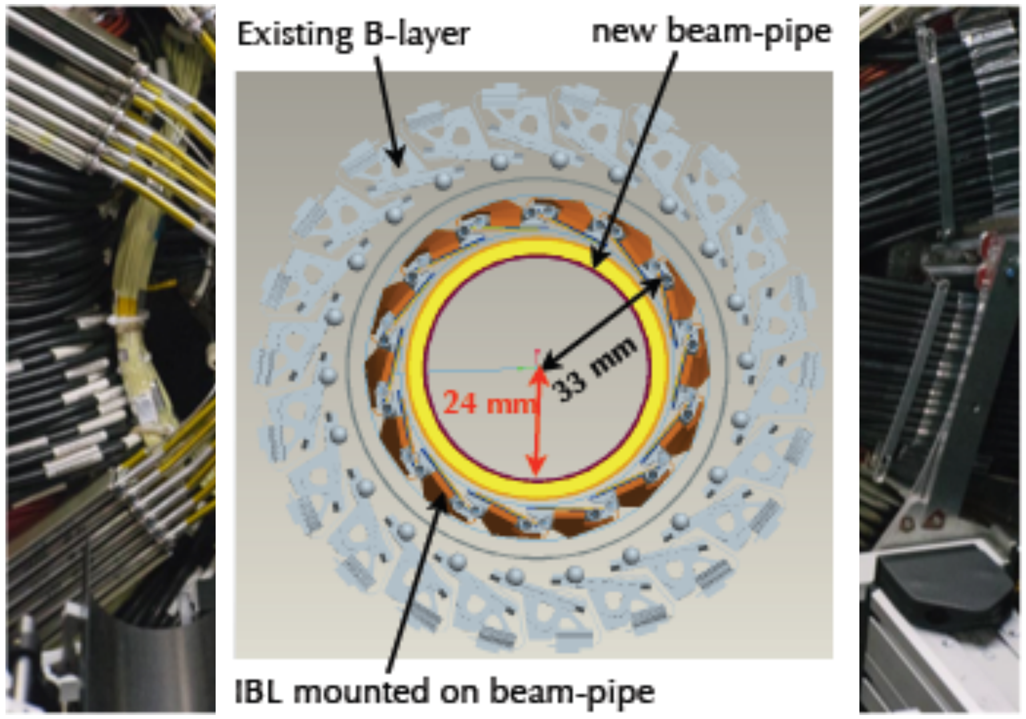
+ several smaller projects

ATLAS Insertable B-Layer (IBL)

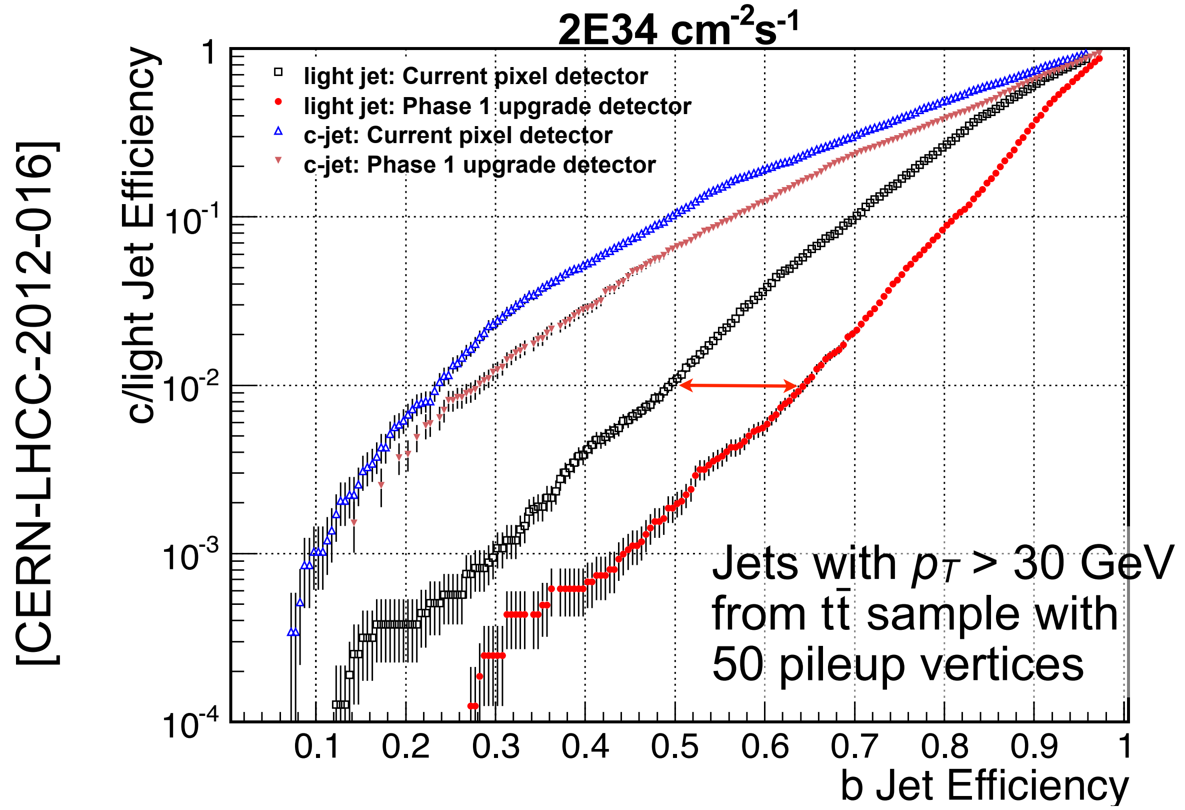
- Goals:
  - Add **redundancy** to current pixel detector
  - **Improve** tracking, vertexing, b-tagging for high pileup
  - Establish **new technologies** for HL-LHC
- ATLAS solution: Insertable B-Layer
  - **4th pixel detector layer**, sensors at $r = 33$ mm
  - New readout chip, advanced planar and 3D pixel sensors
  - Very low material budget: $0.015\ X_0$
- Installation **during LS1** (2013/2014)
  - Completely inserted: May 7, 2014
  - Currently being commissioned

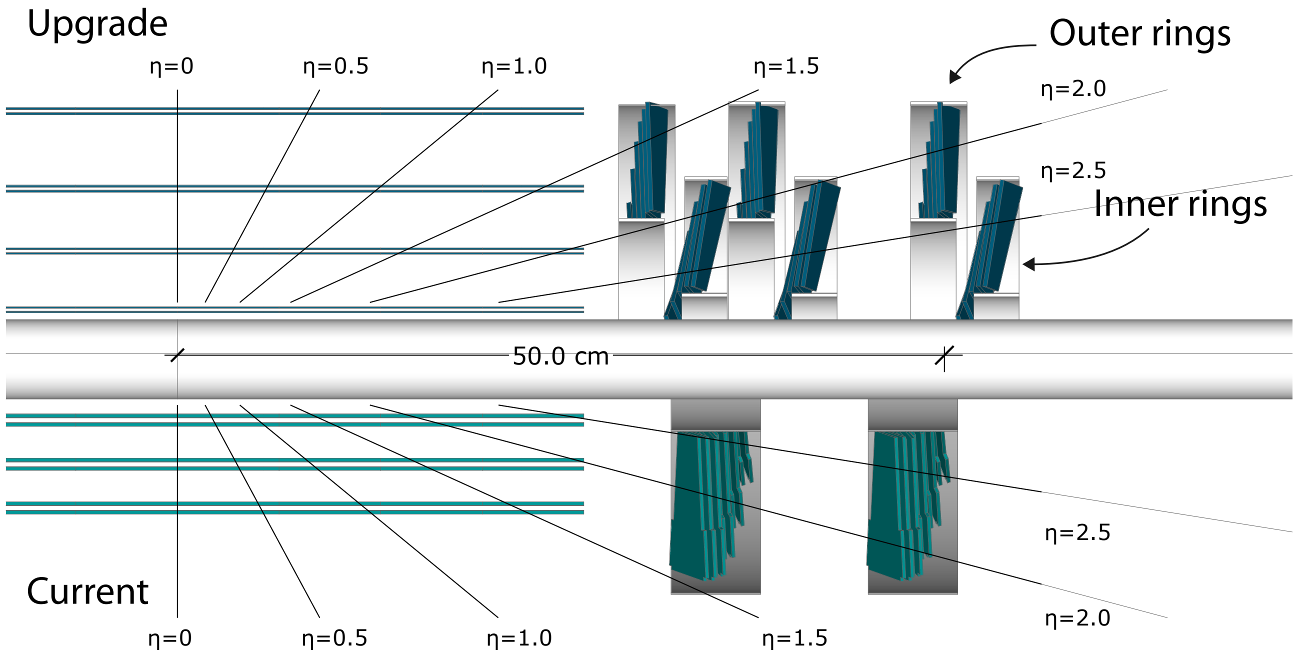


[CERN-LHCC-2010-013]



Upgrade of CMS Silicon Pixel Detector

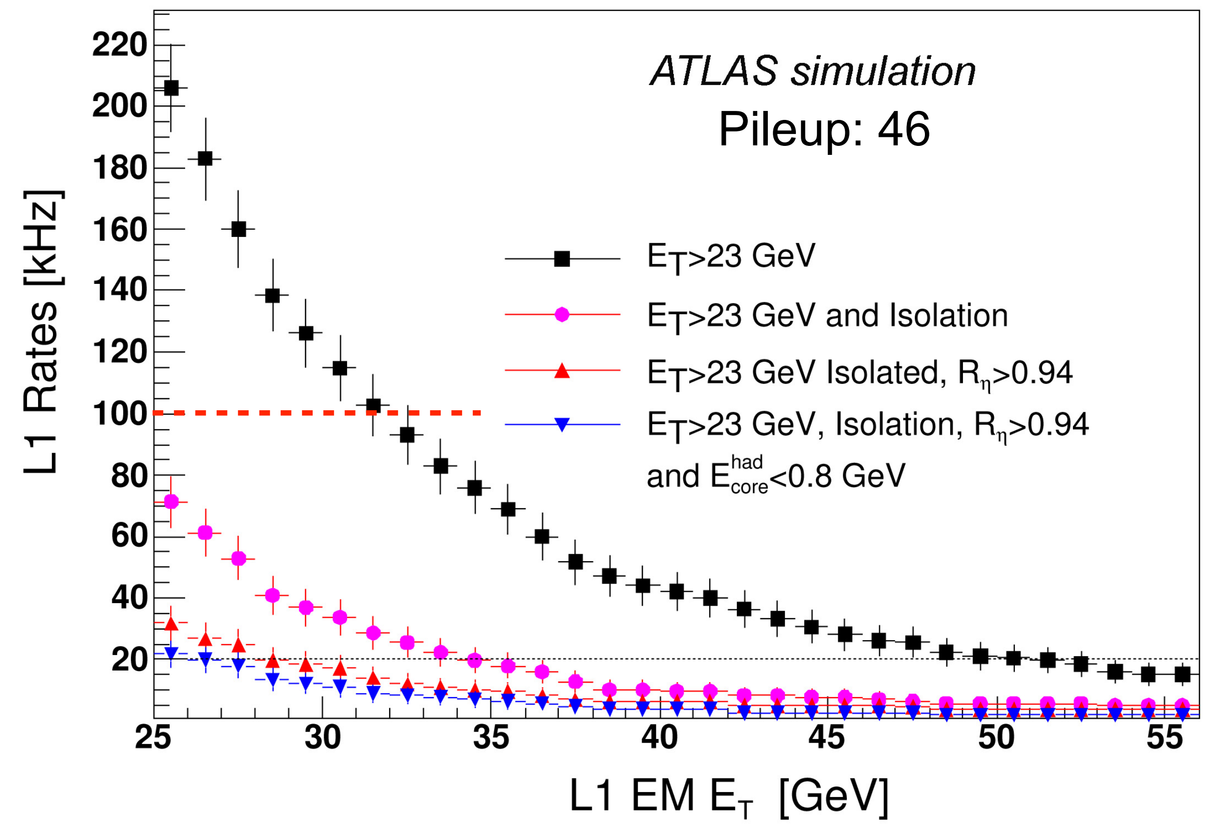


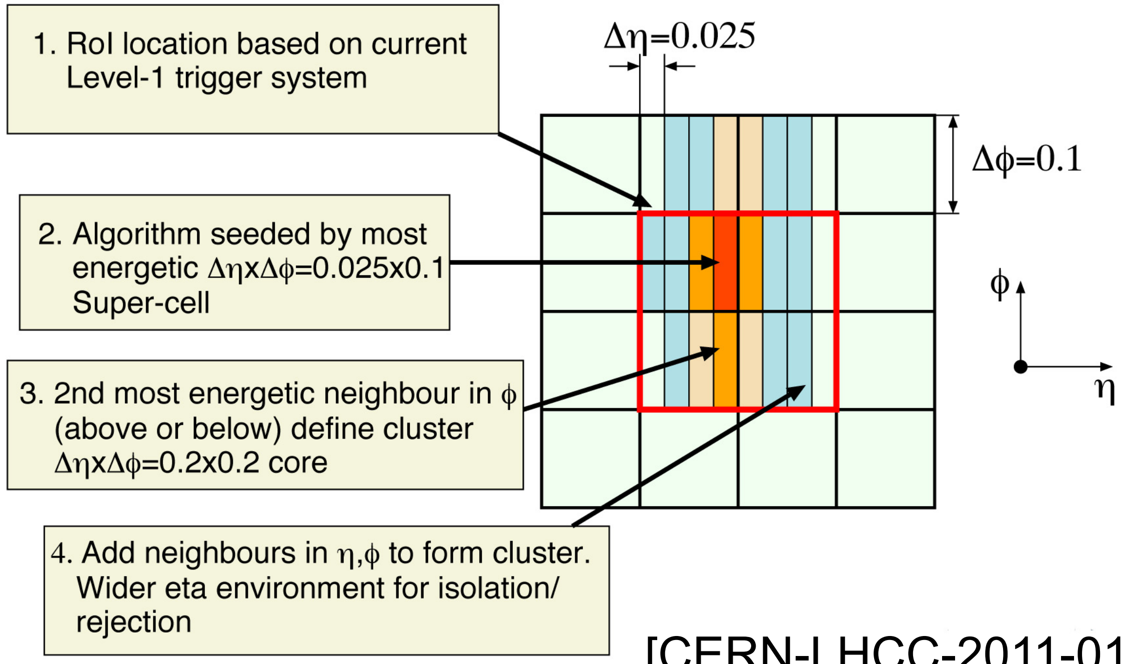


- Goal: **similar performance** in much harsher environment
  → tracking, vertexing, b-tagging, …
- Solution: new **four-layer** pixel detector
  - Innermost radius: 29 mm
  - New digital readout chip
  - Ultra-lightweight mechanics, CO_2 cooling → reduced material budget: 0.015 X_0 per layer
- Installation steps
  - LS1: new **beampipe**
  - **Modular** design: Installation during 3-months technical stop (planned for 2016/2017)

ATLAS Calorimeter Trigger

- Goal: maintain **high electron trigger efficiency** for low-p_T objects
- Solution: improve **electron-jet discrimination** at L1
  - 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 **digital processing** (replacing analog sums) to prepare for HL-LHC
- Installation plan:
  - LS1: slice of new system for tests
  - LS2: full installation

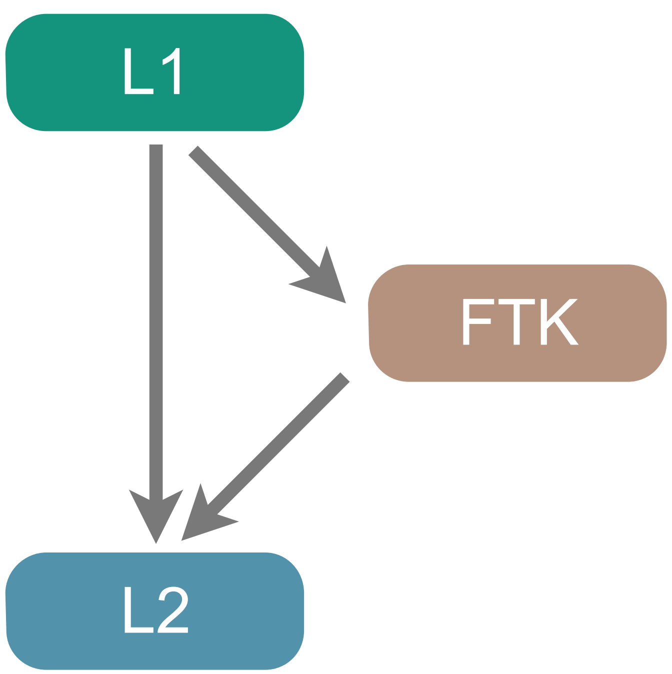


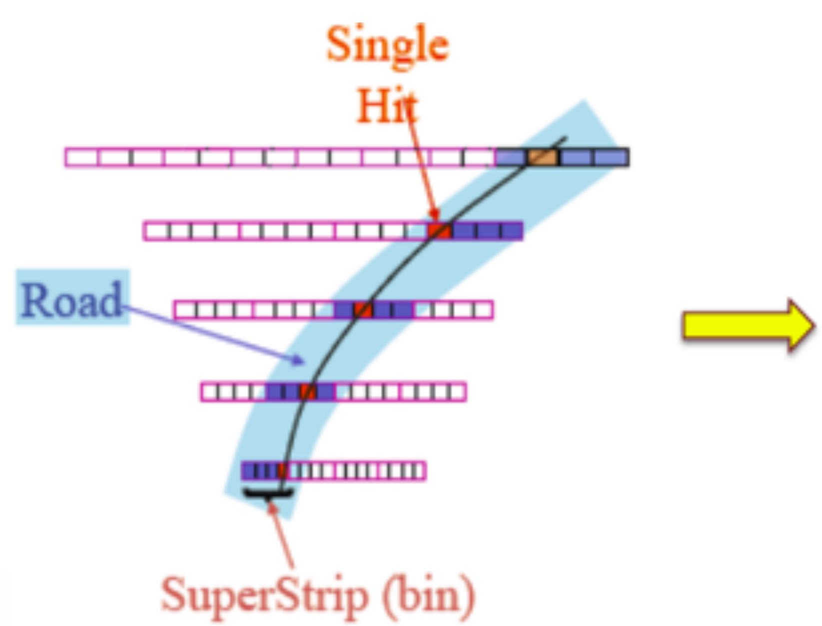


[CERN-LHCC-2011-012]

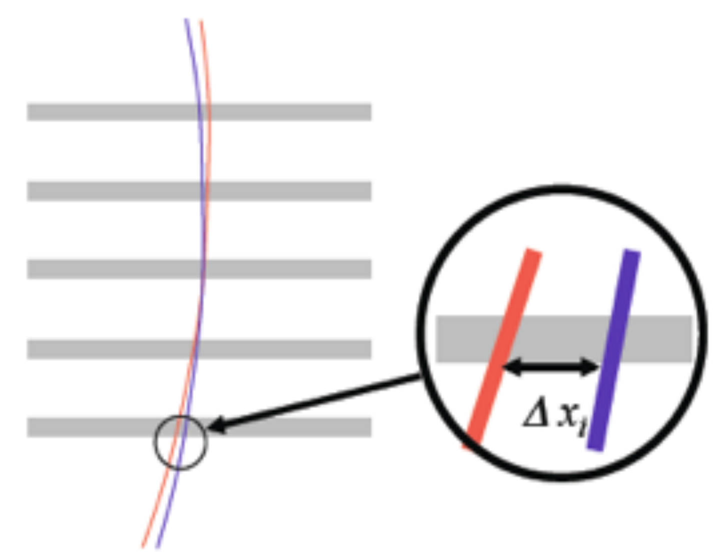
ATLAS Fast TracKer (FTK)

- 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
  - Key technologies: **associative memory** for pattern recognition, fast **FPGAs** for tracking





Pattern recognition in coarse resolution (superstrip→road)



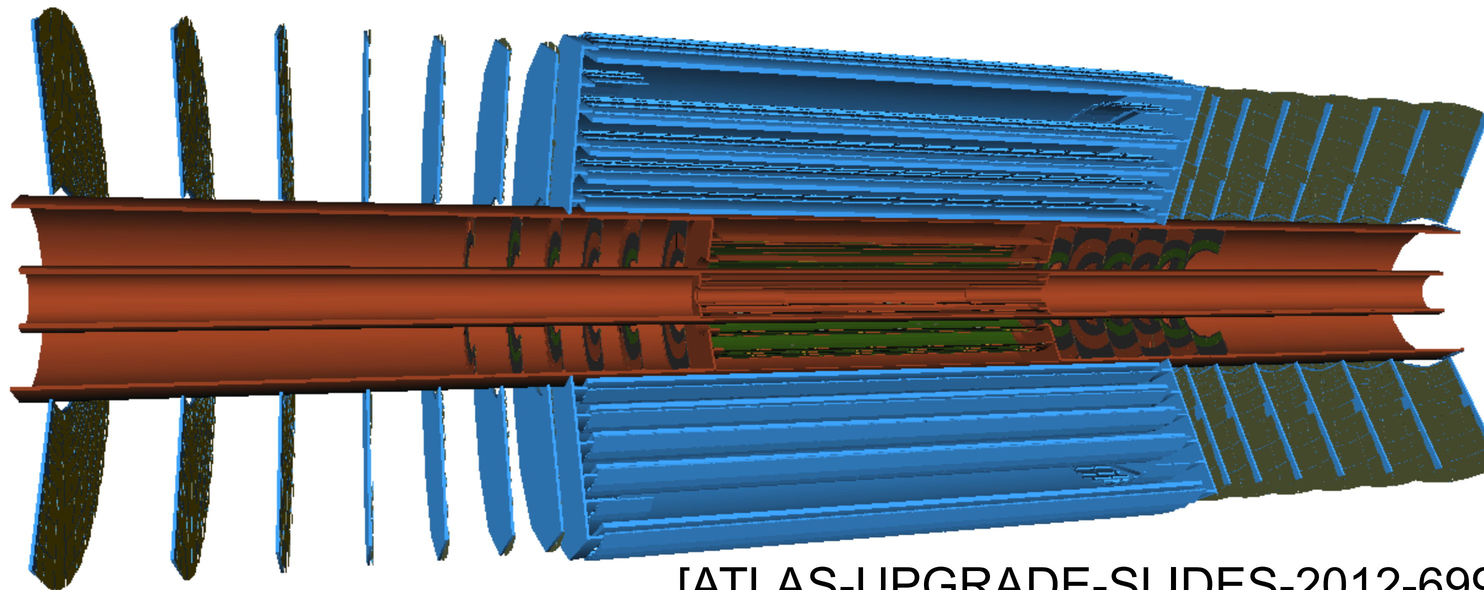
Track fit in full resolution (hits in a road)

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

ATLAS & CMS Trackers for HL-LHC

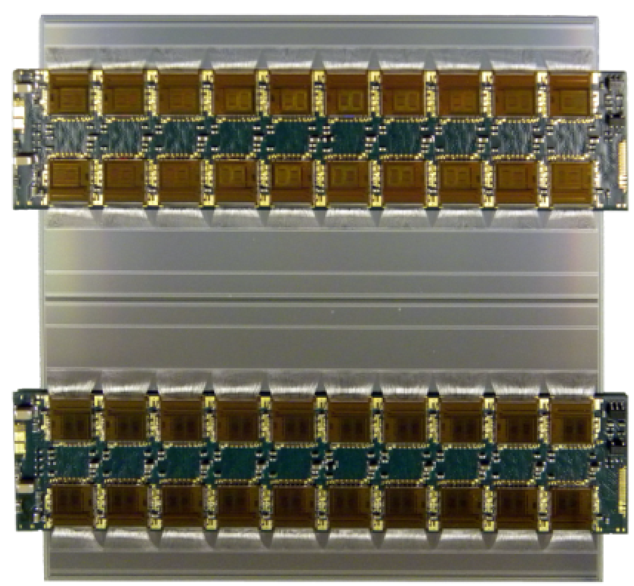
- ATLAS & CMS: replacement of **entire tracker**
  - End of lifetime for current trackers
  - Increase **granularity**, e.g. shorter silicon strips
  - Improved silicon **sensors** and **readout** chips
  - Improved **services**: cooling (CO_2), powering (DC-DC or serial), …
- Extensive **R&D programs**,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

ATLAS HL-LHC Design: 4 Pixel + 5 Strip Layers (Barrel)

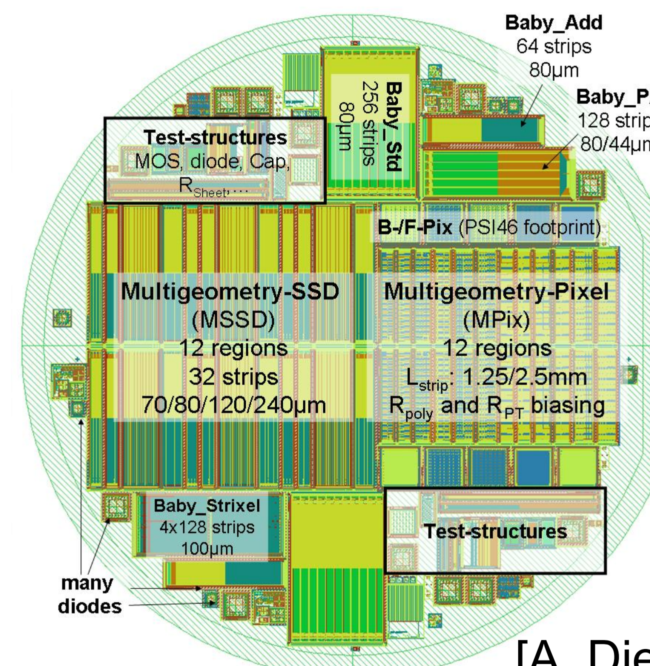


[ATLAS-UPGRADE-SLIDES-2012-699]

ATLAS Prototype Module



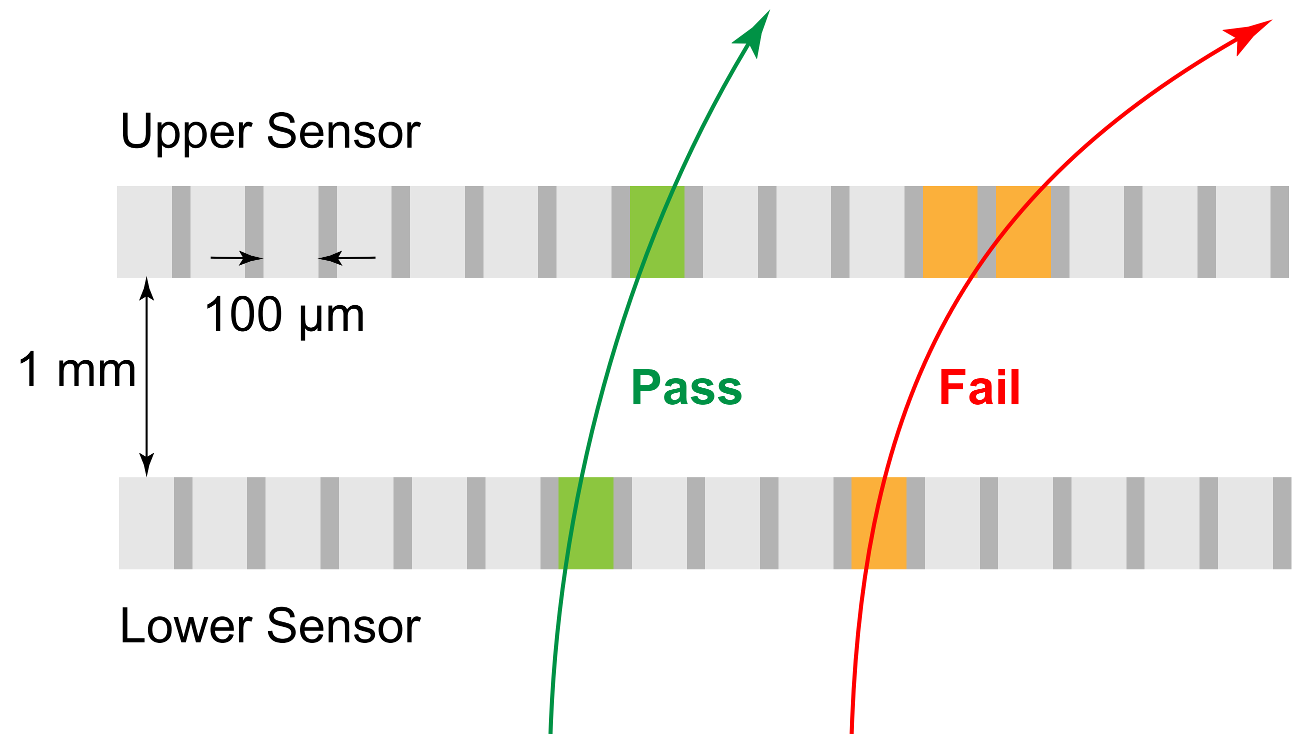
CMS HPK Campaign Wafer

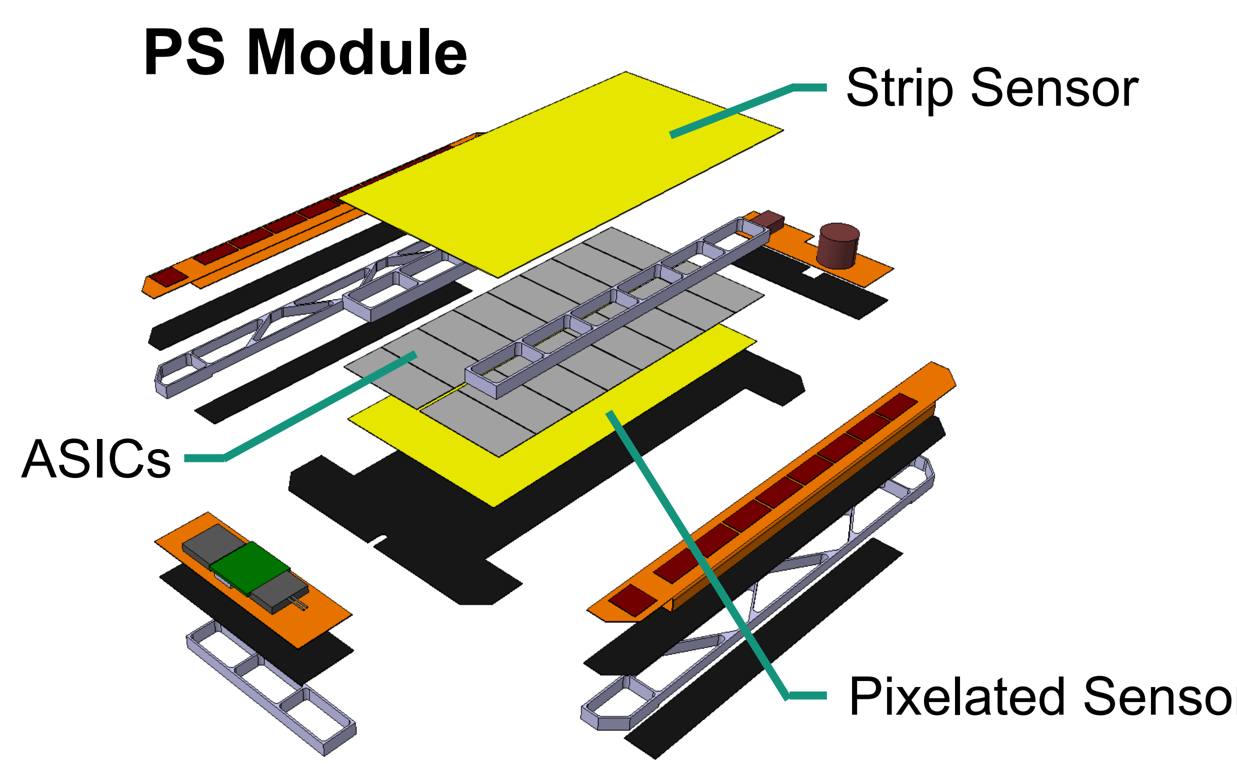


[A. Dierlamm]

CMS Tracker Upgrade: p_T Modules

- Goal: keep p_T thresholds for single lepton triggers low
- Idea: exploit **tracking** information as early as possible in **trigger** (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
  - Close to collision point: **PS modules** (pixels + strips)
  - Larger radii: **2S modules** (strips + strips)





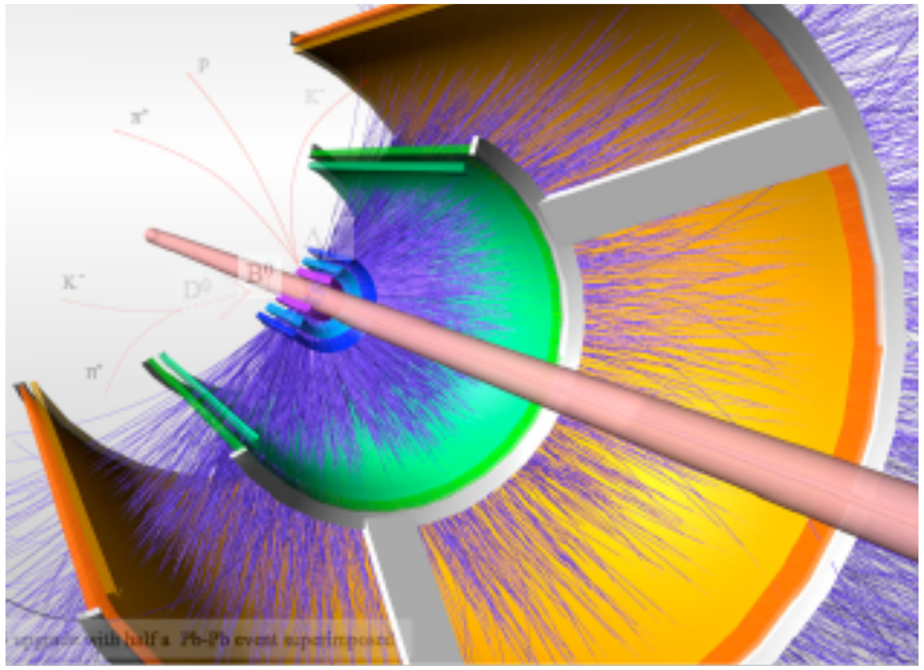
ATLAS and CMS Upgrades: Short Summary

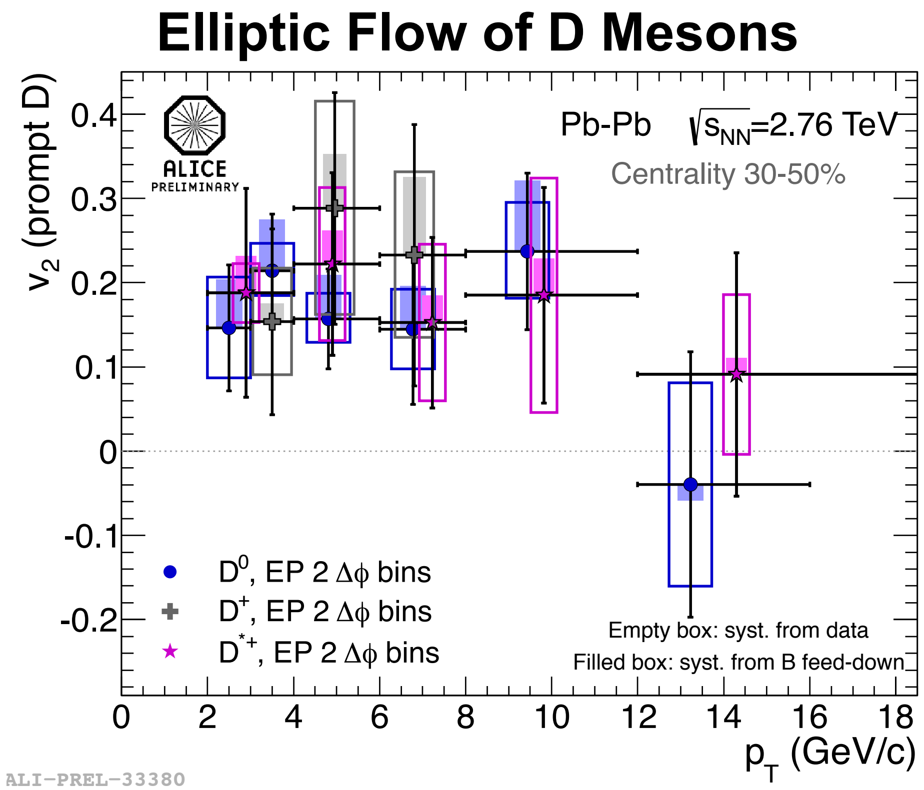
Karlsruhe Institute of Technology

- Physics guidance for upgrade so far: **Higgs**, but nothing else
  - Tracking, vertexing, triggering at **low transverse momenta** stays relevant
  - **Forward instrumentation** increasingly important
- ATLAS and CMS upgrades towards HL-LHC
  - Goal: maintain (at least) **current performance** in much more difficult environment (high occupancy, radiation damage, …)
  - Many improvements to detectors, readout electronics, triggers
  - Special focus: replacement of **tracking detectors**

ALICE and LHCb Upgrades

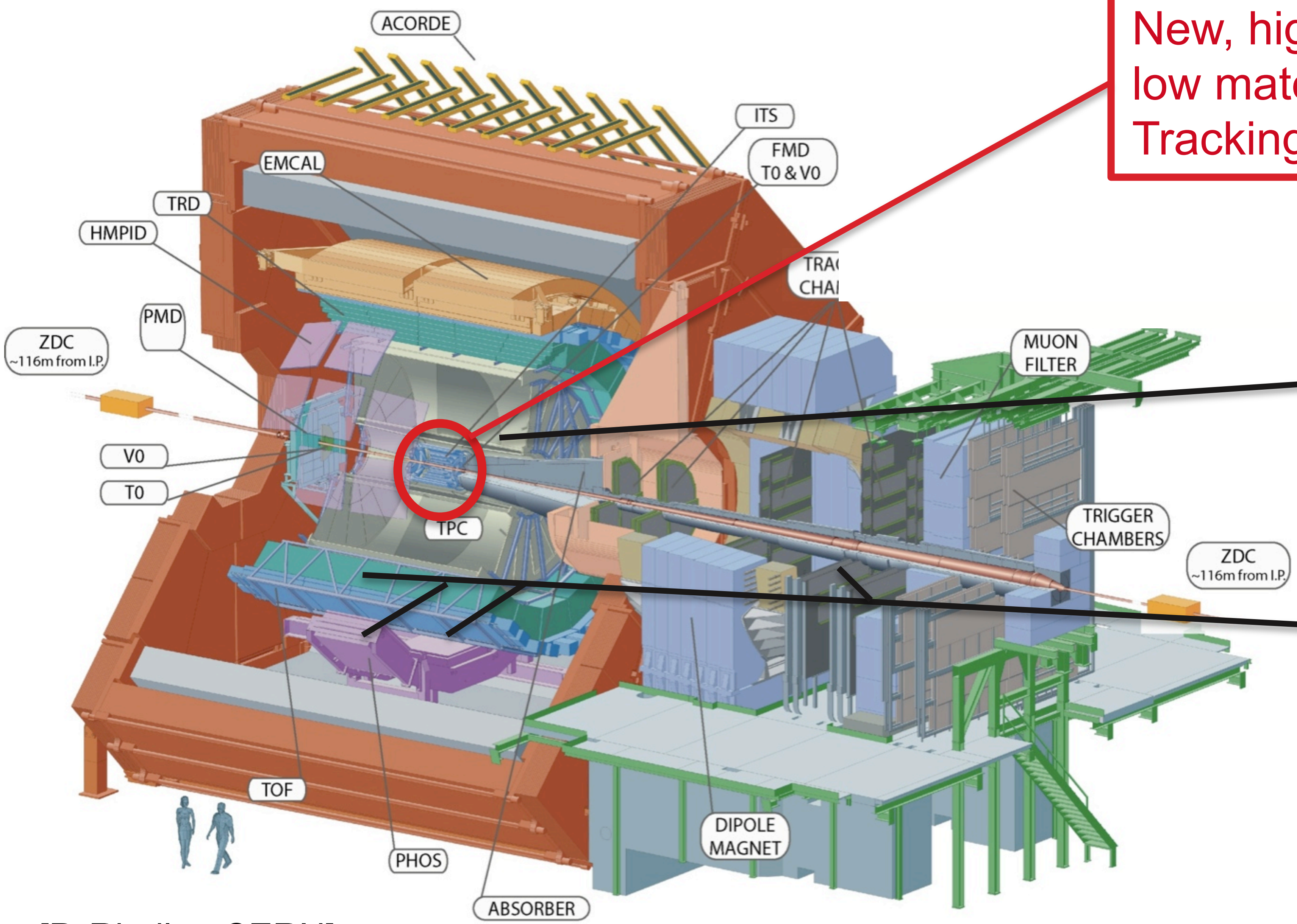
The Case for ALICE Upgrades





- 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 lepton pairs
  - Physics: generation of hadron masses via **chiral symmetry breaking**
  - Detector: low material budget, low-p_T tracking, lepton identification

ALICE Upgrade Plans



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

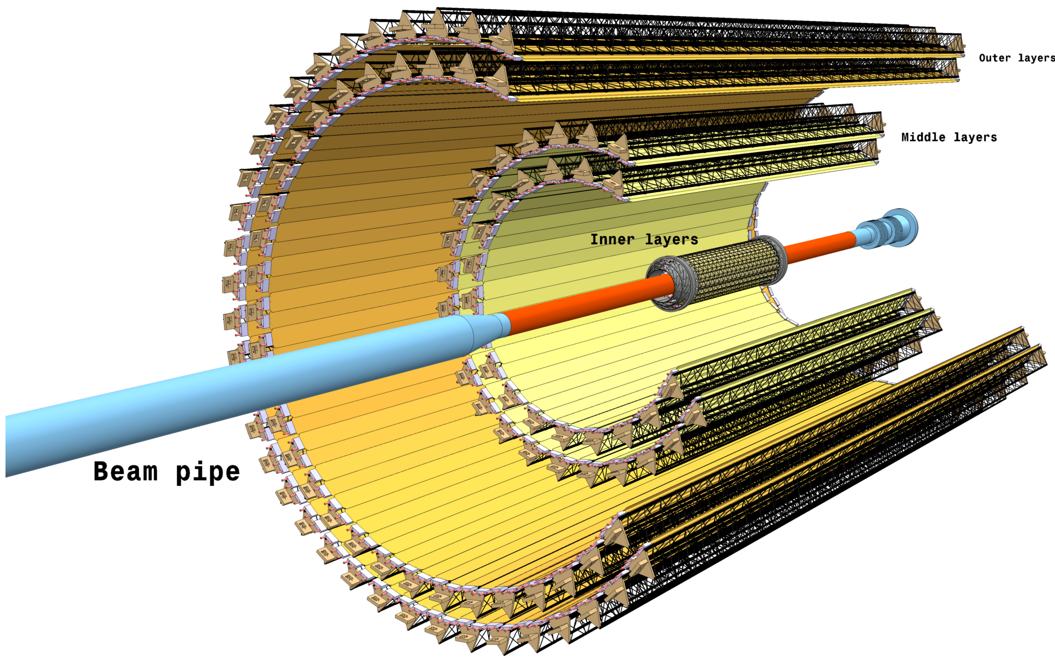
[P. Riedler, CERN]

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

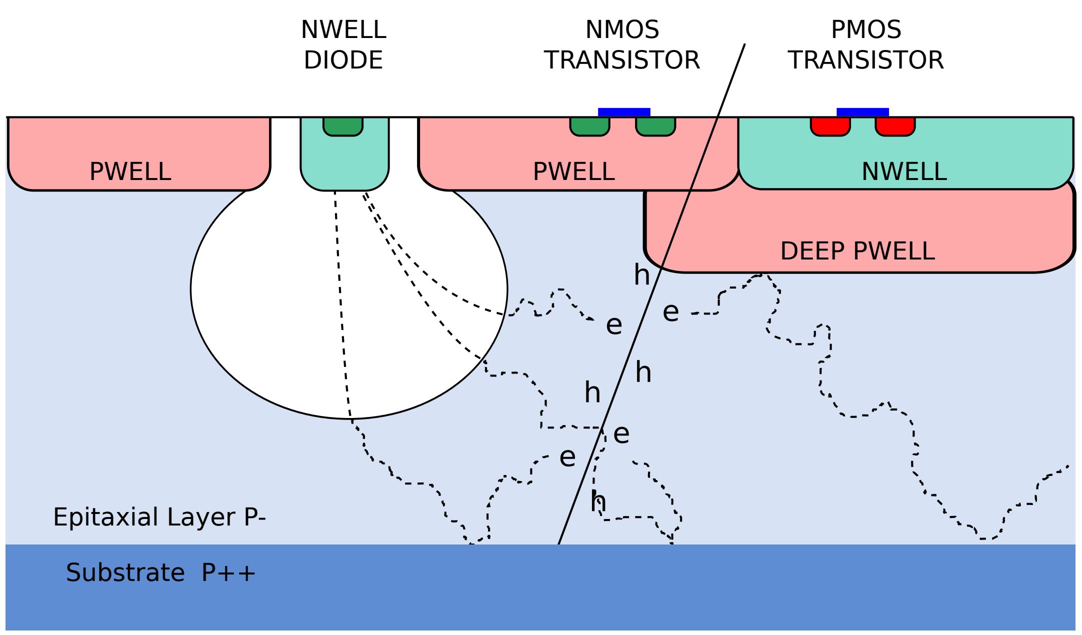
Example: ALICE Tracking Upgrade

- 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)

3D Cutaway View



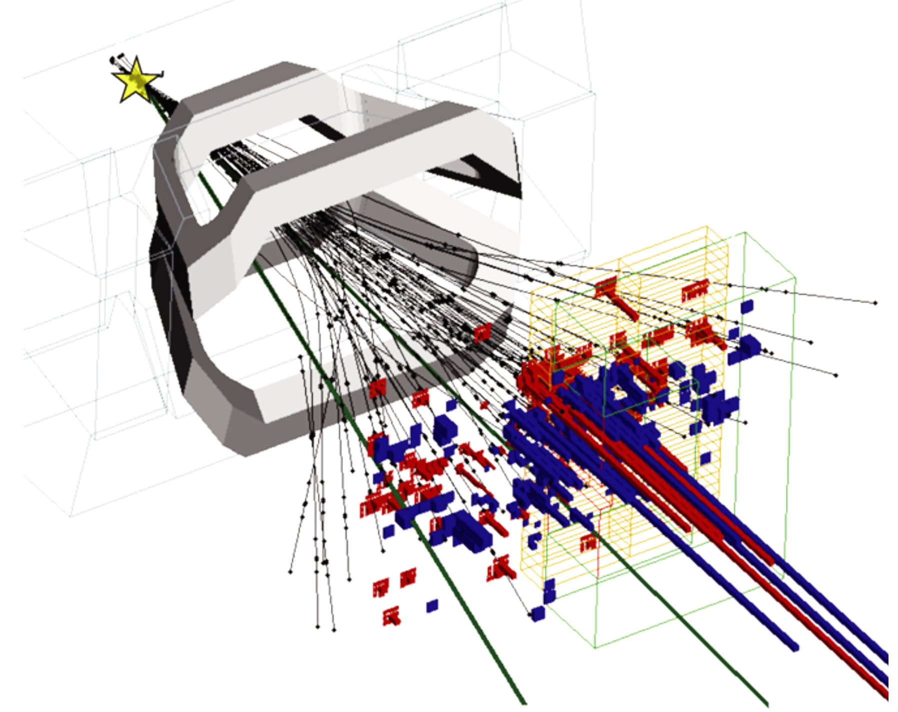
Monolithic Pixels (0.18 µm CMOS)



[CERN-LHCC-2012-013]

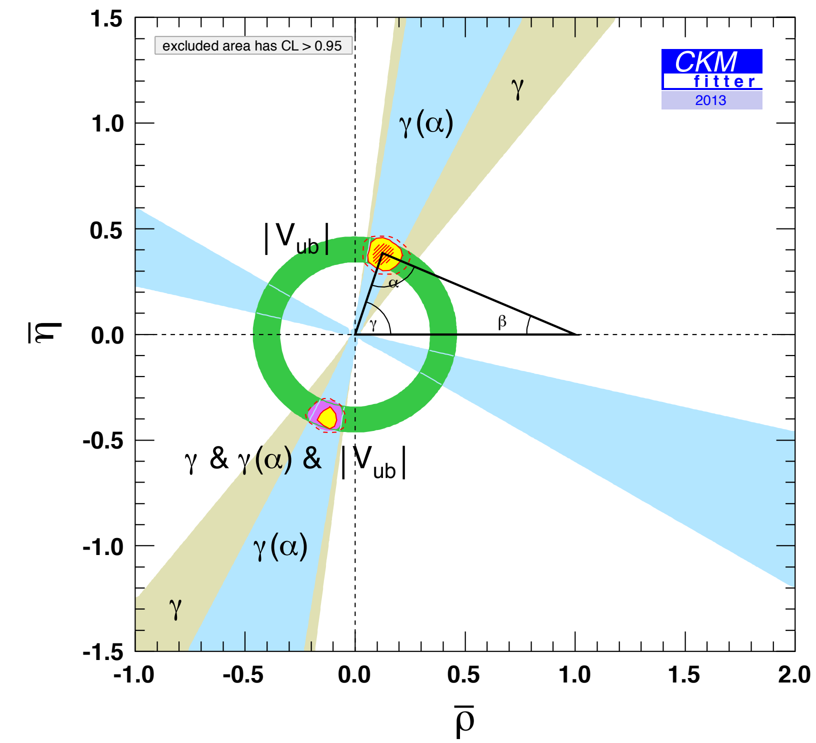
The Case for LHCb Upgrades

- 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
  - Rare decays: **flavor-changing neutral currents** and search for **exotic decays**
  - New sources of CP-violation in the B meson system
  - Mixing and CP violation in the **charm sector**
  - LHCb = **general-purpose** forward detector
- Upgrades not tied to LHC upgrades



[CERN-LHCC-2011-001]

Current Constraints on CKM Angle γ

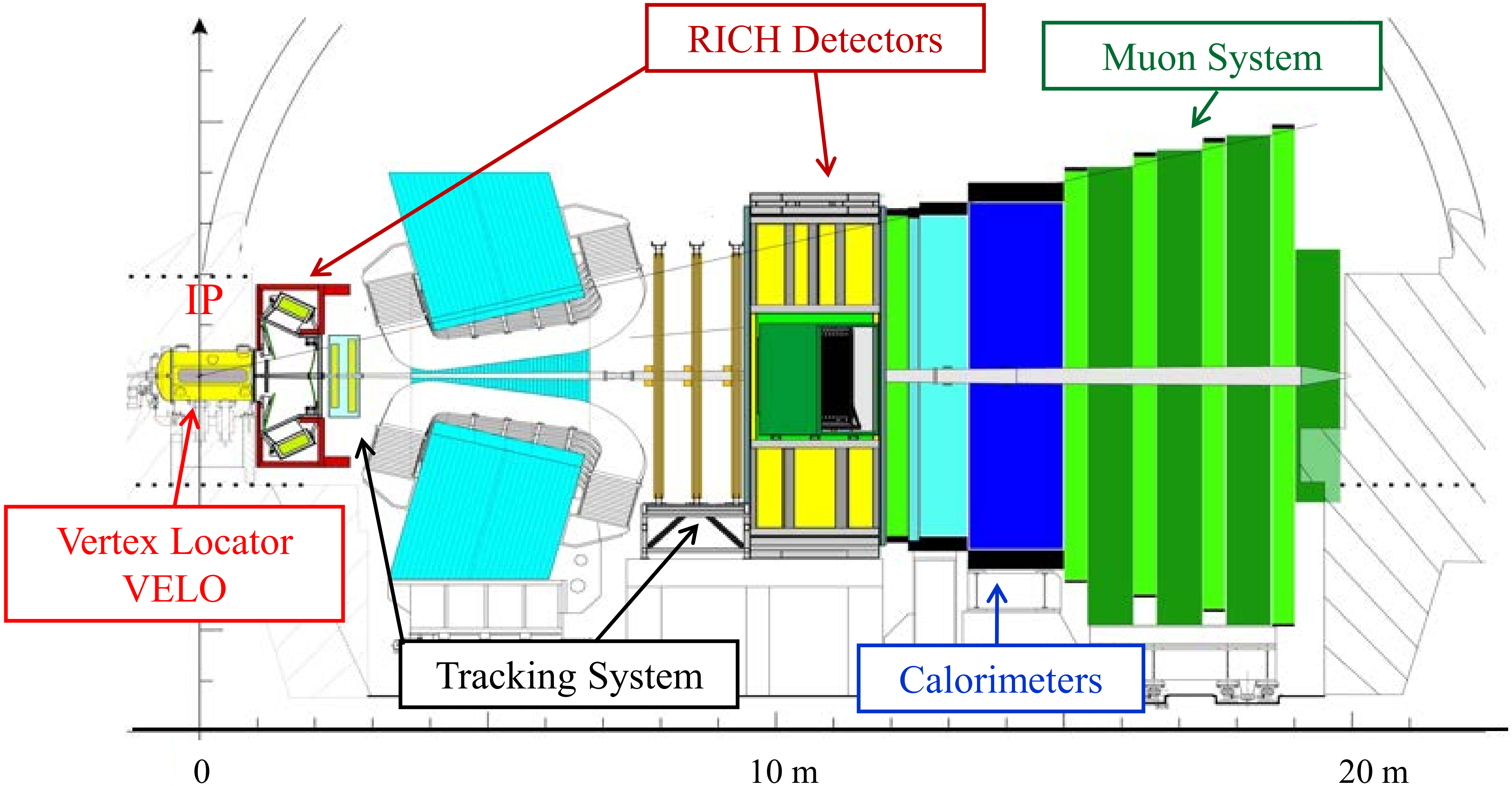


[ckmfitter.in2p3.fr]

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

LHCb Upgrade Plans

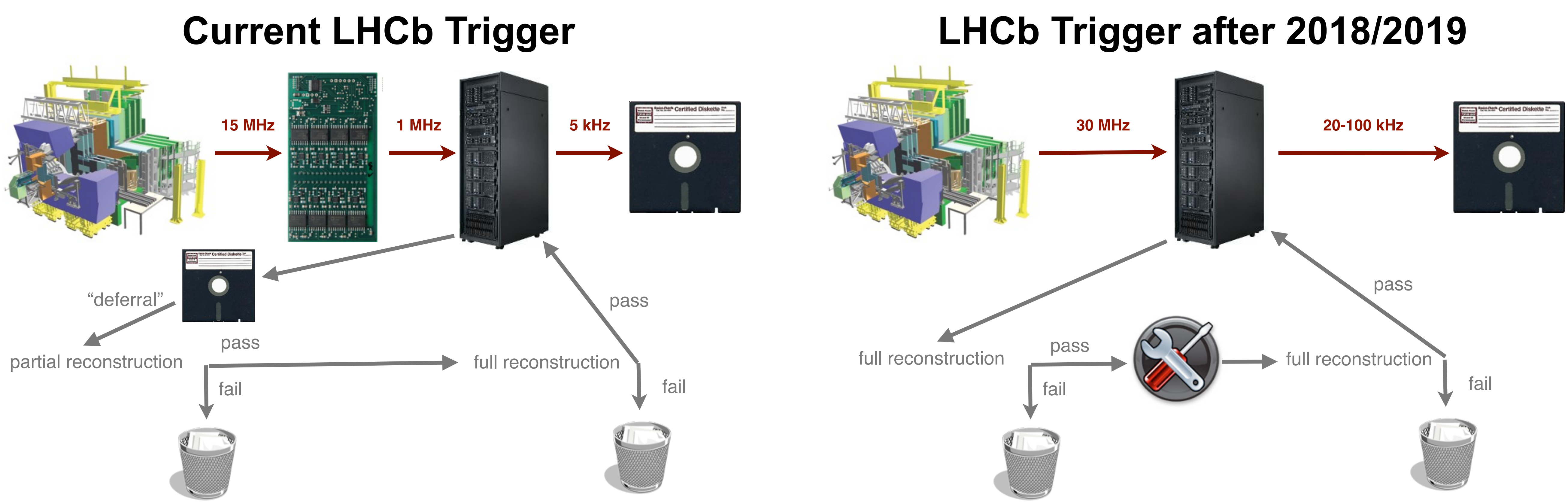
- **Replacement** of VELO and tracking system: new technologies
- All subsystems: new **40 MHz front-end electronics**, adaptations for high-luminosity running



[LHCb-TALK-2014-119]

Example: LHCb DAQ/Trigger Upgrade

- Current L0 hardware trigger upgraded to optional low-level trigger (LLT)
  - Zero-suppression → 30 MHz **trigger-less** readout to high-level trigger (HLT)
  - Replacement of all front-end electronics
- HLT: **full event selection in software** → 20–100 kHz output rate



[M. Williams, LHCC June 2014]

ALICE & LHCb Upgrade Schedules

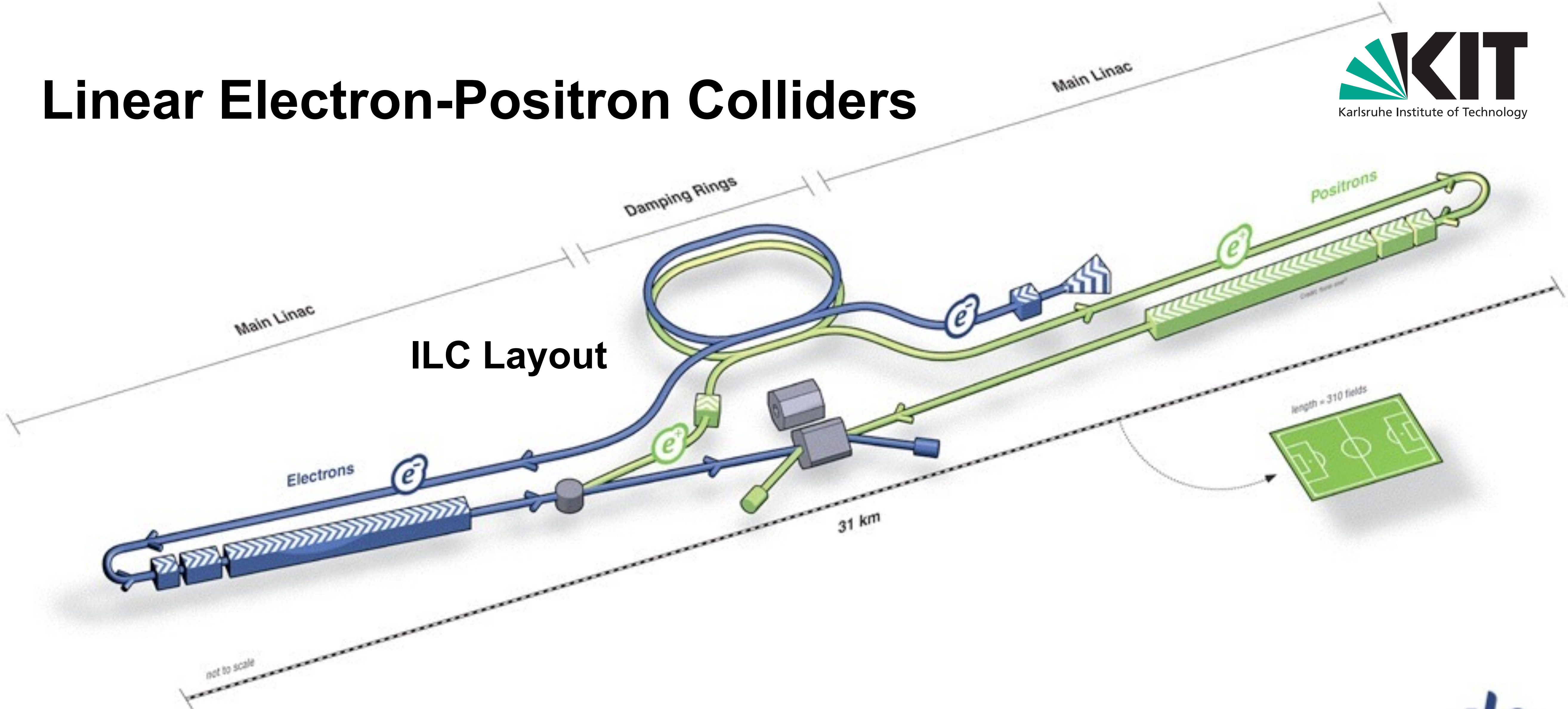
	ALICE	LHCb
Writeups	**Conceptual Design Report** for Inner Tracking (Sep 2012), **TDRs** 2013/4	Framework **Technical Design Report** (2012), Subsystem TDRs 2013/4
Installation/ Commissioning	**LS2** (2018/9)	Preparations: LS1 New Detectors: **LS2** (2018/9)
Luminosity Goals	>10 nb >6 pb	> 50 fb
Running Scenario 2019	PbPb interactions at 50 kHz (6×10 →	pp interactions at 20 kHz (2×10 →

Beyond LHC

Complementary Colliders: e^+e^-

- Physics at **e^+e^- colliders**
  - Traditional distinction: hadron colliders = **discovery** machines – e^+e^- colliders = **precision** machines → **complementary** approaches (however: lots of precision physics at Tevatron and LHC)
  - Physics: e^+e^- collider as **Higgs boson and top quark factory**
  - Advantage of e^+e^-: **clean** leptonic initial state with known kinematics
  - Disadvantage: **lower CM energy** compared to hadron colliders
- Most popular approach: **linear** e^+e^- colliders (see e.g.: linearcollider.org)
  - Advantage: **no energy loss** through synchrotron radiation
  - Disadvantages: **length** (> 30 km), beams can only be used **once**
- Recently: **circular** e^+e^- colliders getting en vogue again

Linear Electron-Positron Colliders

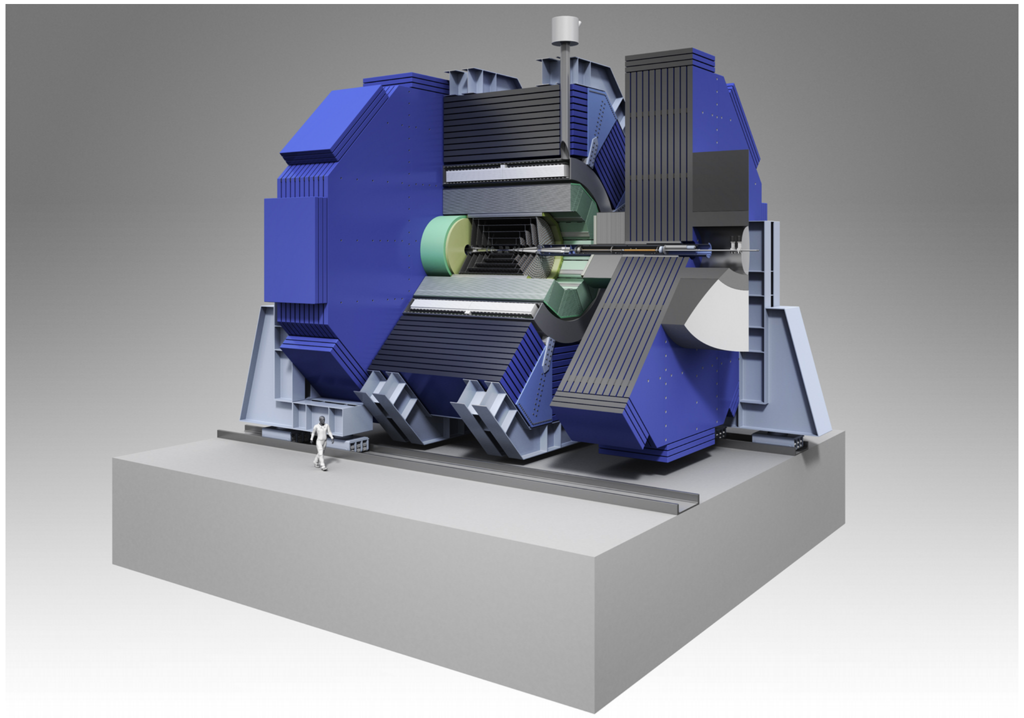


- Most mature concept today: **International Linear Collider** (ILC)
  - **Superconducting** collider with CM energies of **0.5 – 1 TeV**
  - Possible host site: Japan, possible start of construction: after 2018
- Future concept: **Compact Linear Collider** (CLIC) → $\sqrt{s} \leq 5$ TeV
- Common **detector concepts** for both colliders

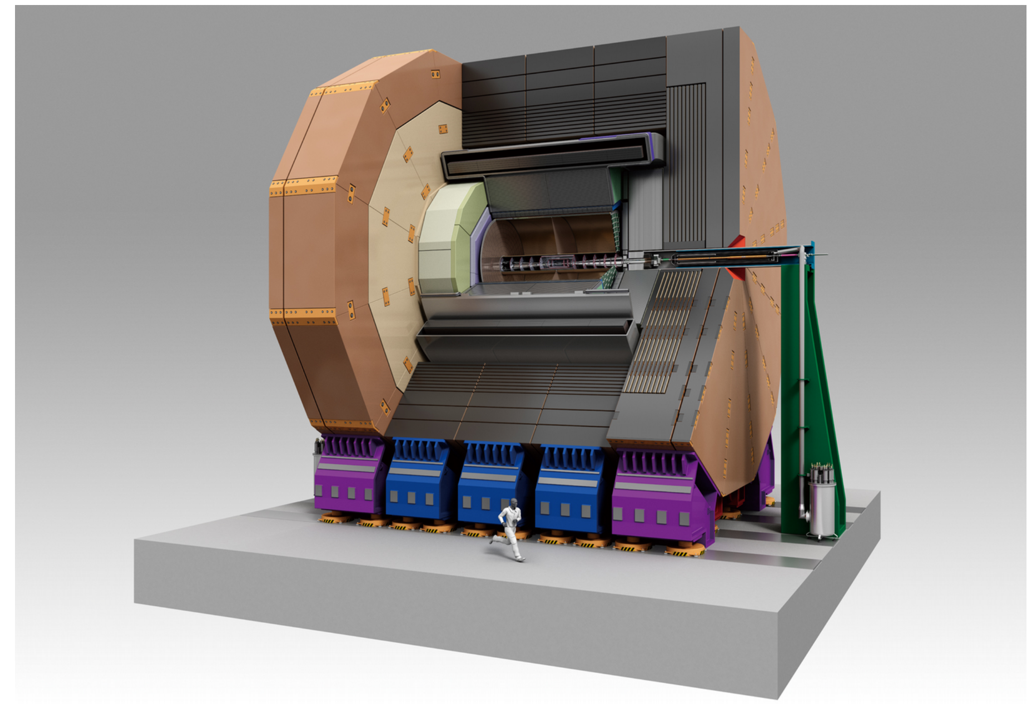
Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

ILC Detectors compared to HL-LHC

Karlsruhe Institute of Technology



SiD



ILD

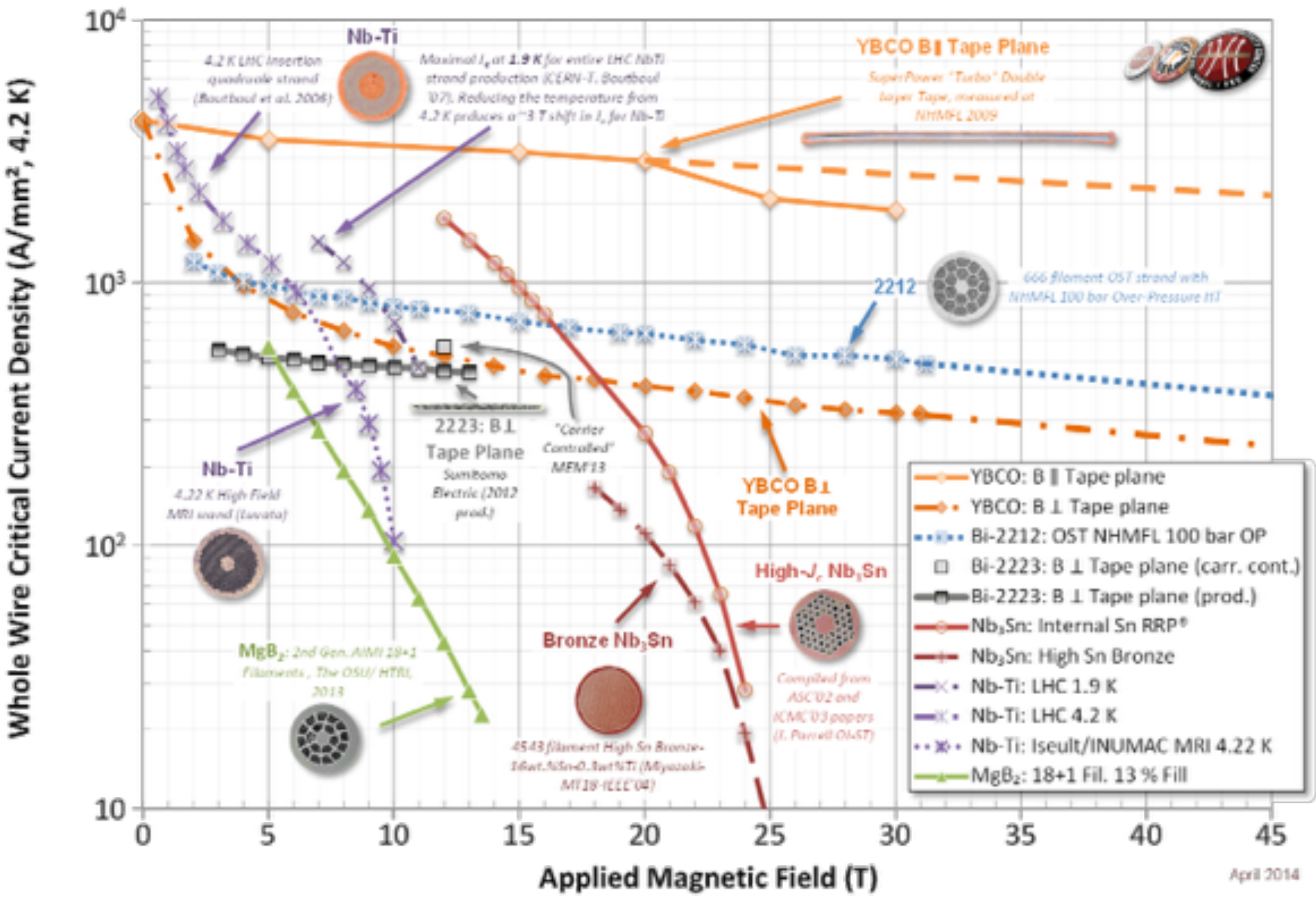
	HL-LHC: ATLAS & CMS	ILC: SiD & ILD
Radiation Hardness	Yes (10	No
Beam Structure	25 ns, synchronous	300 ns, bunch trains
Trigger	Yes, strong data reduction	No, occupancies low
Material Budget (Central)	< 0.5	< 0.2

[after M. Stanitzki]

Karlsruhe Institute of Technology

HE-LHC: High Energy LHC

Superconductor Critical Currents



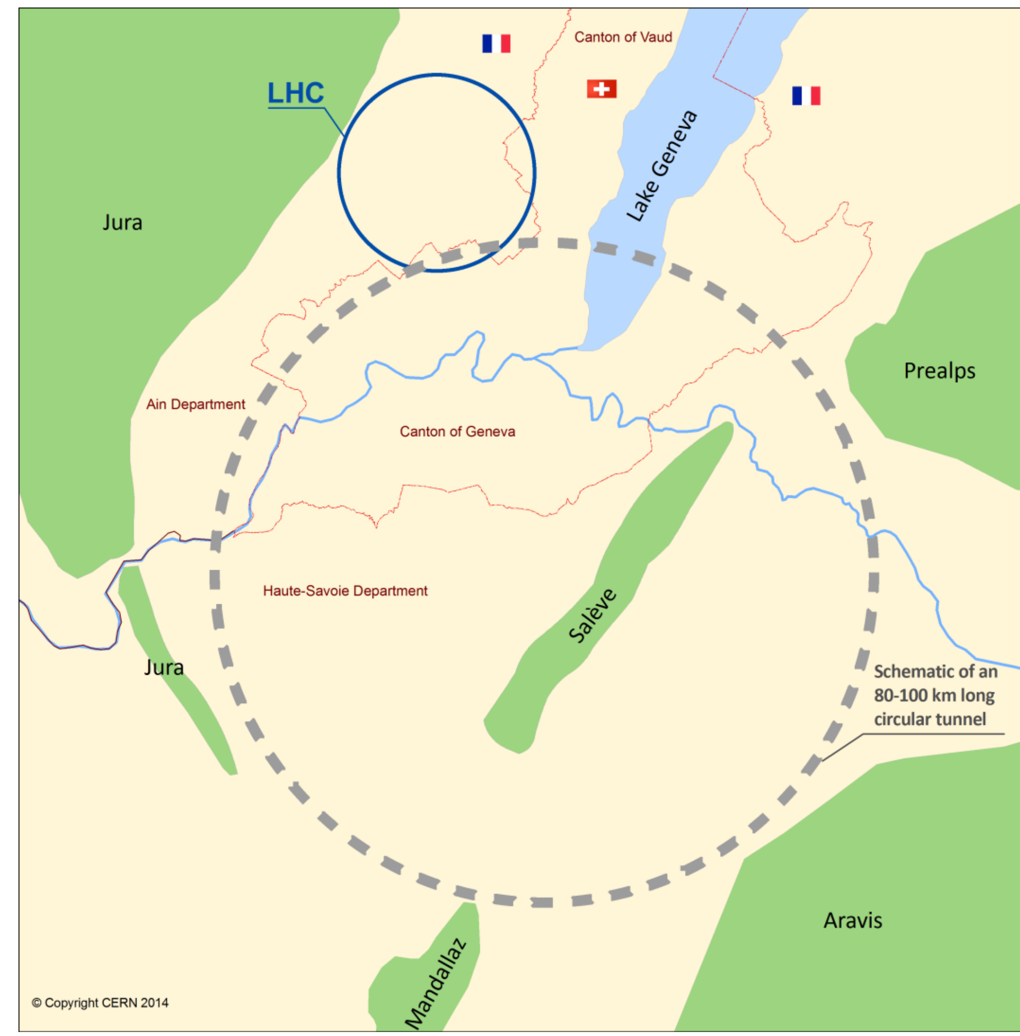
[http://fs.magnet.fsu.edu/~lee/plot/plot.htm]

- Higher energies at the LHC after 2035
  - Increase of LHC center-of-mass energy to **26–33 TeV**
  - Replace **dipole magnets** → practically new machine
  - Physics: **“final word”** on electroweak symmetry breaking, discoveries?
- Technological challenges
  - Novel materials for **high-field superconducting magnets** (up to 20 Tesla)
  - New **injection chain** (SPS at 1–1.3 TeV)
  - Collimation, beam dump, synchrotron radiation, …

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

FCC: Future Circular Colliders

- CERN proposal: new multi-purpose **100 km tunnel** infrastructure
  - FCC-hh: **hadron collider** at **100 TeV CM** energy (with 16-Tesla magnets)
  - FCC-ee (formerly: TLEP): **e^+e^- collider** between Z resonance and $t\bar{t}$ (90–350 GeV CM energy)
  - FCC-ep (optional): ep collider (à la HERA)
  - International **study** launched in February 2014
- Similar study ongoing in **China**
  - **50–70 km** tunnel
  - SppC: **pp @ 50–90 TeV** CM energy
  - CPEC: **e^+e^- @ 120 GeV** CM energy



[http://tlep.web.cern.ch]

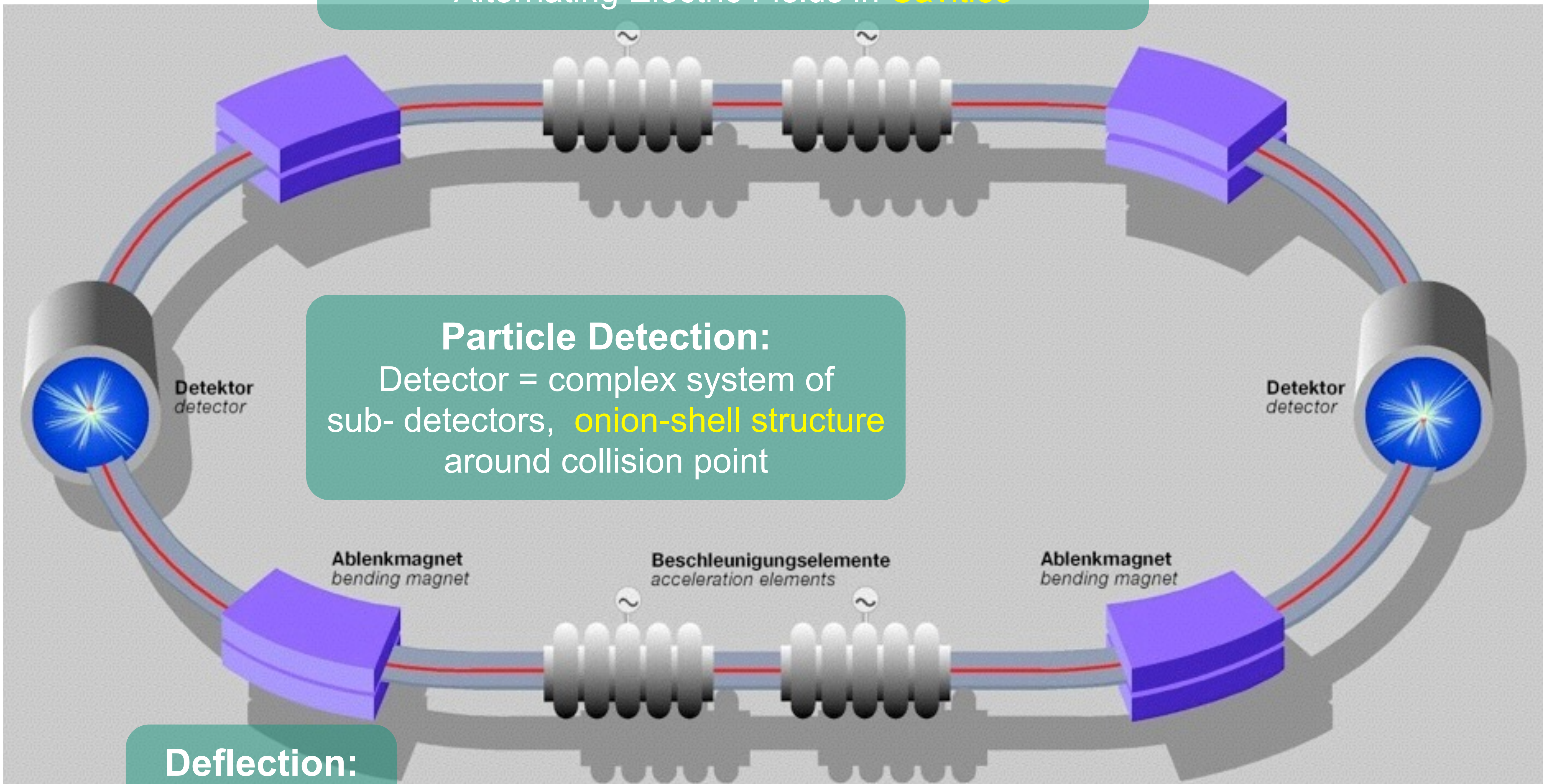
Summary & Conclusions

- CERN's goal: **exploit full LHC physics potential** until ~2035
- Multi-phase **upgrade program** of accelerator chain and experiments
  - Projects grouped around three long shutdowns (LS): LS1 (2013/2014), LS2 (2018/2019), LS3 (2023/2024)
  - ATLAS/CMS: keep comparable performance at highest luminosities
  - ALICE/LHCb: optimize detector and readout for highest rates
- Future **lepton colliders** (linear or circular)
  - Precision machines, complementary to LHC
  - Experimental challenges very different
- Far future: high-energy LHC? Combined pp and ee maschine?

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Working Principle of a Particle Accelerator

Acceleration:
Alternating Electric Fields in Cavities



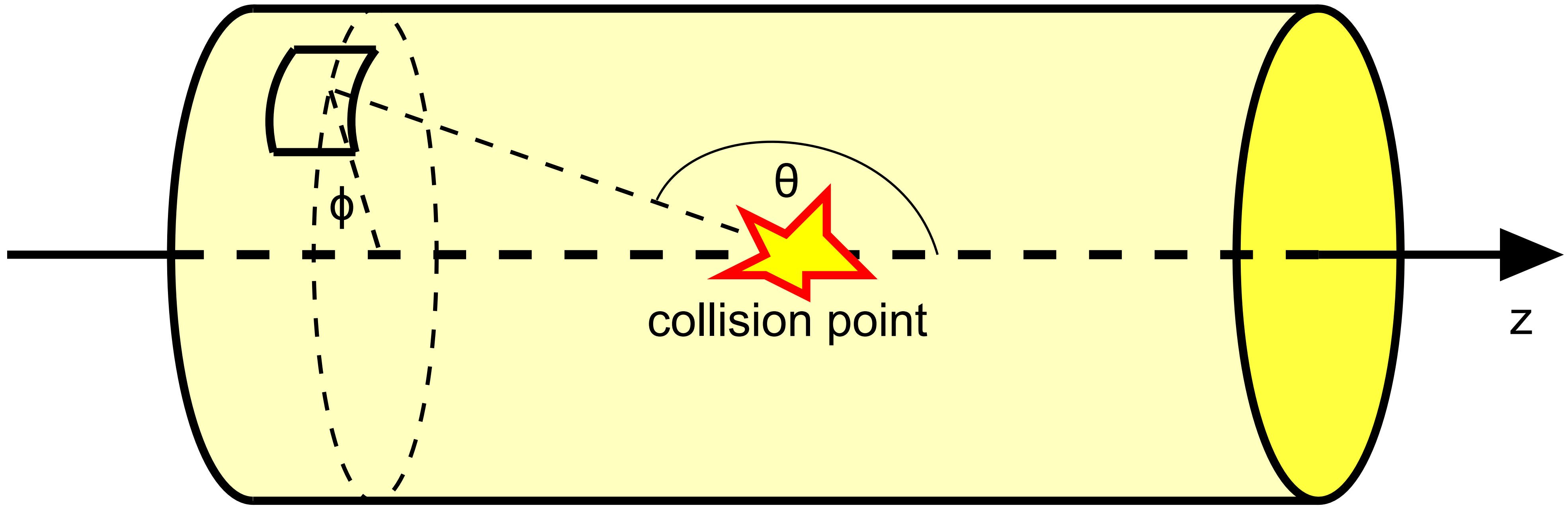
Particle Detection:
Detector = complex system of sub- detectors, onion-shell structure around collision point

Deflection:
Dipole Magnets

[DESY]

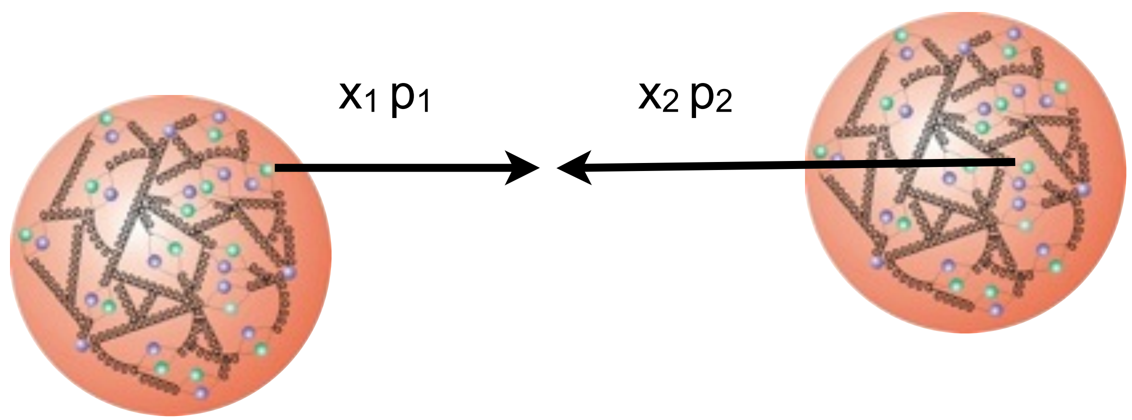
Hadron Collider Kinematics

- Conventional definition of kinematic variables at hadron colliders (derived from onion-shell structure of detectors)
  - Right-handed **cylindrical** coordinate system (r, θ, ϕ)
  - Polar angle θ: angle with *z* axis (= beam axis)
  - Azimuthal angle ϕ: angle with the *x* axis (pointing towards center of the ring)



Transverse Quantities at Colliders

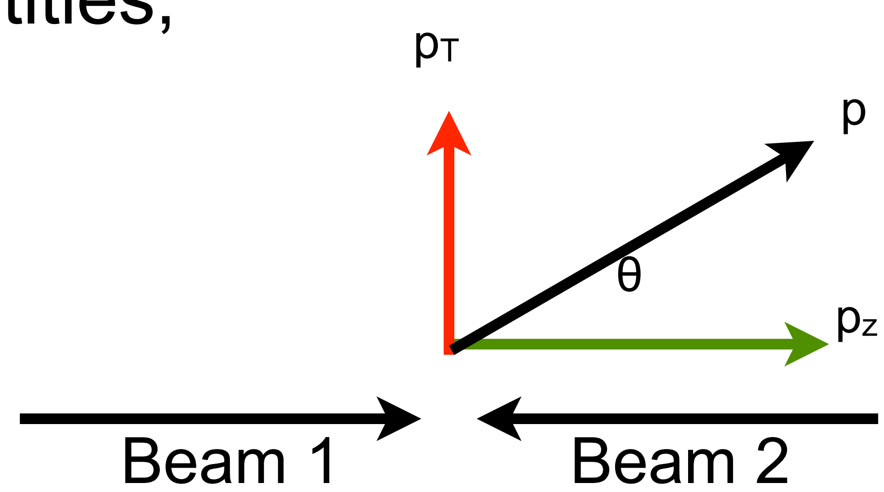
- Hadron collider kinematics (pp, p$\bar{p}$)
  - Collisions of partons with **unknown fraction** $\boldsymbol{x_i}$ of longitudinal component of proton momentum (approximation: all partons collinear to beam)
  - **Rest frame** of parton-parton collision unknown
    → center-of-mass energy unknown



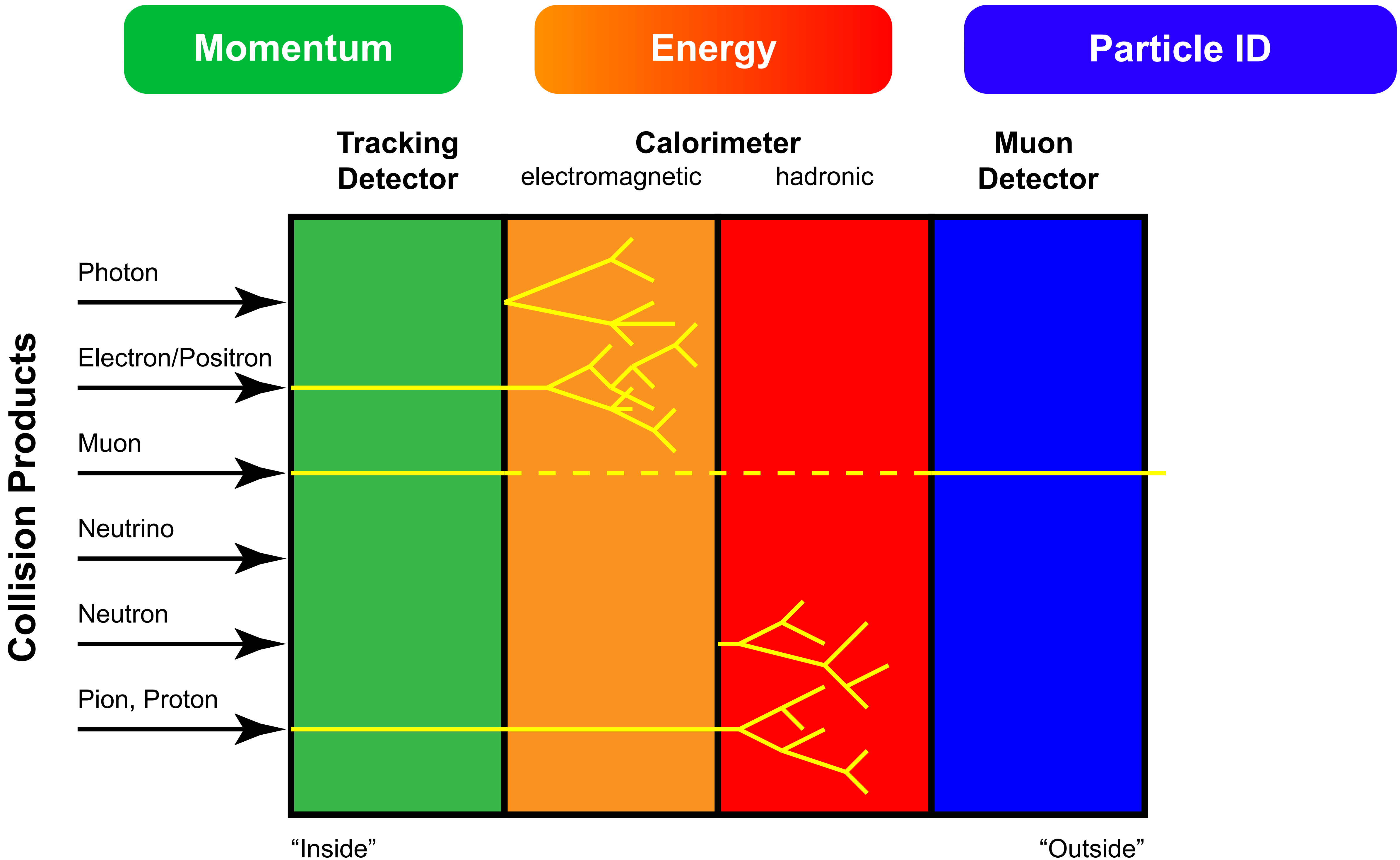
$$\hat{E}^2_{\mathrm{CM}} = x_1\, x_2\, E^2_{\mathrm{CM}}$$

- Transverse variables: Lorentz-invariant quantities, e.g. **transverse momentum** p_T

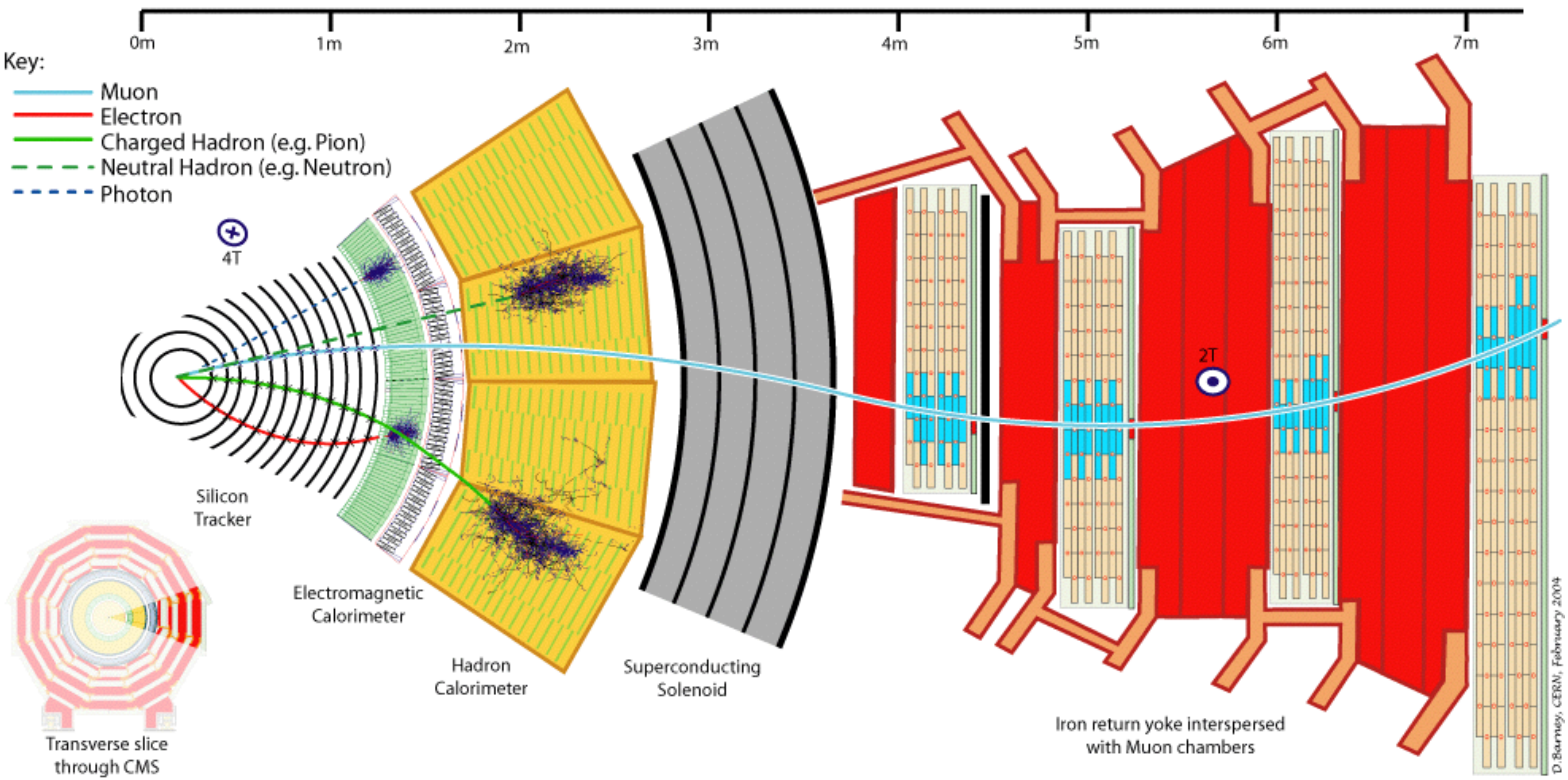
$$p_T = \sqrt{p_x^2 + p_y^2} = p \sin\theta$$



Particle Detectors: Detection Principles



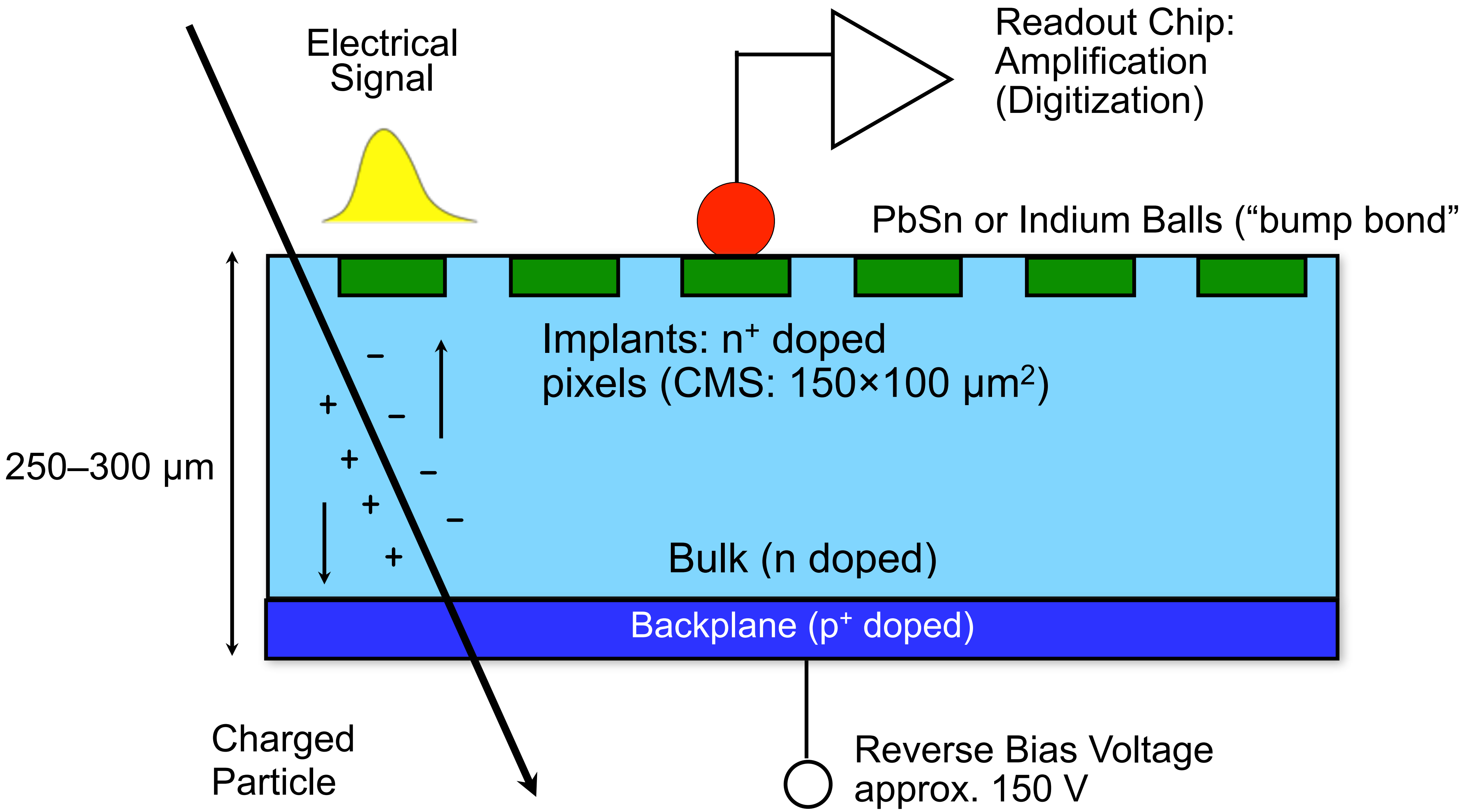
Particle Detection in CMS



Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

LHC Choice for Tracking Detectors: Silicon

- Innermost part of LHC tracking detectors: **silicon hybrid pixel detectors**
  - Detector = semiconductor **diode** with *pn* junction in reverse bias → **depletion zone**
  - Charged particles **ionize** detector material → electron/hole pairs induce signal



Material Budget

- Energy loss of **electrons** in matter
  - Low mass → dominant effect: **bremsstrahlung**
  - **Energy loss** formula (X measured in g cm^{-2}):

$$-\left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\mathrm{rad}} = 4\pi\, r_e^2\, Z^2 \frac{N_A}{A}\, E \ln\frac{183}{Z^{1/3}} \equiv \frac{E}{X_0}$$

$$\text{with } X_0 = \left(4\pi\, r_e^2\, Z^2 \frac{N_A}{A} \ln\frac{183}{Z^{1/3}}\right)^{-1} \quad \text{radiation length}$$

electron intensity reduced by factor 1/e after X_0

- **Photons**: absorption in matter
  - Dominant effect at high energies: **e^+e^- pair production**
  - Lambert-Beer law:

$$I(X) = I_0 \exp[-\mu_p X] \quad \text{with } \mu_p = \sigma_P \frac{N_A}{A} \quad \text{and} \quad \sigma_P = 4\alpha\, r_e^2\, Z^2 \left[\frac{7}{9} \ln\frac{183}{Z^{1/3}} - \frac{1}{54}\right]$$

  - Comparison with above definition of radiation length:

$$\mu_p = \sigma_P \frac{N_A}{A} \approx \frac{7}{9}\frac{1}{X_0}$$

photon intensity reduced by factor $1-e^{-7/9} \approx 0.54$ after X_0

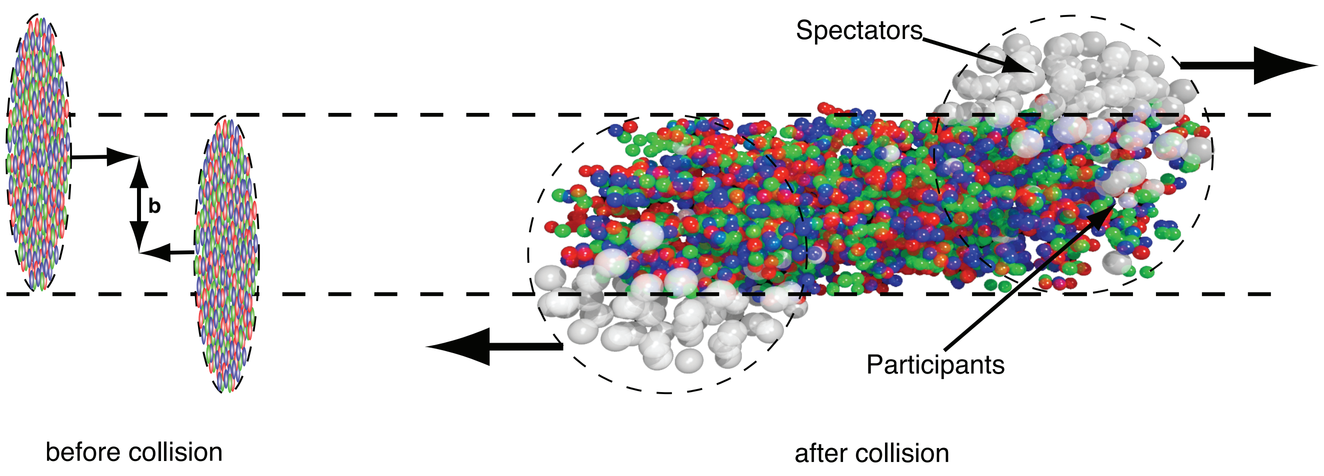
Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Elliptic Flow

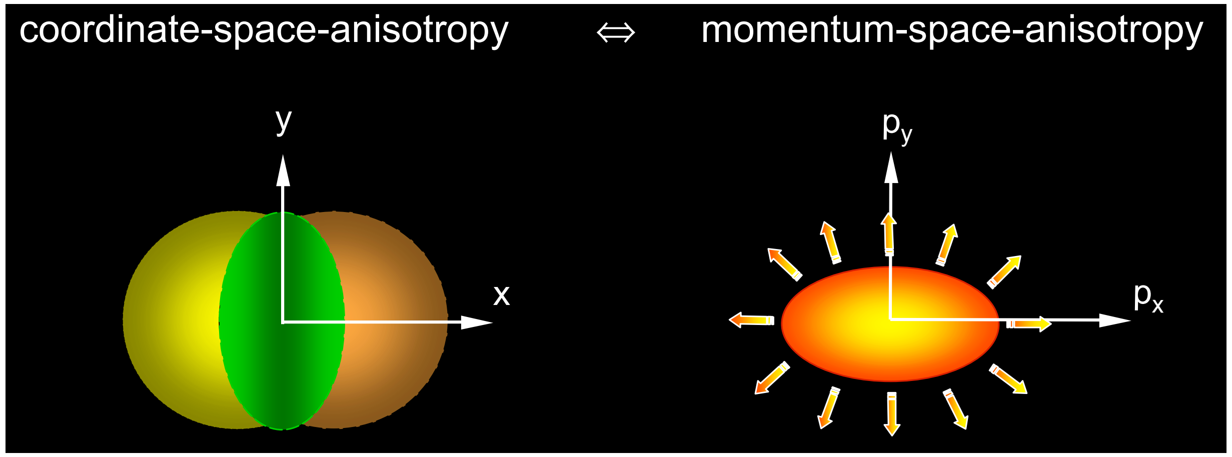
- Heavy ion collision with impact parameter b → anisotropy in momentum space
- Fourier expansion of particle distribution in momentum space

$$E\frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_{RP})]\right)$$

- Fourier coefficients
  - v_1: directed flow
  - v_2: elliptic flow
- Physics: collective flow phenomena



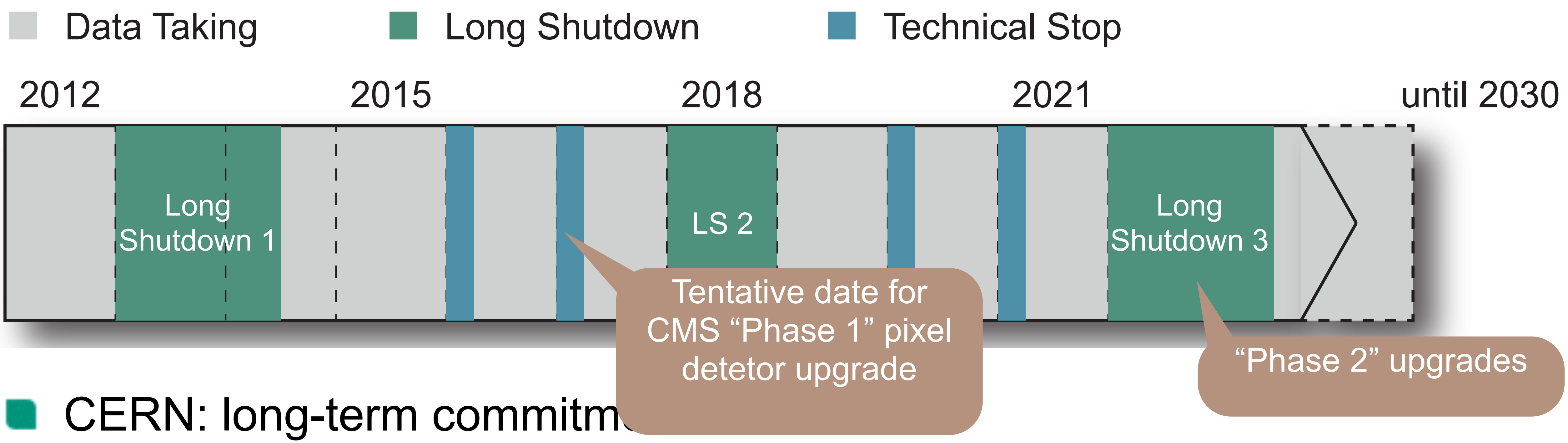
[New J.Phys.13 (2011) 055008]



[K. Schweda]

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

LHC Long Term Plan



- CERN: long-term commitm
  - Goal: deliver 3000 fb^{-1} of integrated luminosity by 2030 → at least 5× increase in instantaneous luminosity
  - Detectors must be upgraded: current detectors suffer from aging and radiation damage, keep similar performance, improve radiation hardness at high luminosity
- According to current planning: three long LHC shutdowns for upgrades
  - 2013/14: LHC center of mass energy to 13–14 TeV
  - 2018: several machine upgrades

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Upgrade Benchmark Scenarios

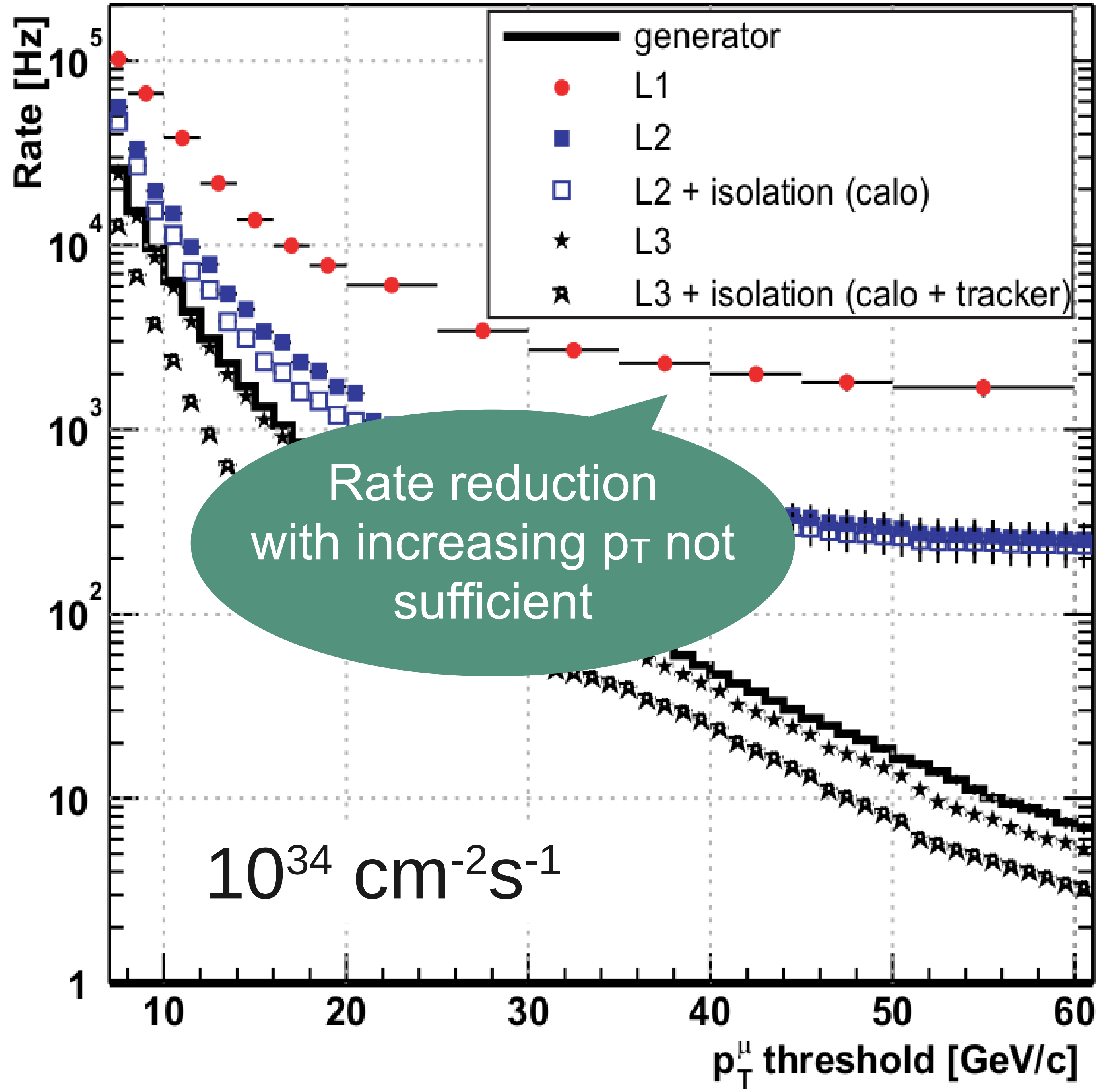
Scenario	Peak Luminosity (cm	Number of Pileup Vertices	Integrated Luminosity (fb
Phase 1 Baseline	2×10		500
Phase 1 Worst Case	2×10 lumi leveling) 4×10		500
Phase 2 Baseline	5×10		3000
Phase 2 Worst Case	5×10 lumi leveling) 10		3000

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Preparing for High Luminosity (10^{35} cm^2 s^{-1})

- Physics case as of 2012: Higgs physics + WW scattering + BSM (e.g. SUSY)
  - Relatively low p_T stay relevant → keep thresholds low
  - Forward instrumentation important → improve coverage (calorimetry & tracking)
- General strategy: exploit synergies between subdetectors
  - Already now: particle flow
  - Phase 2: very close relation between tracking and triggering
- Next step: technical proposals (until 2014)

Simulated Trigger Rates vs. p_T Threshold



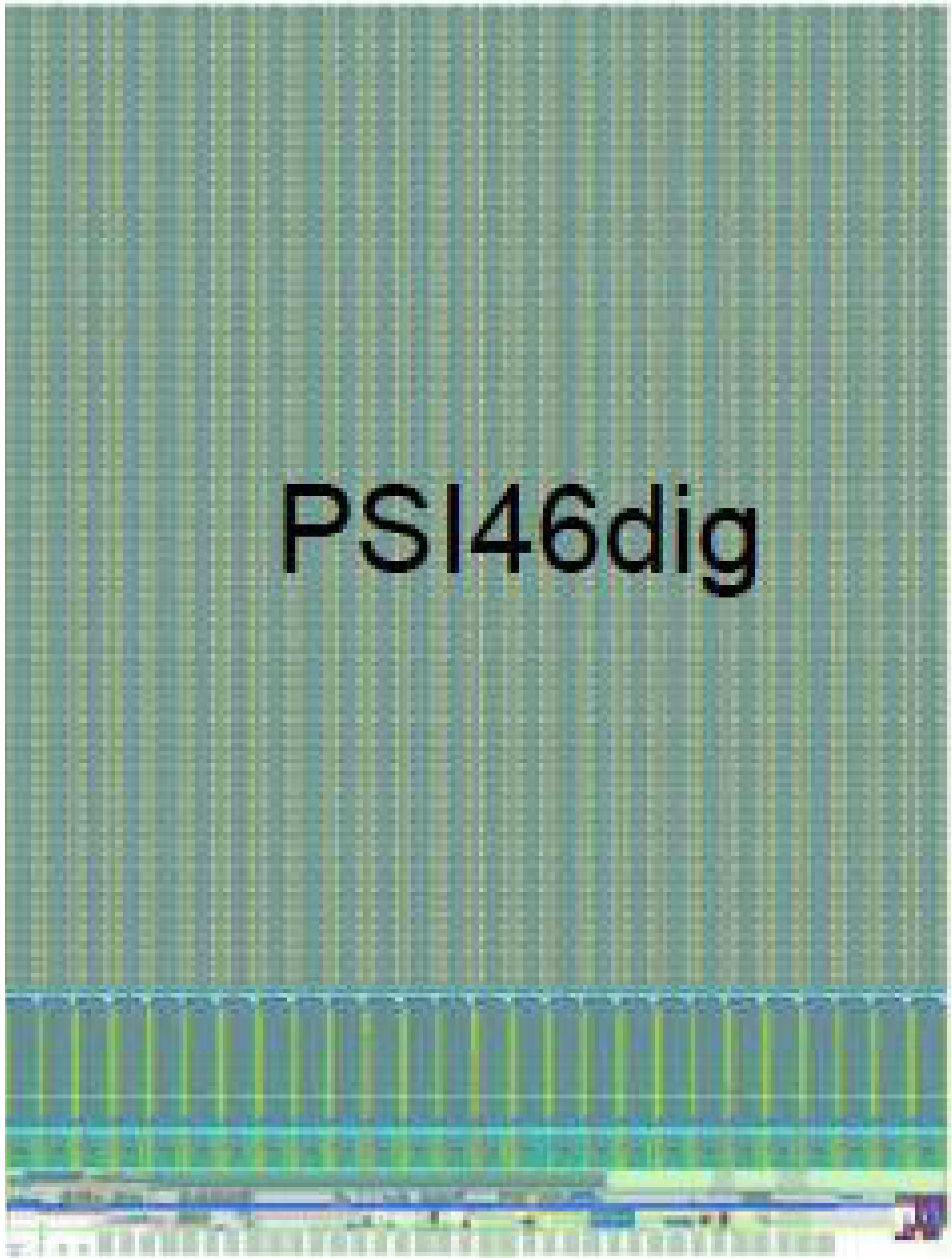
General Phase 1 Pixel Upgrade Strategy

Goal: similar pixel performance in much harsher environment

Modification	Impact
New digital readout chip	Front-end electronics ready for high rates
More layers: 3→4 barrel layers, 2×2→2×3 forward disks	More 3D pixel space points, more tracking redundancy
Smaller radius of innermost layer	Improved impact parameter resolution (key to excellent B-tagging at high pileup)
Improved mechanics, cooling, and powering	Reduced material budget: less multiple scattering, fewer photon conversion

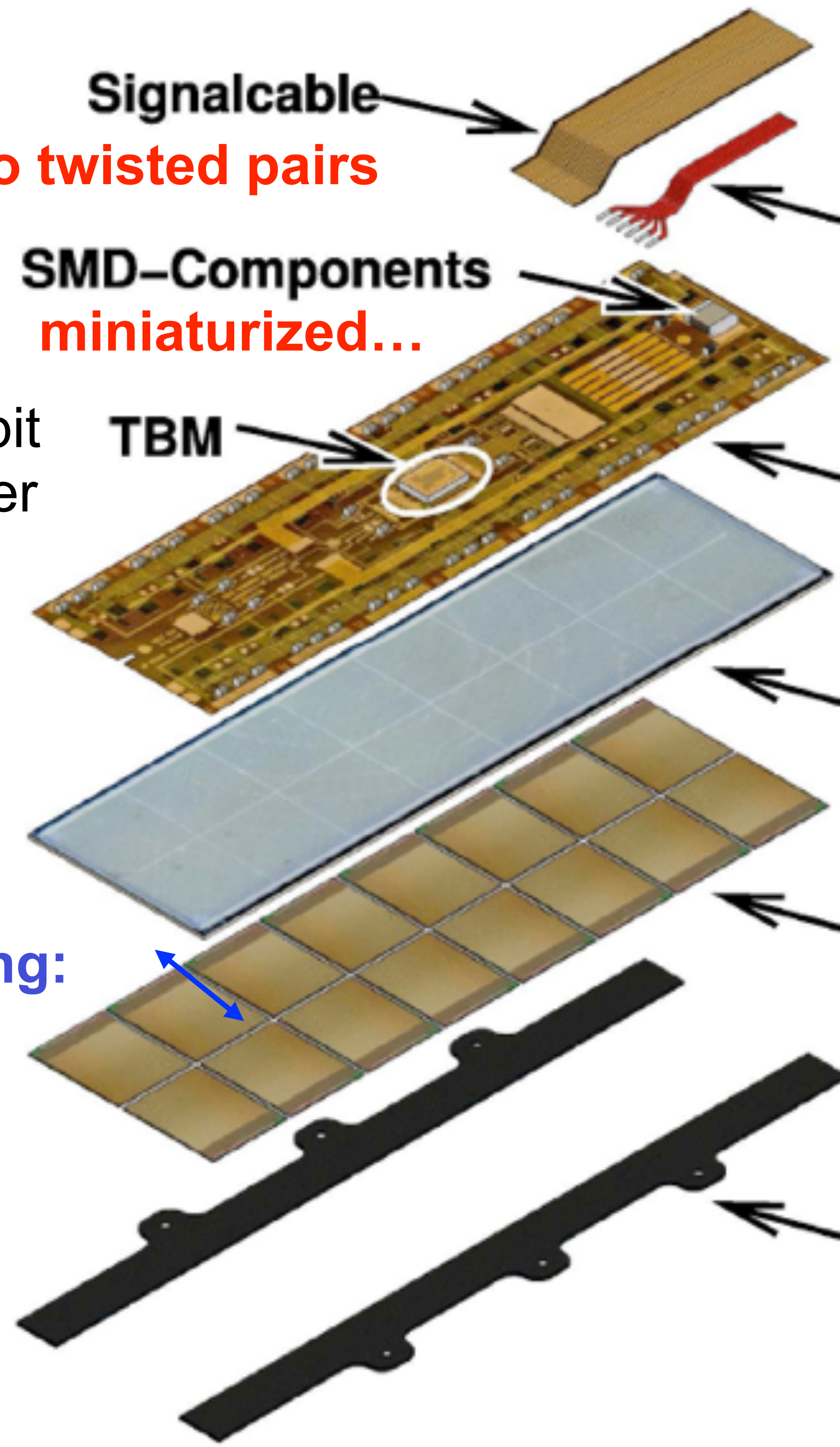
New CMS Pixel Readout Chip

- Goal: overcome rate limitations of current readout chip ($100\ MHz/cm^2 \rightarrow 250\ MHz/cm^2$)
- Strategy: modest evolution of current chip (staying at 250 nm)
- First chip iteration:
  - Digital readout: 8-bit ADC for pulse height
  - 6th metal layer → reduce cross-talk, lower threshold
  - Larger buffers for data and time stamps
  - First version received from foundry, some minor issues, in testing phase
- Second chip iteration:
  - Improved column drain architecture

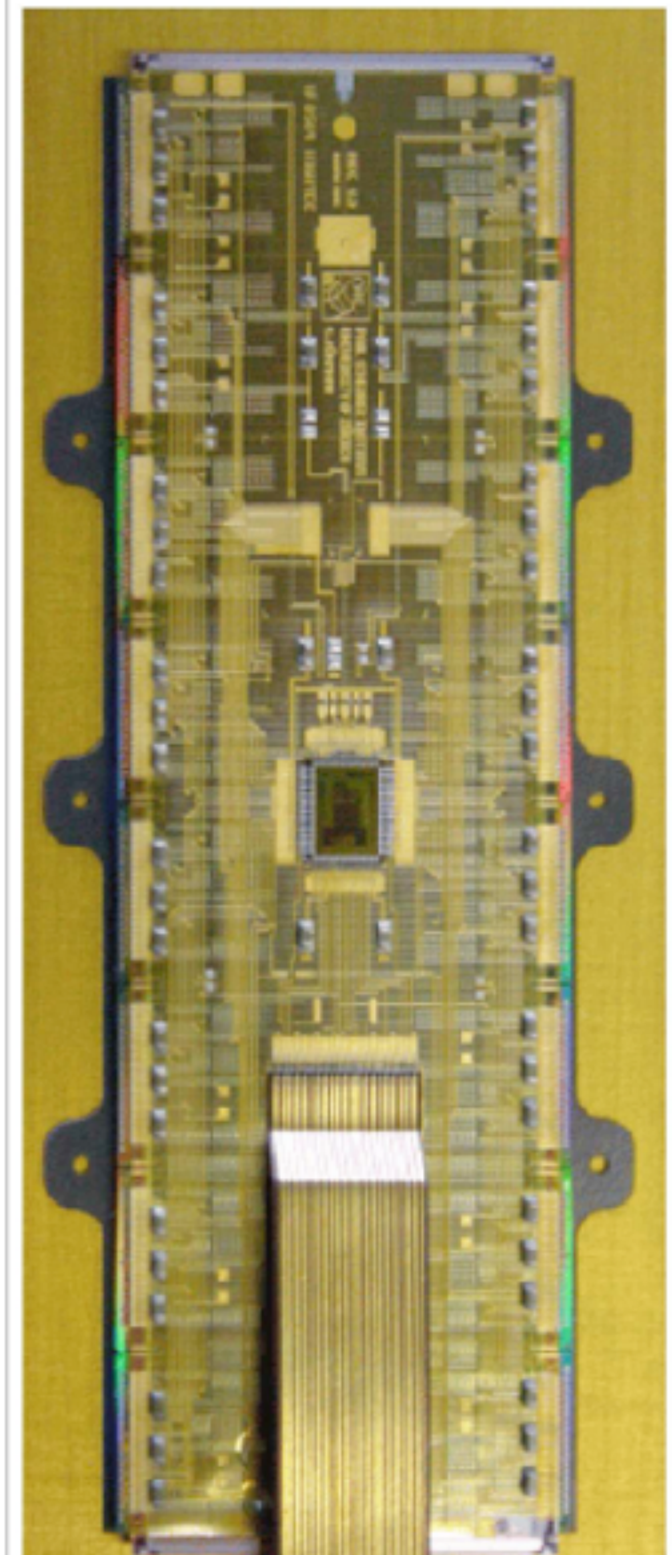


[B. Meier et al., PSI]

Upgraded Barrel Pixel Module



[G. Steinbrück after W. Erdmann]

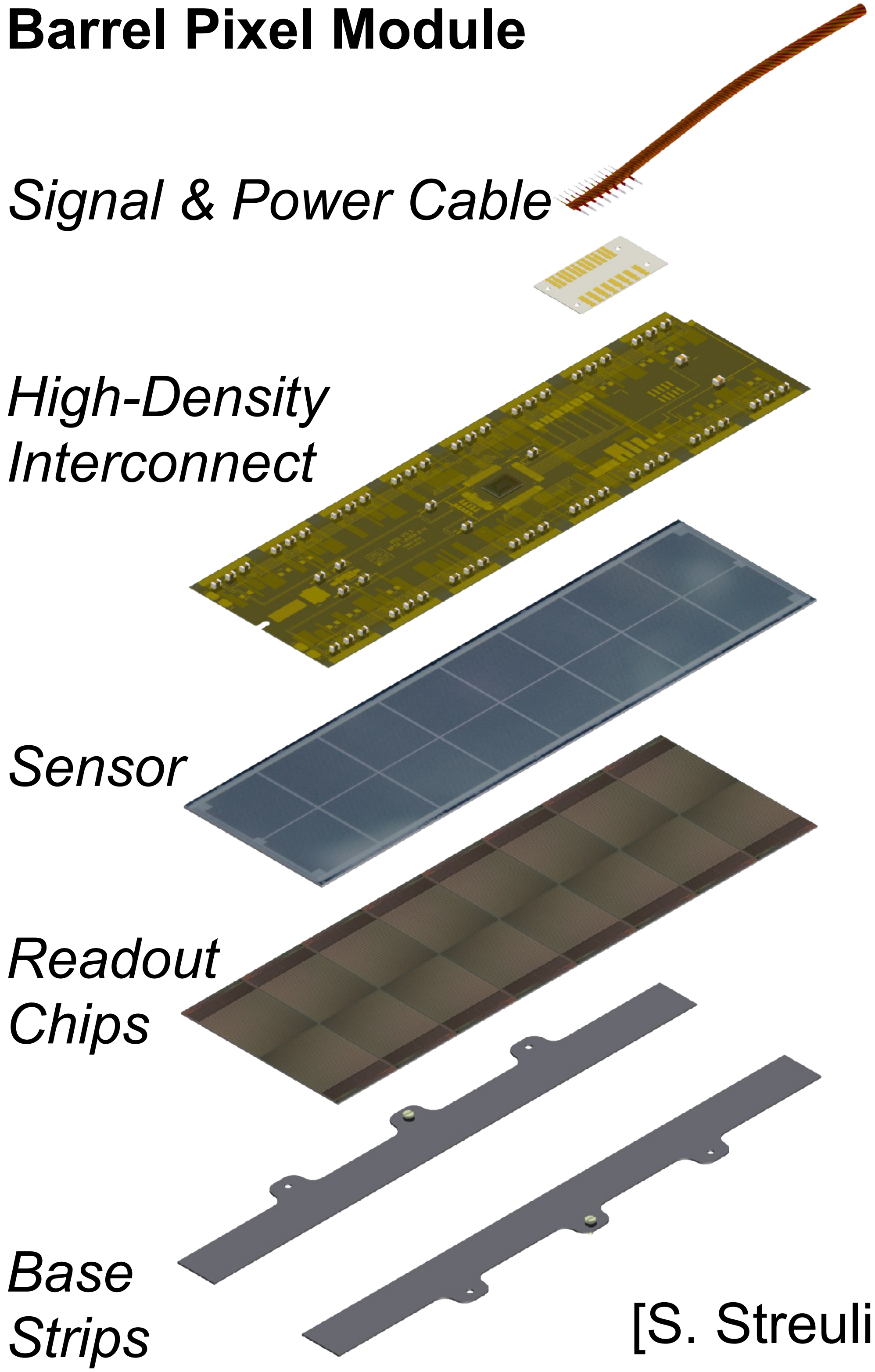


full–module ≙ 16 ROCs

New Silicon Pixel Detector

- Preparatory activities in LS1
  - New beam pipe: thinner, smaller outer diameter
  - (Improve tracker seal to operate strip tracker colder)
- TDR submitted to LHCC (September 2012)
- Installation: year-end shutdown 2016
- German contributions: Aachen IB, DESY, UHH, KIT
  - Production & test of new 4th layer: 768 modules
  - Two production lines: UHH+DESY, KIT+Aachen
  - Bump bonding (partially) in house

Barrel Pixel Module



[S. Streuli]