technische universität dortmund

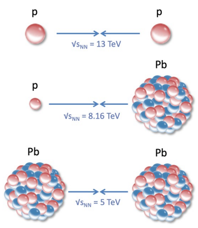
Fakultät Physik

Colliders and Cosmic Rays: Status of LHCb and astroparticle impact

SFB1491

Johannes Albrecht
SFB1491 GA, 9.11.2023

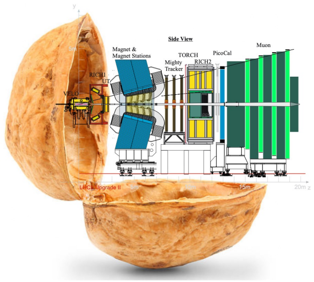
Content



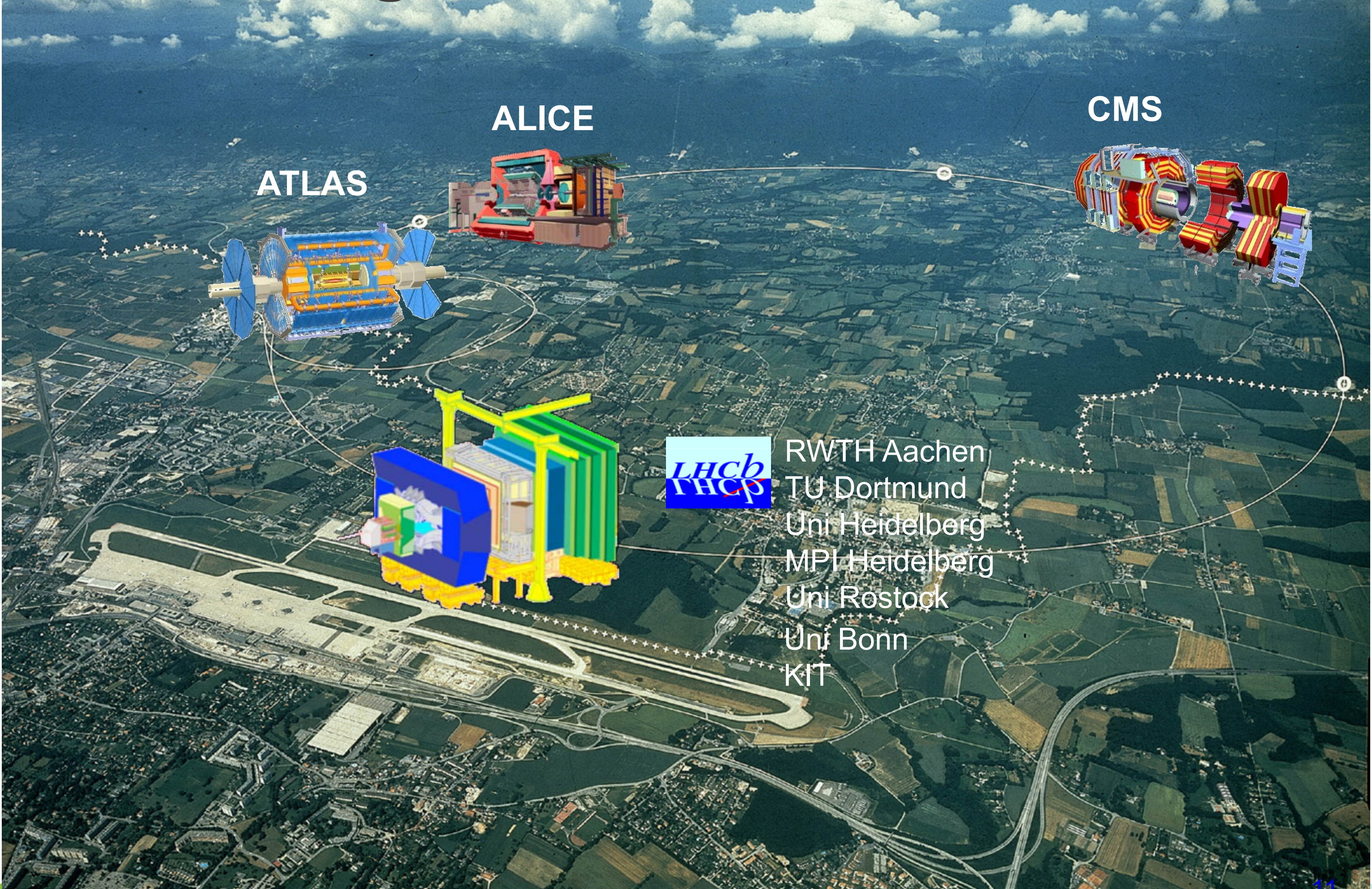
1. Introduction

2. Extend the acceptance: Forward calorimeter for LHCb?
   - Report: CIM fellow V. Aushev
   - Studies for a Forward Calorimeter

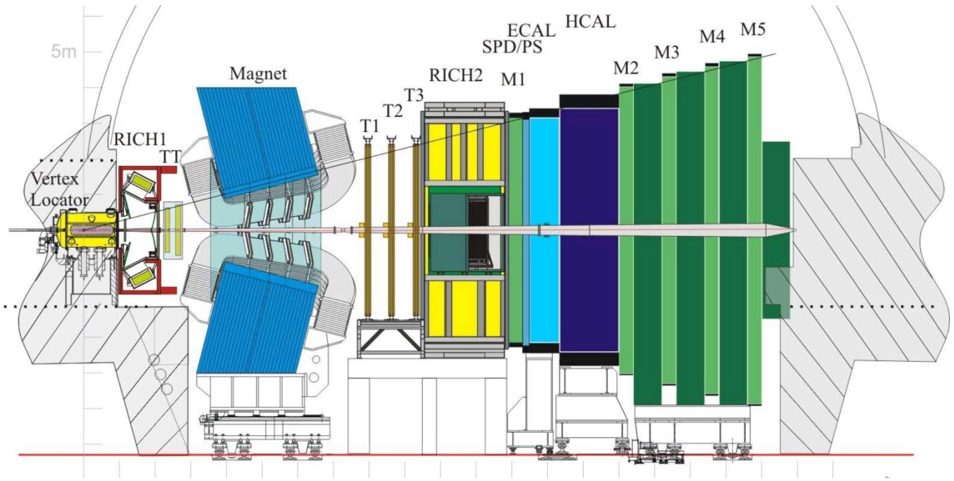
3. The upgraded LHCb experiment at the LHC
   - Triggerless trigger
   - SMOG2
   - How did we come into Run 3? Commissioning

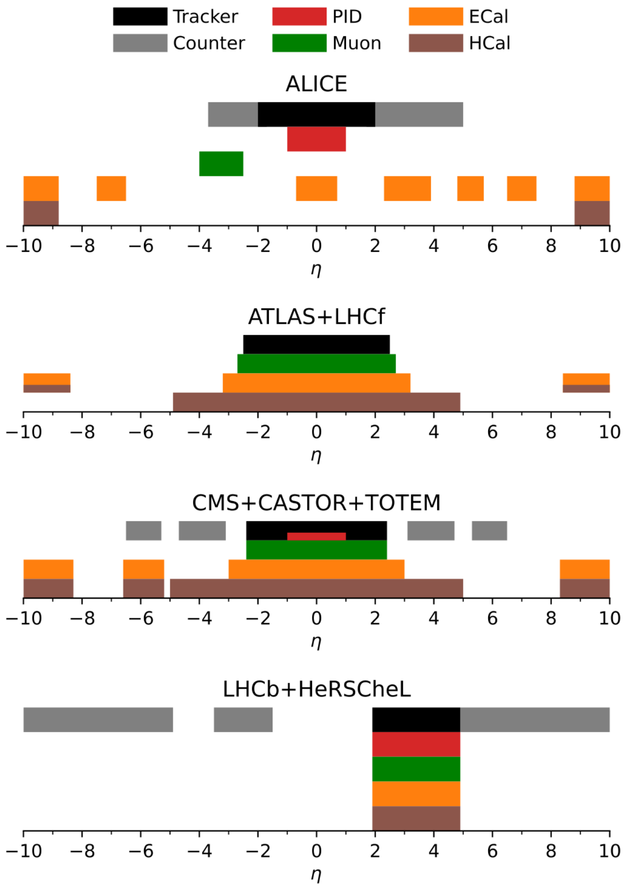


Large Hadron Collider



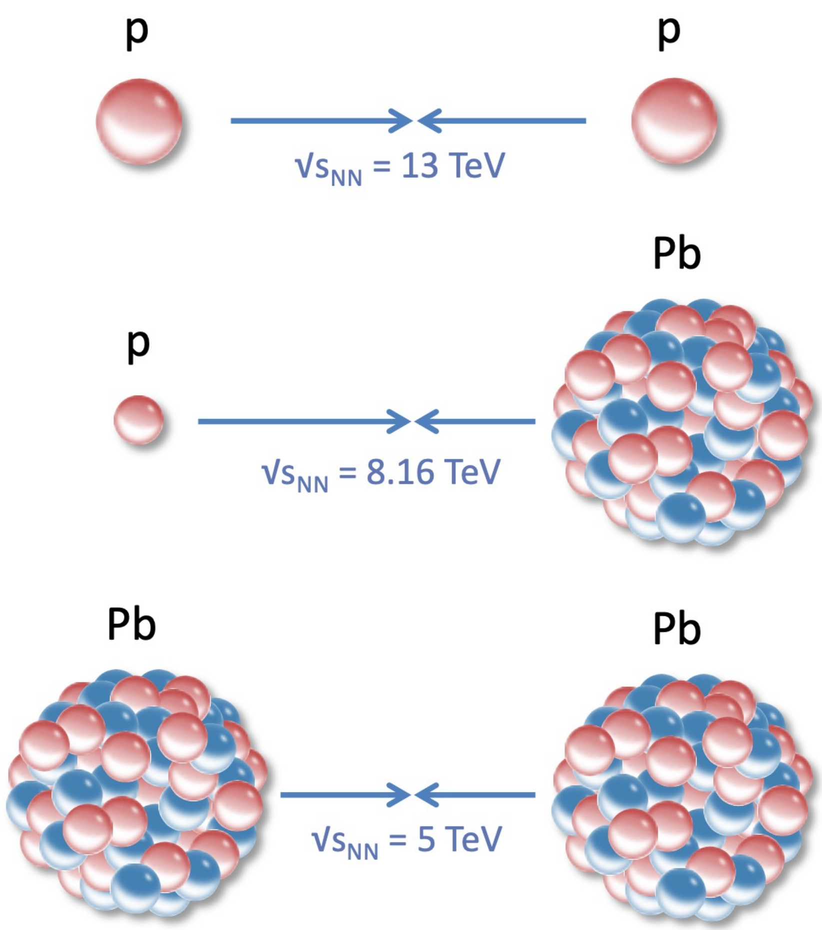
JINST 3 (2008) S08005
IJMP A 30 (2015) 1530022





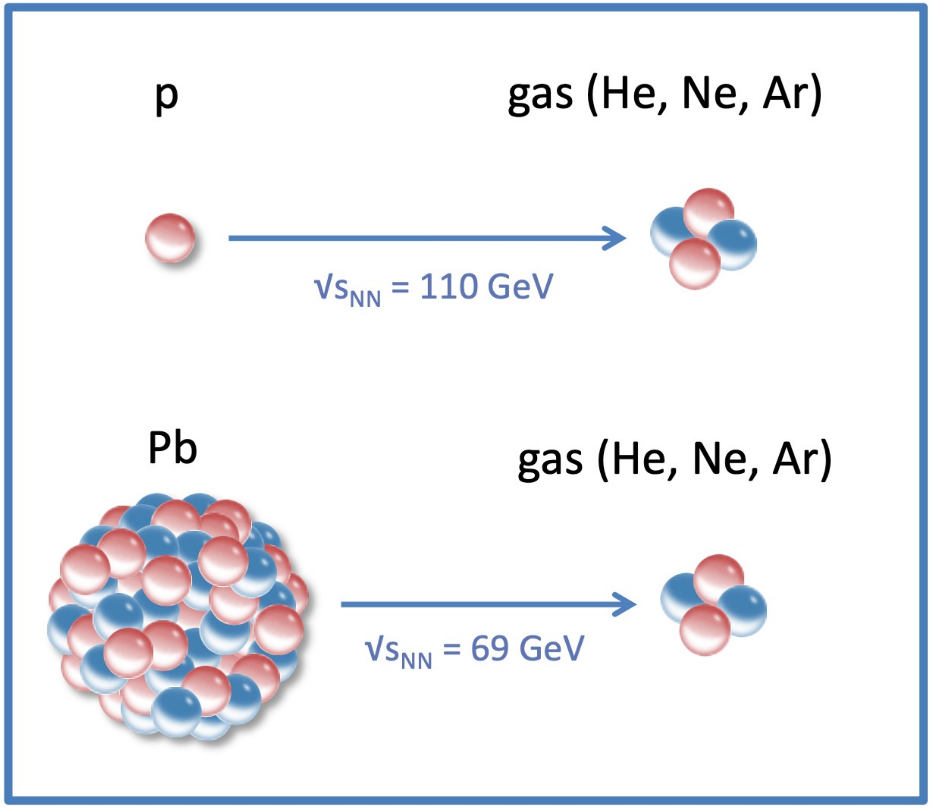
Collision systems

Slide adjusted from Hans Dembinski



Short Xe-Xe run in 2017

Fixed target: LHCb only, lower $\sqrt{s}$

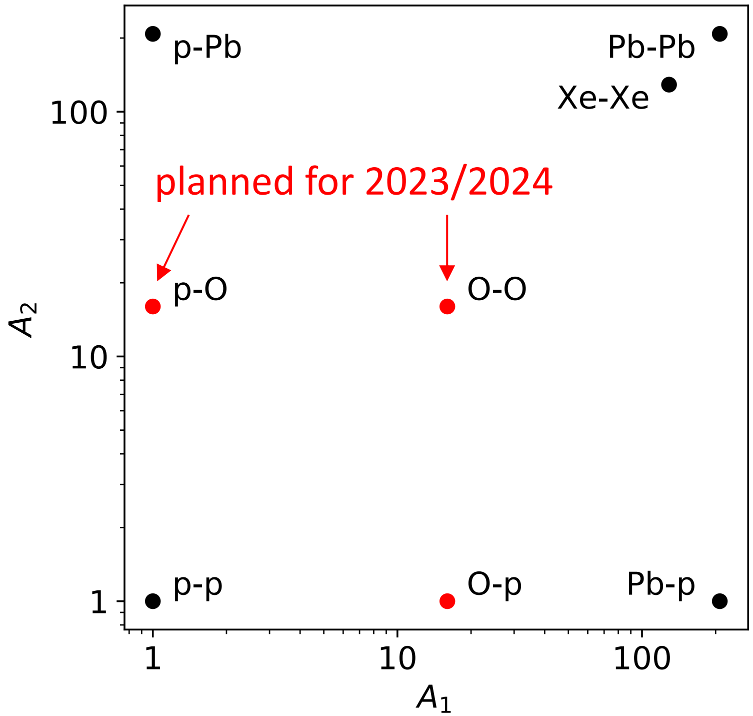


Planned: *p*-O and O-O runs in 2023

Collisions at the LHC and air showers

Slide adjusted from Hans Dembinski

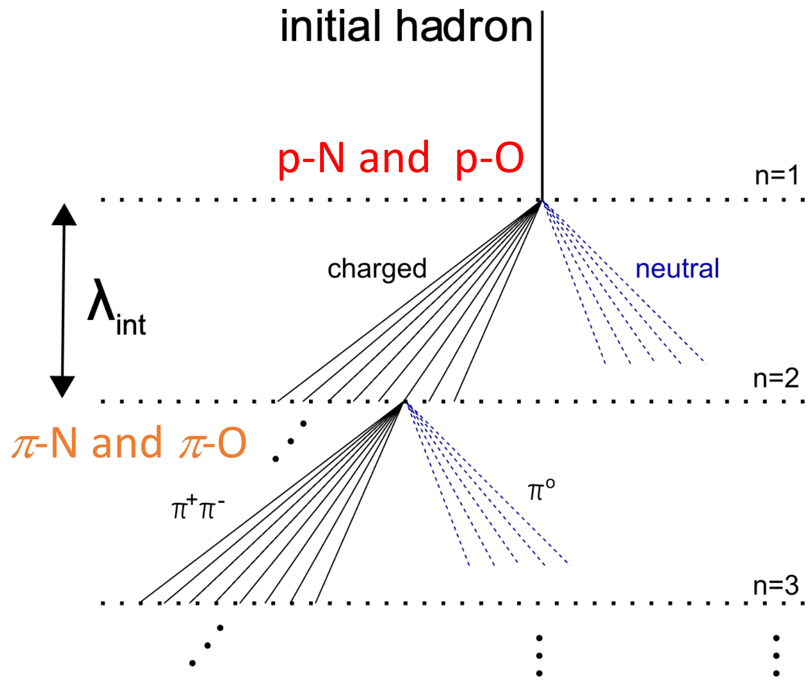
Collision systems at the LHC
Run 3: p-p @ 14 TeV, p-O @ 10 TeV



Fixed target data at sub-TeV (LHCb only)

- p+(p,...,O,N,...) @ 0.11 TeV
- Pb+(p,...,O,N,...) @ 0.07 TeV
- O+O, O+p @ 0.08 TeV (in Run 3)

Air shower collision systems



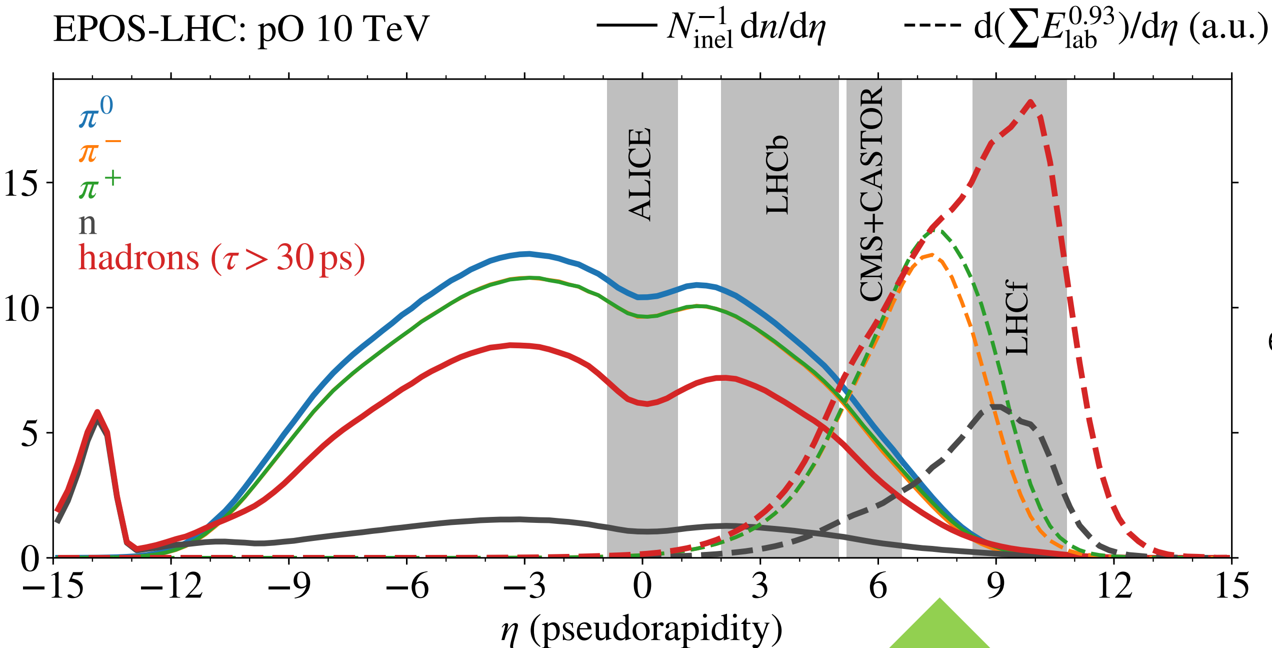
p-O collisions mimic air shower interactions

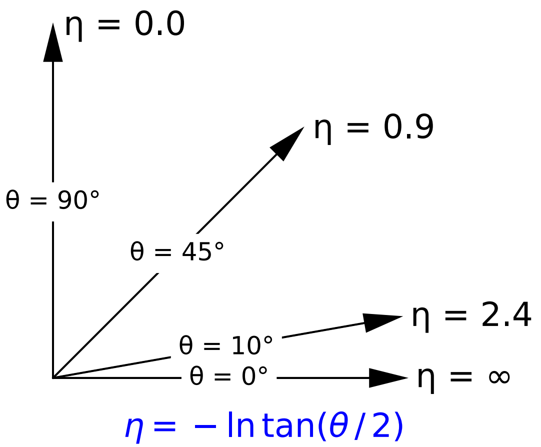
Importance of forward acceptance

Slide adjusted from Hans Dembinski

H. Dembinski, JA, et al.,
Astrophys. Space. Sci. **367**, 27 (2022)

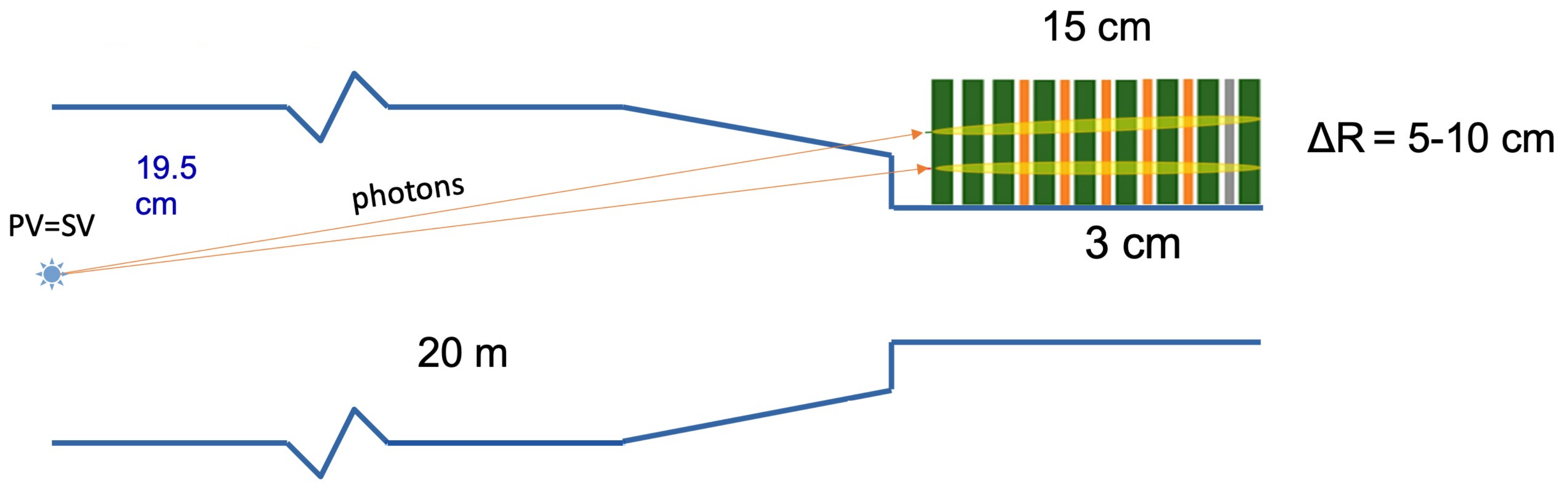
„Muon production weight“
how many muons would be produced in shower
by secondaries in this collision





Data at η=7 missing!

CIM Fellow Volodymyr Aushev: report and forward calorimeter studies



Part 2: Forward Calorimeter studies

Report V. Aushev

- CIM Fellow Volodymyr Aushev (U Kiew)
  - Prof. in Kiew (67 years), did construct detectors with Bernhard Spaans predecessor (D. Wegener)
  - Had to flee from Ukraine with his wife
  - 1. station Bern
  - 2. station CIM fellow @ TuDo
  - 3. station Japan (current)
  - Then again TuDo?

- Field of work:
  1. „Regular“ teaching and student supervision
  2. Graduate program Kiew (23-27)
  3. Forward calorimeter

Aside: „Regular teaching“

Report V. Aushev

- ***Teaching duties.*** Due to the ongoing war in Ukraine, the educational process at the university is significantly hampered. The situation has become especially difficult because of constant attacks by Russian aggressors on our infrastructure. During the autumn and winter, electricity and the Internet were cut off almost every day. Students and teachers were forced to constantly take shelter in a bomb shelter. The explosion of one of the Russian missiles shattered the glass in the windows of the Faculty of Physics and the Department of Nuclear and High Energy Physics. As a result, it was impossible to work in our offices and classrooms. Even in March the temperature there did not rise above 14 degrees. In such a difficult time, the help and support of the DFG Foundation and the Technical University of Dortmund are of particular value.

Aside: „Regular teaching“

Report V. Aushev

- In the fall semester, every week, I taught 4 courses:
  - Dark Matter
  - Application of Neutron/Photon Beam Technology
  - Heavy Flavour Physics
  - Neutrino Physics
- In the spring semester, every week, I now teach 4 courses
  - Astroparticle physics
  - High Energy Physics
  - Modern Experiments
  - B-physics

In parts, lectures duplicated

- At the same time, I supervise the Master/Bachelor theses of 3 students I also teach several 3rd year students to conduct data analysis based on Monte-Carlo simulations for the LHCb collaboration, which are made as part of my research at TU Dortmund.

Aside: Educational Program: V. Aushev

Department of Nuclear and High Energy Physics of the Taras Shevchenko National University of Kyiv, the leading educational institution that trains young specialists in the field of high energy physics for research institutes of the National Academy of Sciences of Ukraine.

Our graduates took part in collider experiments at LHC, Tevatron, HERA, KEKB, in neutrino physics and other experiments in HEP. Training of young scientists is carried out within the framework of the educational program "High Energy Physics". This program is usually valid for 5 years. The preparation and approval of the new 5-year program for 2023-2027 took place in the autumn and winter of 2022/23 during my stay at TU Dortmund. I am in charge of this program, the main responsible person at the university (the so-called "Guarantor of the education program"). More than a dozen professors and associate professors are involved in the program. Preparation includes more than 75 items that need to be described in the program (for example, the purpose of the program, the rules for accepting students to study, interaction with stakeholders, student government, anti-plagiarism, etc.).

The program approval procedure takes many months and involves close interaction with the top management of the university and the National Agency for Quality Assurance in Higher Education of Ukraine. … I was directly involved in the organization of most of these events.

Aside: Educational Program

I am pleased to announce that the new program has been developed and successfully approved in January 2023.

This program is stored in the Ukrainian Unified State Electronic Database on Education:

Educational program ID: 2052

Title: "High energy physics".

Area of knowledge: Natural sciences.

Specialty: Physics and Astronomy.

Level of higher education: Master.

So that for the next 5 years our university has an approved program for the training of young scientists in high energy physics and guaranteed jobs for all our teachers.

→ Thanks to CIM Fellowship by SFB1491

Hans Dembinski, Volodymyr Aushev, Dirk Wiedner

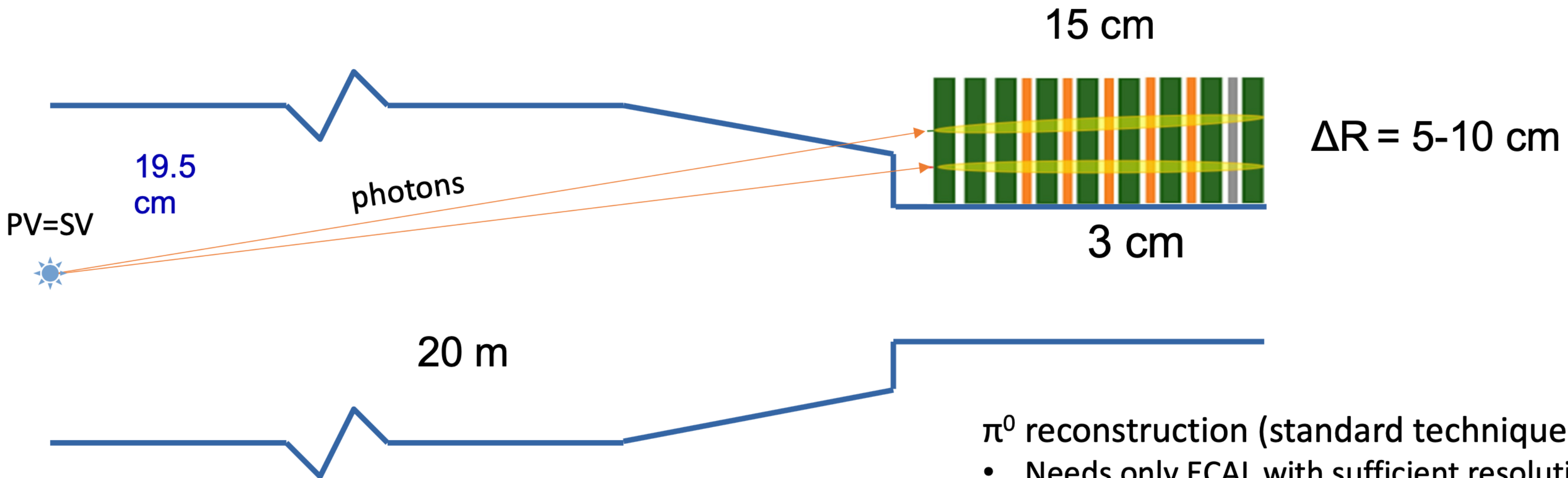
Conditions for experiment

$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

- Measure R at η = 7
- Use ECAL to measure E_{π^0}
- Use HCAL + ECAL to measure E_{total}, then $E_{other\ hadrons} = E_{total} - E_{\pi^0}$
- (Non)Requirements
  - Negligible luminosity: acquired in a few days even with large pre-scale
  - No* material between PV and detector
  - No magnetic field required
  - Average measurement over many events sufficient
    - Energy resolution not important, but good calibration
    - ECAL energy resolution must be sufficient to identify π^0 mass peak
    - Classify events by number of charged tracks: measure in coincidence with LHCb
  - Small coverage in η sufficient, small cross-sectional area possible
  - Full* p_T coverage, especially $p_T < 1$ GeV/c (non-perturbative regime)
  - Radiation hardness: movable detector?
  - Radial symmetry: need to cover only ϕ-slice

*can be relaxed somewhat

Design Sketch



π^0 reconstruction (standard technique)

- Needs only ECAL with sufficient resolution
- π^0 decays immediately, PV = SV
- Get $\vec{p}$ of each photon from impact point and energy deposit → mass(π^0)

W absorber

- 9.3 mm Moliere radius
- 30 layers (3-4 mm, $1X_0$ each)

Active layers

- low granularity layers with 1x1 cm^2 pads
- 2 high granularity layers with 30x30μm^2 pixels

Possible active materials

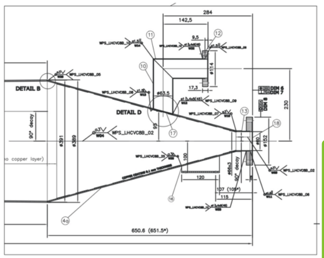
Silicon, fibers (quartz)?

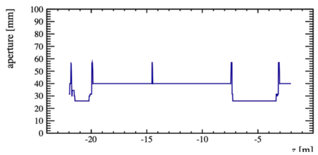
Reduce radiation dose

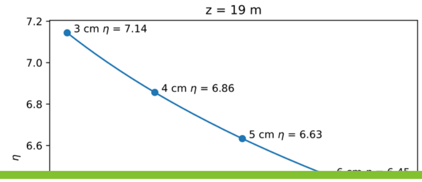
Movable? static?

More detailed studies

η coverage

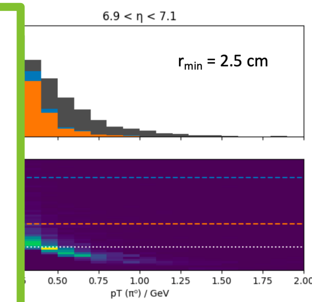






Minimum lateral extension and spatial resolution

- Top: distribution of π^0 after cutting on minimum and maximum lateral photon distance
- Bottom: 2D plot of lateral photon distance vs. p_T of π^0
- Need r_{min} < 1 cm r_{max} > 5 cm, r_{max} = 10 cm preferred
- FOCAL design demonstrated that r_{min} < 5 mm is possible **OK**



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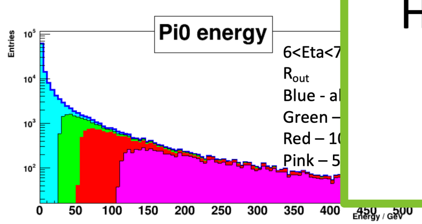
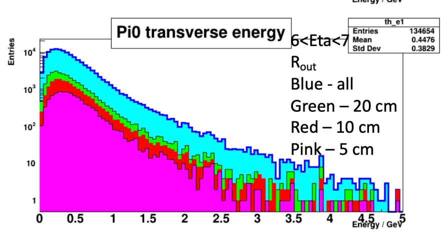
Cost estimates

ECAL	Mechanics	300-500 k€
	Sensors	300-800 k€
	Electronics	~200 k€
	Power supplies and DAQ	~200 k€
	Total	**1-1.7 M€**
HCAL	**Total**	~ **0.5 M€ (?)**

Depends on size and materials (both active and passive)

Lateral an…





- Cheaper
- Larger lateral size
  - Access to lower energies, p_T
  - Study η-dependence
- Length
  - ECAL 15-20 cm
  - HCAL 1-2 m

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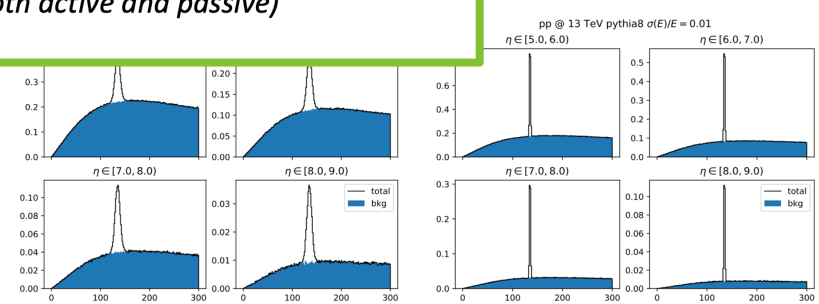
…olution and mass peak



Expected for FOCAL-like ECAL: **σ(E) / E < 2 %** for E > 200 MeV

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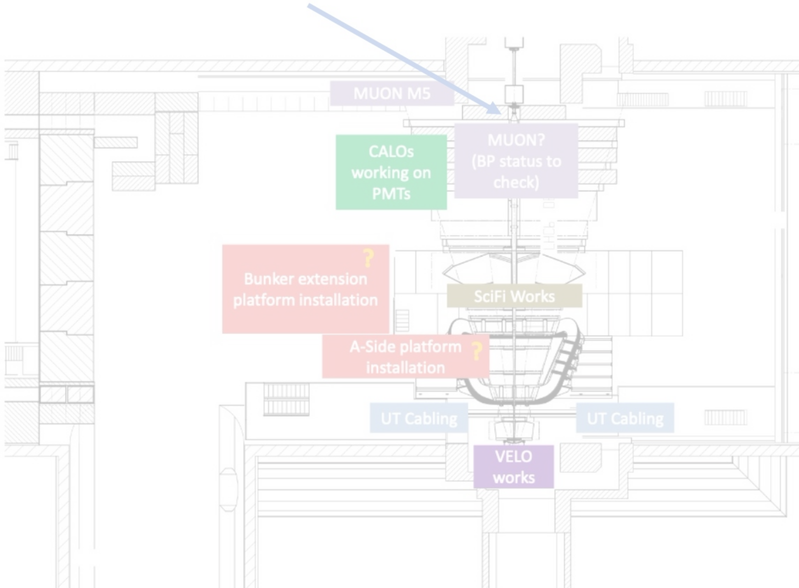
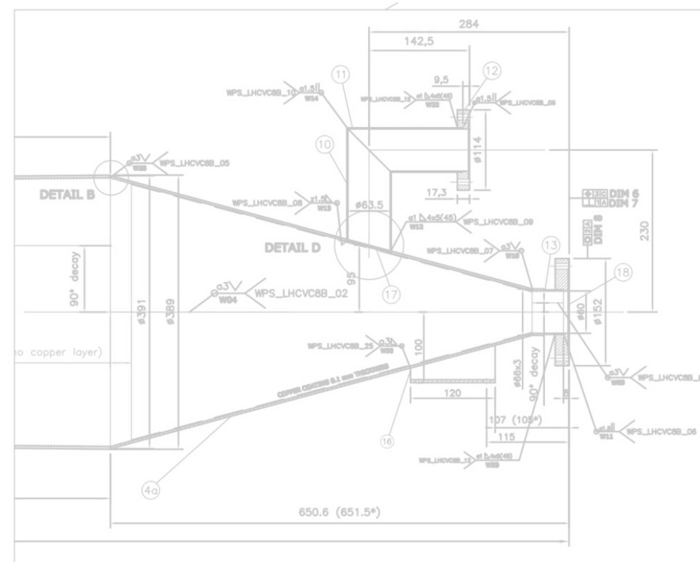
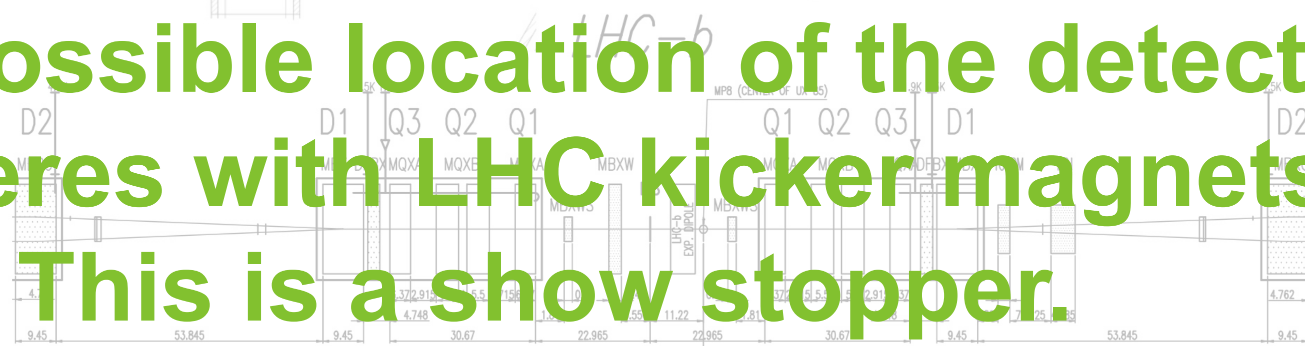
Favorable detector location

19 m downstream of IP, r = 3 cm





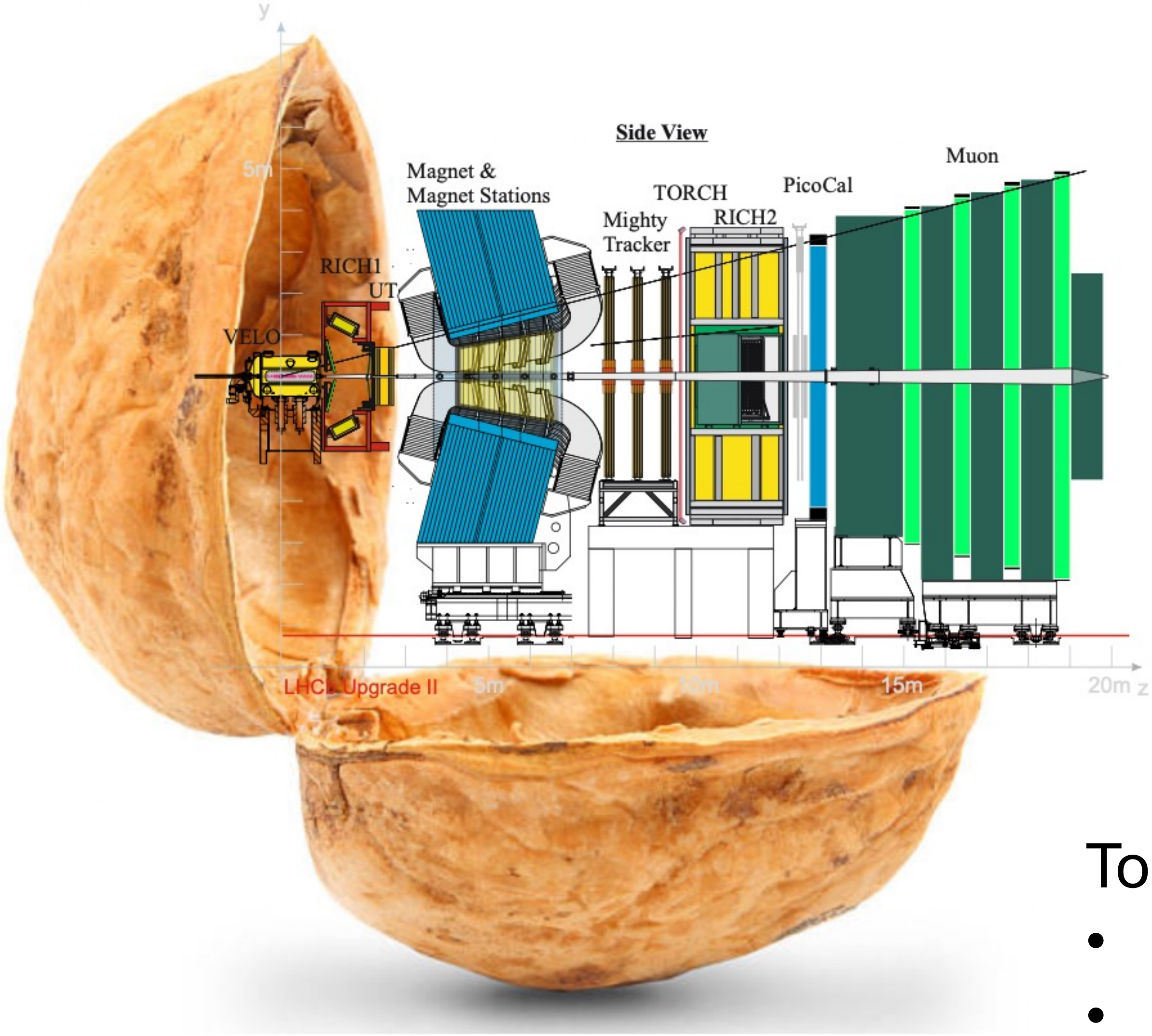


Only possible location of the detector interferes with LHC kicker magnets.

This is a show stopper.

Unfortunately.

Part 3: LHCb physics in a nutshell



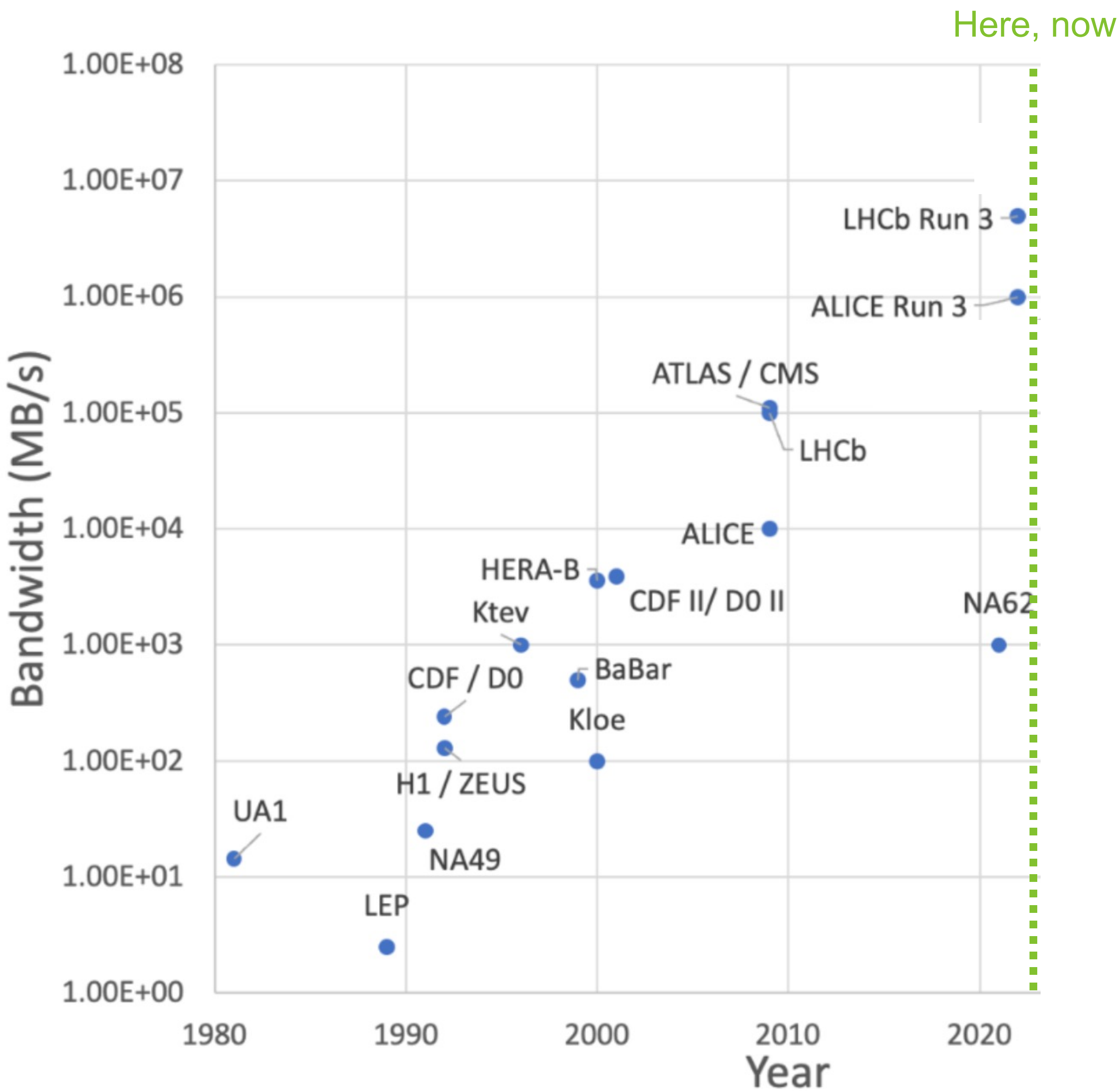
Topics:

- Triggerless trigger
- SMOG2
- Commissioning

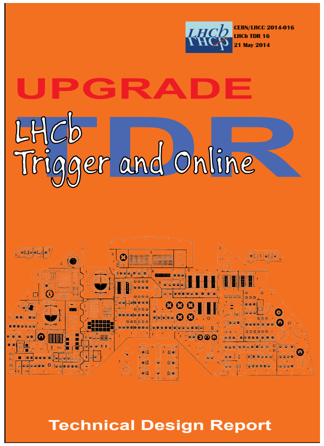
LHC program planned beyond 2040

- LHCb upgrade I: from 2022
  - Pure software trigger
    → novelty for hadron colliders
  - Instantaneous Luminosity: 2 x 10^{33} $cm^{-2}s^{-1}$
    → requires new design of most sub-detectors

Data processing



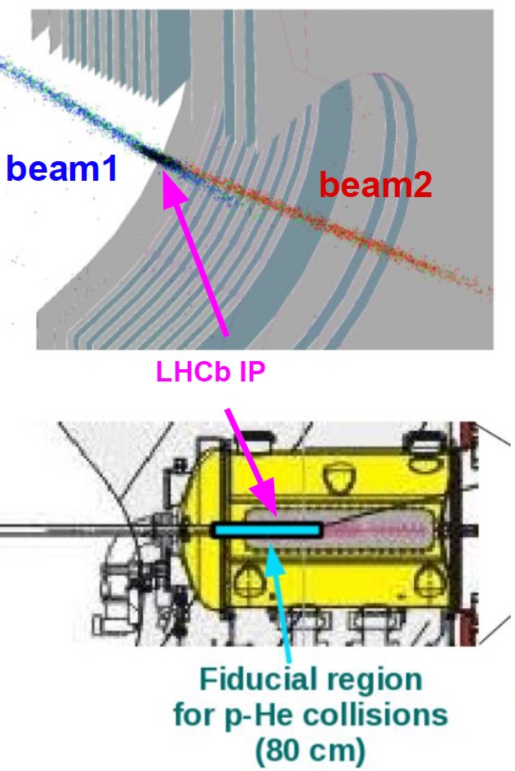
LHCb upgrade



- Trigger-Challenge – Signal-Challenge
  - ~600kHz of b-hadrons, ~8MHz of c-hadrons
  - → Main task of **triggers: Signal classification**
- **First time at hadron collider:**
  - Trigger-less readout and full event reconstruction at 30MHz
  - → Maximally flexible and efficient trigger system
- Paradigm shift in HEP triggering to **real time analysis**
  - Crucial step: Event processing and reconstruction in real time
- This new system allows many new avenues to be explored, especially for hadronic signatures that matter for SFB1491

SMOG

JINST 9, (2014) P12005

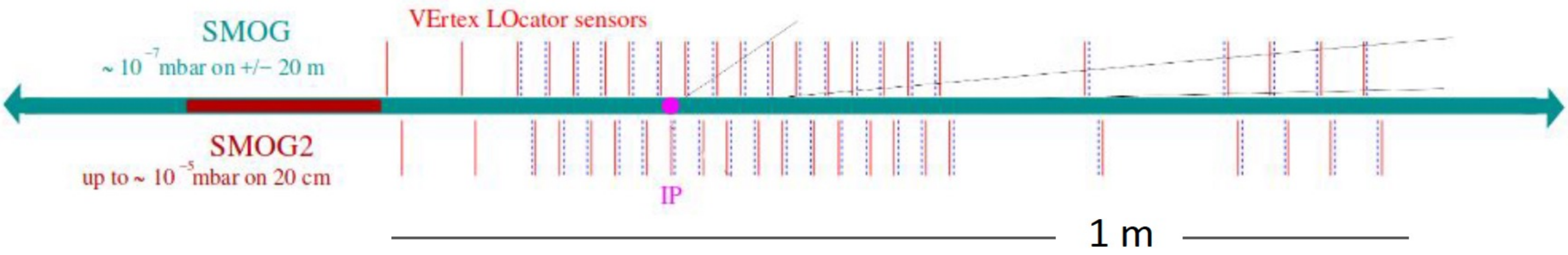


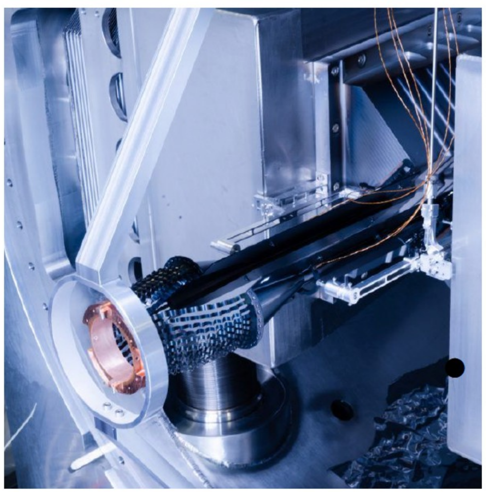
- Cross-section measurements require to precisely know the **luminosity** $\mathcal{L}$ of the LHC accelerator ($dN/dt = \mathcal{L} \cdot \sigma$)
- From 2011, also measured with the LHCb **System for Measuring Overlap with Gas (SMOG)**
  - Proton collisions with the small quantity of injected gas (10^{-7} mbar) used to reconstruct the **transverse profiles of the LHC beams**

- In proximity of the LHCb IP, **the proton-nucleus interaction can be fully reconstructed**!

- Forward detector + gas target = **highest-energy fixed-target ever!**

SMOG2

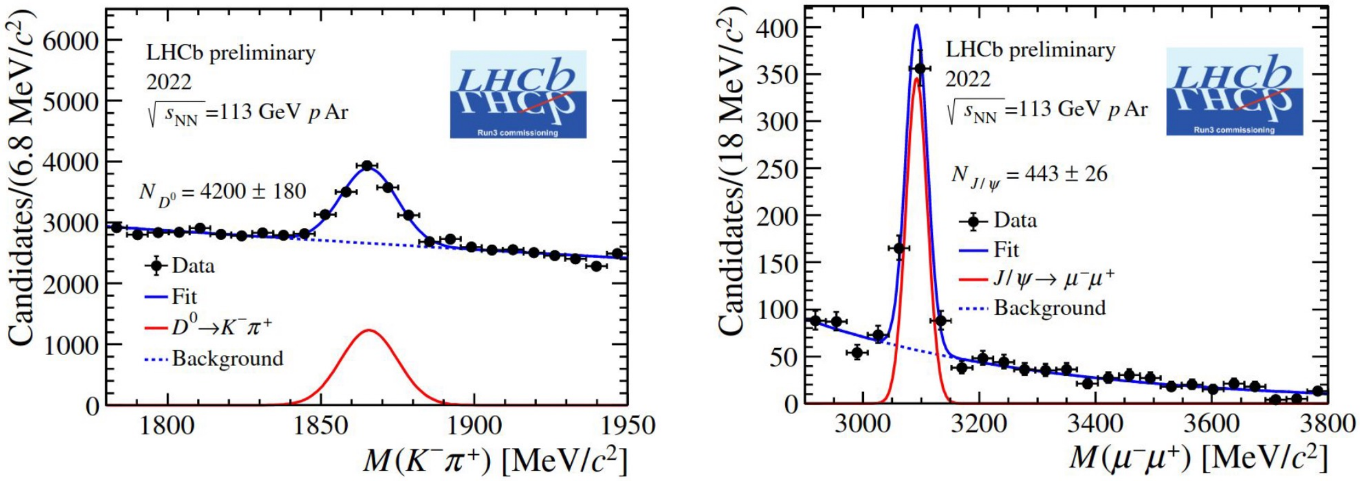




- **SMOG2:** **confinement of the gas in a cell made up of two movable halves upstream of the LHCb IP** (z ϵ [-541, -341] mm)
  - Up to x100 gas **pressure wrt SMOG for the same gas flow**
  - **Heavy noble (Kr, Xe) and non-noble gases (H_2, D_2, O_2, N_2 ...)** can be injected → **extension of the physics programme**!
- **New Gas Feed System**
  - Precise gas flow control → **direct luminosity measurement**
  - More gas recipients → **full switch with no intervention**

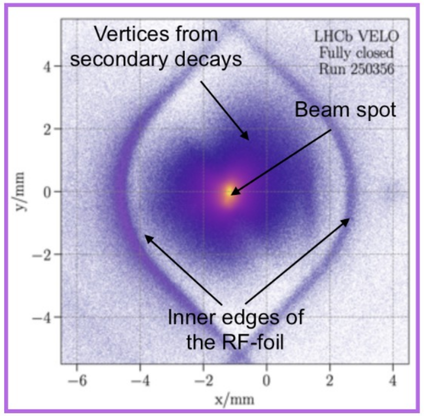
Physics with SMOG2

LHCb-FIGURE-2023-008



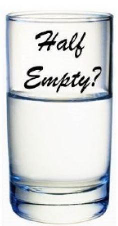
- SMOG 2 benefits:
  - Much larger samples
  - wider injectable gas choice
  - direct lumi measurement
- Extension of the programme of cosmic rays interest: production processes with H2, D2, He, probes for the study of the atmospheric showers with N2, O2; nuclei production
  LHCb-PUB-2018-015

Run 3 commissioning (issues)



- On 10th January 2023 a **failure of the LHC vacuum system** of the VELO happened, leading to a plastic deformation of the RF foils (aluminium foils separating the machine from the detector vacua)

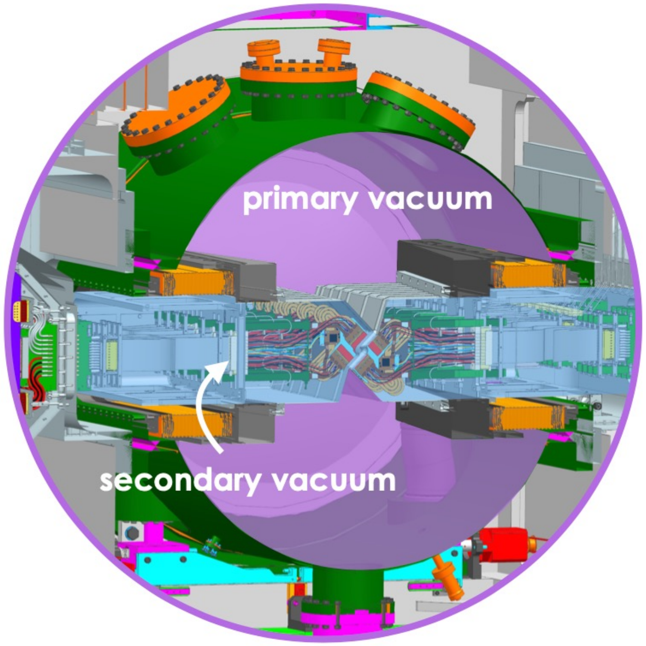
- VELO detectors and motion system seems not to be affected by the incident
- Tracking efficiency, hit resolution still as the design ones



- RF foils replacement could only be possible in 2023/2024 YETS
- VELO (and alas, SMOG2 cell) will have to be partially closed, **significantly impacting the physics programme this year**

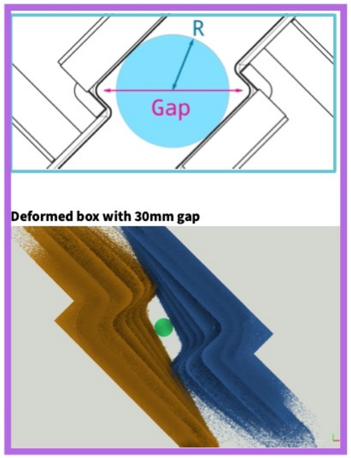
Still, 2023 can be relevant for fixed-target physics and lots of possibilities remain

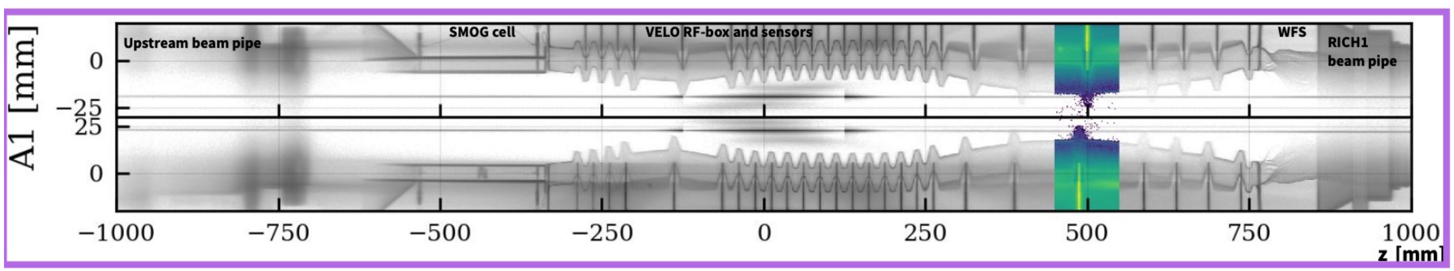
Vacuum incident



- LHC vacuum incident in the VELO volume led to over pressurisation of the detector volume and deformation of the RF foil
- leading factors to velo position in 2023:
  - deformation of the foil allowing for max 30 mm gap
  - damaged coupling piece in the motion system
- decided not to move the VELO halves at every fill, but keep them fixed to the smallest aperture that allows beam injection
- RF foil replacement foreseen in the YETS

VELO 2023 gap = 49 mm GAP





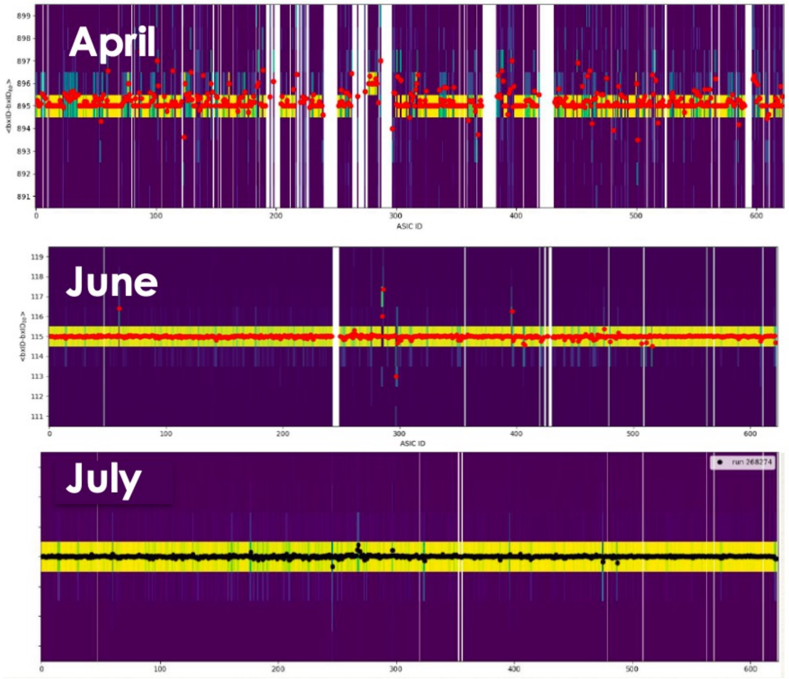
Use the spare time: understand detectors: Velo

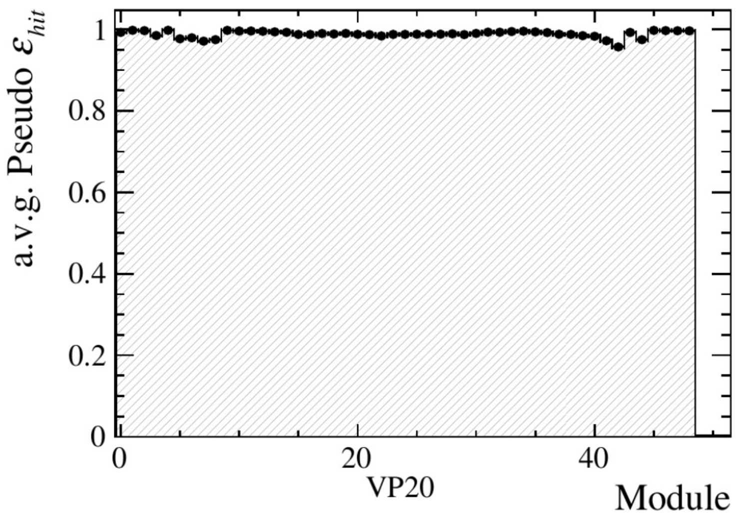
- efficiency improvements: from 90% in 2022 to now 99.6% efficiency in terms of data links
- calibration:
  - robust and fast procedure to check/update time alignment
  - improved pixel equalisation procedure
- better automated mechanisms for DAQ configuration and control

Main challenges ahead:

- replacement of the RF foil
- re-commissioning
- DAQ stability in nominal conditions

Time alignment improvements

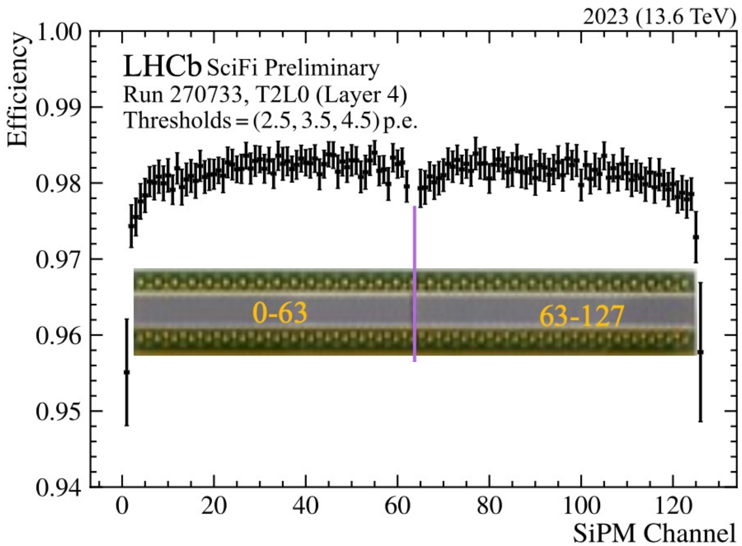




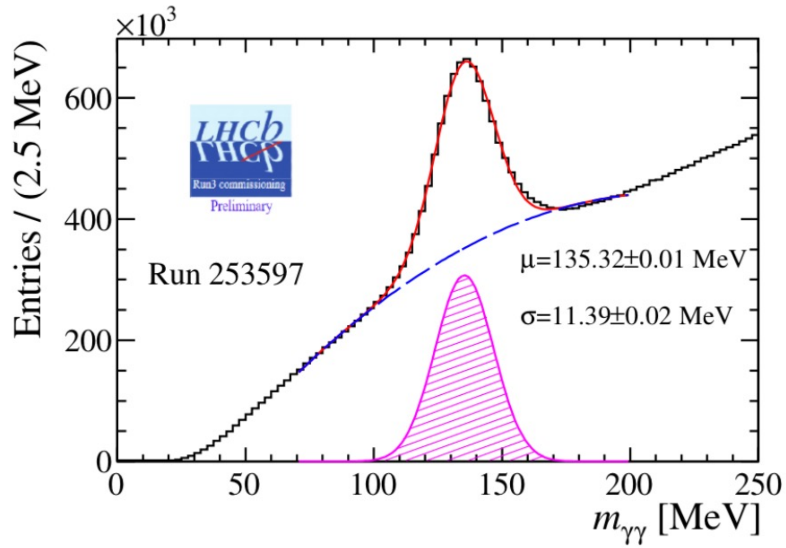
Understanding of VELO behaviour greatly improved in 2023!

Use the spare time: understand detectors

SciFi

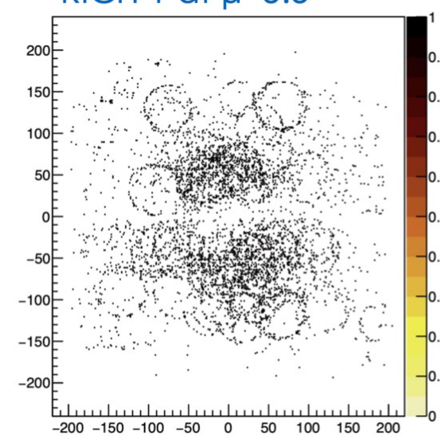


ECAL calibration with π^0

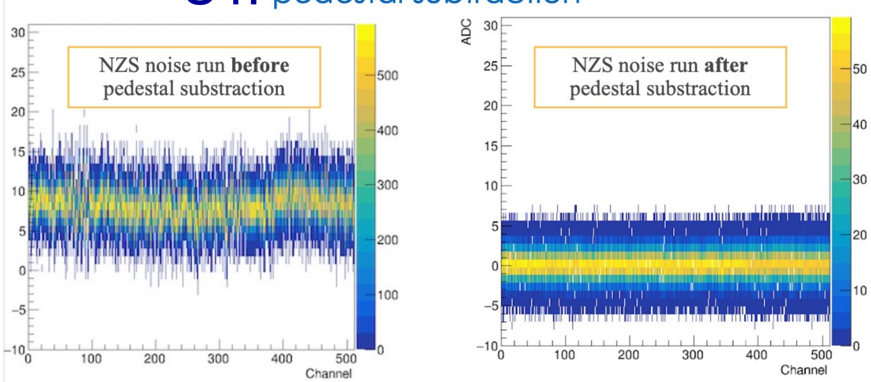


- hit efficiency for single SiPM ~98%
  - close to the design goal of 99%

RICH 1 at μ=5.5

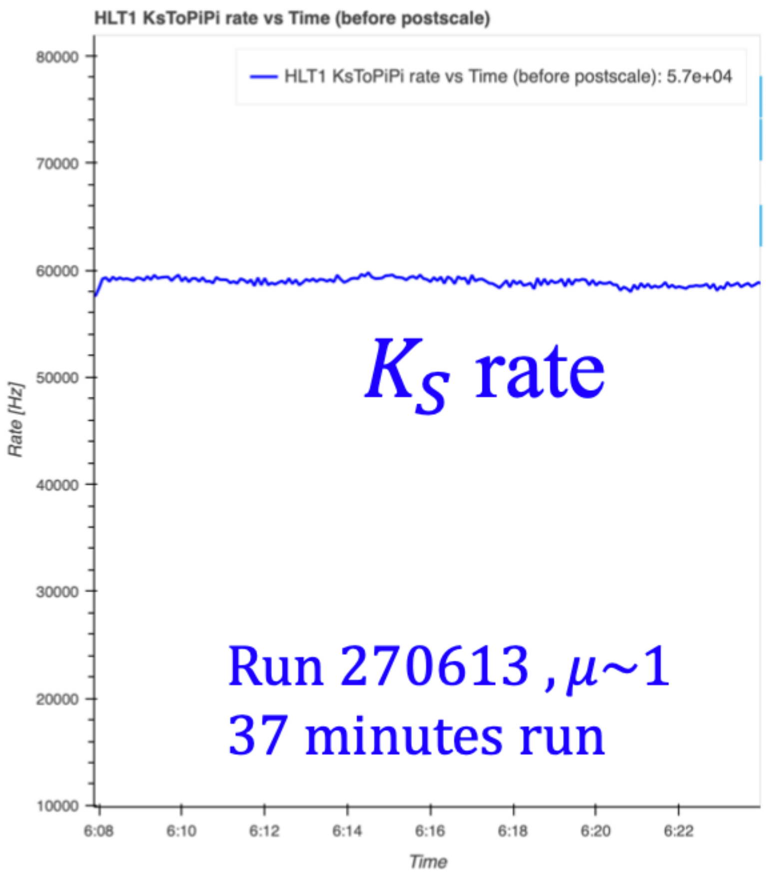


UT: pedestal subtraction

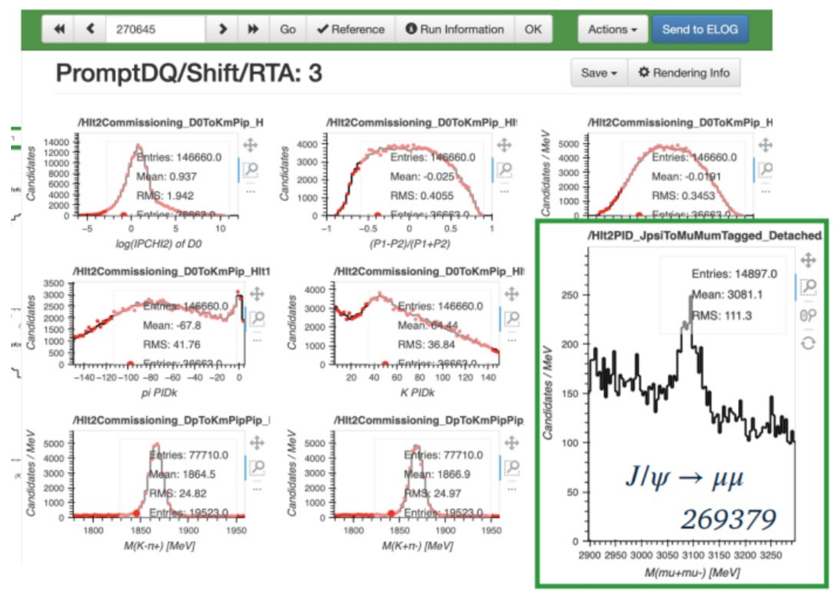


- Versatile low level software trigger with ~35 MHz input rate

online monitoring

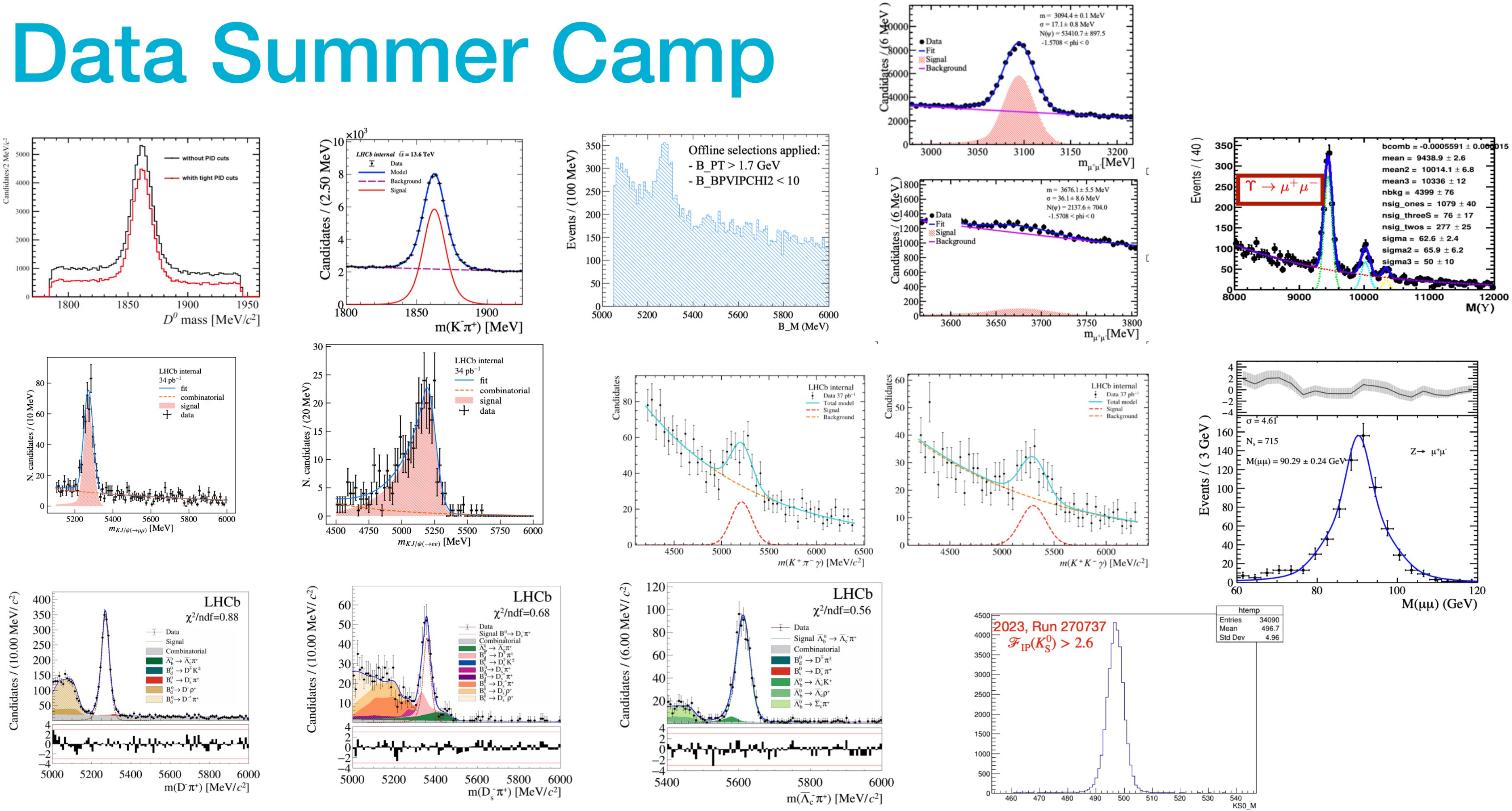


- Next step to do is commissioning with high rates / intensities → 2024



Still quite clean data recorded

Data Summer Camp



LHCb‘s Run 3 detector works, now we need to utilize it to understand nature and especially cosmic rays!

Latest news on LHC schedule

V. Vagnoni, LHCb SP, 7.11.2023

LHCb feedback on 2024/2025 scenario

pp

- Priority: collect 7 fb^{-1} pp data

Heavy ions

- Oxygen: Strong interest in 2024
  - Baseline request: →
  - Encourage studies to optimize luminosity at IP8 (to fully profit from new detector)
  - Welcome ~few more days of oxygen running (p in beam-1, O in beam-2)
- pp reference run in 2024
  - Request >> 25 pb^{-1} of pp-reference run with E_b=2.68 TeV
    - With VELO closed
    - No objection to 5 days
- Pb: preference to concentrate running in 2025
  - Prioritize Pb-Pb over p-Pb
  - Appreciate studies to optimize luminosity at IP8 (β^*, crossing angle, filling scheme)
    - 2023: acceptable (open VELO, UT in commissioning)
  - Share between PbPb and p-Pb and Pb-p data taking to be discussed

SMOG data can be collected parasitically

https://arxiv.org/abs/1812.06772

- **O–O at $\sqrt{s_{NN}} = 7$ TeV**, $L_{int} = 500\ \mu b^{-1}$ (ALICE, ATLAS, CMS, LHCb)
- **p–O at $\sqrt{s_{NN}} = 9.9$ TeV**, $L_{int} = 200\ \mu b^{-1}$ (ALICE, ATLAS, CMS, LHCb)

R.Bruce, Chamonix 2023

Filling scheme	n.o. bunches	n.o. collisions at IP1/5	IP2	IP8	spacing
1240b_1240_1200_0	1240	1240	1200	0	50 ns
1240b_1144_1144_239	1240	1144	1144	239	50 ns
1240b_1088_1088_398	1240	1088	1088	398	50 ns
1240b_1032_1032_557	1240	1032	1032	557	50 ns
1240b_976_976_716	1240	976	976	716	50 ns
733b_733_702_468	733	733	702	468	75 ns

Summary

- CIM Fellow: great way to host international researchers **and** create societal impact

- Forward calorimeter for LHCb at η=7 seems not feasible

- LHCb has been upgraded for Run 3 (2022++)
  - Still many opportunities in recorded data
  - Triggersless readout offers great opportunities
  - Many new collission systems become available (SMOG, p-O, ..)
  - After (a bit of) a rocky start in Run 3, we are confident for 2024 data taking

Many thanks to my group!

Orgateam LHCb Woche, 08/2022

Stamp Collection / Danksagung and Fördergeber

erc
European Research Council
Established by the European Commission

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

Heisenberg-Programm
Deutsche Forschungsgemeinschaft
DFG

SFB1491

Bundesministerium für Bildung und Forschung

SFB 876 Verfügbarkeit von Information durch Analyse unter Ressourcenbeschränkung

LAMARR
Institute for Machine Learning and Artificial Intelligence

FSP
Erforschung von Universum und Materie

PUNCH 4 NFDI

SMARTHEP

European Commission
Marie Skłodowska-Curie Actions

DFG
Deutsche Forschungsgemeinschaft

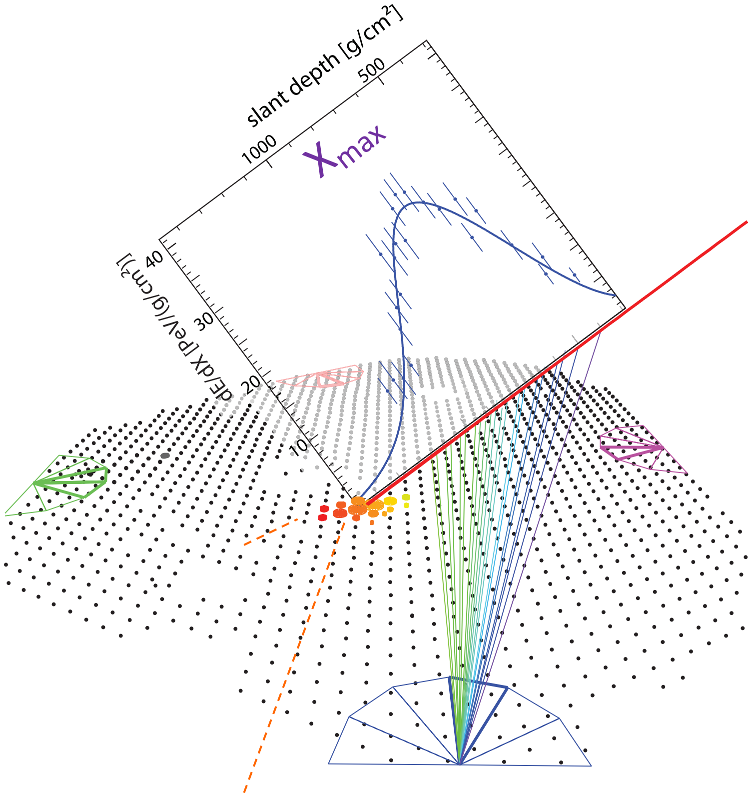
There is still some space left…

EXCELLENCE STRATEGY
of the German federal & state governments

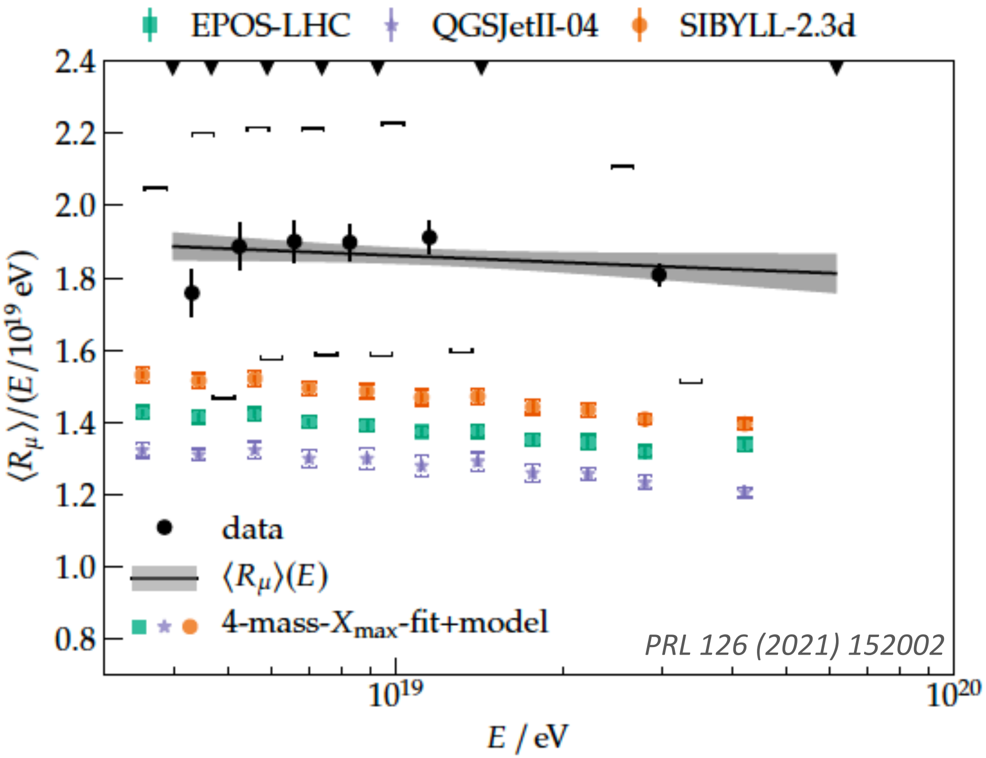
color meets flavor

Muon Puzzle

Example: event observed with Pierre Auger Observatory



- **Direction** from particle arrival times
- **Energy** from size of **eγ component**
- **Mass** from
  depth of shower maximum X_{max}
  size of muonic component N_μ



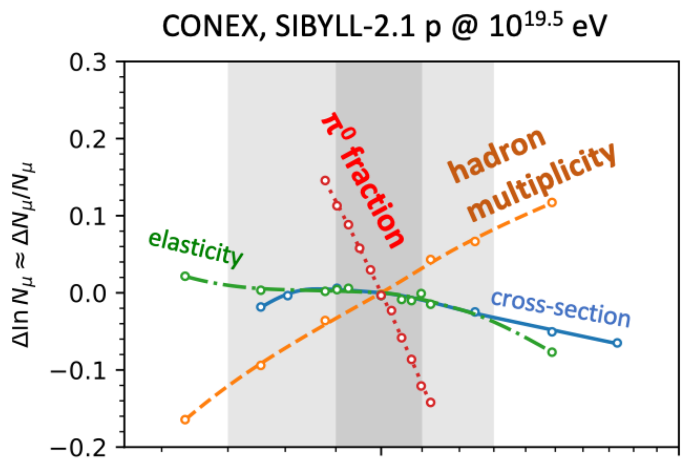
Observation: measured muon component above simulation

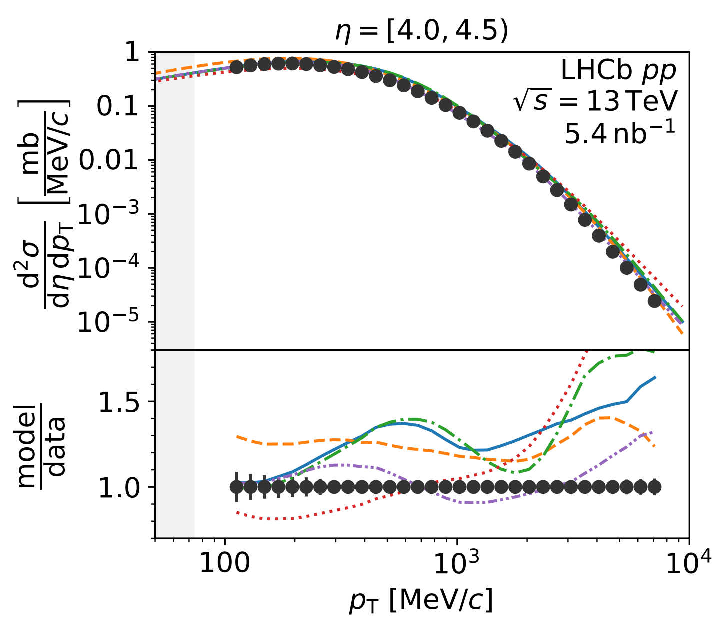
Possible reason:

- Issue with shower data?
- New exotic physcis?
- Muon propagatipon?
- Soft-QCD?

Shower properties and QCD

R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026



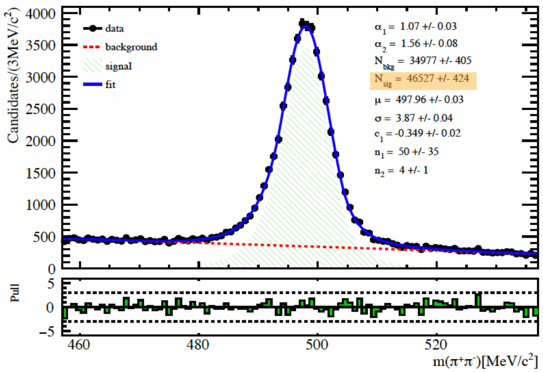


- Number of produced muons N_μ
  - Very sensitive to π^0 fraction
  - Sensitive to hadron multiplicity
- Charged particle cross section measured, more in progress
- Many more activities in this area
  - LHCb as fixed target experiment (SMOG2)
  - Requires precise luminosity measurement
  - Investigation of new Forward Calorimeter

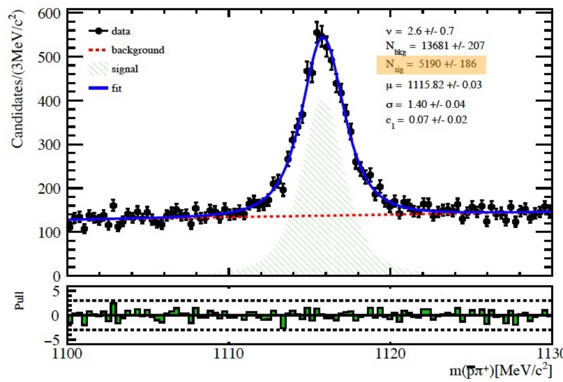
JHEP 01 (2022) 166

- Measurement of Meson to Baryon ratio
  → aim at first LHCb Run 3 paper @ Summer 2023

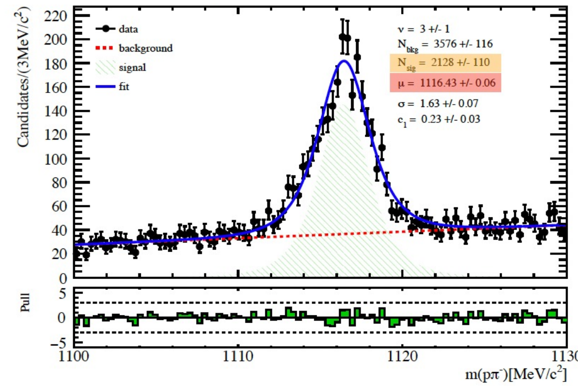
$K_S \rightarrow \pi^+\pi^-$



$\overline{\Lambda}^0 \rightarrow \overline{p}\,\pi^{+-}$



$\Lambda^0 \rightarrow p\,\pi^-$



Internal plots

e5 Dr. Calefice, Dr. Dembinski, Dr. Lisovskyi, Dr. Mitreska, MSc Behling, Osthues

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