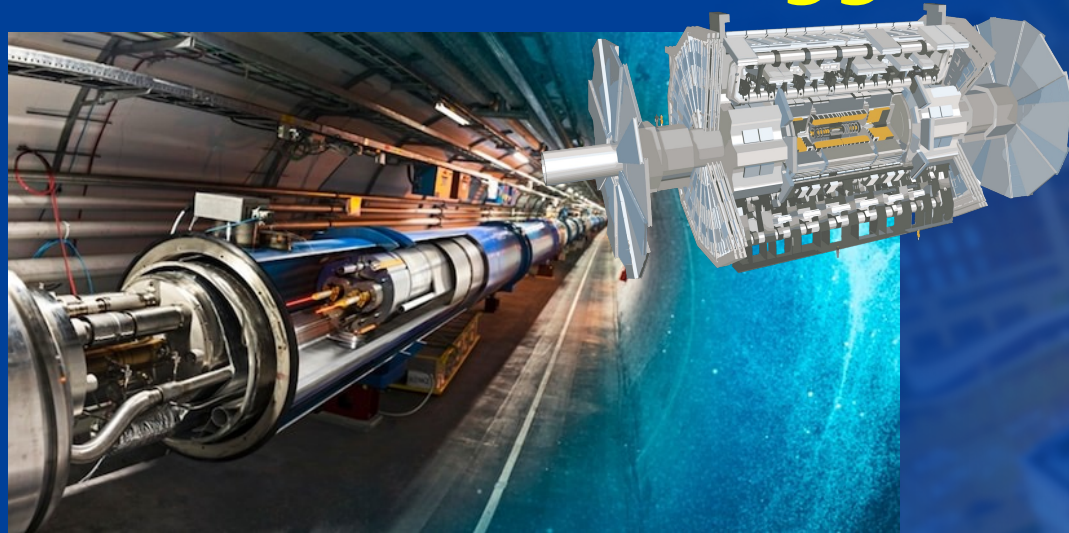




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Illuminating the Dark Sector with Higgs Boson and Dark Photon



李数 (shuli@sjtu.edu.cn)

上海交通大学 | 李政道研究所 & 物理与天文学学院



味物理讲座

2025年第6期



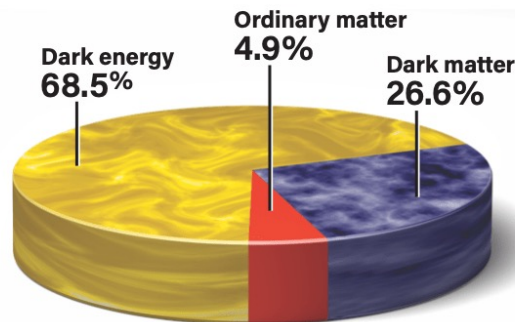
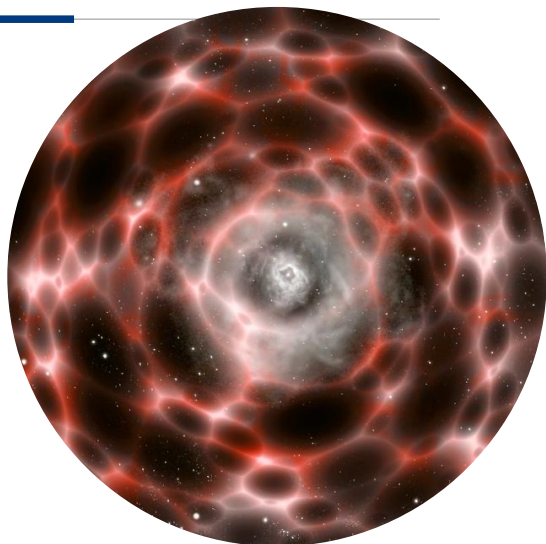
总第七十九期

What EXIST but also what we DON'T know...

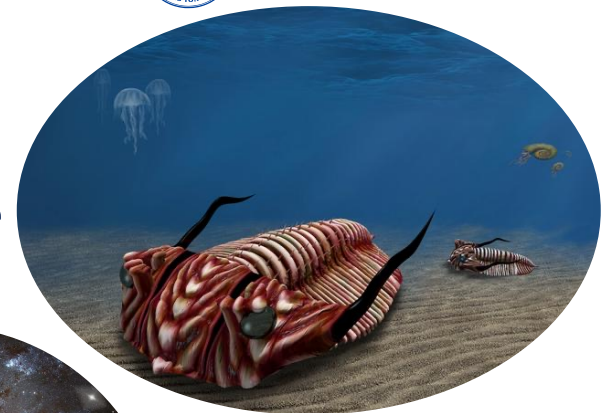


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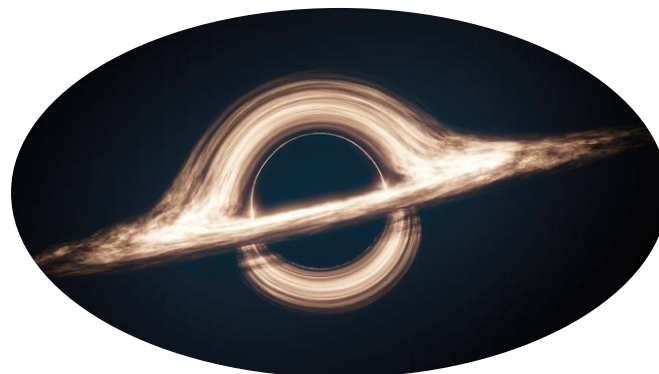
Dark Matter



Origin of Life



Black Hole



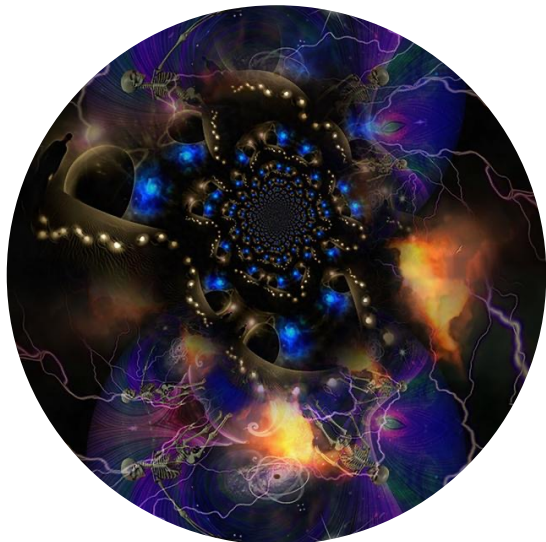
Origin of Universe



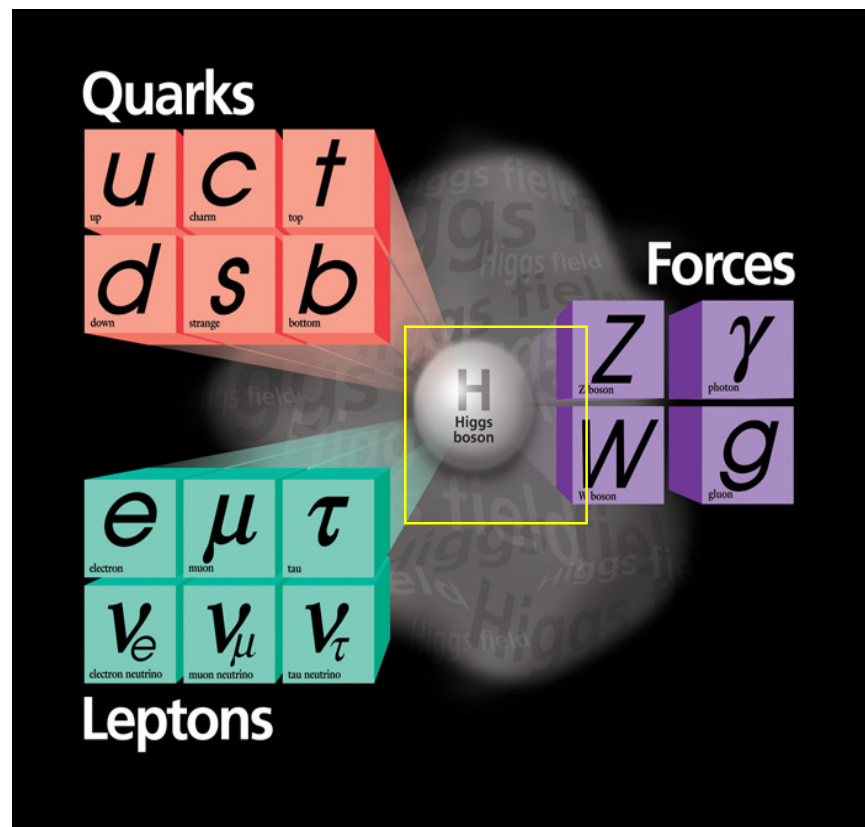
Origin of Consciousness



Dark Energy

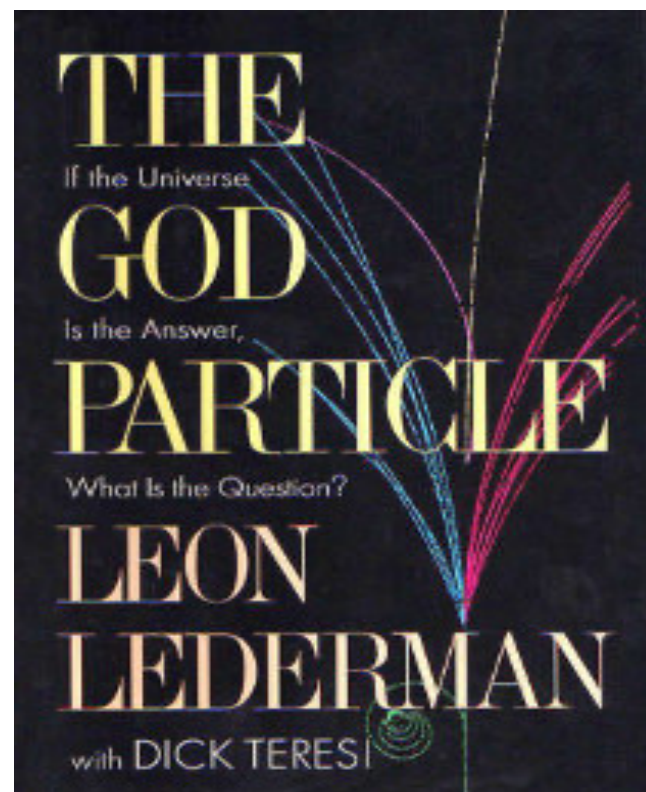


● 微观宇宙的VIP模特：上帝粒子希格斯



1897-2012, 粒子物理标准模型的所有基本粒子都已经在实验上被发现！（荣获18次诺贝尔奖）

→ **Higgs** 玻色子用来解释基本粒子的质量来源，是粒子物理标准模型中最后被发现的关键粒子，常被媒体称为“上帝”粒子



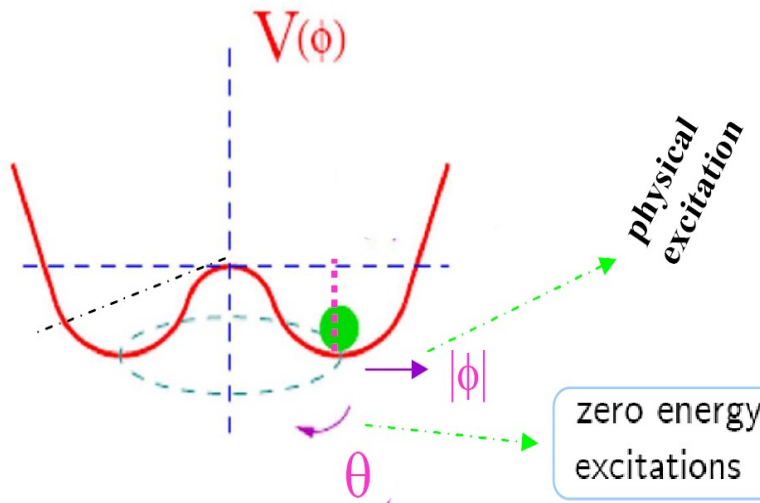
● 希格斯粒子的理论基础



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$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

$$\phi = \begin{pmatrix} iG^+ \\ \frac{v+h-iG^0}{\sqrt{2}} \end{pmatrix}$$



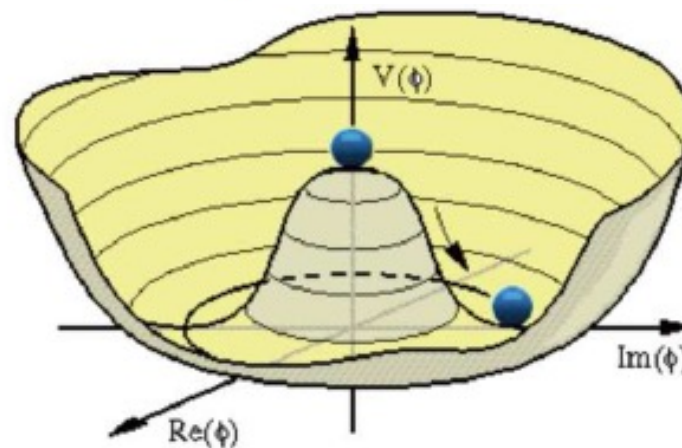
- 连续对称性的自发破缺导致零能激发会产生零静止质量的标量粒子 - Goldstone boson, 它被静止质量为零的规范场粒子 (两个横向极化自由度) “吃掉”, 转化成规范场的纵向极化分量的自由度, 使得规范场粒子具有三个极化自由度, 变成具有静止质量的粒子。

- 剩下一个物理激发态: 希格斯粒子

质量
电荷
自旋

$\approx 125.09 \text{ GeV}/c^2$

0
0
H
希格斯玻色子



Higgs



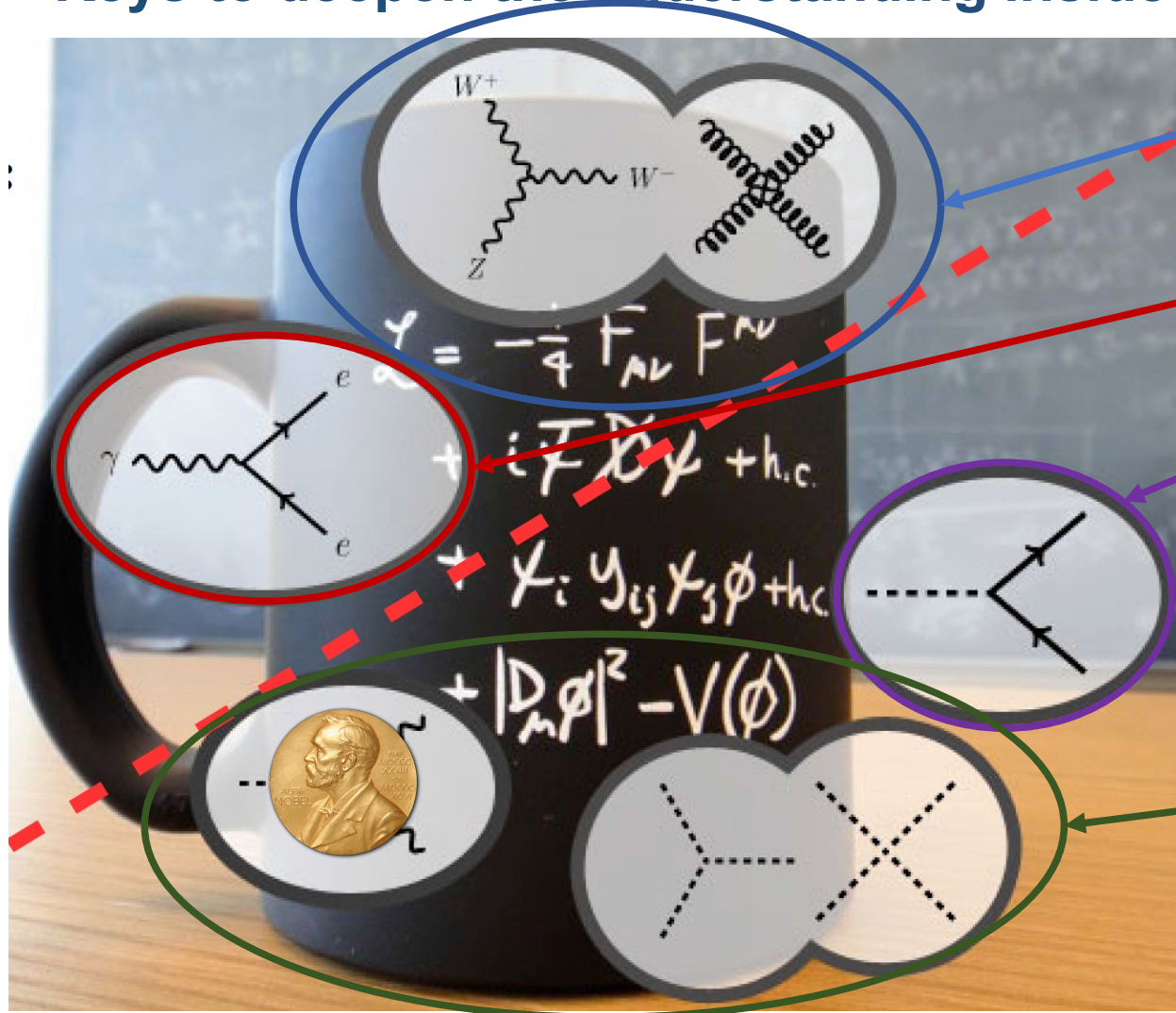
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Higgs and Gauge Bosons:

Keys to deepen the understanding inside the Standard Model



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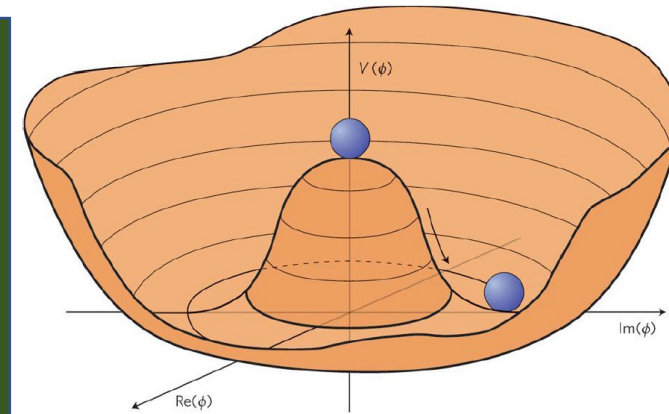


Electromagnetic/Weak/Strong
(Gauge Boson Self-
Interactions)

How Gauge Bosons Interact
with Fermions (Leptons &
Quarks)

Higgs Yukawa Couplings
(Origin of Masses for Leptons
and Quarks)

EWSB (Origin
of Weak
Boson Mass),
Higgs
Potential
(Higgs Self-
Interactions)



● The Higgs Mechanism and the origin of the masses



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They proposed



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量子基础科学研究部

Higgs Discovery: a collider Roadmap

1988-2022 (2-4.8 GeV)

1989 – 2001 (200 GeV)

1988 – 2011 (2 TeV)

2009–2012 (7-8 TeV)

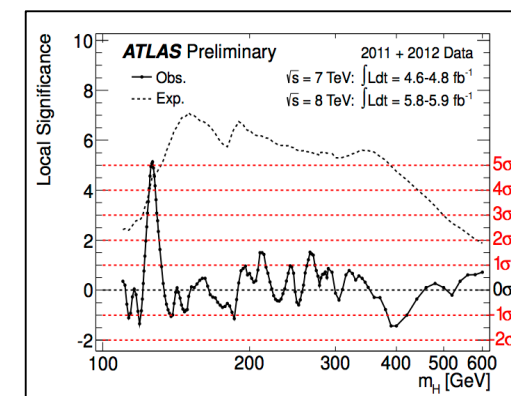
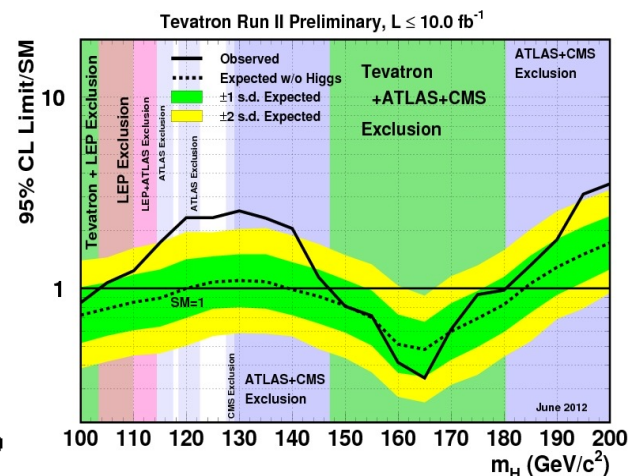
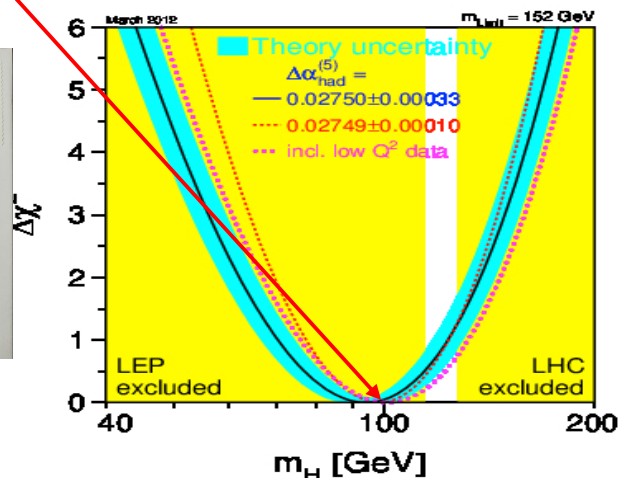
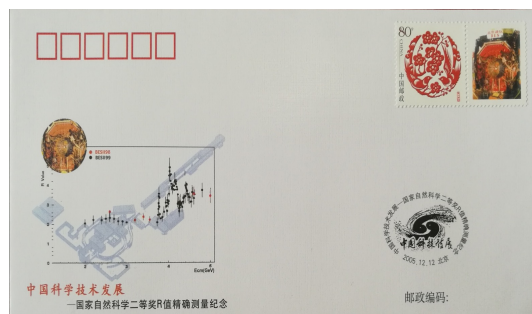


Critical contribution to

Exclude $m_H < 114 \text{ GeV}$

Higgs signal hint at 3σ

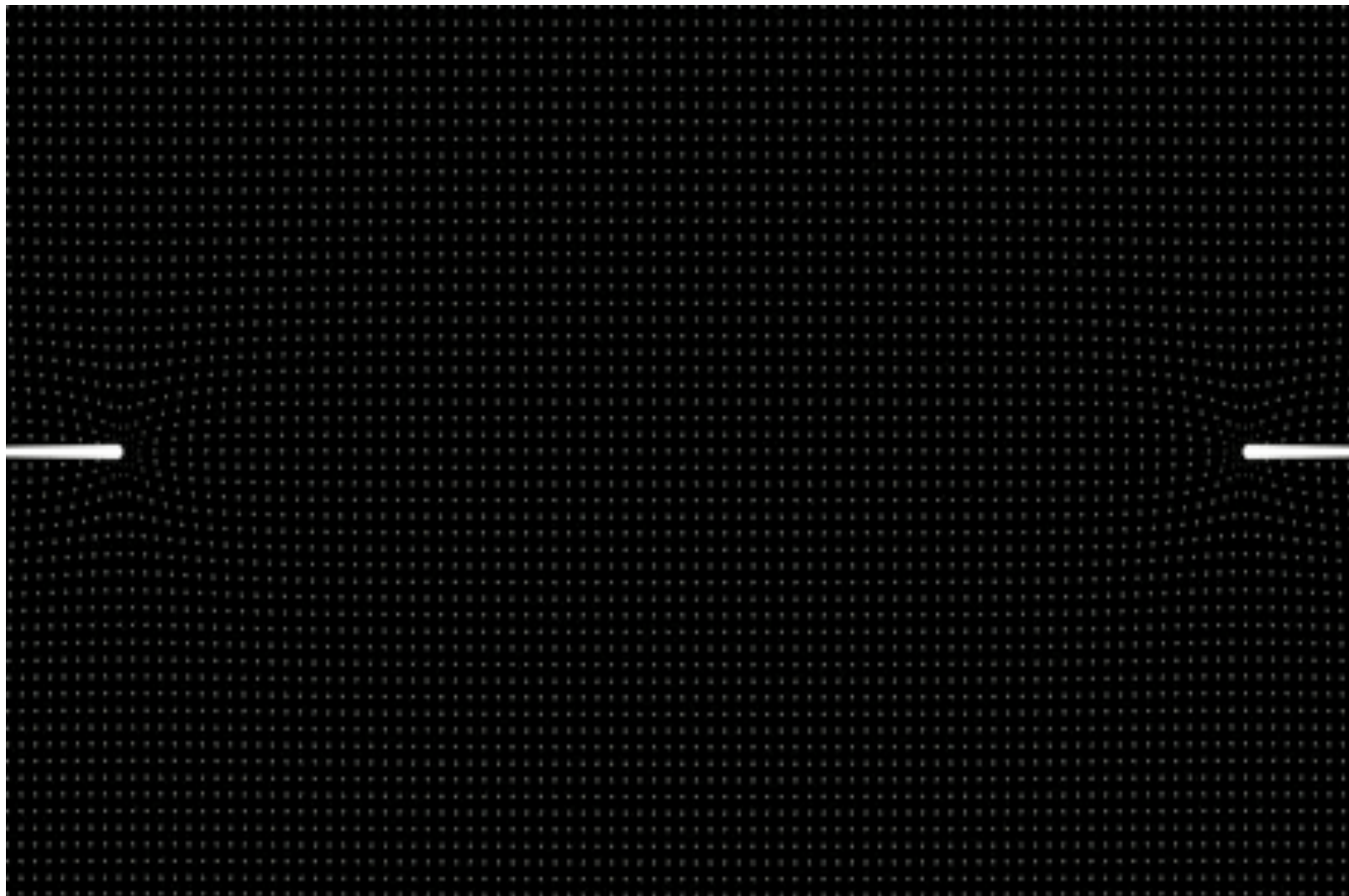
Higgs discovery 5σ



● How Higgs comes into being in collisions



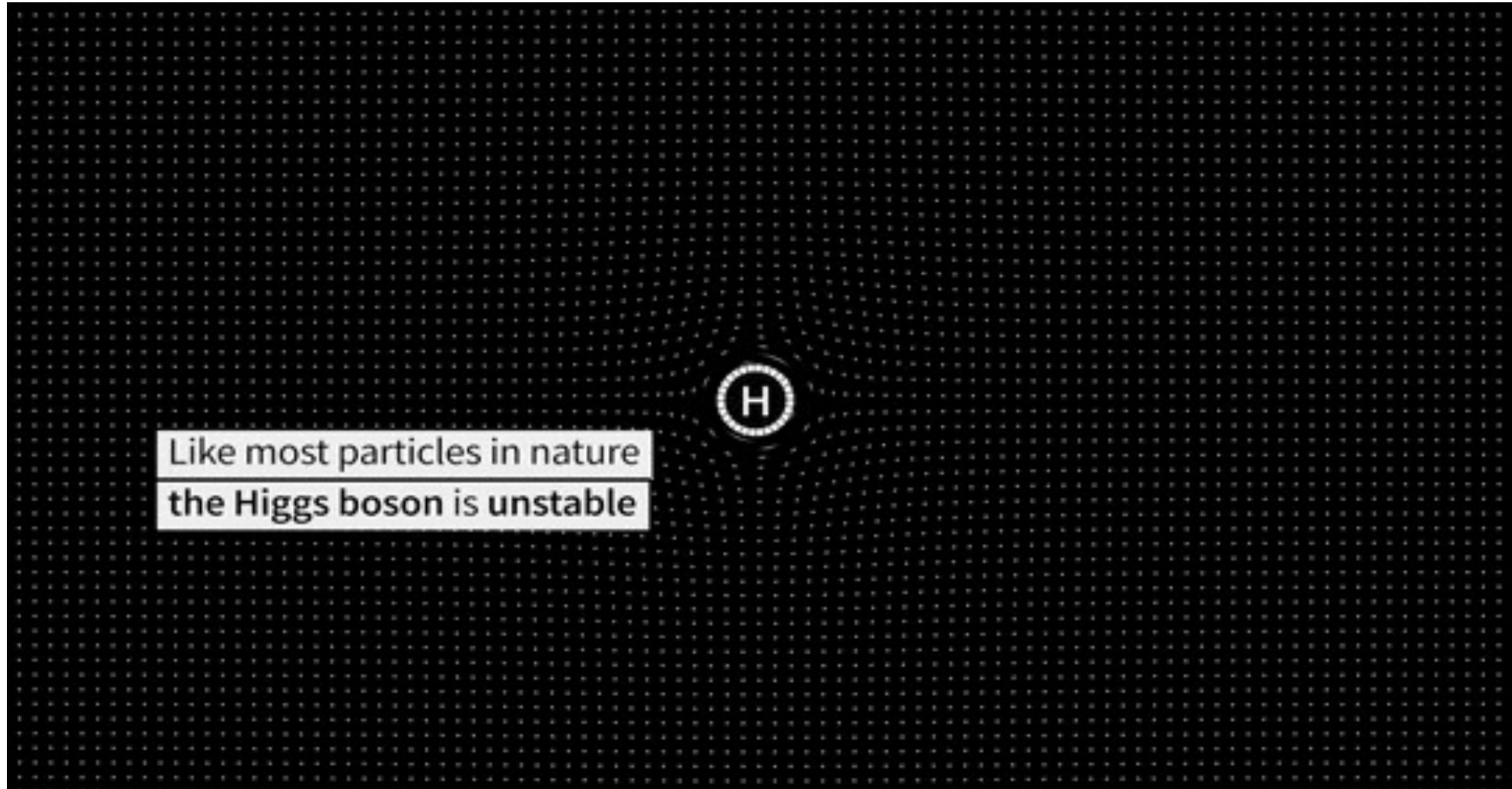
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● How Higgs vanishes in collisions

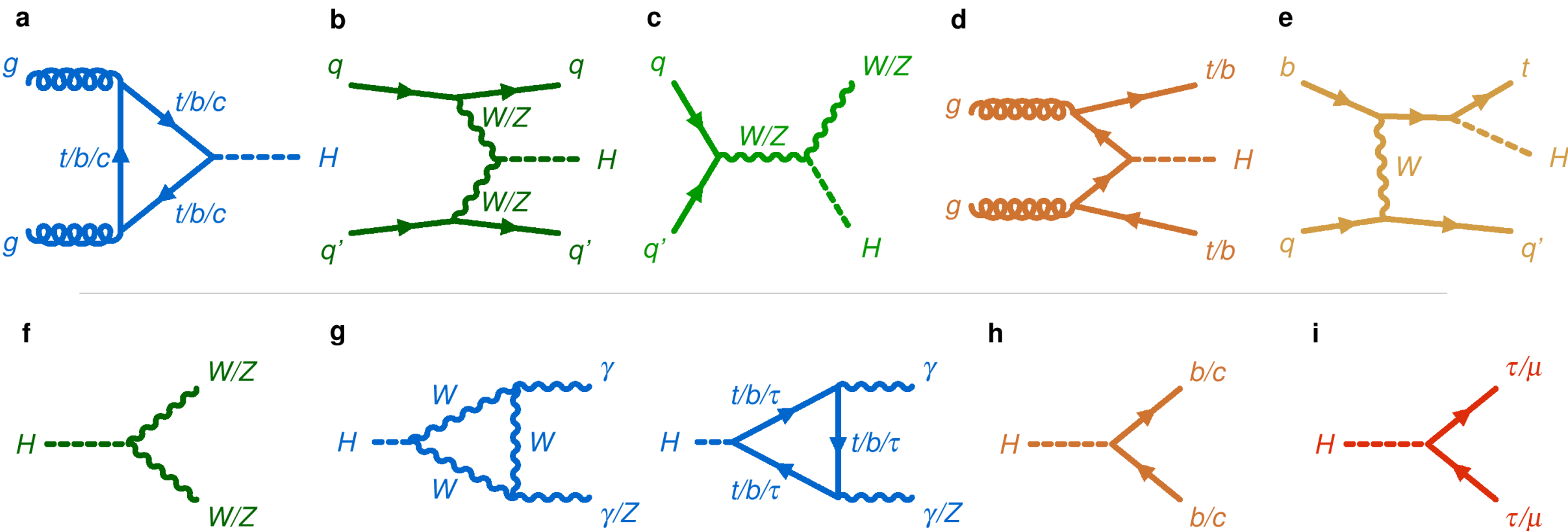


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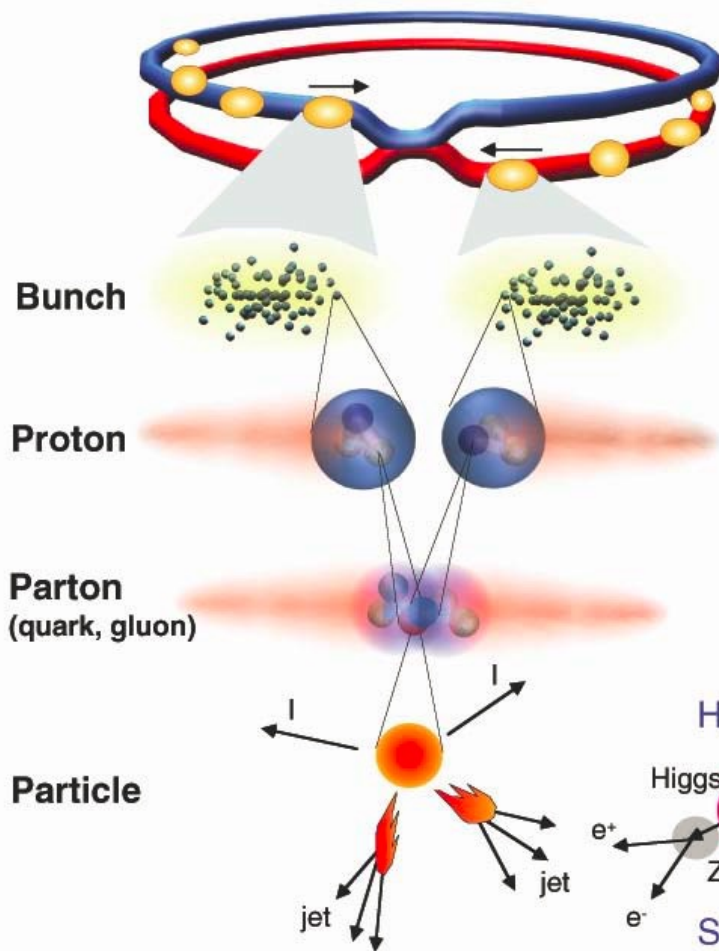
● 希格斯的研究渠道：产生与衰变模式



● 上帝粒子希格斯的发现开拓人类认知疆界



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Proton-Proton 2835 bunch/beam
Protons/bunch 10^{11}
Beam energy 7 TeV (7×10^{12} eV)
Luminosity $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Crossing rate 40 MHz

Collisions $\approx 10^7 - 10^9 \text{ Hz}$

Selection of 1 in
10,000,000,000,000

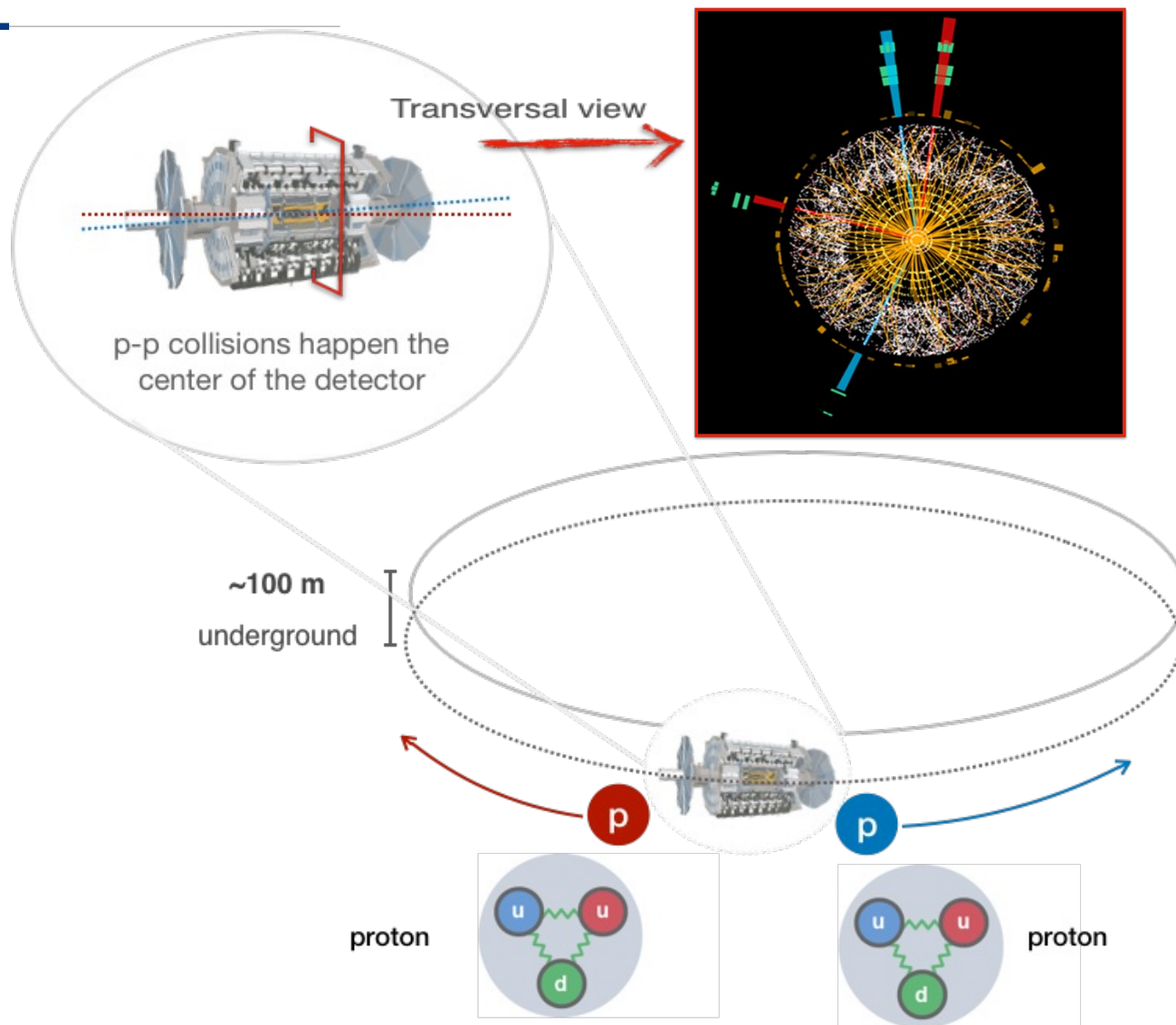
Phys. Lett. B 716 (2012) 1-29 (ATLAS)
Phys. Lett. B 716 (2012) 30-61 (CMS)



大型强子对撞机——人类探索未知的智慧与勇气的结晶



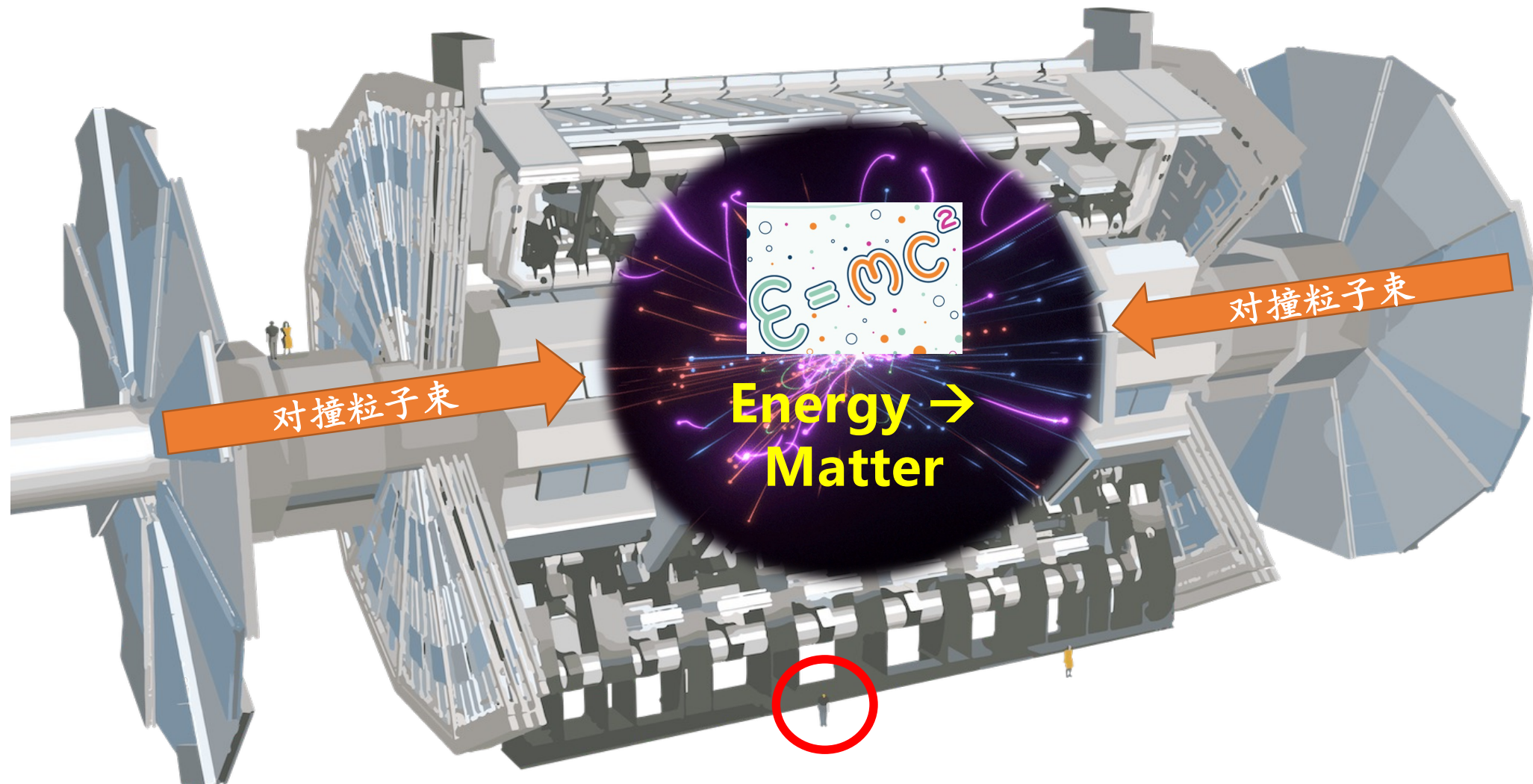
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● 大型强子对撞机——人类探索未知的智慧与勇气的结晶



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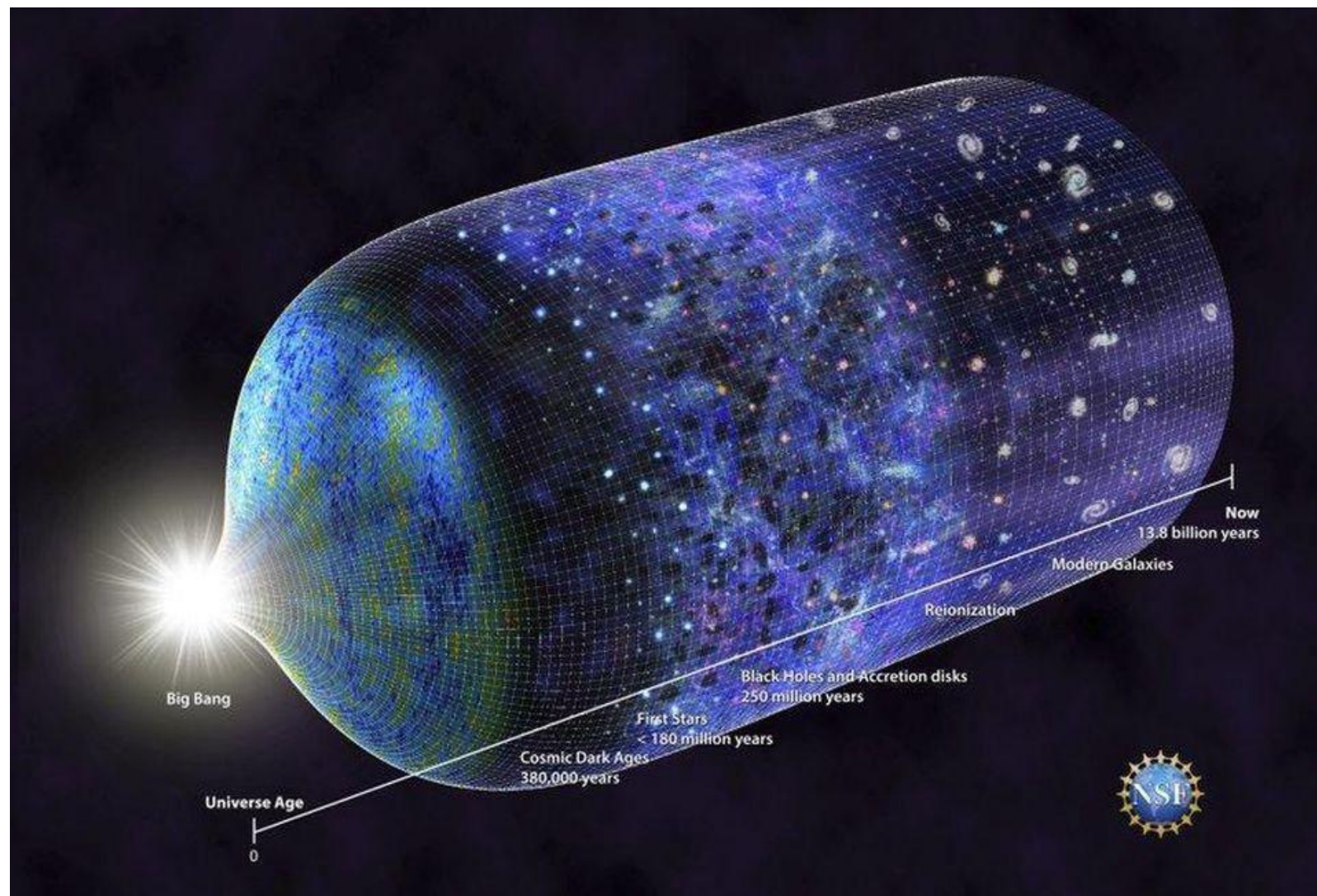
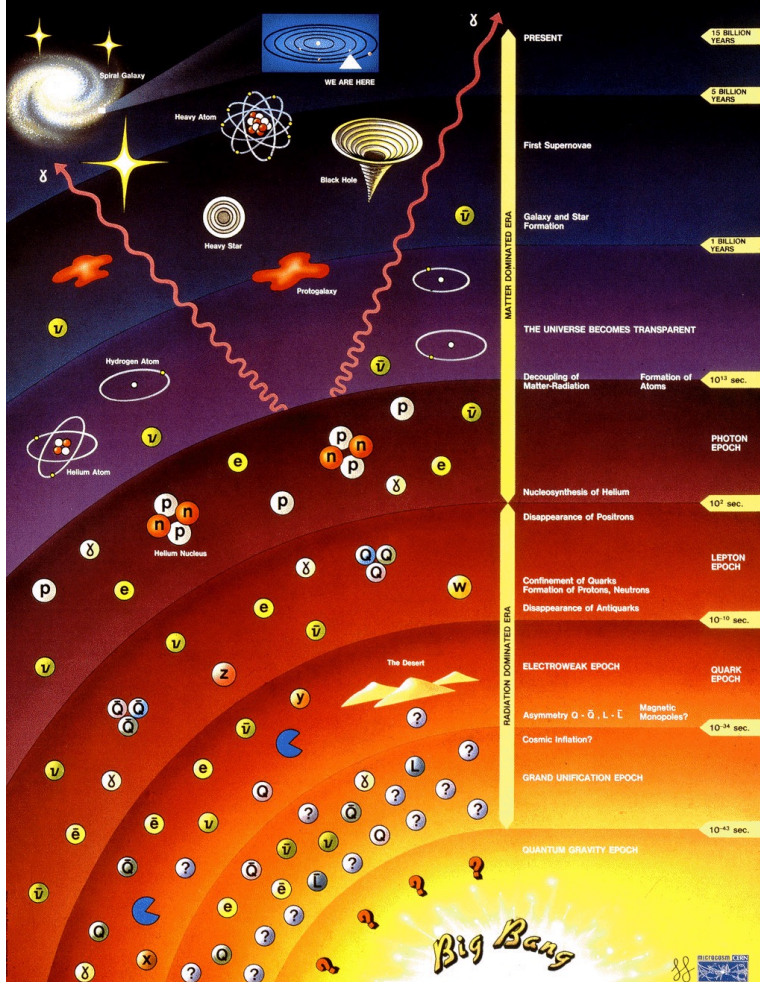


● 探索未知的强大武器：微观宇宙大爆炸模拟器



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History of the Universe



极大与极小的同频 人类的大统一科学之梦



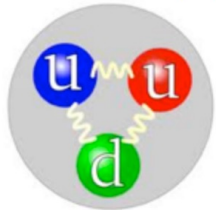
● 欲善其事、必先利其器



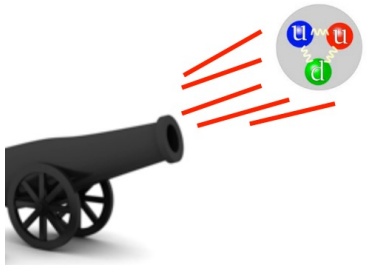
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What's in the Proton ?

Protons are Too
small to look inside.



SMASH THEM!!!



Really Big Camera!!!



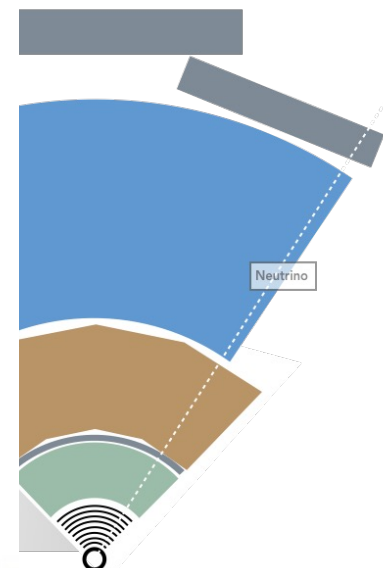
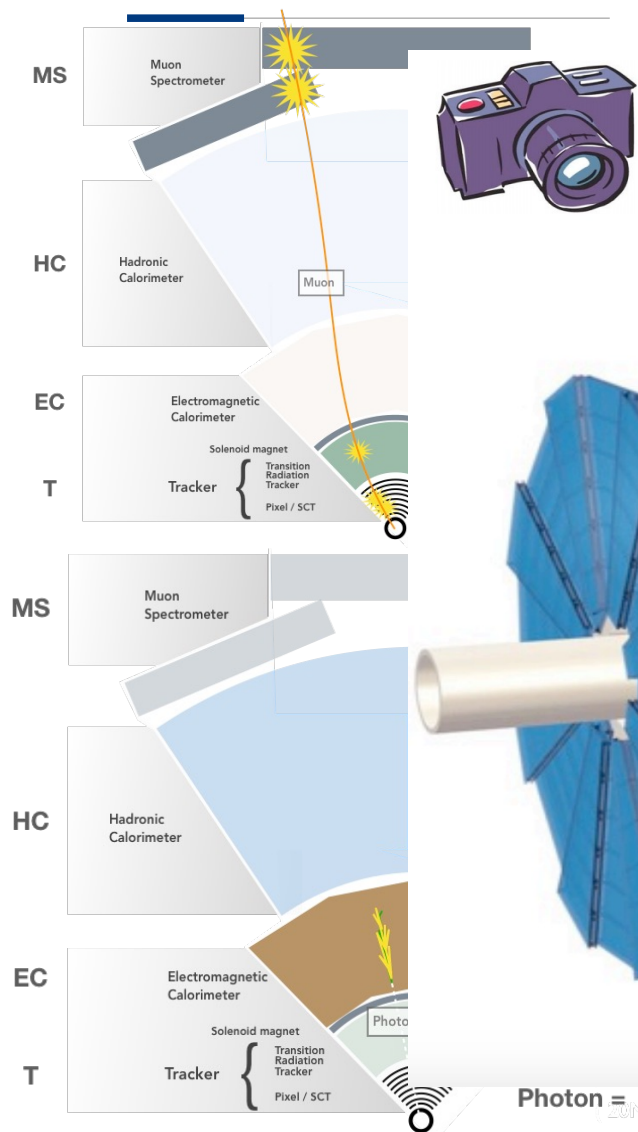
● 微观世界的摄影师开启神奇粒子世界



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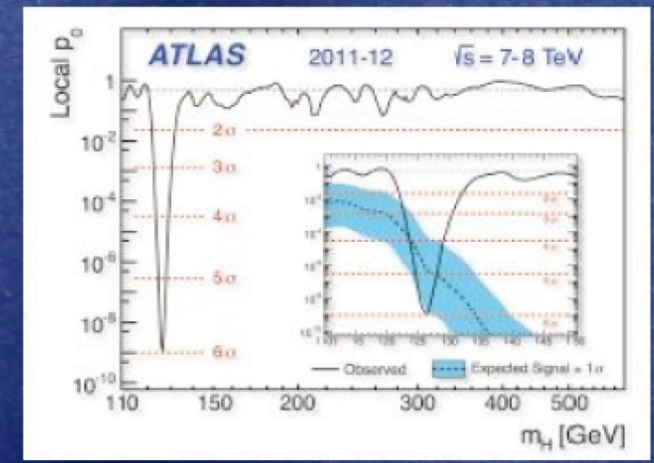
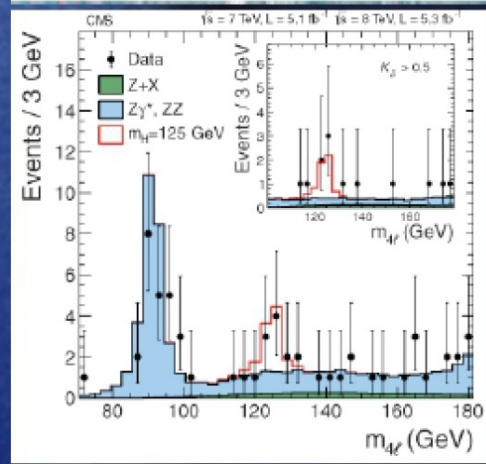
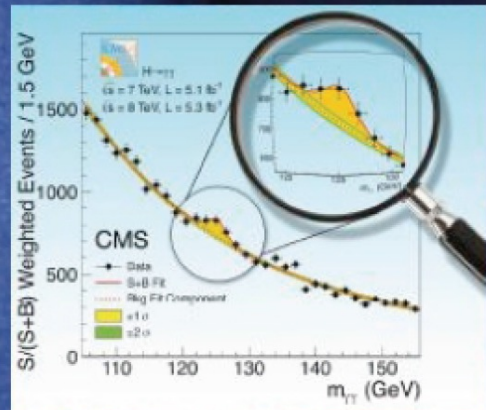
Really Big Camera!!!

无法将基本粒子一网
打尽的探测器不是好
“摄影师”



Photon = IMS & HC & EC & IT

Hadron = IMS & HC & EC & IT



● 2022.7.4 十周年生日快乐!

Nature 607, 52–59 (2022)

Nature 607, 60–68 (2022)



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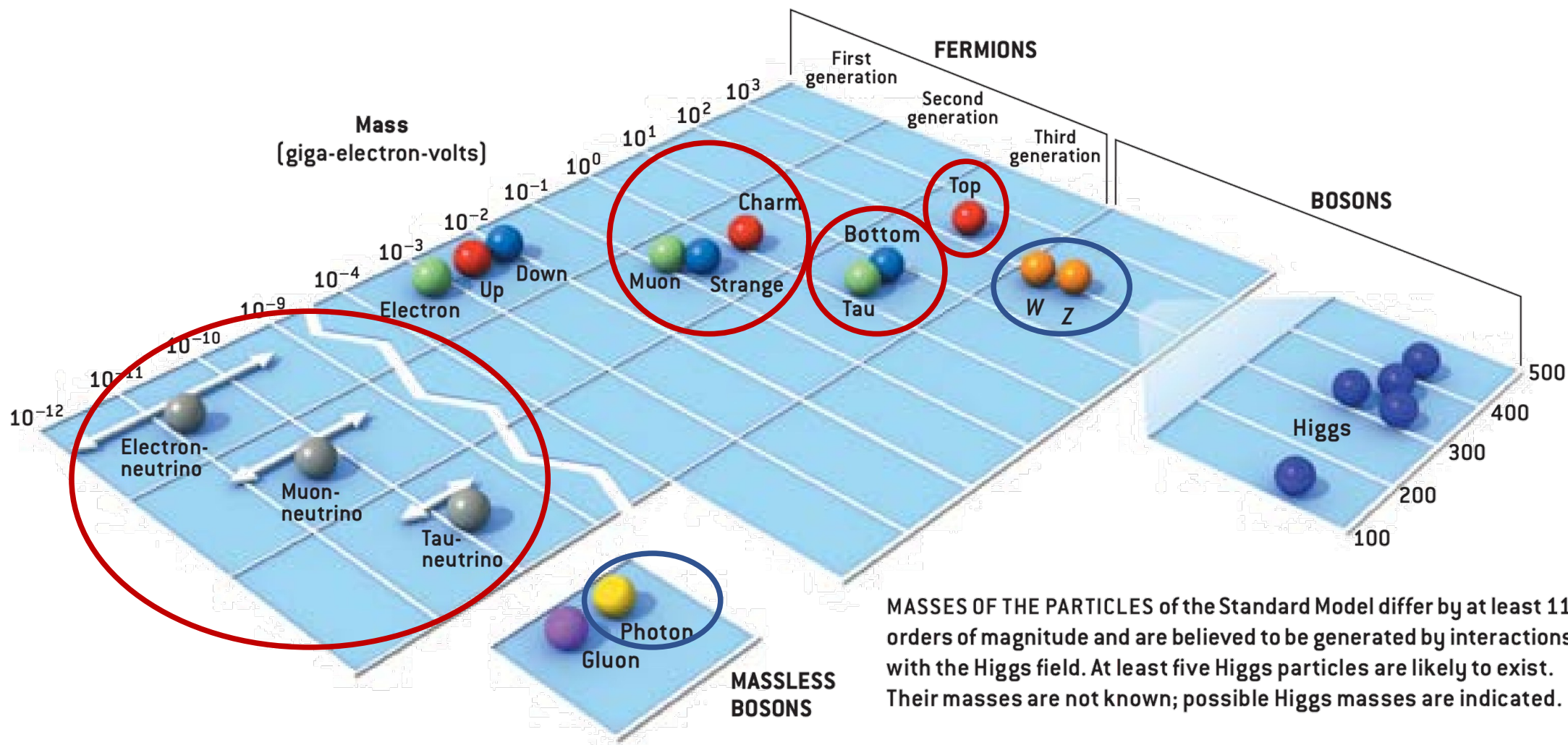


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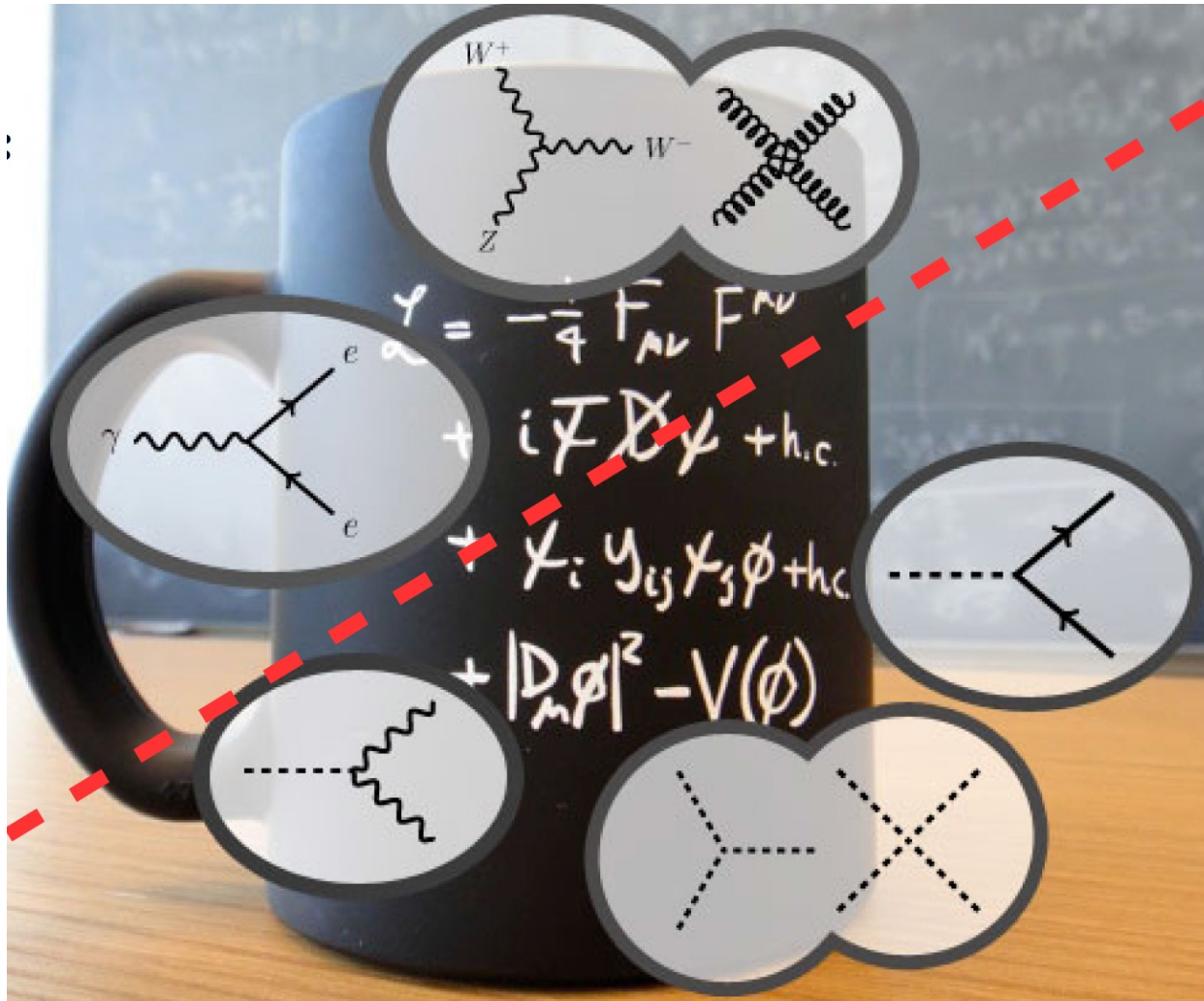
在后希格斯发现时代与希格斯 “对弈质量棋局”



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Why is the Higgs Boson Special?



THE
HIGGS
BOSON

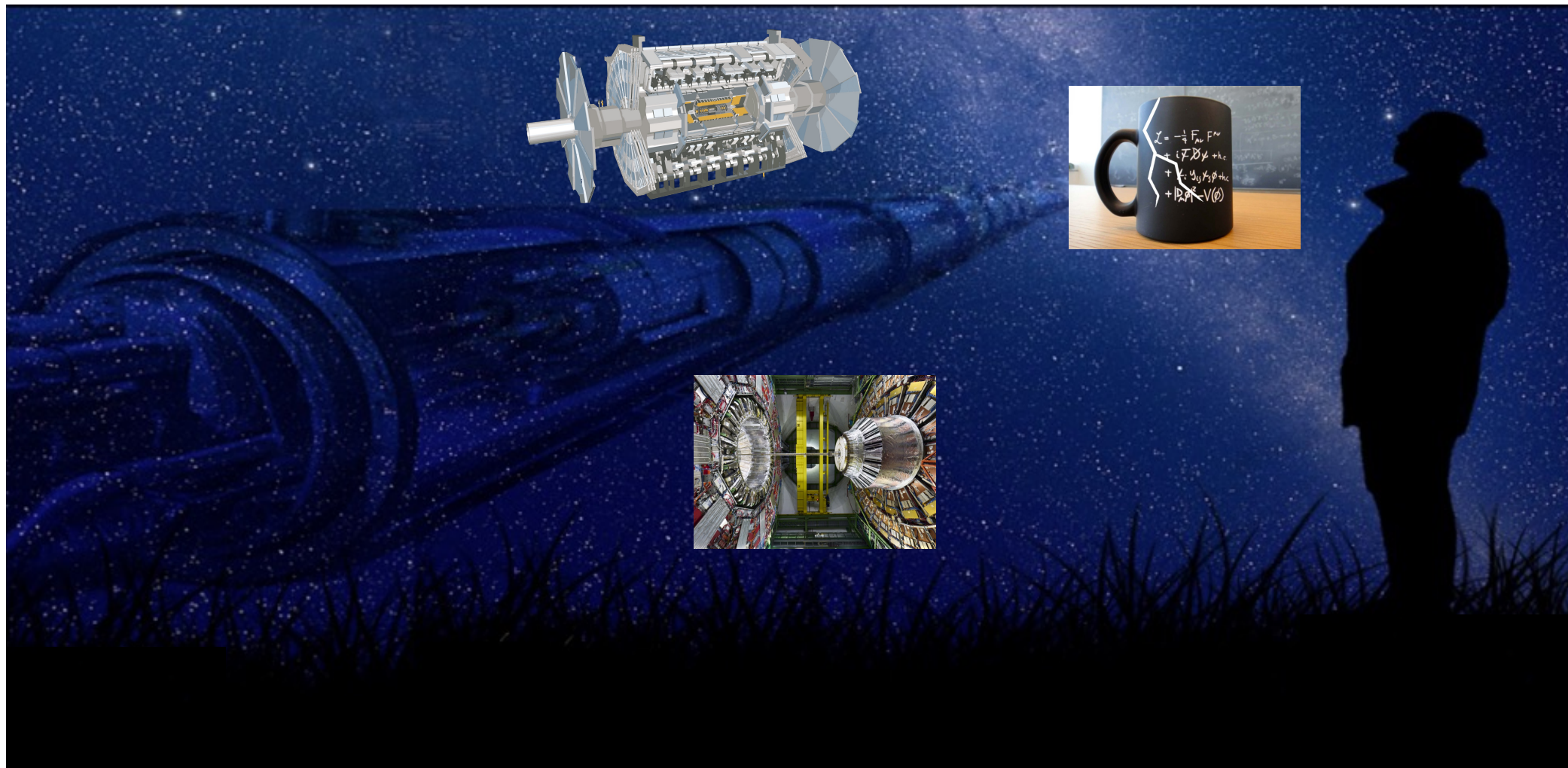


- By now the only scalar boson discovered
- Related to most of free param. of SM and theory puzzles
- Determine the new fundamental interactions in addition to the four known forces
- All such above determine the profiles and destiny of the universe evolutions, Phase Transition in Early Universe
- What if it relates dark matter/dark energy and cosmic inflation?

● LHC primary goals: looking into the “unknowns”

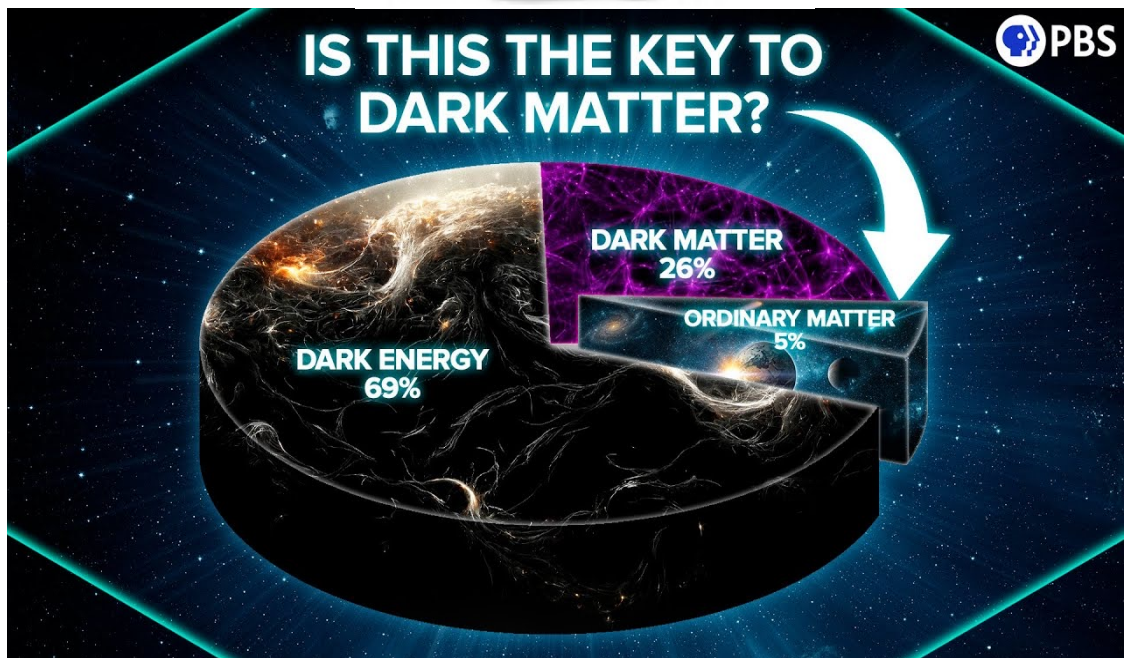


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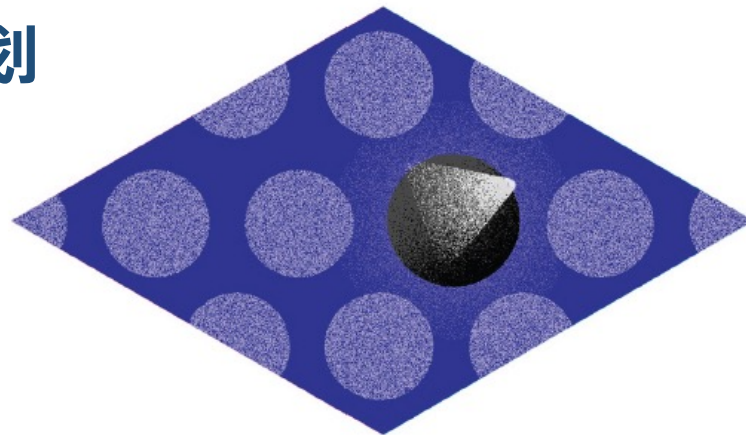


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● 希格斯开启新物理之窗：上帝粒子新物理探针计划



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美国SnowMass高能物理中长期规划战略报告

5.1

Search for Direct Evidence of New Particles

5.1.1 – Science Overview

Particle physics is a field that earned its name through the discovery of many particles that were thought to be the fundamental building blocks of matter. This began with the extraordinary discovery that every object in our world is made of scores of chemical elements. Each of those chemical elements is made of a particular kind of atom, with an atomic nucleus of specific electric charge surrounded by orbiting electrons that negate that electric charge. Although the electrons are understood to be a point-like elementary particle with no internal structure, the atomic nuclei were discovered to consist of protons and neutrons. The number of protons in an atom's nucleus determines the nature of the chemical elements that, in turn, determine the nature of every object we see. This was a unifying paradigm that explained the physical world around us.

But nature is complicated, and further discoveries revealed that the proton and neutron were made of fundamental particles called quarks bound together by a force particle called the gluon, carrier of the “strong force”. It was also discovered that many particles disintegrate over time into lighter ones. This led to the discovery of the “weak force”, which

● 希格斯开启新物理之窗：上帝粒子新物理探针计划



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● Q1: Is Higgs really elementary? → compositeness

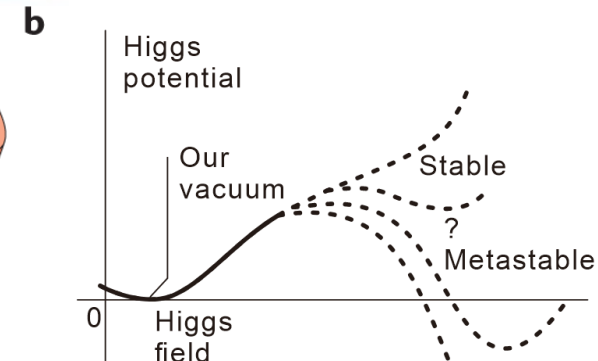
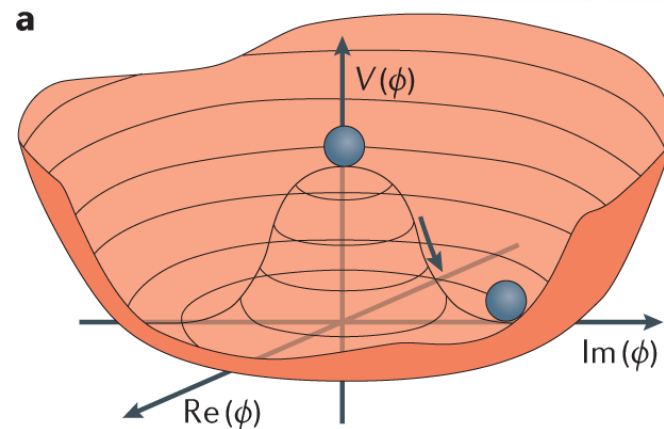
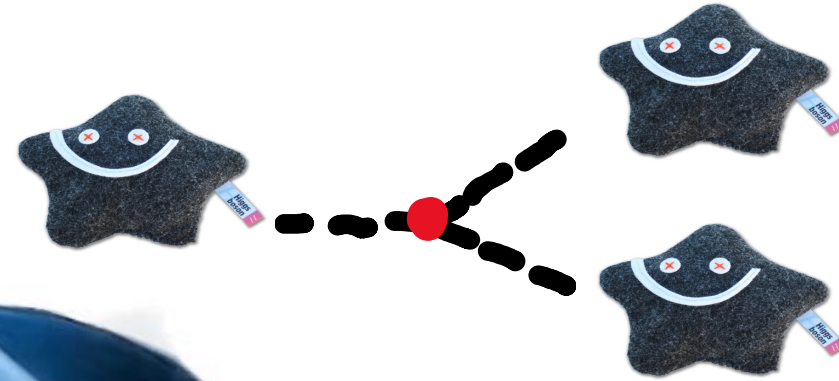
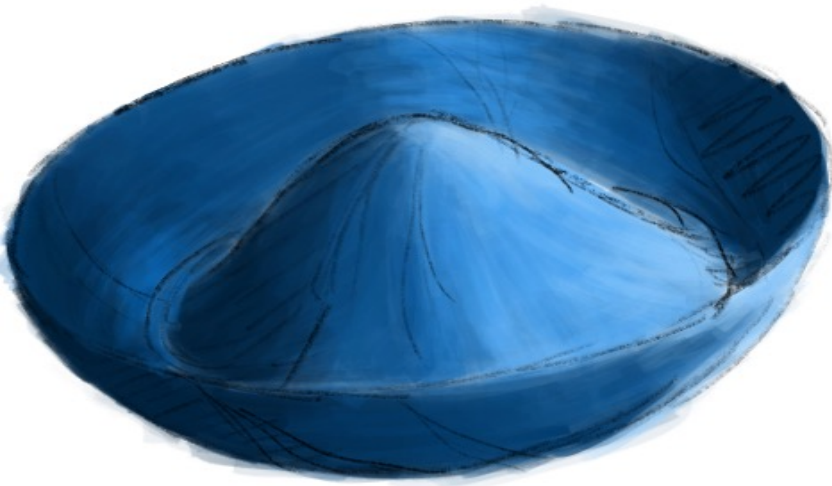


Q2: How the Higgs Boson self-interacts?

→ How stable is our universe?

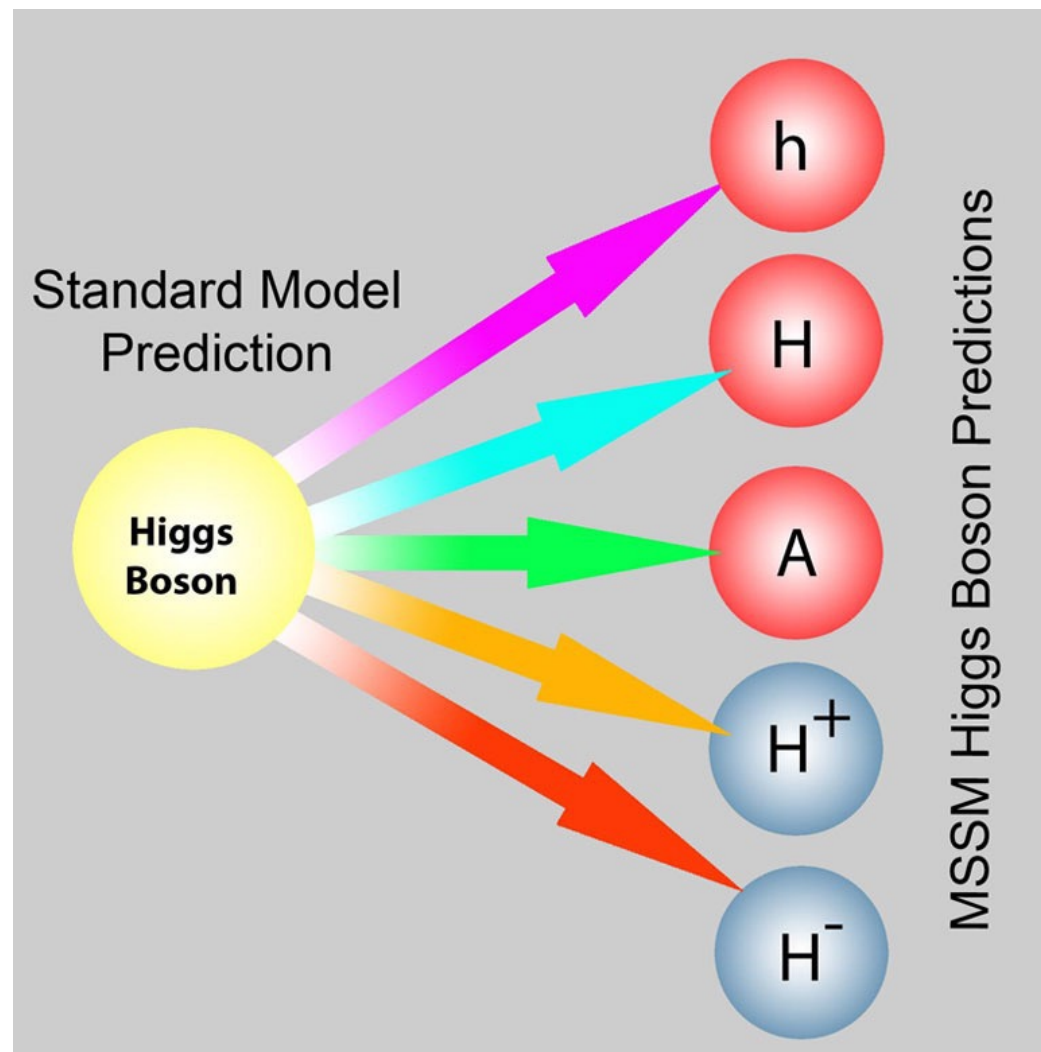


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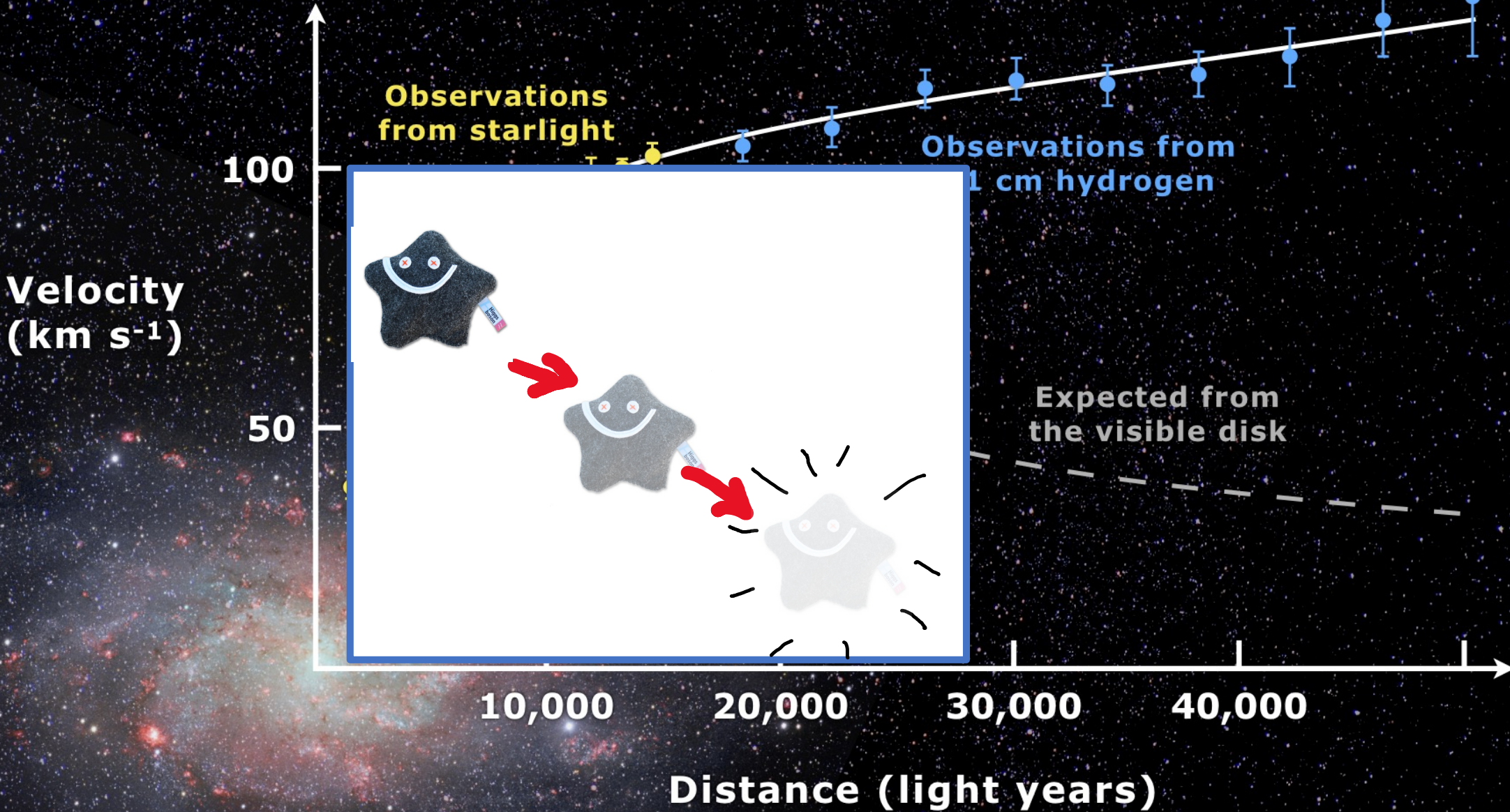


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● Q3: is Higgs boson alone?



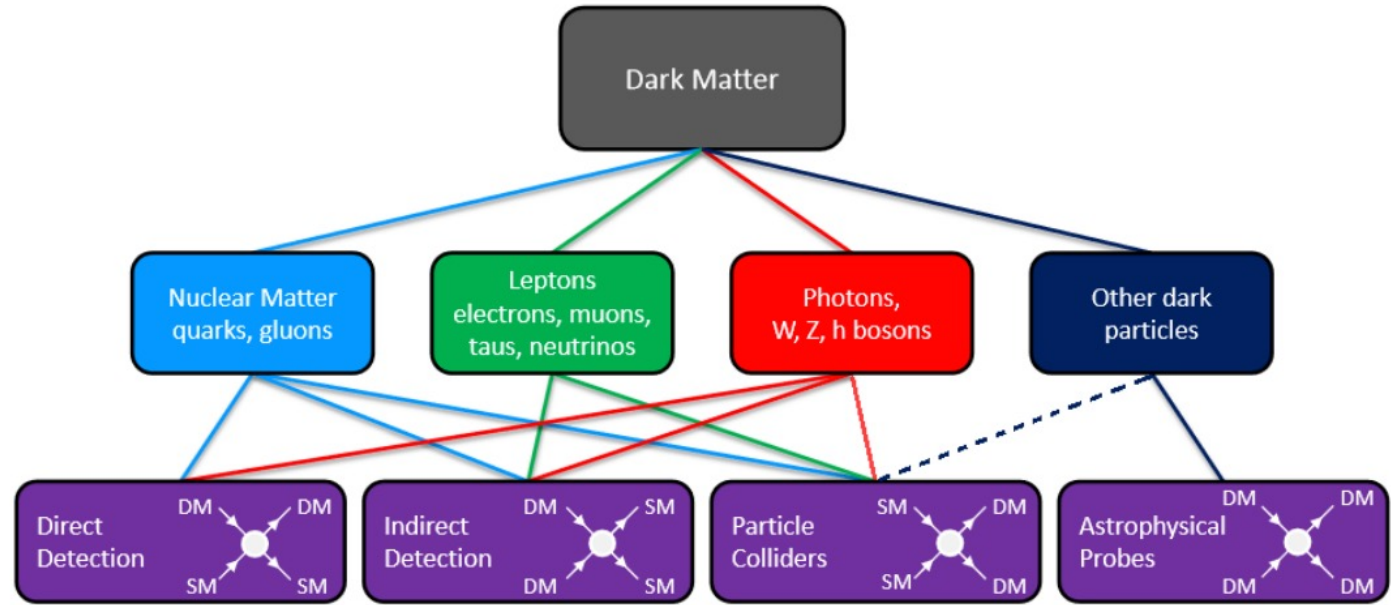
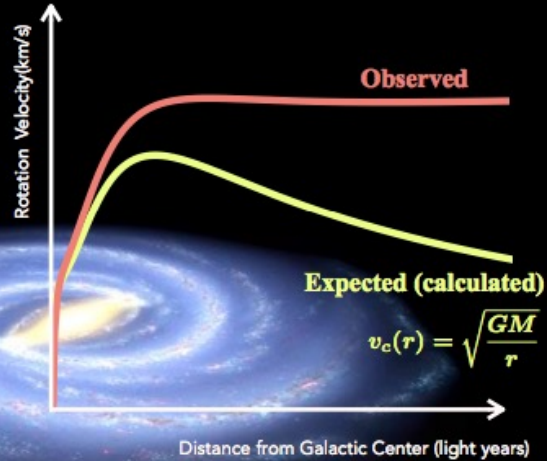
Q4: How much the Higgs boson loves the Dark Matter (invisibles)



Dark Matter Evidence and Theory Context in a nutshell



Galactic Rotation



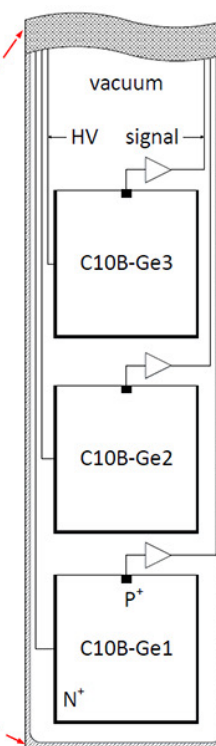
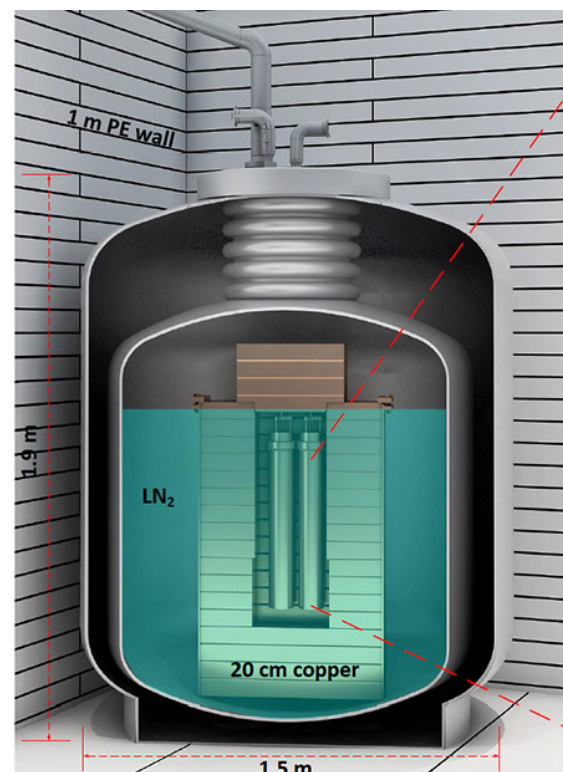
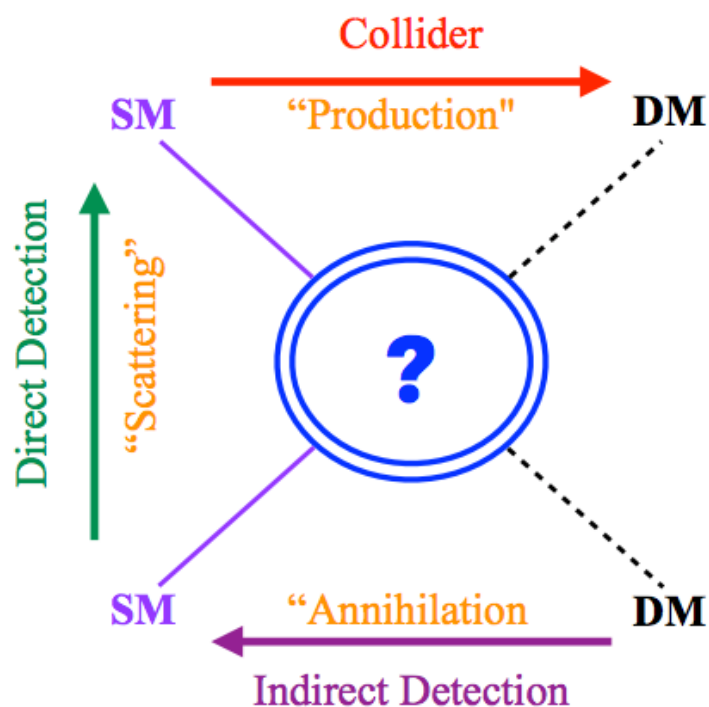
- DM evidence from astronomical observations and gravitational effects:
 - Galactic rotation curves, Gravitational lensing, Cosmic Microwave Background anisotropies, ...
- Characteristics: Non-baryonic, massive, electrically neutral, gravitational, stable → WIMP context
- BSM models predict weakly interacting massive particle (WIMP) -> Dark Matter Candidate. In SUSY models, the lightest SUSY particle LSP is a candidate for dark matter. Being LSP stable in most Models.
- Any WIMP DM produced at collider experiments will interact weakly and pass invisibly through detectors. Inferred through 'Missing E_T ' when event does not balance in plane transverse to beam.

● Frontiers that DM can reach out



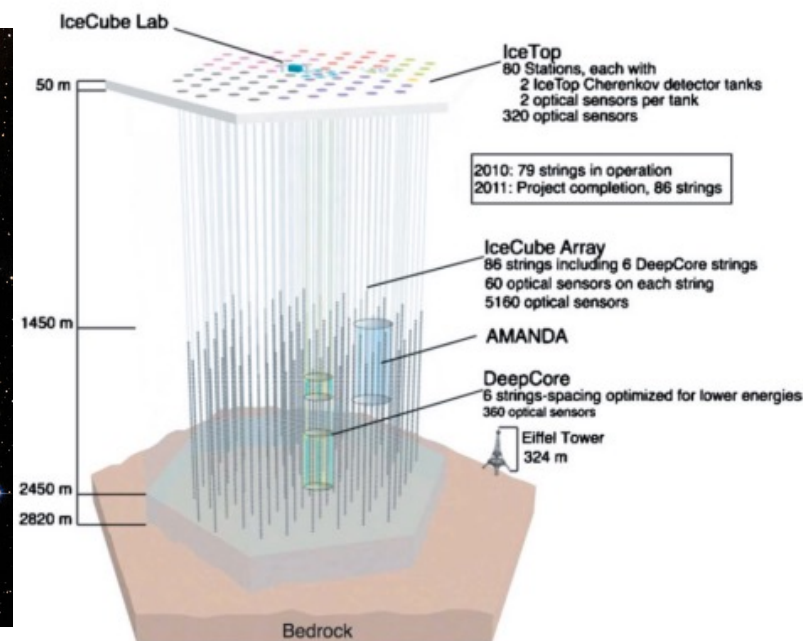
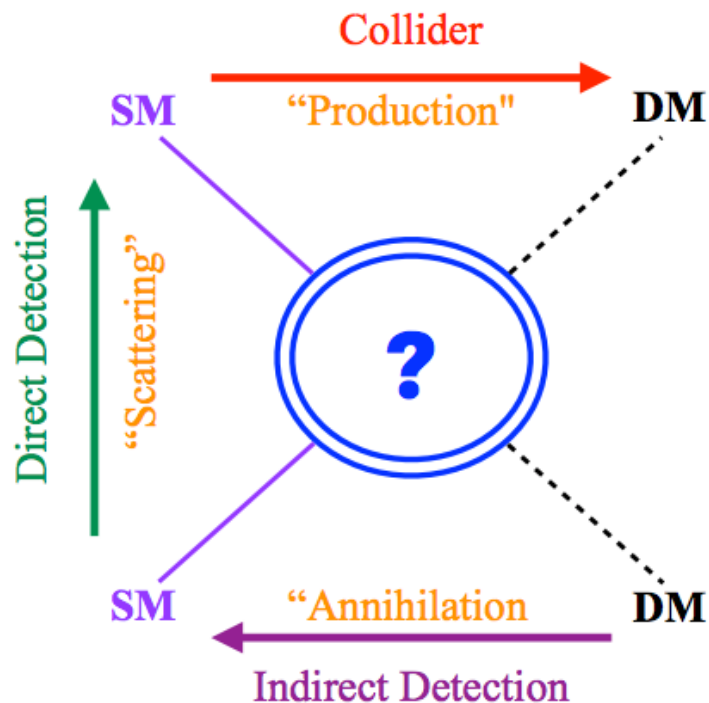
Dark Matter Direct Detections

- Direct Detection (DD): nuclear recoils from DM-nuclei scattering (CDEX, PandaX, LZ, XENONnT, ...)
- Indirect Detection (ID): products from DM annihilation (DAMPE, HESS, IceCube, ..)
- Colliders: DM production in high-energy collisions, focusing on the productions of a SM particle(s) (X) with large missing E_T



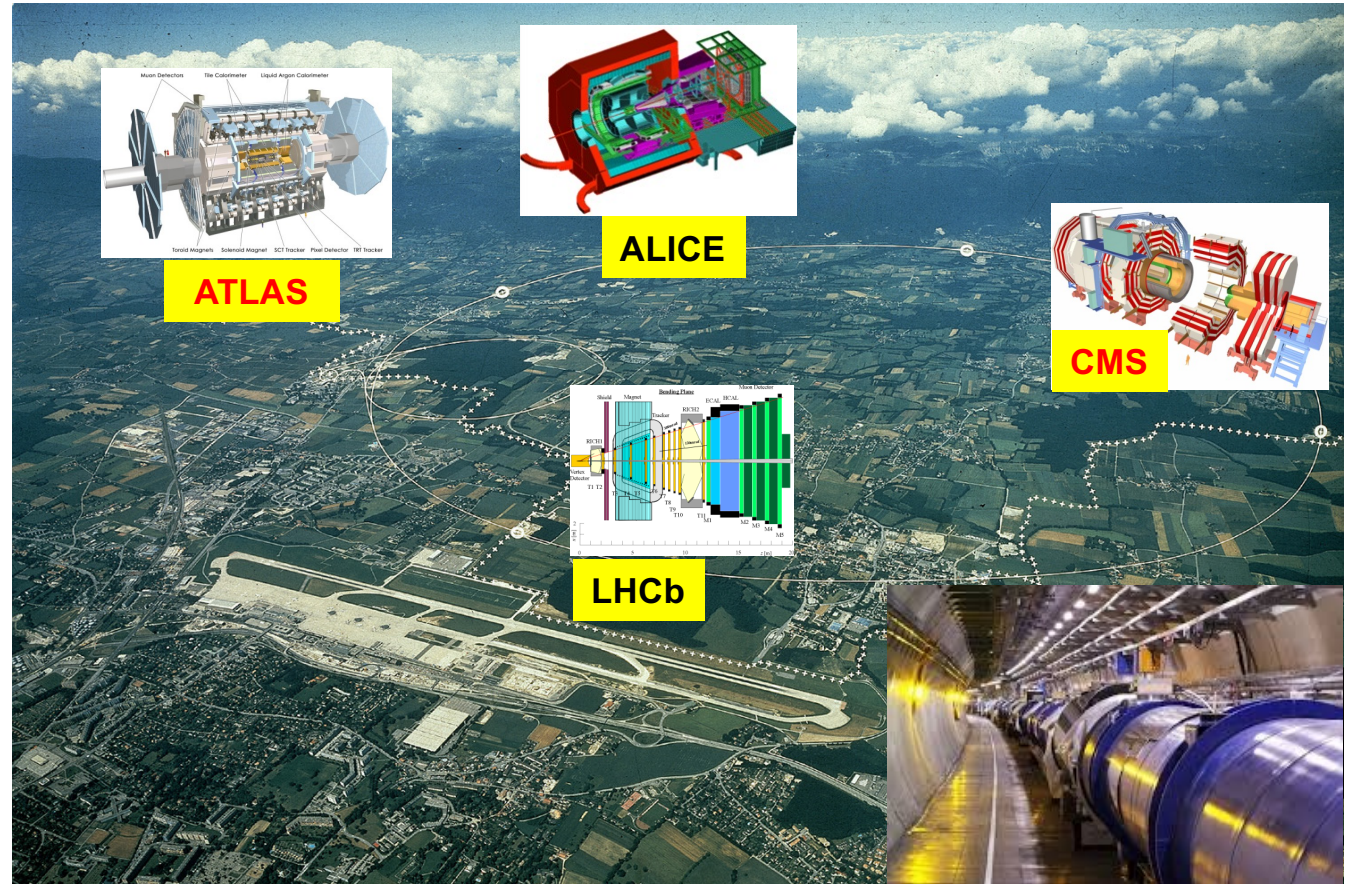
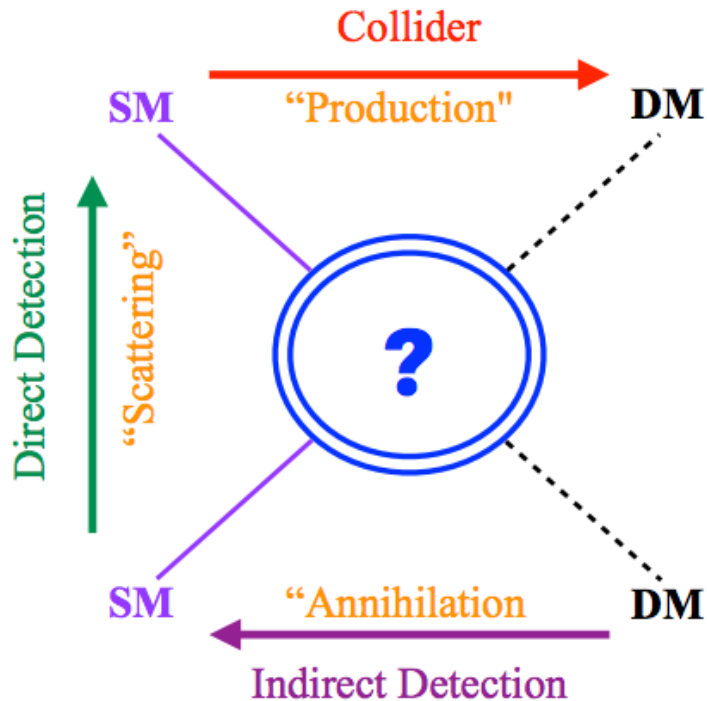
Dark Matter Indirect Detections

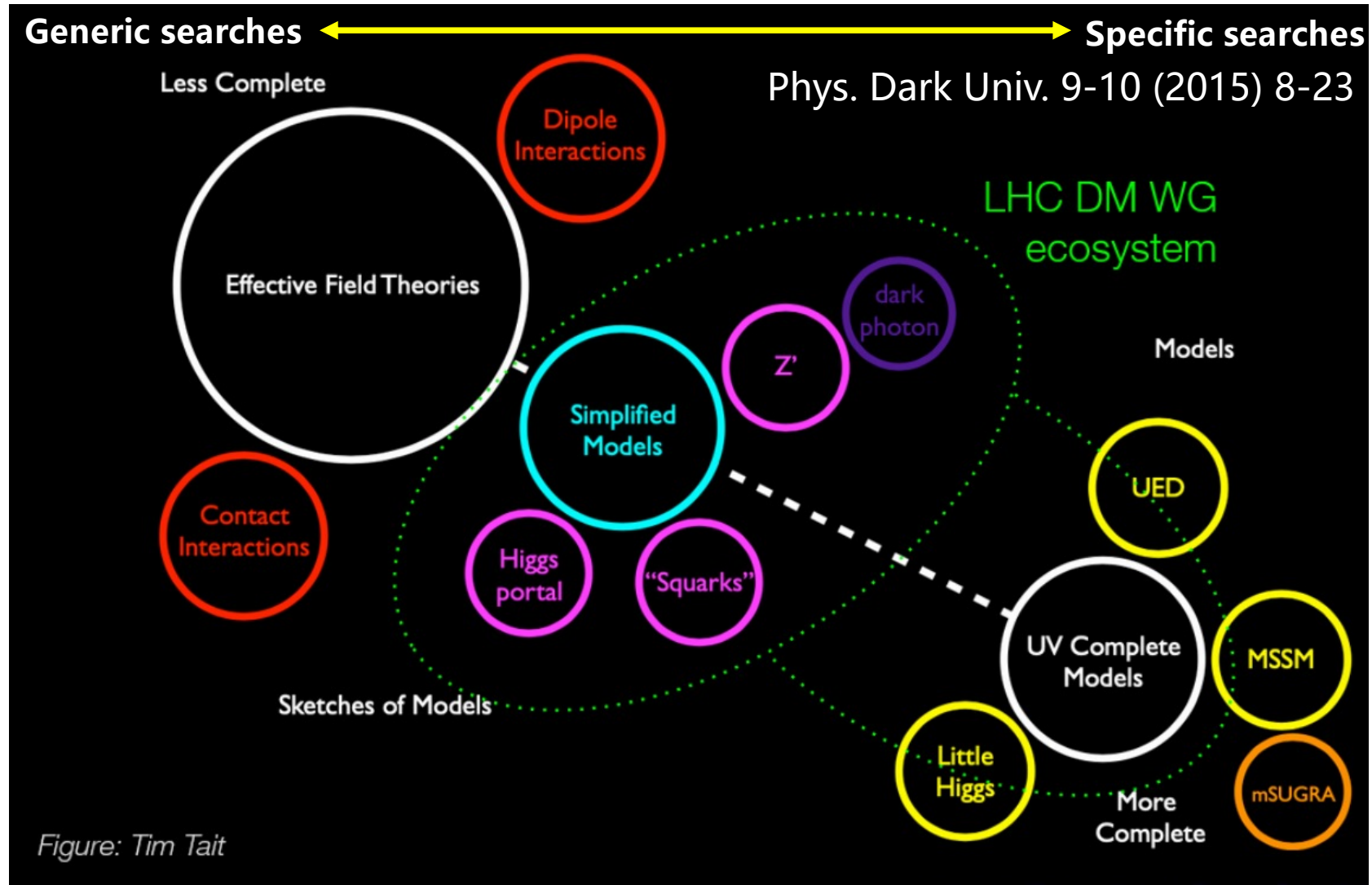
- Direct Detection (DD): nuclear recoils from DM-nuclei scattering (CDEX, PandaX, LZ, XENONnT, ...)
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- Colliders: DM production in high-energy collisions, focusing on the productions of a SM particle(s) (X) with large missing E_T



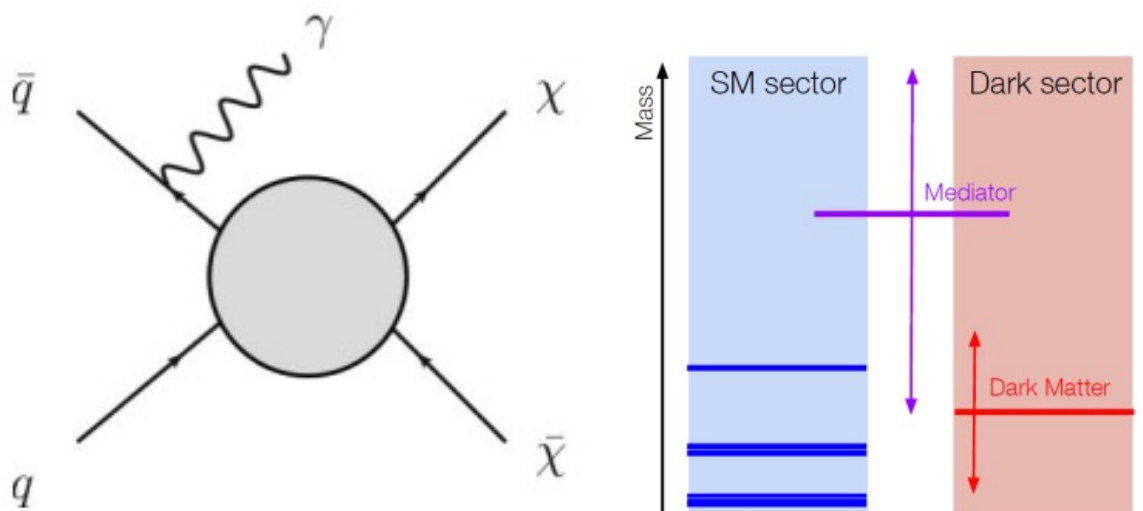
Dark Matter Collider productions

- Direct Detection (DD): nuclear recoils from DM-nuclei scattering (CDEX, PandaX, LZ, XENONnT, ...)
- Indirect Detection (ID): products from DM annihilation (DAMPE, HESS, IceCube, ..)
- Colliders: DM production in high-energy collisions, focusing on the productions of a SM particle(s) (X) with large missing E_T

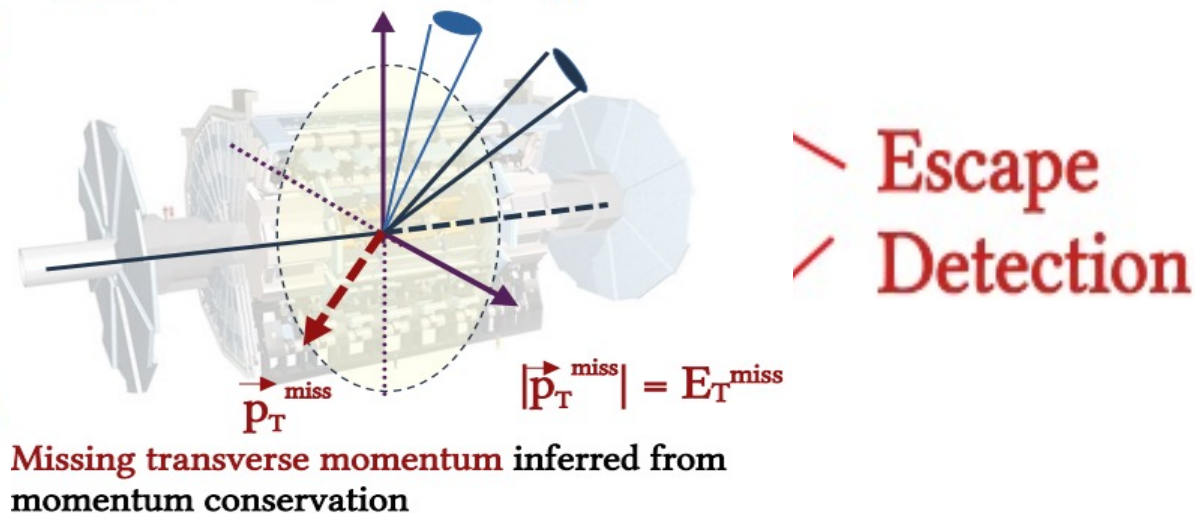




S-channel Mediator Simplified Models



DM produced together with a visible object
e.g. γ , jet, Z-boson, W-boson, Higgs-boson



Simplified model:

- Starting point to build complete theories
- Colliders can search for the mediator directly
- Benchmark model @ Run II

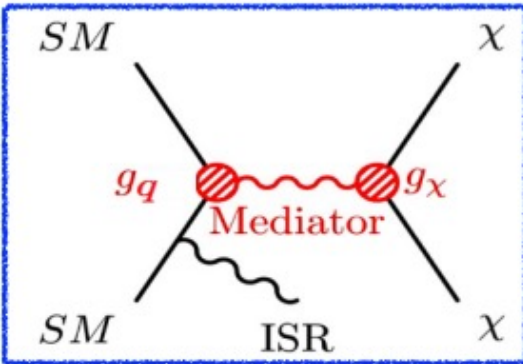
Two complementary approaches:

- Look for DM - mono-X signature
- Look for mediator - resonance search

Dark Matter Search programs at LHC

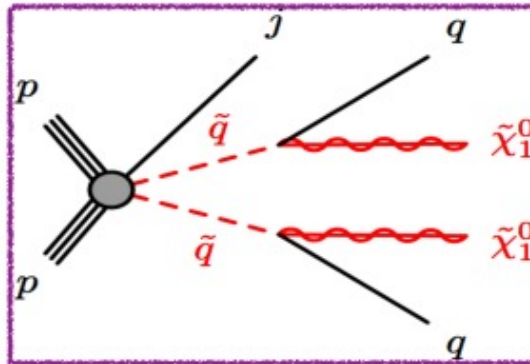


Simplified models



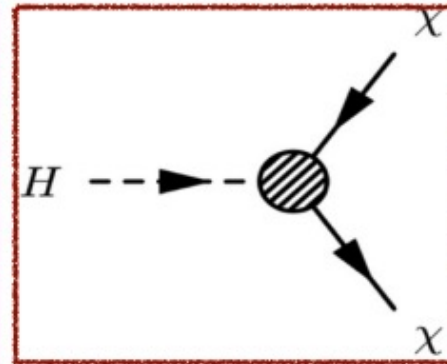
- SM-DM boson mediator:
- Spin-0: Scalar (S) or pseudo-scalar (a)
 - Spin-1: Vector (V/Z') or axial-vector (A)
 - Minimal set of parameters: $M_\chi, M_{\text{mediator}}, g_\chi, g_q, g_\ell$

SUSY



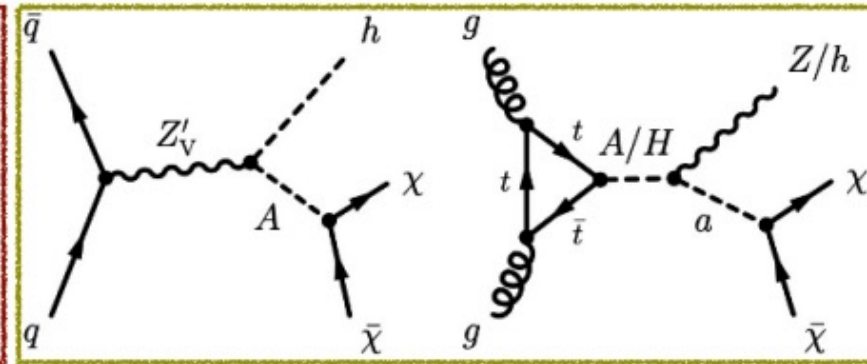
- Provides good candidate for DM
- R-parity conservation
- Lightest supersymmetric Particle (LSP)
- Model-dependent limit on DM candidate

Higgs portal



- Higgs boson mediates DM-SM interaction:
 $H \rightarrow \text{invisible}$
- Parameters: m_χ, χ spin

Extended Higgs sector



- More complete models (more free parameters and better sensitivity) involving several Higgs-like (or scalar) bosons: 2HDMa, Dark Higgs, ..



1st ATLAS Paper @ Science Bulletin



[DOI:10.1016/j.scib.2024.06.003](https://doi.org/10.1016/j.scib.2024.06.003)

Science Bulletin 69 (2024) 3005

PART 01

Recent Dark Matter Combination Summary by ATLAS in the context of 2HDM+a

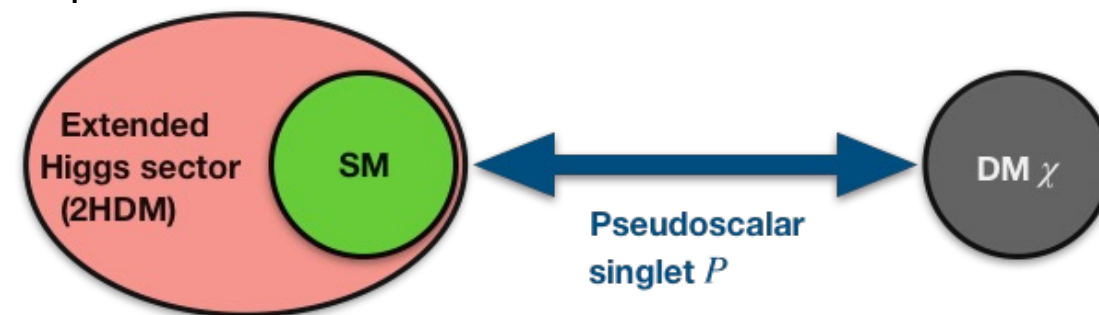
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Credits :

- Michigan(→Fudan): Zirui Wang (**Analysis Contact**)
- USTC: Chuanshun Wei, Lailin Xu (**Analysis Contact**)
- **TDLI/SJTU**: Changqiao Li (**Analysis Contact**), Shu Li, Qibin Liu, Ngoc Khanh Vu (**Approval Talk**)
- +...

2HDM+a context

- One of the popular ATLAS DM benchmark context
 - Searches interpreted in Two-Higgs-Doublet Model plus a pseudo-scalar mediator (2HDM+a):
 - Minimal, UV-complete extension.
 - EWK Symmetry Breaking:
 - 5 Higgs: $h, H, H^\pm, A$
 - 1 light pseudo-scalar: a



2HDM+a fully defined by 14 parameters

$$v, M_h, M_A, M_H, M_{H^\pm}, M_a, m_\chi, \cos(\beta - \alpha), \tan \beta, \sin \theta, y_\chi, \lambda_3, \lambda_{P1}, \lambda_{P2}$$

EWK, flavour constraints and to simplify parameter space

5 unconstrained parameters

$$m_A = m_H = m_{H^\pm}$$

$$m_a$$

$$m_\chi$$

$$\sin \theta$$

$$\tan \beta$$

masses of heavy Higgs

mass of pseudo-scalar mediator

DM mass

mixing angle between CP-odd states a and A

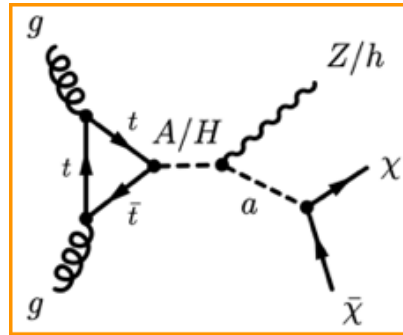
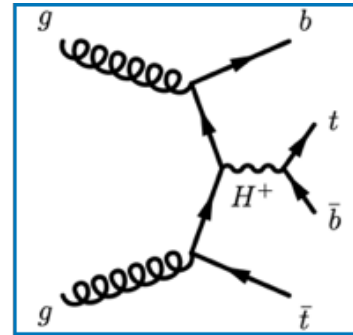
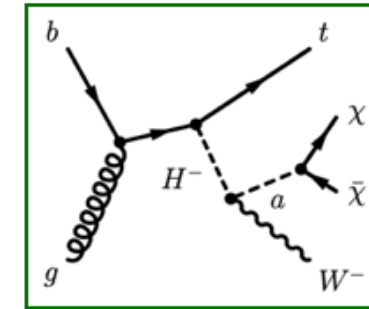
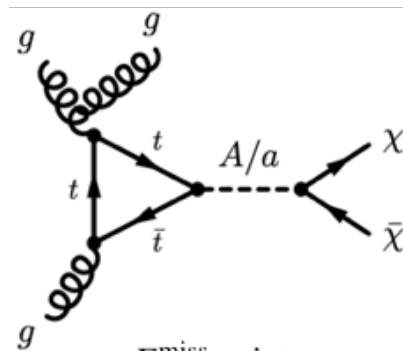
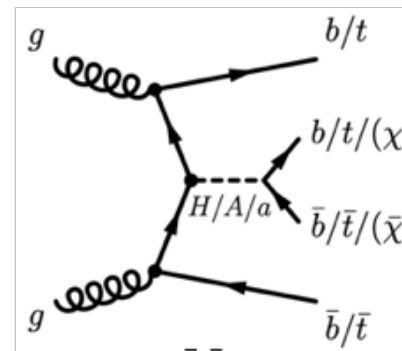
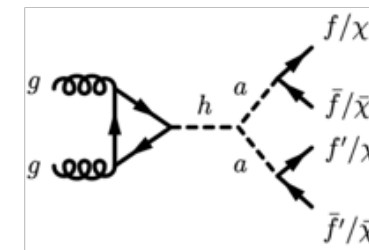
ratio of 2 Higgs doublet VEVs

* h : SM-like CP-even Higgs with mass of 125 GeV

LHC Dark Matter Working Group
[Phys. Dark Univ. 27 \(2020\) 100351](#)
 Bauer, Haisch, Kahlhoefer
[JHEP05\(2017\) 138](#)

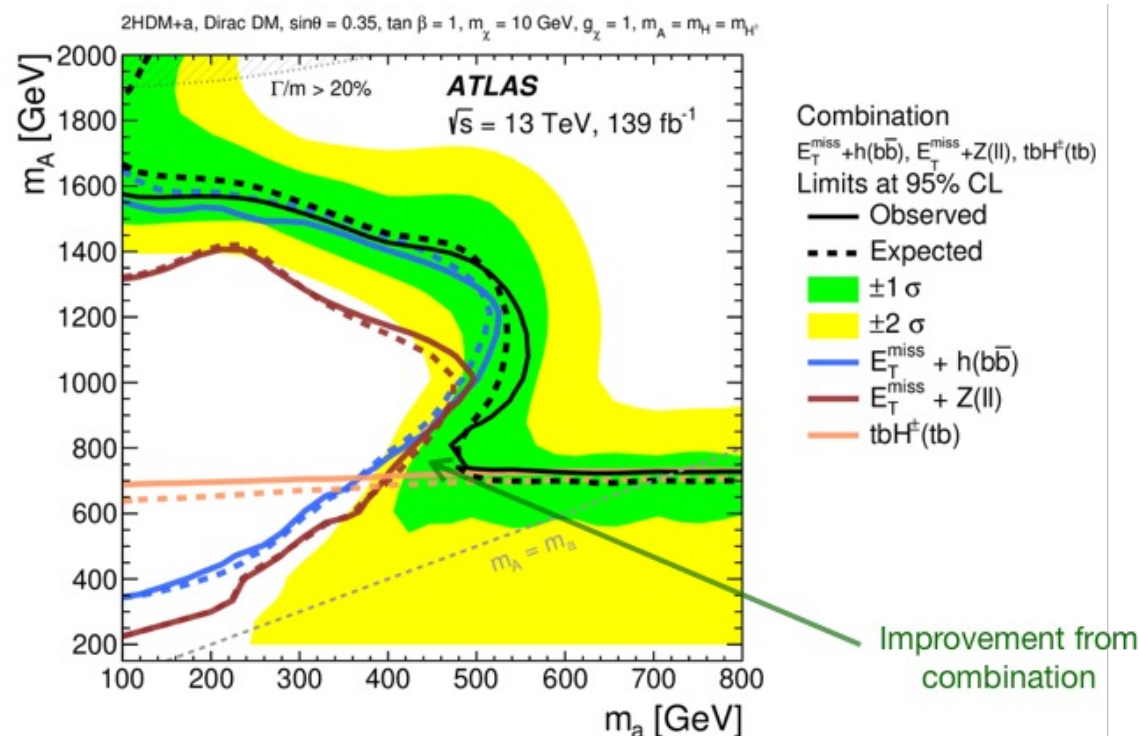
2HDM+a Experimental Signatures at ATLAS

- 2HDM+a has rich phenomenology predicting wide range of signatures with both visible and invisible decays
 - resonant production of $E_T^{\text{miss}} + Z/h$
 - additional (pseudo-)scalar bosons, e.g. $tbH^\pm(tb)$
 - new signatures, e.g. $E_T^{\text{miss}} + tW$


 $E_T^{\text{miss}} + Z/h$

 $tbH^\pm(tb)$

 $E_T^{\text{miss}} + tW$

 $E_T^{\text{miss}} + \text{jet}$

 $t\bar{t}t\bar{t}$

 $h \rightarrow aa \rightarrow 4f / h \rightarrow \text{invisible}$

Statistical Combination

- $E_T^{\text{miss}} + h(bb)$, $E_T^{\text{miss}} + Z(ll)$ and $tbH^\pm(tb)$: Most constraining signatures of 2HDM+a.
 - $tbH^\pm(tb)$ gives significant complementarity to sensitivities of $E_T^{\text{miss}} + X$
 - stat. combination of 3 channels to maximize 2HDM+a constraints in parameter space.
- Combined exclusion limits obtained from **profile likelihood ratio** corresponding to **3-channel-combined likelihood**.
- Decorrelate over-constrained/pulled uncertainties to avoid any phase-space-specific biases across channels.



Summary of constraints on 2HDM+a

- constraints on 2HDM+a interpreted in 6 benchmark scenarios.
 - highlight diverse phenomenology of 2HDM+a.
 - study the interplay and complementarities between different signatures.

Scenario		$\sin \theta$	Fixed parameter values		Varied parameters
			m_A [GeV]	m_a [GeV]	$\tan \beta$
1	a	0.35	—	—	1.0
	b	0.70	—	—	1.0
2	a	0.35	—	250	—
	b	0.70	—	250	—
3	a	0.35	600	—	—
	b	0.70	600	—	—
4	a	—	600	200	1.0
	b	—	1000	350	1.0
5		0.35	1000	400	1.0
6		0.35	1200	—	1.0

shows interplay due to mass hierarchies

motivated by similar scans done for general 2HDMs

illustration a - A mixing parameter effect

connection with cosmological constraints and direct/indirect searches

showed for the 1st time

m_χ set to 10 GeV in all scenarios, except 5 and 6

< 41 >



Summary of constraints on 2HDM+a

Variety of searches interpreted in the context of different 2HDM+a benchmark scenarios

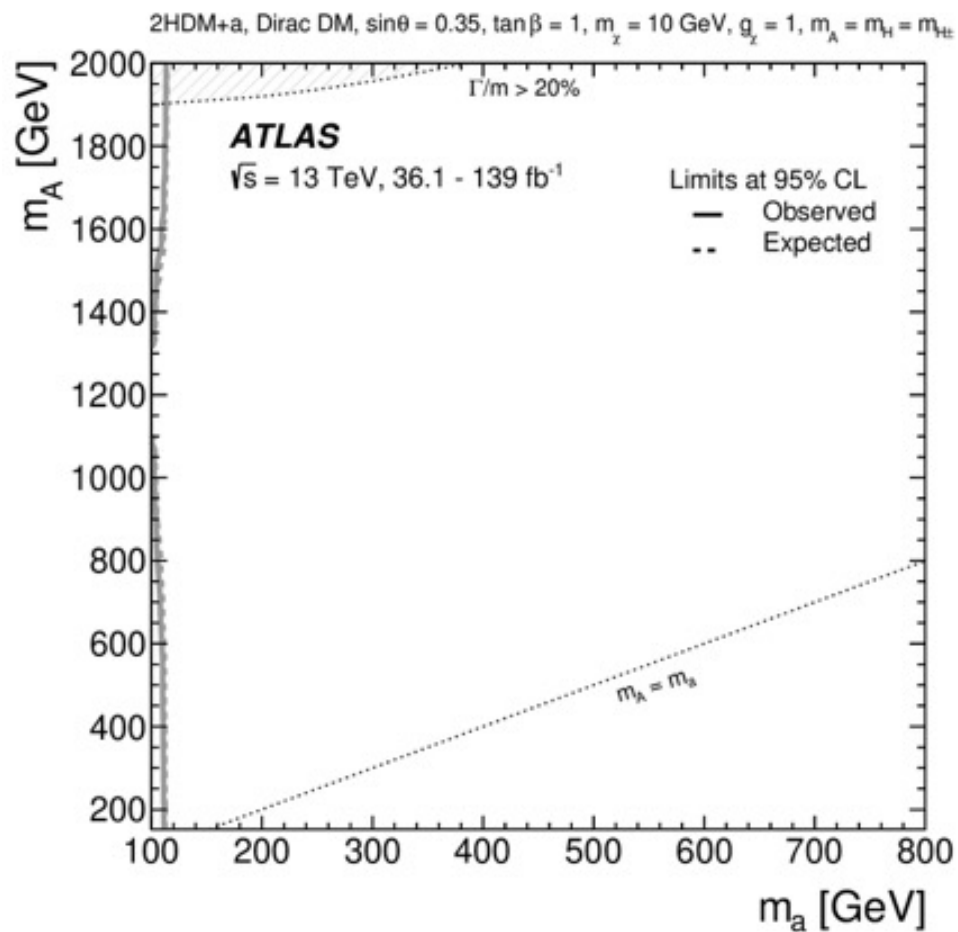
Analysis/Scenario	1a	1b	2a	2b	3a	3b	4a	4b	5	6
$E_T^{\text{miss}} + Z(\ell\ell)$ [74]	x	x	x	x	x	x	x	x	x	
$E_T^{\text{miss}} + h(b\bar{b})$ [75]	x	x	x	x	x	x	x	x	x	x
$E_T^{\text{miss}} + h(\gamma\gamma)$ [84]	x	x			x	x	x	x		
$E_T^{\text{miss}} + h(\tau\tau)$ [78]	x			x						
$E_T^{\text{miss}} + tW$ [77]	x	x	x	x	x	x	x	x		
$E_T^{\text{miss}} + j$ [45]	x	x			x	x	x	x		
$h \rightarrow \text{invisible}$ [86]	x	x			x					x
$E_T^{\text{miss}} + Z(q\bar{q})$ [127]	x						x	x		
$E_T^{\text{miss}} + b\bar{b}$ [128]							x	x		
$E_T^{\text{miss}} + t\bar{t}$ [128,129]							x	x		
$t\bar{t}t\bar{t}$ [85]	x	x	x	x	x	x	x	x	x	
$tbH^\pm(tb)$ [76]	x	x	x	x	x	x	x	x	x	
$h \rightarrow aa \rightarrow f\bar{f}f'\bar{f}'$ [79,80,81,82,83]										x



● Scenario 1a: $\sin\theta=0.35$, $m_A - m_a$ plane



- $h \rightarrow$ invisible constrains very low m_a .

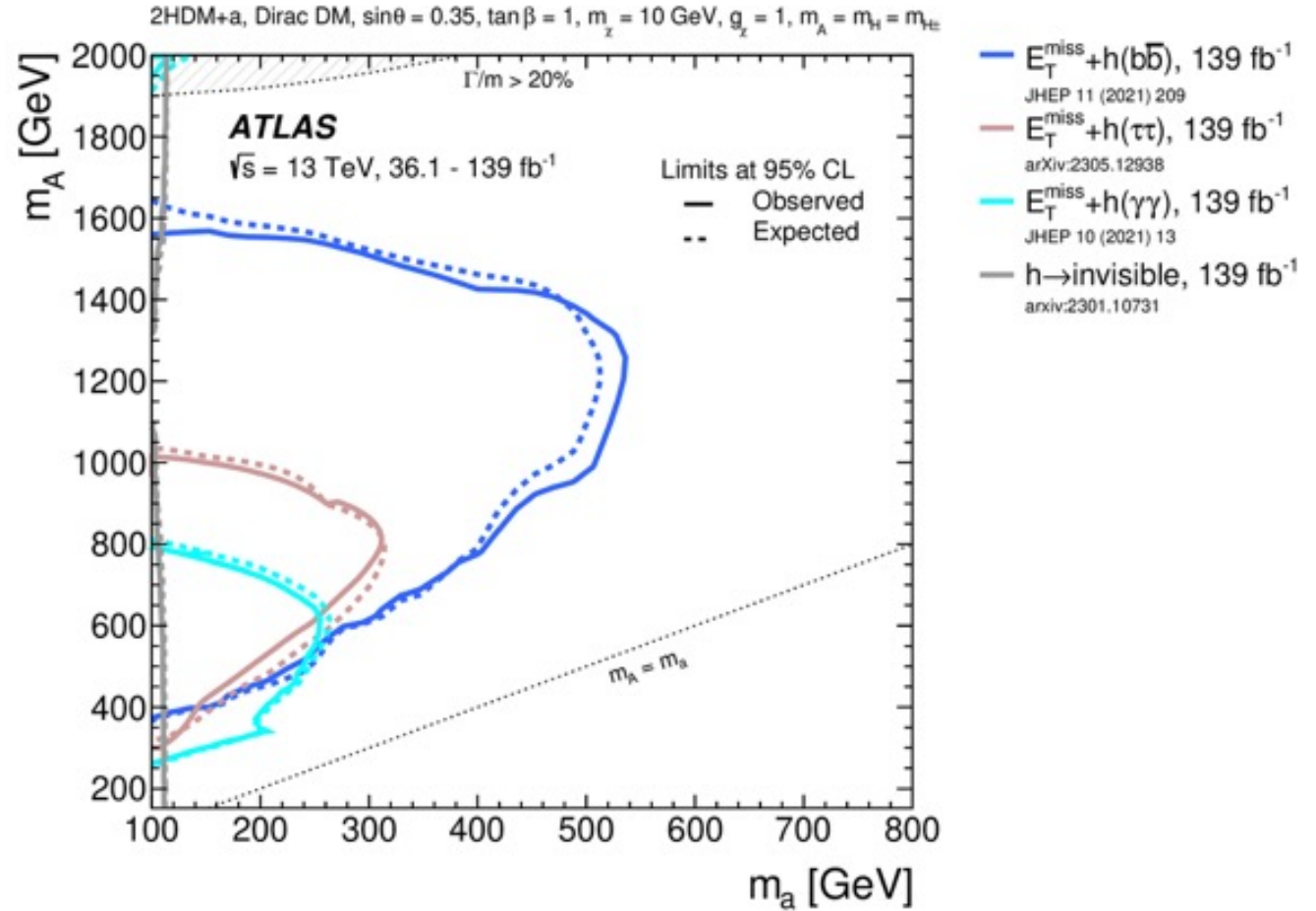


— $h \rightarrow$ invisible, 139 fb $^{-1}$
arXiv:2301.10731

● Scenario 1a: $\sin\theta=0.35$, $m_A - m_a$ plane



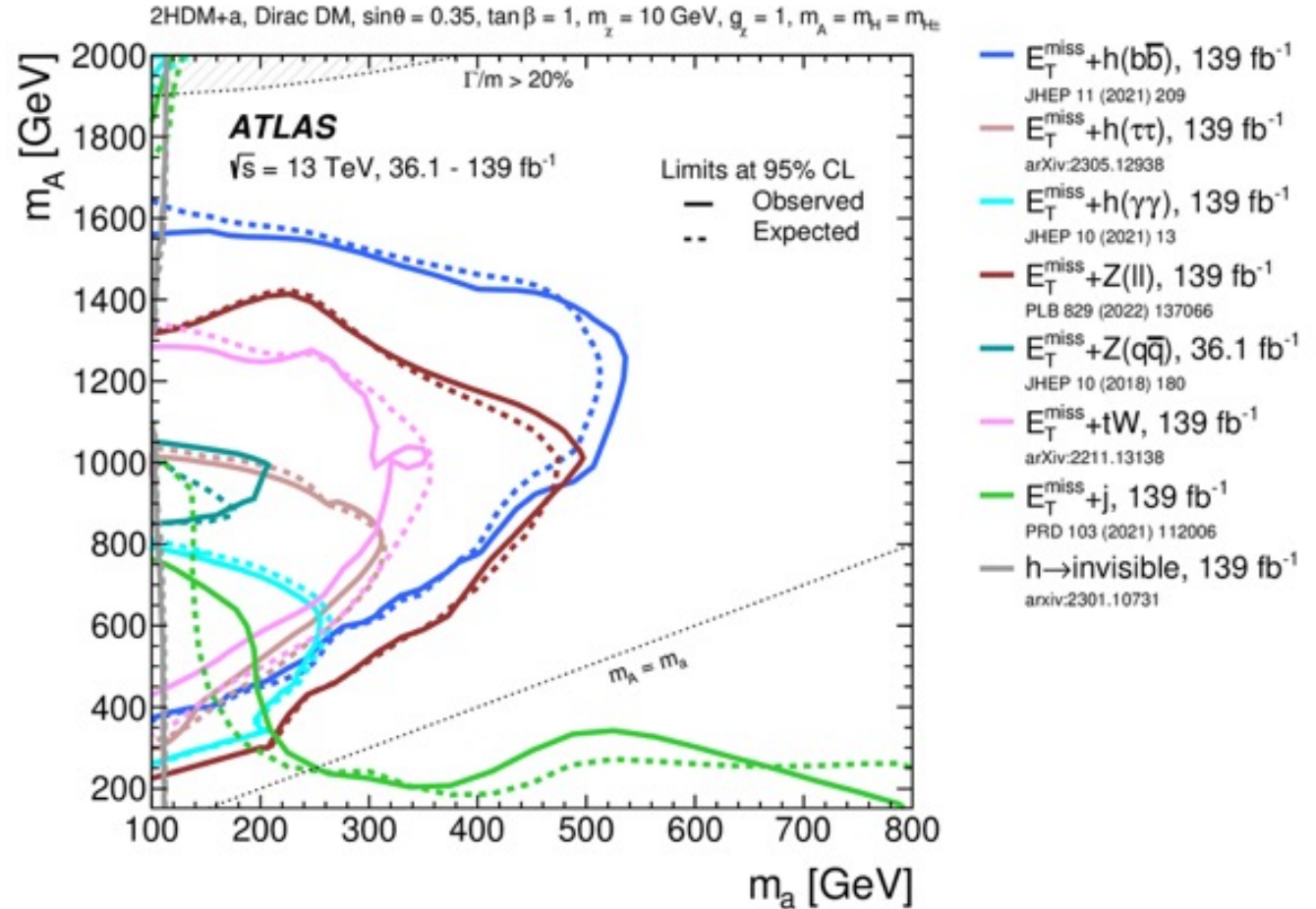
- $h \rightarrow$ invisible constrains very low m_a .
- constraints from $E_T^{\text{miss}} + h$ signatures: similar m_A - m_a dependence, with $h \rightarrow b\bar{b}$ most sensitive.



Scenario 1a: $\sin\theta=0.35$, $m_A - m_a$ plane



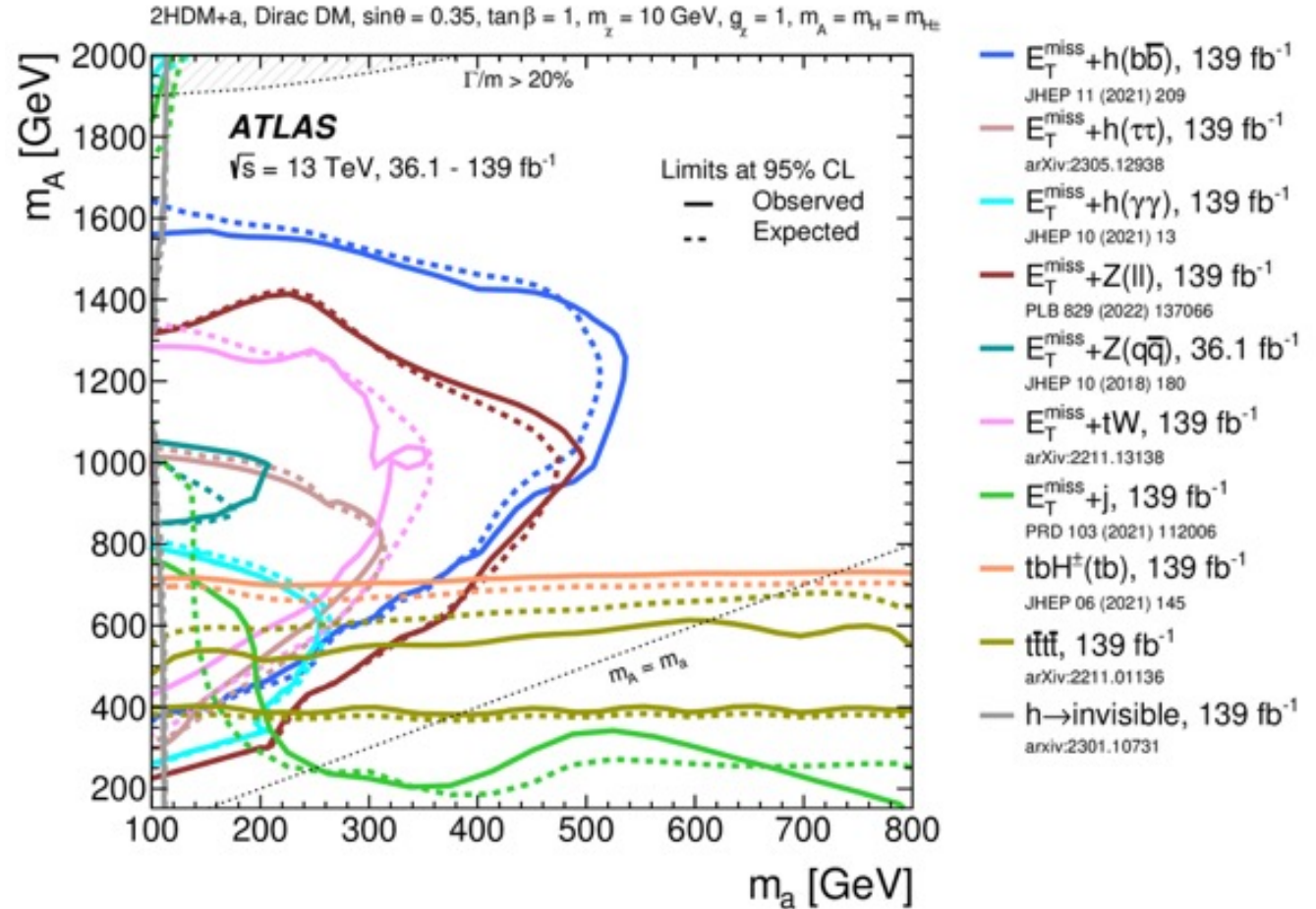
- $h \rightarrow$ invisible constrains very low m_a .
- constraints from $E_T^{\text{miss}} + h$ signatures: similar m_A - m_a dependence, with $h \rightarrow bb$ most sensitive.
- $E_T^{\text{miss}} + tW$ similar to $E_T^{\text{miss}} + Z(l\bar{l})$ but with smaller excl. region.
- $E_T^{\text{miss}} + \text{jet}$ sensitivity notably different from those of $E_T^{\text{miss}} + Z$ and $E_T^{\text{miss}} + h$.



Scenario 1a: $\sin\theta=0.35$, $m_A - m_a$ plane



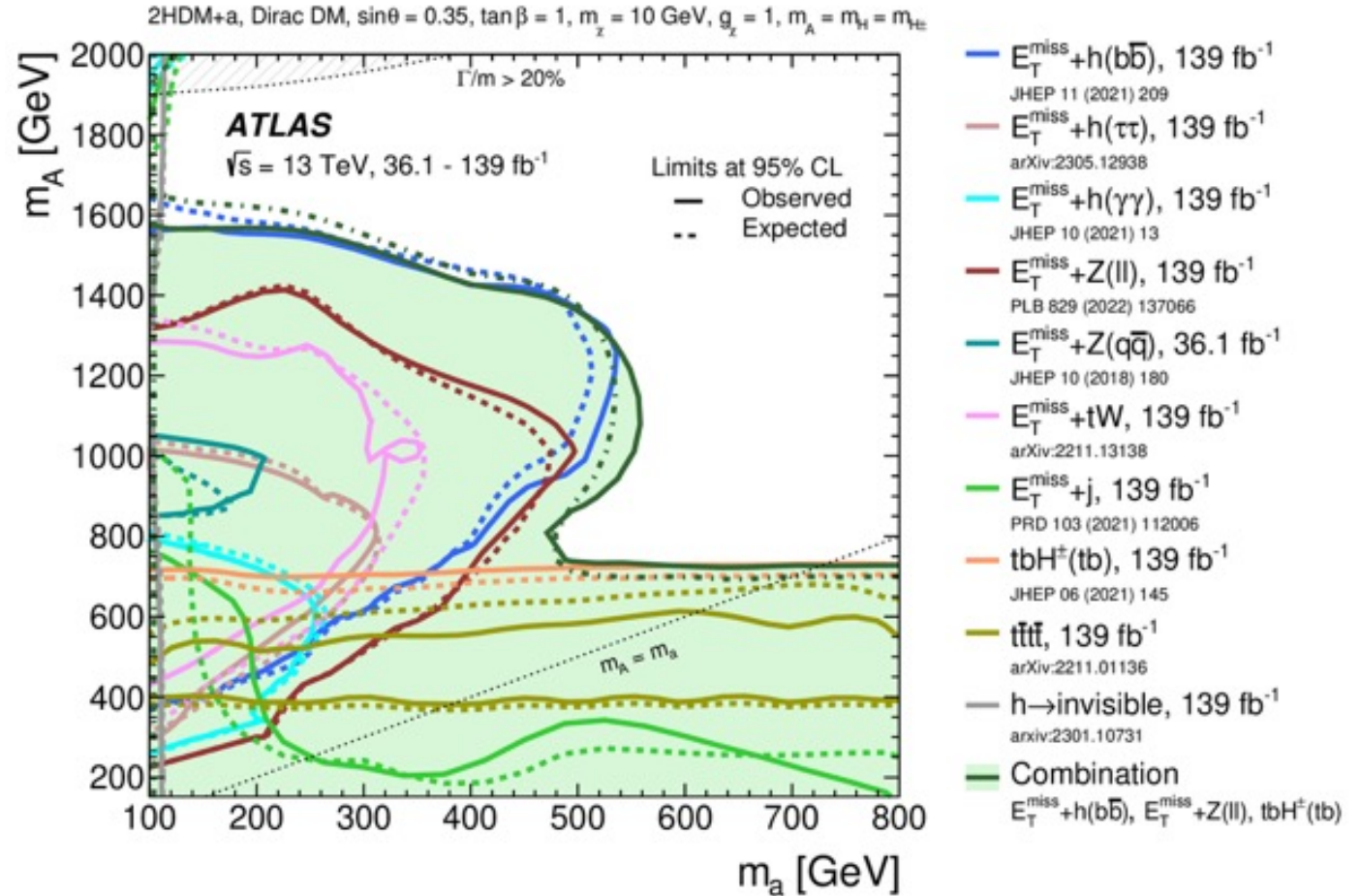
- $h \rightarrow$ invisible constrains very low m_a .
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- $E_T^{\text{miss}} + \text{jet}$ sensitivity notably different from those of $E_T^{\text{miss}} + Z$ and $E_T^{\text{miss}} + h$.
- Complementary constraints from searches not targeting DM.



Scenario 1a: $\sin\theta=0.35$, $m_A - m_a$ plane



- $h \rightarrow$ invisible constrains very low m_a .
- constraints from $E_T^{\text{miss}} + h$ signatures: similar m_A - m_a dependence, with $h \rightarrow bb$ most sensitive.
- $E_T^{\text{miss}} + tW$ similar to $E_T^{\text{miss}} + Z(\ell\ell)$ but with smaller excl. region.
- $E_T^{\text{miss}} + \text{jet}$ sensitivity notably different from those of $E_T^{\text{miss}} + Z$ and $E_T^{\text{miss}} + h$.
- Complementary constraints from searches not targeting DM.
- Sensitivity of 2HDM+a driven by the combination.



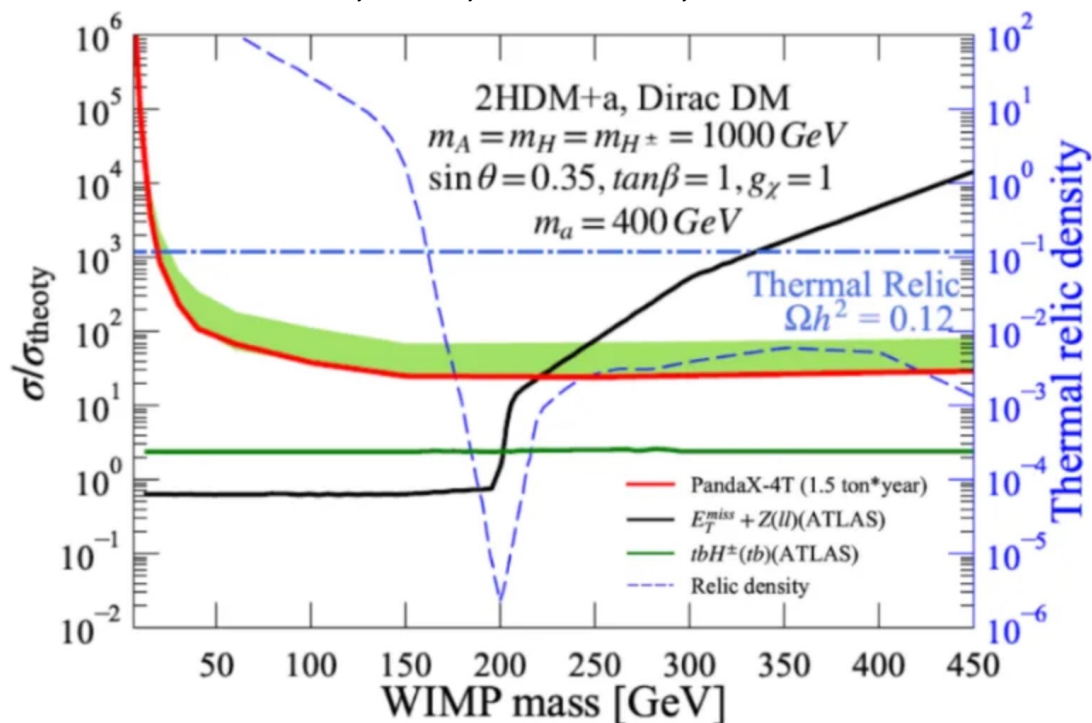
DM search: Collider & Direct Search Experiment



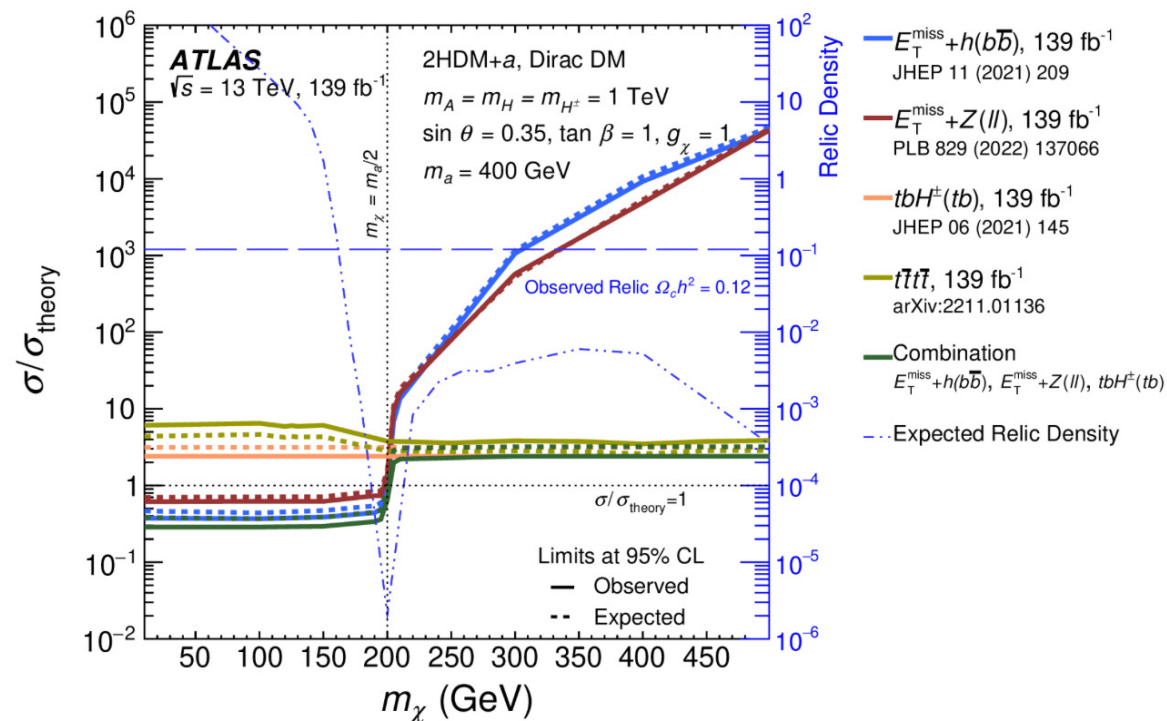
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<https://mp.weixin.qq.com/s/l1Mgrwyh15KMKnf9r9yjsQ>

Credits: X.-G. He, J. Liu, J. Tandean, N. Zhou



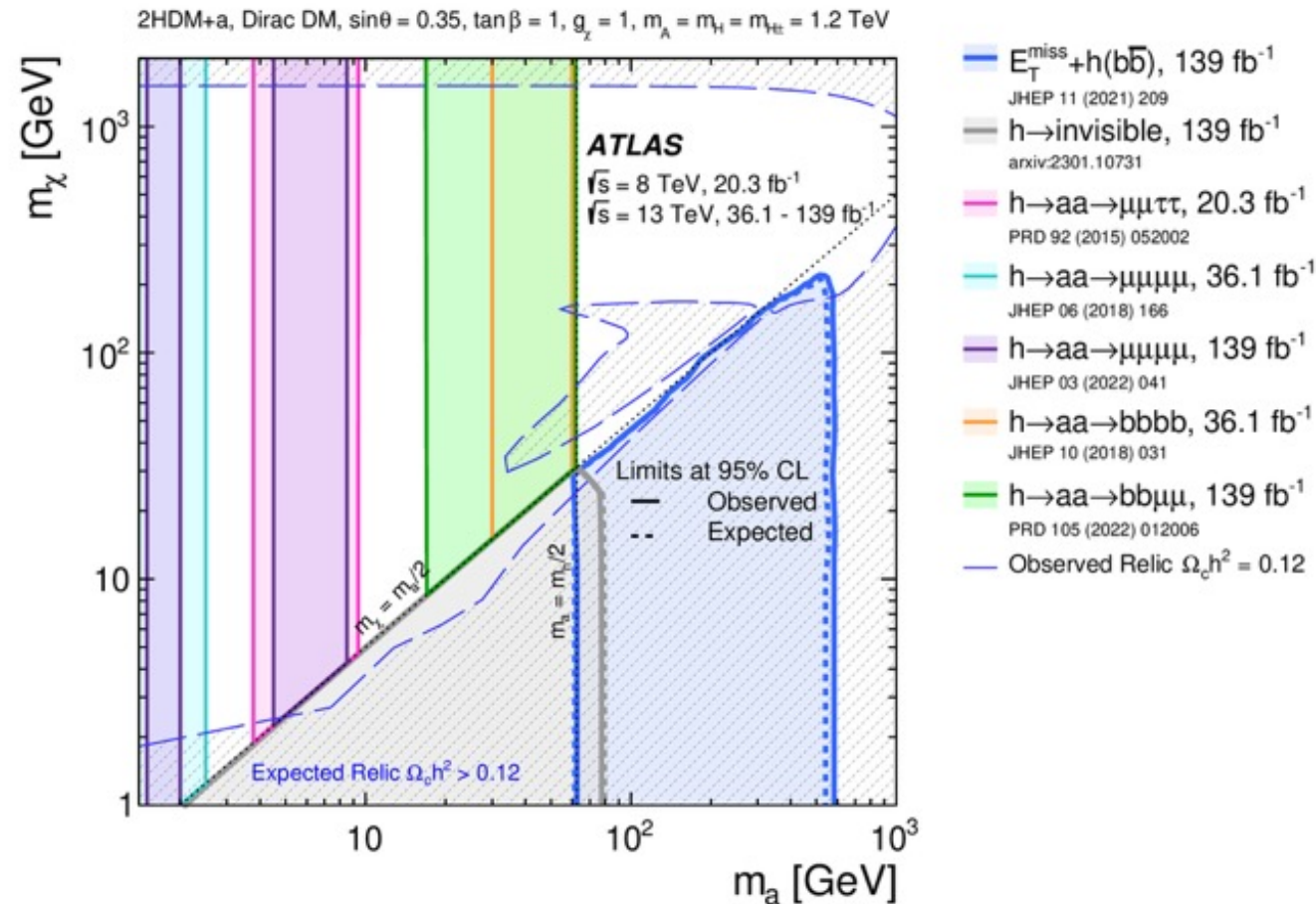
Science Bulletin 69 (2024) 3005



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● Scenario 6: $m_a - m_\chi$ plane

- New interpretation in $m_a - m_\chi$ plane:
- Searches for SM Higgs decaying to 4 fermions via constrain previously unprobed region of 2HDM+a.
- Complementarity to $h \rightarrow \text{inv.}$ and $E_T^{\text{miss}} + h(bb)$ searches.





PART 02

Recent Dark Higgs Searches at ATLAS

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Credits :

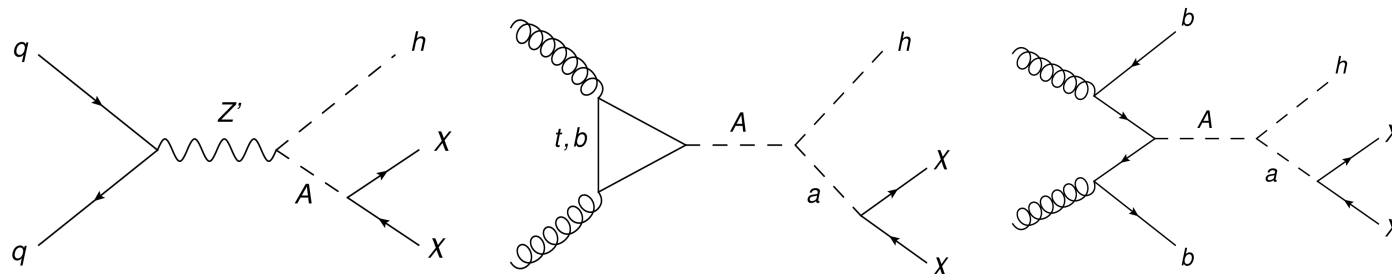
- UW: Shih-Chieh Hsu (**Analysis Contact**)
- **TDLI/SJTU**: Changqiao Li (**Analysis Contact**), Shu Li, Qibin Liu (**Approval Talk**)
- +...

Higgs portal to DM: Mono-H(bb)

JHEP 11 (2021) 209



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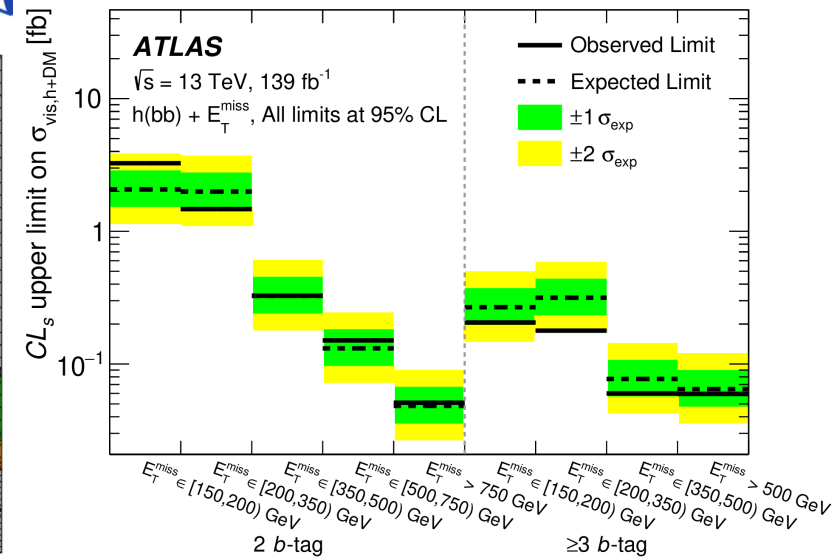
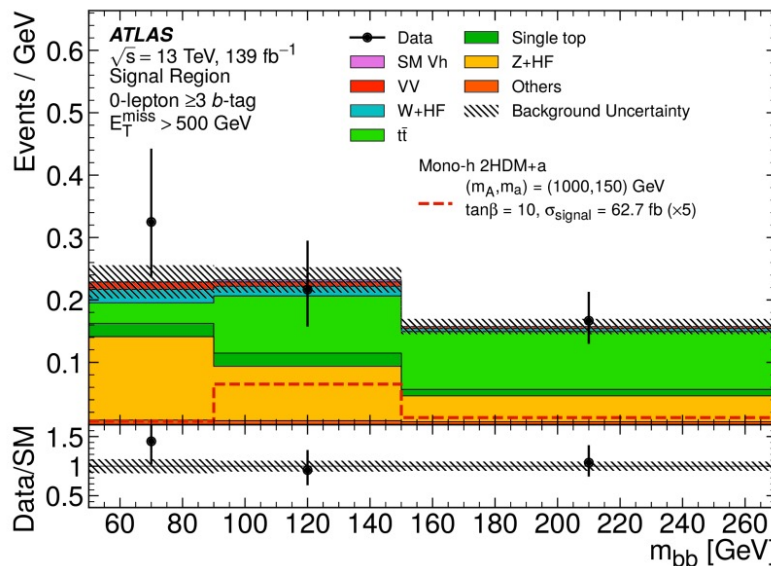
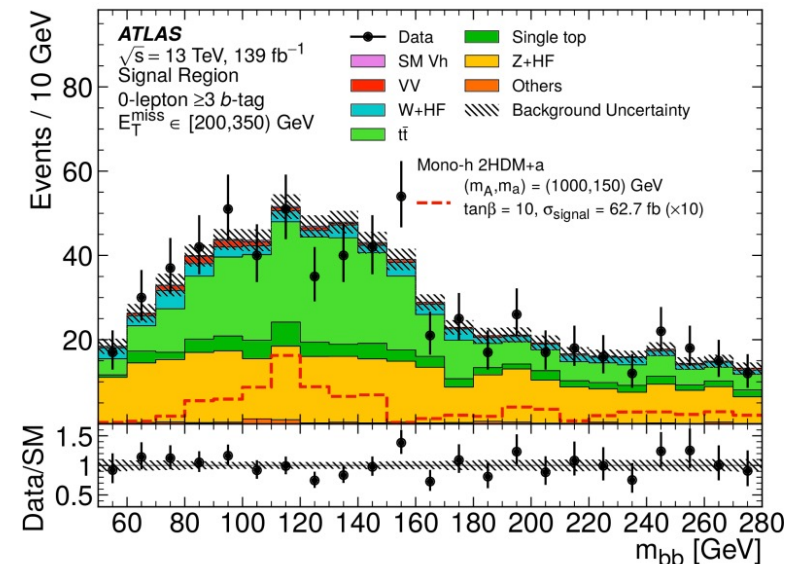
Resolved topology

$150 < E_T^{miss} < 500 \text{ GeV}$
 $50 \text{ GeV} < m_h < 280 \text{ GeV}$
 At least 2 small-R jets

Merged topology

$E_T^{miss} > 500 \text{ GeV}$
 $50 \text{ GeV} < m_h < 270 \text{ GeV}$
 At least 1 large-R jet

- Interpreted with 2HDM+Z' , 2HDM+a in both ggF and bbH.
- Also Model-independent upper limits on the visible cross-section



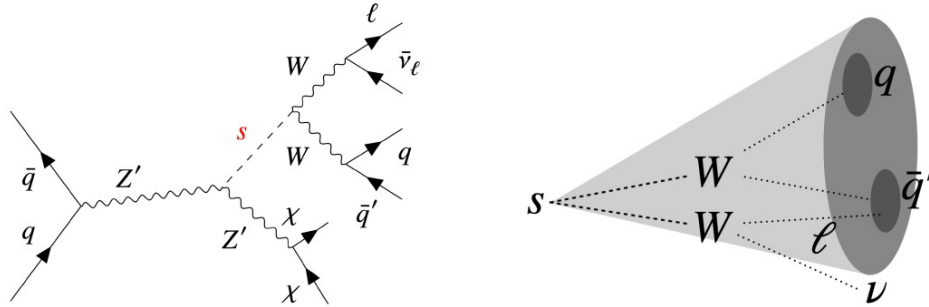
Dark Higgs Search: Mono-S($\rightarrow$ WW) semileptonic

JHEP 07 (2023) 116

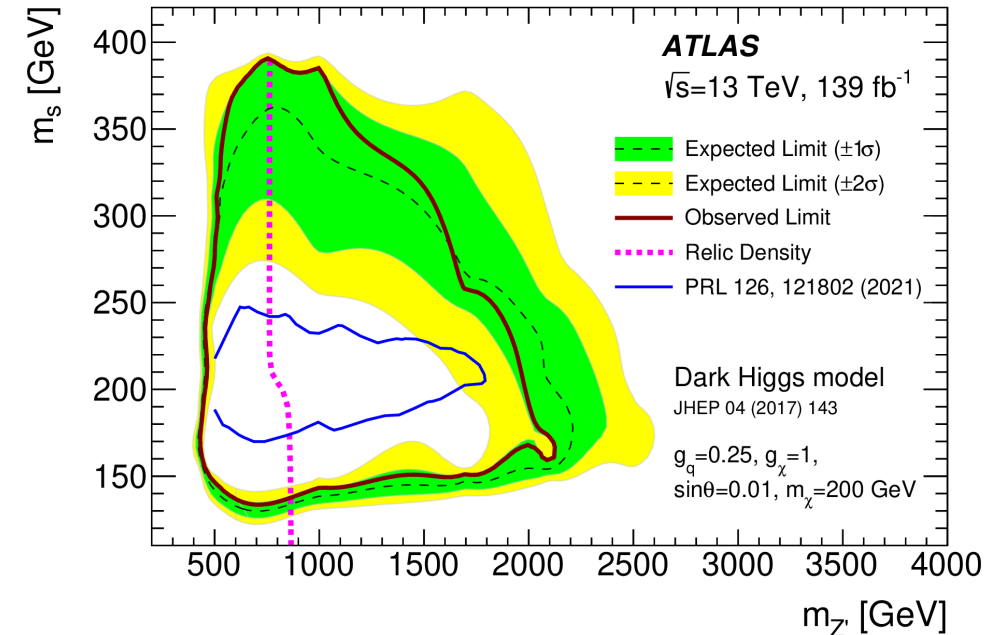
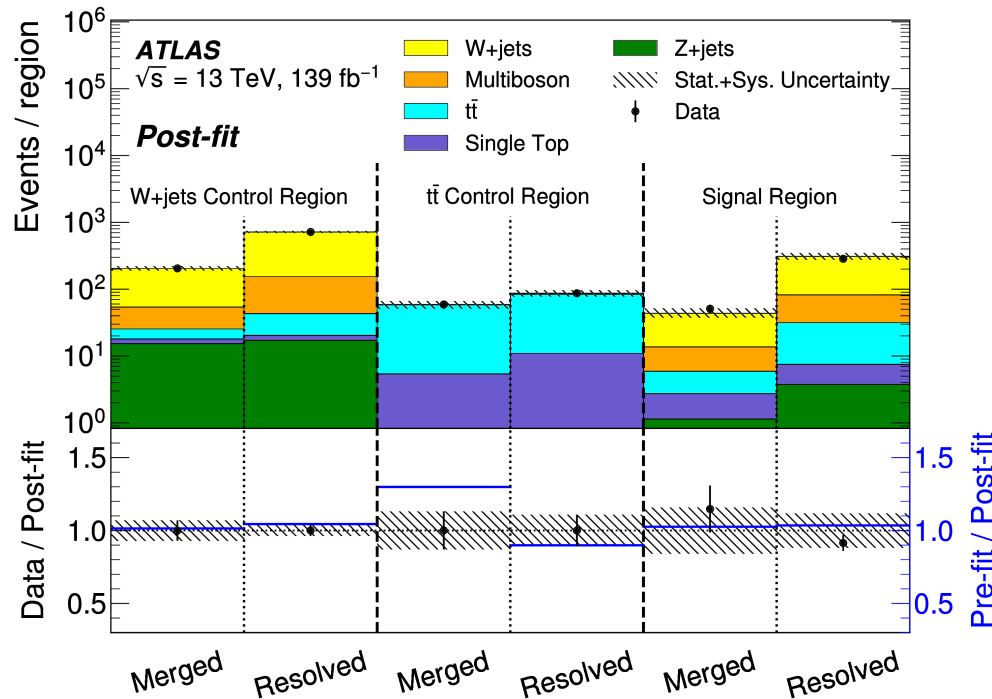
PRL 126 (2021) 121802



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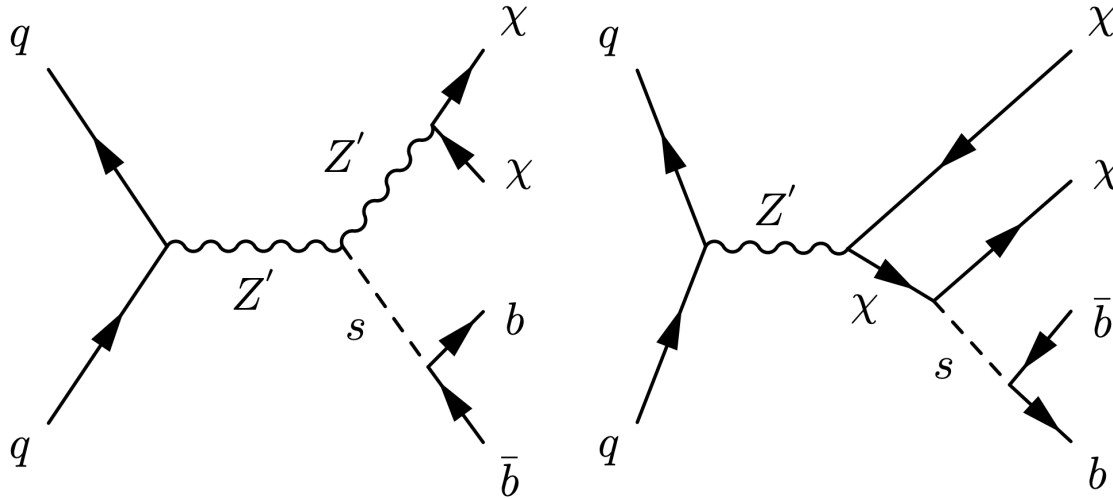


- Two mediator model: Z' + Dark Higgs
- Utilize both resolved calorimeter-measured jet pair or merged from track-assisted reclustered jets
- Scenarios with dark Higgs boson masses ranging between 140 and 390 GeV are excluded.





NEW Dark Higgs Search: Mono-S($\rightarrow$ bb)



$$\mathcal{L}_\chi = -\frac{1}{2}g_\chi Z'^\mu \bar{\chi} \gamma^5 \gamma_\mu \chi - g_\chi \frac{m_\chi}{m_{Z'}} s \bar{\chi} \chi + 2g_\chi Z'^\mu Z'_\mu (g_\chi s^2 + m_{Z'} s)$$

- Dark Higgs boson (scalar particle s) introduced together with Z' and Majorana DM [Ref. JHEP 04 (2017) 143]
- New annihilation channel to SM opened up ($\chi\chi \rightarrow s \rightarrow \dots$): relax the constraint from cosmology $\rightarrow$ Prevent DM Relic Density (Ωh^2) over-production issue of common WIMP model
- Scalar particle mixing with SM Higgs: detectable decay products depending on mass, $s \rightarrow VV$, $s \rightarrow b\bar{b}$
- Done Searches for high mass dark Higgs in Mono-S(VV) analyses (previous slide)

First search aiming for a low-mass dark Higgs boson + new benchmark scenarios





● **NEW** Dark Higgs Search: Mono-S($\rightarrow$ bb)

- Six parameters controlling the interaction with SM and DM
- Fixed- g_χ search as benchmark (scenario 1)
 - Scan m_S v.s. $m_{Z'}$ with fixed $m_\chi = 200$ GeV, $g_\chi = 1.0$
- Cosmological constraint: freeze-out relic density Ωh^2
 - Observation from PLANCK2018: $\Omega h^2 = 0.1200 \pm 0.0012$
- Introduce two new benchmark scenarios [**First time!**] satisfying the observed relic density (scenario 2, 3)
 - Scan m_S v.s. $m_{Z'}$ with fixed $m_\chi = 900$ GeV
 - Scan m_χ v.s. $m_{Z'}$ with fixed $m_S = 70$ GeV

Parameter	Explain
m_S	mass of dark higgs
m_χ	mass of DM
$m_{Z'}$	mass of heavy mediator
g_χ	coupling in dark sector between s, X, Z'
g_q	coupling with SM: $q \leftrightarrow Z'$ fixed 0.25 as benchmark
θ	mixing angle of SM Higgs $\leftrightarrow$ dark Higgs fixed according to [1]

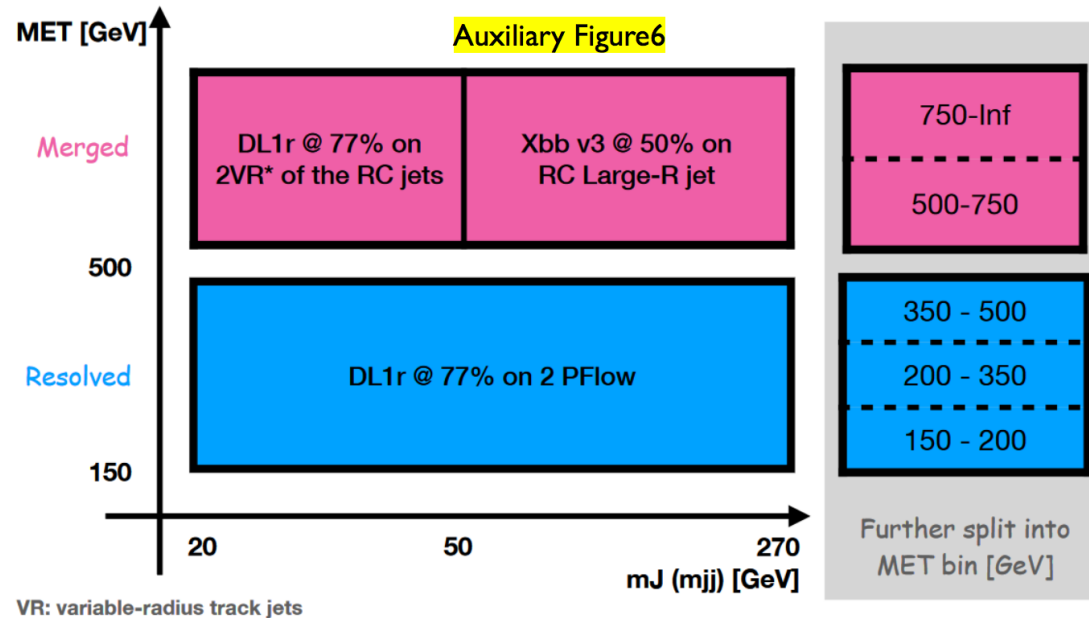
● NEW Dark Higgs Search: Mono-S($\rightarrow$ bb)

Analysis Strategy overview

- Search for low mass dark Higgs with $bb + E_T^{\text{miss}}$ signature
- Data triggered with E_T^{miss} and search starts from 150GeV
- Regions divided by E_T^{miss} : from resolved to merged topology to cover all the interesting phase space

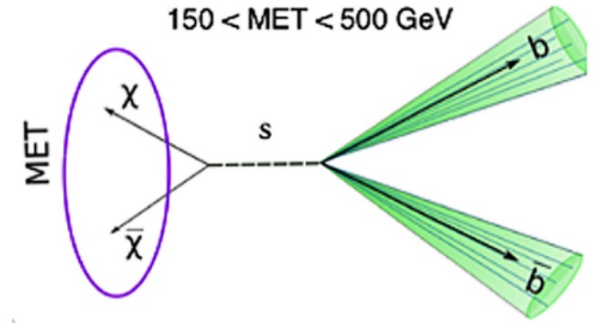
Resolved regions: reconstructed by 2 small-R jets and tagged using DL1r 77%

Merged region: 1 reclustering large-R jet and mixed tagging methods $\rightarrow$ benefit from advanced techniques



Resolved Topo.

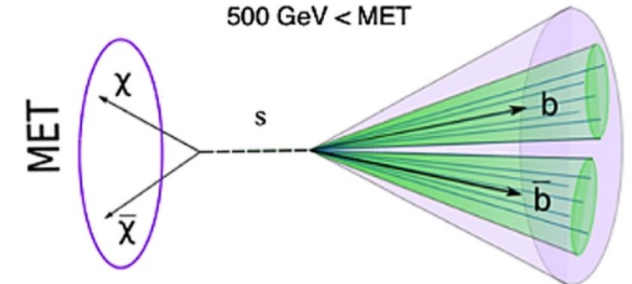
$150 < MET < 500$ GeV



Good statistics

Boosted Topo.

$500 \text{ GeV} < MET$



Sensitive to high $m_{Z'}$
dominates for $m_{Z'} > 2 \text{ TeV}$

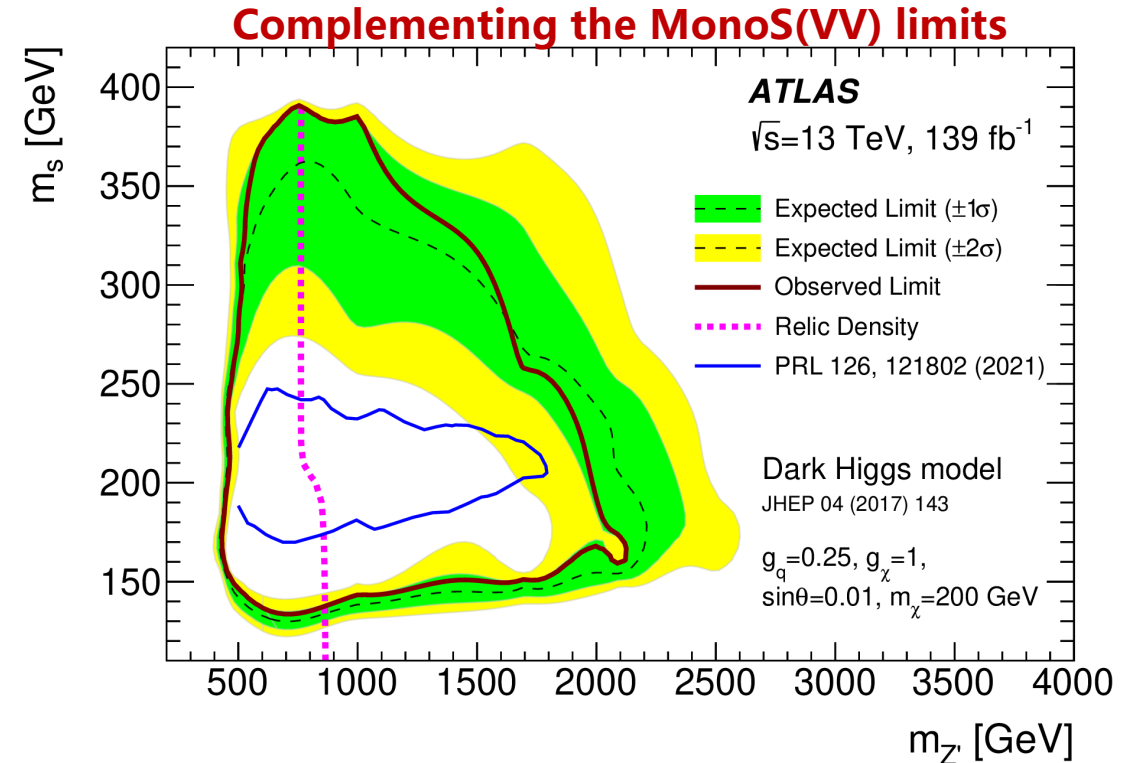
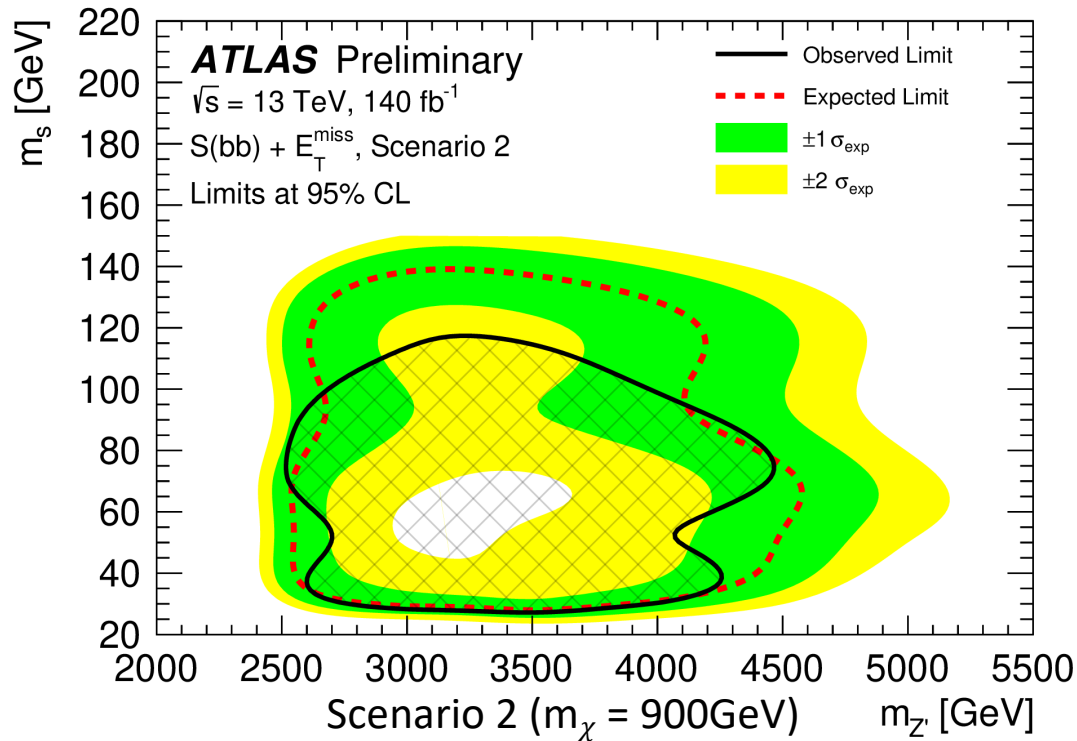
Reclustering(RC) jet extend searched scalar mass down to 20GeV
Large-R jet kin. and sub-jet info. combined for boosted Xbb tagging: DXbb



● Mono-S(bb) Exclusion Limit: relic-density inspired scenario

DM coupling varies to satisfy the observed relic density throughout

- $m_{Z'}$ excluded up to 4.1 TeV with fixed m_χ at 900 GeV (scenario2)
- $m_{Z'}$ excluded up to the perturbative limit and m_χ excl. to 1 TeV at $m_s = 70$ GeV (scenario3)



First LHC dark Higgs search in cosmology coherent context





PART 03

Recent Higgs $\rightarrow$ Dark Photon decay search combination at ATLAS

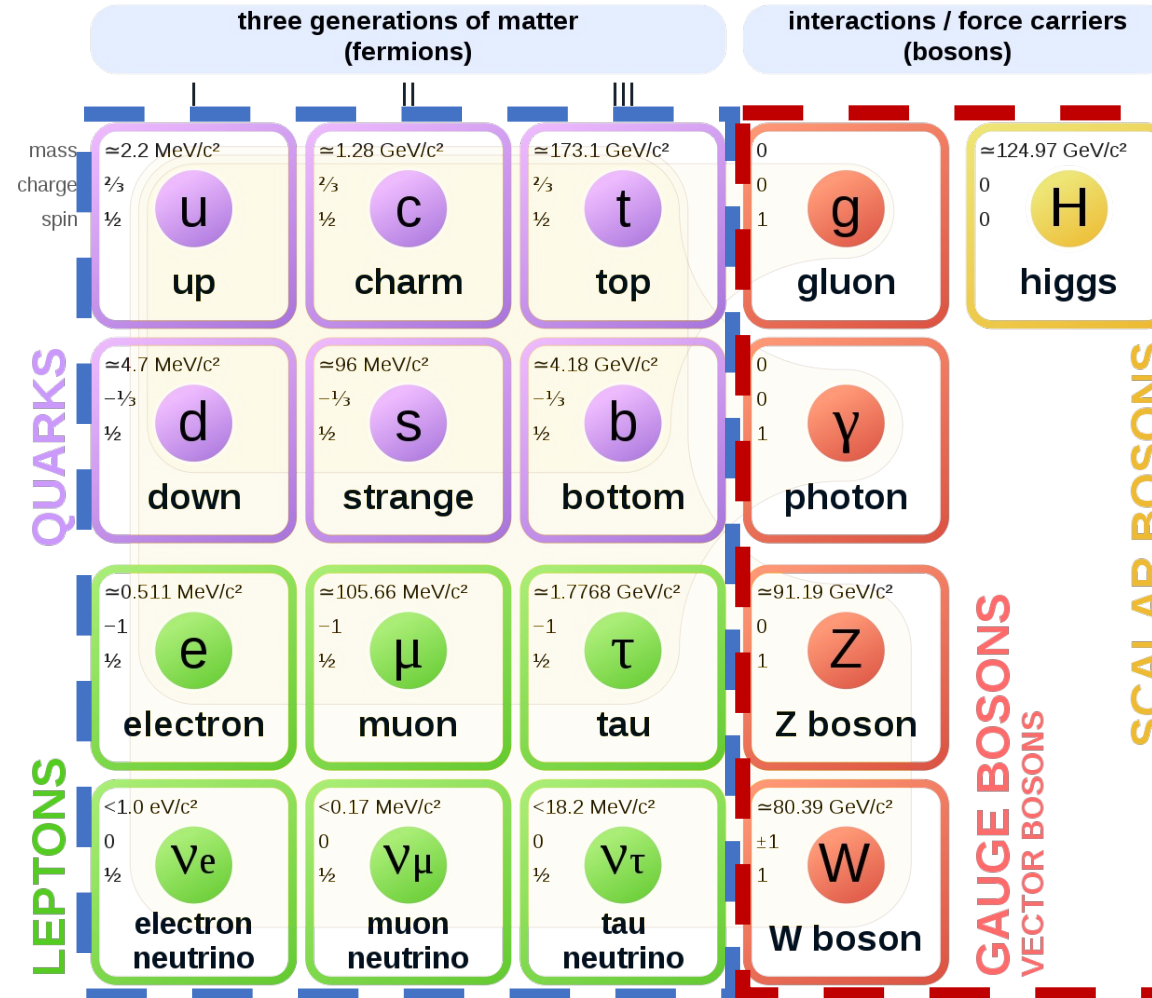
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Credits :

- Milan: Silvia Resconi (**Analysis Contact**)
- **TDLI/SJTU**: Ngoc Khanh Vu (**Analysis Contact**), Shu Li, Qibin Liu (**Approval Talk**)
- +...

Looking into the SM particle bible

Standard Model of Elementary Particles



Fermions:
making
up
ordinary
matter

Bosons:
mediator
portal for
ordinary
matter

● Searching for Dark Force Mediators



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The world of Dark Matter

**Dark
Matter
candidate
particles**



**Dark
Matter
Mediators**

Dark Photon Theory in a nutshell

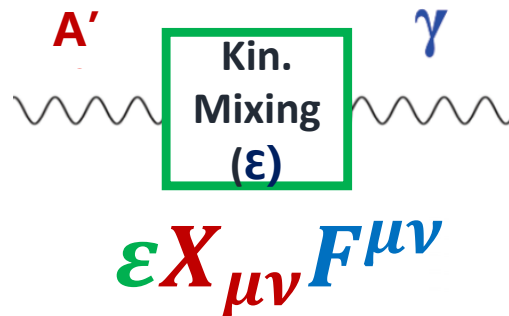
Introduce extra $U(1)_X$ symmetry $\rightarrow$ New Gauge Field $X \rightarrow$ Dark Photon Mediator A'
 $U(1)_{em} \rightarrow U(1)_{em} \times U(1)_X$

5th fundamental interaction in our universe

$$\mathcal{L} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + A_\mu j_{em}^\mu}_{\text{SM Photon } \gamma} \underbrace{-\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + X_\mu j_X^\mu}_{\text{Dark Photon } A'}$$

SM Photon γ

Dark Photon A'

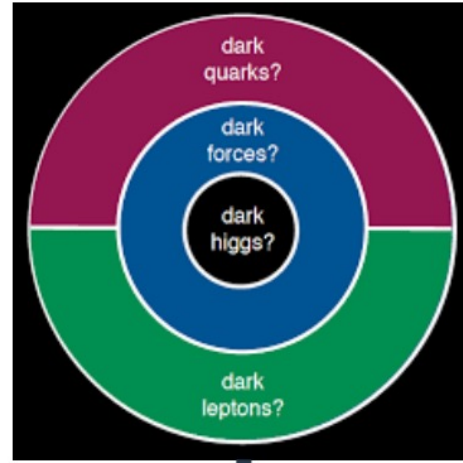
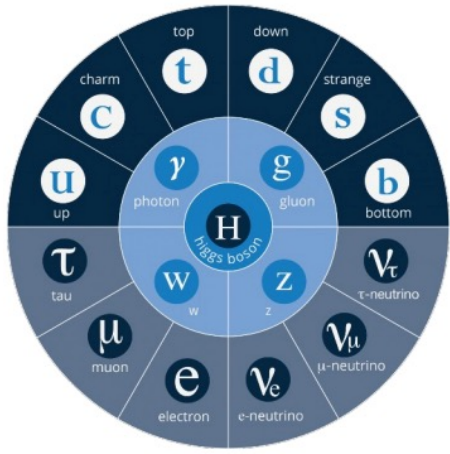


- A' & γ kin. mixing
- Renormalizable and Gauge Invariant
- Straightforward for experimental search
 - Free param, kin. mixing (ϵ), mass ($m_{A'}$)

B. Holdom, Phys. Lett. B 166, 196 (1986)

R. Foot & X.-G. He, Phys. Lett. B 267, 509 (1991)

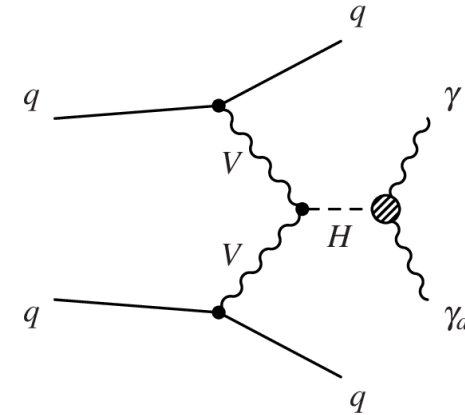
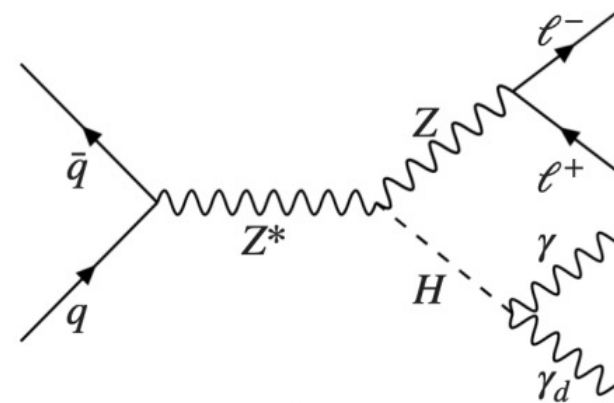
Dark Higgs → more Dark Portals connecting hidden sectors



portals

- **Vector portal – dark photons**
- Scalar portals - dark Higgs
- Neutrino portal
- Axion portal

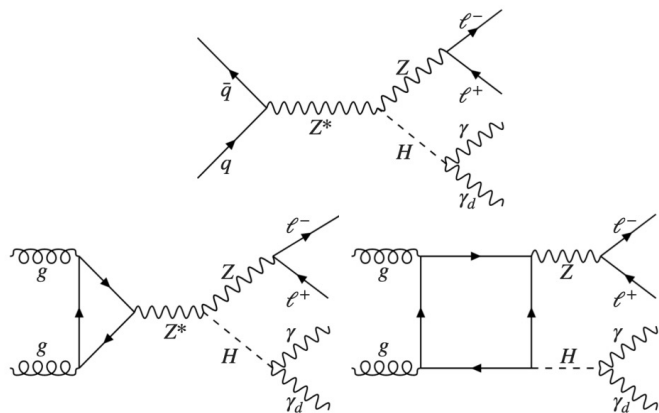
- **Dark Photon BSM extensions:**
 - U(1) extension of the SM
 - Hidden gauge boson A' → kinetic mixing (ϵ) with the SM photon
 - the magnitude of ϵ affects production rate and lifetime



Dark Photon searches: ZH and VBF



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For massless γ_d

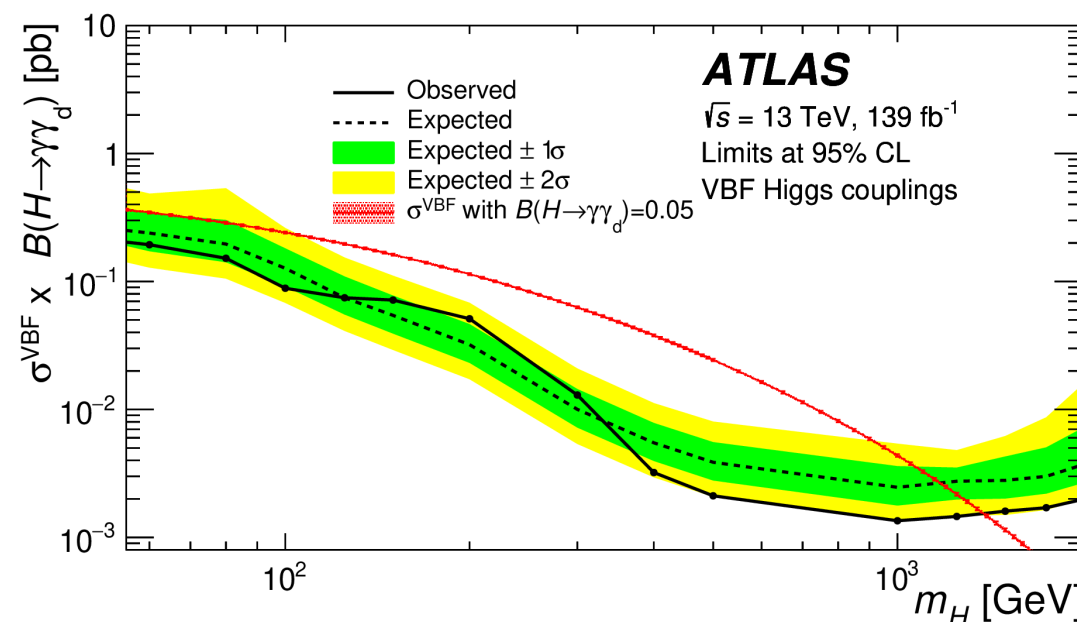
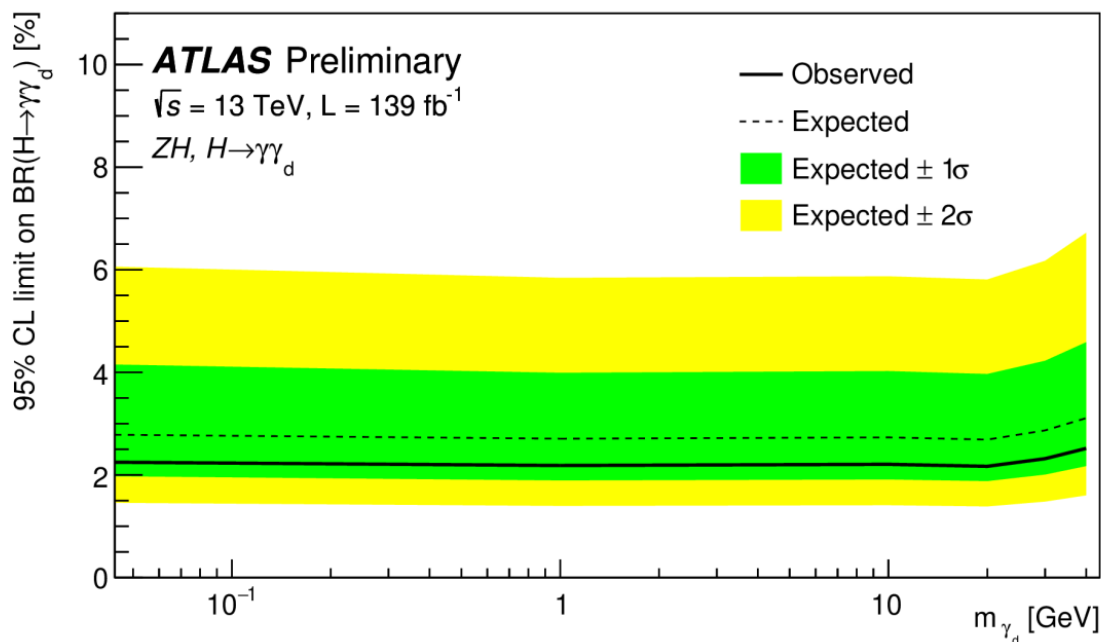
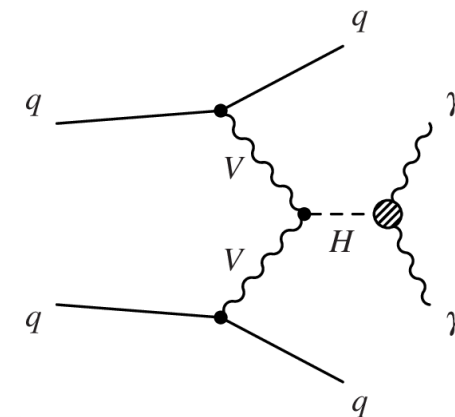
		Obs.	Exp.
CMS	VBF	3.5%	2.8%
CMS	ZH	4.6%	3.6%
ATLAS	VBF	1.8%	1.7%
ATLAS	ZH	2.3%	2.8%

[JHEP03\(2021\)011](#)

[JHEP10\(2019\)139](#)

[CERN-EP-2021-137](#)

[ATLAS-CONF-2022-064](#)



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● ATLAS Dark Photon Combination Prospects

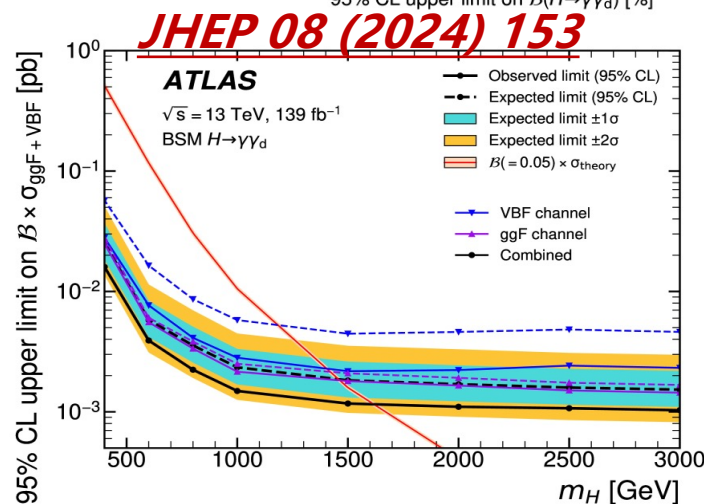
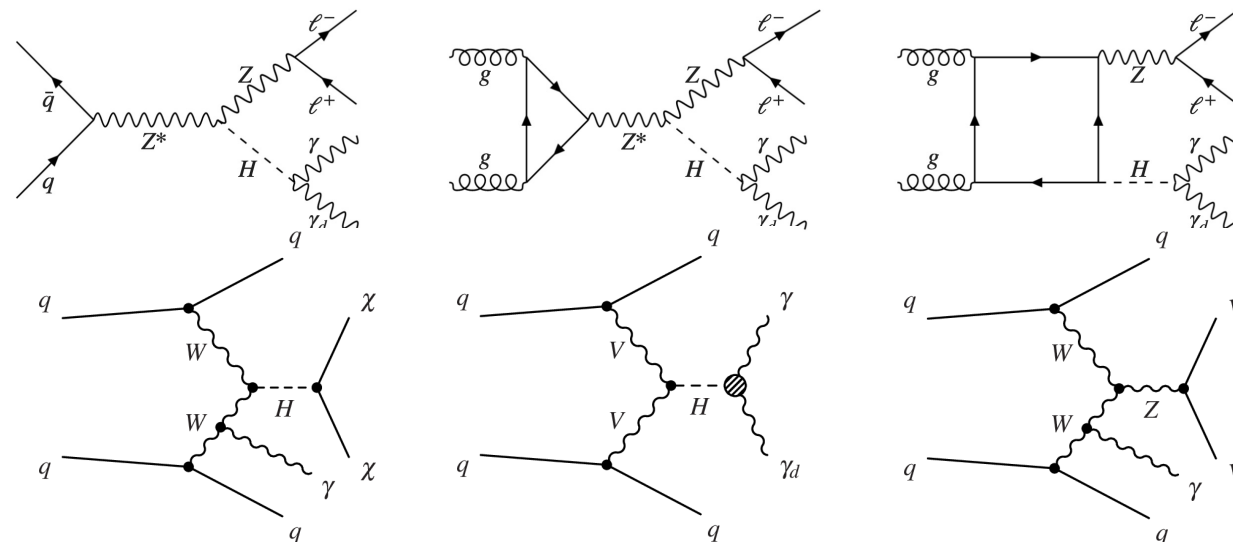
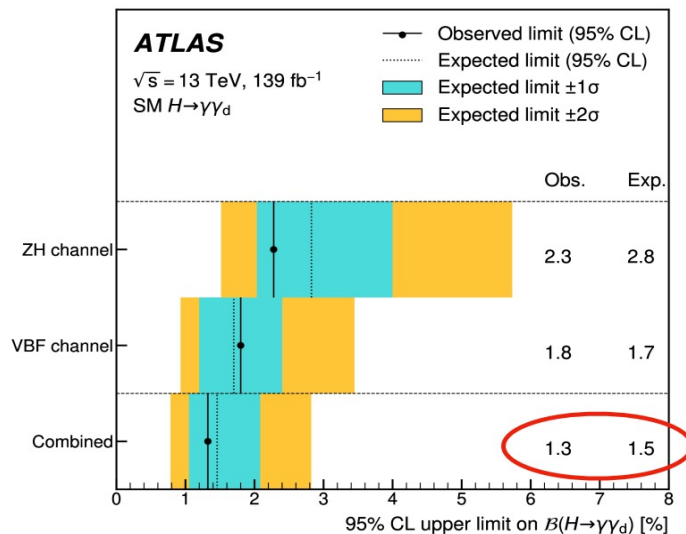
- Combination of VBF and ZH channels for SM Higgs (125 GeV) decaying into photon and massless dark photon
- Combination of VBF and ATLAS mono-photon re-interpretation for heavy Higgs decaying into photon and massless dark photon. (Our ongoing work)

Production	ZH	VBF	Combined
ATLAS	2.3(2.8)%	1.8(1.7)%	This work! (next slide)
CMS	4.6(3.6)%	3.5(2.8)%	2.9(2.1)%

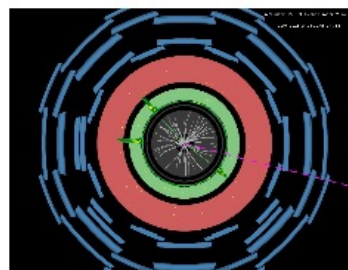
NEW Higgs → Dark Photon decay combination by ATLAS@ LHC



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Eur. Phys. J. C 82 (2022) 105



Using the Higgs boson to search for dark photons

The ATLAS Collaboration has been looking for signs of dark photons in data collected by the experiment during LHC Run 2 (2015-2018). Their newest search targets, for the first time in ATLAS, the production of a Higgs boson in association with a Z boson, with subsequent decay of the Higgs into a photon and a dark photon.

Physics Briefing | 15 September 2022

<https://atlas.cern/Updates/Briefing/Higgs-Dark-Photon>



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PART 04

New prospect and opportunity
with **DarkSHINE** initiative at
Shanghai

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Thanks and credits to DarkSHINE R&D team

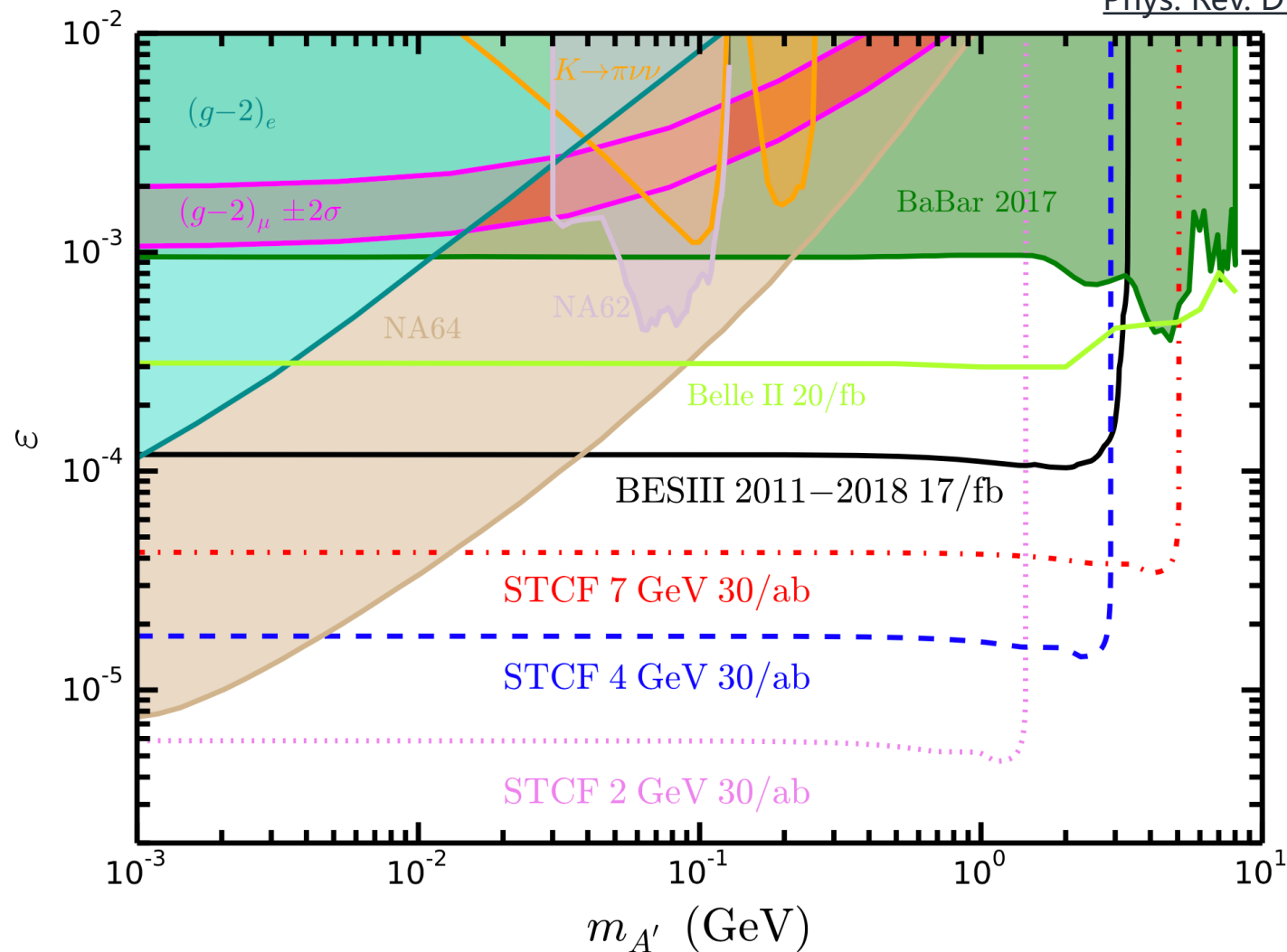


Dark Photon search sensitivity: collider vs fixed-target



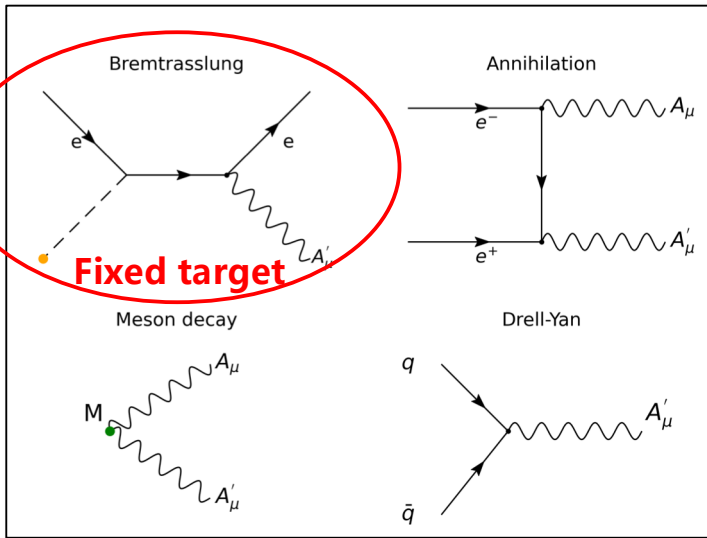
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Phys. Rev. D 100, 115016 (2019)

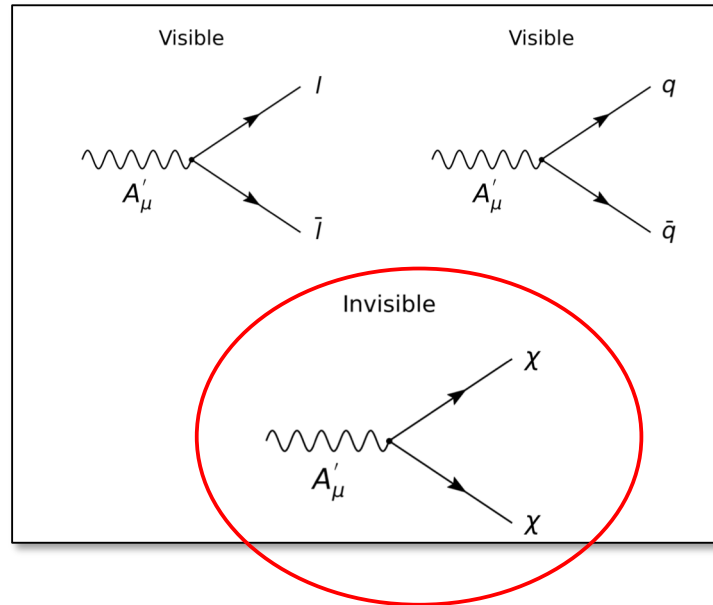


Physics process and anticipated signatures

Processes to search for **dark photon A'** : Bremsstrahlung, Annihilation, Meson decay and Drell-Yan process



(Dark photon production)

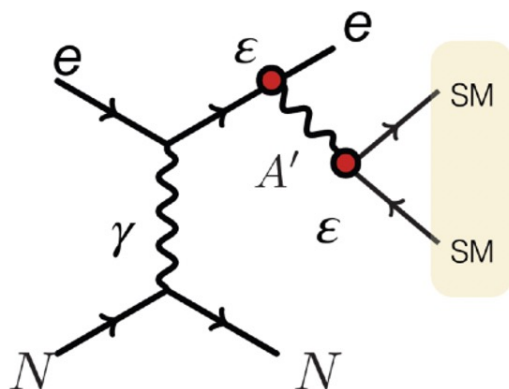


(dark photon decay)

- **Goal:** put constraints on the kinetic mixing parameter ϵ .
- **Challenge:** small production rate $\rightarrow$ suppress bkg. from SM processes.
- **Experimental signatures:** missing energy, missing momentum.

Dark SHINE Conceptual Design in a Nutshell

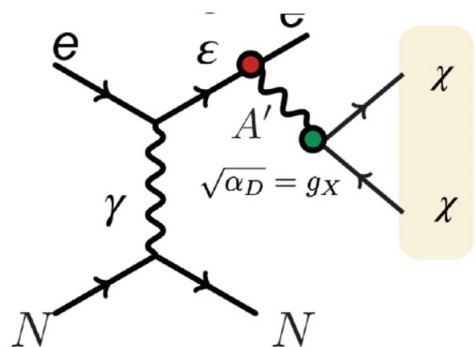
VISIBLE DECAY MODE $m'_A < 2m_X$



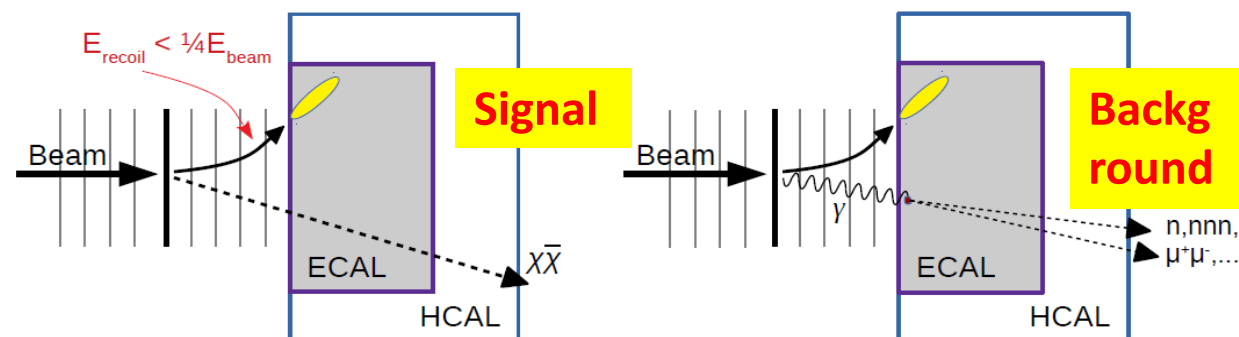
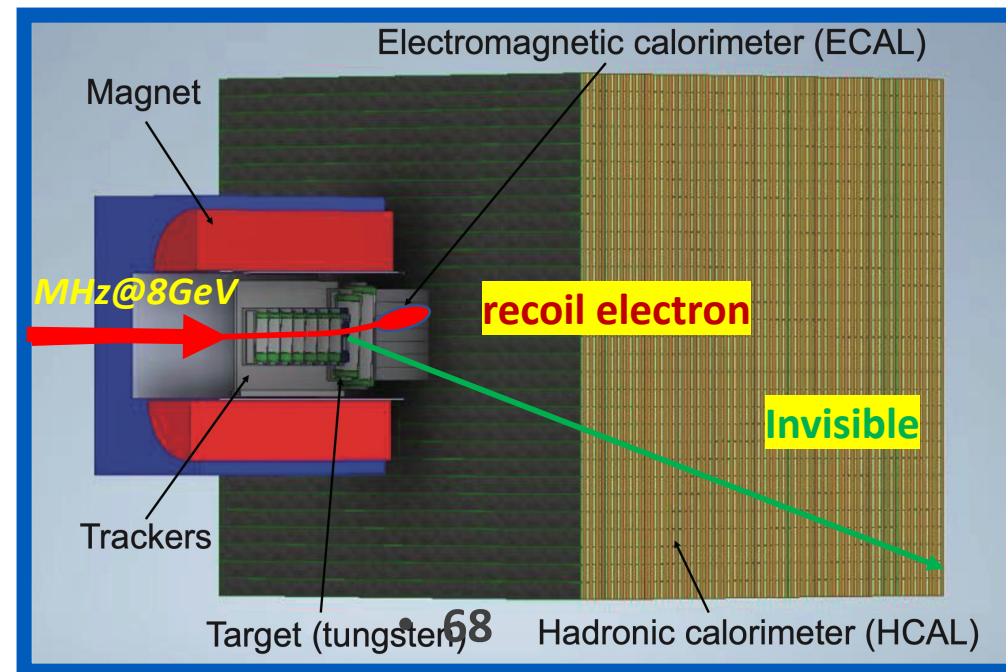
Having two interaction vertices $\rightarrow$ production rate highly suppressed

$$N \propto \epsilon^4 \ll N \propto \epsilon^2(1 - \epsilon^2) \approx \epsilon^2$$

INVISIBLE DECAY MODE $m'_A > 2m_X$

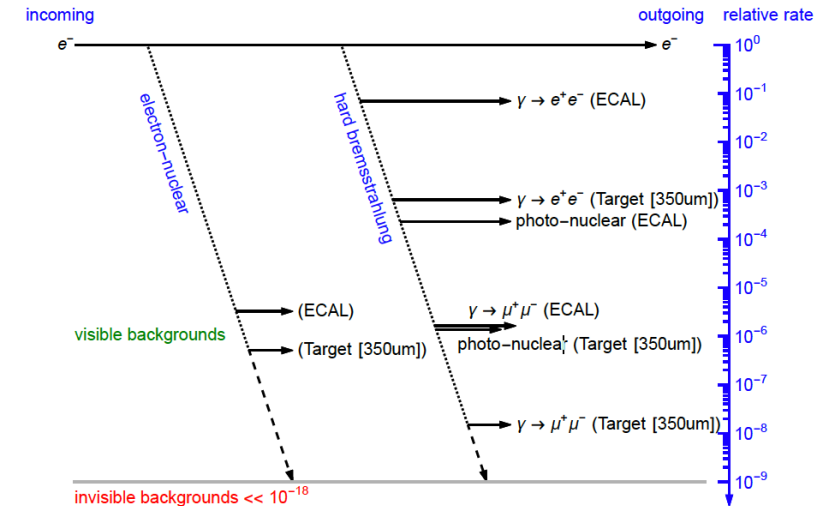
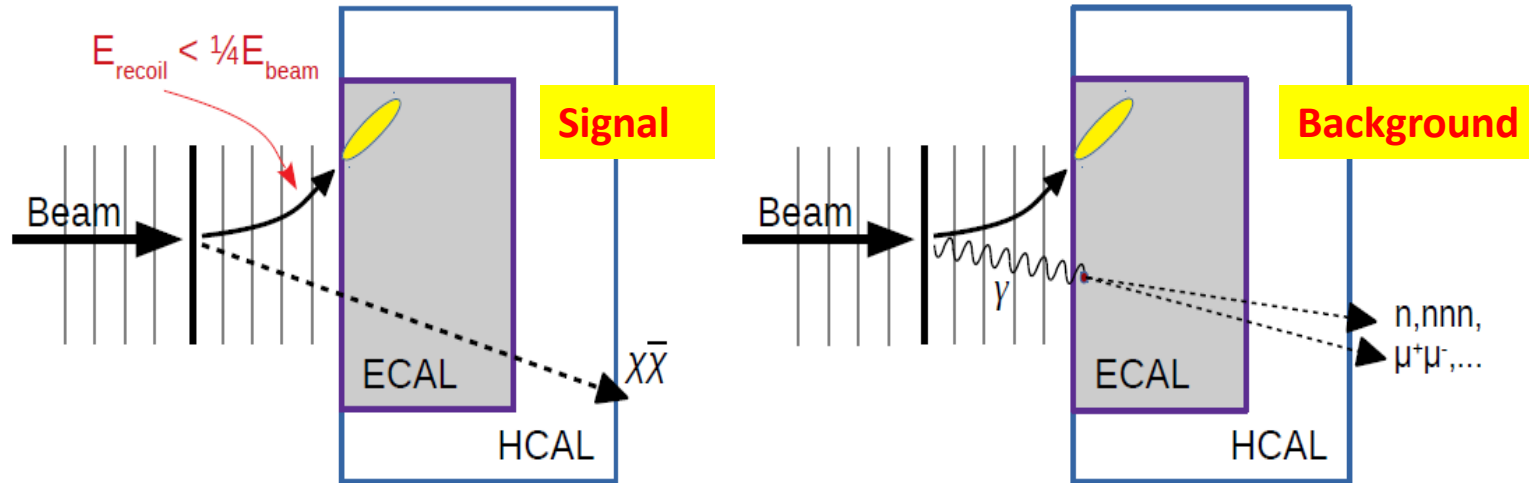
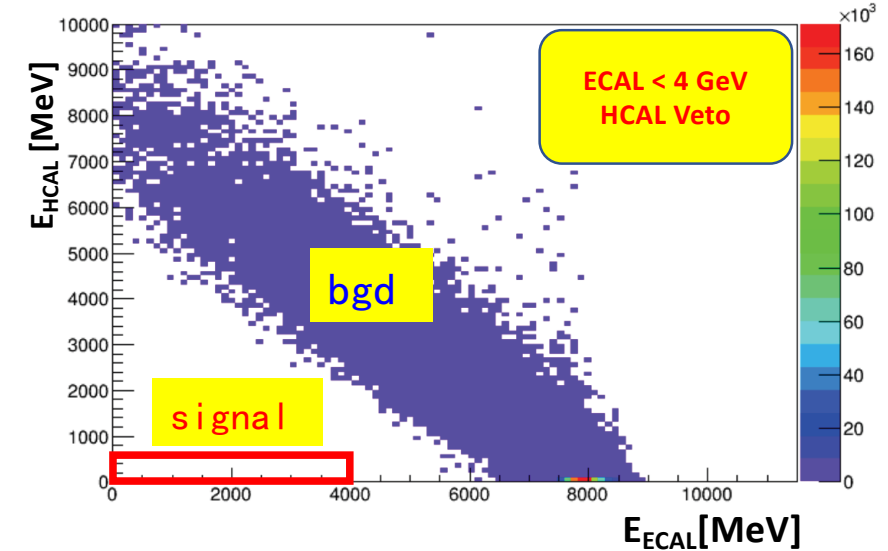


Focusing on invisible decays of dark photon into light dark matter $\rightarrow$ Missing Energy/Missing Momentum phenomena to hint the Dark Photon Signal



Experimental approaches

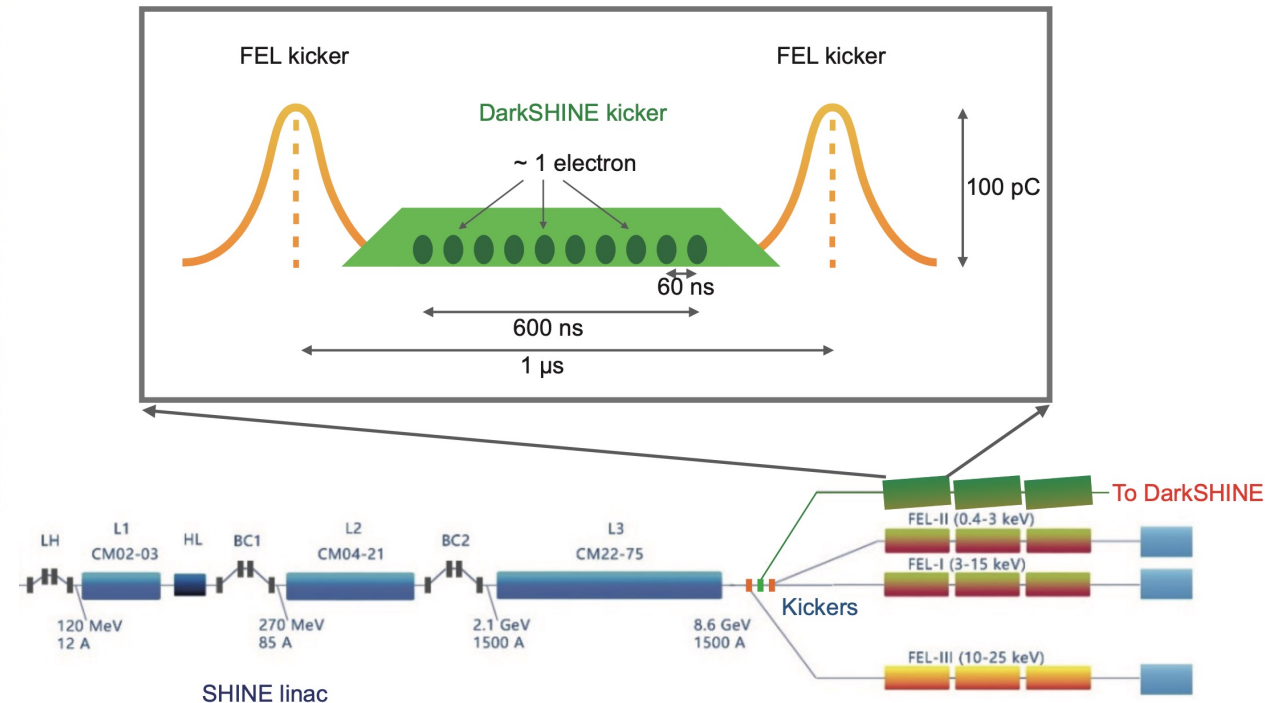
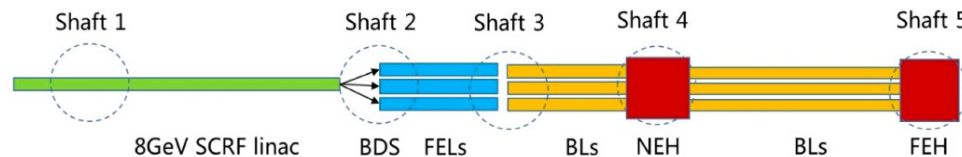
- **High repetition rate single electron beam**
 - More striking record of single electron-on-target event energy loss after recoiling
 - Require: fast detector responses and readout electronics, radiation hardness to allow high e-on-target statistics.
- **Energy + Momentum loss detection**
 - Synergy of high precision tracking and calorimetry



● The SHINE Facility

Shanghai High Repetition-Rate XFEL and Extreme Light Facility (SHINE) can provide high repetition rate single electron beams → with dedicated kicker to be designed and deployed

- Electron energy: 8 GeV, Rep. Rate: 1MHz
- Beam intensity: 100pC (6.25E8 electrons/bunch)
- $\sim 3 \times 10^{14}$ electrons-on-target (EOT) per year.
- Under construction in ZhangJiang area (2018-2026)
- Beamline R&D: ShanghaiTech. / SARI,CAS
- Detector R&D: SJTU / FDU / USTC / SIC-CAS / IHEP

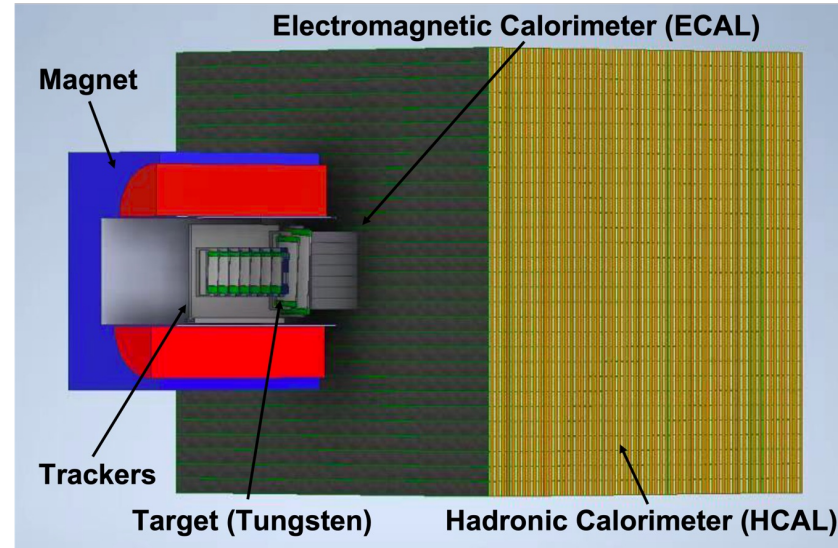


● Detector system conceptual design

The Dark SHINE detector hardware technical R&D is carried out in parallel to the full detector system simulation and prospective study/optimization

Tracking system

Measure the track of the incident and recoil electrons.



Dark SHINE detector sketch

Electromagnetic calorimeter

Measure the deposited energy: electron and photon.

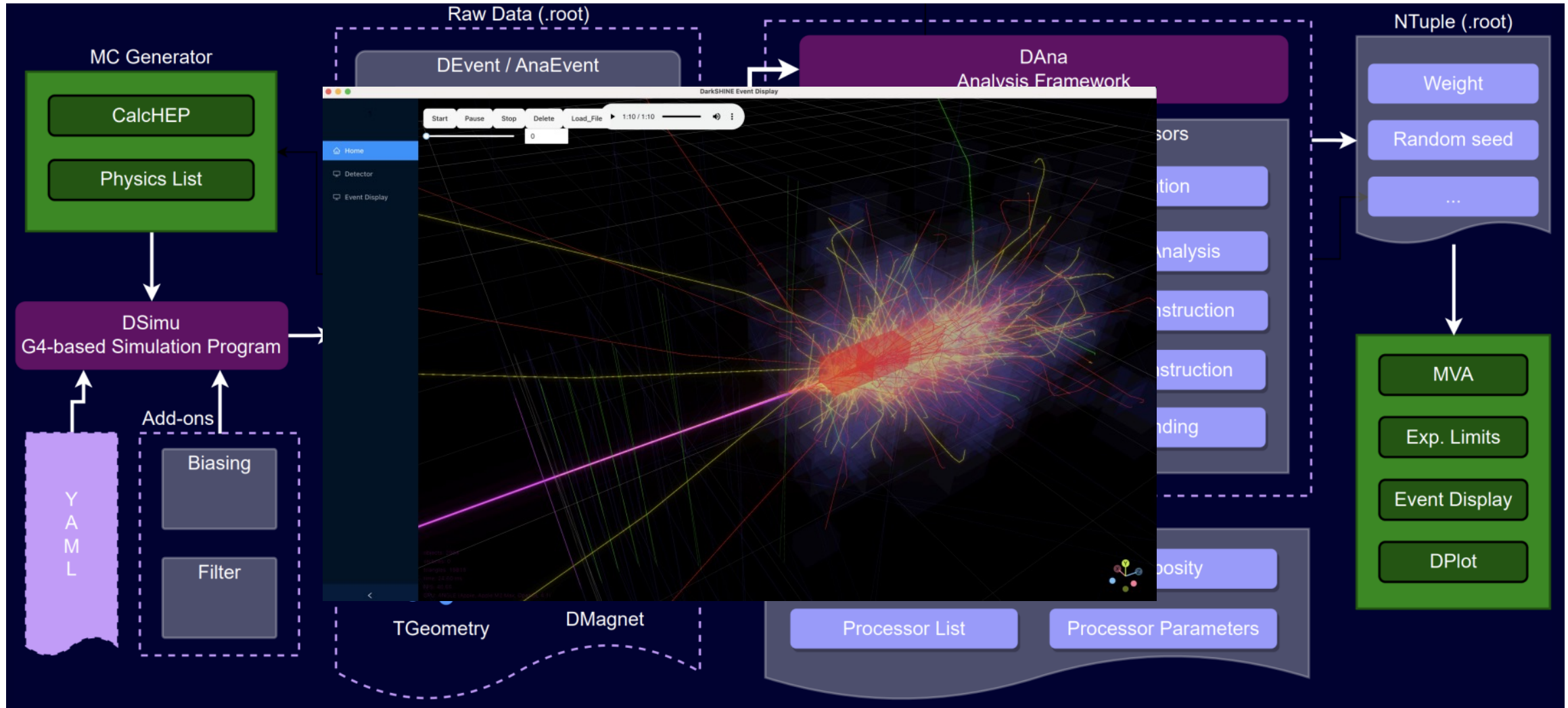
Hadronic calorimeter

Measure the deposited energy: veto muon and hadron backgrounds.

Additional system:

Readout electronics, trigger system, TDAQ, magnetic system (1.5 T), etc.

● Software Framework Further Optimization



- Now, let the Dark SHINE shining on the DM



● 《Science China》 publication with highlights



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Sci. China-Phys. Mech. Astron., 66(1): 211062 (2023)

SCIENCE CHINA
Physics, Mechanics & Astronomy



June 2022 Vol. 63 No. 1: 000000
<https://doi.org/??>

• Article •

Prospective Study of Light Dark Matter Search with a Newly Proposed DarkSHINE Experiment

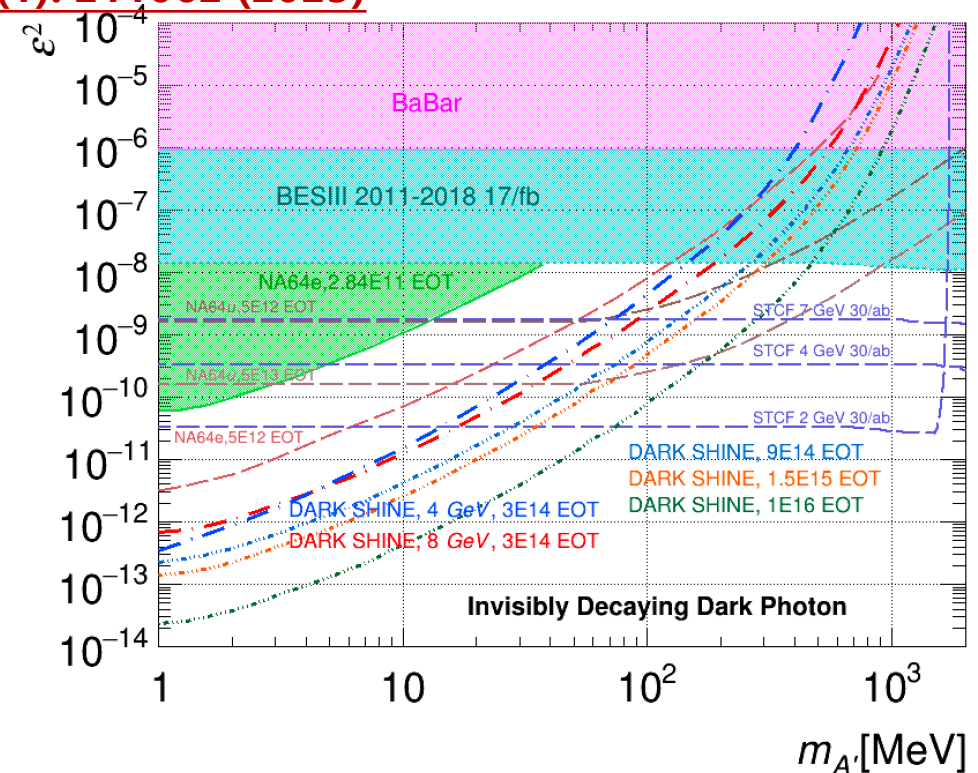
Jing Chen^{†b,c,a}, Ji-Yuan Chen^{b,c}, Jun-Feng Chen^h, Xiang Chen^{b,c}, Chang-Bo Fu^{ij}, Jun Guo^{b,c},
Le He^f, Zheng-Ting He^{a,n}, Kim Siang Khaw^{a,b,c}, Jia-Lin Li^{b,c}, Liang Li^{b,c}, Shu Li^{a,b,c,d,e*}, Meng Lv^g,
Dan-Ning Liu^{a,b,c}, Han-Qing Liu^{b,c}, Kun Liu^{a,b,c*}, Qi-Bin Liu^{a,b,c}, Yang Liu^{a,b,c}, Ze-Jia Lu^{b,c},
Cen Mo^{b,c}, Si-Yuan Song^{b,c}, Xiao-Long Wang^{ij}, Yu-Feng Wang^{†a,b,c}, Zhen Wang^{a,b,c}, Zi-Rui Wang^m,
Wei-Hao Wu^{b,c}, Dao Xiang^{k,a,l}, Hai-Jun Yang^{b,c,a*}, Jun-Hua Zhang^{a,b,c}, Yu-Lei Zhang^{†b,c},
Zhi-Yu Zhao^{a,b,c}, Xu-Liang Zhu^{a,b,c}, Chun-Xiang Zhu^{b,c}, and Yi-Fan Zhu^{b,c}

Highlight remarks

Sci. China-Phys. Mech. Astron. 66(1): 211063 (2023)

“Editor’ s Focus”

Sci. China-Phys. Mech. Astron. 66(1): 211061 (2023)

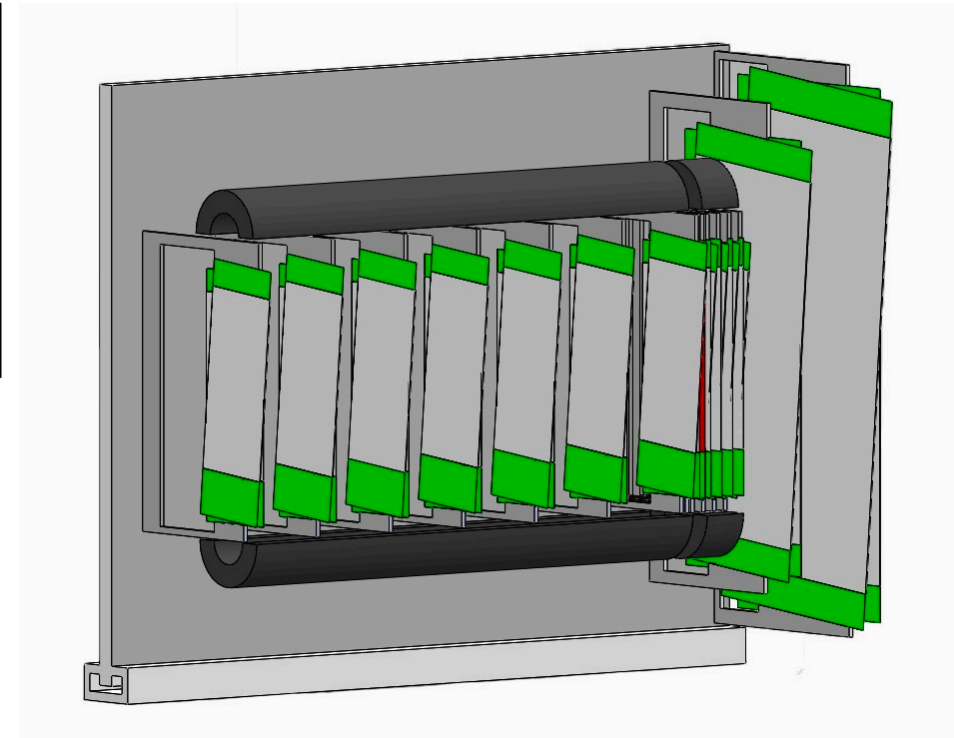


- Anticipated to have the sensitivity improved by one order of magnitude compared to other experiment (e.g. NA64)
- Aim to deliver 10^{16} EOT stat. and cover most of the sensitivity regions of interests

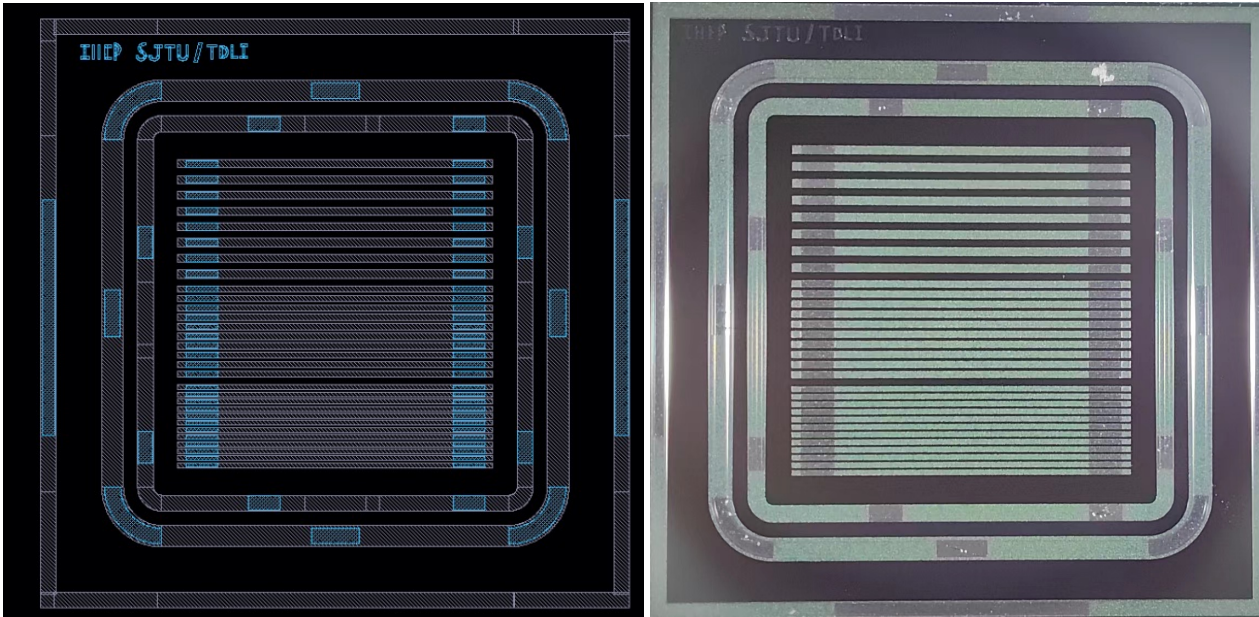
● Hardware R&D: Tracking

• Tracker:

- Tagging tracker (7 layers) + recoil tracker (6 layers)
- Incident and recoil electron tracks
- Two silicon strip sensors w/ a small angle (0.1rad)
- Resolution: $10\mu\text{m}$ (horizontal), $60\mu\text{m}$ (vertical)

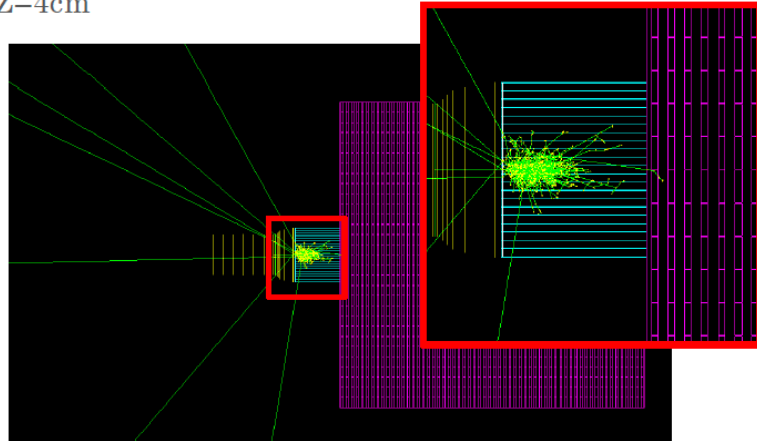


AC-LGAD silicon strip sensor 1x1 mm² designed, in collaboration with IHEP.

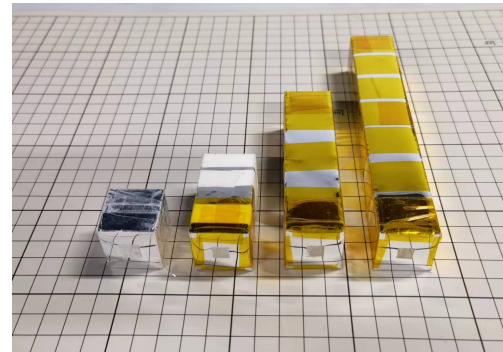
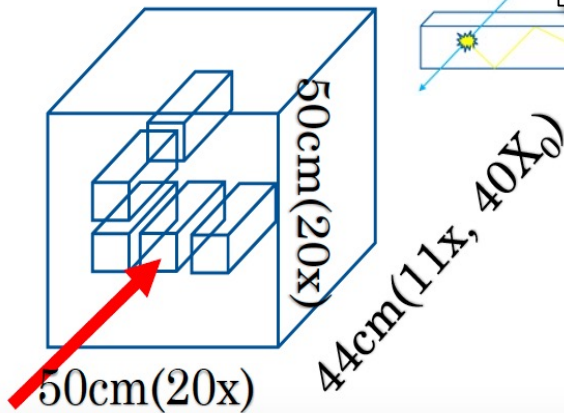


Crystal ECAL R&D

Z=4cm



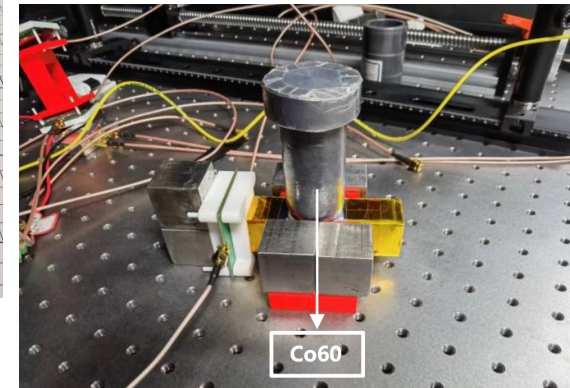
SiPM



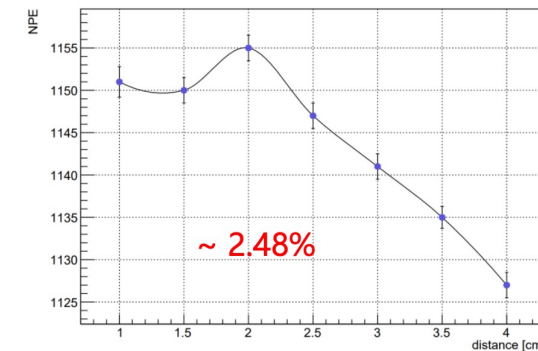
Baseline design of each crystal: X,Y = 2.5 cm,
Z = 4 cm (radiation length: 1.14 cm)

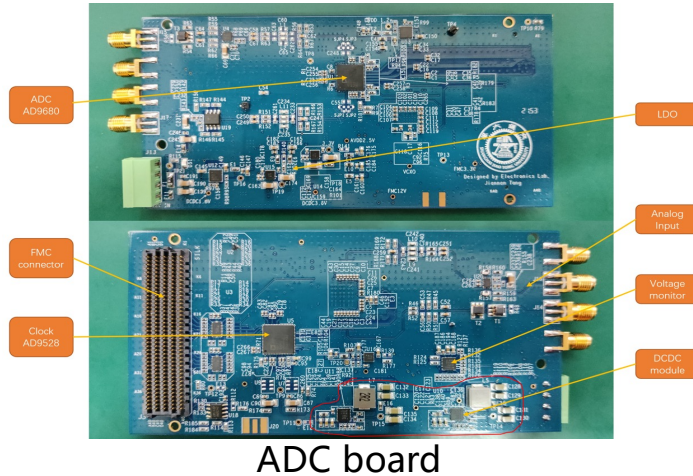
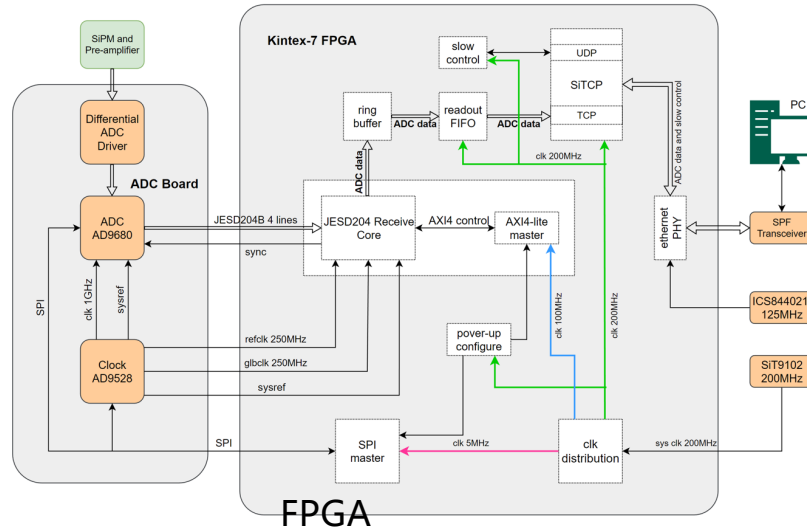
Measure the deposited energy of electron and photon.

- Designed resolution: better energy resolution than 5%.
- LYSO crystal ($Lu_{(1-x-y)}Y_{2y}Ce_{2x}SiO_5$):
 - high light yield (30000 p.e/MeV) with good linearity.
 - short decay time (40 ns).
- **20×20×11 crystals, 2.5cm×2.5cm×4cm**
- Readout with SiPM and waveform sampling.
- More intrinsic radiation and radioactive source tests.



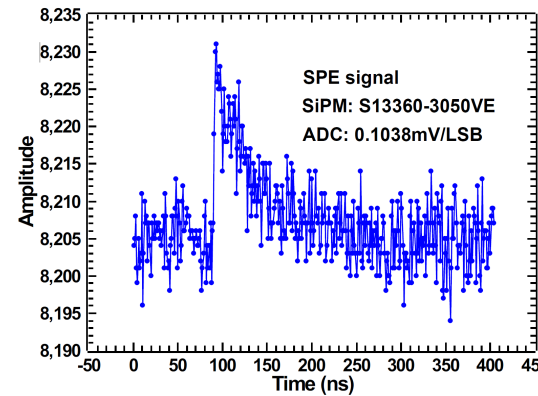
5cm LYSO



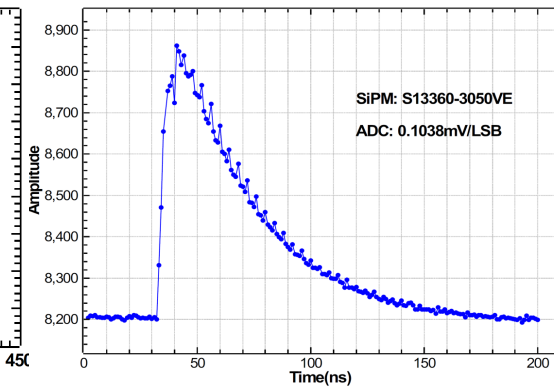


Photons from ECAL crystal are detected using SiPM + fast readout system.

- SiPM (width~10s ns, rising edge ~2ns)
- ADC chip (AD9680 from ADI)
- ADC Mezzanine Card
- Data transfer and processing
- ADC performance has been tested.
 - Analog input: Cosmic ray + SiPM (S13360-3050VE) + plastic scintillator
 - Amplitude of SPE signal : ~42 LSB, 4.4mV
 - Noise level : ~10 LSB, 1mV



An SPE signal



A cosmic ray signal

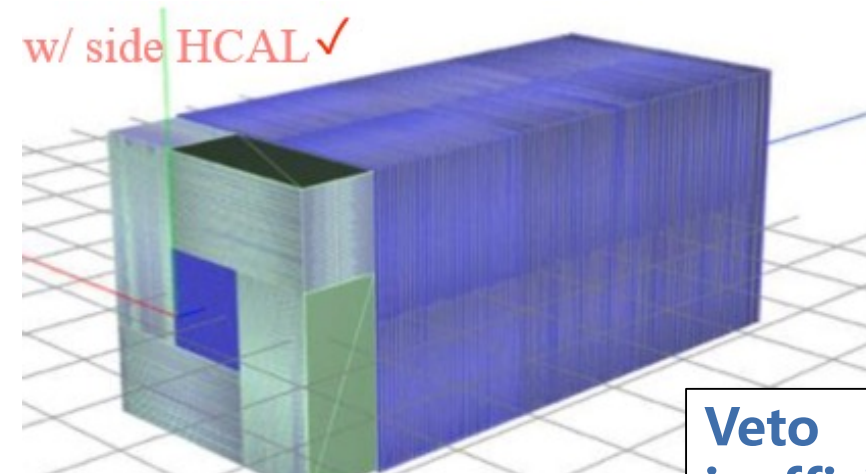
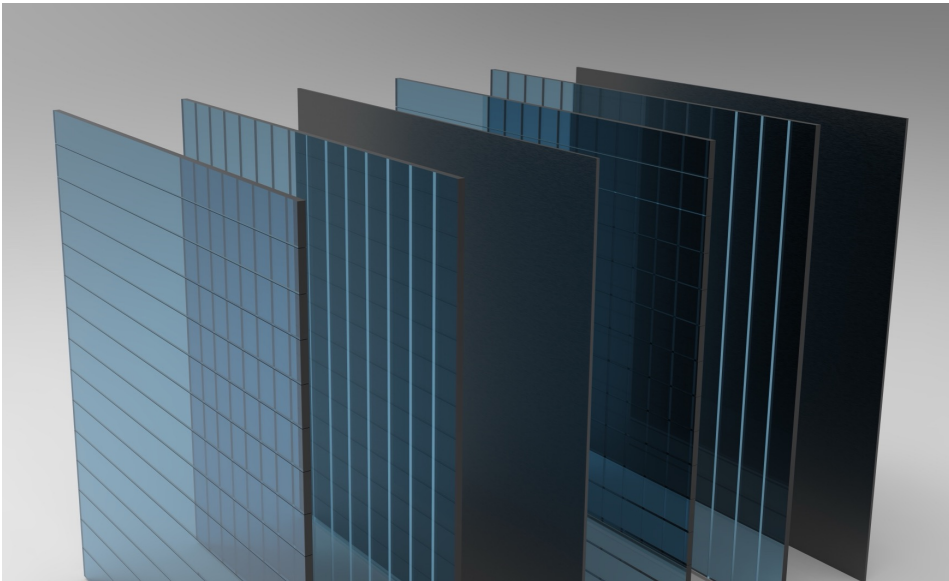
● HCAL R&D

Nucl. Sci. Tech. 35, 148 (2024)



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- Veto backgrounds with same behavior as signal in ECAL
- 1.5 m × 1.5 m × 2.5 m (perpendicular to the beam), ~11 λ (~160 cm iron, parallel to the beam)
 - Split to 4 modules, 75 cm × 75 cm each
 - Iron absorber: 10 mm/50 mm thick, 75 cm × 75 cm
 - Plastic scintillator: 10 mm thick, 75 cm × 5 cm, 15 bars per layer per module
 - 90 degree rotation between 2 adjacent layers
 - Wavelength shift fiber + SiPM
- Side-HCAL: encircling the ECAL
- Design has been optimized



**Veto
inefficiency**

Particle \ Energy[MeV]	n	k ⁰	π^0	p
100	1.17E-03	3.16E-02	7.30E-06	3.07E-02
500	1.84E-05	3.30E-06	1.00E-07	8.04E-06
1000	3.70E-06	4.30E-06	1.00E-07	1.00E-07
2000	2.70E-06	1.15E-05	1.00E-07	1.00E-07

● DarkSHINE: a dream to be realized nearby





SHINE SCIENCE Plus 的白皮书撰写

1. 高重频超快电子衍射 (UED) 平台
2. 高性能缪子束流的产生与科学技术研究平台
3. 暗光子研究 (Dark Photon)
4. 新一代极紫外光刻光源研究
5. GeV电子与PW级激光的强强碰撞
6. 基于时间分辨SFX, 蛋白质动态结构的研究

- SHINE项目副经理刘志教授首次于SHINE国际科学论坛主旨报告展示本实验项目
- 本项目纳入《SHINE Science PLUS》白皮书用于指导未来项目建设

● International Conference shows

ICHEP 2024

Lepton Photon 2023

Dark Matter 2023

HKUST-IAS-HEP 2024、2023

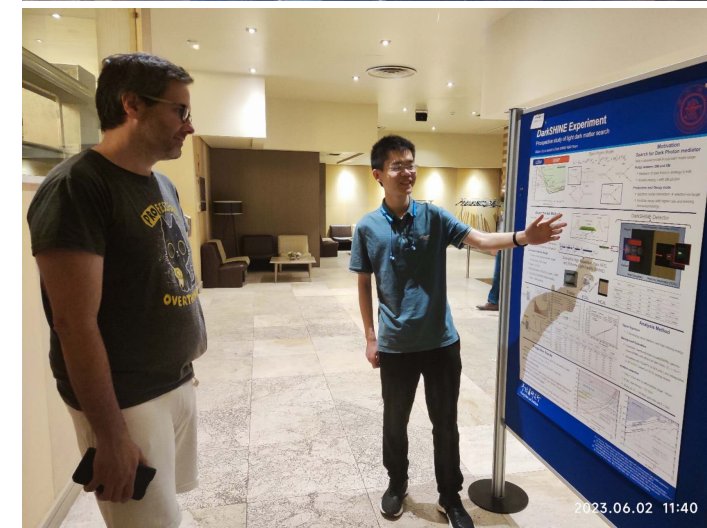
AEI 2023、2022

IPAC 2023

...



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CP-violating dark photon interaction

Kaori Fuyuto,^{1,*} Xiao-Gang He,^{2,3,4,†} Gang Li,^{2,‡} and Michael Ramsey-Musolf^{1,5,§}

¹Amherst Center for Fundamental Interactions, Department of Physics,
University of Massachusetts Amherst, Massachusetts 01003, USA

²Department of Physics, National Taiwan University, Taipei 106, Taiwan

³T-D. Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University,
800 Dongchuan Road, Shanghai 200240, People's Republic of China

⁴National Center for Theoretical Sciences, Hsinchu 300, Taiwan

⁵Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA



Constraining photon portal Dark Matter with TEXONO and COHERENT data

Shao-Feng Ge^{a,b} and Ian M. Shoemaker^c

Regular Article - Theoretical Physics

Probing the dark axion portal with muon anomalous magnetic moment

Shao-Feng Ge^{1,2,a}, Xiao-Dong Ma^{1,2,b}, Pedro Pasquini^{1,2,c}

Search for a heavy dark photon at future e^+e^- colliders

Min He,^a Xiao-Gang He,^{a,b,c} Cheng-Kai Huang^b and Gang Li^b



Dark photon dark matter in the minimal $B - L$ model

Gongjun Choi,^a Tsutomu T. Yanagida^{a,b} and Norimi Yokozaki^c

PHYSICAL REVIEW D **102**, 075001 (2020)

Strongly-interacting massive particle and dark photon in the era of the intensity frontier

Ayuki Kamada¹, Masaki Yamada^{2,3,4} and Tsutomu T. Yanagida^{5,6}

Dark SHINE shown for the 1st time at SHINE Science Forum International Conference by SHINE management!

Integrated into 《SHINE Science Plus》 White Paper

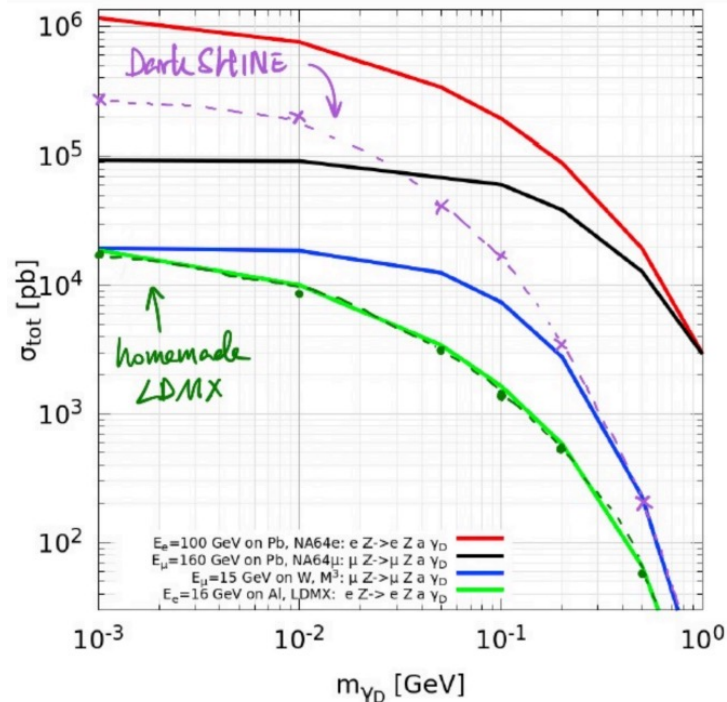
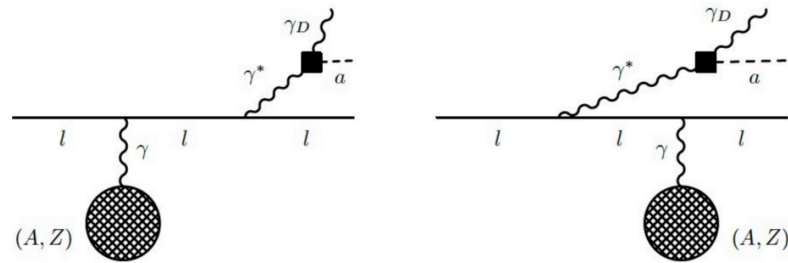
Moving on to further collaborations with facility end for beamline deployment



More Physics Opportunities:

ALP+DP, positron-on-Target mode

Minimal dark Axion-like particle portal and Axion+DP co-existence



- Dramatically different sensitivity curve of Dark Photon search when changing from **electron beam** to **positron beam**
- Extra s/t-chan annihilation diagrams come into play for Dark Photon production
- SHINE can also deliver positron beam with low current...

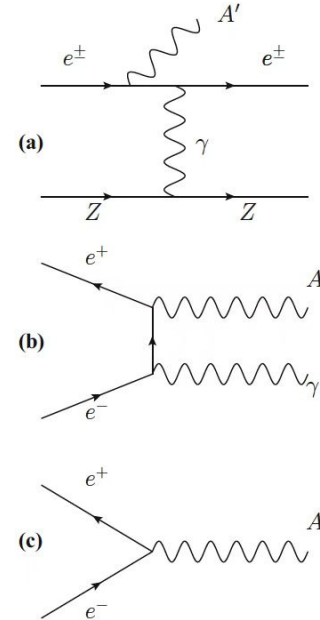
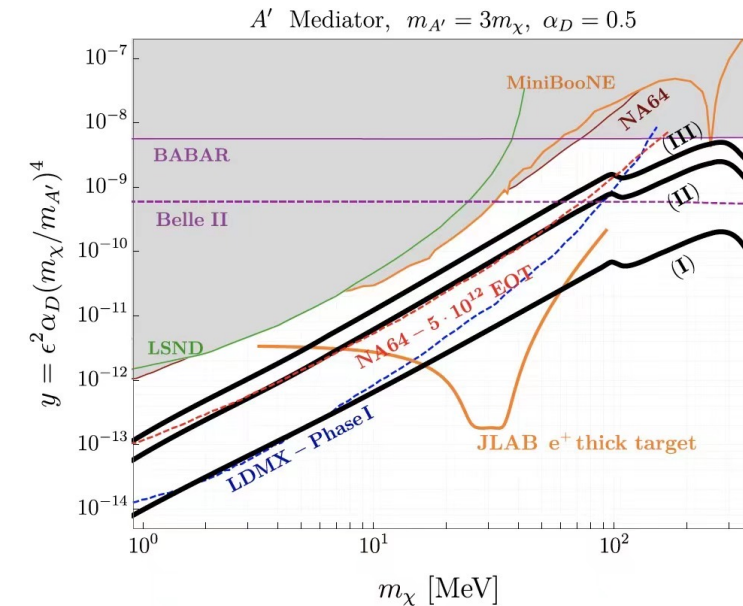


Fig. 1 Three different A' production modes in fixed target lepton beam experiments: (a) A' -strahlung in e^-/e^+ -nucleon scattering; (b) A' -strahlung in e^+e^- annihilation; (c) resonant A' production in e^+e^- annihilation



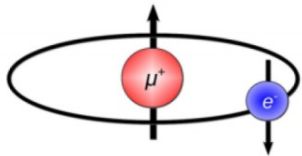
Eur. Phys. J. A (2021) 57:253

More Physics Opportunities: search for muonium

A brief history

- The term Muonium was “stolen” by μ^+e^- when it was discovered in the 1950s

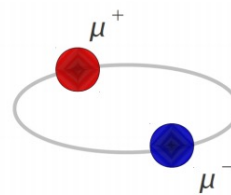
- pure leptonic bound state of μ^+ and e^-
- investigate μ -e interactions
- test bound-state QED
- 1S-2S transition frequency (4 ppb)
ground state HFS (12 ppb)
- extract fundamental constants (m_μ/m_e , q_μ/q_e , μ_μ/μ_p)
- probe physics beyond the standard model (LFV, etc ...)



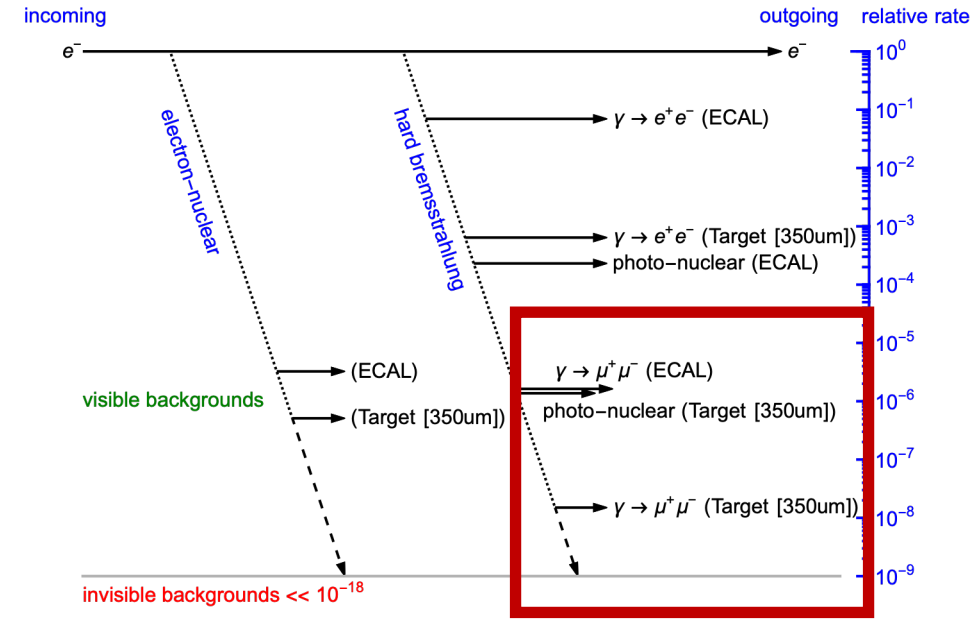
“fake” muonium

8

Smallest atom!
Test bound-state QED



“true” muonium



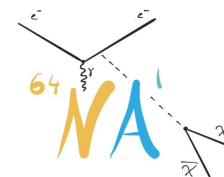
Inspired by Prof. Kim-Siang Khaw

• More physics motivations...

Dark SHINE could explore a vast array of sub-GeV physics with unique sensitivity

- New force carriers coupling to electrons, decaying visibly or invisibly
- Quasi-thermal DM, e.g. asymmetric DM or ELDER DM
- New long-lived resonances produced in the dark sector (SIMP)
- Freeze-in models with heavy mediators
- Axion-like particles (ALP)
- Milli-charged dark sector particles
- Probe neutrino-nuclear interactions (νN) via electro-nuclear (eN) measurements and constrain nuclear models
- ...

MEPA 2025 WS → Nanjing Univ. & BIT

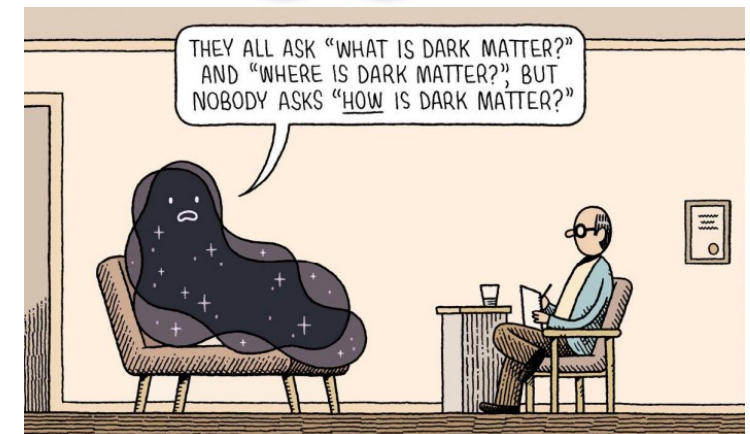
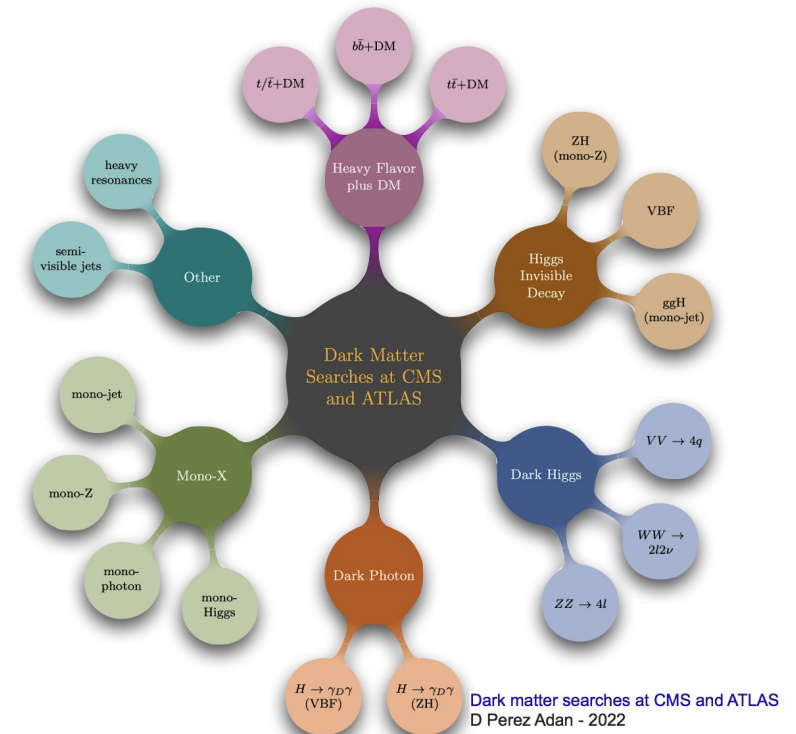


Summary

- LHC continues to deliver highly valuable physical results while Run-3 is cooking new results in the pipeline
- Dark Matter mystery remains puzzling while collider searches provide sensitivity complementarity with non-collider DM searches: **Higgs Boson, Dark Photon (+ other magic bosons...)** could be the keys to “mediate” the dark mystery!
- Many hypotheses, diverse processes and signatures are broadly surveyed and searched for but by far no hints of Dark Matter
- Need to further diversify the data mining aspects in the collisions covering more unconventional signatures and untouched stones
- In need of also future Fixed target experiments light the way to DM mysteries such as DarkSHINE...



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● backup



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Particle and Nuclear Physics Division
粒子与核物理研究部

● Hardware R&D: Tracking

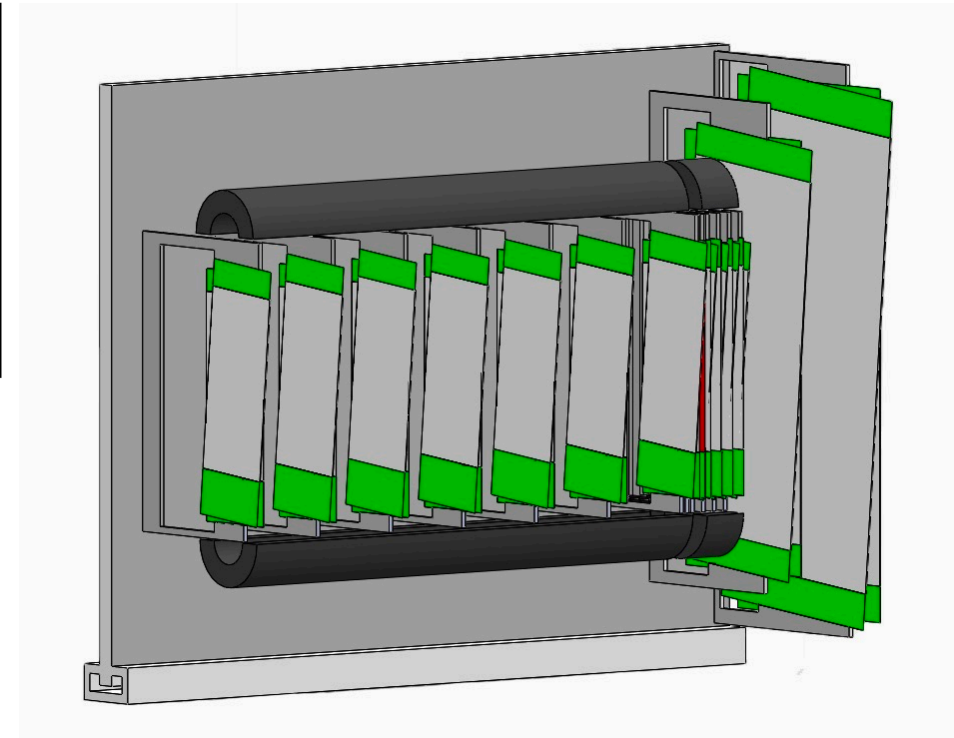
arXiv:2310.13926
accepted by NST



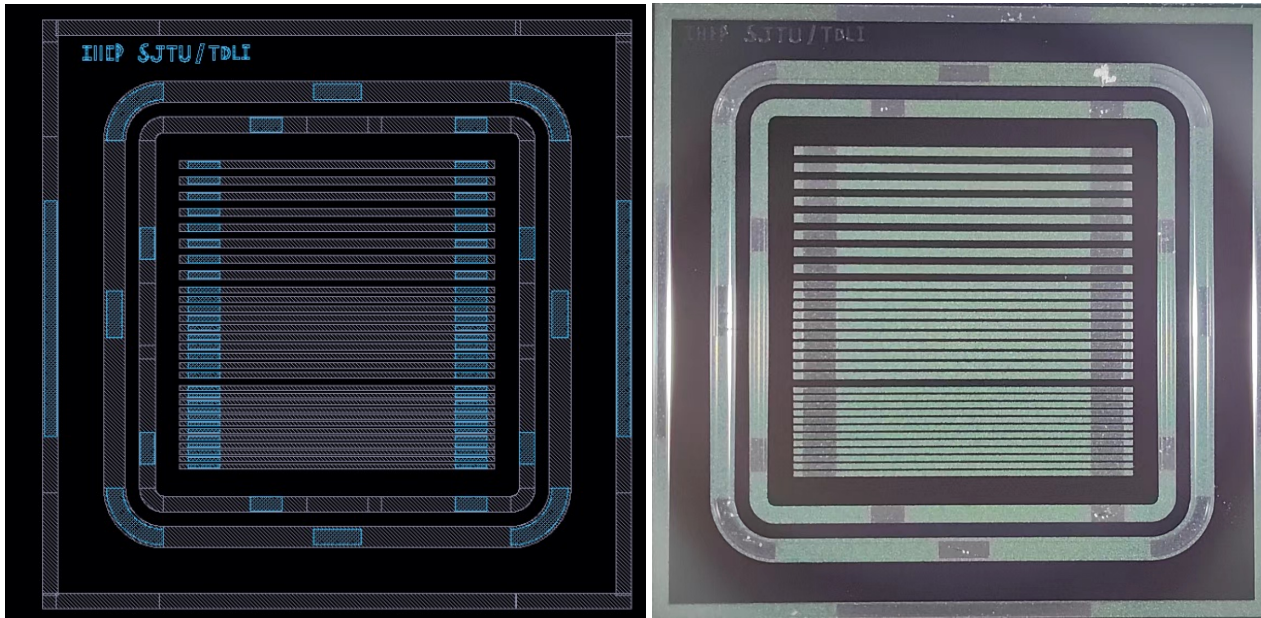
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• Tracker:

- Tagging tracker (7 layers) + recoil tracker (6 layers)
- Incident and recoil electron tracks
- Two silicon strip sensors w/ a small angle (0.1rad)
- Resolution: $10\mu\text{m}$ (horizontal), $60\mu\text{m}$ (vertical)



AC-LGAD silicon strip sensor 1×1 mm² designed, in collaboration with IHEP.

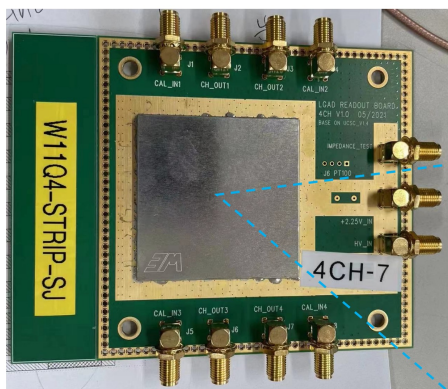
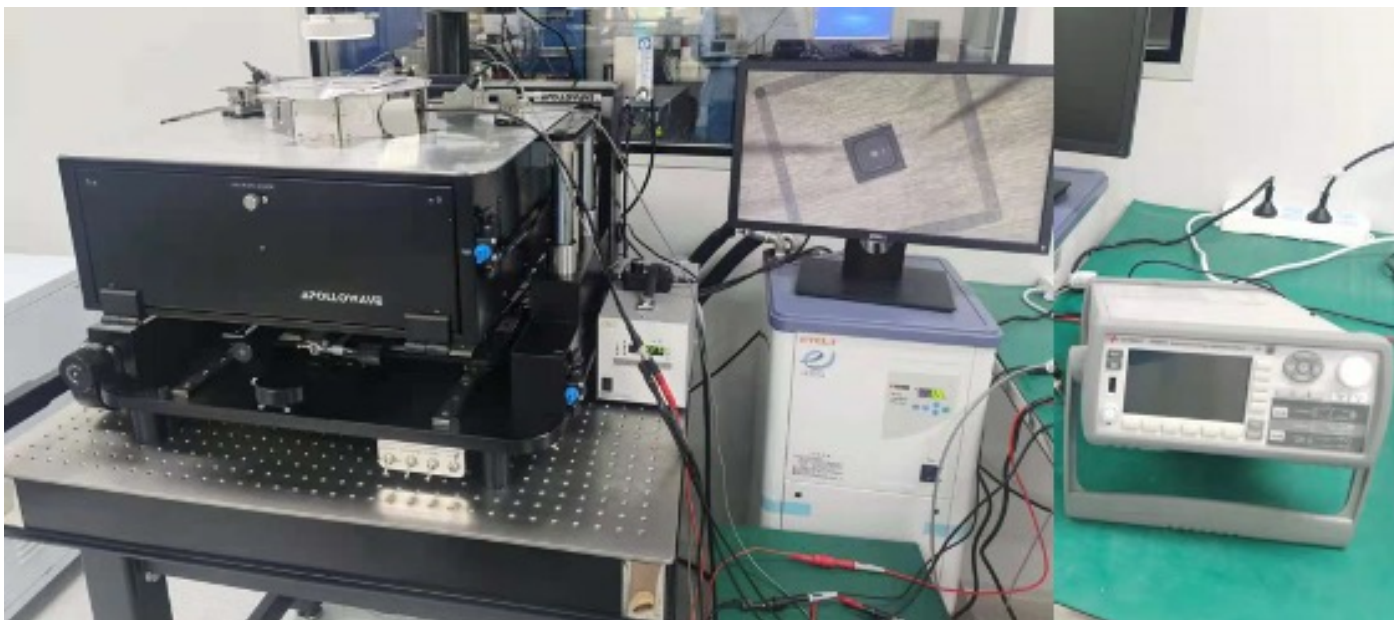


Hardware R&D: Tracking

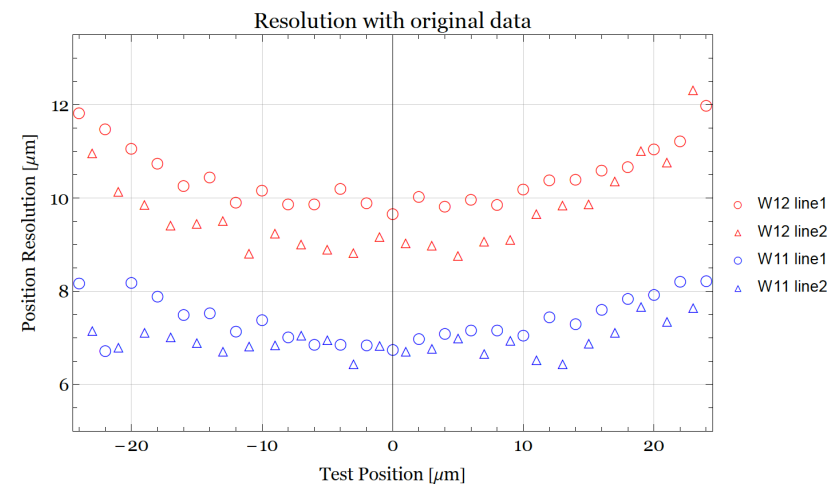
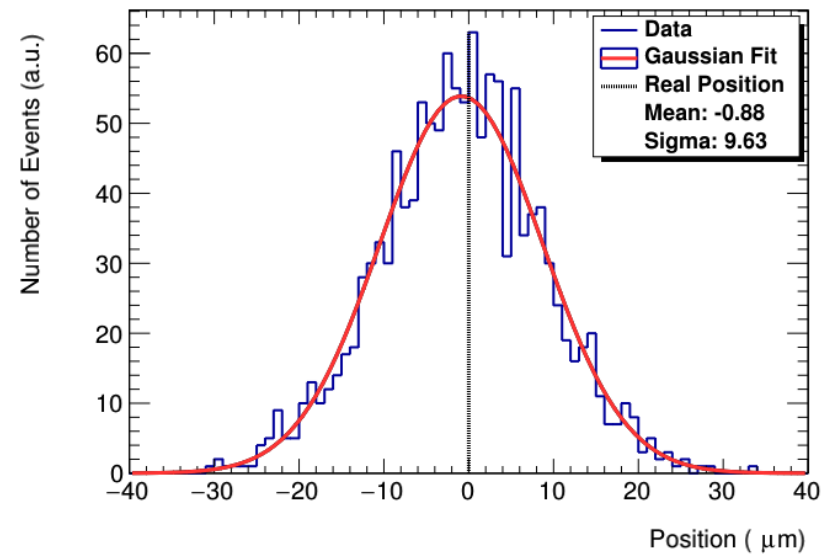
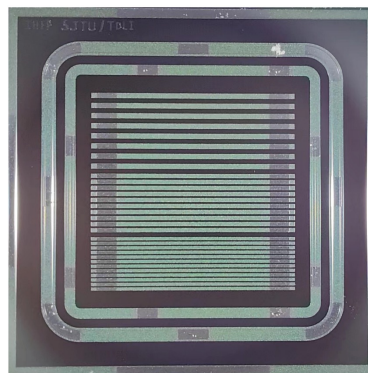
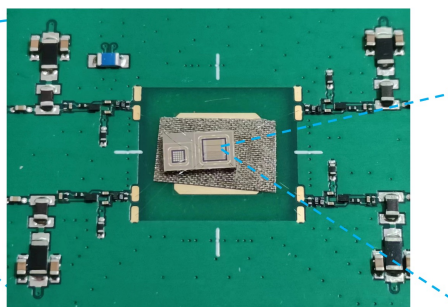
arXiv:2310.13926
accepted by NST



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Working point
W11: 350V
W12: 150V



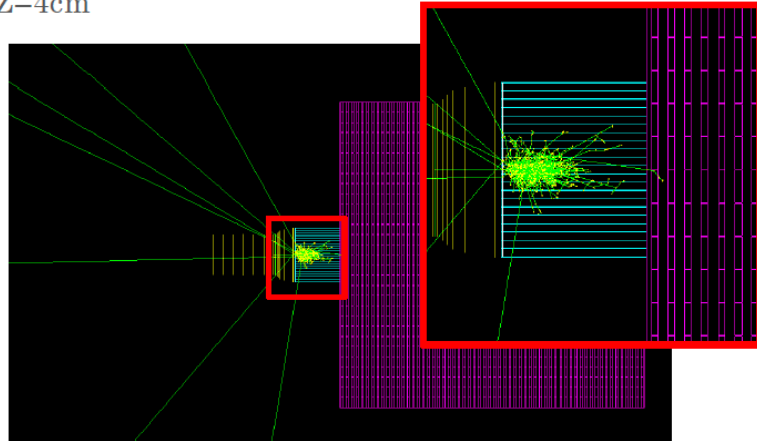
Crystal ECAL R&D

arXiv:2407.17800
submitted to NST

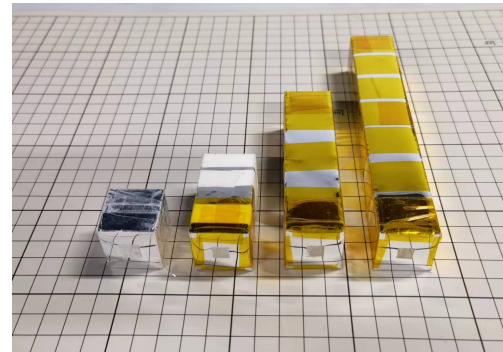
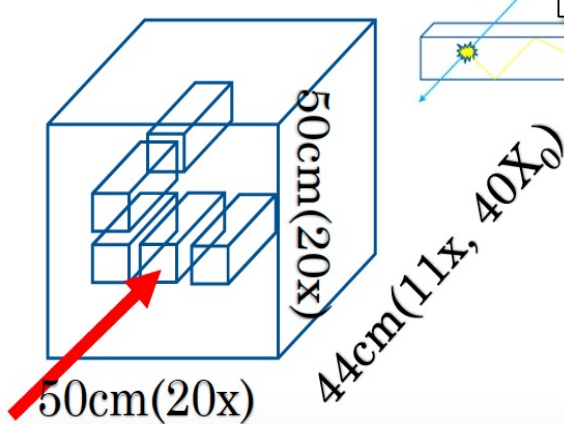


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Z=4cm



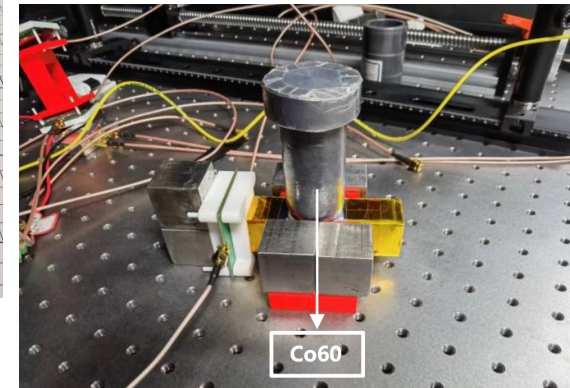
SiPM



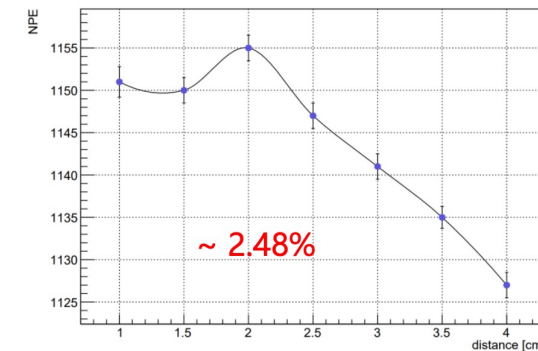
Baseline design of each crystal: X,Y = 2.5 cm,
Z = 4 cm (radiation length: 1.14 cm)

Measure the deposited energy of electron and photon.

- Designed resolution: better energy resolution than 5%.
- LYSO crystal ($Lu_{(1-x-y)}Y_{2y}Ce_{2x}SiO_5$):
 - high light yield (30000 p.e/MeV) with good linearity.
 - short decay time (40 ns).
- **20×20×11 crystals, 2.5cm×2.5cm×4cm**
- Readout with SiPM and waveform sampling.
- More intrinsic radiation and radioactive source tests.



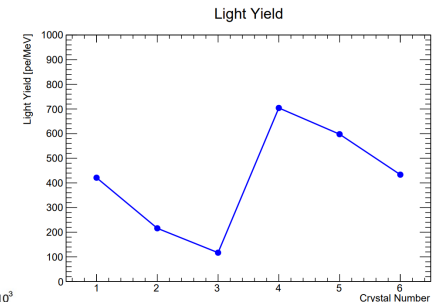
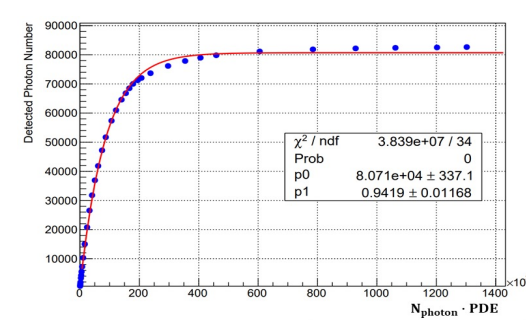
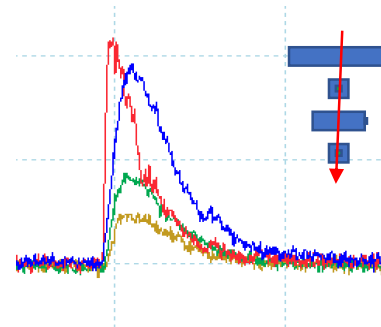
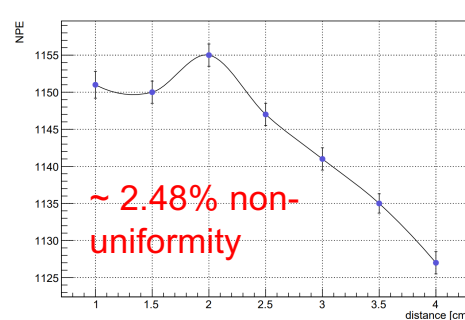
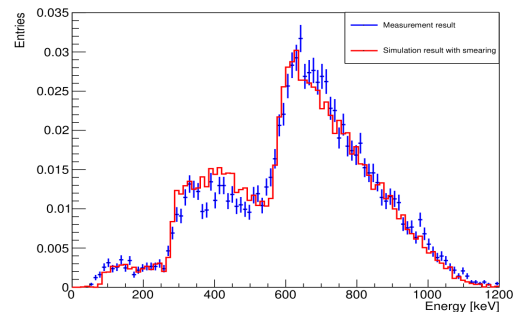
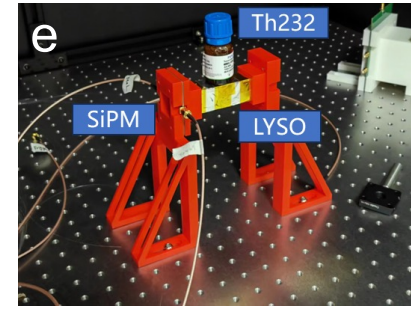
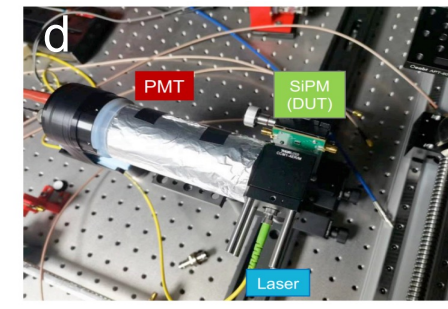
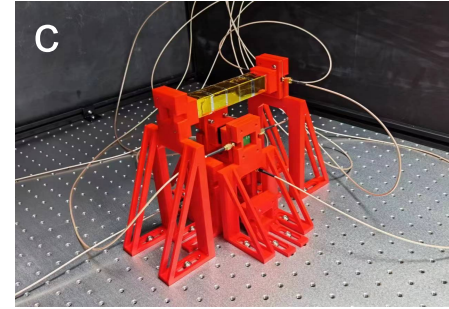
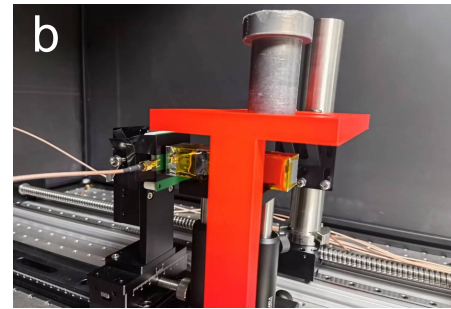
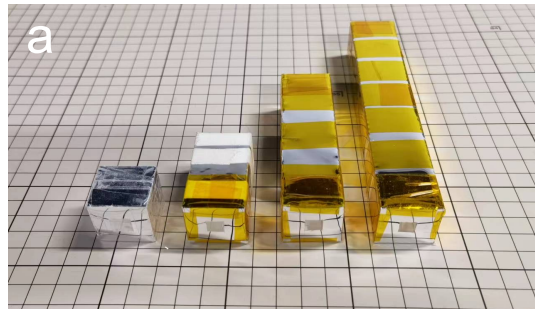
5cm LYSO



● ECAL Unit Test

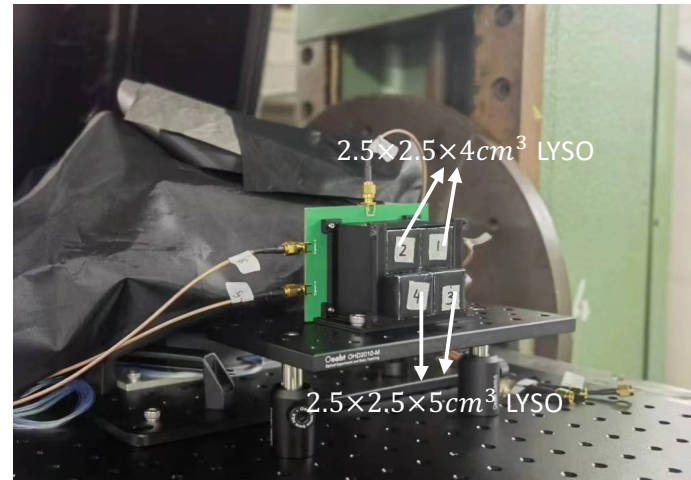
arXiv:2407.17800
submitted to NST

- Experiments based on LYSO and SiPM to study their properties
 - a. LYSO intrinsic radiation from $^{176}_{71}\text{Lu} \rightarrow ^{176}_{72}\text{Hf}$
 - b. Uniformity test with $^{60}_{27}\text{Co}$ source
 - c. Cosmic ray test
 - d. SiPM dynamic range test
 - e. Light yield changed with crystal size

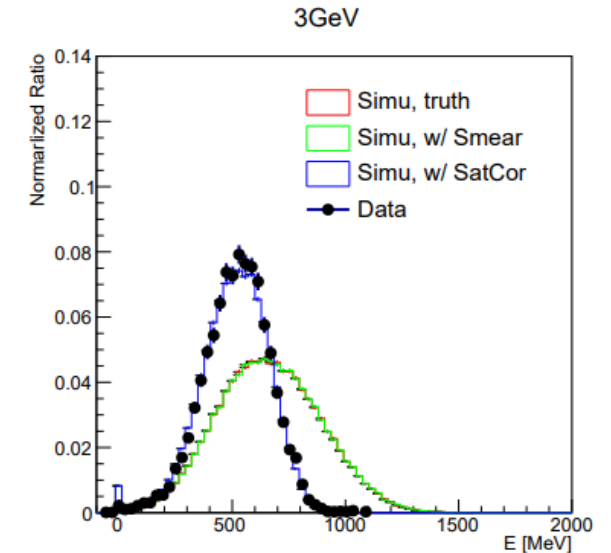


● Design and beam test for 1st prototype Module

- Motivation:
 - Performance study under high energy and high repetition beam.
 - Technical validation for the whole detector system
- Prototype conceptual design: hybrid materials with LYSO as core scintillator, and PWO as outer scintillator
- **1st prototype module for beam test (2x2 LYSO) at DESY**
 - 8GeV electron beam, ~2 kHz repetition rate
 - Crystal unit dynamic range test and digitization method validation



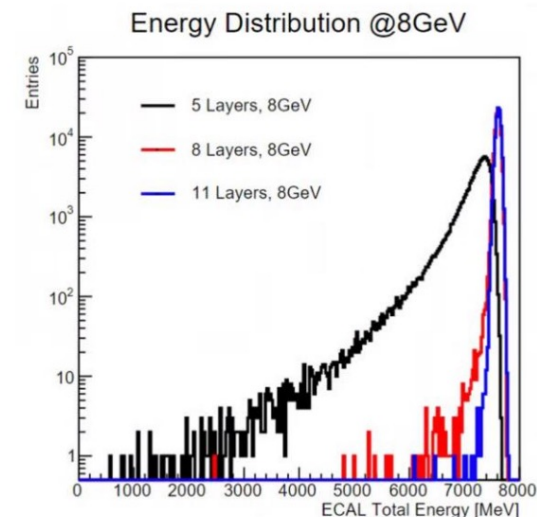
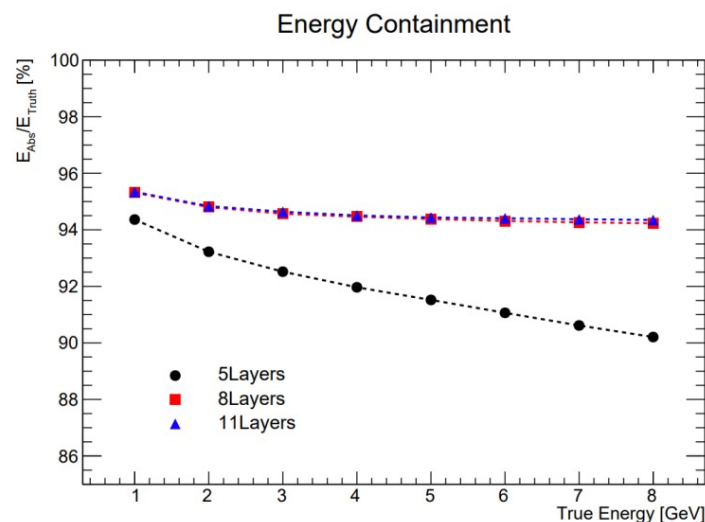
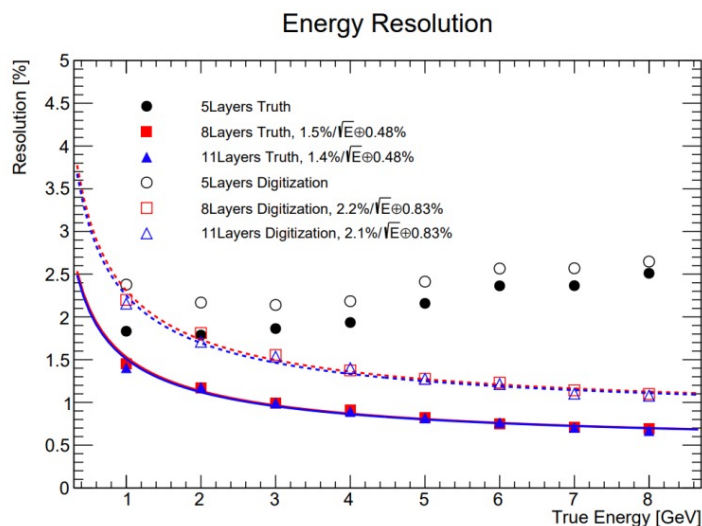
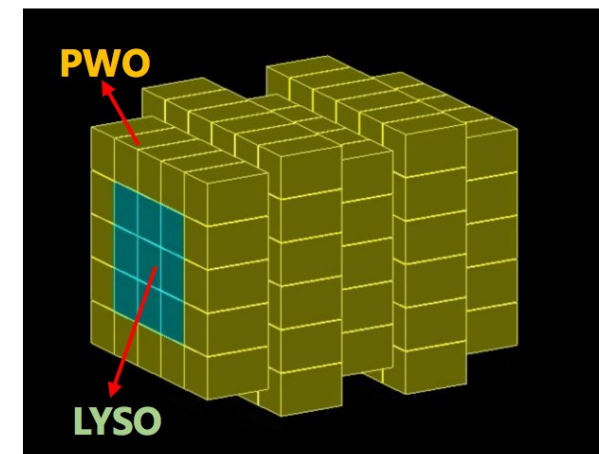
Simulation and experiment
can be in good agreement



Prototype Design



- Motivation:
 - Performance study under high energy and high repetition beam.
 - Technical validation for the whole detector system
- Hybrid material design
 - LYSO as the core scintillator, with high radiation resistance
 - PWO as the outer scintillator, with high density and more economical
- Energy resolution is better than 3%(244 ch). Very low energy leakage below 2.5 GeV.

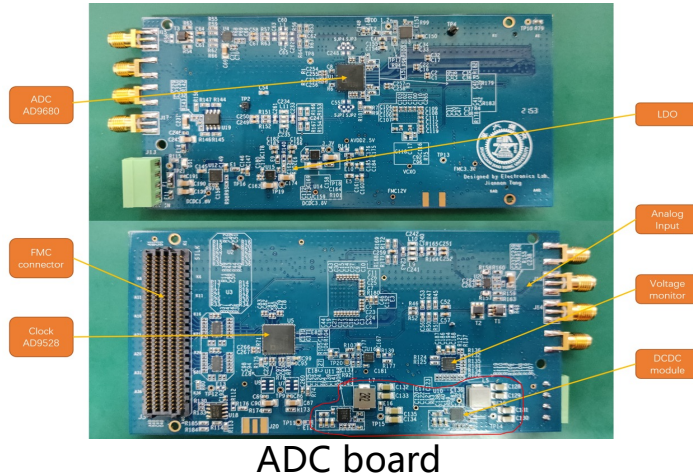
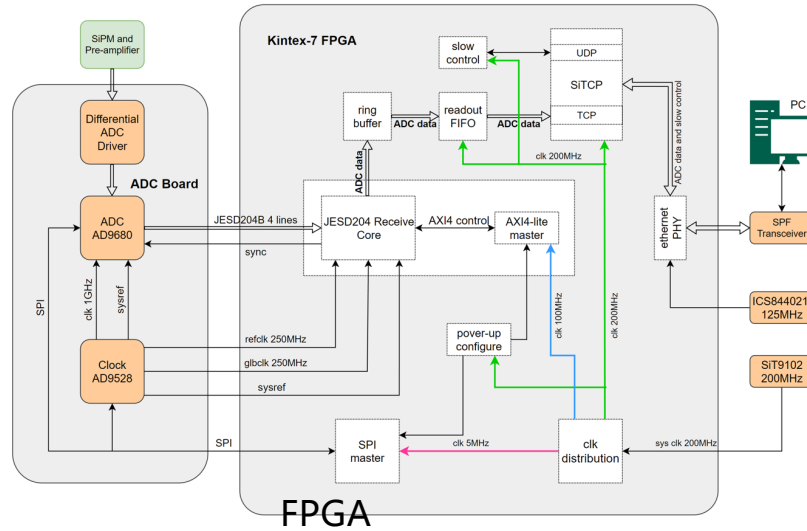


Crystal ECAL readout electronics

arXiv:2407.20723
submitted to JINST



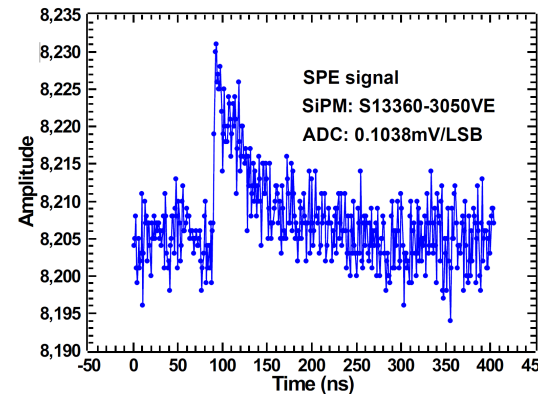
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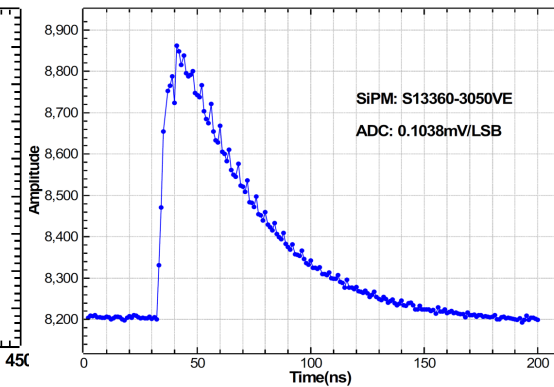
ADC board

Photons from ECAL crystal are detected using SiPM + fast readout system.

- SiPM (width~10s ns, rising edge ~2ns)
- ADC chip (AD9680 from ADI)
- ADC Mezzanine Card
- Data transfer and processing
- ADC performance has been tested.
 - Analog input: Cosmic ray + SiPM (S13360-3050VE) + plastic scintillator
 - Amplitude of SPE signal : ~42 LSB, 4.4mV
 - Noise level : ~10 LSB, 1mV



An SPE signal



A cosmic ray signal

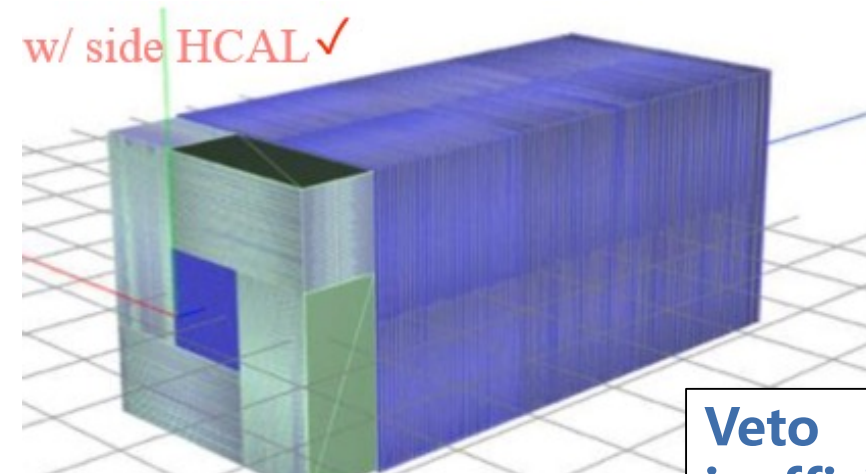
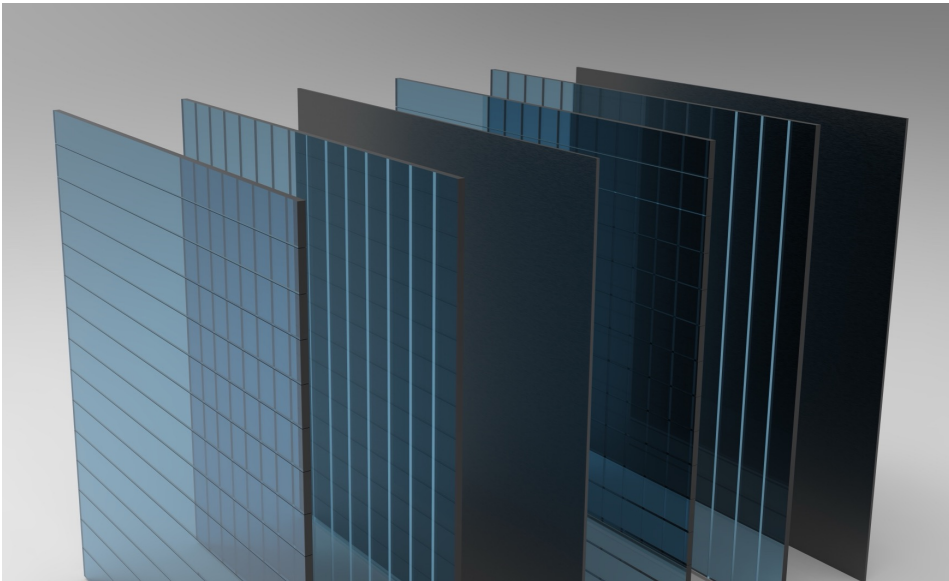
● HCAL R&D

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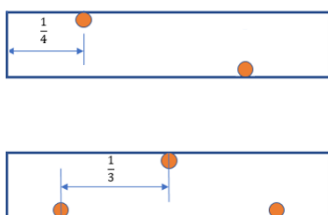
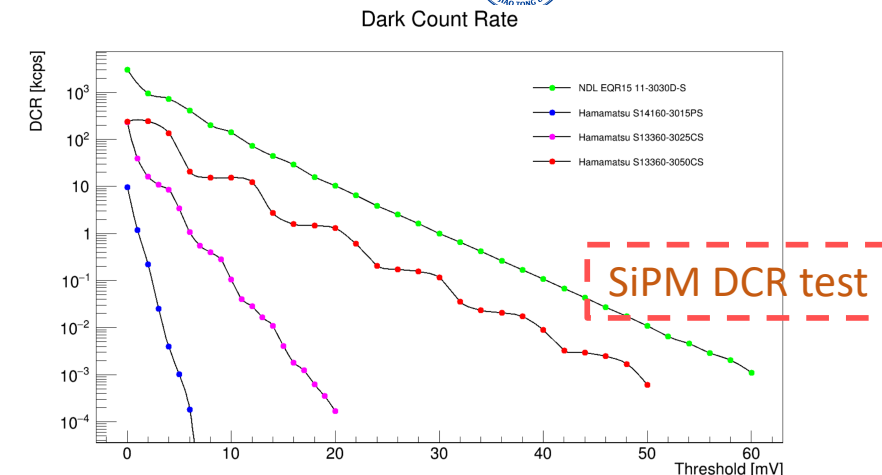
- Veto backgrounds with same behavior as signal in ECAL
- 1.5 m × 1.5 m × 2.5 m (perpendicular to the beam), ~11 λ (~160 cm iron, parallel to the beam)
 - Split to 4 modules, 75 cm × 75 cm each
 - Iron absorber: 10 mm/50 mm thick, 75 cm × 75 cm
 - Plastic scintillator: 10 mm thick, 75 cm × 5 cm, 15 bars per layer per module
 - 90 degree rotation between 2 adjacent layers
 - Wavelength shift fiber + SiPM
- Side-HCAL: encircling the ECAL
- Design has been optimized



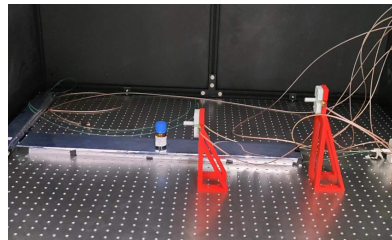
**Veto
inefficiency**

Particle \ Energy[MeV]	n	k ⁰	π^0	p
100	1.17E-03	3.16E-02	7.30E-06	3.07E-02
500	1.84E-05	3.30E-06	1.00E-07	8.04E-06
1000	3.70E-06	4.30E-06	1.00E-07	1.00E-07
2000	2.70E-06	1.15E-05	1.00E-07	1.00E-07

- **Scintillator test in TDLI lab**
 - SiPMs performance are studied first, both size, gain and noise are considered, and picked one type (Hamamatsu S13360-3050, gain 1.7×10^6) for the rest tests
- **Radioactive source test for uniformity**
 - Very good uniformity of the scintillator along the 75 cm side



Fiber grooves

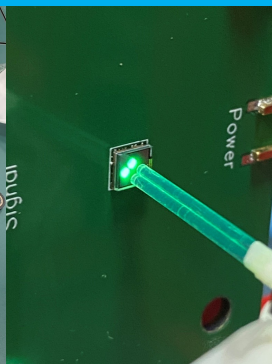


Radioactive source test

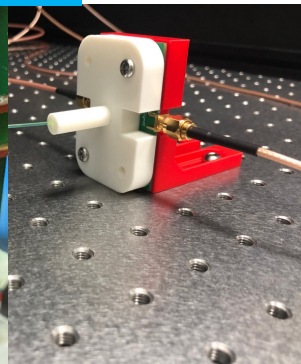
- **Cosmic ray test for photon yields**
 - Various types of scintillator are tested : sizes (75cm×5cm/10cm×1cm/2cm), number of fiber grooves/used, manufacturer/composition are tested
 - Noise test: to decide the minimal cut we could use in analysis



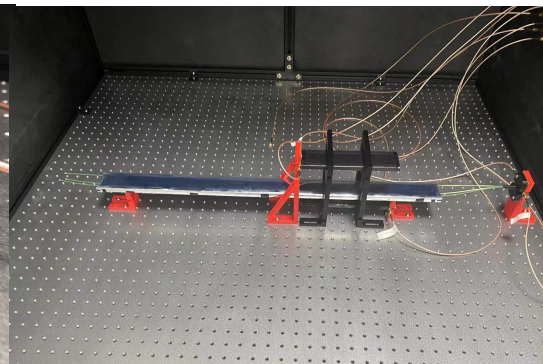
Scintillator (w/ & w/o wrap)



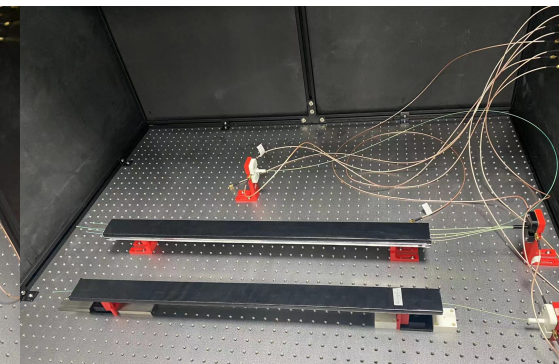
WLS & SiPM



Fiber collimation



Cosmic ray test: photon yields test (left) and noise test (right)



● Collaboration with SHINE

