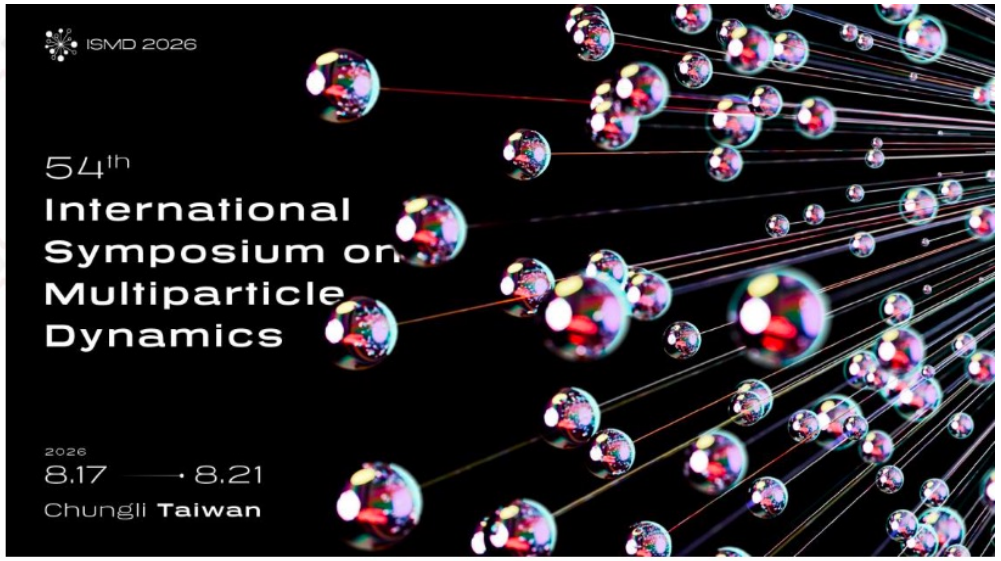
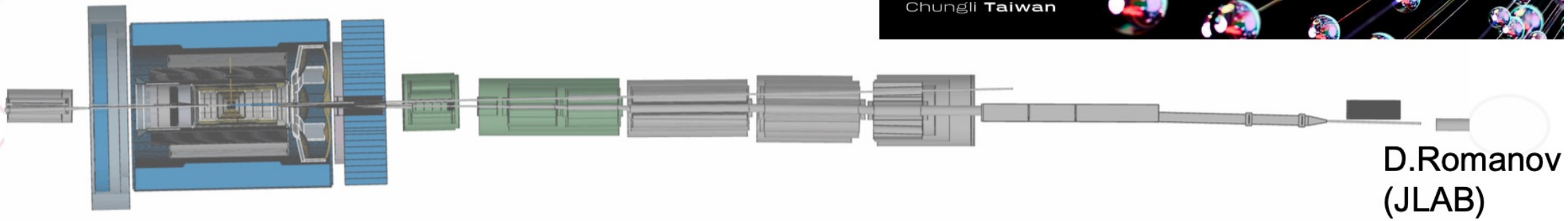
Experiment design and detector R&D of the ePIC experiment





D.Romanov
(JLAB)

54th International symposium on Multiparticle dynamics,
Chungli, Taiwan, August 18, 2026,

Ralf Seidl (UTokyo, QNSI)

26 countries
> 200 institutes

ePIC

東京大学 THE UNIVERSITY OF TOKYO

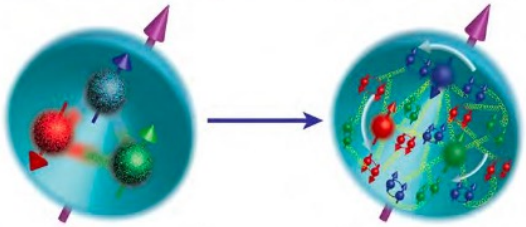
QNSI Quark-Nuclear Science Institute, UTokyo

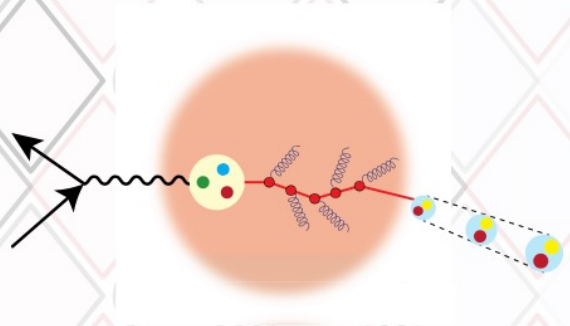
https://www.epic-eic.org

Questions, EIC wants to answer

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?





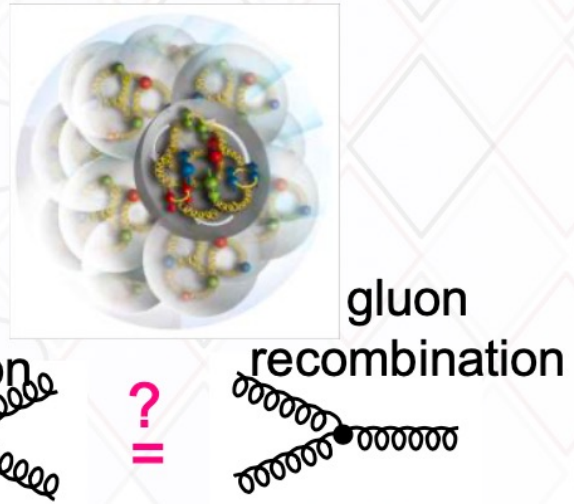
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

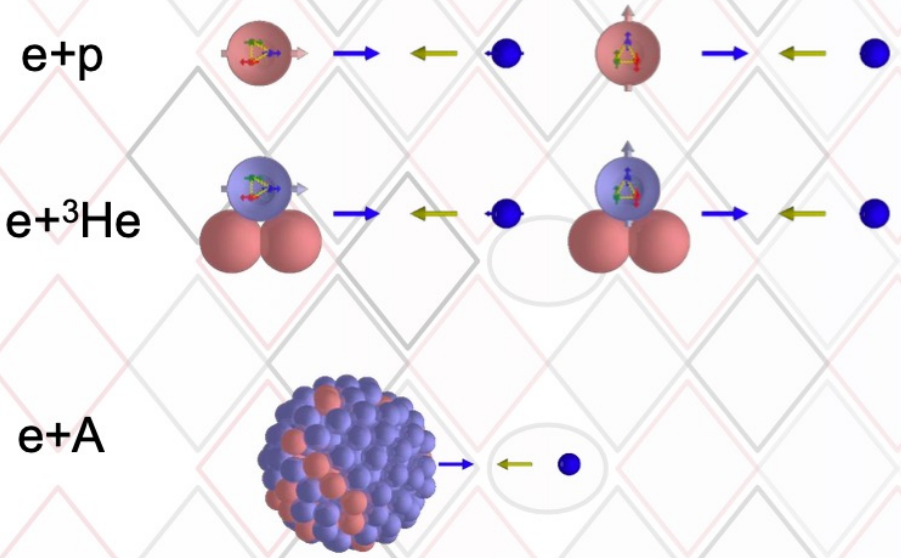
How do the quark-gluon interactions create nuclear binding?

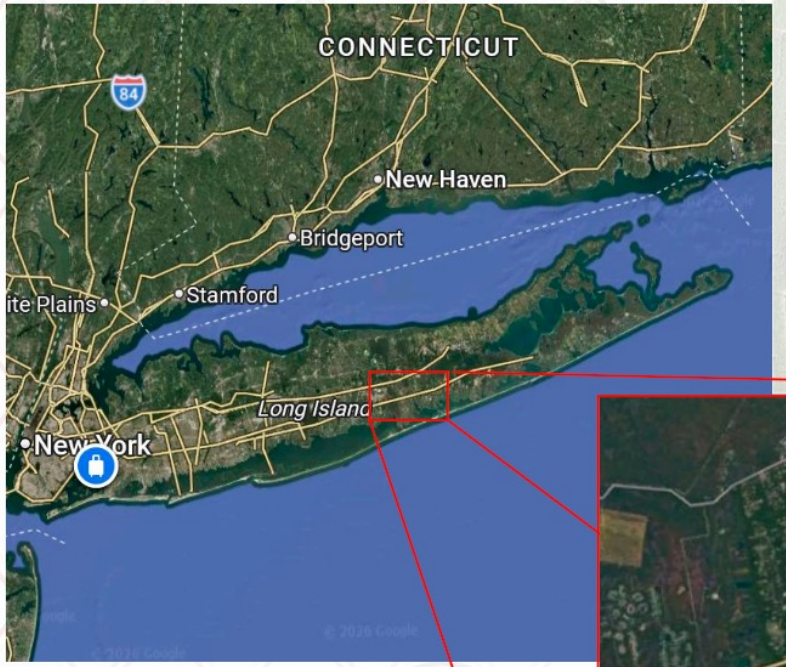
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

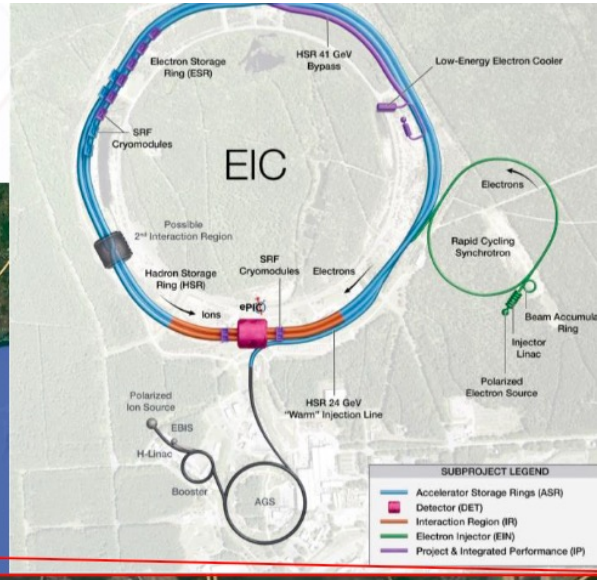
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

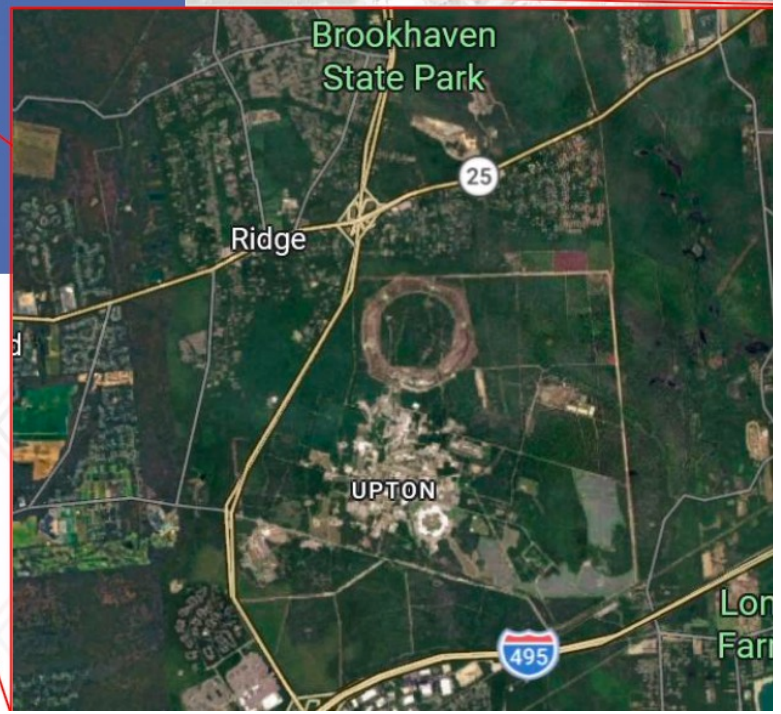


EIC accelerator to be build at BNL





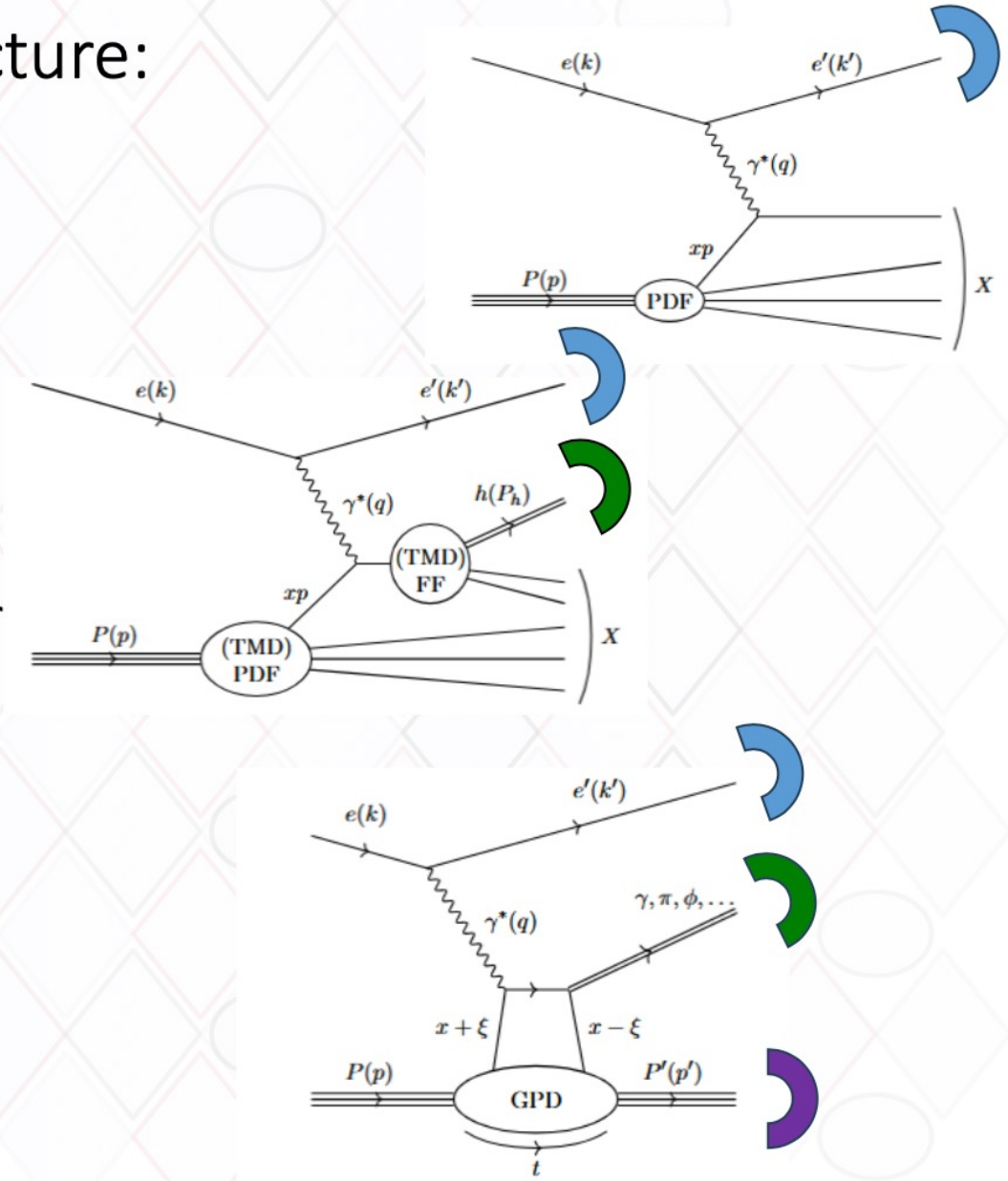




- 80% polarized electrons from 5-18 GeV
- 70% polarized protons from 40-275 GeV
- Ions from 40-110 GeV/u, Polarized light ions 40 -184 GeV (^{3}He)
- CMS energies $\sqrt{s}$ = 29 – 140 GeV
- 1000 x HERA luminosities: 10^{33}-10^{34} cm^{2}s^{-1}
- Production started, first physics in mid 2030s

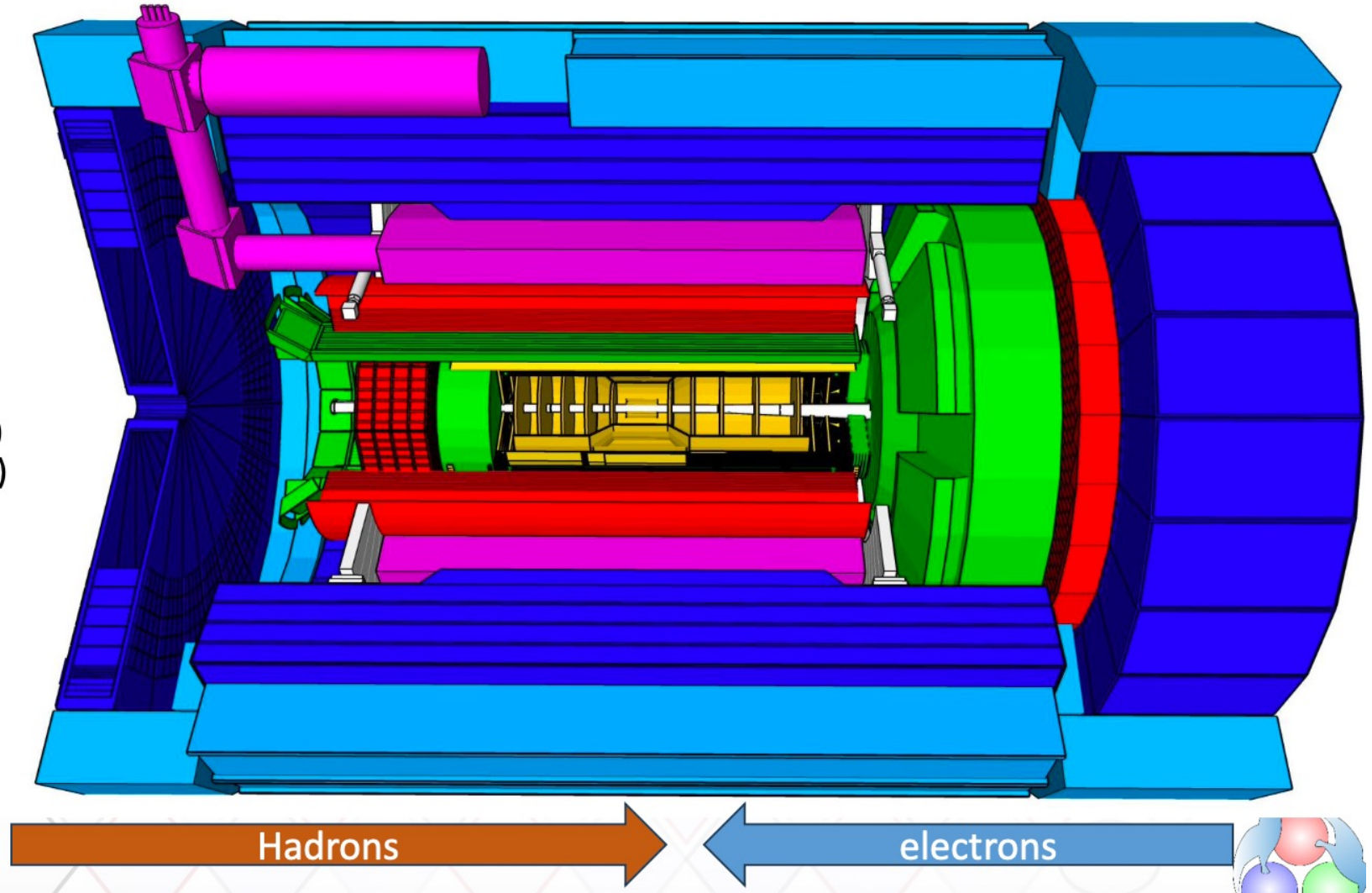
Tools to study the nucleon structure: General detector requirements

- Inclusive DIS e+p→e'+X
  - scattered lepton
  - Good lepton ID, tracking
- Semi-inclusive DIS e+p→e'+h+X
  - scattered lepton + hadron(s)
  - + hadron ID
- Exclusive DIS e+p→e'+γ/h+p'/n
  - scattered lepton + proton/neutron and one g or hadron
  - + Far forward p/n detection
- Tagging of spectators in e+A collisions (eg e+^{3}He →e'Xpp), coherent vs incoherent scattering
  - Far forward coverage for decay products and spectator nucleons
- Photoproduction, luminosity monitoring, local polarimetry
  - Far backward detectors, polarimeters



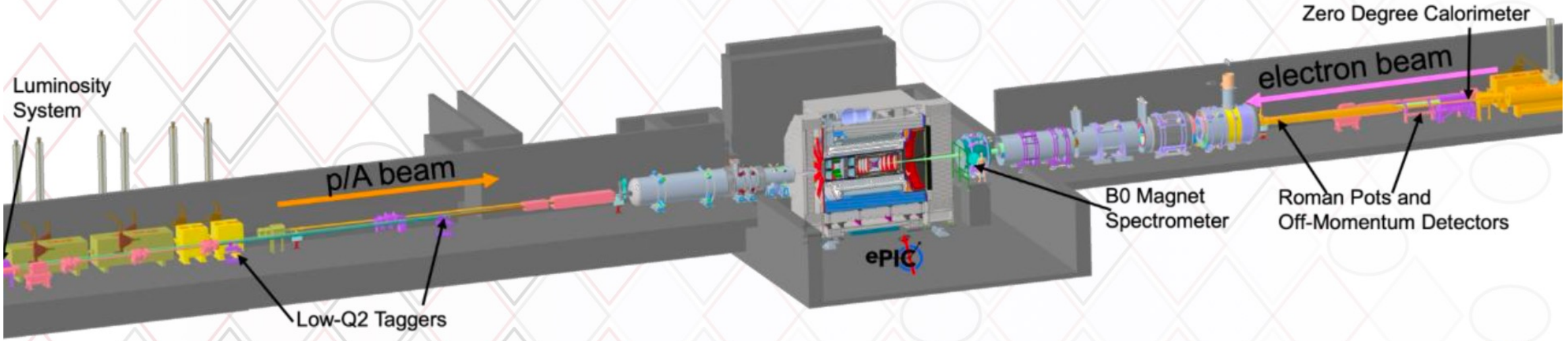
Central ePIC detector

- Magnet
  - New 1.7 T magnet
- Tracking
  - MAPS based tracking (ITS3)
  - MAPS barrel and discs
  - MGD (central)
- PID
  - high performance DIRC (central)
  - Dual radiator RICH (forward)
  - Proximity focused RICH (backward)
  - AC-LGAD TOF (central and forward)
- EM Calorimetry
  - $PbW0_4$ crystals (backward)
  - Imaging EMCAL (central)
  - W powder/SciFi (forward)
- Hadronic Calorimetry
  - FeScintillator (reuse sPHENIX)
  - Steel/Fe – Scintillator (forward/backward)



The full ePIC detector

- Closely integrated in the Accelerator lattice
- About 60 m long



EIC Early Science Program in First Years of Operations

Year - 1	Year - 2	Year - 3	Year - 4	Year - 5
Start with Phase 1 EIC	Phase 1 EIC + long. electron polarization	Phase 1 EIC + long. electron polarization + proton polarization	Phase 1 EIC + long. electron polarization + proton polarization + spin rotators	Phase 1 EIC + long. electron polarization + proton polarization + operation of hadron spin rotators
New Capability: Commission electron polarization in parallel	**New Capability:** Commission proton polarization in parallel	**New Capability:** Commission running with hadron spin rotators	**New Capability:** Commission hadron accelerator to operate with not centered orbits	
Run: 9 GeV electrons on 115 GeV/u heavy ion beams (Ag, Nb, Cu, Ru)	**Run:** 9 GeV long. polarized electrons on 130 GeV/u Deuterium	**Run:** 9 GeV long. polarized electrons on 130 GeV transverse polarized protons	**Run:** 9 GeV long. polarized electrons on 110 GeV Au	**Run:** 9 GeV long. polarized electrons on 110 GeV Au
Physics: Dense Gluon Systems QCD in Nuclei	**Physics:** QCD in Nuclei Flavor structure of nucleons and nuclei	**Physics:** Flavor structure of nucleons and nuclei	**Physics:** Dense Gluon Systems QCD in Nuclei	**Physics:** Dense Gluon Systems QCD in Nuclei
	Run: Last weeks: 9 GeV long. polarized electrons and 130 GeV polarized protons	**Run:** Last weeks switch to longitudinal proton polarization	**Run:** 9 GeV long. polarized electrons on 275 GeV transverse and longitudinal polarized protons	**Run:** 9 GeV long. polarized electrons on 166 GeV transverse and longitudinal polarized He-3
	Physics: Flavor structure of nucleons and nuclei	**Physics:** Spin	**Physics:** Spin	**Physics:** Spin

Unique science questions addressed as EIC performance ramps up to ultimate performance: More details in ePIC Early Science Report (to be submitted to NIMA soon)

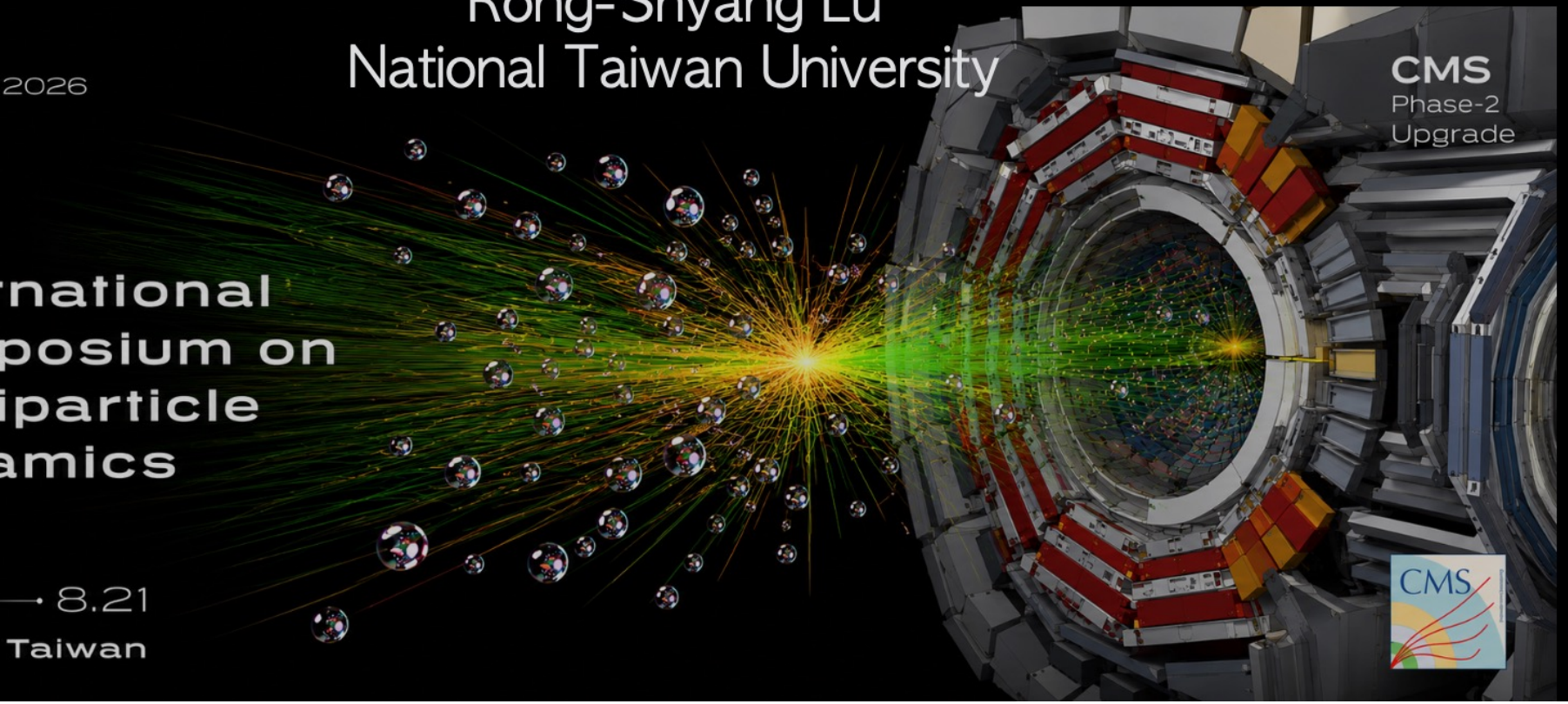
Overview of the Experiment Design and Detector R&D for the CMS Upgrade

Rong-Shyang Lu
National Taiwan University

ISMD 2026

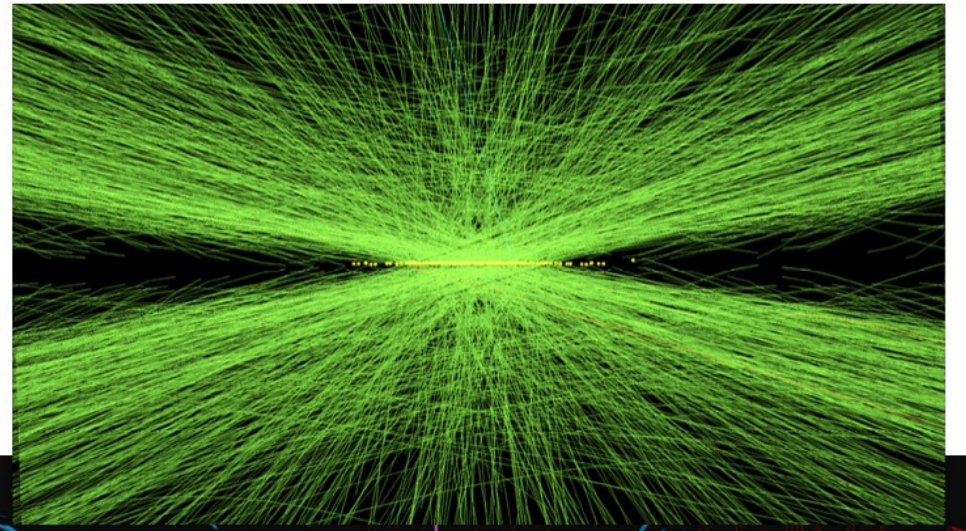
54th International Symposium on Multiparticle Dynamics

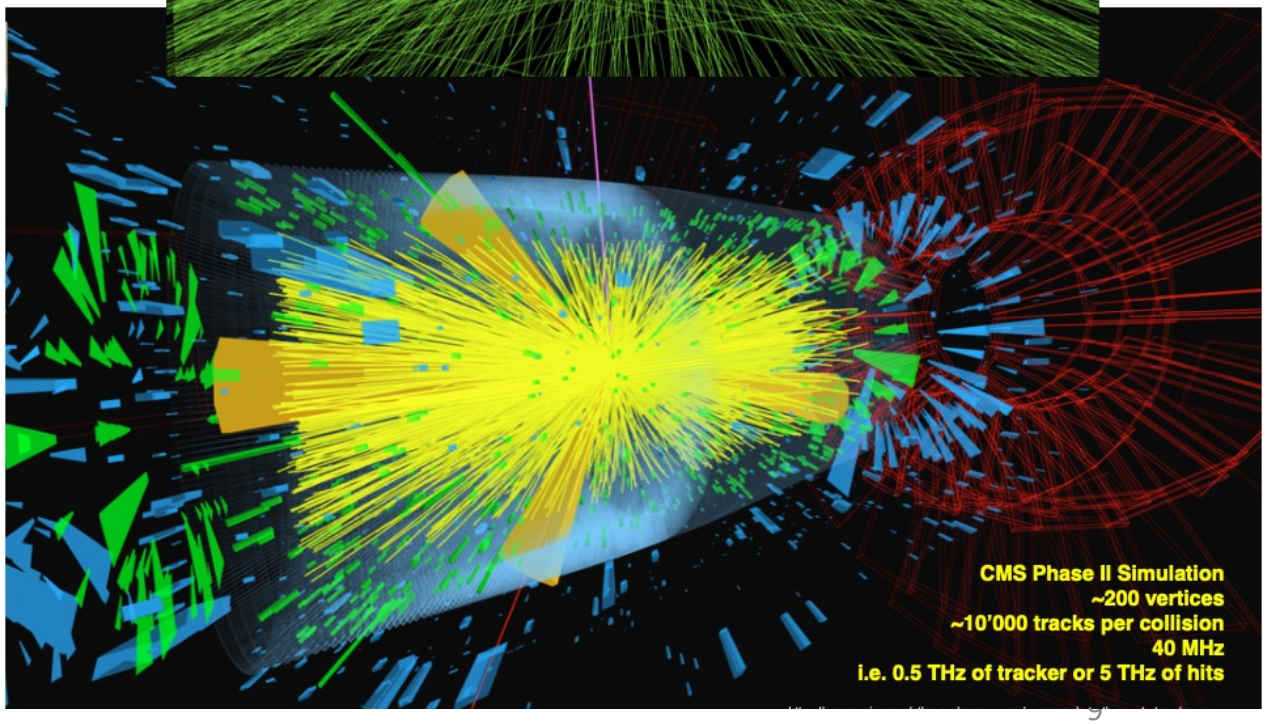
2026
8.17 → 8.21
Chungli Taiwan



Introduction

- Why CMS needs an upgrade?
  - ✦ CMS was designed for pile-up 20 and an integrated luminosity of about 250 fb^{-1}
- The High-Lumi LHC aims for
  - ✦ Pile-up 200 and 250/fb^{-1}/year
- High luminosity running poses
  - ✦ Accumulated radiation damage
  - ✦ Huge amount of accumulated data
  - ✦ Increase in pileup interactions

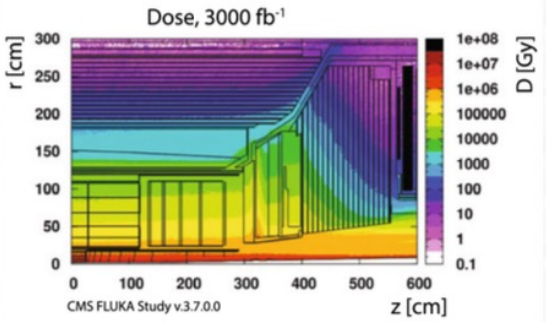




CMS PHASE-2 UPGRADE: FOUR DESIGN STRATEGIES

Four complementary strategies to preserve physics performance at the HL-LHC

1 SURVIVE
Radiation Hardness

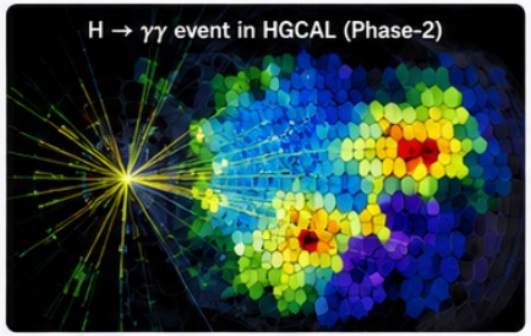


- Radiation levels up to 10^{16} n_{eq}/cm^2 in the innermost tracker
- Radiation-hard silicon sensors and electronics (ASICs)
- Low-power design and advanced cooling
- Replaceable innermost tracker layer

Key Subsystems: IT • OT • HGCAL

Operate after 3000 fb^{-1} in extreme radiation environment

2 MEASURE
High Granularity

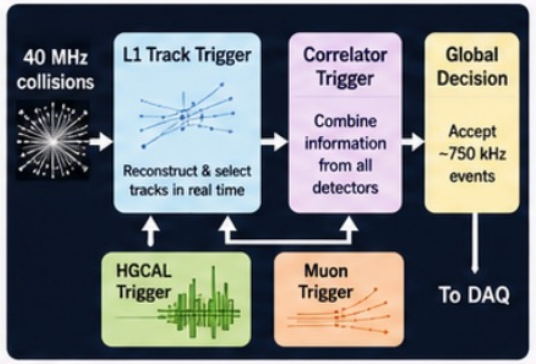


- Fine pixels in the tracker (25×100 μm^2)
- High-granularity calorimetry (HGCAL: ~6M channels)
- Better spatial resolution and pattern recognition
- Extended η coverage up to $|\eta| \approx 4$

Key Subsystems: IT • HGCAL • Muons

Preserve detector performance with finer granularity and coverage

3 SELECT
Real-time Intelligence

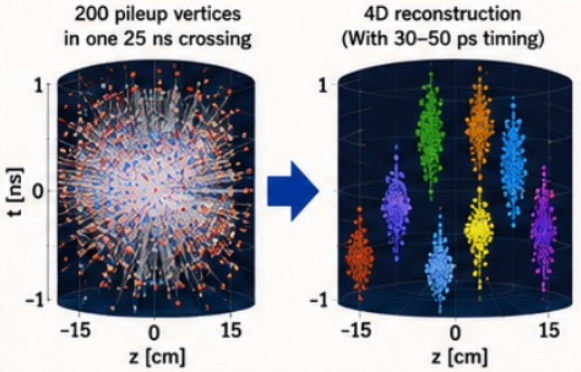


- L1 Track Trigger with p_T resolution
- HGCAL Trigger with high granularity
- Correlator Trigger for global event selection
- 40 MHz collisions → 750 kHz to storage

Key Subsystems: Tracker • HGCAL • Muons • DAQ

Identify rare physics events in the 40 MHz collision stream

4 SEPARATE
Precision Timing



- Precision timing: 30–50 ps
- MTD: precision timing for charged particles (30–40 ps)
- HGCAL: timing for hadrons and photons (30–50 ps)
- ECAL: improved timing (≈ 30 ps)

Key Subsystems: MTD • HGCAL • ECAL

Separate the hard-scatter interaction from ≈ 200 pileup collisions

THE HL-LHC CHALLENGE

- 7.5×10^{34} $cm^{-2}s^{-1}$ — Peak luminosity
- <PU> ~ 200 — Interactions per 25 ns crossing
- Extreme radiation — Up to 10^{16} n_{eq}/cm^2 in the tracker
- 40 MHz — Bunch crossings (25 ns)
- O(10) GB/s — Raw data rate

FOUR DESIGN PRINCIPLES MAINTAIN OR IMPROVE CMS PHYSICS PERFORMANCE IN THE HL-LHC ERA

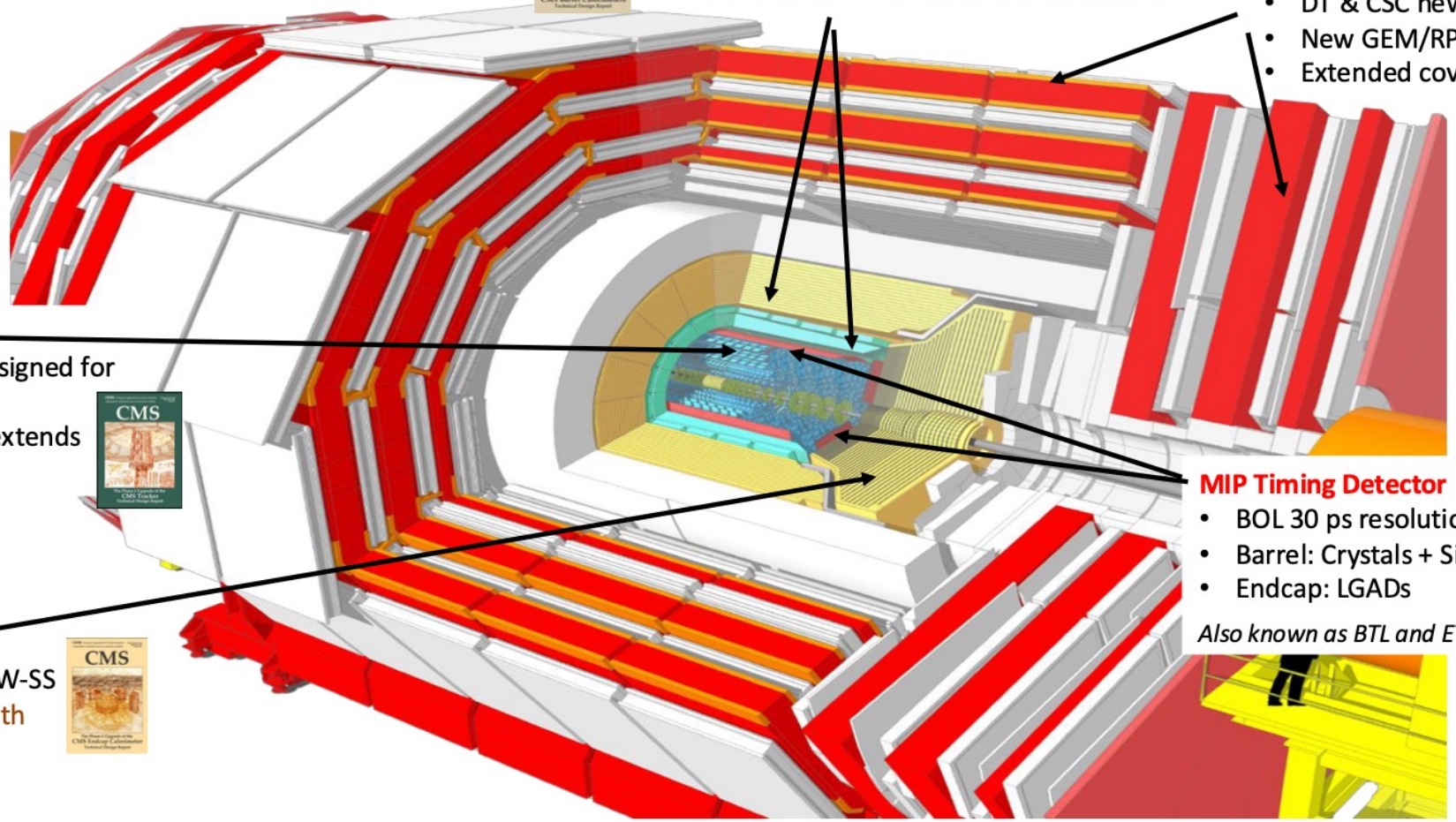
CMS HL-LHC Upgrade Program

L1 Trigger/HLT/DAQ
- L1 40 MHz in/750 kHz out
- Tracking for PF-like selection
- HLT 7.5 kHz out

Beam Radiation and Luminosity
- Bunch-wise Luminosity
- Beam Monitoring

Barrel Calorimeters
- ECAL single crystal granularity in L1 Trigger with precise timing for e/γ at 30 GeV
- ECAL and HCAL new back-end electronics

Muon Systems
- DT & CSC new FE/BE readout
- New GEM/RPC $1.6 < |\eta| < 2.4$
- Extended coverage to $|\eta| < 3.0$



Tracker
- Si Strip **O**uter **T**racker designed for L1 Track Trigger
- Pixelated **I**nner **T**racker extends coverage to $|\eta| < 3.8$

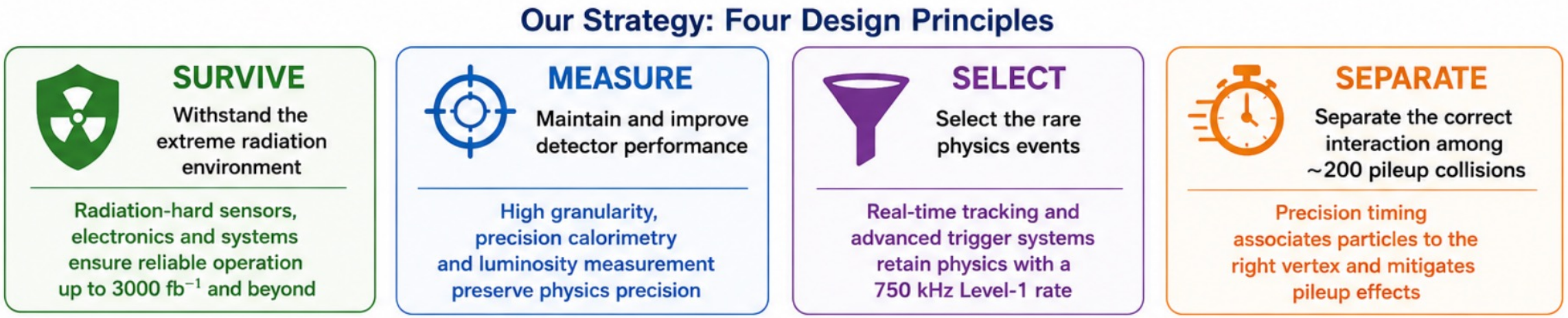
MIP Timing Detector
- BOL 30 ps resolution
- Barrel: Crystals + SiPMs
- Endcap: LGADs

Also known as BTL and ETL

Calorimeter Endcap
- Si, Scint + SiPM in Pb-W-SS
- 3D shower imaging with precise timing

Also known as HGCal

Summary



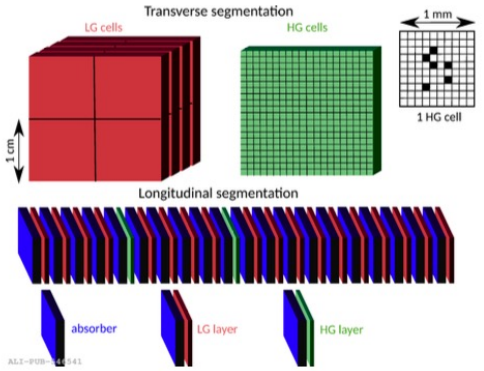
- The CMS Phase-2 upgrade is not a collection of detector replacements - it is an integrated system designed to preserve and extend the CMS physics capability throughout the HL-LHC program.

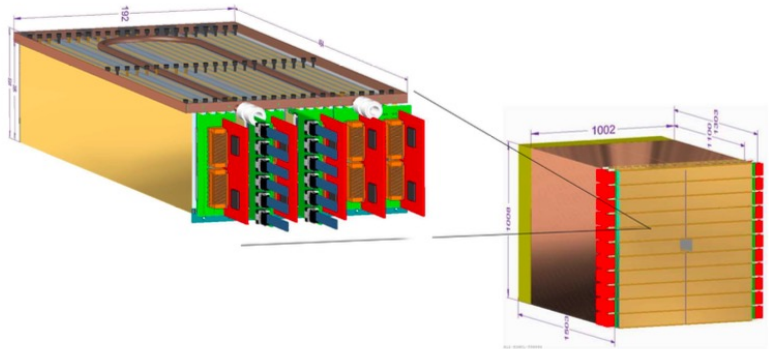
ALICE Detector Upgrades for Future Precision Measurements: FoCal and ITS3

Hadi Hassan for the ALICE Collaboration (University of Tsukuba)

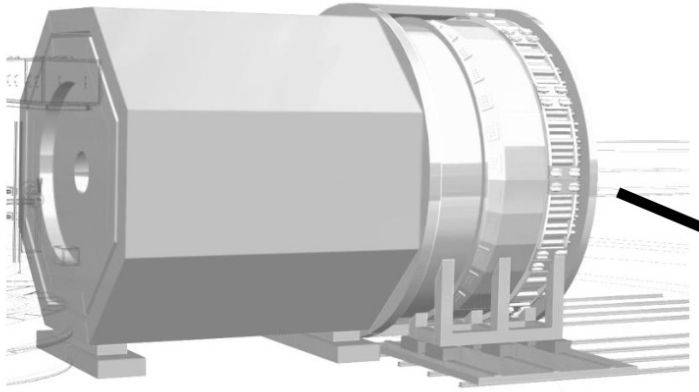
Electromagnetic calorimeter (FOCAL-E)

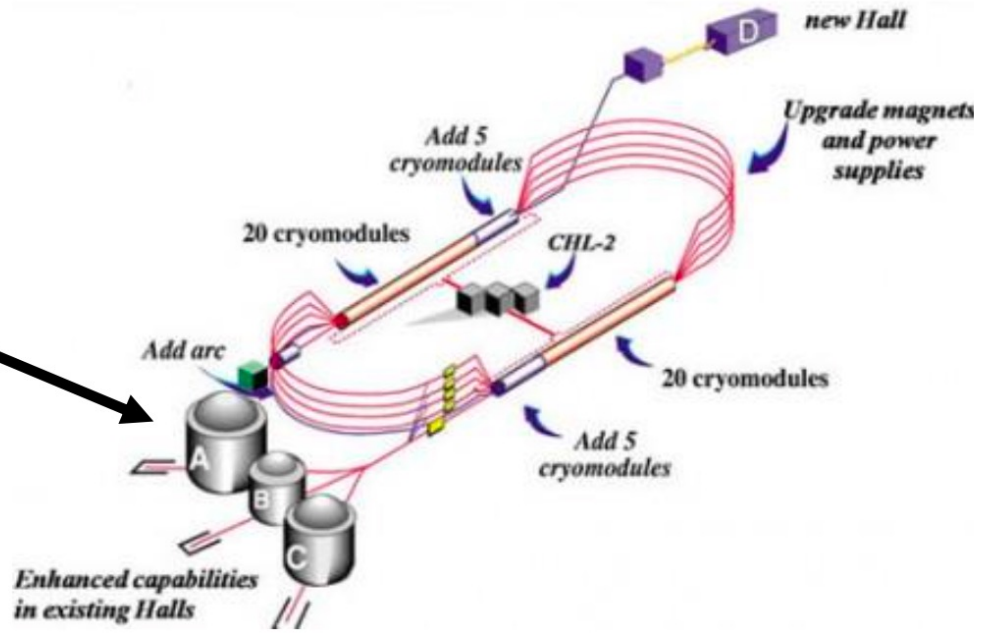
- The electromagnetic calorimeter is a Si+W sampling calorimeter with high granularity.
- It has 18 layers W+Si pads, and 2 W+Si pixels, with total length of $\approx$ 20cm.
- Silicon sensor with pad size of 1 cm $\times$ 1 cm with 8 $\times$ 9 pads per sensor.
- Si pixels: ALPIDE technology (ALICE ITS vertex detector pixel sensor) with pixel size of 30 μm $\times$ 30 μm
- 1024 x 512 pixels per chip of size 30 mm $\times$ 15 mm.
- Main goal of pixel layers is shower separation.





Nilanga Liyanage
University of Virginia

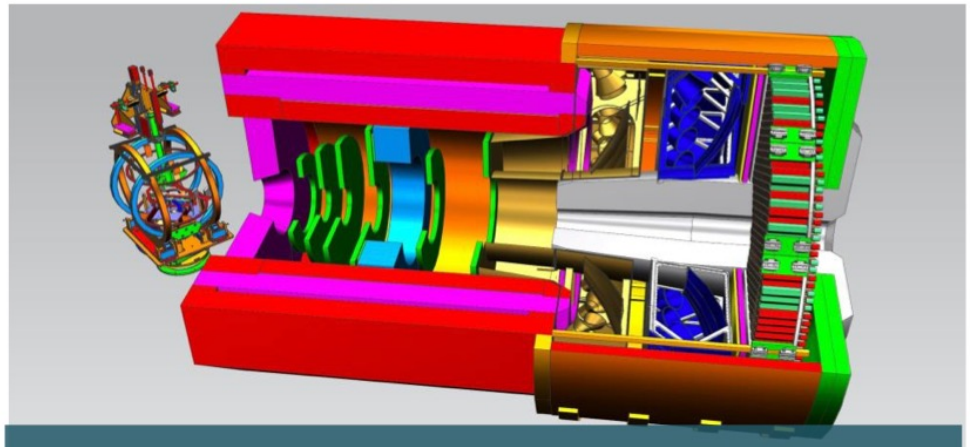




JLab12

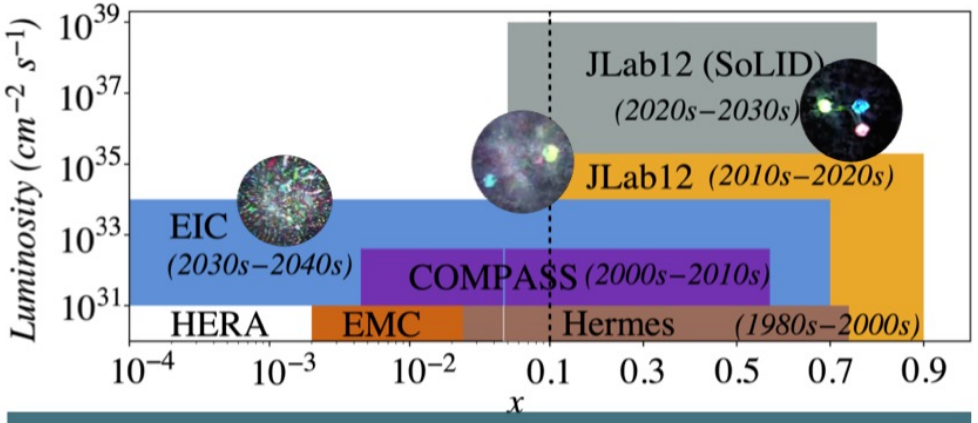
SoLID (Solenoid Large Intencity Device)

Nucleon spin, mass and BSM search experiments. Precision measurements of small cross sections and asymmetries. Critical: high luminosity (10^{37}-10^{39} $cm^{-2}s^{-1}$) and large acceptance (at least 100 times better than existing facility in terms of Figure of Merit)



Solenoidal Large Intensity Device (SoLID)

- Precision 3D imaging of the nucleon in the valence region (GPDs, TMDs). Unique, critical to NP science mission but complementary to EIC.
- Exploring the origin of the proton mass and confining color forces. Mass and scalar energy distributions in the proton. Unique, critical to NP science, but complementary to EIC.
- Search beyond the Standard Model of Particle Physics. Unique and complementary to MOLLER



Luminosity Frontier in the Valence Region

- DOE/JLab supported pre-R&D activities on cutting-edge technologies.
- Enhanced credibility of the design with greatly reduced cost/schedule risks
- Scientific excellence and students training ground with a growing impactful science portfolio

Summary

- SoLID: A **large acceptance** device which can handle **very high luminosity** to allow full exploitation of JLab 12 GeV potential

  → pushing the limit of the intensity frontier for Cold QCD

- SoLID has a rich and vibrant science program complementary and synergistic to the proposed EIC science program

  Three pillars on 3-d (TMDs/GPDs), PVDIS and J/Psi production + …

- After a decade of hard work, we have a mature pre-conceptual design meeting the challenging requirements for the approved experiments
- DOE/JLab supported pre-R&D activities on cutting-edge technologies, including advanced detectors and readout electronics, AI/ML, …
- Excellent training ground for workforce

Unpolarized Gluon PDF from Lattice QCD







Chen Chen
HIAS, UCAS (formly at IMP CAS)

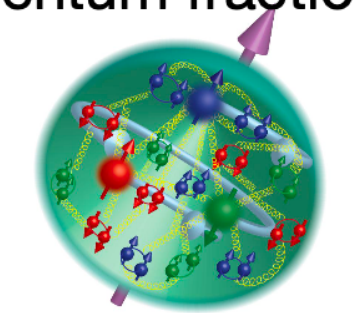
in collaboration with

Chunhua Zeng, Hongxin Dong, Liuming Liu, Peng Sun,
Yi-Bo Yang, Fei Yao, Jian-Hui Zhang, and Shiyi Zhong

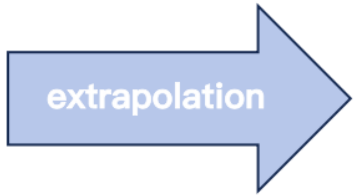
17–22 Aug , ISMD 2026

Introduction & Motivation

- Nucleons: complicated dynamical systems of quarks and gluons
- PDFs: decribe the probability density of finding a parton with momentum fraction x inside a nucleon
- Phenomenological studies : model dependent
- Lattice QCD study of gluon PDFs :



- Previous studies: mostly based on pseudo-PDF method
  Phys.Rev.D 104 (2021) 9, 094516; Phys.Rev.D 108 (2023) 1, 014508; Phys.Rev.D 108 (2023) 9, 094515
- Recent LaMET calculations: unphysical pion mass
  Phys.Lett.B 872 (2026) 140067, e-Print: 2510.17758, e-Print: 2511.14708
- Our study: P_z up to 3 GeV
  a : 0.0519fm~0.105fm
  m_π: 136~317 MeV



infinite momentum limit ☑
continuum limit ☑
physical pion mass ☑

Lattice Setup

Ensemble	a (fm)	m_π (MeV)	P_z (GeV)	$N_{\text{conf.}}$
C24P29	0.105	292	0, 1.95	878
C32P29	0.105	292	1.84, 2.21	980
C32P23	0.105	228	1.84, 2.21	597
C48P14	0.105	136	1.72, 1.96, 2.21, 2.46	347
E32P29	0.0897	287	0, 1.72, 2.16, 2.59	1700
F32P30	0.0775	300	0, 2.0, 2.5, 2.99	777
G36P29	0.0688	297	0, 2.0, 2.5, 3.0	349
H48P32	0.0519	317	0, 1.99, 2.48, 2.98	650

CLQCD

PRD109(2024)5,054507
PRD111(2025)5,054504

- **Continuum limit**
  Five different lattice spacings
- **Physical pion mass**
  Pion mass: 136 - 317MeV
- **Infinite-momentum limit**
  Various momenta up to 3GeV

Summary and outlook

- We calculated the unpolarized gluon PDF of the nucleon in LaMET framework.
- Extrapolated to infinite momentum-limit, continuum limit and physical pion mass.
- Our result agrees with the global fit result within 2σ.

Recent Advances and Challenges in Proton PDF Determination

54th International Symposium on Multiparticle Dynamics (ISMD 2026)

Emanuele R. Nocera

Università degli Studi di Torino and INFN, Torino

19 August 2026







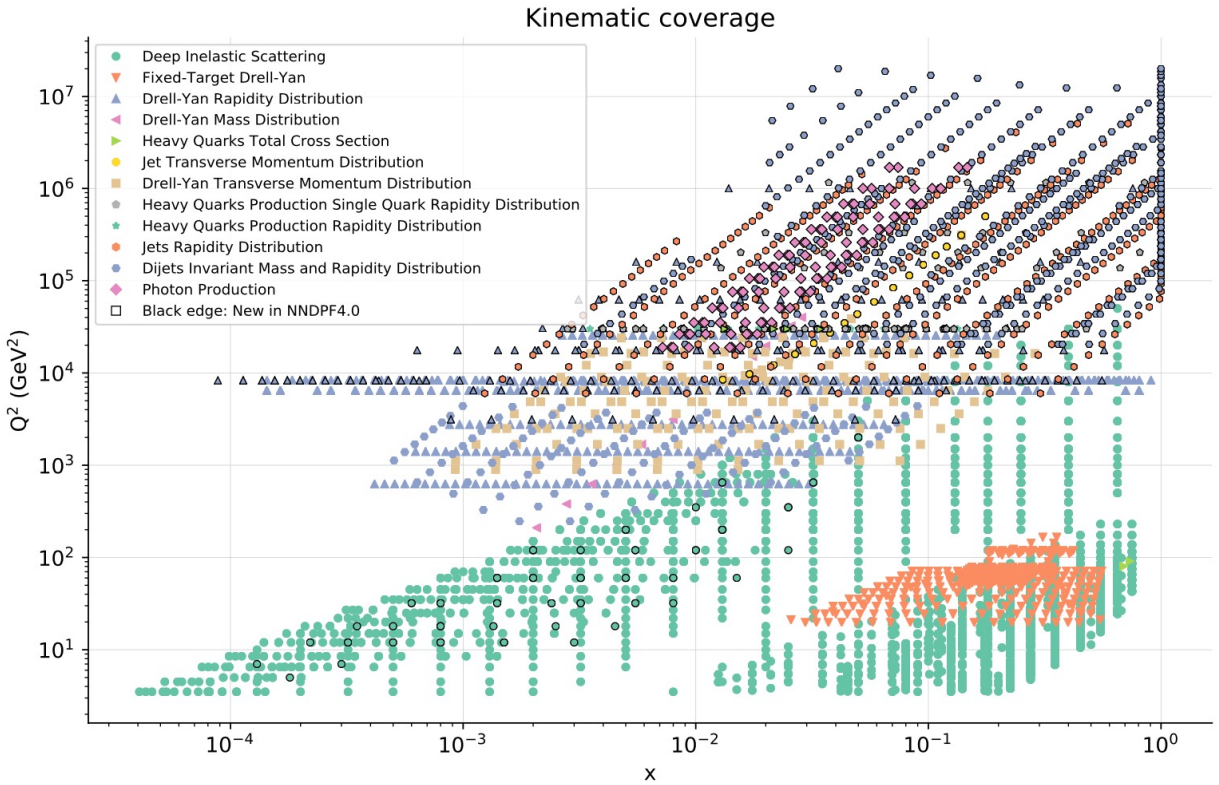
UNIVERSITÀ DI TORINO

Parton Distribution Functions at the LHC

$$\sigma(Q^2,\tau,\mathbf{k}) = \sum_{ij}\int_\tau^1 \frac{dz}{z}\mathcal{L}_{ij}(z,Q^2)\hat{\sigma}_{ij}\left(\frac{\tau}{z},\alpha_s(Q^2),\mathbf{k}\right) \quad \mathcal{L}_{ij}(z,Q^2) = (f_i^{h_1}\otimes f_j^{h_2})(z,Q^2)$$

PDF uncertainty is often the dominant source of uncertainty in LHC cross sections

The data set



$N_{\rm dat} \sim 4618$ $N_{\rm proc} \sim 13$ $\chi^2/N_{\rm dat} \sim 1.16$ (NNLO)

Summary

A precise and accurate determination of PDFs is key to do precision phenomenology.

LHC measurements are being instrumental to reduce PDF uncertainties to few percent.

The goal of achieving PDF determinations accurate to 1% opens up some challenges.

Understand the interplay between data, theory, and methodology into PDF uncertainties.

Refine the theoretical accuracy of a PDF determination.

Represent theory uncertainties into PDF uncertainties.

Deploy a robust fitting methodology and good statistical tests of it.

Benchmark efforts may benefit from public releases of PDF codes and inputs.

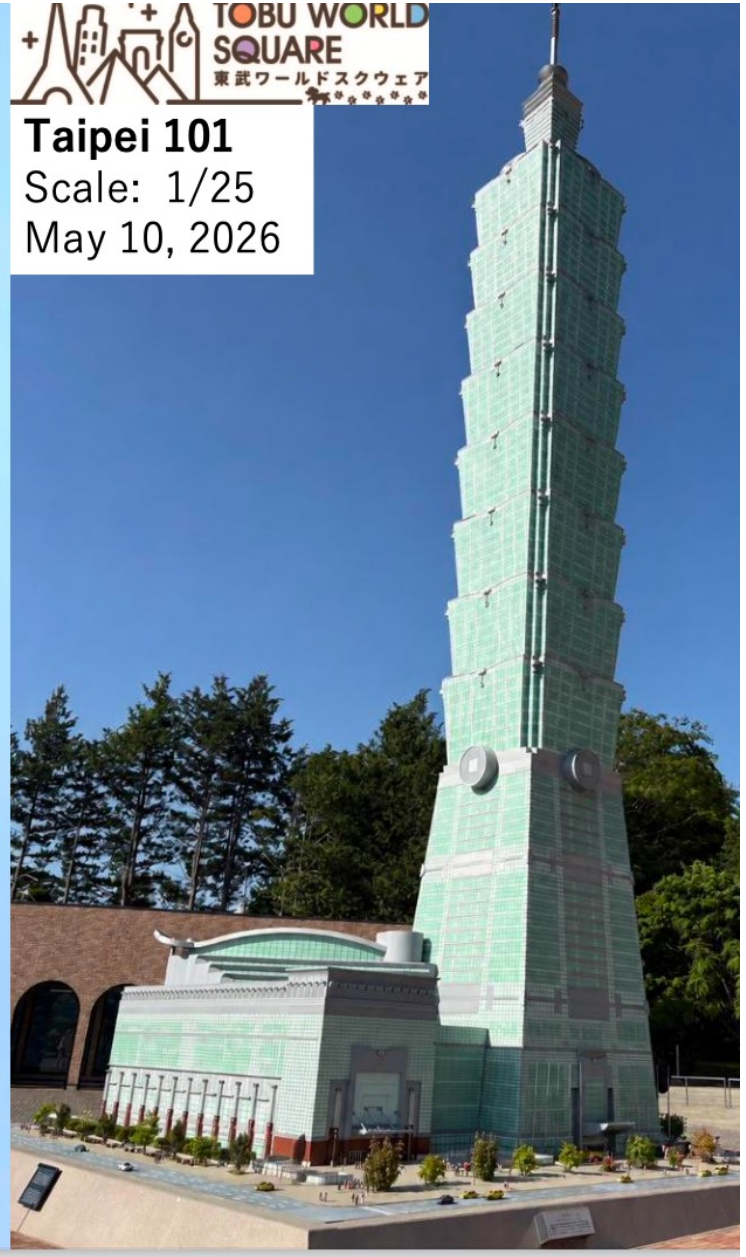
Hadron Physics at the J-PARC Hadron Experimental Facility

K. Aoki (青木和也)
KEK/J-PARC

54th International Symposium on Multiparticle Dynamics 2026, National Central University, Chungli Taiwan. Aug. 17-21, 2026



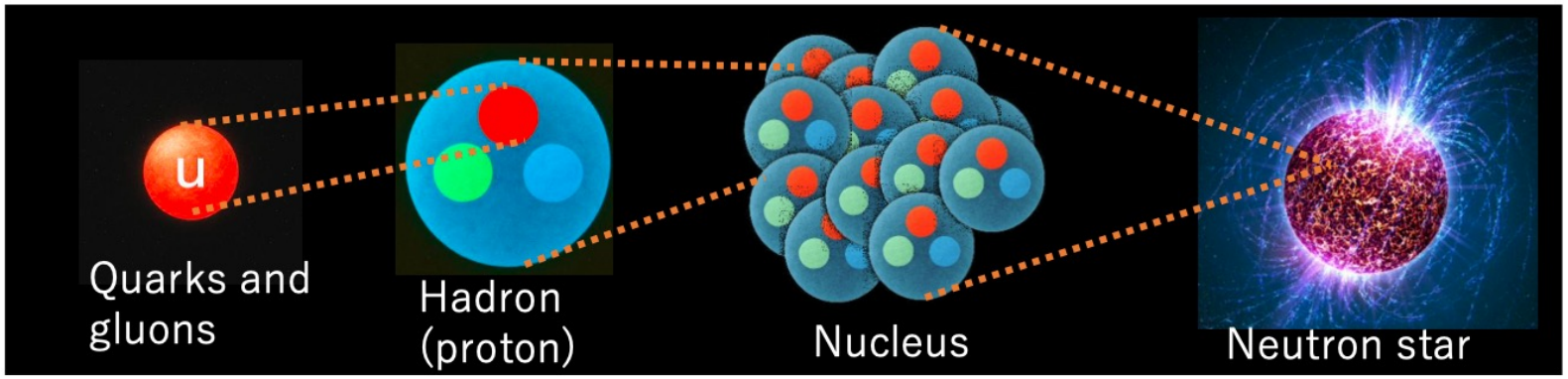
Genuine Taipei 101
Sep 11, 2024



Taipei 101
Scale: 1/25
May 10, 2026

Physics motivation in one slide:

To understand strongly interacting systems from quarks to neutron stars.



The core is the densest matter except BH, even denser than nucleus.

- Quarks → Hadron : How quarks and gluons form hadrons?
  - Quarks are confined. Constituent quarks emerge. Chiral symmetry spontaneously broken.
  - Meson in nuclei as a probe of QCD vacuum structure.
  - Hadron spectroscopy.
- Hadron → Nucleus → Neutron star : Property of matter up to dense env?
  - Precision Baryon-Baryon int. including hyperons and its density dependence
  - Hyper-nuclear spectroscopy.
  - Y-N Scattering experiment

Experiments completed/data-taking/near future.

- K1.8 beam line:YN int. by S=-1, -2 hypernuclei and scatt.
  - Completed
    - E19: Search for Θ^+ pentaquark in π^- p → K^- X reactions
      - Θ^+ not observed.
    - E27: Search for a nuclear K^{bar} bound state K^-pp in $d(\pi^+,K^+)$
    - E10 1st : Neutron rich Λ hypernuclei ($^6_\Lambda$H) search (S=-1)
      - $^6_\Lambda$H not observed.
    - E13: γ–ray spectroscopy of light hypernuclei $^4_\Lambda$He
      - Precise measurement of M1 transition ($^4_\Lambda$He $1^+ \rightarrow 0^+$), showing spin-dependent CSB.
    - E05: Spectroscopic study of Ξ^- hypernuclei, $^{12}_{\Xi}$Be, via ^{12}C (K^-,K^+) (S=-2)
      - Events in bound region. E70 measured it with x4 resolution.
    - E07: Systematic study of double strangeness system with an emulsion-counter hybrid method.
      - Xi- hypernuclei (IBUKI 1st uniquely identified state, IRRAWADY)
    - E40: Cross sections of Σp scatterings.
    - E03 1st: Measurement of X rays from Ξ^- atom.
      - No clear peak. Fe target. Ge det. KURAMA. 1.8GeV/c $(K^-,K^+)\Xi^-$. →E96.
    - E42: Search for H-dibaryon with a Large Acceptance Hyperon Spectrometer
    - E70 : Proposal for the next E05 run with the S-2S spectrometer
    - E96 : X rays from Ξ^- C atom with an active fiber target system
  - On-going
    - E63 : Precision measurement of M1 transition of $^3_\Lambda$He ($1^+ \rightarrow 0^+$). CSB.

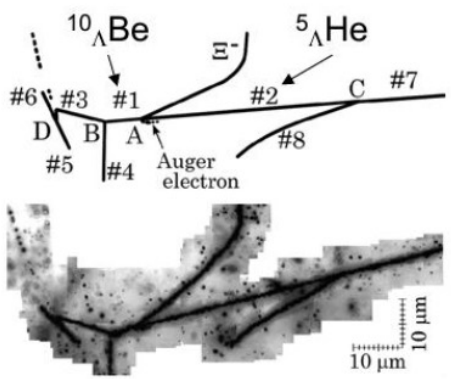
(incomplete list)

6

J-PARC E07[DONE]：S=-2 hypernuclei by Hybrid emulsion method

- (K^-, K^+) reactions：**s** in the beam and **s-s**^{bar} created. K^+ take away **s**^{bar}. **ss** are put into the system of interest.
- Emulsions – photographic films that capture particle reactions.
- Hybrid – Ξ^- productions were recorded by counters, later search for corresponding position in emulsion by microscope
- Ξ^- + ^{14}N hypernuclei are found:

(KEK-E373)
KISO event



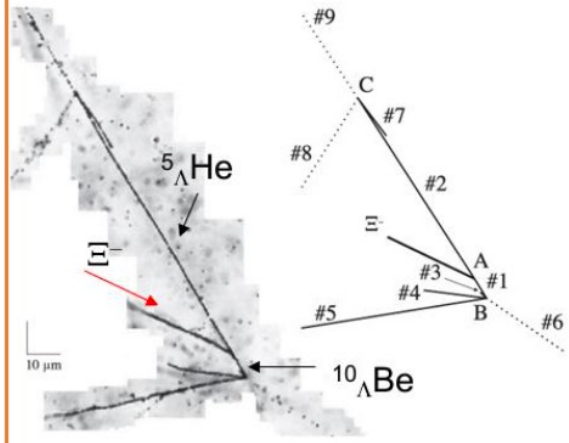
K. Nakazawa et al., PTEP. 2015, 033D02

1st discovery of clear Ξ nuclear state

Two possibilities of B_{Ξ^-} depending on $^{10}_{\Lambda}$Be state

- B_{Ξ^-} ($^{10}_{\Lambda}Be_{g.s.}$) = 3.87 ± 0.21 MeV
- B_{Ξ^-} ($^{10}_{\Lambda}Be_{1st.\ Ex.}$) = 1.03 ± 0.18 MeV

(J-PARC E07)
IBUKI event



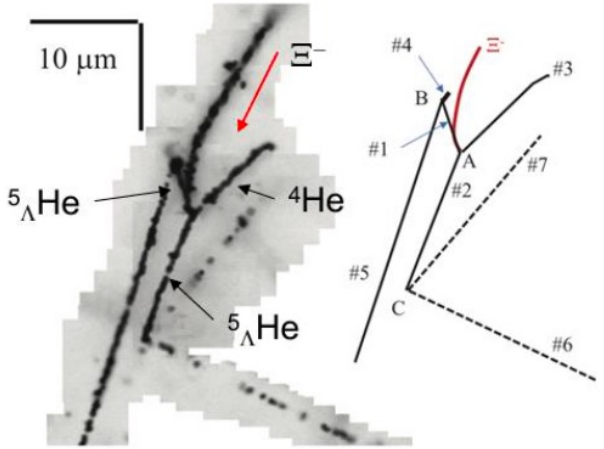
S. H. Hayakawa et al.,
Physical Review Letters, 126, 062501 (2021)

1st uniquely identified Ξ nuclear state

One reaction process satisfied kinematical consistency.

- B_{Ξ^-} = 1.27 ± 0.21 MeV
(1p-state)

Ξ^- + ^{14}N → $^{5}_{\Lambda}$He + $^{5}_{\Lambda}$He + ^{4}He + n
IRRAWADDY event



M. Yoshimoto et al., PTEP. 2021, 073D02

1st observation of nuclear s-sate of Ξ hypernucleus

(This maybe [Ξ^0 + ^{14}C] lighter by 6.18 MeV)
E.Friedman, A.Gal PLB837, 137640(2023)

- B_{Ξ^-} = 6.27 ± 0.27 MeV
→ B= 0.09 MeV if [Ξ^0 + ^{14}C]

Ξ^- + ^{14}N hypernuclei

Slide by
K. Miwa 2nd HEF-EX.

J-PARC E07 [Reanalysis using ML]

Nature communications (2025)16:11084

- ML-based analysis found a new event, uniquely identified double-Λ hyper-nuclei w/o trigger information.
- Nuclear emulsion is an old-fashioned streaming DAQ with new technology.

Article https://doi.org/10.1038/s41467-025-66517-x

$$\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{13}_{\Lambda\Lambda}\mathrm{B} + \mathrm{p} + \mathrm{n}$$

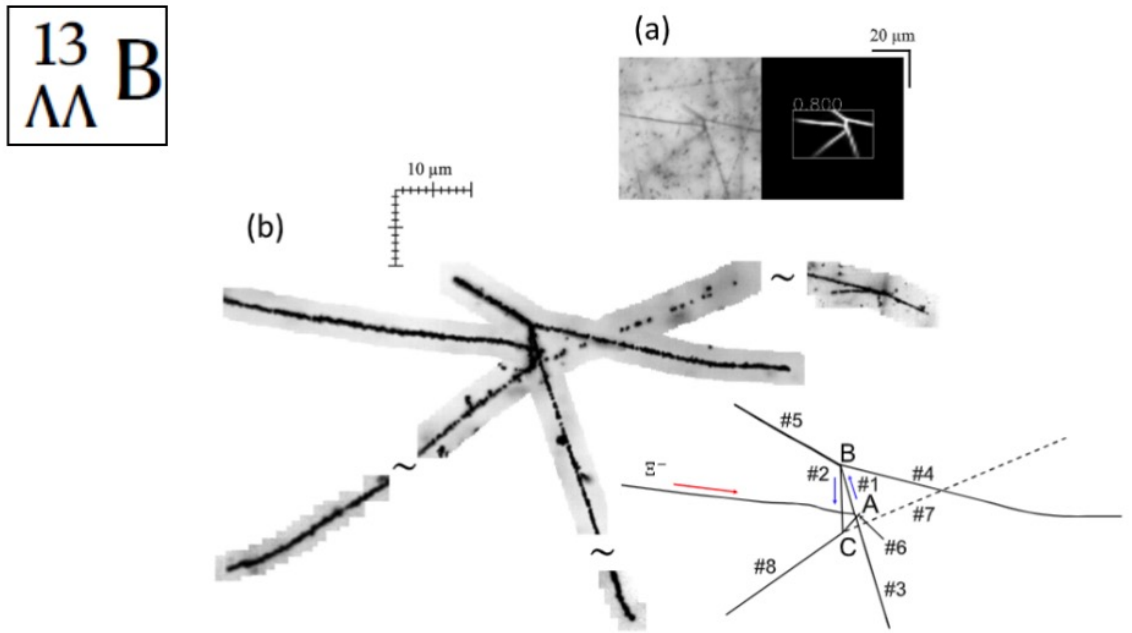


Fig. 1 | Detection of the double-Λ hypernuclear event using machine learning. **a** The detection result of the event from the machine learning analysis pipeline. The left panel depicts the input emulsion image, acquired under an optical microscope with a 20× objective lens, and the right panel presents the model's output, highlighting the event topology with a confidence score of 0.8. **b** Photograph and vertex A, producing a double-Λ hypernucleus (#1) and particle #3. Cascade decay (blue arrows) of double-Λ hypernucleus (#1) occurred at vertices B and C, with emitted particles #4 and #5 from B, and #6, #7, and #8 from C, all stopping in the emulsion. Track #7 is identified as a π^- particle, represented by a dashed line. Particle length and angle measurements are detailed in Table 1.

$$B_{\Lambda\Lambda} = 25.57 \pm 1.18(\mathrm{stat.}) \pm 0.07(\mathrm{syst.})\mathrm{MeV}$$

$$\Delta B_{\Lambda\Lambda} = 2.83 \pm 1.18(\mathrm{stat.}) \pm 0.14(\mathrm{syst.})\mathrm{MeV}$$

NAGARA(E373)	${}^{6}_{\Lambda\Lambda}\mathrm{He}$: $\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$
MINO(E07)	${}^{11}_{\Lambda\Lambda}\mathrm{Be}$: $\Delta B_{\Lambda\Lambda} = 1.87 \pm 0.37$
This event	${}^{13}_{\Lambda\Lambda}\mathrm{B}$: $\Delta B_{\Lambda\Lambda} = 2.83 \pm 1.18$

Suggesting that $\Delta B_{\Lambda\Lambda}$, $\Lambda\Lambda$ bond energy, is A dependent.

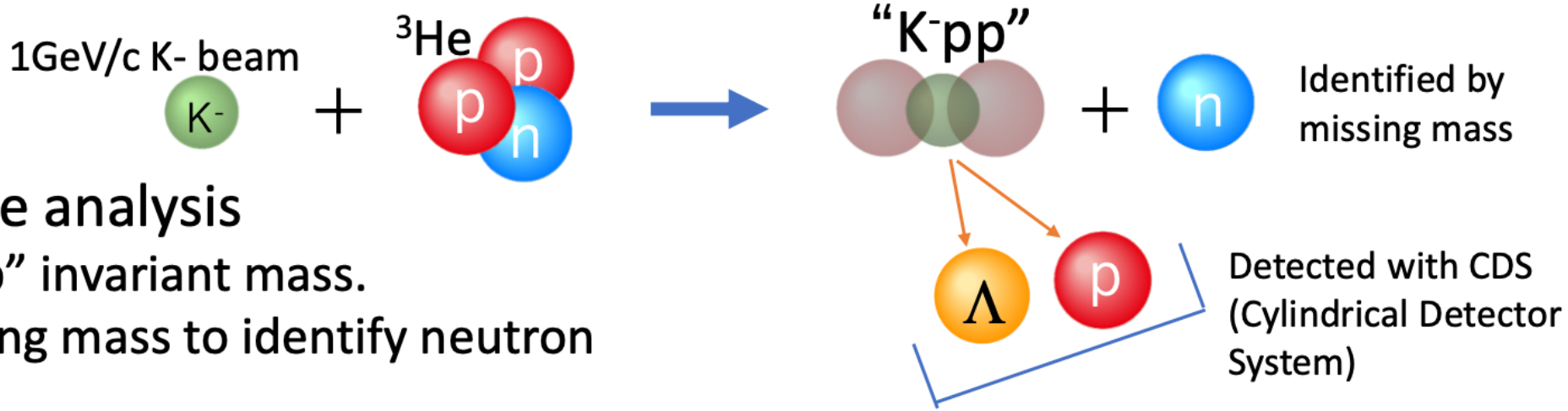
K1.8BR : J-PARC E15 – $\bar{K}NN$ ("K⁻pp")

$K : K^-$ and K^0

A search for deeply-bound kaonic states by in-flight 3He(K⁻,n)

- $\bar{K}N$ Strongly attractive in I=0. $\Lambda(1405) = \bar{K}N$ molecule
- Larger Kaonic nucleus? $\bar{K}NN$, $\bar{K}NNN$ ⋯

E. A. Veit et al.,
Phys. Rev. D 31, 1033 (1985)

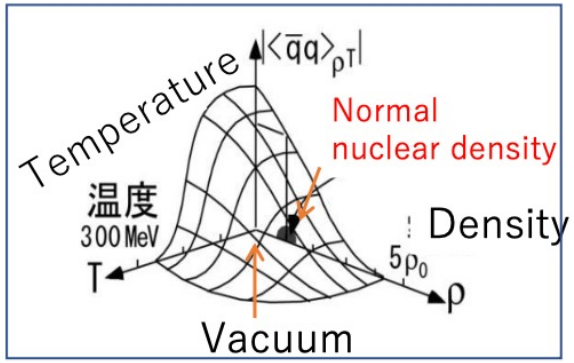


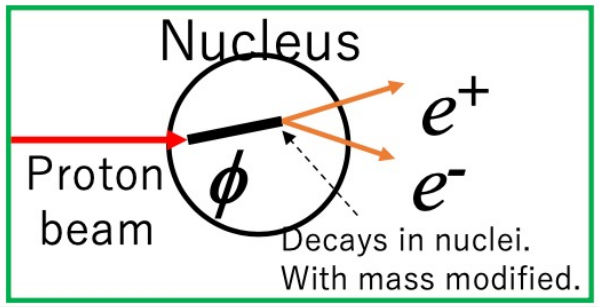
- Exclusive analysis
  - "K-pp" invariant mass.
  - Missing mass to identify neutron

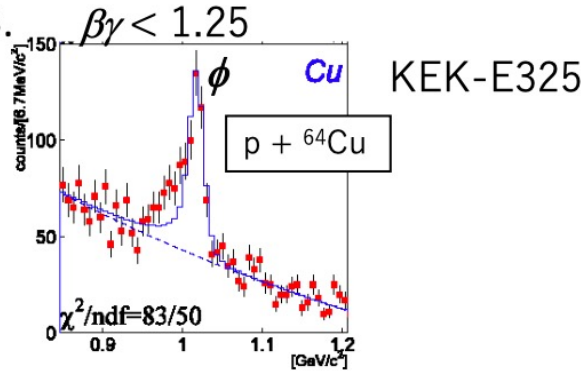
High-p : J-PARC E16 [on-going] ϕ meson in nuclei

- Spontaneous breaking of chiral symmetry plays an important role in generating hadron mass.
- Chiral symmetry breaking $\langle \bar{q}q \rangle \neq 0$ depends on density, so the hadron mass.
- Aims to measure mass modification (spectral change) in nuclear medium.
- KEK E325
  - 12GeV **p + A → ρ/ω/φ → e⁺e⁻**
  - Observed what can be interpreted as an in-medium spectral change.
    ϕ mass 3.4% reduction at ρ_0 → symmetry restored?
- J-PARC E16 experiment:
  - 30GeV **p + A → ρ/ω/φ → e⁺e⁻,** (**K⁺K⁻** E88)
  - Compared to E325, 6 times stat in 1st Run, Resolution 11→6 MeV
  - Spectrometer constructed for 1st physics run.
  - Commissioning run finished in June 2024.
  - 1st physics RUN started in FY2025.

NJL model
M. Lutz et al.
Nucl. Phys. A542,52(1992)







KEK-E325



Investigation of the $\Lambda\overline{\Lambda}$ configuration in a constituent quark model

Aaron Park

Yonsei University

Contents

- Introduction
- Baryon antibaryon configuration in a constituent quark model
- Results : $\Lambda\overline{\Lambda}$, $\Lambda_c\overline{\Lambda_c}$
- Summary

Quark model – SU(3) Flavor

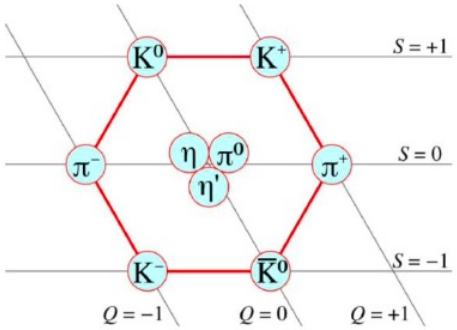


Figure 1.1: Meson nonet for spin 0.

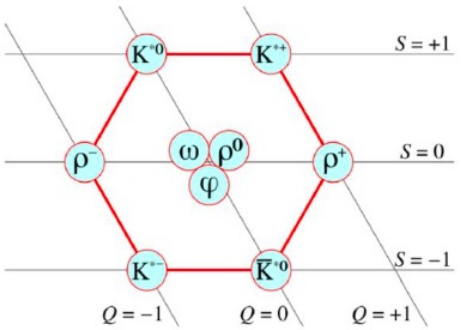


Figure 1.2: Meson nonet for spin 1.

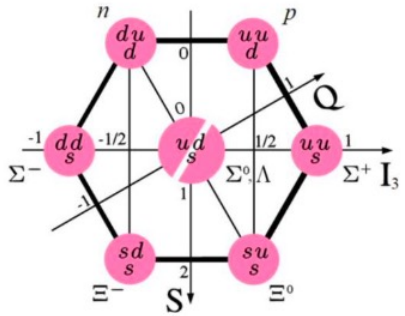


Figure 1.3: Baryon octet with spin 1/2

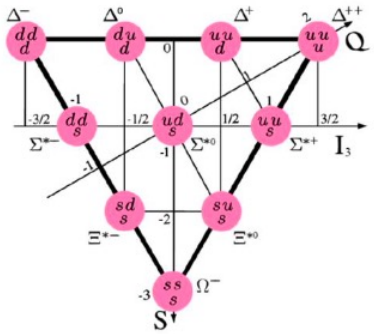
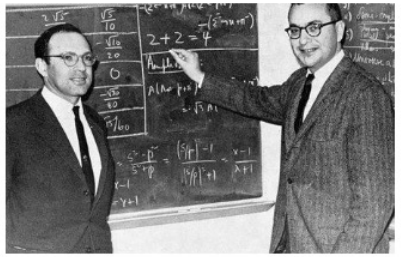


Figure 1.4: Baryon decuplet with spin 3/2



Yuval Ne'eman and Murray Gell-Mann

Mesons

$$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{8} \oplus \mathbf{1}$$

Baryons

$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{1} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{10}$$

Color state of Tetraquark ($q(1)q(2)\bar{q}(3)\bar{q}(4)$)

$$(\mathbf{3}\otimes\mathbf{3})\otimes(\bar{\mathbf{3}}\otimes\bar{\mathbf{3}}) = (\bar{\mathbf{3}}\oplus\mathbf{6})\otimes(\mathbf{3}\oplus\bar{\mathbf{6}})$$

$$= (\bar{\mathbf{3}}\otimes\mathbf{3})\oplus(\bar{\mathbf{3}}\otimes\bar{\mathbf{6}})\oplus(\mathbf{6}\otimes\mathbf{3})\oplus(\mathbf{6}\otimes\bar{\mathbf{6}})$$

$$|\bar{3}_{12}3_{34}\rangle, |6_{12}\bar{6}_{34}\rangle$$

$$(\mathbf{3}\otimes\bar{\mathbf{3}})\otimes(\mathbf{3}\otimes\bar{\mathbf{3}}) = (\mathbf{1}\oplus\mathbf{8})\otimes(\mathbf{1}\oplus\mathbf{8})$$

$$= (\mathbf{1}\otimes\mathbf{1})\oplus(\mathbf{1}\otimes\mathbf{8})\oplus(\mathbf{8}\otimes\mathbf{1})\oplus(\mathbf{8}\otimes\mathbf{8})$$

Pentaquark

$$(\mathbf{3}\otimes\mathbf{3}\otimes\mathbf{3})\otimes(\mathbf{3}\otimes\bar{\mathbf{3}}) = (\mathbf{1}\oplus\mathbf{8}\oplus\mathbf{8}\oplus\mathbf{10})\otimes(\mathbf{1}\oplus\mathbf{8})$$

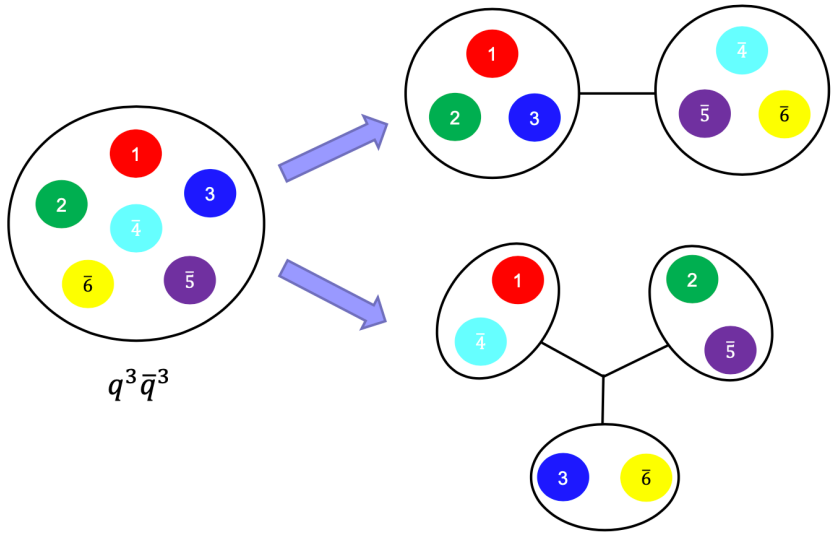
$$\Rightarrow \quad |1_{123}1_{45}\rangle, |8_{123}8_{45}\rangle, |8_{123}8_{45}\rangle$$

Dibaryon

$$(\mathbf{3}\otimes\mathbf{3}\otimes\mathbf{3})\otimes(\mathbf{3}\otimes\mathbf{3}\otimes\mathbf{3}) = (\mathbf{1}\oplus\mathbf{8}\oplus\mathbf{8}\oplus\mathbf{10})\otimes(\mathbf{1}\oplus\mathbf{8}\oplus\mathbf{8}\oplus\mathbf{10})$$

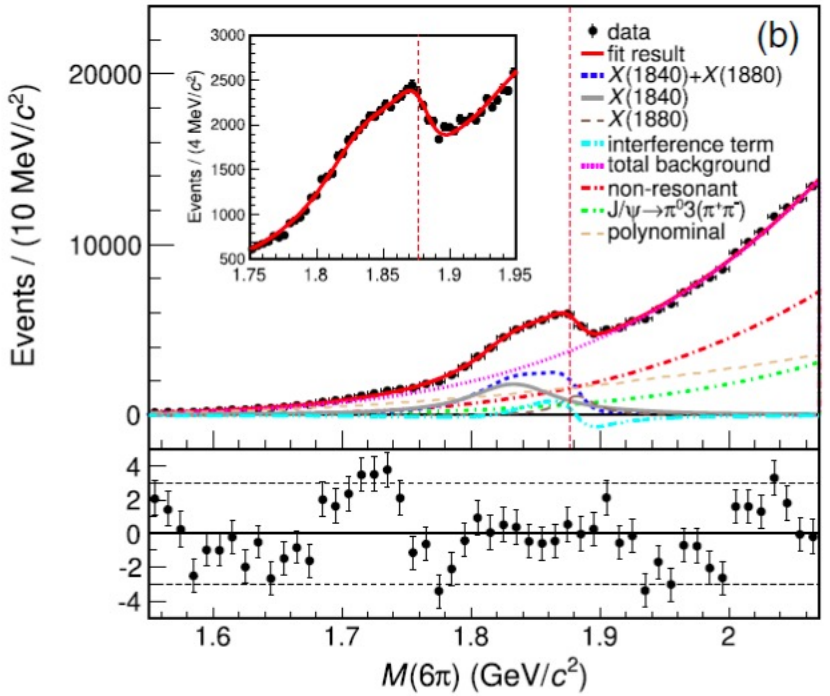
$$\Rightarrow \quad |1_{123}1_{456}\rangle, |8_{123}8_{456}\rangle, |8_{123}8_{456}\rangle, |8_{123}8_{456}\rangle, |8_{123}8_{456}\rangle$$

Baryon-antibaryon and Three-meson configurations



$q^3\bar{q}^3$

$J/\psi \to \gamma 3(\pi^+\pi^-)$



M. Ablikim et al.(BESIII Collaboration)
Phys. Rev. Lett. 132, 151901(2024)

These observations suggest a possible $p\bar{p}$ bound state.

X(1840)

$M = 1832.5 \pm 3.1 \pm 2.5\ \mathrm{MeV}/c^2$

$\Gamma = 80.7 \pm 5.2 \pm 7.7\ \mathrm{MeV}$

X(1880)

$M = 1882.1 \pm 1.7 \pm 0.7\ \mathrm{MeV}/c^2$

$\Gamma = 30.7 \pm 5.5 \pm 2.4\ \mathrm{MeV}$

Summary

- We have investigated the $\Lambda\overline{\Lambda}$ and $\Lambda_c\overline{\Lambda}_c$ states using baryon-antibaryon configuration using a constituent quark model.
- The baryon-antibaryon interaction is strongly attractive and suggests the possibility of a compact bound state at short distances for both cases.
- However, a complete description of the system requires the inclusion of the three-meson configuration and annihilation effects.

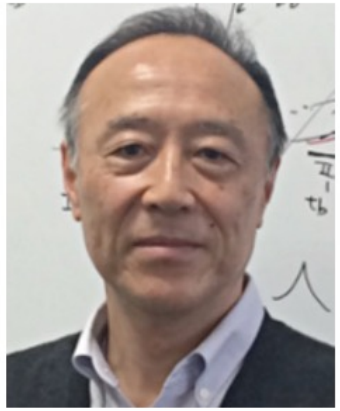
Quark-model search for hidden-charm pentaquark states

Georg Wolschin (ITP, Heidelberg University)

with

Emiko Hiyama, Atsushi Hosaka, Makoto Oka







ISMD 2026

ISMD2026_Taiwan

1. The quark-parton-model and multiquark systems
2. Searches for charmed tetra- and pentaquarks
3. **Five-body Schrödinger calculation for hidden-charm**

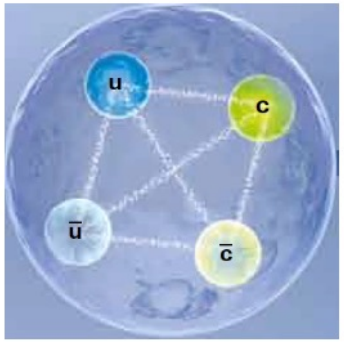
   $P^0_{c\bar{c}s} = (c\bar{c}uds)^0$ **pentaquarks**

4. Conclusion

Compact vs. molecular multiquarks

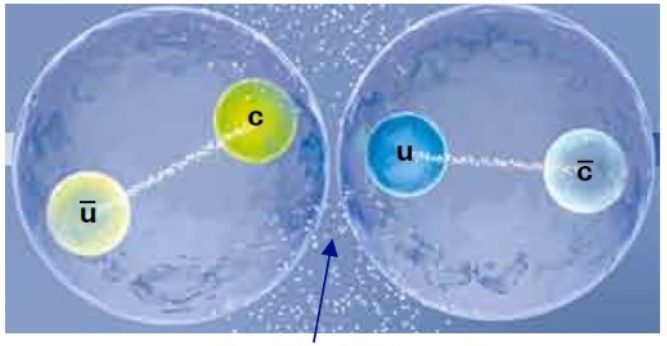
Tetraquarks

$X(3872) = (c\bar{c}u\bar{u})$

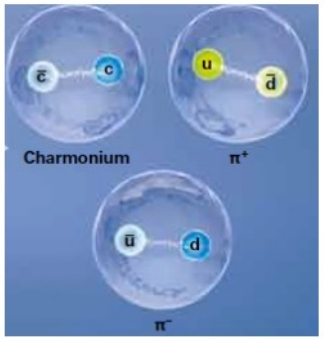


or

D⁰ meson $\overline{D^0}$ meson



decay

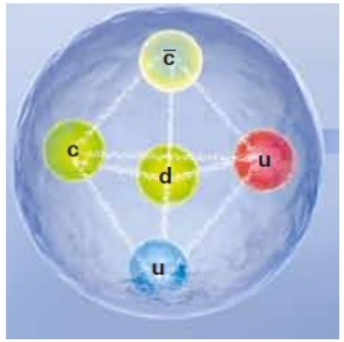


?

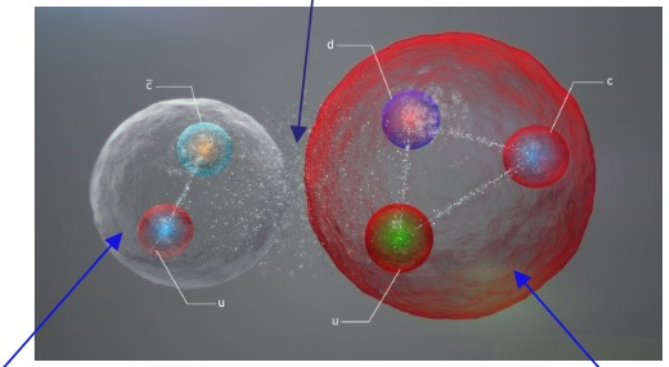
Residual interaction

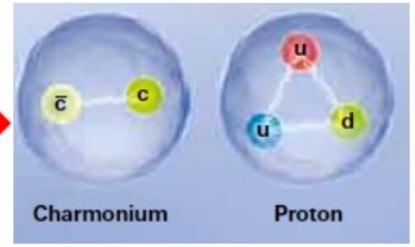
Pentaquarks

$P^{+}_{c\bar{c}} = (c\bar{c}uud)^{+}$



or





Compact multiquarks: single confinement volume

$\overline{D^0}$ meson

"Molecular" states

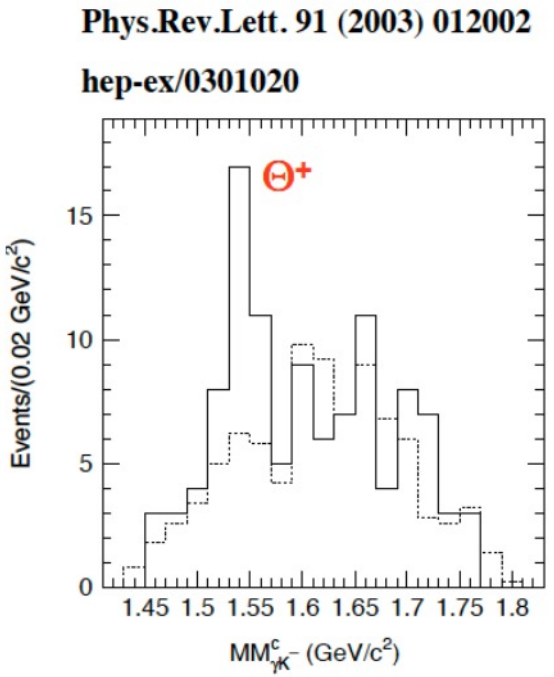
Λ_c^+ baryon

Decay products

Early searches for strange pentaquarks

- Pentaquarks are made of 4 quarks and an antiquark
- No convincing experimental evidence for many years following the 1964 ff predictions
- In 2002/3, a Japanese group (LEPS) at the synchrotron SPring-8 published evidence for the Θ^+, a pentaquark consisting of a strange antiquark and 4 quarks, $\bar{s}uudd$- followed by ~ a dozen supporting experiments worldwide.
  However, when repeated with better statistics, the evidence vanished.
- "Today, there is little belief that the Θ^+ is real, and it remains a mystery how so many experiments could have claimed statistically-significant evidence for the pentaquark",
  K.H. Hicks, Eur. Phys. J. H 37, 1–31 (2012).

- In 2025/26, new experiments are performed with an upgraded LEPS2 facility, $\gamma n \rightarrow K^- \Theta^+$
  Acta Phys. Pol. B 56, 3-A13(2025):
  so far, null result



T. Nakano et al., LEPS collaboration
(Laser Electron Photon Experiment at SPring-8)

Lifetime $\tau \approx 10^{-23}$ s

2. Searches for charmed tetra- and pentaquarks

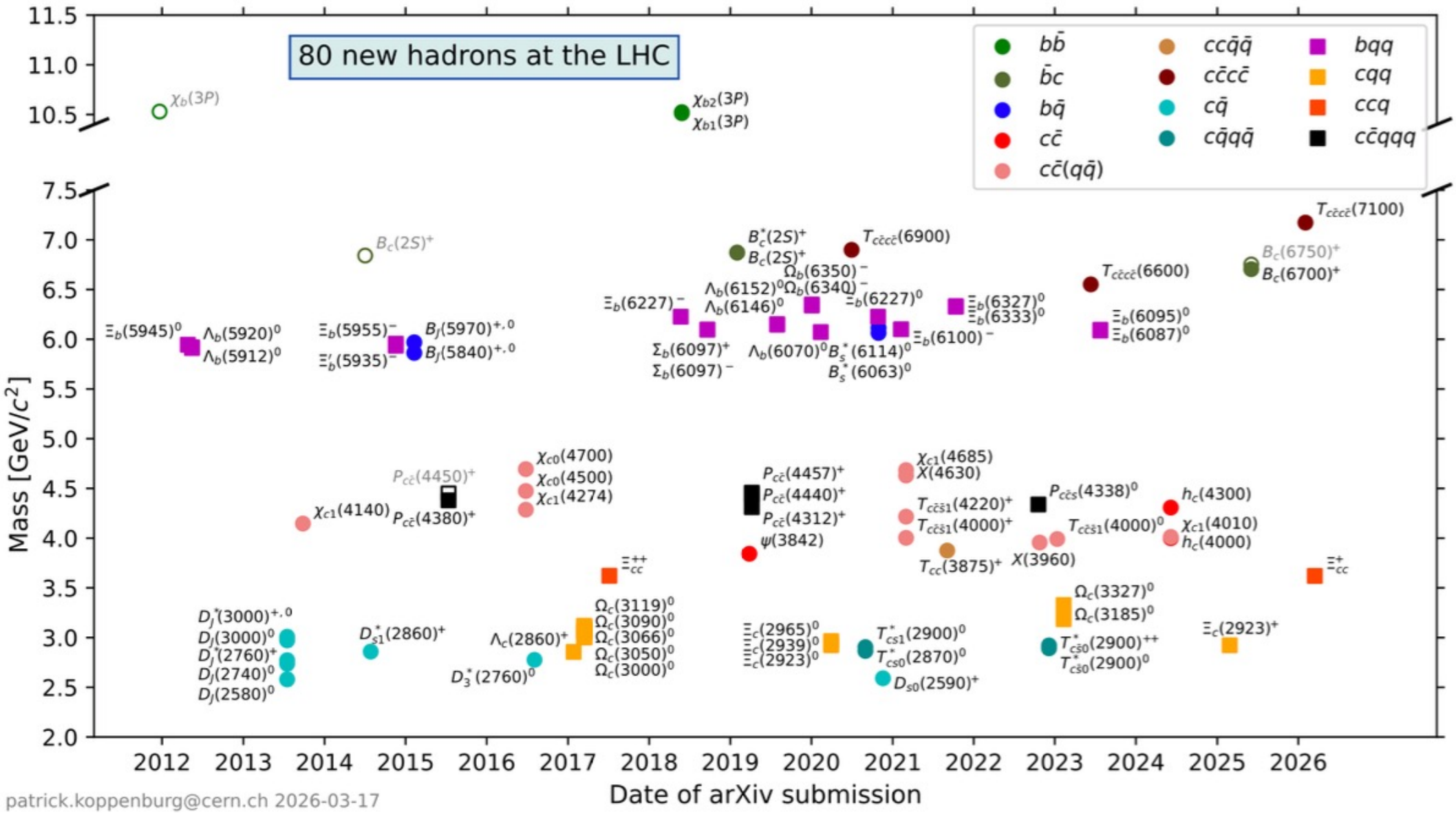
- Multiquarks could be discovered more easily when they contain the much heavier charm quarks (m ≈ 1.27 GeV) rather than strange quarks (m ≈ 93.5 MeV): Although the strong interaction is "flavor-blind" according to quantum chromodynamics (QCD), the quark mass influences the dynamics indirectly because the binding strength is proportional to the mass (for heavier quarks like charm quarks, the intrinsic Higgs-generated mass dominates).

- The expected charmed multiquarks have higher masses than strange multiquarks.

- An early success was the discovery of a tetraquark candidate, X(3872) in e^+e^- collisions in 2003 by the BELLE collaboration at KEK Tsukuba.

- In *pp* collisions at the Large Hadron Collider in Geneva, the LHCb collaboration has successfully searched for such short-living tetraquark and pentaquark states.

New hadrons discovered by LHCb



Pentaquark candidates: Mass spectrum of Λ_b^0 decay

LHCb collab., PRL **115**, 072001 (2015):
Observation of $J/\psi\ p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays

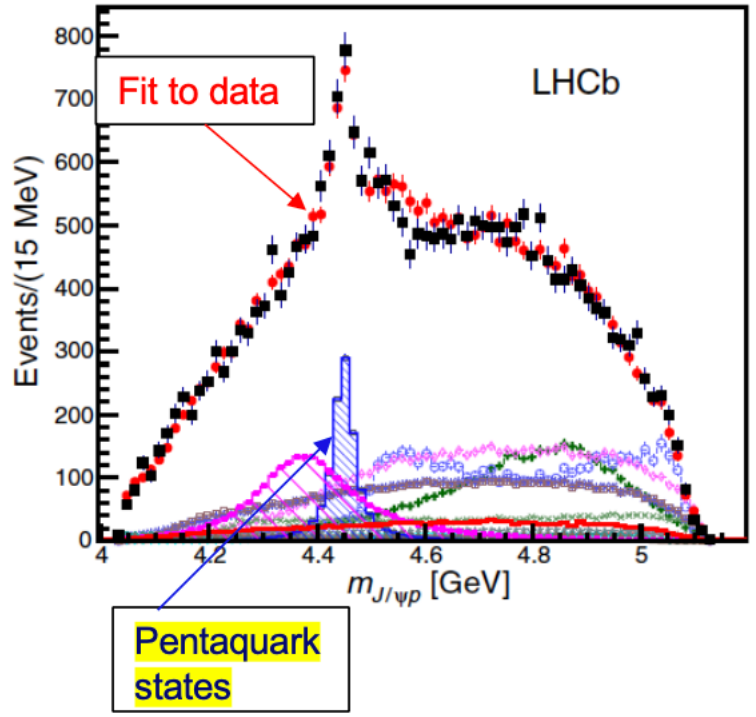
Observed in 7 and 8 TeV pp collisions

1) mass of 4380 MeV,
   width of 205 MeV

2) mass of 4449.8 MeV,
   width of 39 MeV.

Quark content: P ($c\bar{c}uud$); Λ_0^b= (udb); K^- = ($\bar{u}s$); p=(uud)
J/ψ=($c\ \bar{c}$)

$$P_{c\bar{c}}^0 = (c\bar{c}uud)^0$$



Lifetime ≈ $1.7 \cdot 10^{-23}$ s

A new sharp pentaquark resonance at LHCb in 2023: Mass spectrum of B^- decay

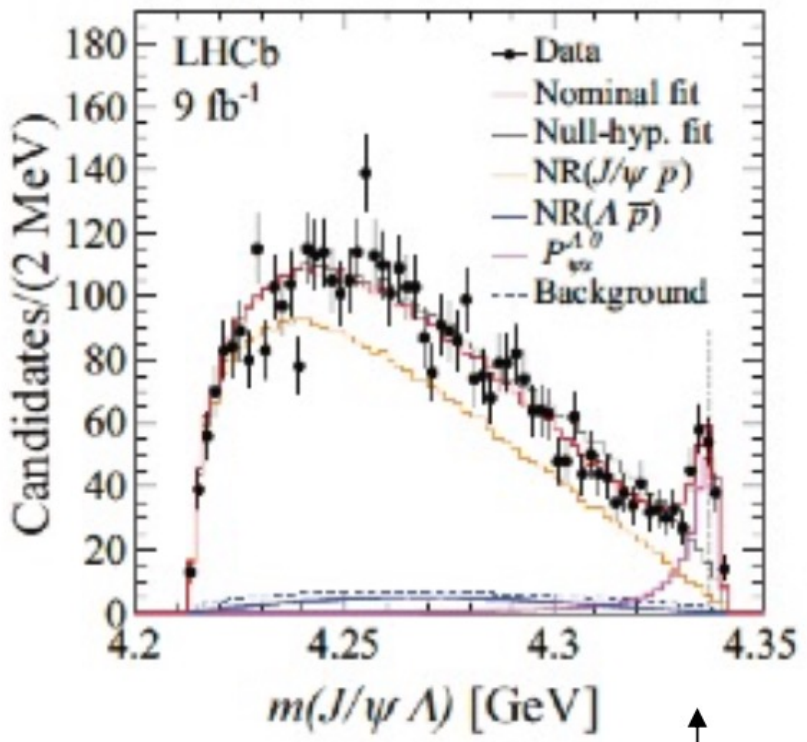
$B^- \rightarrow J/\psi\, \Lambda\, \bar{p}$
$(ub) \rightarrow (c\bar{c})(uds)(\bar{u}\bar{u}\bar{d})$

Pentaquark resonant state

$$P^0_{c\bar{c}s} = (c\bar{c}uds), J^P = 1/2^-$$

at 4338.2 MeV, $\Gamma \approx$ 7 MeV width,
lifetime $\tau \approx 10^{-22}$ s, high statistical significance
$\approx 14\sigma$

Compact multiquark $(c\bar{c}uds)^0$ or hadronic molecule (such as $\Xi_c \bar{D}$?



R. Aaij *et al.* (LHCb Collaboration), Observation of a $J/\psi\Lambda$ resonance consistent with a strange pentaquark candidate in $B^- \rightarrow J/\psi\Lambda\bar{p}$, Phys. Rev. Lett. **131**, 031901 (2023).

$P^0_{c\bar{c}s} = (c\bar{c}uds)^0$

3. Five-body Schrödinger calculation

- Experimental results must be compared with model predictions to decide whether the exotic short-lived multiquark systems are compact or molecular states.

- Compact tetra-/pentaquark states are expected to correspond to solutions of the four-/ five-body Schrödinger equation

$$(H - E)\Psi_{JM} = 0$$

with the Hamiltonian in a nonrelativistic quark model [λ_i^a(a=1…8) color SU(3) matrices]

$$H = \sum_i \left(m_i + \frac{\mathbf{p}_i^2}{2m_i} \right) - T_{cm}$$
$$- \frac{3}{16} \sum_{i<j=1}^{5} \sum_a^8 \lambda_i^a \lambda_j^a V_{ij}(\mathbf{r}_{ij})$$

- Aim: Perform a full 5-body calculation for $P^0_{c\bar{c}s} = (c\bar{c}uds)^0$ using the Gaussian Expansion Method (GEM) with updated quark-model parameters. Include not only color-singlet configurations, but also color-octet excitations.

E.Hiyama, A. Hosaka, M. Oka, G. Wolschin, Phys. Rev. D 113, 054006 (2026)

4. Conclusion

- The possible existence of short-lived multiparton states – in particular, tetraquarks and pentaquarks –, has been predicted by Zweig and Gell-Mann in 1964

- Likely candidates for tetraquarks have been found since the discovery of the X(3872) resonance by Belle in 2003. LHCb has since 2015 discovered charmed pentaquarks, with a new, statistically very significant result for ($c\bar{c}uds$) in 2023

- We have performed a five-body Schrödinger calculation to look for compact pentaquark $J^P=1/2^-$, $3/2^-$ resonances in the energy region near $P^0_{c\bar{c}s} = (c\bar{c}uds)^0$, but found none

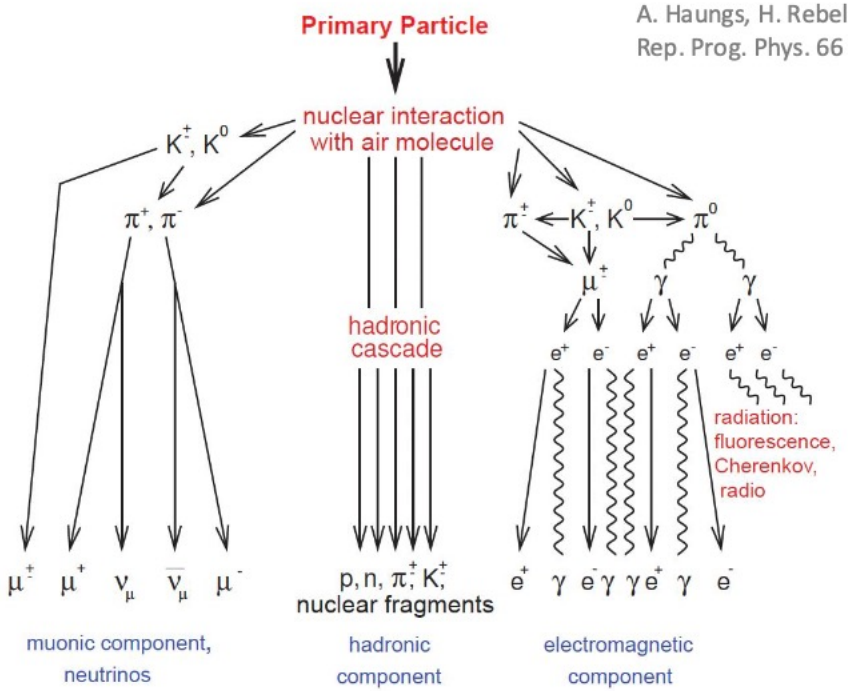
- This is indirect evidence for a molecular nature of the pentaquarks found experimentally by LHCb. To produce compact pentaquarks, *b*-quarks may be necessary, such as $P^+_{b\bar{b}usc} = (b\bar{b}usc)^+$. However, threshold effects may prevent this.

Recent Results and New Developments from the
Telescope Array Experiment

Kozo Fujisue
Academia Sinica Institute of Physics (ASIoP)

The Telescope Array Project is a ground-based cosmic-ray observatory located in Millard County, Utah, USA, designed to detect and study ultra-high-energy cosmic rays (UHECRs)

Schematic view of air shower

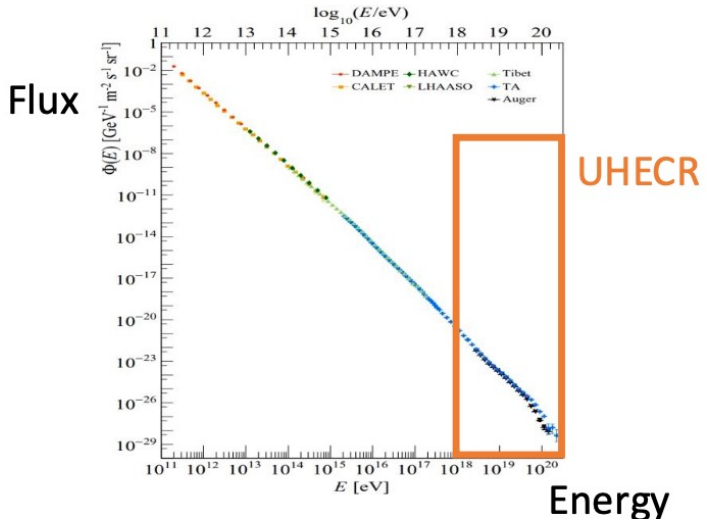


- High energy cosmic ray interacts with atmospheric nuclear and generates particle cascade (extensive air shower)

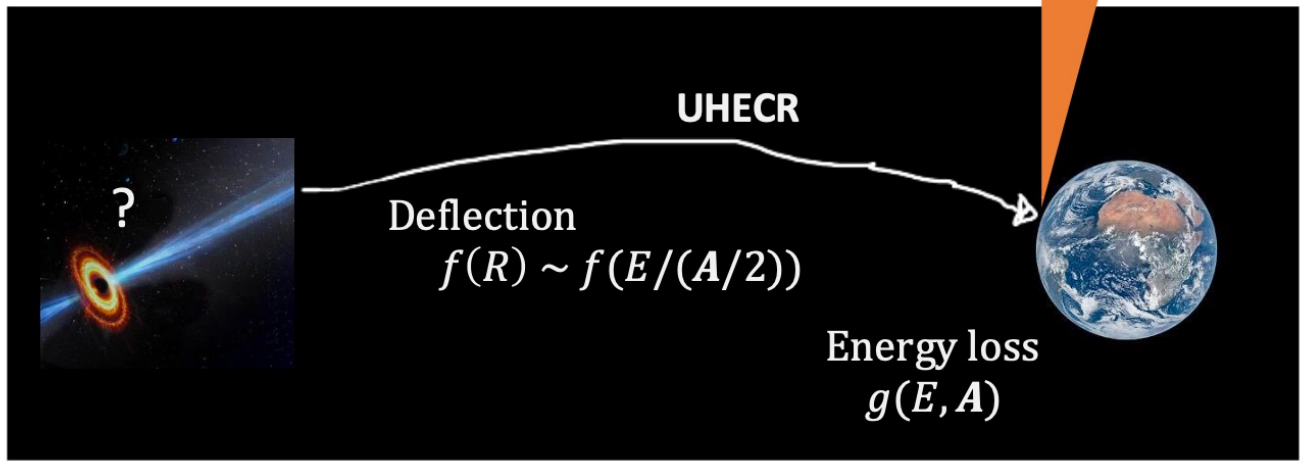
  → Detects it at ground, and reconstruct the energy, direction, (and mass) of cosmic ray

Ultra-high-energy cosmic rays (UHECRs) and challenges

- The **highest-energy particles (E > 10^{18} eV)** in the Universe.
  - What are their origins? How do they obtain energies?
    - The primary goals of the **Telescope Array (TA)** experiment.
- Challenges to understand the nature of UHECR.
  - Deflected by magnetic fields
    → Energy + charge (**mass**, $\boldsymbol{A}$) measurement is important
  - Very rare: $<$ 1 particle / 100 km^2 / year (> 10^{20} eV)
    → Need a large area (> 100 km^2)







TA experiment – hybrid detection of UHECR

- Located in Utah (USA) @ 1380 m (a.s.l.), observing Northern sky since 2008.

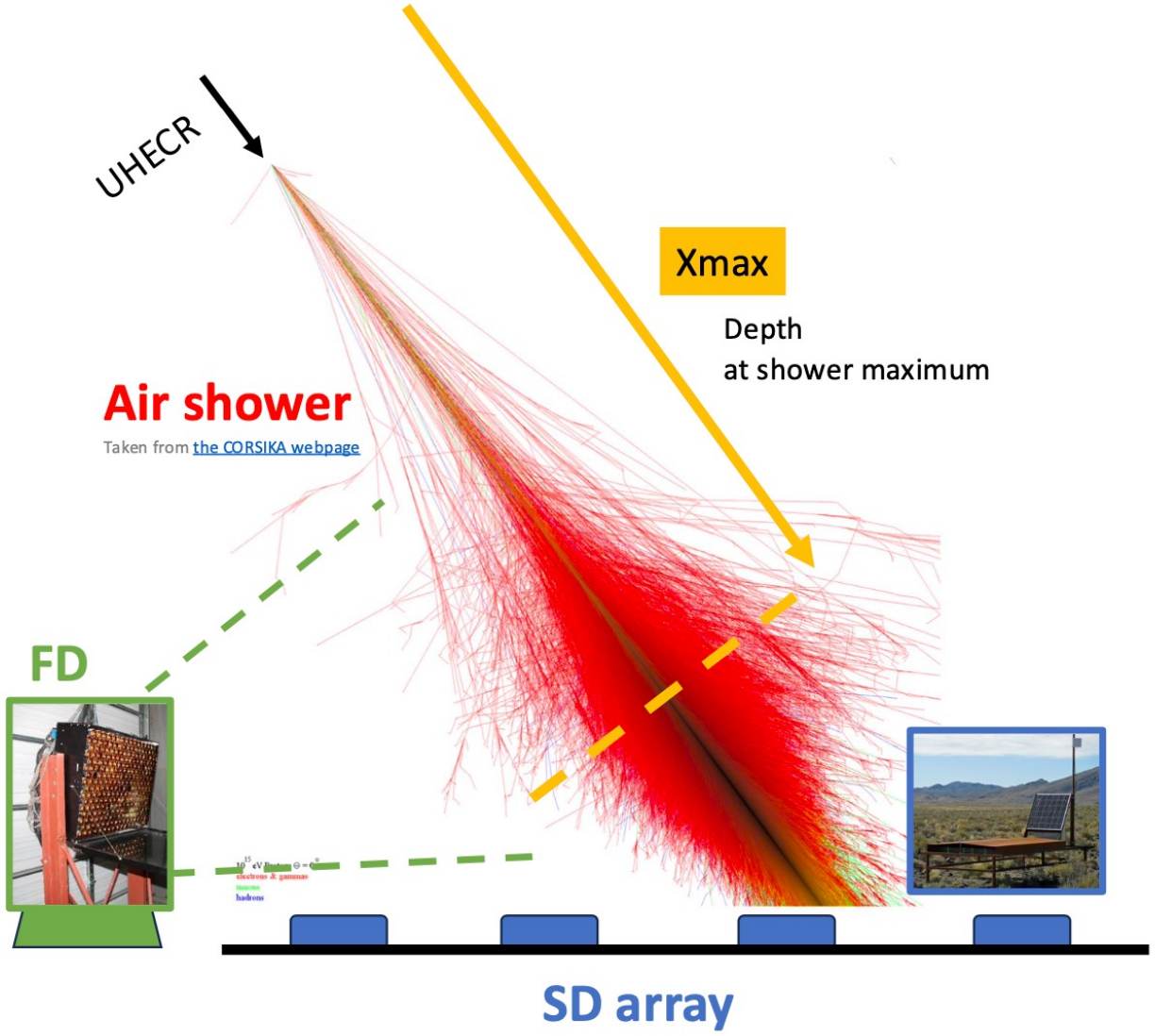


Surface Detector (SD)



Fluorescence detector (FD)

Detection of UHECR via air shower



Surface Detector (SD) array:
Observes **lateral distribution** of air showers
(**Electromagnetic** + **hadronic** components)

- Hit timing → arrival direction
- Signal size → energy

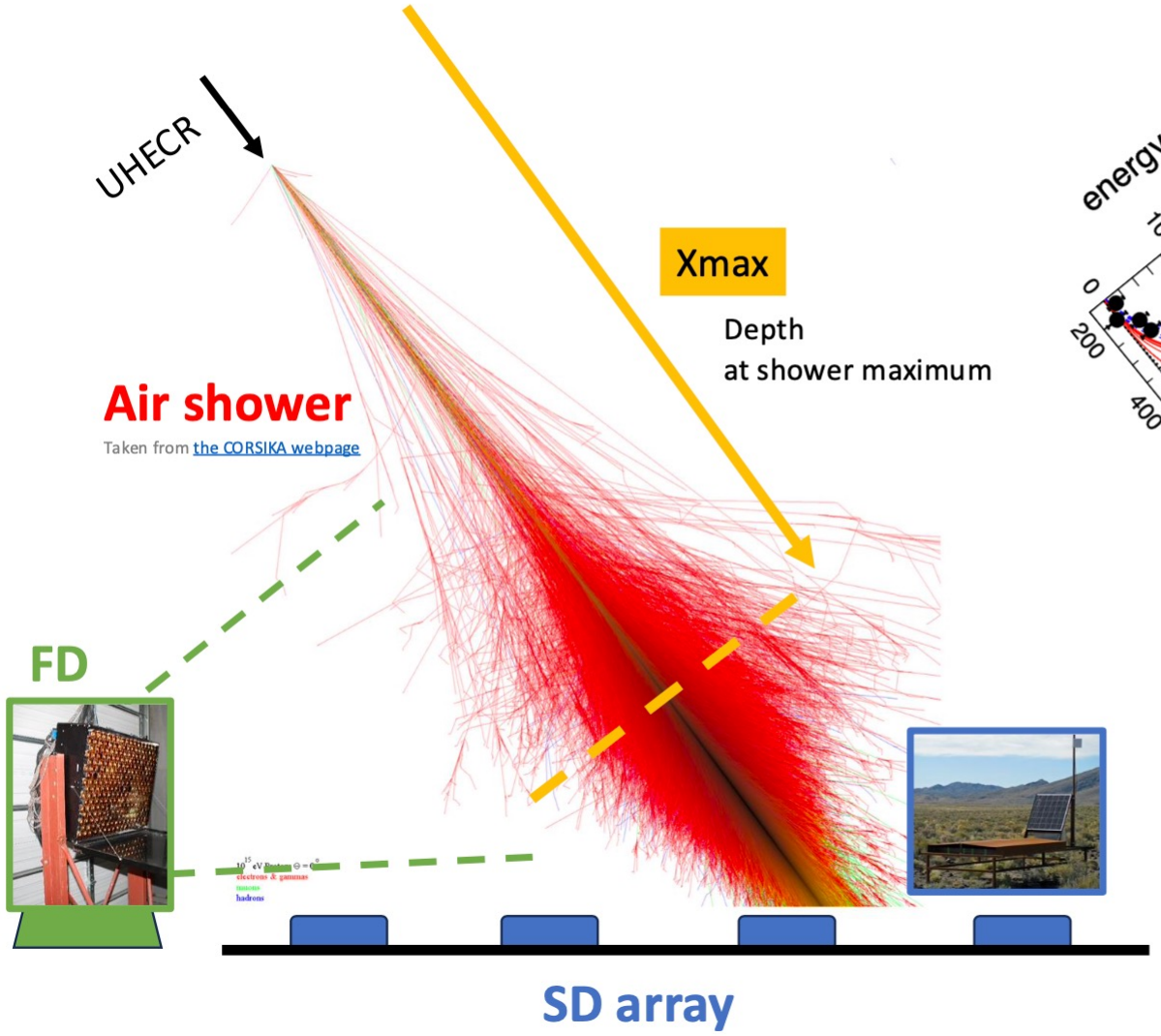
Fluorescence detector (FD):
Observes **longitudinal profile** of air showers
(**Electromagnetic** component)

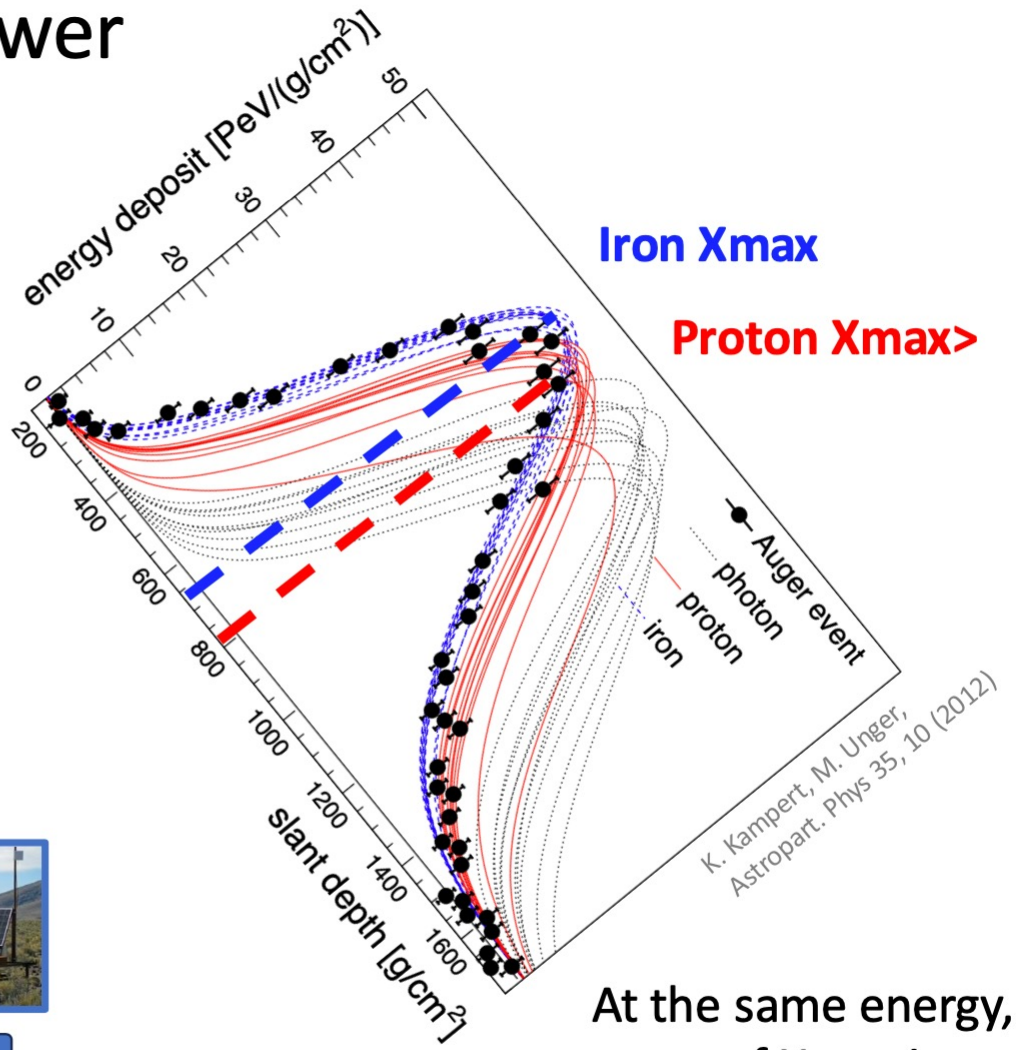
- Timing and geometry → arrival direction
- Nearly **calorimetric** estimation of energy
- **Mass** sensitive: Xmax

- High energy cosmic ray interacts with atmospheric nucleus and generates particle cascade (extensive air shower)

  → Detects it at ground, and reconstruct the energy, direction, (and mass) of cosmic ray

Detection of UHECR via air shower

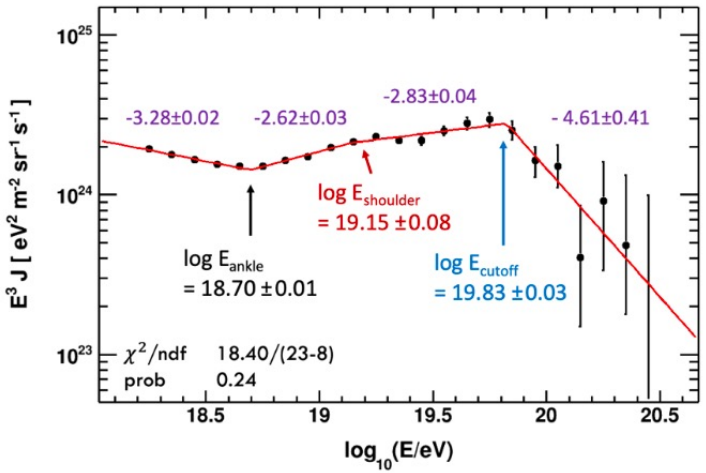




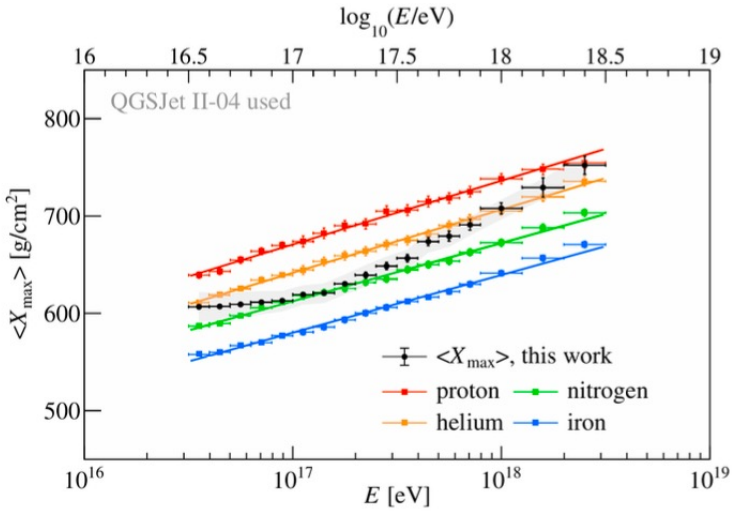
At the same energy, mean of Xmax is **deeper for lighter mass**.

Key observables

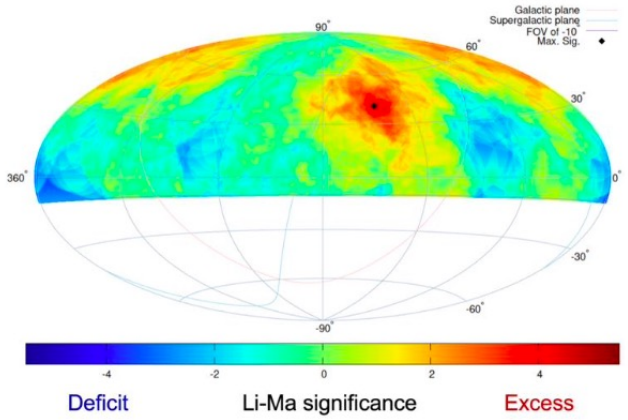
Energy spectrum



Mass composition



Arrival direction

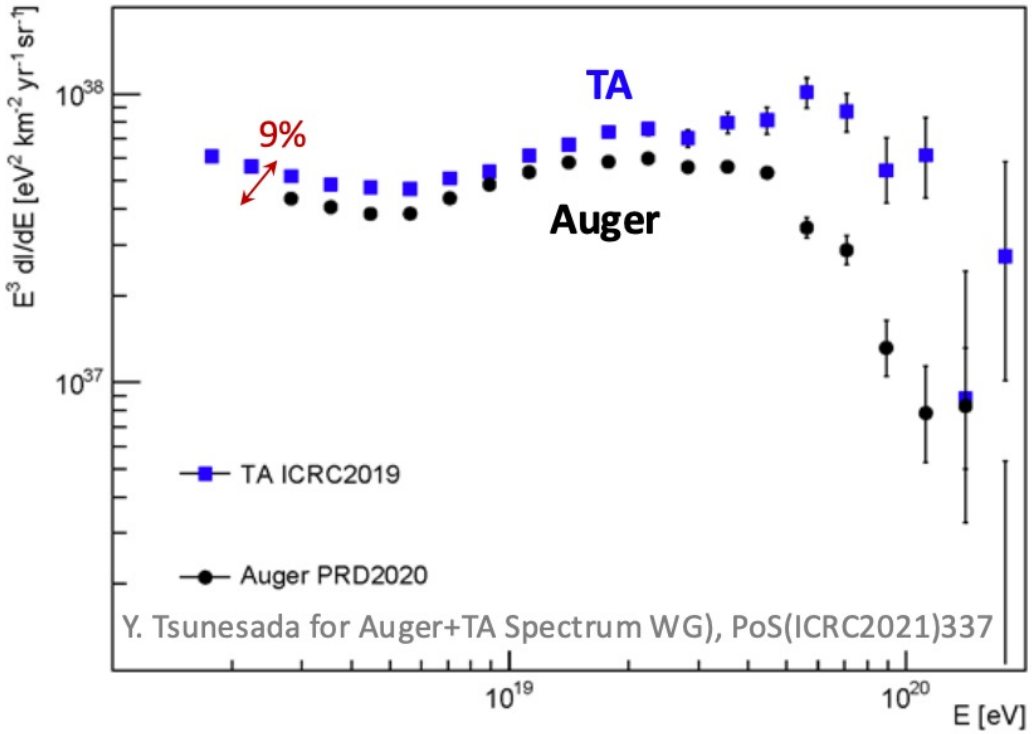


This talk focuses on **recent results** and **new developments** regarding the **energy spectrum** and **mass composition** from TA (with an emphasis on mass composition).

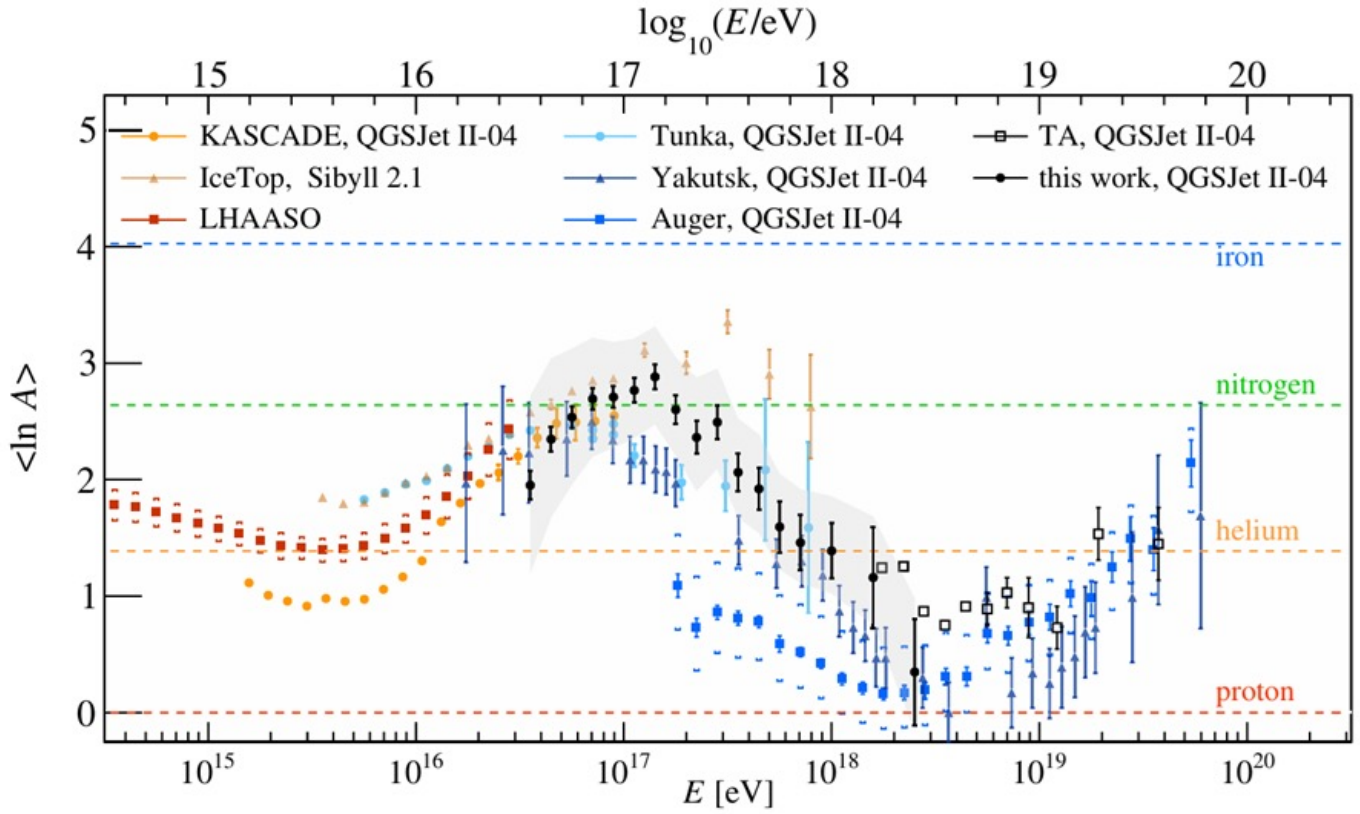
and more

Energy spectrum





- The discrepancy between spectra observed by TA and Pierre Auger Observatory.
  - The overall difference can be explained by their energy-scale uncertainties (21%, 14%).
  - The highest-energy region difference:
    - Experimental systematics?
    - Astrophysical origin?
      - TA sees Northern sky, Auger sees Southern sky
      - TA observes declination dependence of the energy spectrum. TA, arXiv:2406.08612
- The joint Auger–TA working group is investigating this.



Summary

- The Telescope Array (TA) experiment has been detecting cosmic rays over five orders of magnitude in energy.
- To estimate mass-composition with greater statistical power with SD data, machine-learning reconstruction has been developed.
- A new Bayesian framework has been developed to estimate the spectrum and mass composition using SD data, simultaneously calibrating the SD energy with the calorimetric FD energy.

Constraints on forward hadron production in proton-air interactions at √s ~ 100 TeV from the Pierre Auger Observatory

Pierre Auger Collaboration, arXiv:2607.22323

Miguel Alexandre Martins[1,*] for the Pierre Auger Collaboration[2,**]

[1]Institute of Physics of the Czech Academy of Sciences, Prague, Czechia

[2]Observatory Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina

54th International Symposium on Multiparticle Dynamics

Chungli, Taiwan August 20, 2026

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**spokespersons@auger.org

FZU Institute of Physics of the Czech Academy of Sciences

ISMD 2026

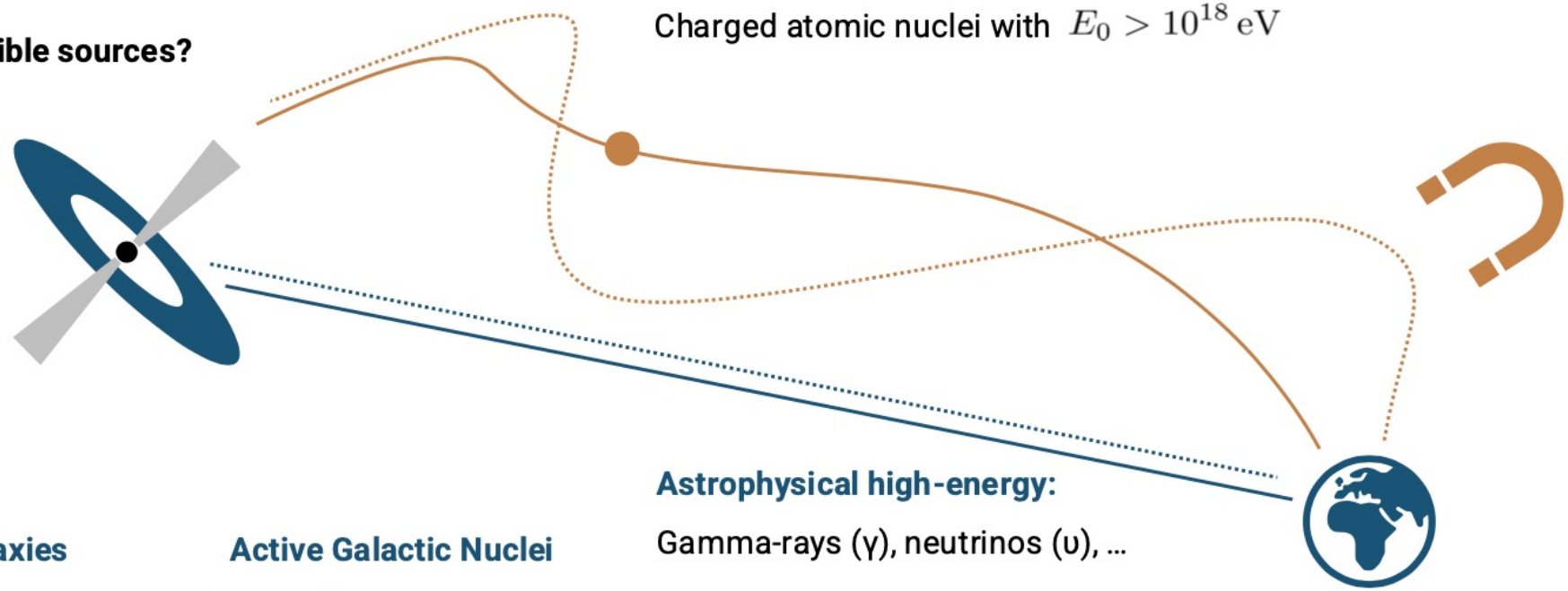
PIERRE AUGER OBSERVATORY

Ultra-high-energy cosmic rays

Ultra-high-energy cosmic rays (UHECRs):

Charged atomic nuclei with $E_0 > 10^{18}\,\mathrm{eV}$

Possible sources?



Astrophysical high-energy:

Gamma-rays (γ), neutrinos (υ), …

Starburst Galaxies



Active Galactic Nuclei



Open questions:

1. What is the mass composition of UHECRs
2. What are the sources of UHECRs
3. What are the acceleration mechanisms

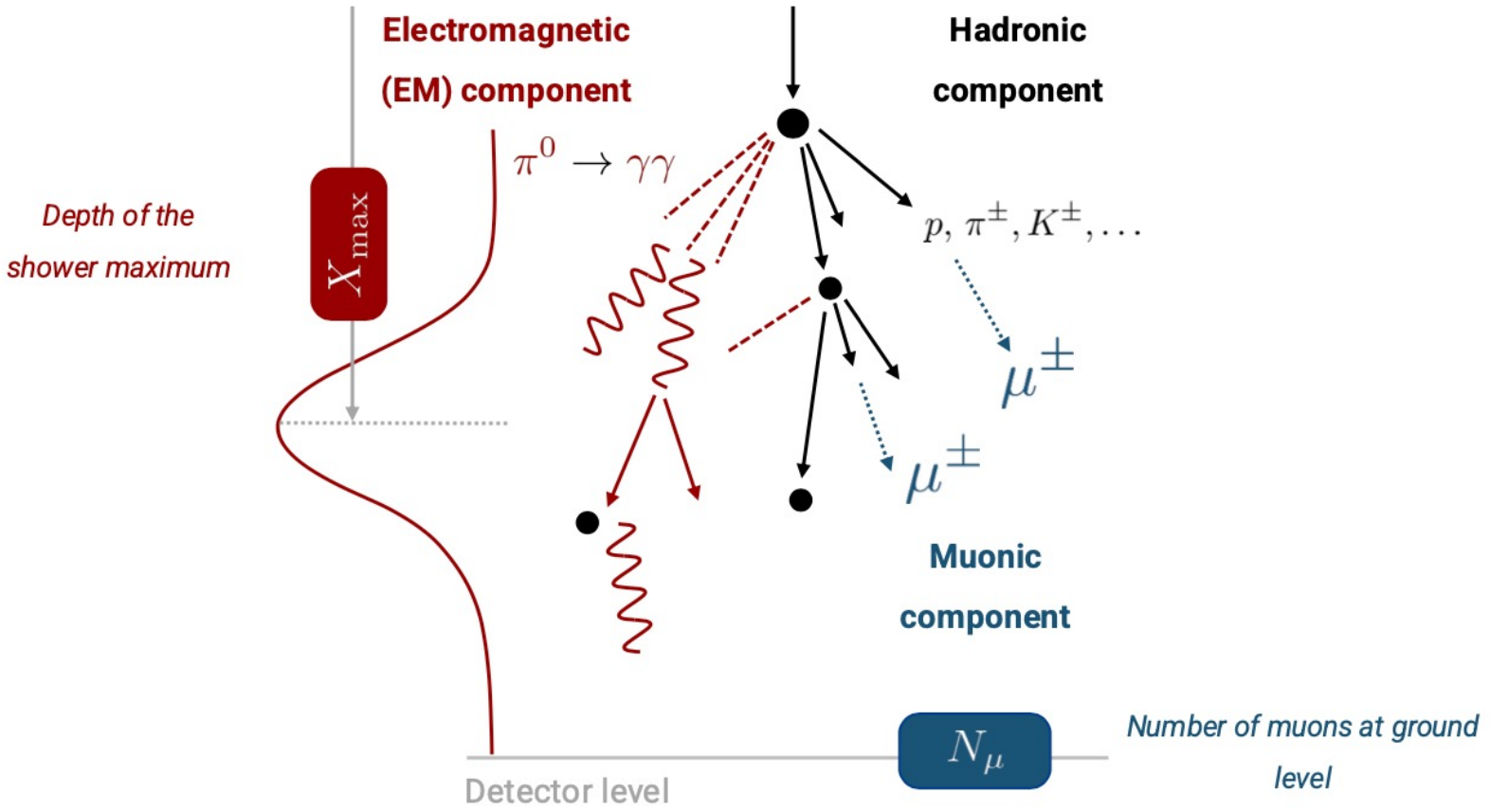
Starburst Galaxies

Галактики со вспышкой звездообразования — это особый класс галактик, в которых новые звёзды рождаются с аномально высокой скоростью. В спокойных галактиках за год формируется около 1–3 солнечных масс новых звёзд, в starburst этот показатель может составлять **даже до тысяч солнечных масс в год**

Active Galactic Nuclei

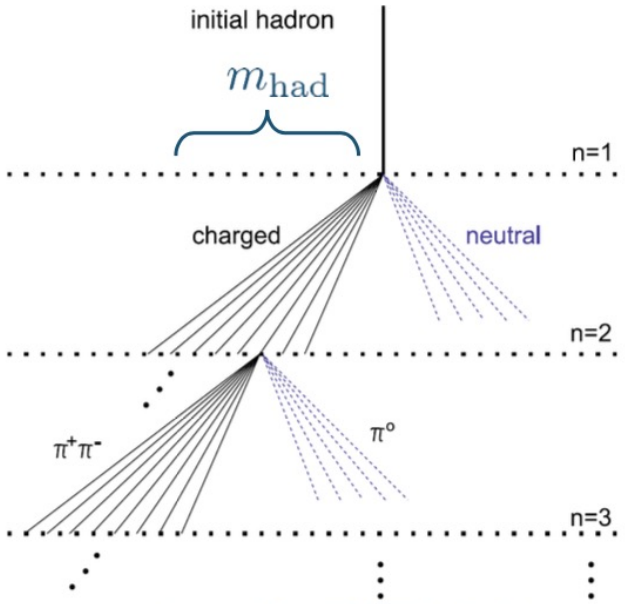
Активные ядра галактик (AGN) — это компактные центральные области некоторых галактик, которые излучают колоссальное количество энергии во всех диапазонах электромагнитного спектра (от радиоволн и инфракрасного света до рентгеновского и гамма-излучения), часто превосходя суммарный свет всех звезд своей галактики.

Air-shower observables



1. What information can be derived from X_{max} and N_{μ} measurements?
2. How do we measure them?

Heitler-Matthews model: relating X_{max} and N_μ with UHECR properties



Adapted from: *Astropart.Phys. 22 (2005) 387-397*

Applying the **Heitler-Matthews framework for proton showers** under several assumptions (*see backup*):

$$N_\mu \propto \left(\frac{E_0}{\xi_c^\pi}\right)^\beta \qquad X_{\max} \propto \ln\left(\frac{E_0}{3m_{\mathrm{had}}\xi_c^e}\right)$$

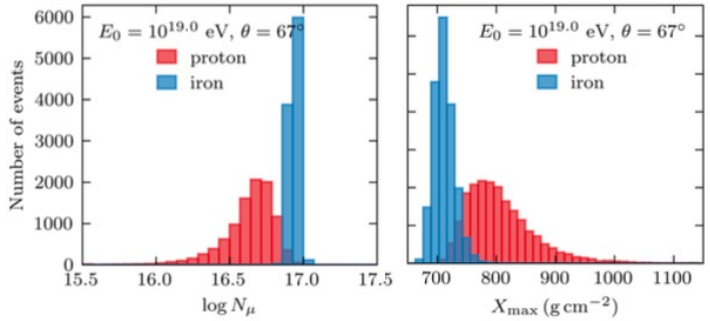
Superposition principle

E_0 ⟺ $\frac{E_0}{A}$ … $\frac{E_0}{A}$

1 2 3 … A

Mass number of UHECR

$$N_\mu(A) \propto A^{1-\beta} N_\mu(1) \qquad X_{\max}(A) - X_{\max}(1) \propto -\ln A$$



X_{max} and **N_μ** are proxies of cosmic-ray **mass number (A) + energy (E_0)**. **BUT: proper primary mass inference** ⟹ detailed air-shower simulations!

Data interpretation: the issue with Hadronic Interaction Models

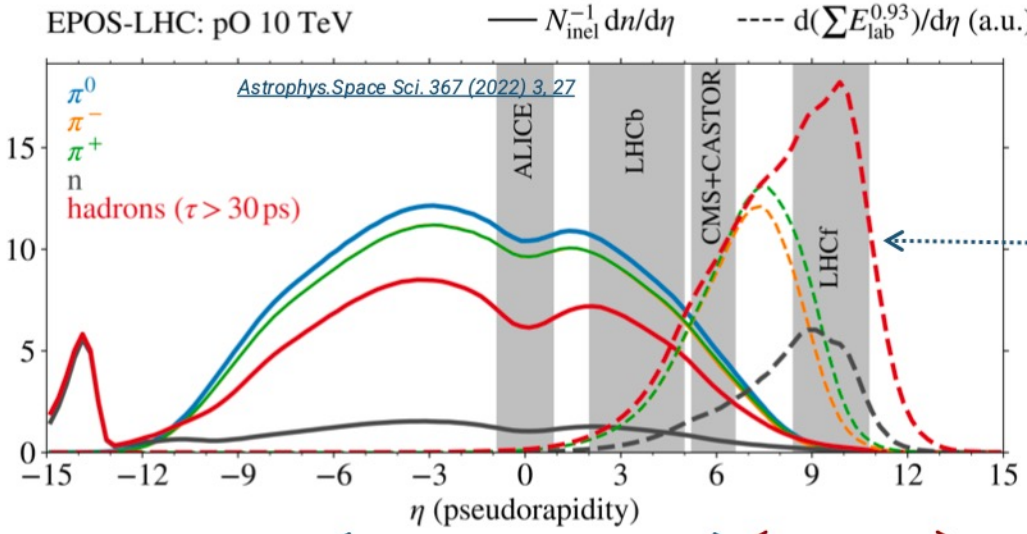
Accurate description of air-showers ⟹ calculating:

1. Particle production in hadronic interactions
2. Interaction rates in atmosphere

Calculations cannot be done from 1st principles using perturbative QCD

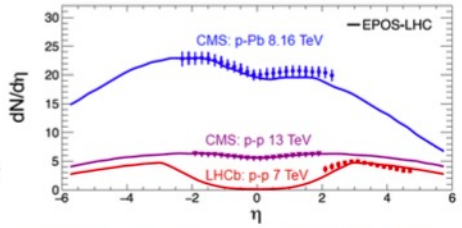
Simulated with **phenomenological hadronic interaction models** **tuned to collider data**:
EPOS LHC-R[1], QGSJET-III.01[2], SIBYLL2.3e[3]

[1]T. Pierog, K. Werner, PoS(ICRC2025)358
[2]S. Ostapchenko, *Phys.Rev.D* 109 (2024) 3, 034002
[3]F. Riehn et al., *Phys.Rev.D* 102 (2020) 6, 063002



Peaks of energy flow in far **forward region** ⟹ **relevant kinematic region** for air-showers

Collider data on charged hadron production (now for **p-O collisions*** also!)



CERN Yellow Rep.Monogr. 7 (2019) 1159-1410

BUT we need data here!

Extrapolation into relevant phase-space ⟹ **inconsistent** + **unprecise** inference of the primary composition!

*ATLAS Collaboration, arXiv:2604.05512

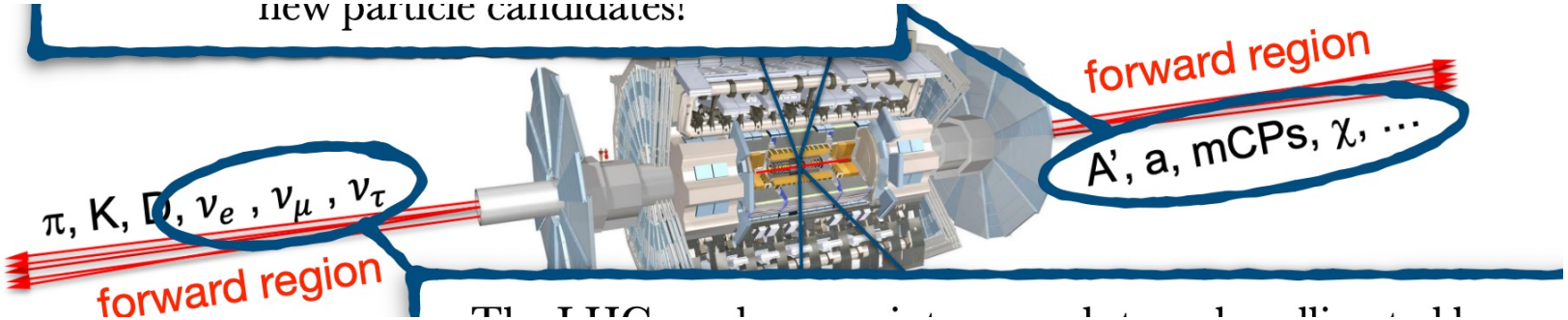
Conclusions

1. There is a set of universal relations between X_{max} and multiparticle production variables of the primary interaction
2. The X_{max} scale favored by Auger data can be explained by increasing the fraction of hadronic energy in proton-air interactions and shifting the differential energy flow into hadrons towards higher pseudo-rapidity (increase of diffractive cross-section?)
3. The increased fraction of hadronic energy is ~5% consistent with cumulative origin of the Muon Puzzle!
4. **First time that air-shower data can be interpreted in terms of modified particle production in proton-air interactions at $\sqrt{s}$~100 TeV!** e-Print: 2607.22323 [hep-ex]

High-Energy Neutrinos at the LHC

Dennis Soldin (University of Utah)

- The LHC produces a huge number of hadrons in the forward direction: $10^{17}\pi^0$, $10^{16}\eta$, 10^{15} D, ..., within 1 mrad of the beam in Run 3 (low p_T but large energy!
- What opportunities are we currently missing from a lack of coverage off far-forward physics?
- These particles escape down the beam pipe and remain undetected!
- Indeed, the existing big LHC detectors are perfectly designed NOT to see them...

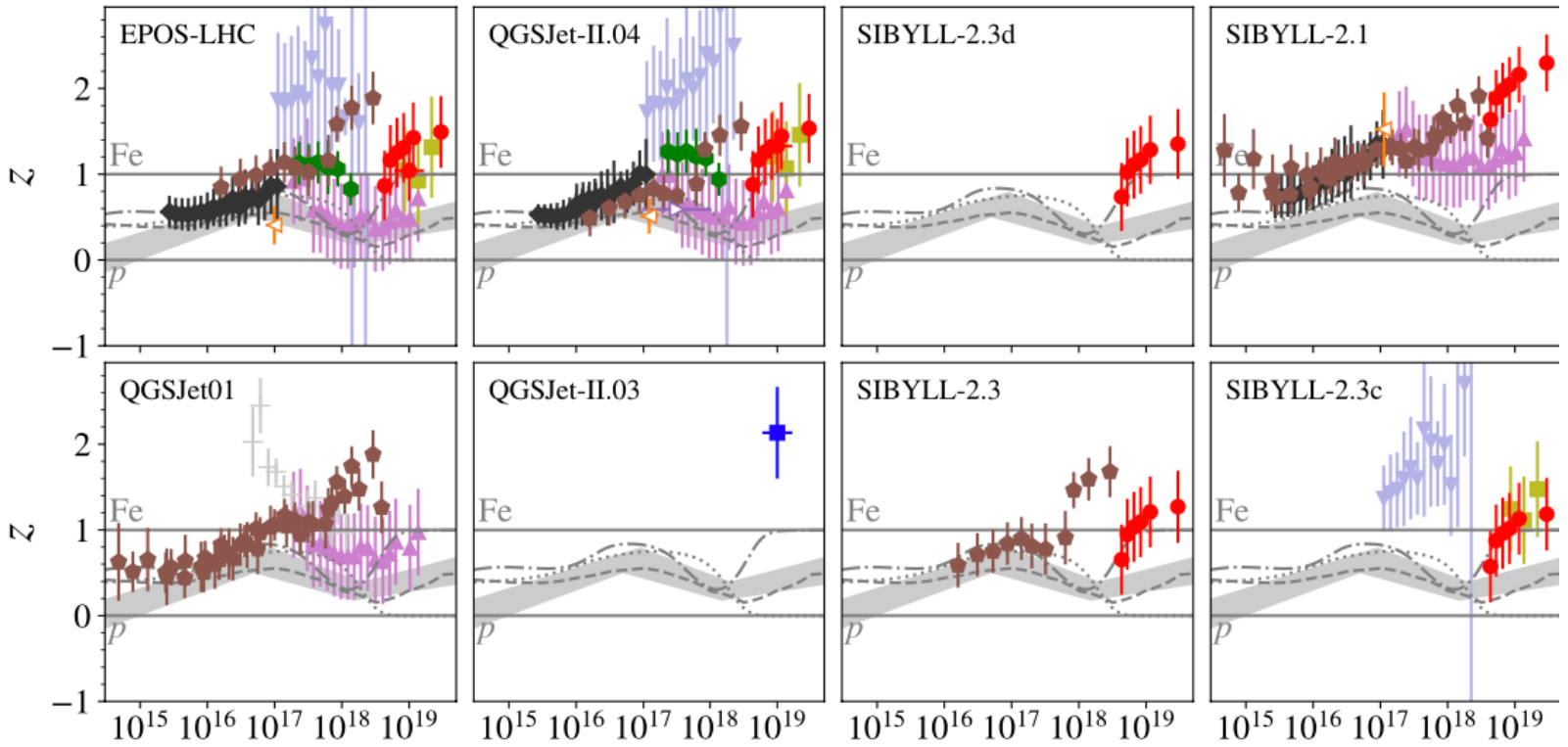


The Muon Puzzle

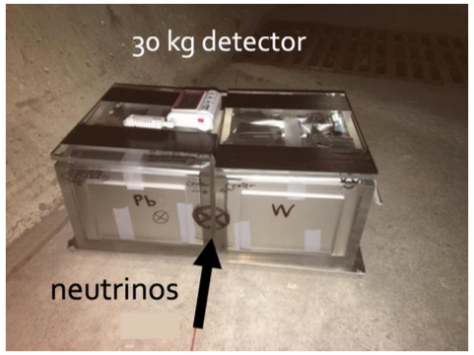
- EAS measurements:
  - ~30% more muons observed than expected at the highest energies!
- z-scale:

$$z = \frac{\ln(N_\mu) - \ln(N_{\mu,\mathrm{p}})}{\ln(N_{\mu,\mathrm{Fe}}) - \ln(N_{\mu,\mathrm{p}})}$$

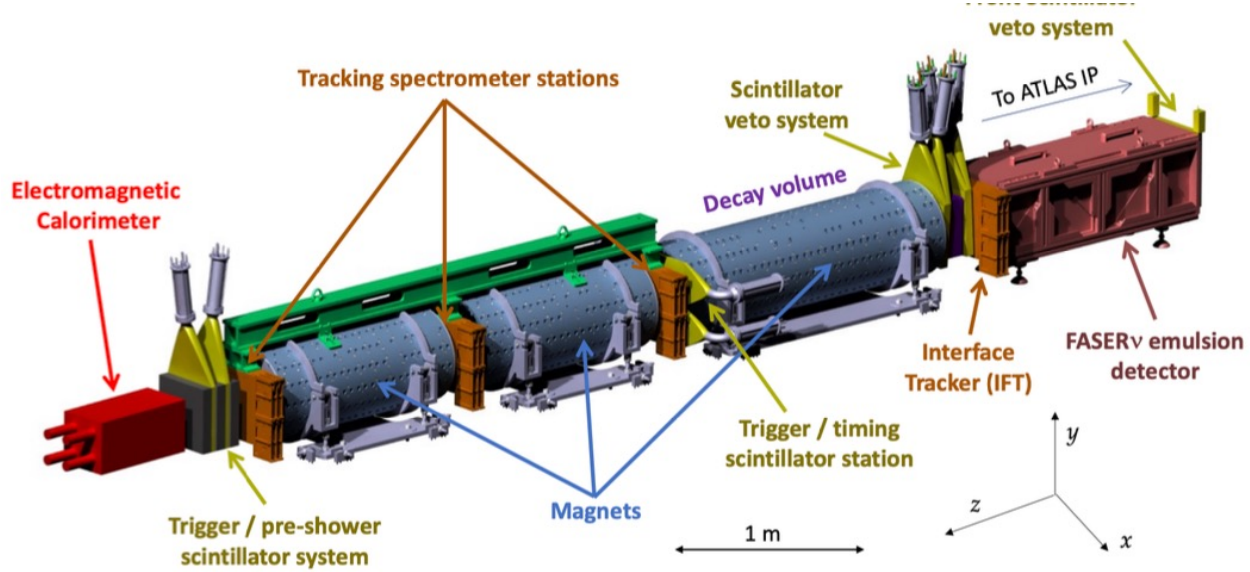
  - $z = 0$: proton
  - $z = 1$: iron
- Large uncertainties in EAS measurements!



In 2018:
FASERν pilot detector
Suitcase size, 4 weeks of data
Costs: $0 (recycled parts)
6 TeV neutrino candidates
[FASER Collaboration,
Phys. Rev. D 104 (2021)]

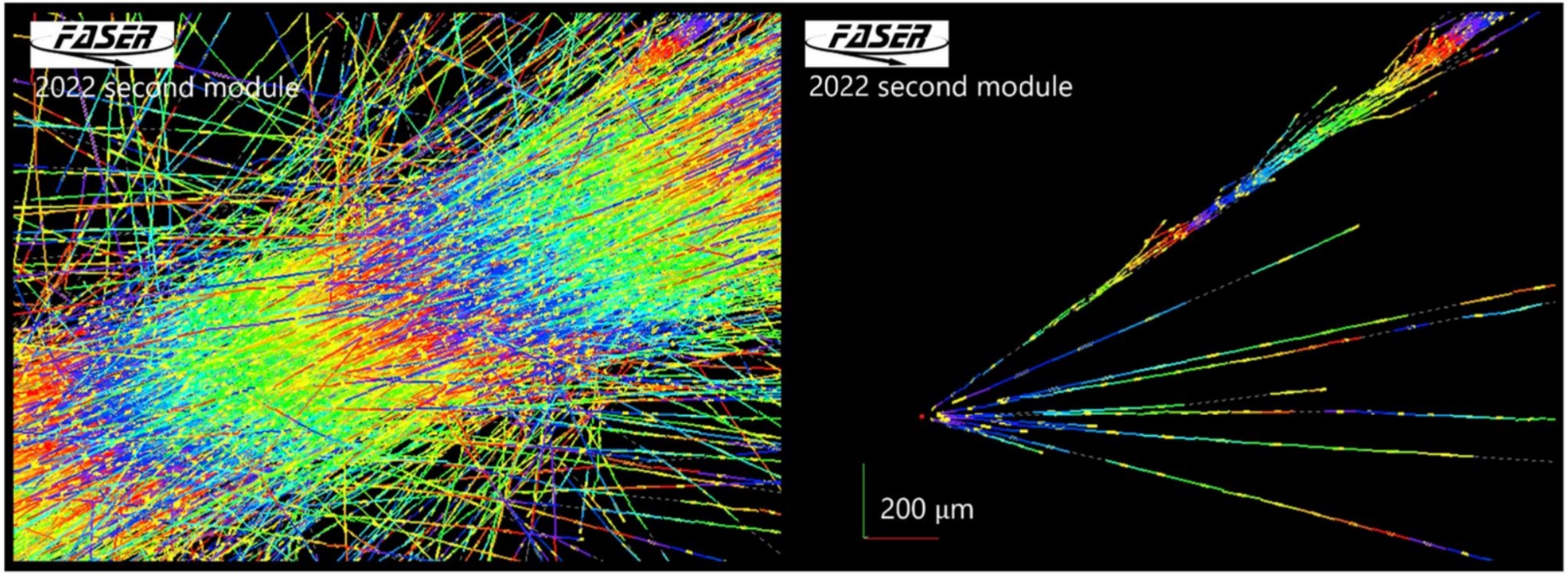


Multiple electronic detector components.
Veto scintillators. Tracking spectrometer
(30μm position resolution).
Electromagnetic calorimeter
730 tungsten plates, interleaved with
nuclear-emulsion films 1,100 kg target
mass.

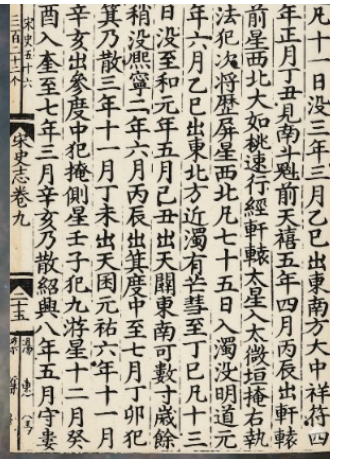


First Collider Neutrinos!

- First search for charged current ν_e and ν_μ events in emulsion detector (FASERν)
- 128.8 kg subset of volume analyzed ($9.5\ \mathrm{fb}^{-1}$)



[FASER Collaboration, Phys. Rev. Lett. 133 (2024)]



Treatise on Astronomy
History of Song Dynasty
(SN 1054, aka Crab nebula)

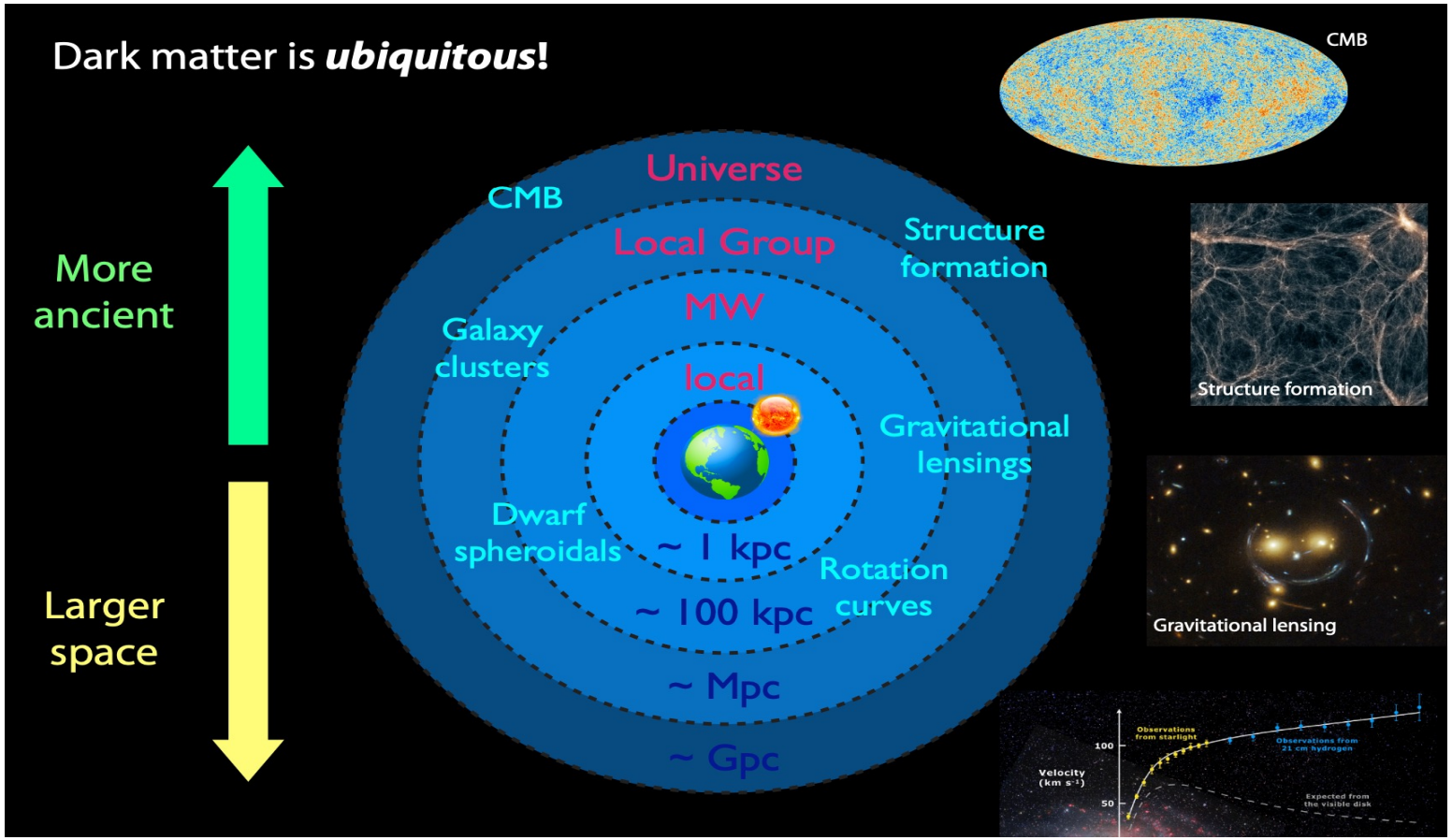
54th ISMD, Nat'l Central U, Chungli, Taiwan, Aug. 17 - 21

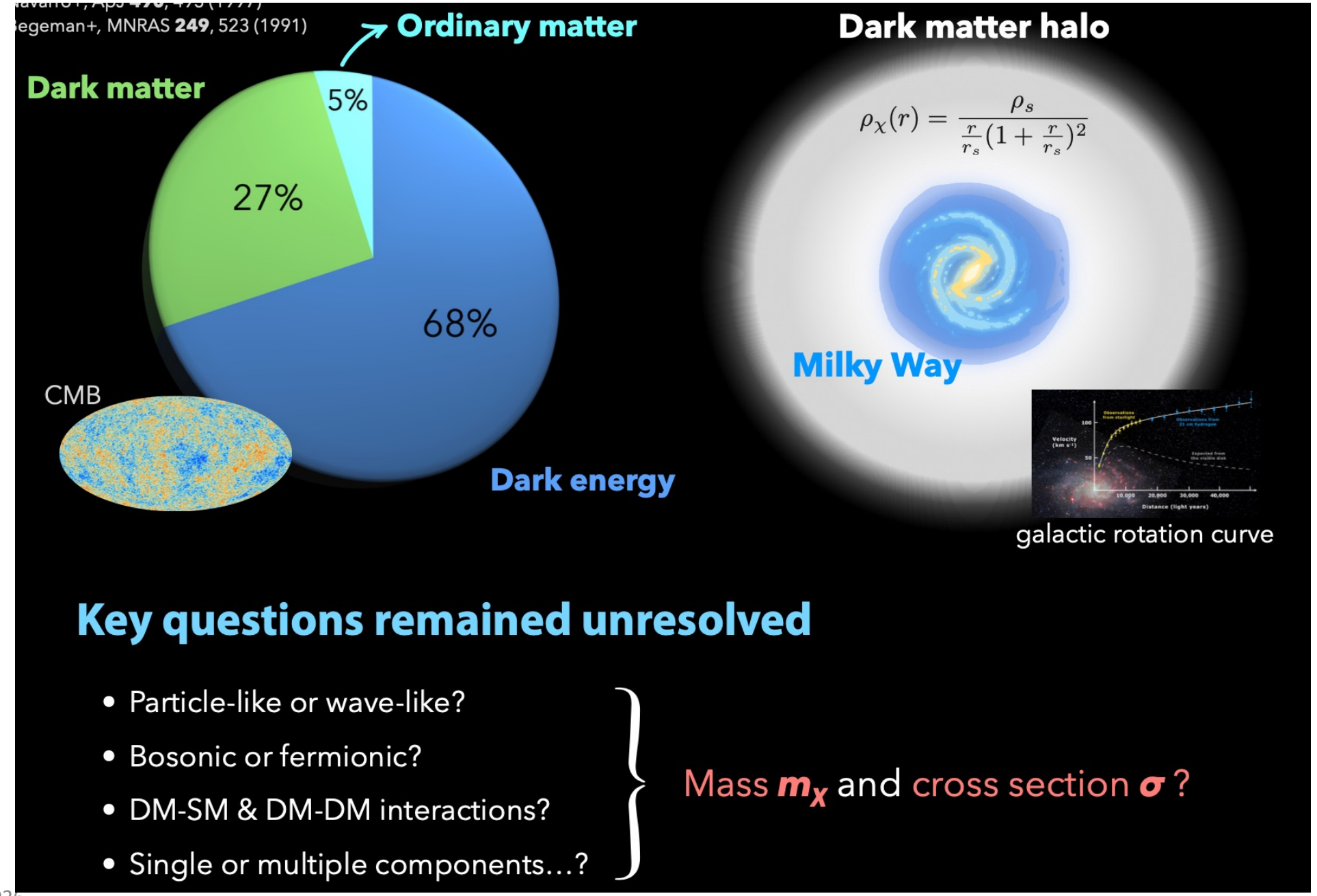
Supernovae as versatile probes of physics beyond the Standard Model

Yen-Hsun Lin (NSTC Research Scholar)
Institute of Physics, Academia Sinica

1. Cheng, Kong, **YHL**, Wu, Yun, 2603.09615 (*Phys. Rev. Lett. accepted*)
2. **YHL** & Wu, *Phys. Rev. Lett.* **133**, 111004 (2024)
3. **YHL**, Wu, Wong & Wu, *Phys. Rev. Lett.* **130**, 111002 (2023)

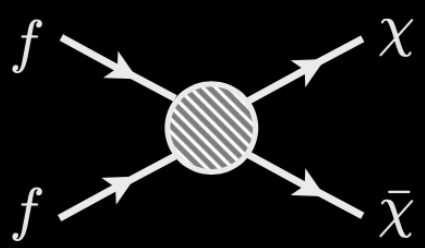
- Key questions of dark matter (DM)
- Probing beyond the Standard Model physics with supernova (SN)
  - ***Circumstellar medium*** as new probes of feebly-interacting particles
  - ***Direct DM mass determination*** via the ***time-delay signal*** of SN-neutrino boosted DM




Begeman+, MNRAS 249, 523 (1991)
Ordinary matter
Dark matter
5%
27%
68%
CMB
Dark energy
Dark matter halo
$\rho_\chi(r) = \frac{\rho_s}{\frac{r}{r_s}(1+\frac{r}{r_s})^2}$
Milky Way
Velocity (km s⁻¹)
Distance (light years)
galactic rotation curve
Key questions remained unresolved
Particle-like or wave-like?
Bosonic or fermionic?
DM-SM & DM-DM interactions?
Single or multiple components…?
Mass m_χ and cross section σ ?

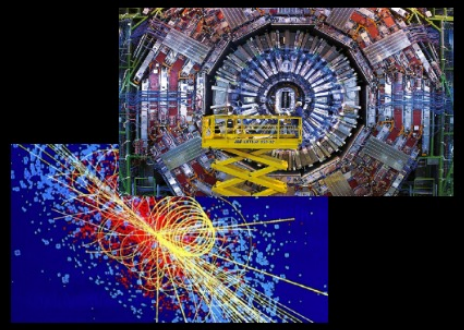
To resolve the key questions

MAKE

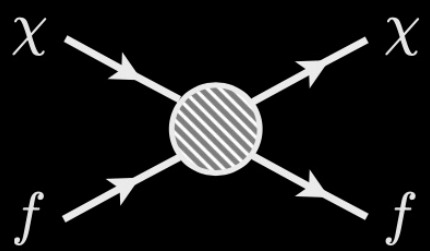


~ Collider search

LHC

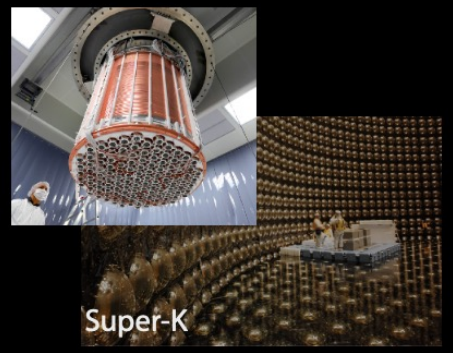


SHAKE

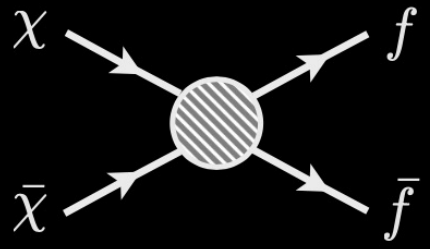


~ Direct search

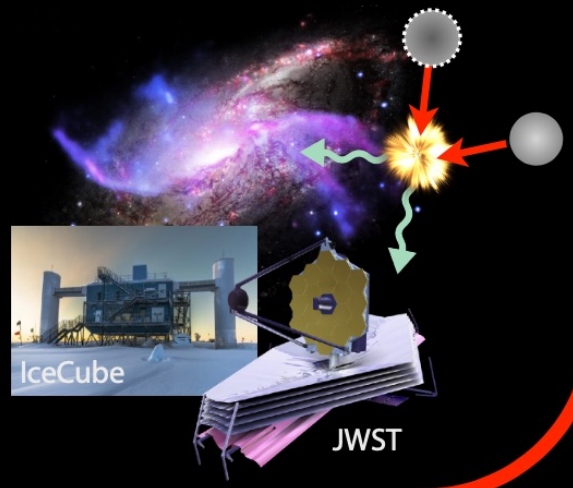
XENON



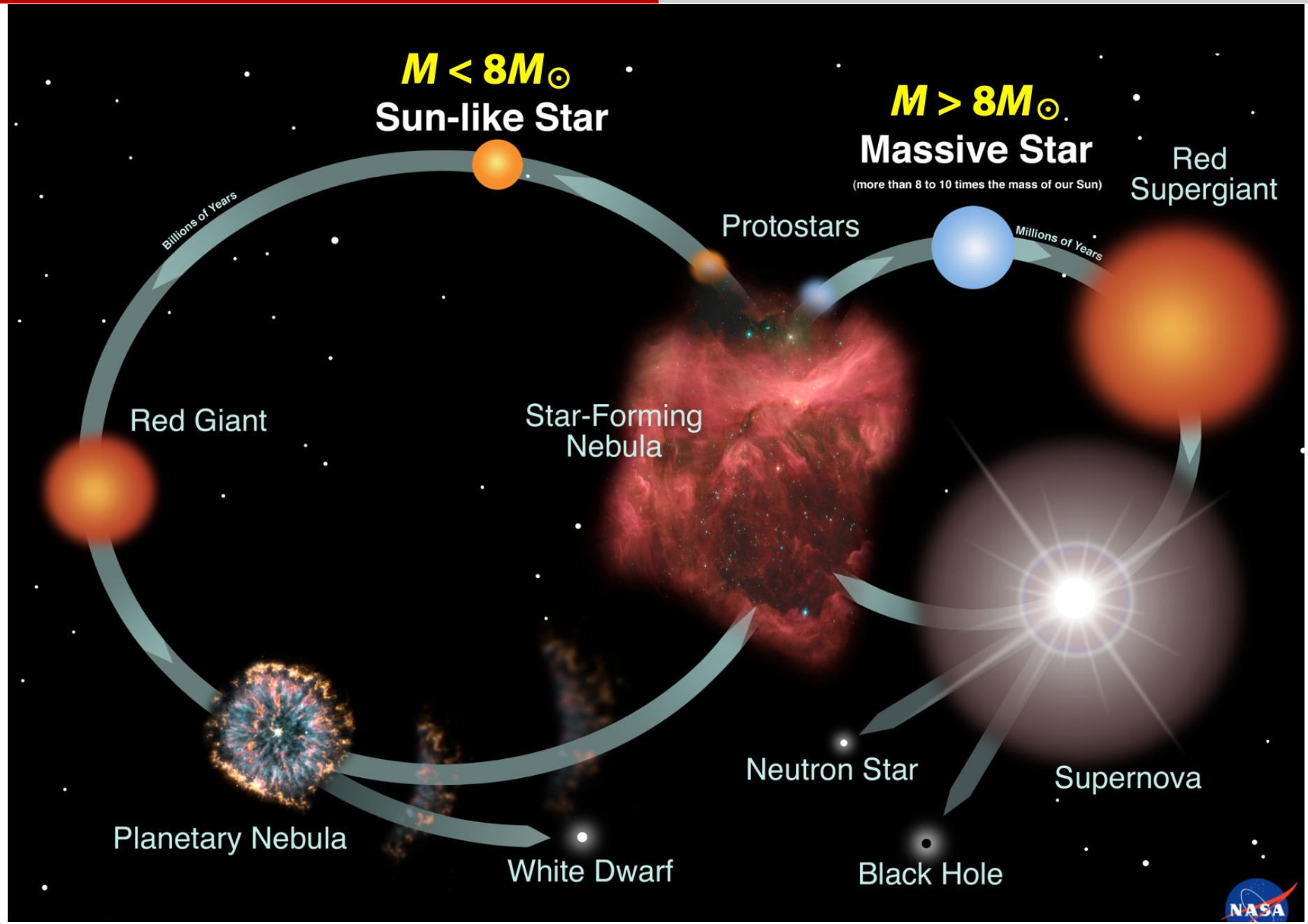
BREAK



~ Indirect search



not-to-scale


M < 8M⊙
Sun-like Star
M > 8M⊙
Massive Star
(more than 8 to 10 times the mass of our Sun)
Billions of Years
Millions of Years
Protostars
Red Supergiant
Red Giant
Star-Forming Nebula
Neutron Star
Supernova
Planetary Nebula
White Dwarf
Black Hole
NASA

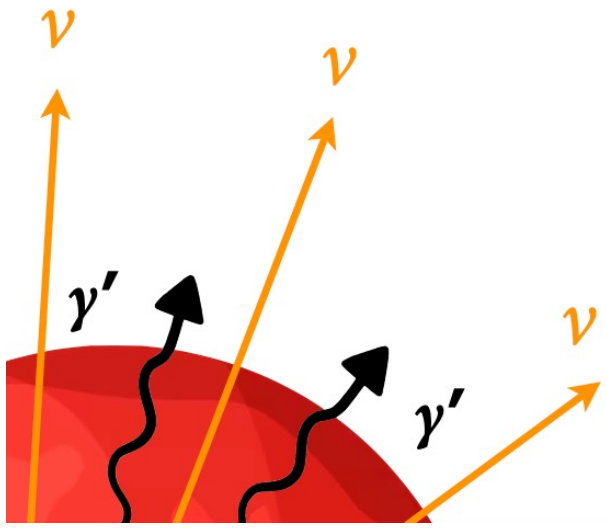
- An enormous number of particles are produced during a SN explosion
- Neutrinos carry more than 99% of the explosion energy

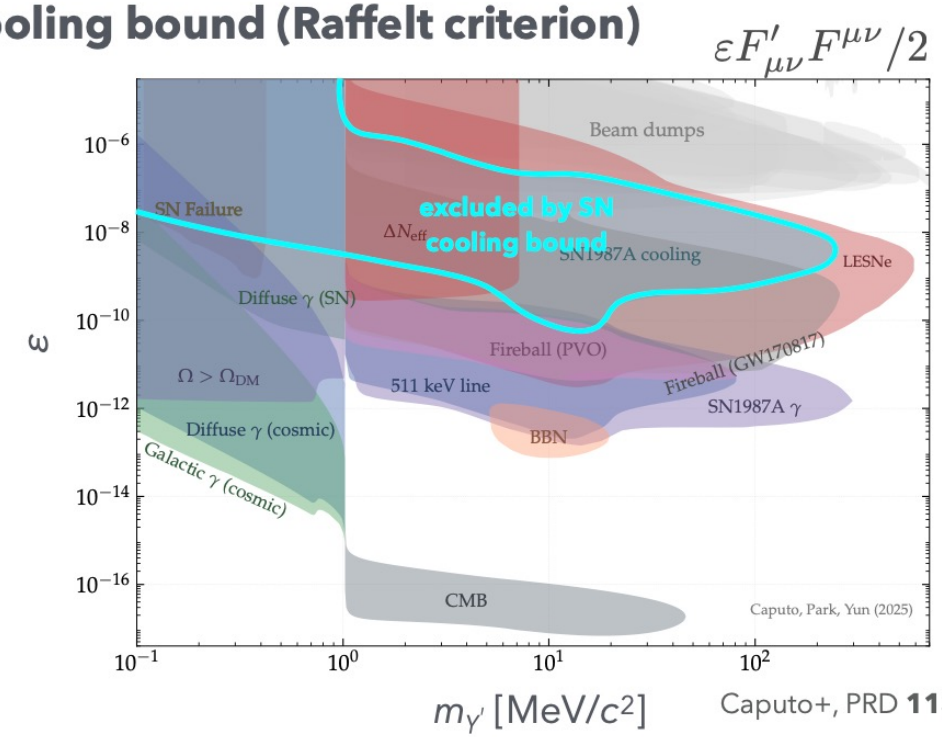
$$E_\nu \sim 10^{53}\ \mathrm{erg} \quad \text{where} \quad L_\nu \sim 10^{52}\ \mathrm{erg/s}$$

- If feebly-interacting particles (FIPs), eg., dark photons γ', are also produced, the explosion energy is shared between them and neutrinos

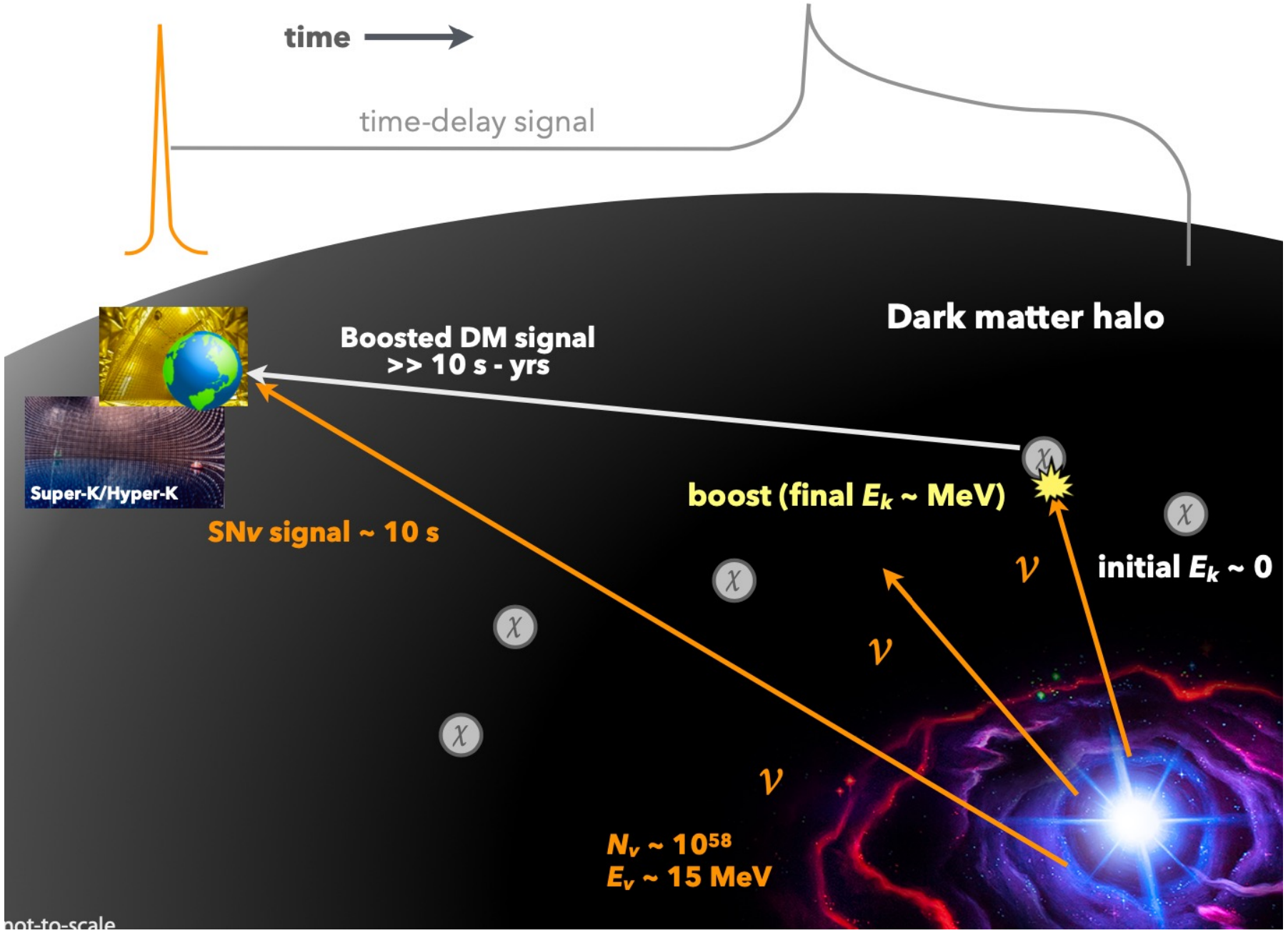
$$L_{\gamma'} \uparrow \qquad L_\nu \downarrow$$

- The FIPs $L_{\gamma'}$ cannot exceed L_ν; otherwise, it would violate SN 1987A observations → **SN cooling bound (Raffelt criterion)**





Caputo+, PRD **113**, 075001 (2026)

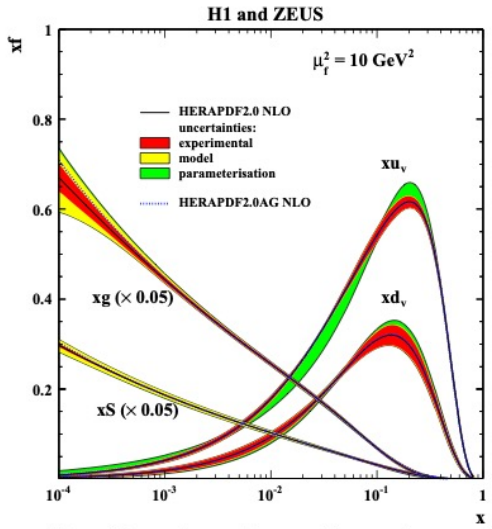

time
time-delay signal
Dark matter halo
Boosted DM signal
>> 10 s - yrs
Super-K/Hyper-K
SNν signal ~ 10 s
boost (final E_k ~ MeV)
initial E_k ~ 0
$N_\nu \sim 10^{58}$
E_ν ~ 15 MeV

not-to-scale


54th International Symposium on Multiparticle Dynamics
Aug/17/2026 – Aug/21/2026
sPHENIX Spin Program Highlights
Genki Nukazuka (JAEA)
for the sPHENIX Collaboration
Brookhaven National Laboratory
sPHENIX
JAEA
ISMD 2026

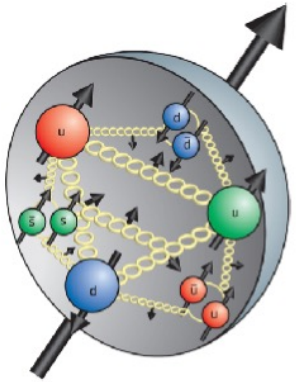
Proton spin Structure and transverse single spin asymmetry (TSSA)

Eur. Phys. J. C 75(2015)580



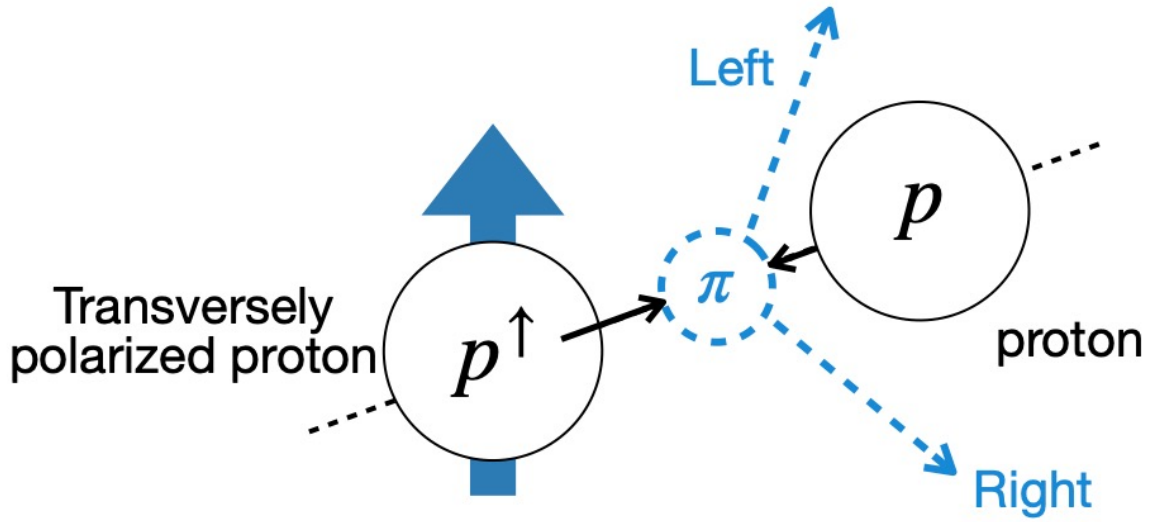
Parton distribution function describes 1-dimensional parton structure of the proton.

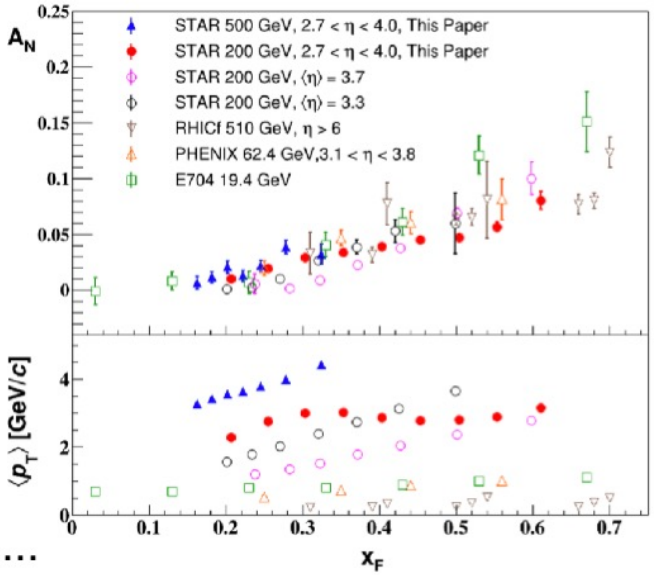
But the proton must be a 3-dimensional object…



Good example for the necessity of a multi-dimensional description of nucleon structure is …

Left-right asymmetry in $p^\uparrow + p \to \pi + X$





The asymmetry defined as $A_N = \dfrac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$ found to be up to 30%, while the leading order calc. in pQCD can make it about ~0.01%.

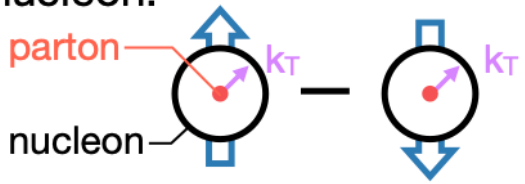
Yes, we need multi-dimensional structure for the proton!

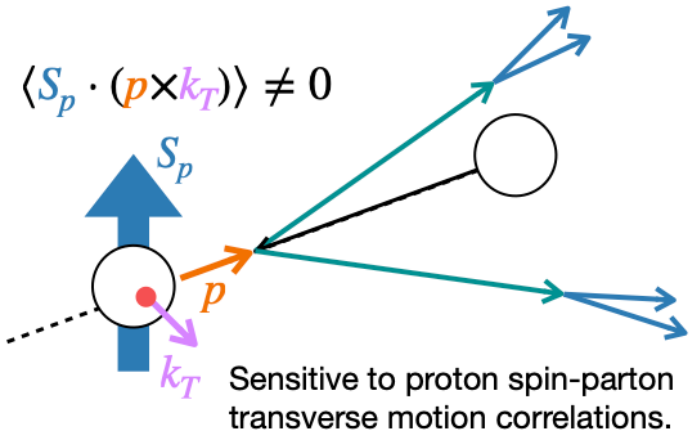
Parton/Nucleon Correlations and Transverse Single Spin Asymmetry

Transverse-momentum dependent (TMD) distribution functions and fragmentation functions

Sivers mechanism

Correlations of nucleon transverse spin and parton transverse momentum in the nucleon.

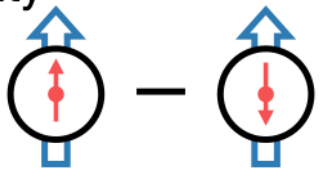




Sensitive to proton spin-parton transverse motion correlations.

Collins mechanism

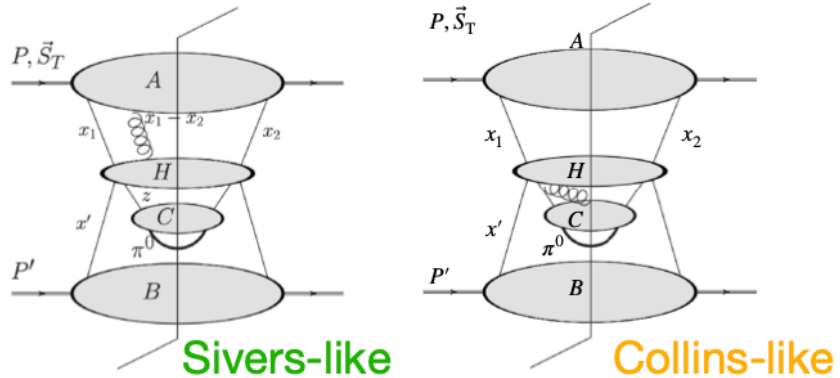
- Transversity



- Collins fragmentation function
  Spin dependent fragmentation function of a transversely polarized parton into a final-state hadron

Multi-parton correlation in collinear twist-3 factorization

Twist-3 Quark-gluon-quark and Tri-gluon correlations in the initial-state or in the final-state

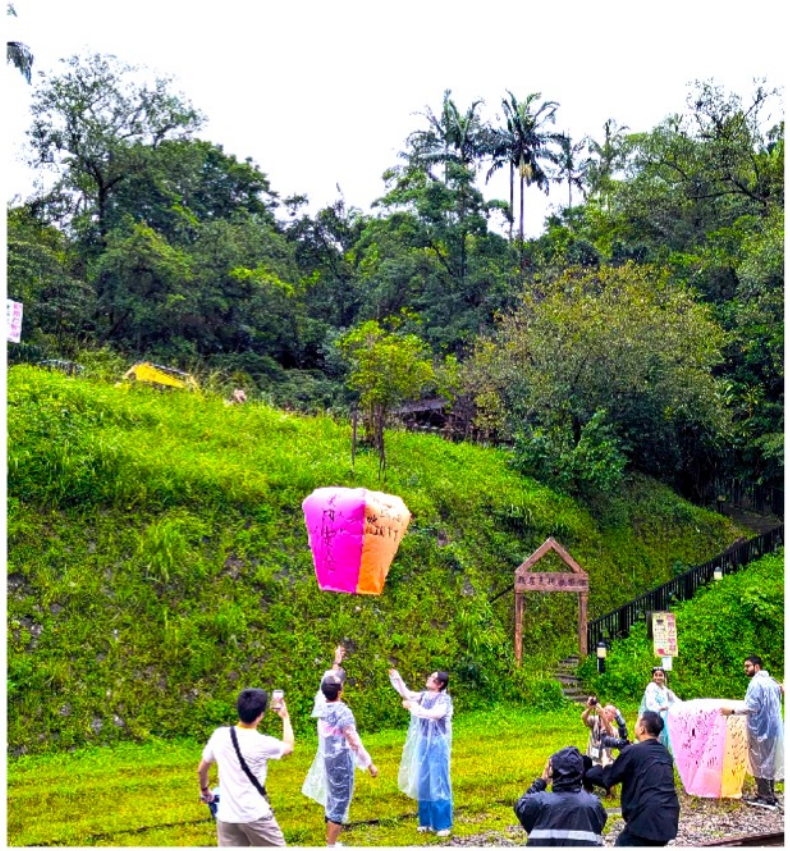


Sivers-like Collins-like

These factorizations are related each other.

Summary

- sPHENIX successfully completed the operation for 3 years to study QGP and proton spin structure. sPHENIX data are unique before EIC.
- We are analyzing transverse single-spin asymmetries for various channels to access
  - collinear twist-3 qgq and ggg correlators.
  - transverse momentum-dependent PDFs
  - fragmentation functions
- 3 analysis topics were reported:
  - Light mesons: Preliminary results agree with the PHENIX results and consistent to zero within uncertainty. The analysis is almost finalized and will be submit soon.
  - Inclusive jet: Preliminary results agree with the PHENIX results and consistent to zero within uncertainty. The analysis will be completed soon.
  - Isolated prompt photon: The cross-section results indicated the great performance of the measurement. The preliminary TSSA results will be released soon.
- Visit our homepage for more public results: https://www.sphenix.bnl.gov/PublicResults



LOTS OF ANALYSIS HAVE LAUNCHED NOW. STAY TUNED.

Evidence of $\Lambda\bar{\Lambda}$ spin correlation in p+p collisions at STAR

Qinghua Xu (Shandong University)

for the STAR collaboration

ISMD 2026, August 20, 2026

Supported in part by:

U.S. DEPARTMENT OF ENERGY | Office of Science

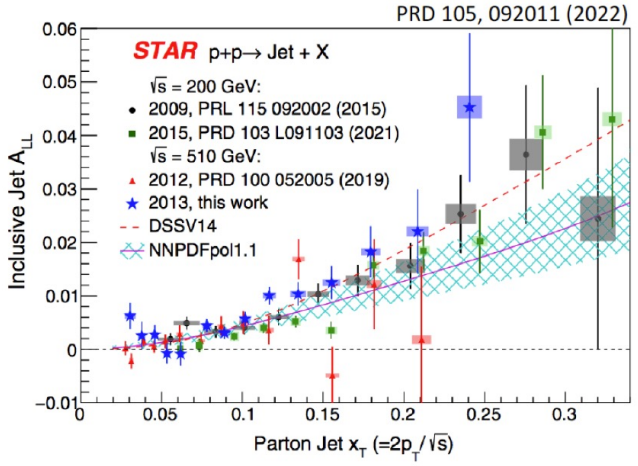
NSFC National Natural Science Foundation of China

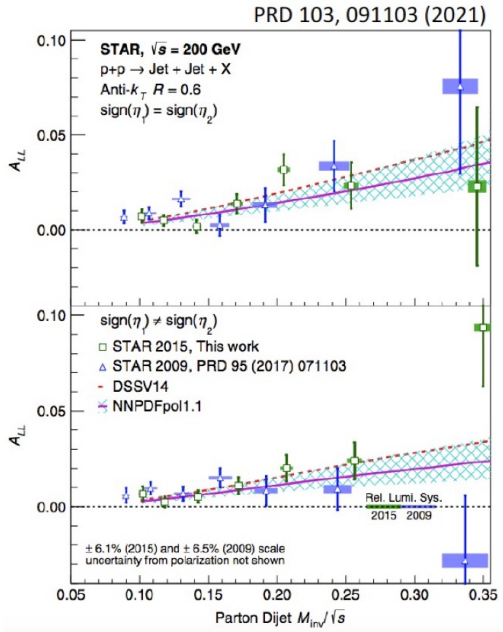
Results on gluon polarization from STAR

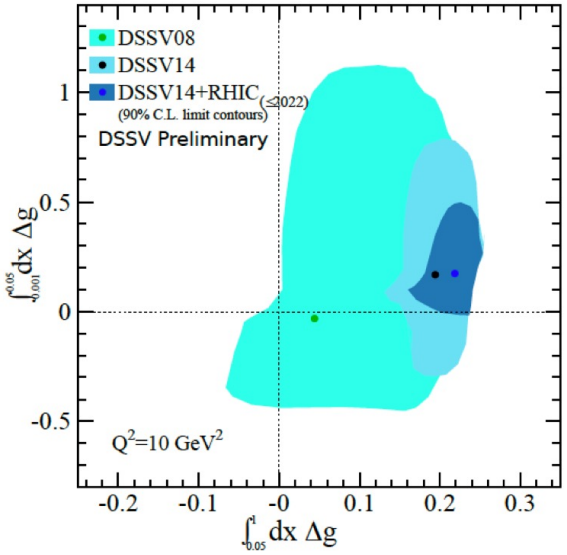
- Longitudinal double spin asymmetry A_{LL} of jets provide real constraints on gluon polarization

- **Gluon spin accounts for >40% of proton spin!**

$$\int_{0.05}^{1} \Delta g(x, Q^2) dx = 0.218 \pm 0.027$$







$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + < L_{q,g} >$$

Quark spin, (~30%)-DIS | Gluon spin, RHIC | Orbital Angular Momenta Little known

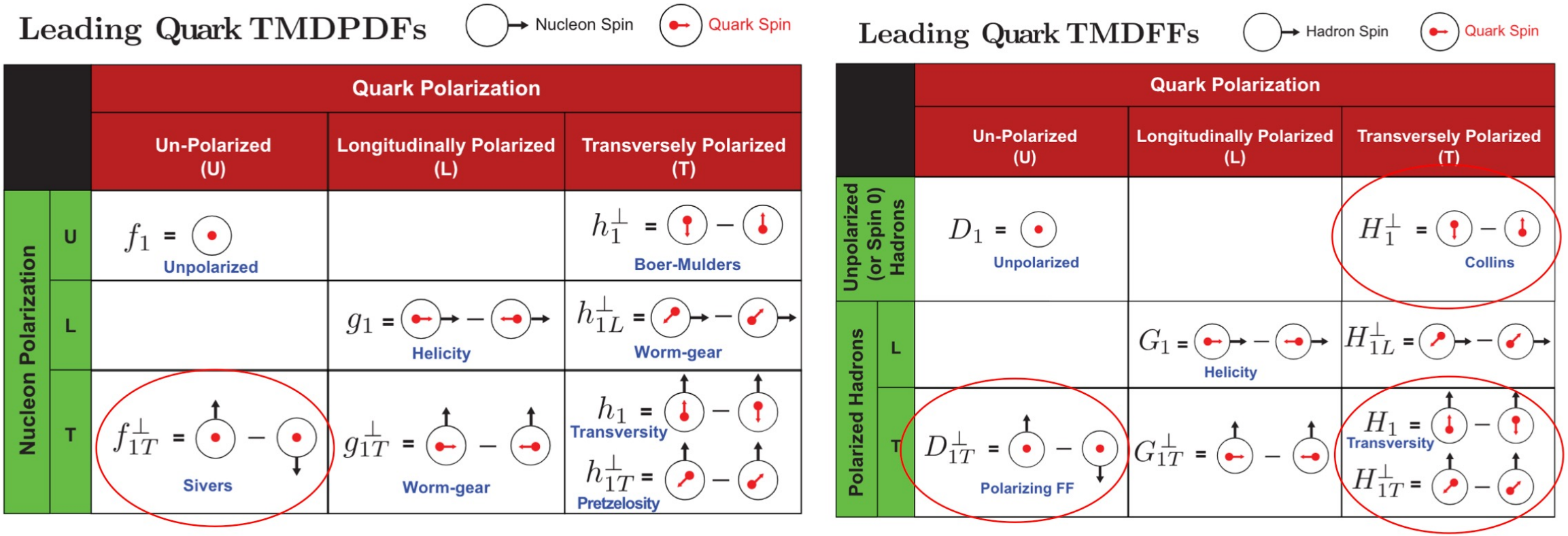
RHIC Cold QCD White Paper, arXiv2302.00605

Recent NNLO analysis by DSSV24

- ✓ 55% of proton spin in x > 0.01 comes from gluons.
- ✓ 40% of the proton spin in x > 0.01 comes from quarks.

Nucleon 3d-structure & TMD distribution

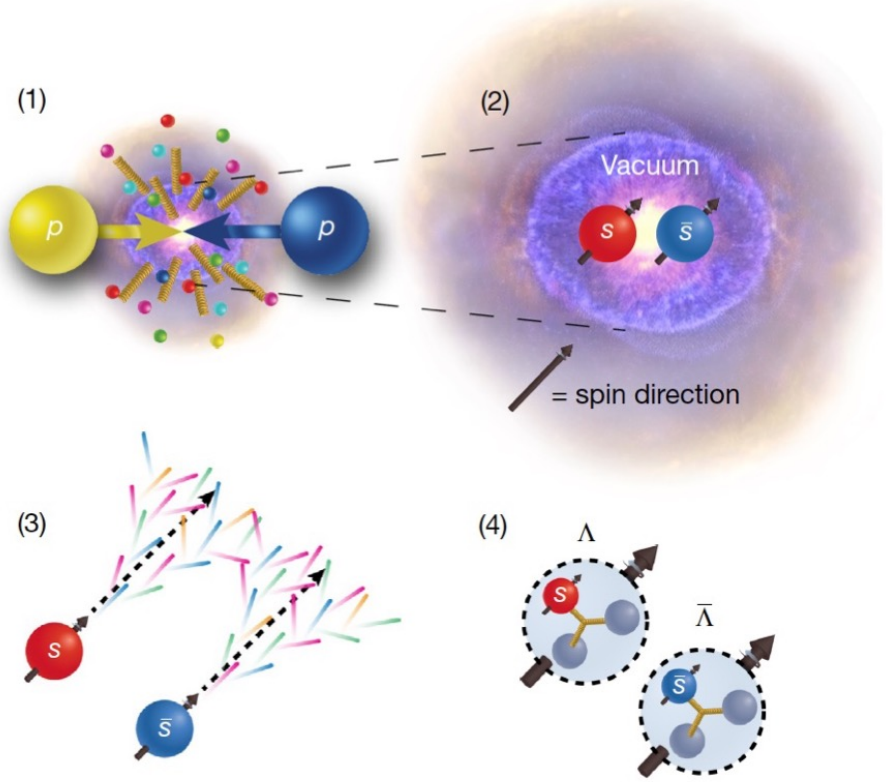
- Transverse momentum dependent distribution (TMD) parton distribution function (PDF) and fragmentation functions (FF):

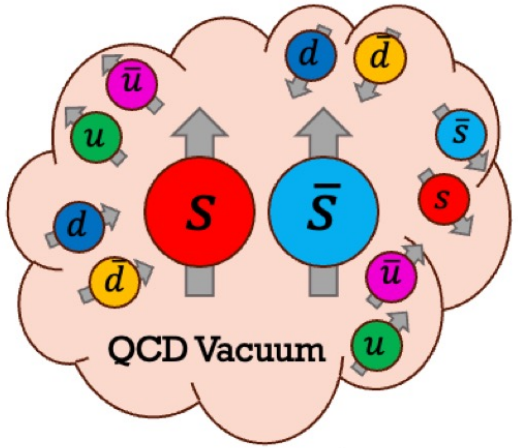


TMD handbook: ariXiv-2304.03302

Λ hyperon pair spin-spin correlation in p+p collisions

- Spin-spin correlation of $\Lambda\bar{\Lambda}$ hyperon pair in *p+p* collisions to study the hadronization of the entangled $s\bar{s}$ quark pairs produced from the QCD vacuum





- Quark pairs from the vacuum are expected to emerge as **maximally entangled spin-triplet states**

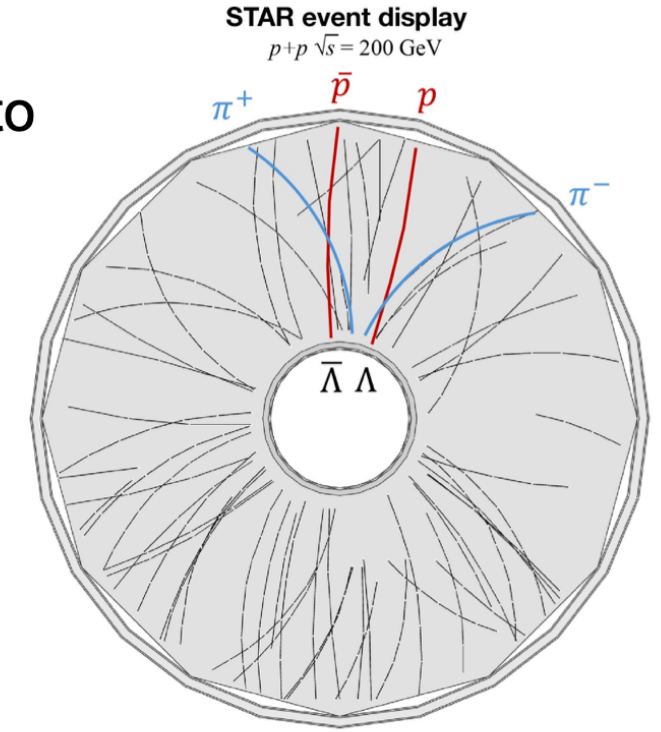
J. R. Ellis, D. Kharzeev, and A. Kotzinian, Z. Phys. C 69, 467 (1996)

Spin-spin correlation: experimental method

- Find a Λ hyperon pair (any combination) in one event
  - Decay channel $\Lambda \rightarrow p\pi^-$ and charge conjugate
- Boost proton (anti-proton) from decay of the corresponding $\Lambda(\overline{\Lambda})$ to **rest frame**
- Measure angle θ^* between the two **boosted protons**
  - The distribution of pair angle is given by:

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^*)} = \frac{1}{2}\left[1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos(\theta^*)\right]$$

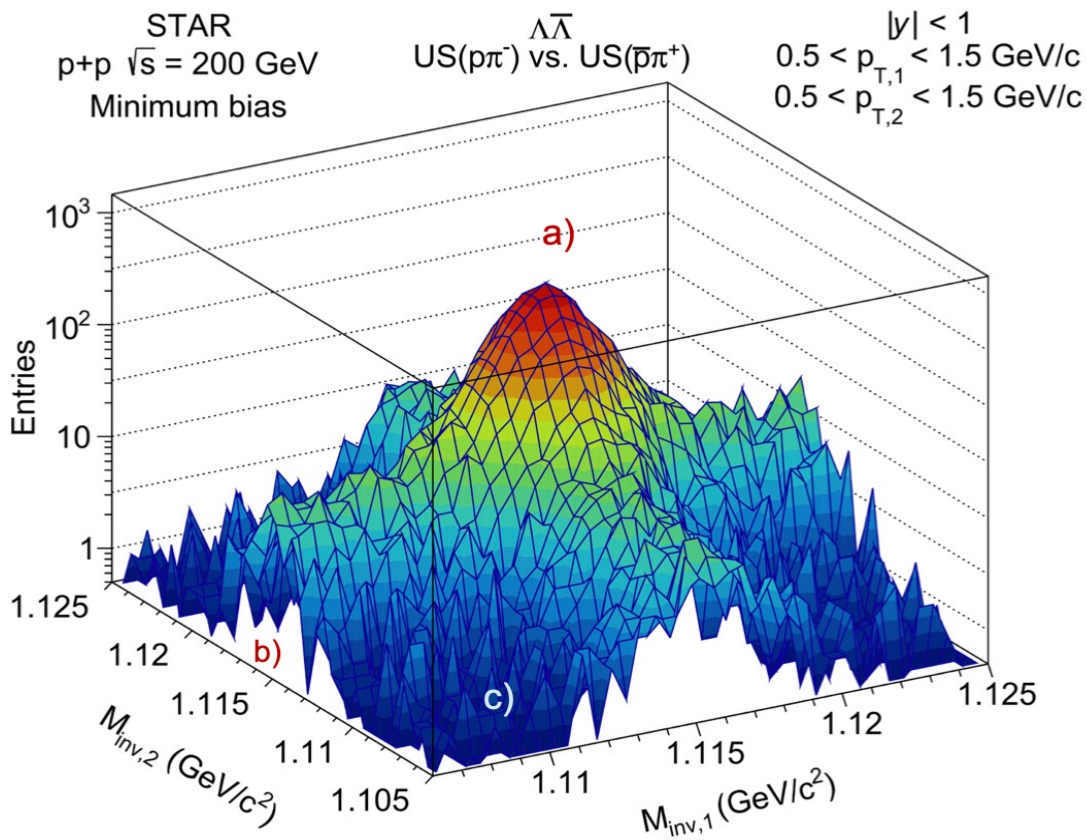
  - α_1 and α_2 are weak decay parameters of Λ or $\overline{\Lambda}$ (α_- or α_+)



- **A non-zero $P_{\Lambda_1\Lambda_2}$ would indicate spin correlation between the two $\Lambda(\overline{\Lambda})$ hyperons**
  - No global single Λ hyperon polarization expected at STAR at mid-rapidity

Spin−spin correlation: Λ signal extraction

- Signal extraction determined from 2D M_{inv} distributions of unlike-sign (US) πp pairs
- Three components:
  a) Peak: πp from $\Lambda(\bar{\Lambda})$ decay paired with another πp from $\Lambda(\bar{\Lambda})$ decay
  b) Ridges: πp from $\Lambda(\bar{\Lambda})$ decay paired with combinatorial background
  c) Continuum: combinatorial background paired with combinatorial background
- Contributions (b) and (c) are subtracted from (a) and fitted with 2D Gaussian function
  – Signal region is defined as mean $\pm 2\sigma$



$\Lambda\bar{\Lambda}$ spin-spin correlation results in p+p

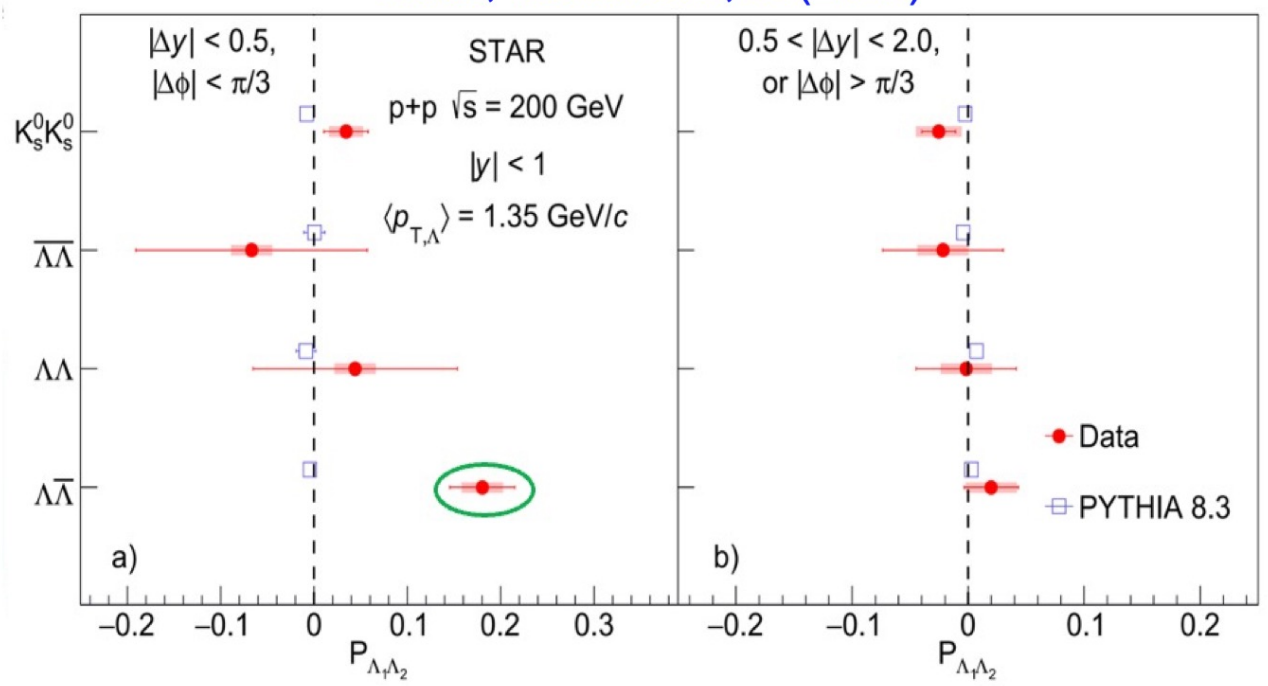
- Spin-spin correlation for short-range and long-range hyperon pairs

  -compared to null measurements of K_{0s} and PYTHIA calculation

- Short-range pairs show non-zero spin-spin correlation

$$P_{\Lambda_1\Lambda_2} = 0.181 \pm 0.035_{stat} \pm 0.022_{sys}$$

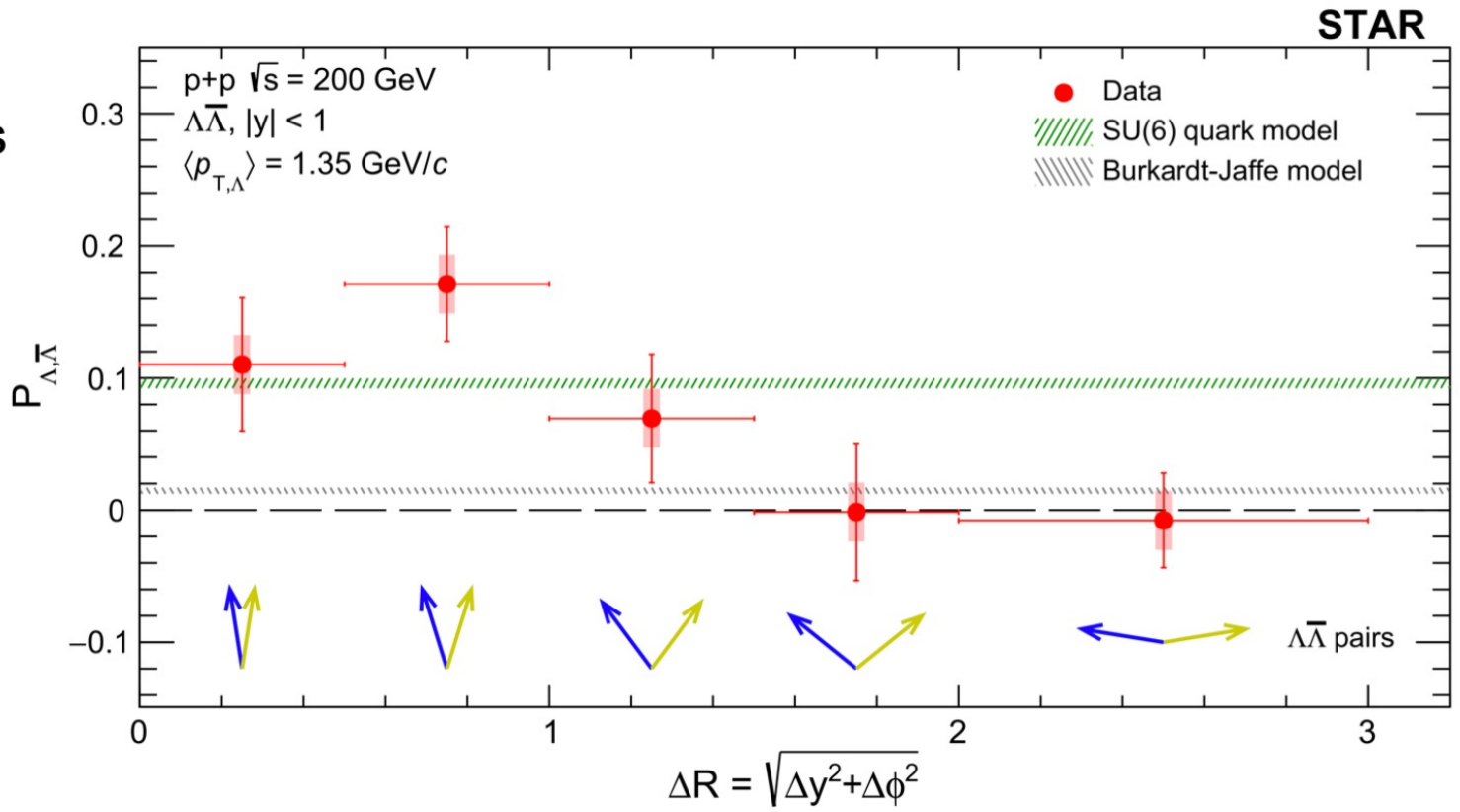
STAR, Nature 650, 65(2026)



$\Lambda\bar{\Lambda}$ spin-spin correlations

- Spin-spin correlation of $\Lambda\bar{\Lambda}$ pairs as a function of $\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$
  - Compared to SU(6) and BJ models
- Short range $\Lambda\bar{\Lambda}$ pairs appear to be in triplet state
  - direct probe of QCD vacuum?
- Possible observation of quantum decoherence
  - Spin-spin correlation seem to "turn off" with larger pair separation

STAR, Nature 650, 65(2026)



➢ Future measurement in A+A may probe property of Quark Gluon Plasma, chiral symmetry restoration etc.

BSM CP Violation and the Neutron EDM

Jangho Kim
Seoul National University

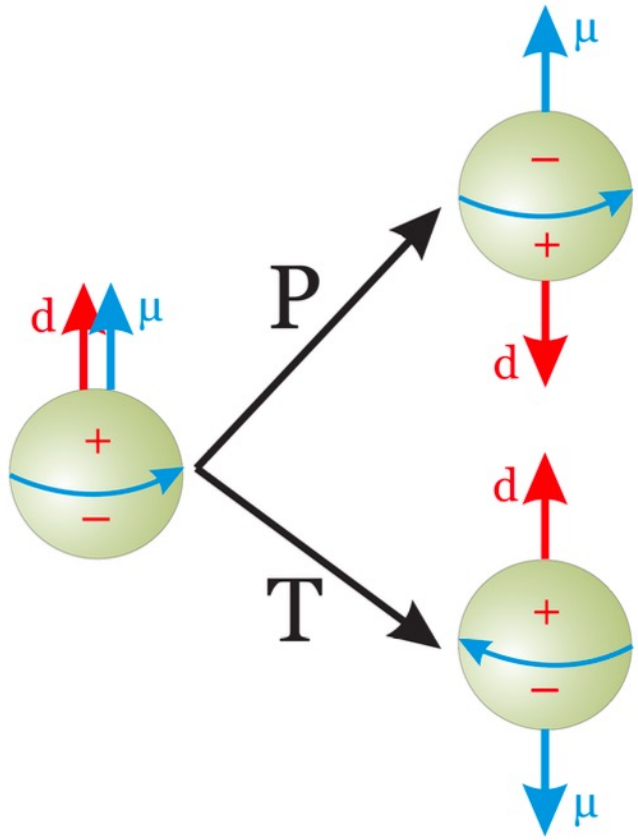
The 54th International Symposium on Multiparticle Dynamics
(ISMD 2026)
National Central University in Chungli, Taiwan
August 21, 2026





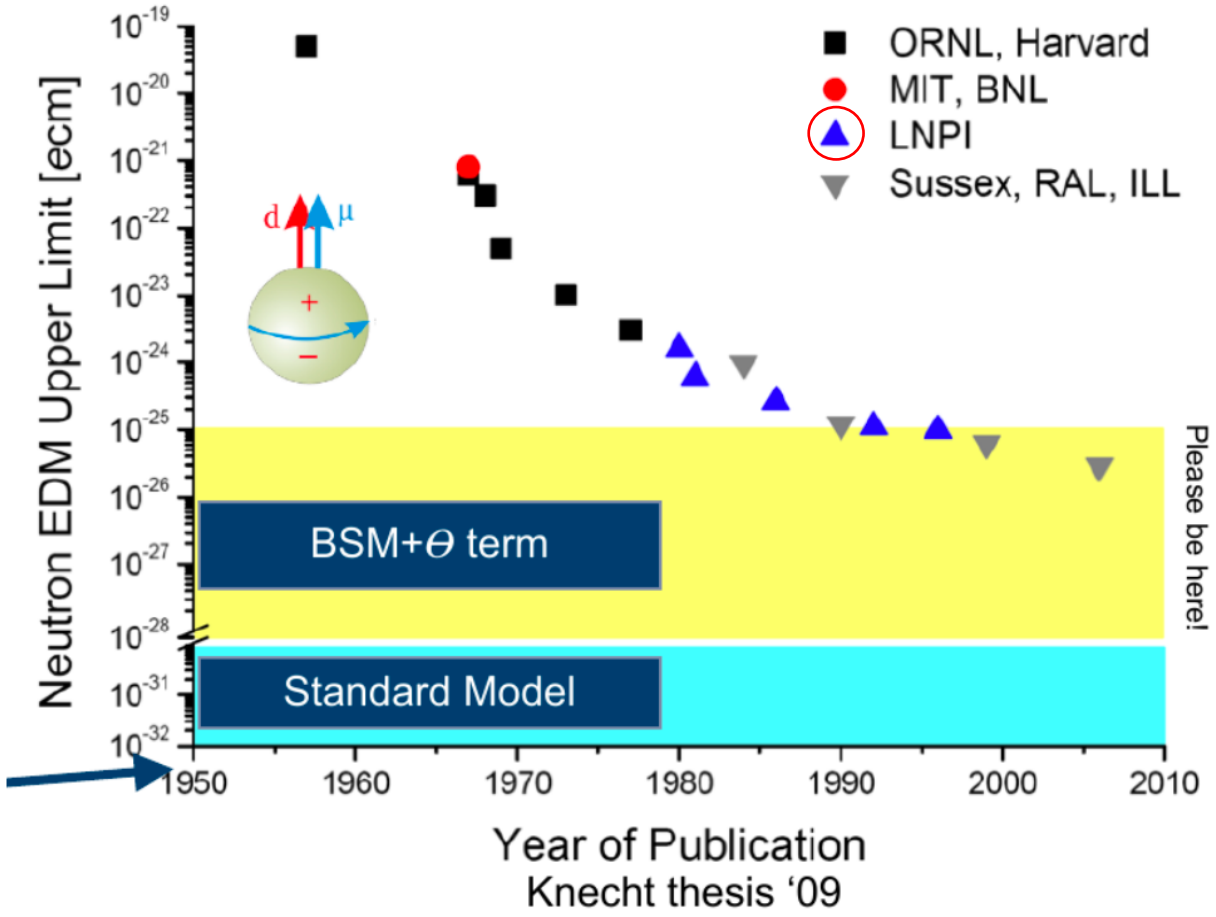
- CP-violation based on the Standard Model doesn't cover the amount needed for the observed baryon asymmetry.
- New CP-violation sources are needed.
- Via the electric dipole moment (EDM) study, we can investigate the CP-violation.

Neutron Electric Dipole Moment(nEDM)



- Under parity(P) or time-reversal(T), EDM changes orientation.
- Permanent EDM is not symmetric with either P or T.
- CPT is preserved. Therefore CP and T are separately violated.

Not enough CP violation from the Standard Model



- Weak interactions of SM violate CP within CKM matrix.
- However, does not provide sufficient amount of CP violation.

Summary

- Gradient flow provides a controlled path from BSM CP-violating operators to the neutron EDM.
- Ringed and caron schemes now enable direct nonperturbative renormalization of flowed fermion fields, beyond cancellations in ratios.
- Scheme-consistent matching followed by the $t \to 0$ limit yields renormalized observables and a handle on normalization systematics.
- A four-point-function calculation remains necessary to complete the qCEDM contribution to neutron-EDM.

Generative AI for Discovery in Fundamental Physics

54th Symposium on Multiparticle Dynamics
National Central University, Taiwan

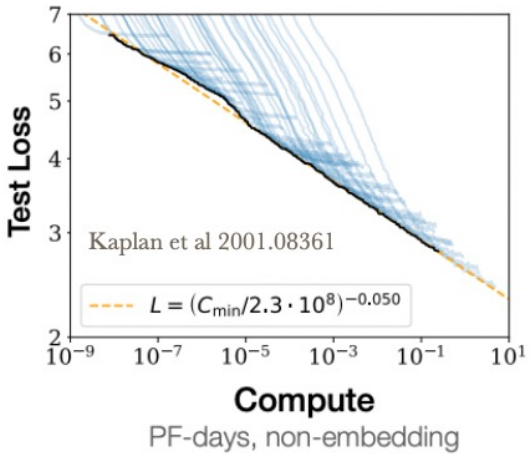
David Shih
August 21, 2026

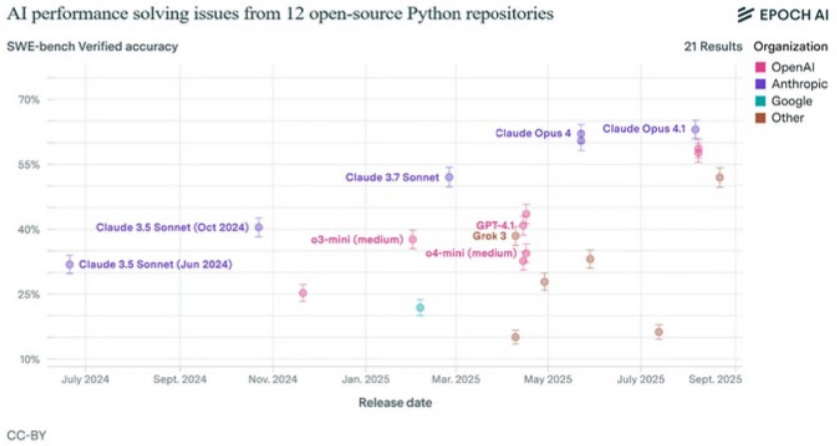


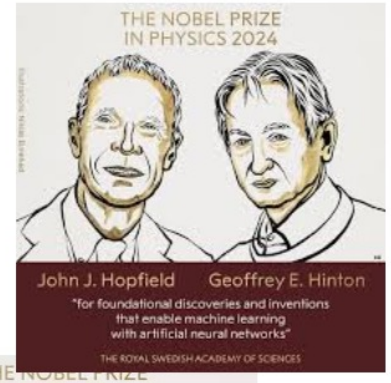
RUTGERS
THE STATE UNIVERSITY
OF NEW JERSEY

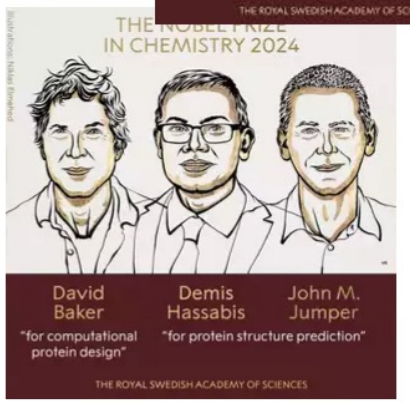
AI Revolution

We are witnessing a historic moment of technological advancement



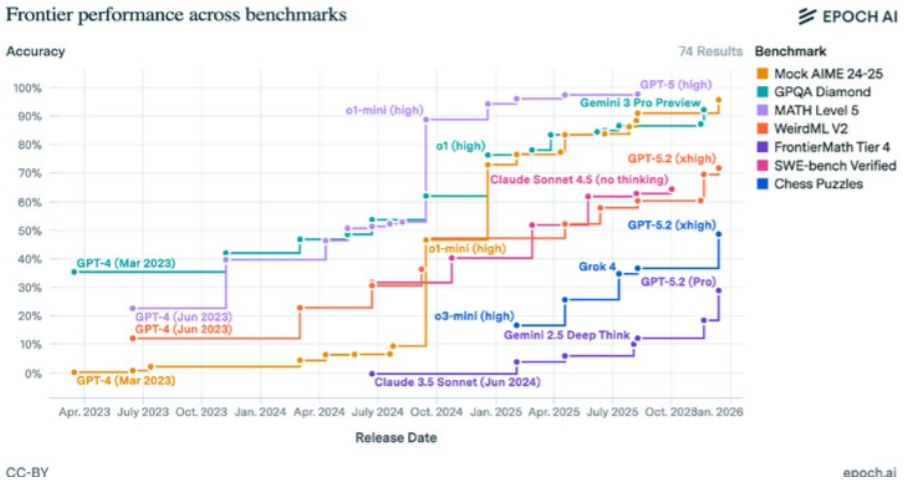






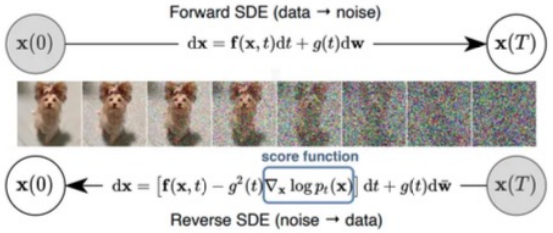
Google A.I. System Wins Gold Medal in International Math Olympiad

OpenAI said it, too, had built a system that achieved similar results.



2

Drivers of progress



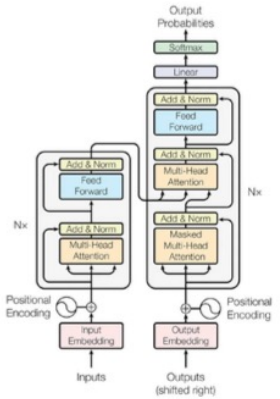
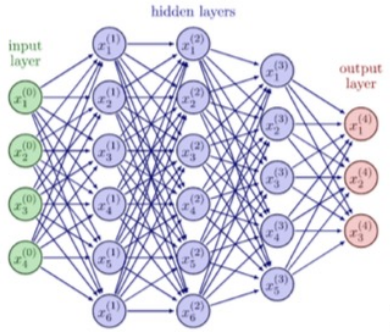
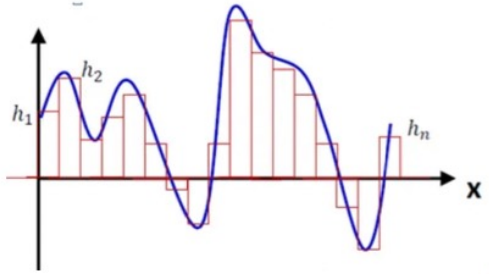
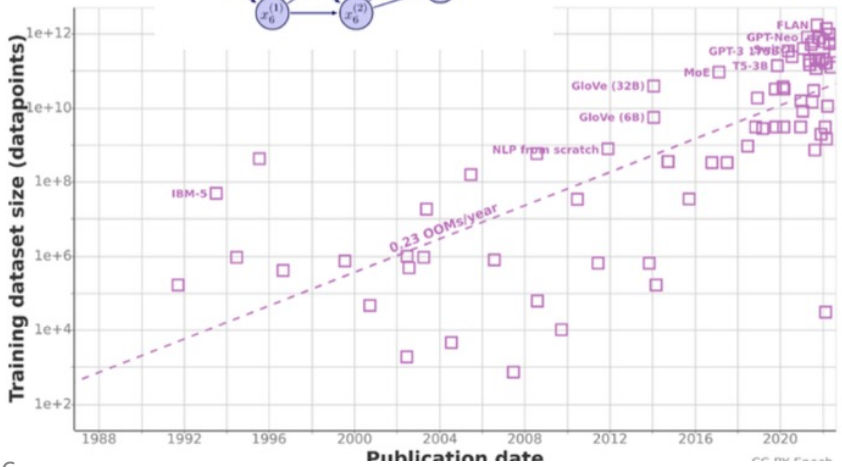


Figure 1: The Transformer - model architecture.

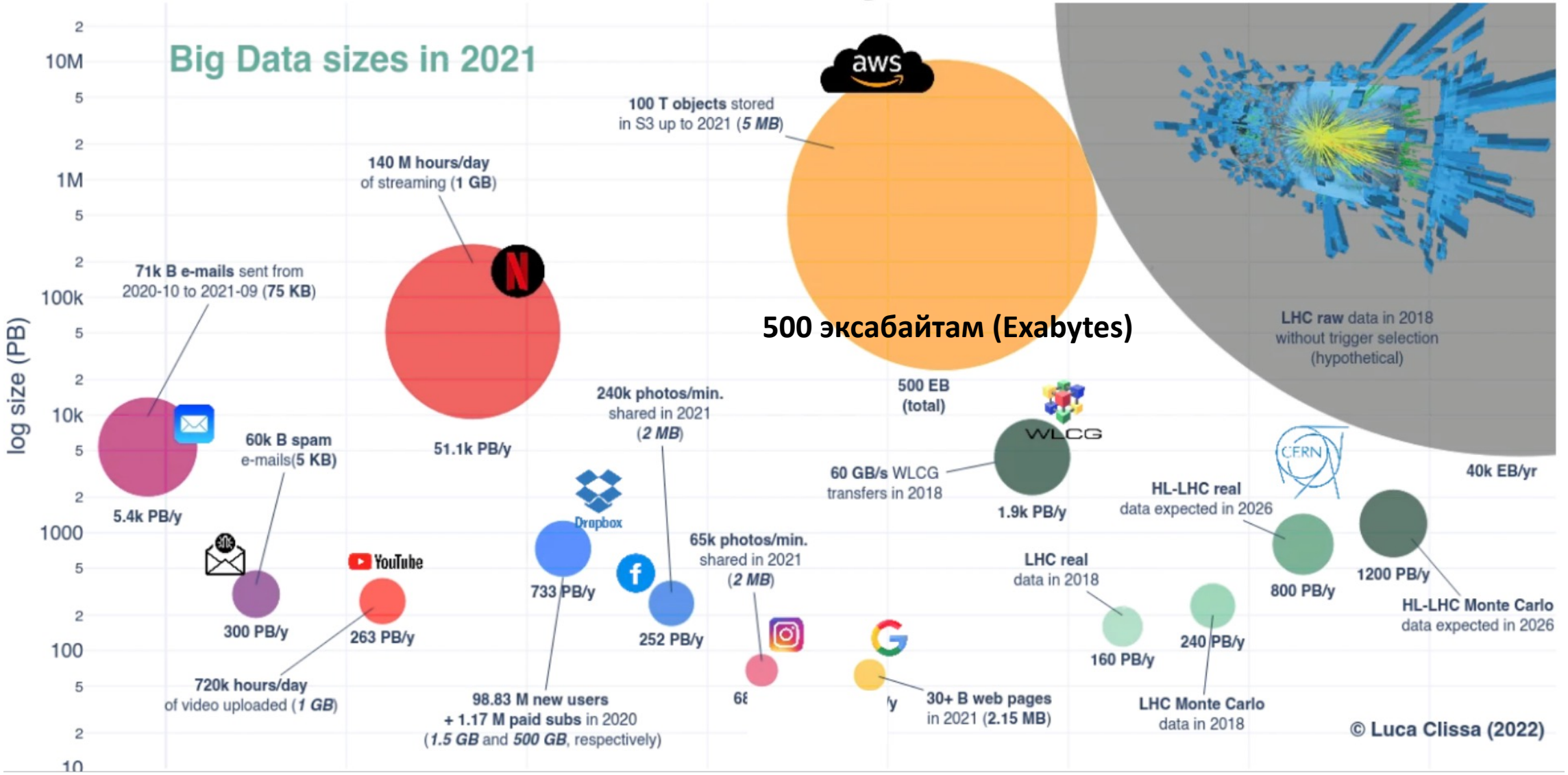




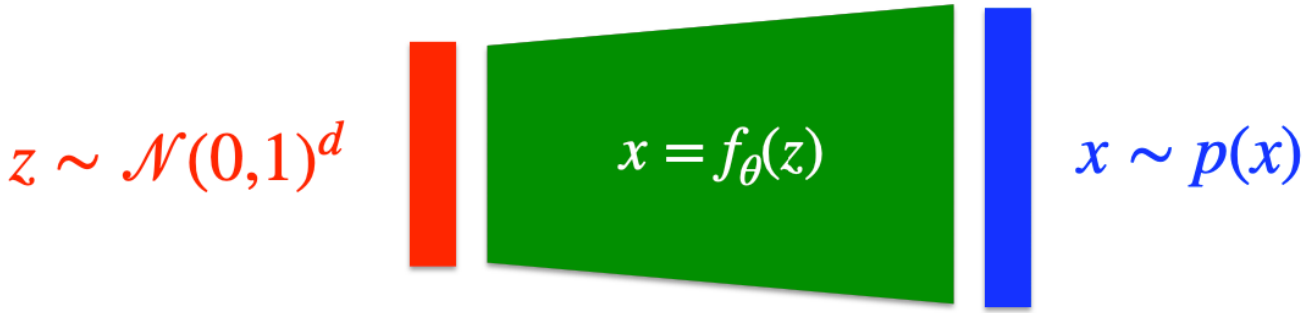


HEP also has plenty of big data

Amazon Web Services (AWS)



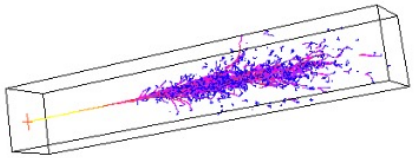
Generative Models: A Key Building Block of Modern ML



- **Objective**: generate more samples $x \sim p(x)$
  - Need a source of randomness: $z \sim \mathcal{N}(0,1)^d$
  - **Generative model** $f_\theta(z)$ transforms this into $x \sim p(x)$
    θ : parameters of a NN
  - Model fit to data $x_i \sim p(x), \ i = 1, \ldots, N$

Closely related to
density estimation:
learn $p(x)$ from data

Fast simulation

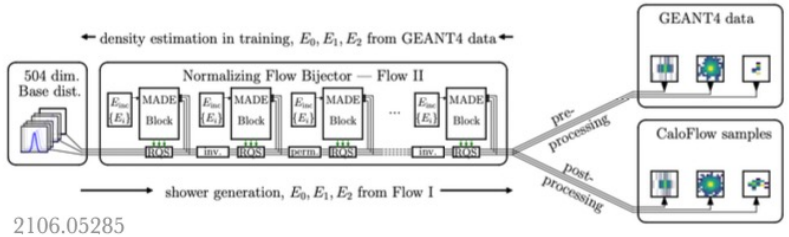


CaloChallenge 2022: A Community Challenge for Fast Calorimeter Simulation

2410.21611



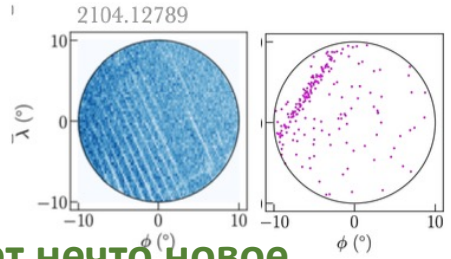
"Calorimeter Simulation", generated via midjourney, 2022

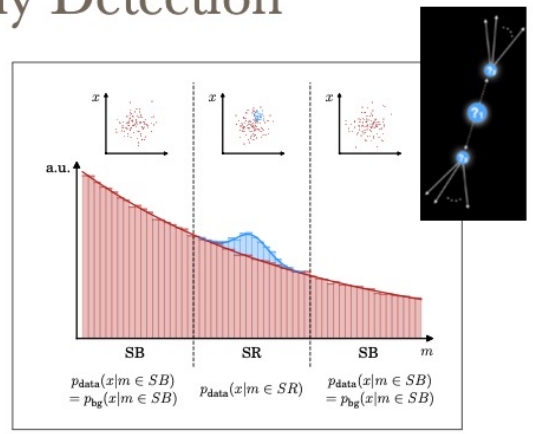


2106.05285

Anomaly Detection

2104.12789





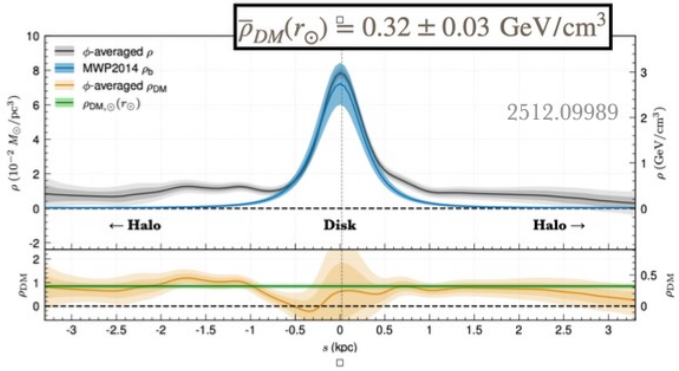
2109.00546

создает нечто новое

в ответ на подсказку

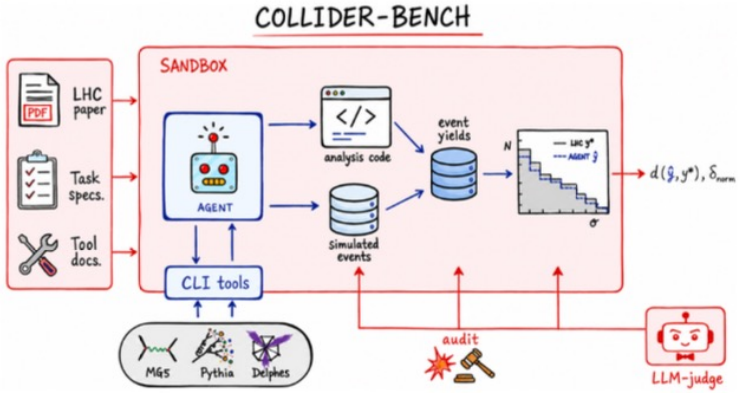
Generative AI for HEP

Novel measurements



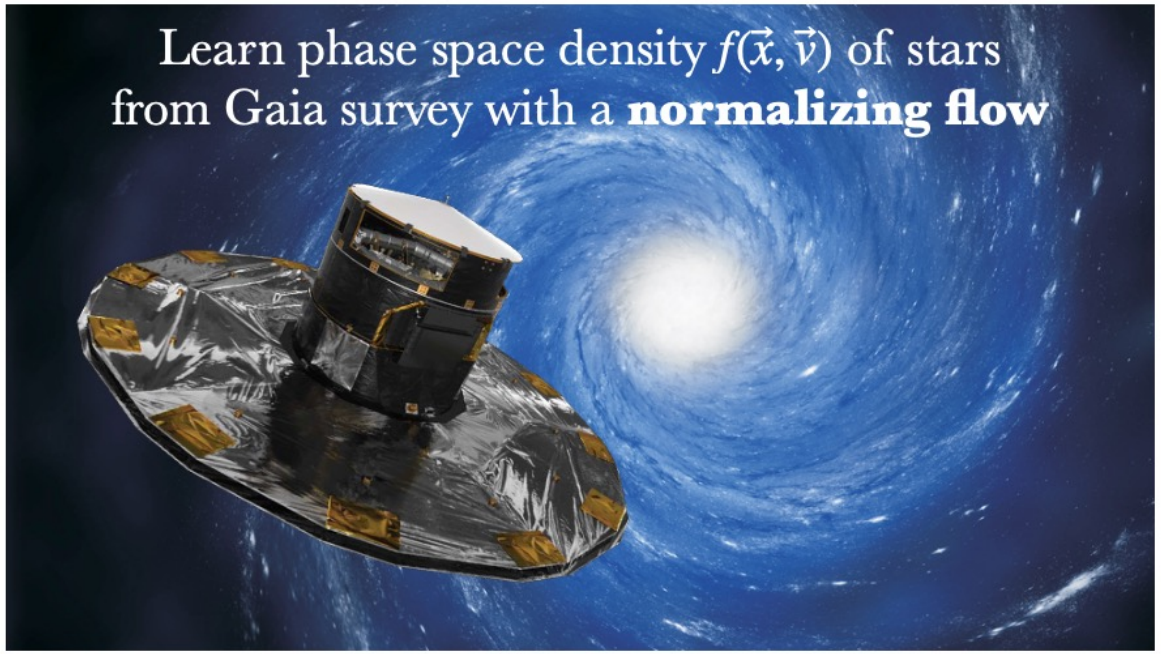
Agentic AI

мыслит стратегически



And much, much more…

A novel measurement of dark matter density



Solve equilibrium collisionless Boltzmann Equation for gravitational potential parametrized with NN

$$\vec{v} \cdot \frac{\partial f}{\partial \vec{x}} - \nabla \Phi_{NN}(x) \cdot \frac{\partial f}{\partial \vec{v}} = 0$$

Green et al 2011.04673, 2205.02244; Naik et al 2112.07657;
An et al 2106.05981; Kalda et al 2310.00040 2507.03742
Buckley, Lim, Putney & DS 2205.01129, 2305.13358, 2412.14236, 2512.09989

Derivatives of potential give acceleration field and mass density

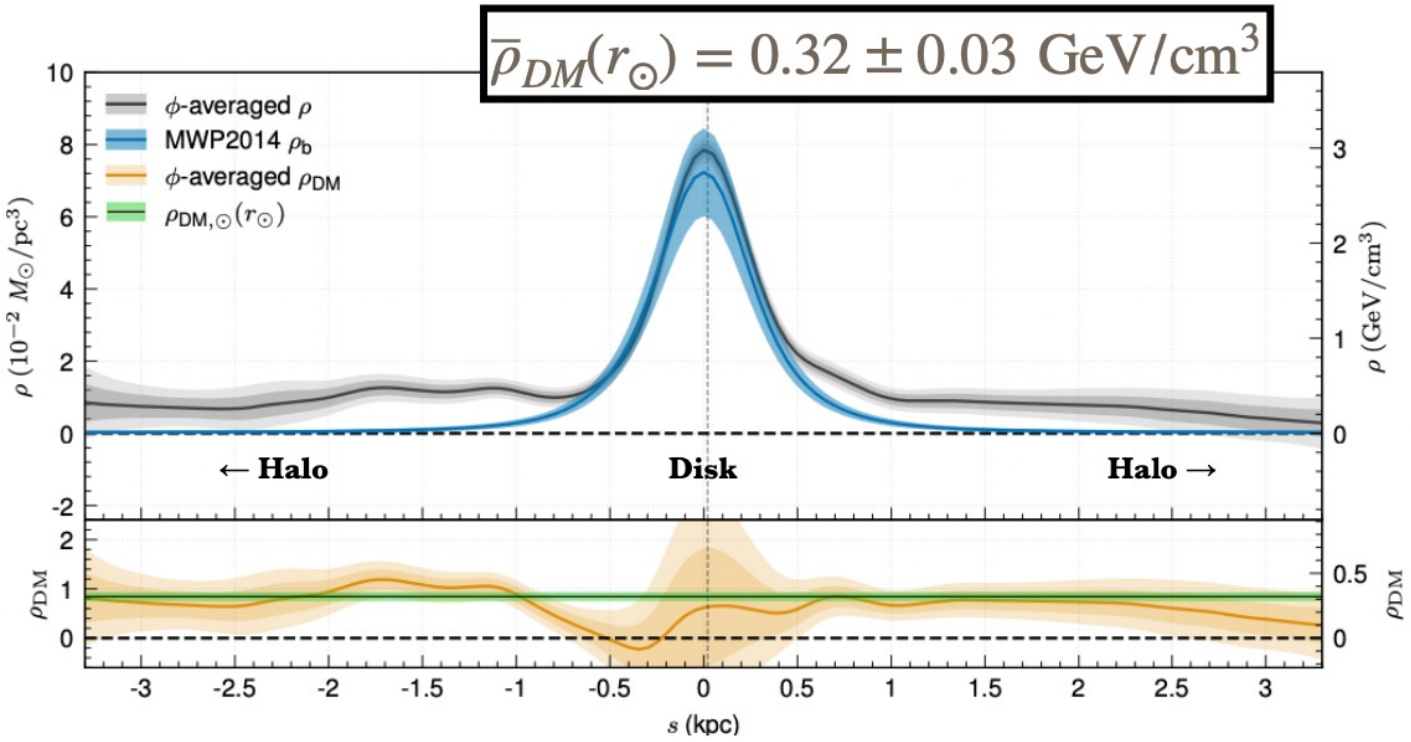
$$\vec{a}(x) = -\nabla \Phi(x)$$

$$4\pi G\rho(x) = \nabla^2 \Phi(x)$$

Unbinned, symmetry-free, data-driven, fully 3d measurement with ~ 4 kpc of Solar location!

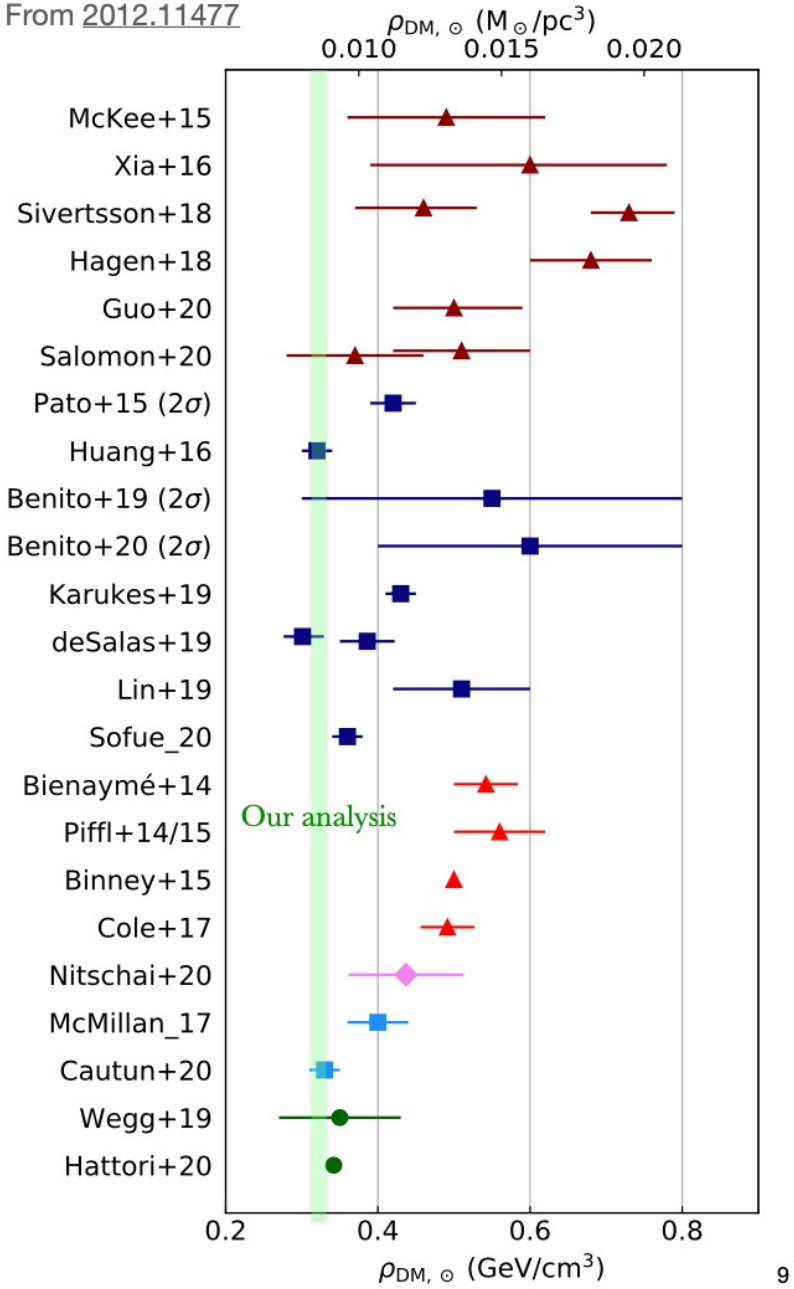
Results: mass density

DS+ Putney et al 2512.09989

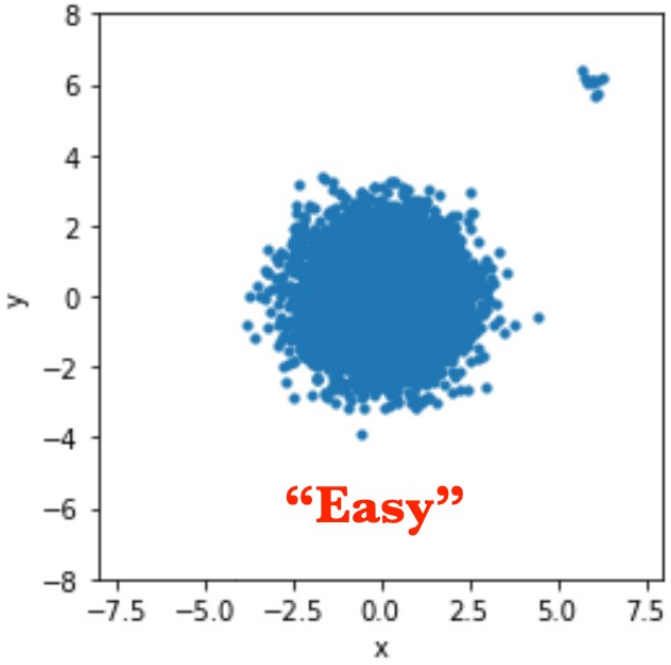


mass density vs arc height off disk, azimuthally averaged

From 2012.11477

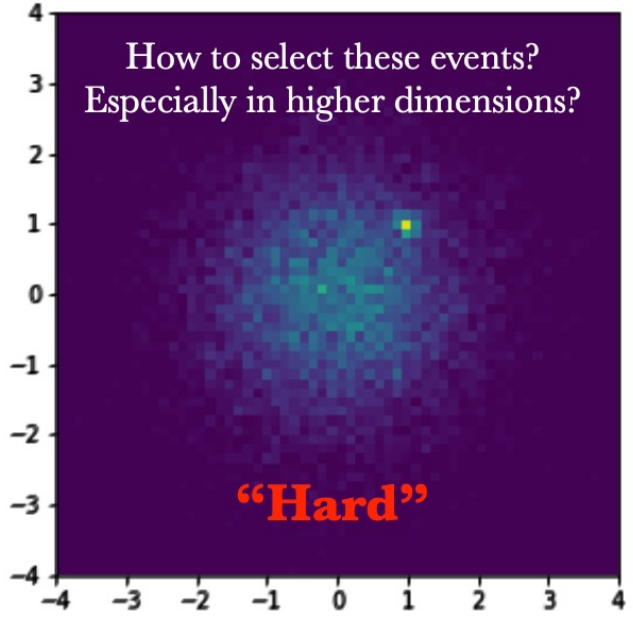


Anomaly Detection



Outliers

Resonant AD @ LHC



Overdensities

Anomaly Detection - это метод машинного обучения и статистики в обнаружение аномалий , который автоматически находит редкие события, точки данных или шаблоны, сильно отличающиеся от нормального поведения системы

• Генеративные модели ускоряют моделирование и выводы во многих различных областях.
• Оценка плотности фазового пространства звезд Gaia позволяет проводить новые трехмерные измерения локального потенциала, поля ускорения и плотности массы.
• Существует множество новых идей для обнаружения аномалий, и они постепенно превращаются в новые, не зависящие от модели, поиски в рамках Запредельной модели на БАК.
• Появляется гораздо больше данных, включая HL-LHC, DESI, Gaia DR4/DR5, Euclid, LSST, Roman, SKA.
• Современное машинное обучение дает нам новые способы гораздо глубже изучать данные. Нас ждет огромный нераскрытый потенциал открытий!
• Кроме того: генеративный искусственный интеллект — в виде агентов-помощников на основе ИИ — может ускорить темпы исследований в области машинного обучения в физике высоких энергий и за ее пределами.