



# High-Pressure Gas TPC R&D : Simulation Studies

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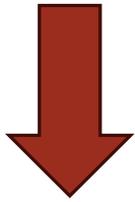
CPAD, OCT 2025

BRENNA MCCONNELL, INDIANA UNIVERSITY

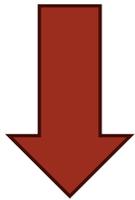
# Motivation: HPGTPCs for Neutrino Oscillation Experiments

- Neutrinos are not detected directly– we rely on kinematics of particles (like low-energy hadrons) to infer neutrino energy

Difficulty predicting low energy hadrons

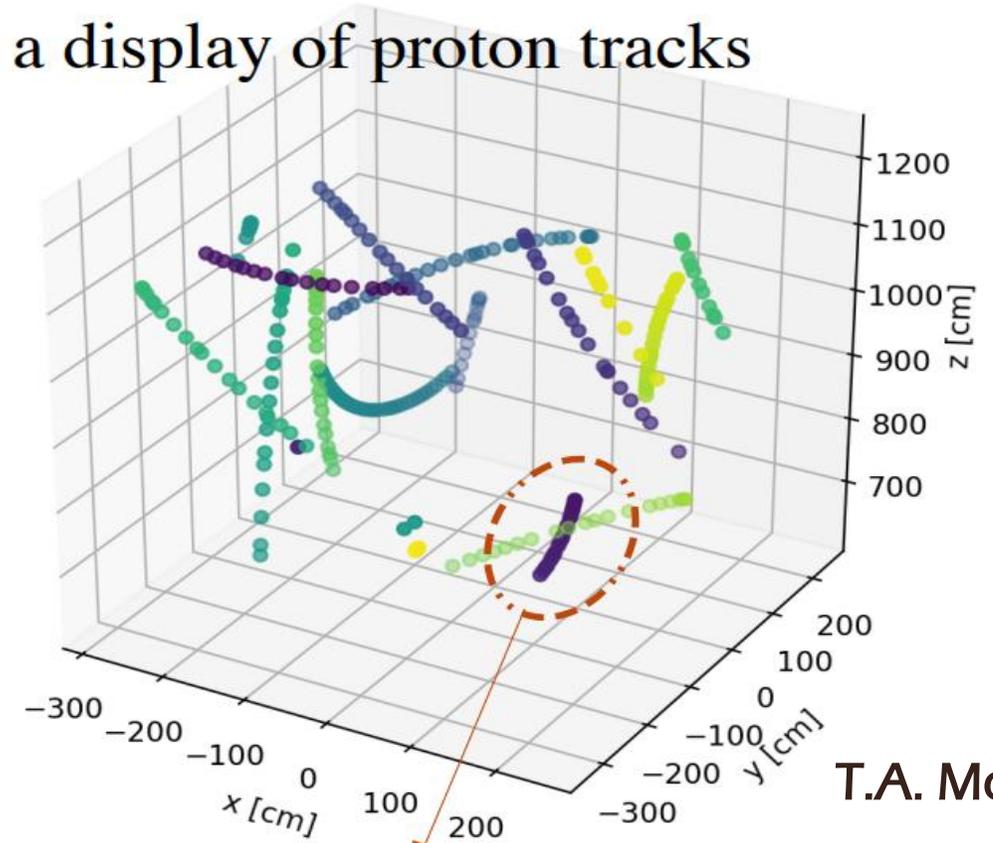


Uncertainty in neutrino interactions



Uncertainty in oscillation parameters

a display of proton tracks



T.A. Mohayai

**40 MeV proton** with range of  $\sim 1\text{m}$

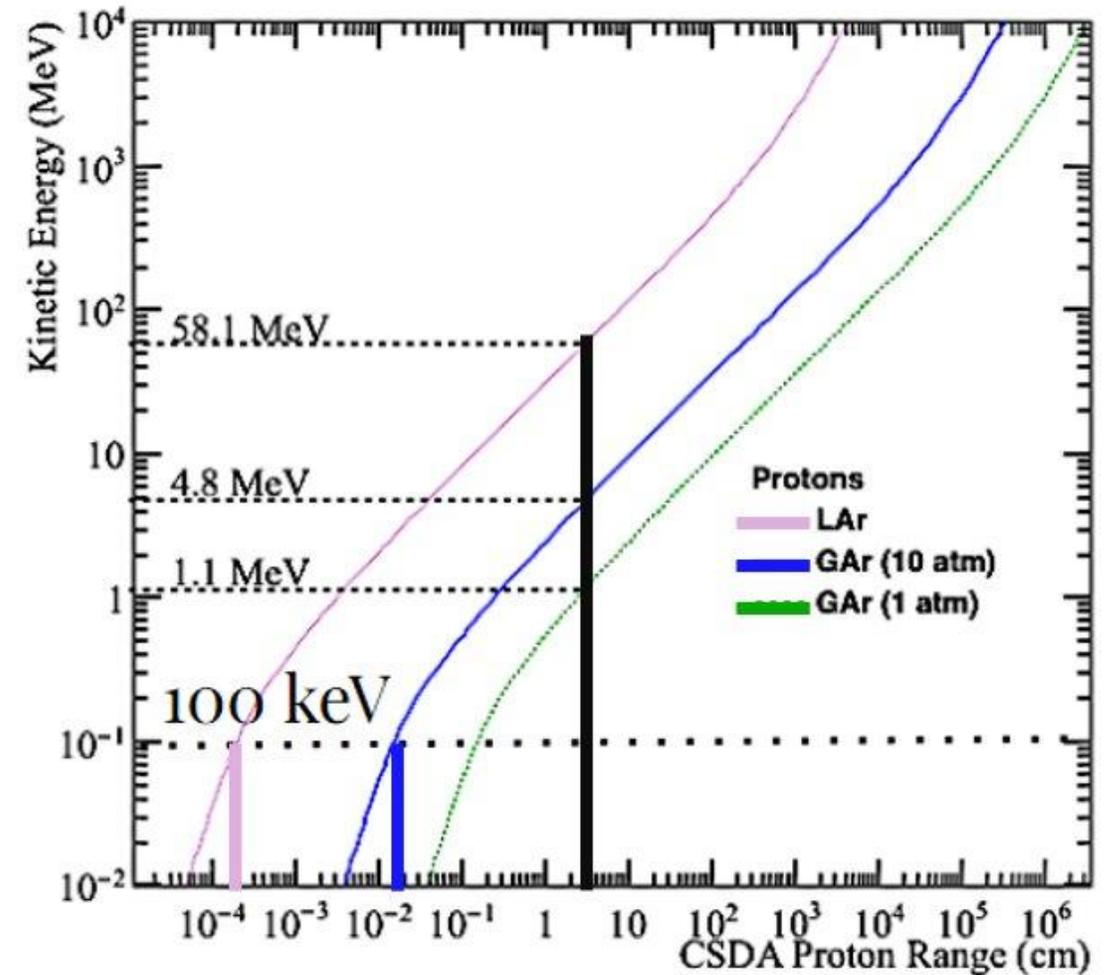
# Motivation: HPGTPCs for Rare Event Searches

- Low energy hadrons have longer track lengths in high pressure GAr compared to LAr.
- Rare events can have low-energy signals, making them undetectable in LAr detectors

Ex) CEvNS has signal  $O(\sim 100 \text{ keV})$  in SNS beam at Oak Ridge

Range in LAr:  $O(1 \mu\text{m})$

Range in GAr:  $O(100 \mu\text{m})$



# Motivation: Modern Charge Readout Structures Relatively Untested in HP GAR

- Target material = detecting medium density
  - E.g. oscillation experiments aim for ~million neutrino on argon – achievable with 5x5 m TPC pressurized to 10 bar (comparable to e.g. baseline liquid argon detector)

**High pressure reduces multiplication gain of charge readout structures, presenting opportunity to develop novel high-gain designs for high pressure GAR**

• **Future prospects & open questions:**  
★ Optimizing GEMs for pressurized gas medium

T.A. Mohayai, the community-wide DUNE Phase II Workshop

Employ high-granularity GEM-based readout in HPGArTPC

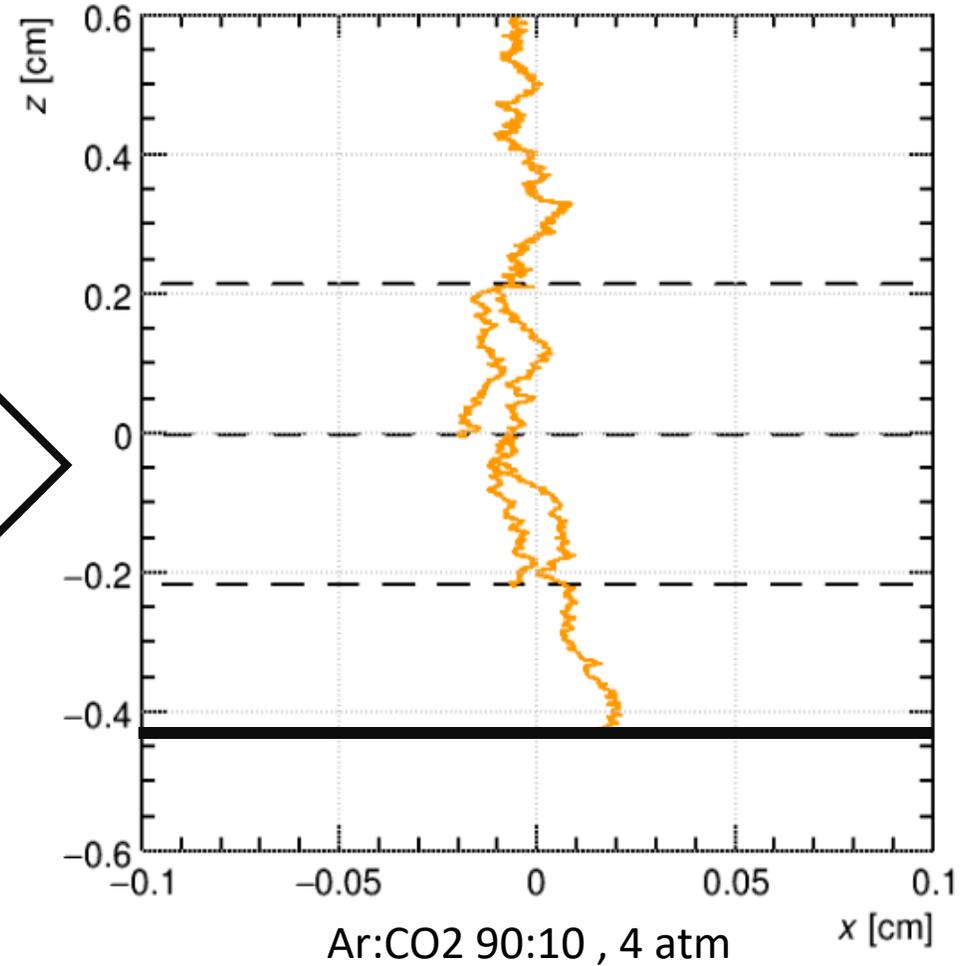
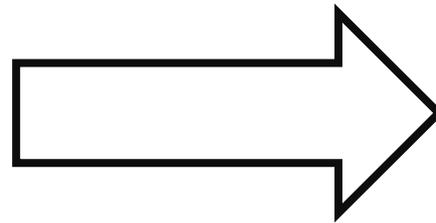
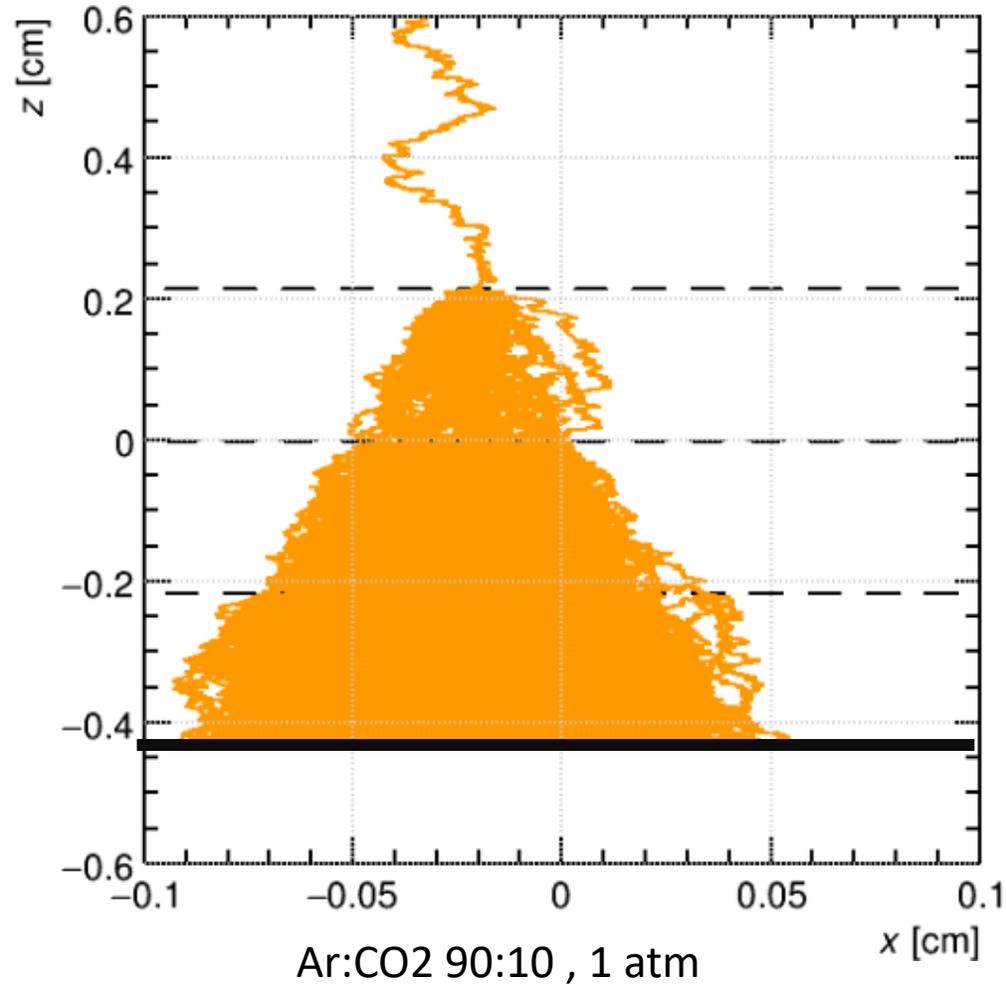
J. Zettlemoyer, Snowmass 2021 Noble Elements Meeting

**Starting point: Triple-GEMs**

**Goal: Identify optimizations to increase gain of Triple-GEM at high pressure & characterize sources of loss**

# Background: Recreating GORG in Simulation

- **Garfield ++ and ANSYS were used to model GORG in simulation, giving a first look at GEMs in high pressure**



Increase in pressure → decreases mean free path → decreases gain

# Background: Charge Transport in Garfield ++

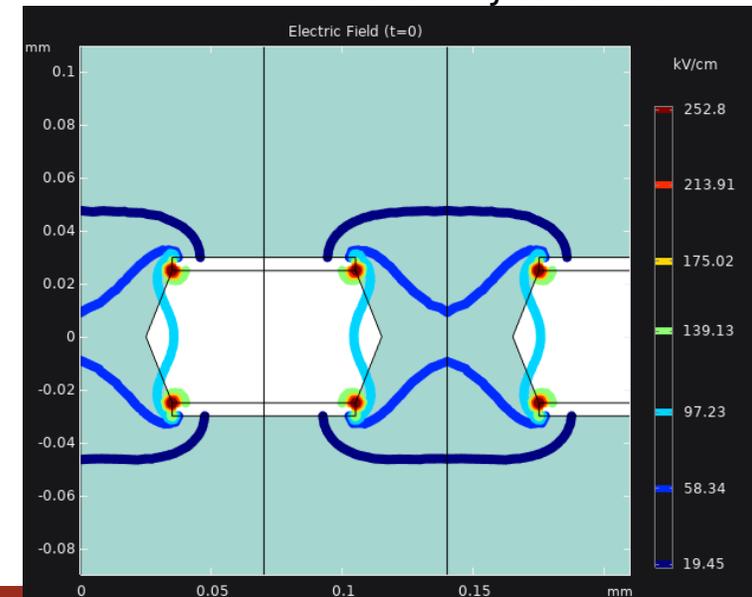
Garfield++ has a microscopic tracking method that simulates every electron collision and the collision mechanism that takes place, allowing for evaluation of parameters that vary with pressure.

- Attachment– high pressure increases frequency of collisions, increasing probability of attachment which decreases gain
- Diffusion– increasing collision frequency with high pressure limits spread of electrons, improving ratio of charge collected into amplification region which increases gain
- Ionizations – high pressure reduces mean free path, resulting in fewer ionizing collisions which decreases gain

Garfield++ cannot describe some effects directly, like space charge effects.

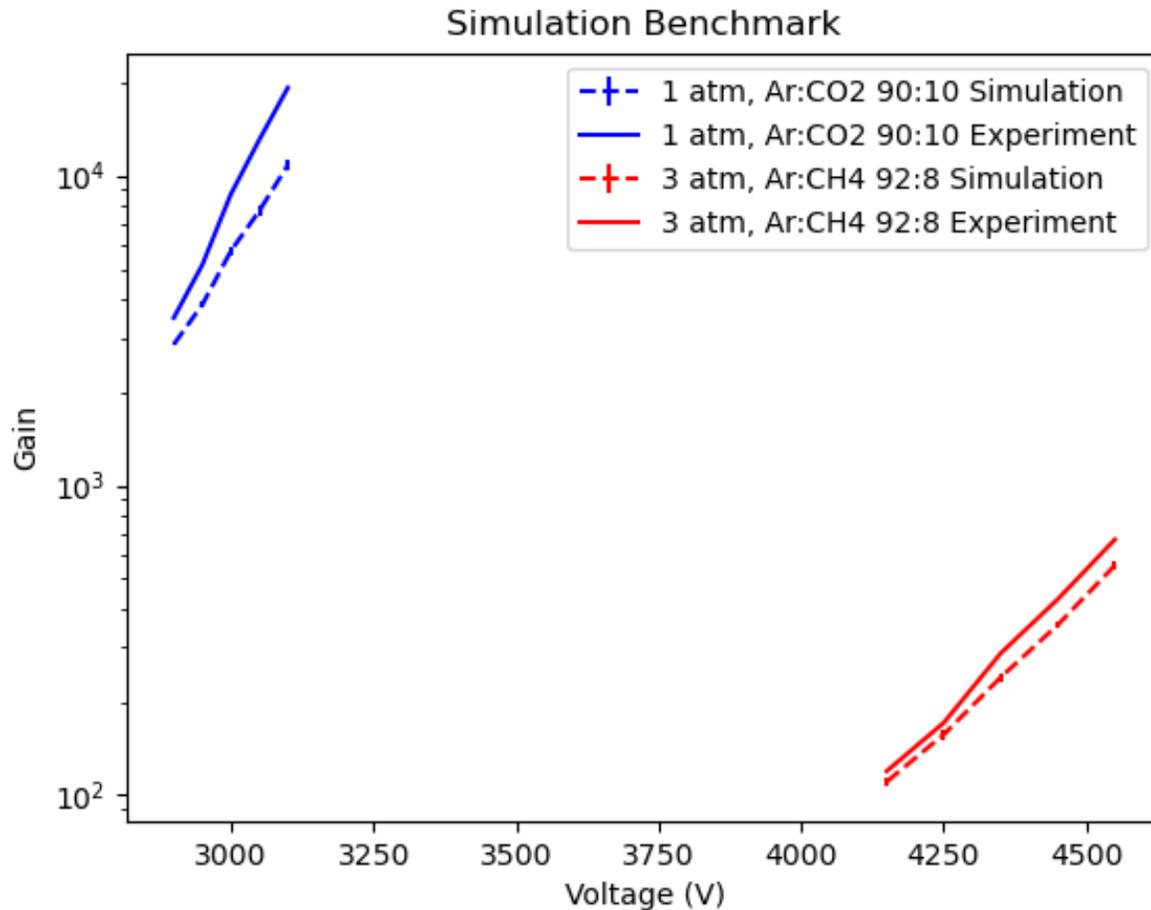
- COMSOL simulations in progress to determine effect of design changes on stability

*Natalie Mujica-Schwahn*



# Benchmark: Comparing simulation to experiment

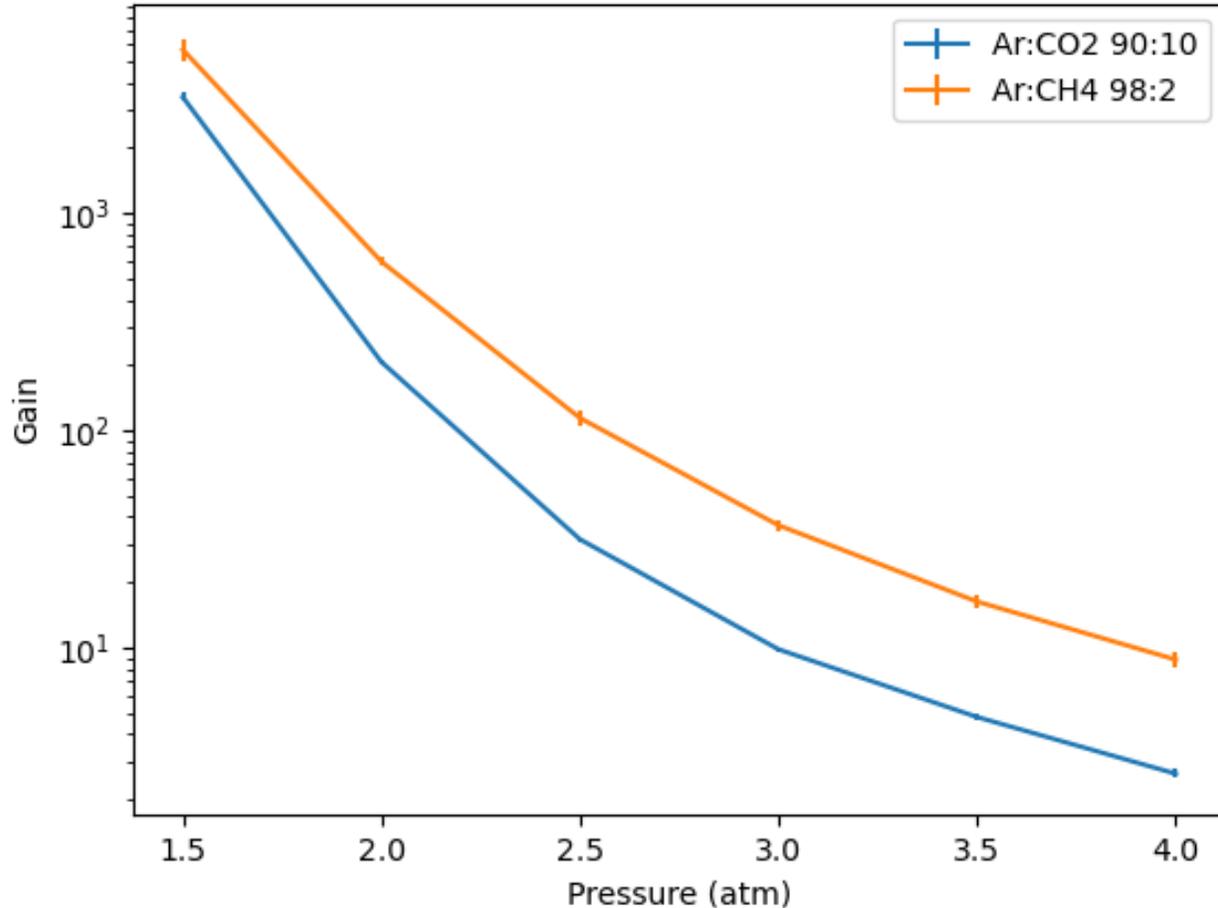
- 1 atm benchmarking completed with Ar:CO<sub>2</sub> 90:10, 3 atm benchmarking completed with Ar:CH<sub>4</sub> 92:8



- Agreement between simulation & experiment at high pressure shows how Garfield++ can be used as a predictive tool
  - Though disagreement exists, Garfield++ can help identify trends in data & optimal parameter settings
- Small discrepancies between experimental setup and the simulated setup can cause large disagreement (non-uniform fields, hole misalignment, defects...)
  - Observe improved agreement ( $\sim 2x$ ) with simulation of GORG vs. outside sources

# Optimizations: Quenching Gas

Gain vs. Pressure : Quenching Gas

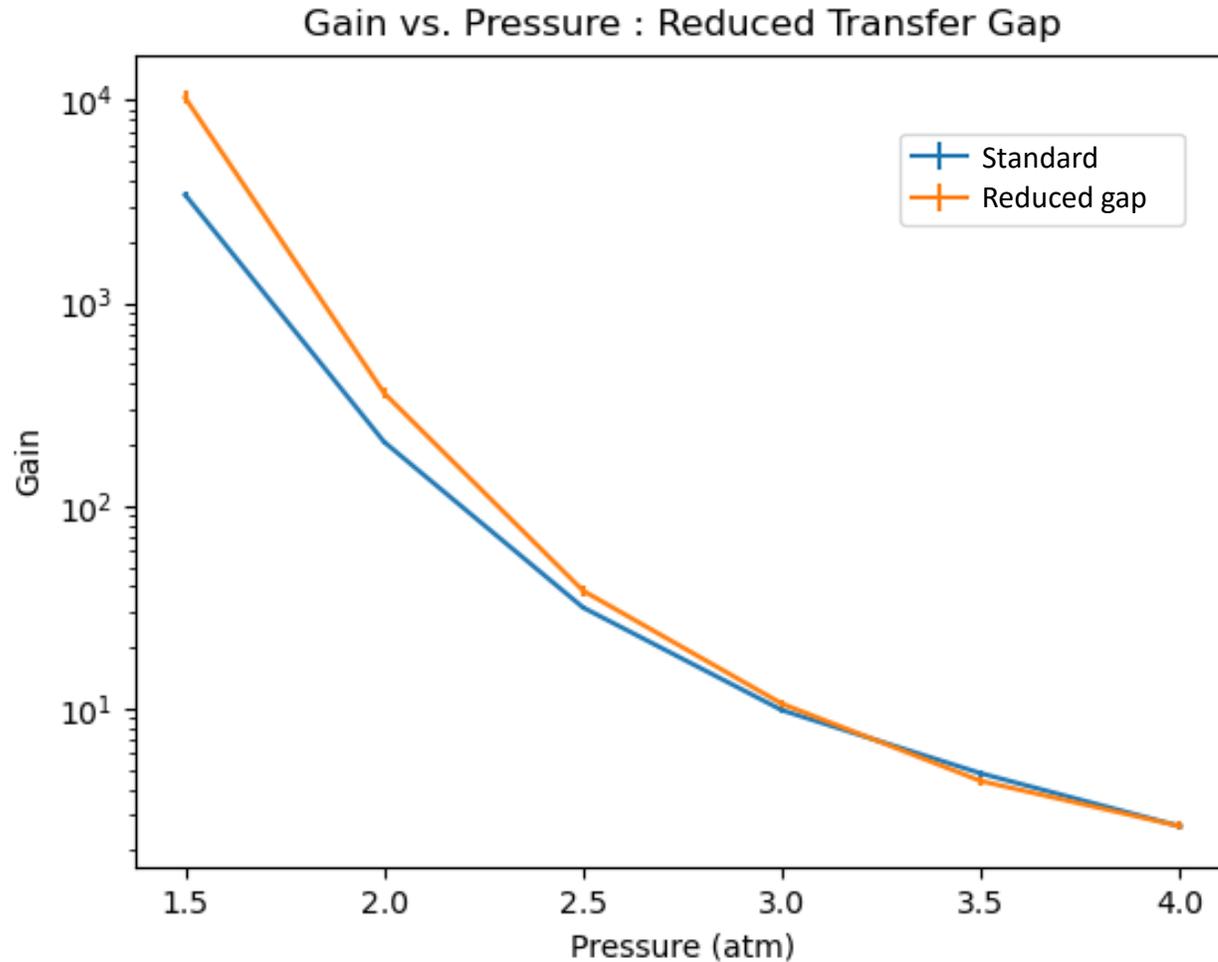


Ar: heavy nuclei = larger interaction rates

CH4: less electronegative, lower ionization potential, reduced diffusion

- The difference in performance becomes more apparent at higher pressure – **about 5x increase in gain at 4 atm!**
  - Estimate gain of ~100 could be envisioned for oscillation experiment purposes– observe gain ~100 around 2.5 atm

# Optimizations: Transfer Gaps

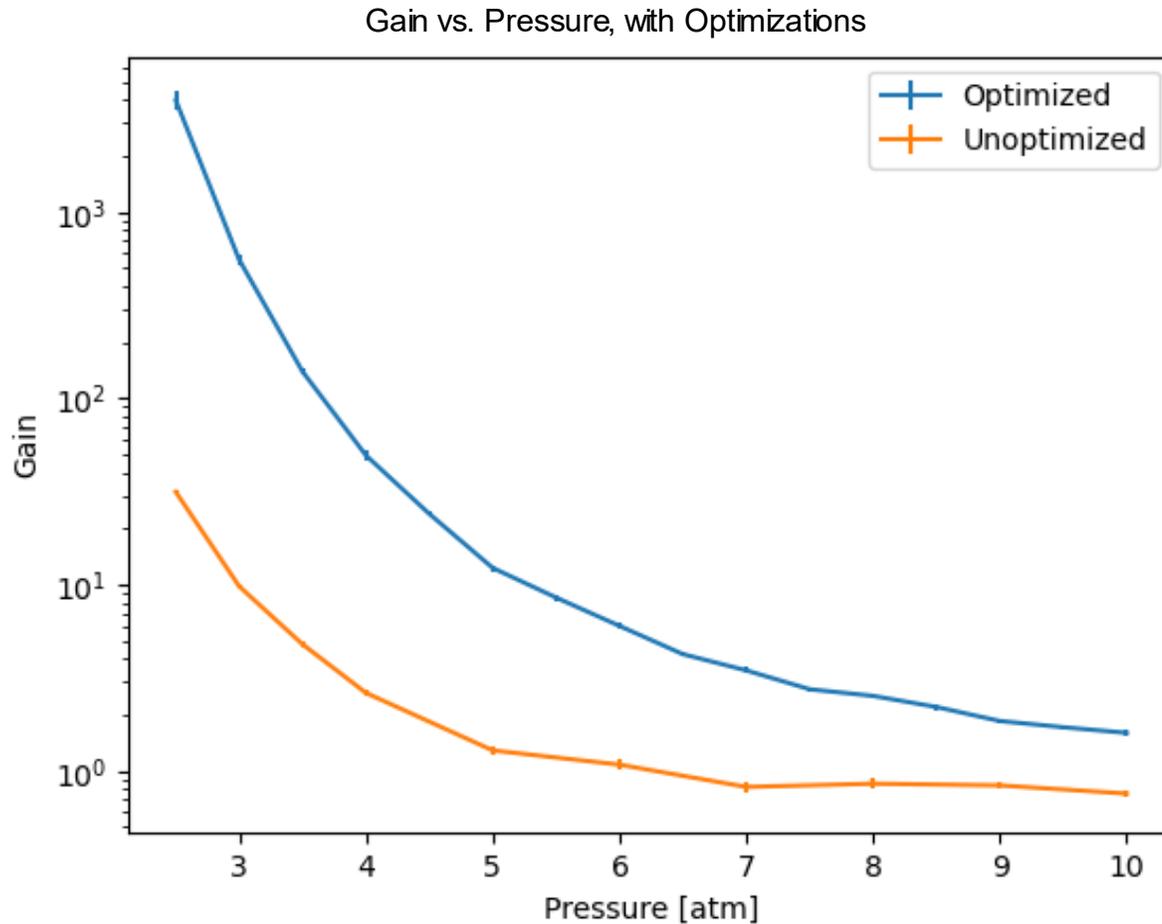


- Adjusting transfer gap size effects the electric field strength, impacting gain
- About 3x increase in gain at 1.5 atm!

## Parameters:

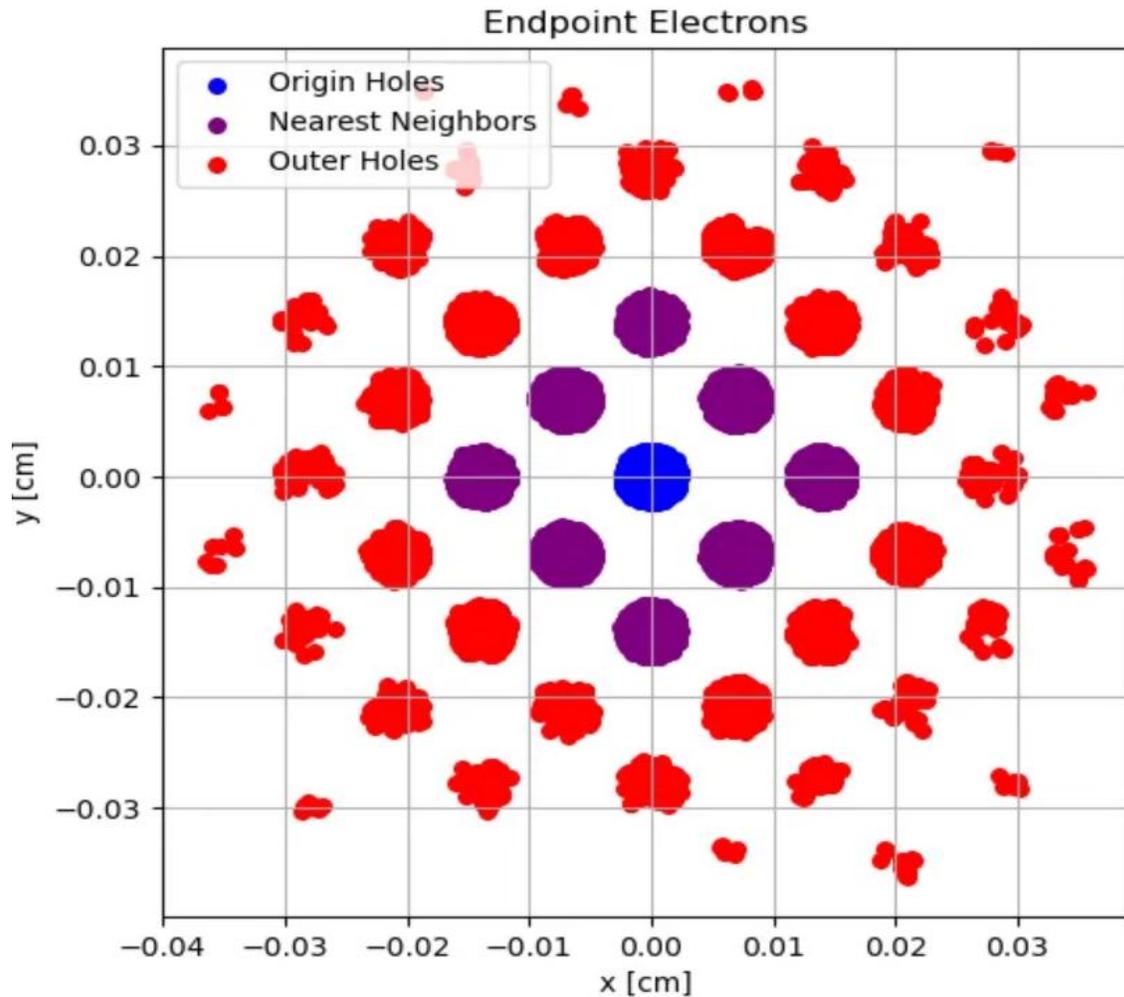
- 3500 V to GEMs
- Ar:CO<sub>2</sub> 90:10
- Transfer Gap 1 = 0.5 mm
- Other transfer gaps remain at standard values

# Optimizations : Implementing All Optimizations

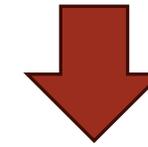


- Parameters for optimized curve:
  - 3800 V to GEMs
  - Transfer gap 1 reduced to 0.5 mm
  - Gas mixture Ar:CH4 98:2
- At 2.5 atm, optimized curve has ~130x greater gain
  - Target gain ~100 at about 3.5 atm—more optimizations needed to get signal at 10 bar
- Additional optimizations (resistive coatings) could improve stability
  - COMSOL can show if exceeding traditional voltage limits is safe

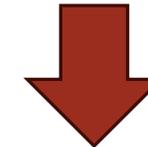
# Charge Distribution & Loss Studies



Increase in pressure reduces mean free path of electrons



Diffusion is reduced

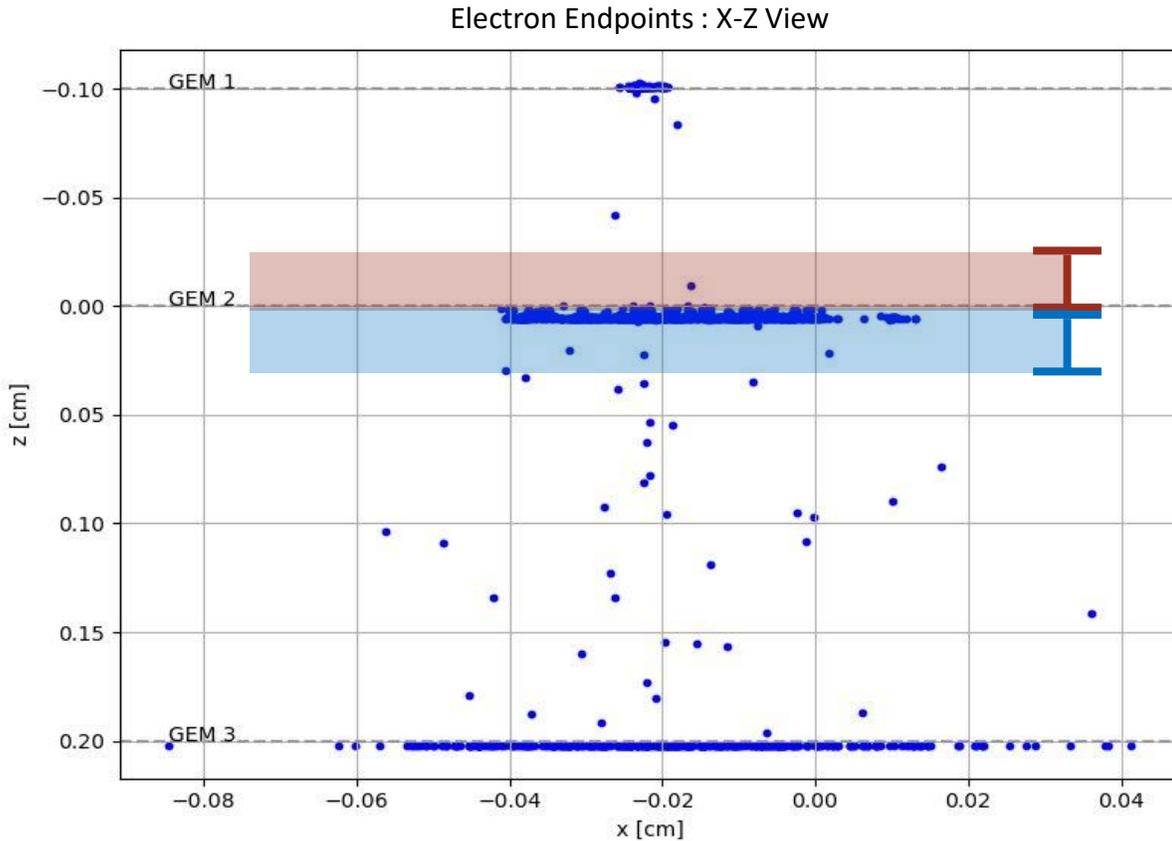


## Effects:

- Larger ratios of charge are contained in fewer GEM holes—increase risk of exceeding modified Raether limit  $O(10^6)$
- Optimal fields will change with pressure

# Charge Distribution & Loss Studies

- Simulation studies evaluated charge distribution in GEM layers and sources of loss



**Diffusion loss** can cause electrons to strike the GEM electrodes rather than continue multiplication.

- Attachment also contributes to loss, but only quenching gases are likely to capture electrons

Example for GEM 2:

Collection efficiency:

$$\epsilon_c = \frac{n_c}{n_0}$$

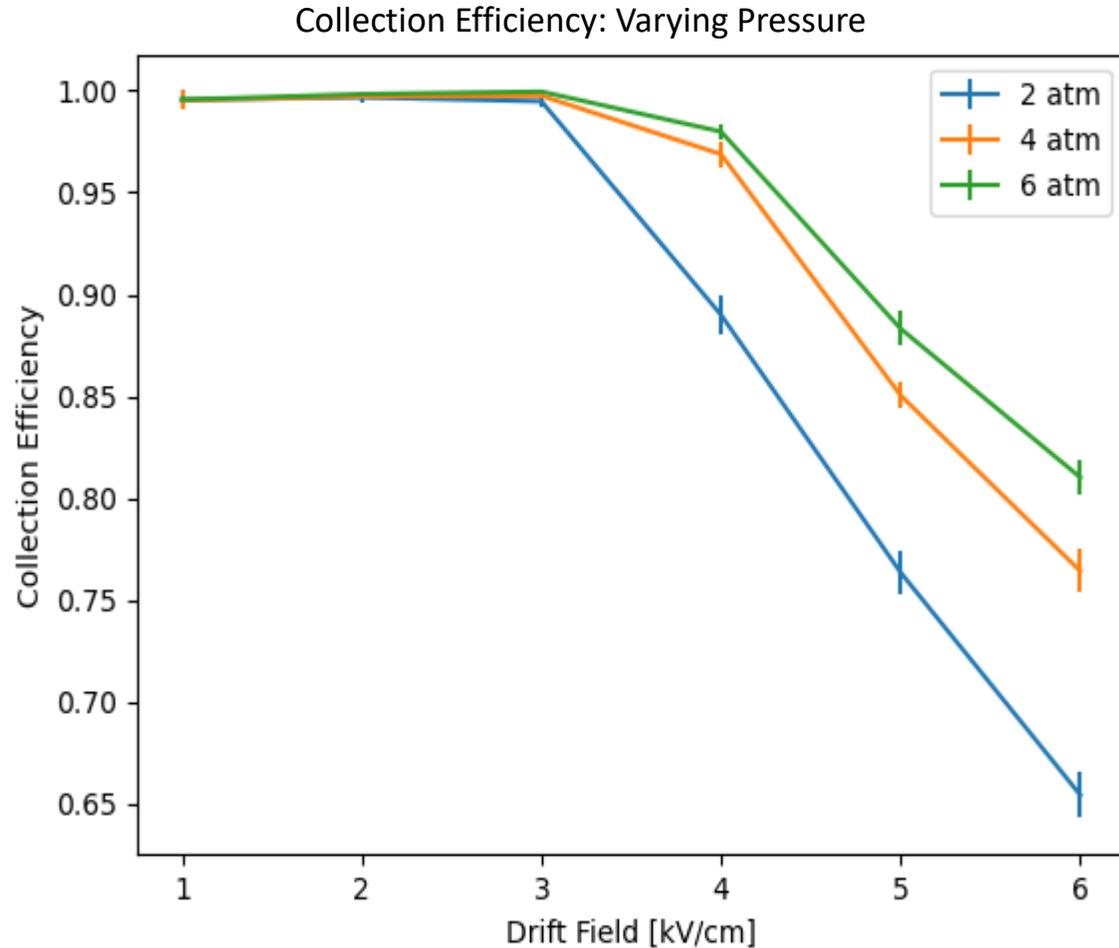
Measures ratio of electrons successfully collected in GEM holes from transfer gap

Extraction efficiency:

$$\epsilon_{ext} = \frac{n_{ext}}{n_{in}}$$

Measures ratio of electrons successfully extracted from bottom of GEM hole to next transfer region

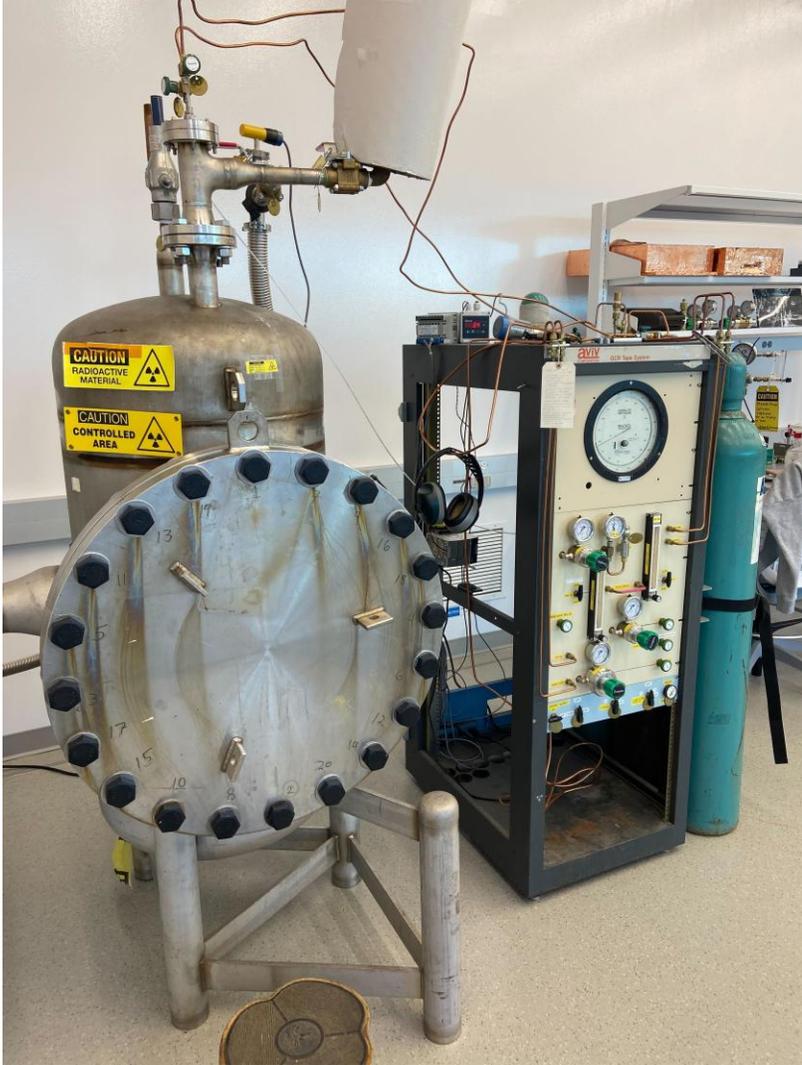
# Loss Studies : Optimal Drift Fields at Varying Pressure



## Parameters:

- Pitch/Outer Diameter/Inner Diameter : 140  $\mu\text{m}$ /70  $\mu\text{m}$ /50  $\mu\text{m}$
- Drift Gap/Transfer Gaps : 18 mm / 2.1 mm
- Voltage to GEM : 400 V
- Gas Mixture: Ar-CH<sub>4</sub> 92-8
  
- Optimizing the drift field increases likelihood for primary electrons to reach first amplification region
  
- **Above 3 kV/cm**, electrons are lost to top electrode— cannot increase drift field arbitrarily high!
  - Framework developed for drift field optimization lays foundation for transfer field optimization

# Future Studies



- Results from loss studies highlight need for field optimization to improve collection and extraction efficiencies
  - Framework developed for drift field optimization can also optimize transfer fields
- Disagreement between simulation and experiment motivates adjustment to simulation to account for real-world effects
  - Hole misalignment studies in progress: in real world, perfect alignment is impossible
- Optimizations are effective but may influence stability, which Garfield++ does not account for.
  - COMSOL simulation studies in progress

# Summary

- ◆ Goal : develop a novel high-gain charge readout structure for high pressure GAr or any challenging environments requiring high gain structures
- ◆ Used simulation framework to evaluate several key parameters in maintaining gains at high pressure: voltage, gas mixture, and transfer gaps
- ◆ Began optimization of electric fields in triple-GEM
- ◆ Focus currently on optimizing Triple-GEM setup :
  - ◆ Facility development underway at Indiana University
  - ◆ Simulation work developed to guide and benchmark experimental efforts



Backup Slides:

## Preliminary Gain Calculation:

In Ar at 10 atm – 5 MeV proton loses energy at 250,000 eV/cm and will only travel ~3 cm

Creating ionization electron takes 26.3 eV → ~285,000 electrons for full track

If we estimate noise  $O(10^6)$ , gain of 100 is sufficient to amplify above electronics noise level

*This estimate is not final and represents a first attempt to set an estimate goalpost for the gain.*

# Loss Studies : Benchmarking Simulation

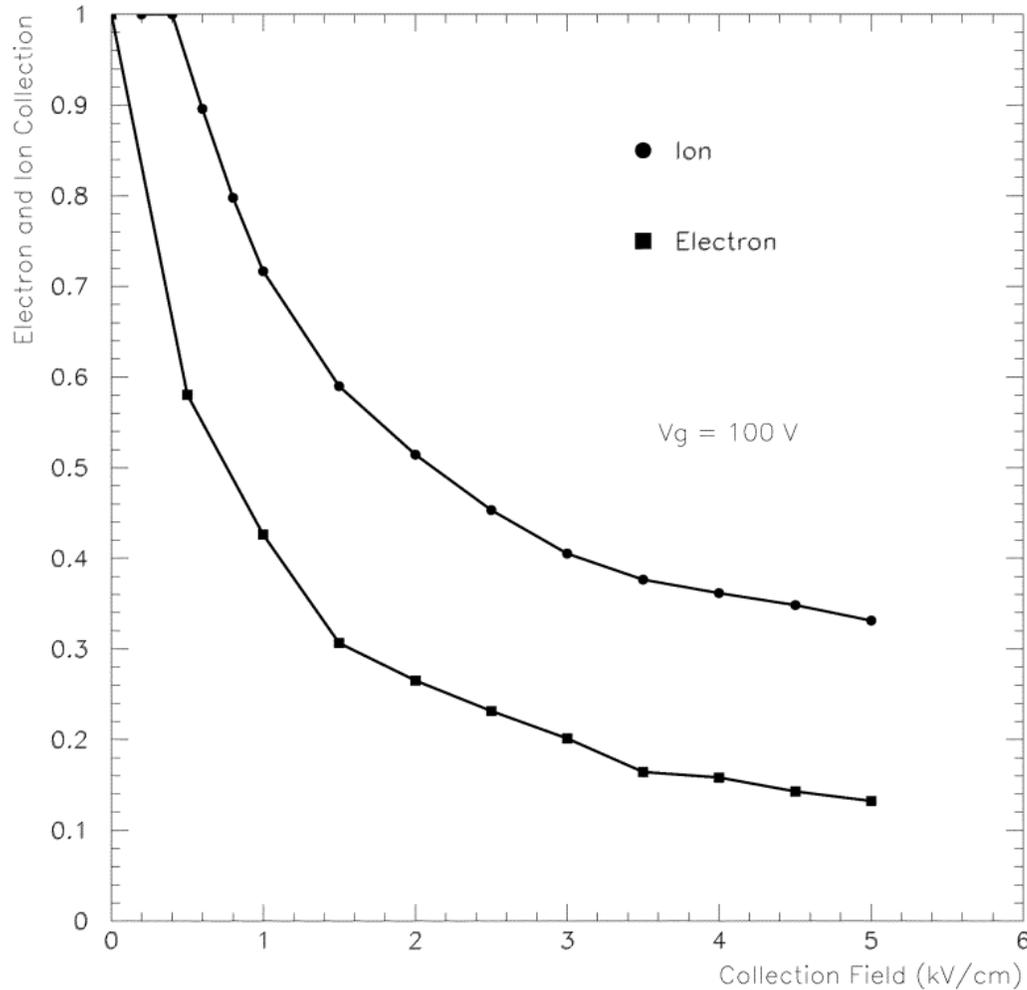


Fig. 15. Electron and ion collection efficiency in Ar/CO<sub>2</sub> (70/30) as a function of the collecting field, for  $V_{\text{GEM}} = 100$  V.

Collection Efficiency – from *Measurement of GEM Parameters with X-Rays*

## Parameters:

- Single GEM
- Pitch/Outer Diameter/Inner Diameter : 140  $\mu\text{m}$ /70  $\mu\text{m}$ /50  $\mu\text{m}$
- Voltage to GEM : 100 V
- Gas mixture : Ar-CO<sub>2</sub> 70-30
- Drift Gap/Induction Gap = 3 mm/1 mm

*Optimizing electric fields is essential for minimizing loss.*

- Increasing GEM voltage improves collection efficiency, but *reduces* extraction efficiency

-With too high of a drift field, electrons may strike top electrode