

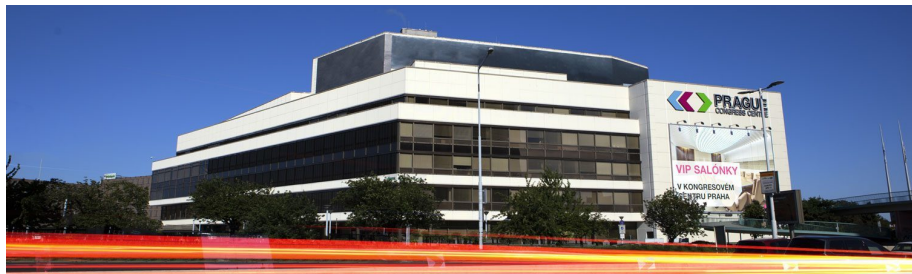
Report from the ICHEP-2024
42nd International Conference on High Energy Physics,
17 - 24 July 2024, Prague, Czech Republic

Grzegorz Grzelak

Faculty of Physics
University of Warsaw



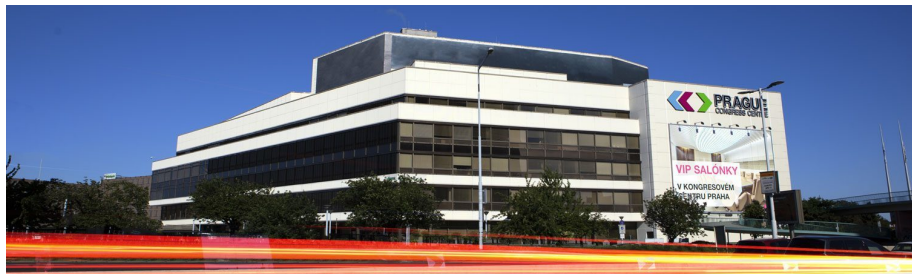
High Energy Physics Seminar, 4-OCT-2024



- Capacity: up to 9,300 participants in more than 50 halls and meeting rooms
- originally: the Palace of Culture, communist party conventions: 1981 - 1989
- reconstruction in January 2018

- ICHEP-2024: 1400 participants from 55 countries,
- about 1000 lectures, 18 blocks of parallel sessions
- **excellent organization !**

Congress Centre at Prague: upon the Vyšehrad Hill



Congress Centre at Prague: interiors



Congress Centre at Prague: interiors ... and the Zeitgeist



- Present: LHC Era (Higgs, AI)
- Future collider(s) (on Earth)
- In Space: AMS-02 (+LHCb)
- In Mind: New ideas (see also backup plots)

- **01. Higgs Physics**
- 02. Neutrino Physics
- 03. Beyond the Standard Model
- **04. Top Quark and Electroweak Physics**
- 05. Quark and Lepton Flavor Physics
- 06. Strong Interactions and Hadron Physics
- 07. Heavy Ions
- **08. Astro-particle Physics and Cosmology**
- 09. Dark Matter Detection
- 10. Formal Theory
- **11. Accelerator: Physics, Performance, and R&D for Future Facilities**
- 12. Operation, Performance and Upgrade (incl. HL-LHC) of Present Detectors
- **13. Detectors for Future Facilities, R&D, Novel Techniques** (→ backup plots)
- 14. Computing, AI and Data Handling

- 15. Education and Outreach
- 16. Equity, Diversity and Inclusion
- 17. Technology Applications and Industrial Opportunities
- **18. Sustainability (accelerators, detectors, computing)**

This is a new session in ICHEP2024. Nowadays, the need for sustainability impacts any human activity. This session will discuss the sustainability of fundamental high-energy particle research. Visionary contributions that would help set the direction of the field for decades to come are welcome.

→ for example: carbon footprint in HEP

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Dear Grzegorz Grzelak

For your information:

your jobs for user grzelak and group HERA on NAF @ DESY

in the past seven days

accounted for 79.5942 hours in 105 different jobs

equivalent to 2.27412 kWh power consumption

equivalent to 1.10295 kg CO₂ production according

to the usual conversion factor from UBA

equivalent to CO₂ production of driving 7.55444 km

in an average fossile fuel powered VW Golf

The General Framework

Raymond Volkas

Two main outcomes of the LHC: The discovery of the Higgs boson and nothing else (so far)!

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c.$$

Simplicity, governed by symmetries only 3 (EW) and 2 (QCD) parameters!

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + \frac{c_{ij}}{\Lambda} L_i L_j H H ?$$

$$+ \frac{1}{\Lambda^2} \phi^2 - V(\phi) + \Lambda^4 ?$$

Not governed by symmetries and with **26 parameters set by "hand" of experiments!**

Open problems

Hierarchies

- Gauge Hierarchy and Naturalness
- Flavour hierarchy including neutrino masses

The strong CP problem

$$\theta \frac{\alpha_s}{8\pi} F_{\mu\nu}^A \tilde{F}^{A\mu\nu} \quad \theta < 10^{-10} \quad \text{From neutron electric dipole moment}$$

The existence of Dark Matter (new field?)

The nature of Dark energy

Open questions

- What is the origin of the asymmetry between matter and anti-matter in the universe?
- What are the properties of QCD confinement?
- Why do electrons have precisely the same charge as the protons?

Strong statement, contested in many talks

One fundamental particle was discovered at the LHC so far...but also 75 new hadrons at the LHC

Hadron

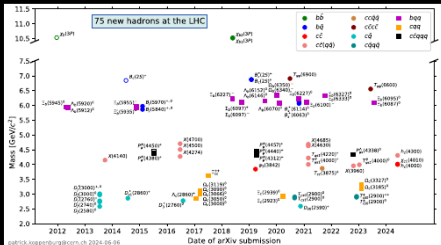
Article Talk Read Edit View history Tools

From Wikipedia, the free encyclopedia
(Redirected from Hadrons)

In particle physics, a **hadron** (/ˈhædrɒn/ ⓘ ⓘ; from Ancient Greek ἄδρῶν (*hadrón*) /'sɒut, 'θɪk/) is a composite subatomic particle made of two or more quarks held together by the strong interaction. They are analogous to molecules, which are held together by the electric force. Most of the mass of ordinary matter comes from two hadrons: the proton and the neutron, while most of the mass of the protons and neutrons is in turn due to the binding energy of their constituent quarks, due to the strong force.

A hadron is a composite subatomic particle. Every hadron must fall into one of the two fundamental classes of particle, **bosons** and **fermions**.

Hadrons are categorized into two broad families: **baryons**, made of an odd number of quarks (usually three quarks) and **mesons**, made of an even number of quarks (usually two quarks: one quark and one antiquark).^[1] Protons and neutrons (which make the majority of the mass of an atom) are examples of baryons; pions are an example of a meson. "Exotic" hadrons, containing more than three valence quarks, have been discovered in recent years. A tetraquark state (an exotic meson), named the Z(4430)[−], was discovered in 2007 by the Belle Collaboration^[2] and confirmed as a resonance in 2014 by the LHCb collaboration.^[3] Two pentaquark states (exotic baryons), named P_c⁺(4380) and P_c⁺(4450), were discovered in 2015 by the LHCb collaboration.^[4] There are several more exotic hadron candidates and other colour-singlet quark combinations that may also exist.



What a privilege to contribute to "textbook" physics !

LHC(b) contribution to "textbooks" physics, accumulating data on precise hadron spectroscopy (→ non-pQCD)

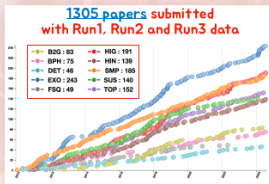
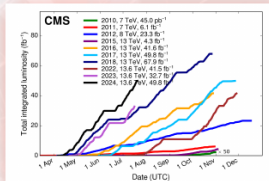
CMS mission

Maurizio Pierini

Integrated luminosity
for various years



- ① CMS is many experiments at once
 - ① At the energy frontier: our search program at the TeV scale
 - ① At the intensity frontier: our Higgs and EW precision program
 - ① As a flavor experiment: top physics + dedicated data streams for b , c , and τ
 - ① As a heavy ion experiment: PbPb and pPb LHC runs
 - ① As a photon collider experiment: ultra-peripheral Heavy Ion collisions + proton tagging in pp runs, ...
 - ① As a technology driver for the entire field (reconstruction on GPUs, real-time analysis, AI applications)
- ① This talk will guide you through all these aspects, presenting the latest news from CMS

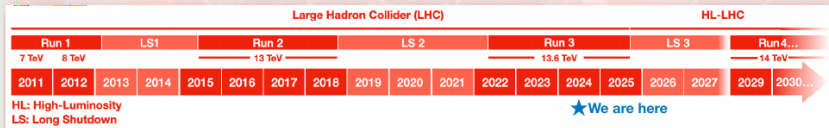


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Impressive number of results (all LHC experiments)

At the middle of our journey



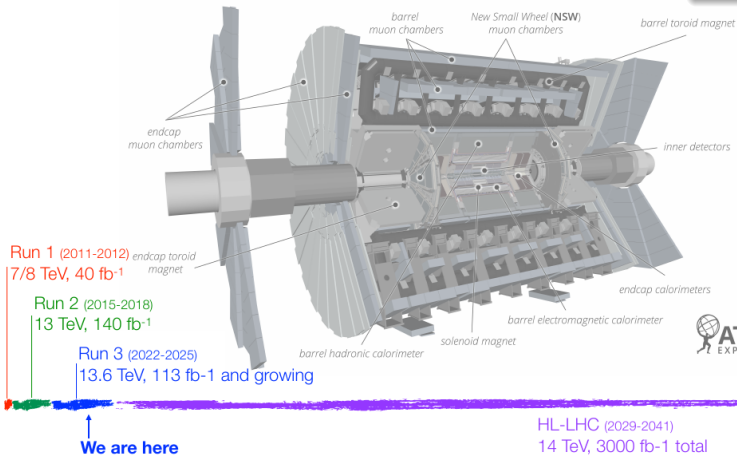
- First phase of LHC program to be completed soon
- Aiming at $>300 \text{ fb}^{-1}$ (Run2+Run3) by the end of 2025
- Working on upgrading the detector for the High-Luminosity phase
 - The target is 3000 fb^{-1} by 2041

The future is NOW

- Meanwhile, we are pushing the detector beyond its limits
 - Recording up to **63 simultaneous collisions/event** (2.5x CMS design, 45% of HL-LHC)
 - Collecting data **@7 kHz** (70% of HL-LHC, 7x Run2 normal operations)

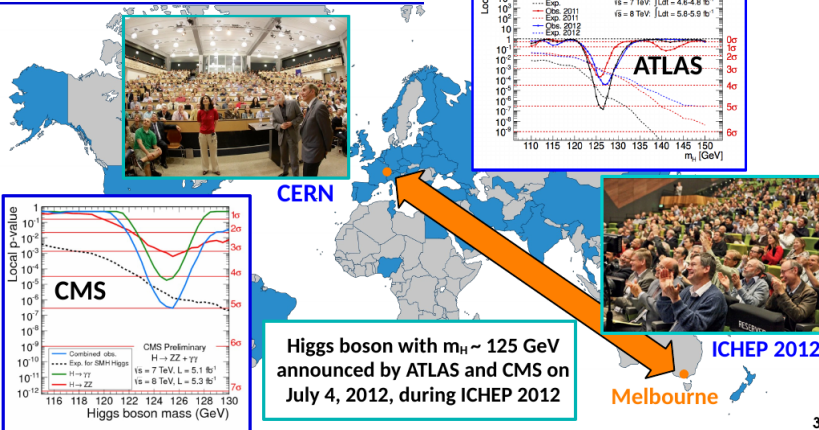


LHC is already running with 45% of HL-LHC !



Much more data still to come

Twelve years since the discovery



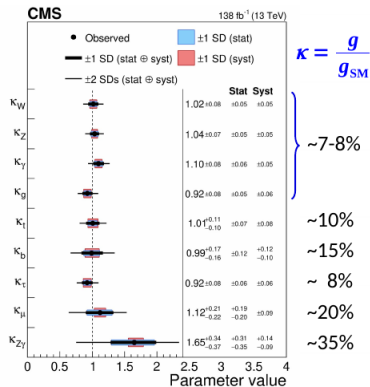
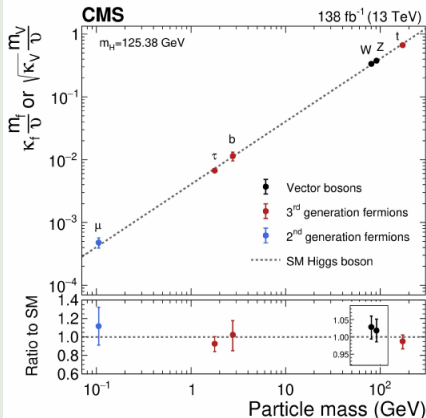
ICHEP-2012 at Melbourne: Higgs announced by ATLAS and CMS

Higgs couplings ("A portrait of the Higgs boson...by CMS")

Nicolas Berger

Current state-of-the-art: Higgs boson couplings

Nature 607 (2022) 60
Nature 607 (2022) 52

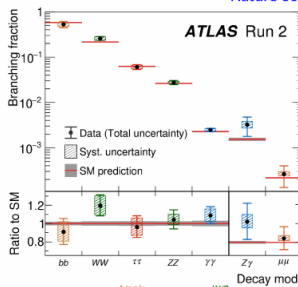
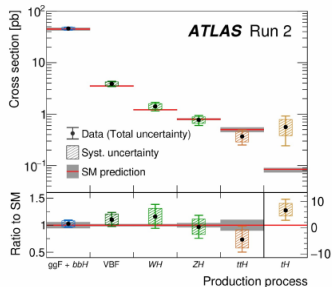


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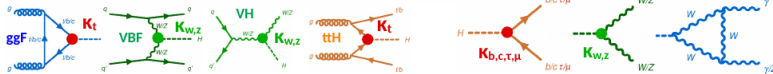
Higgs boson couplings, scaling with particle mass

Current state-of-the-art: Production and Decay

Nature 607 (2022) 52
Nature 607 (2022) 60



See talks by Xiao Yang and Jan Lukas Späth for more



Main production and decay processes observed, measured with <10% - 20% precision

Higgs boson production xsections and decay BR, agreement with SM

The Higgs Sector - Pillars of Higgs physics

Nicolas Berger, Matthew McCullough, Maurizio Pierini

The pillars of Higgs physics:

$H \rightarrow V V$ $\frac{2m_V^2}{v}$

$\mathcal{L} \supset \frac{1}{2} \partial_\mu \phi \partial^\mu \phi$ This term could not exist without a vev

$H \rightarrow f \bar{f}$ $\frac{m_f}{v}$

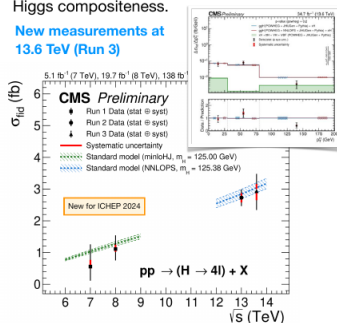
$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$

$H \rightarrow H H$ $\frac{3m_H^2}{v}$

$H \rightarrow t \bar{t}$ $\frac{3m_t^2}{v^2}$ $V(\phi)$

Message 1 (Matthew McCullough): It is of utmost importance to measure the most precisely measured coupling (hZZ) to probe the Higgs compositeness.

New measurements at 13.6 TeV (Run 3)



Higgs physics pillars, couplings to Vector Bosons, hZZ : window to Higgs compositeness

Current state-of-the-art: Mass

CMS: using $H \rightarrow ZZ^* \rightarrow 4l$: [CMS-PAS-HIG-21-019](#)

$$m_H = 125.08 \pm 0.10 \text{ (stat)} \pm 0.05 \text{ (syst)} \text{ GeV}$$

Most precise single measurement ($< 1\%$)

ATLAS: combining $H \rightarrow 4l$ + $H \rightarrow \gamma\gamma$:

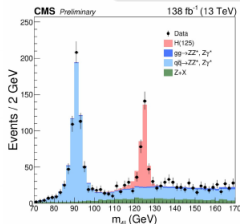
[Phys. Lett. B 843 \(2023\) 137880](#),

[Phys. Lett. B 847 \(2023\) 138315](#)

$$m_H = 125.11 \pm 0.11 \text{ GeV (syst: 0.09 GeV)}$$

Most precise measurement to date

$H \rightarrow \gamma\gamma$ mass resolution systematics reduced by a factor 4 !



See talks by [Camila Pazos](#),
[Léo Boudet](#), [Badder Marzocchi](#) and
[Federica Primavera](#) for details

[JINST 19 \(2024\) P02009](#)

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Most precise measurement to date ($H \rightarrow 4l$, $H \rightarrow 2\gamma$)

The Higgs Sector - Pillars of Higgs physics

Nicolas Berger, Matthew McCullough

The pillars of Higgs physics:

$H \rightarrow V V$ $\frac{2m_V^2}{v}$ $t_\mu \phi^2$ This term could not exist without a vev

$H \rightarrow f \bar{f}$ $\frac{m_f}{v}$ $\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$

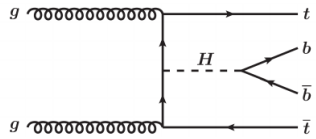
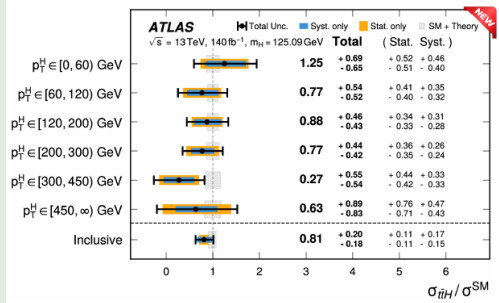
$H \rightarrow H H$ $\frac{3m_H^2}{v}$ $V(\phi)$

	Current	HL-LHC	FCC (ee)
$K_{W,Z}$	6%	1.5%, 1.7 %	0.4%, 0.2 %

	Current	HL-LHC	FCC (ee)	FCC (hh)
K_t	11%	3.4%	-	1%
K_b	11%	3.7%	0.7%	-
K_τ	8%	1.9%	0.7%	-
K_μ	20%	4.3%	8.9%*	

Higgs physics pillars, coupling to fermions (3rd and 2nd generation)

Precision Higgs - ttH to bb



Total uncertainty reduced by factor of ~ 2 , 4.6σ observed

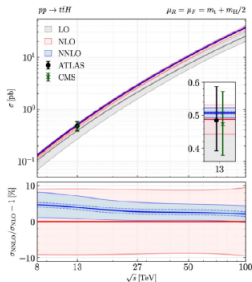
Towards HL-LHC, 4.6σ visible, very complex final state, $tt + bb$ bkg. (ML !)

Top Yukawa Coupling at the LHC

Nicolas Berger, Matthew McCullough, Monica Dunford, Francesco di Bello

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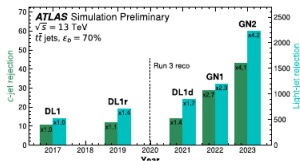
Recent example from Mathew (ttH)



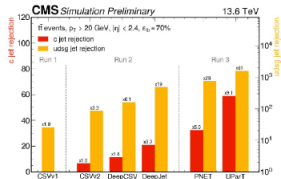
Message 2 (again) (Matthew McCullough):
Precision in Higgs physics is key.

ttH from ATLAS

AI in HEP reconstruction has a significant impact!



The most shown plot at this conference!



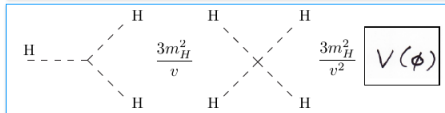
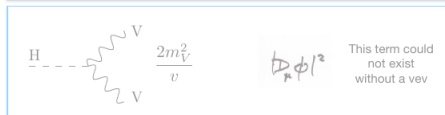
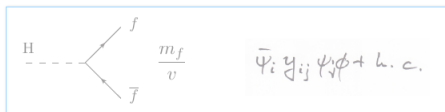
There are 4 b-quark jets in the ttH(bb) event topology!

Higgs physics pillars, ttH Yukawa coupling, $H \rightarrow bb$

The Higgs boson self coupling!

Nicolas Berger, Matthew McCullough

The pillars of Higgs physics:



Despite the fact that in “Vanilla SUSY and vanilla composite models it is difficult to have large deviations in trilinear w.r.t. vector boson coupling”

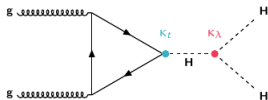
Matthew McCullough

Message 3 (Matthew McCullough - as well as Georg Weiglein in parallel session): Large trilinear deviations are possible while deviations of the Higgs to Z coupling remain small.

[“Arguably the most important of them all!”](#)

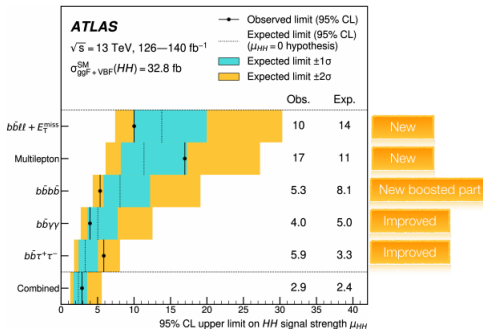
Higgs physics pillars, self couplings

Di-higgs production



Best expected sensitivity on HH cross section, self-coupling, κ_λ

$$\mu_{HH} = 0.5^{+0.9}_{-0.8}(\text{stat.})^{+0.7}_{-0.6}(\text{syst.})$$



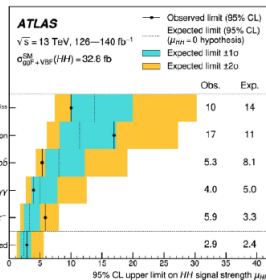
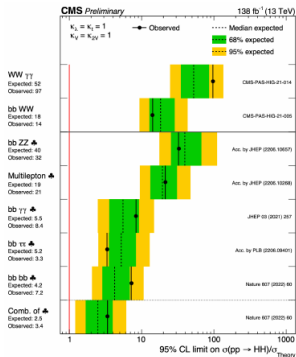
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Towards HL-LHC, process is visible already now

Higgs Self Coupling and HH Production

Nicolas Berger, Matthew McCullough

“Arguably the most important of them all!”



Observed limits start deviating from expectation!!

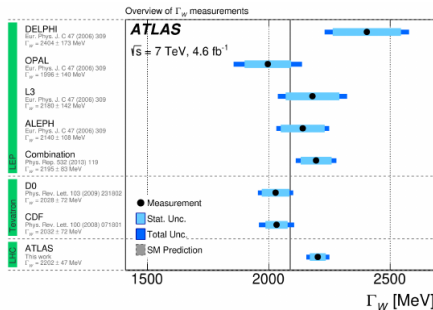
Both experiments have $\sim 1\sigma$ sensitivity to a signal (Obs. ATLAS 0.4σ and CMS $\sim 1\sigma$) with Run 2!!

Naive comb. ATLAS-CMS sensitivity with Run 3 close 2.5σ with improvements (and as much data as possible) **aim at 3σ**

Looking for tension...

Properties of the W boson

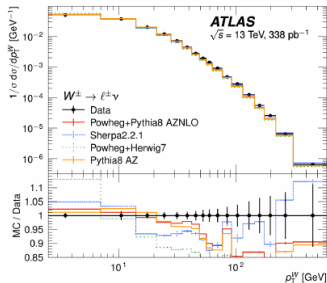
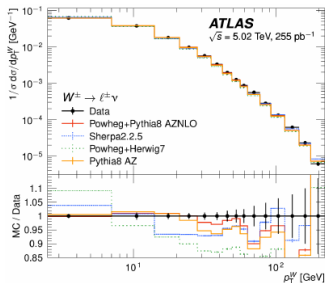
- First measurement of the W width at the LHC, together with an improved W mass
- Largest systematics from the calibration, the theoretical modeling and the parton density functions



Best world value.

Where can we go - improved modeling

- Dedicated measurements under optimal running conditions can play a key role to improve these limitations



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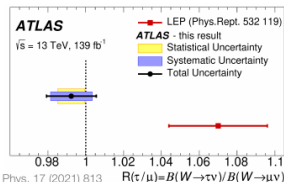
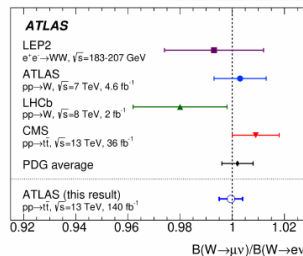
Experimental data better than theoretical modeling.

Lepton universality in W decays

- Exploits clean W bosons from top-pair decays
- Higher precision than current world average

$$R_W^{\mu/e} = 0.9995 \pm 0.0045$$

- This adds to a previous result with taus, solving a decade old puzzle from LEP



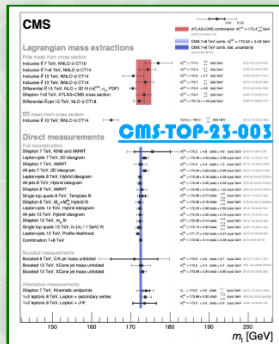
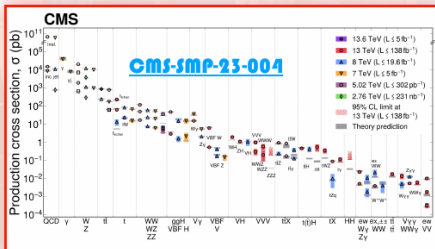
Nature Phys. 17 (2021) 813

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$R_W^{\mu/e}$ - better than world average so far. $R_W^{\tau/\mu}$ - consistent with 1.0.

CMS as a precision physics experiment

- Since Run1, carrying out a fully comprehensive measurement program, to improve our understanding of the SM
- Spanned 14 orders of magnitude in cross sections, going from abundant QCD processes to rare multi boson production
- Measuring fundamental parameters of the Standard Model with multiple techniques at unprecedented precision



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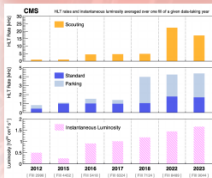
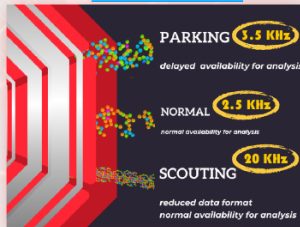
Agreement with SM

Rethinking Data Taking Strategy



CMS-EXO-23-007

- LHC high-intensity challenge: retain sensitivity to high rate processes (e.g., low p_T) w/o compromising high- p_T core program. Two solutions:
- (Since 2011) **Scouting Stream** to work around trigger constraints: store 10 kB of HLT reco objects rather than the full RAW event (~1 MB)
- (Since 2012) **Parking Stream** to work around computing constraints: store extra data on tape and reco them when extra computing resources are available
- For Run3, we pushed this effort to maximum capacity
- **Scouting** now covers ~20 kHz out of ~100 kHz of incoming rate (at maximum of available online CPU power)
- Promoted **Parking** program to default (not just last-year-of-run effort)
- Big benefits to our core physics program (Higgs physics, searches, etc.) and beyond-core areas (e.g., flavor)



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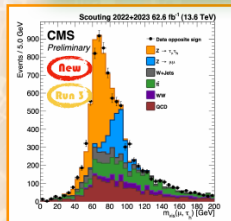
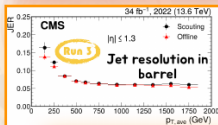
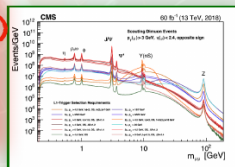
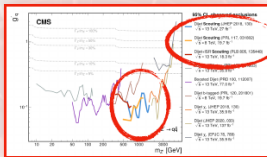
Scouting and Parking. Future: only Scouting for High Rate Physics.

Data Scouting

CMS-EXO-23-007



- Scouting introduced to probe light resonances (dijet in Run1 + muons in Run2)
- Generalized to all objects in Run3 (photons, electrons, taus, hadrons)
- Reached ~ offline-like resolution with excellent HLT calibration & reconstruction
- It will extend our physics reach in the 1-100 GeV region (light Z', Heavy Neutral Leptons, long-lived light particles, ...)



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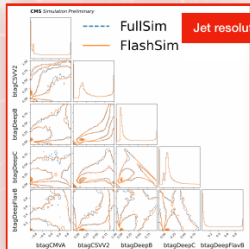
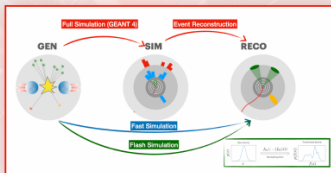
CMS NOTE-2024/006



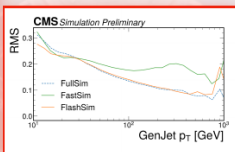
Possible thanks to excellent understanding of detector calibration.

The Impact of AI

- CMS has been an early adopter of AI solutions :
- To enhance our computational performance, e.g. with AI-based super-fast simulation (**FlashSim**)
- Same paradigm now used at analysis level to correct simulation of specific quantities with data control samples

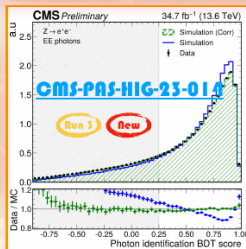


Jet resolution for Full Sim vs Fast Sim vs Flash Sim



[CMS-NOTE-2023-003](#)

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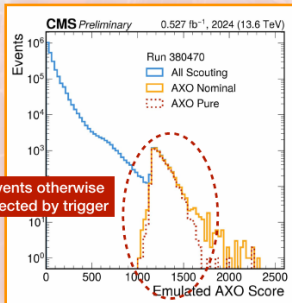
Application of AI for fast detector simulation

The Impact of AI

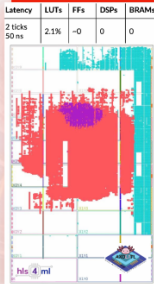


- CMS has been an early adopter of AI solutions:
 - To expand our physics reach with novel applications, such as anomaly detection in offline analysis and in the L1 (hardware) trigger

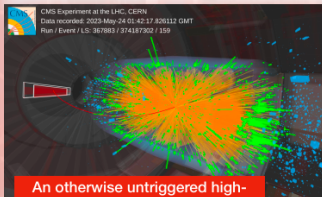
CMS-DP-2024-059



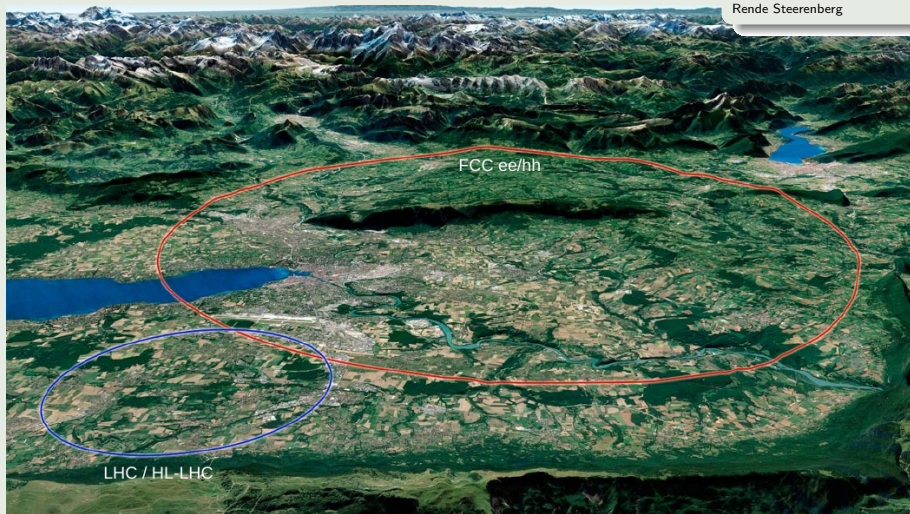
Algorithm Footprint on FPGA



CMS-DP-2023-079



Application of AI for anomaly detection (at trigger Level 1 !)



FCC: Future Circular Collider

Optimised placement and layout

Layout chosen:

- One out of ~100 initial variants, based on geology and surface constraints, environment, infrastructure

Baseline:

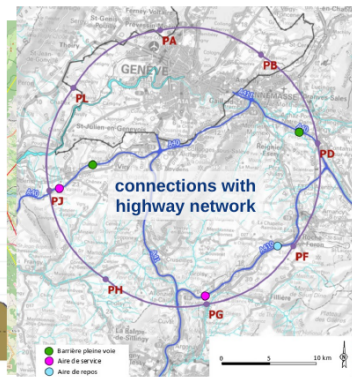
- 90.7 km ring
- 8 surface points
- 4-fold super-periodicity
- 4 interaction points for experiments

Integration with regional services:

- Connections with highway network
- Electrical connection concept developed with the French electricity grid operator

Sustainability is an integral part of the study:

- Commitment to environmental protection
- Heat recuperation, reduced water consumption, etc.



Latest version of FCC layout: optimized for existing network of public roads

FCC-ee

2-ring collider with full energy booster in a single tunnel

- Integration of all services and transport corridor

Designed to operate in multiple energy stages to address the different physics cases:

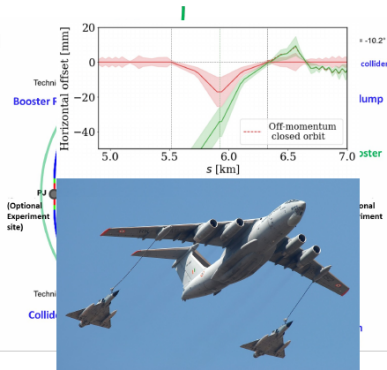
- Z: 45.6 GeV (~4 years)
- WW: 80 GeV (~2 years)
- H(ZH): 120 GeV (~3 years)
- ttbar: 182.5 GeV (~5 years)

Scalable superconducting RF system

- Increase needs as physics evolves Z \Rightarrow W \Rightarrow H \Rightarrow ttbar
- SRF is a main area of R&D for the FCC-ee

On-axis top-up injection for high luminosities

- Beam lifetime and high bunch charge require continuous top-up injection



Parameter table available in the back-up slides

FCC: A comprehensive long-term programme

Maximising physics opportunities:

- Stage 1: **FCC-ee** (Z, W, H, $t\bar{t}$) as a **Higgs factory**, electroweak & top factory at highest luminosities
- Stage 2: **FCC-hh** (~100 TeV) as natural continuation at energy frontier, **proton-proton** with options



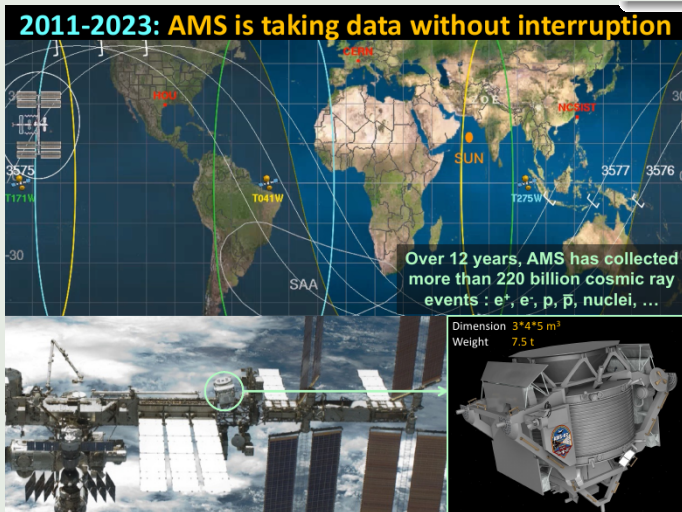
- The program is highly synergetic and complementary **enhancing the physics potential of both colliders**
- **Common civil engineering** and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project **allows the development of a significant new facility at CERN**, within a few years of the completion of the HL-LHC physics programme

FCC: data taking in 2045 (FCC-ee) and 2070 (FCC-hh)



Fabiola Gianotti, Lia Meringa,
Yifang Wang, Shoji Asai

60 minutes, 4 directors of HEP labs, 1:1:2 - Europe : America : Asia



2.2×10^{11} events over 12 years \rightarrow and more to come (till 2030)

AMS: a unique TeV precision, accelerator-type spectrometer in space

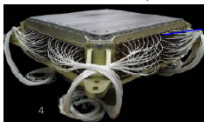
TRD: Identify e^+ , e^- , Z



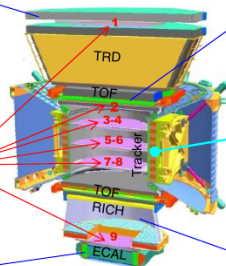
Silicon Tracker: Z, P



ECAL: E of e^+ , e^-



Particles and nuclei are defined by their charge (Z) and energy (E) or momentum (P).
Rigidity $R = P/Z$

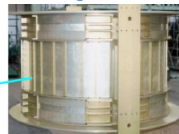


Z and P (or E) are measured independently by the Tracker, RICH, TOF, and ECAL

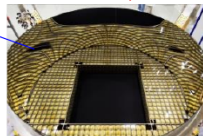
TOF: Z, E



Magnet: $\pm Z$



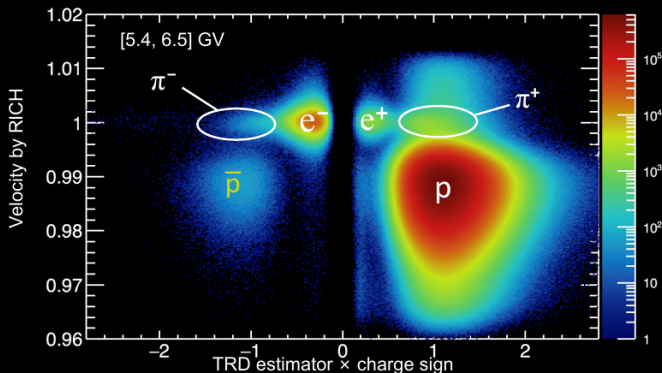
RICH: Z, E



“full function” HEP detector in space

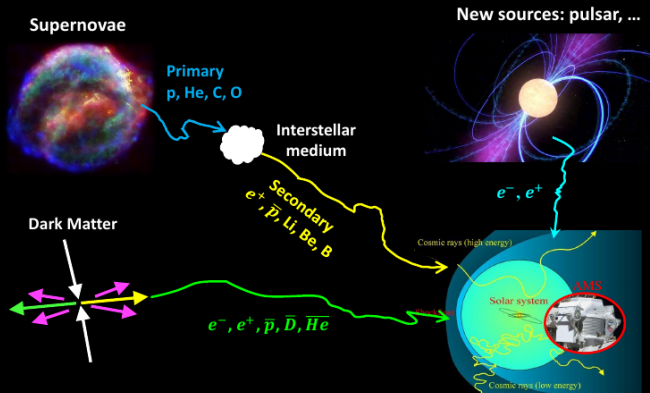
Antiproton Identification

AMS is able to identify particles precisely.
Antiproton signal are well separated from backgrounds (π^- produced in detector, e^- and protons)



matter antimatter separation

Origin and Propagation of Cosmic Rays

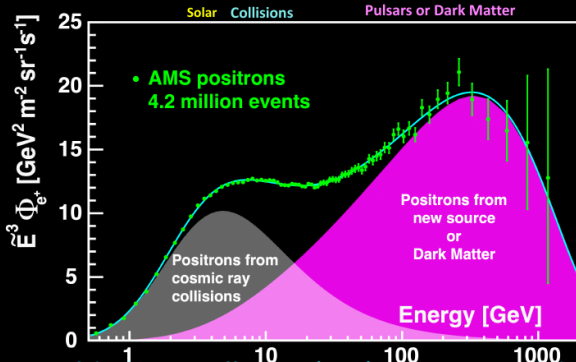


Before being detected by AMS,
All the galactic cosmic rays propagate in the solar system (heliosphere)

a lot of effort to understand CR propagation in heliosphere

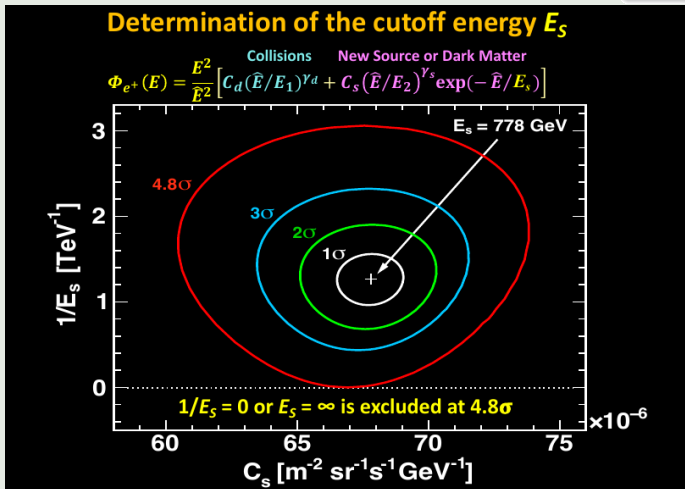
The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from pulsars or dark matter both with a cutoff energy E_c .

$$\Phi_{e^+}(E) = \frac{E^2}{\tilde{E}^2} \left[C_d (\tilde{E}/E_1)^{\gamma_d} + C_s (\tilde{E}/E_2)^{\gamma_s} \exp(-\tilde{E}/E_c) \right]$$



The existence of the finite cutoff energy (4.8σ) is an unexpected observation

positron flux decomposition

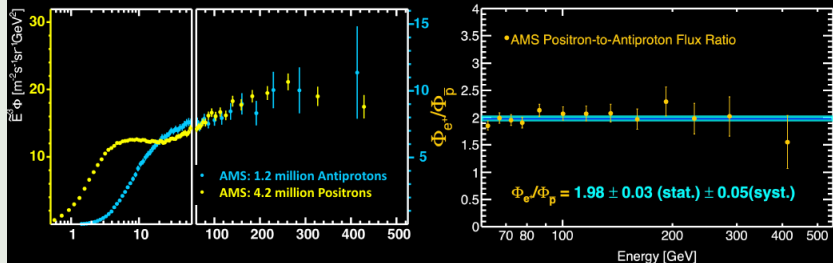


spectrum cut-off significance: 4.8σ

Unique Observation from AMS:

Positron and Antiproton have nearly identical energy dependence
 The positron-to-antiproton flux ratio is independent of energy.

Presented by C. Zhang



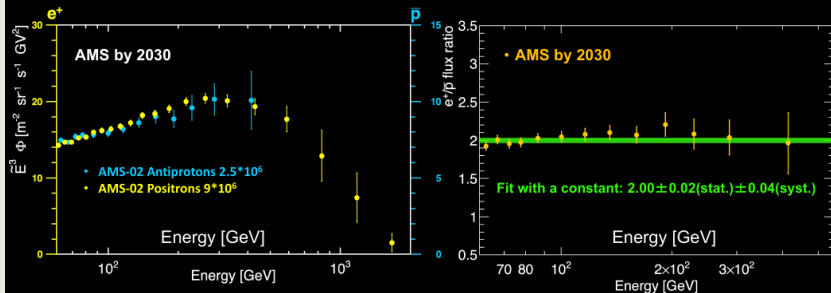
Antiprotons cannot come from pulsars.

11

positron and antiprotons have similar energy dependence

By 2030, AMS will greatly improve the accuracy of the antiproton spectra

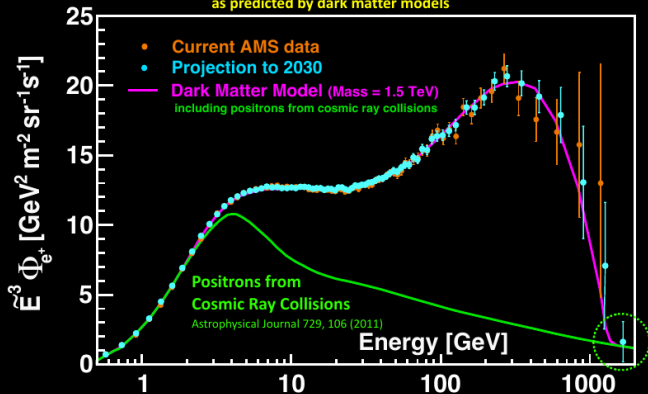
The identical behaviour of positrons and antiprotons
excludes the pulsar origin of positrons



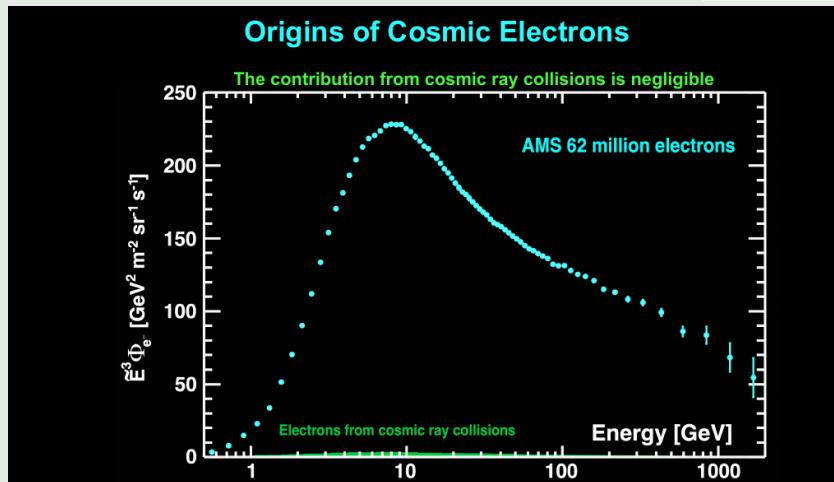
tendency is already visible, expected projections by 2030

Determination of the Origin of Cosmic Positrons by 2030

AMS will ensure that the measured high energy positron spectrum indeed drops off quickly and, at the highest energies, the positrons only come from cosmic ray collisions as predicted by dark matter models



Precision of positron spectrum projected to 2030



negligible contribution from secondary interactions → more clean picture

Origins of Cosmic Electrons

Traditionally, Cosmic Ray spectrum is described by a power law function

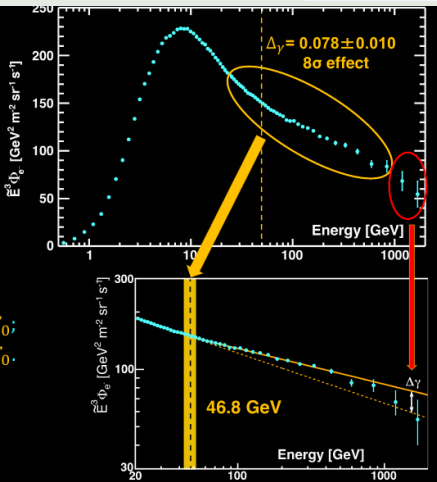
Change of the behavior at 46.8 GeV and at ~ 1 TeV

Fit to data

$$\Phi_{e^-}(E) = \begin{cases} CE^\gamma, & E \leq E_0; \\ CE^\gamma (E/E_0)^{\Delta\gamma}, & E > E_0. \end{cases}$$

8 sigma excess at

$$E_0 = 46.8 \pm 3.1 \text{ GeV}$$



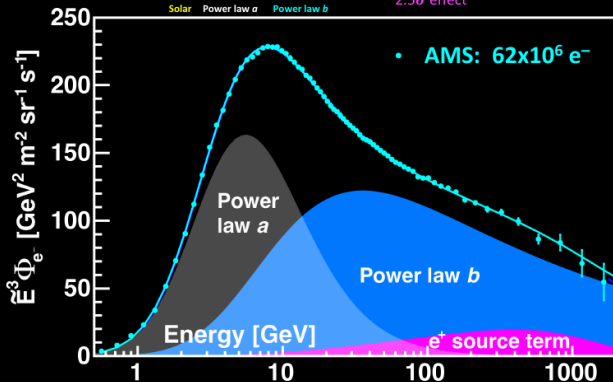
cannot be described only by power law dependency (Fermi mechanism)

AMS Result on the electron spectrum

The spectrum fits well with two power laws (a , b) and a source term like positrons

$$\Phi_{e^-}(E) = \frac{E^2}{\widehat{E}^2} (C_a \widehat{E}^{\gamma_a} + C_b \widehat{E}^{\gamma_b} + \text{Positron Source Term})$$

Solar Power law a Power law b 2.5σ effect



visible contribution from source “positron-like counterpart” term
(2.5σ at present, 4σ expected at 2030)

- AMS-2 reports of ~ 10 events (#COSPAR2022) of ${}^3\overline{\text{He}}$ and ${}^4\overline{\text{He}}$ nuclei
- **possible sources:**
- Supernovas explosions \rightarrow extremely low rate, (should be correlated to anti-protons)
- Cosmic Rays interaction plus Supernovas Shock Waves acceleration ?
 \rightarrow too small flux...
- Dark Matter annihilation:
like $X + X \rightarrow WW, ZZ, bb, \dots$ (as product of single heavy particle decay from $W, Z, bb \rightarrow jets$ fragmentation and hadronization)
- More Exotic Sources ?

Cosmic-Ray Propagation Models Elucidate the Prospects for Antinuclei Detection

EJ 19 Apr 2024

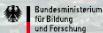
Pedro De La Torre Luque^{a,b} Martin Wolfgang Winkler^c Tim Linden^b

^aInstituto de Física Teórica, IFT UAM-CSIC, Departamento de Física Teórica, Universidad Autónoma de Madrid, ES-28049 Madrid, Spain

flux from both astrophysical and dark matter annihilation models. We show that astrophysical sources are capable of producing $\mathcal{O}(1)$ antideuteron events and $\mathcal{O}(0.1)$ antihelium-3 events over 15 years of AMS-02 observations. Standard dark matter models could potentially produce higher levels of these antinuclei, but showing a different energy-dependence. Given the uncertainties in these models, dark matter annihilation is still the most promising candidate to explain preliminary AMS-02 results. Meanwhile, any robust detection of antihelium-4

arXiv:2404.13

flux from both astrophysical and dark matter annihilation models. We show that astrophysical sources are capable of producing $\mathcal{O}(1)$ antideuteron events and $\mathcal{O}(0.1)$ antihelium-3 events over 15 years of AMS-02 observations. Standard dark matter models could potentially produce higher levels of these antinuclei, but showing a different energy-dependence. Given the uncertainties in these models, dark matter annihilation is still the most promising candidate to explain preliminary AMS-02 results. Meanwhile, any robust detection of antihelium-4 events would require more novel dark matter model building or a new astrophysical production mechanism.



FSP LHCb
Erforschung von
Universum und Materie



Antihelium production in $\bar{\Lambda}_b^0$ decays

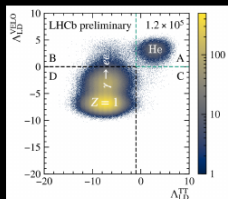
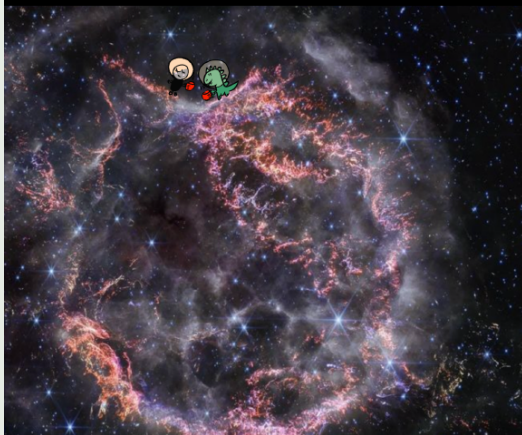
Dan Moise,
on behalf of the LHCb collaboration

ICHEP Prague
18th July 2024

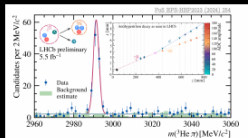
LHCb: looking for anti-helium production in pp collisions

Yasmine Amhis

In the last years LHCb opened a new area of physics with heavy ions and fixed targets



Clean identification of He !



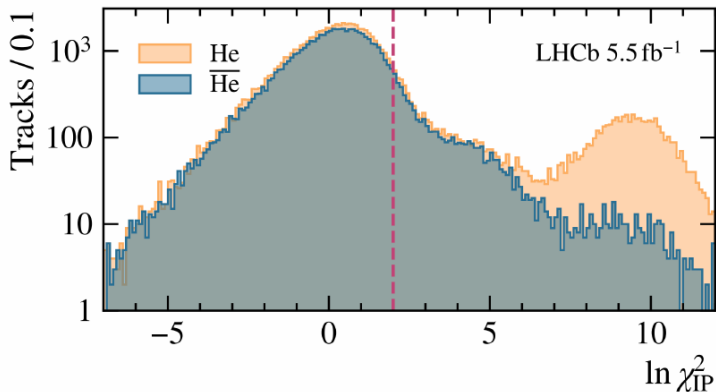
Observation of antihypertritons

LHCb-DP-2023-003

LHCb-CONF-2023-002

LHCb: contribution to AMS observations

Prompt and displaced helium



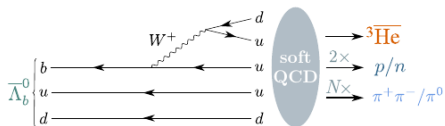
LHCb: prompt (anti)helium : from fragmentation of recombination of QCD strings

Dark Matter Annihilation Can Produce a Detectable Antihelium Flux through $\bar{\Lambda}_b$ Decays

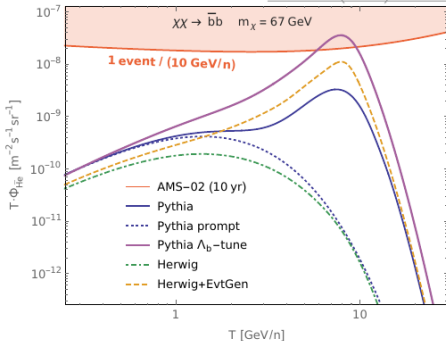
Martin Wolfgang Winkler^{1,*} and Tim Linden^{1,†}

¹Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden

PRL 126(2021)101101



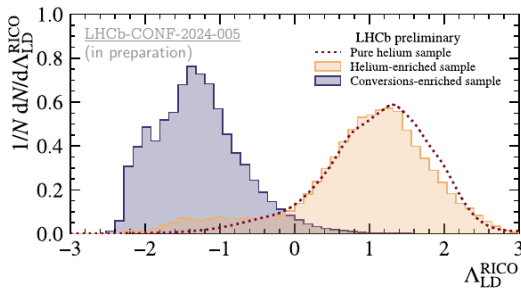
$\mathcal{B}(\bar{\Lambda}_b^0 \rightarrow {}^3\bar{\text{He}}X)$ predicted as high as 3×10^{-6} (modified Pythia 8.2) well within reach of LHCb



NB: discussion ongoing, e.g. PRC 1018(2023) 024903

LHCb: BR predictions from Pythia within LHCb reach, soft-QCD uncertainties

Helium selection: conversion rejection



- **RICH, Isolation, Calorimetry, and OT** information combined into additional log-likelihood estimator: Λ_{LD}^{RICO}
 - ⇒ removes residual background from conversions
 - ⇒ signal ↗ 10%, background ↘ 3x *cf.* previous publications

Background: $\gamma \rightarrow e^+e^-$ conversion with small opening angle (mimics $Z=2$ ionization)

Kowalski,
 $\Lambda_b^0 \rightarrow ^3\text{He}X$
analysis

Penguins analysis :).

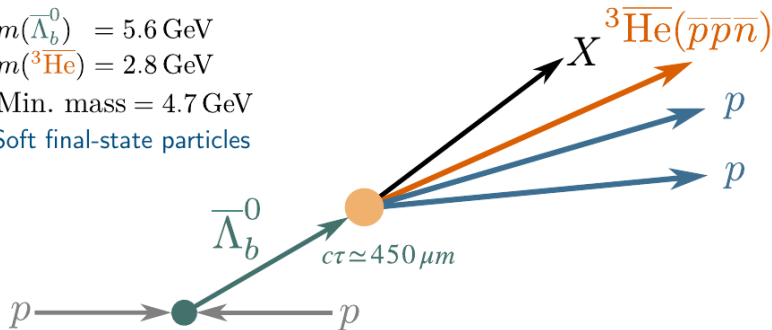
Topology & kinematics

$$m(\bar{\Lambda}_b^0) = 5.6 \text{ GeV}$$

$$m(^3\bar{\text{He}}) = 2.8 \text{ GeV}$$

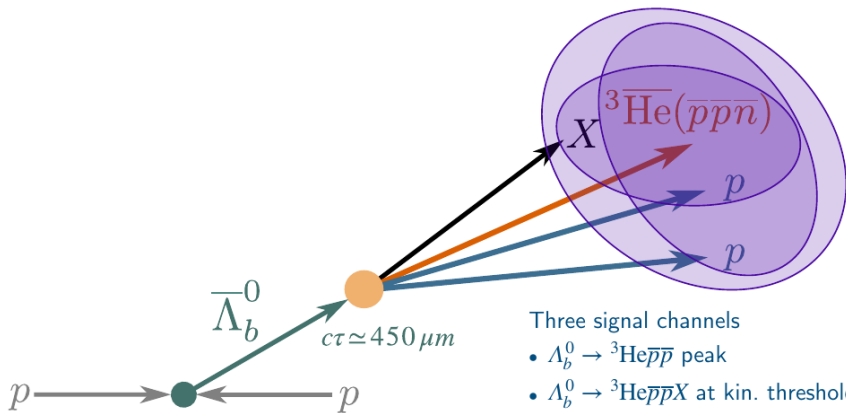
Min. mass = 4.7 GeV

Soft final-state particles



barion number conservation \rightarrow 2 nucleons are expected (+X)

Topology & kinematics

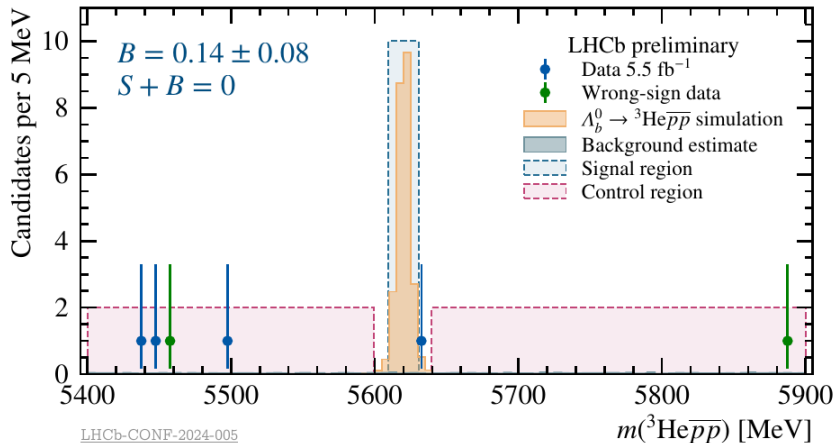


Three signal channels

- $\bar{\Lambda}_b^0 \rightarrow {}^3\text{He}\bar{p}\bar{p}$ peak
- $\bar{\Lambda}_b^0 \rightarrow {}^3\text{He}\bar{p}\bar{p}X$ at kin. threshold
- $\bar{\Lambda}_b^0 \rightarrow {}^3\text{He}\bar{p}X$ at kin. threshold

barion number conservation \rightarrow 2 nucleons are expected (+X)

$\Lambda_b^0 \rightarrow {}^3\text{He}\bar{p}\bar{p}$ data

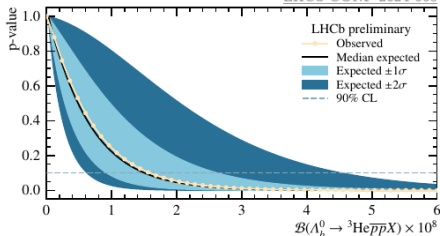


LHCb-CONF-2024-005
(in preparation)

exclusive channel, similar for inclusive channels, no signal...

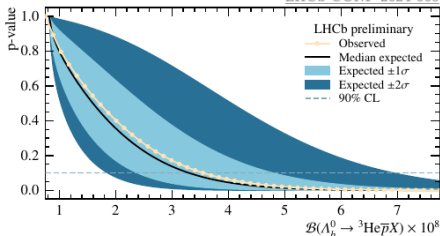
Upper limits

LHCb-CONF-2024-005



$$\mathcal{B}(\Lambda_b^0 \rightarrow {}^3\text{He} p \bar{p} X) < 1.6 \times 10^{-8}$$

LHCb-CONF-2024-005



$$\mathcal{B}(\Lambda_b^0 \rightarrow {}^3\text{He} \bar{p} X) < 3.6 \times 10^{-8}$$

isospin

$$\mathcal{B}(\Lambda_b^0 \rightarrow {}^3\text{He} X) < 6.3 \times 10^{-8}$$

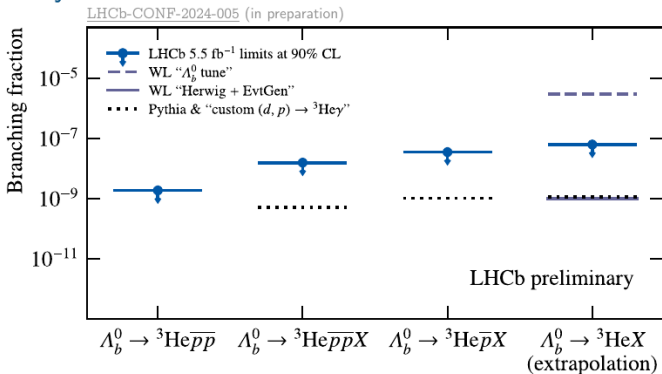
$\bar{p}p$: 25% $\bar{p}n$: 25%
 $n\bar{p}$: 25% $n\bar{n}$: 25%
 (Pythia: $\bar{p}p \sim 40\%$)

$$\mathcal{B}(\Lambda_b^0 \rightarrow {}^3\text{He} \bar{p} \bar{p}) < 1.9 \times 10^{-9}$$

profile likelihood [NIMA458\(2001\)745-758](#)

limits well below (naive ?) Pythia BR expectations...

Summary



These are the first results on (anti)helium production in (anti) Λ_b decays.

They significantly restrict abundance of ${}^3\bar{H}e$ in cosmic rays.

LHCb Upgrade II offers the potential to cover current estimates.

translation to the abundance of ${}^3\bar{H}e$ in CR requires more work... (what about ${}^4\bar{H}e$?)

Where do the *AMS-02* anti-helium events come from?

Vivian Poulin,¹ Pierre Salati,² Ilias Cholis,^{3,1} Marc Kamionkowski,¹ and Joseph Silk^{1,4,5}

¹*Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA*

²*LAPTh, Université Savoie Mont Blanc & CNRS, 74941 Annecy Cedex, France*

³*Department of Physics, Oakland University, Rochester, MI 48309, USA*

⁴*Sorbonne Universités, UPMC Univ. Paris 6 et CNRS, UMR 7095,*

Institut d'Astrophysique de Paris, 98 bis bd Arago, 75014 Paris, France

⁵*Beecroft Institute of Particle Astrophysics and Cosmology, Department of Physics, University of Oxford, Denys Wilkinson Building, 1 Keble Road, Oxford OX1 3RH, UK*

(Dated: March 26, 2019)

We discuss the origin of the anti-helium-3 and -4 events possibly detected by *AMS-02*. Using up-to-date semi-analytical tools, we show that spallation from primary hydrogen and helium nuclei onto the ISM predicts a ${}^3\text{He}$ flux typically one to two orders of magnitude below the sensitivity of *AMS-02* after 5 years, and a ${}^4\text{He}$ flux roughly 5 orders of magnitude below the *AMS-02* sensitivity. We argue that dark matter annihilations face similar difficulties in explaining this event. **We then entertain the possibility that these events originate from anti-matter-dominated regions in the form of anti-clouds or anti-stars.** In the case of anti-clouds, we show how the isotopic ratio of anti-helium

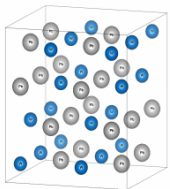
Thank You For Your Attention



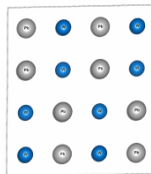
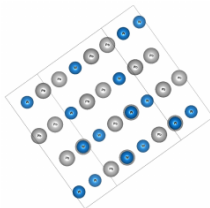
BACKUP PLOTS FOLLOWS...

OREO - ORiEnted calOrimeter

Randomly oriented crystal



Oriented crystals



Planar orientation

Axial orientation

Bethe-Heitler bremsstrahlung and standard pair production

Coherent mechanisms 

Modification of the electromagnetic processes

Coherent mechanism of Electromagnetic shower development along crystal axis

Relativistic particle incident
on atomic string



STRONG FIELD REGIME



Lorentz factor

$$\chi = \frac{\gamma E}{E_0} > 1$$

Field experienced by the
electron in its rest frame

QED critical electric field $\sim 1.3 \cdot 10^{18} \frac{V}{m}$

The particle experiences an **intense field** that can be considered constant along the string

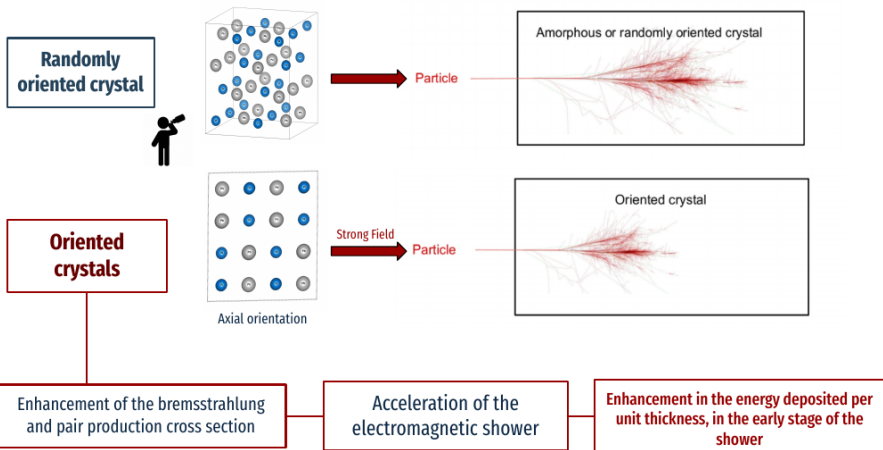


Coherent interactions
all over the string of atoms



Shift of bremsstrahlung spectra towards
higher energies and **enhancement** of pair
production cross section

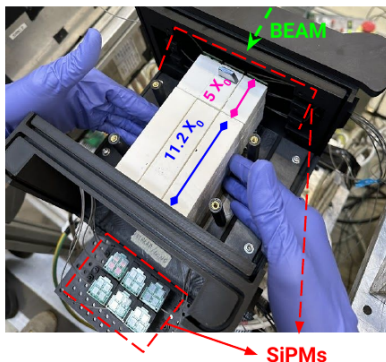
alignment of crystal axes wrt. the impact particle is crucial: ~ 1 mrad



acceleration of EM shower: simulation by Geant4 extension

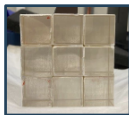
OREO - ORiEnted calOrimeter → Prototype of compact crystal based calorimeter

National Coordinator
Laura Bandiera, INFN FE



GOAL

1. Demonstrate the possibility to **align a layer of crystals along the same crystallographic direction**
2. Prove that it's possible to **contain e.m. showers in a reduced volume/weight and cost**



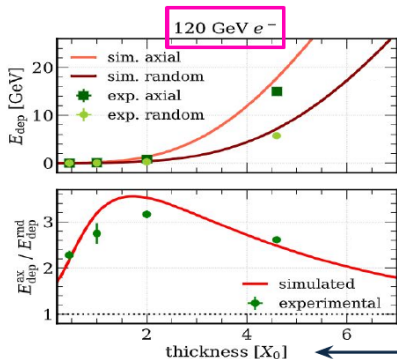
Front face

$PbWO_4$ prototype assembled within INFN project at test beam: proof of principle

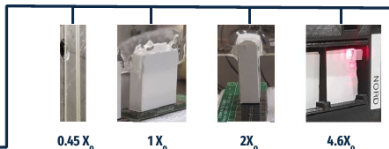
Experimental investigation of the Strong Field effects in oriented PbWO_4 .

Results: shower acceleration → enhancement of the effective thickness !

[Soldani et al.](#)



thickness [X_0]	effective thickness [X_0]	thickness enhancement [%]
0.45	0.745	165.48
1	1.520	151.98
2	2.923	146.17
4.6	6.208	134.96



shower acceleration was observed for the first time



ORiEnted calORimeter for...

space-borne γ -ray (VHE/UHE) detectors
with pointing systems
e.g. Fermi LAT

- reduced thickness
- improved shower containment with less longitudinal leakage
- higher γ efficiency
- better γ /hadron discrimination



[Bandiera, CRIS-MAC 2024](#)
[Bandiera et al.](#)

forward-geometry
accelerator-based experiments
fixed-target collider forward region

- improved shower containment and energy resolution
- higher γ efficiency: ideal for γ vetoes
- better γ /hadron discrimination: ideal for γ /n in small-angle calorimeters on neutral hadron beamlines



[Monti-Guarnieri et al.](#)

possible fields of application