CERN and Future Plans in HEP

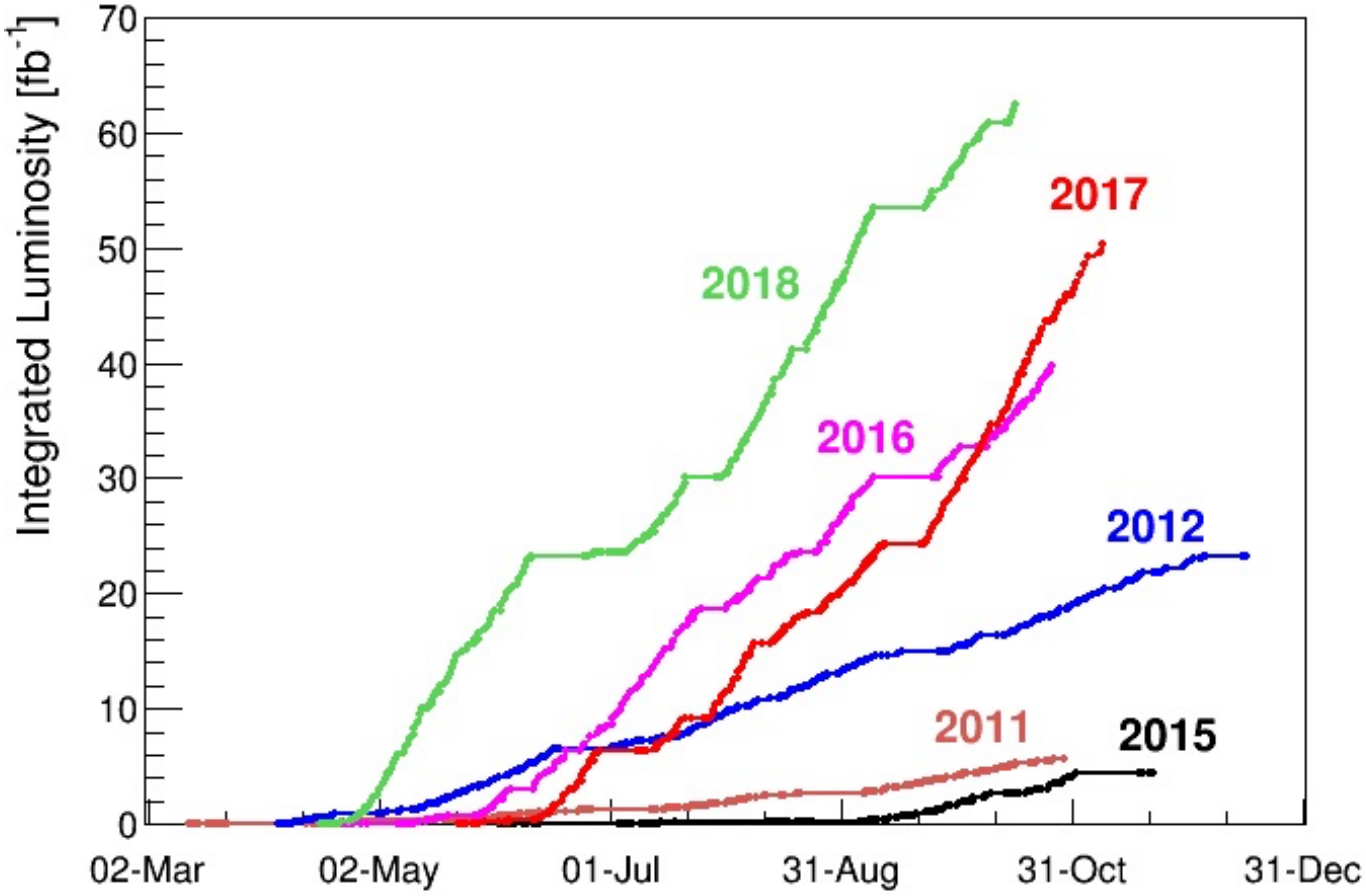
Eckhard Elsen

Director Research and Computing

International Conference on Instrumentation for Colliding Beam Physics 24-28 February 2020, Budker Institute of Nuclear Physics, Russia

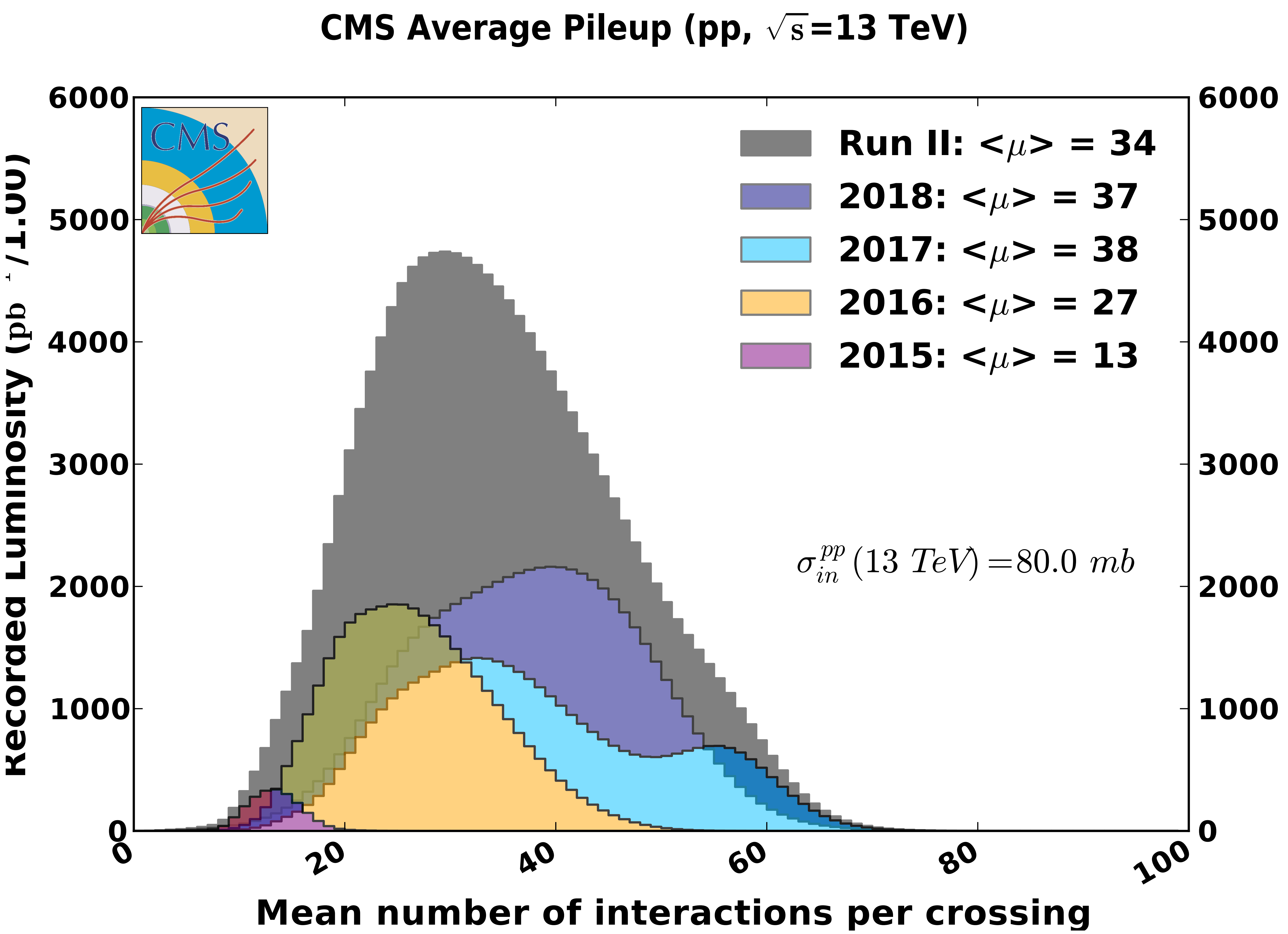
Experiments enjoying a large data sample of Runs 1 and 2

LHC Luminosity by year



Pile-up during Run 2

- ATLAS and CMS coping with large pile-up
  - calorimeter pile-up correction robust and reliable
  - track reconstruction distinguishes vertices
- LHC operating conditions in 2017 so far most demanding (8b4e scheme)
  - more favourable running (and computing) conditions since



Some selected Physics Results

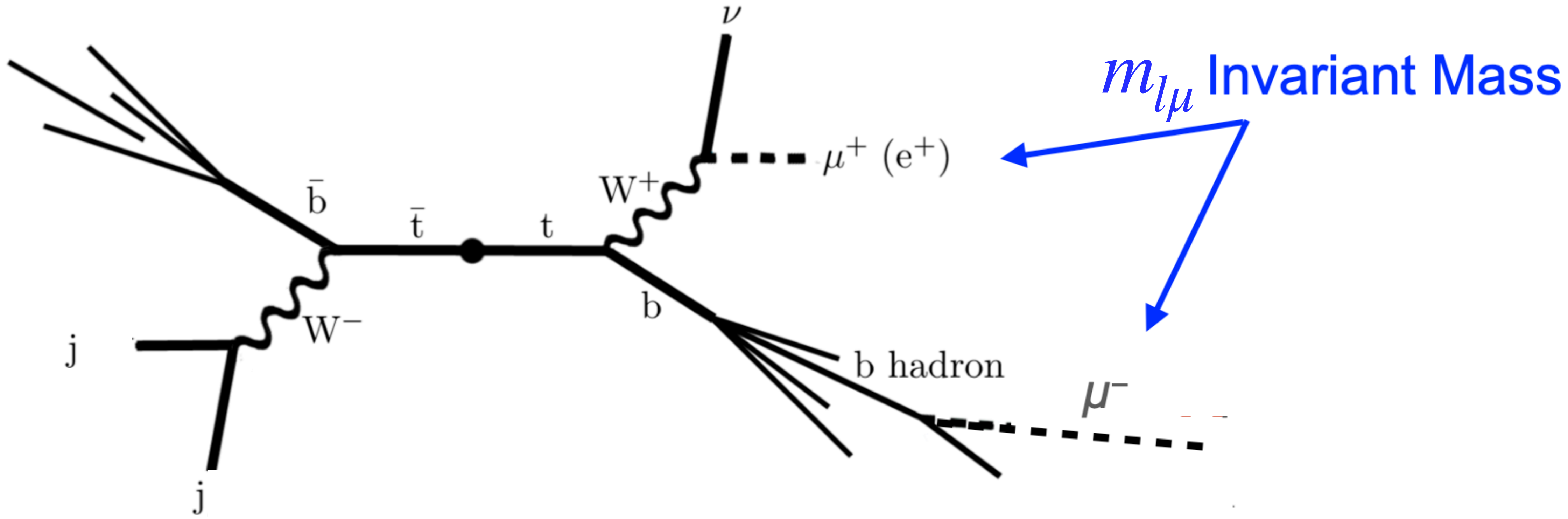
ATLAS

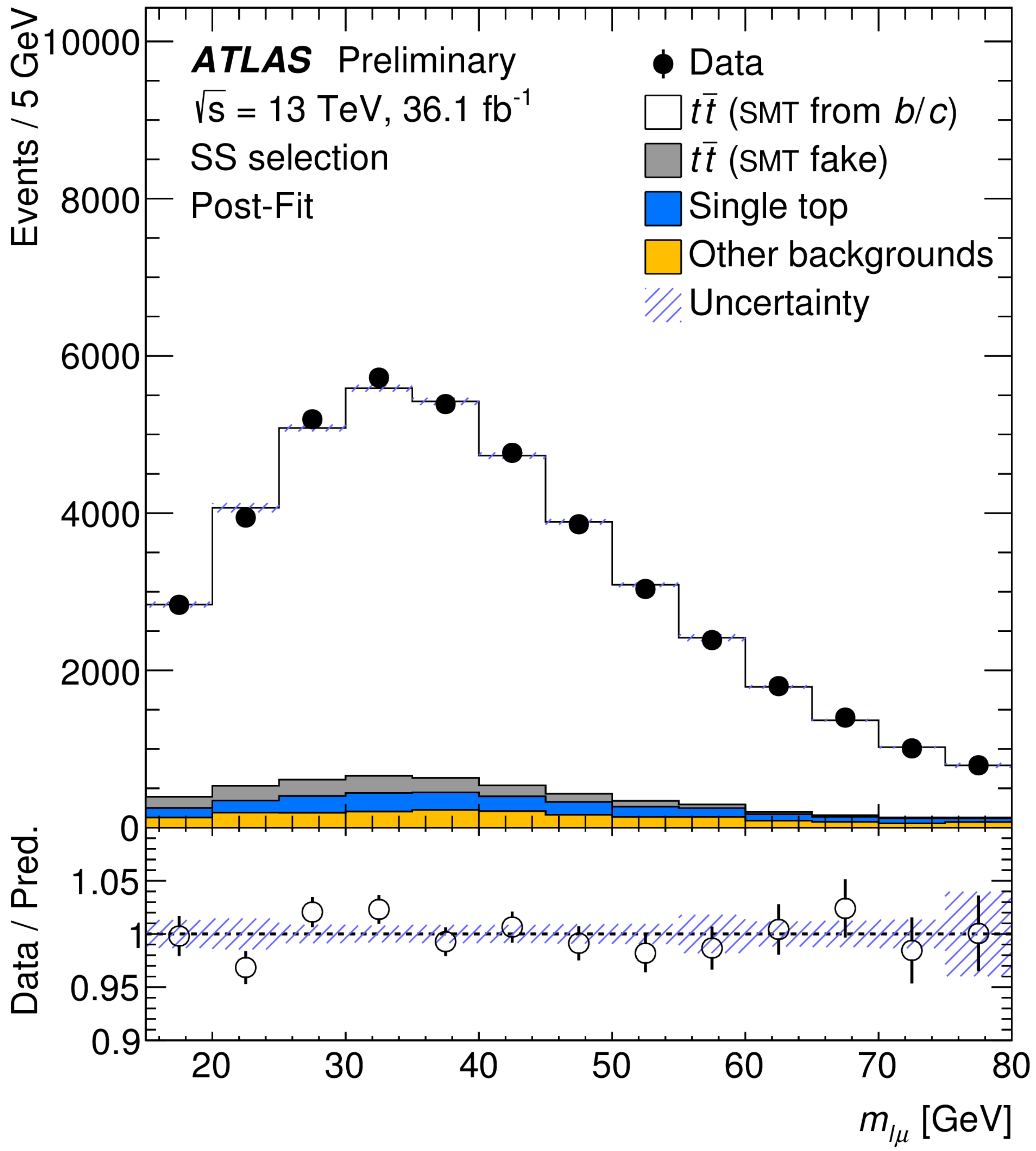
Top mass using soft muon tag

ATLAS

$$m_t = 174.48 \pm 0.40\ (\text{stat}) \pm 0.67\ (\text{syst})\ \text{GeV}$$

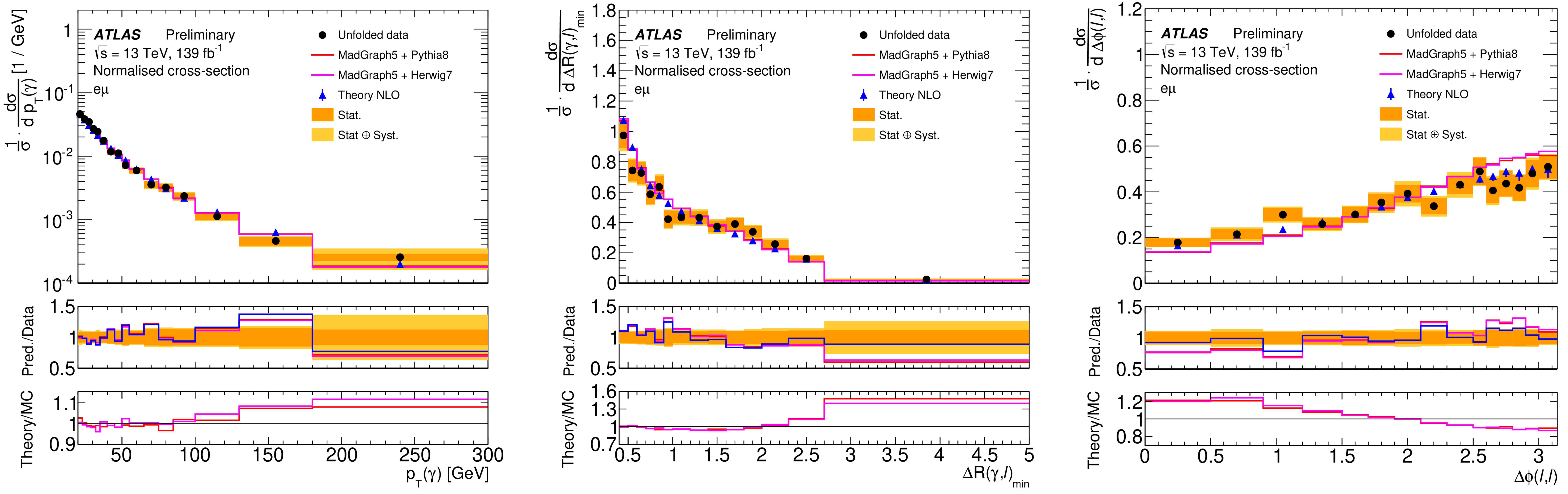
➡ **0.45% uncertainty**



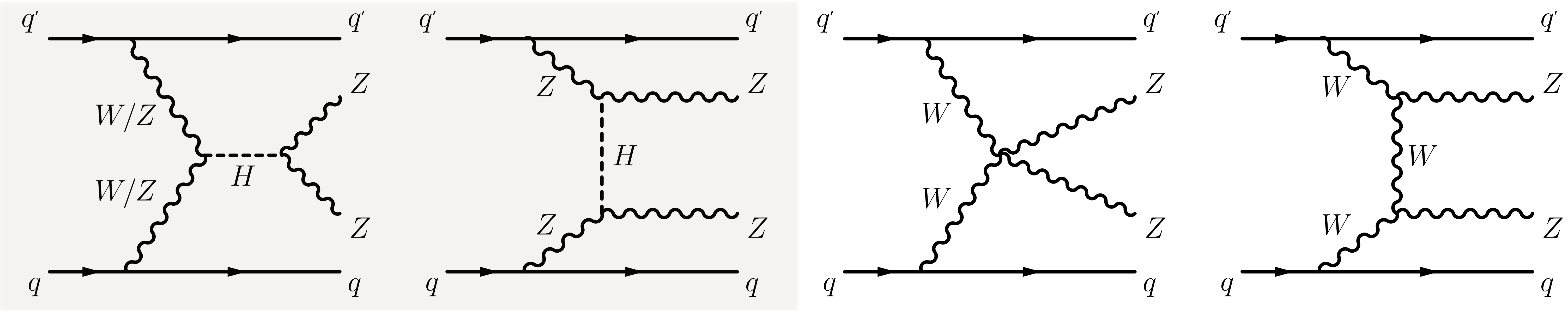


reduce uncertainty from hadronic energy scale

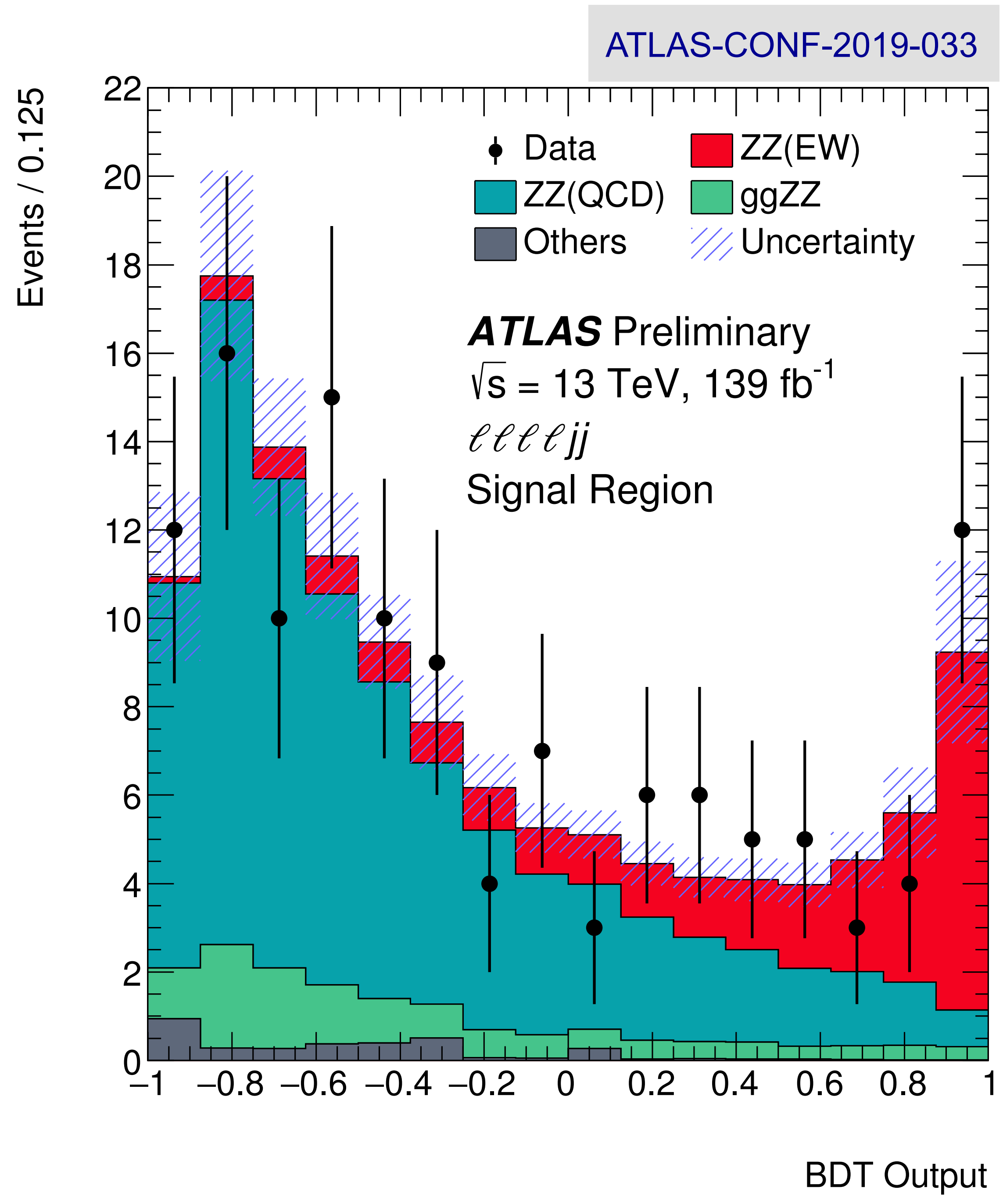
Measurement of $t\bar{t}\gamma$ in the eμ-channel

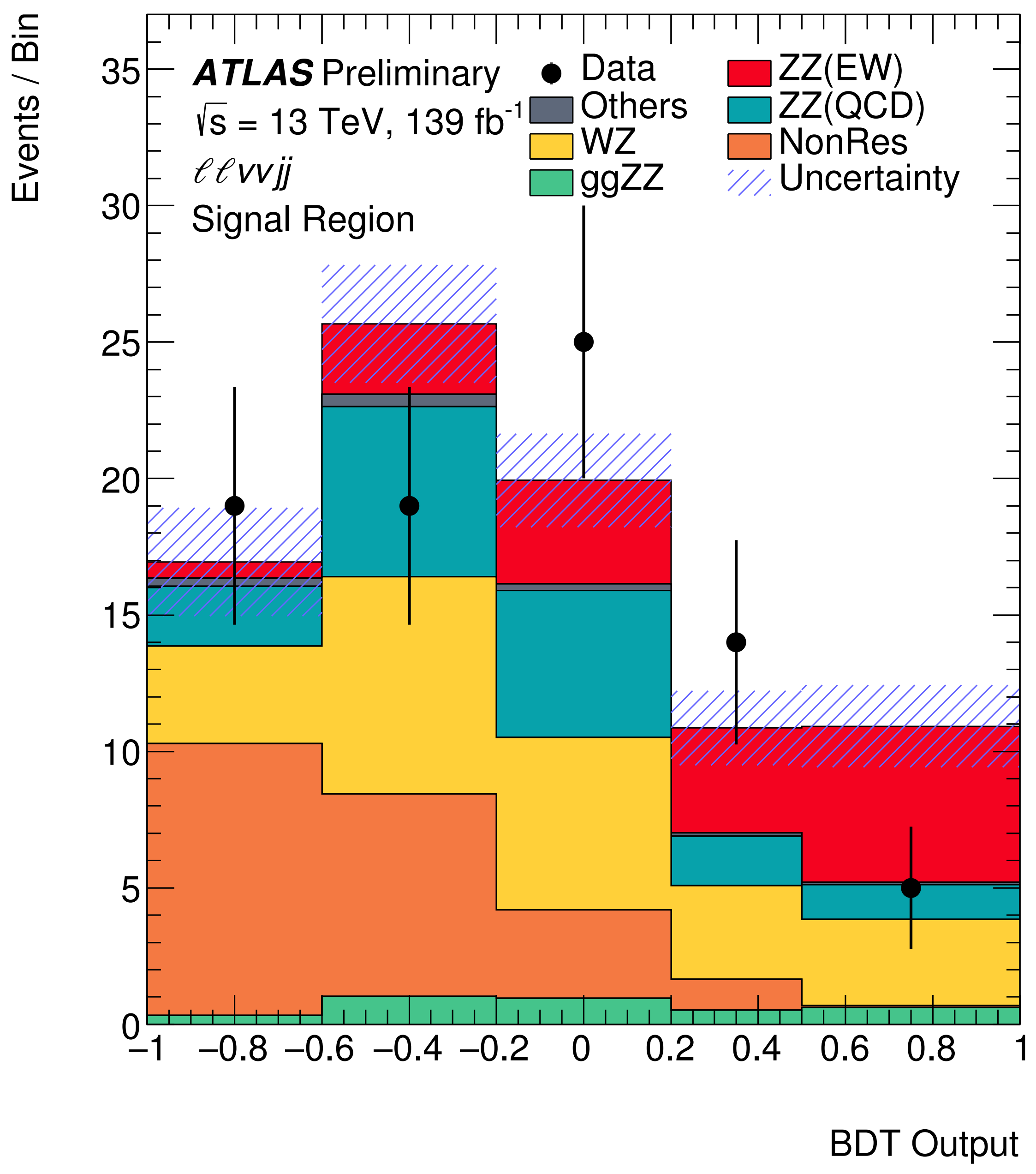


Observation of Vector Boson Scattering in $ZZjj$



Higgs required to regularise cross section





Significance for EW production 5.5σ

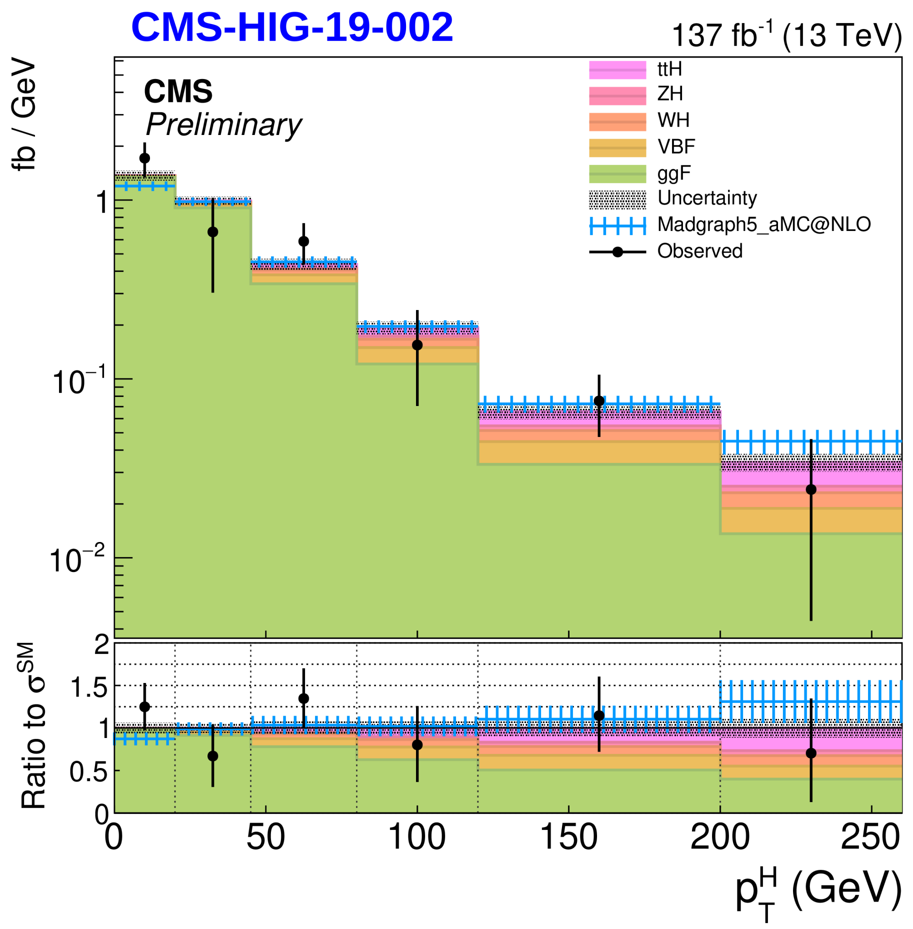
$$\sigma_{\text{fid}}(\text{EW}) = 0.82 \pm 0.21 \text{ fb}$$
$$\sigma_{\text{pred}} = 0.61 \pm 0.03 \text{ fb}$$

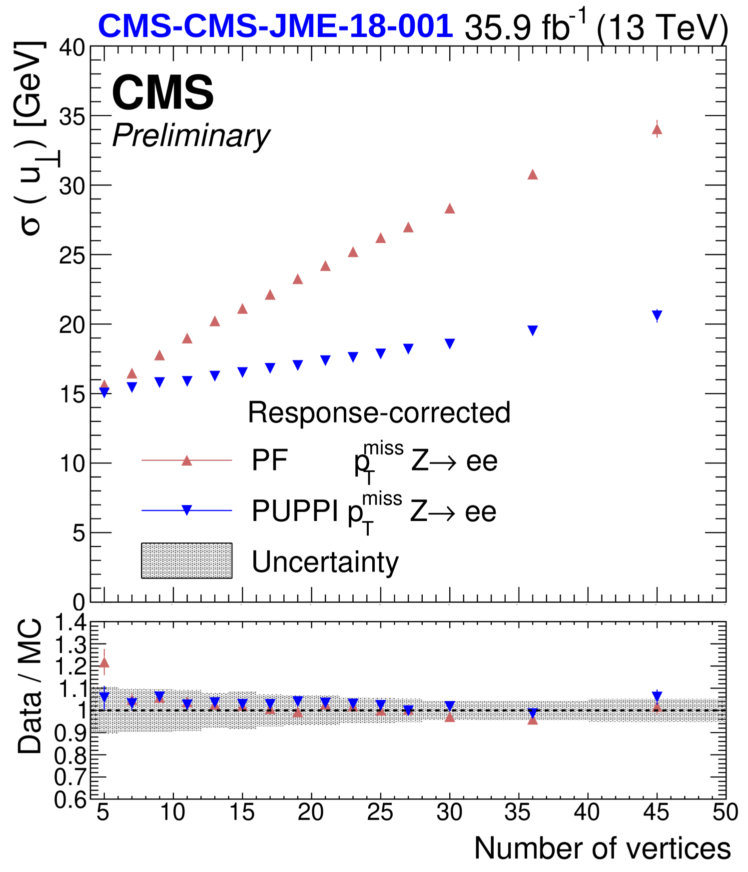
CMS

Higgs Precision Measurements

$H \rightarrow WW$ **differential cross section**

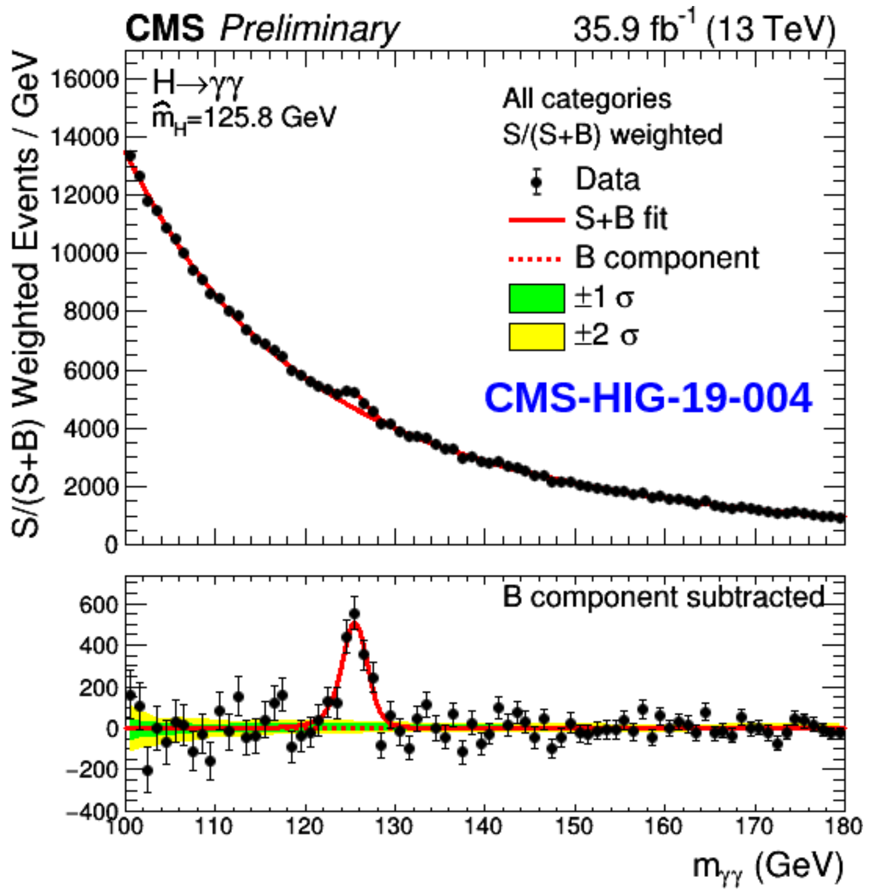
- **Full Run 2 result**
- Leptonic decays ($e\mu$ channel)
- Multidimensional binning in $M_{e\mu}$, $M_T(H)$, lepton p_T, to unfold $\frac{d\sigma}{dN\ jets}$ and $\frac{d\sigma}{dp_{T,H}}$
- Amongst the first analyses using missing E_T computed with the "pile up per particle identification" (PUPPI) algorithm

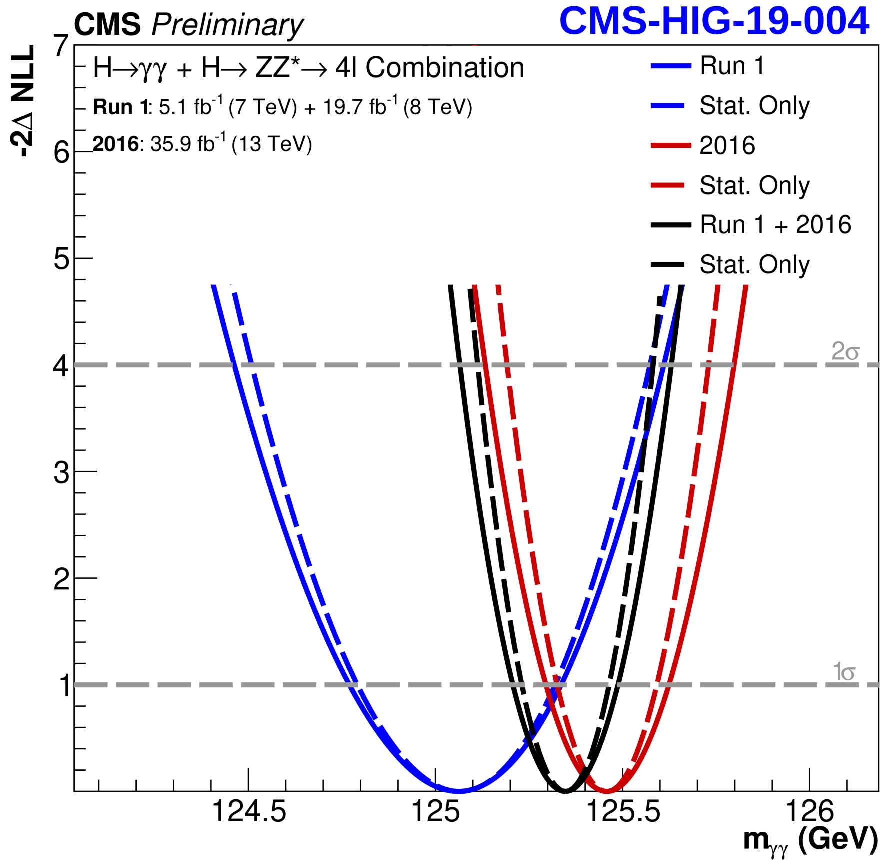




Mass measurement with $H \rightarrow \gamma\gamma$

- Photon energy from ML regression, calibrated with $Z \rightarrow ee$.
- $\mathbf{M_H = 125.35 \pm 0.15}$ **GeV** (Combined with H(4l), Run 1 + 2016)
- A the 0.1% level.
- Uncertainty still stat dominated !
- Importance of final reconstruction campaign for full Run 2.



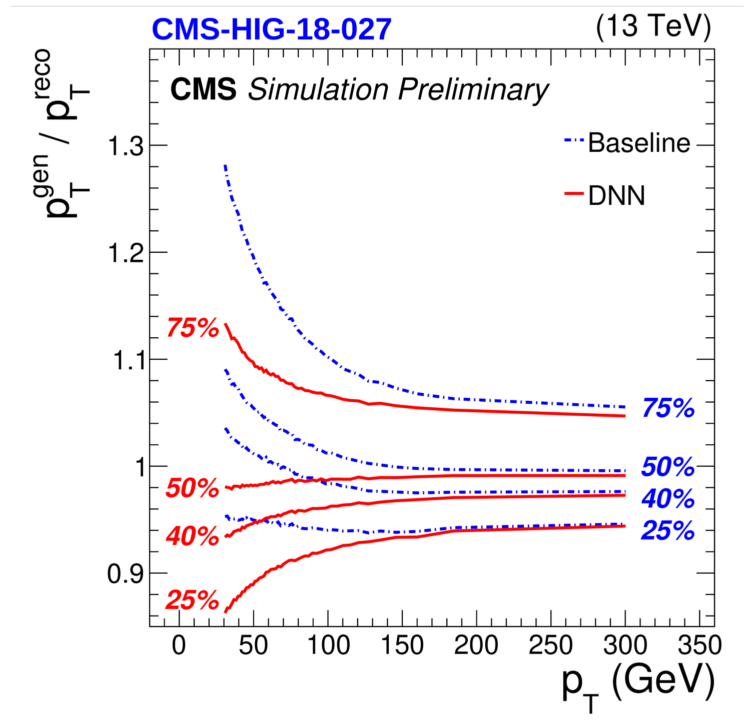


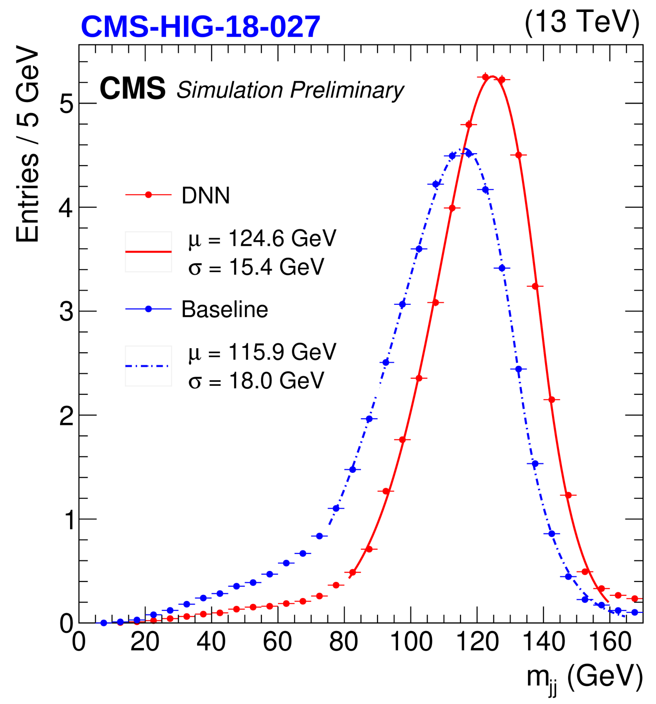
Machine Learning Techniques

Growing usage of deep neural networks in object reconstruction and analyses.

b-quark energy regression.

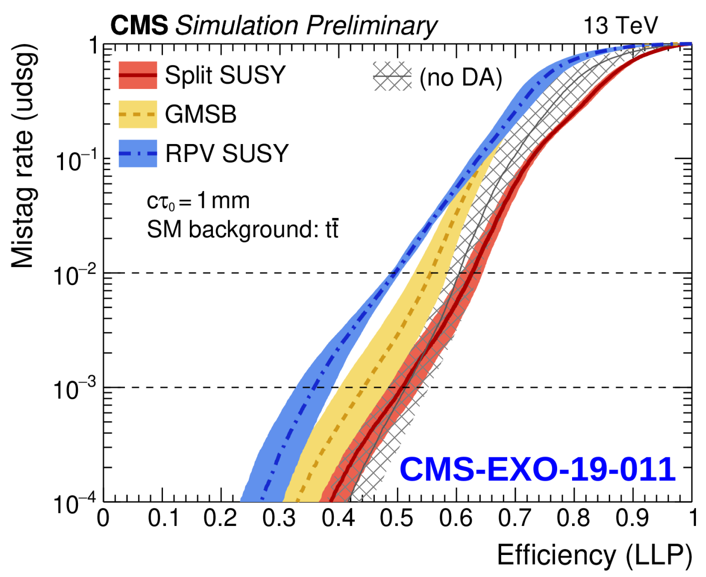
- Simultaneously estimates energy and resolution.
- Used e.g. in $VH(b\bar{b})$, improves $M(b\bar{b})$ by 20%.

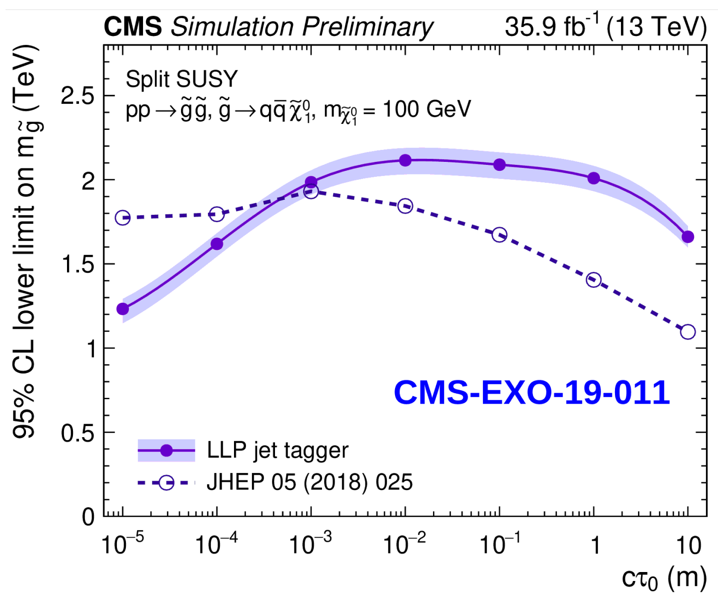




Techniques for long lived particles identifications.

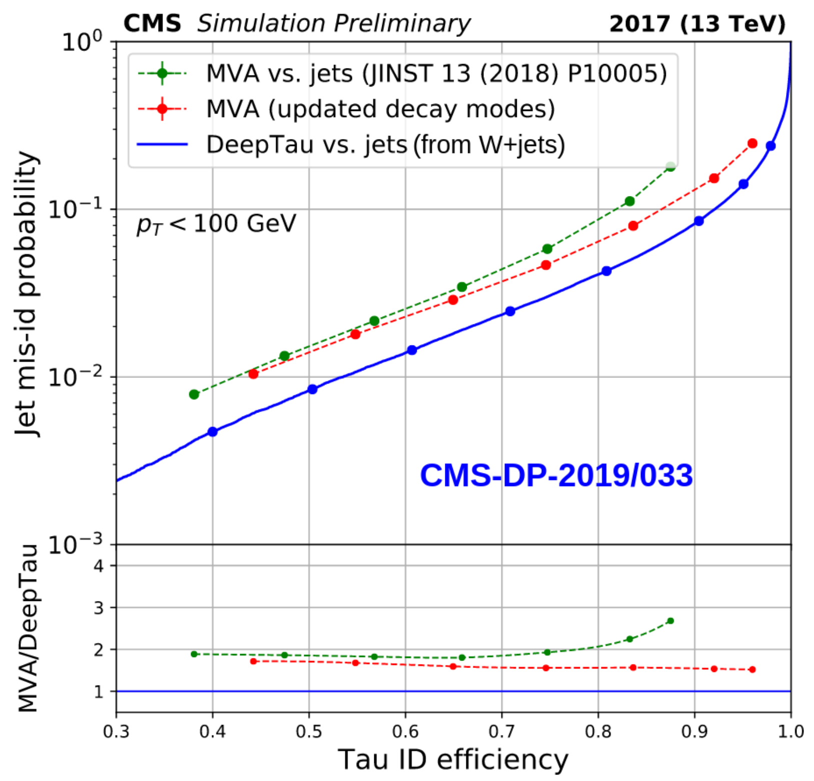
- DNN with ≈ 600 input variables (jet constituents p4 and more...).
- LLP lifetime $c\tau$ as an additional input. Allows to probe a large range of $c\tau$ with a single network.





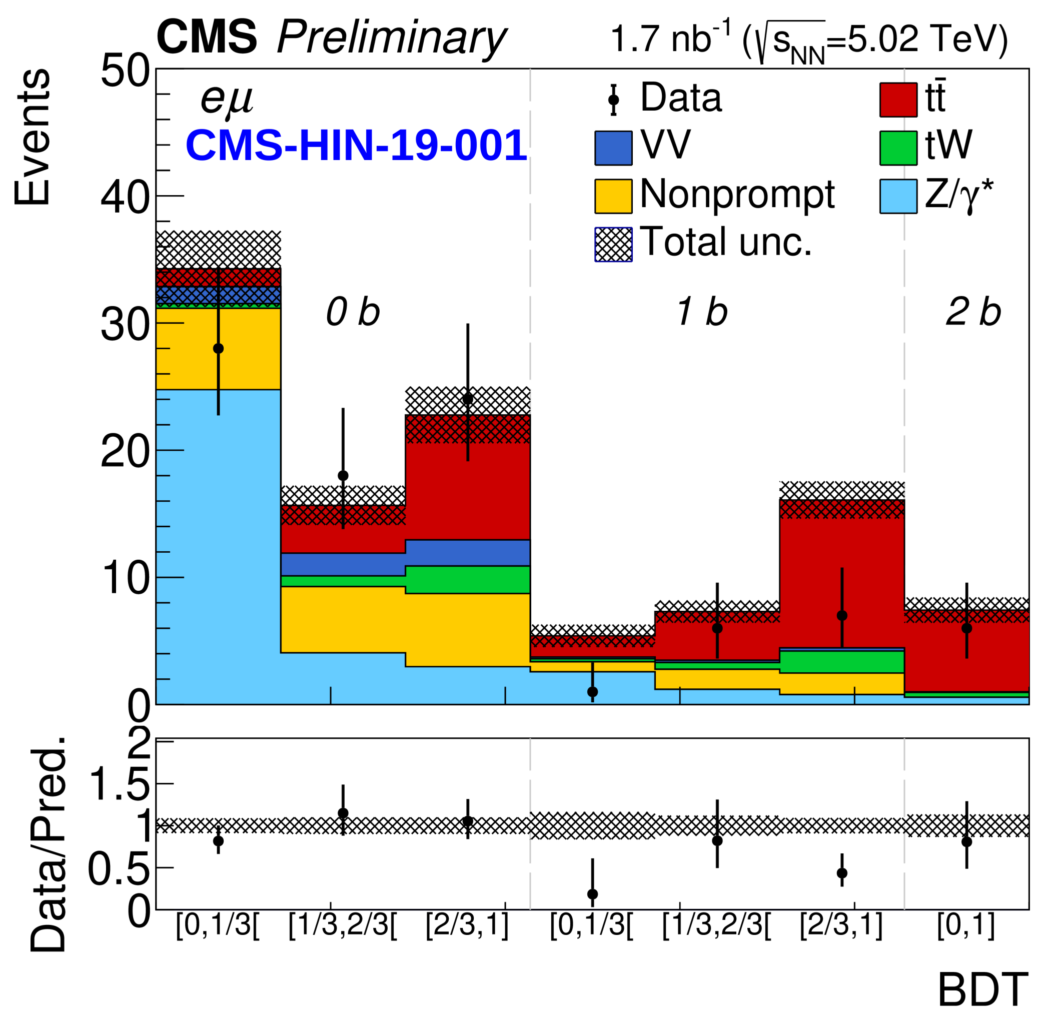
τ_h identification.

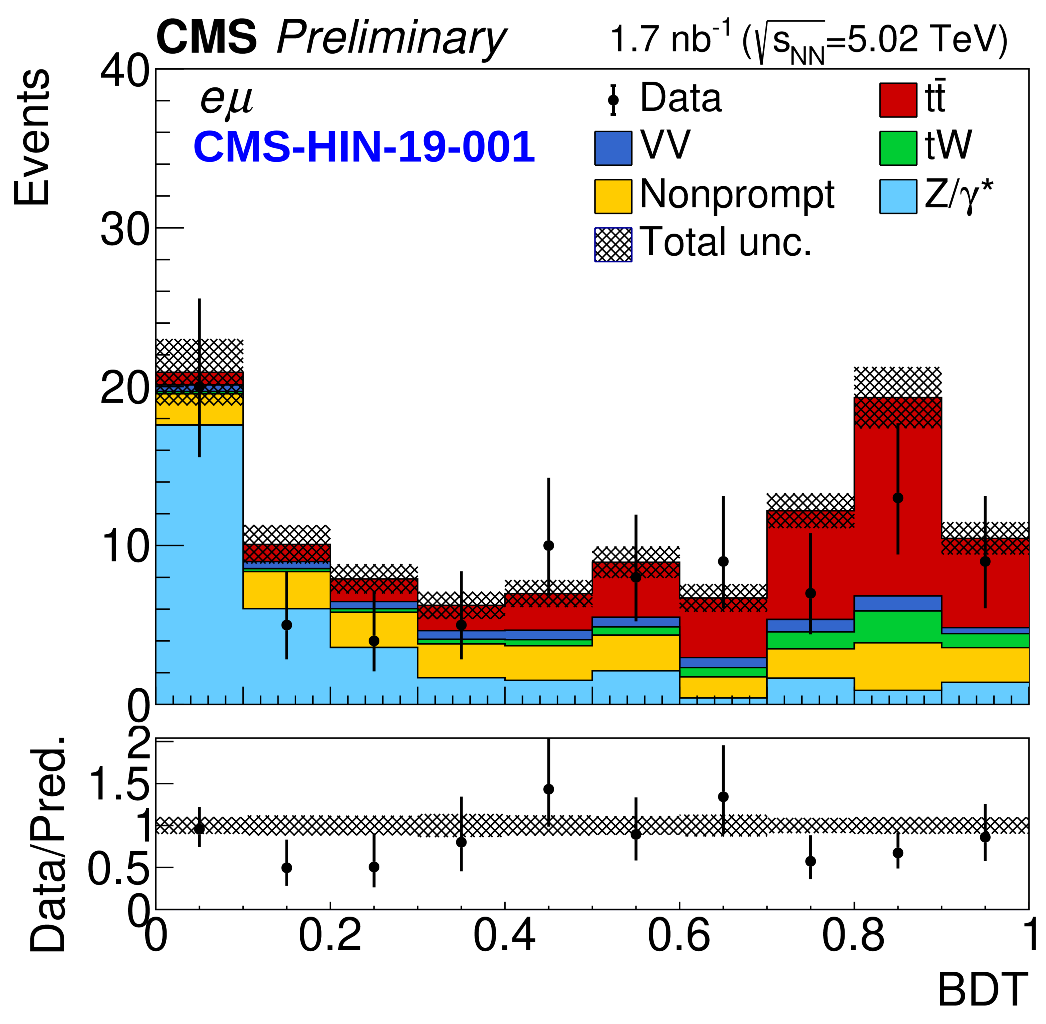
- $\approx$ twice better jet rejection for same efficiency

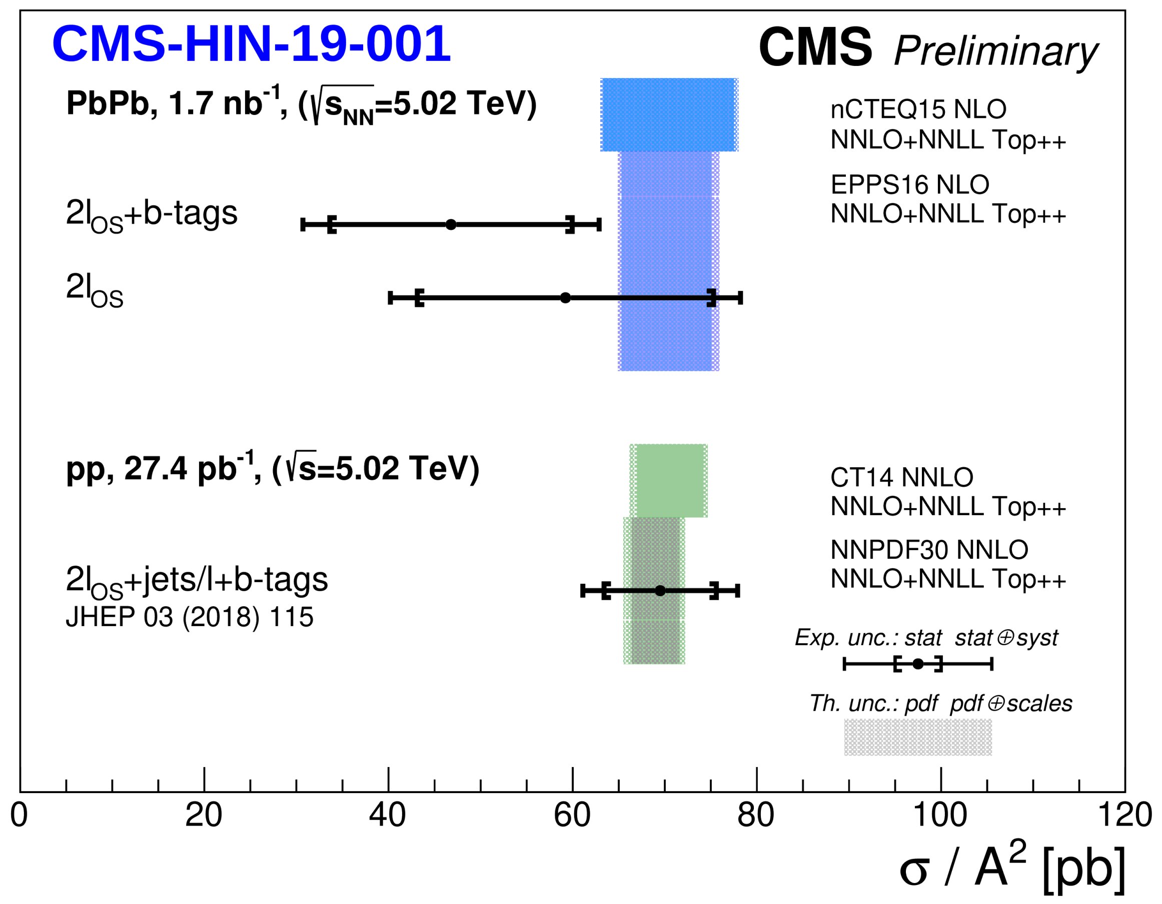


Evidence for Top Pair Production in PbPb collisions

- Analysis of the full 2018 PbPb dataset.
- Dileptonic channel $t\bar{t}$ $(ee/\mu\mu/e\mu)$
- Signal extracted from maximum likelihood fit to a BDT using lepton information, with/without splitting events according to their b-jet multiplicity (N_b).
- Observed (expected) significance of 4.0 (6.0) standard deviations (with N_b).
- **Strong evidence for $t\bar{t}$ production in Pb-Pb collisions**
- Measured cross section (with N_b) is $2.02 \pm 0.69\ \mu b$
- Theoretical cross section is $2.98 \pm 0.14 (PDF \bigoplus \alpha_S(m_Z))\ ^{+0.08}_{-0.10} (scale)\ \mu b$



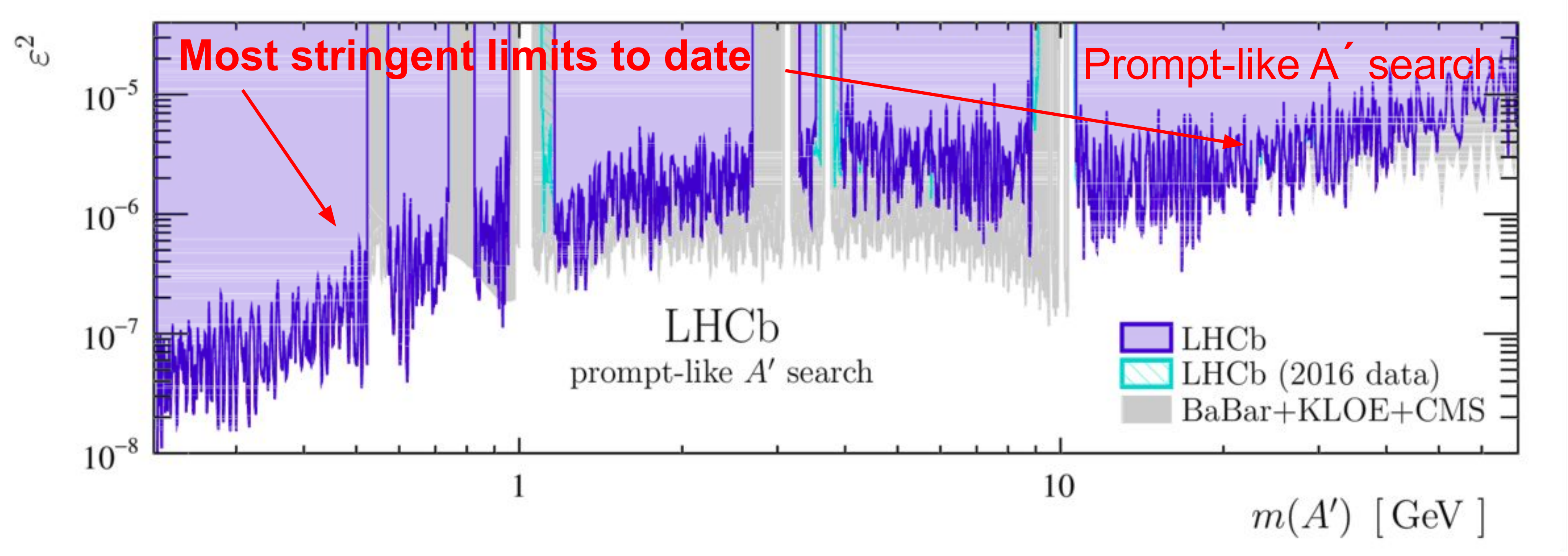




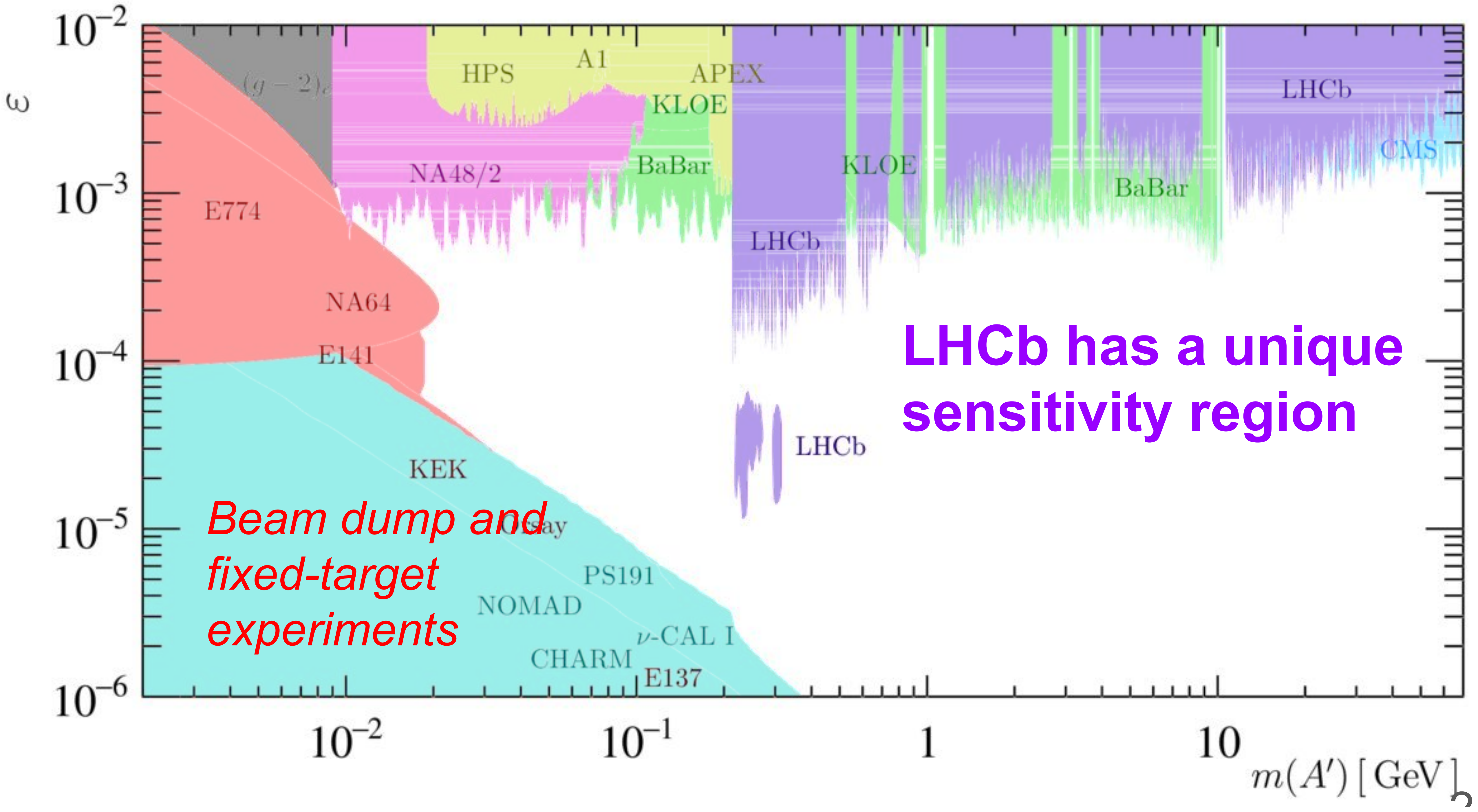
LHCb

Search for $A' \to \mu^+\mu^-$ decays

LHCb

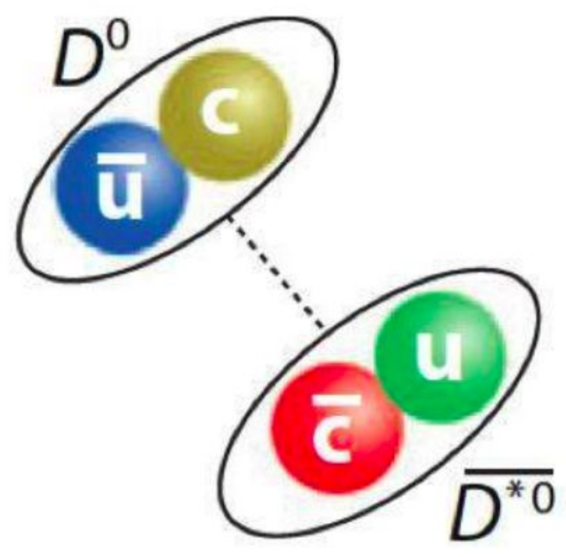


- Based on coupling to dark sector ~ε
- Using 2016-2018 data: 5.5 fb^{-1}

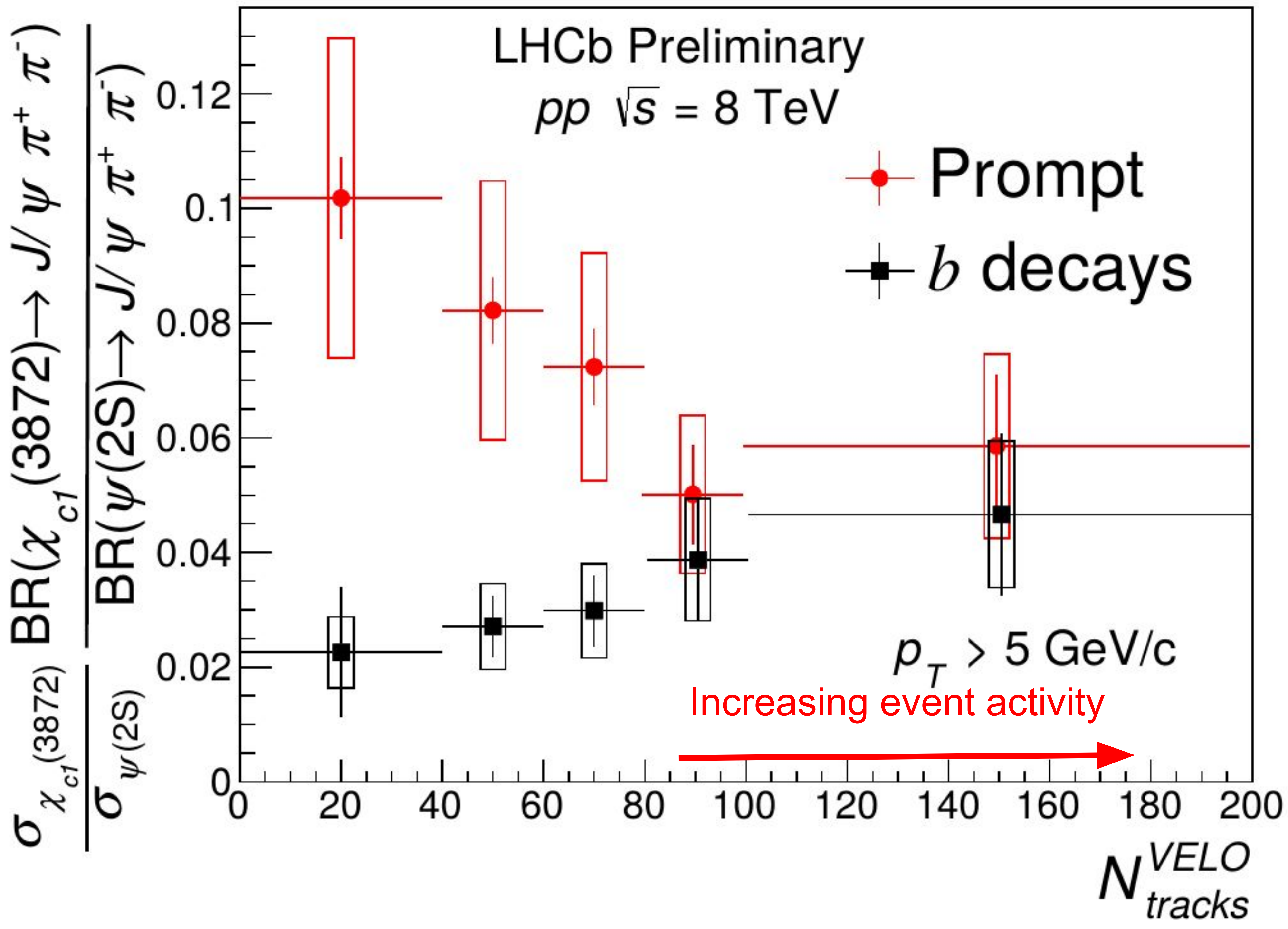


Multiplicity Dependence of $X_{c1}(3872)$ Production

$m(\chi_{c1}(3872))-m(D^0)-m(\overline{D^0}^*)=0.01\text{MeV}$

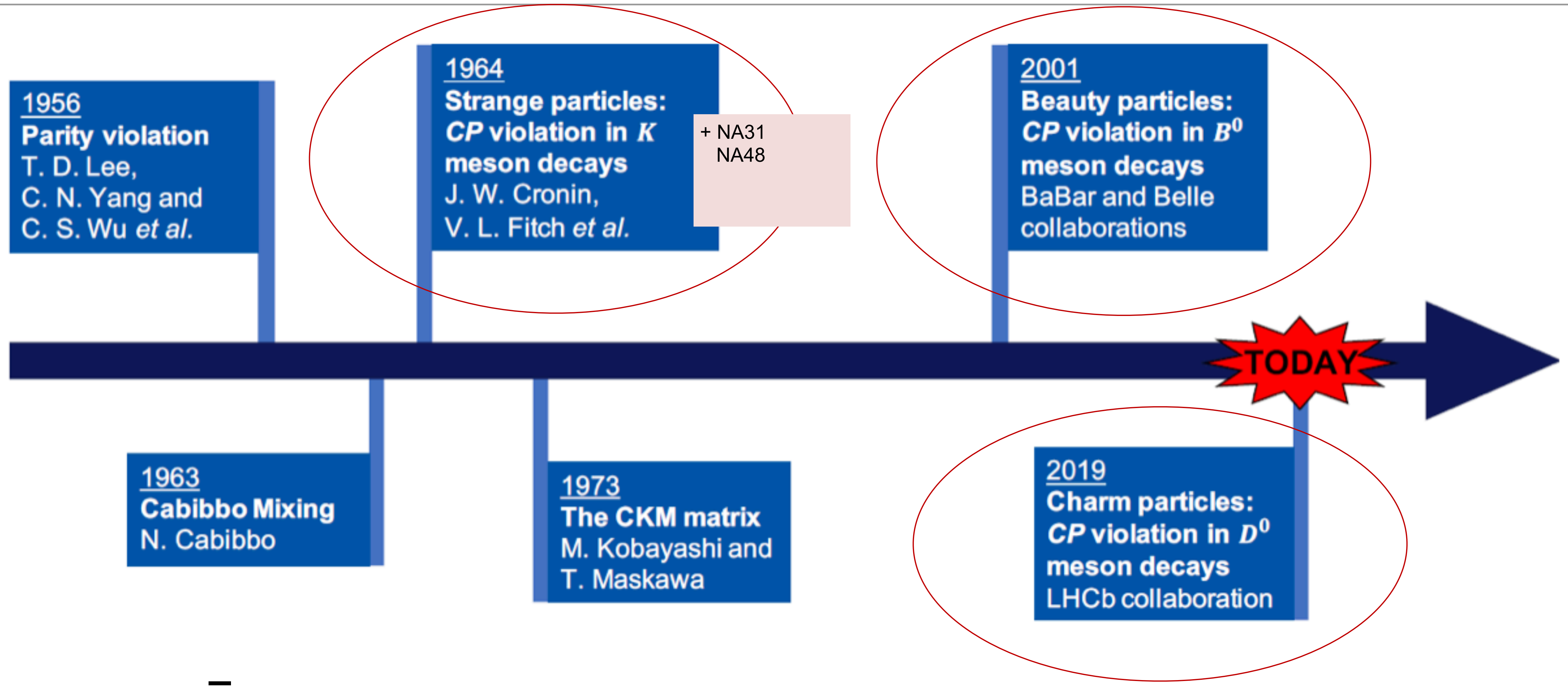


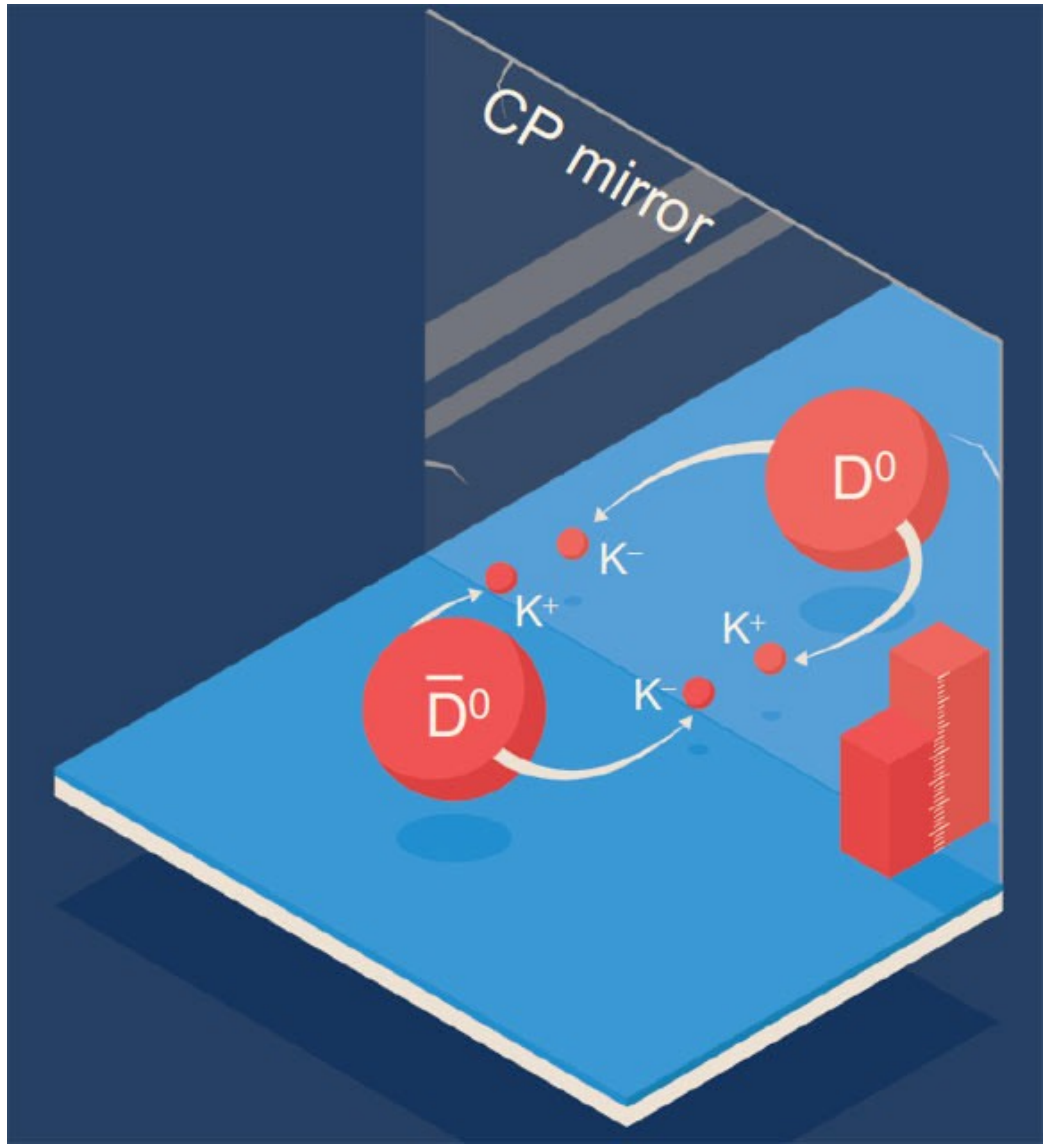
$X_{c1}(3872)$ consistent with a weakly bound molecule



Observation of CP-violation in charm mesons with LHCb

LHCb





Count D^0 and $\bar{D}^0$ decays into $\pi^+\pi^-$ and K^+K^-
if CP conserved:

- the numbers of D^0 and $\bar{D}^0$ in each final state should be equal and D^0 - $\bar{D}^0$ asymmetry is zero

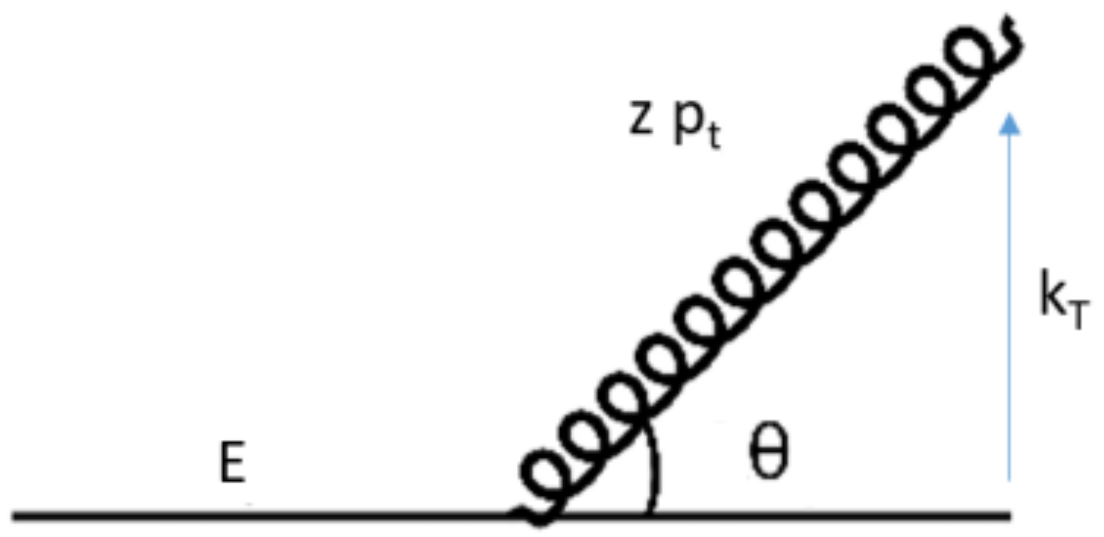
to reduce uncertainties: measure the difference between the D^0 - $\bar{D}^0$ asymmetries in the two final states. If CP conserved: $\Delta A_{CP} = 0$.

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

consistent with (uncertain) theory expectations

ALICE

Direct Measurement of Dead Cone Effect



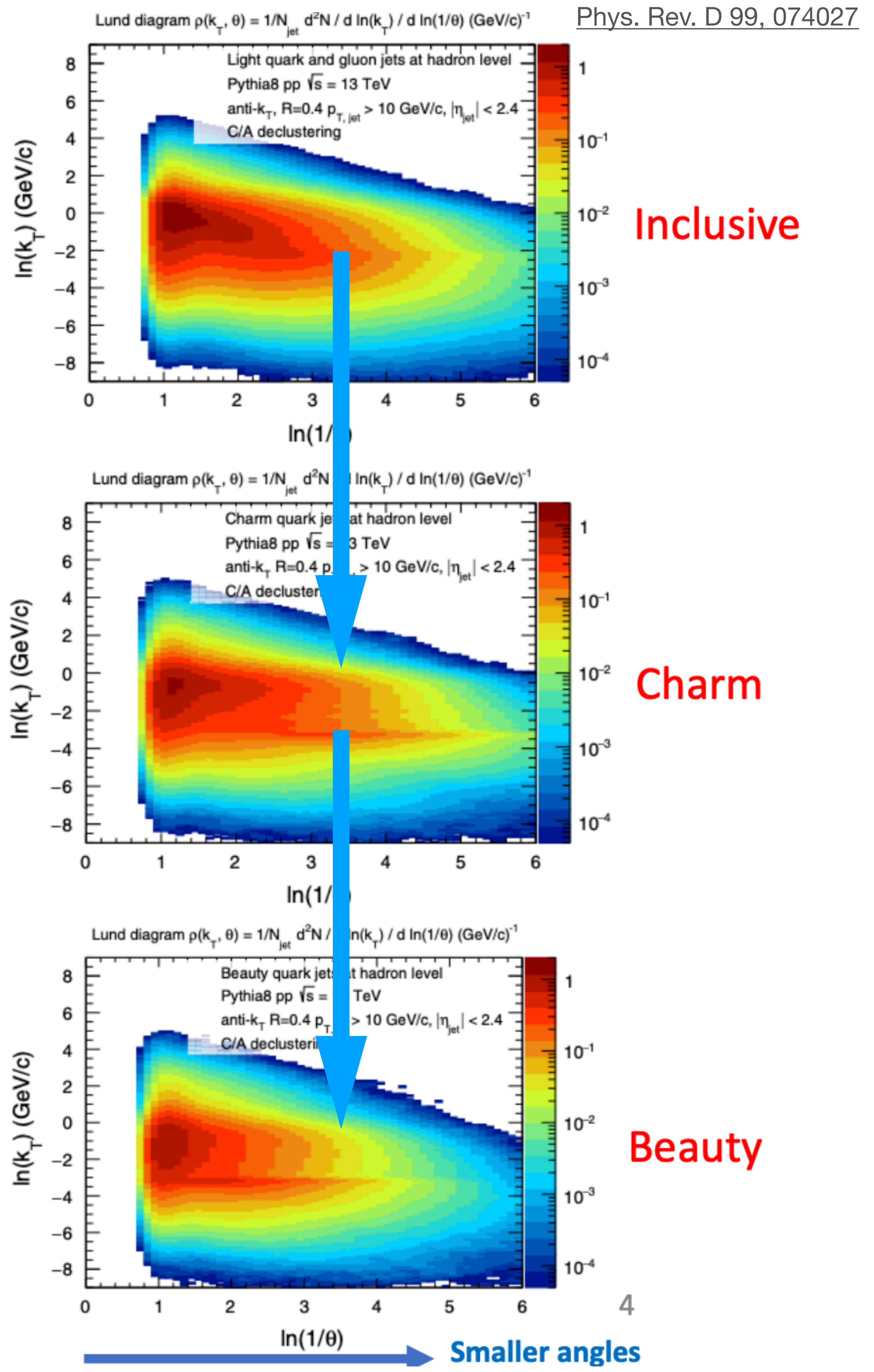
Suppression of emissions from a radiator (quark) within

$$\theta < \frac{m_q}{E_q}$$

- Dead cone effect: suppression of small angle emission

- Identified by iterative de-clustering

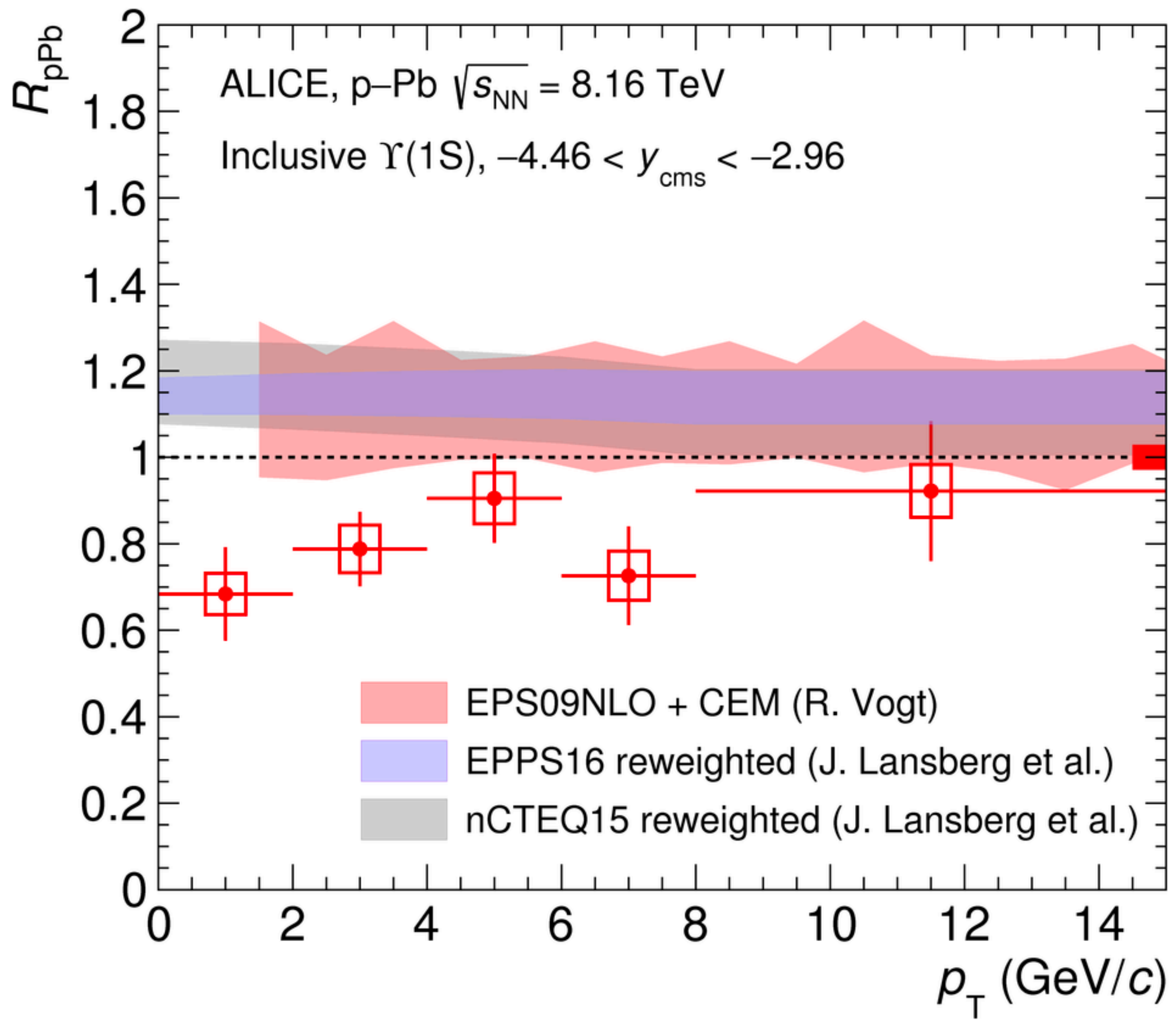
Phys. Rev. D 99, 074027

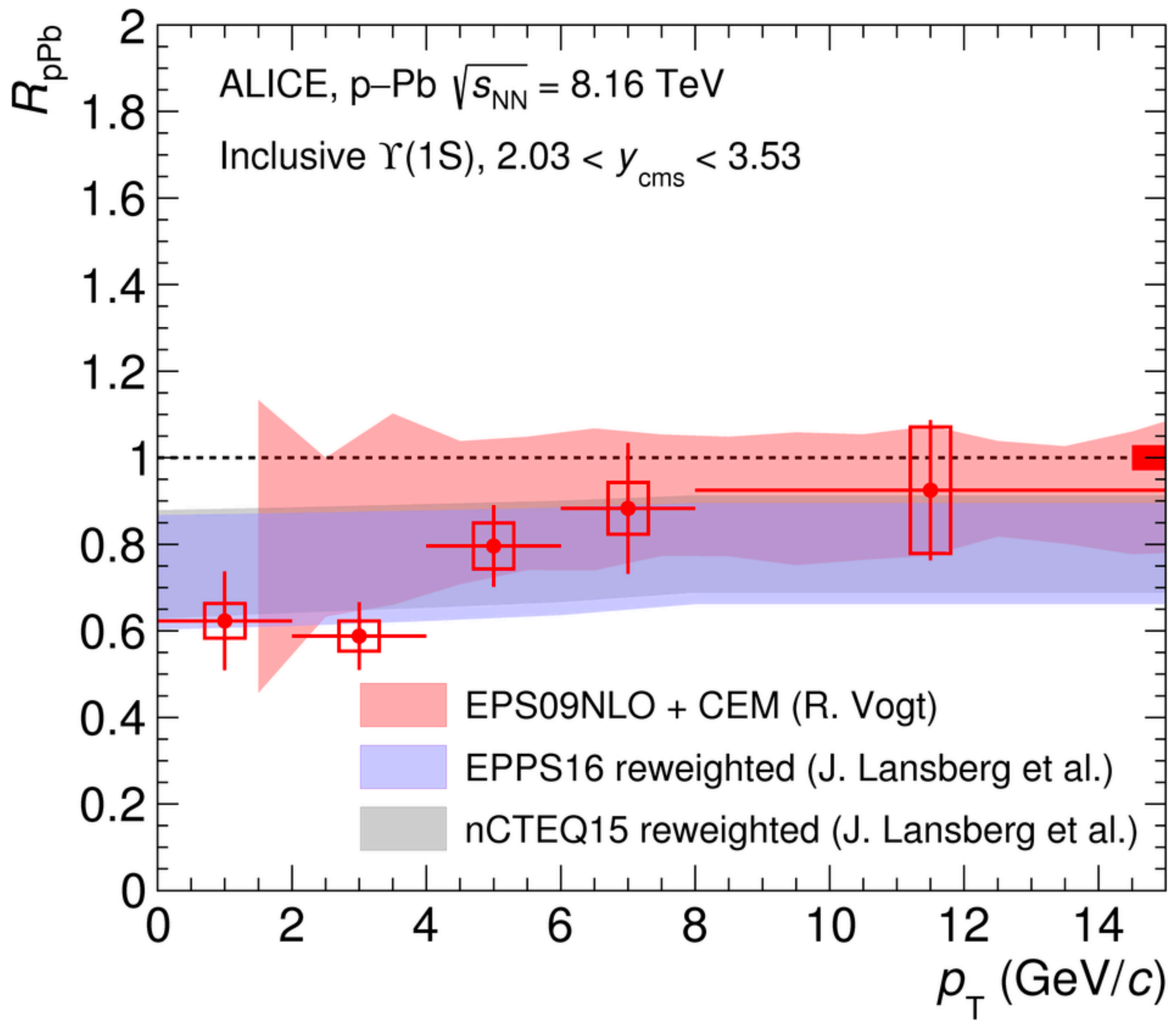


Bottomonia Production in pPb collisions

Significant suppression of the Υ(1S) and Υ(2S) production in p-Pb with respect to pp

$$R_{\mathrm{pPb}} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}N/\mathrm{d}p_{\mathrm{T}}|_{\mathrm{pPb}}}{\mathrm{d}N/\mathrm{d}p_{\mathrm{T}}|_{\mathrm{pp}}} < 1$$





- Backward rapidity (large x): suppression instead of enhancement from “anti-shadowing"
- Forward rapidity (small x): suppression in agreement with nuclear shadowing

HL-LHC Upgrades

LHC Long Shutdown 2 activities

Opening and final reclosure of 1360 interconnections

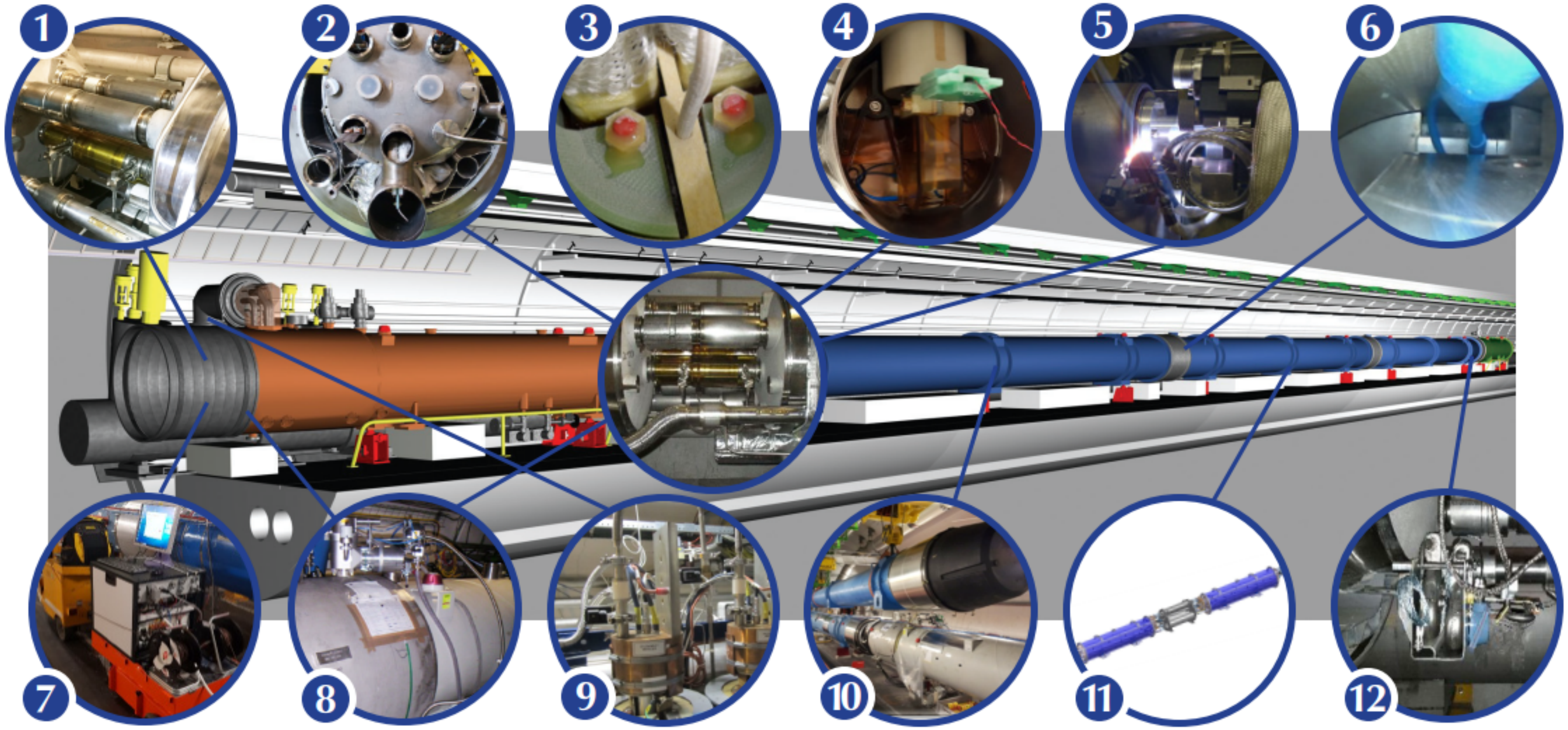
Mechanical opening of 2464 diode container covers

Cleaning and consolidation of 1232 dipole diode insulation systems

Installation of 1232 insulating inserts

Rewelding of 2464 diode container covers

More than 10 000 quality checks



More than 8 000 electrical quality assurance tests

2 500 leak tightness tests

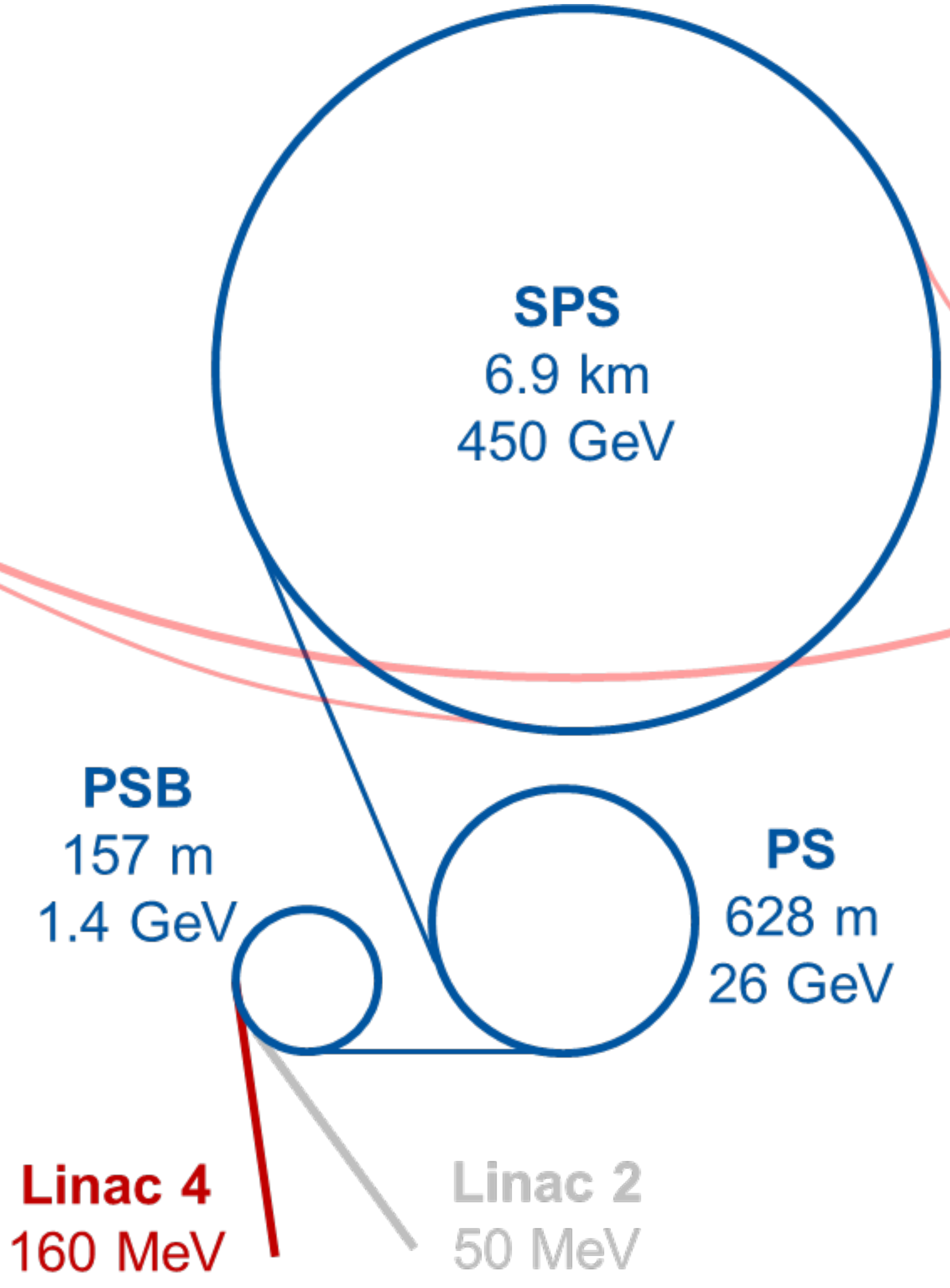
Maintenance of 2 829 current leads

Replacement of 22 cryomagnets

Installation of 4 full HL-LHC cryo-assemblies

Installation of 10 instrumentation systems for beam induced heat load study

LHC Injector Upgrade

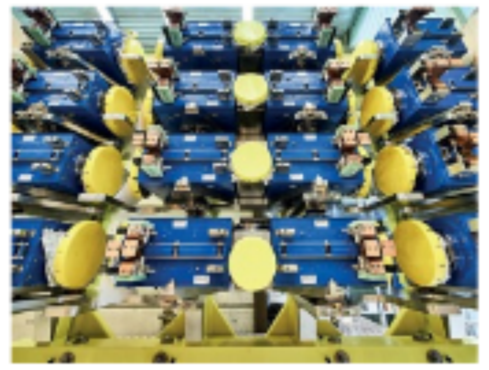


SPS upgrade

- **Main RF system upgrade** (new solid state power plants – 2 x 1.6 MW)
- **Impedance mitigation** to improve beam stability
- More robust **beam dump and protection devices**

PSB upgrade

- **H^- charge exchange injection** at 160 MeV → improved beam brightness (weaker space charge forces)
- **Energy : 1.4 GeV → 2 GeV**
  - New main power supply
  - New RF systems

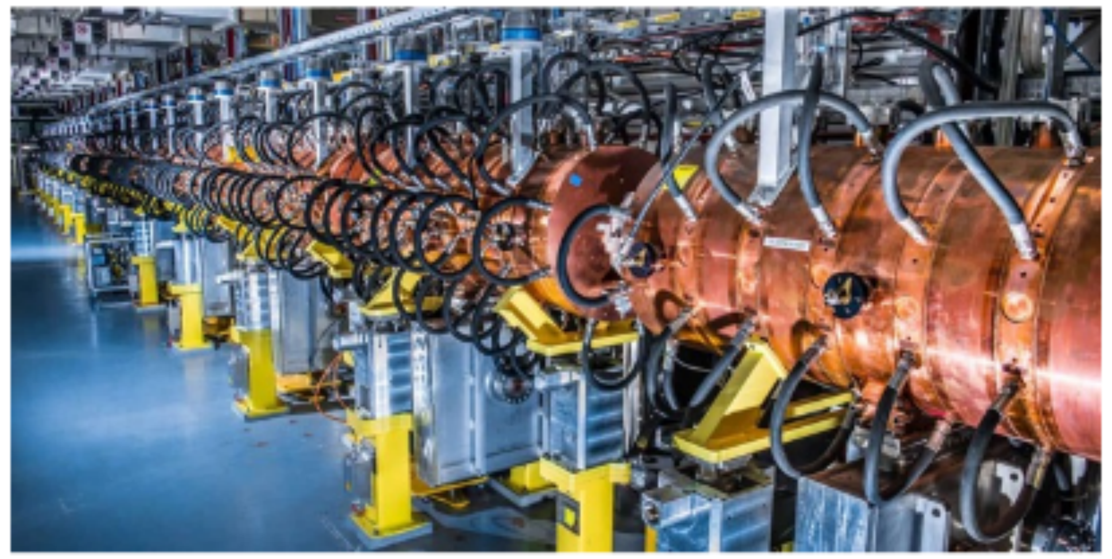


Linac 4, has been built to take over.

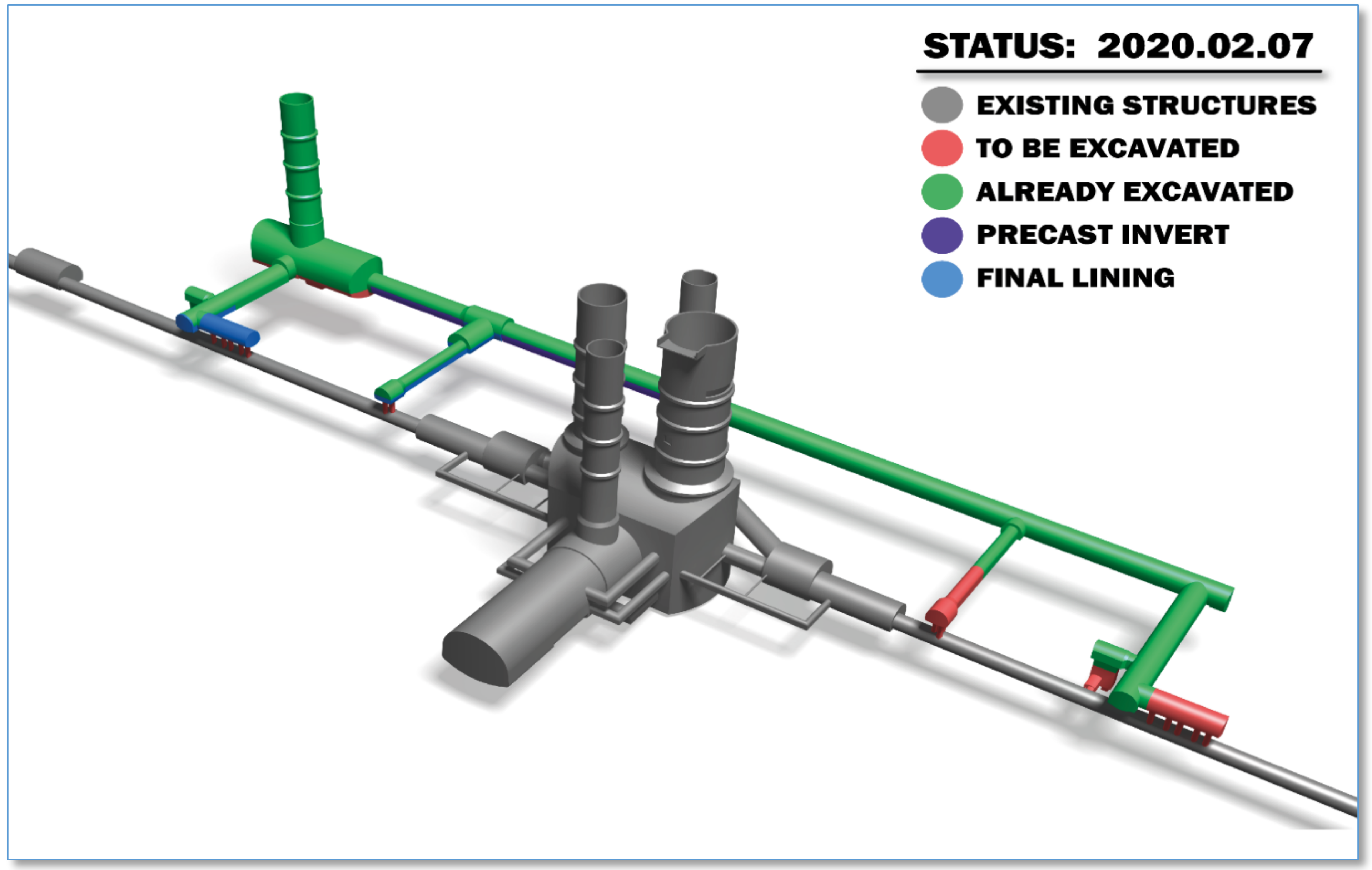
- Higher energy **160 MeV**
- Acceleration of **H^- ions** (charge exchange $H^- \rightarrow p^+$ in the PSB)

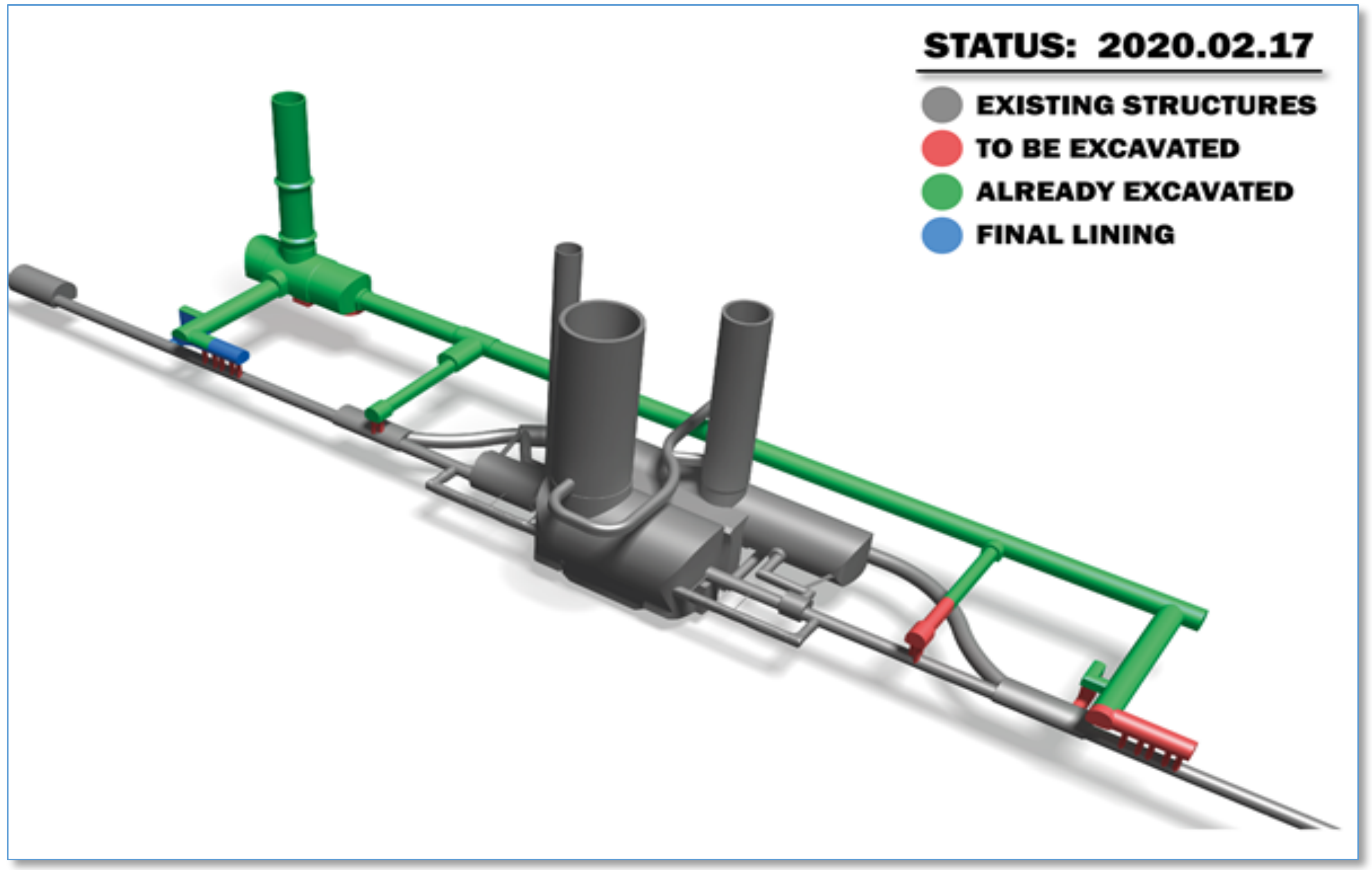
Construction **completed in 2017**

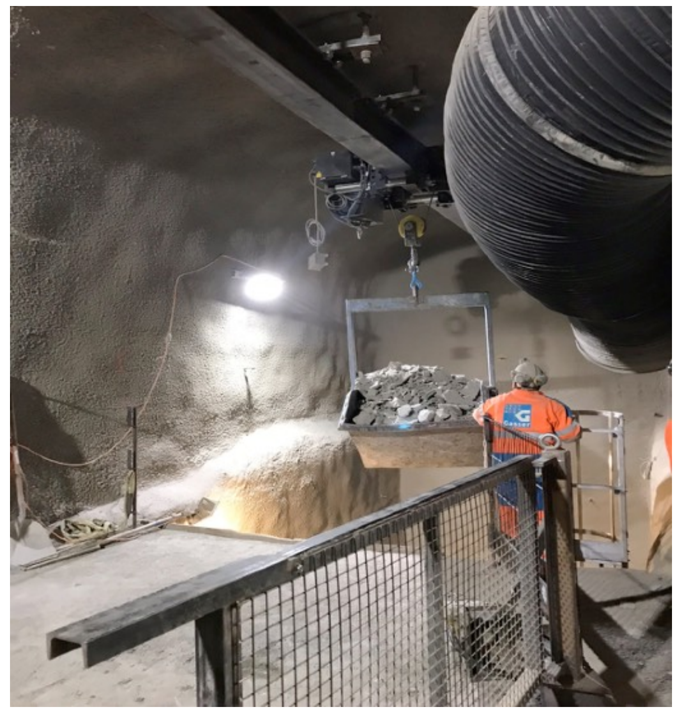
- Extensively tested in 2017-2018
- Ongoing **work in LS2 to connect it to the rest of the chain**



HL-LHC Civil Engineering







Preparation of Nb_3Sn magnets

S1 successfully qualified

S2 @ SM18, cooldown, to be tested wk8-9

S3 failed the test, back to workshops Bldg.180/SMI2

S4 ready for test in SM18, wk10-11

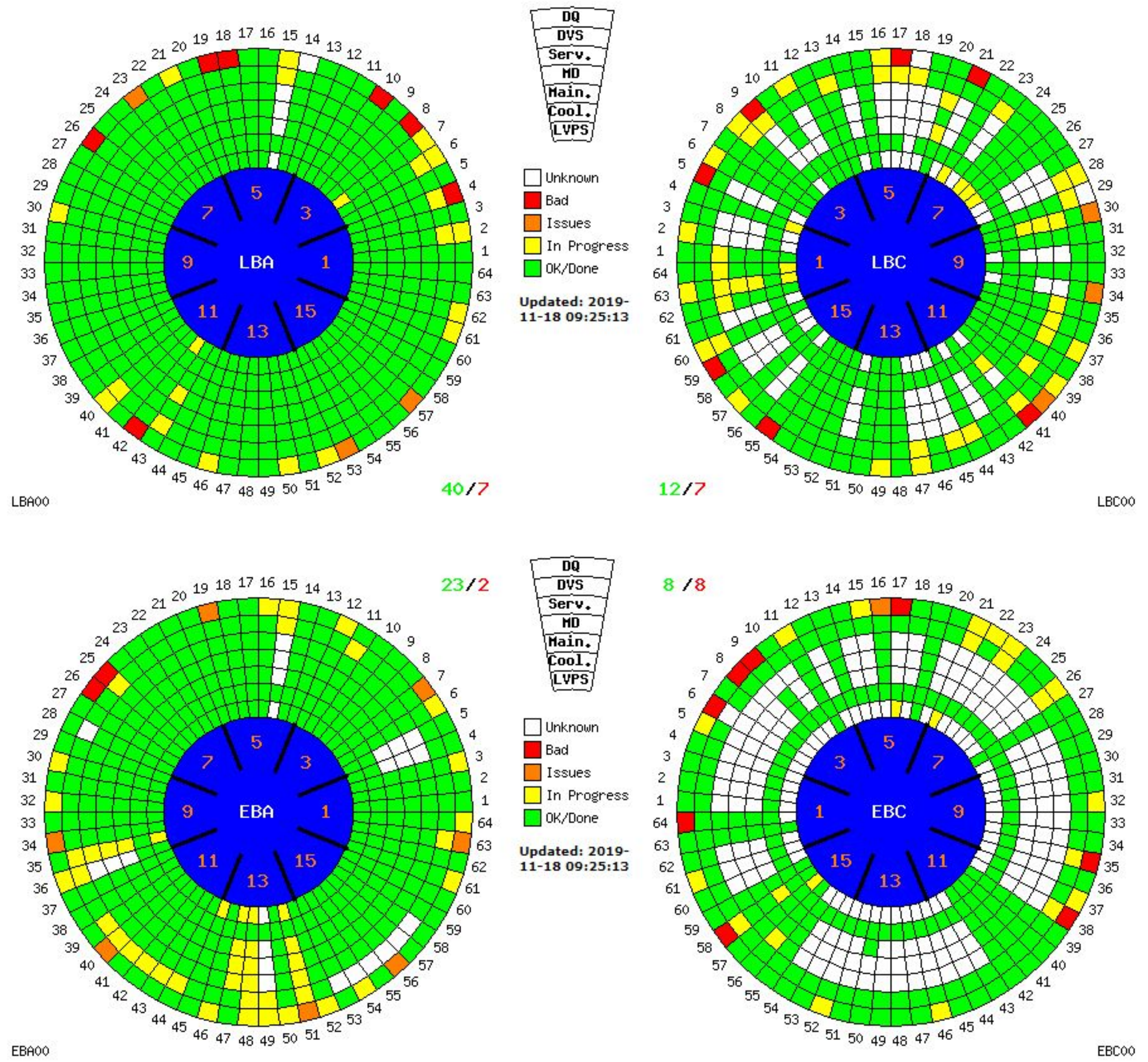
Experiments

New Small Wheel

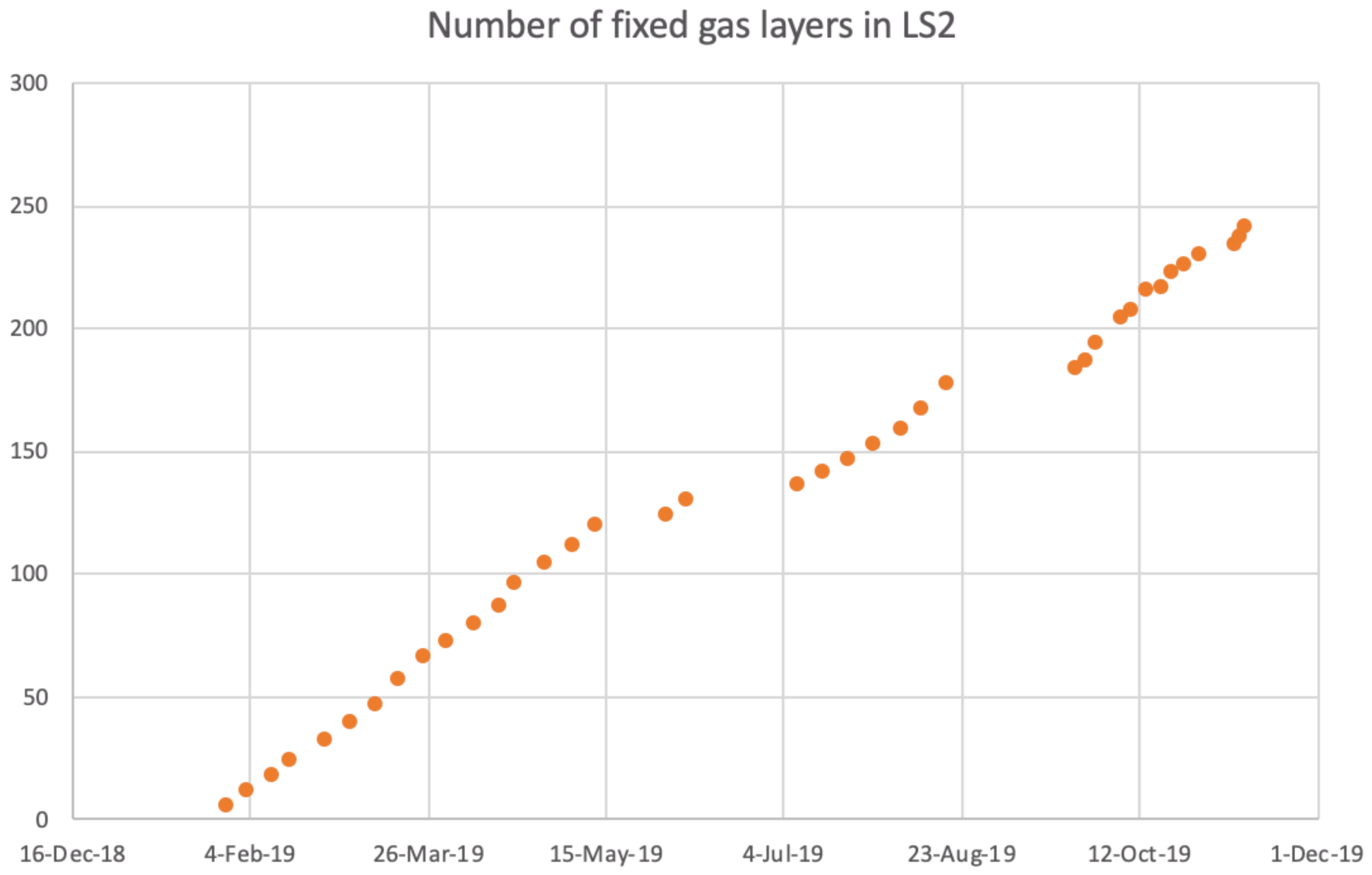
- Good progress overall with sTGC and MM production
- Full sector test (originally planned in November 2019)
- Production remains on the critical path with schedule unchanged
    - new uncertainty with halt of delivery of electronics from China (Corona-virus)

Calorimeters and Muons

- Liquide Argon calorimeter (LAr)
  - ➡ Consolidation work on power supplies and cooling system proceeding as planned
- Tile calorimeter
  - ➡ Cooling connector replacement done
  - ➡ Maintenance of electronics well advanced (completed on A-side, nearly done on C-side)
  - ➡ Crack and MBTS scintillators installed on both sides



- Muon spectrometer
  - ➡ Fixing RPC of gas leaks (**242 leaks repaired, ~40% of work done**)
  - ➡ Upgrade of gas system to mitigate risks of producing new leaks - **racks under production** (available by end of November)
  - ➡ Installation of BIS7/8 chambers in Q1/Q2 of 2020: preparation of the chambers in BB5 well advanced



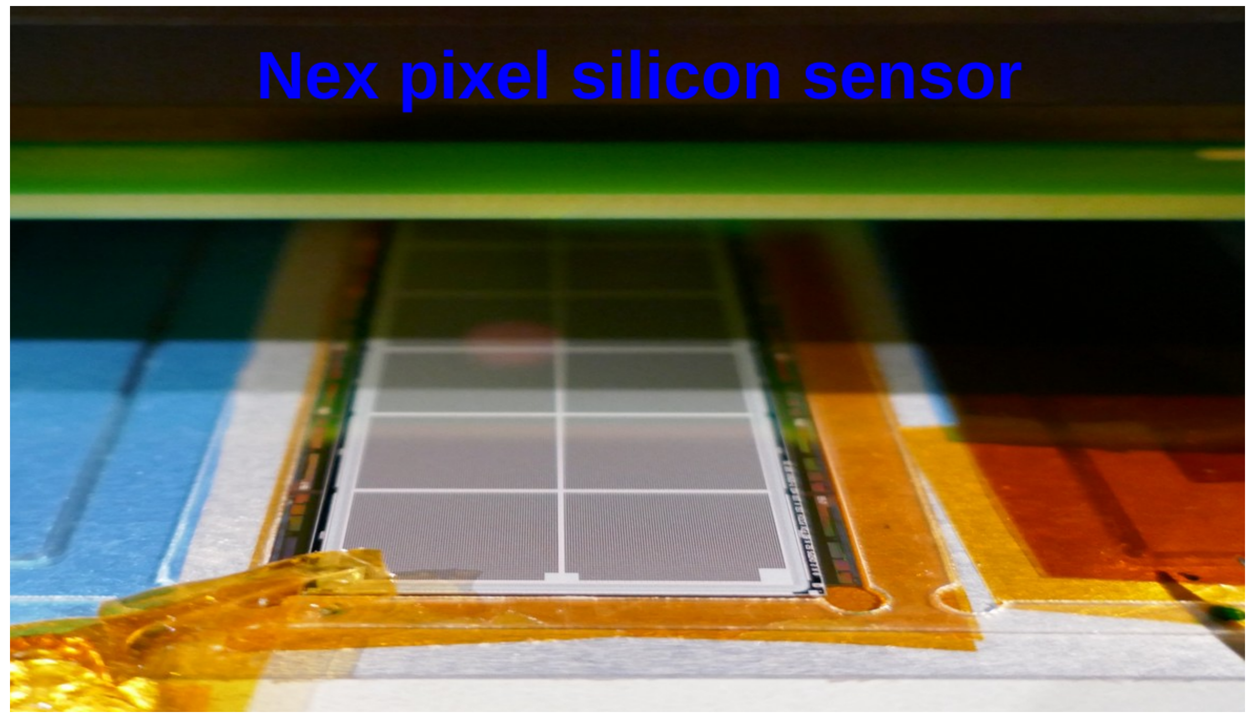
CMS Pixel Detector

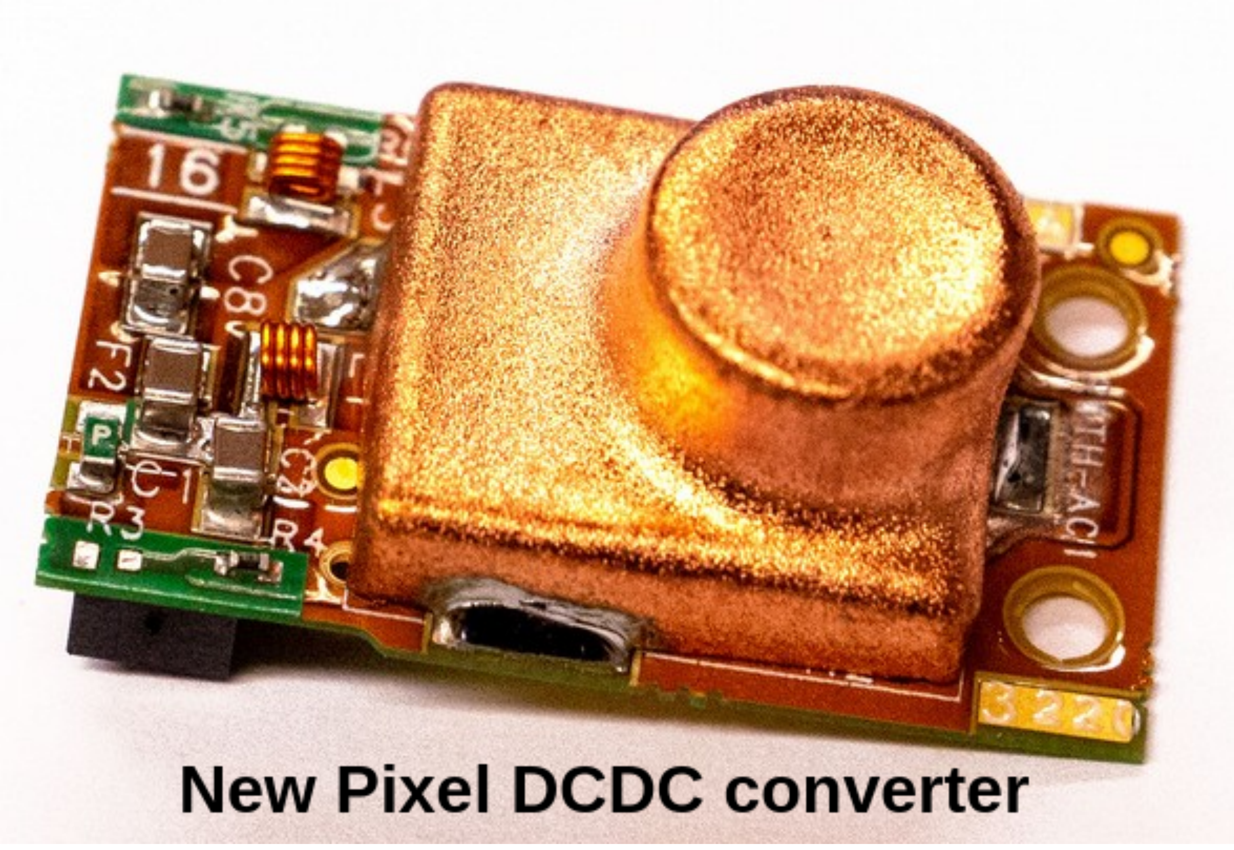
Strips:

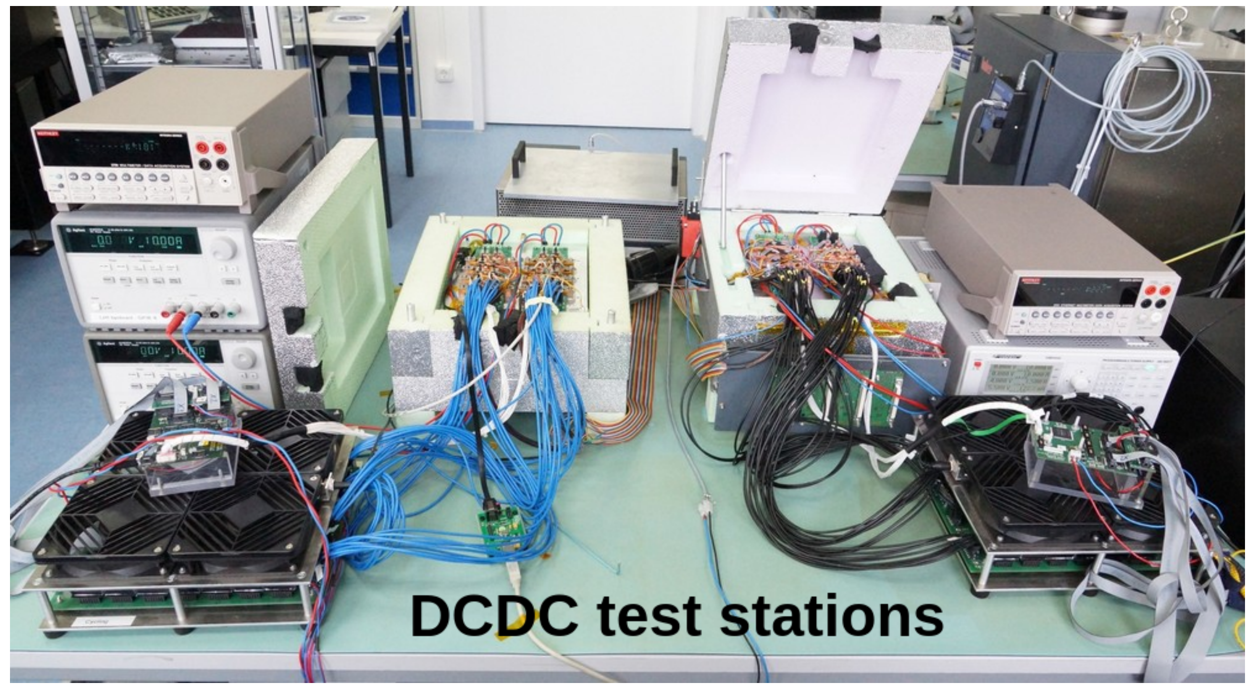
- Maintained at 0°C to prevent "reverse annealing".
- Operating at -25°C will be exercised during LS2.

Pixels:

- Scheduled replacement of the barrel layer 1 is ongoing
  - New readout chip (lower thresholds, good radiation tolerance)
  - Bump bonding of modules is 2/3 completed.
  - Module production completion expected by next Spring.
- DCDC converters: production on track for mounting next Spring.





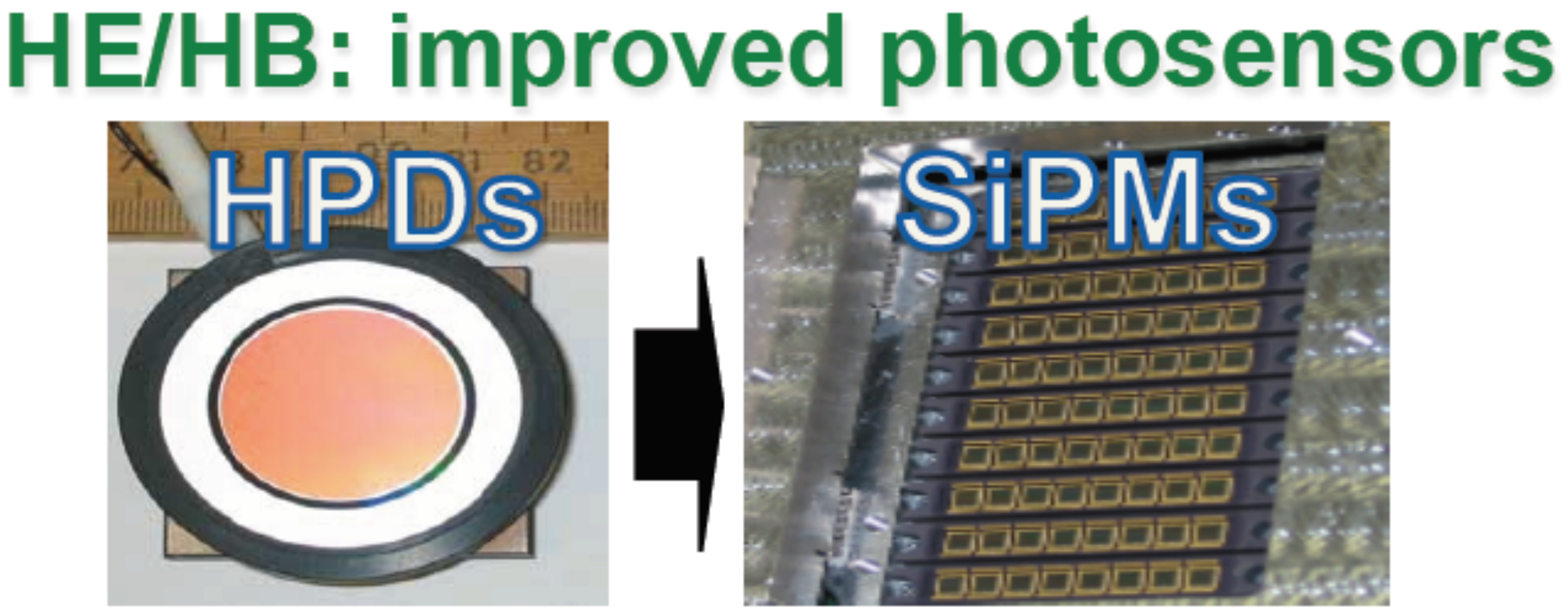


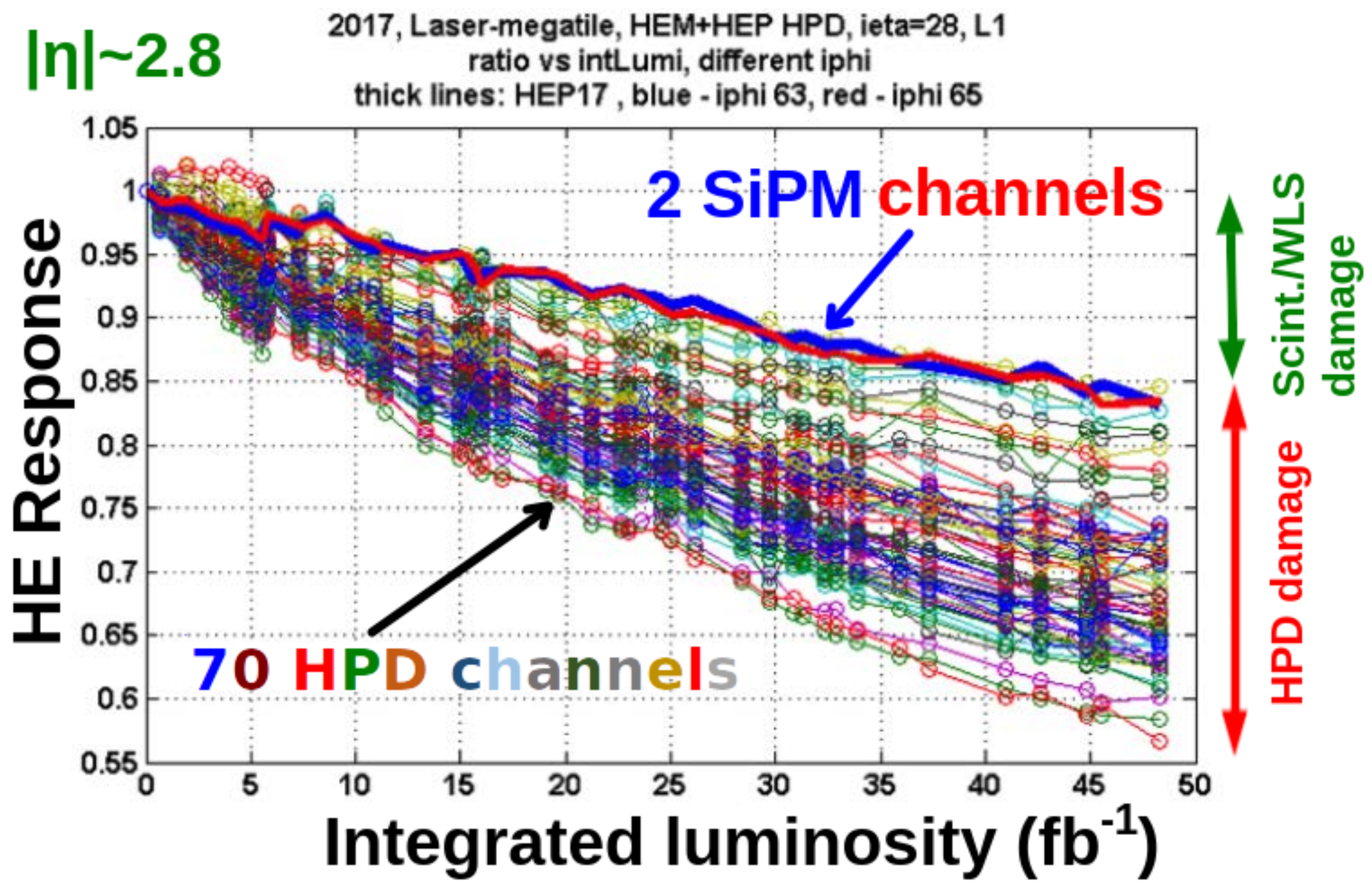
Hadronic Calorimeter: Installation of SiPM completed

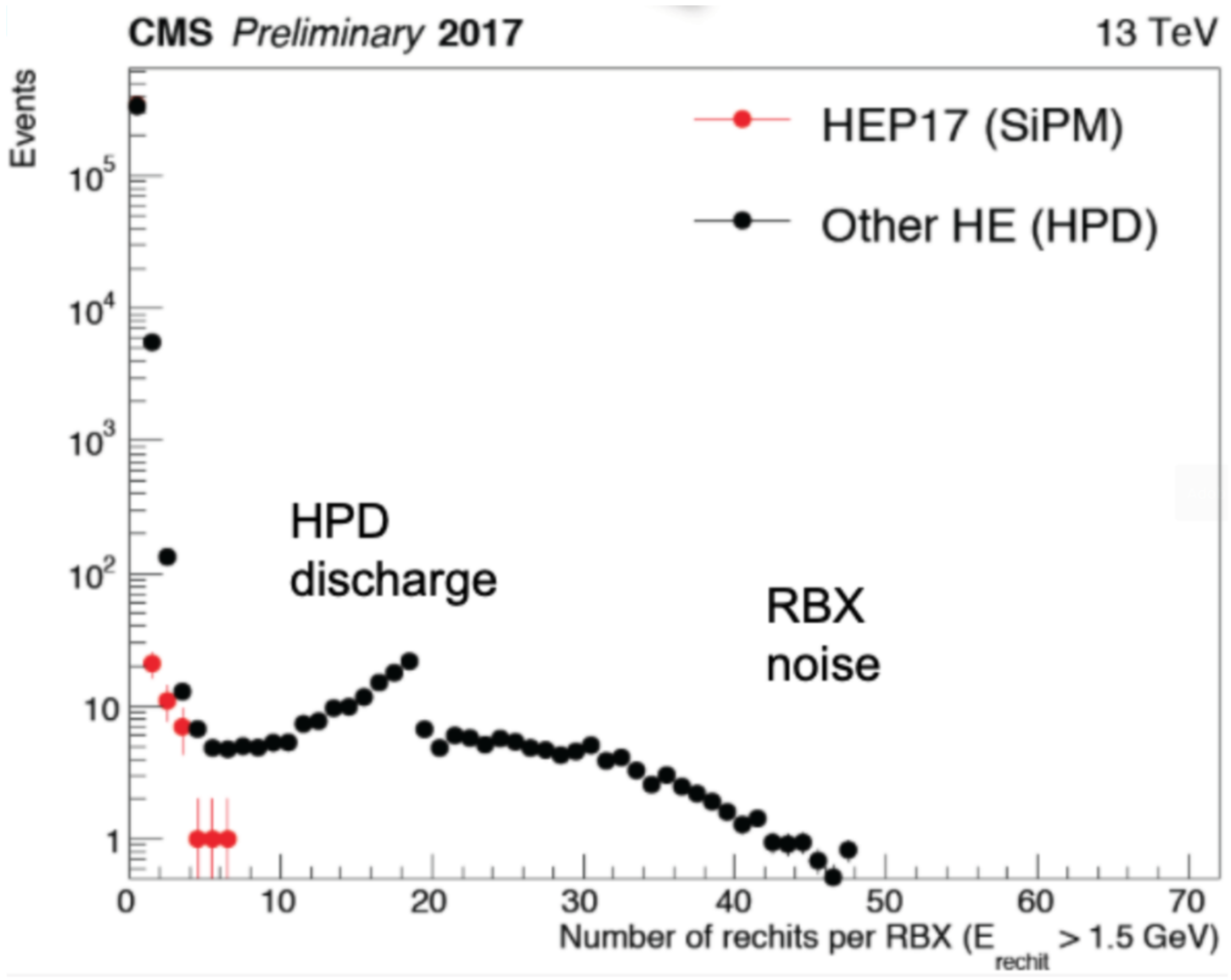
CMS

SiPM outperforms HPD in several aspects:

- 2.5 increase in photon detection efficiency.
- Strong noise reduction (avoids the need of noise cleaning at HLT/offline level)
- Almost no response loss vs integrated luminosity
  - Remaining loss due to scintillator ageing.



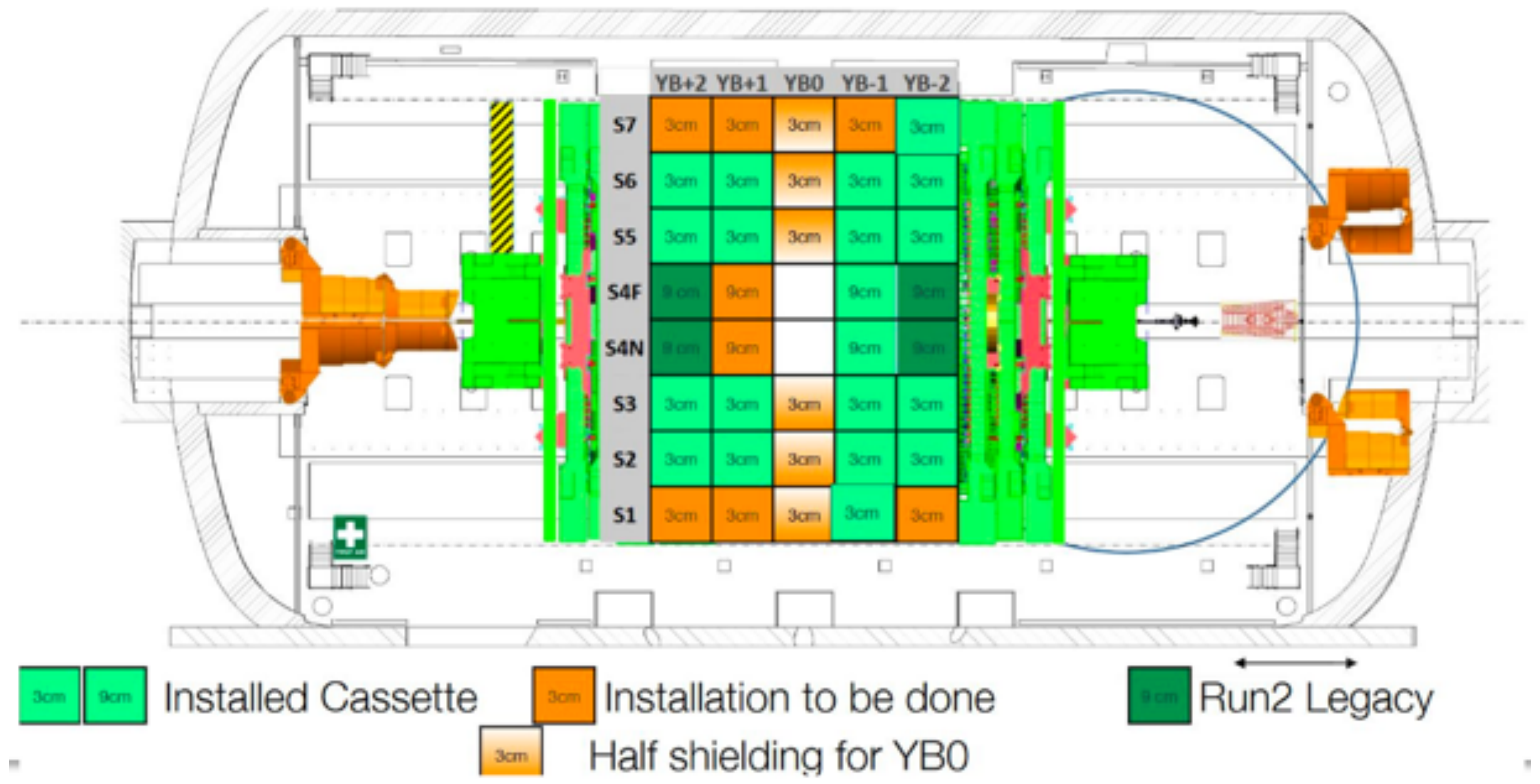




Muon system: Drift Tubes and Resistive Plate Chambers

DT:

- Extension of external shielding to protect from neutron backgrounds.
- Phase2 readout/trigger installed in one sector and being tested.



RPC:

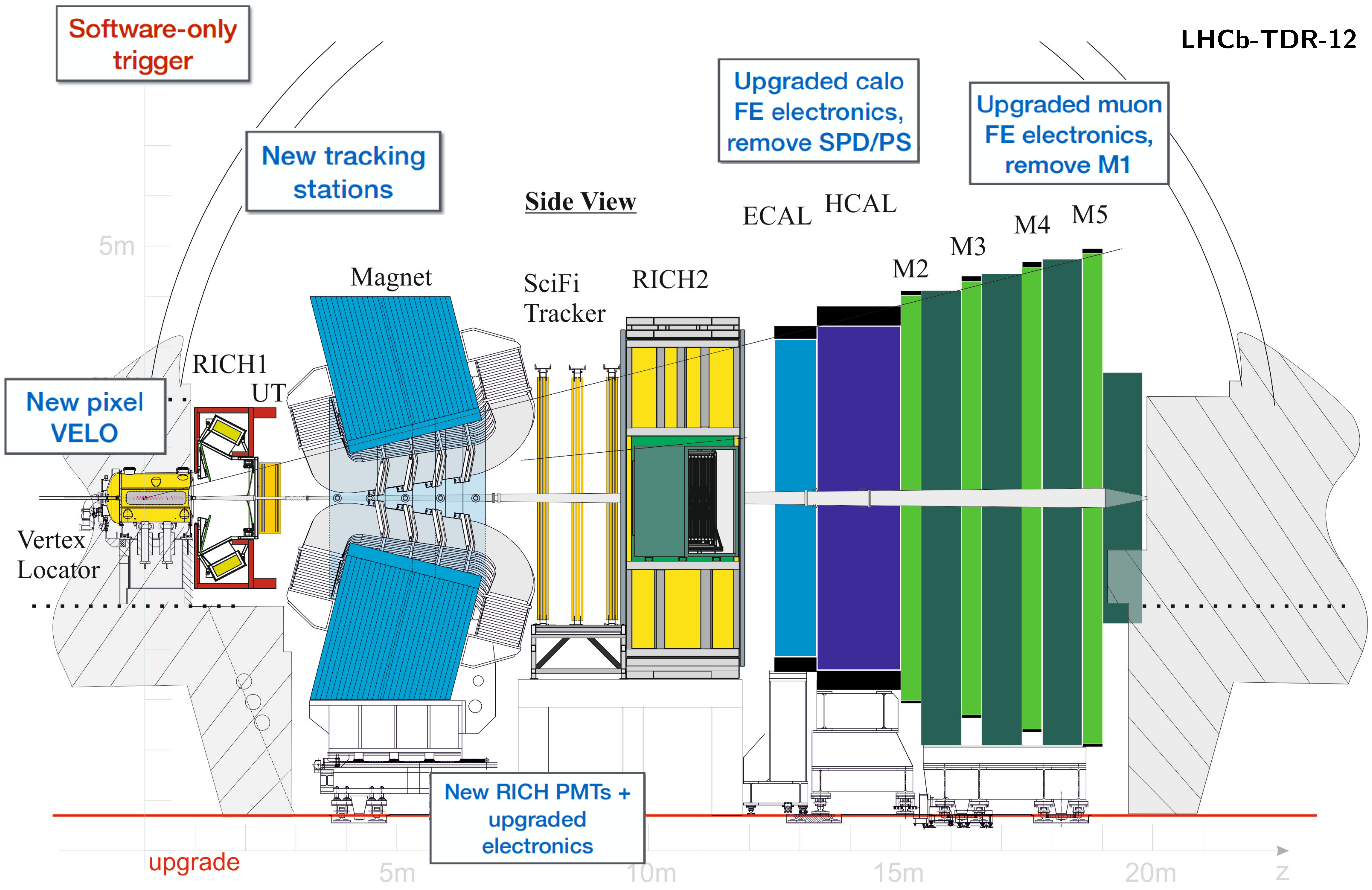
- Ongoing campaign to repair leaky chambers (75 out of 1056).
- 45 already repaired, 3 more will be. (others cannot be accessed/leak not identified)

Cathode Strip Chambers

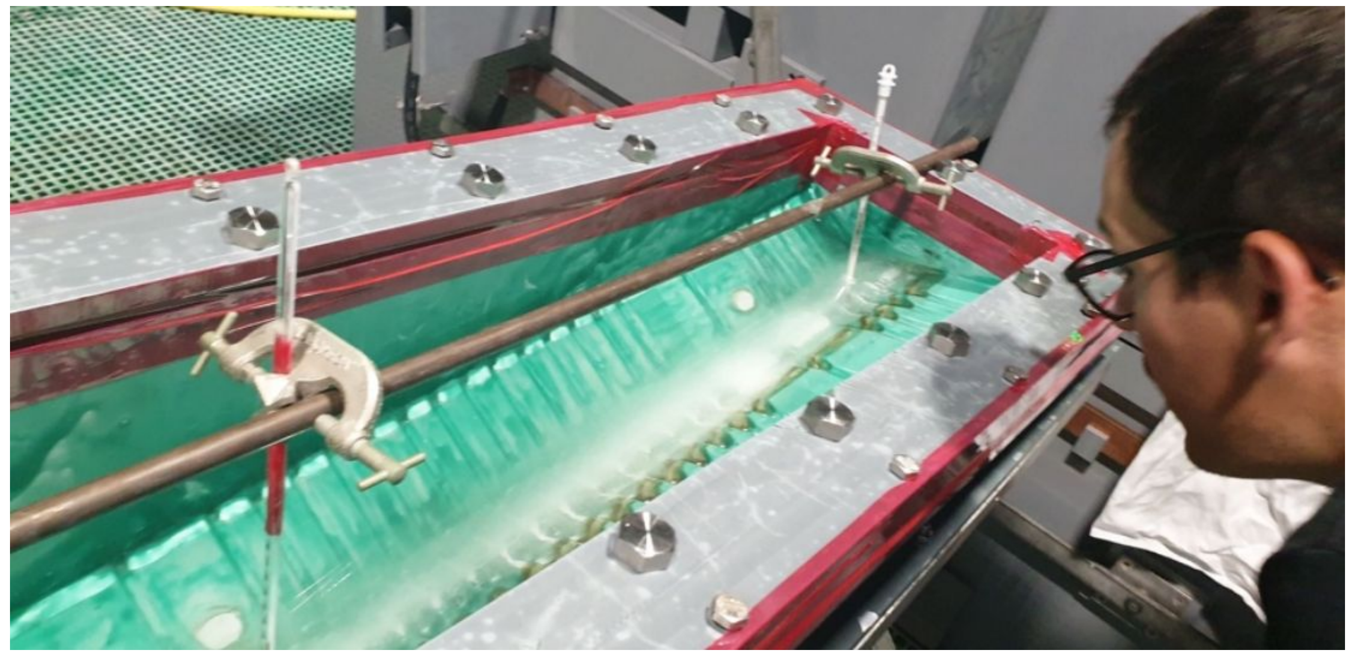
CMS

- Phase 2 front end electronics upgrade of all chambers close to be the beam line (ME X/1).
  - Needed to sustain HL-LHC radiation rates.
  - All chambers need to be brought to surface.
  - Half way done.
- New (more robust) cooling circuit with continuous pipe bent being installed in ME+1/1 after detecting some weakness in the previous one.

LHCb Phase I upgrades



Machining rails for SciFi



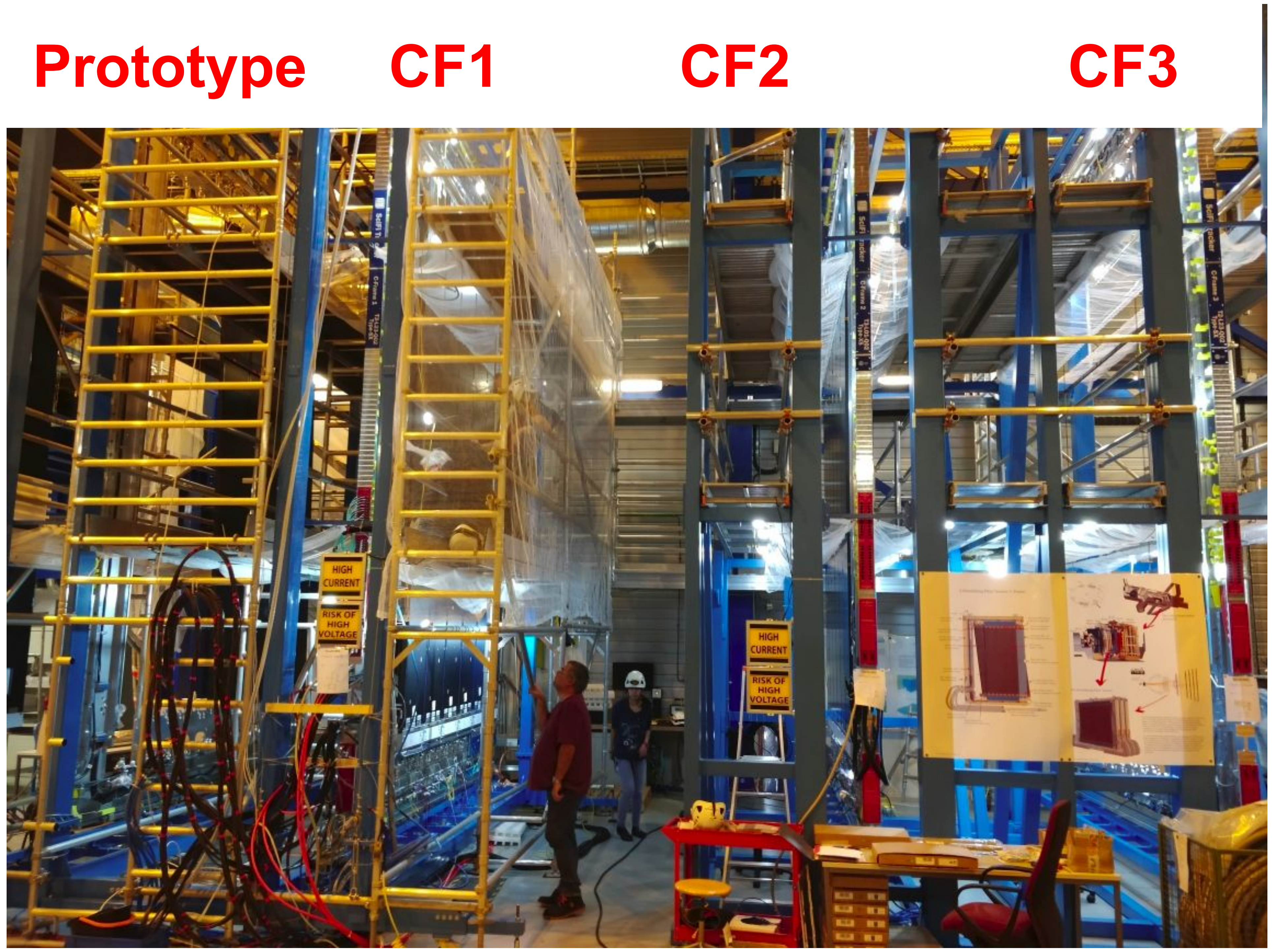
Thickness reduced from 250µm →150µm
(Achieved through NaOH etching)

Trackers

upstream Tracker

- SALT chip v3.8
- Flex Cable
- Production of Hybrids

12 C-frames
complex assembly

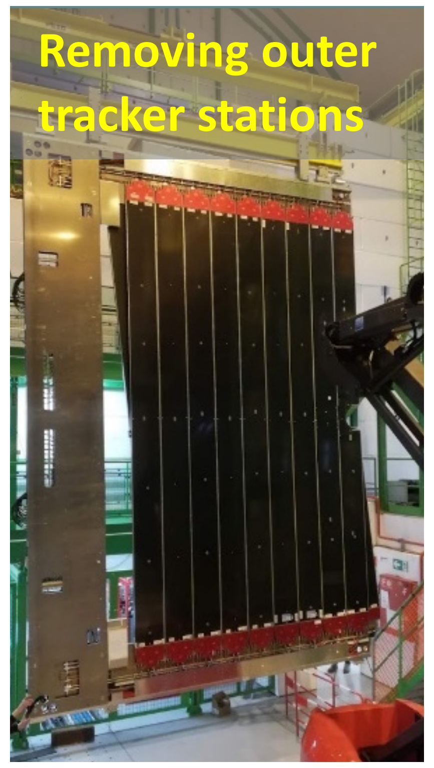


Sci-Fi assembly hall

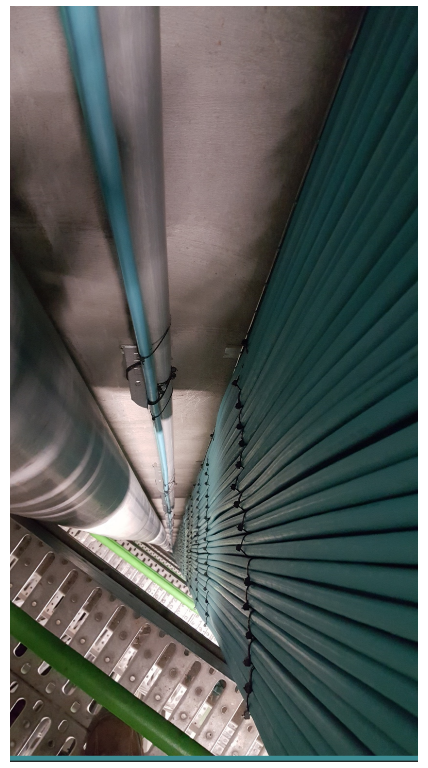
LHCb upgrade progressing well

LHCb

- All old detectors and obsolete equipment removed
- All new cooling systems installed
- All optical fibers in place
- New computing center containers in place

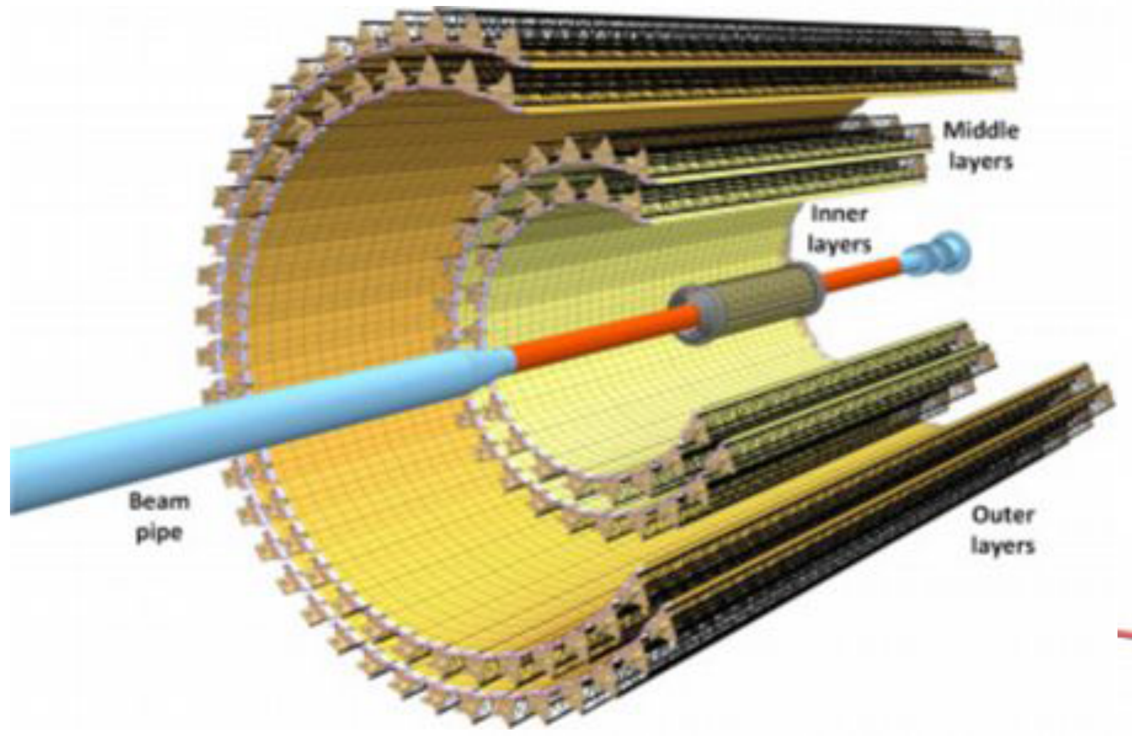


19000 fibres



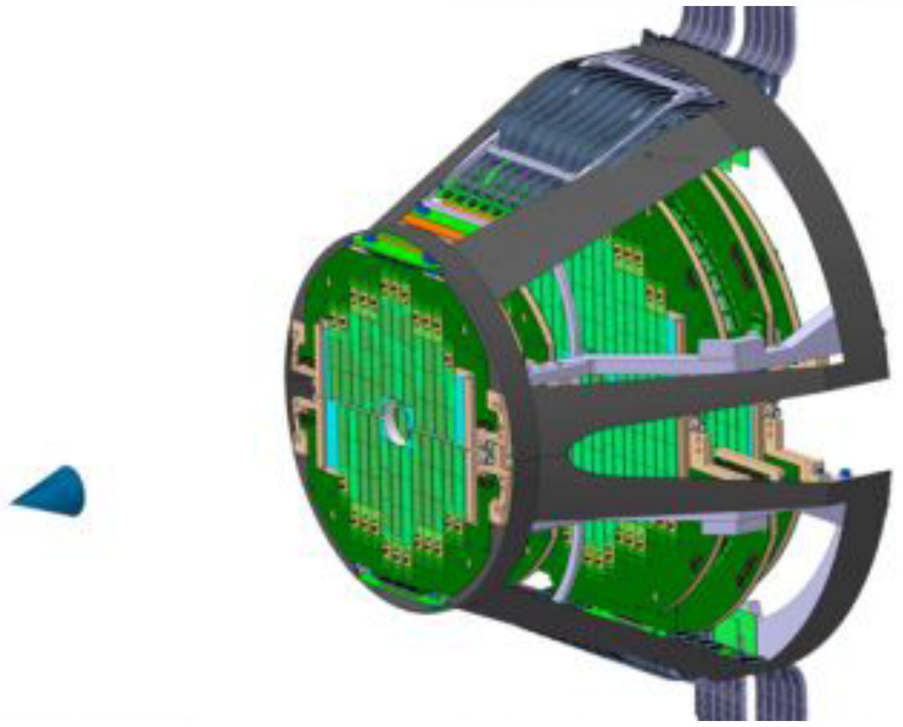
ALICE LS2 Upgrade

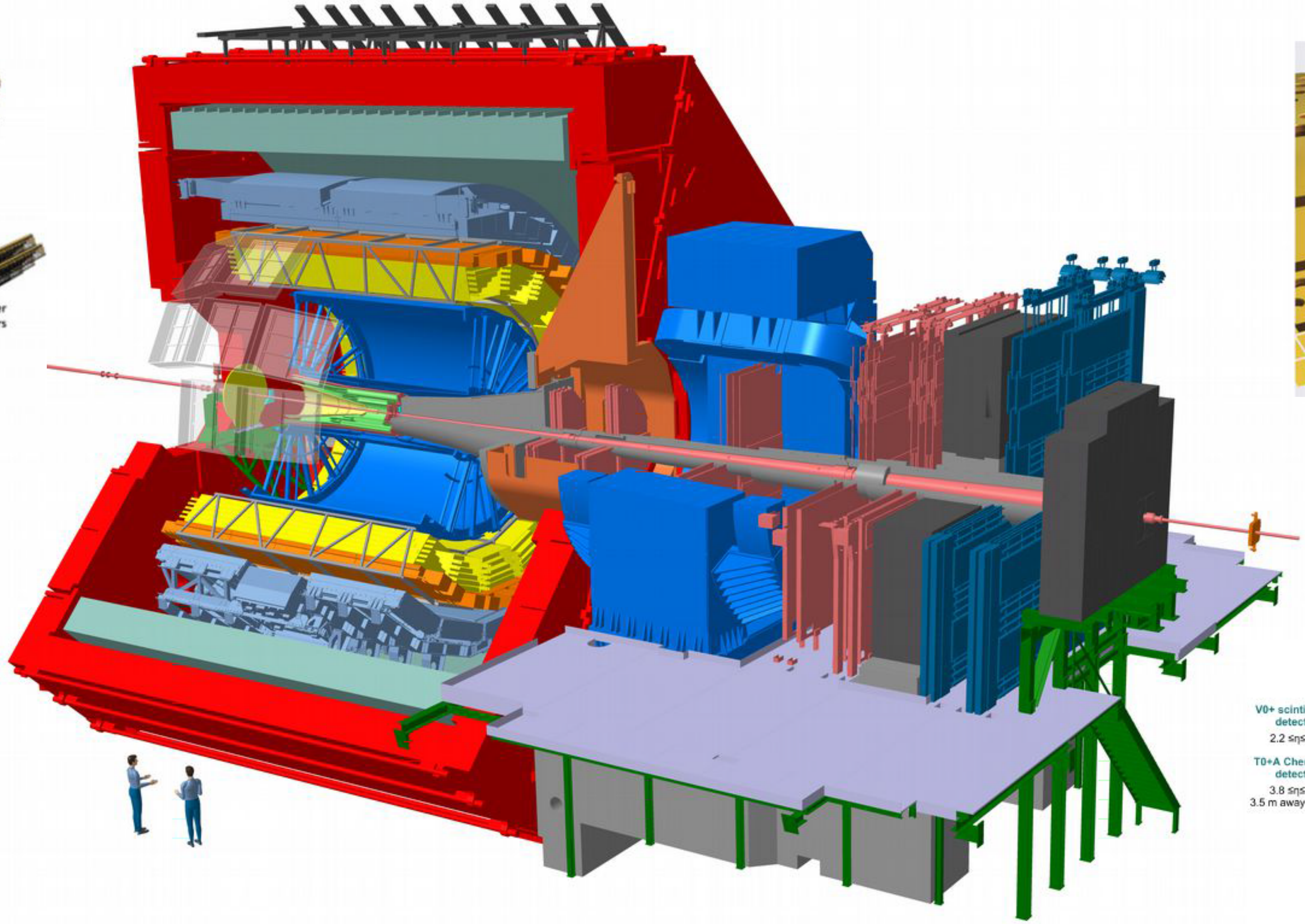
Inner Tracking System



Both based on Monolithic Active Pixel Sensors

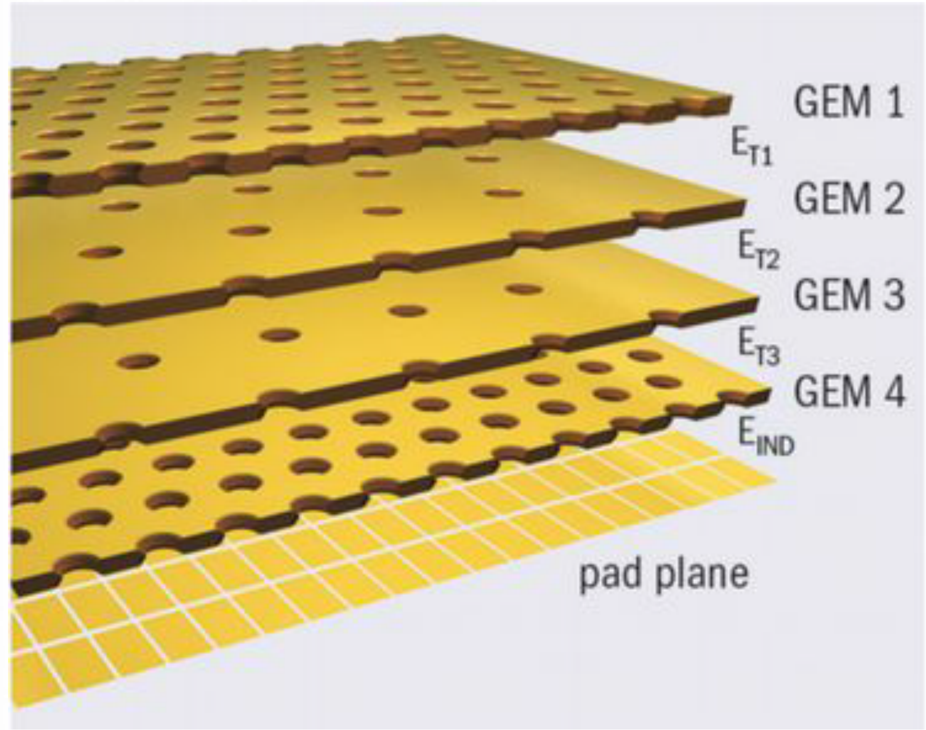
Muon Forward Tracker





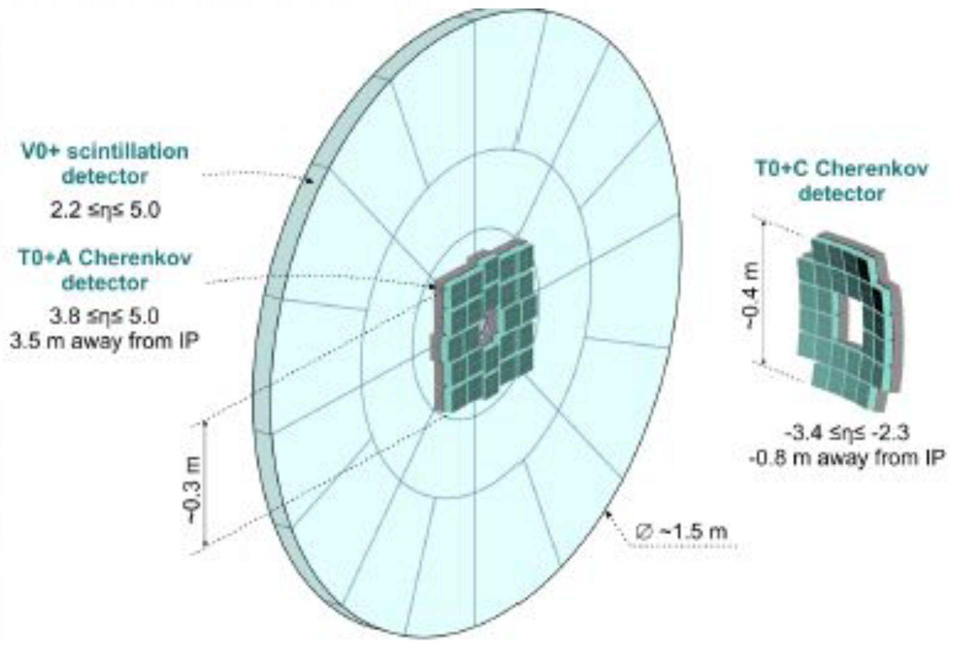
+ improved readout for calorimeters, TOF, TRD, Muon arm, ZDC
+ new Central trigger Processor
+ new DAQ and Online-Offline System (O^2)

Time Projection Chamber



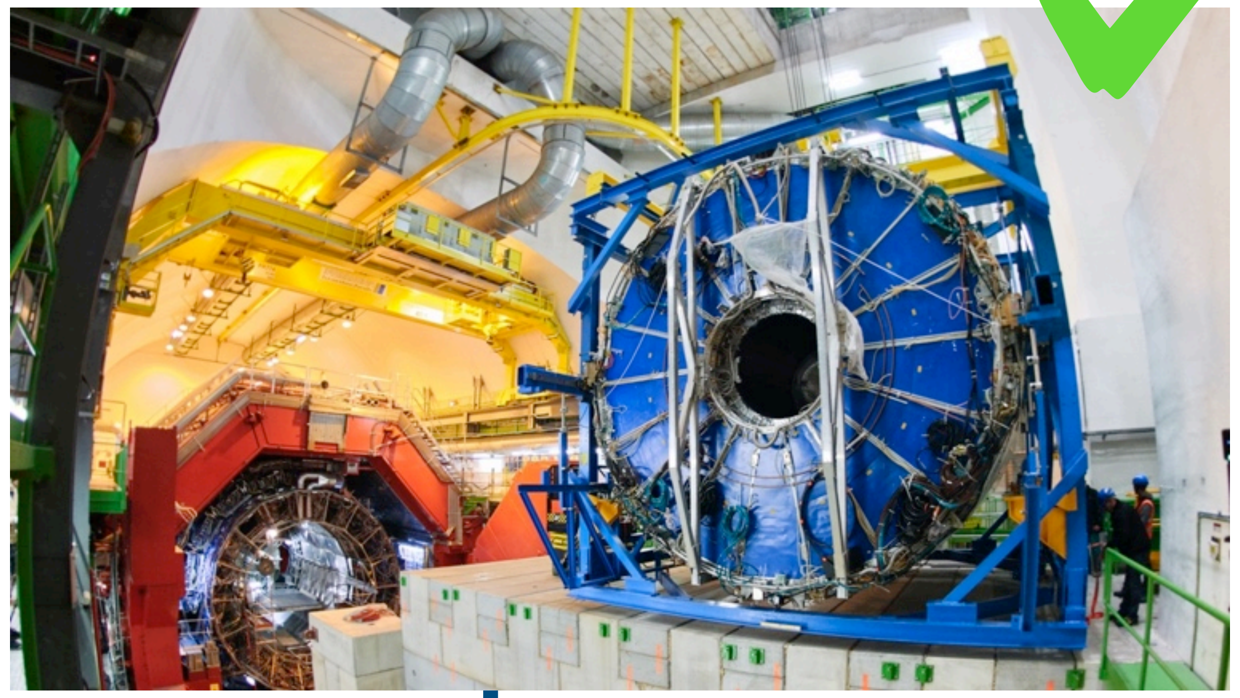
GEM readout chambers

Forward Interaction Trigger



To replace the V0 and T0 detector

TPC Upgrade

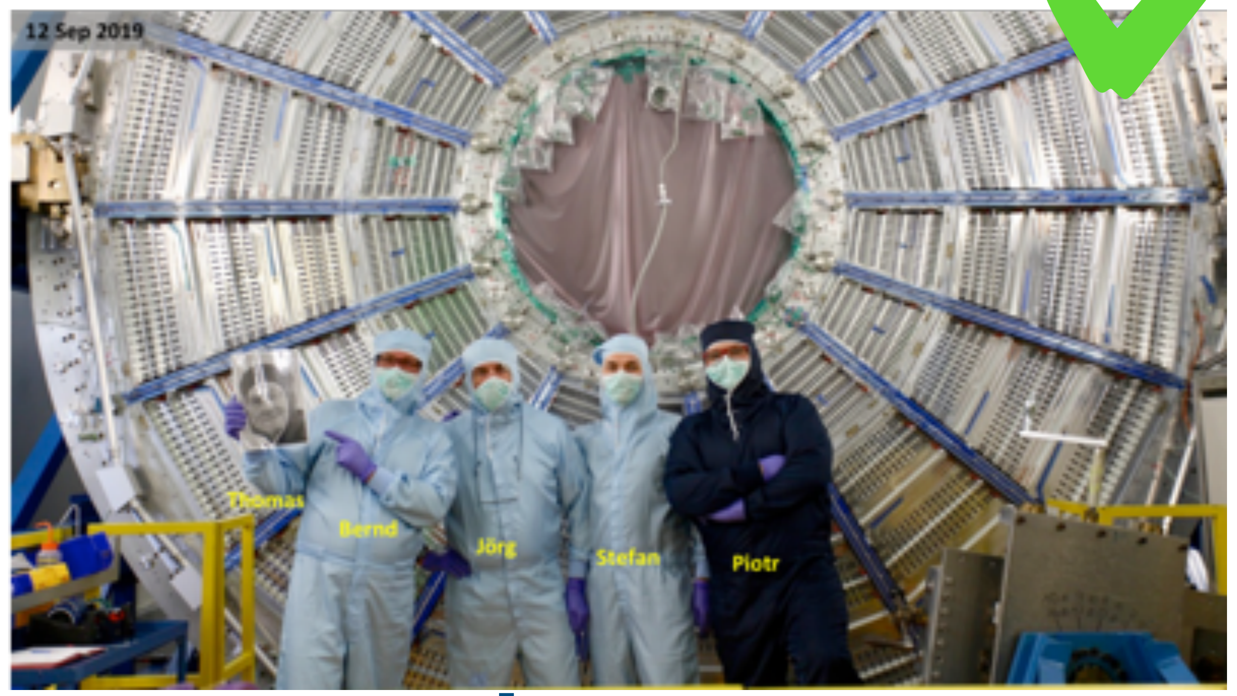


TPC extracted from ALICE

4th Mar ‘19

Move TPC to clean-room

5th Apr ‘19



All GEMs are installed

12th Sept ‘19

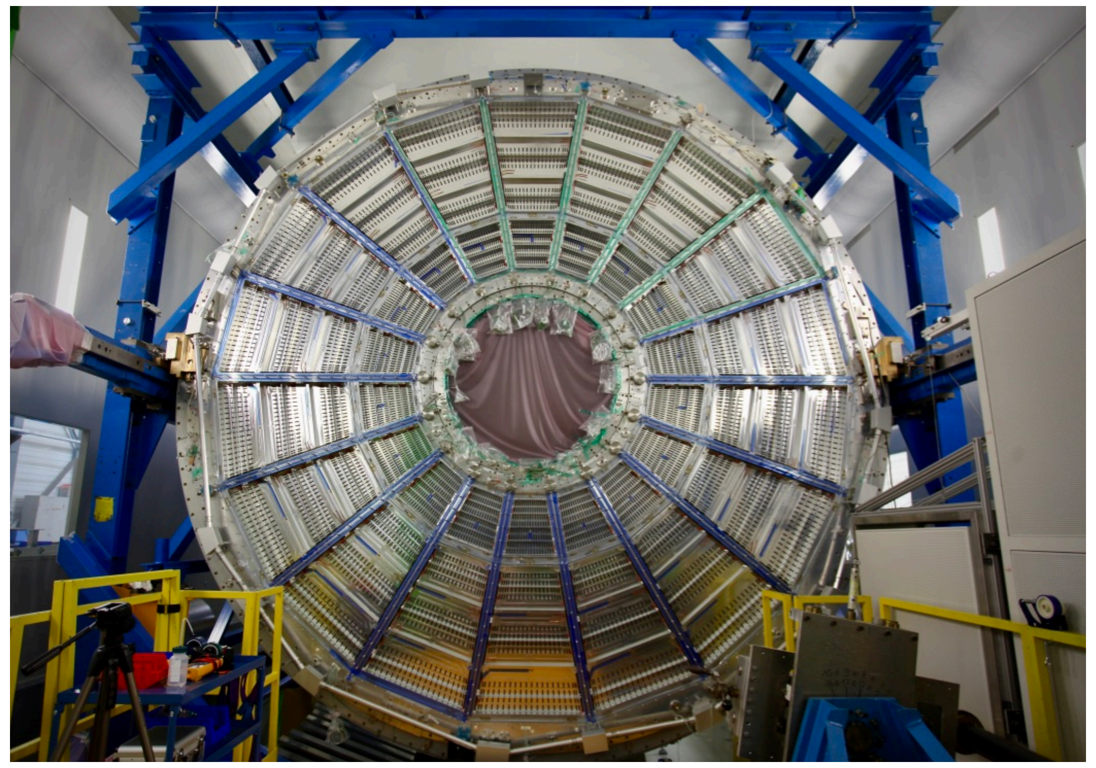
Install FEC and test, TPC ready

28th Feb ‘20

- ✓ All 72 wire chambers were replaced by GEM based readout chambers
- ✓ HV system and readout electronics installed
- ✓ First HV tests of field cage and GEM chambers in air successful
- TPC surface commissioning with gas, LV, HV and cooling as from next week
  - TPC being filled with Neon at this moment

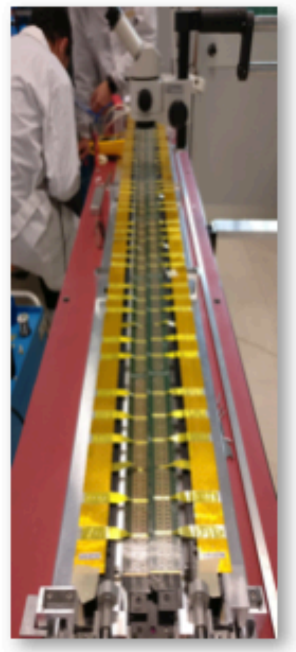
…only some impressions

- Excellent progress on TPC installation
  - CRUs for TPC have been ordered from qualified vendor; negotiations for funding continue
- ITS and MFT proceeding well
- Containers for Online/Offline Readout system (O^2) in place

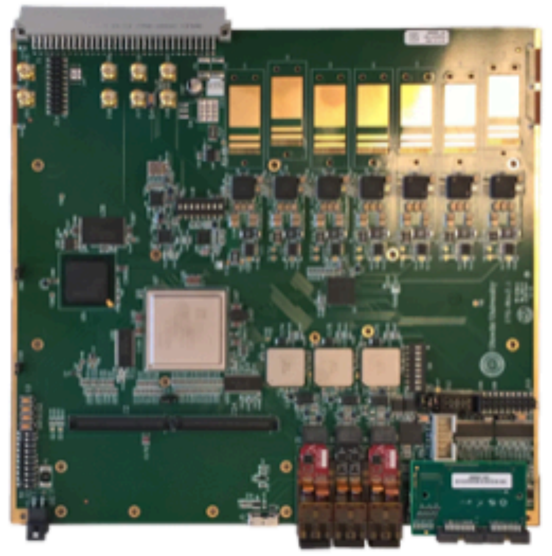


GEM installation on A-side complete

ITS production and assembly proceeding well

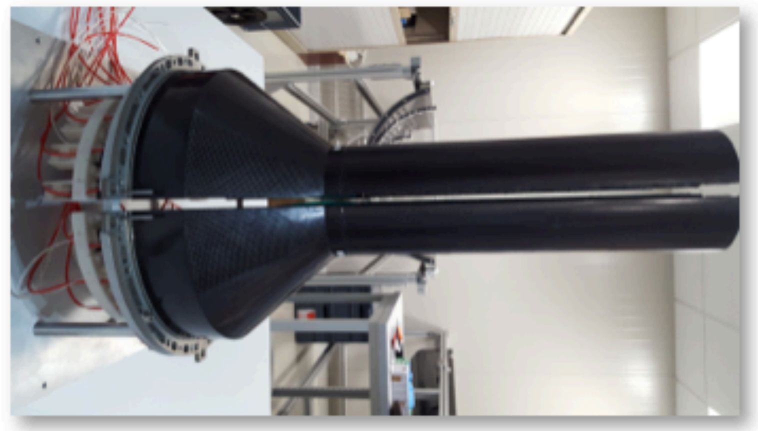


Stave

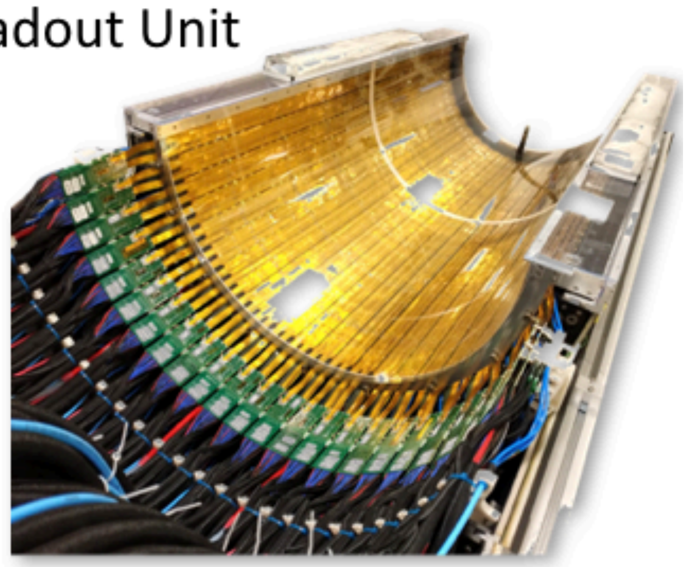


Readout Unit

Containers for O^2 system

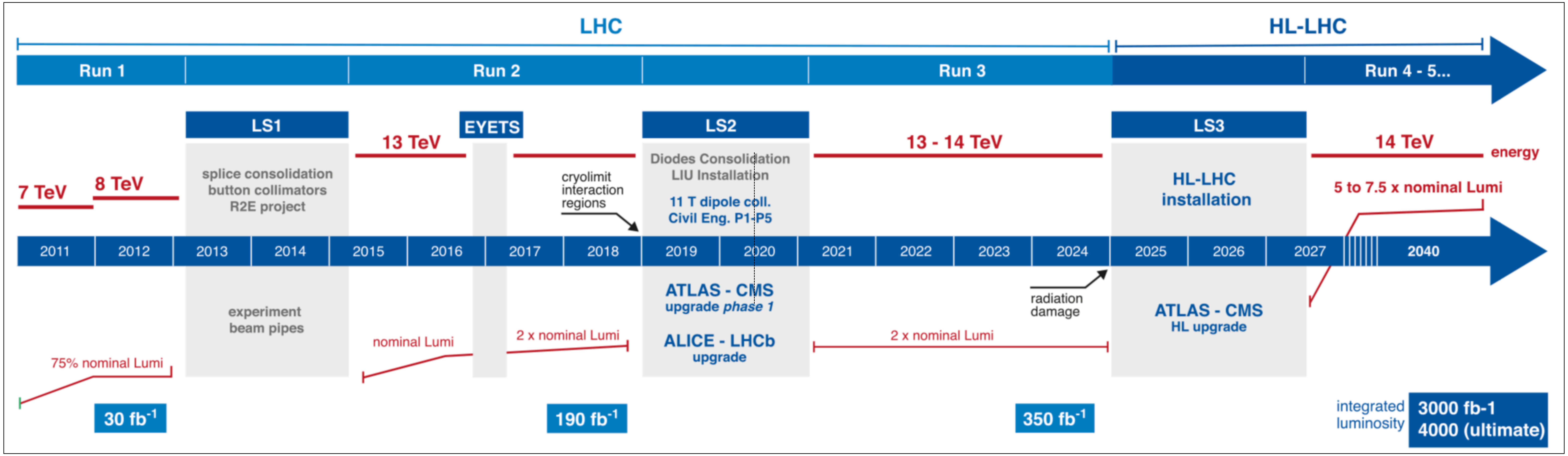


Inner Barrel Assembly



Outer Barrel Assembly

Past Operation and (revised) Schedule

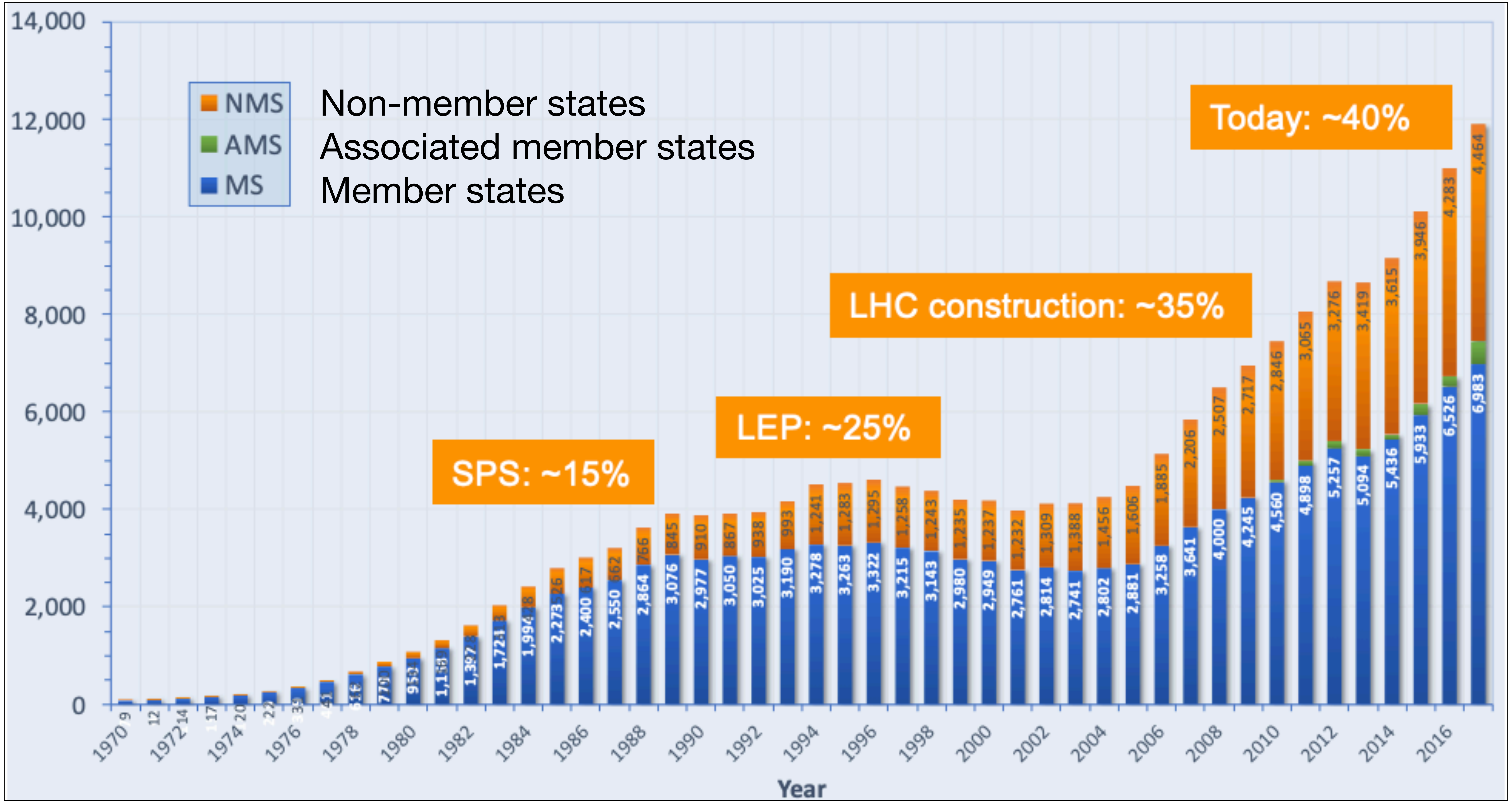


Revised Schedule

- LS2 extended by 2 months
  - Injectors and Fixed Target start in 2020
- Run 3 extended by 1 year; LS3 begin in 2025

European Strategy of Particle Physics Update

Users at CERN



2017 | **2018** | **2019** | **2020**

✓ **Jan.2018**
Call for proposals for venues for Open Symposium and Strategy Drafting Session

✓ **Febr.2018**
Call for scientific input

✓ **March.2018**
Call for nominations of PPG & ESG members

✓ **June 14,2018**
Council decision on venues and dates

✓ **Sept 27,2018**
Council launches the Strategy Update process & establish the PPG and ESG

organisation & input preparation by community

✓ **Dec 18.2018**
Closing submission community input

✓ **May 13-16,2019**
Open Symposium
Granada, ES

Sept.2019
Physics Briefing Book available

consultation & consensus building

Physics results appearing after May 2019 will be taken into account in the process

Jan 20-24,2020
Strategy Update Drafting Session
Bad Honnef, DE

March.2020
Strategy Update submitted to Council

next step

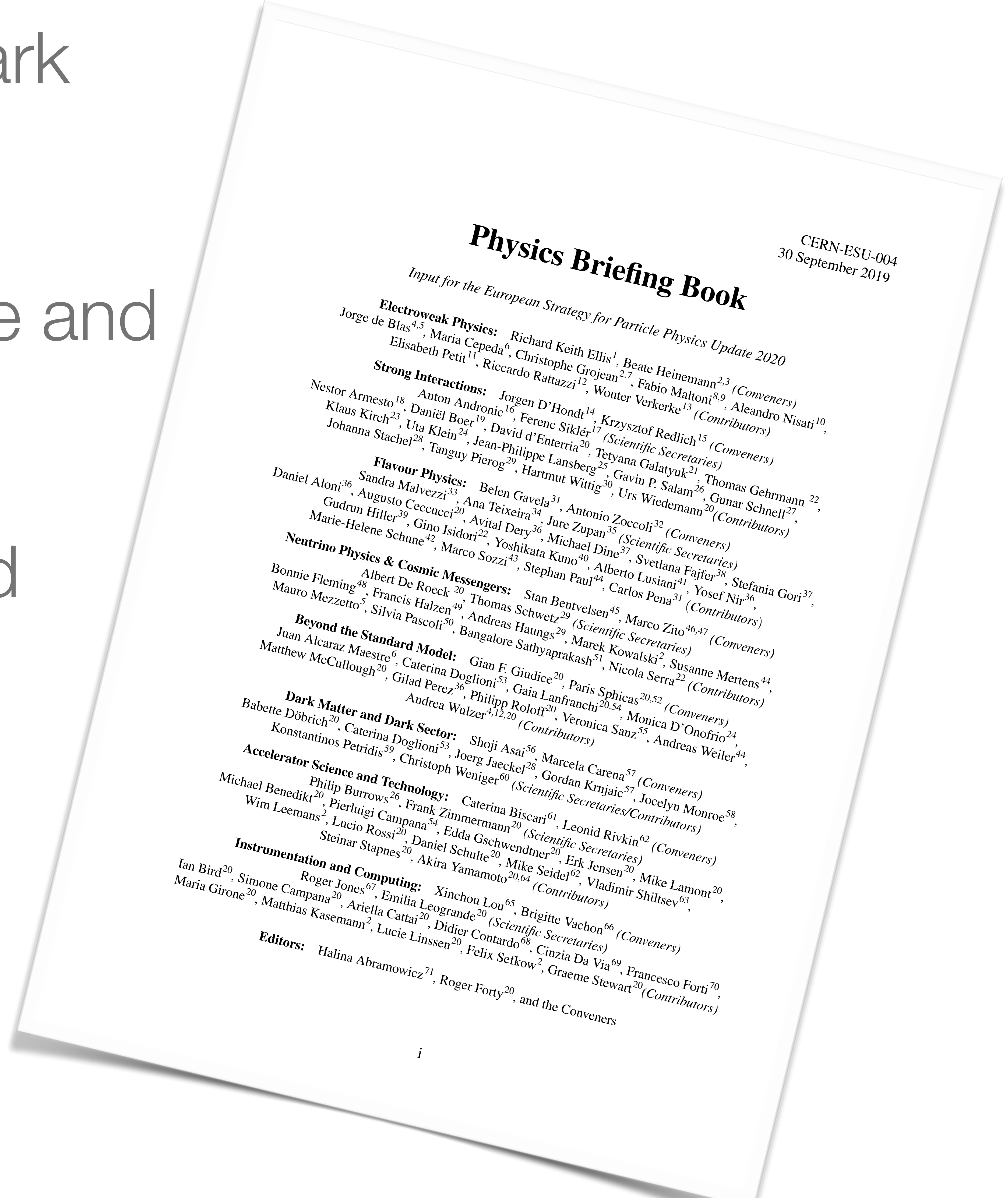
May.2020
Council to approve Strategy Update

Longterm options for large facilities


Possible scenarios of future colliders
Proton collider
Electron collider
Electron-Proton collider
Construction/Transformation: heights of box construction cost/year
Preparation
Japan
4 years
20km tunnel
ILC: 250 GeV 2 ab-1
31km tunnel
500 GeV 4 ab-1
40 km tunnel
1 TeV ≈ 4-5.4 ab-1
China
100km tunnel
CepC: 90/160/240 GeV 16/2.6/5.6 ab-1
SppC: ≈ FCC-hh
CERN
5 years
11 km tunnel
CLIC: 380 GeV 1.5 ab-1
29 km tunnel
1.5 TeV 2.5 ab-1
50 km tunnel
3 TeV 5 ab-1
8 years
100km tunnel
FCC-ee: 90/160/250 GeV -150/10/5 ab-1
350-365 GeV 1.7 ab-1
FCC hh: 150 TeV ≈20-30 ab-1
FCC hh: 100 TeV 20-30 ab-1
8 years
100km tunnel
FCC hh: 100 TeV 20-30 ab-1
HL-LHC: 13 TeV 3-4 ab-1
HE-LHC: 27 TeV 10 ab-1
2 years
1.7 B/ 6 year
LHeC: 1.2TeV 0.25-1 ab-1©
FCC-eh: 3.5 TeV 2 ab-1
2020
2030
2040
2050
2060
2070
2080
2090
Large Facilities world-wide
Technical driven scenarii for longterm provision of infrastructures (assuming funding to be available everywhere).
from U Bassler
26/09/2019
UB

ESPPU Briefing Book

- Theoretical overview
- Electroweak Physics
- Strong Interactions
- Flavour Physics
- Neutrino Physics
- Cosmic Messengers
- Beyond the Standard Model
- Dark Matter and Dark Sectors
- Accelerator Science and Technology
- Instrumentation and Computing


CERN-ESU-004
30 September 2019

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

Electroweak Physics: Richard Keith Ellis[1], Beate Heinemann[2,3] *(Conveners)*
Jorge de Blas[4,5], Maria Cepeda[6], Christophe Grojean[2,7], Fabio Maltoni[8,9], Aleandro Nisati[10], Elisabeth Petit[11], Riccardo Rattazzi[12], Wouter Verkerke[13] *(Contributors)*

Strong Interactions: Jorgen D'Hondt[14], Krzysztof Redlich[15] *(Conveners)*
Anton Andronic[16], Ferenc Siklér[17] *(Scientific Secretaries)*
Nestor Armesto[18], Daniël Boer[19], David d'Enterria[20], Tetyana Galatyuk[21], Thomas Gehrmann[22], Klaus Kirch[23], Uta Klein[24], Jean-Philippe Lansberg[25], Gavin P. Salam[26], Gunar Schnell[27], Johanna Stachel[28], Tanguy Pierog[29], Hartmut Wittig[30], Urs Wiedemann[20] *(Contributors)*

Flavour Physics: Belen Gavela[31], Antonio Zoccoli[32] *(Conveners)*
Sandra Malvezzi[33], Ana Teixeira[34], Jure Zupan[35] *(Scientific Secretaries)*
Daniel Aloni[36], Augusto Ceccucci[20], Avital Dery[36], Michael Dine[37], Svetlana Fajfer[38], Stefania Gori[37], Gudrun Hiller[39], Gino Isidori[22], Yoshikata Kuno[40], Alberto Lusiani[41], Yosef Nir[36], Marie-Helene Schune[42], Marco Sozzi[43], Stephan Paul[44], Carlos Pena[31] *(Contributors)*

Neutrino Physics & Cosmic Messengers: Stan Bentvelsen[45], Marco Zito[46,47] *(Conveners)*
Albert De Roeck[20], Thomas Schwetz[29] *(Scientific Secretaries)*
Bonnie Fleming[48], Francis Halzen[49], Andreas Haungs[29], Marek Kowalski[2], Susanne Mertens[44], Mauro Mezzetto[5], Silvia Pascoli[50], Bangalore Sathyaprakash[51], Nicola Serra[22] *(Contributors)*

Beyond the Standard Model: Gian F. Giudice[20], Paris Sphicas[20,52] *(Conveners)*
Juan Alcaraz Maestre[6], Caterina Doglioni[53], Gaia Lanfranchi[20,54], Monica D'Onofrio[24], Matthew McCullough[20], Gilad Perez[36], Philipp Roloff[20], Veronica Sanz[55], Andreas Weiler[44], Andrea Wulzer[4,12,20] *(Contributors)*

Dark Matter and Dark Sector: Shoji Asai[56], Marcela Carena[57] *(Conveners)*
Babette Döbrich[20], Caterina Doglioni[53], Joerg Jaeckel[28], Gordan Krnjaic[57], Jocelyn Monroe[58], Konstantinos Petridis[59], Christoph Weniger[60] *(Scientific Secretaries/Contributors)*

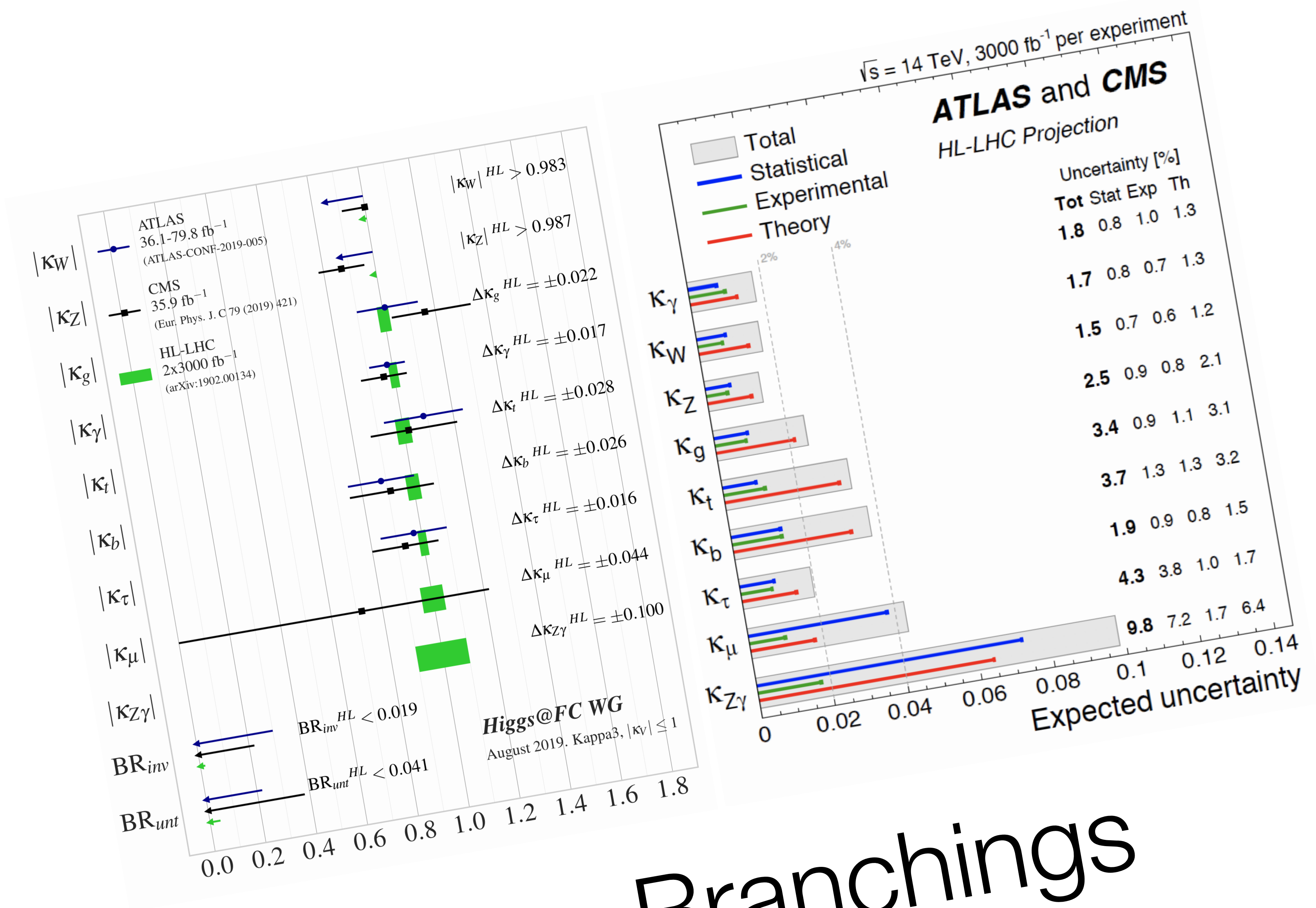
Accelerator Science and Technology: Caterina Biscari[61], Leonid Rivkin[62] *(Conveners)*
Philip Burrows[26], Frank Zimmermann[20] *(Scientific Secretaries)*
Michael Benedikt[20], Pierluigi Campana[54], Edda Gschwendtner[20], Erk Jensen[20], Mike Lamont[20], Wim Leemans[2], Lucio Rossi[20], Daniel Schulte[20], Mike Seidel[62], Vladimir Shiltsev[63], Steinar Stapnes[20], Akira Yamamoto[20,64] *(Contributors)*

Instrumentation and Computing: Xinchou Lou[65], Brigitte Vachon[66] *(Conveners)*
Roger Jones[67], Emilia Leogrande[20] *(Scientific Secretaries)*
Ian Bird[20], Simone Campana[20], Ariella Cattai[20], Didier Contardo[68], Cinzia Da Via[69], Francesco Forti[70], Maria Girone[20], Matthias Kasemann[2], Lucie Linssen[20], Felix Sefkow[2], Graeme Stewart[20] *(Contributors)*

Editors: Halina Abramowicz[71], Roger Forty[20], and the Conveners

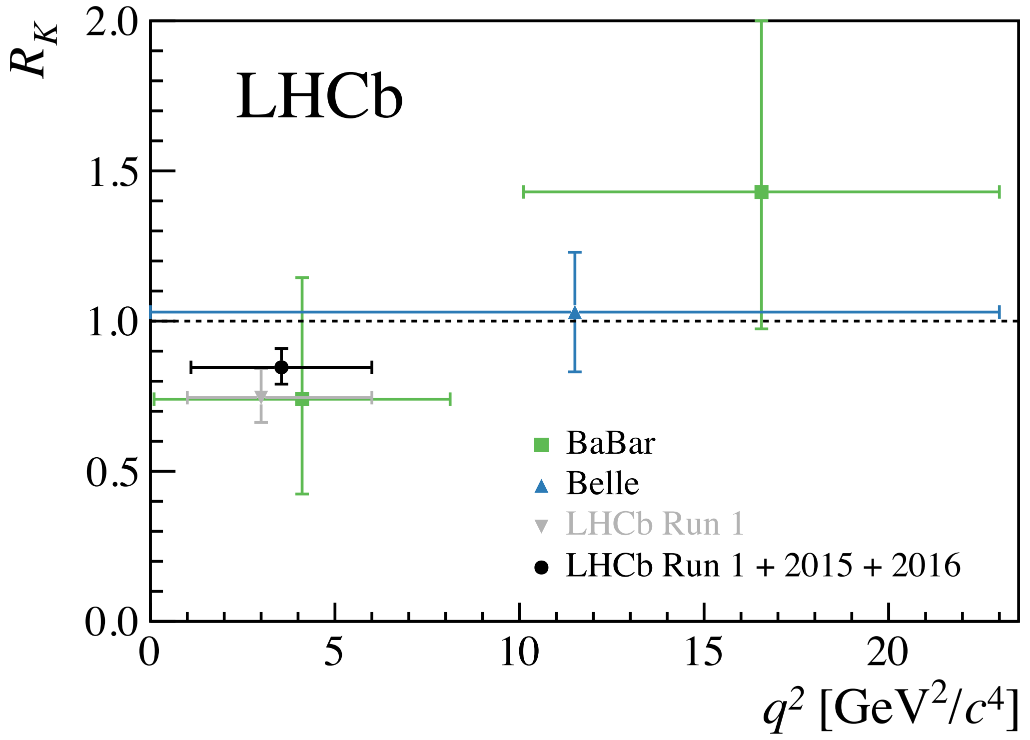
i

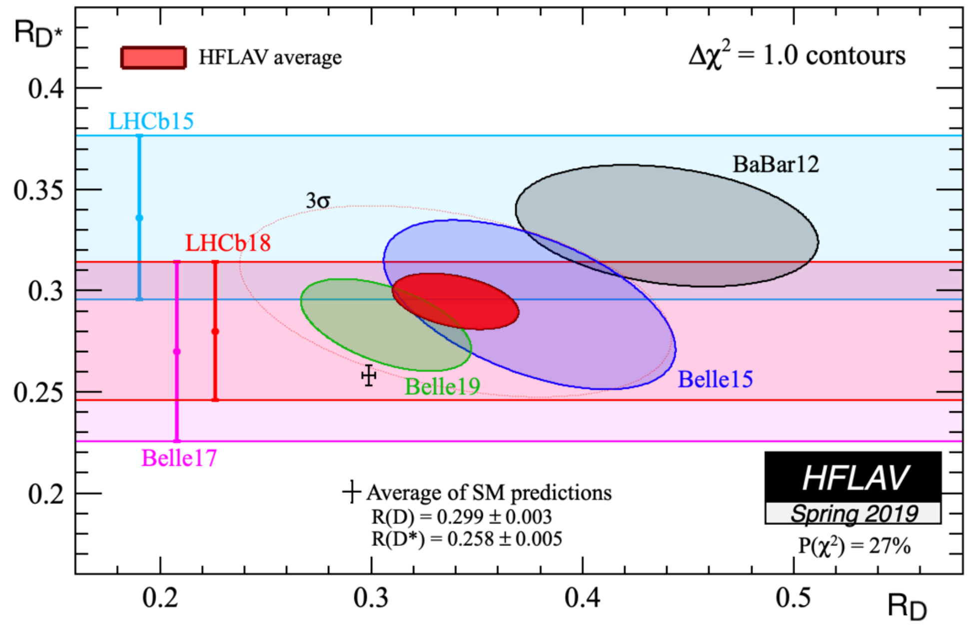
Some elements of the Briefing Book

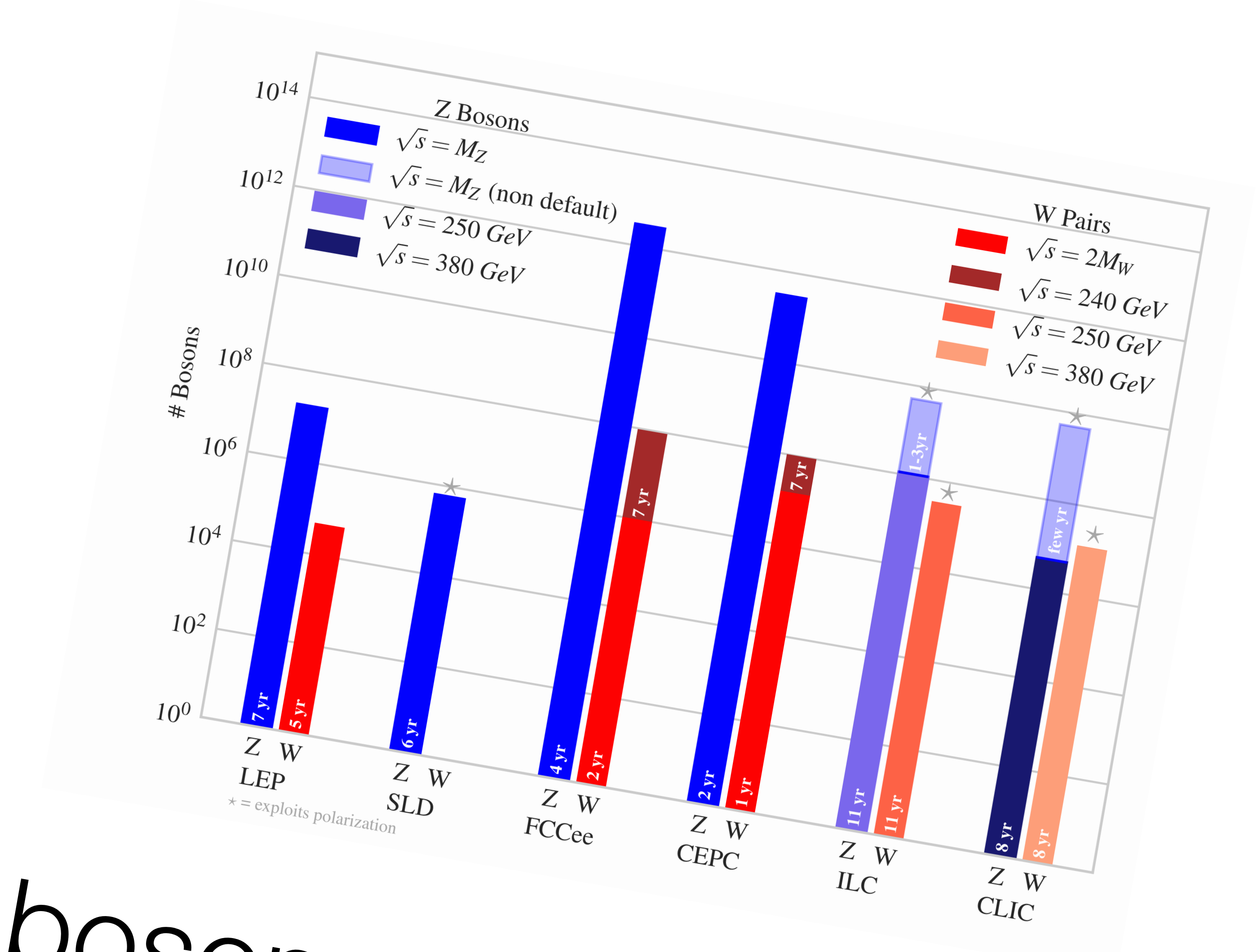


Higgs Branchings

R_K







Z-boson and WW from ee

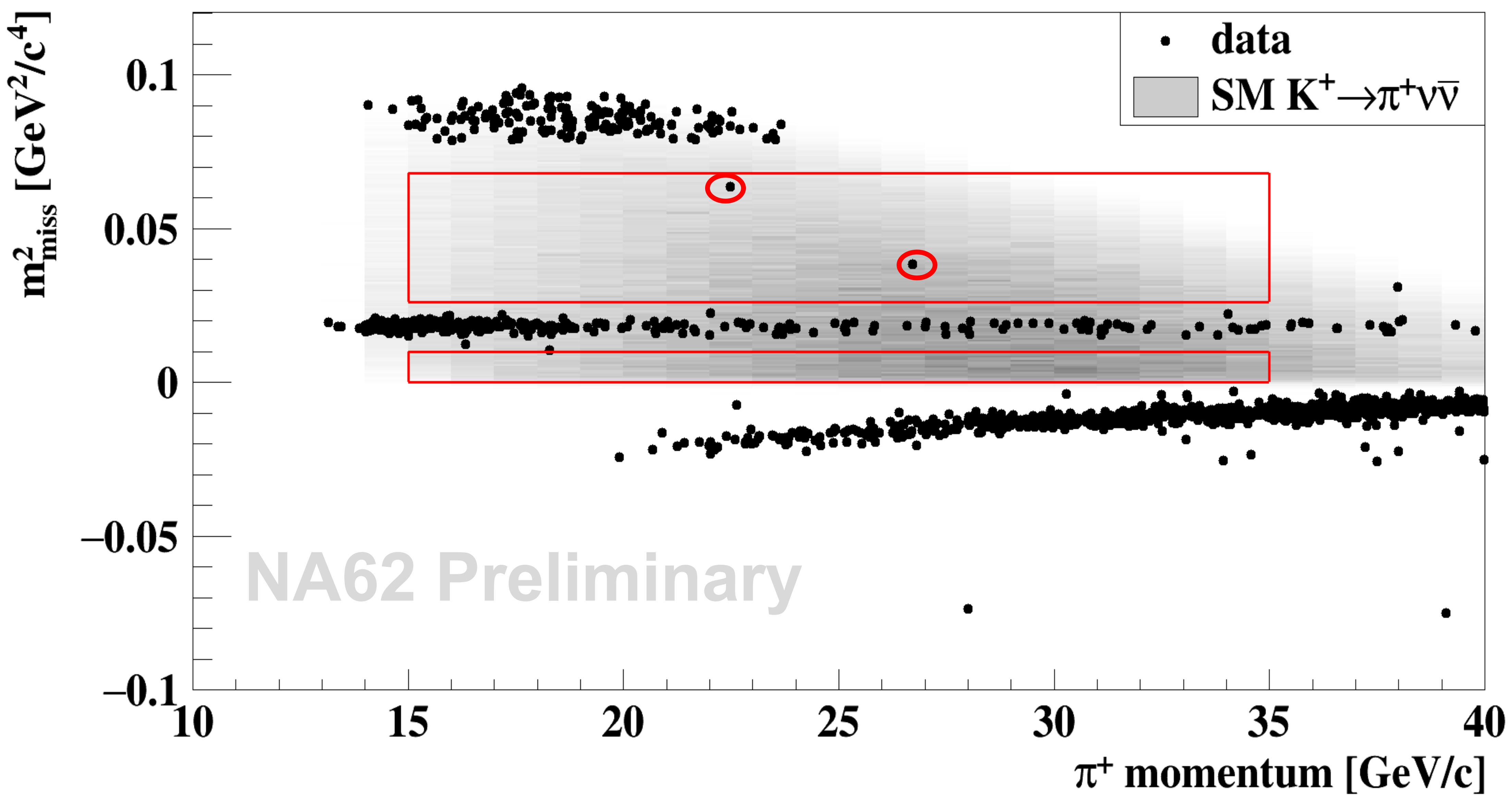
Beyond Colliders

Selected Fix-Target Experiments: NA62

NA62 rare Kaon decay: $K^{\pm} \rightarrow \pi^{\pm}\nu\nu$

- 2017 analysis: SES 3.89 x 10^{-11}
- observe 2 events

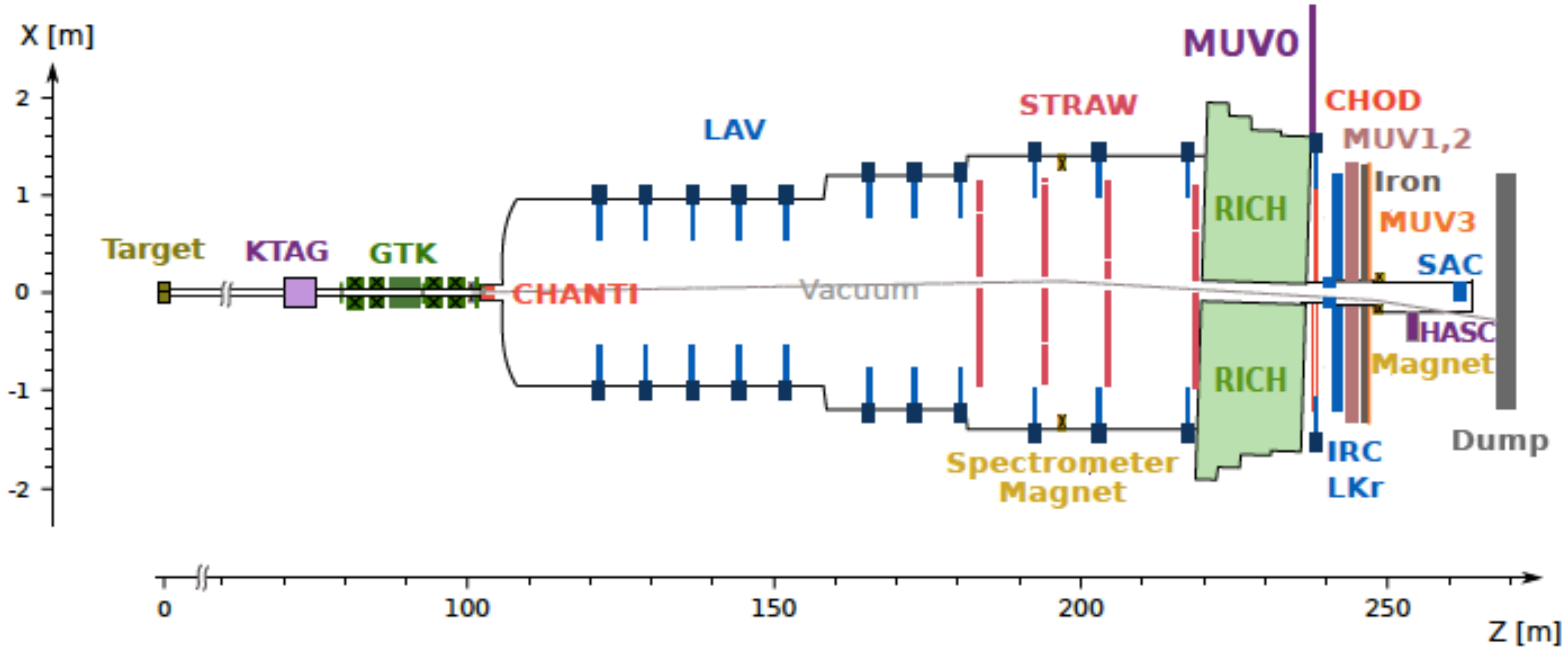
2 events observed in signal region



- expect 2.16±0.12±0.26 events

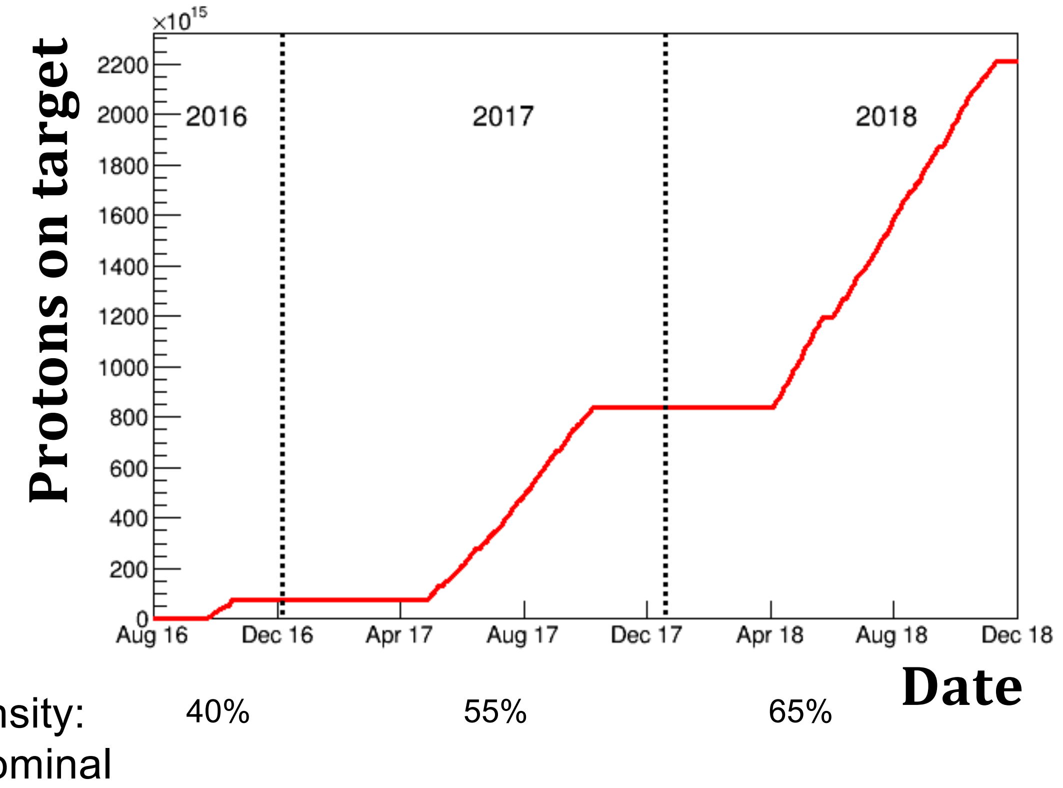
Background

- 1.5±0.2±0.2 events



4th GTK has been added to reduce backgrounds further. SPSC looking forward to 2018 (and 2021) results.

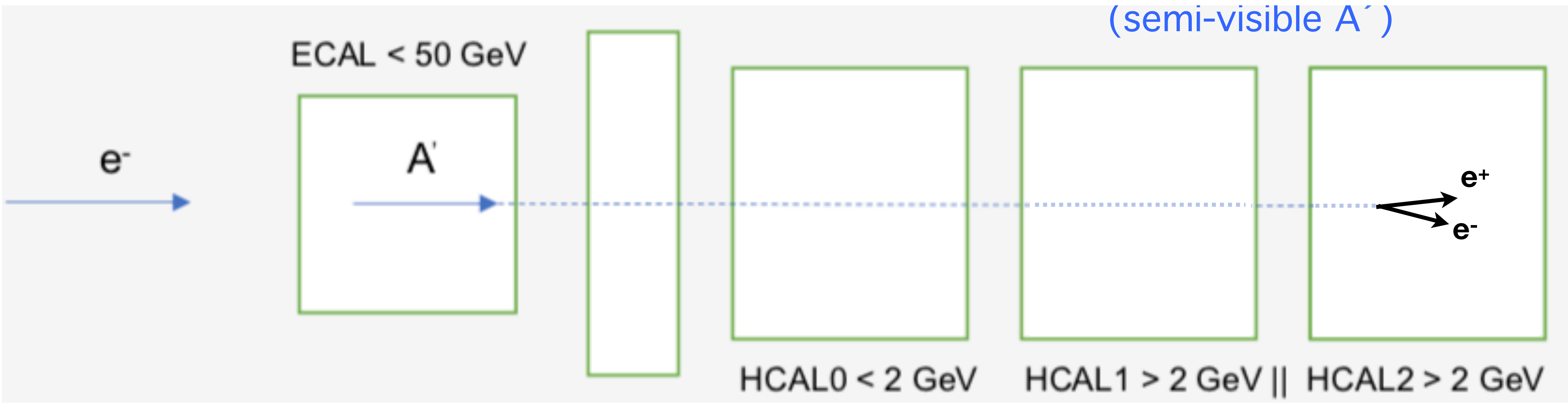
NA62 data samples

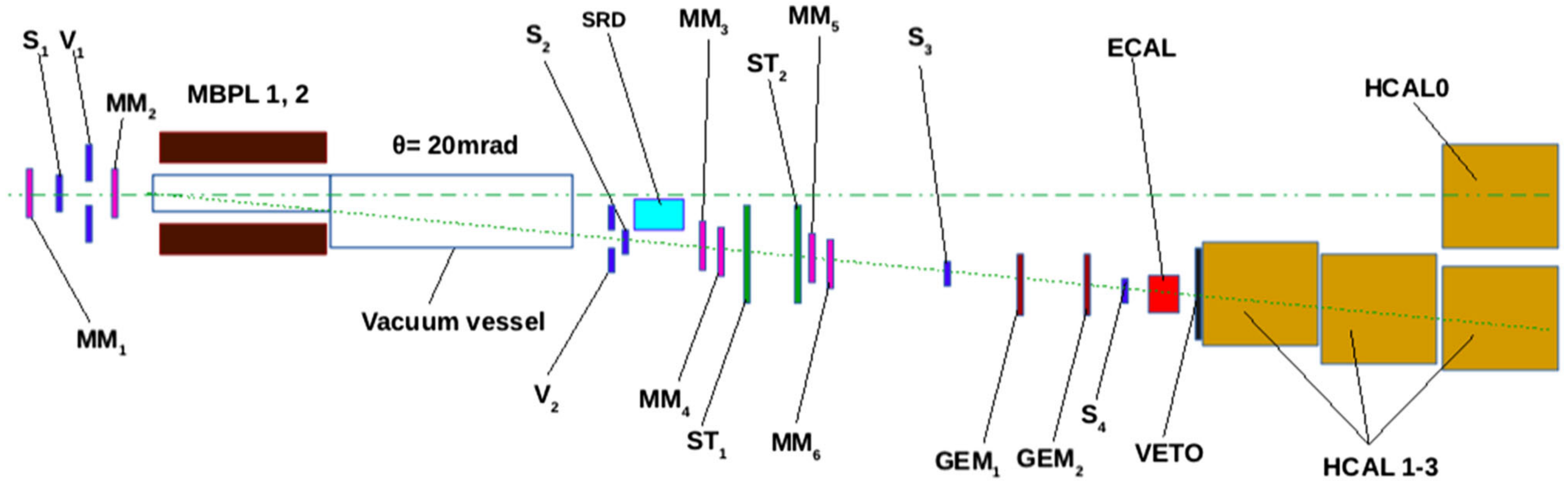


Results from 2018 data still to be released. More sophisticated data analysis techniques being investigated.

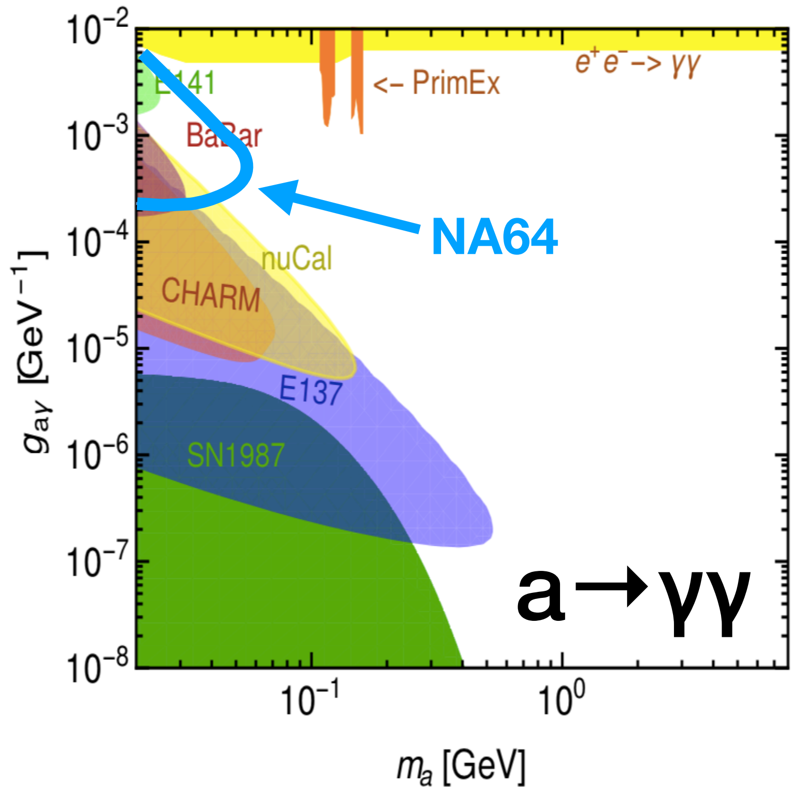
Selected Beam Dump Experiment: NA64

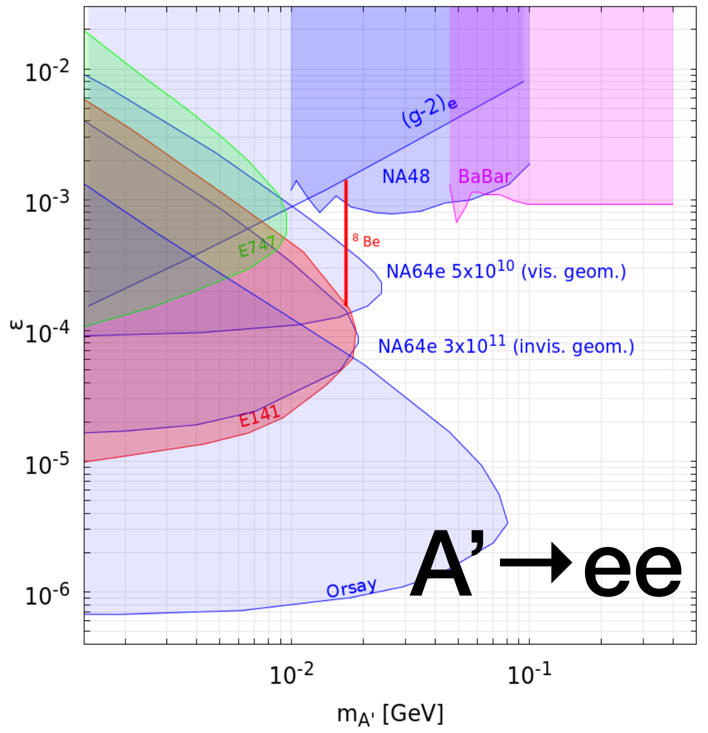
NA64 e-beam dump experiment
- active target
- search for dark photons



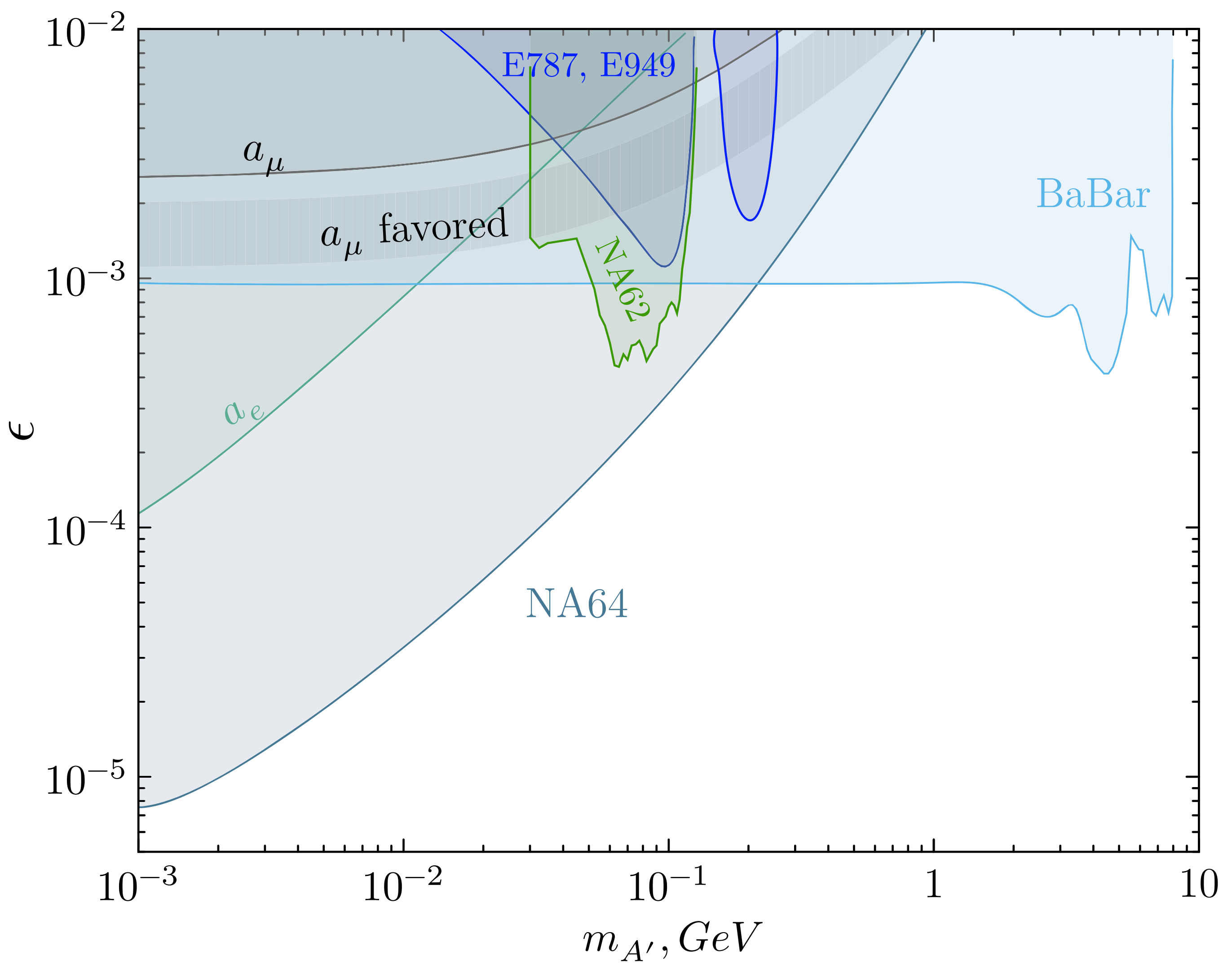


preliminary results on a→γγ and A'→ee





Complementarity to the short-lived A´-> ee search

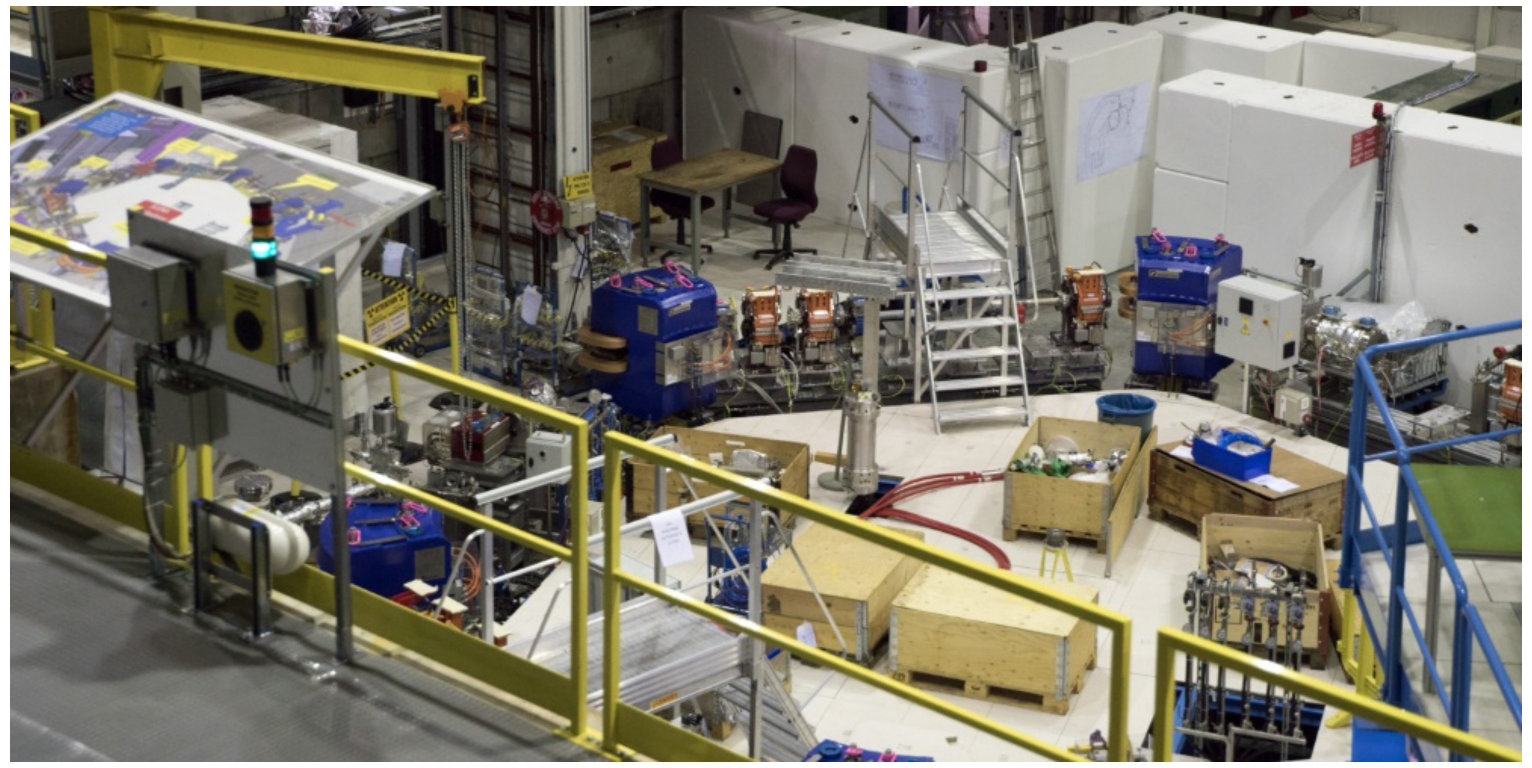


Eventually plan to run with μ to explore second generation.

AD Experiments

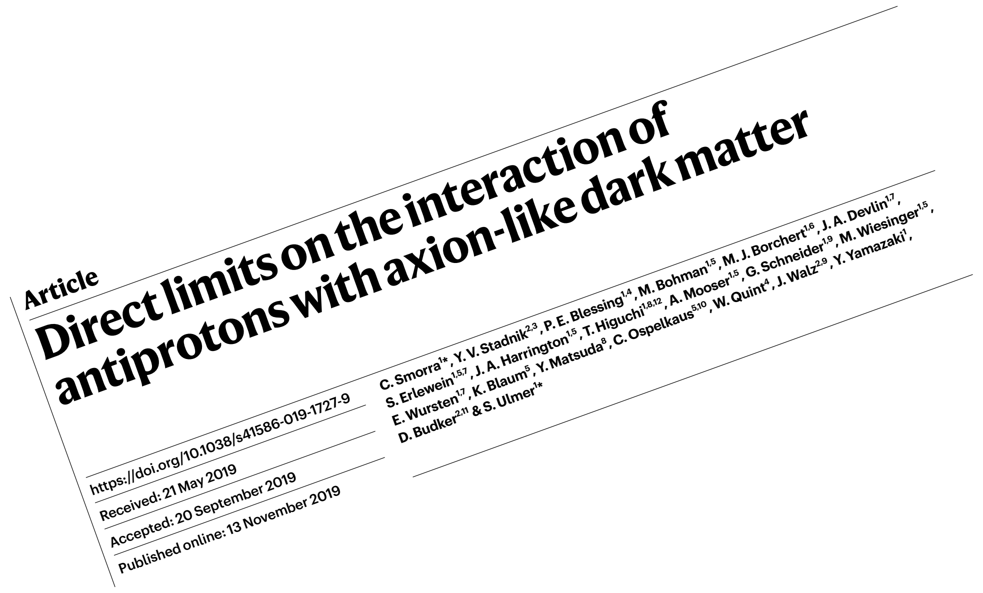
Suite of experiments
- AeGIS
- ALPHA and APHA-g
- ATRAP
- Asacusa
- Base
- GBAR

with many beautiful results on a precision comparison of matter and anti-matter.



ELENA being commissioned

Led to SPSC call for new experiments or extensions of ongoing experiments for the era of Run 3.
- including PUMA experiment


Article

Direct limits on the interaction of antiprotons with axion-like dark matter

C. Smorra[1*], Y. V. Stadnik[2,3], P. E. Blessing[1,4], M. Bohman[1,5], M. J. Borchert[1,6], J. A. Devlin[1,7], S. Erlewein[1,5,7], J. A. Harrington[1,5], T. Higuchi[1,8,12], A. Mooser[1,5], G. Schneider[1,9], M. Wiesinger[1,5], E. Wursten[1,7], K. Blaum[5], Y. Matsuda[8], C. Ospelkaus[5,10], W. Quint[4], J. Walz[2,9], Y. Yamazaki[1], D. Budker[2,11] & S. Ulmer[1*]

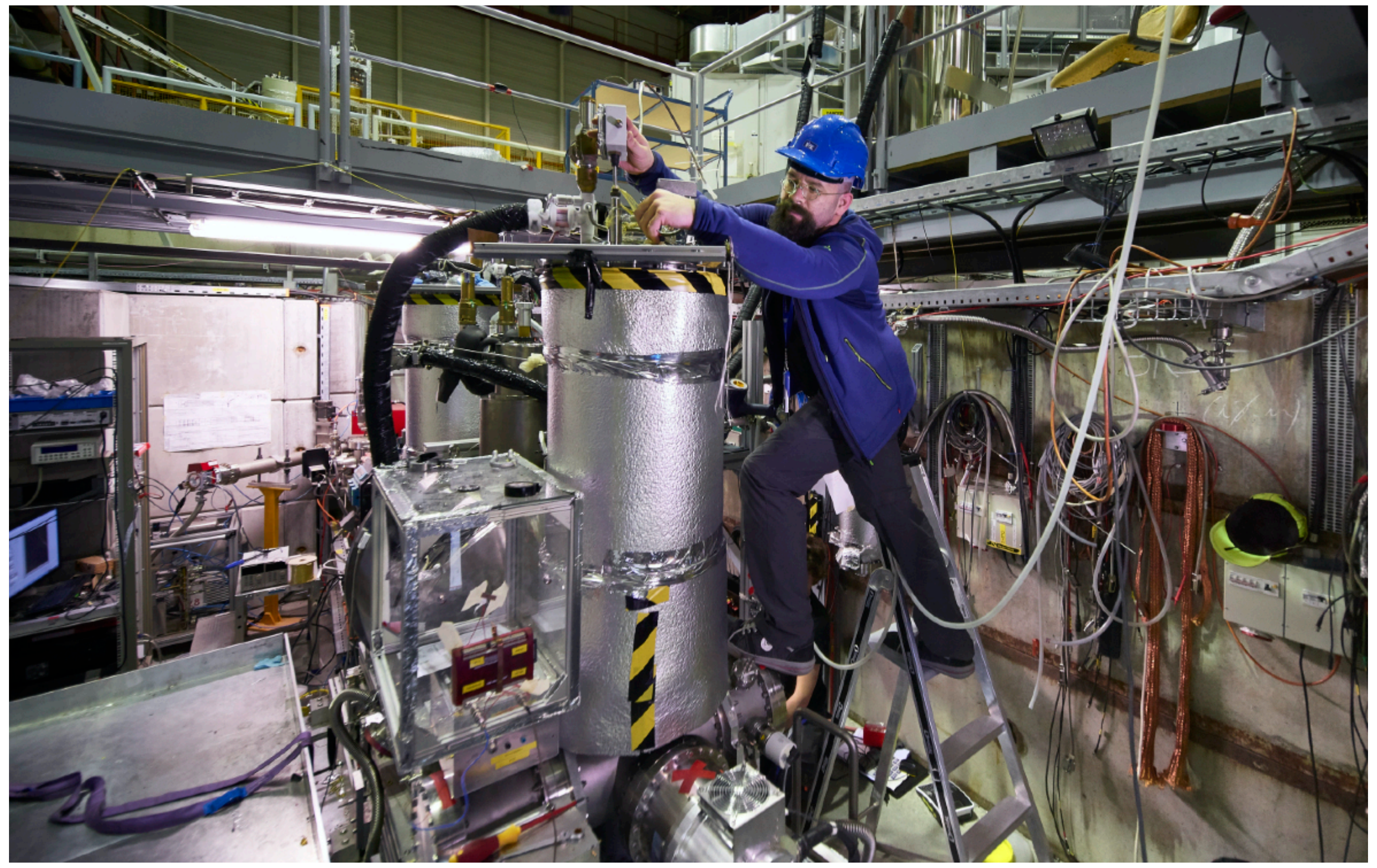
https://doi.org/10.1038/s41586-019-1727-9

Received: 21 May 2019

Accepted: 20 September 2019

Published online: 13 November 2019

Search for Dark Matter in a hypothesised interaction with anti-matter using the BASE experiment.

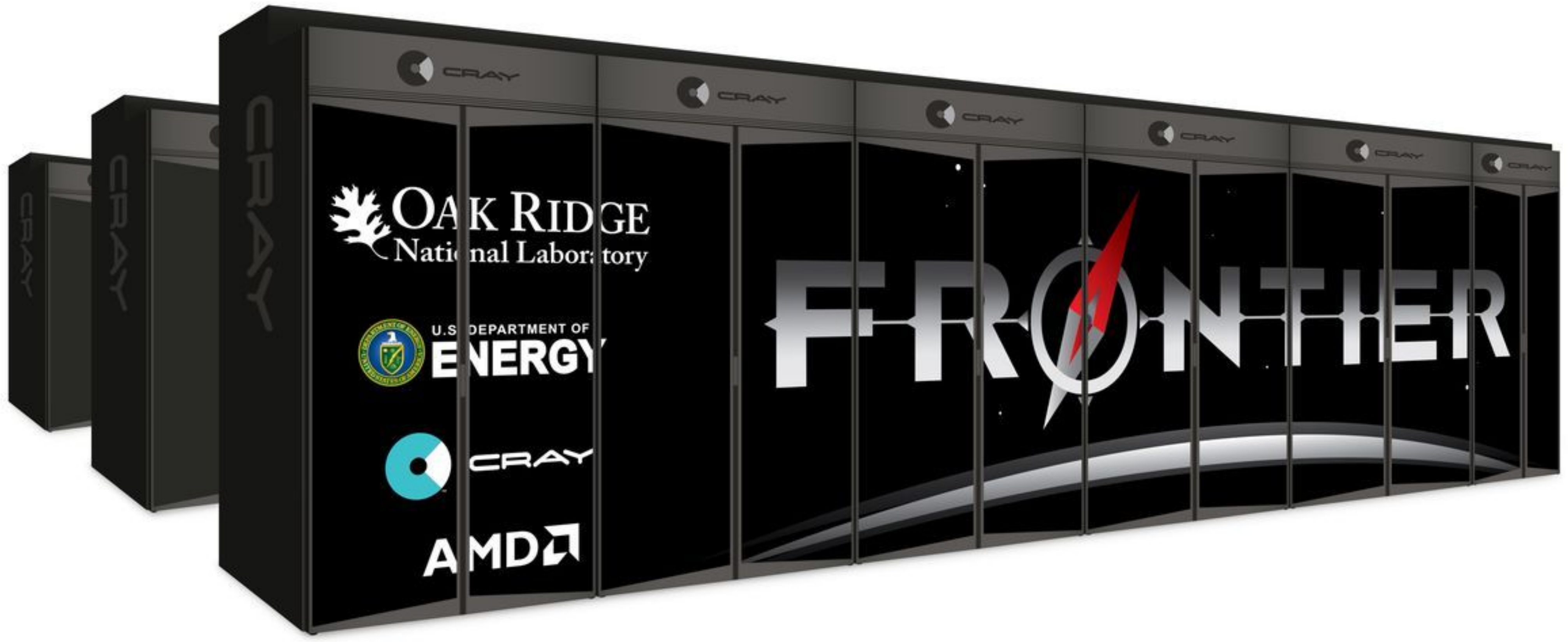


Computing

LHC Computing – towards a change of paradigm

Computing infrastructure so far has been largely based exclusively on X86 architecture using CPUs.
GPUs are gaining a lot of popularity as co-processors due to the success of Machine Learning and „Artificial Intelligence".

– ALICE will employ a GPU based Online/Offline system (O^2)
– CMS is porting part of their trigger software to run on GPU processors
– LHCb is exploring GPUs for their online data reduction
– ATLAS is developing algorithms to run on GPUs



High Performance Computers (HPC) often employ GPU architectures to achieve record breaking results (towards exa-scale).

This will require a fundamental re-write/optimisation of the LHC software

At this time largely still an exploratory approach.

How to maintain a single high-level code base?
– Vendor-based languages (CUDA,…)
– Open-source based environments (Kokkos, Alpaka, SYCL)

Conclusions

- HL-LHC will be the focus of Particles Physics for many years
- There needs to be room for new ideas
- Detectors and Instrumentation are driving progress
  - smaller, less material, integrated electronics, radiation hard
- What will be the role of quantum sensors in Particle Physics?