Some new physics studies with LHC and PKMu experiments

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Workshop on Multi-front Exotic phenomena in Particle and Astrophysics (MEPA 2025)
2025.04.12

In this talk, I will mostly discuss results that I contributed to

1. Some new physics studies with LHC experiments

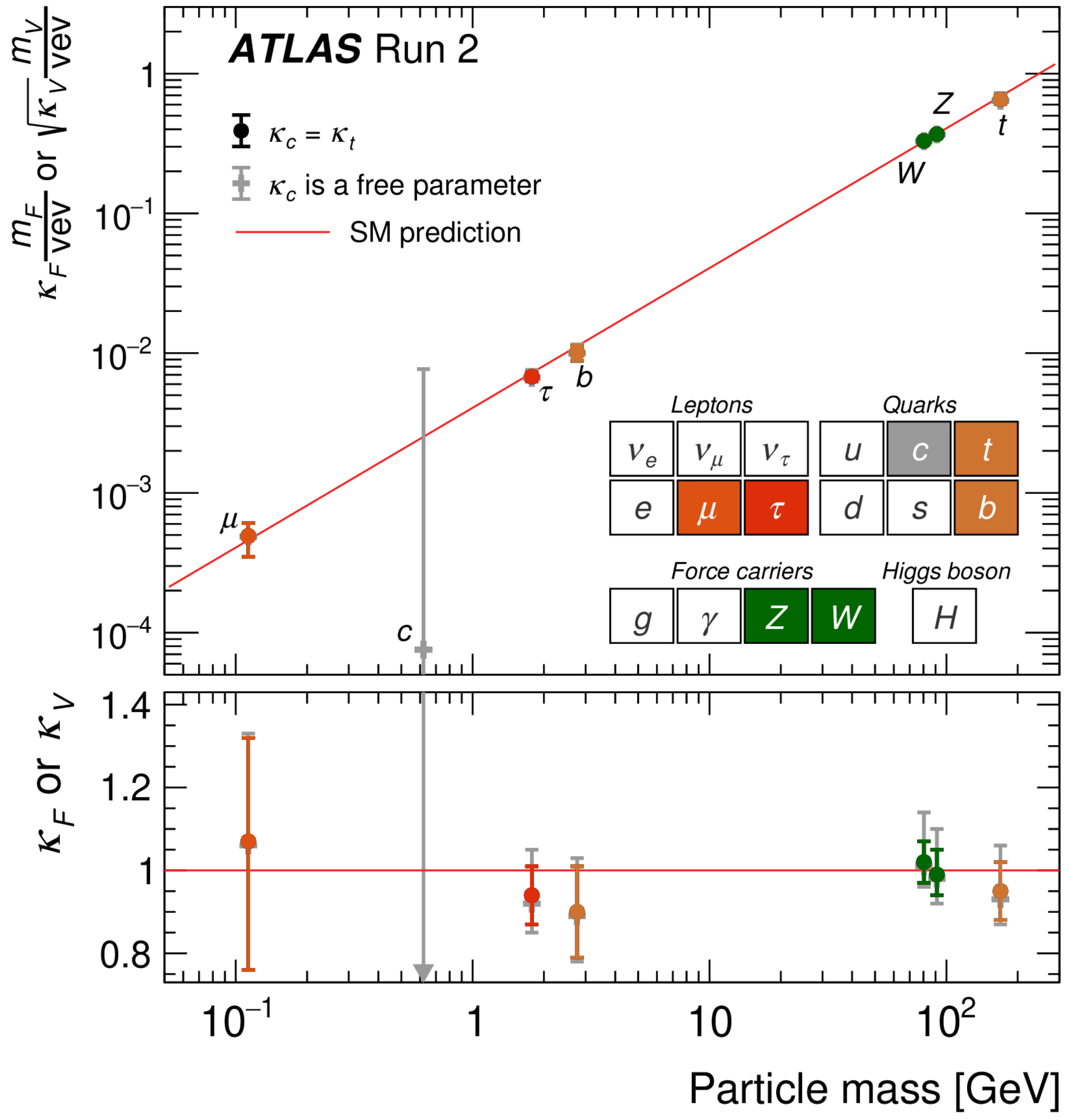
using the discovered Higgs boson as a tool


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

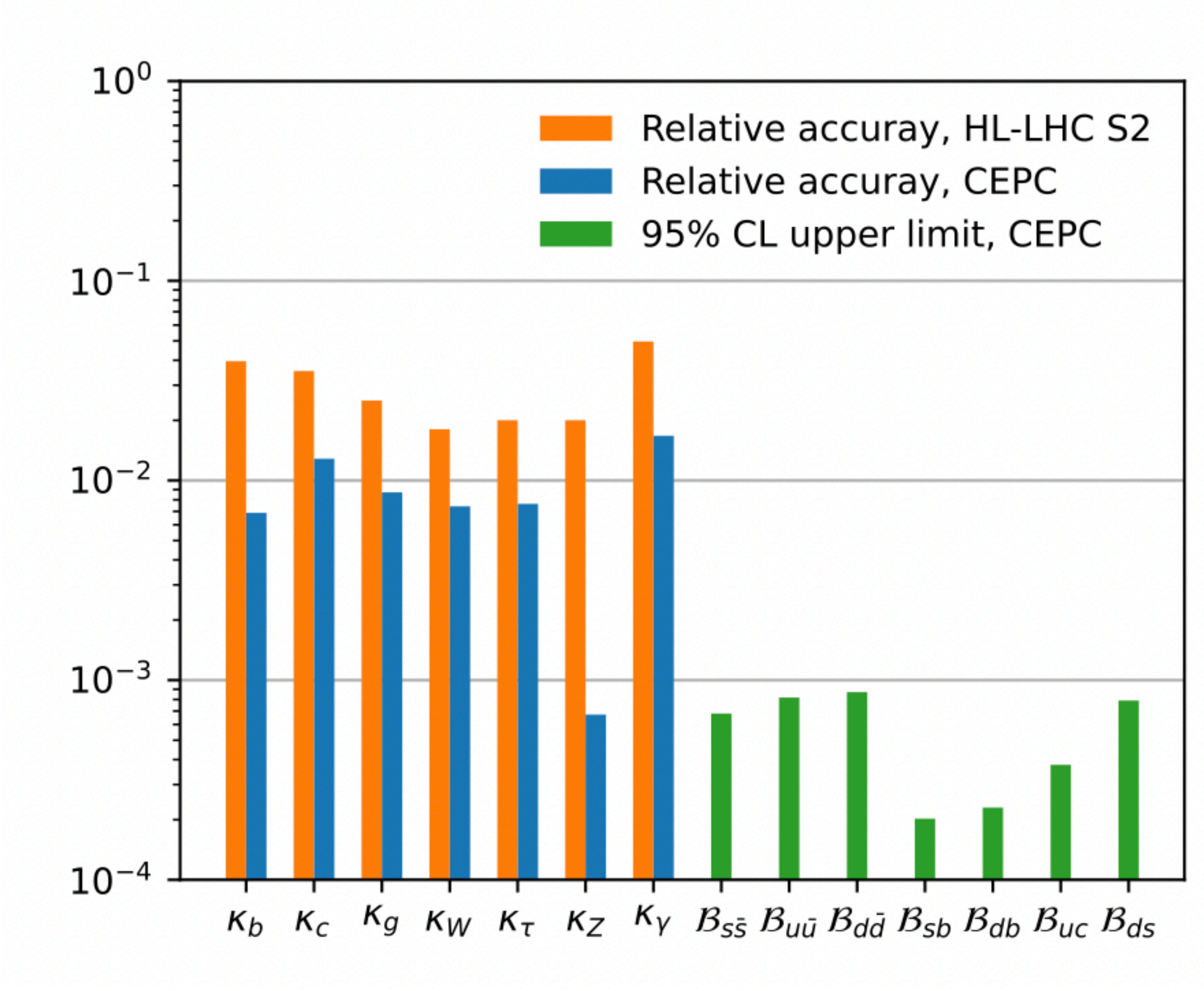

2025
BREAKTHROUGH PRIZE
IN FUNDAMENTAL PHYSICS
ALICE
ATLAS
CMS
LHCb
COLLABORATIONS AT
CERN'S LARGE HADRON COLLIDER

1.1 Coupling properties of Higgs boson

Higgs couplings with other fundamental particles



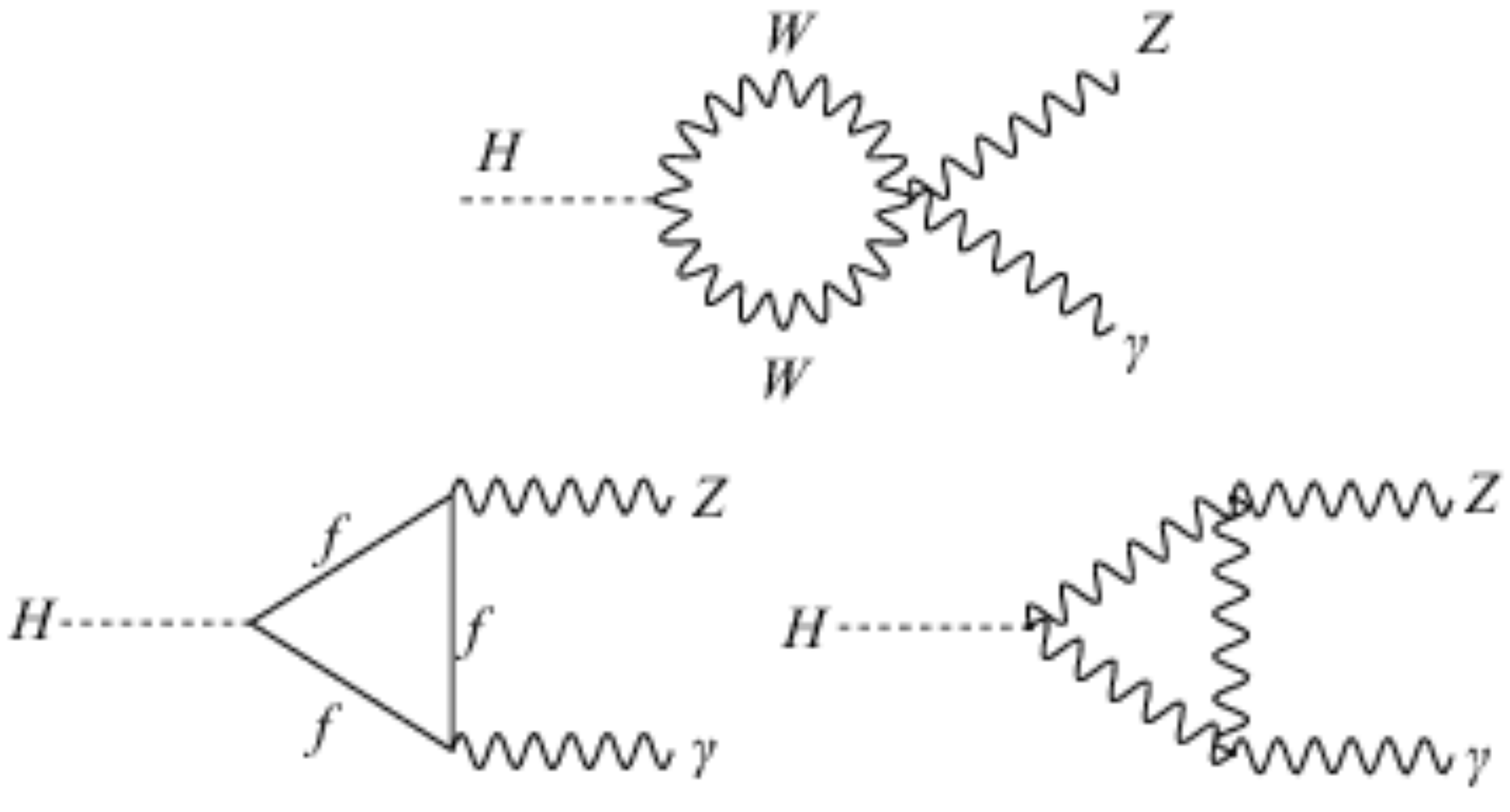
[Nature 607 (2022) 52-59]

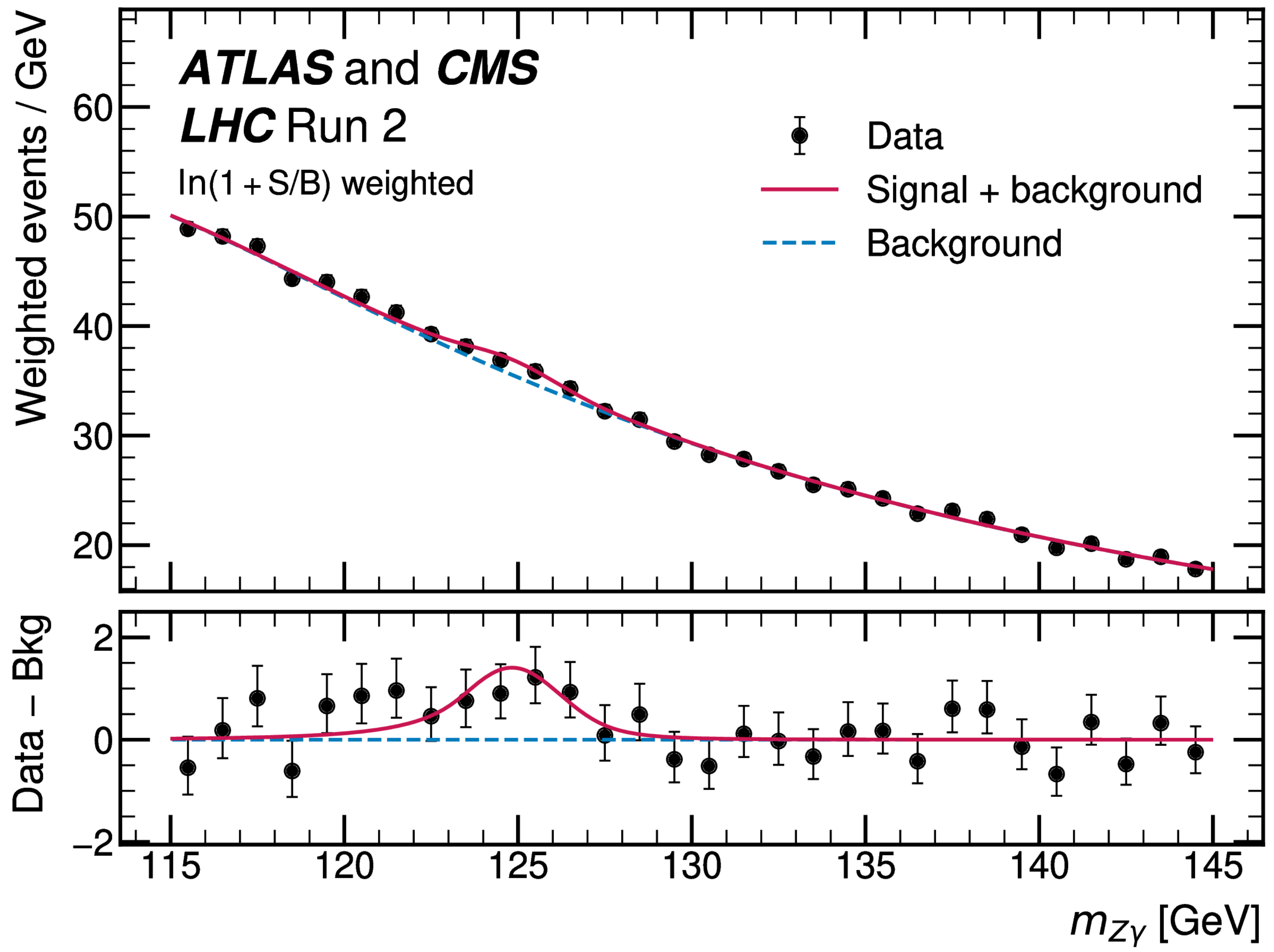


[Phys. Rev. Lett. 132 (2024) 221802]

- “Kappa” framework: assign coupling modifier to each interaction vertex (e.g. κ_t, …)
- LHC Run 2: good agreement with the SM across 3 orders of magnitude in particle mass
- CEPC: improved precision; sensitivity to Higgs→ss/Higgs→sb decays with jet origin ID

H→Zγ decay

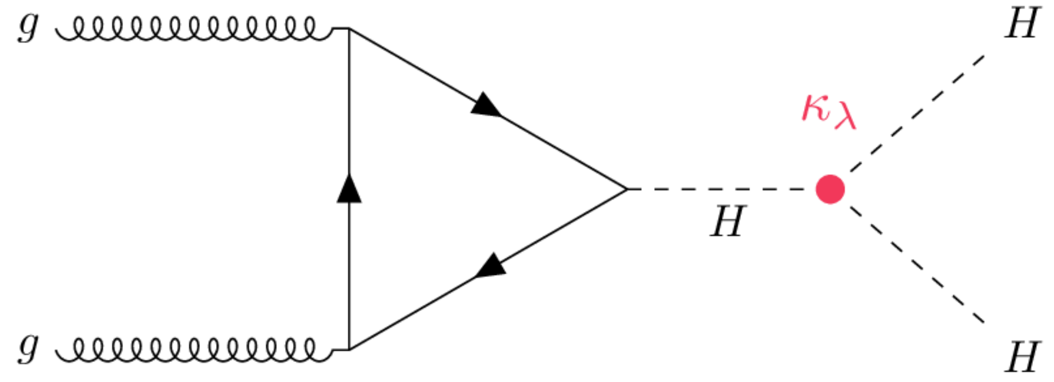


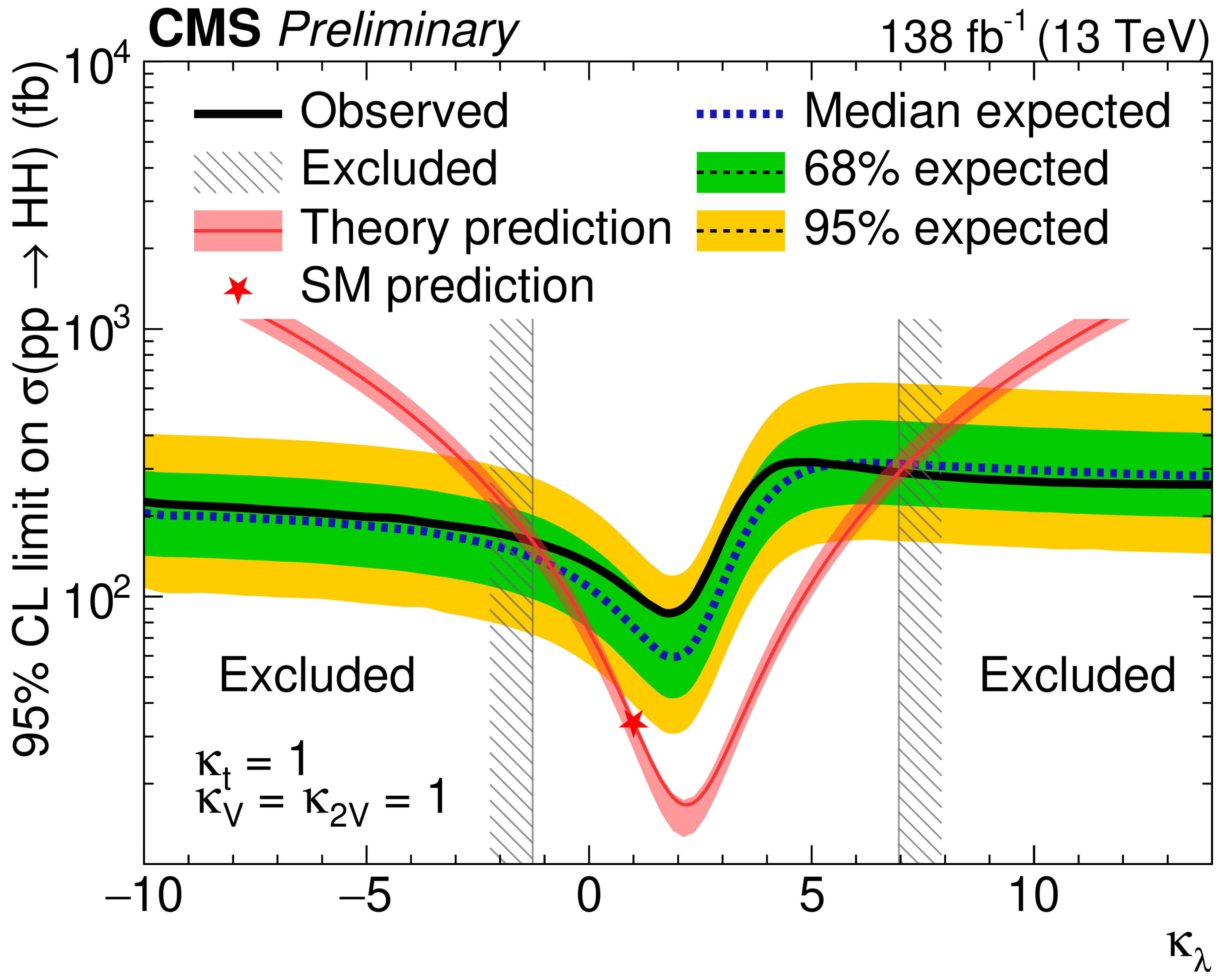


Phys. Rev. Lett. 132 (2024) 021803, Editor's Suggestion, Featured in Physics, Collection of the Year

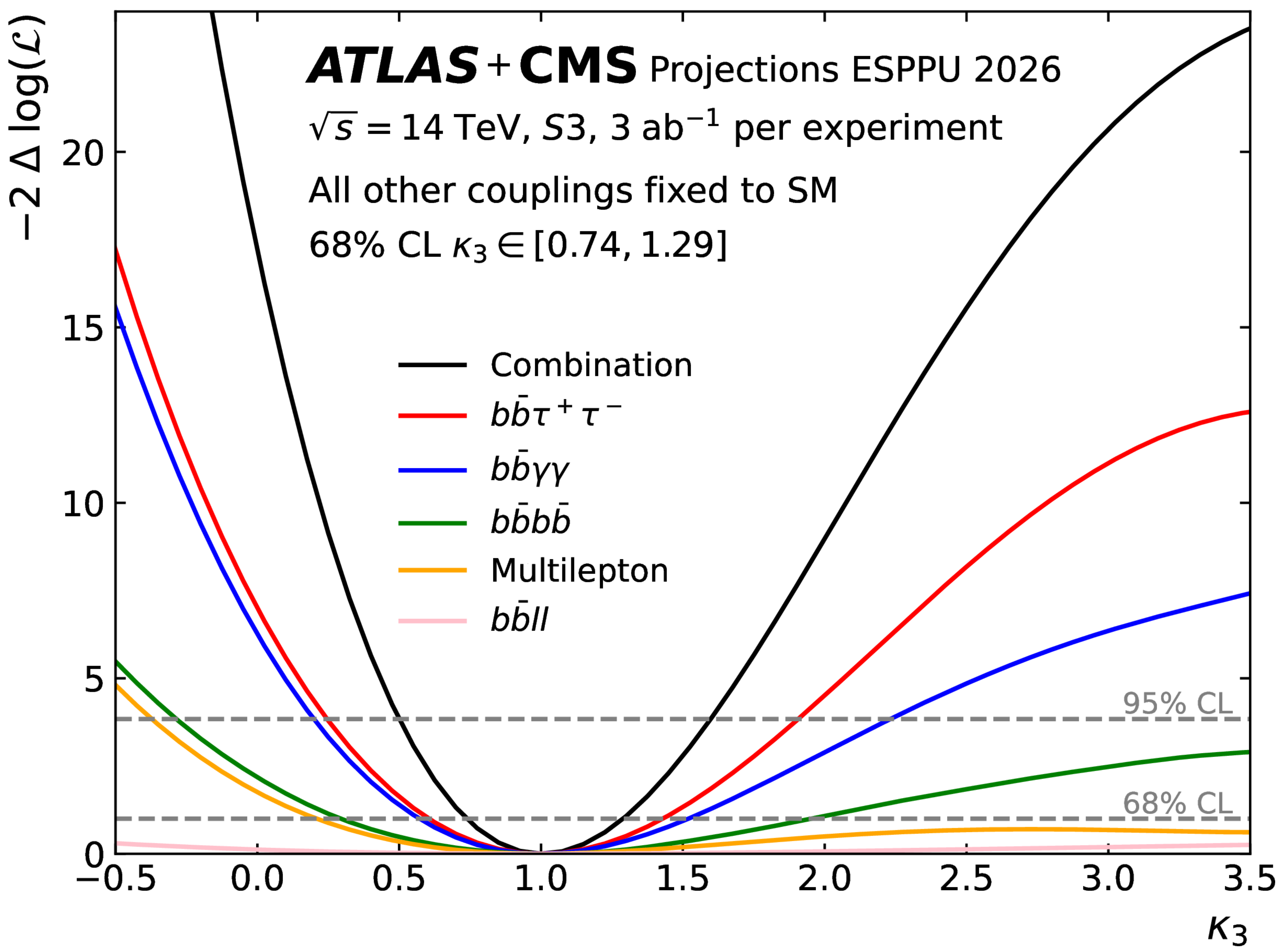
- BSM particles & couplings could be present in the quantum loops of H→Zγ
- The observed H→Zγ significance in ATLAS+CMS combined result is **3.4σ** (expected 1.6σ)
  - **First evidence** of the H→Zγ decay

Higgs self-couplings





[CERN Seminar 2024]



[arxiv:2504.00672]

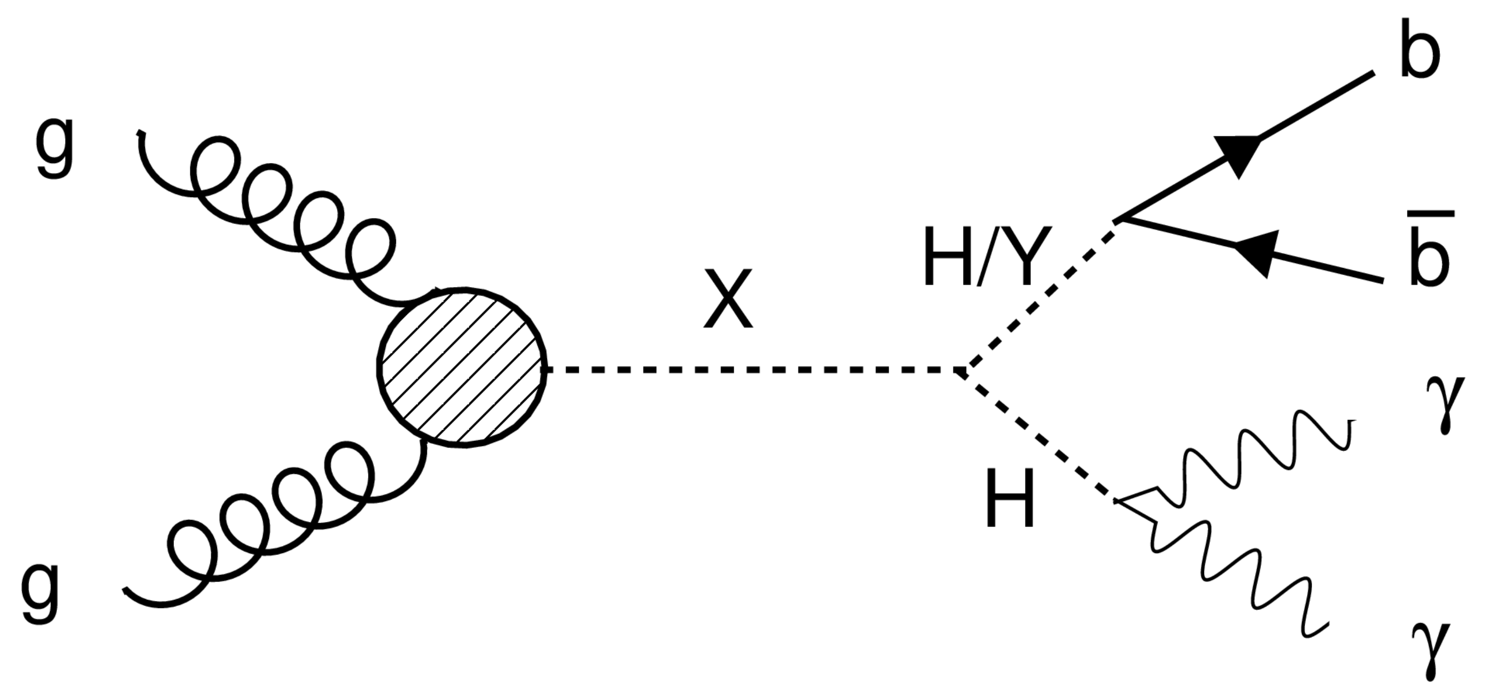
- **Higgs self-coupling may provide a portal to new physics beyond it**
  - Vacuum stability, early universe evolvement, …
- LHC Run 2: $-1.4<\kappa_\lambda<7.0$ (CMS); $-1.2<\kappa_\lambda<7.2$ (ATLAS)
- HL-LHC: $0.5<\kappa_\lambda<1.6$ (ATLAS+CMS)

1.2 Resonant production of Higgs boson

Resonant production of Higgs boson

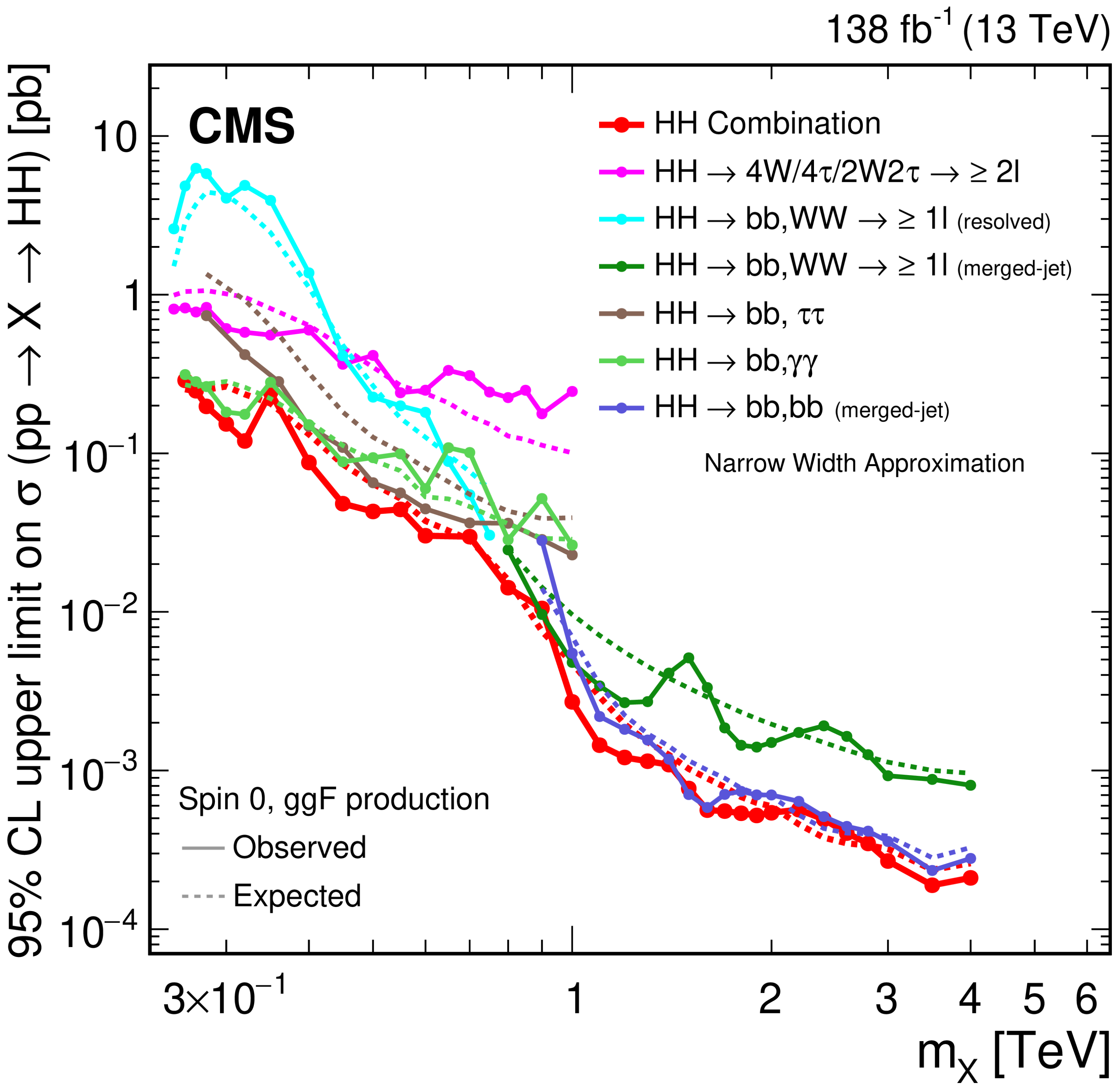
- Heavy resonance search channels including at least one Higgs boson plus another particle have formed an important part of the program of new physics searches at the LHC

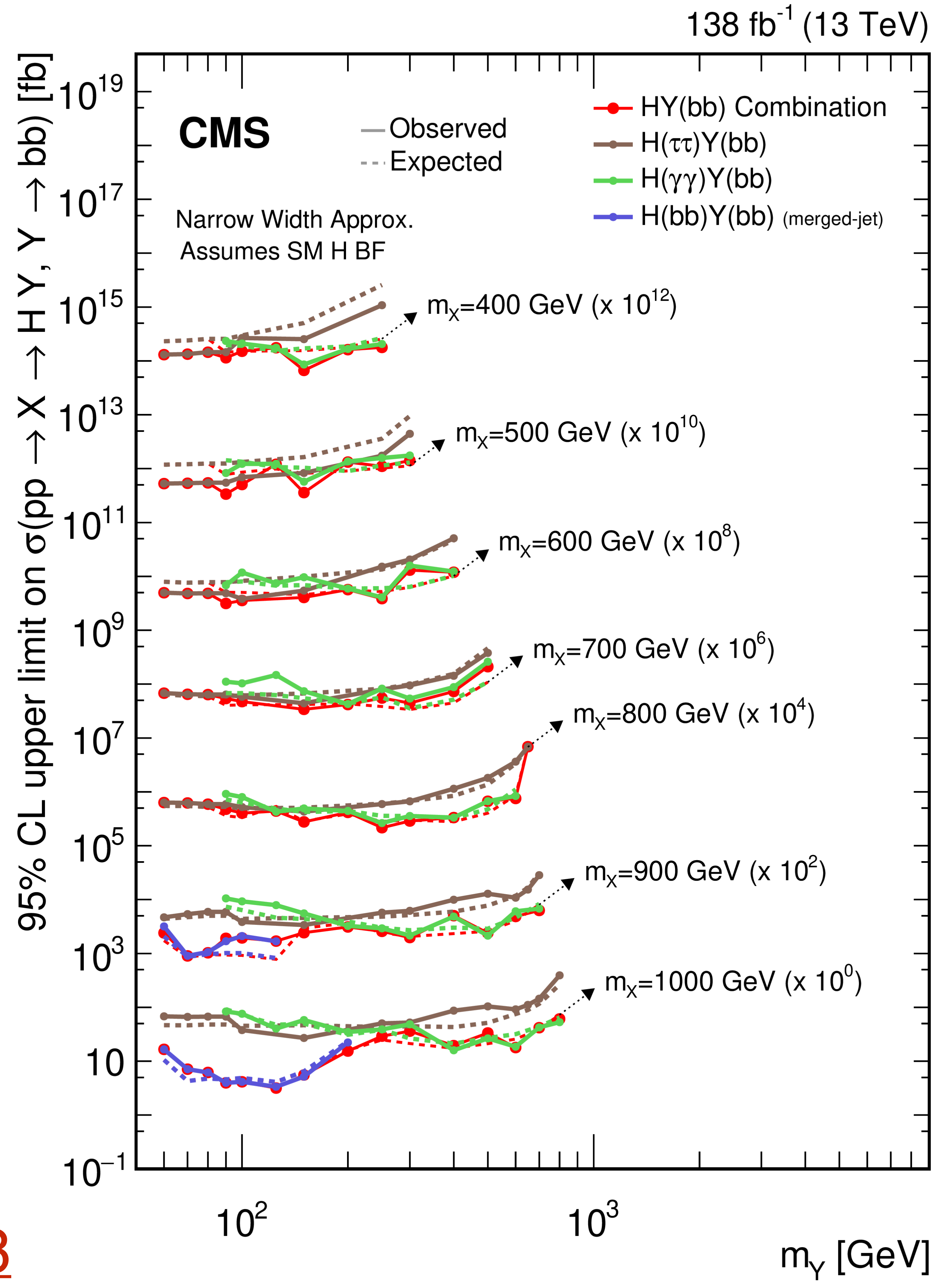
- Sensitive to many new physics models, including extended Higgs sectors and extra dimensions



Resonant production of Higgs boson

- Summarizing and combining search channels at CMS, we obtain cross section limits on resonant production of Higgs boson and constraints on relevant new physics models





Physics Reports 1115 (2025) 368

Resonant production of Higgs boson

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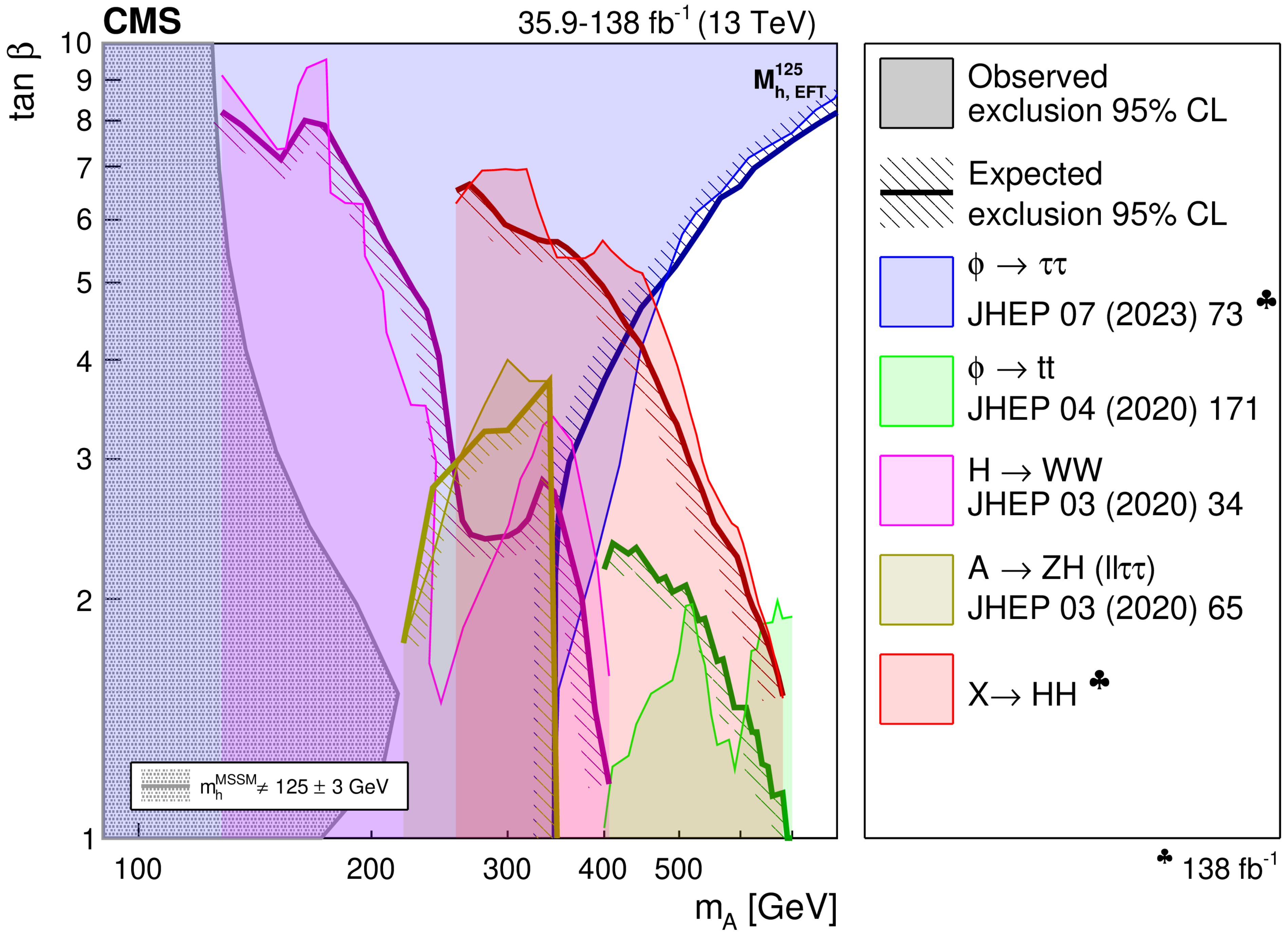
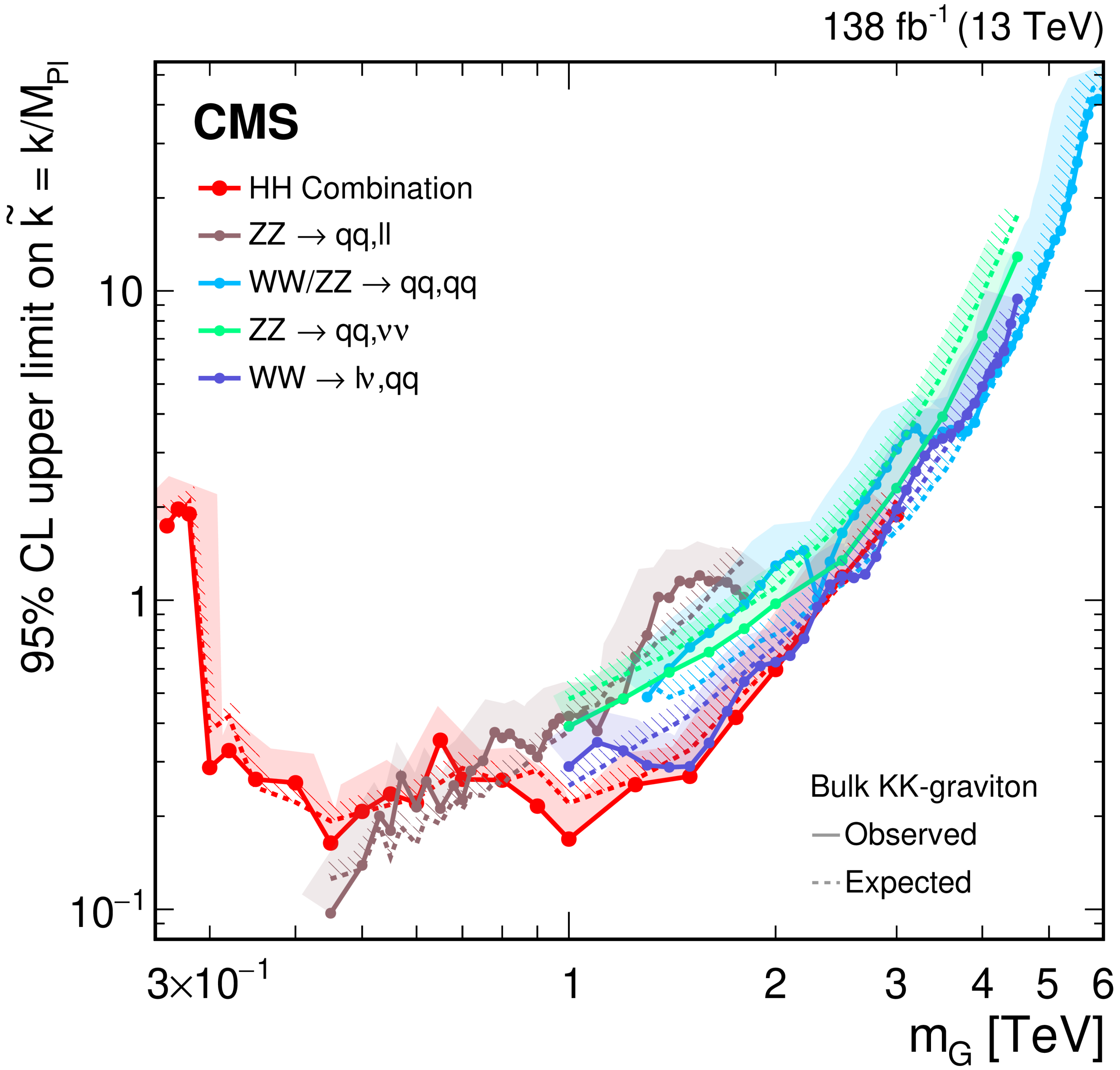


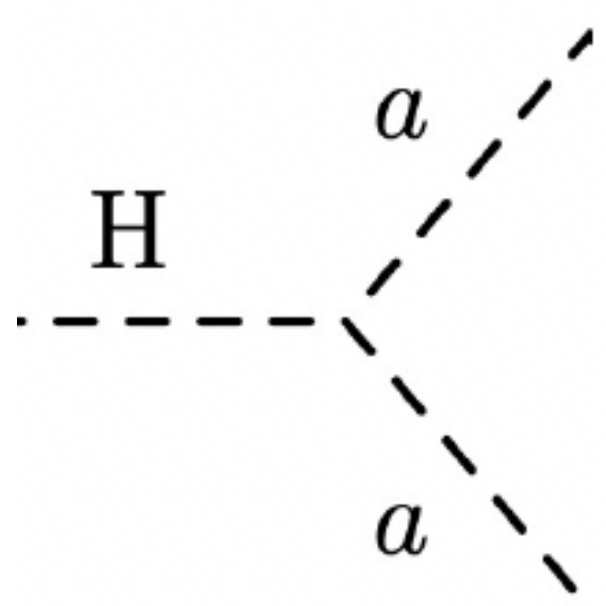


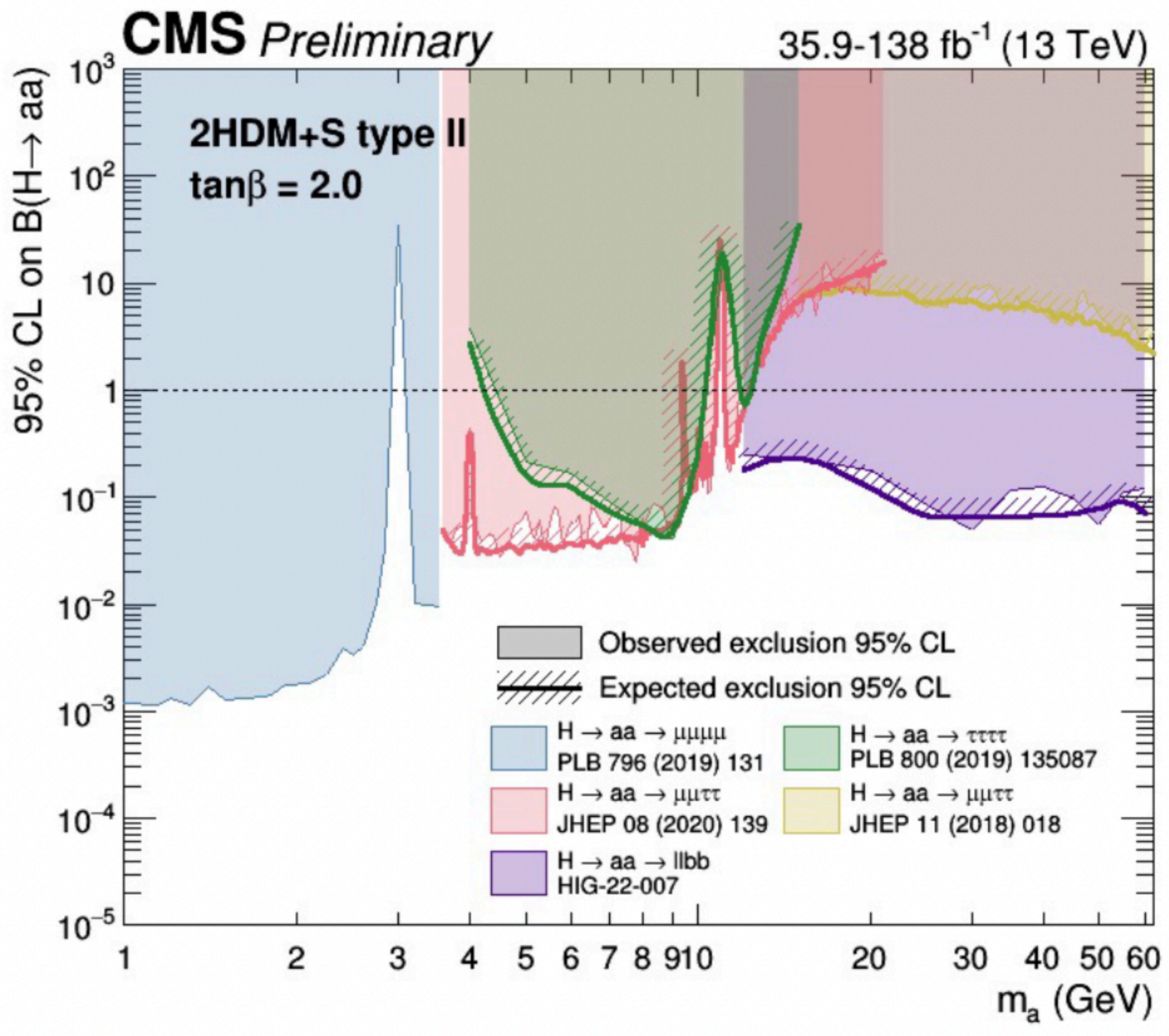
[Physics Reports 1115 (2025) 368]

1.3 Exotic decay of Higgs boson

Exotic decay of Higgs boson

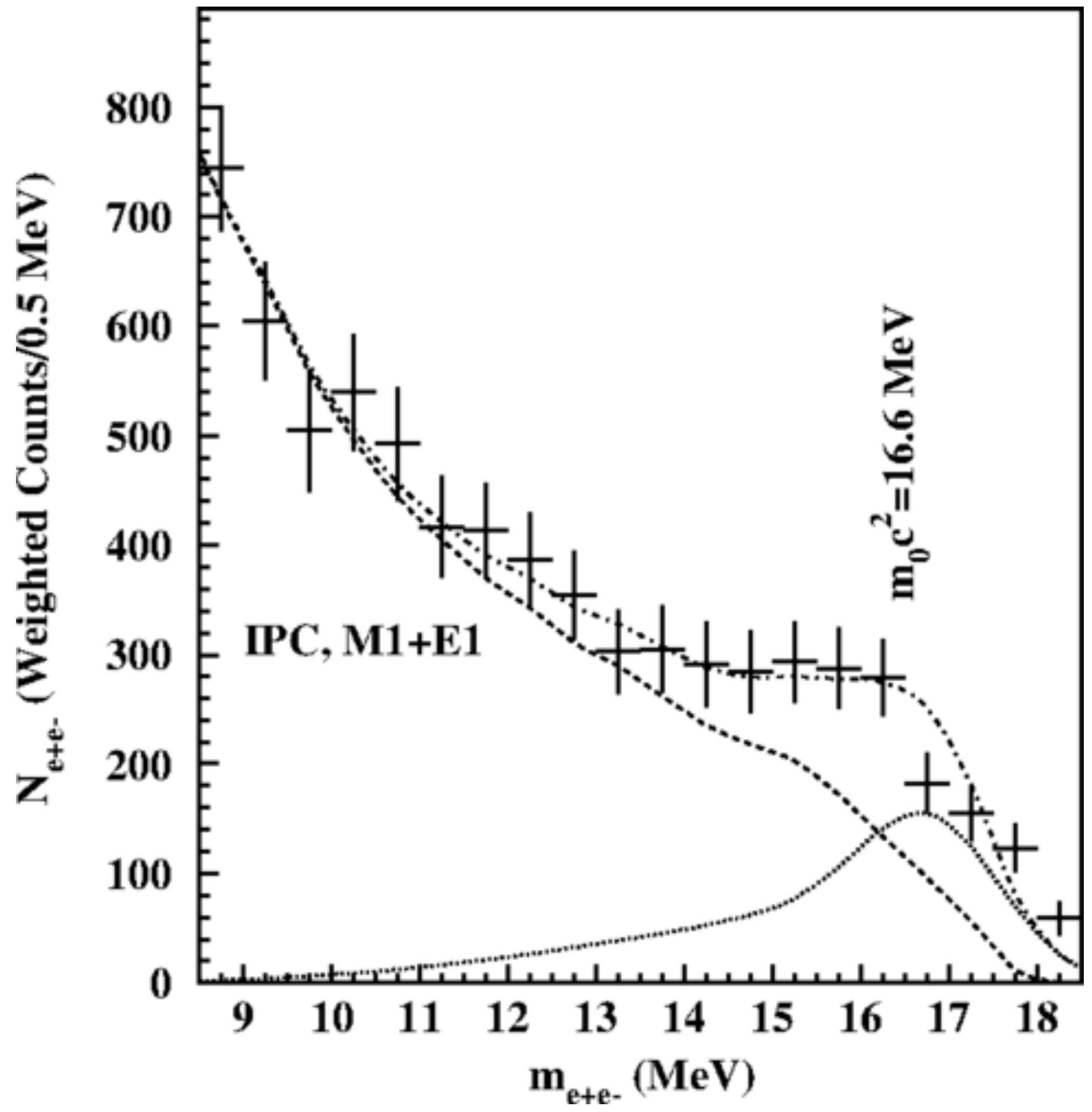
- Higgs decays to exotic particles predicted by various BSM models: two-Higgs-doublet-like models, axion-like particle, etc.



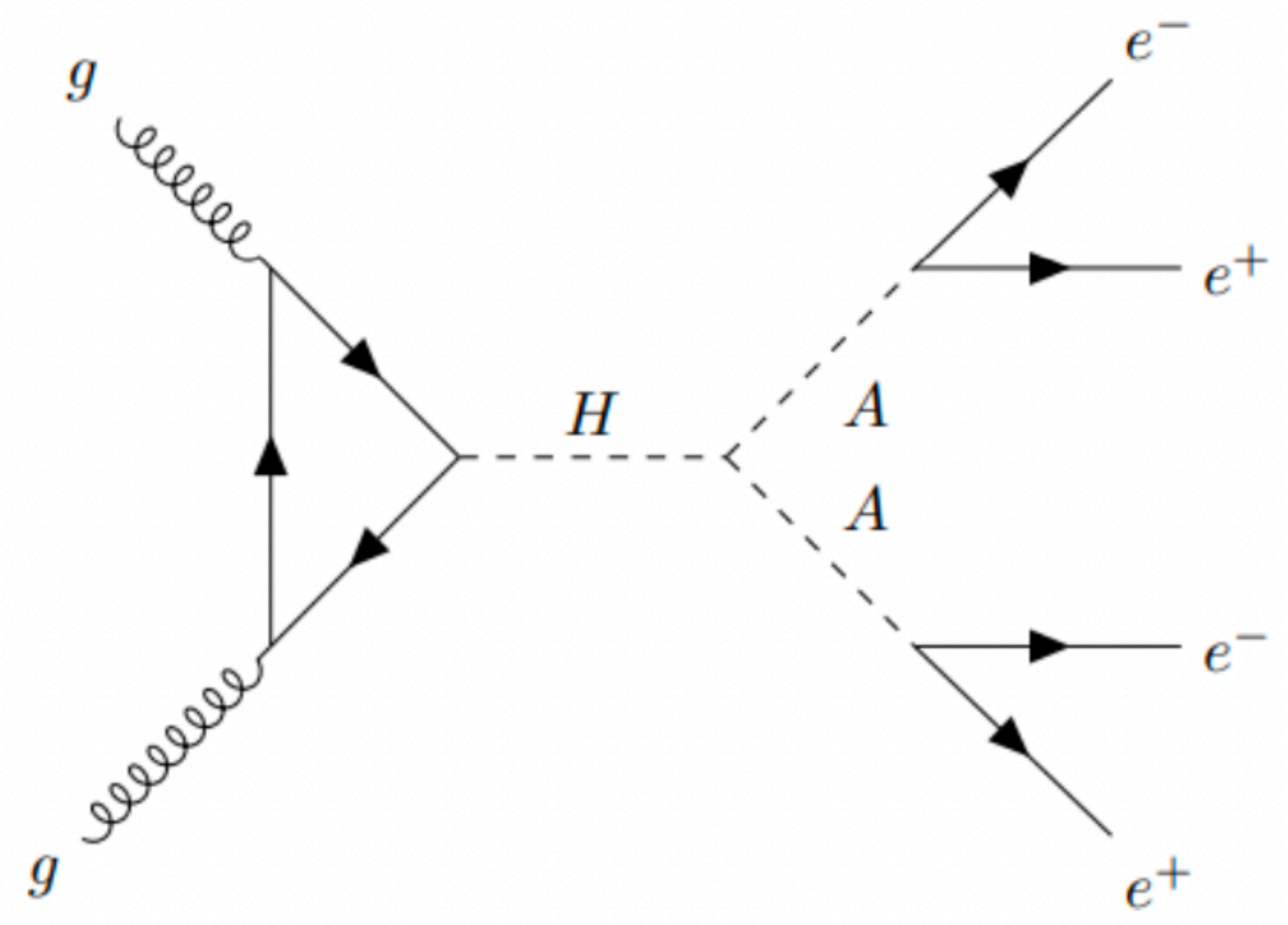


Exotic decay of Higgs boson

- ATOMKI anomaly give us motivation to search tens of MeV ALPs
- Electron channel is important for searching for ALPs in that range
- Theoretical work by Liu Jia et al: JHEP 05 (2021) 138
- We are preforming first search for H→aa→4electrons at CMS, aiming for LHCP2025



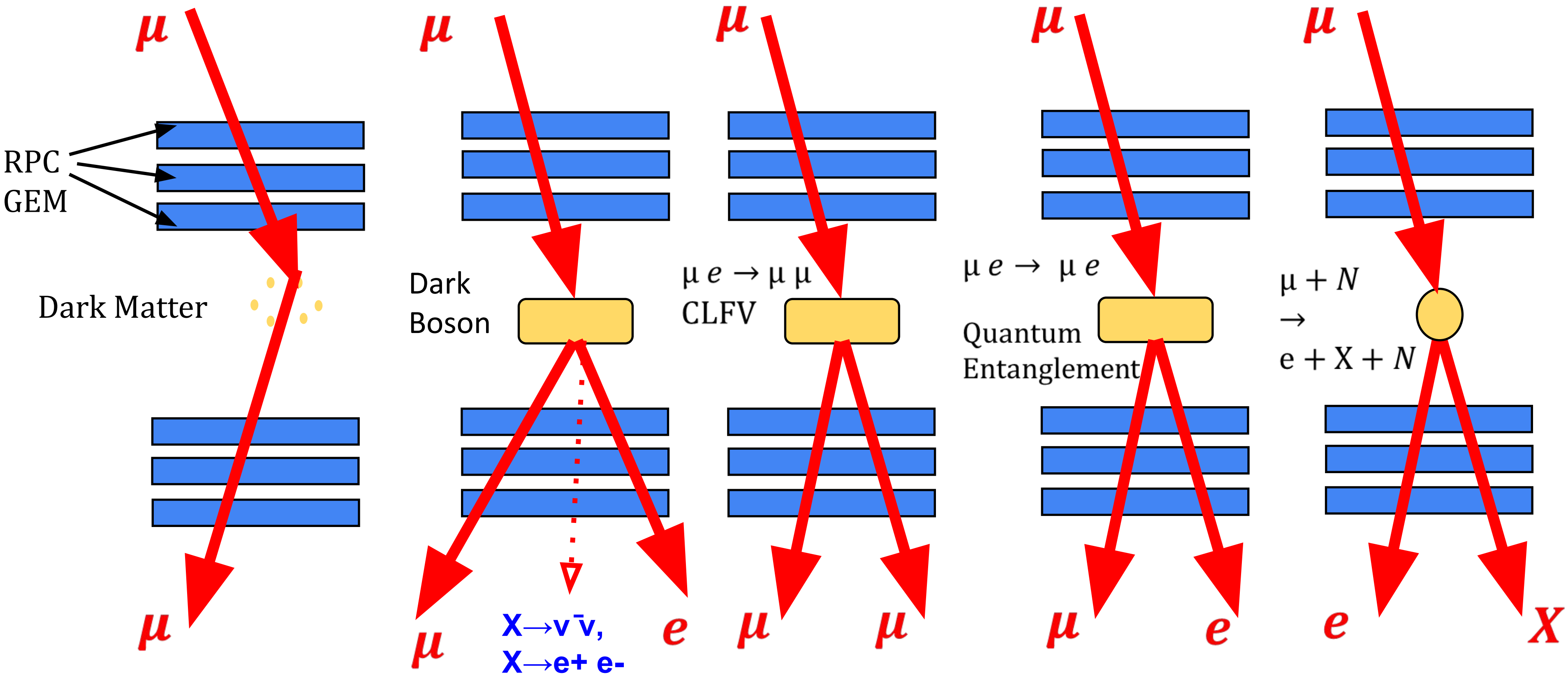
ATOMKI anomaly



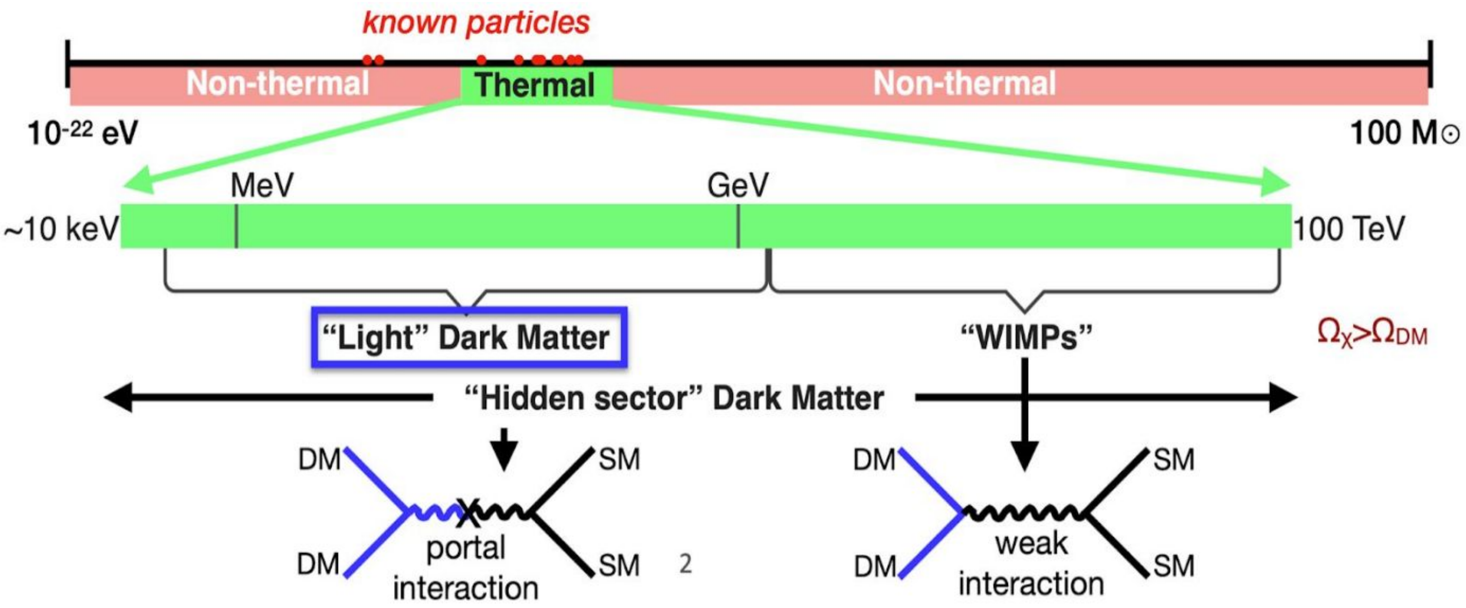
2. Some new physics studies with PKMu project

Microscope: multi-purpose platform

→Cosmic μ or μ beam



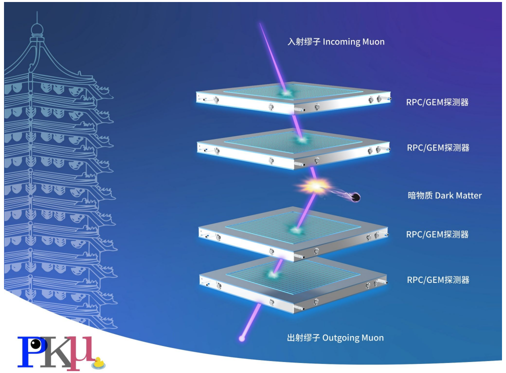
Light Dark Matter → Dark Sector

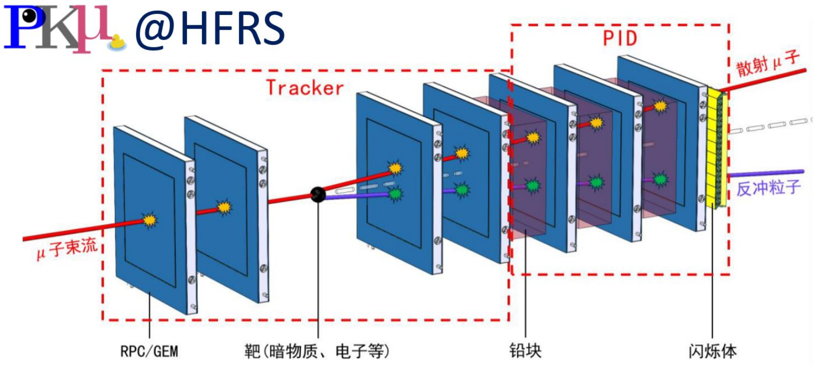


Minimal scenarios with light (sub-GeV) dark matter whose relic density is obtained from thermal freeze-out must include new light mediators. In particular, a very well-motivated case is that of a new "dark" massive vector gauge boson mediator. JHEP03(2018)084 Granada19 LDMX2024
(获得热遗留下来的轻(次GeV)暗物质的最低限度情景必须包含新的轻媒介粒子。特别是，一个非常有动机的情况是存在一种新的"暗"质量矢量规范玻色子作为媒介粒子。)

Muon Philic Dark Sector

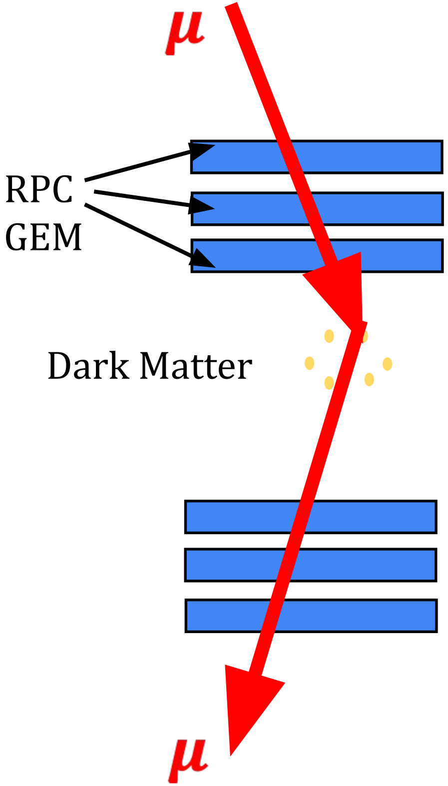
- Muon Philic Dark Matter may be possible or even <u>necessary</u>!
    - $L\mu - L\tau$ gauged model (Z', χ) quite popular recently
  - 1) Direct searches for DM
    - See the PKMu proposal: <u>*Phys.Rev.D* 110 (2024) 1, 016017</u>
  - 2) On target experiments for Dark Boson: (see also <u>cosmology constraints</u>)
    - <u>LDMX</u>,<u>DarkShine</u>; eN → eNZ', $Z' \to \nu\bar{\nu}$ or $Z' \to \chi\chi$ (dark matter)
    - <u>NA64μ</u>, <u>MMM</u> μN → μNZ', $Z' \to \nu\bar{\nu}$ or $Z' \to \chi\chi$ (dark matter)
    - <u>MuonE</u> μe → μeZ', $Z' \to \nu\bar{\nu}$ or $Z' \to \chi\chi$ (dark matter)

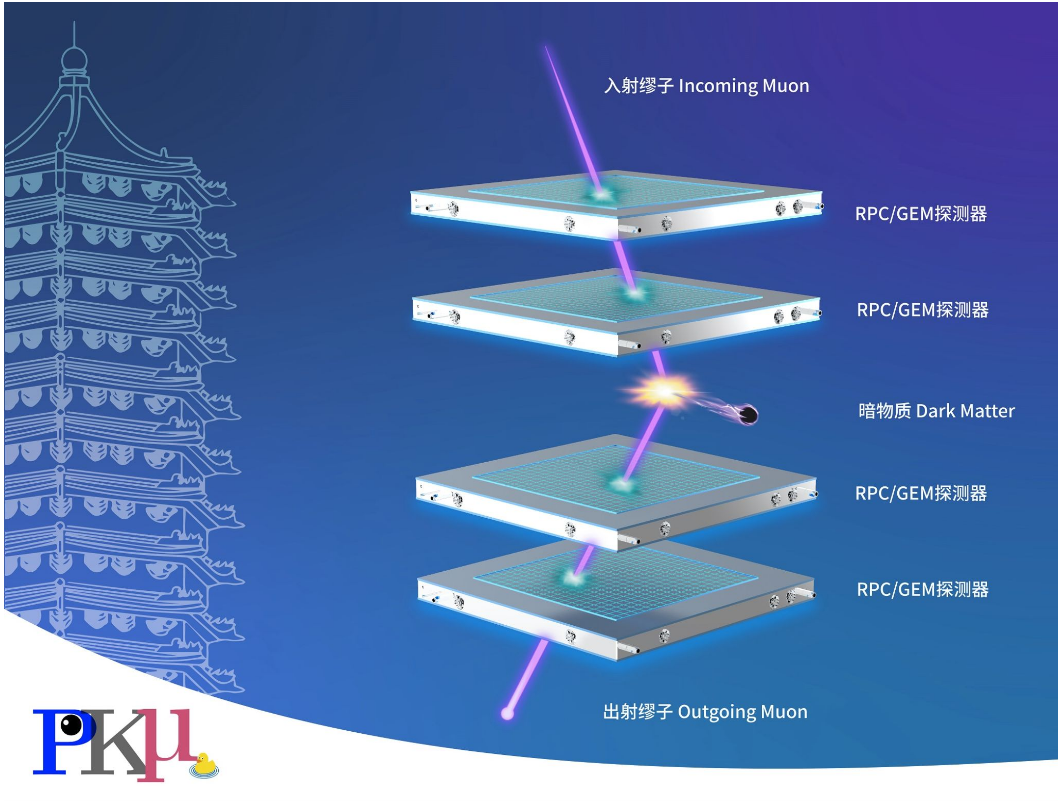




参考文献: [1] Phys. Rev. D 110, 016017 [2] arxiv:2410.20323 [3] arXiv:2411.12518 [4] Nucl. Instrum. Methods. Phys. Res. A 663 (2012) 22-25

1) Direct searches for DM



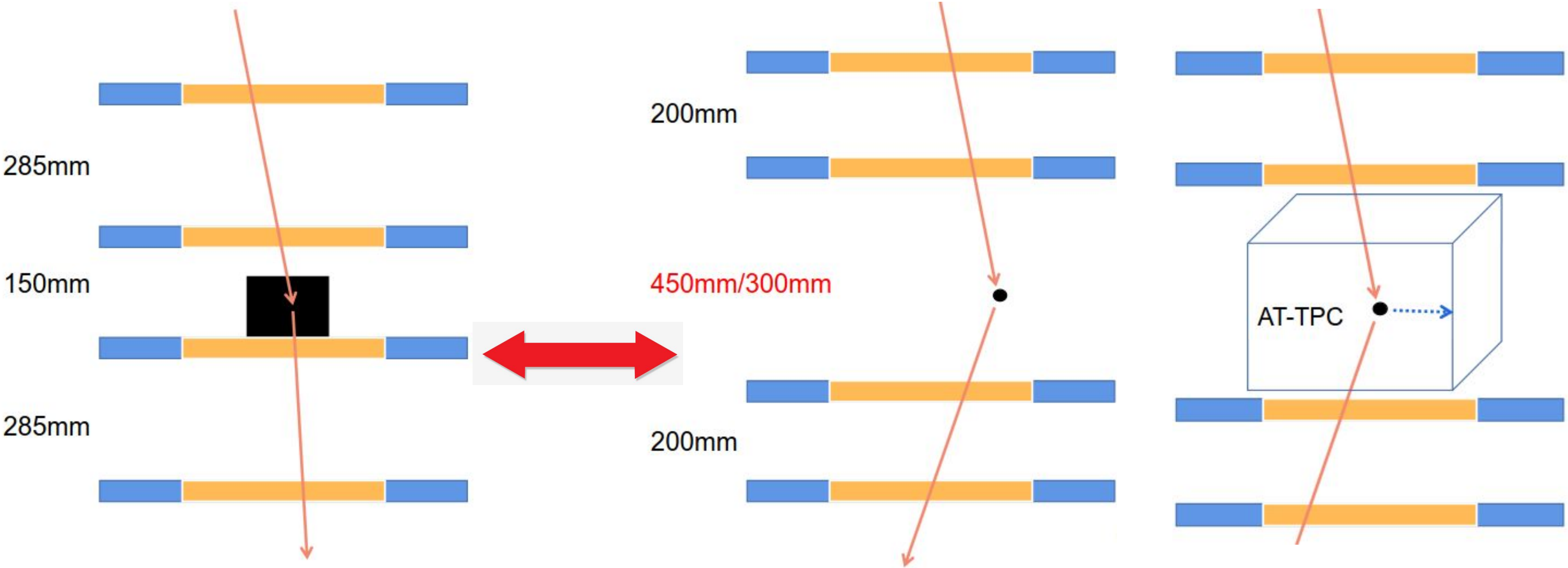


Muon Tomography and Muon-DM scattering

Muon Tomography ⟷ Dark Matter Search

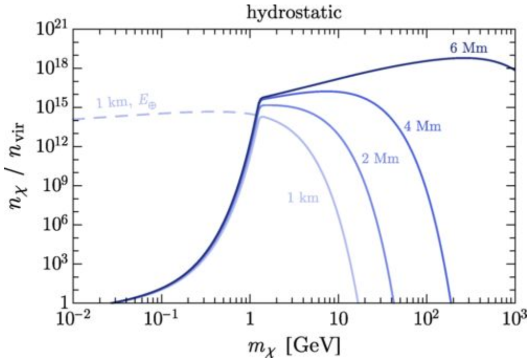
缪子成像 暗物质寻找

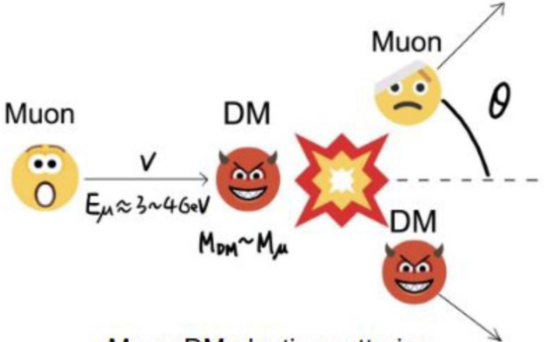
Phys.Rev.D 110 (2024) 1, 016017



Slow Dark matter

- Earth bounded Dark Matter: terrestrial density of strongly-coupled relics
  PRL. 131 (2023), 011005, PRD 109 (2024), 075027 PRD 103, 115031 (2021)
  - A fraction (fD) of strongly interacting dark matter
  - can be trapped in the Earth, and distributed more uniformly.
  - The density (fE) can be large! **fE=fD×nD** ~ fD*10^15/cm^3
- Alternative detection techniques needed
  - to detect such a large density of slowly moving DM
  - Superconducting Cloud Chamber (for Milli-charged Particle though)
- **<u>For slow or frozen DM, no proposal yet!</u>**
  - → **limits on both cross section and <u>fE=fD×nD</u>**

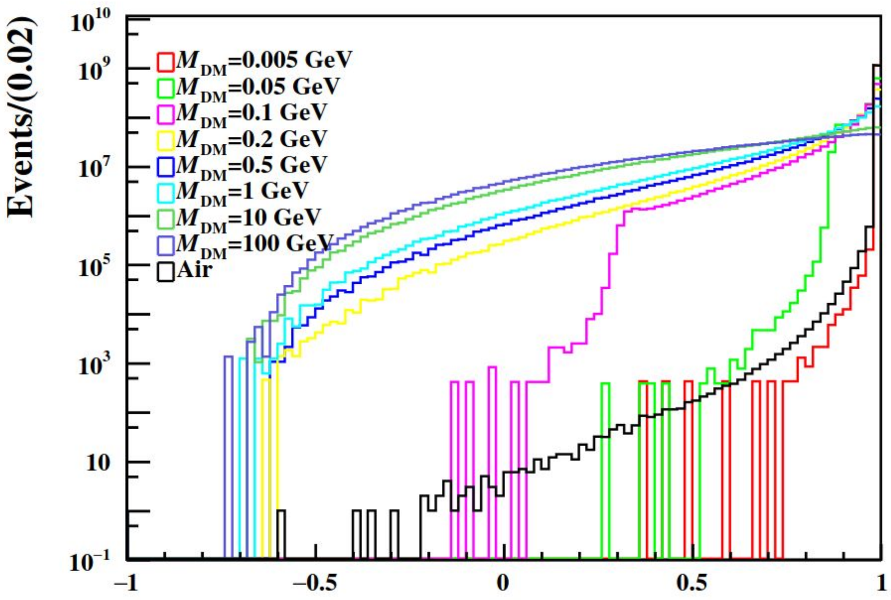


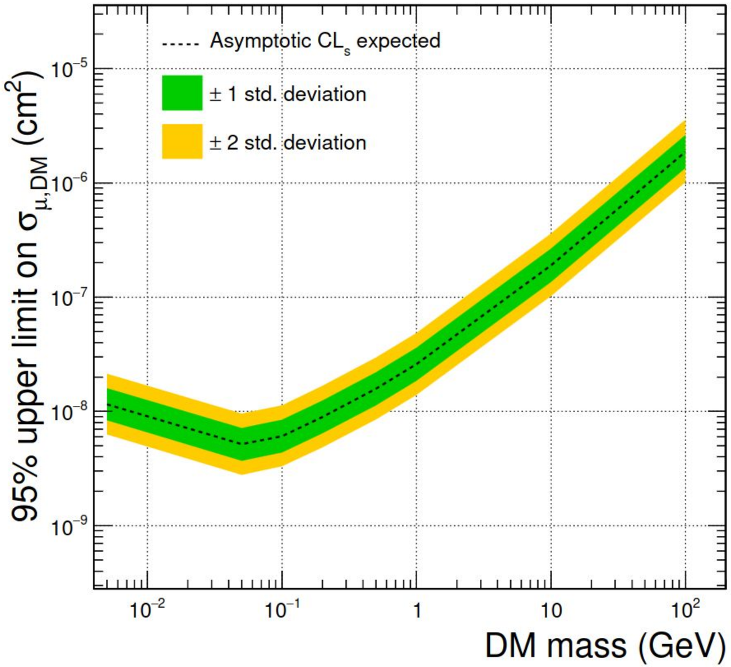


Muon-DM elastic scattering

Different from XENON/PandaX:
Relativistic muon hit quasi-static DM

Muon DM Box experiment: expected results





- "Asimov" data is used
- Binned maximum likelihood fits
- UL determined by CLs method
- Only take statistical uncertainty into consideration

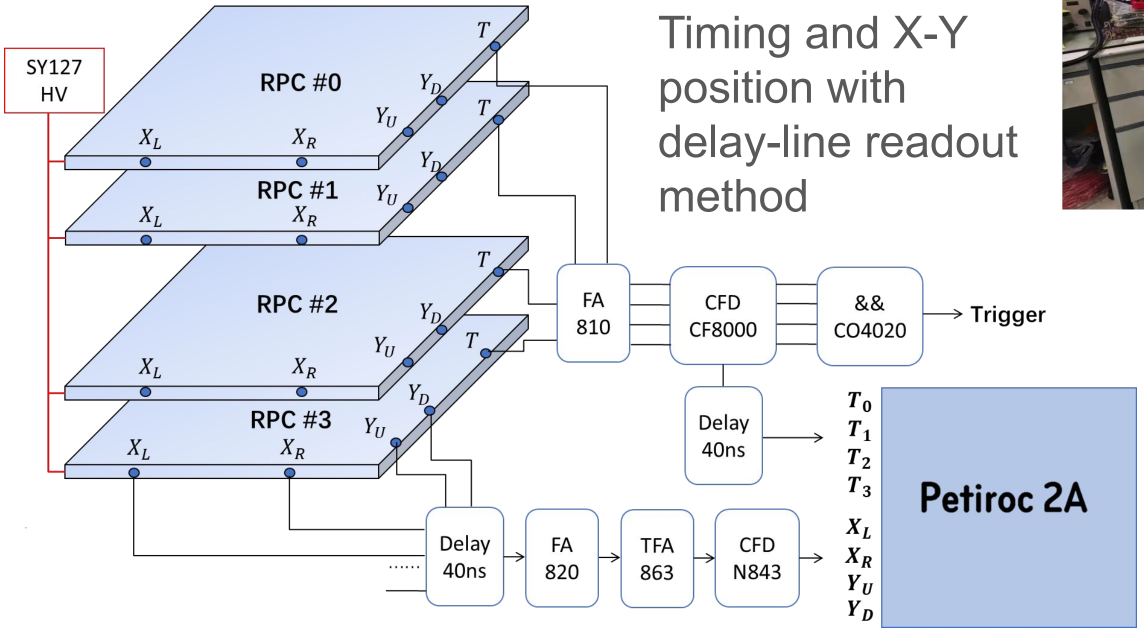
In the exotic DM scenario as mentioned previously, the limit can approach μb

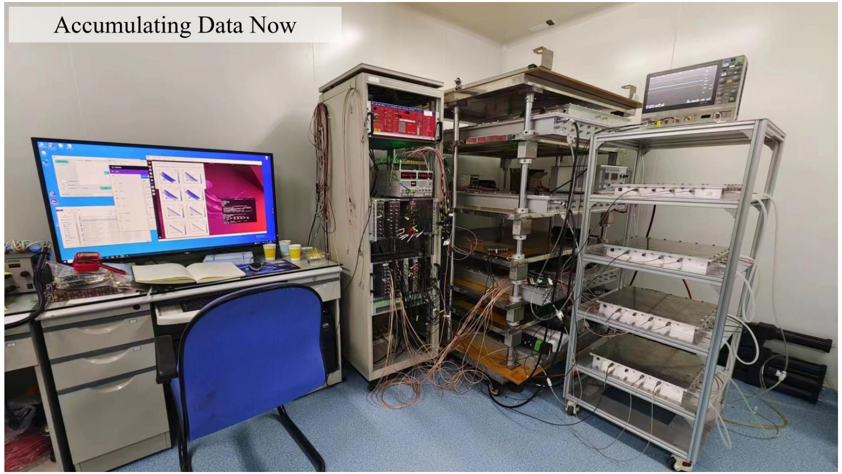
Current Box Exp. Status

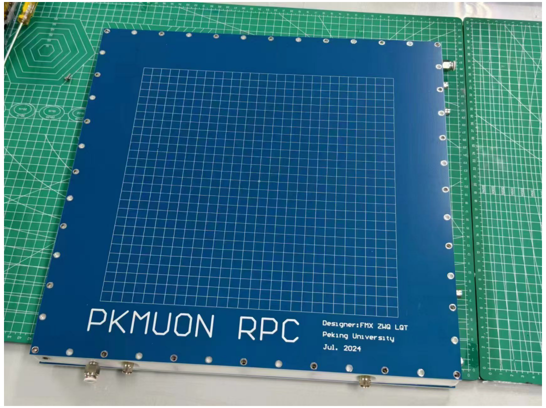
4-station 20cm*20cm RPC for the moment

Petiroc 2A is a 32-channel front-end ASIC

Timing and X-Y position with delay-line readout method

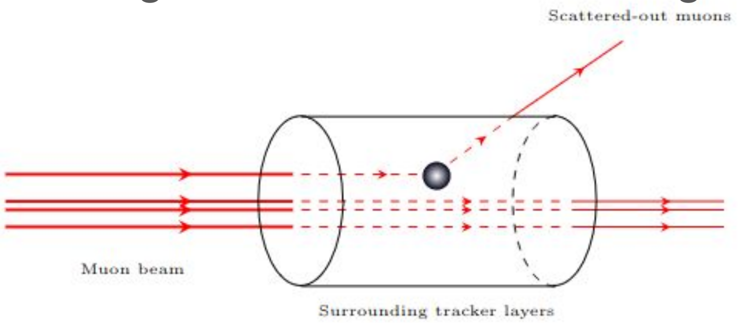




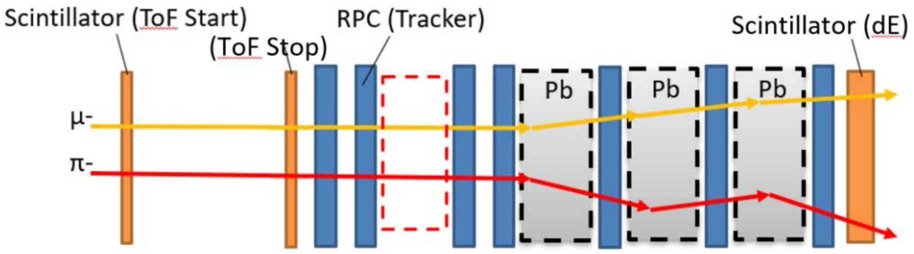


Current Beam Exp. Status

Interfacing with a muon beam at e.g. HIAF



Cylindrical GEM (CGEM) detector structure for BESIII inner tracker system upgrade



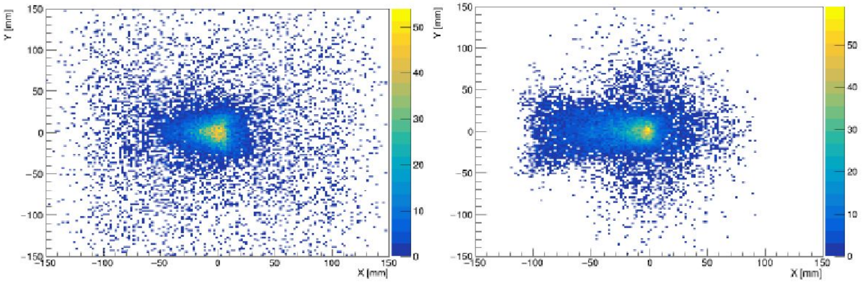


图 6.9: 左：1GeV 缪子束流束斑轮廓。右：3GeV 的缪子束流的束斑轮廓

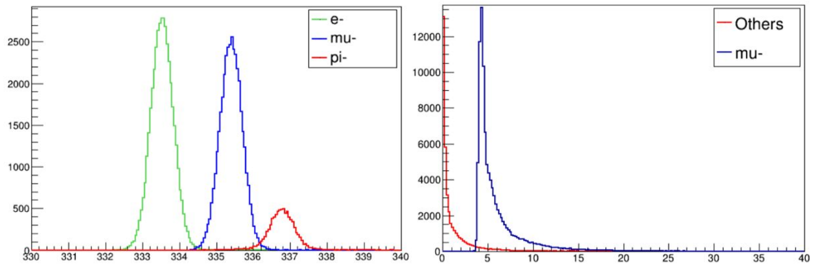
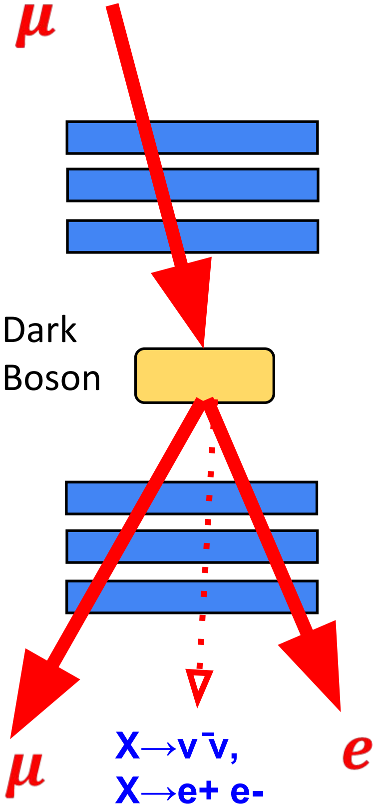
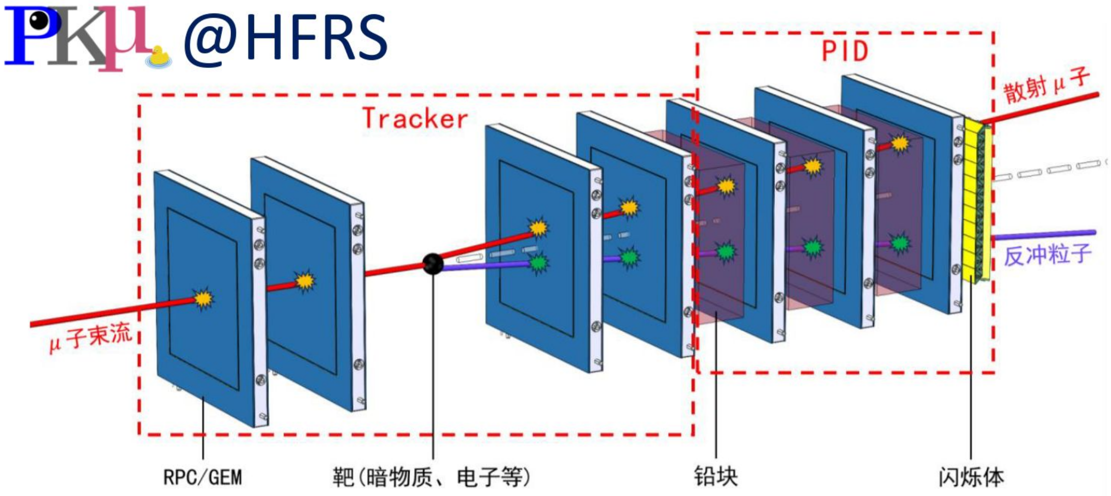


图 6.13: 缪子散射探测系统信号与背景响应模拟：成像系统前飞行时间谱（左）；末端闪烁体能量损失谱（右）

2) On target experiments for Dark Boson

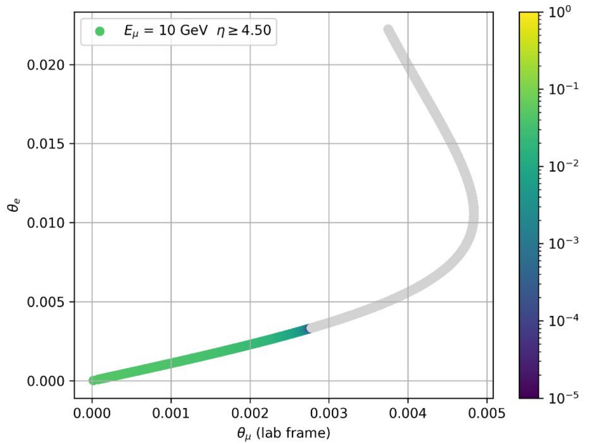




参考文献：[1] Phys. Rev. D 110, 016017 [2] arxiv:2410.20323 [3] arXiv:2411.12518 [4] Nucl. Instrum. Methods. Phys. Res. A 663 (2012) 22-25

Z' and X at PKMu@HFRS

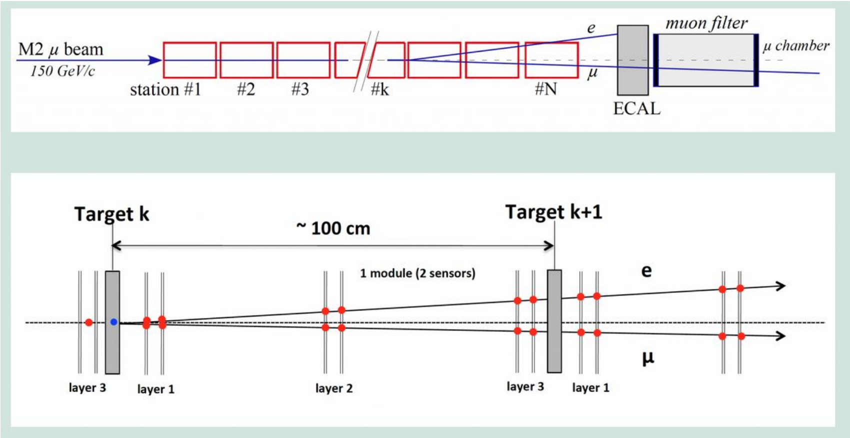
- **1-10 GeV muon scattered on electrons in target:**
  - C.O.M energy is around 10 MeV!
  - Sensitive to $L_\mu - L_\tau$ Z' boson at around 1-100 MeV:
    - μe → μeZ', Z'→ν ν̄
  - Also matches the mass range for ATOMKI X17 MeV anomaly
    - μe → μeX, X→ ν ν̄, e+ e-;
    - Search for pseudoscalar bosons decaying into e+e− pairs in the NA64 experiment at the CERN SPS: *PRD 104 (2021) 11, L111102* e-N→e-N + a, a → e+ e-
    - See also tensor and scalar options in arXiv:2501.05507
      - *"the measurements from the two experiments (ATOMKI and MEGII) remain compatible within 2σ" and "A CP-even scalar could serve as potential solution to the anomalies observed in the Helium and Carbon data and that will become relevant in case the null result from the MEG-II search in Beryllium transitions will be confirmed."*

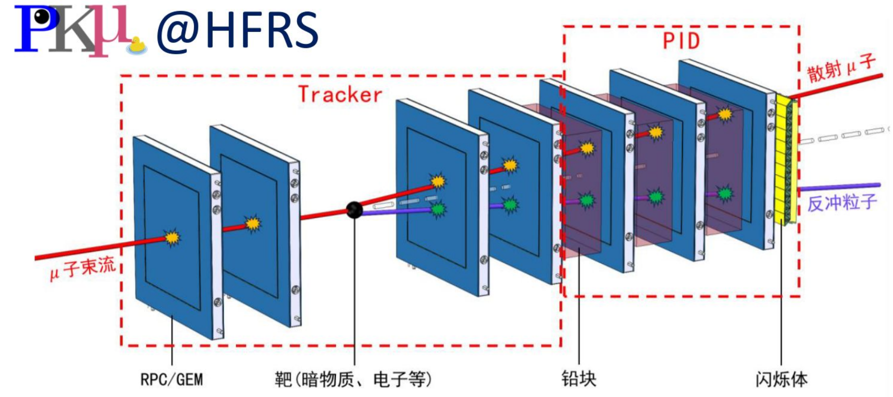


arXiv:2411.12518

PKMu@HFRS vs. MuonE

- Muon Beam energy: 150 GeV vs. 1-10 GeV
- C.O.M energy for PKMu@HFRS is around 10 MeV
  - suitable for low mass searches
- Detector Can be more compact





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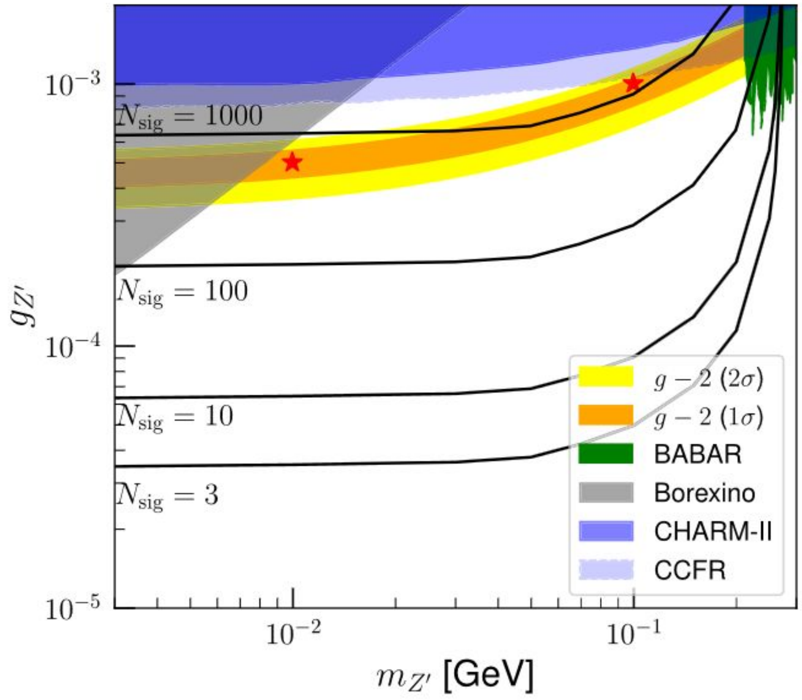
NA64 has limited angle acceptance (the beam energy is high as 150GeV), that may be the reason it is not sensitive to Mx>16 MeV

PKMu@HFRS vs. MuonE



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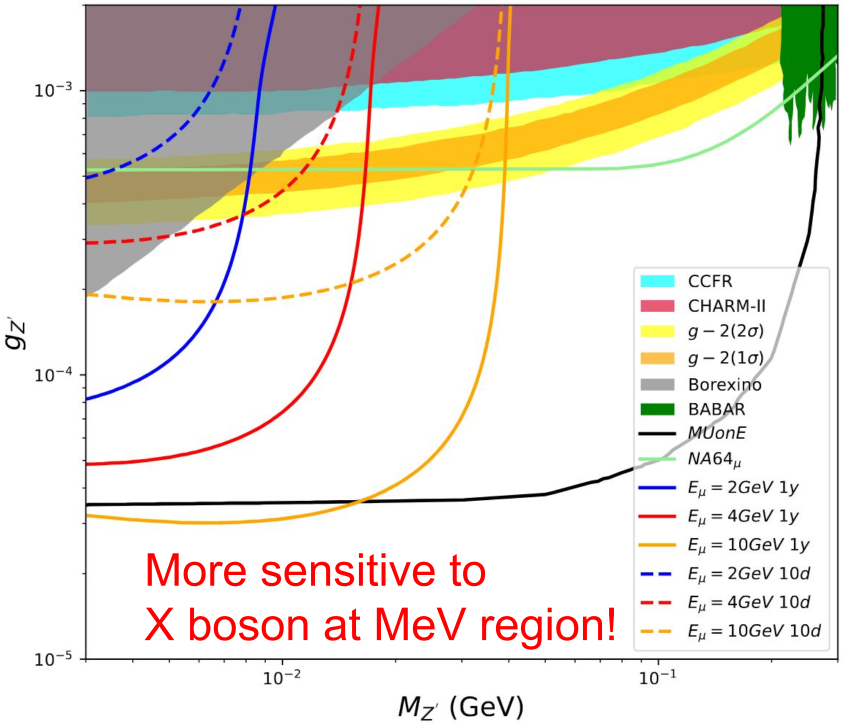


Preliminary results

Our roadmap to detect Dark Sector

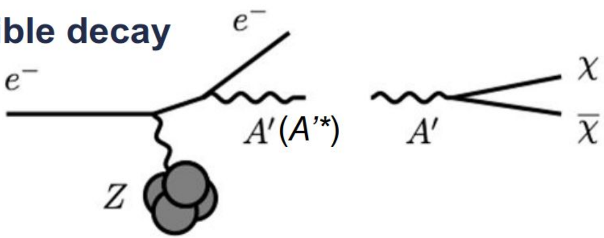
A compact detector for muon scattering with target electrons or nuclei:

Using RPC+GEM to measure angular direction; Scintillator and absorber for PID

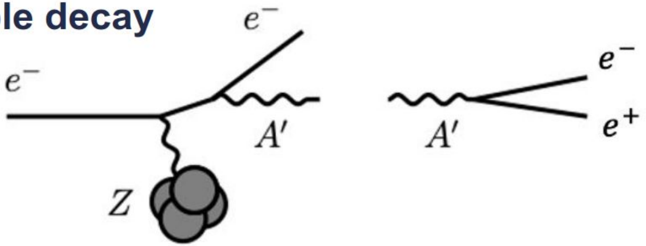
- $\mu e \to \mu e Z'$, $Z' \to \nu\bar{\nu}$ final state leptons with wide scattered angle
- $\mu e \to \mu e X$,
  - $X \to \nu\bar{\nu}$ final state leptons with wide scattered angle
  - $X \to e^+ e^-$ **electron energy measurement**
- $ee \to eeX$,
  - $X \to \nu\bar{\nu}$ final state leptons with wide scattered angle
  - $X \to e^+ e^-$ **electron energy measurement**

先只通过角度测量来进行探测(very small coupling->very long flying distance, thus ~invisible)，进而再利用能量测量信息(量能器)

Invisible decay



Visible decay



Summary

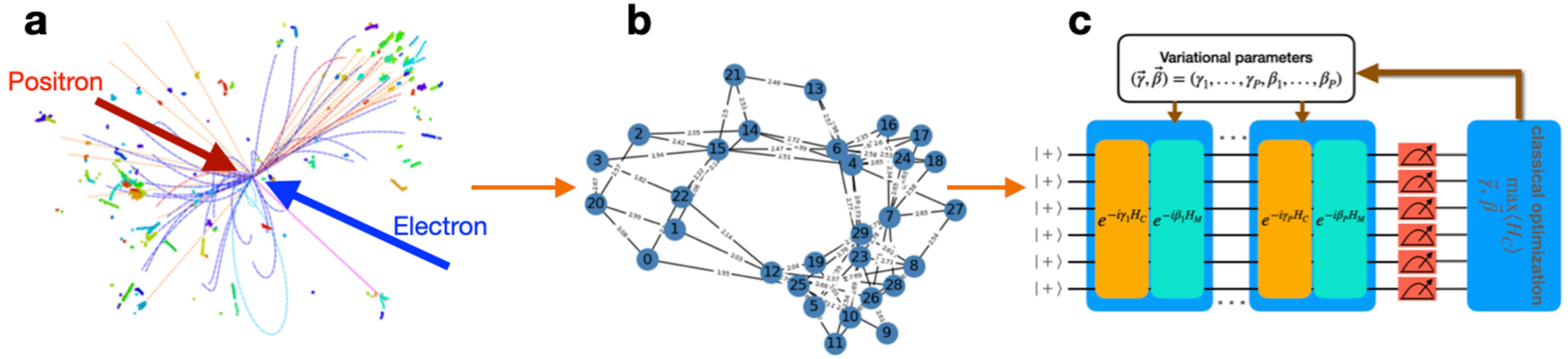
Search for new physics is our mission:

- Utilizing the high energy proton-proton collisions (and the discovered Higgs boson)
- Starting the PKMu experiments with cosmic muons and muon beam

Thank you！

高能物理喷注重建的量子计算实现

- 精确的喷注重建对于夸克和胶子的研究以及希格斯玻色子性质的测量至关重要
- 量子近似优化算法（QAOA）是在中等规模带噪量子硬件（NISQ）中有望展示量子优越性的量子经典混合算法
- 通过将对撞事例表示为图（粒子表示为图的节点，粒子之间的距离表示为图的边），我们首次得到了量子近似优化算法在喷注重建问题上的实验结果



The collision of e^+ and e^- can generate quarks, gluons, and leptons. Quarks and gluons immediately transform into collimated particle sprays, known as jets.

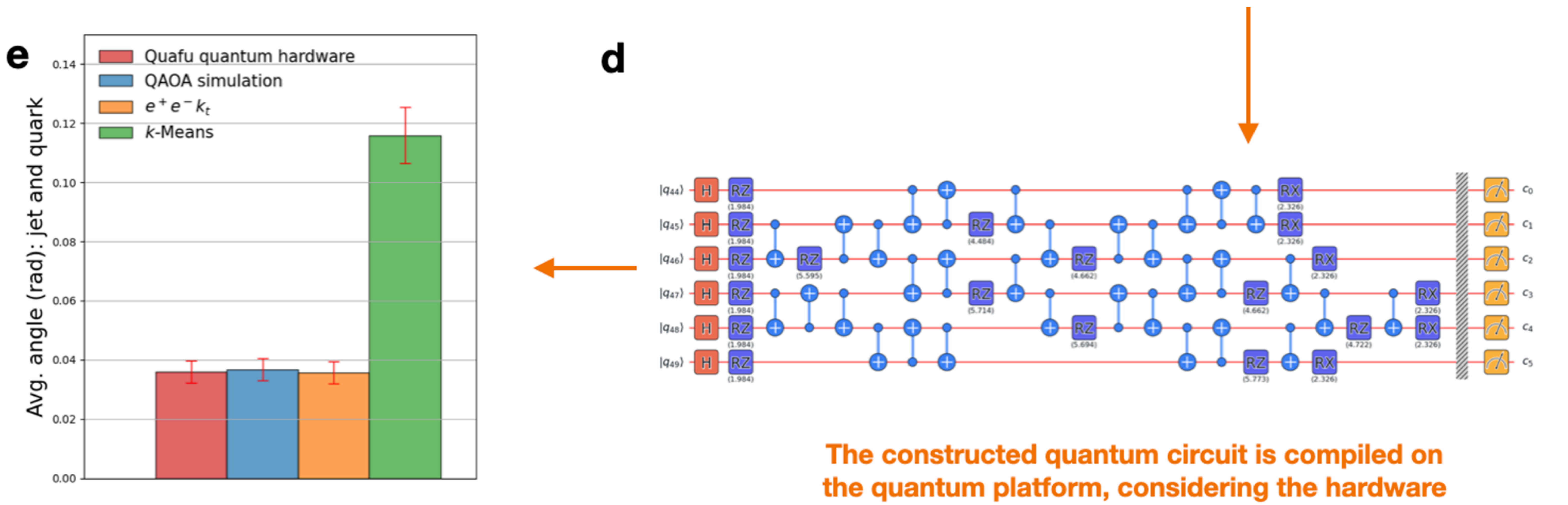
View the event as a graph, where particles as nodes and the angle of two particles as edges.

Construct a quantum circuit.

$$\widehat{H}_C = \frac{1}{2} \sum_{(i,j)\in E} W_{ij} \left(I - \sigma_i^z \sigma_j^z\right)$$

Science Bulletin 70 (2025) 460

高能物理喷注重建的量子计算实现



The performance of jet clustering using various methods.

The constructed quantum circuit is compiled on the quantum platform, considering the hardware topology and the available quantum gates.

- 在量子模拟器以及量子硬件上的结果表明：在小规模喷注重建问题上，量子近似优化算法的性能达到了经典的喷注重建算法的性能
- 展示了量子计算在喷注重建问题中的潜力，是量子计算在高能物理实验中应用的重要一步

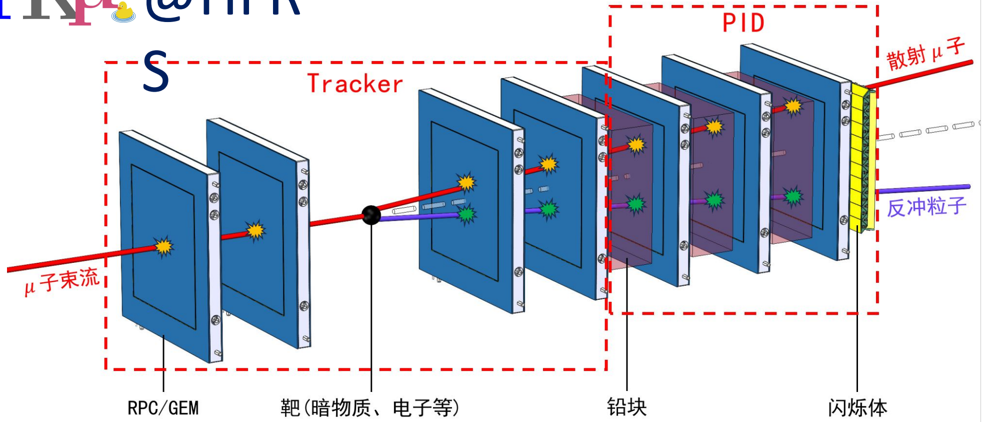
Science Bulletin 70 (2025) 460

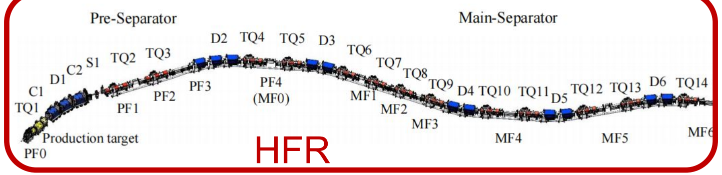
基于HIAF-HFRS装置的缪子散射实验

PKMu(Probing and Knocking with Muons)：由**北京大学** 物理学院技术物理系、核物理与核技术全国重点实验室原创提出的的缪子散射实验合作项目，旨在结合缪子散射成像技术与前沿物理研究，通过对缪子散射的测量研究核物理、标准模型和超出标准模型的新物理，如暗物质和暗玻色子探寻、量子纠缠探测、缪子与核散射规律的研究等。

HFRS：**中国科学院近代物理研究所** 建设的强流重离子加速器(HIAF)可加速从质子到铀的重离子，可提供高达 10^{11}/s 的高能离子束流。放射性次级束流分离器(HFRS)是 HIAF上的重要装置，HFRS 束线长 192 米，磁刚度最大 25 Tm，可传输动量高达 7.5 GeV/c 的π/μ粒子。研究表明，基于HIAF-HFRS装置，可获得流强可达 10^6–10^7/s 的GeV能量缪子束流，动量展宽约 4%，束斑直径约 10 cm。

PKμ @HFRS





HFRS

参考文献：[1] Phys. Rev. D 110, 016017 [2] arxiv:2410.20323 [3] arXiv:2411.12518 [4] Nucl. Instrum. Methods. Phys. Res. A 663 (2012) 22-25

Current Software and Simulation Status

PKMuon Collaboration

PKMuon Collaboration

3 followers · China · https://lyazj.github.io/pkmuon-site/ · seeson@pku.edu.cn

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Pinned

PKMUON_G4sim Public
Forked from yuxdPKU/PKMUON_G4sim
Geant4-based simulation of PKMUON
C++

geomu Public
Forked from lyazj/geomu
Geographic Muon Simulation
C++

pkmuon-site-src Public
Forked from lyazj/pkmuon-site-src
source code of PKMUON site
Stylus

root-easy-debug Public
Forked from lyazj/root-easy-debug
Debug CERN ROOT macros in an extremely easy way
C

PHYSICAL REVIEW D **110,** 016017 (2024)

Proposed Peking University muon experiment for muon tomography and dark matter search

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A set of new methods are proposed here to directly detect light mass dark matter through its scattering with abundant atmospheric muons or accelerator beams. A first plan is to use the free cosmic-ray muons interacting with dark matter in a volume surrounded by tracking detectors, to trace the possible interaction between dark matter and muons. Secondly, the same device can be interfaced with domestic or international muon beams. Due to the much larger muon intensity and focused beam, it is anticipated that the detector can be made further compact, and the resulting sensitivity on dark matter searches will be improved. Furthermore, it may also be possible to measure precisely directional distributions of cosmic-ray muons, either at mountain or sea level, and the differences may reveal possible information about dark matter distributed near the Earth. Specifically, methods described here can have advantages over "exotic" dark matters that are either muonphilic or slowed down due to some mechanism, and the sensitivity on dark matter and muon scattering cross section can reach as low as microbarn level.

DOI: 10.1103/PhysRevD.110.016017

NA64μ recent results

$$\mathcal{L} \supset -\frac{1}{4}F'_{\alpha\beta}F^{\alpha\beta\prime} + \frac{m_{Z'}^2}{2}Z'_\alpha Z^{\alpha\prime} - g_{Z'}Z'_\alpha J^\alpha_{\mu-\tau},$$

$$-g_\chi Z'_\alpha J^\alpha_\chi,$$