R&D status of μRWELL for the ePIC experiment

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KSHEP 2025 Fall @ CNU

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- Signal FPC for ePIC BTOF

1. Introduction to the ePIC

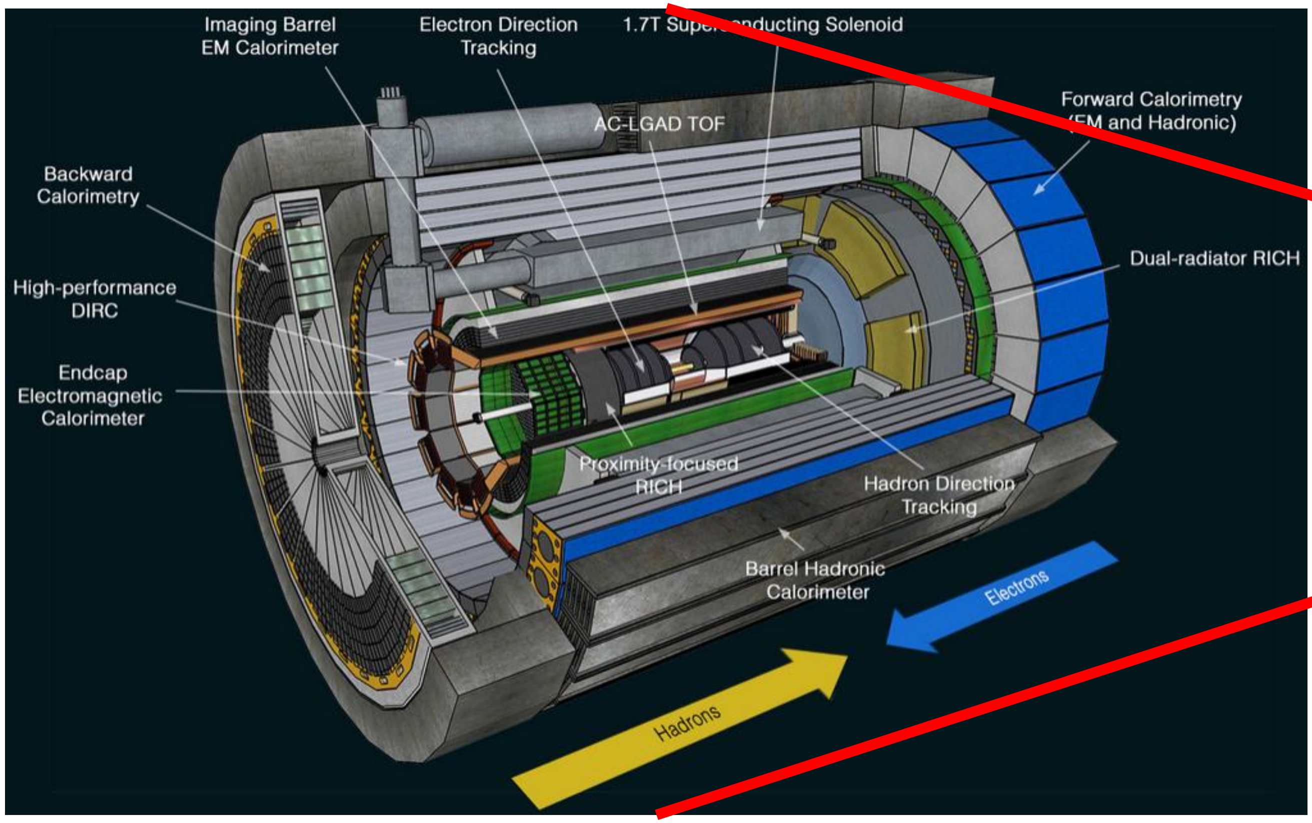
- Electron-Ion Collider @ BNL

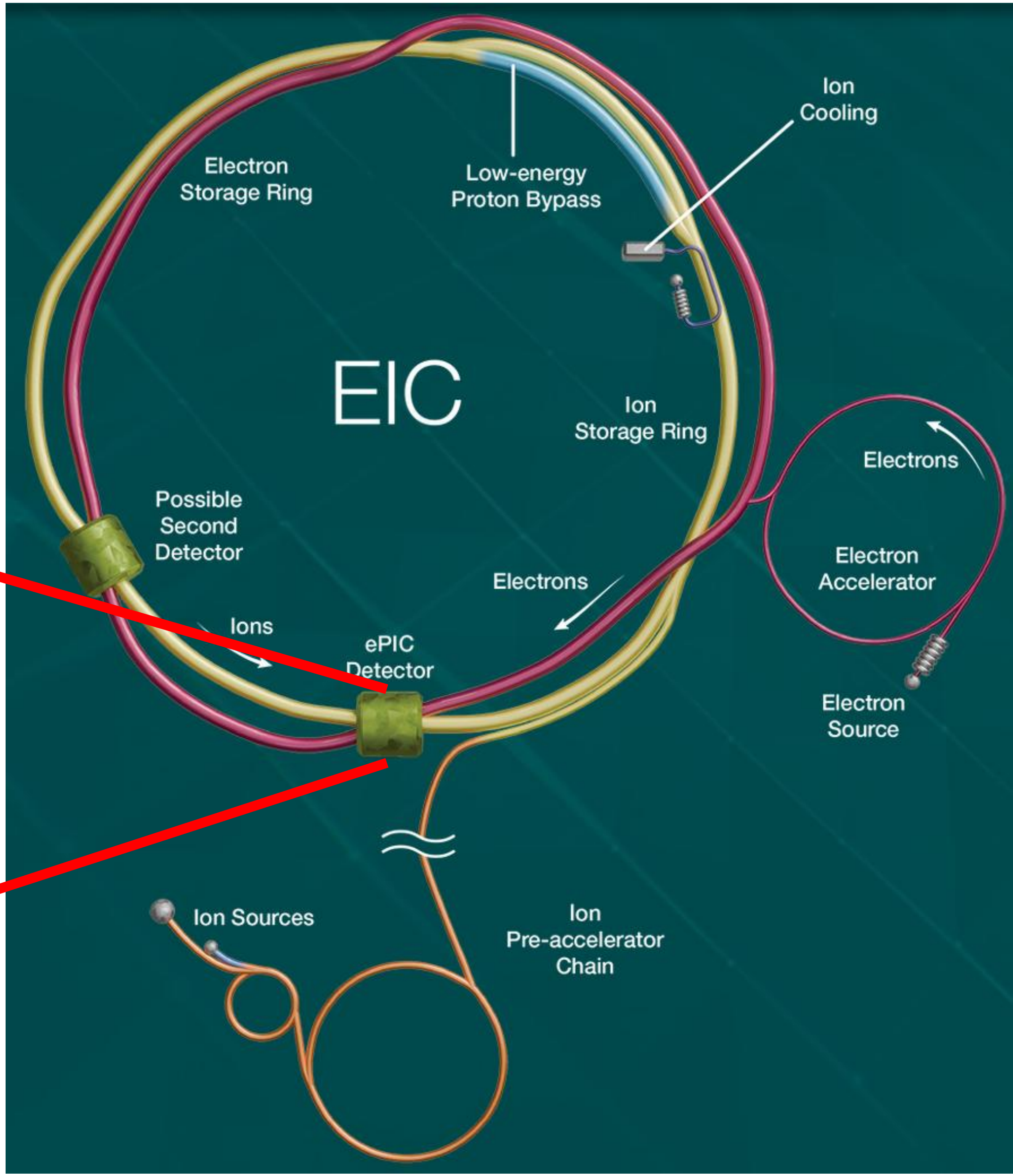
 - Installing polarized electron beam

 - P ~ 70%

 L ~ $10^{34} cm^{-2} s^{-1}$

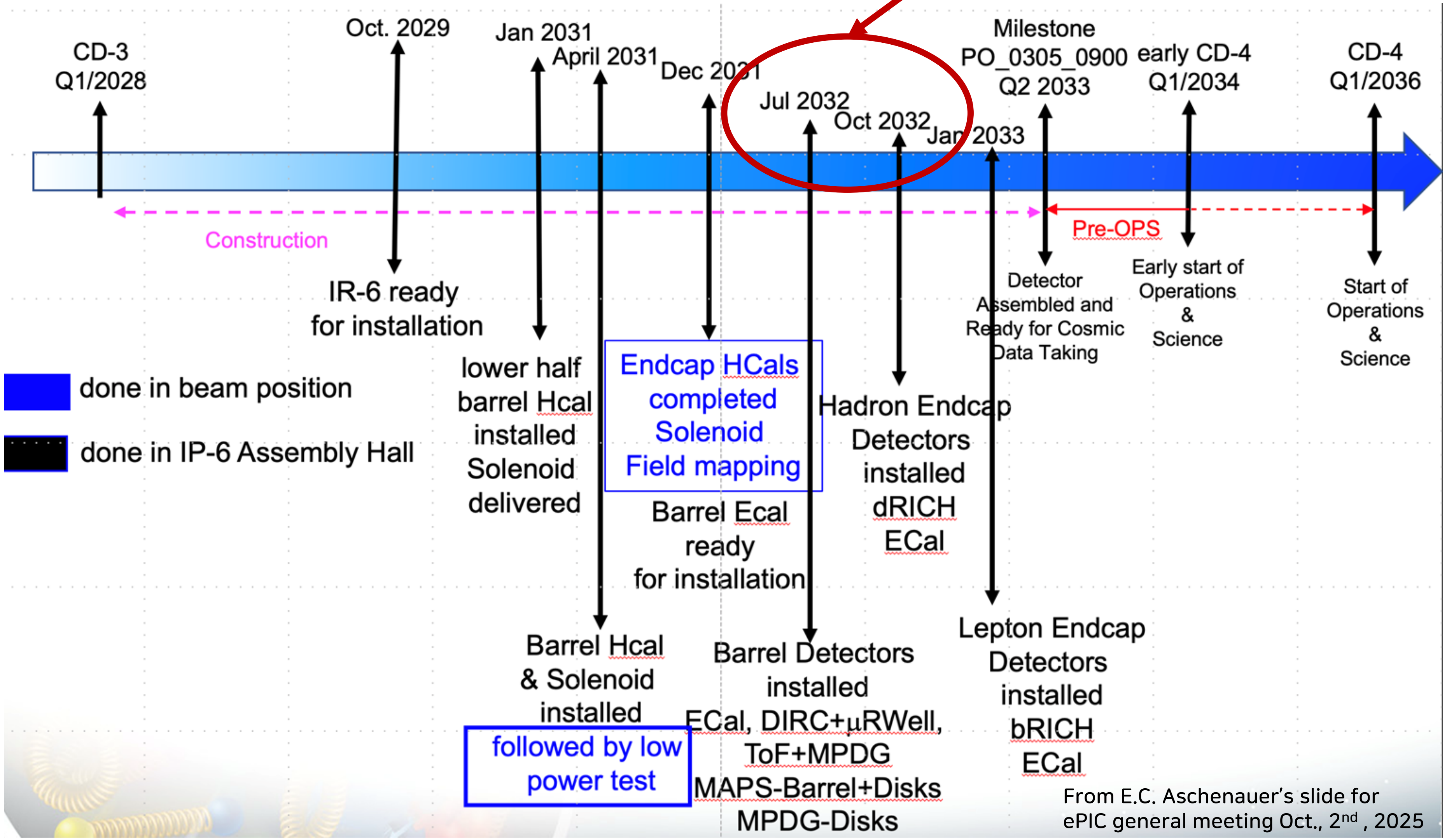
 $\sqrt{s}$ ~ 29-140 GeV





1. Introduction to the ePIC

Delayed by 2 years compared to the original plan

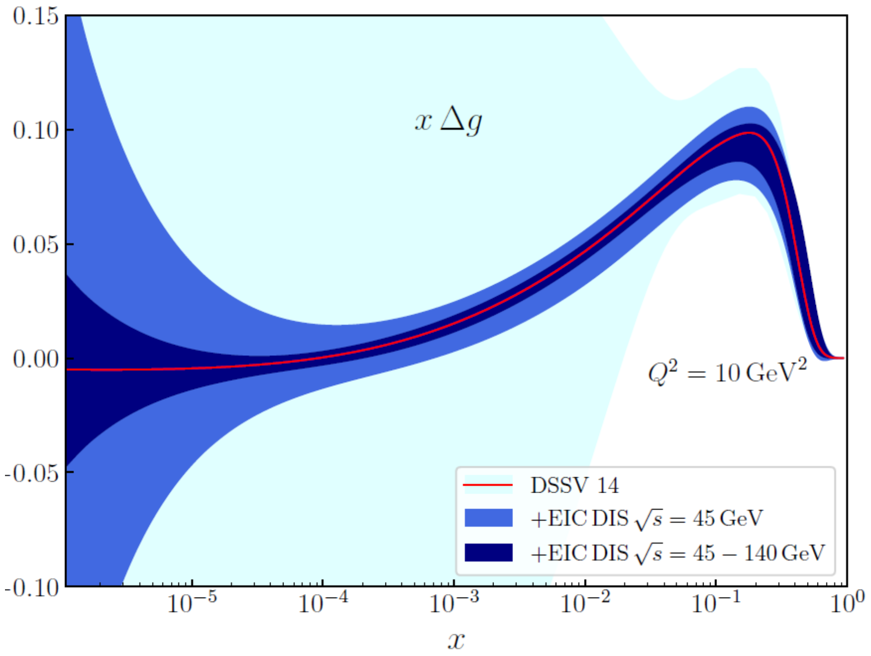


From E.C. Aschenauer's slide for ePIC general meeting Oct., 2nd , 2025

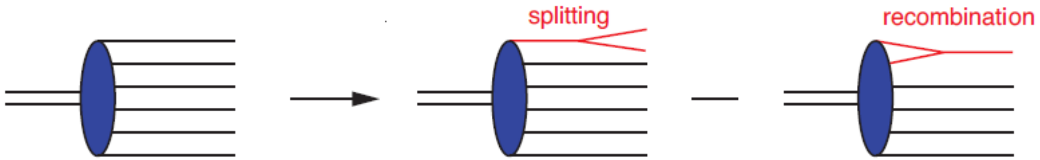
1. Introduction to the ePIC

- Spin structure of proton
  - Quarks carry only ~ 30% of proton spin
  - RHIC confirmed gluon polarization, but large uncertainties remain, especially at low-x
  - Inclusive A_{LL} and g_1. Δg is encoded in scale violation of g_1

arXiv:2103.05419

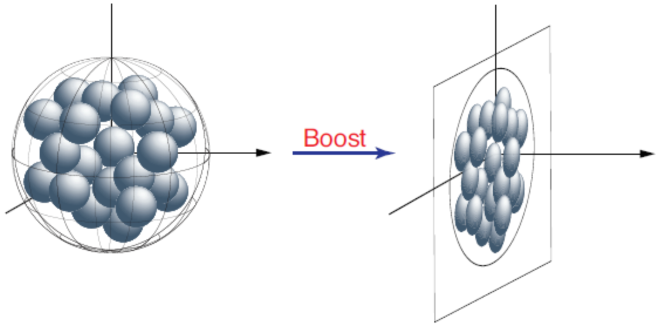


- Color glass condensation

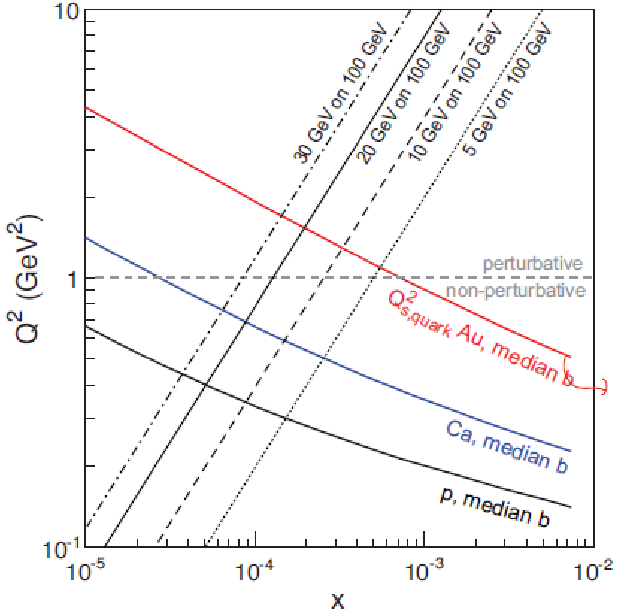


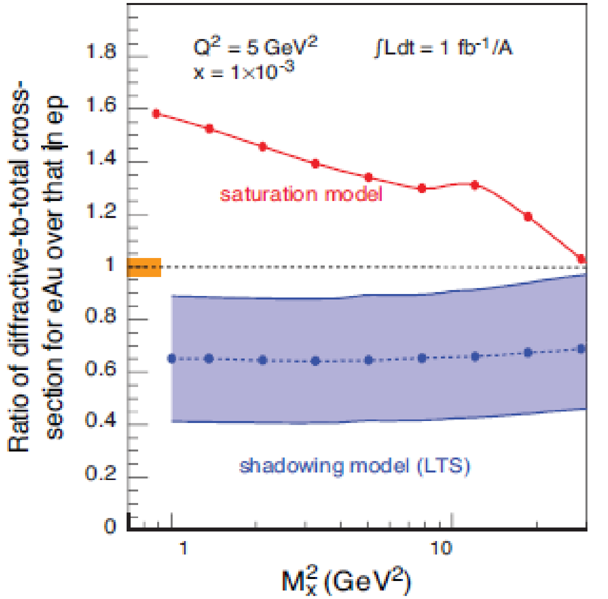
- Nuclear "oomph" factor

$Q_s^2(x) \sim A^{1/3}(\frac{1}{x})^{\lambda}$ where $\lambda = 0.2 - 0.3$



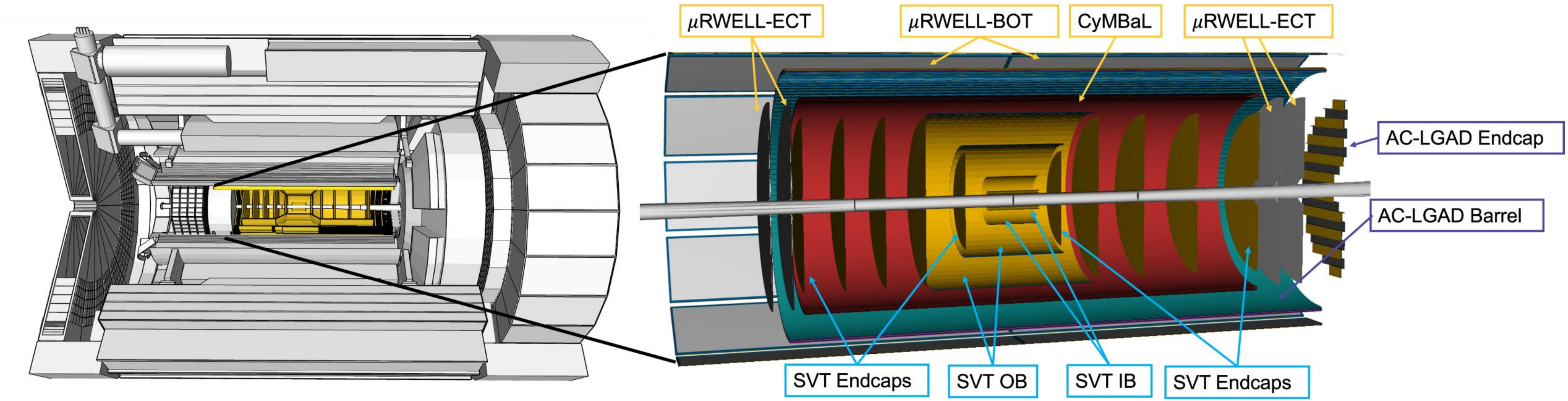
arXiv:1212.1701





1. Introduction to the ePIC

- Central tracker
  - Barrel: Maps → resistive MM → GEM+μRWELL → AC-LGAD
  - Endcap: Maps → <u>GEM+μRWELL</u> → AC-LGAD

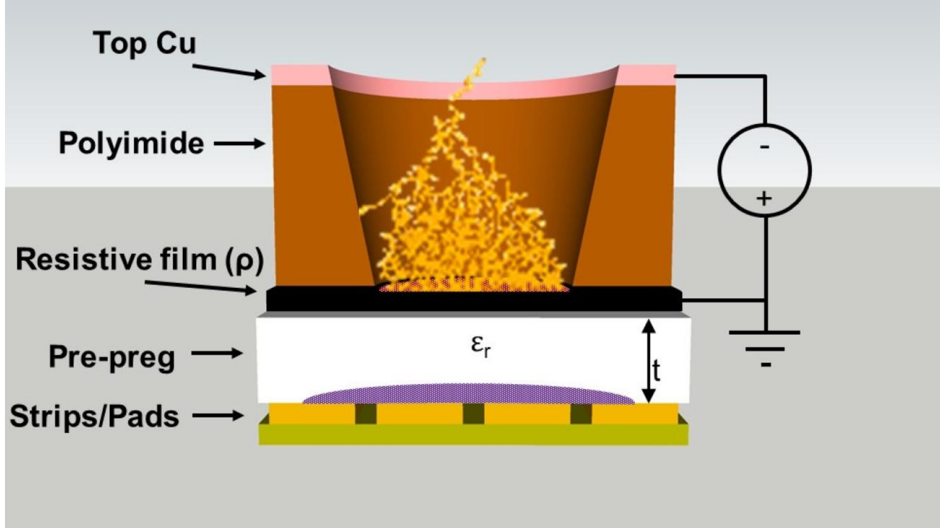


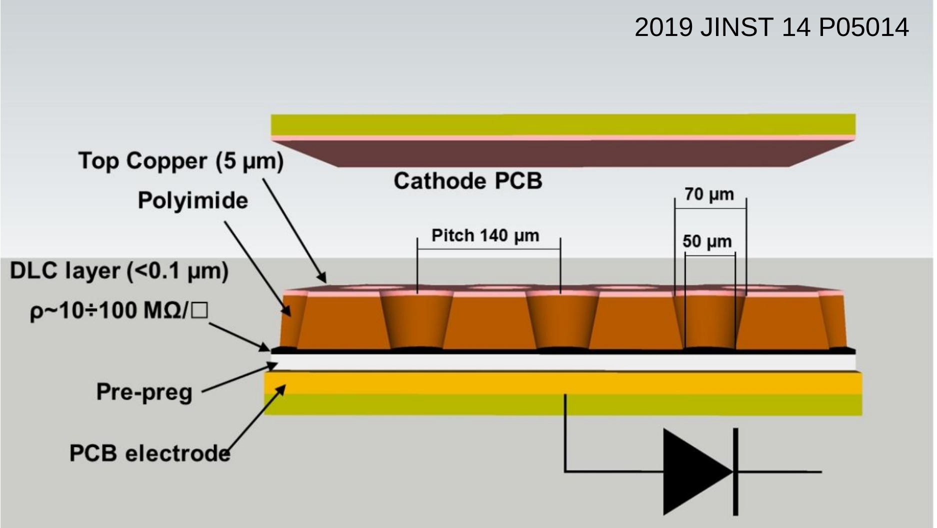
2. Introduction to μRWELL technology

- Micro Resistive WELL, the resistive variant of GEM
  - Resistive layer, DLC, prevents streamer from evolving discharge
  - → Free from discharges
  - ⇒ Simple structure, easy handling & assembly → cost friendly

- Many experiments are planning to use μRWELL
  - ePIC, DAMSA, CLAS12, LHCb, IDEA (FCC-ee), …
  - Suffering from supply shortage ∵ CERN MPT is the only one supplier

- Using KCMS GEM facilities, we can be a leader in μRWELL as well

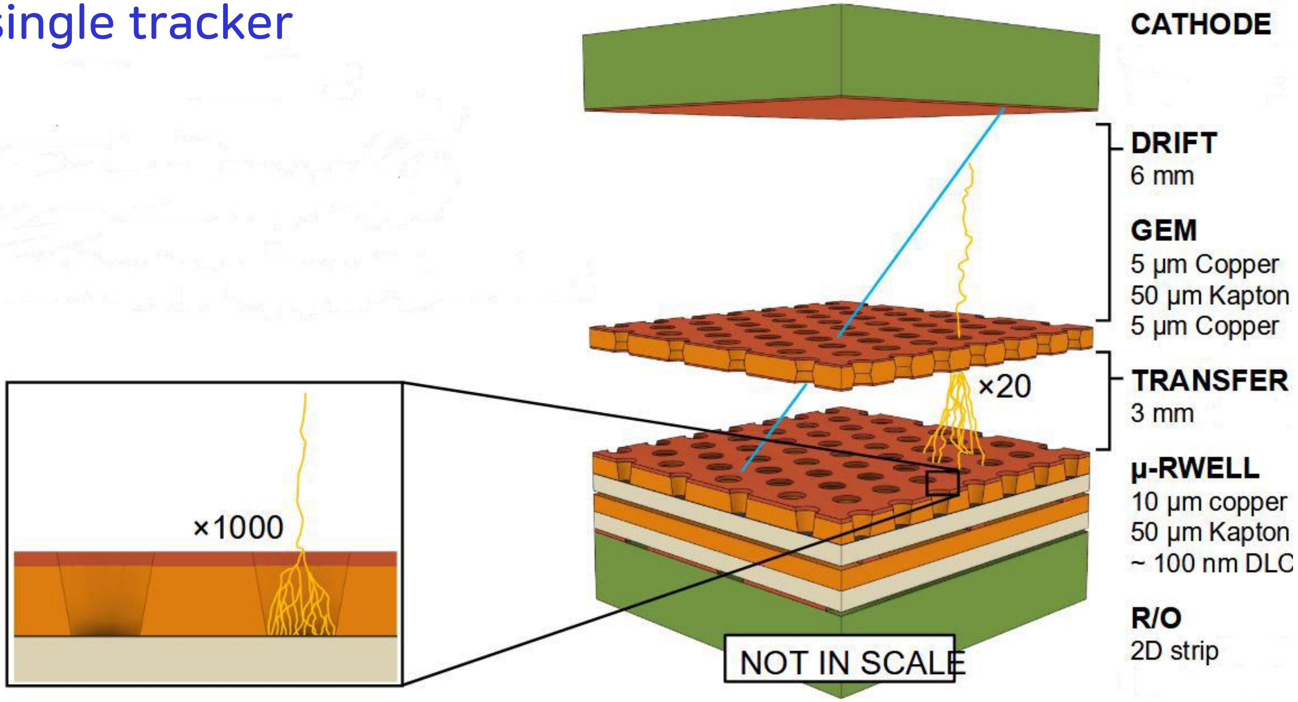




3. μRWELL for the ePIC endcap tracker

- GEM + μRWELL hybrid detector
  - GEM acts as a preamplifier, used to achieve high efficiency in 2D tracking and ensure detector stability
  - $\delta t < 10\ ns$, $\delta x < 150\ \mu m$, ~0.2% X_0, 96-97 % for single tracker
  - Active area: R=45 cm

Annalisa



- SNU hopes to contribute to the ePIC by supplying GEM and μRWELL
  - *"Main risk is related to CERN being the unique producer of μRWELL detector layer"*, Annalisa, Incremental Design and Safety Review of the EIC Tracking Detectors, Mar. 20-21, 2024

4. Project goal & timeline

- Support Korean researcher's participation in ePIC via in-kind contribution of GEM & μRWELL for the ePIC ECT
  - Contributing to detector design, including beam test participation
  - Dispatching student researchers to participate in detector assembly at INFN/JLab

- 26, 27년: 셋업 및 프로토타이핑
  - 공정 조건 확보 및 프로토타입 검출기의 μRWELL PCB와 GEM 공급
  - 26년 목표: 장비 셋업 및 공정 조건 확보
    27년 목표: 프로토타입 검출기용 μRWELL PCB와 GEM 공급

- 28, 29년: 대량생산
  - GEM, μRWELL 각 ~20장
  - 28년 목표: 물량의 60% 생산
    29년 목표: 물량의 40% 생산, 검출기 조립 참여 (학생 파견)

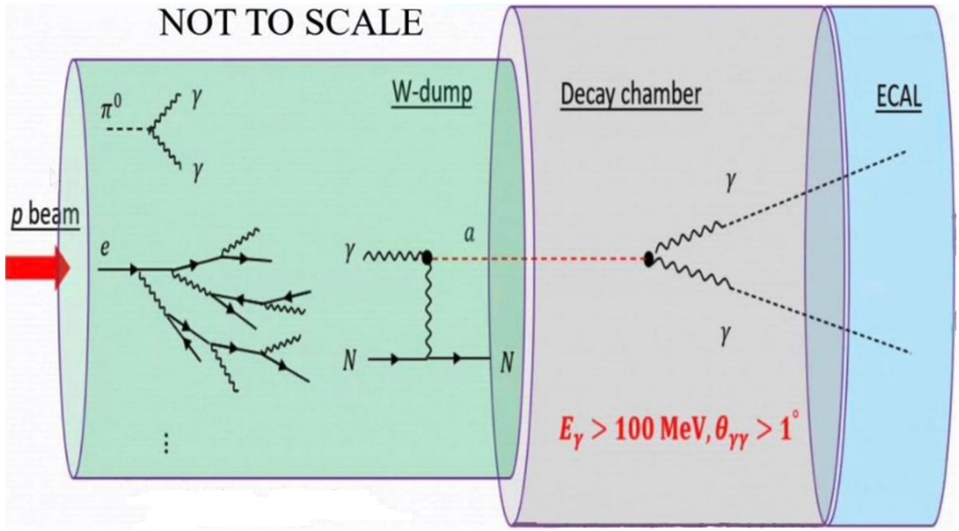
- 30, 31년: 검출기 조립 및 QA/QC

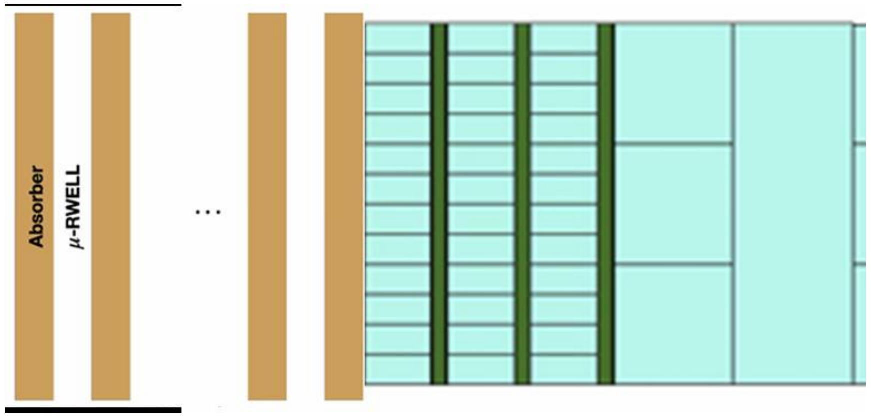
5. Other application – DAMSA experiment

- DAMSA experiment
  - Search for $a \rightarrow \gamma\gamma$ and $A' \rightarrow e^+e^-$ using beam dump

- Tracker for charge veto and A' reconstruction
  - ~ 4 layers of μRWELLs
  - Cost friendly

- ECal: high granularity is required
  - For 50 MeV ALP, overlap prob. is ~ 80% even with $1 \times 1\ cm^2$ CsI
  - R&D on μRWELL sampling Cal. is ongoing





5. Other application – LHCb experiment?

• For HL LHC upgrade, LHCb will replace MWPC to GEM+high rate μRWELL

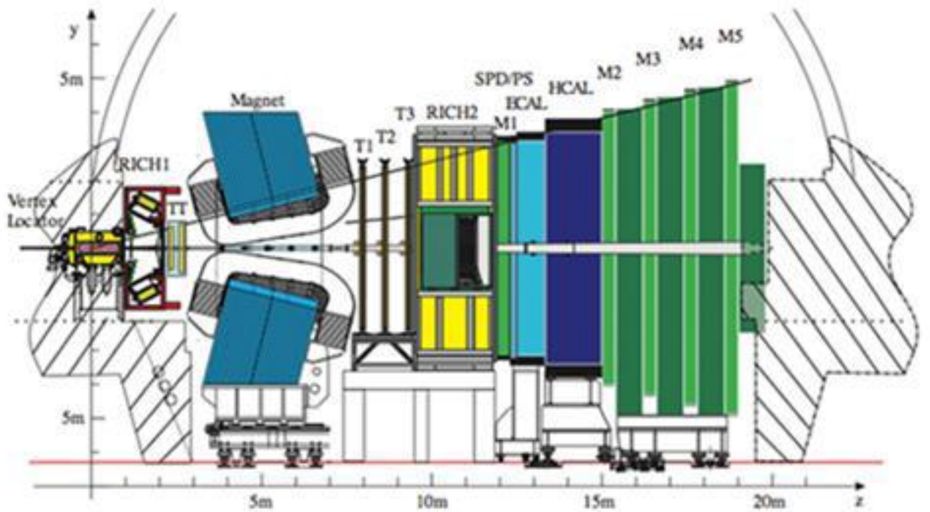
• LHCb has suggested collaboration

∵ Because CERN MPT alone cannot produce the GEM & μRWELL for the upgrade

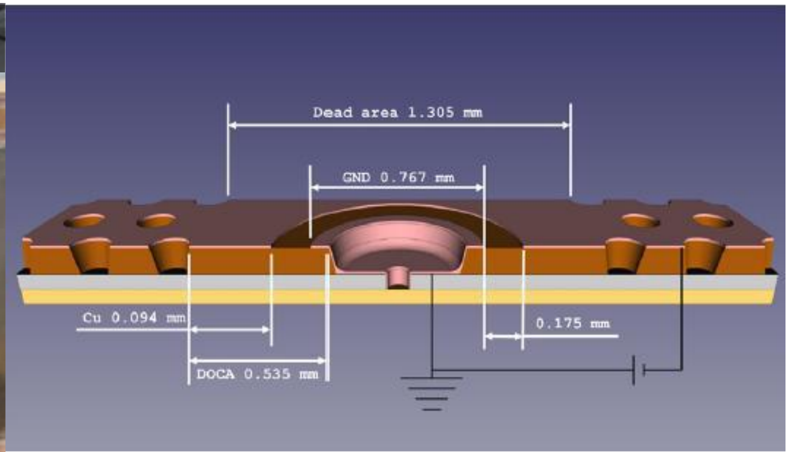
- PCB production @ Eltos Co., Italy
- GEM & μRWELL @ Korea

• Establishing the technical foundation required for these decisions

- Contract manufacturing is possible if LHCb bears the cost (?)



NIM A 1069 (2024) 169725

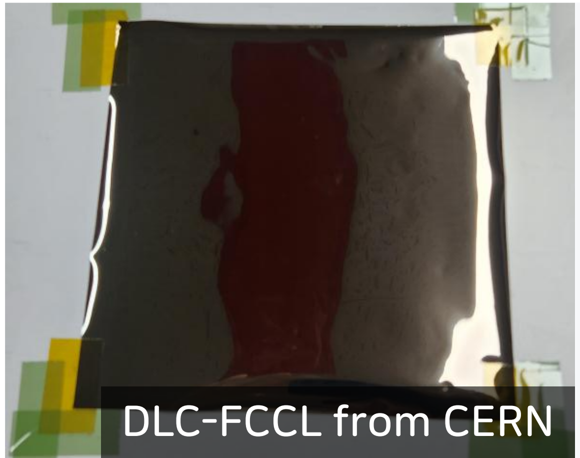


6. R&D status - Overview

- $10 \times 10\ cm^2$ μRWELL production is ongoing
  - To validate the feasibility of the expansion of GEM production technology to μRWELL production

- Maskless fabrication of GEM foil: Laser Direct Imaging
  - Need for a new production method for high-mix, low-volume

- DLC sputtering R&D to make DLC-FCCL
  - To secure more flexibility in production process
  - Surface resistance: $40 - 80\ \mathrm{M\Omega}/sq$
  - The R&D just began in collaboration with domestic company

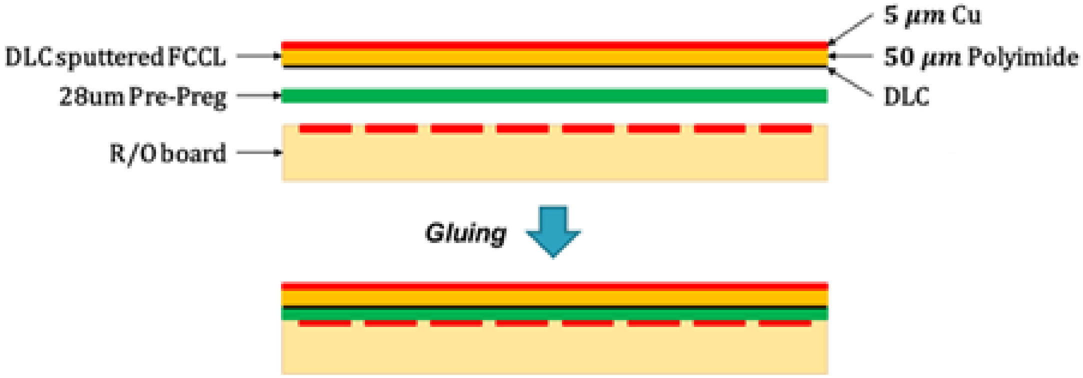


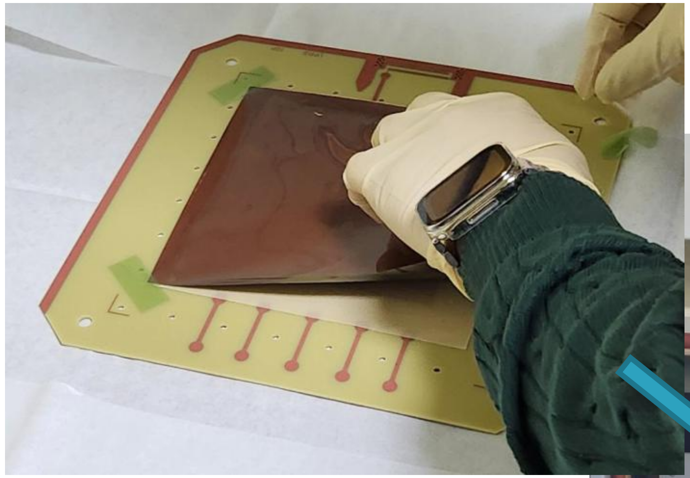
DLC-FCCL from CERN

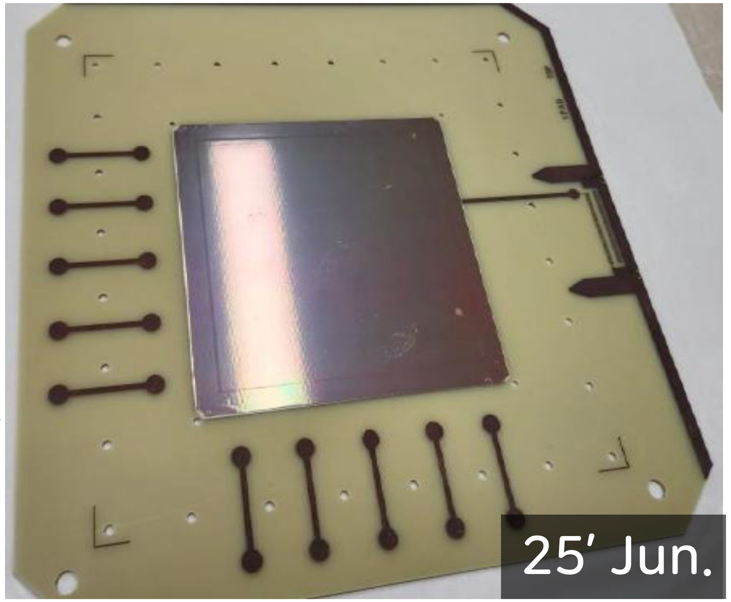
DLC sputtering machines @ 안산

6. R&D status - μRWELL production

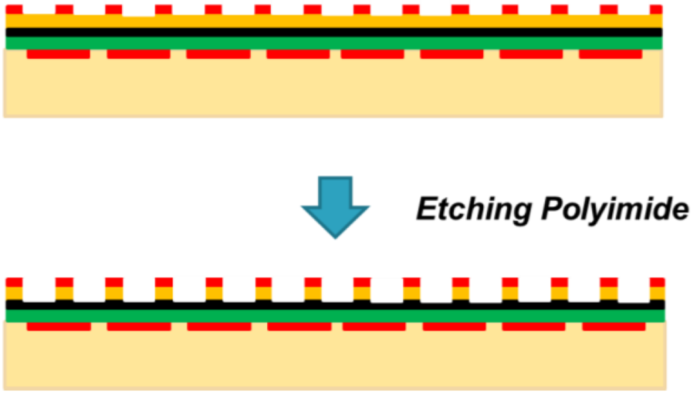
- Gluing process
  - Encountered a low peel strength issue
  - The process stabilized after optimizing adhesive layer and temperature, pressure & duration conditions







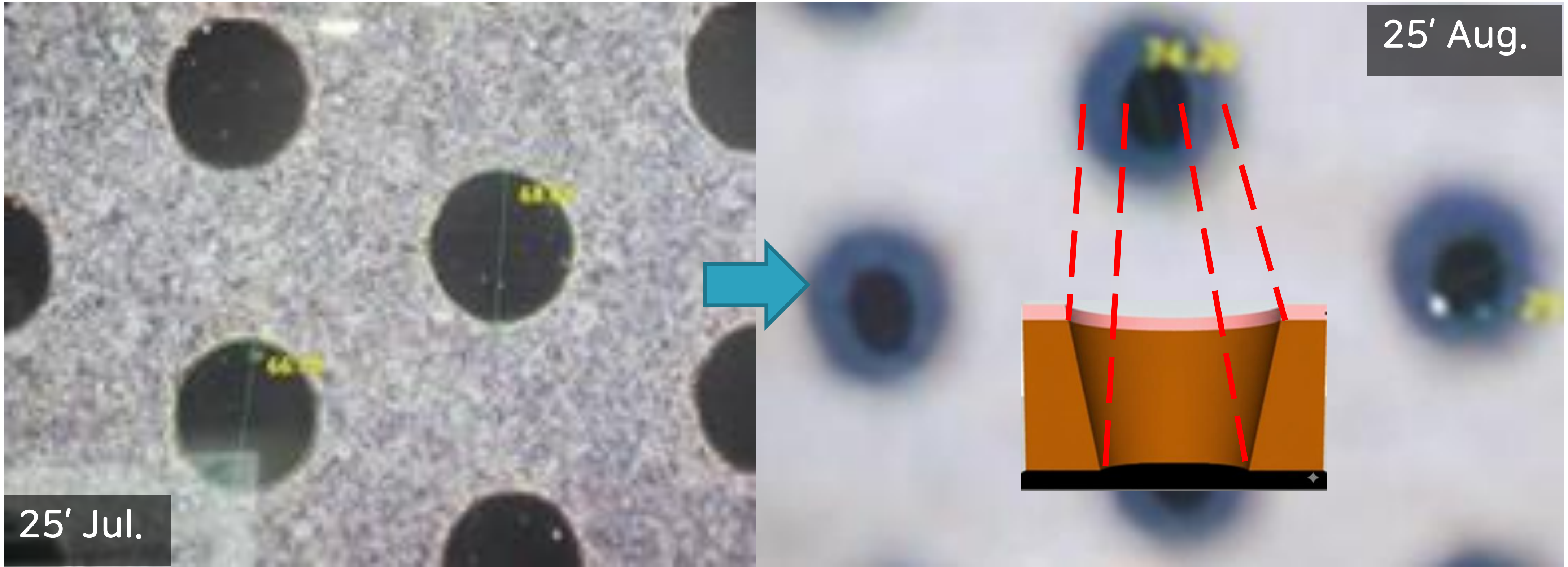
6. R&D status - μRWELL production



- Patterning Cu layer using photo lithography

- Patterning polyimide layer to make well
  - Top Cu layer acts as mask

- This single-sided PI etching experience also allows for single-mask GEM foil production

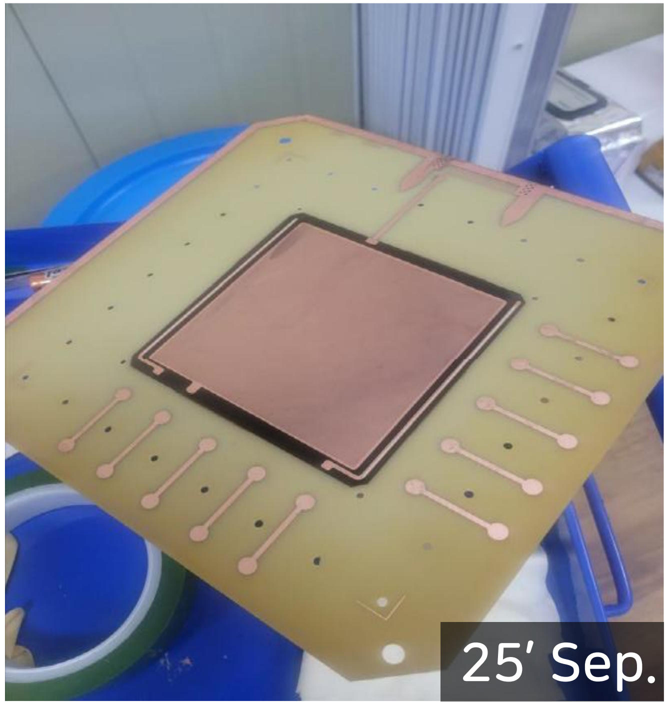


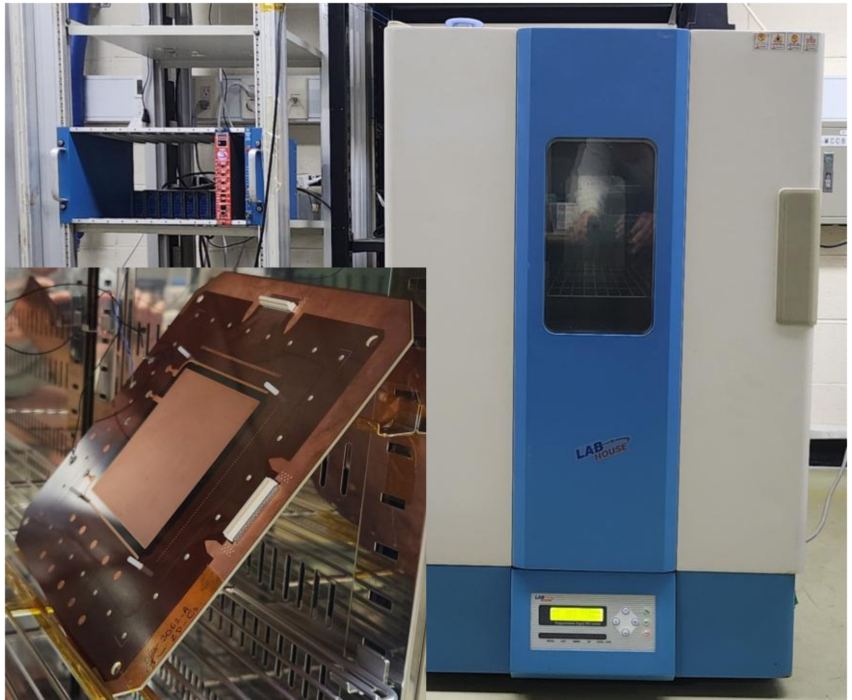
6. R&D status - μRWELL production

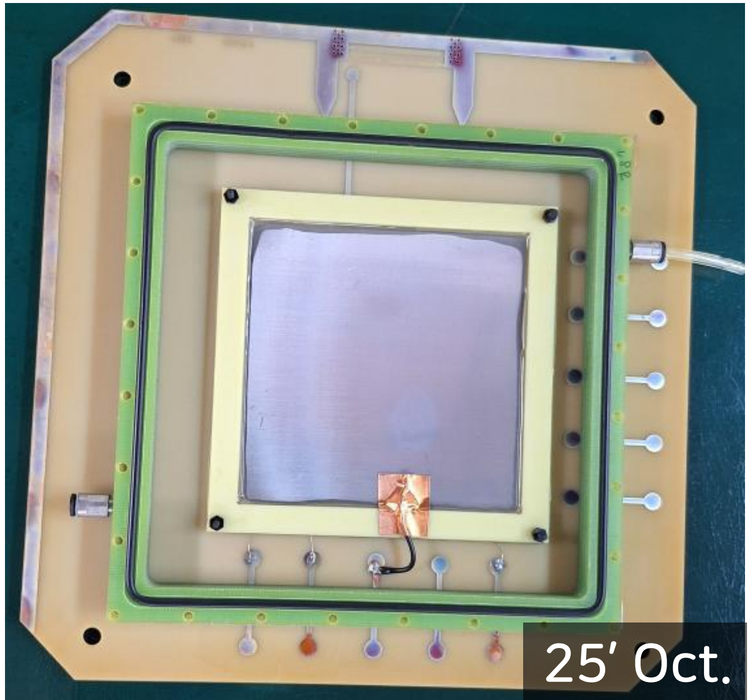
• Formation of HV trace

• Giving HV stability using electrical cleaning @ $90\ ℃$

- Burn off contaminants remaining in the well until leakage current ($< 1nA$) with HV up to 680 V
- Due to the high resistance of DLC, it is difficult to electrically burn off contaminants remaining in the well at room temperature







6. R&D status – Process to improve

- Unfortunately, the 1st detector failed to function

- Thin residual PI were left some area which interrupt proper formation of electric field inside well

 - Fail to maintain temperature due to the makeshift PI etching bath & lack of experience

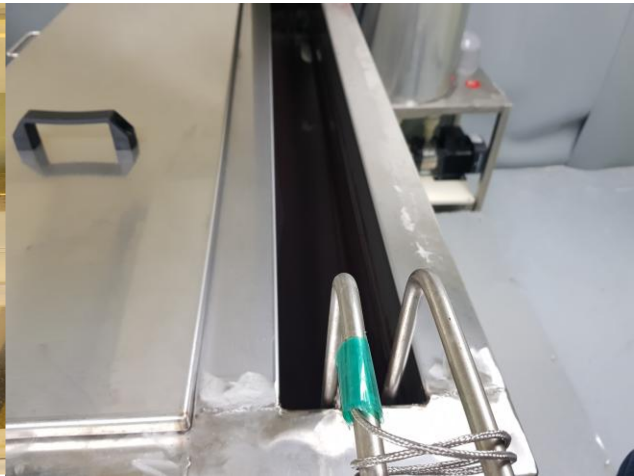
 - With CMS GEM production finished, the proper PI bath is now available

- The Cu passivation process

 - The current method using organic acid failed at high temperature as the acid degraded and lost their anti-corrosion property

 - Chromic (III) acid as the alternative; procurement is finished

⇒ Re-attempting production after addressing these two points



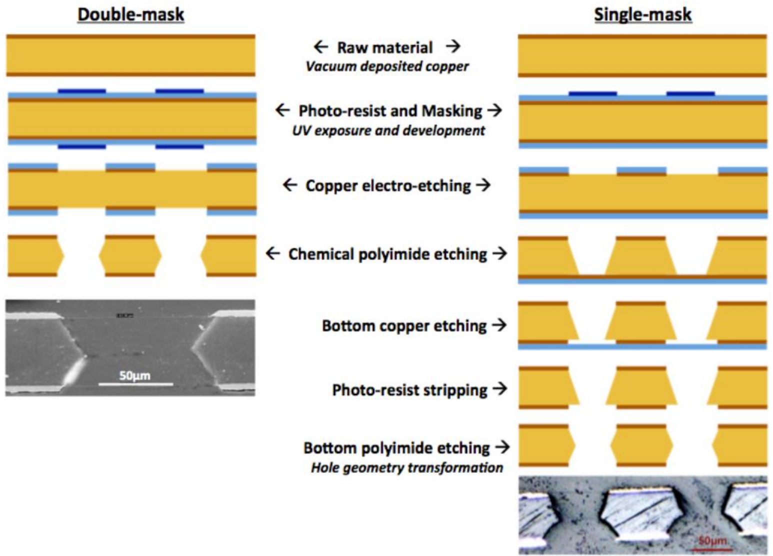
6. R&D status – the alternative GEM foil production

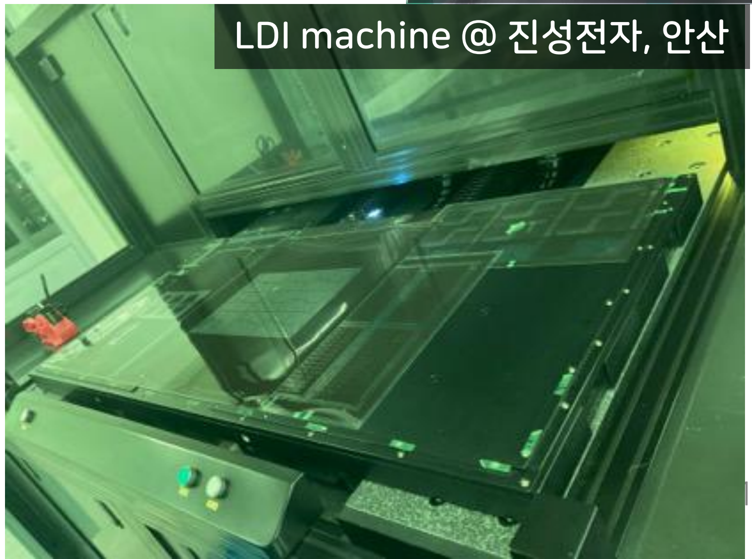
- Drawback of the double mask technique
  - Double mask method is suited for mass production but has large-area alignment issues
  - Therefore, expensive glass masks are required

  ⇒ Double mask method is good for mass production, but unsuitable for HMLV
  - Glass masks are being phased out as LDI replaces them

- Testing LDI before single mask to maintain the simple process advantage
  - Pattern OK, but alignment is not satisfactory; maker requests one more trial, confident of success

ECT GEM in production via LDI





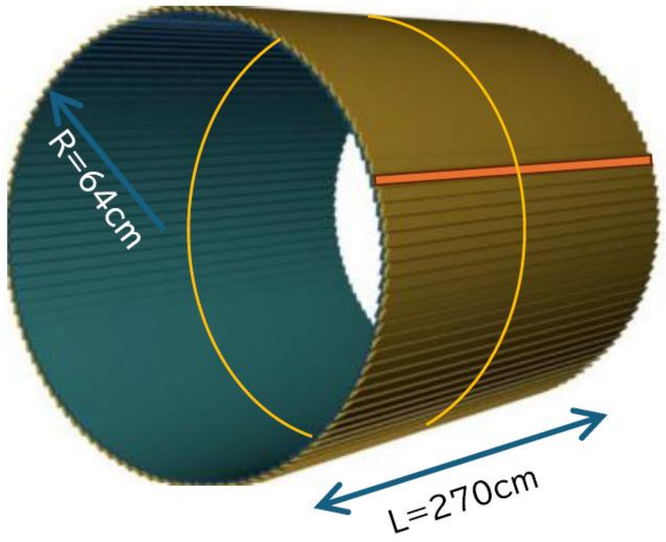
LDI machine @ 진성전자, 안산

7. Signal FPC for ePIC BTOF

• ePIC BTOF requires the fine pitch & long signal FPC

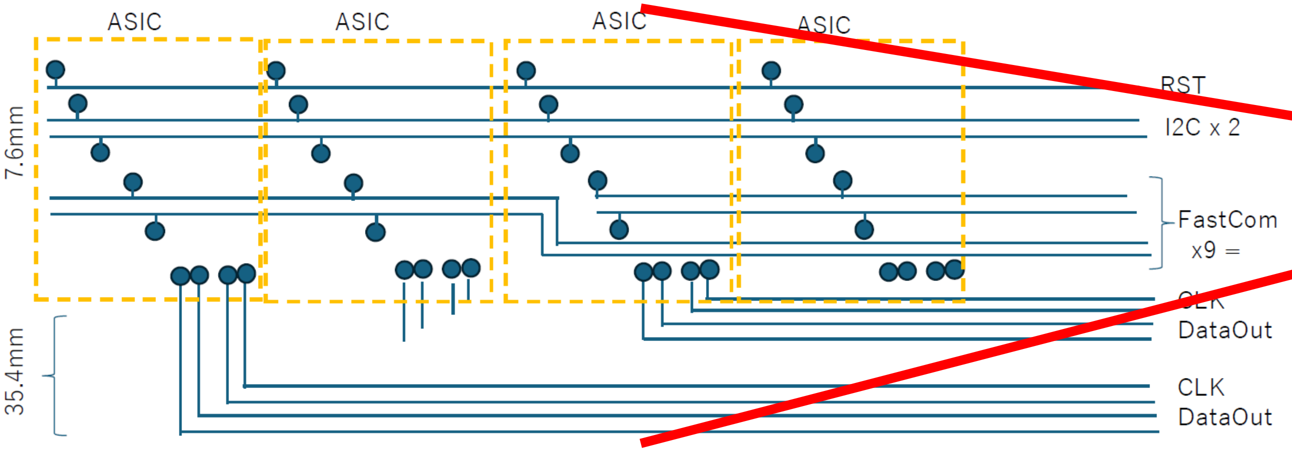
- 1.3 m long, max line pitch $< 100\ \mu m$
- However, large-scale, fine-pitch FPC production is technically challenging

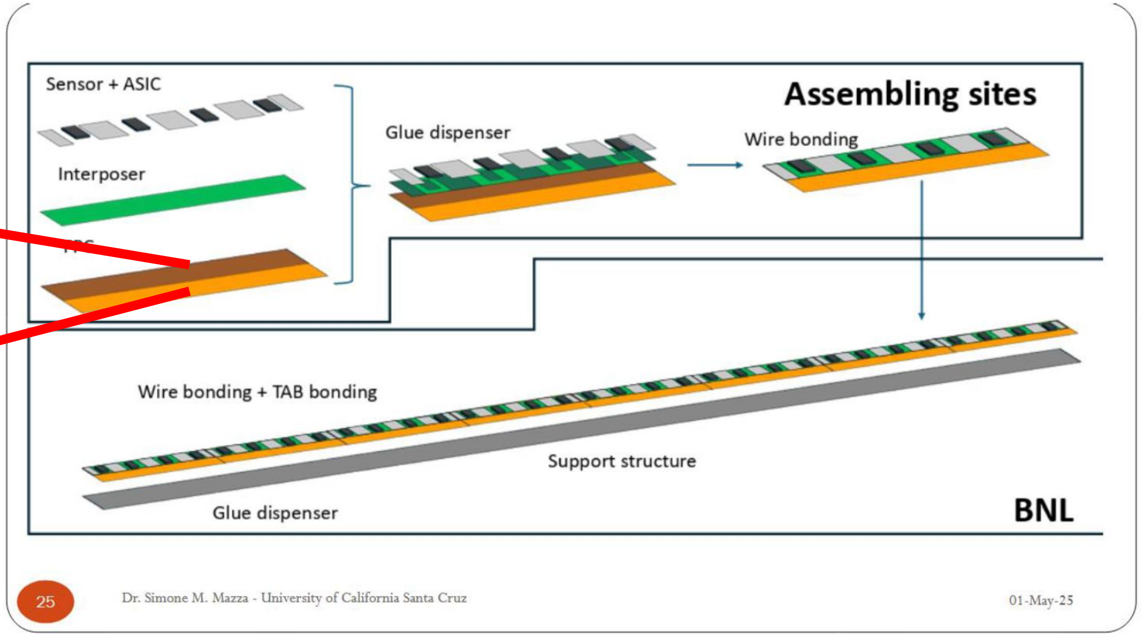
⇒ We, experienced in large FPC via GEM, has been asked to assist



• Had first in-person meeting @ PnF Co., Ltd. (the contractor for GEM wet etching) for technology validation

- PnF stably achieved $70\ \mu m$ width & pitch on a 1.4 m cable





7. Signal FPC for ePIC BTOF

- Contract between RIKEN & PnF Co., Ltd. for simplified validation production is forthcoming

- Additionally, local access to a 1.5m hot press & 1.4m LDI in 안산 enables 1.3m FPC production
  - Therefore, it has been decided that the 1.3m signal FPC will be produced in Korea
  - If LCP is used, R&D is required for Cu plating of via holes

- A contract for mass production is expected to follow
  - $144 \times 2 \times 2 + 20\% \; of \; spare$

~ 700 sheets of FPCs

- An ideal case of industry-academia collaboration

Summary

- EIC & ePIC Underway: Exploring proton spin/mass, high-dimensional structure, & CGC

- μRWELL, the resistive variant of GEM
  - Thanks to its spark-protected nature, many experiments are planning to adopt the μRWELL detector

- The ePIC experiment plans to construct its central tracker using μRWELL + GEM hybrid detectors
  - SNU is preparing an in-kind contribution of GEM and μRWELL for the production of the ePIC ECT

- $10 \times 10\ cm^2$ μRWELL production is ongoing
  - Based on the experience gained from the first attempt, we expect to succeed in the second attempt

- Maskless GEM foil production is ongoing using LDI

- Fabricating a large-area & fine-pitch FPC for the ePIC BTOF using GEM technology

Back Up

Physics programs – spin structure of proton

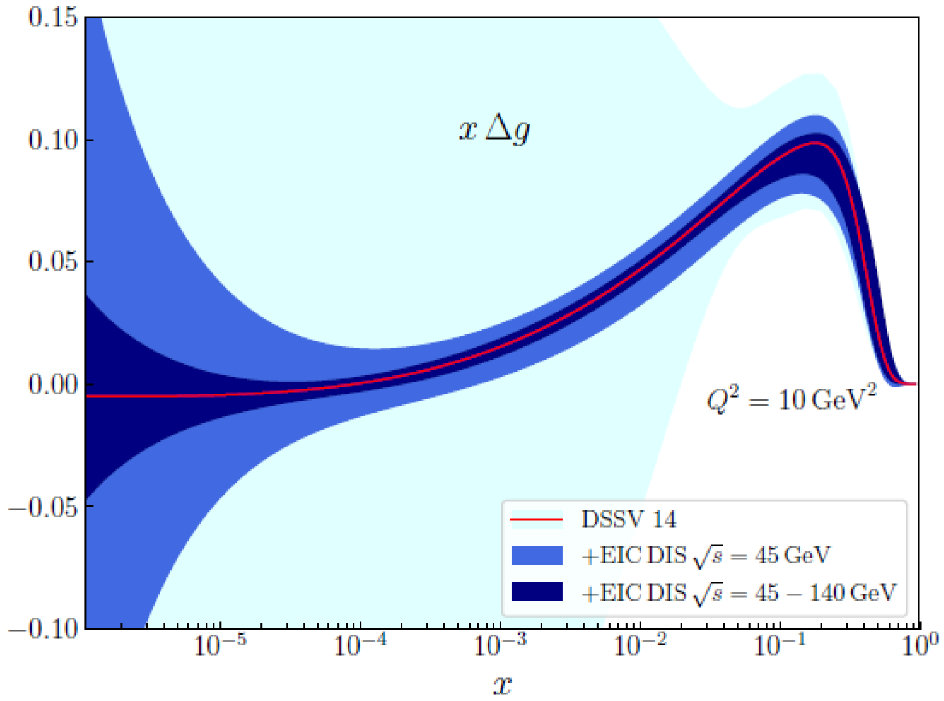
- Inclusive A_{LL}

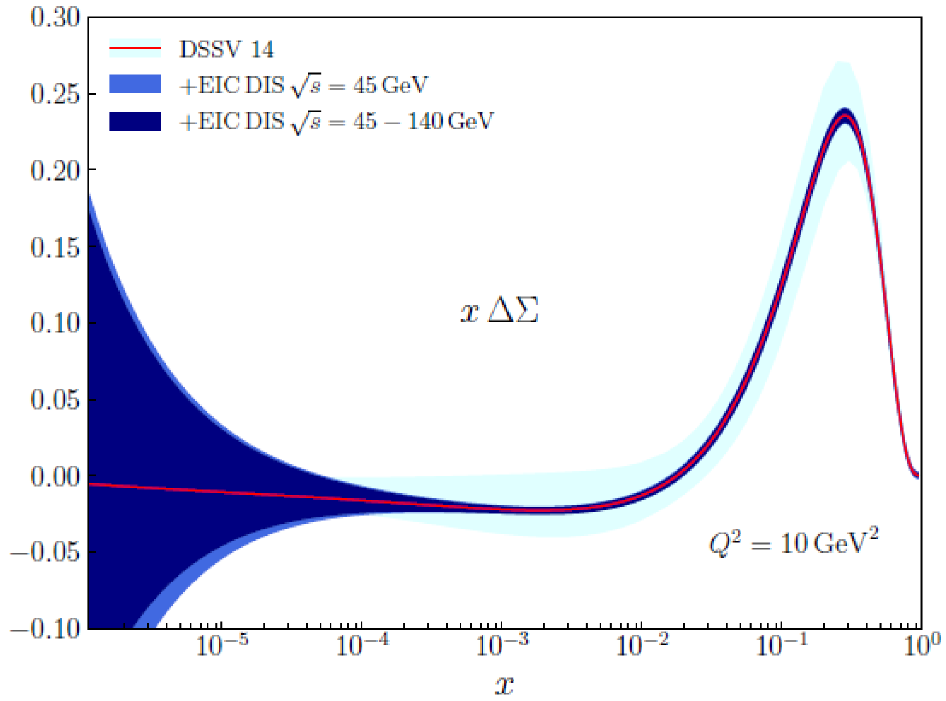
$$\frac{1}{2}\left[\frac{d^2\sigma^{\leftrightarrows}}{dxdQ^2} - \frac{d^2\sigma^{\rightrightarrows}}{dxdQ^2}\right] \cong \frac{4\pi\alpha^2}{Q^4} y(2-y) g_1(x, Q^2)$$

, where $g_1(x, Q^2) = \frac{1}{2}\sum e_q^2[\Delta q(x, Q^2) + \Delta\bar{q}(x, Q^2)]$.

- Δg is encoded in scale violation of g_1

arXiv:2103.05419



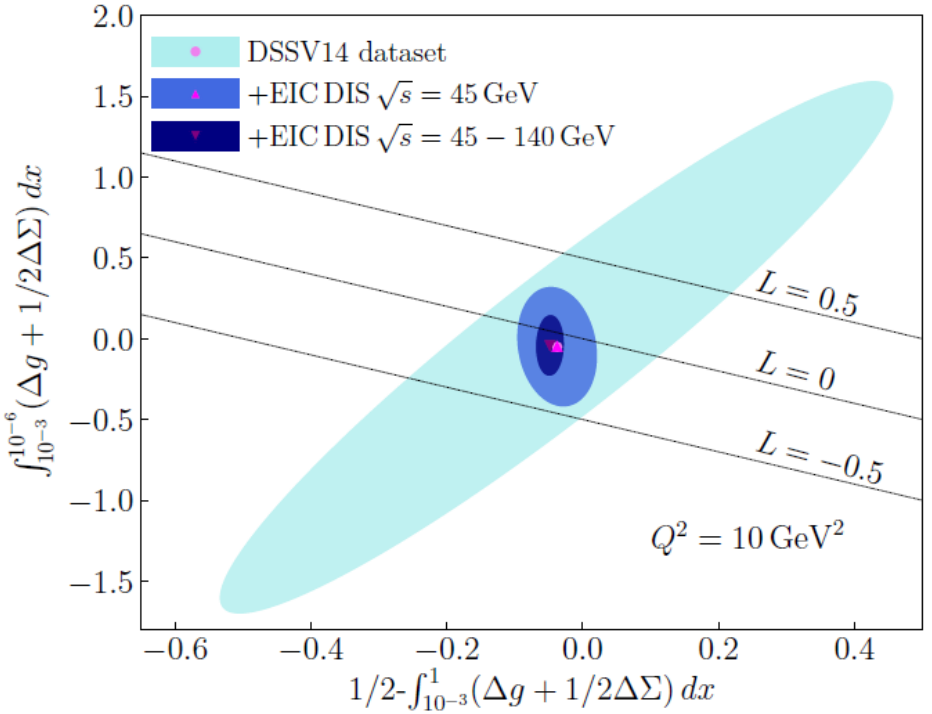


Physics programs – spin structure of proton

- OAM
  - As S_q and S_g are expected to be precise, OAM will be constrained
  - $J^q = \frac{1}{2} - J^g = \frac{1}{2}\int dx x[H^q(x, \xi = 0, t = 0) + E^q(x, \xi = 0, t = 0)]$, where H and E are GPD

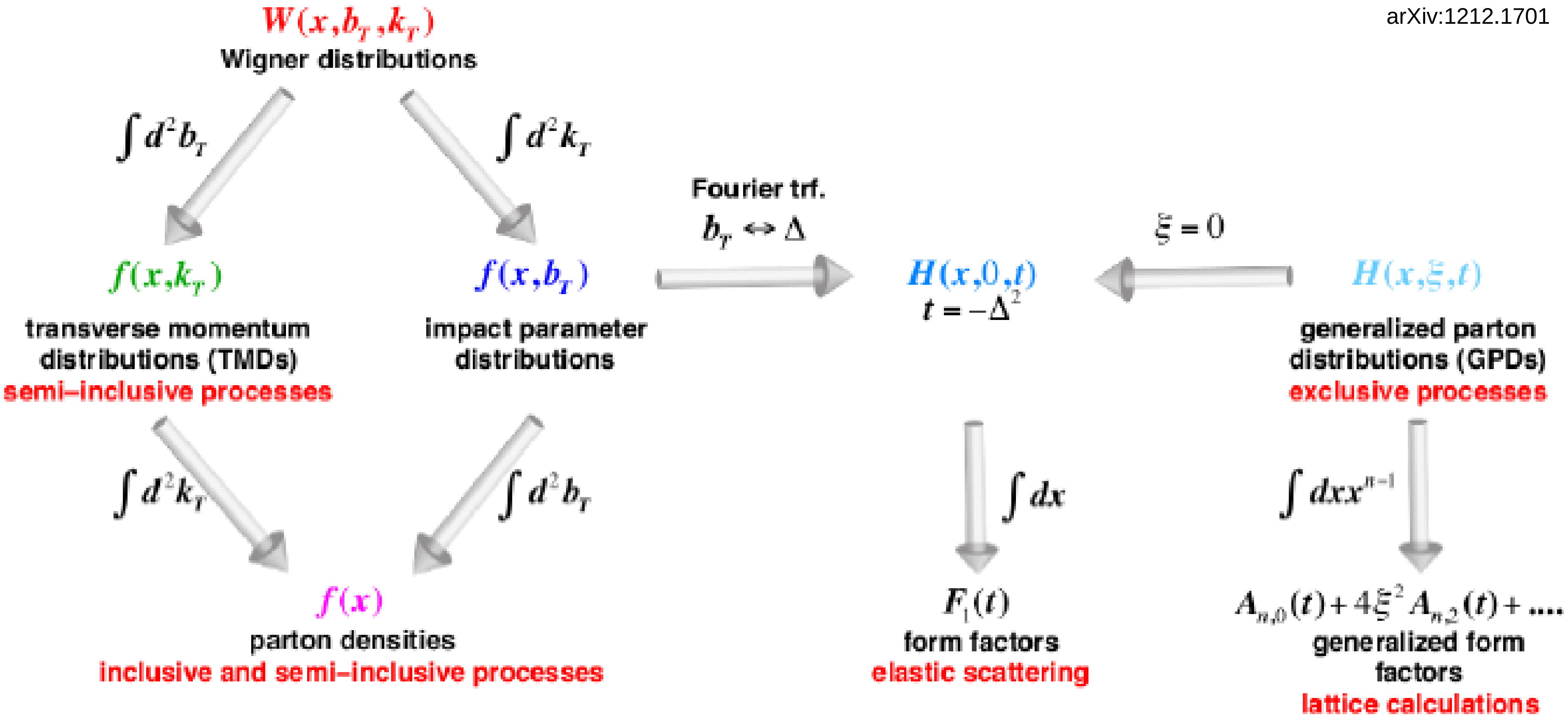
    $OAM_q = J^q - S_q$ and $OAM_g = J^g - S_g$
  - H and E are accessible at EIC and JLab via DVCS and DVMP

arXiv:2103.05419



Physics programs – Multi. D. imaging of proton

arXiv:1212.1701

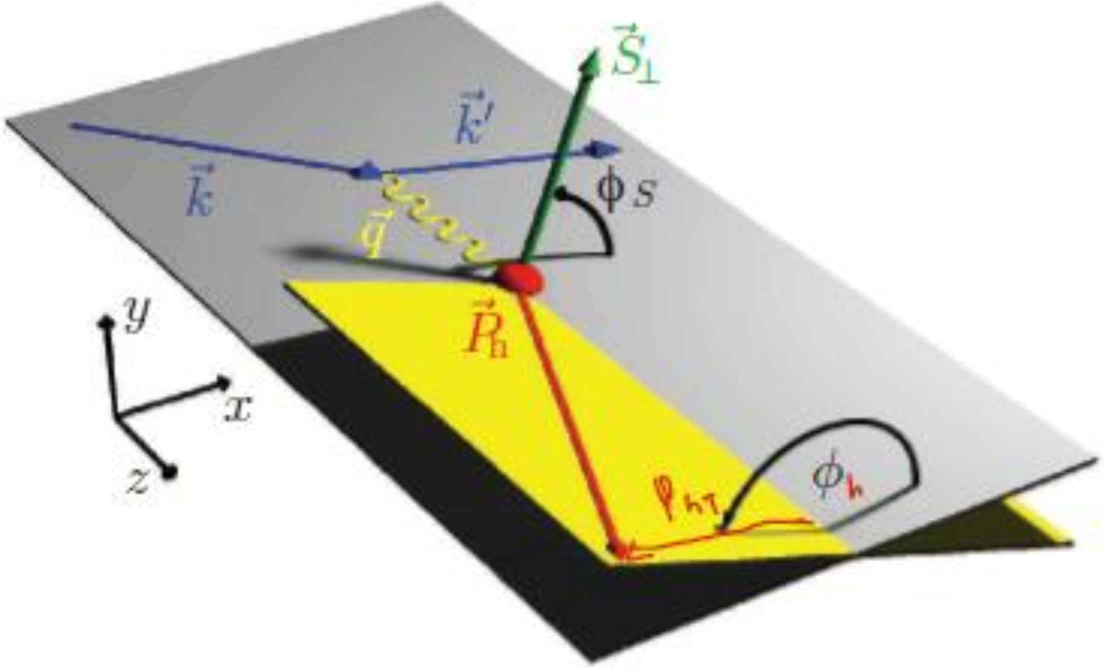


Physics programs – TMDs

- $\frac{d\sigma}{dxdyd\phi_S dzd\phi_h dP_{hT}^z} \propto F_{UU} + |S_\perp| \sin(\phi_h - \phi_S)\, F_{UT}^{\sin(\phi_h-\phi_S)} + \cdots$

  , where $F_{UT}^{\sin(\phi_h-\phi_S)} = \sum_q e_q^2 |C_V\ (Q)|^2 [R(Q;\mu_0) \otimes f_{1T}^{\perp q}(x;\mu_0) \otimes D_1^q\ (z;\mu_0)](P_T)$

  , where $|C_V\ (Q)|^2$ perturbative coefficient, $R(Q;\mu_0)$ evolution factor, $f_{1T}^{\perp q}(x;\mu_0)$ Sivers TDM, and $D_1^q\ (z;\mu_0)$ unpolarized TMD FF

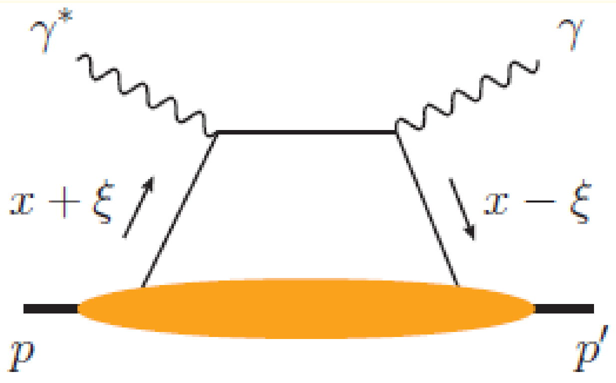


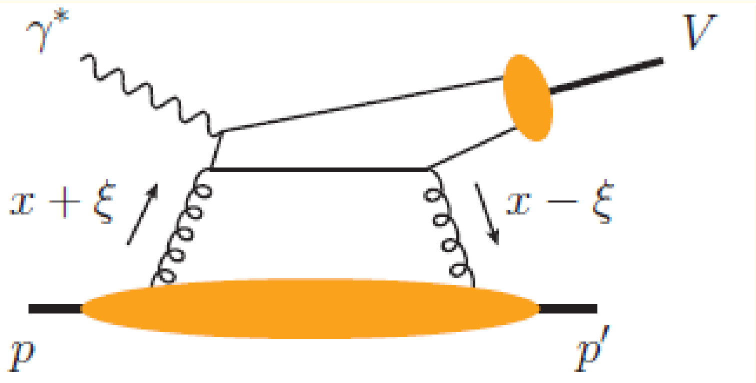
Physics programs – GPDs

- GPDs provide a connection between PDFs and form factors

- The cleanest channels to access GPDs are DVCS and DVMP

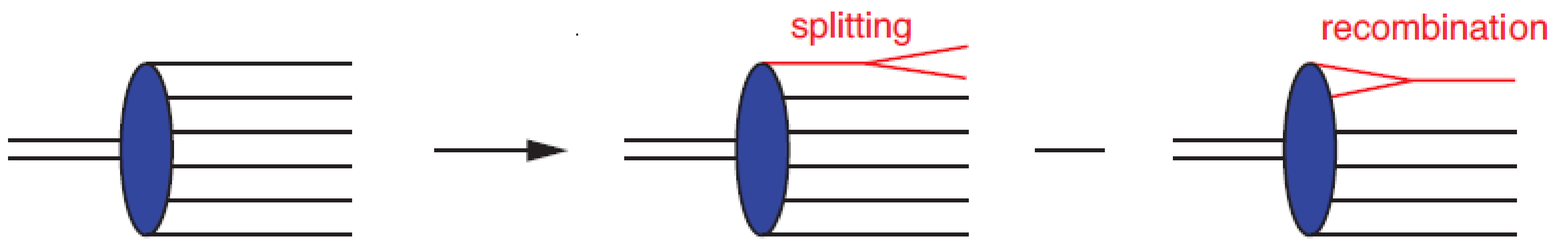
  - $x+\xi$ and $x-\xi$ are longitudinal parton momentum fractions with respect to the average proton momentum $\frac{p+p'}{2}$ before and after scattering





Physics programs – Gluon saturation

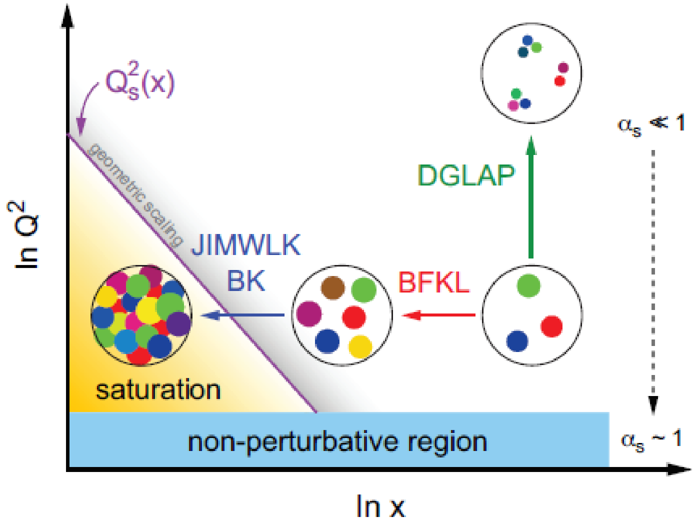
- Will gluon density continue to increase in low enough x region?
  - Probably not



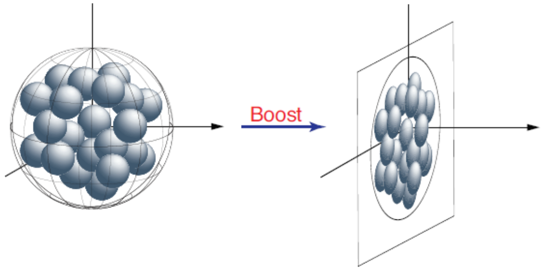
- BFKL evolution
  - The evolution eq. that allows one to construct the PDF at low-x
  - $\frac{\partial N(x,r_T)}{\partial \ln(1/x)} = \alpha_s K_{BFKL} \otimes N(x,r_T)$, where $r_T \sim 1/Q$ (transverse distance) and Fourier Tr. of $N(x,r_T)$ is related to gluon TMD

- BK evolution
  - $\frac{\partial N(x,r_T)}{\partial \ln(1/x)} = \alpha_s K_{BFKL} \otimes N(x,r_T) - \alpha_s [N(x,r_T)]^2$

- HERA implied the existence of CGC



Physics programs – Gluon saturation



• Nuclear "Oomph" factor

- To access CGC, we need higher beam energy or heavy ion collision
- Gluon fields are overlapped by Lorentz contraction and higher density gluon field can be probed wo/ increasing beam energy
- $Q_s^2(x) \sim A^{1/3} (\frac{1}{x})^{\lambda}$ where $\lambda = 0.2 - 0.3$

• Observables

- Nuclear structure function
- Di-hadron correlations
- Diffractive events

arXiv:1212.1701