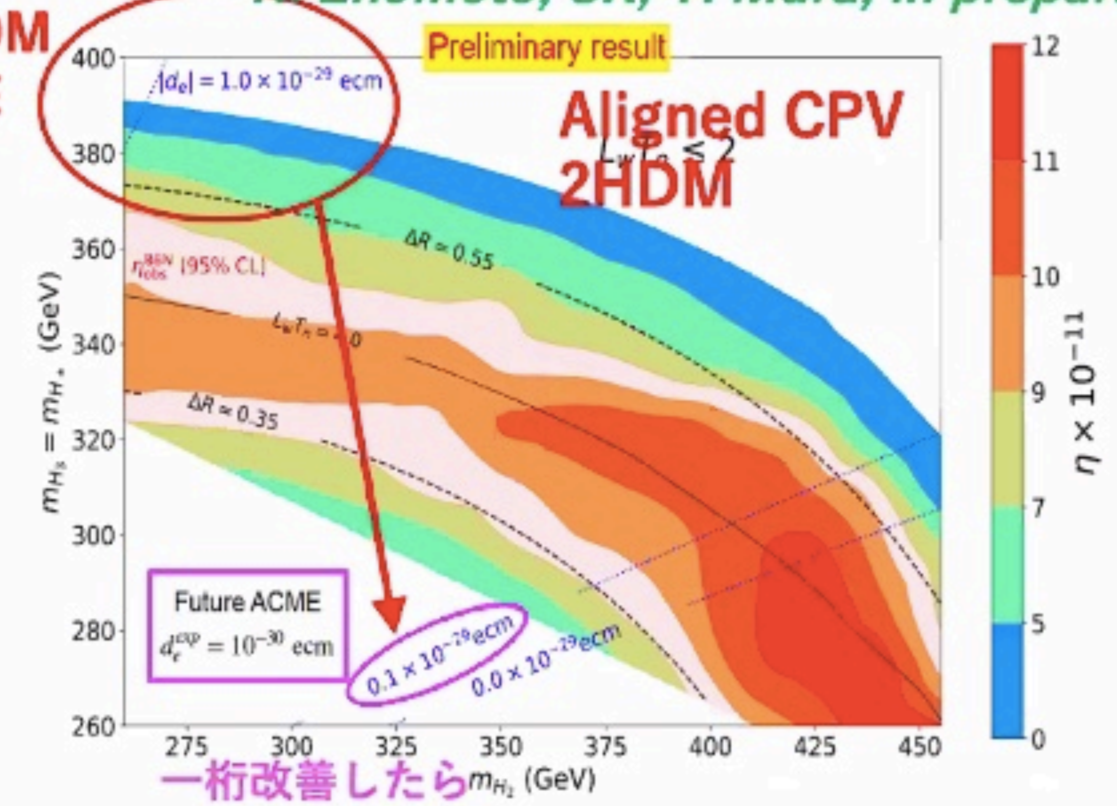
CPの破れ

- EDM実験の今後（一桁程度改善）

  多くの模型は強い制限を受け棄却

  この模型でも一桁程度の改善でかなりの領域を
  検証できる

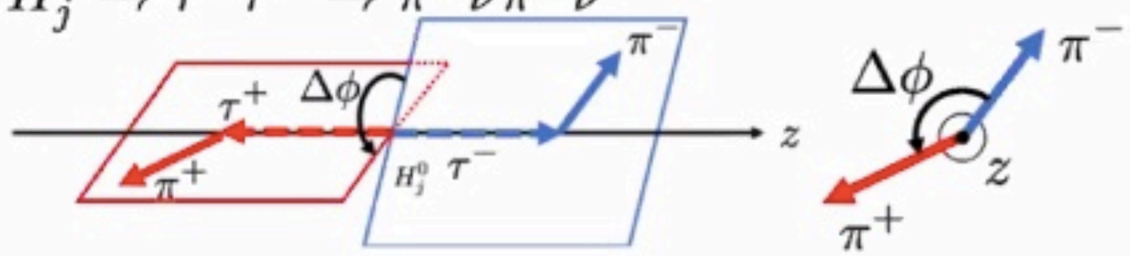
K. Enomoto, SK, Y. Mura, in preparation



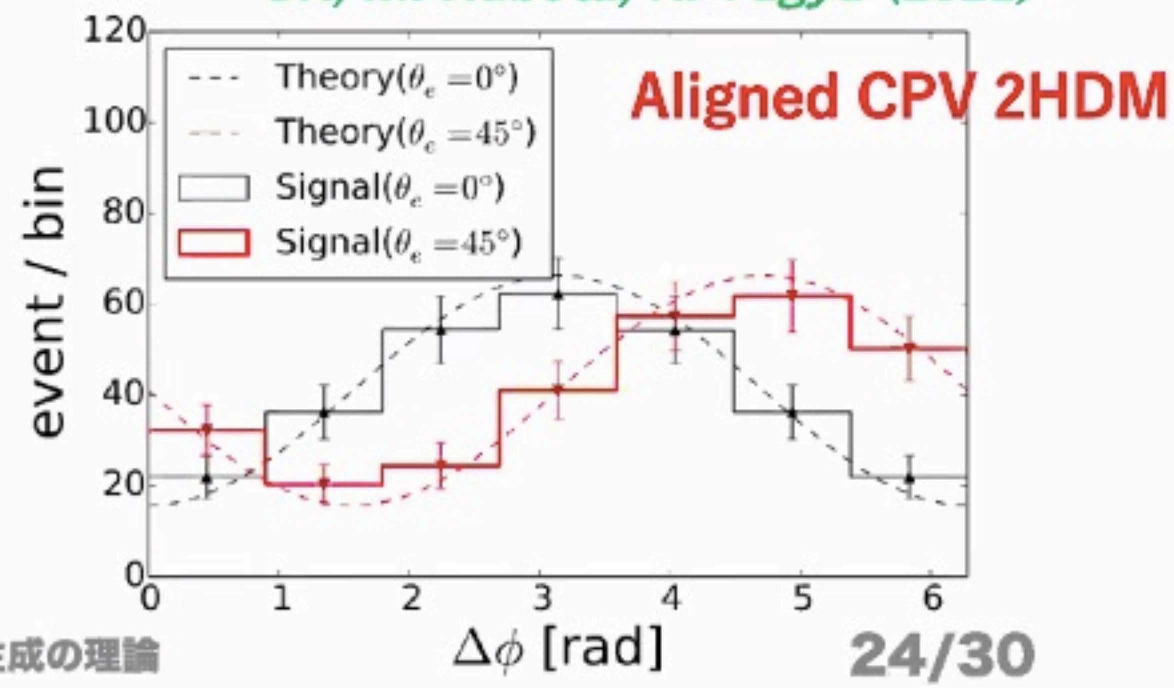
- ILCでの重いヒッグス崩壊 *D. Jeans (2016)*

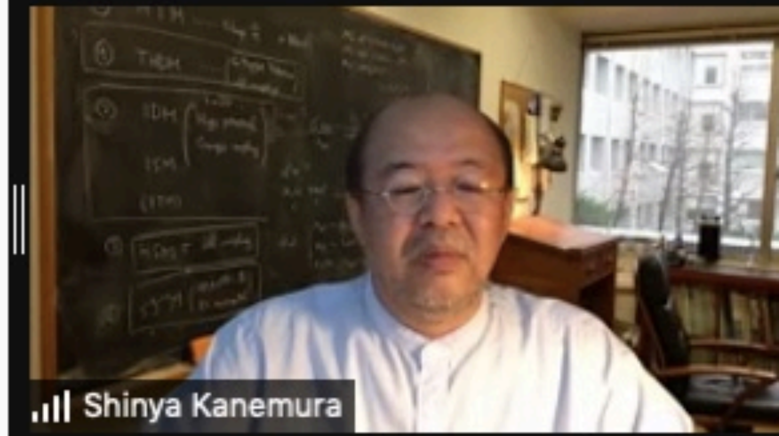
  $e^+ e^- \rightarrow H_2 H_3$

  $H_j^0 \rightarrow \tau^+\tau^- \rightarrow \pi^+\bar{\nu}\pi^-\nu$



SK, M. Kubota, K. Yagyu (2021)

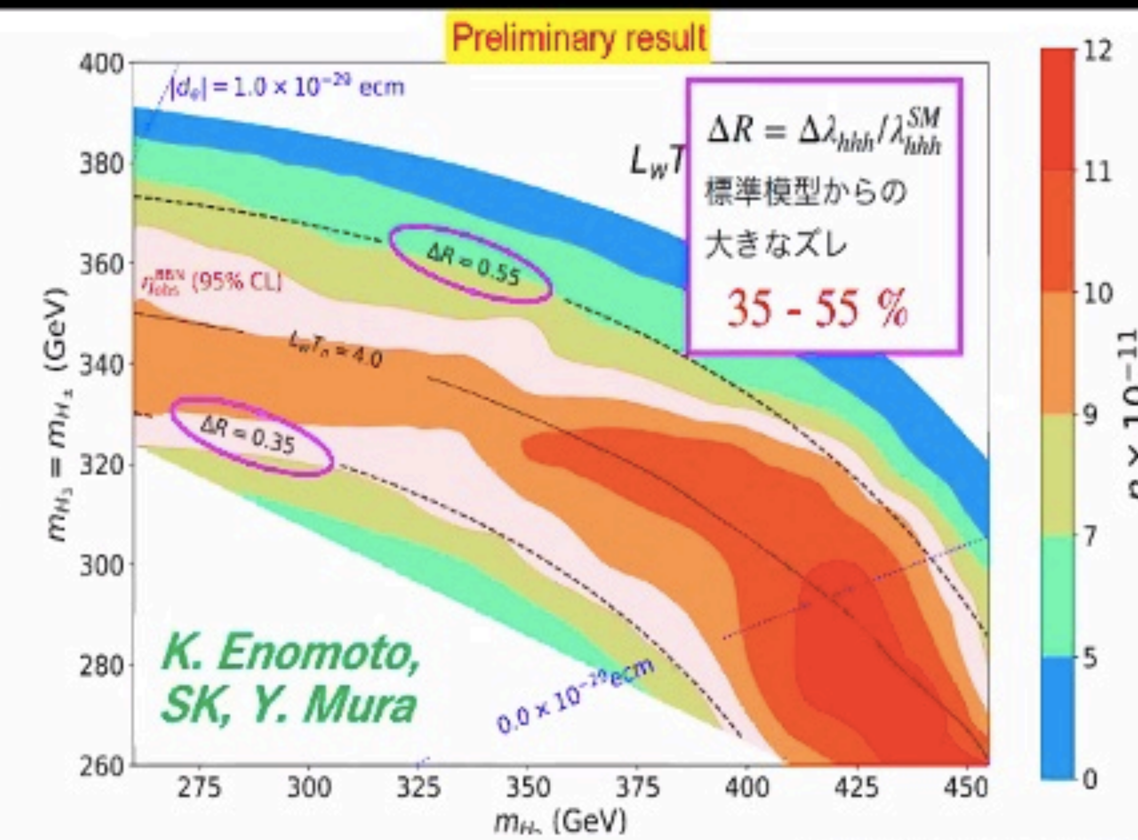




強い電弱一次相転移

強い一次的相転移 → ヒッグス３点結合(hhh)に20%以上の大きなずれ

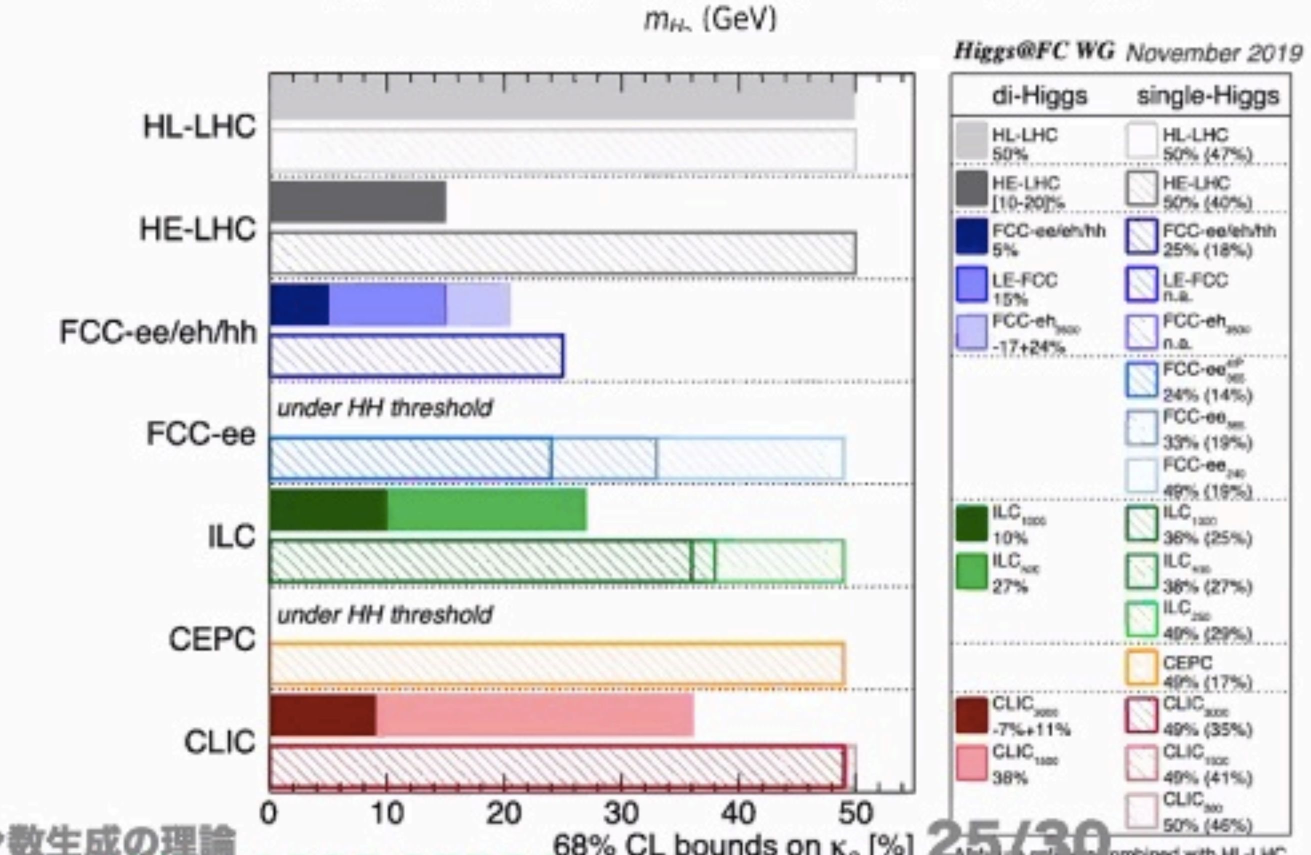
Grojean, Servant, 2005
SK, Y. Okada, E. Senaha 2005



将来実験で３点結合は
10% 程度(68%CL)で測られる

$$pp \to hhX$$

$$e^+e^- \to Zhh$$
$$e^+e^- \to \nu\bar{\nu}hh$$



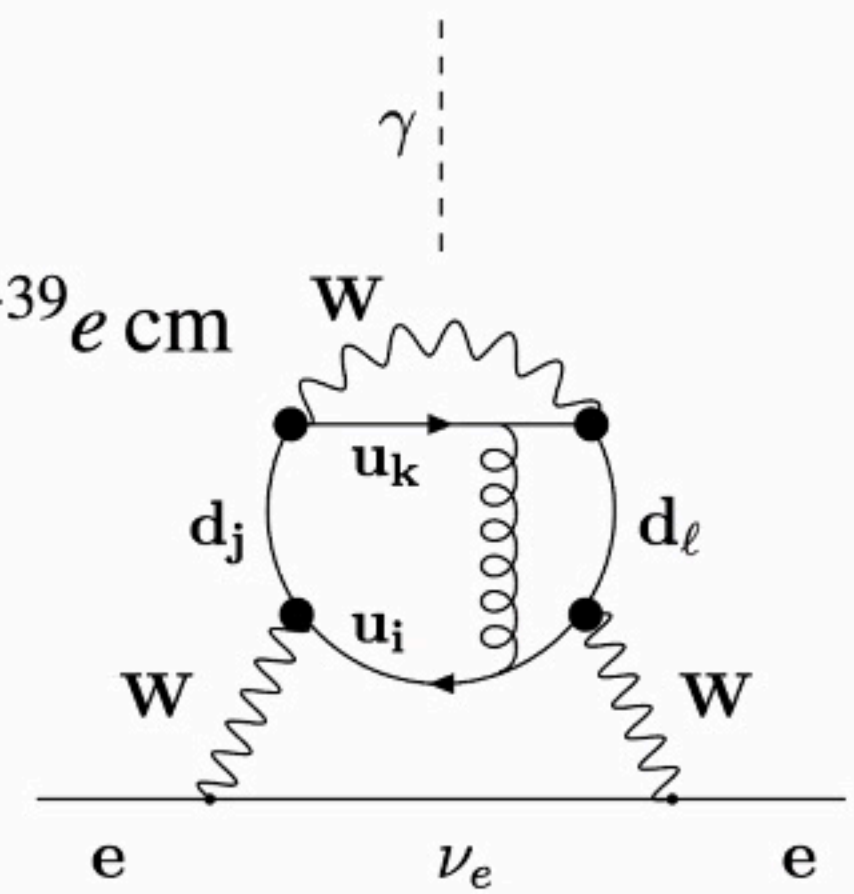
arXiv: 1905.03764

EDMの理論値

<u>標準理論内</u>

(4-loops!)

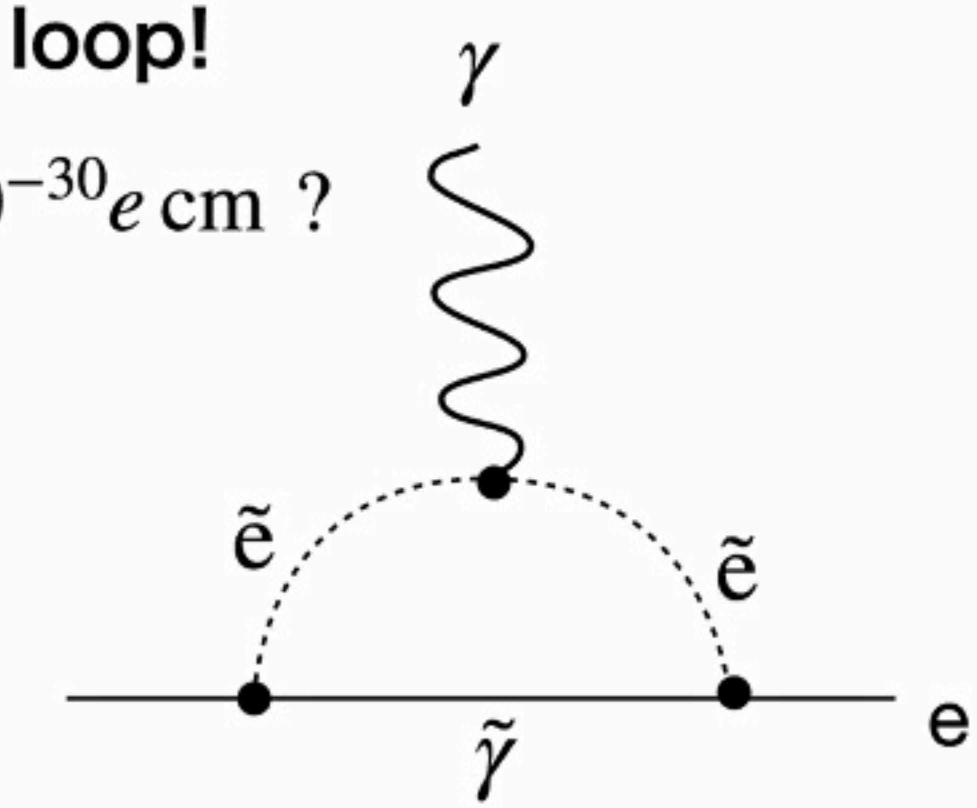
$d_e^{(\mathrm{SM})} \simeq 10^{-39} e\,\mathrm{cm}$



<u>超対称性粒子を仮定</u>

Only 1 loop!

$d_e^{(\mathrm{BSM})} \sim 10^{-30} e\,\mathrm{cm}$?

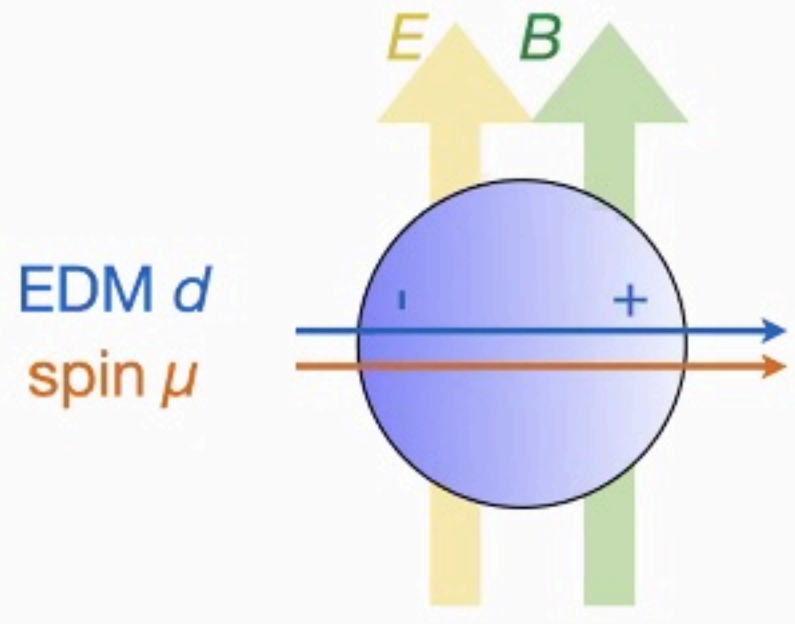


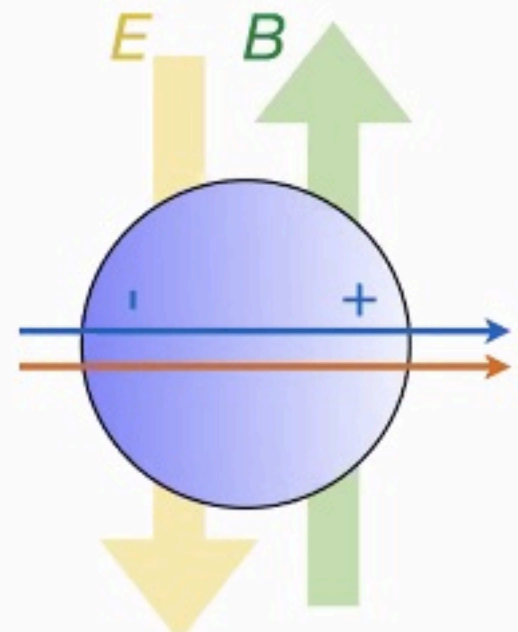
標準理論でのEDMは非常に小さい

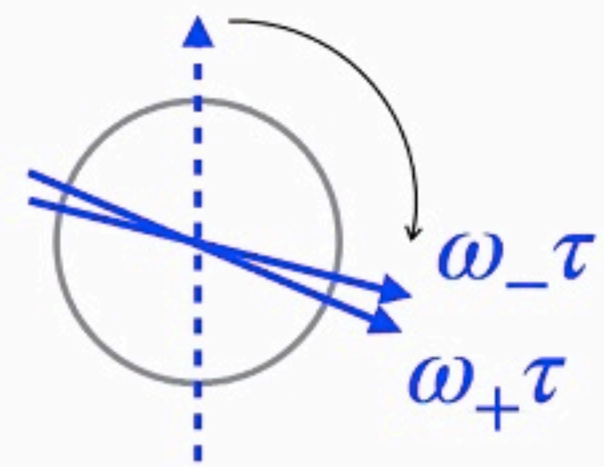
→ 標準理論を超えたCP非保存項の、極めて優れたプローブ

EDM測定方法

電磁場を反転させ、スピン歳差周波数の差を測る







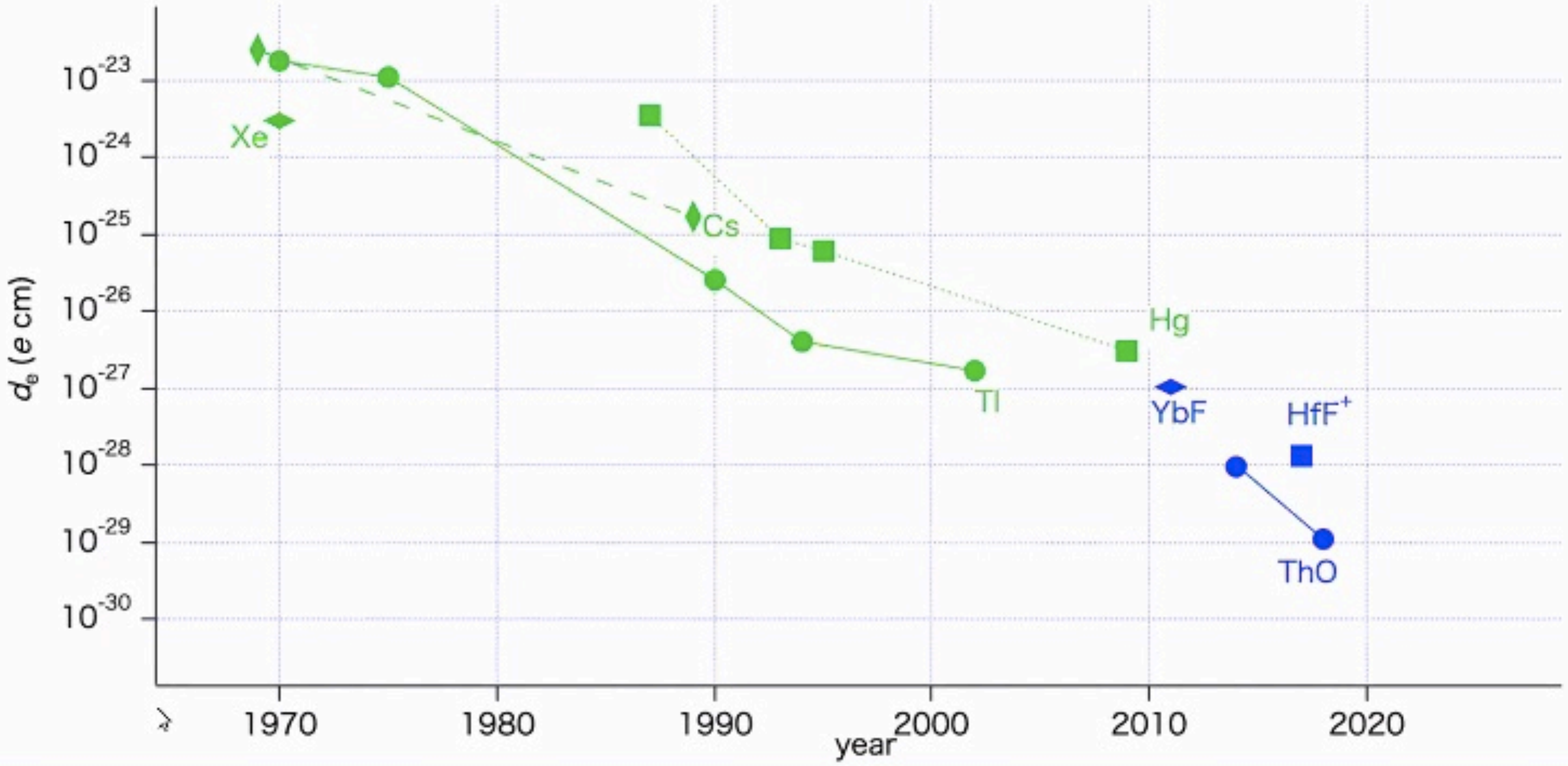
$$\omega_+ = 2\frac{\mu B + dE}{\hbar} \qquad \omega_- = 2\frac{\mu B - dE}{\hbar} \qquad \Rightarrow d = \frac{\hbar(\omega_+ - \omega_-)}{4E}$$

（統計）実験精度： $\Delta d_{\mathrm{e}} \sim \frac{\hbar}{E\tau}\frac{1}{\sqrt{\dot{n}T}}$

電子 EDM (eEDM, d_e)

- 素過程のd_eは（例えBSMでも）とても小さい。
- 複合粒子系でd_eを測定することで、**感度を増幅**することが可能。

原子・分子を用いた電子EDM測定



$$\Delta d_e \sim \frac{\hbar}{E\tau}\frac{1}{\sqrt{\dot{n}T}}$$

⇩

$$\Delta d_e \sim \frac{\hbar}{E_{\mathrm{eff}}\tau}\frac{1}{\sqrt{\dot{n}T}}$$

Key factors

東大CNS 長濱さん、小澤さんより提供

$$\delta d_e \sim \frac{\hbar}{2KE\tau\sqrt{Nn}}$$

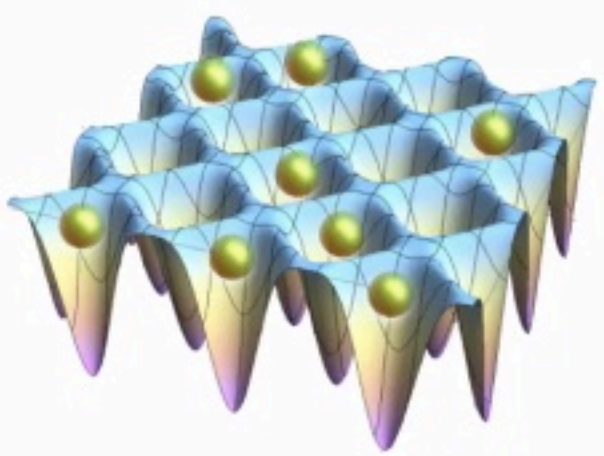
EDM 増幅度K:

電場強度

相互作用時間

測定あたりの原子数

測定回数



Regan, B.C., *et al.*, Phys. Rev. Lett **88**(2002)071805.

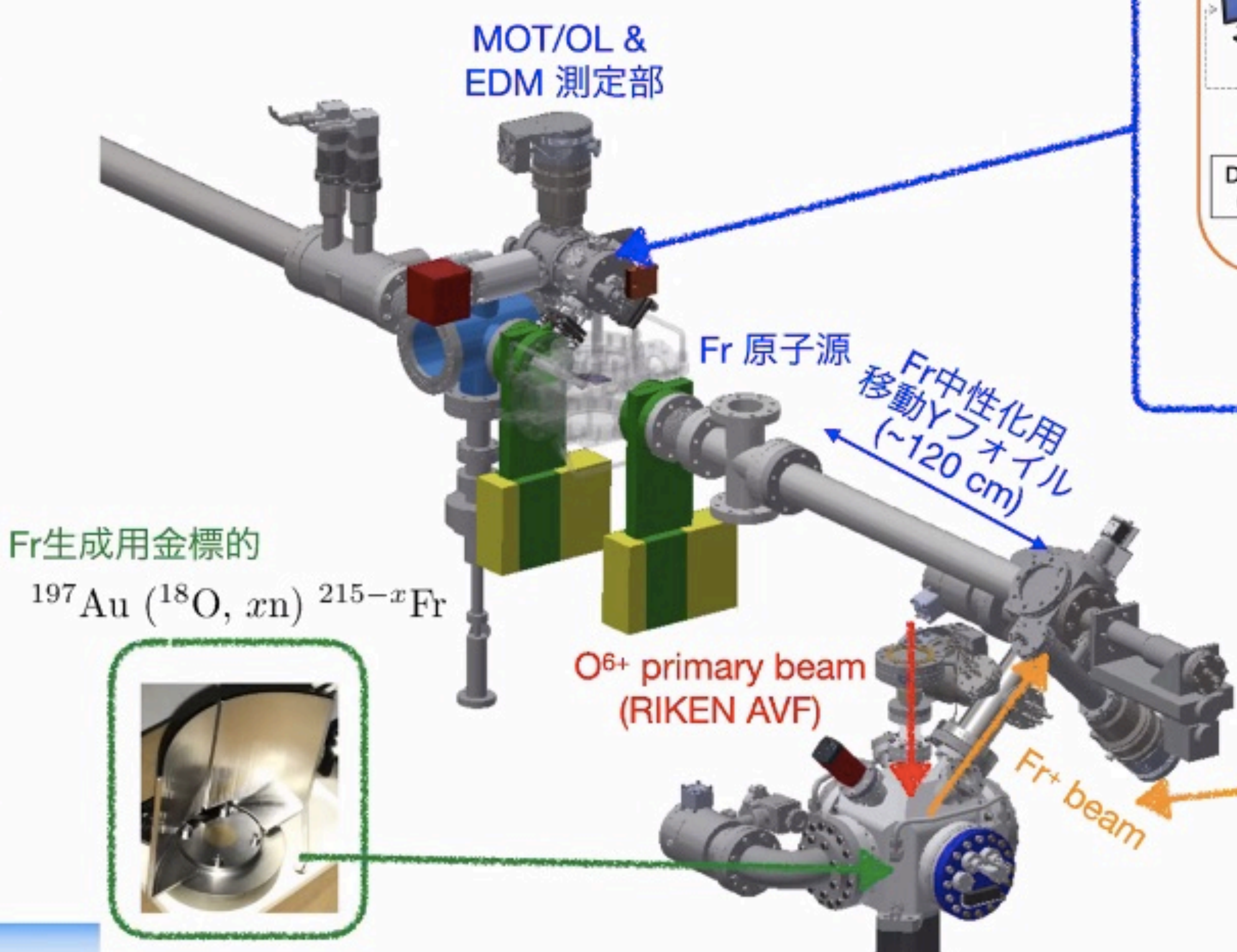
Chin, C., *et al.*, Phys. Rev. A **63**(2001)033401.

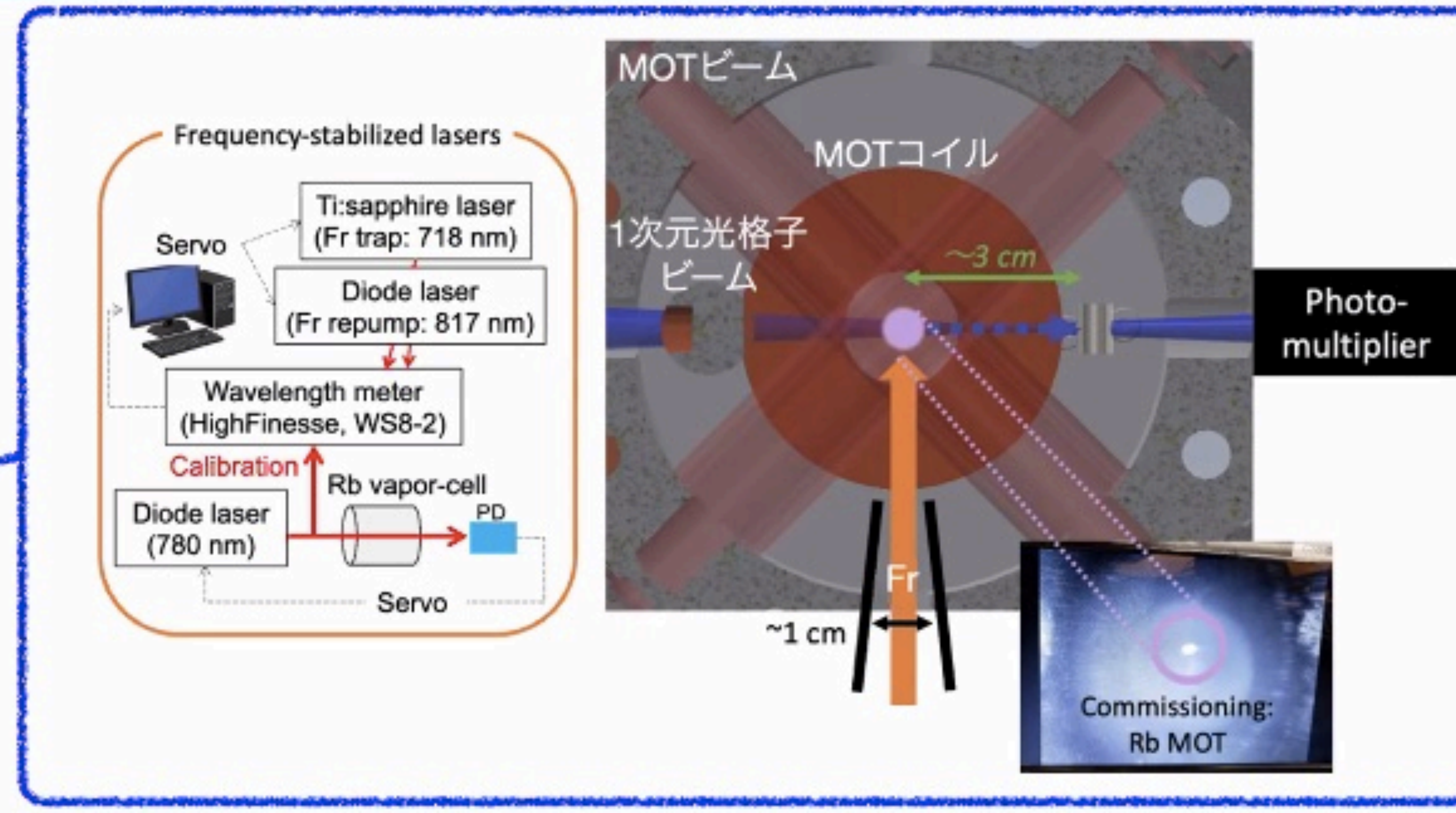
	K	*E*	*τ*	*N*	*n*	δd_e
Tl beam	550~600	123 kV/cm	~2 ms	10^7 - 10^9/s	1988 bp	1.6×10^{-27} e cm
Cs lattice	114	100 kV/cm	1 s	10^8	10^4	3×10^{-29} e cm
Fr lattice	799	100 kV/cm	1 s	10^6	10^6	4×10^{-30} e cm

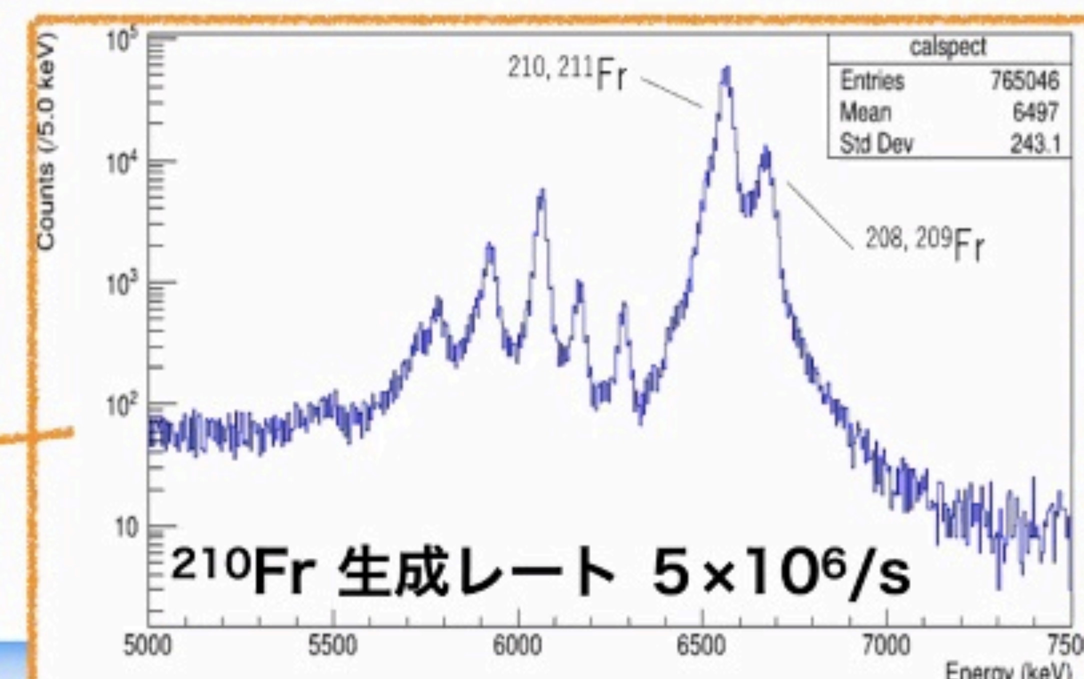
R&D

東大CNS 長濱さん、小澤さんより提供

- ^{210}Fr 生成レート 5×10^6/s を達成
- Rb原子での中性化、MOTに成功

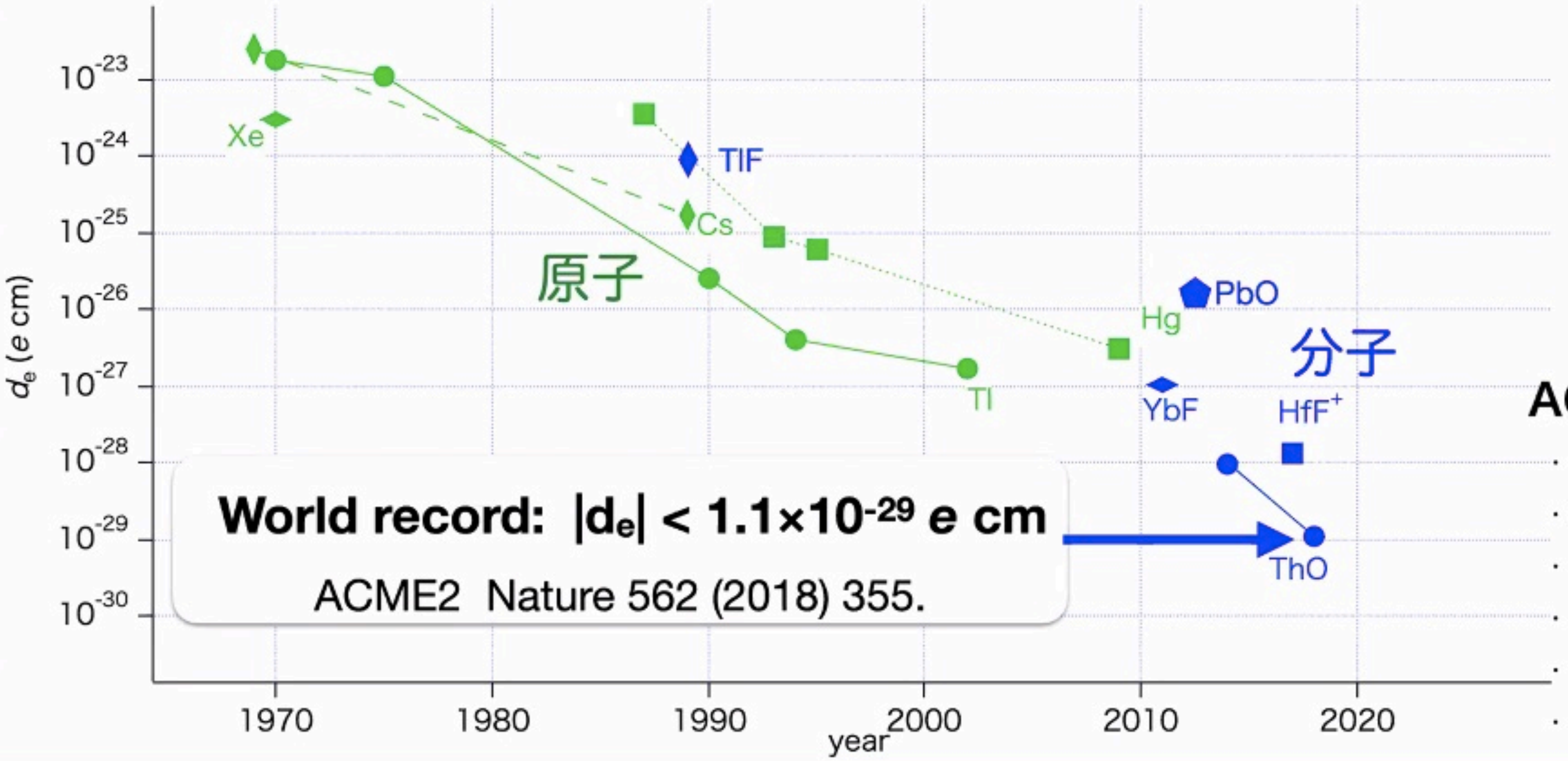






分子で測るeEDM

近年の冷却分子制御技術の発達により、分子でのeEDM測定が感度を押し上げている。



ACME3 Collaboration:

- Harvard University
- Northwestern University
- University of Chicago
- CalTech
- UC Berkeley
- 岡山大学

分子のメリット (ThOなどの場合)

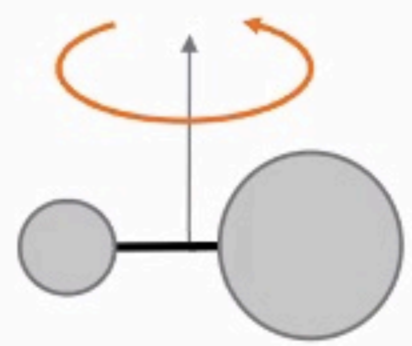
"DeMille method"

Ω-doublet

弱い外部電場で**大きな内部電場**が発生

回転準位間エネルギー

ΔE ~ 10 GHz
P ~ O(1) @ 10 kV/cm

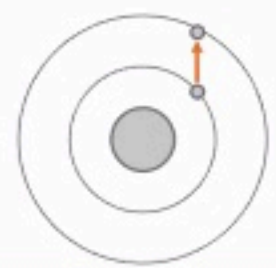


<u>Ω-doublet の場合</u>

ΔE ~ 10 MHz
P ~ O(1) @ 10 V/cm

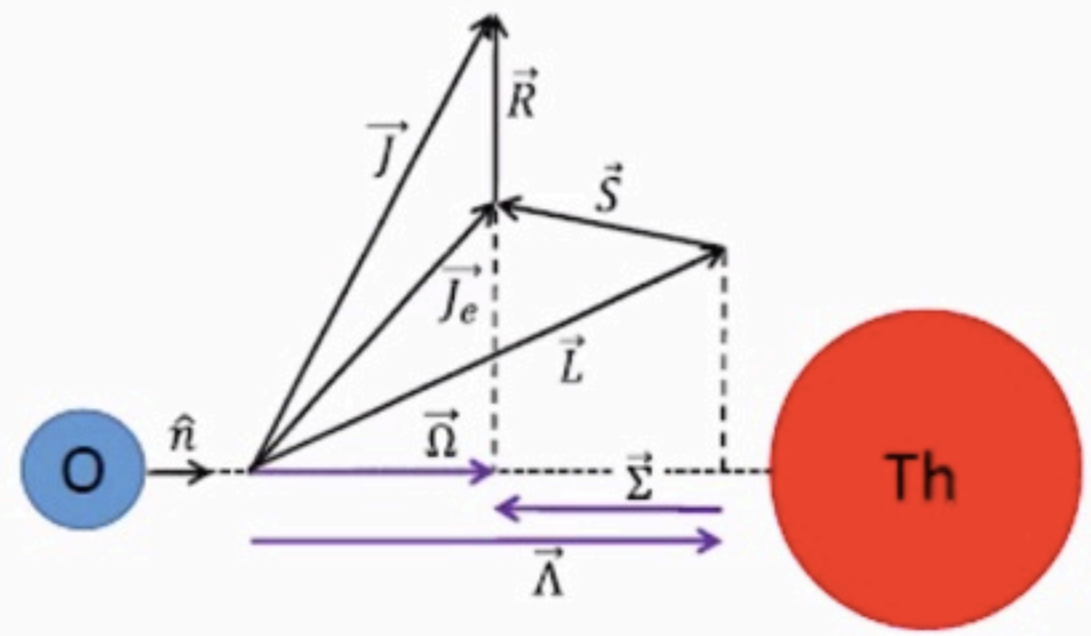
<u>（参考）原子の場合</u>

ΔE ~ 10 THz
P ~ O(10-3) @ 10 kV/cm



$^3\Delta_1$

電子スピンと軌道角運動量で、
磁気モーメントを相殺
→ **磁場に不感**



$\mu_L = g_L \Lambda \mu_B = -2\mu_B$ $\mu_S = g_S \Sigma \mu_B \approx +2\mu_B$

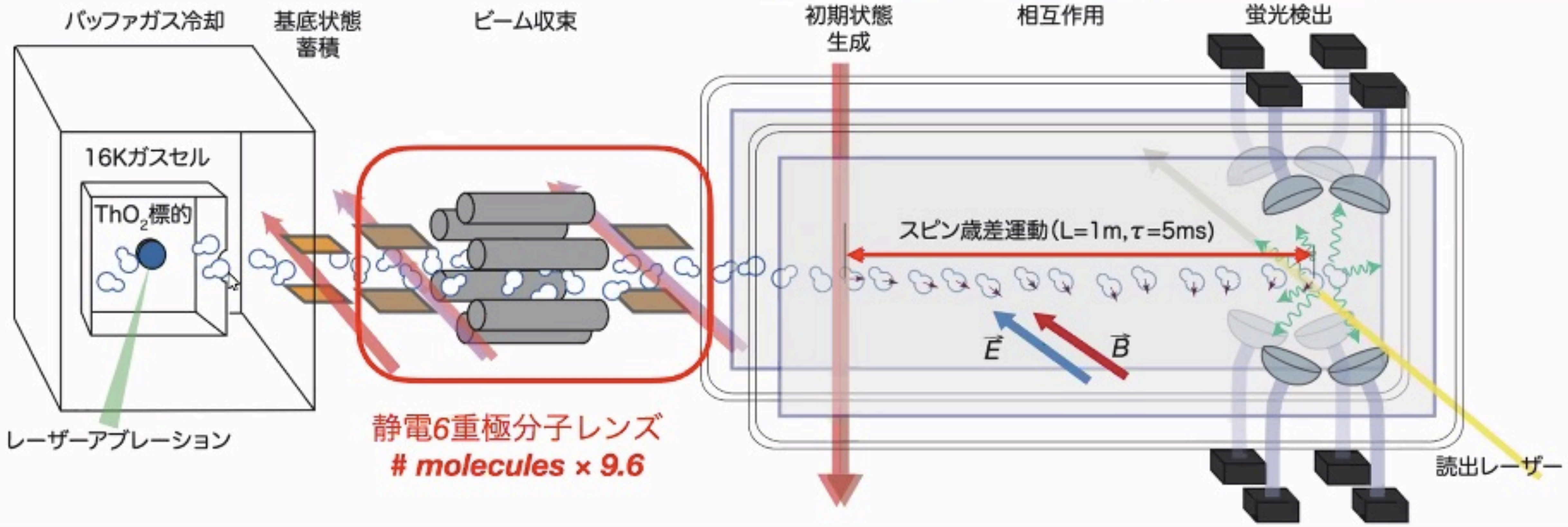
$\mu_H = \mu_L + \mu_S \approx 0$

ACME 2 → ACME 3

Statistical sensitivity:

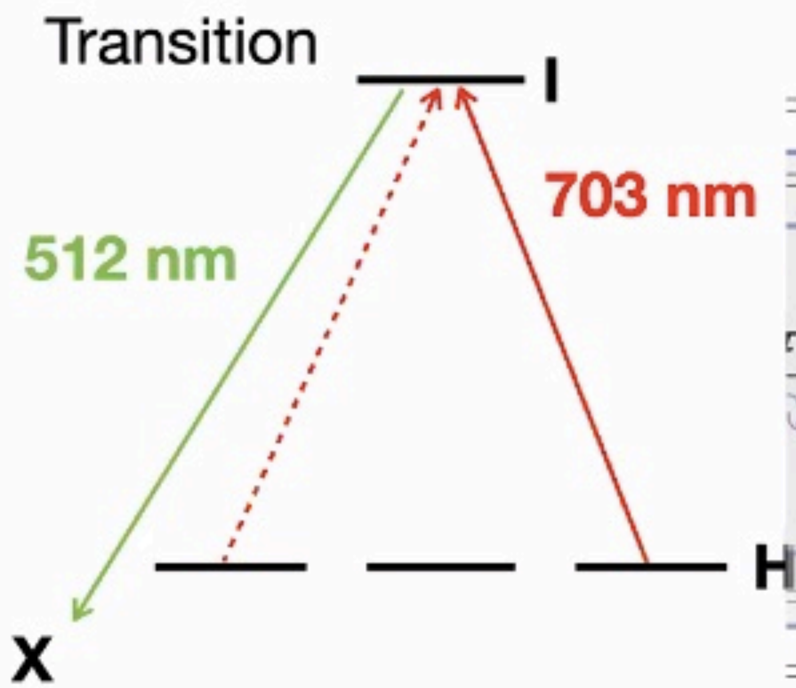
$$\Delta d_e \sim \frac{\hbar}{E_{\rm eff}\tau}\frac{1}{\sqrt{\dot{n}_{\rm mol}T}}\sqrt{\frac{F}{\varepsilon_{\rm det}}}$$

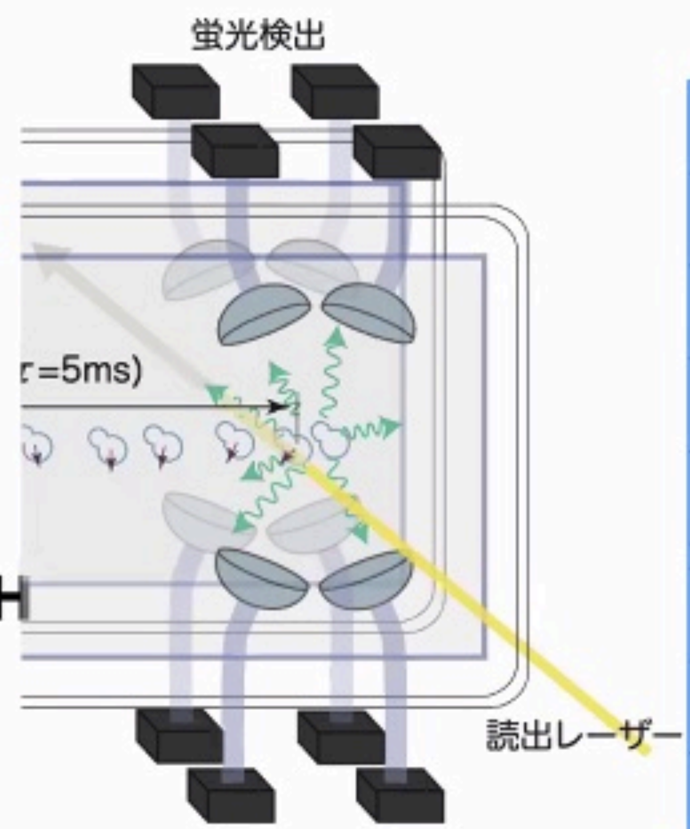
Improvement	Signal gain	EDM sensitivity gain
Longer precession time	0.45	3.1
Electrostatic lens	9.6	3.1
Detector upgrade	2.3	1.5
Collection optics	1.5	1.2
Timing jitter reduction	1	1.7
Total	**14.9**	**31.8**



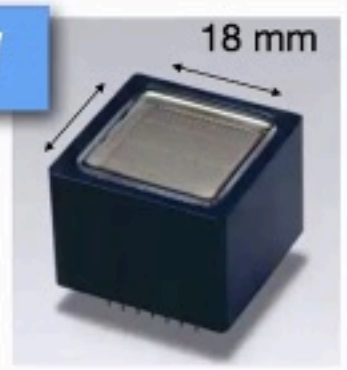
光検出器アップグレード: PMT → SiPM

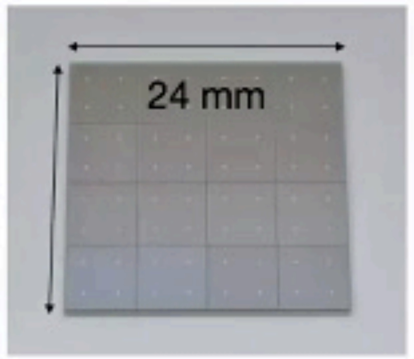
Final state readout





PMT vs. SiPM





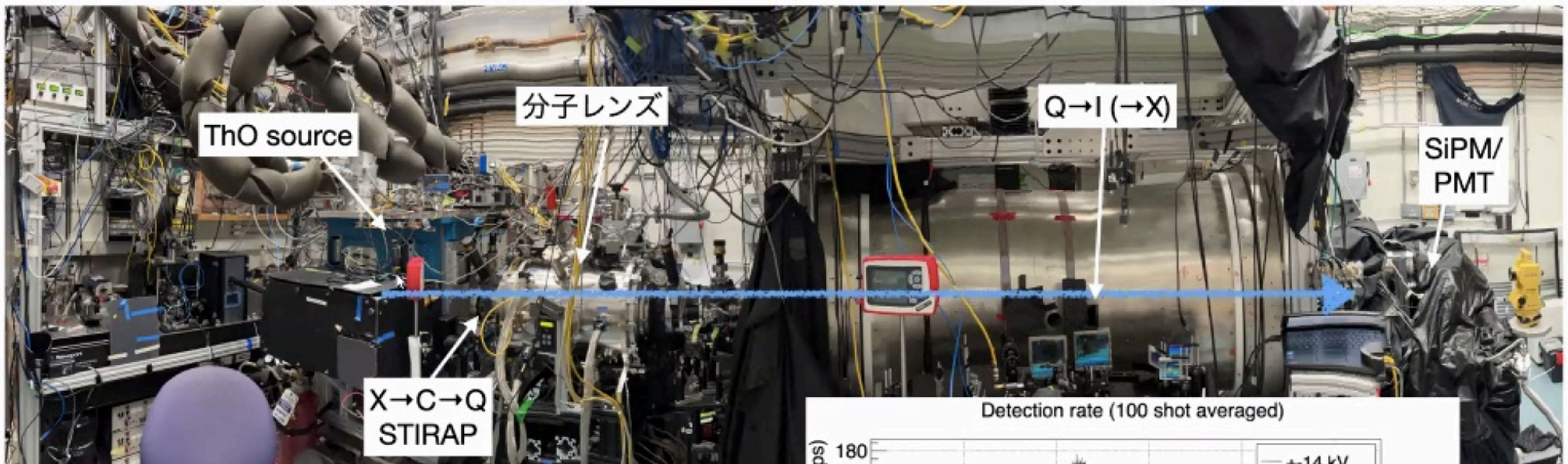
	ACME II PMT	Advanced ACME SiPM	
Part No.	R7600U-300	S13361-6075NE-04	
Sensitive area	18×18 mm²	24×24 mm² (16 ch.)	*pros.*
Q.E. @ 512 nm	**~25%**	**~45%**	*pros.*
Excess noise *F*	~1.2	~1.2 (depend on CT & AP)	
Q.E. @ 703 nm	~0.6%	~ 20%	*cons.*
Dark count @ 25°C	~ 3 kcps	~ 2 Mcps/ch	*cons.*
Capacitance	few pF	1.4 nF	*cons.*

***PMT**から**SiPM**に変えることで、量子効率を2倍改善。面積も拡大し幾何効率も向上。*

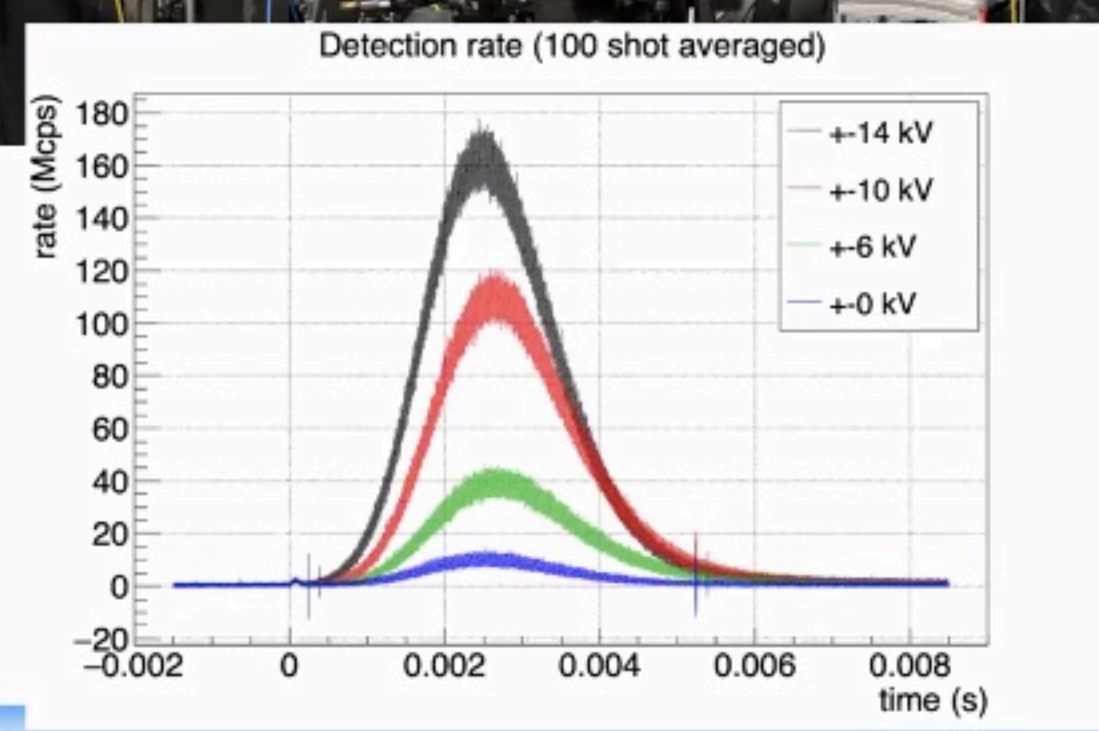
平本綾美 16aT3-5
T. Masuda *et al*., Opt. Express **29** 16914 (2021).

第二試作機試験状況 (2021/8末)

- 新規開発の分子レンズと組み合わせ、分子蛍光検出試験を実施　@Harvard



2021/8/27,30
SiPM検出器での分子信号初観測



Spin precession

- 電磁場中でのμのspin precession

$$\boldsymbol{\omega} = \boldsymbol{\omega}_s - \boldsymbol{\omega}_c = -\frac{e}{m_\mu}\left[a_\mu \boldsymbol{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\boldsymbol{\beta}\times\boldsymbol{E}}{c} + \frac{\eta_\mu}{2}\left(\boldsymbol{\beta}\times\boldsymbol{B} + \frac{\boldsymbol{E}}{c}\right)\right]$$

spin　cyclotron

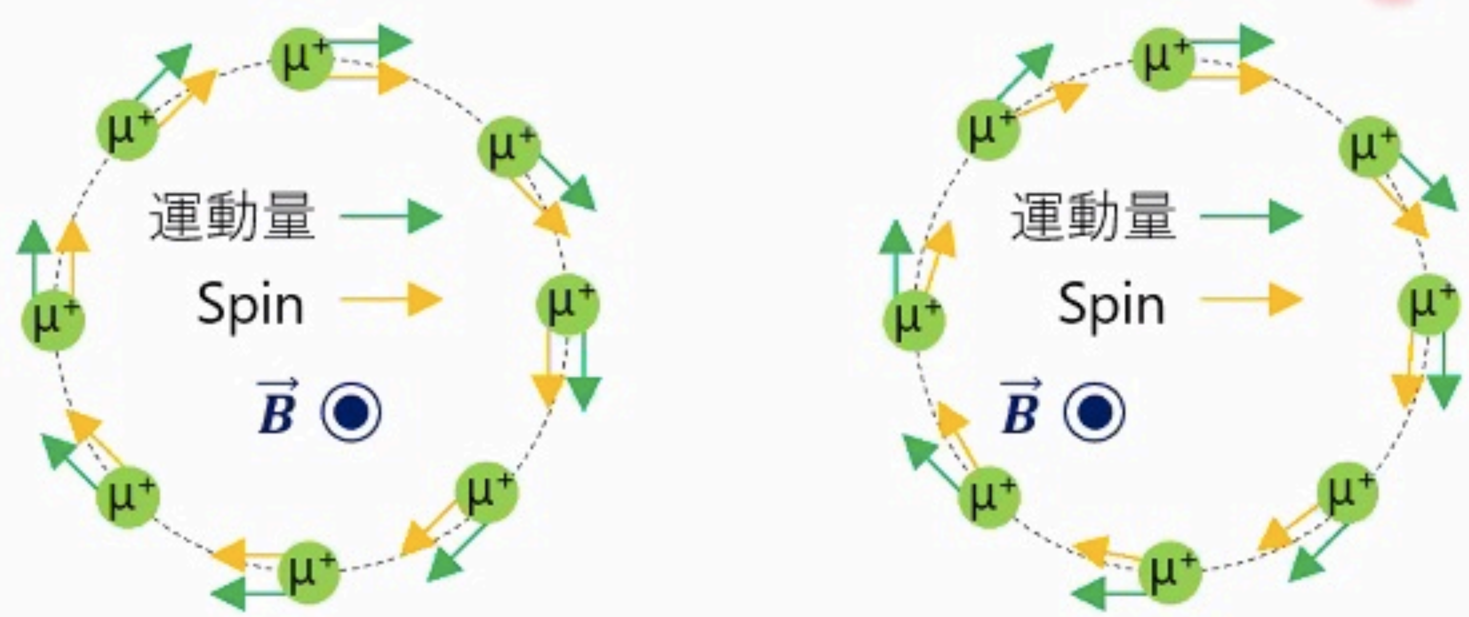
$\boldsymbol{\omega}_a$: MDM, g-2測定

$\boldsymbol{\omega}_\eta$: EDM

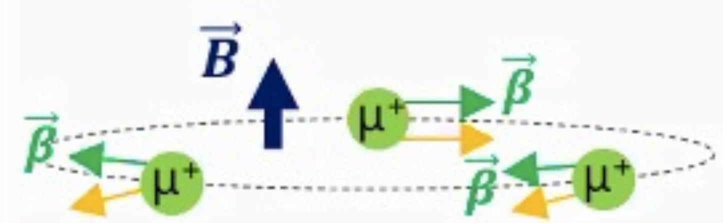
直交

仮にg-2=0 (a_μ=0) なら
$\boldsymbol{\omega}_s = \boldsymbol{\omega}_c$ なので
スピンと運動量はずっと同じ向き

実際は主要項 $a_\mu \sim \alpha/2\pi = 0.00116$
なのでだんだんズレる



回転軸はg-2と直交



$d_\mu \sim 10^{-21}$ e cmのときに
$\omega_\eta/\omega_a \sim 10^{-5}$ 程度

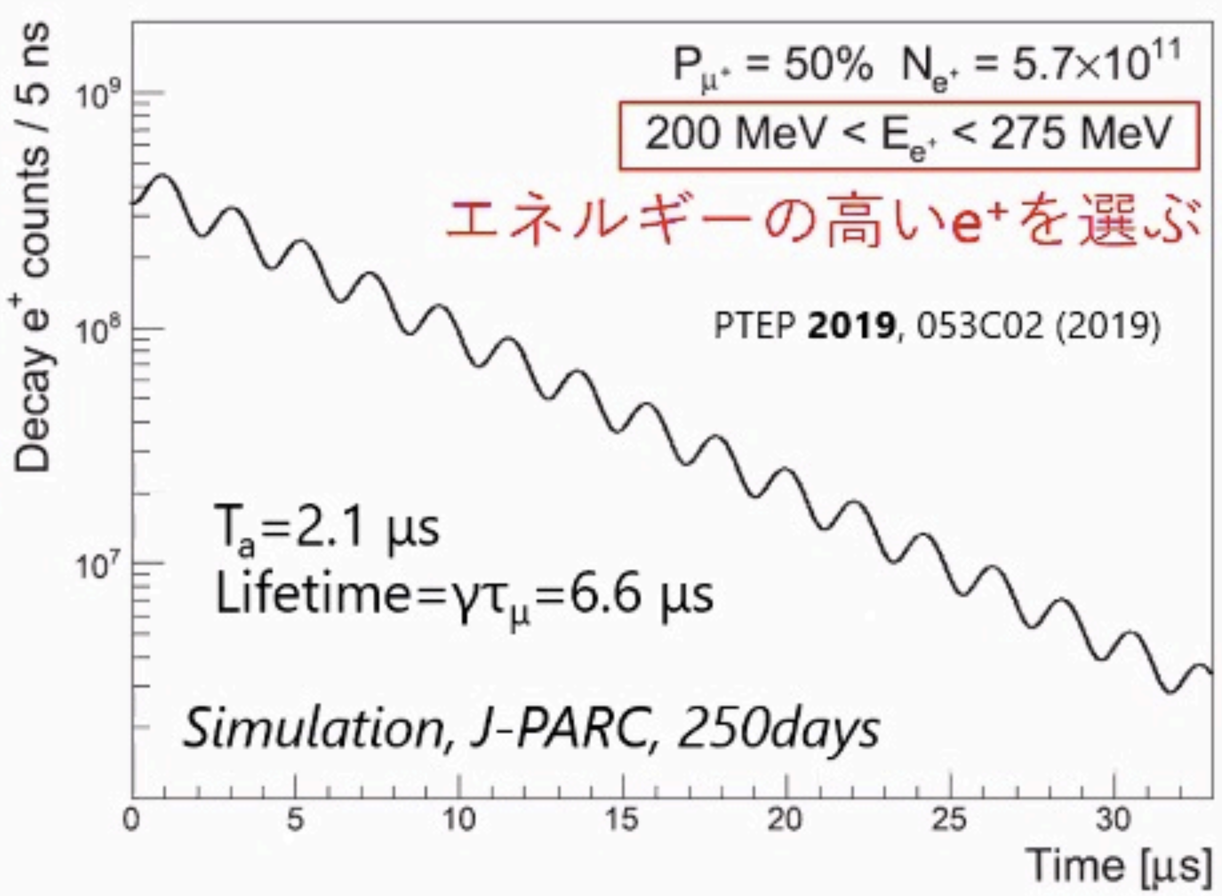
先にg-2測定について

- 仮に10^{-21} *e* cmあったとしても$\omega_\eta/\omega_a \sim 10^{-5}$しかないので、$\omega_a$が主要項

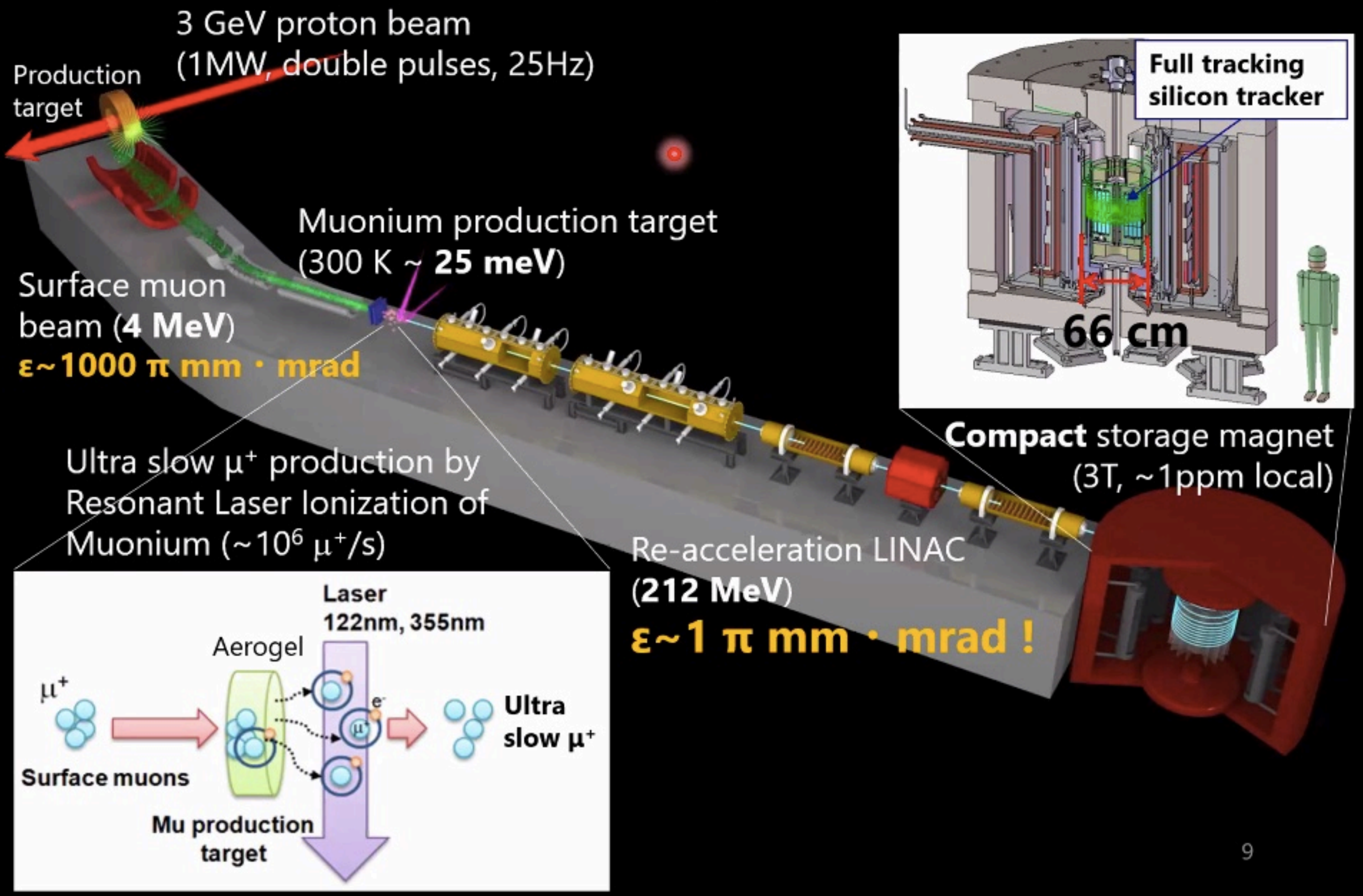
$$\boldsymbol{\omega} = \boldsymbol{\omega}_a + \boldsymbol{\omega}_\eta = -\frac{e}{m_\mu}\left[a_\mu \boldsymbol{B} + \frac{\eta_\mu}{2}\boldsymbol{\beta} \times \boldsymbol{B}\right]$$

- $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$崩壊で$e^+$は$\mu^+$のspinの向きに出やすい
- ブーストされてμ^+偏極と崩壊e^+のエネルギーに相関
- 検出器でエネルギーの高い崩壊e^+を選んで時間スペクトルを作ると$\omega \sim \omega_a$での振動が見える→g-2測定

- EDMは？



J-PARC muon g-2/EDM実験



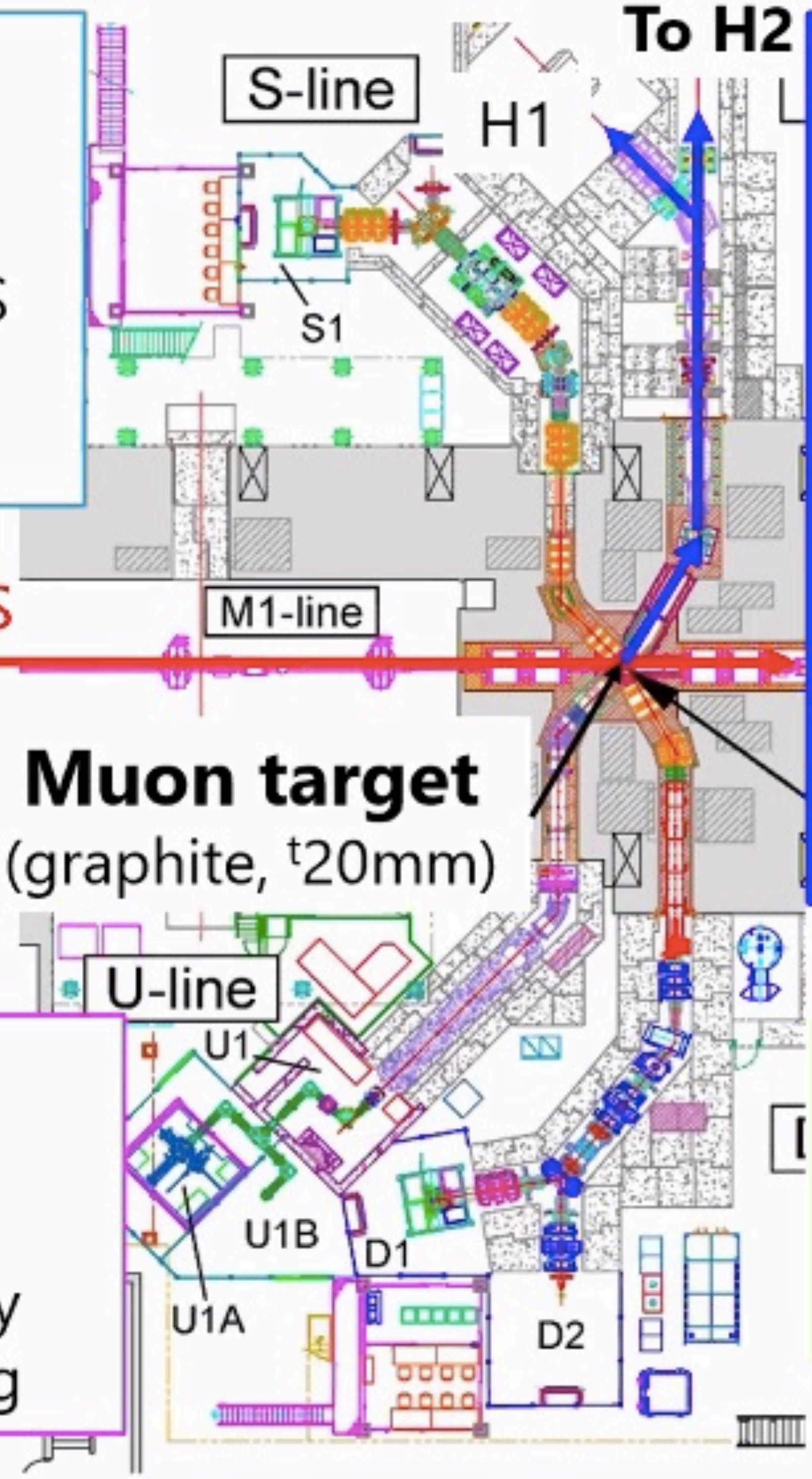
MLFミュオン実験施設（MUSE）

- MUSE (MUon Science Establishment) in the MLF

S-line
- surface μ^+
- S1 area for μSR
- S2 area for Mu 1S-2S
- S3/S4 will be constructed

3GeV proton from RCS

2e15 /s @1MW



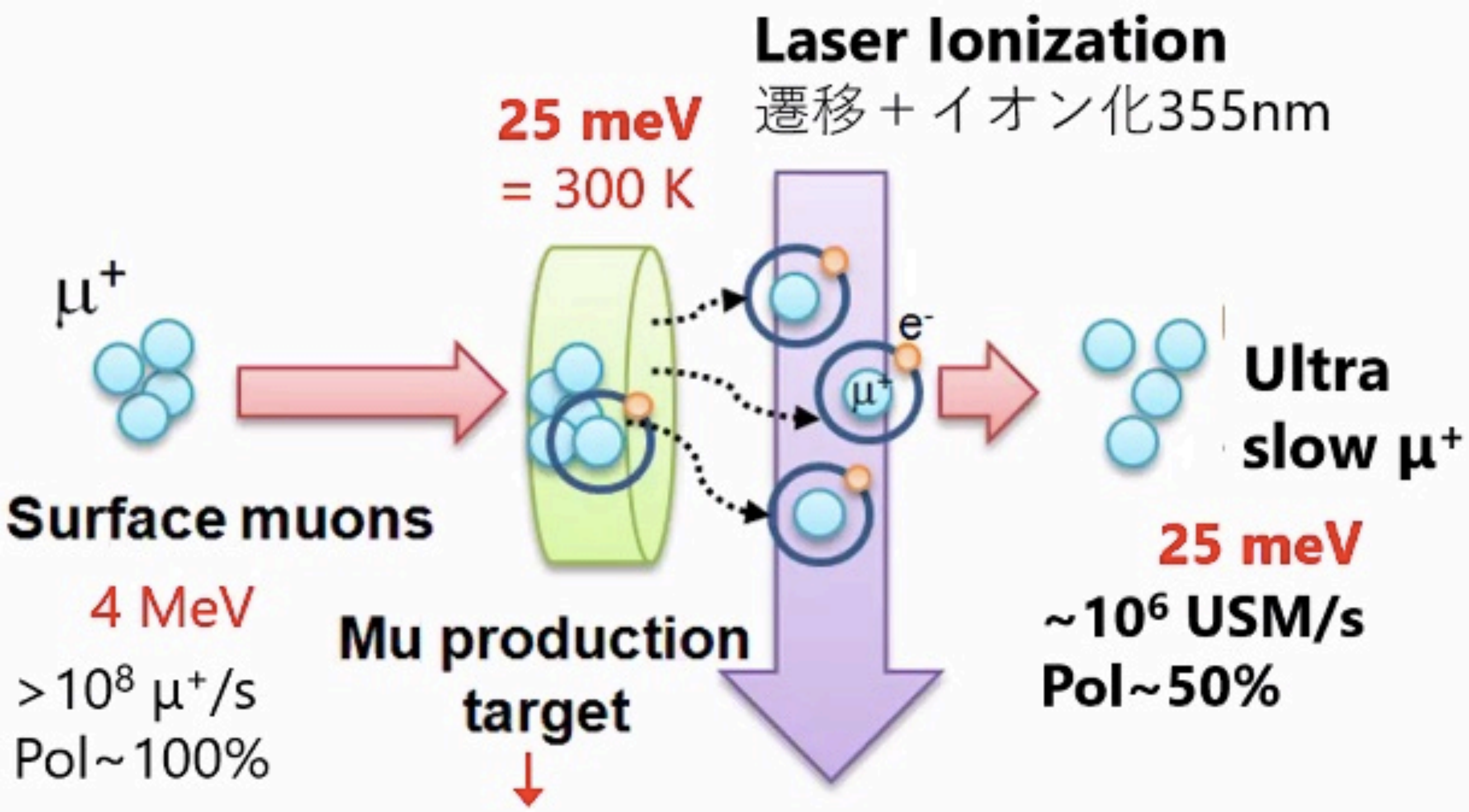
Muon target
(graphite, ^{t}20mm)

H-line
- **surface μ^+ (>10^8 μ^+/s)**, decay μ^+/μ^-, e^-
- **for high intensity & long beamtime** experiments
- H1 for DeeMe & MuSEUM
- **H2** for **muon g-2/EDM** & transmission muon microscopy (TμM)
- **under construction**

U-line
- ultra slow μ^+
- U1A for nm-μSR
- U1B for μ microscopy
- under commissioning

D-line
- decay μ^+/μ^-, surface μ^+
- D1 area for μSR
- D2 for variety of science

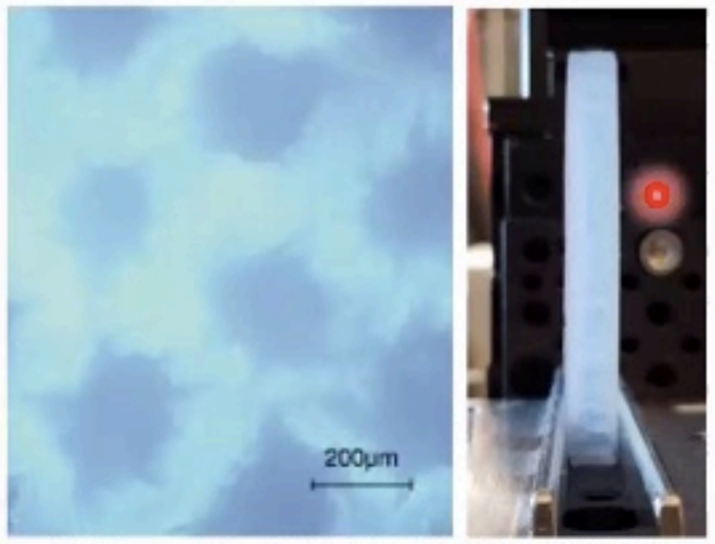
Ultra Slow Muon (USM)



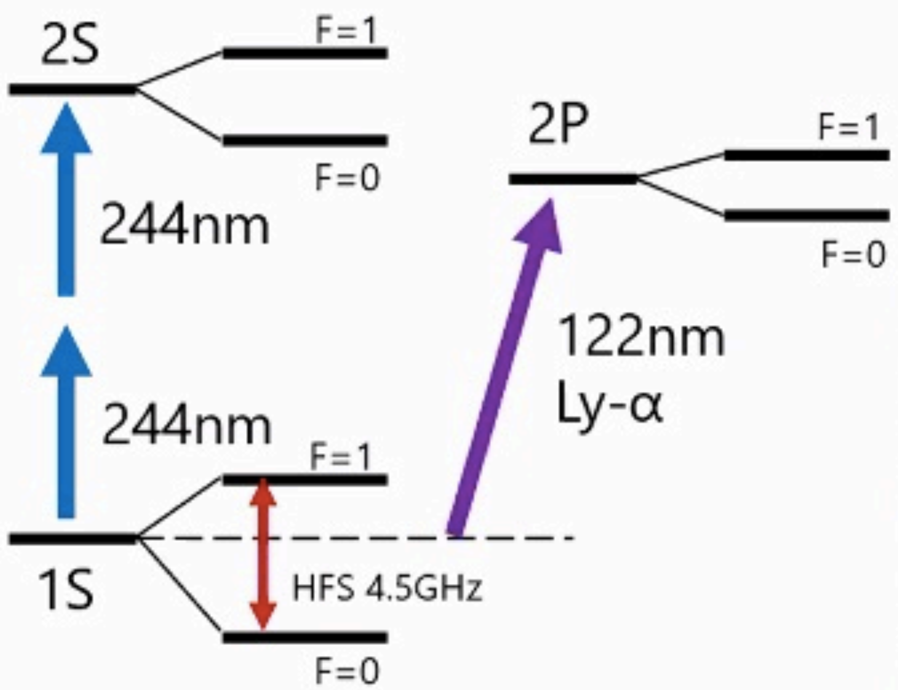
遷移用レーザーの候補

- 1S-2P（122nm, 1光子）
  Uラインで100μJのハイパワー化に向けた開発
- 1S-2S（244nm, 2光子）
  Mu 1S-2S実験@Sラインに向け開発が大きく進展中（岡山大、KEK）

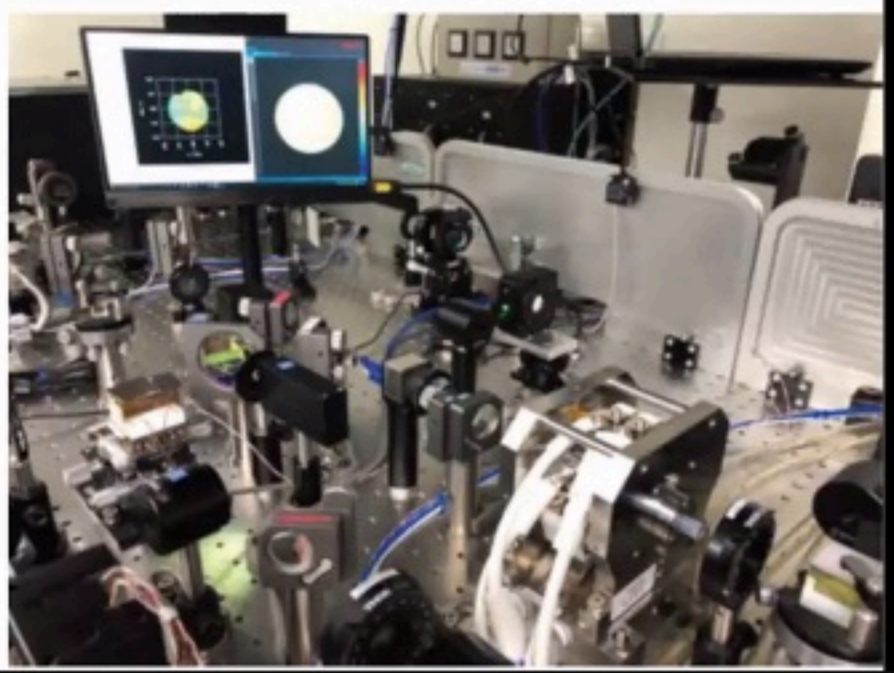
Laser-ablated silica aerogel



G. Beer et al., PTEP (2014)091C01



@U-line

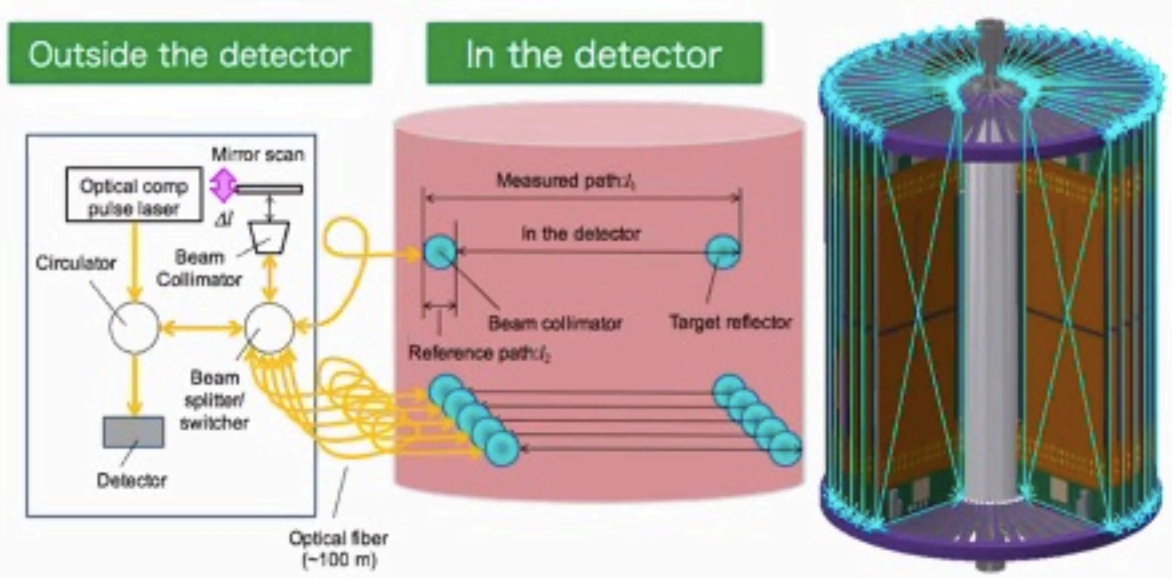


Expected sensitivity

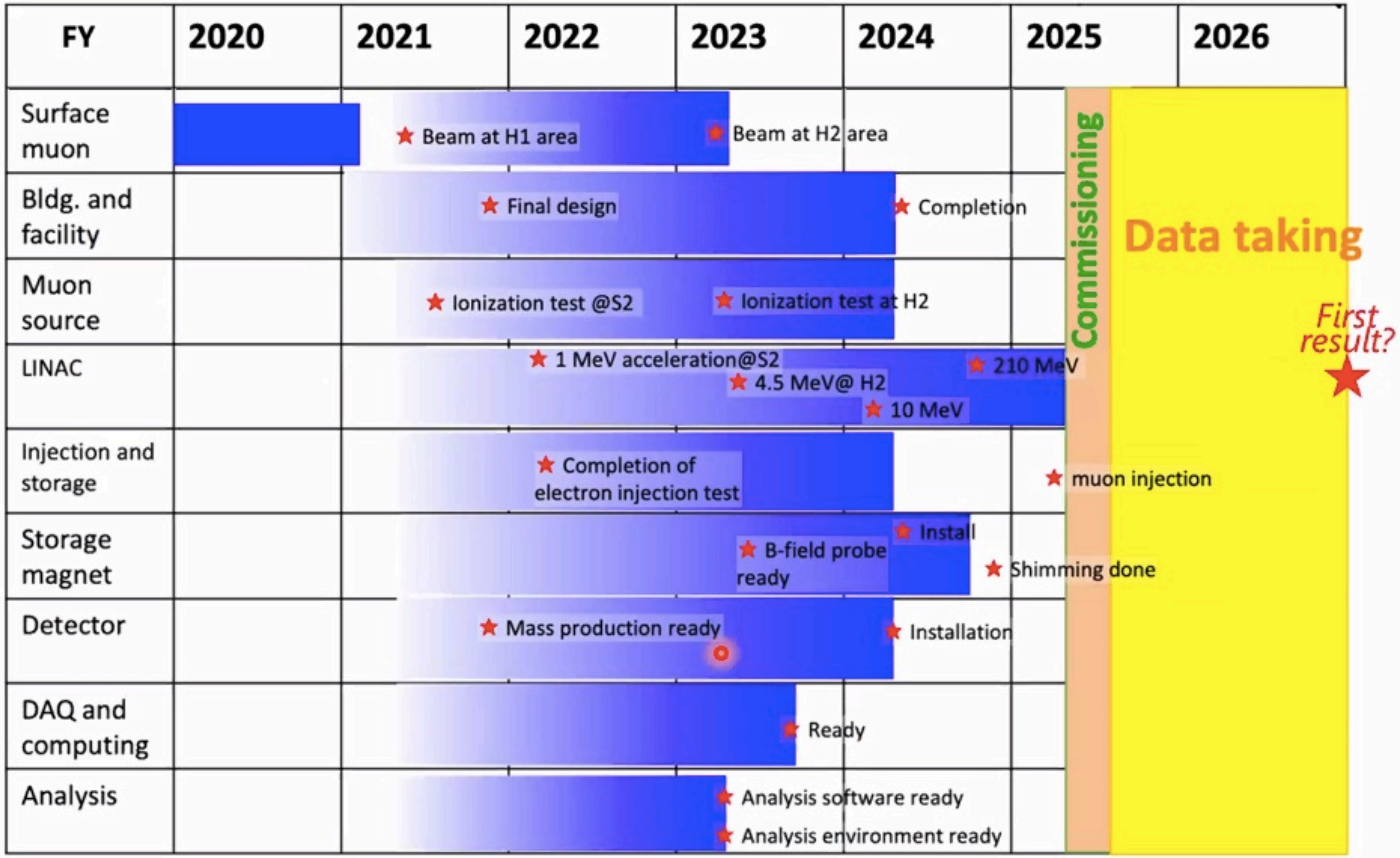
- 250日間のデータ取得でEDMは1.5×10^{-21} *e* cm（g-2は450ppbでFNAL Run 1, BNLとコンパラ）

	Estimation
Total number of muons in the storage magnet	5.2×10^{12}
Total number of reconstructed e^+ in the energy window [200, 275 MeV]	5.7×10^{11}
Effective analyzing power	0.42
Statistical uncertainty on ω_a [ppb]	450
Uncertainties on a_μ [ppb]	450 (stat.)
	< 70 (syst.)
Uncertainties on EDM [10^{-21} e·cm]	1.5 (stat.)
	0.36 (syst.)

- 系統誤差は前ページの検出器のアライメント精度からくる。現在開発中の光コムレーザー干渉計を用いたアライメントモニターの精度が3.6μrad



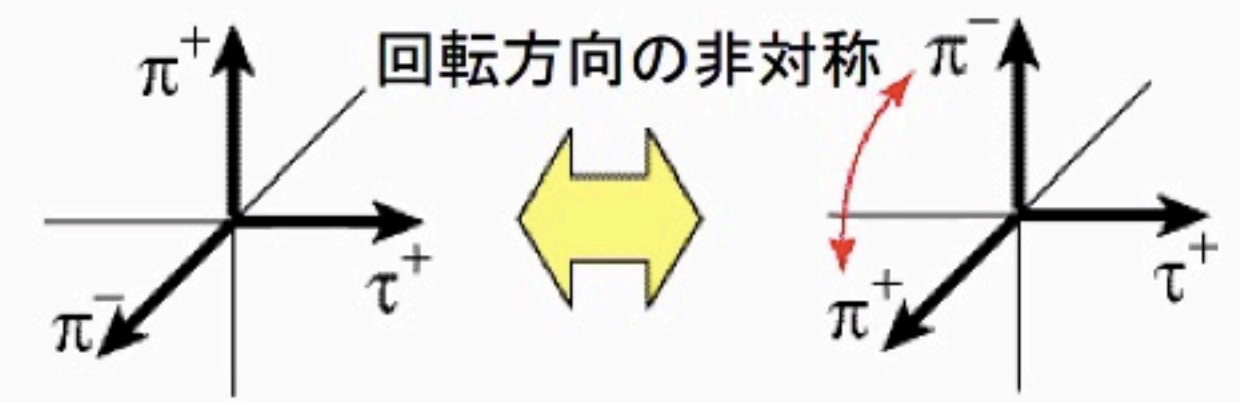
Schedule


FY
2020
2021
2022
2023
2024
2025
2026
Surface muon
Beam at H1 area
Beam at H2 area
Bldg. and facility
Final design
Completion
Muon source
Ionization test @S2
Ionization test at H2
LINAC
1 MeV acceleration@S2
4.5 MeV@ H2
10 MeV
210 MeV
Injection and storage
Completion of electron injection test
muon injection
Storage magnet
Install
B-field probe ready
Shimming done
Detector
Mass production ready
Installation
DAQ and computing
Ready
Analysis
Analysis software ready
Analysis environment ready
Commissioning
Data taking
First result?

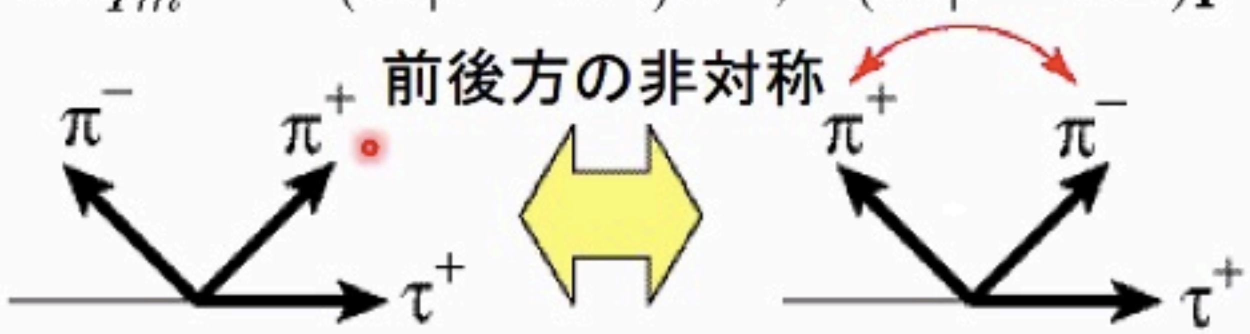

山崎高幸（KEK）

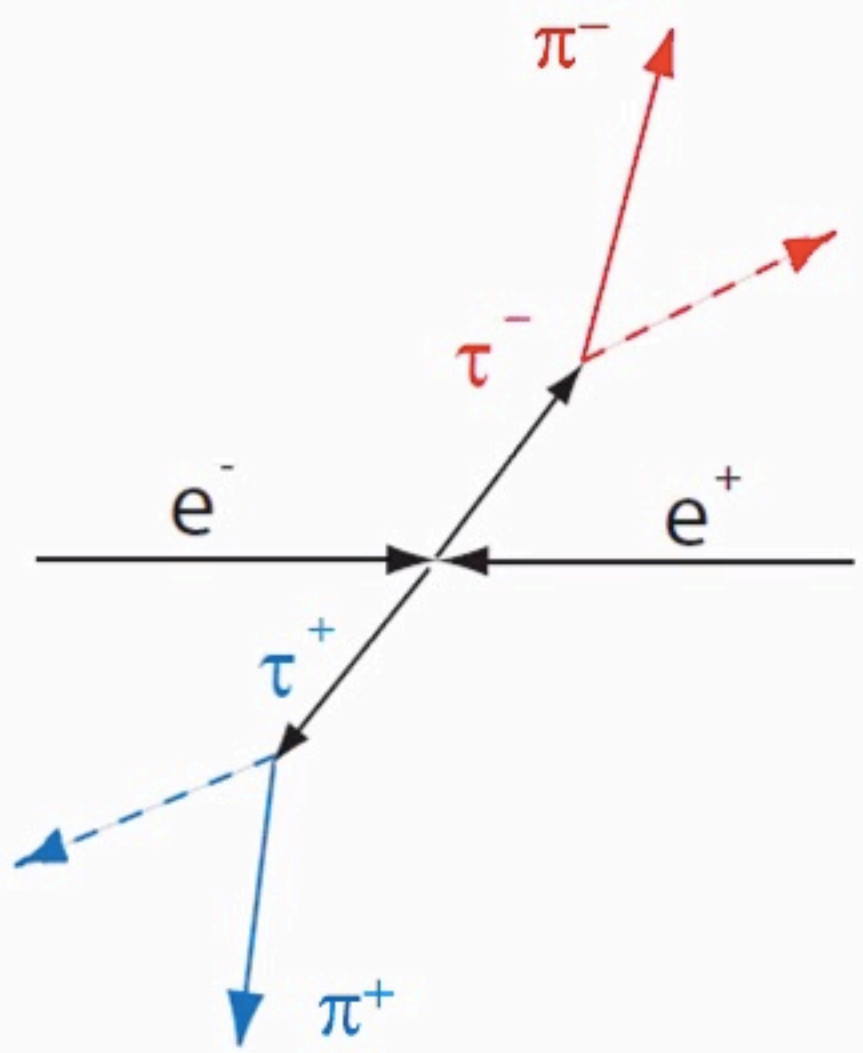
Asymmetry in event shape

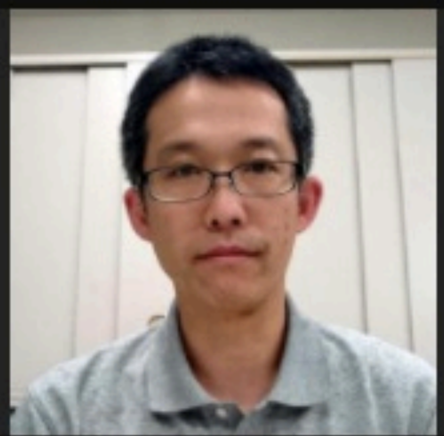
$$\mathcal{M}^2_{Re} \sim (\boldsymbol{S}_+ \times \boldsymbol{S}_-)\hat{\boldsymbol{k}} \;,\; (\boldsymbol{S}_+ \times \boldsymbol{S}_-)\hat{\boldsymbol{p}}$$



$$\mathcal{M}^2_{Im} \sim (\boldsymbol{S}_+ - \boldsymbol{S}_-)\hat{\boldsymbol{k}} \;,\; (\boldsymbol{S}_+ - \boldsymbol{S}_-)\hat{\boldsymbol{p}}$$







- タウのスピンの方向と崩壊生成物の方向が相関することを利用
- $\mathrm{Re}(d_\tau)$: 回転方向の非対称, $\mathrm{Im}(d_\tau)$: 前方後方の非対称
- 解析では、感度を最大化する“optimal observable”を導入

CP violation in tau decay (BaBar)

Phys. Rev. D85 (2012) 031102

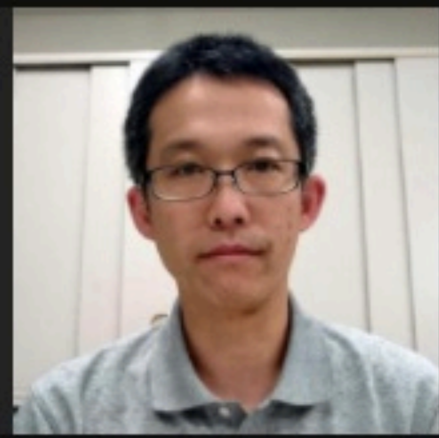
- 崩壊分岐比のCP非対称性の測定

$$A_Q = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}$$

- BaBar実験(SLACでのBファクトリ)による測定
  - $\tau^- \to \pi^- K_S^0 (\geq 0\pi^0) \nu_\tau$ (π^0 が含まれる崩壊モードを含む)
- 476fb^{-1} のタウ対データを用いた結果

$$A_Q = (-0.36 \pm 0.23 \pm 0.11)\%$$

- 標準理論の予想から2.8シグマのずれ
  - 標準理論予想： $A_Q = (0.33 \pm 0.01)\%$ (K^0 mixingによって0でない)
- Belle II のデータにより、より高い感度で測定可能
  - 測定器・事象選別のアクセプタンスの理解が重要になってくる



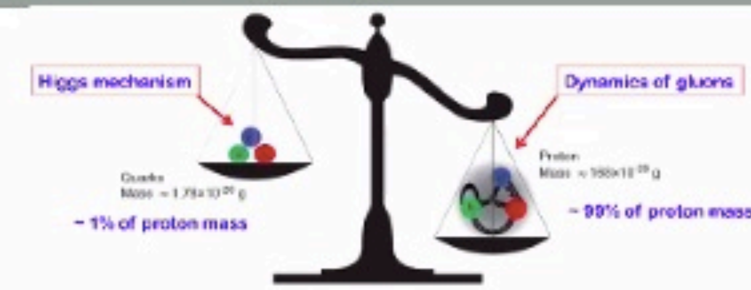
Non-linear Dynamics of QCD has Fundamental Consequences

Emergence of spin, mass & confinement, gluon fields

- Quark (Color) confinement:
  - Unique property of the strong interaction
  - Consequence of nonlinear gluon self-interactions
- Strong Quark-Gluon Interactions:
  - Confined motion of quarks and gluons – Transverse Momentum Dependent Parton Distributions (TMDs)
  - Confined spatial correlations of quark and gluon distributions -- Generalized Parton Distributions (GPDs)
- Ultra-dense color (gluon) fields in all nucleons and nuclei?
  - Runaway growth in gluon number is tamed by existing mechanisms in QCD: Is there a universal many-body structure due to ultra-dense color fields at the core of **all** hadrons and nuclei?

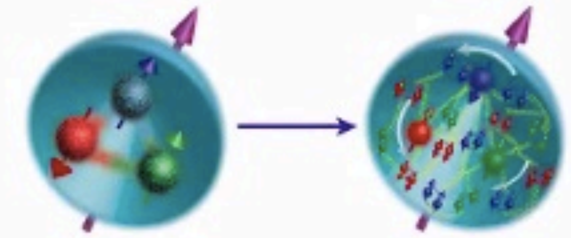
LHC/RHIC/CBAF & EIC are all essential for the deeper understanding of QCD
Along with theoretical advances in QCD, Lattice QCD methods

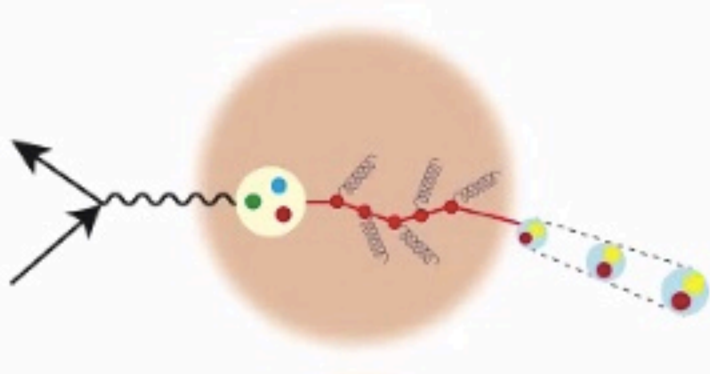
EIC Physics at-a-Glance



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

How do the nucleon properties (mass & spin) emerge from 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?

EIC Physics at-a-Glance

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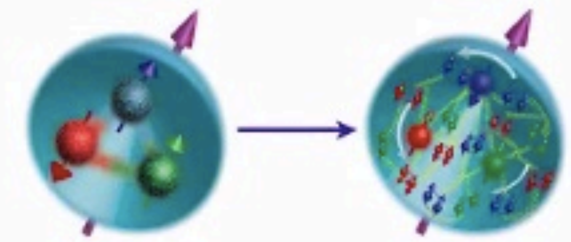
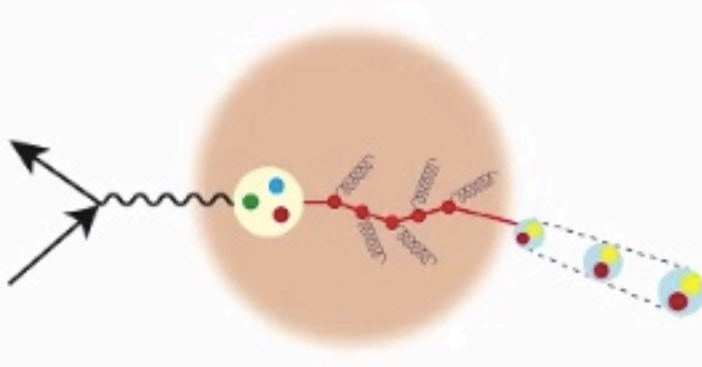




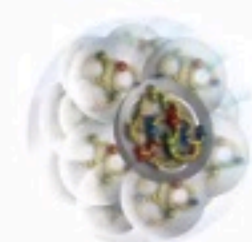
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

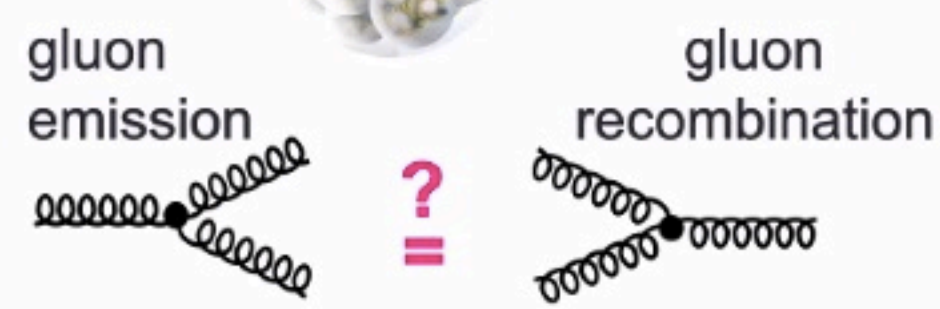
How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

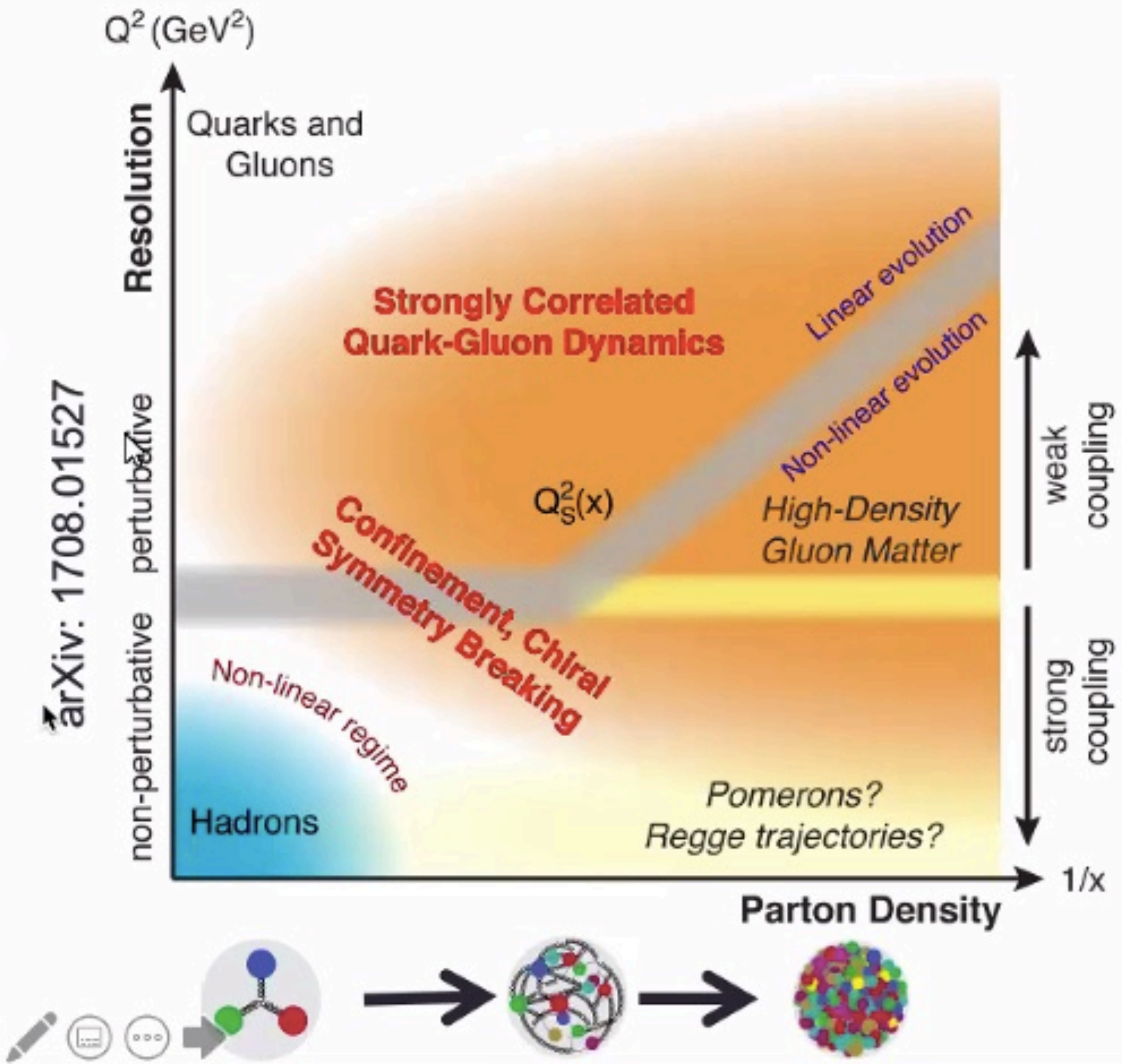
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

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?





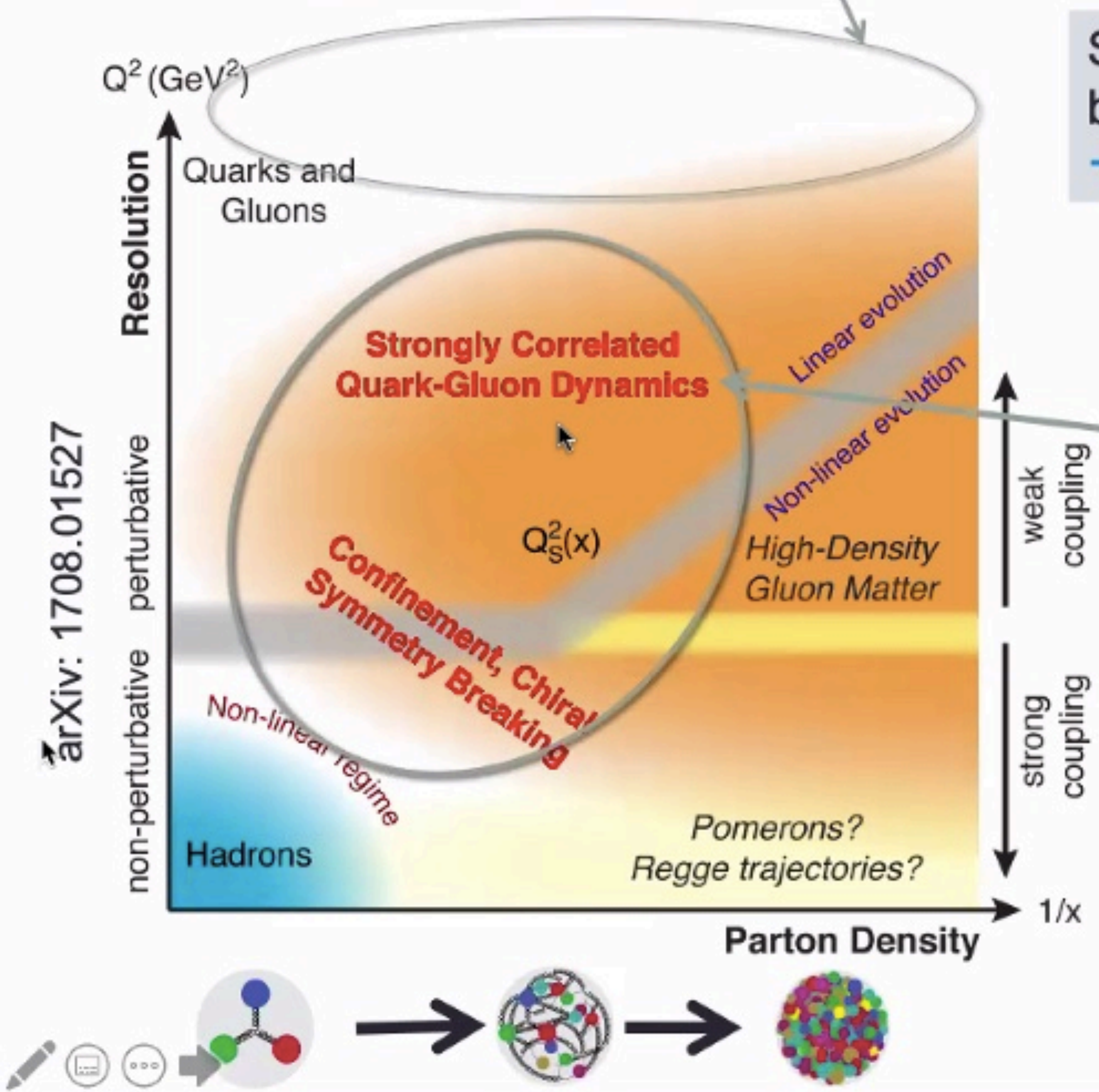
QCD Landscape to be explored by a future facility



Need Precision and Control

QCD Landscape to be explored by a future facility

QCD at high resolution (Q^2) —weakly correlated quarks and gluons are well-described



Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges

Systematically explore correlations in this region.

Need Precision and Control

QCD Landscape to be explored by a future facility

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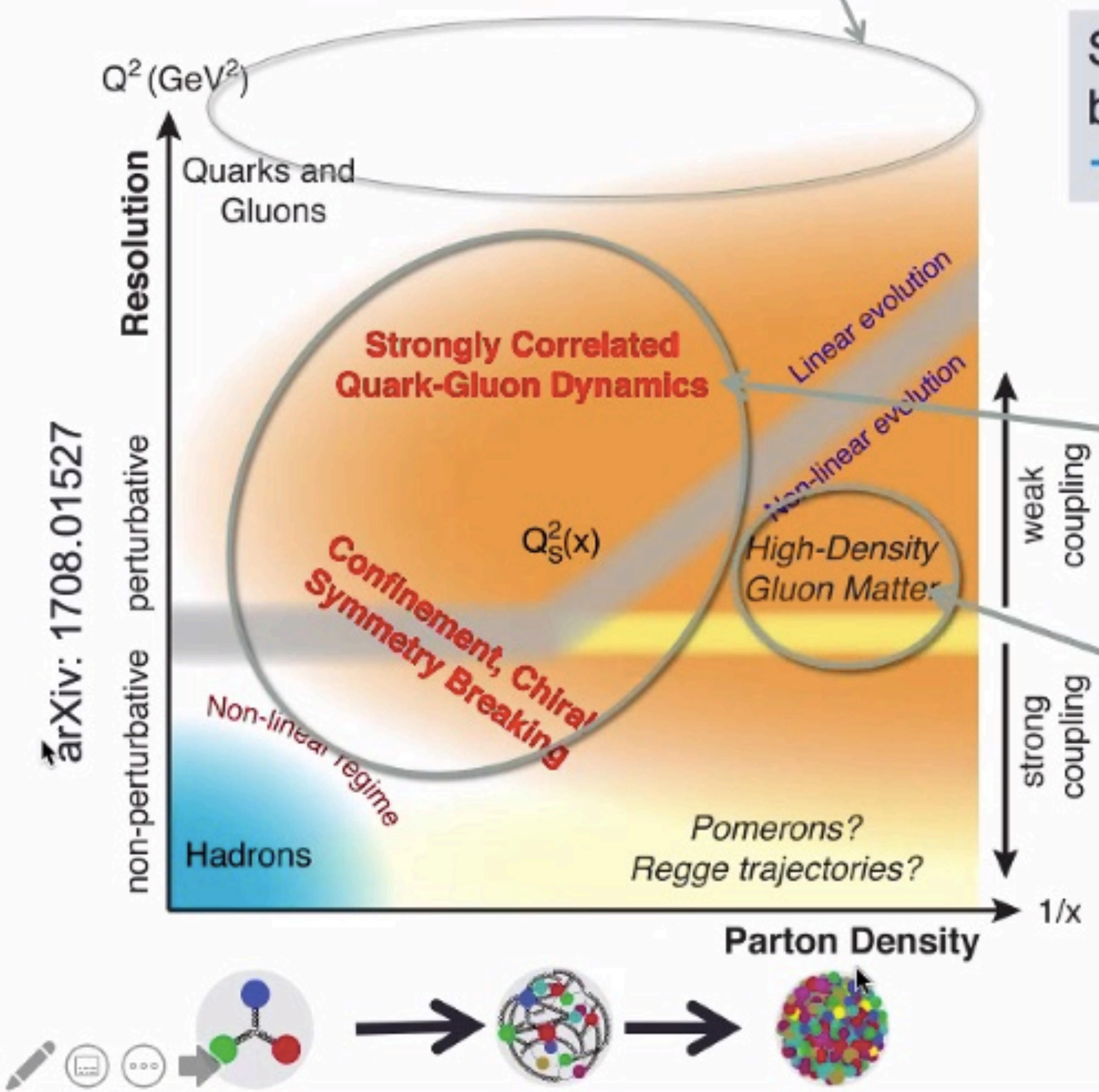


Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges

Systematically explore correlations in this region.

An exciting opportunity: Observation of a new regime in QCD of weakly coupled high-density matter

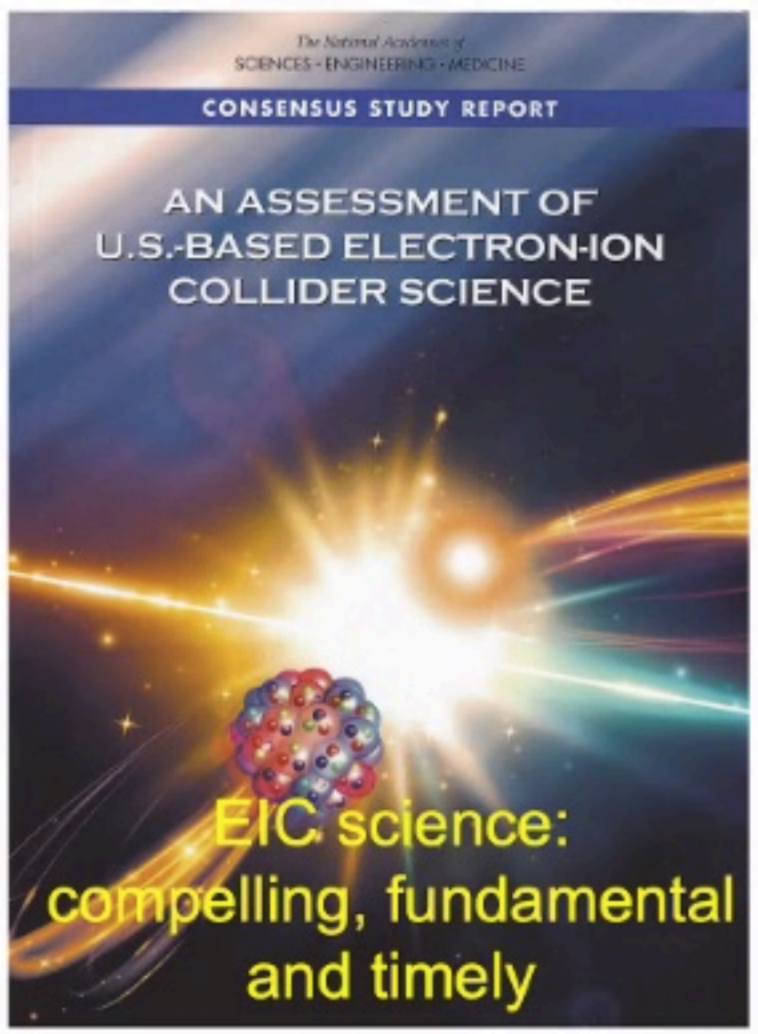
Need Precision and Control

NAS Consensus: EIC science compelling, fundamental, and timely

July 26, 2018

- **Finding 1**: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:
  - How does the mass of the nucleon arise?
  - How does the spin of the nucleon arise?
  - What are the emergent properties of dense systems of gluons?
- **Finding 2:** These three high-priority science questions can be answered by an EIC with highly polarized beams of electrons and ions, with sufficiently high luminosity and variable, center-of-mass energy.

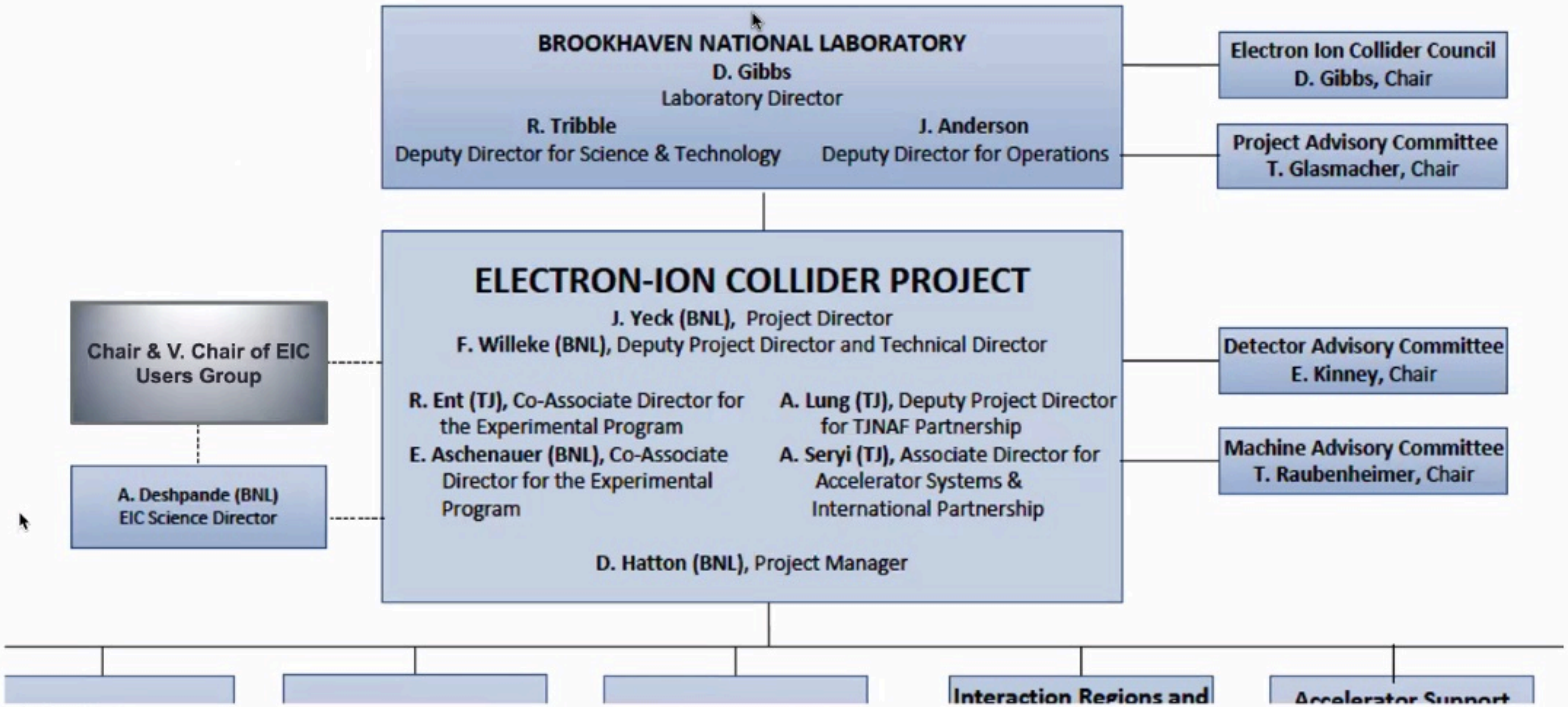
National Academy's Assessment

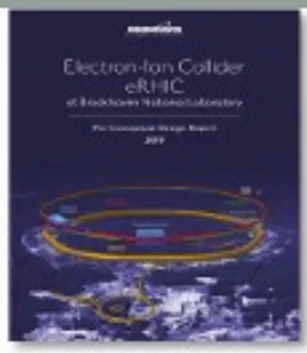


Machine Design Parameters:

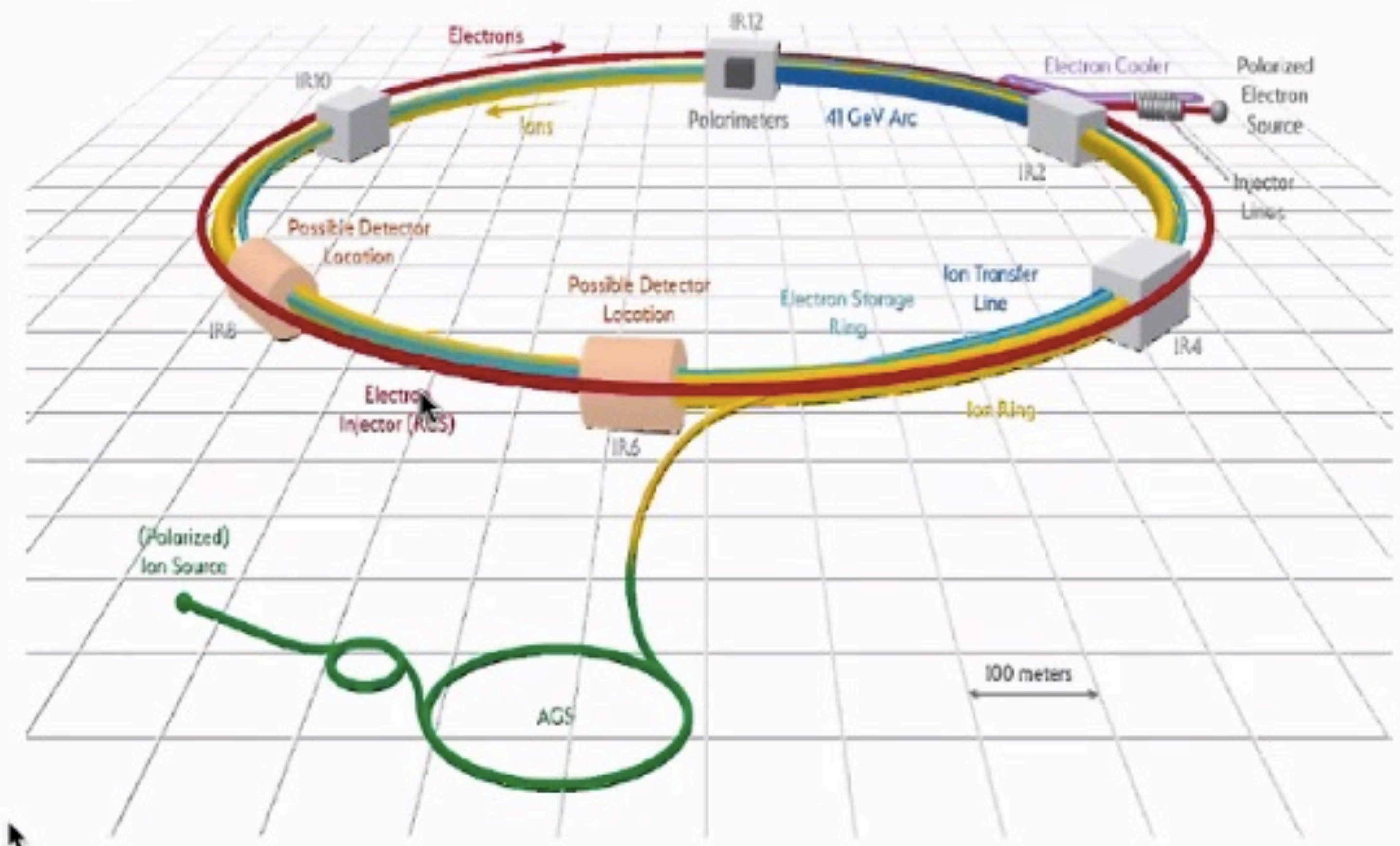
- High luminosity: up to 10^{33}-10^{34} $cm^{-2}sec^{-1}$
  - a factor ~100-1000 times HERA
- Broad range in center-of-mass energy: ~20-100 GeV upgradable to 140 GeV
- Polarized beams e-, p, and light ion beams with flexible spin patterns/orientation
- Broad range in hadron species: protons…. Uranium
- Up to two detectors well-integrated detector(s) into the machine lattice

Project Organization





The US Electron Ion Collider



- ❖ Electron storage ring with frequent injection of fresh polarized electron bunches
- ❖ Hadron storage ring with strong cooling or frequent injection of hadron bunches

Hadrons up to 275 GeV

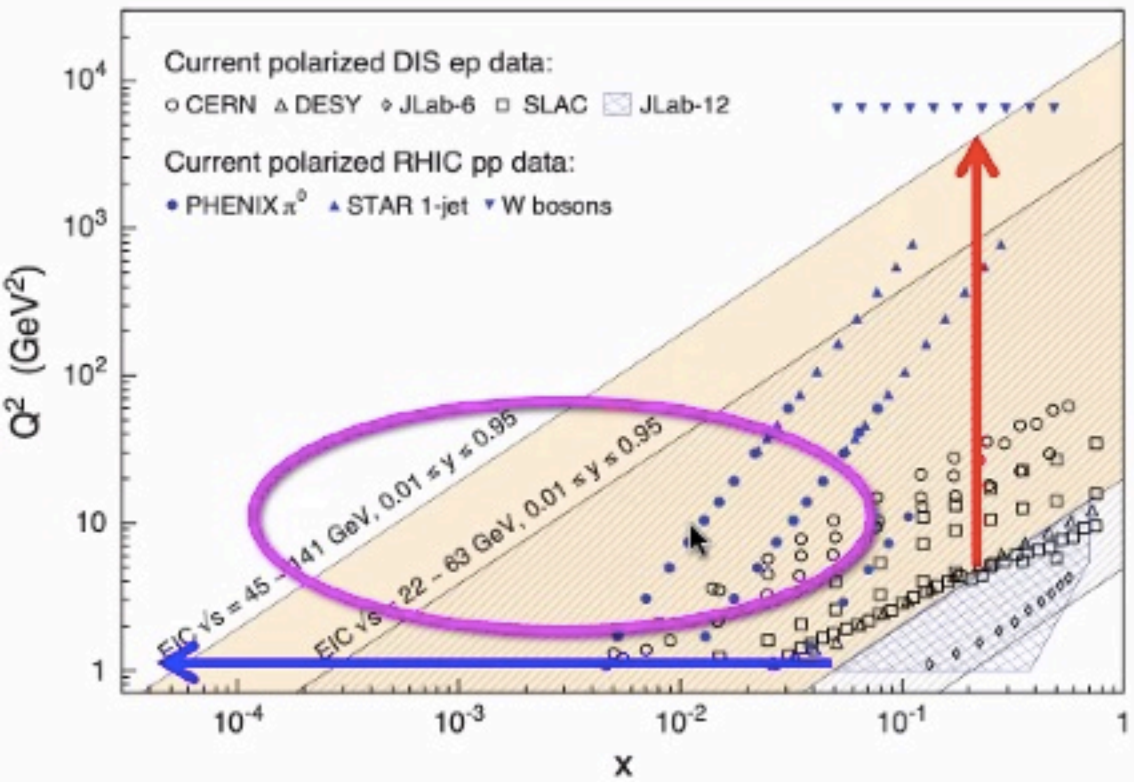
- ➢ Existing RHIC complex: Storage (Yellow), injectors (source, booster, AGS)
- ➢ Need few modifications
- ➢ RHIC beam parameters fairly close to those required for EIC@BNL

Electrons up to 18 GeV

- ➢ Storage ring, provides the range sqrt(s) = 20-140 GeV. Beam current limited by RF power of 10 MW
- ➢ Electron beam with variable spin pattern (s) accelerated in on-energy, spin transparent injector (Rapid-Cycling-Synchrotron) with 1-2 Hz cycle frequency
- ➢ Polarized e-source and a 400 MeV s-band injector LINAC in the existing tunnel

Design optimized to reach 10^{34} $cm^{-2}sec^{-1}$

EIC: Kinematic reach & properties

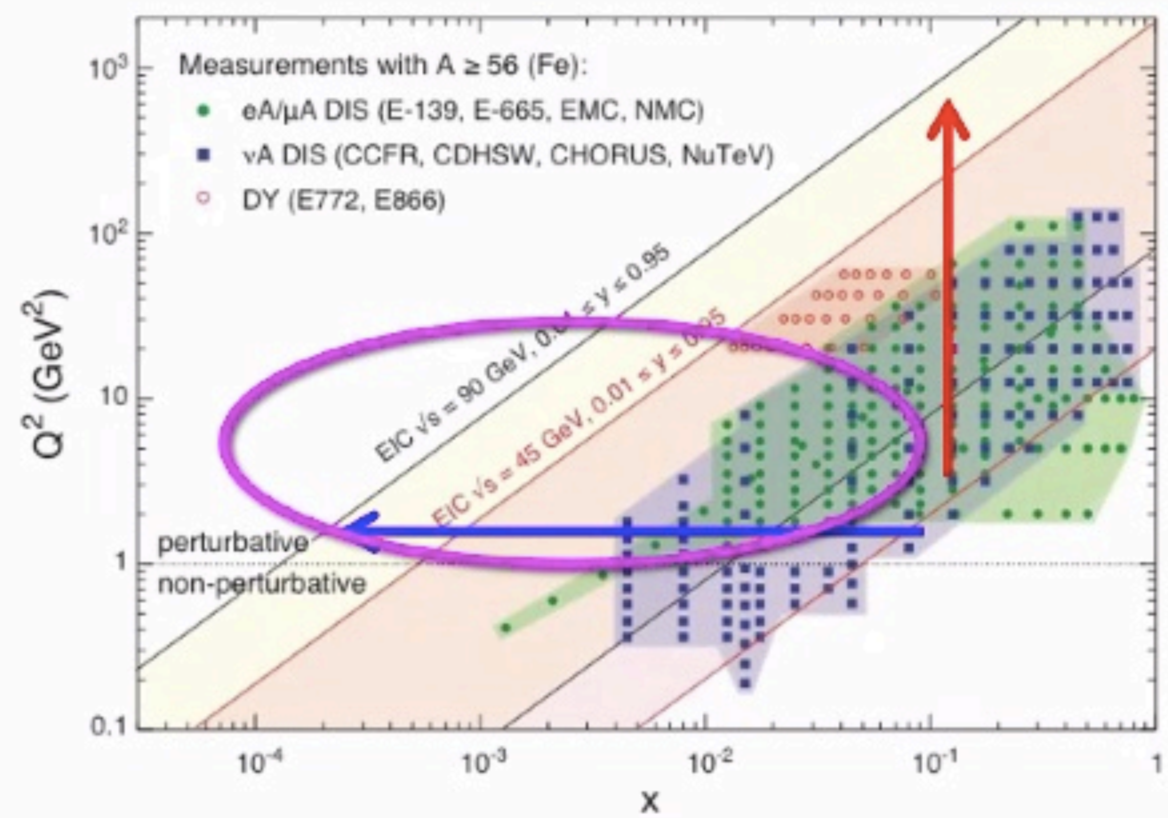


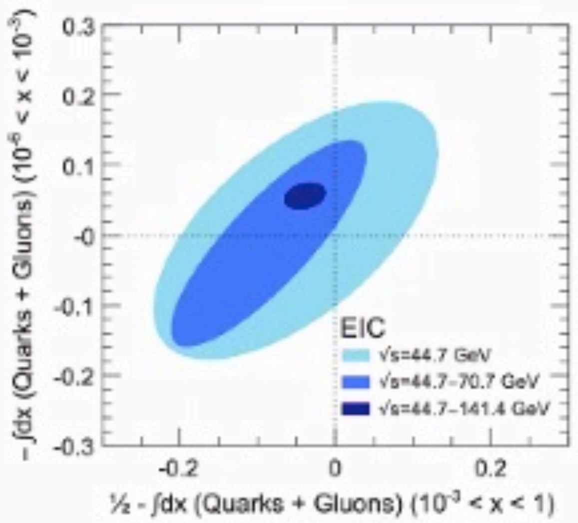
For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

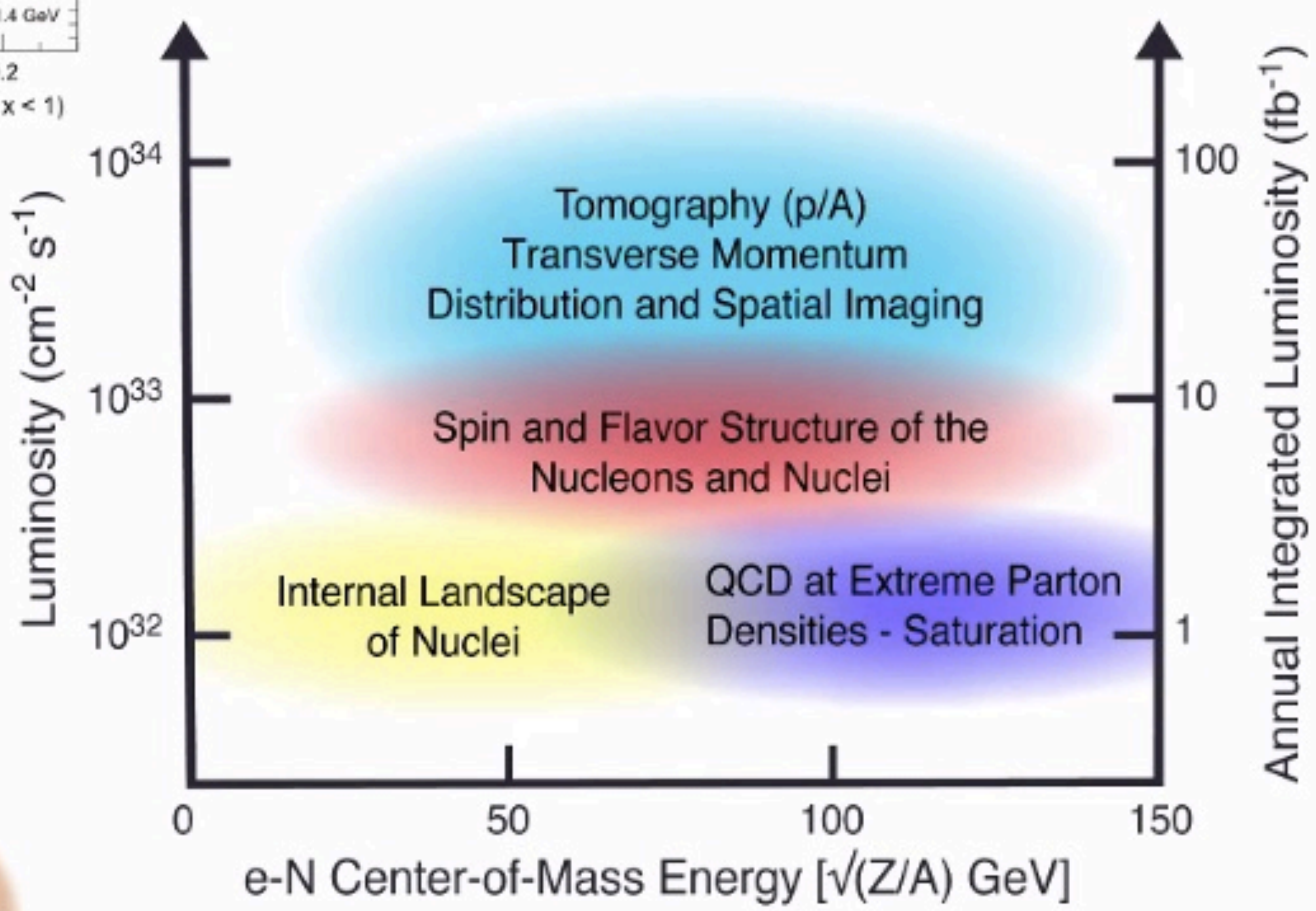
For e-A collisions at the EIC:

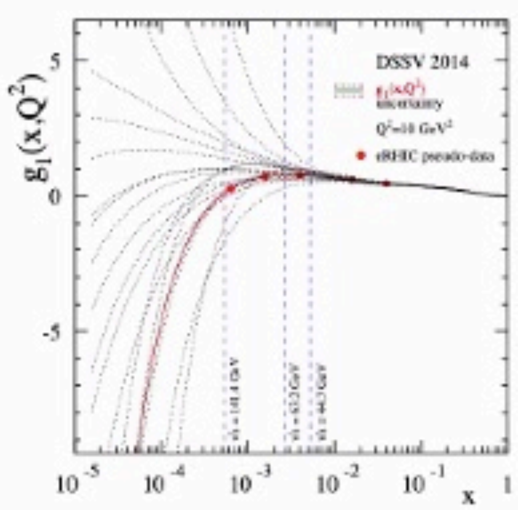
- ✓ Wide range in nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities)

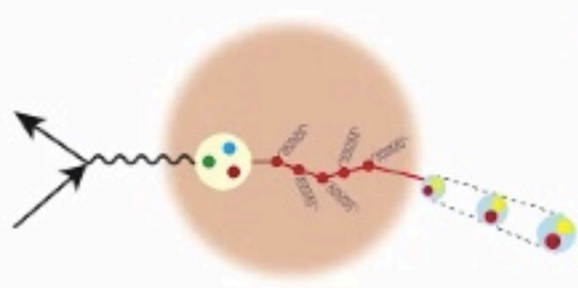


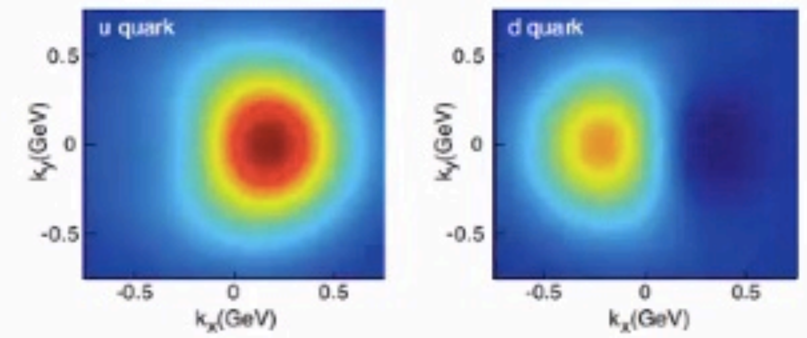


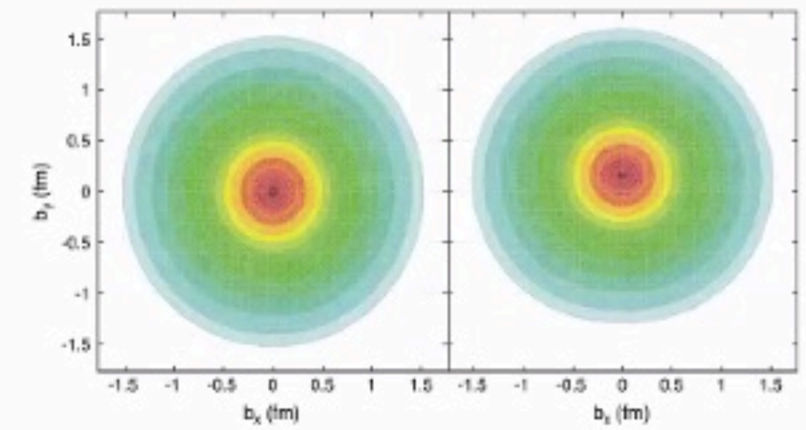
EIC science highlights

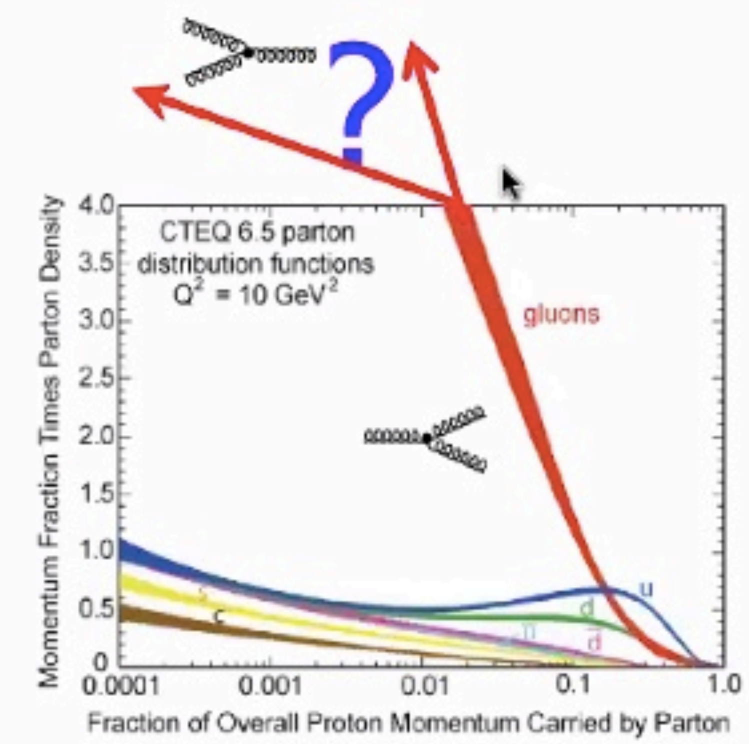






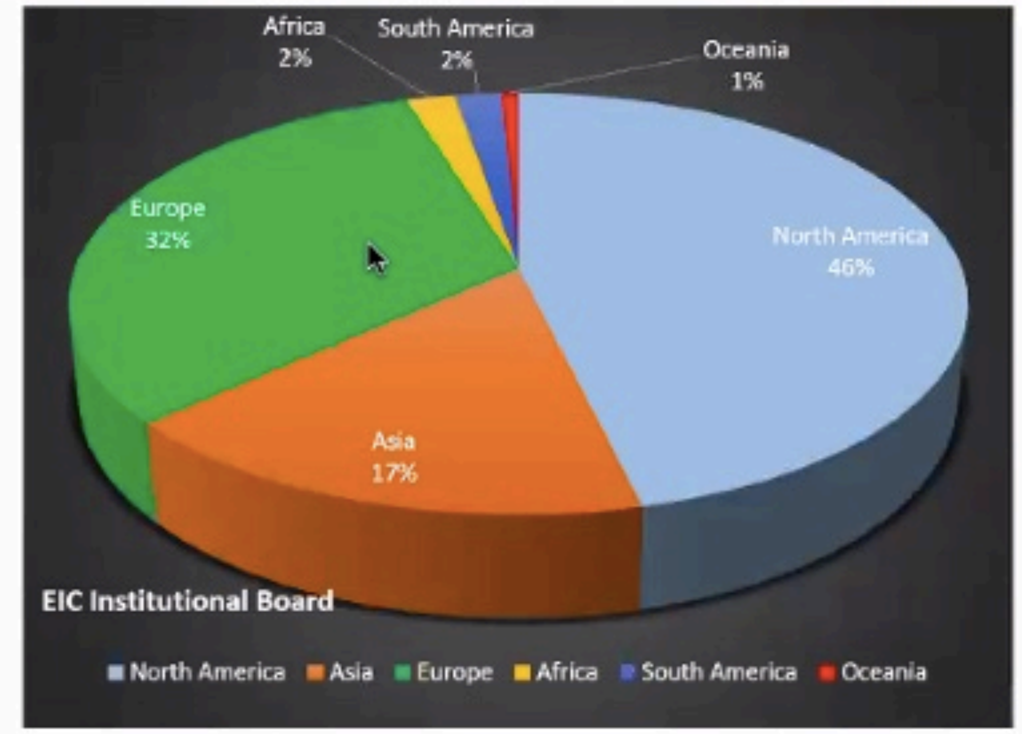






The EIC Users Group: EICUG.ORG

Formally established in 2016, now we have:
~1300 Ph.D. Members from 34 countries, 254 institutions
New members welcome



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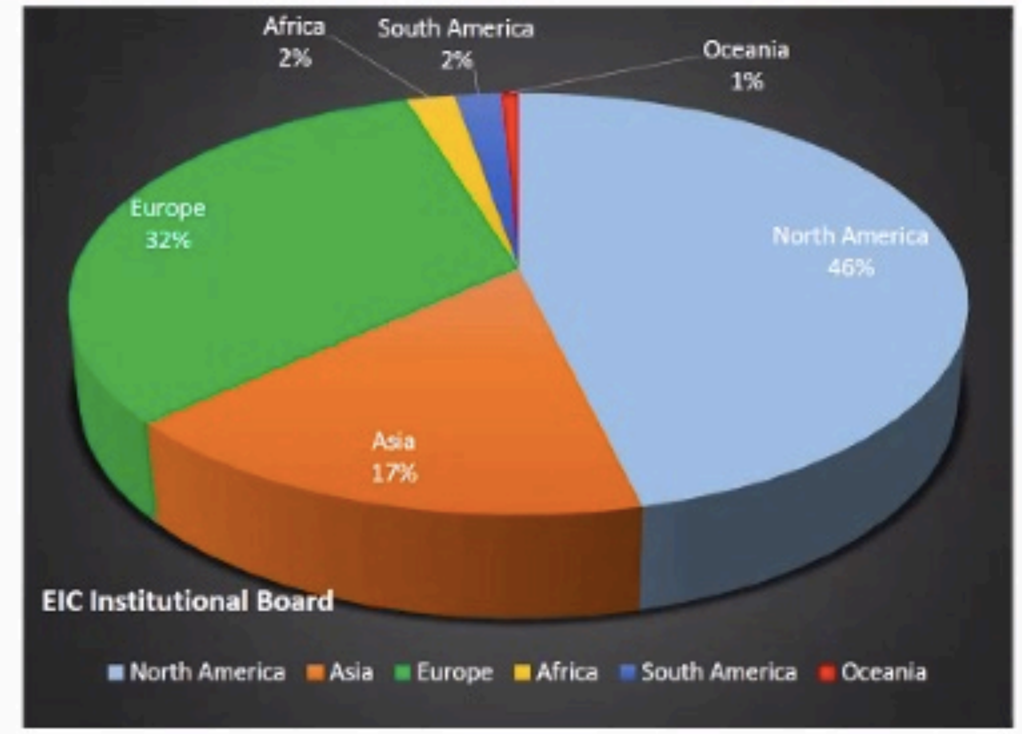

EICUG Structures in place and active:
EIC UG Steering Committee, Institutional Board, Speaker's Committee, Election & Nominations Committee

Year long workshops: Yellow Reports for detector design

Annual meetings: Stony Brook (2014), Berkeley (2015), **ANL (2016)**, **Trieste (2017)**, **CAU (2018)**, **Paris (2019)**, **FIU (2020)**, **Remote (2021)**, **Warsaw (2022)**

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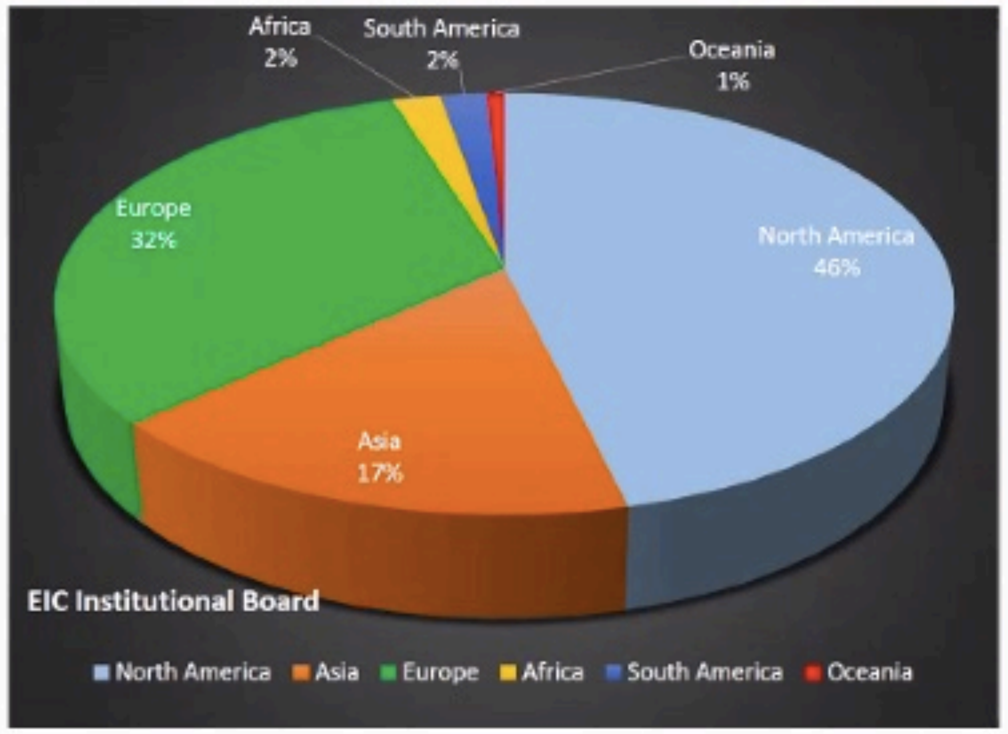

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Physics @ the US EIC beyond the EIC's core science

Of HEP/LHC-HI interest to Snowmass 2021 (EF 05, 06, and 07 and possibly also EF 04)

New Studies with proton or neutron target:

- Impact of precision measurements of unpolarized PDFs at high x/Q^2, on LHC-Upgrade results(?)
- What role would TMDs in e-p play in W-Production at LHC? Gluon TMDs at low-x!
- Heavy quark and quarkonia (c, b quarks) studies with 100-1000 times lumi of HERA
- Does polarization of play a role (in all or many of these?)

Physics with nucleons and nuclear targets:

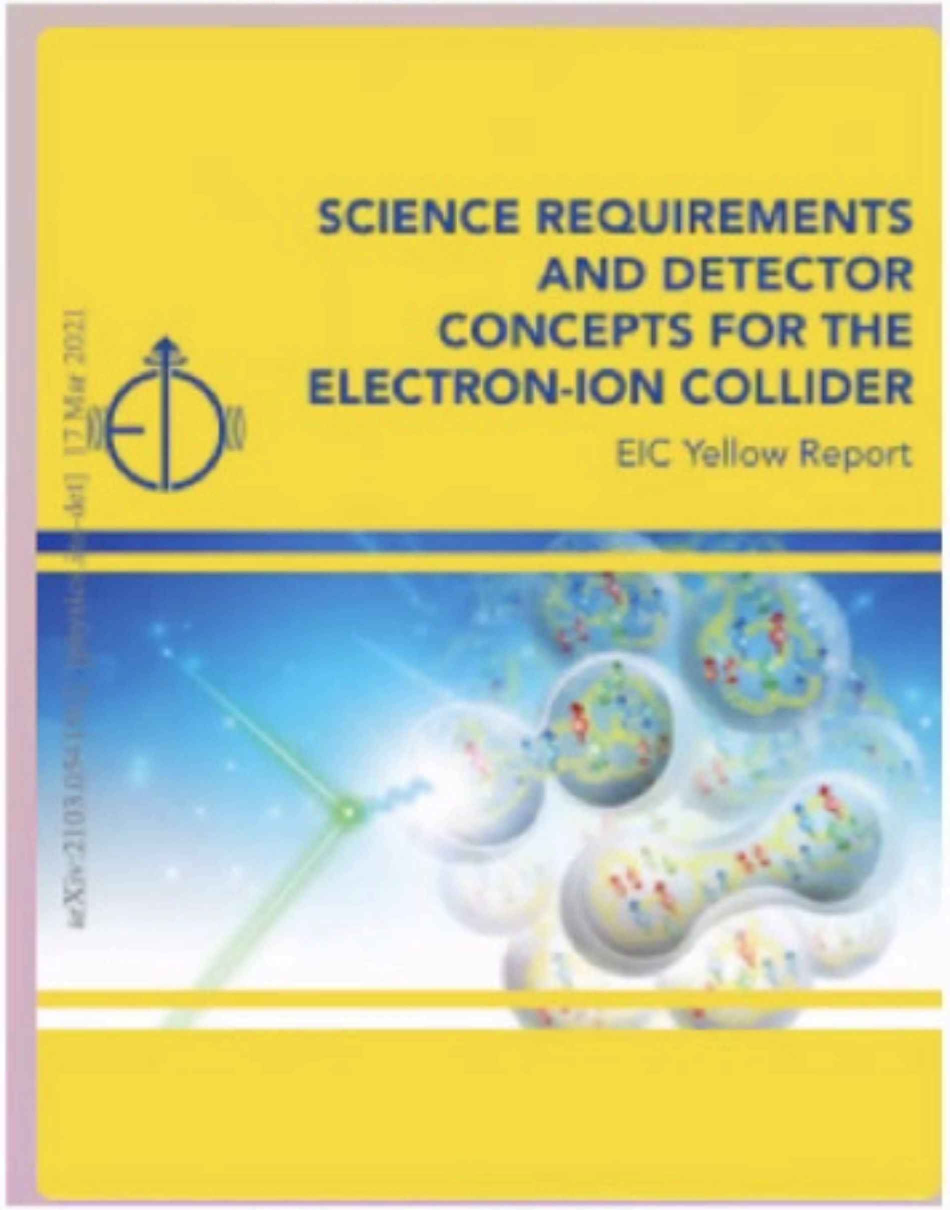
- Quark Exotica: 4,5,6 quark systems…? Much interest after recent LHCb led results.
- Physic of and with jets with EIC as a precision QCD machine:
  - Internal structure of jets : novel new observables, energy variability, polarization, beam species
  - Entanglement, entropy, connections to fragmentation, hadronization and confinement
  - Studies with jets: Jet propagation in nuclei… energy loss in cold QCD medium
- Connection to p-A, d-A, A-A at RHIC and LHC
- Polarized light nuclei in the EIC

Precision electroweak and BSM physics:

December 2019 – March 2021
EICUG Yellow Report

- Led by EICUG Steering Committee, with R. Ent & T. Ullrich as point people for the effort, initiated a UG-wide effort towards a detector design effort with a detailed document.

- Kick off meeting at MIT in December 2019 followed by 4 more meetings in 2020 all remote: Philadelphia, Pavia, Miami, Washington DC, Berkeley

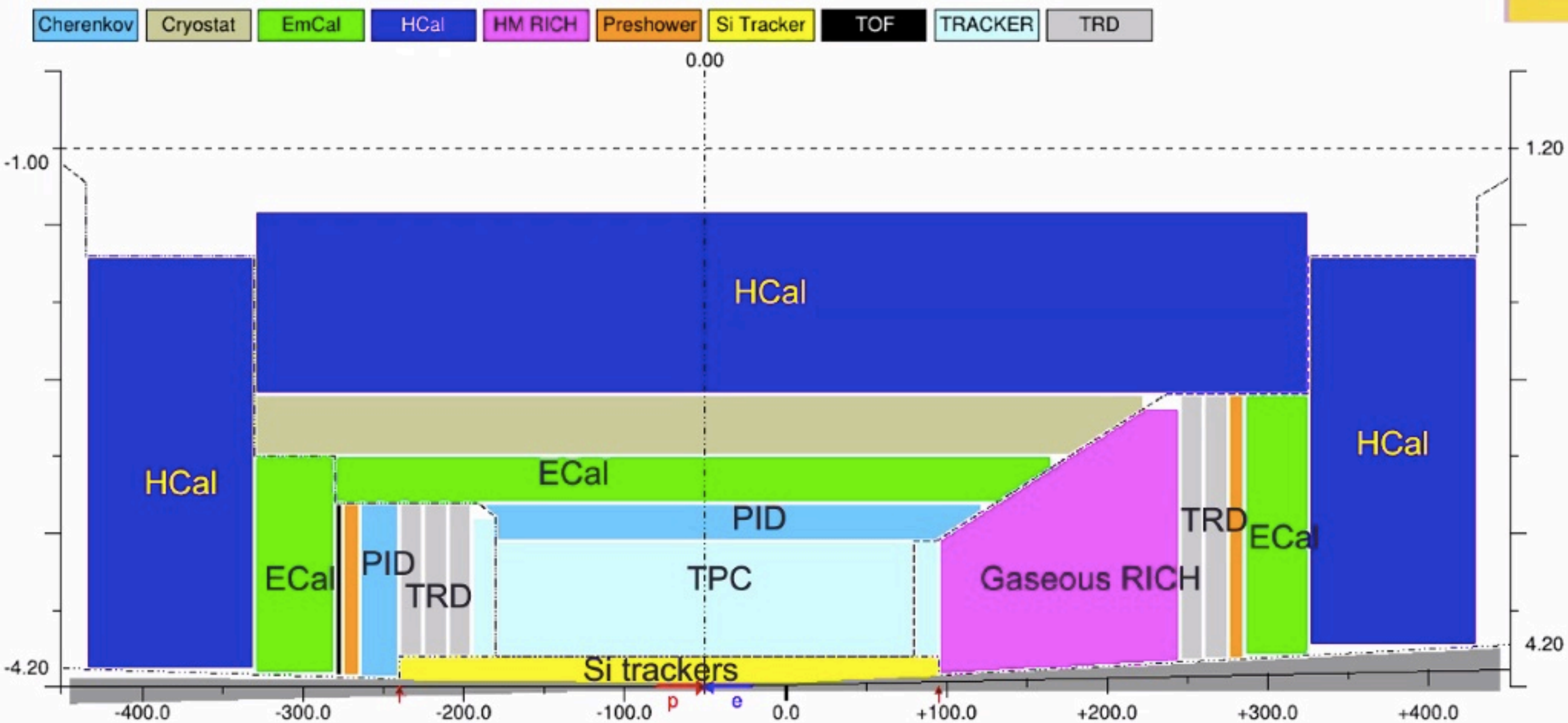


902 pages
415 authors
151 institutions

120 MB

arXiv:2103.05419

Concept DETECTOR



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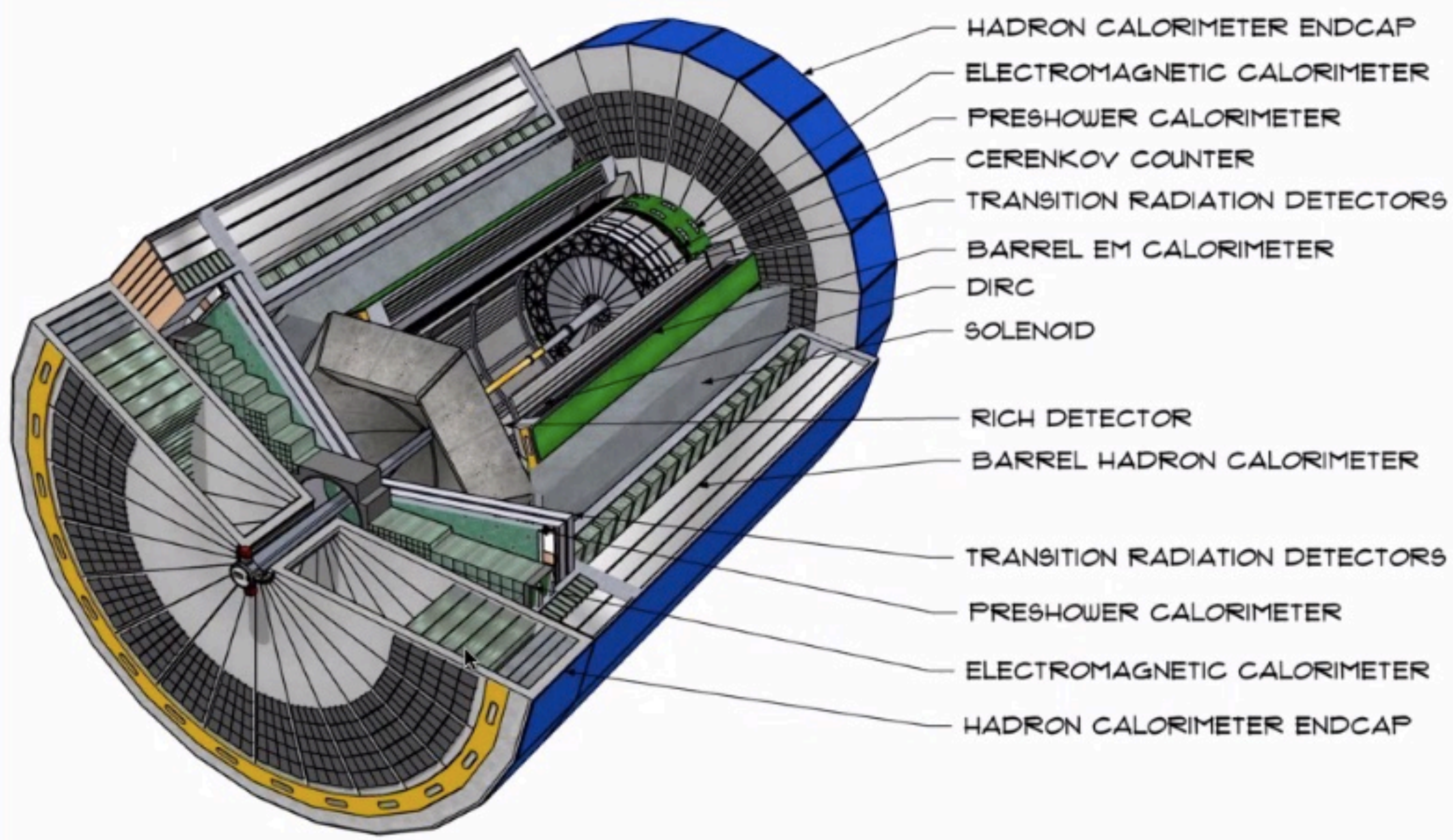


EIC Project planning & path forward

EIC project

- EIC will have the technical capacity to host two interactions regions with detectors.
- EIC project scope includes the machine and (funds for significant part of) 1 detector, .
- Ways to make the 2^{nd} detector/IR possible are being explored.

Call for detector proposals was jointly issued by BNL/JLab in March 2021

- Due date : December 1, 2021
- Independent external committee appointed by the Lab Managements will evaluate and advise the Labs and EIC project
- *Under all circumstances: ALL Users will be accommodated*
- *Currently 3 detector proto-proposals (ATHENA, ECCE & CORE) and a White Paper for a dedicated IR/detector for lower CM Energy are being prepared*

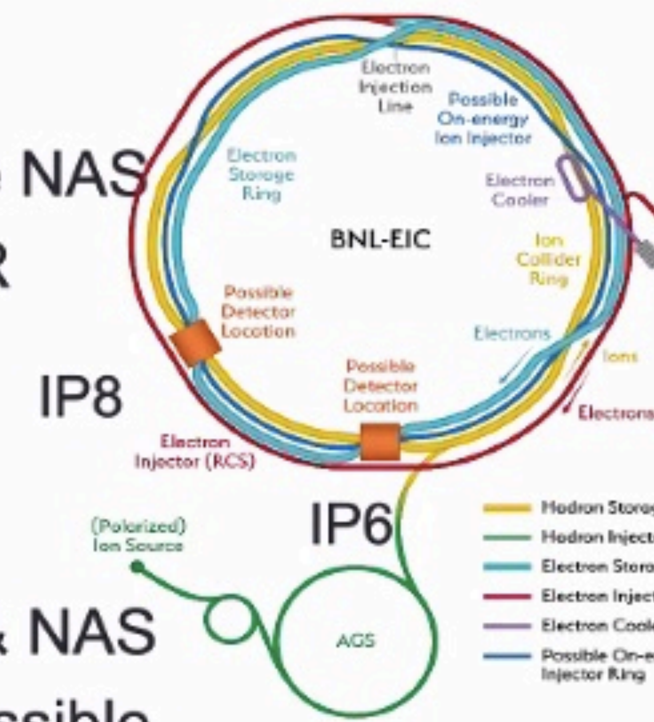
Call for detector proposals

- **Detector 1 (D1) :** within the scope of the EIC project
  - Will cover most but not all acquisitions

- **Detector 2 (D2):** not within the scope of the EIC project

Call for detector proposals

- **Detector 1 (D1) :** within the scope of the EIC project
  - Will cover most but not all acquisitions
  - Must satisfy EIC "mission need" ➔ Physics of EIC White Paper "blessed" by the NAS
  - Design should be compatible with accelerator & interaction region layout in CDR
  - Completion mandatory by **CD4A** -- @ beginning accelerator operation
- **Detector 2 (D2):** not within the scope of the EIC project
  - How to realize it are being explored
  - Focus on **specific topic within EIC WP** or (and) **science beyond** the EICWP & NAS
  - IR should be consistent with machine design in CDR, but modified IR design possible
  - Detector should be ready by **CD4 – about 2 years later**



Siting location of D1 and D2 between IP6 and IP8 is left open, with the caveat that the EIC project has so far assumed D1 will go to IP6

Proposal Advisory Panel : membership & charge

(Note: proto-collaborations should not engage in unsolicited communication with the Panel)

Patty McBride, co-chair	**FNAL**
Rolf Heuer, co-chair	**Former CERN Director General**
Sergio Bertolucci	University of Bologna and INFN
Daniela Bortoletto	Oxford
Markus Diehl	DESY
Ed Kinney	U. Colorado
Fabienne Kunne	Paris-Saclay
Andy Lankford	UC Irvine
Naohito Saito	KEK
Brigitte Vachon	McGill
Tom Ludlam, Scientific Secretary	BNL

Evaluation of the **science** addressed and estimated **performance**, **risk**, **cost**, and **schedule** for the proposed experiment.

The EIC Project Detector Advisory Committee (DAC) will be asked to provide input to the Panel on **detector technology, design choices, risk, cost, schedule, and collaboration strength**.

Panel will advise BNL, JLab, and the EIC project leadership on how to realize an optimal set of experimental equipment at the EIC.

Summary: Challenging but EXCITING times ahead

Electron Ion Collider: Enthusiastically supported by NAS & 1300+ (growing) users, 254 institutions and 34 countries

EIC Project moving full steam ahead: machine and detectors

- International partners are significant component of the success: Actively seeking partners

EIC Detector: unique in its demanding : IR integration

Emerging international detector collaboration(s) will realize EIC Science in **early 2030's**

EIC and Japan: Personal perspective

- The US Japan Collaboration & RIKEN-BNL Research Center (RBRC): critical pillars of US-Japan collaborations since 1990's. : Excellent science & superb scientists came out of those
- Successful legacy of international collaboration could easily be extended for another 20 years with Japanese involvement (and leadership) in the EIC.
- **Abundant opportunities exist for such collaboration.**

ECCE

The ECCE Proposal for an EIC Detector

John Lajoie

Iowa State University

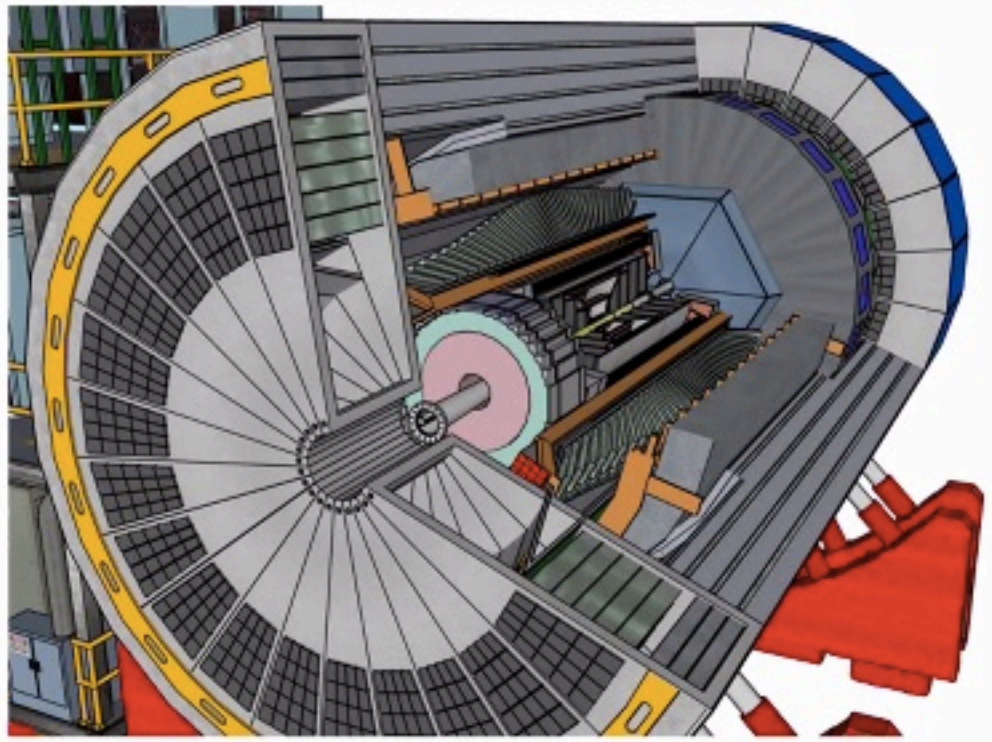
for the ECCE Consortium

What is ECCE ?

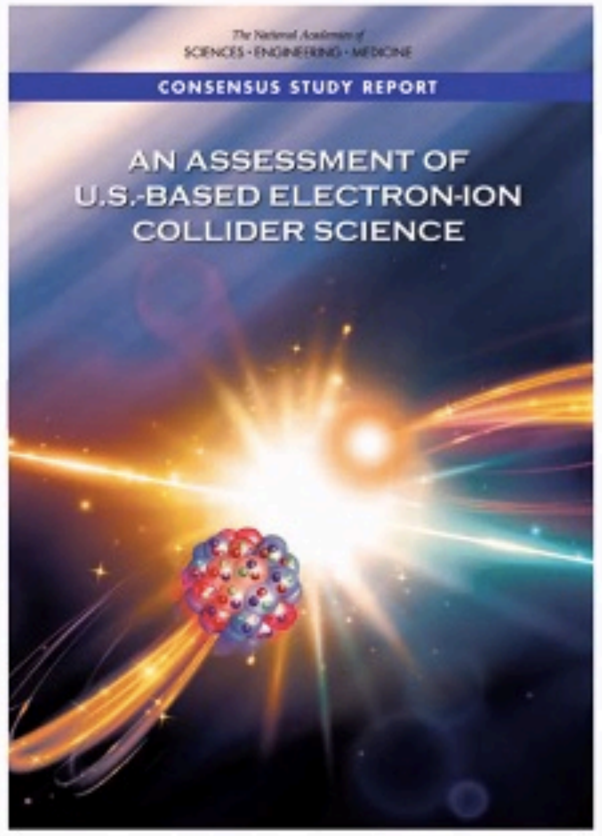
ECCE

Scientist from
80 institutions

Designing
(& building!)
a detector



To deliver on EIC
science mission



The Science

ECCE

- Detector 1 should be based on the "reference" detector described by the EIC User Group (EICUG) in the Yellow Report (YR) and CDR
  - Must address the EIC White Paper and NAS Report science case
  - The collaboration should propose a system that meets the performance requirements described in the EIC CDR and EICUG YR
  - The design should be compatible with that of the accelerator and interaction region layout of the CDR
  - Completion of detector construction must be achieved by Critical Decision CD-4a, the start of EIC accelerator operations.
- Detector 2 could be a complementary detector that may focus on optimizing particular science topics or address science topics beyond those described in the White Paper and the National Academies of Science (NAS) 2018 report
  - Completion at Critical Decision (CD)-4

ECCE 101

ECCE

EIC Comprehensive Chromodynamics Experiment

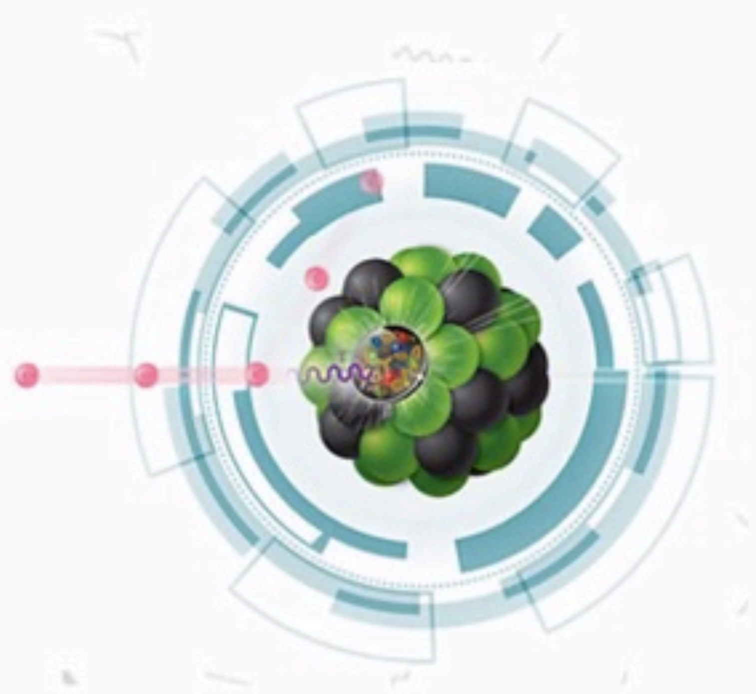
ECCE is 80 institutions collaborating to design an EIC detector offering full kinematic coverage and an optimized far forward detector system

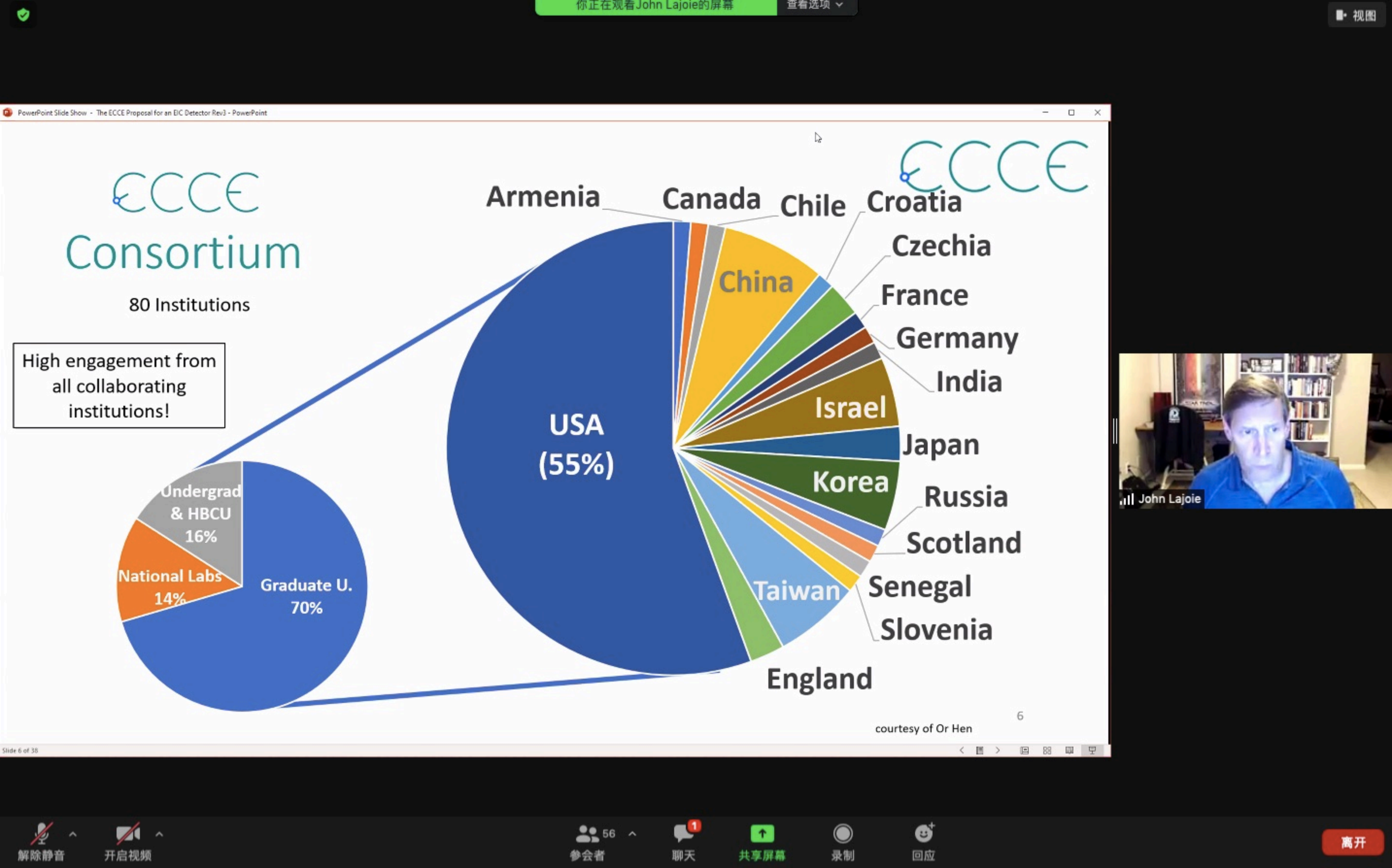
ECCE will submit a proposal to be the EIC project detector ("Detector 1"), which will address the complete science program outlined in the NAS and Yellow Reports

ECCE is investigating a design which incorporates the existing 1.5T BaBar magnet, which will help reduce cost and risk, to allow it to be ready for first EIC operations (CD-4a)

ECCE is fully supportive of two detectors at the EIC, in both IP6 and IP8, to maximize the scientific output of the EIC. ECCE is also investigating key science measurements in either IP6 with 25 mrad crossing angle, or IP8 with 35 mrad

ECCE is open to everyone in the community to participate, even if they wish to contribute to other proposals.





你正在观看John Lajoie的屏幕
查看选项
视图
PowerPoint Slide Show - The ECCE Proposal for an EIC Detector Rev3 - PowerPoint
ECCE
ECCE
Consortium
80 Institutions
High engagement from all collaborating institutions!
Undergrad & HBCU 16%
National Labs 14%
Graduate U. 70%
USA (55%)
Armenia
Canada
Chile
China
Croatia
Czechia
France
Germany
India
Israel
Japan
Korea
Russia
Scotland
Senegal
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Taiwan
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PowerPoint Slide Show - The ECCE Proposal for an EIC Detector Rev3 - PowerPoint

ECCE

ECCE Consortium Structure

EIC Project POC
Rolf Ent (JLab)

ECCE Steering Committee
Or Hen (MIT)
Tanja Horn (CUA)
John Lajoie (ISU)

Institutional Board

Computing Team
Cristiano Fanelli (MIT)
David Lawrence (JLab)

Computing Working Groups:
- Artificial Intelligence
  William Phelps (CNU/JLab)
- Computing and Software
  Joe Osborn (ORNL)

Diversity, Equity and Inclusion
Narbe Kalantarians (VUU, co-chair)
Christine Nattrass (UTK, co-chair)
Simonetta Liuti (UVA)
Elena Long (UNH)

Detector Team
Doug Higinbotham (JLab)
Ken Read (ORNL)

Detector Working Groups:
- IP8/Equipment Re-use
  John Haggerty (BNL)
- Far Forward/Far Backward*
  Michael Murray (KU), Yuji Goto (RIKEN), Igor Korover (MIT)
- Tracking
  Xuan Li (LANL), Nilanga Liyanage (UVA)
- Calorimetry
  Friederike Bock (ORNL), Yongsun Kim (Sejong U.)
- Particle ID
  Greg Kalicy (CUA), Xiaochun He (GSU)
- Magnetic Field
  Paul Brindza (JLab), Renuka Rajput-Ghoshal (JLab)
- DAQ/Electronics/Readout
  Chris Cuevas (JLab), Martin Purschke (BNL)

*Alex Jentsch, Yulia Furletova (far-forward/backward POC)

Physics Benchmarks Team
Carlos Munoz-Camacho (IJCLab-Orsay)
Rosi Reed (Lehigh U.)

Physics Working Groups:
- Simulations
  Cameron Dean (LANL), Jin Huang (BNL)
- Inclusive Processes
  Tyler Kutz (MIT), Claire Gwenlan (Oxford)
- Semi-Inclusive
  Ralf Seidl (RIKEN), Charlotte Van Hulse (Orsay)
- Exclusive
  Rachel Montgomery (Glasgow), Julie Roche (OU)
- Diffractive and Tagging
  Wenliang Li (W&M), Axel Schmidt (GWU)
- Jets and Heavy Flavor
  Cheuk-Ping Wong (LANL), Wangmei Zha (USTC)
- BSM and Precision Electroweak
  Sonny Mantry (UNG), Xiaochao Zheng (UVa)

Editorial Team
Tom Cormier (ORNL)
Richard Milner (MIT)
Peter Steinberg (BNL)

Editorial Working Groups:
- Proposal Editing, Verification and Version Control
- Costing and Management

Website:
https://www.ecce-eic.org/

Mailing Lists:
https://lists.bnl.gov
- ecce-eic-public-l
- ecce-eic-ib-l
- ecce-eic-comp-l
- ecce-eic-dei-l
- ecce-eic-det-l
- ecce-eic-phys-l
- ecce-eic-prop-l

Indico:
https://indico.bnl.gov/category/339/

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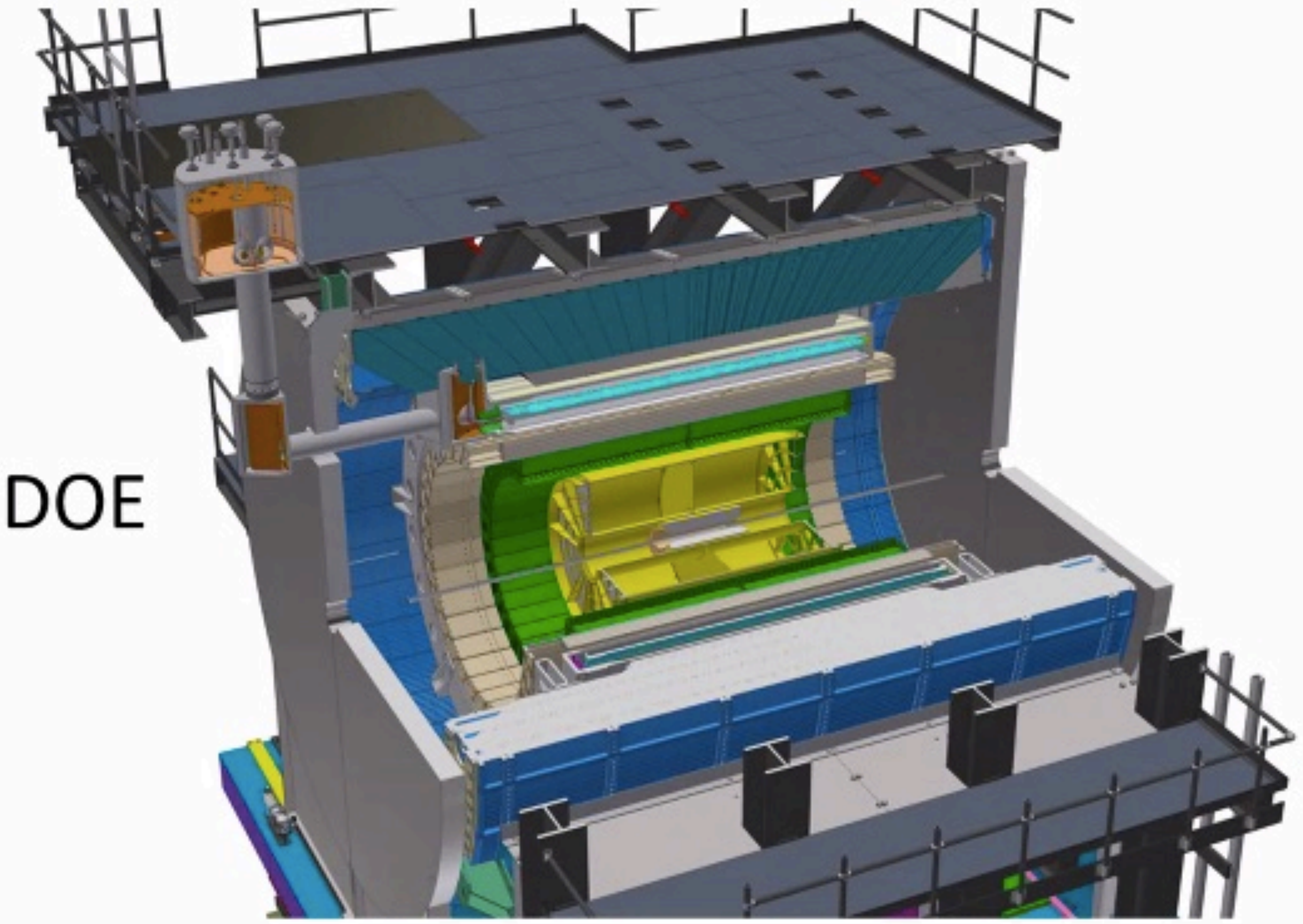
ECCE

Existing Infrastructure

- Existing BaBar solenoid (1.5T), flux return and cradle
  - Substantial investment/risk reduction
- IP6/8 infrastructure
  - Cryogenic connection to RHIC
  - Racks, mechanical, safety, electrical, etc.
- Potential re-use/refurbish existing sPHENIX detectors as appropriate
- Additional in-kind contributions from DOE labs and consortium members
- ECCE consortium has considerable recent DOE project experience

Currently under construction, sPHENIX represents a $27M investment by DOE (MIE)



1.5T BaBar Solenoid

ECCE

- Built in 1997 (Ansaldo)
- Very conservative design
- 3.7m long,
  1.4m bore radius
- Designed for 1.5T @ 5kA
  - 27MJ stored energy
- Transported to BNL 2015
  - Successful low and high field tests
- Extensive risk analysis shows that the magnet is in excellent shape
  - Some refurbishment required

under construction

shipping to BNL

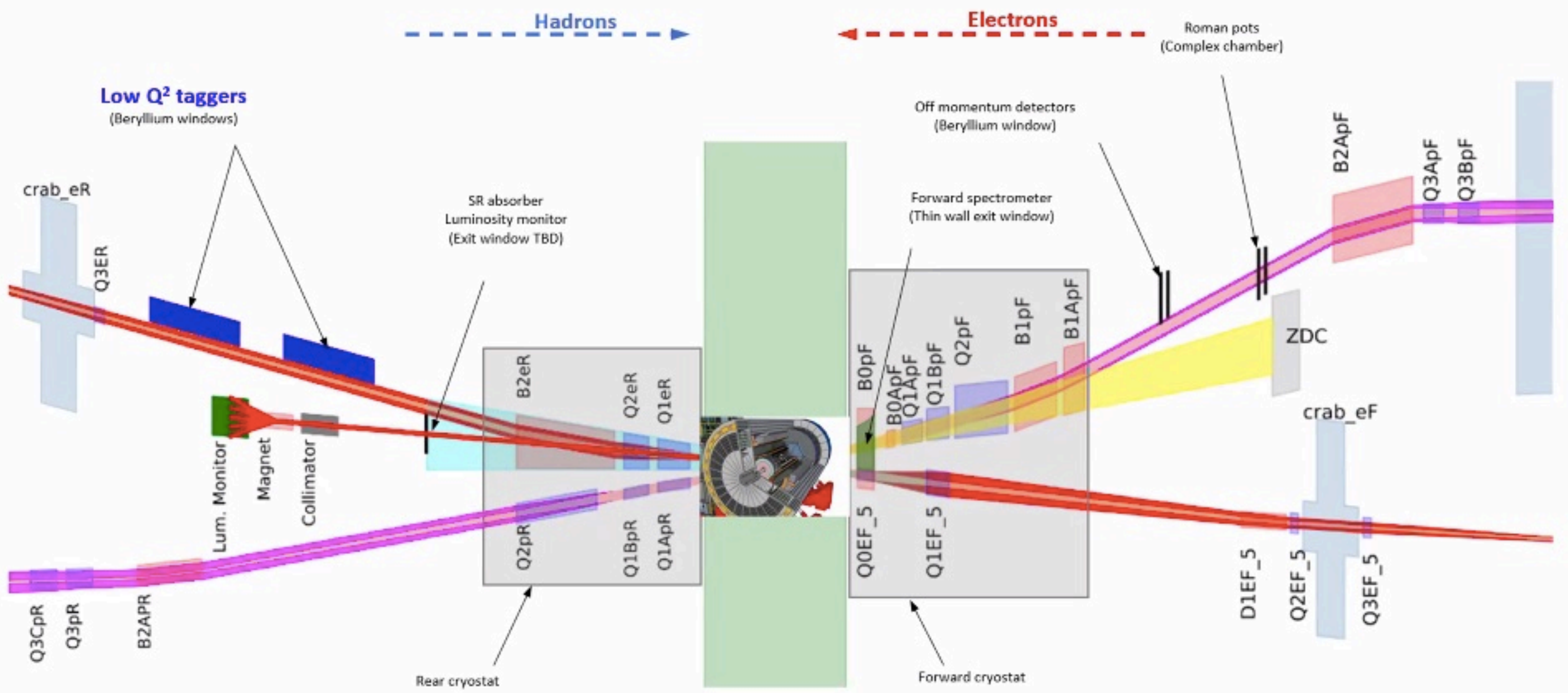
Pasquale Fabbricatore

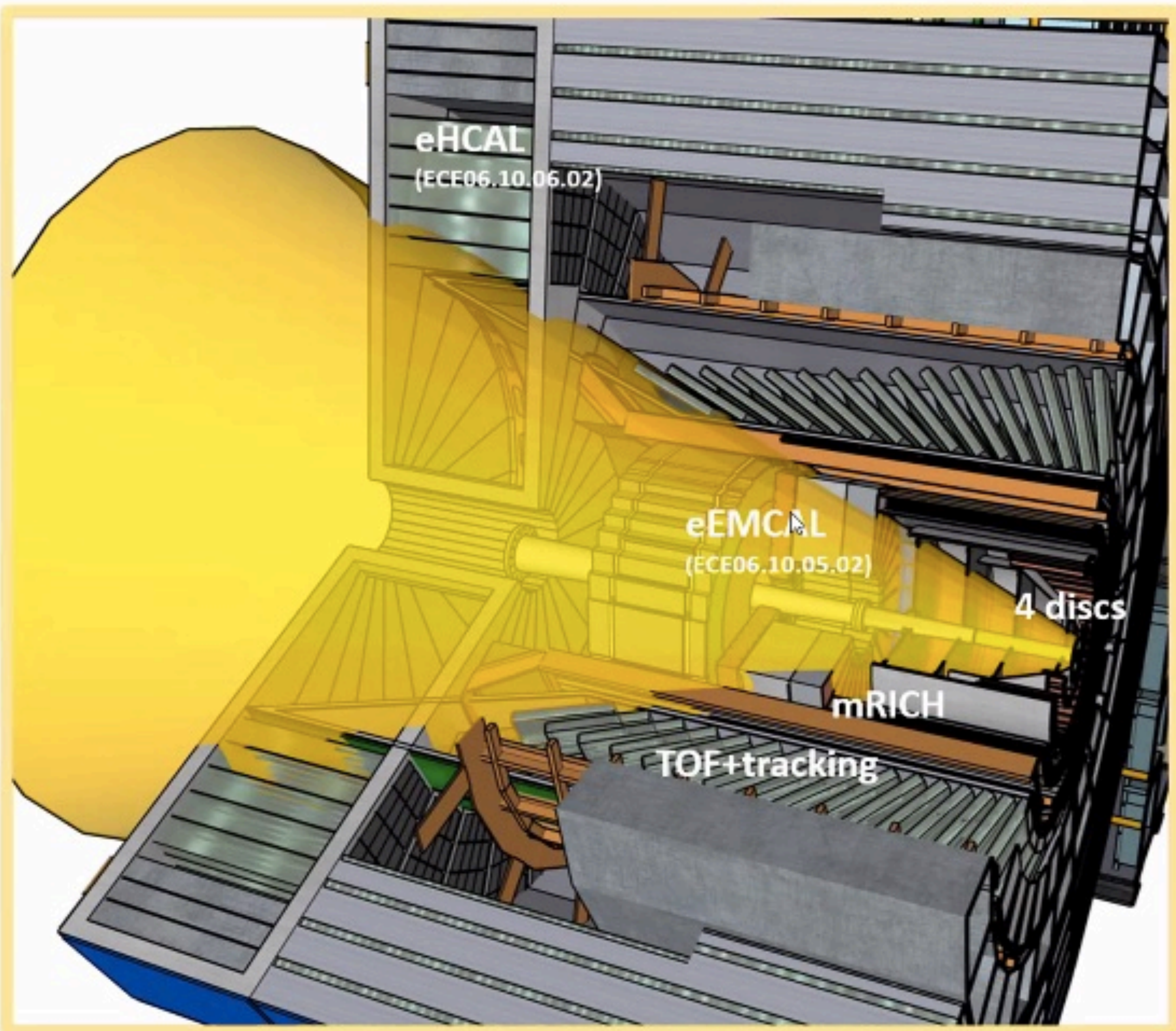
Designed BaBar and CMS 4T superconducting magnets

Recipient of IEEE Award for Continuing and Significant Contributions in the Field of Applied Superconductivity (2020)

ECCE

The EIC Interaction Region (IP6)





ELECTRON ENDCAP

Tracking: MPGD (large area μRWell)
Electron Detection:
- reference: PbWO4 crystals (reuse some)
- Option to replace outer rings with SciGlass (backup PbGl)

h-PID: mRICH & TOF
HCAL: Fe/Sc (STAR re-use)

CENTRAL BARREL

Tracking: ITS3 based MAPS Si for vertexing, sagitta, and endcaps; mRWell outer layer (optimization underway)
Electron PID: SciGlass
(alt: PbGl or upgraded W/SciFi)
(plus instrumented frame)
h-PID: hpDIRC & TOF
HCAL: Fe/Sc (sPHENIX re-use)

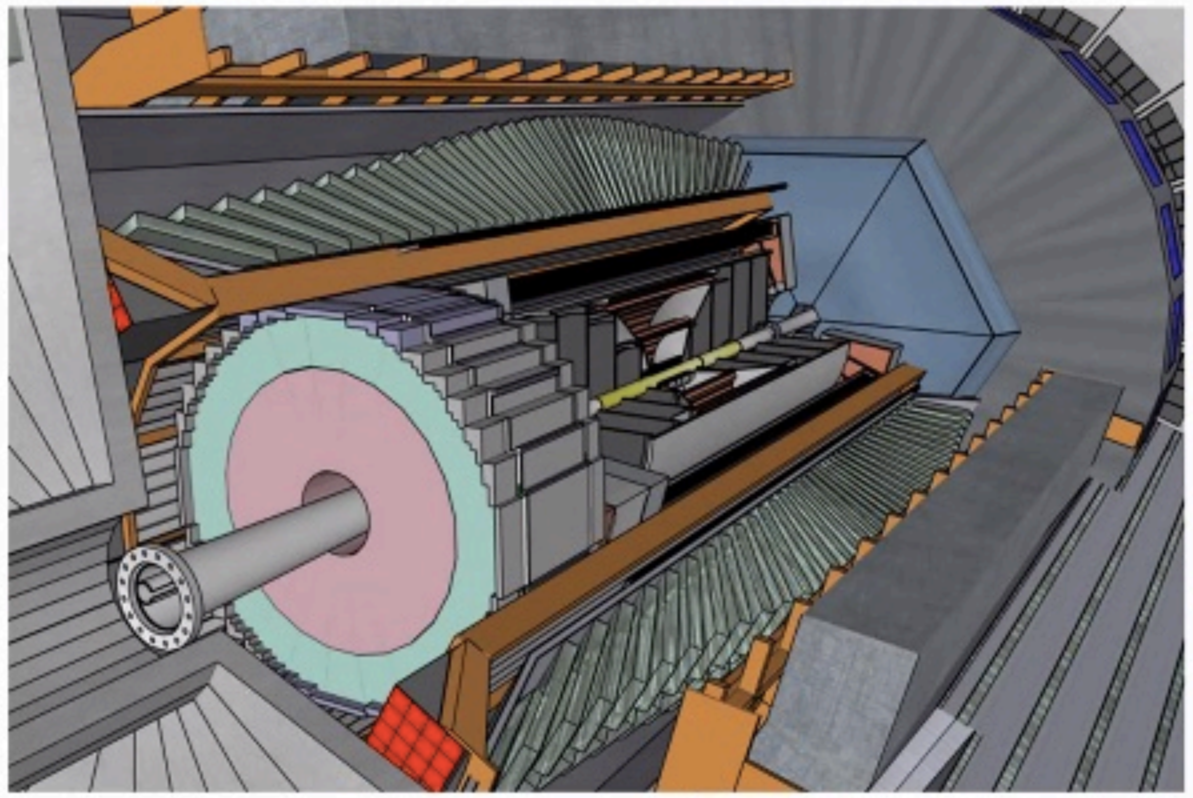
HADRON ENDCAP

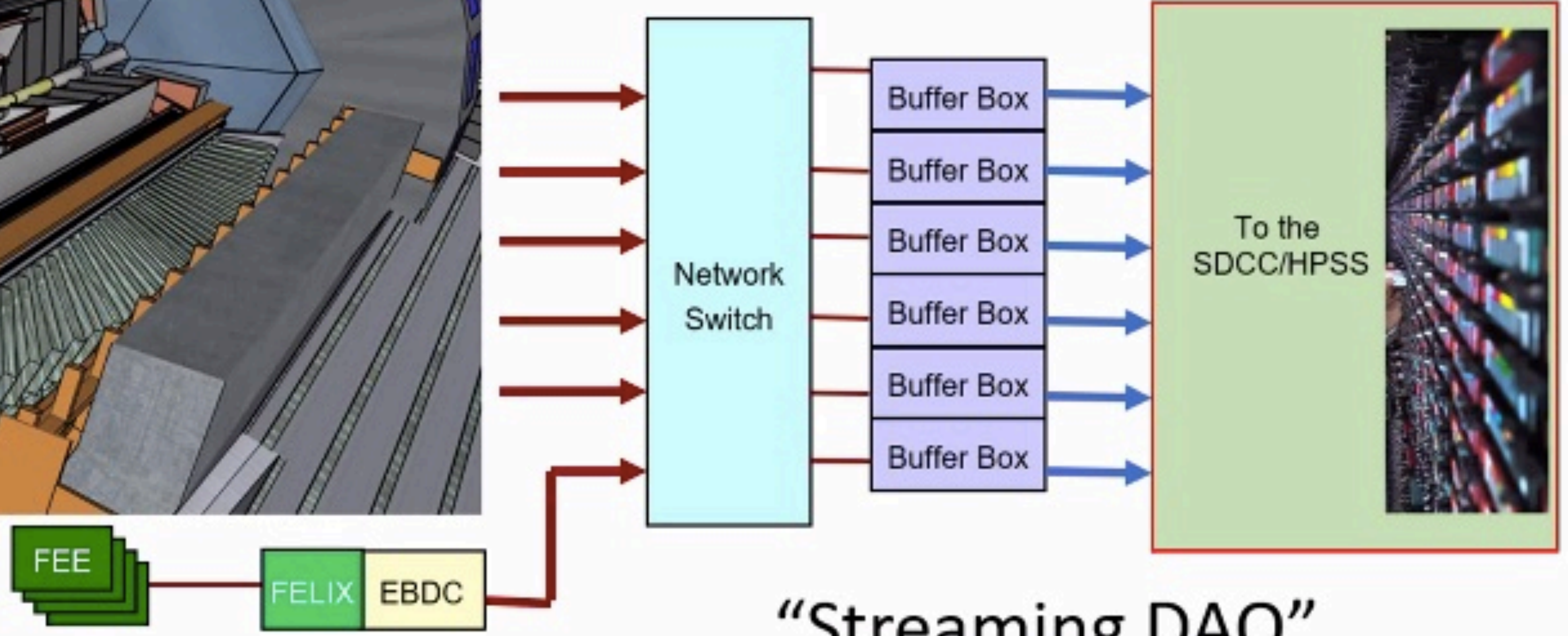
Tracking: MPGD (large area μRWELL)
PID: dual-RICH & TOF
Calorimetry:
- reference: standard W/ScFi shashlik (PHENIX re-use) for EMCal and long. sep. HCAL
- Upgrade path: dual readout

ECCE Streaming Data Acquisition

ECCE

Chris Cuevas
Martin L Purschke





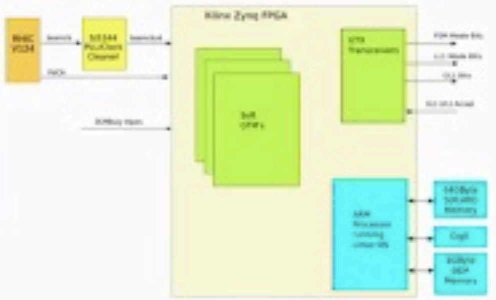
"Front End Electronics"
Each Detector SubSystem

"Streaming DAQ"

Local Level 1

Global Level 1

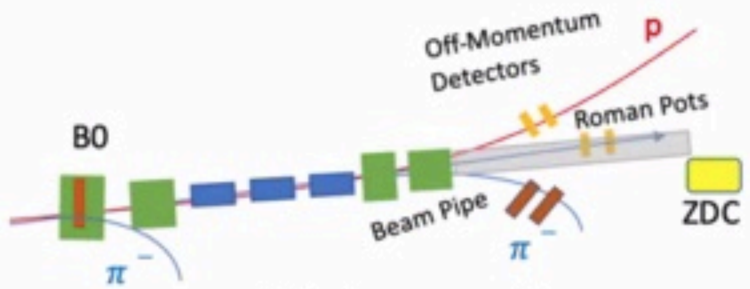
Slow control system



Timing System

Example of ECCE Physics : Origin of Hadron Mass

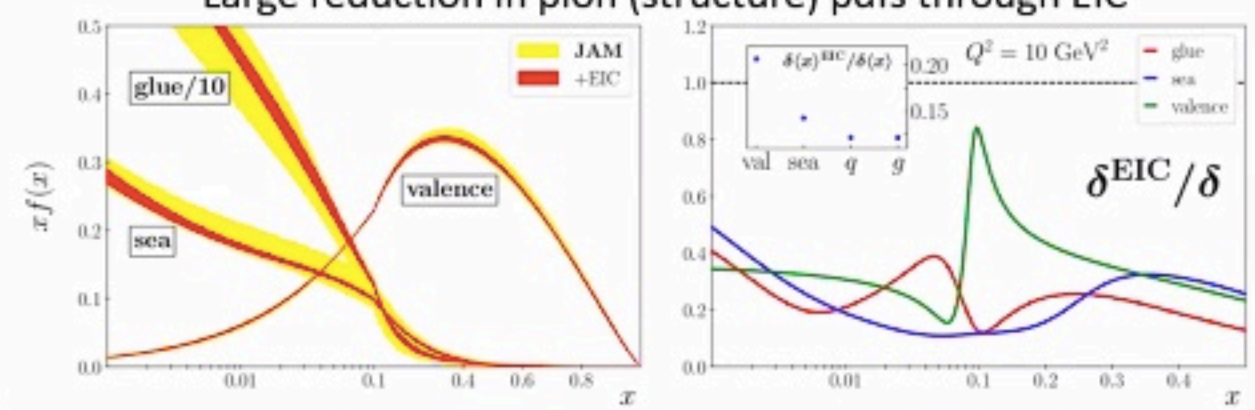
ECCE



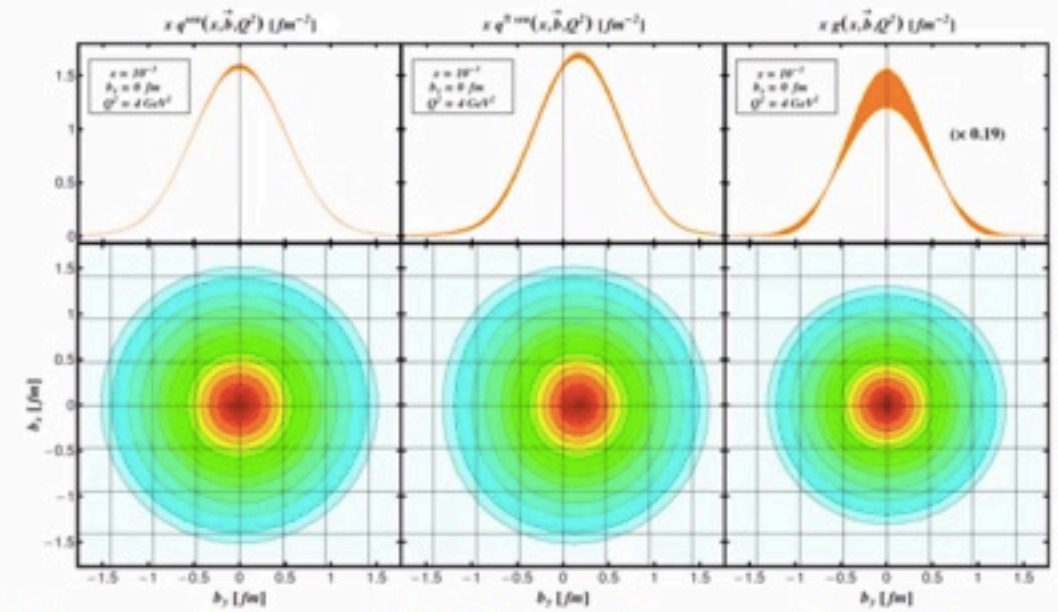
Major requirements

- ❑ Far-forward detection to tag n and Λ (or Σ°) (meson structure) and to tag p (for DVCS/3D).
- ❑ Scattered electron detection in electron endcap
- ❑ Good hadron endcap and far-forward calorimetry (goal: 35%/E, <50%/E acceptable)
- ❑ For pion form factor: pion in hadron endcap

Large reduction in pion (structure) pdfs through EIC



Yellow Report, Volume 2, Fig. 7.24



Yellow Report, Volume 2,Fig. 7.46

ECCE – physics reach enhanced in x_L and x_B with beam focus with dispersion – relevant for diffraction (e-p, e-A) and tagging (e-d, e-^{3}He, etc), and exclusive measurements

#	Parameter	EIC IR #1	EIC IR #2	Impact
8	Minimum $\Delta(B\rho)/(B\rho)$ allowing for detection of $p_T = 0$ fragments	0.1	0.003 – 0.01	Beam focus with dispersion, reach in x_L and p_T resolution, reach in x_B for exclusive processes

From 4th YR Workshop – talks on complementarity (Y. Zhang, V. Morozov)

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视图

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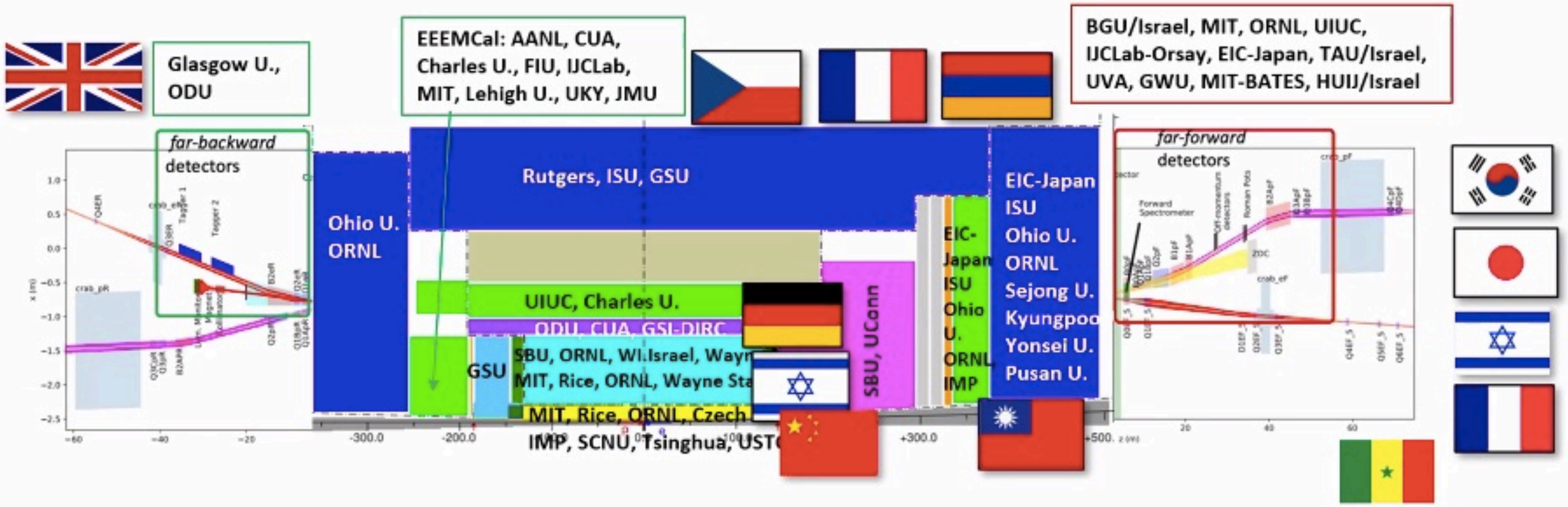
ECCE International

ECCE



Polarized Beam and polarimetry: MIT, UNH, SBU

Electronics: Columbia, ORNL

DAQ/Trigger: ISU, CU Boulder, OU, ORNL, SBU, UConn, LLNL

Artificial Intelligence: MIT, CNU, Brunel U.

CENTRAL

Tracking:
- Silicon: China, Czech Republic, Japan

Calorimetry
- PWO and SciGlass: Czech Republic, Armenia, France
- Forward Calo/Dual Readout: China, Japan, South Korea

Particle ID
- DIRC: GSI/Germany

FAR FORWARD – FAR BACKWARD
- Roman pots: France
- Off momentum: Israel
- ZDC: Japan
- Luminosity monitors: Israel
- Low Q2 tagger: UK

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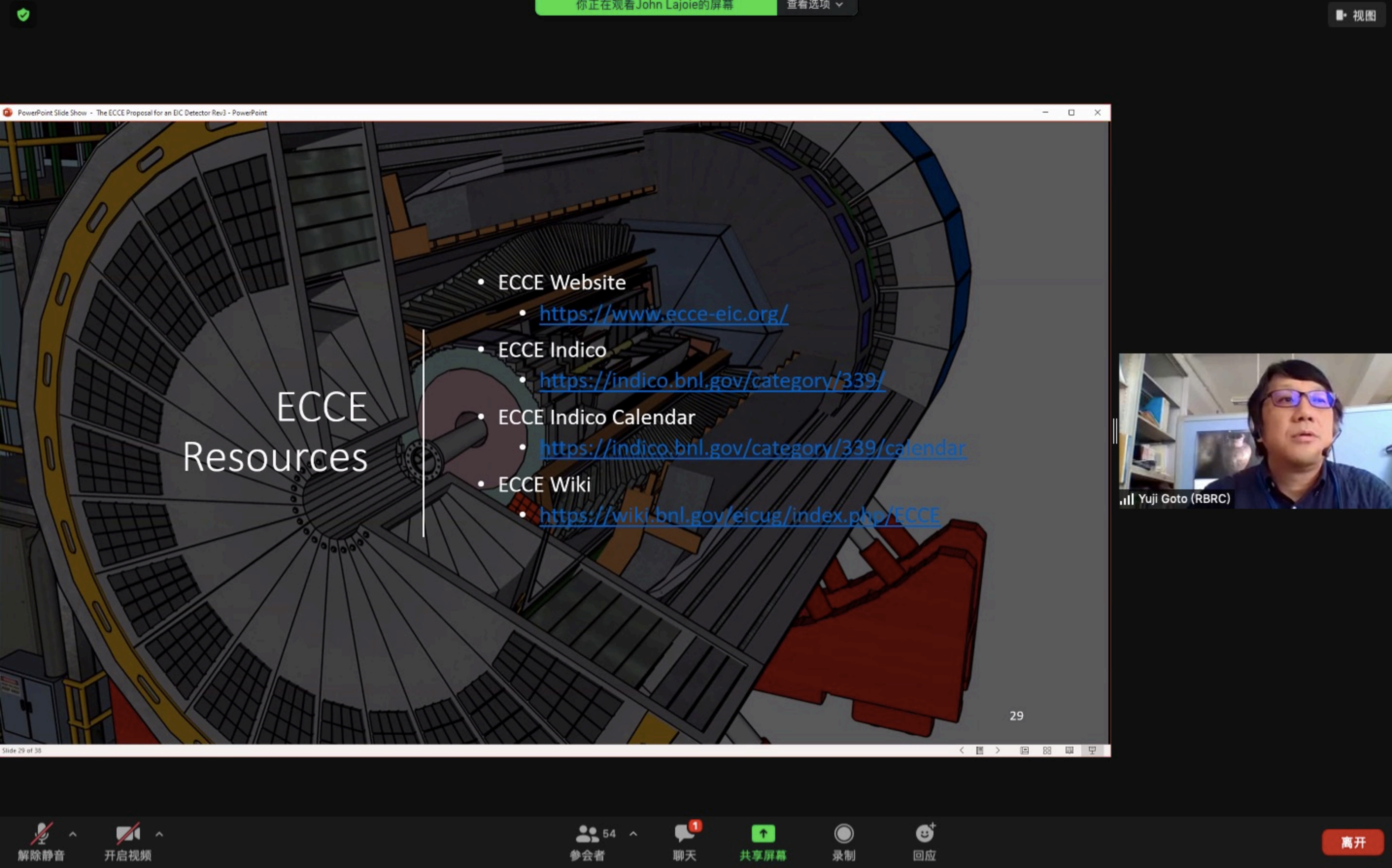
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Future DIS experiments worldwide

Planned DIS Colliders around the world 1812.08110

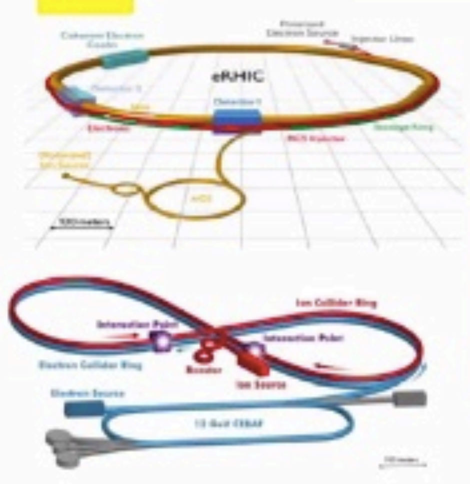
Facility	Years	E_{cm} (GeV)	Luminosity $(10^{33} cm^{-2} s^{-1})$	Ions	Polarization
EIC in US					l, ^{3}He, Li
EIC in Chin					ight nuclei
LHeC (HE-I					ible
PEPIC					ible
VHEeP					ible
FCC-eh					ible

U DIS Input

The era of the precision study of nucleon and nuclear structures in the next >20 years!

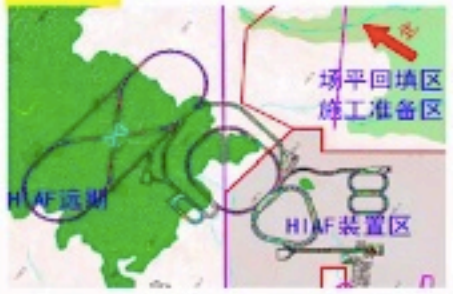
Uni

EIC



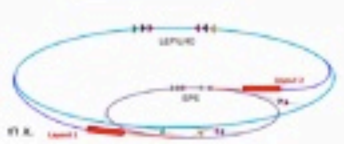
China

EicC



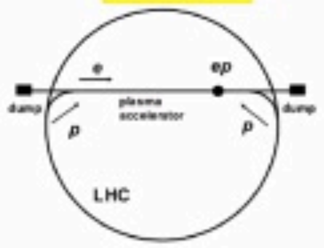
Europe (CERN)

PEPIC

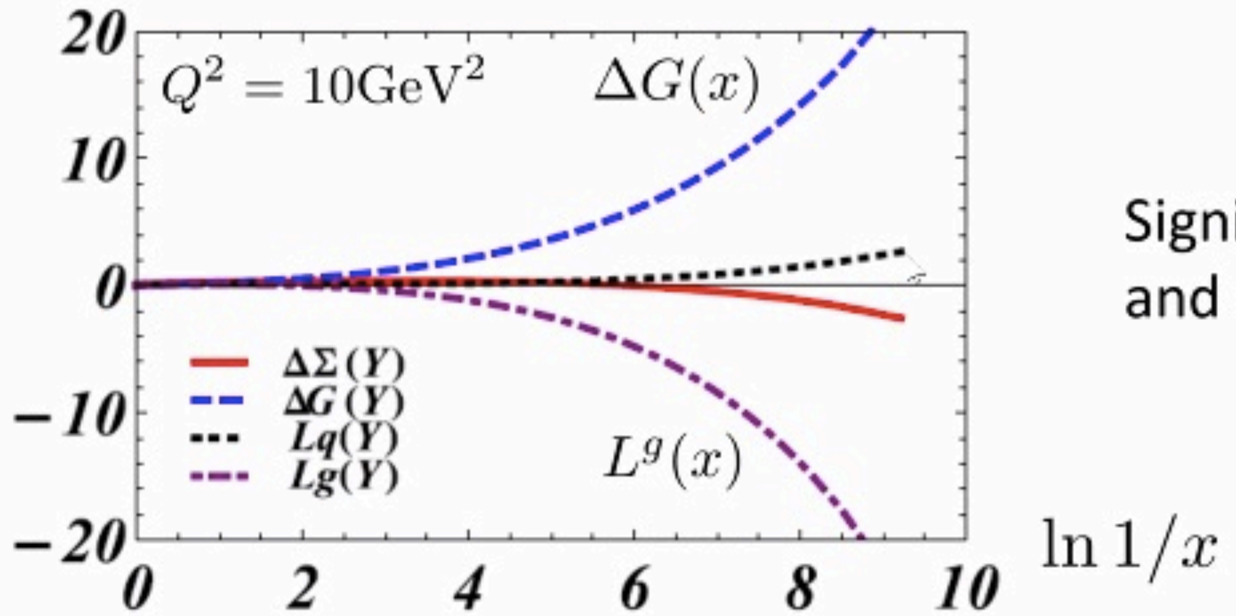


VHEeP

VLEeP



Don’t forget OAM, it’s there.



Significant cancellation between spin and OAM at small-x YH, Yang (2018)

All-order result Boussarie, YH, Yuan (2019) See also, Kovchegov (2019)

$$\Delta G(x) \sim \frac{1}{x^\alpha} \;\Rightarrow\; L_g(x) \approx -\frac{2}{1+\alpha}\Delta G(x)$$

Interplay between spin and small-x will be an important topic at EIC

Direct measurement of OAM is a challenge

Generalized parton distributions (GPD)

Non-forward $\Delta = P' - P$ generalization of PDF

$$P^+ \int \frac{dy^-}{2\pi} e^{ixP^+y^-} \langle P'S'|\bar{\psi}(0)\gamma^\mu \psi(y^-)|PS\rangle$$

$$= H_q(x,\Delta)\bar{u}(P'S')\gamma^\mu u(PS) + E_q(x,\Delta)\bar{u}(P'S')\frac{i\sigma^{\mu\nu}\Delta_\nu}{2m}u(PS)$$

Fourier transform $\Delta_\perp \to b_\perp$

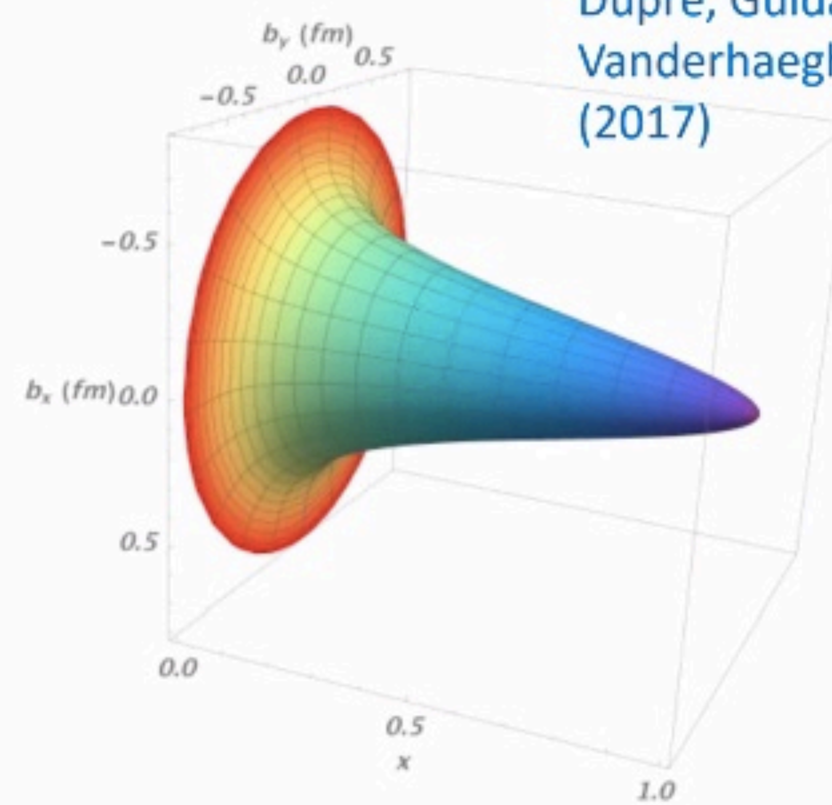
Distribution of partons in impact parameter space

First moment → elemag form factors

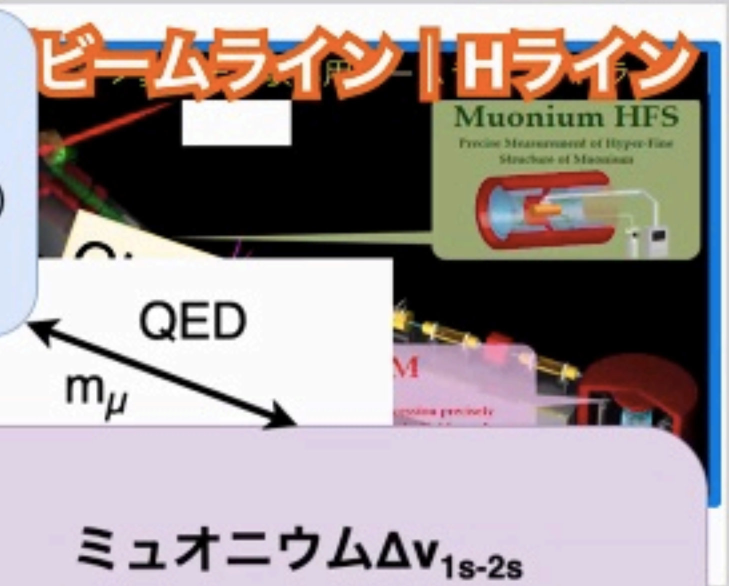
Measurable in
Deeply Virtual Compton Scattering (DVCS)

For the first time, we will have access to
GPD E_q Aschenauer, Fazio, Kumericki, Muller (2013)

Dupre, Guidal, Vanderhaeghen (2017)



ミュオン基礎物理実験



ミュオンg–2

- 標準模型で精密計算
  （強い相互作用と弱い相互作用の寄与）
- プラス新物理の寄与？

$$\vec{\mu}_\mu = g_\mu \frac{eh}{2m_\mu c}\vec{s}$$

QED ↔ μ_μ, α, g_μ

QED ↔ m_μ

ミュオニウム $\Delta\nu_{HFS,\ n=1}$

- 磁気双極子モーメント μ_μ
- 微細構造定数 α
- 量子電磁力学QED補正
- 弱い相互作用の寄与

QED ↔ m_μ

ミュオニウム$\Delta\nu_{1s\text{-}2s}$

- ミュオン質量 m_μ 1ppb
- 量子電磁力学QED補正

西村昇一郎（KEK）

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ミュオン基礎物理実験

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QED m_μ

ミュオニウム$\Delta\nu_{1s\text{-}2s}$
- ミュオン質量 m_μ 1ppb
- 量子電磁力学QED補正

束縛状態・加速状態のミュオンを精密に測定

ミュオンペニングトラップ実験 世界初

ほぼ自由粒子かつ静止状態のミュオンを精密に測定

西村昇一郎（KEK)

ミュオンペニングトラップ実験

目的｜ミュオン基礎物理定数の精密測定

- q/m（~1ppb）
- muon magnetic moment（~1ppb）
- muon life（~1ppm）

$116\ 592\ 061(41)\times10^{-11}$ 0.35 ppm

Table 1: Summary of Measured Muon Properties and Selected Decay Rates and Limits

Property	Symbol	Value	Precision
Mass	m_μ	105.658 3715(35) MeV	34 ppb
Mean Lifetime	τ_μ	$2.196\,9811(22)\times10^{-6}$ s	1.0 ppm
Anom. Mag. Moment	a_μ	~~$116\,592\,091(63)\times10^{-11}$~~	~~0.54 ppm~~
Elec. Dipole Moment	d_μ	$< 1.9\times10^{-19} e\cdot$cm	95% C.L.

B. Abi *et al.*, Phys. Rev. Lett. **126**, 141801 (2021)

第一目標｜Muonをtrapする装置開発、実証試験

Muon penning trapを実現させるポイント

- 単寿命のミュオンをトラップして振動周波数を測定（困難）
- 大強度超低速ミュオンビームが必要

J-PARC MUSEの大強度ミュオンビームで初めて実現

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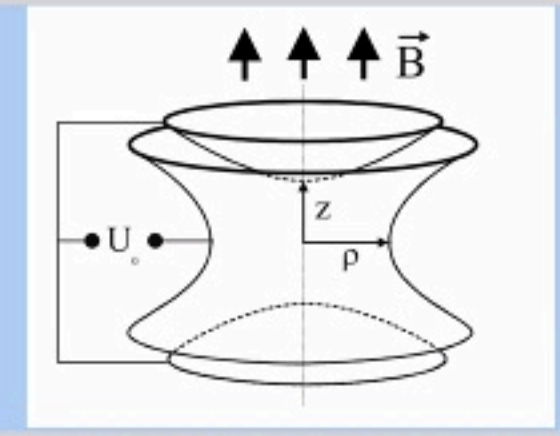
ミュオンのペニングトラップ

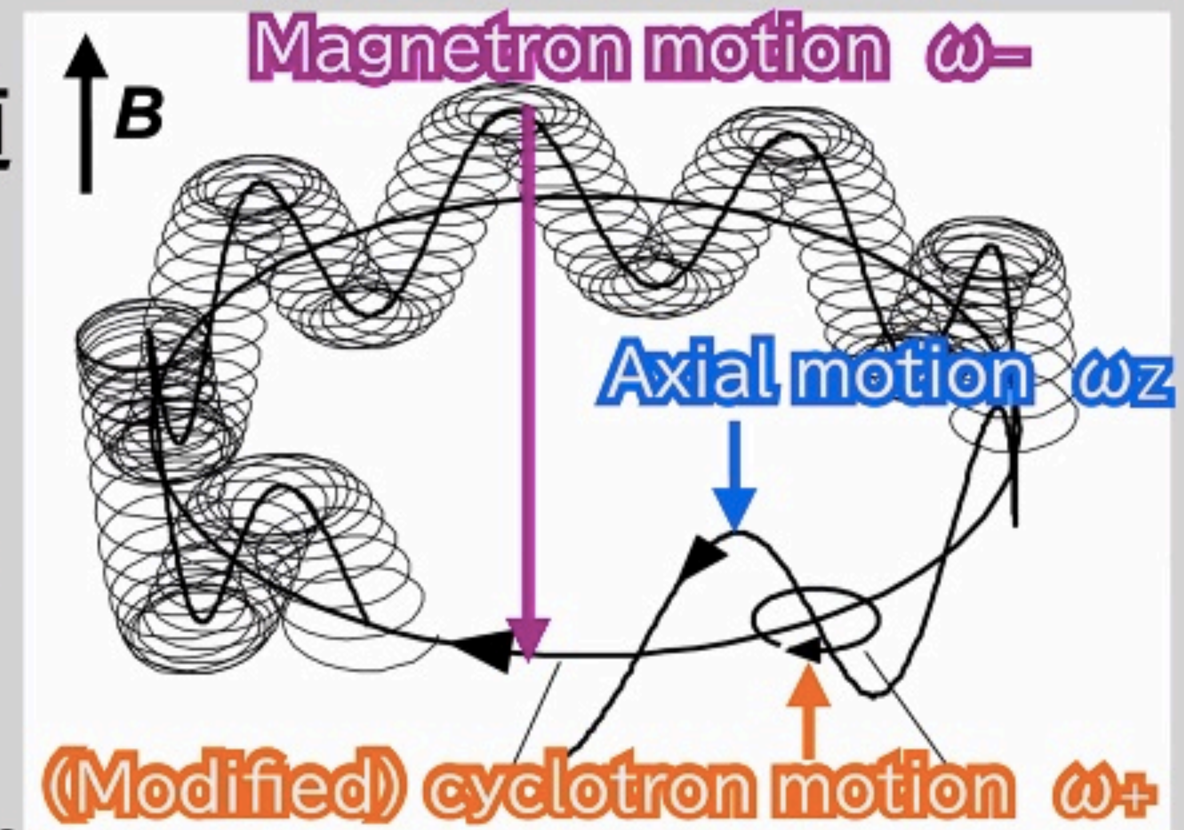
ペニングトラップ

- 電場と磁場でμを捕獲
- ミュオンで初の試み



トラップ中の粒子軌道

- Cyclotron motion
- Axial motion
- Magnetron motion
  - ✦ E×B drift



J. Dilling, Ph.D. thesis, Rupertus Carola University of Heidelberg, Germany

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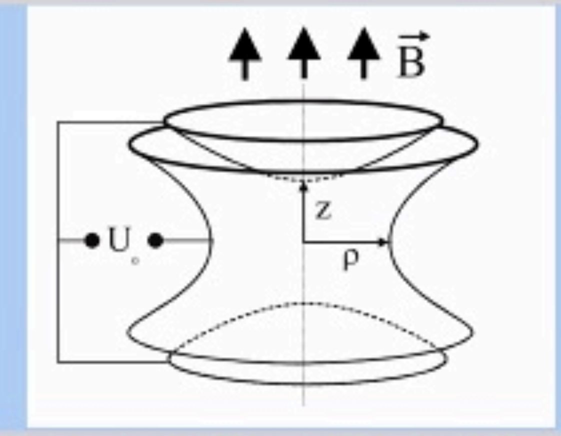

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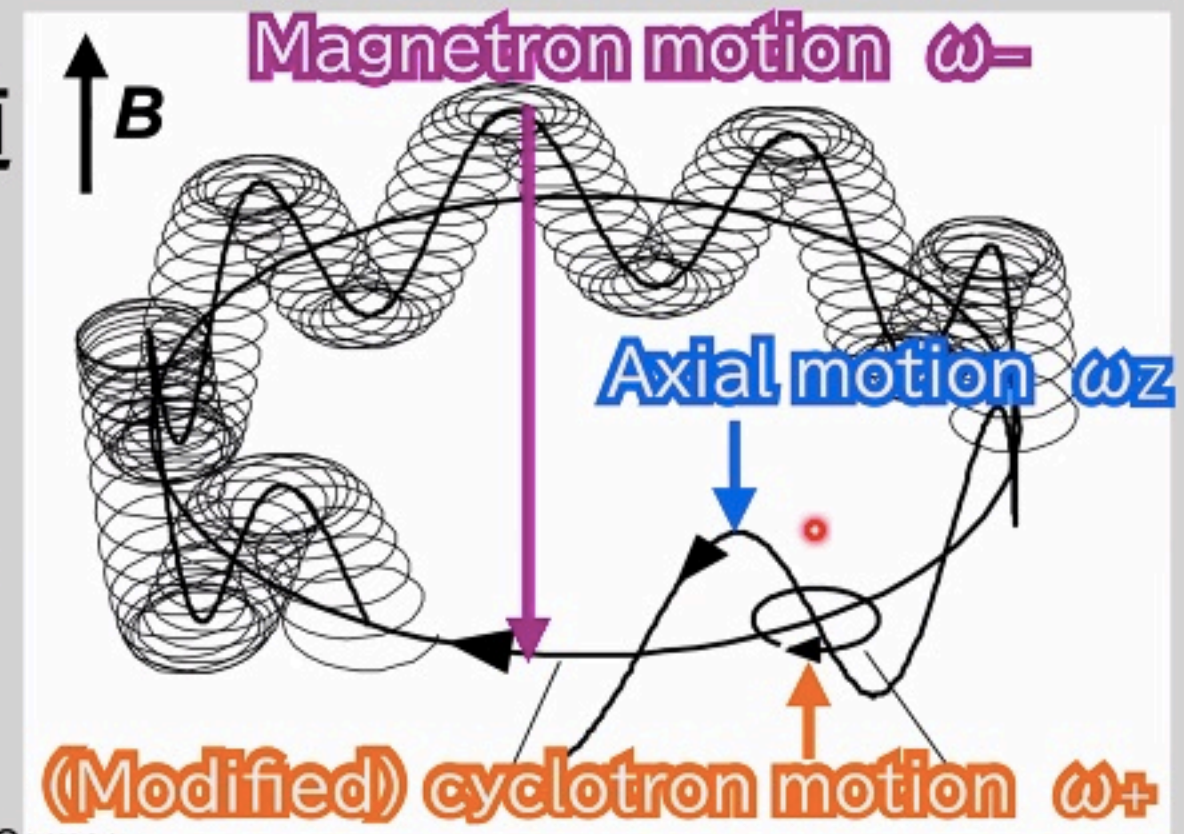

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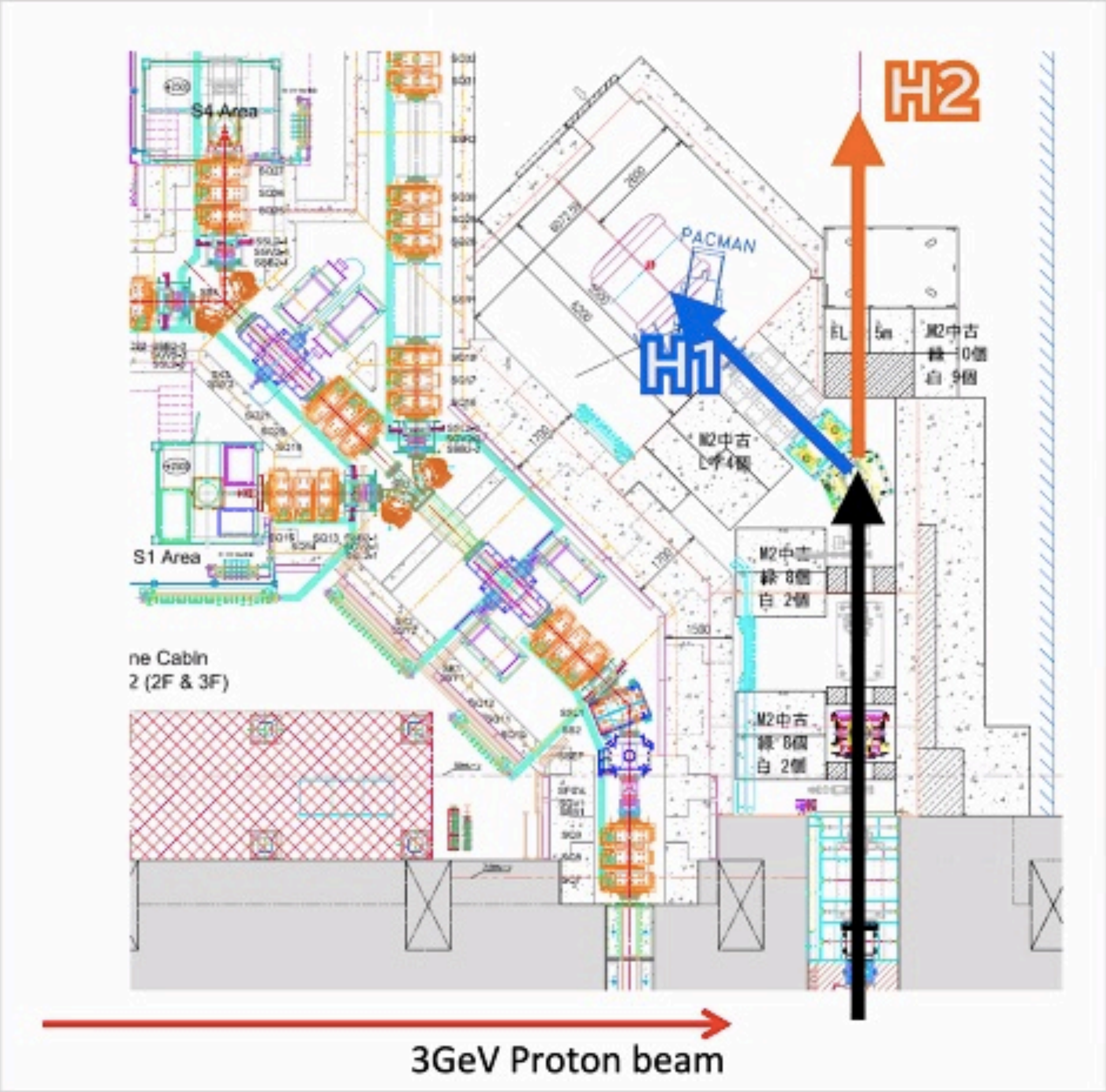
西村昇一郎（KEK)

J-PARC MLF H Line

H Line

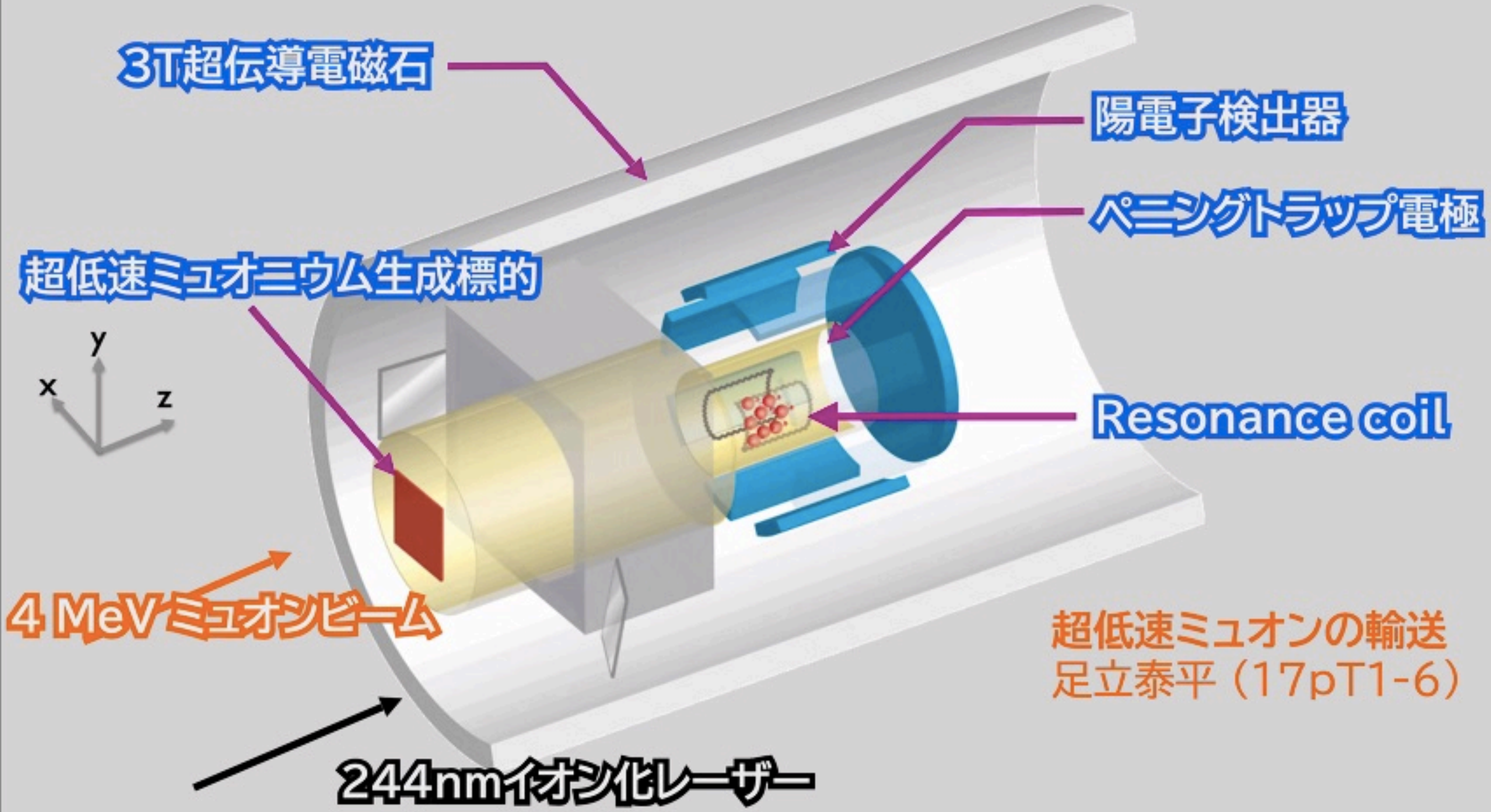
- 表面正ミュオン
  - ✦ $2\times10^8\ \mu^+/s$
  - ✦ 偏極度 100%
- 負ミュオン (~30 MeV/c)
  - ✦ $\sim10^7\ \mu^-/s$
  - ✦ 偏極度 30%

今年度中に完成予定



西村昇一郎（KEK）

実験セットアップ（Resonance Mode）



超低速ミュオンの輸送
足立泰平（17pT1-6）

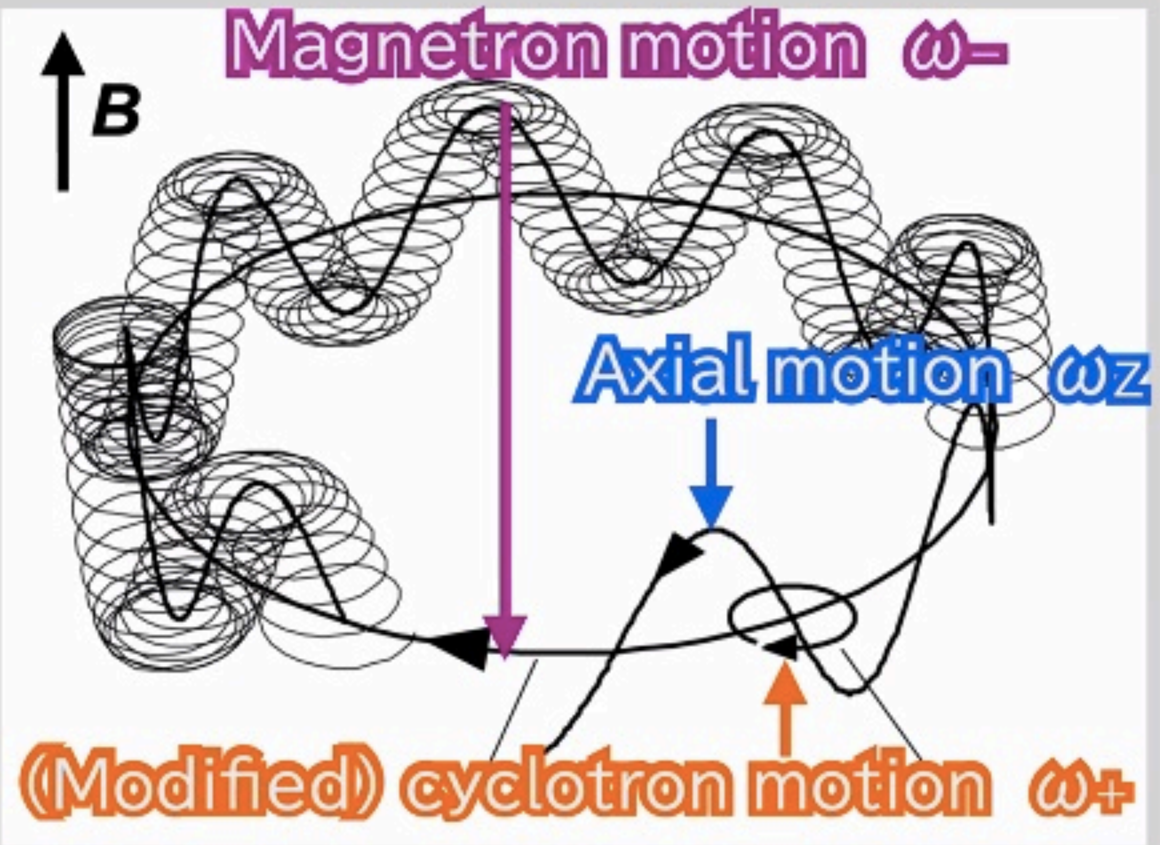
西村昇一郎（KEK)

ペニングトラップ中での粒子運動

古典的な非相対論的力学の解

- Cyclotron frequency
  $$\omega_c = \frac{qB}{m}$$
- axial frequency
  $$\omega_z = \sqrt{\frac{2qV_0}{m}}$$ これを測りたい
- 3つの固有振動モード

$$\omega_z = \sqrt{\frac{2qV_0}{m}} \qquad \omega_\pm = \frac{1}{2}\left(\omega_c^2 \pm \sqrt{\omega_c^2 - 2\omega_z^2}\right)$$



西村昇一郎（KEK）

ペニングトラップ中での粒子運動

エネルギー｜3つの独立な調和振動＋スピン

$$\mathcal{H} = \hbar\omega_+ \left(\frac{1}{2} + n\right) - \hbar\omega_- \left(\frac{1}{2} + k\right) + \hbar\omega_z \left(\frac{1}{2} + l\right) + \frac{g}{2}\hbar\omega_c \frac{s}{2}$$

重要な周波数 @2.9 T

$\omega_c/2\pi = 392.6\ \mathrm{MHz}$

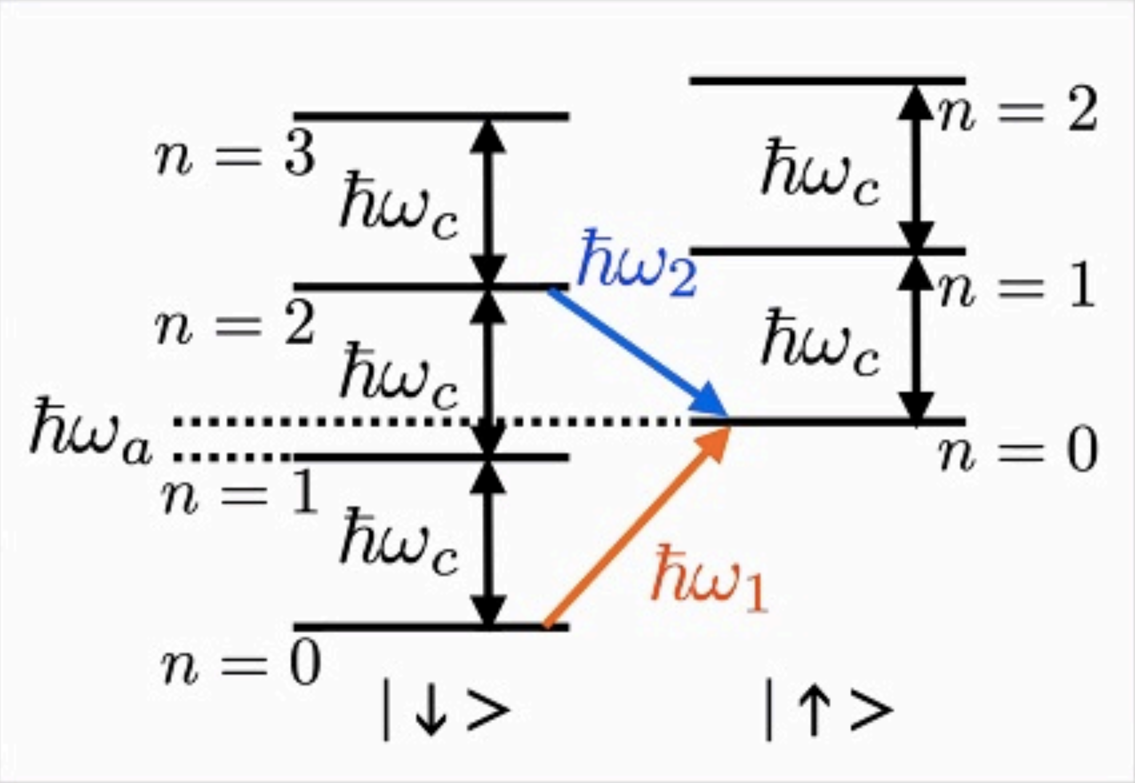
$\omega_a/2\pi = 0.4\ \mathrm{MHz}$

測定する周波数

$\omega_1/2\pi = 393.0\ \mathrm{MHz}$

$\omega_2/2\pi = 392.2\ \mathrm{MHz}$

2周波数の平均を求める



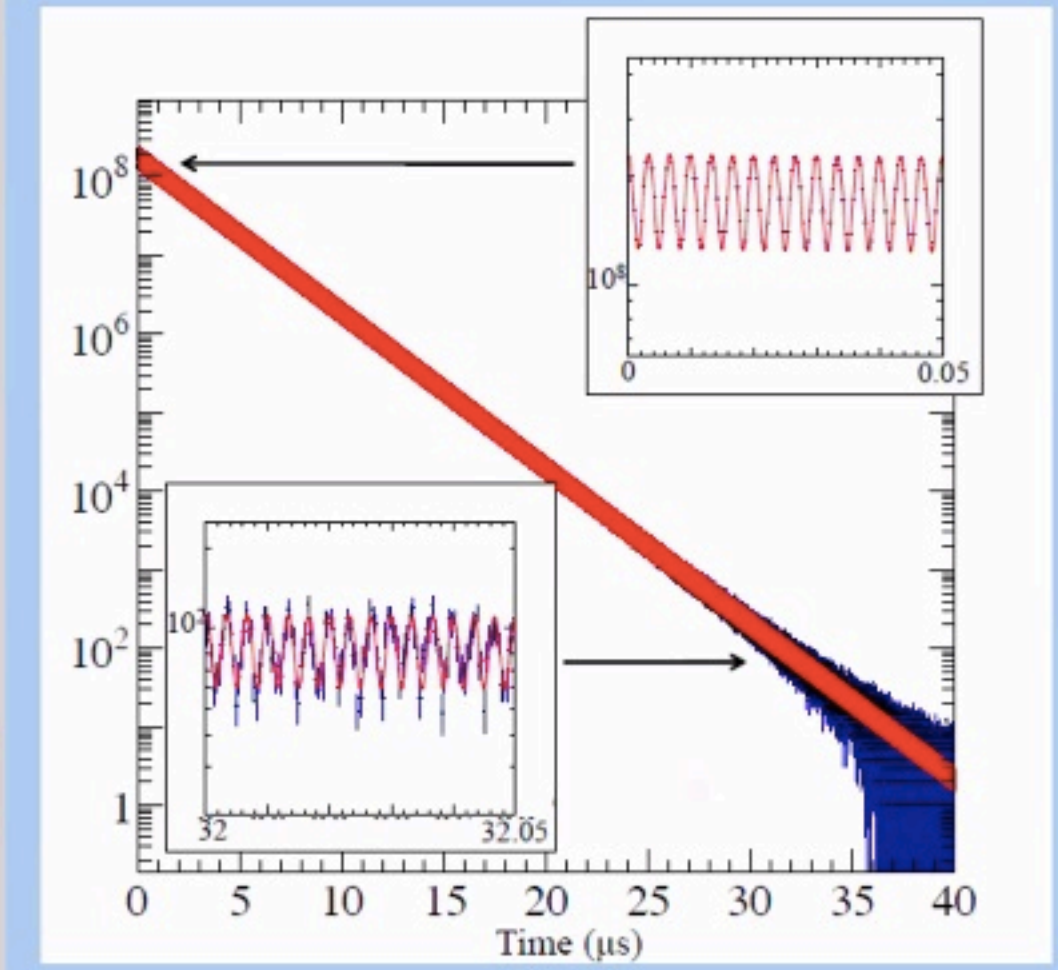
西村昇一郎（KEK)

Simulation for $\pi/2$ Pulse Mode (B=2.9 T)

Condition

- Muon spin polarization | 100%
- Muon spin rotation frequency @2.9T | 135.35 MHz/T×2.9T = 393.037 MHz
  - ✦ 880 wiggles in a life
- Beam time ~100 days (10^{12} events)

ミュオン磁気モーメント | 1ppb
ミュオン寿命 | 1ppm
を達成できる



西村昇一郎（KEK）

Muon Spin Flip（当初案）

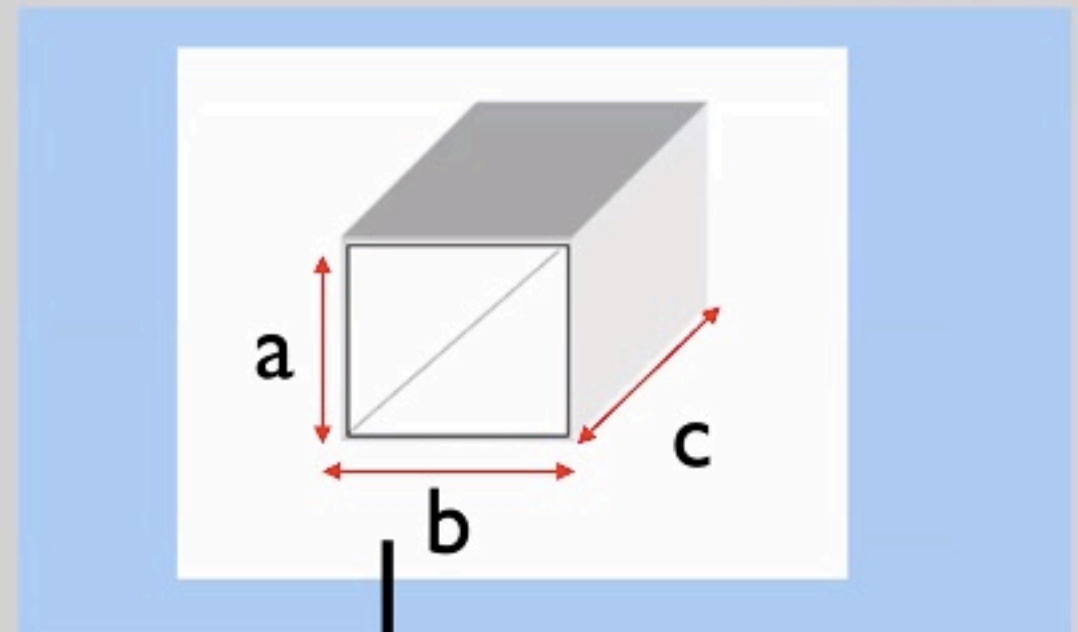
ミュオンの磁気回転周波数 @2.9T

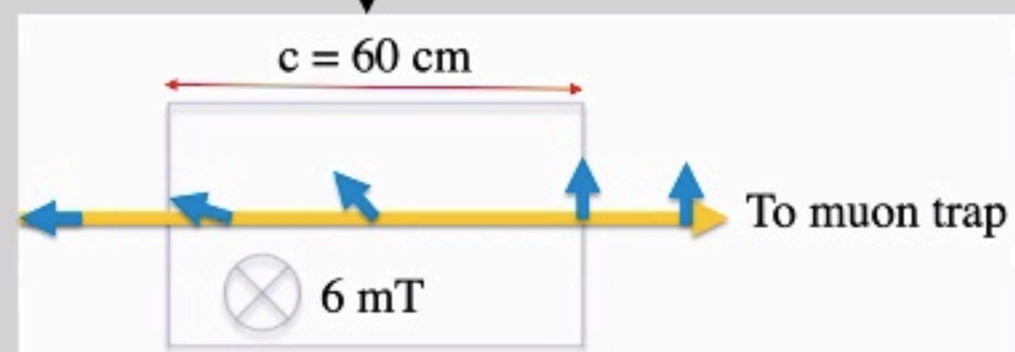
- 135.53 MHz/T×2.9 T ＝393.037MHz

π/2パルスでスピン方向を90°回転する場合

- γ_{μ}= 135.53 MHz/T = 135.53 kHz/mT
- H_{RF}=6 mT (60G)
- ν = 813kHz ~ 1.23μs, π/2 pulse ~ 0.3μs,

直方体型キャビティで実現





2.2 keV slow muon
Flight time of 60cm~0.3 ms

西村昇一郎（KEK)

Muon Spin Flip

ミュオンの磁気回転周波数 @2.9T

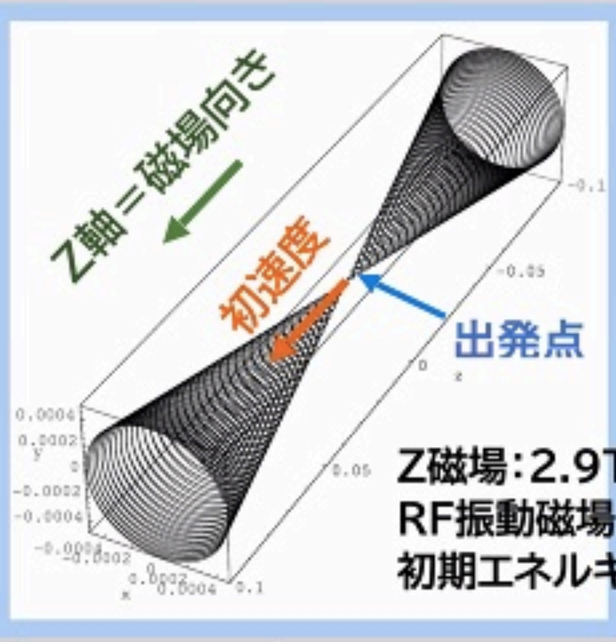
- 135.53 MHz/T×2.9 T
＝393.037MHz

π/2パルスでスピン方向を90°回転する場合

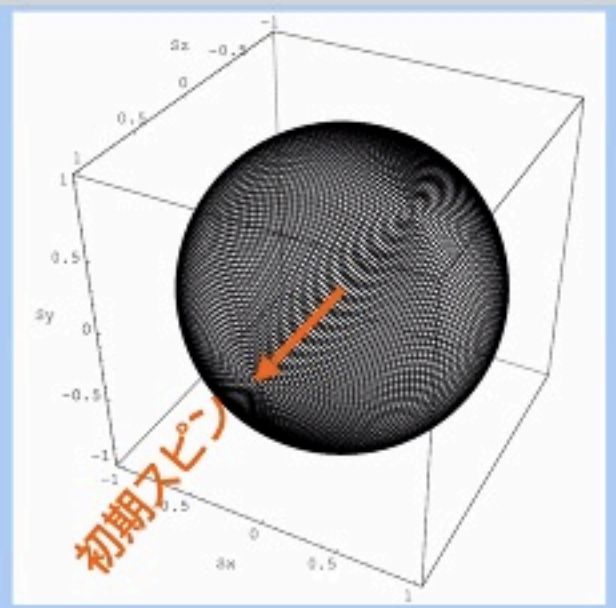
- γ_{μ}= 135.53 MHz/T
= 135.53 kHz/mT
- H_{RF}=6 mT (60G)
- ν = 813kHz ~ 1.23μs,
π/2 pulse ~ 0.3μs,

スピンの向きと一緒に運動量も変化

- Z方向の運動量は減少
- スピンフリップと同時に減速
  - ✦ トラップに応用検討



Z磁場:2.9T
RF振動磁場:290G
初期エネルギ:1keV

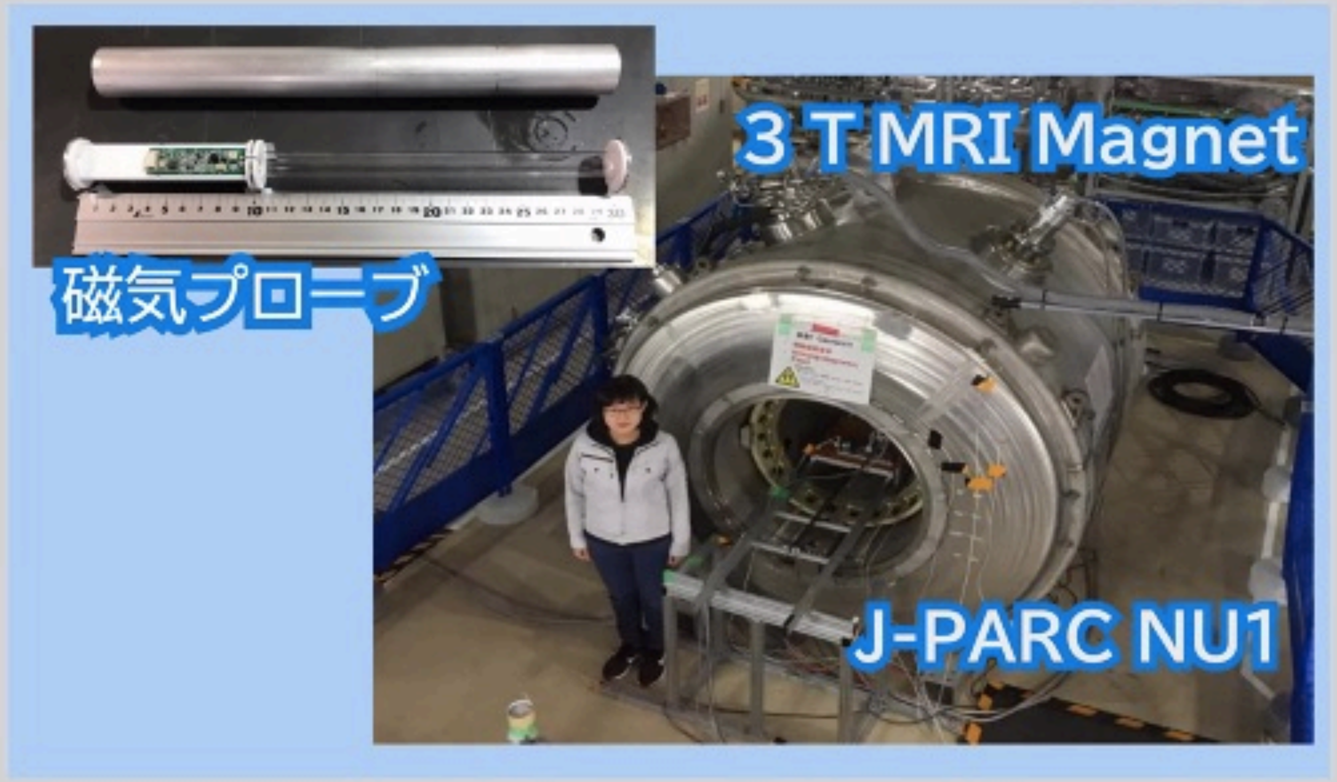


西村昇一郎（KEK)

トラップ電磁場設計

一様磁場

- ミュオニウム超微細構造測定実験の磁石を利用
  - 一様性は0.27ppbを達成済み



四極電場

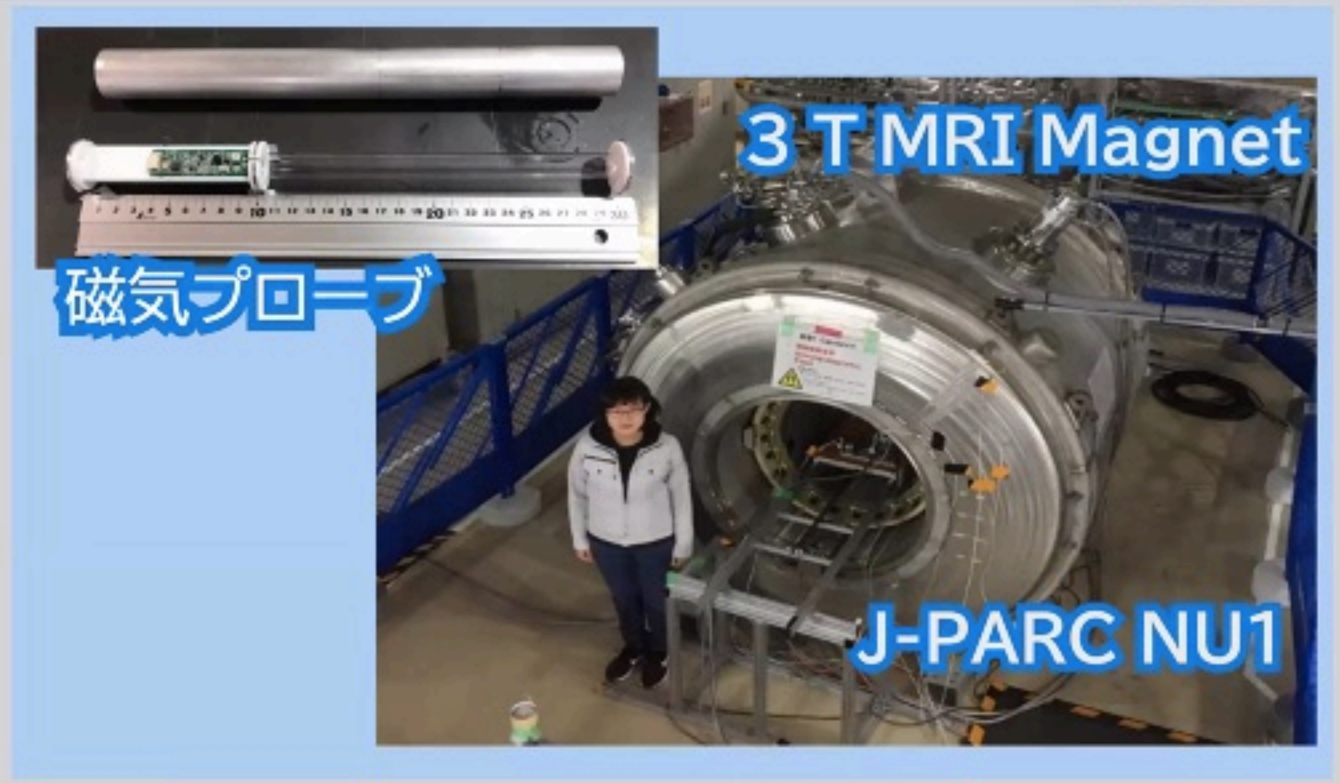
- 直方体型の電極を設計、検討中
  - 多くのミュオンをトラップ可能

西村昇一郎（KEK)

トラップ電磁場設計

一様磁場

- ミュオニウム超微細構造測定実験の磁石を利用
  - 一様性は0.27ppbを達成済み



四極電場

- 直方体型の電極を設計、検討中
  - 多くのミュオンをトラップ可能

西村昇一郎（KEK）

Summary

Muon penning trap

- 世界初
- Muon基礎物理定数の精密測定

Resonance mode

- Resonance coilで共鳴周波数を測定
- Muon質量~1 ppbでの測定精度を目指す

$\pi/2$ pulse mode

- Muon磁気モーメントと寿命を測定
- 軸方向の減速とスピン回転を両立

你正在观看足立泰平(KEK物構研)的屏幕 查看选项

目次

- ペニングトラップ実験の概要
- ミュオンの超低速化
- 各過程の評価
  - H-Lineでのミュオンビームの輸送
  - 実験装置への入射
  - エアロゲルでのミュオンの停止
  - エアロゲルからのミュオニウム湧き出し
  - 真空中でのミュオニウムの拡散
  - ミュオニウムのレーザーイオン化
- まとめ

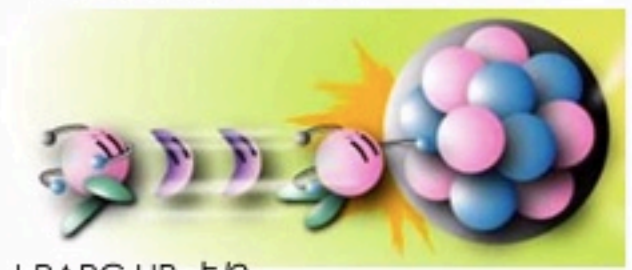
角 直幸[17pT1:後半座長]対所有人说
17pT1-6

解除静音 开启视频 参会者 53 聊天 共享屏幕 录制 分组讨论 回应 离开 视图

ミュオンペニングトラップ実験

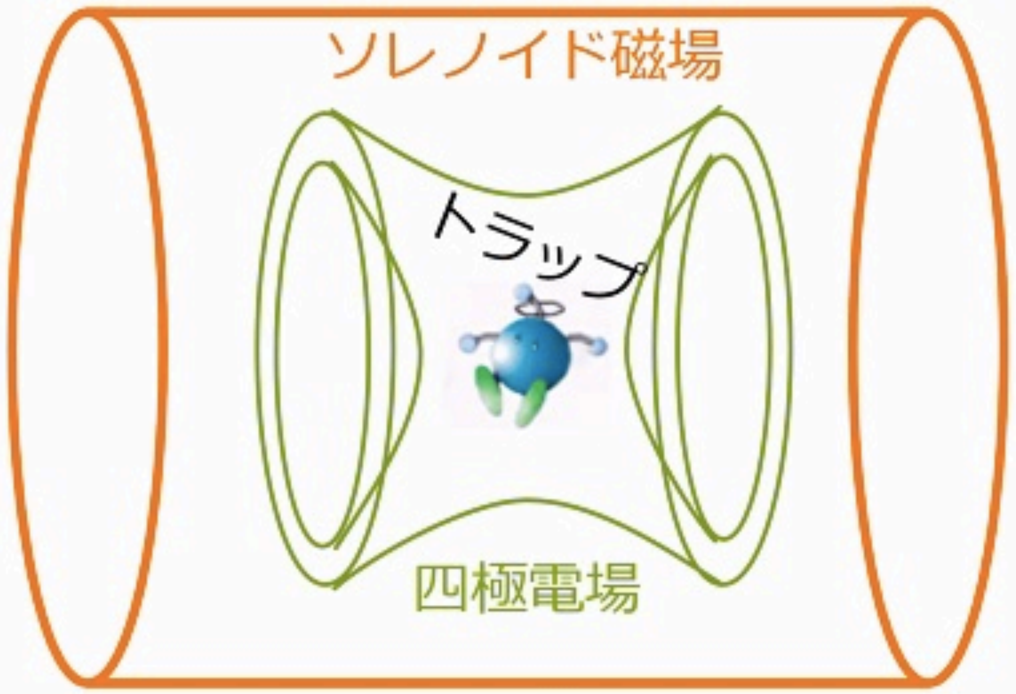
- ミュオンをペニングトラップに入れて運動を観測する実験
- 質量電荷比、磁気能率、寿命などの精密測定が可能

大強度陽子ビームによる
ミュオン生成



J-PARC HP より

ミュオンビーム

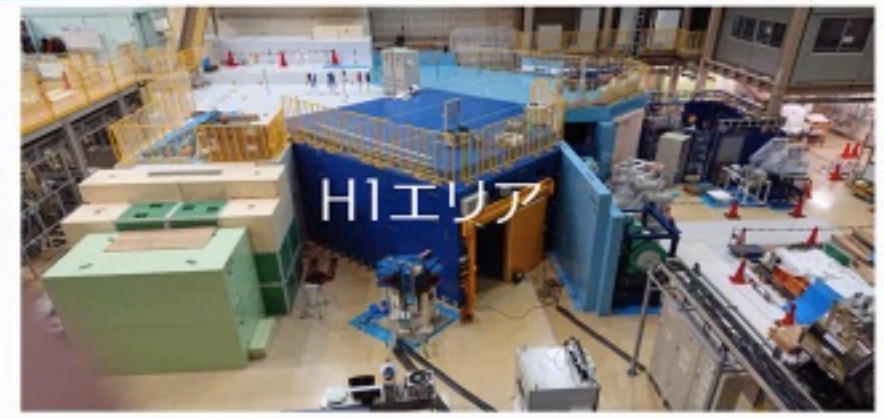


ペニングトラップ

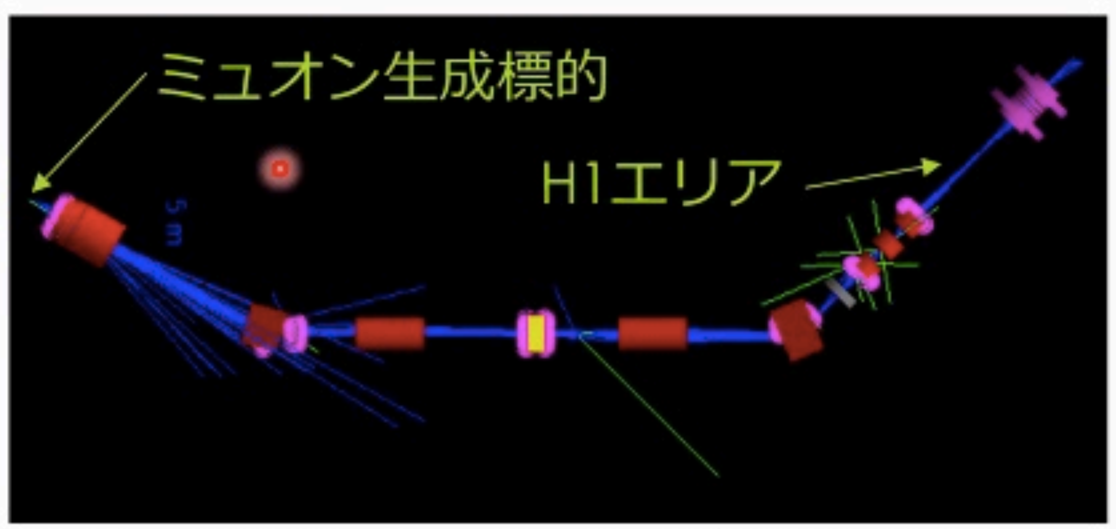
ペニングトラップに入れるには
普通のミュオンは速過ぎる
→超低速化が必要

ステップ１ H-Lineでのミュオンビーム輸送

- H-Line
  J-PARC 物質・生命科学実験施設(MLF)の
  第１実験ホールにあるミュオンビームライン
- トラップ実験はH-LineのH1エリアで実施予定
- 約 28 MeV/c のミュオンビームを取り出す
- Geant4ベースの G4beamlineにてシミュレーション
  （H-Line担当の山崎高幸氏よりデータを貰う）



H1エリア写真



H-Lineのシミュレーション上のジオメトリ

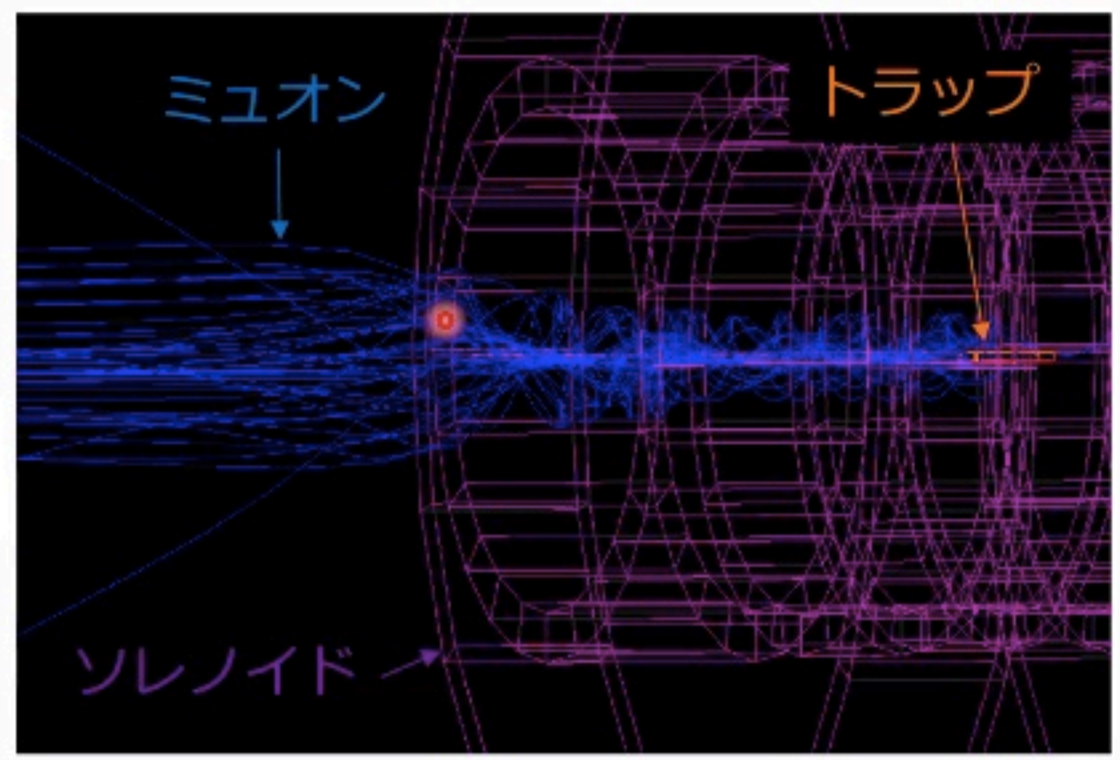
H1エリアでのミュオンビーム

- レート：$1.4\times10^{8}\ \mu^{+}/s$
- 運動量：27.6 MeV/c
  (σ 1.5 MeV/c)

ステップ２
実験装置へのビーム入射

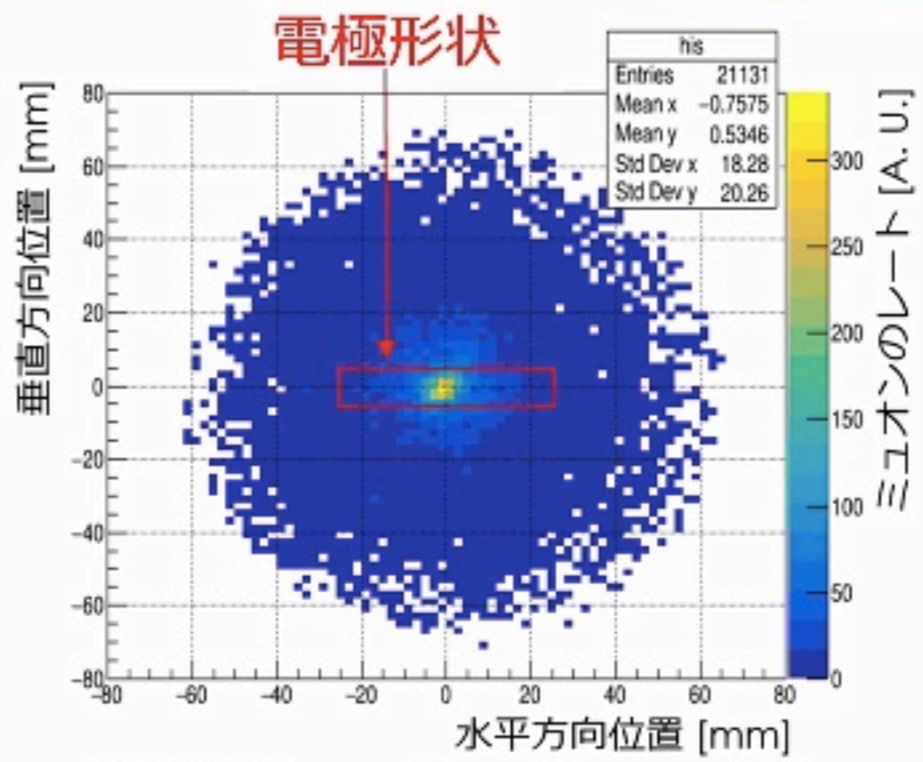
- トラップ用ソレノイド：超伝導、中心磁場 2.9 T
- G4beamlineでシミュレーション

超伝導ソレノイド

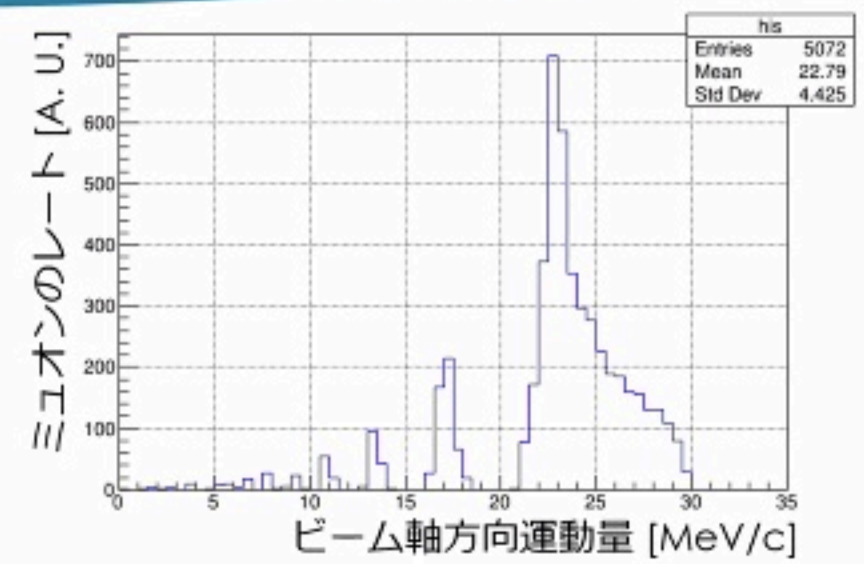


ソレノイドへ入射するミュオンビーム（青線）
平行だった軌道が、螺旋軌道になり絞られる。

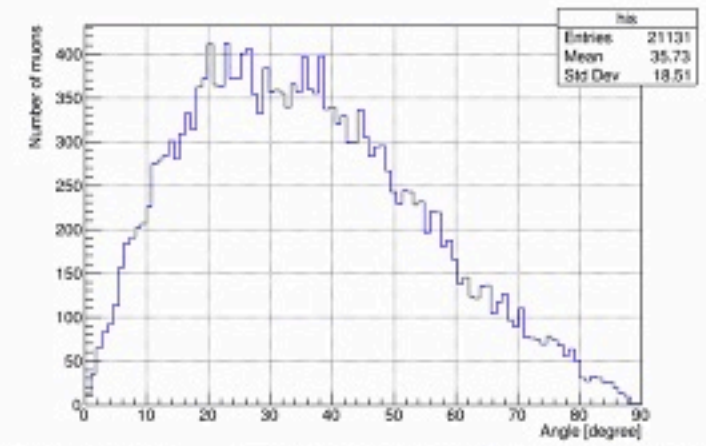
ステップ２　実験装置へのビーム入射
入射直前の分布



電極直前でのミュオンのXY分布



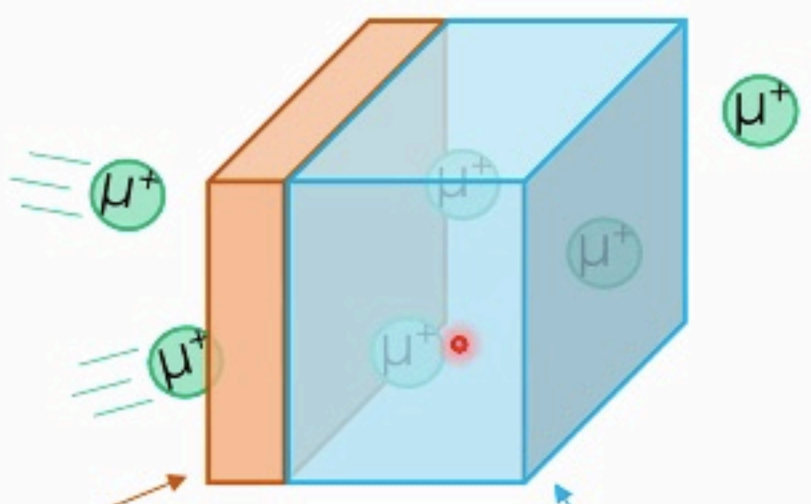
箱に入るミュオンの軸方向の運動量分布



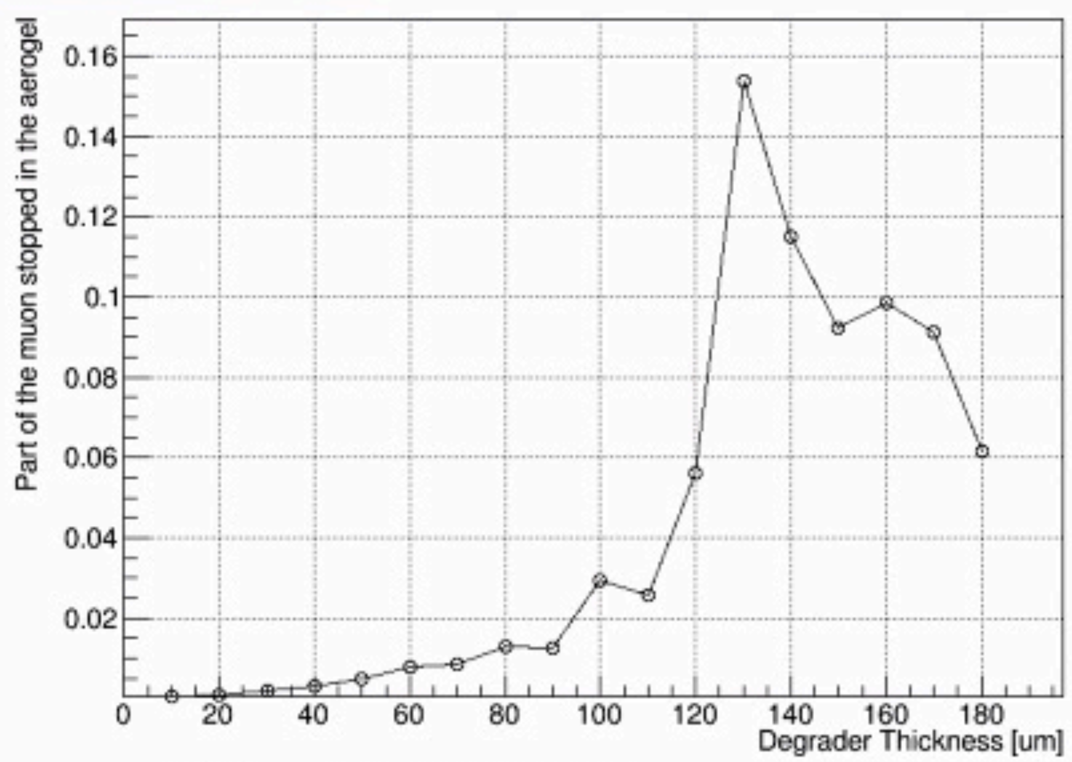
箱に入るミュオンの入射の角度分布

- H1に来たミュオンの19%が入射
- 入射レートは $2.7\times10^{7}\ \mu^{+}/s$
- 詳細な最適化は未実施。改善の余地あり

ステップ 3
エアロゲル中での停止

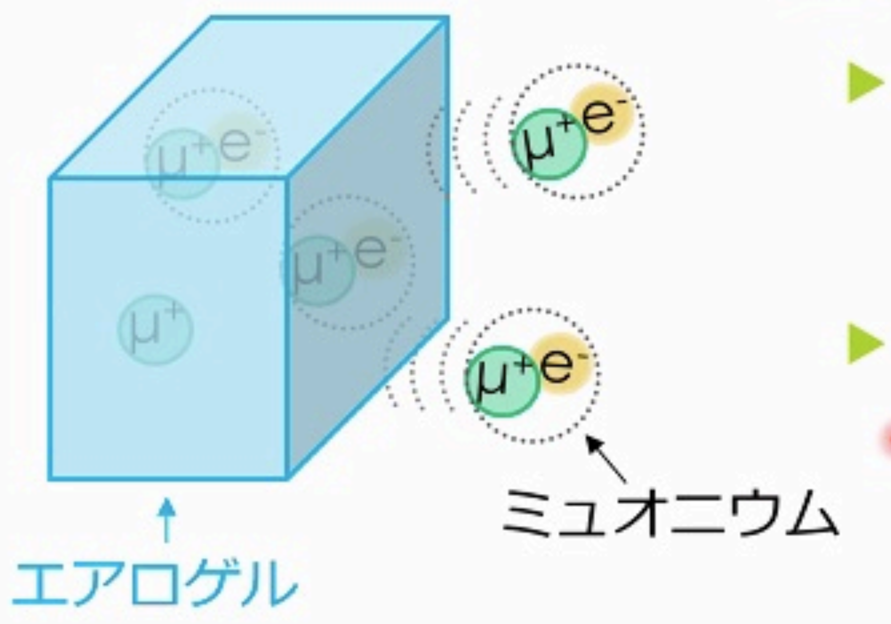


- エアロゲルの厚みを2mmとしデグレーダの厚さを最適化
- 130 um の時、エアロゲルに止まるミュオンが最大化
- 入射ミュオンの15%, 4.1×10^{6} μ^{+}/s がエアロゲル中に止まる



デグレーダーの厚み毎の、
エアロゲル中へ停止するミュオンの比率
厚み 130 um のとき、最大の16%となる

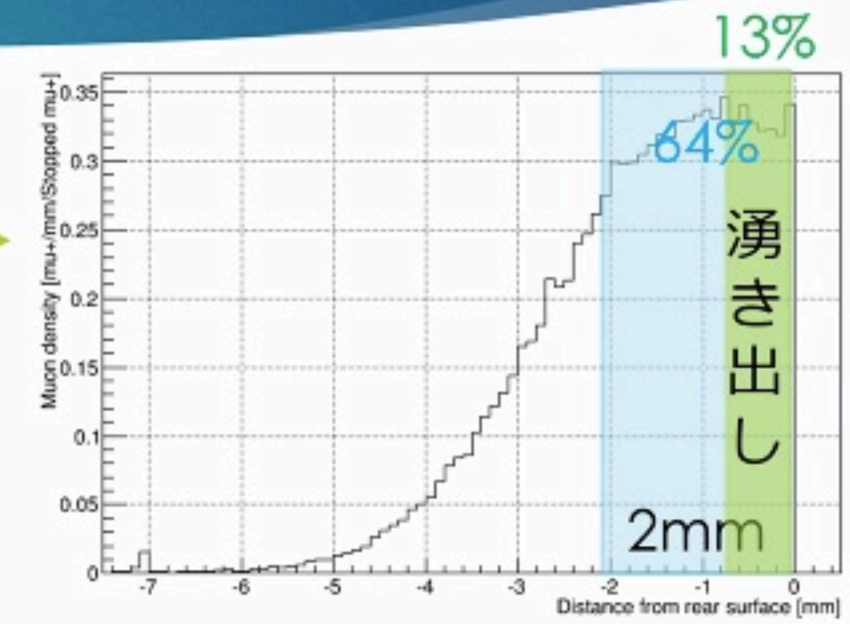
ステップ４　Aerogelからのミュオニウムの湧き出し



- エアロゲル中に停止したミュオンの一部がミュオニウムとなって拡散し、表面から湧き出す
- g-2実験にむけた開発として<u>TRIUMFでの実験結果</u>がある (G. A. Beer, etc., PTEP 2014)
  - 入射ミュオンの平均運動量 23 [MeV/c] 運動量幅 5% (FWHM)
  - エアロゲル表面からの距離が、10 ~ 40 mm の区間で崩壊したミュオニウムの数をカウント
  - 得られたレート：0.0305 [Decay Mu/ incident μ+]

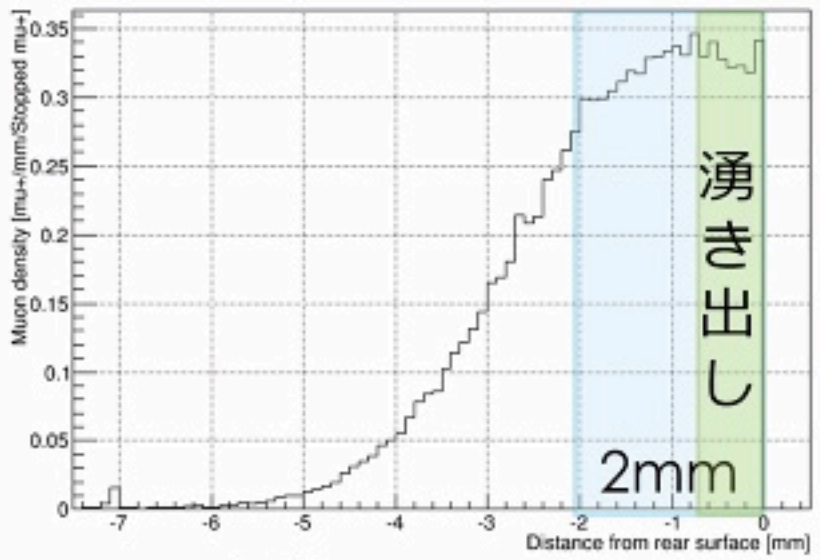
ステップ４　Aerogelからのミュオニウムの湧き出し
TRIUMFでの実験の評価

- エアロゲル中での停止分布を計算
  - 23 MeV/c, FWHM 5%
  - アエロゲル背面近傍 2 mm に
    停止ミュオンの 64% が存在
- 湧き出したミュオニウムの総量を計算
  - 停止ミュオン10^3個当たり、
    観測された崩壊は、30.5±0.3 個
  - 10 ~ 40 mm で崩壊する確率は、0.23
  - 湧き出しミュオニウム/停止ミュオン 0.0305 / 0.23 = 0.13
    エアロゲルに止まったミュオンの13%が湧き出した計算
- 0.13/0.64 =0.21
  深さ 2 mm までのミュオンの内 21%が湧き出したことに相当

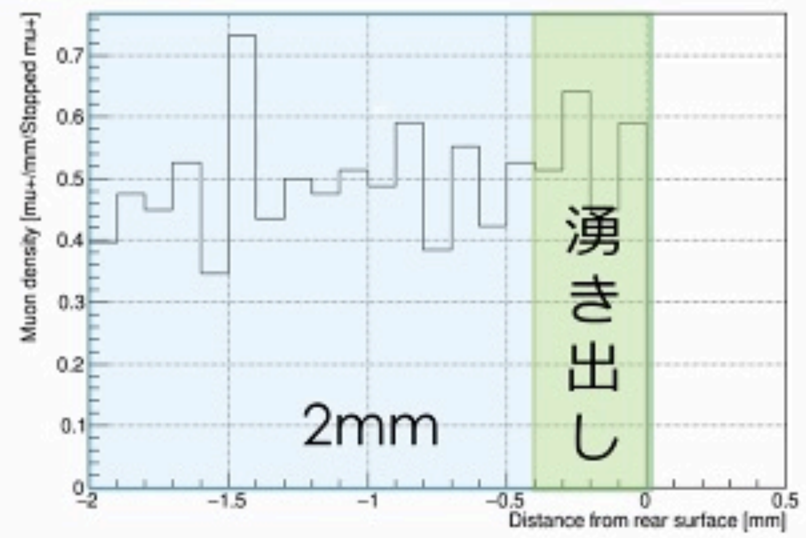


TRIUMF実験での停止位置分布
(シミュレーション:SRIM)

ステップ４　Aerogelからのミュオニウムの湧き出し
Trap実験への適用

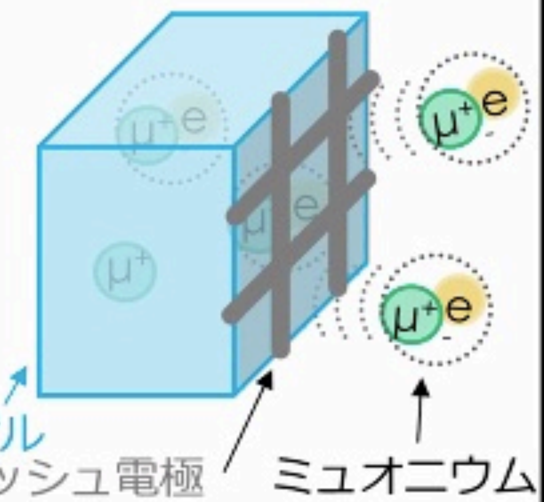


TRIUMF実験では
2 mm の深さまでに64%が停止し
13%が湧き出す。(2mm中の21%)



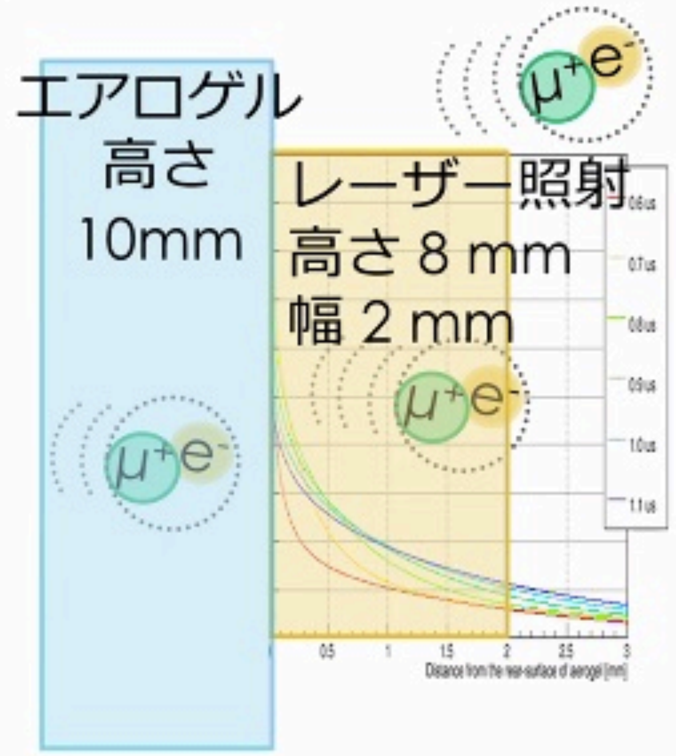
Trap実験で 2 mm の深さの
21 %が湧き出す

- 4.1×10^6 [μ^+/s] × 21% = 8.5×10^5 Mu/s が湧き出す。
- エアロゲル下流に、開口率90%のメッシュ電極がある。
- 7.6×10^5 Mu/s がメッシュを通過



ステップ６ ミュオニウムのレーザーイオン化

- レーザーは、
  幅 2 mm, 高さ 8 mmの領域の
  ミュオニウムを８０%イオン化
  できると仮定する。
- 0 ~ 2 mm に存在するミュオニウムは、
  t = 0.9 us のとき最大となり、
  メッシュを通過する全体の３０%
- 高さ10 mm のエアロゲルに対し、
  8 mm のレーザーなので、８０%
- よって、レーザーイオン化で発生する超低速ミュオンは、
  7.6×10^{5} Mu/s × 80% × 30% × 80% = 1.4×10^{5} μ^{+}/s



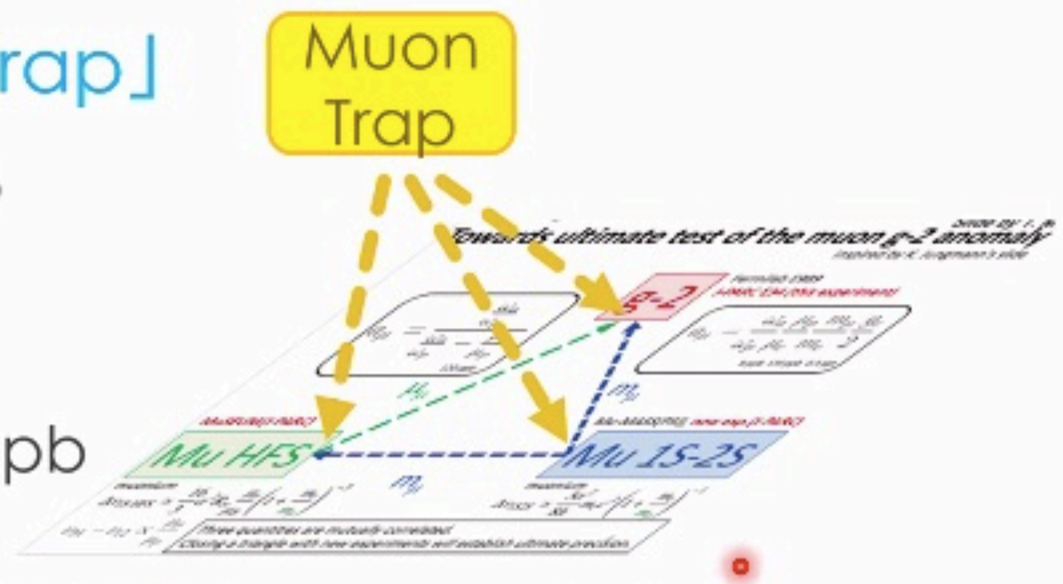
評価結果

ステップ	レート(1MW換算)	比率
H1エリア入射	1.4×10^{8} μ^+/s	
実験装置入射	2.7×10^{7} μ^+/s	19%
エアロゲル中に停止	4.1×10^{6} μ^+/s	15%
Mu湧き出し	8.4×10^{5} Mu/s	20%
メッシュ電極通過	7.6×10^{5} Mu/s	90%
エアロゲルから2mm以内に存在	2.3×10^{5} Mu/s	30%
上下方向 8mm以内に存在	1.8×10^{5} Mu/s	80%
レーザーイオン化	1.4×10^{5} μ^+/s	80%

- 約１００日で、10^{12} 個の超低速ミュオンが得られる
- H1エリアの入射量や、実験装置入射、エアロゲルへの停止などの過程は、まだ最適化による改善の余地があると考える。

まとめ

- まったく新しい実験「Muon Trap」
  - 手法の違う他の実験の検証になる
  - 高い精度での測定を目指す
    muon mass ~ 1 ppb
    muon magnetic moment ~ 1 ppb
    muon life ~ 1 ppm



- 大強度の超低速ミュオンが、精密測定の１つの要
  - 現実的な条件で計算、１００日で10^{12}個のミュオンが得られる。
  - まだ、効率の低いところがあり、さらなる最適化を図ることで、崩壊陽電子検出で10^{12}個/100日を目指す。