Overview of ZDC Requirements for the EIC

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ePIC TIC Meeting
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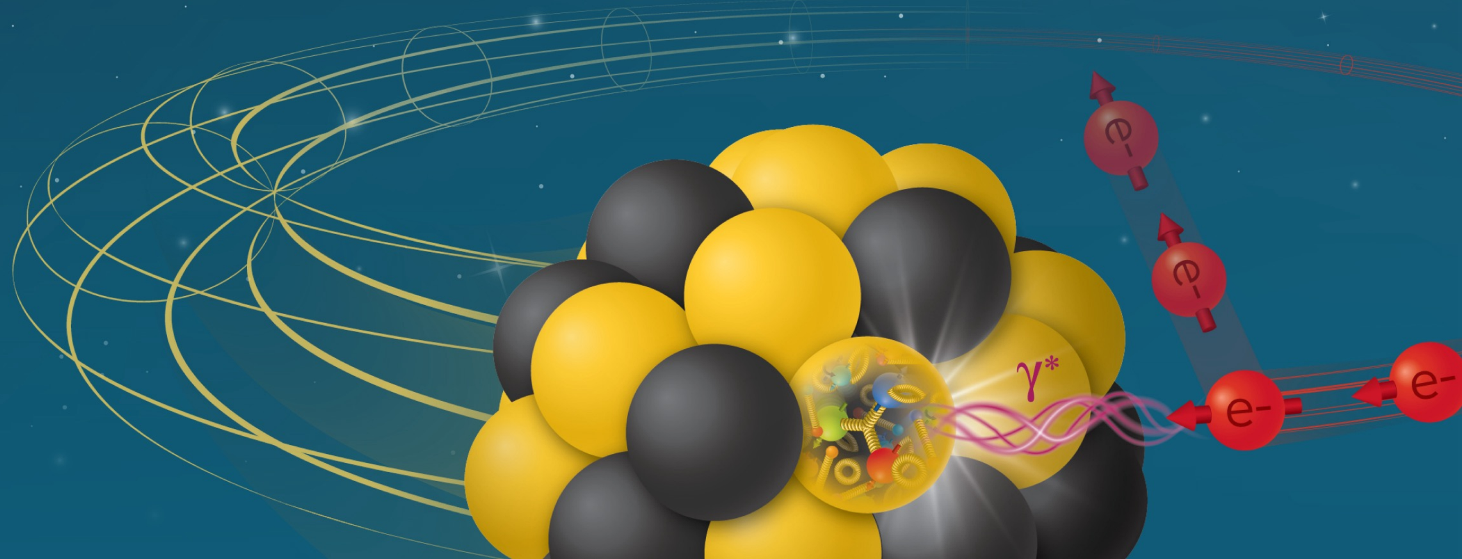


Electron-Ion Collider

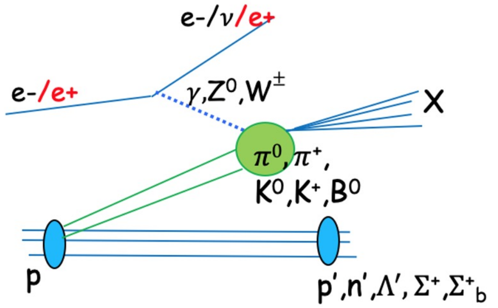
Basic “Requirements”

- Initial ZDC requirements were put together prior to the Yellow Report, and before any comprehensive study of the physics was really put together.
  - Hadronic energy resolution: $\frac{\sigma_E}{E} \leq \frac{50\%}{\sqrt{E}} \oplus 5\%$
  - EM energy resolution: $\frac{\sigma_E}{E} \leq \frac{25\%}{\sqrt{E}} \oplus 2\%$
  - Soft photon sensitivity for $E \sim 100$ MeV
  - Sufficient dynamic range for energy deposits from breakup of heavy nuclei (several neutrons with $E \sim 110$ GeV)
  - Sufficient granularity to provide angular resolution for pT reconstruction: $\frac{\sigma_\theta}{\theta} \leq \frac{3\ mrad}{\sqrt{E}}$
- ZDC acceptance: θ < 5mrad (not ϕ-symmetric) – driven by aperture, not detector.
  - Fixed by machine, we “get what we get.”

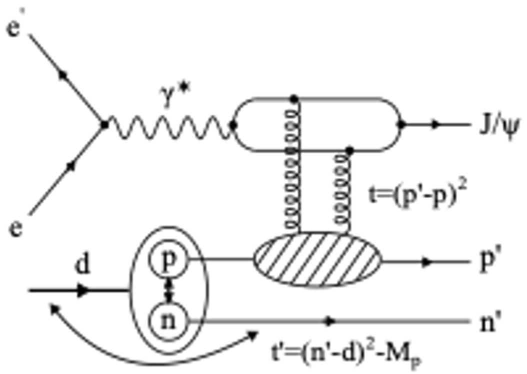
General NB: Previous and current studies and extracted resolutions all assume “perfect” ZDC performance, except for transverse and longitudinal leakage. They do not include effects of backgrounds, electronics, light collection, etc.

(some) Physics channels relying on ZDC

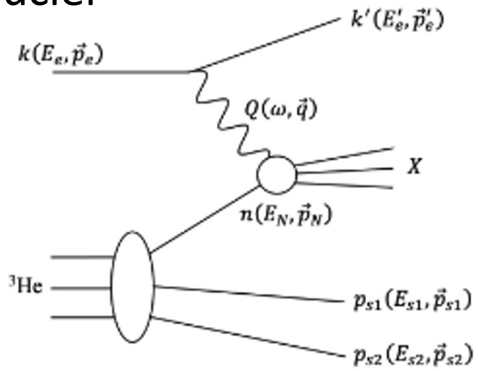
Sullivan process



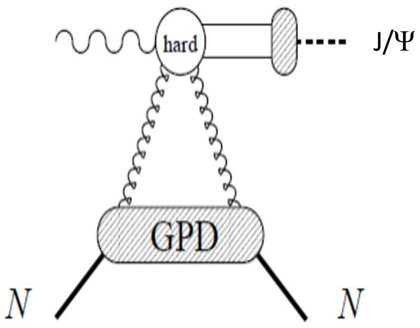
e+d exclusive J/Psi with p/n tagging



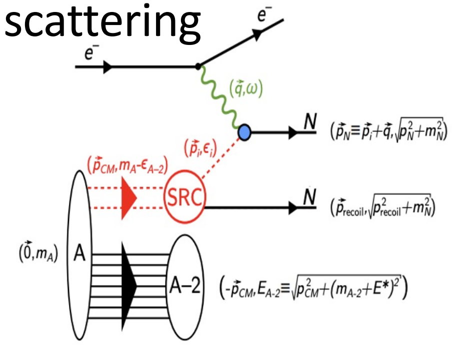
spectator tagging in light nuclei



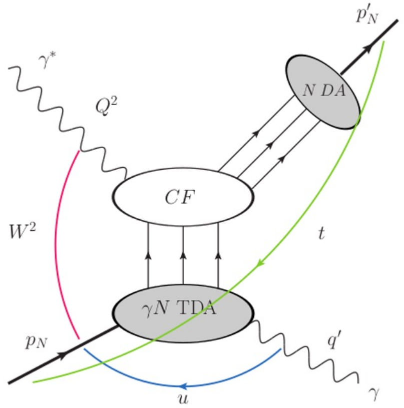
coherent/incoherent J/ψ production in e+A



Quasi-elastic electron scattering



u-channel backward exclusive electroproduction



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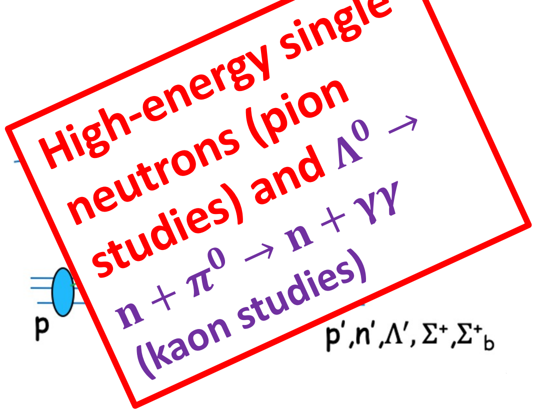
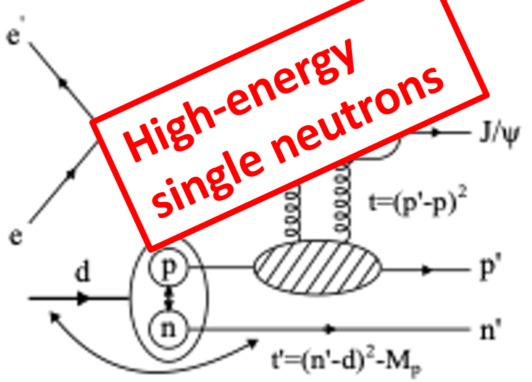


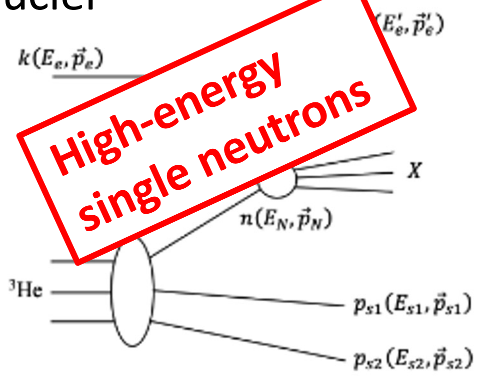
High-energy single neutrons (pion studies) and $\Lambda^0 \rightarrow n + \pi^0 \rightarrow n + \gamma\gamma$ (kaon studies)

e+d exclusive J/Psi with p/n tagging



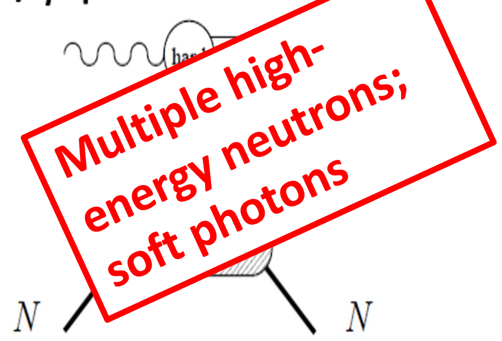
High-energy single neutrons

spectator tagging in light nuclei



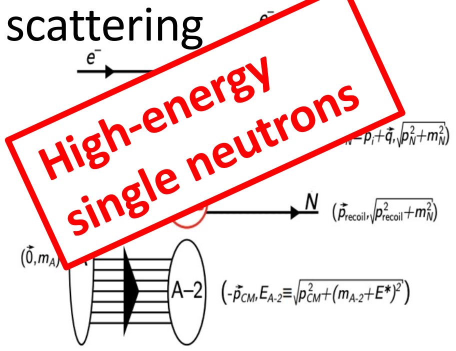
High-energy single neutrons

coherent/incoherent J/ψ production in



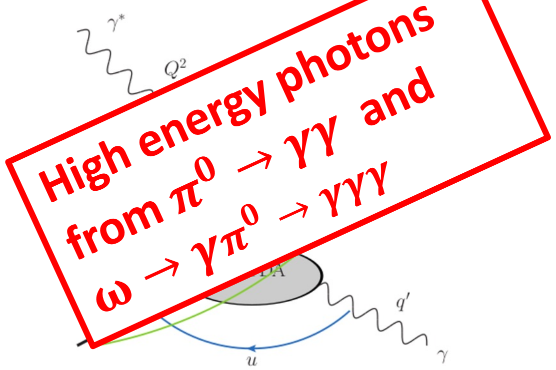
Multiple high-energy neutrons; soft photons

Quasi-elastic electron scattering



High-energy single neutrons

u-channel backward exclusive electroproduction



High energy photons from $\pi^0 \rightarrow \gamma\gamma$ and $\omega \rightarrow \gamma\pi^0 \rightarrow \gamma\gamma\gamma$

Top-level Summary of Requirements

Physics process	Final State particles (for ZDC)	Required HCAL E resolution	Required HCAL angular resolution	Required EMCAL E resolution	Required EMCAL spatial resolution	Notes
Spectator tagged e+d breakup	Neutrons	$\frac{\sigma_E}{E} \leq \frac{50\%}{\sqrt{E}} \oplus 5\%$	$\frac{\sigma_\theta}{\theta} \leq \frac{2\,mrad}{\sqrt{E}}$	N/A	N/A	https://arxiv.org/pdf/2005.14706.pdf https://arxiv.org/abs/2108.08314
Exclusive π^+ production	Neutrons	$\frac{\sigma_E}{E} \leq \frac{50\%}{\sqrt{E}} \oplus 5\%$	$\frac{\sigma_\theta}{\theta} \leq \frac{2\,mrad}{\sqrt{E}}$	N/A	N/A	https://indico.bnl.gov/event/23814/contributions/92533/attachments/55095/94308/Love_slides.pdf
Incoherent vetoing of e+A events	Neutrons/photons	$\frac{\sigma_E}{E} \leq \frac{100\%}{\sqrt{E}}$	N/A	100 MeV photon sensitivity	N/A	https://arxiv.org/abs/2108.01694
u-channel backward VCS	Photons	N/A	N/A	$\frac{\sigma_E}{E} \leq \frac{20\%}{\sqrt{E}} \oplus 3\%$	< 1-2cm	https://arxiv.org/pdf/2308.10478.pdf https://indico.bnl.gov/event/21074/contributions/82988/attachments/50847/86922/23_11_07%20ZDC%20Update.pdf
Kaon structure functions	$\Lambda^0 \longrightarrow n + \pi^0$	$\frac{\sigma_E}{E} \sim \frac{35-50\%}{\sqrt{E}} \oplus 3-5\%$	$\frac{\sigma_\theta}{\theta} \leq \frac{2\,mrad}{\sqrt{E}}$	$\frac{\sigma_E}{E} \leq \frac{10-20\%}{\sqrt{E}} \oplus 2-3\%$	< 1-2cm	https://arxiv.org/pdf/2102.11788.pdf

Photons

- Soft photon tagging important for vetoing of incoherent e+A events (about 3.25% of events produce *only* soft photon).

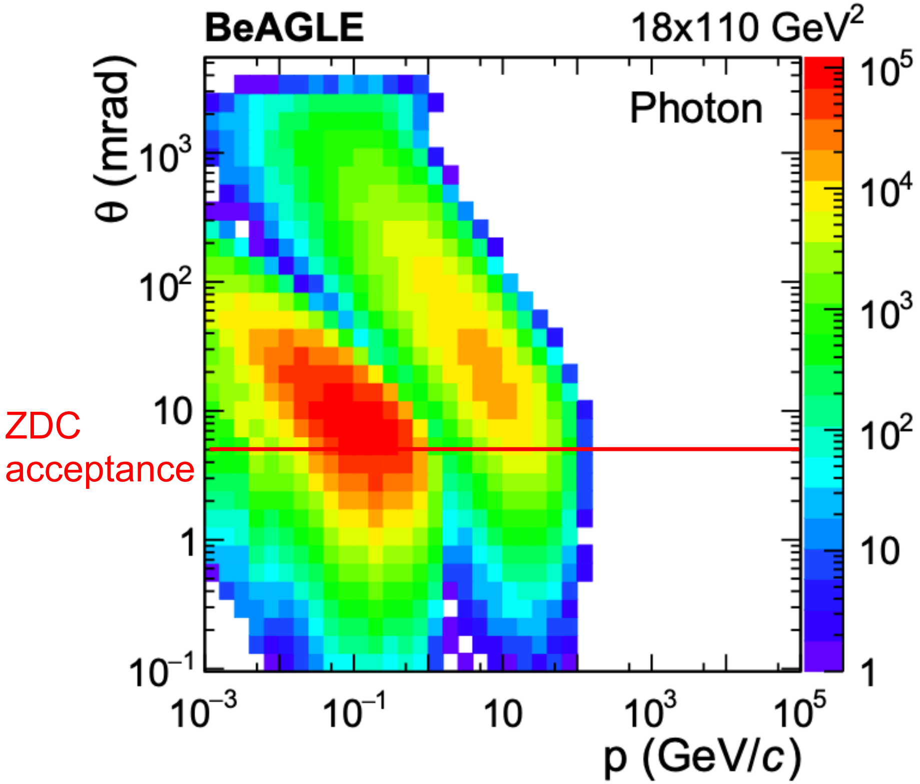
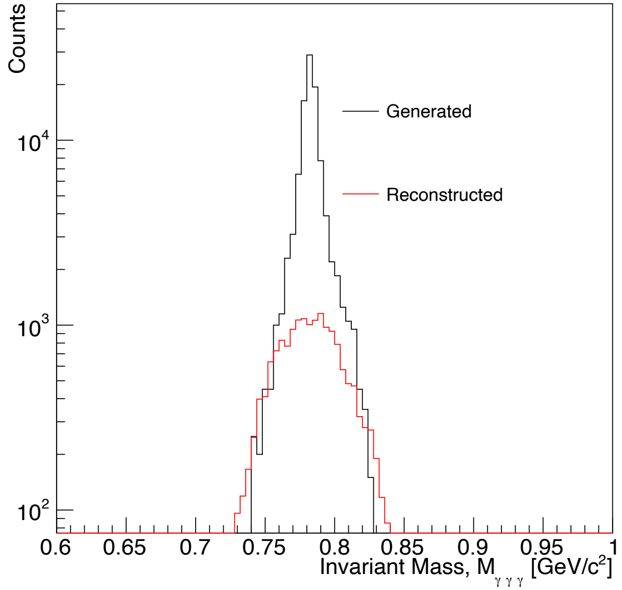
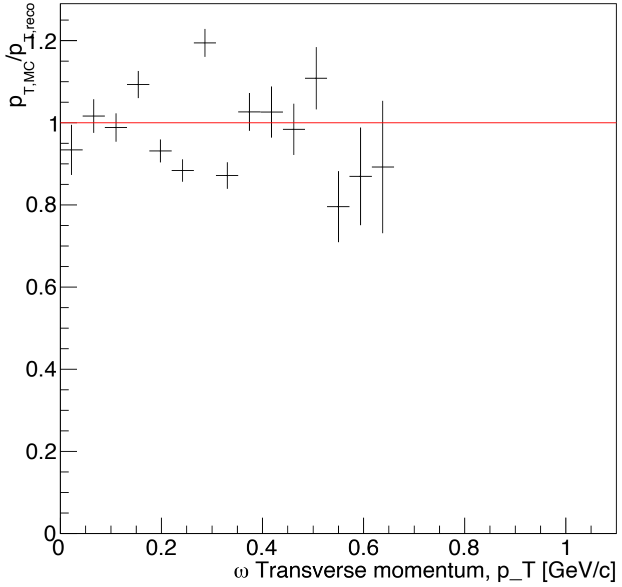


Figure from: W. Chang, E.C. Aschenauer, M. D. Baker, A. Jentsch, J.H. Lee, Z. Tu, Z. Yin, and L.Zheng, Phys. Rev. D **104**, 114030 (2021)

- Backward u-channel ω production.





- Study performed with STARLIGHT events using EICROOT.
- Final state: $\omega \rightarrow \gamma\pi^0 \rightarrow \gamma\gamma\gamma$ (ZDC acceptance ~ 16%)
- Study assumed $\frac{\sigma_E}{E} \leq \frac{10\%}{\sqrt{E}} \oplus 3\%$ and $\frac{\sigma_\theta}{\theta} \leq \frac{1\, mrad}{\sqrt{E}}$

Photons

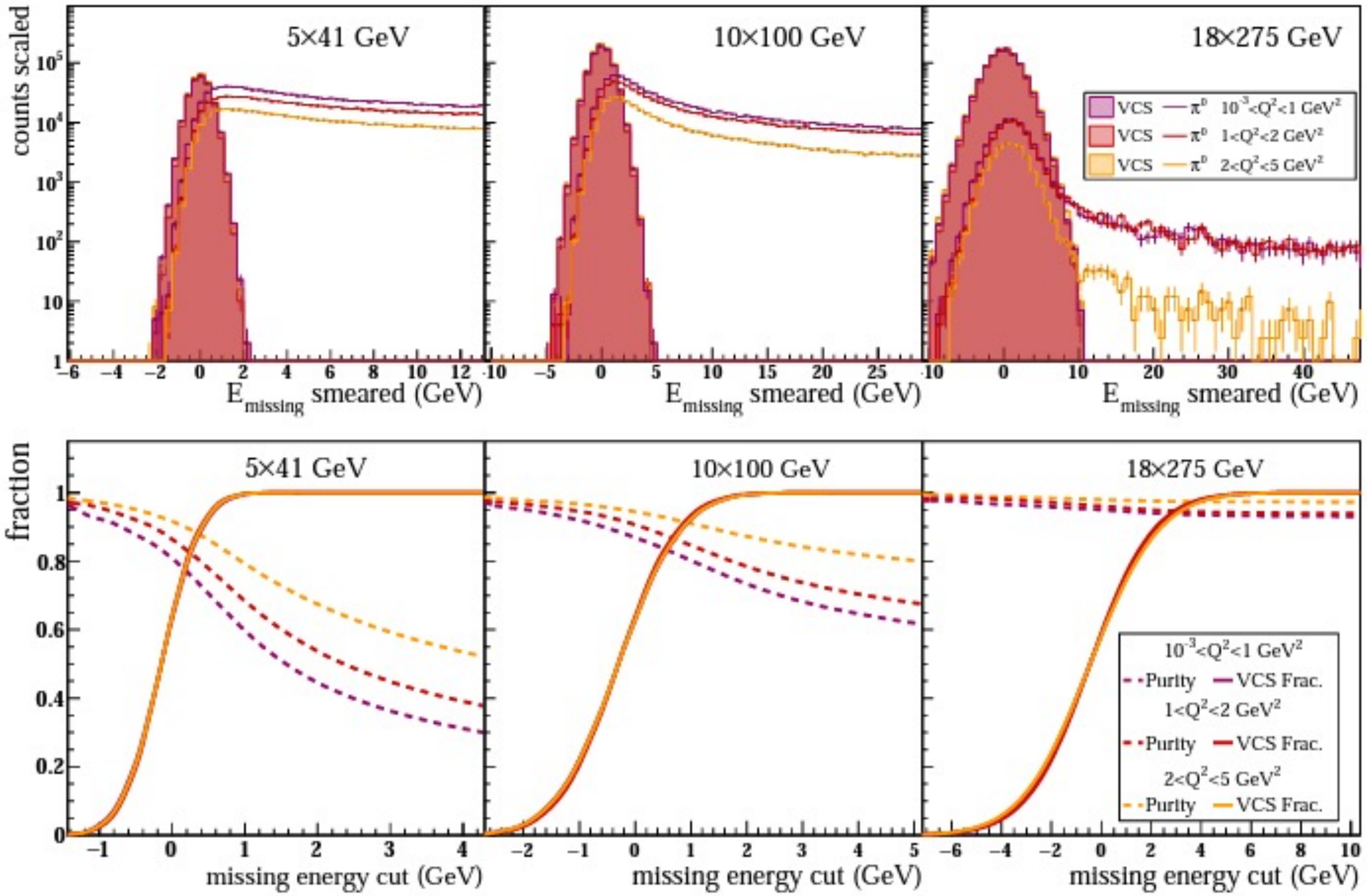


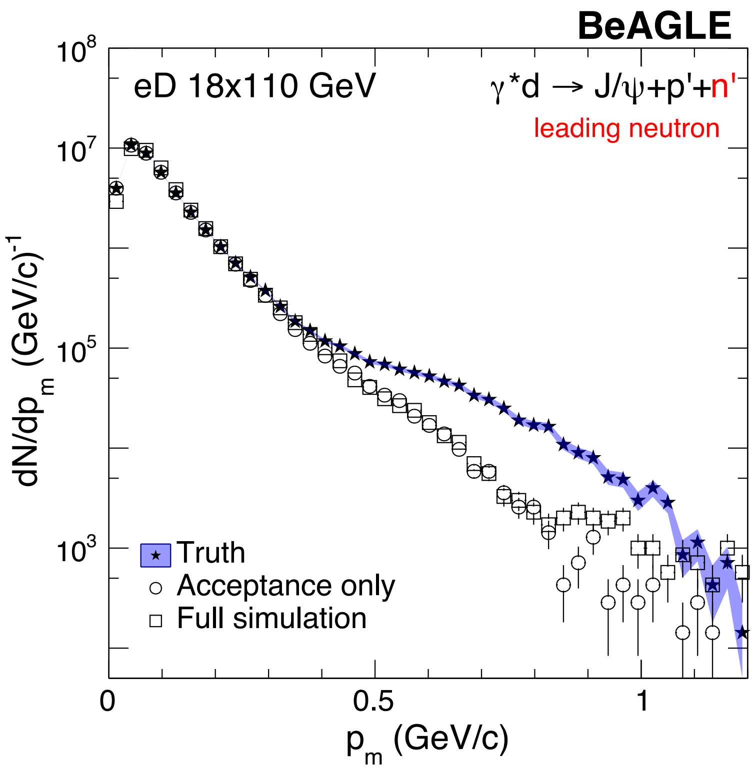
FIG. 9. (top) Missing energy distribution of single photons within ZDC acceptance. The π^0 distributions are scaled to the Compton distributions by the ratio of their cross sections as shown in Tab. II. (bottom) Purity fraction and fraction of signal collected for a given missing energy cut.

- Calculation of missing energy requires precise knowledge of the photon energy from the $\pi^0 \to \gamma\gamma$ decay.
- Reference for the study implies need for **1-2cm spatial resolution** to resolve decay photons and separate $\pi^0 \to \gamma\gamma$ from desired Compton photon, and implies need for $\frac{\sigma_E}{E} \leq \frac{20\%}{\sqrt{E}} \oplus 3\%.$
  - https://arxiv.org/pdf/2308.10478.pdf

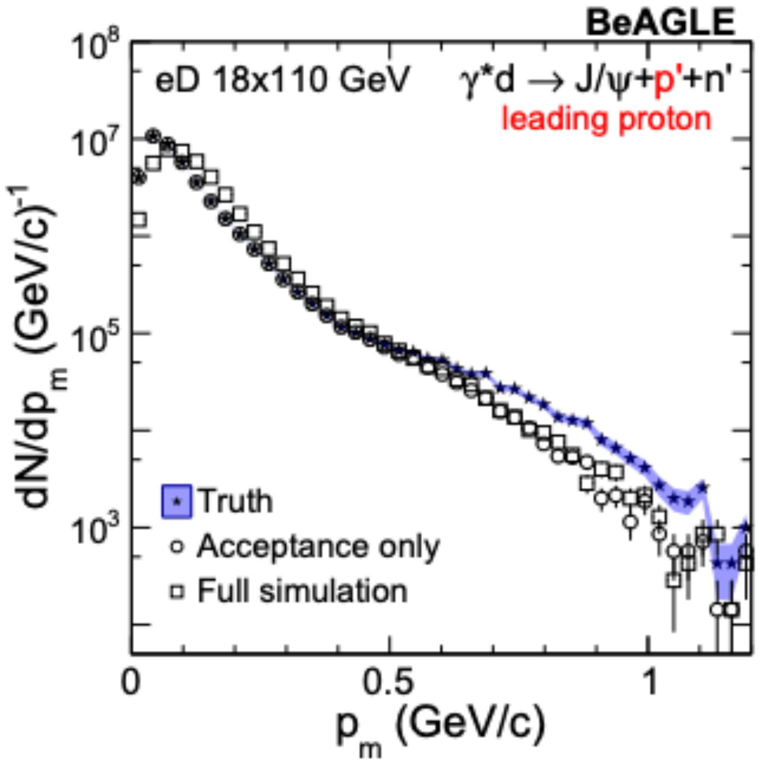
Single Neutrons

From: Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, 811 (2020)

- e+d spectator tagging to study short-range correlations.

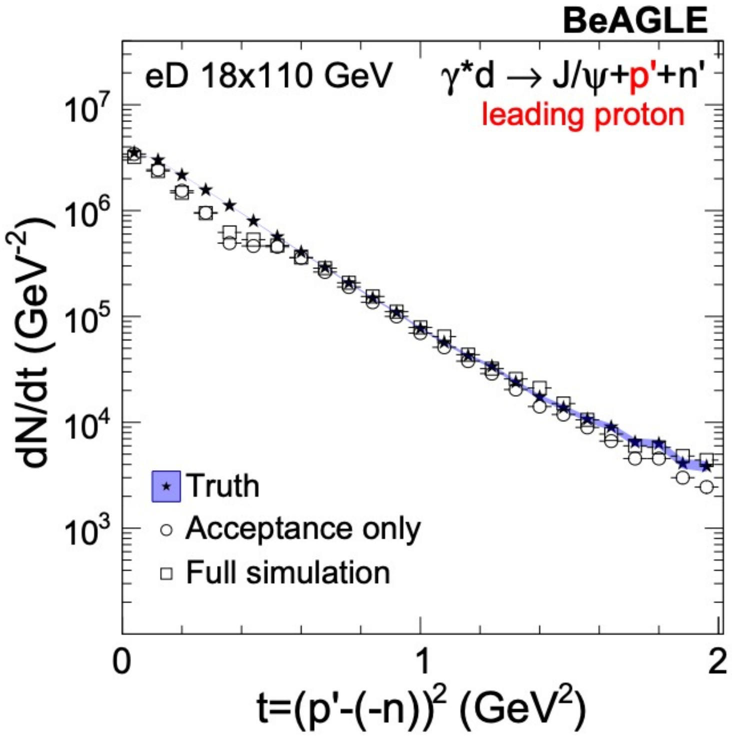


Proton spectator from OMD.



Neutron spectator from ZDC.

Assuming $\frac{\sigma_E}{E} \leq \frac{50\%}{\sqrt{E}} \oplus 5\%$ and $\frac{\sigma_\theta}{\theta} \leq \frac{3\,mrad}{\sqrt{E}}$



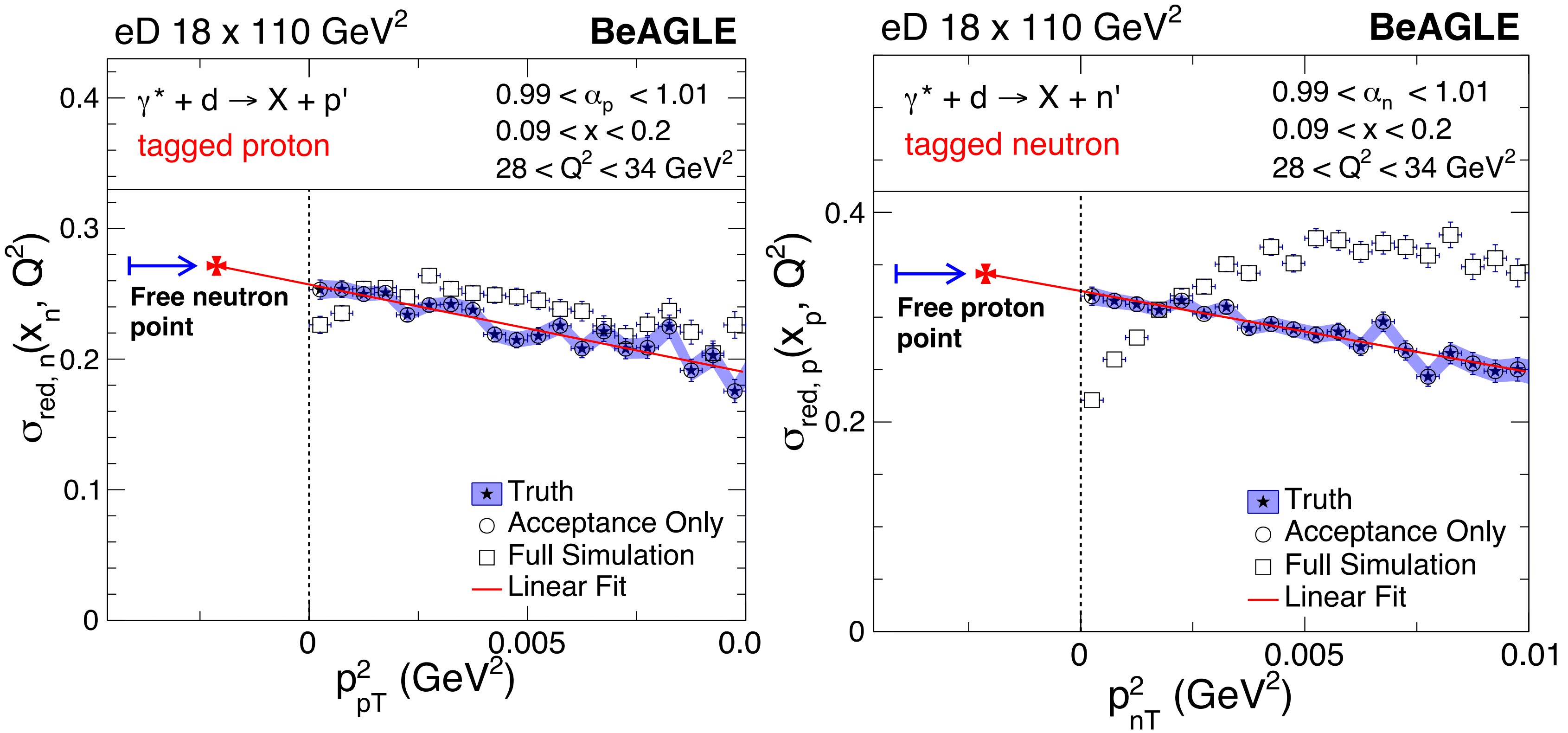
Ultimate goal:

active neutron in ZDC;
proton spectator in OMD

Single Neutrons

From: A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C 104, 065205, (2021)

- e+d spectator tagging to study neutron structure functions → focus on very small angle neutrons near $\theta \sim 0\, mrad$.



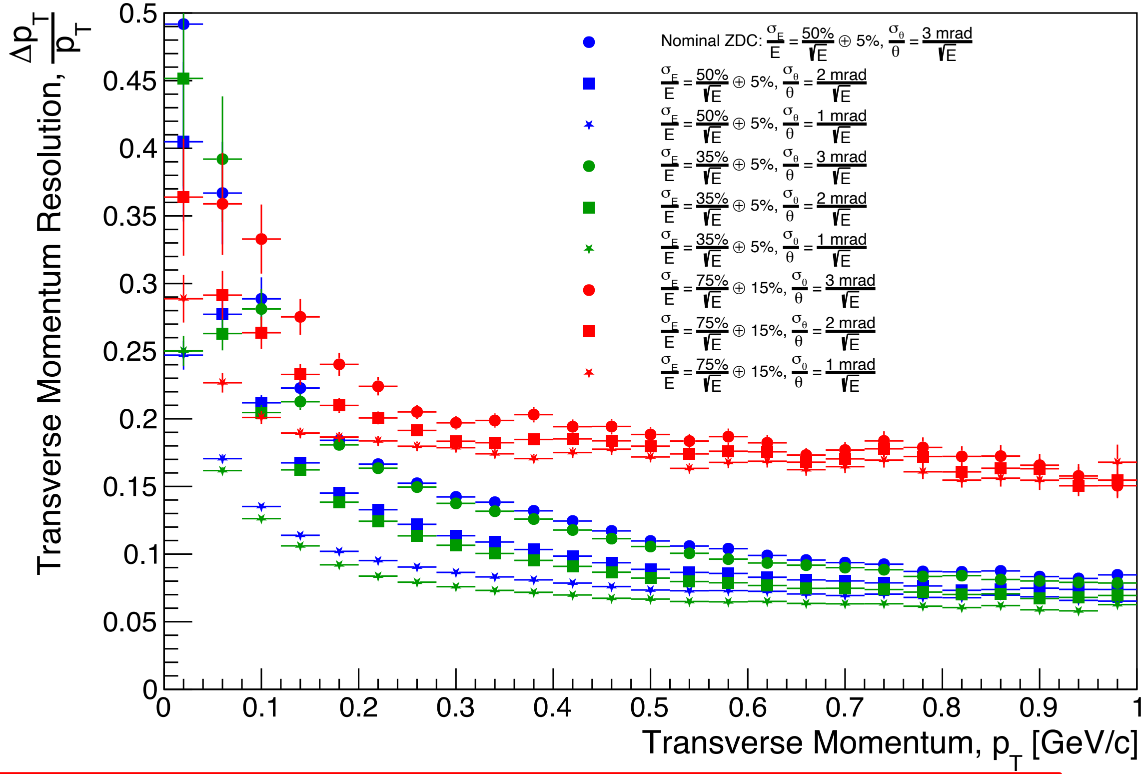
Original ZDC assumptions is problematic here – would benefit from improved neutron energy and angular resolution. → **goal to have smearing on F_2 extraction between proton/neutron spectator at a similar level.**

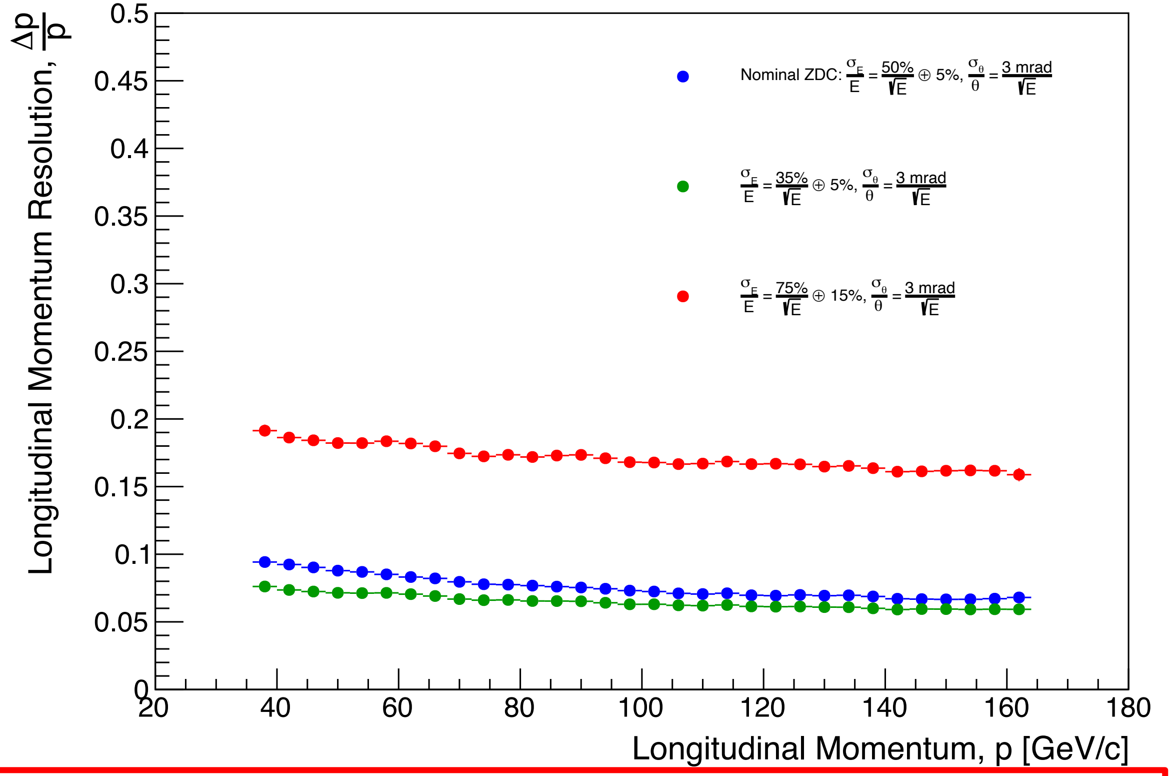
Proton spectator from OMD. → **Neutron F_2**

Neutron spectator from ZDC. → **Proton F_2**

Assuming $\frac{\sigma_E}{E} \leq \frac{50\%}{\sqrt{E}} \oplus 5\%$ and $\frac{\sigma_\theta}{\theta} \leq \frac{3\, mrad}{\sqrt{E}}$

Single Neutrons





- If energy resolution is too poor, better spatial/angular resolution does very little to improve pT-resolution.
  - ➢ **Need minimum $\frac{\sigma_E}{E} \leq \frac{50\%}{\sqrt{E}} \oplus 5\%$**

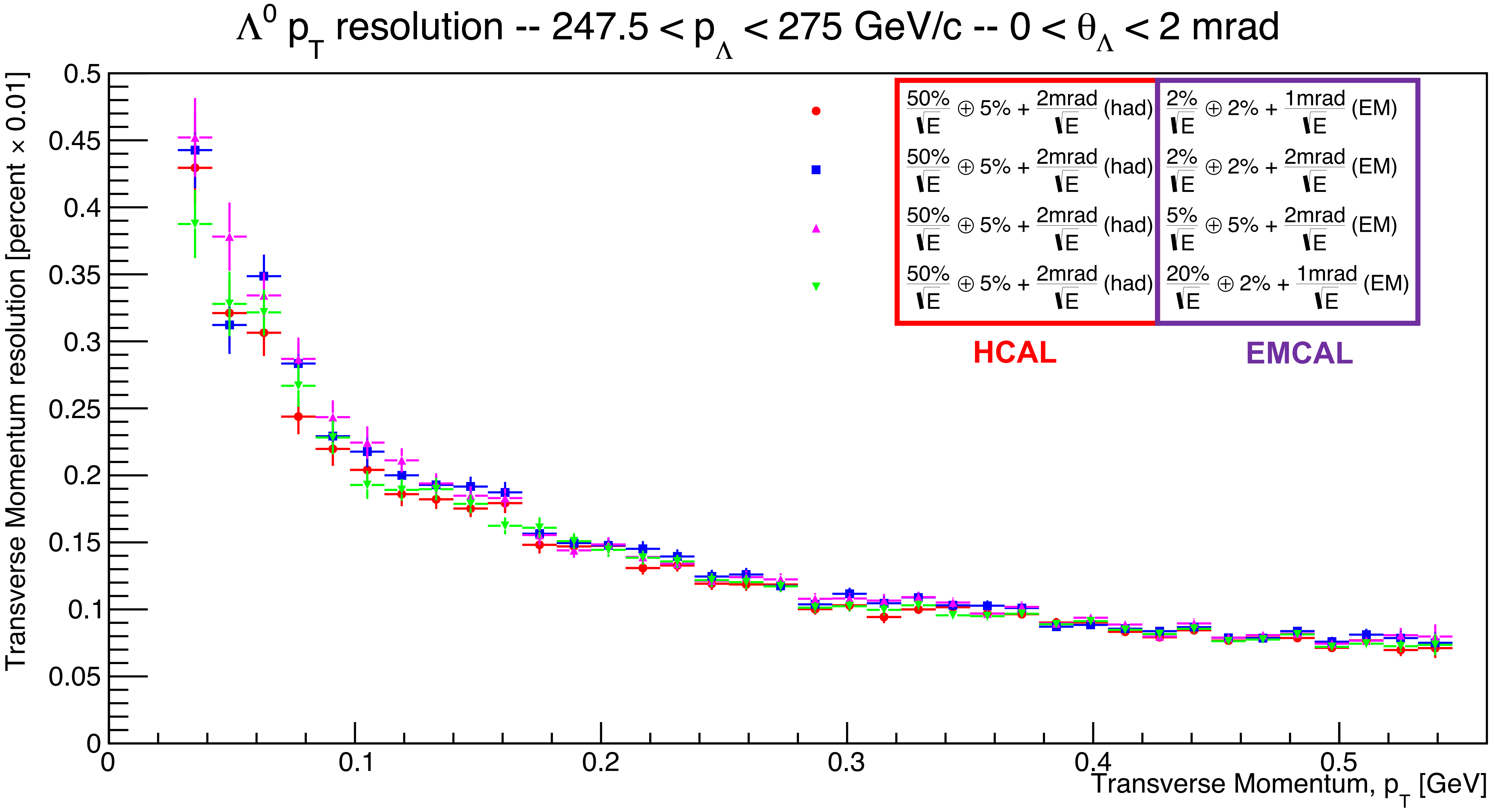
To get pT resolution competitive with the tagged-proton case would require $\frac{\sigma_\theta}{\theta} \leq \frac{2\ mrad}{\sqrt{E}}$

Very little difference between $\frac{\sigma_E}{E} \leq \frac{50\%}{\sqrt{E}} \oplus 5\%$ and $\frac{\sigma_E}{E} \leq \frac{35\%}{\sqrt{E}} \oplus 5\%$ → Improved constant term has small effect.

A very challenging case for the FULL ZDC: $\Lambda^0 \longrightarrow n + \pi^0$

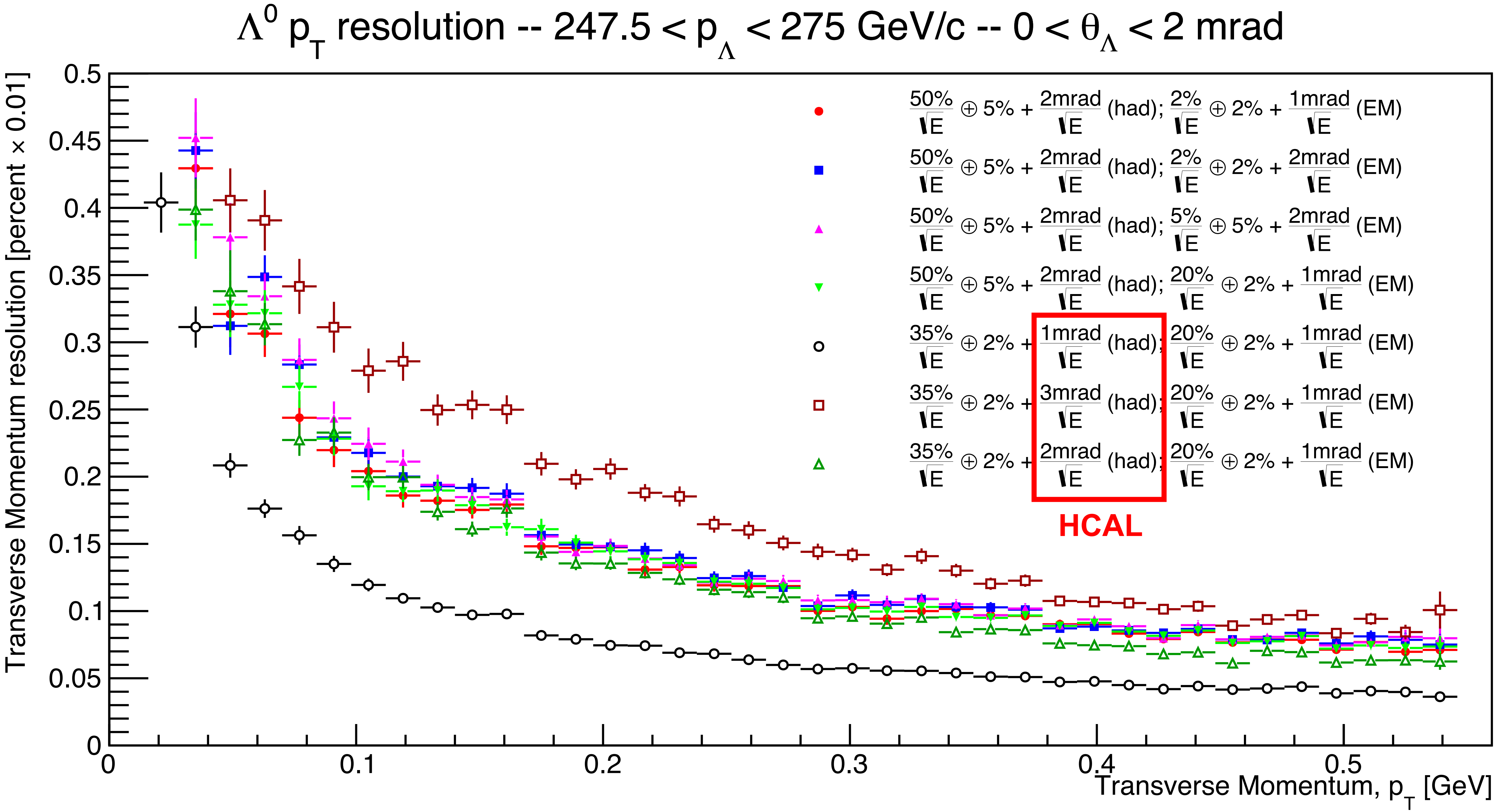
- Using particle gun to rule out any issues with generator:
  - Sample I had on-hand was with crossing angle with wrong sign.
- Shooting Λ^0 with:
  - 247.5 < p < 275 GeV (90% beam energy to 100%).
  - $0 < \theta < 2$ mrad
- GEANT handles the decay → confirmed proper branching fractions:
  - $\Lambda^0 \rightarrow p + \pi^- \ (\sim 67\%)$
  - $\Lambda^0 \rightarrow n + \pi^0 \rightarrow \gamma\gamma \ (\sim 33\%)$
- Particles shot through magnets for proper aperture, but with beampipe “off” and no real ZDC – just using for acceptance.
  - Acceptance of $\Lambda^0 \rightarrow n + \pi^0 \rightarrow \gamma\gamma$ in this study is around ~65%.
- Smearing applied “by-hand” and ignoring reconstruction itself – only looking at effect of resolution assumptions for energy and angle.
  - Specifically, $n\gamma\gamma$ final-states which successfully arrive at the ZDC have their MC truth vectors smeared by various energy/angular resolution values → **assumes nothing about *how* the reconstruction is carried-out.**
- **Note:** This study does not answer the question of what Λ^0 p_T (which leads to the Kaon t) resolution is ***required***, just how this depends on the energy and angular resolutions of the ZDC

Results



Λ0 pT resolution -- 247.5 < pΛ < 275 GeV/c -- 0 < θΛ < 2 mrad
50%/√E ⊕ 5% + 2mrad/√E (had)
2%/√E ⊕ 2% + 1mrad/√E (EM)
50%/√E ⊕ 5% + 2mrad/√E (had)
2%/√E ⊕ 2% + 2mrad/√E (EM)
50%/√E ⊕ 5% + 2mrad/√E (had)
5%/√E ⊕ 5% + 2mrad/√E (EM)
50%/√E ⊕ 5% + 2mrad/√E (had)
20%/√E ⊕ 2% + 1mrad/√E (EM)
HCAL
EMCAL
Transverse Momentum resolution [percent × 0.01]
Transverse Momentum, pT [GeV]
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0
0.1
0.2
0.3
0.4
0.5

Results



Λ^0 p_T resolution -- 247.5 < p_Λ < 275 GeV/c -- 0 < θ_Λ < 2 mrad
Transverse Momentum resolution [percent × 0.01]
Transverse Momentum, p_T [GeV]
$\frac{50\%}{\sqrt{E}} \oplus 5\% + \frac{2mrad}{\sqrt{E}}$ (had); $\frac{2\%}{\sqrt{E}} \oplus 2\% + \frac{1mrad}{\sqrt{E}}$ (EM)
$\frac{50\%}{\sqrt{E}} \oplus 5\% + \frac{2mrad}{\sqrt{E}}$ (had); $\frac{2\%}{\sqrt{E}} \oplus 2\% + \frac{2mrad}{\sqrt{E}}$ (EM)
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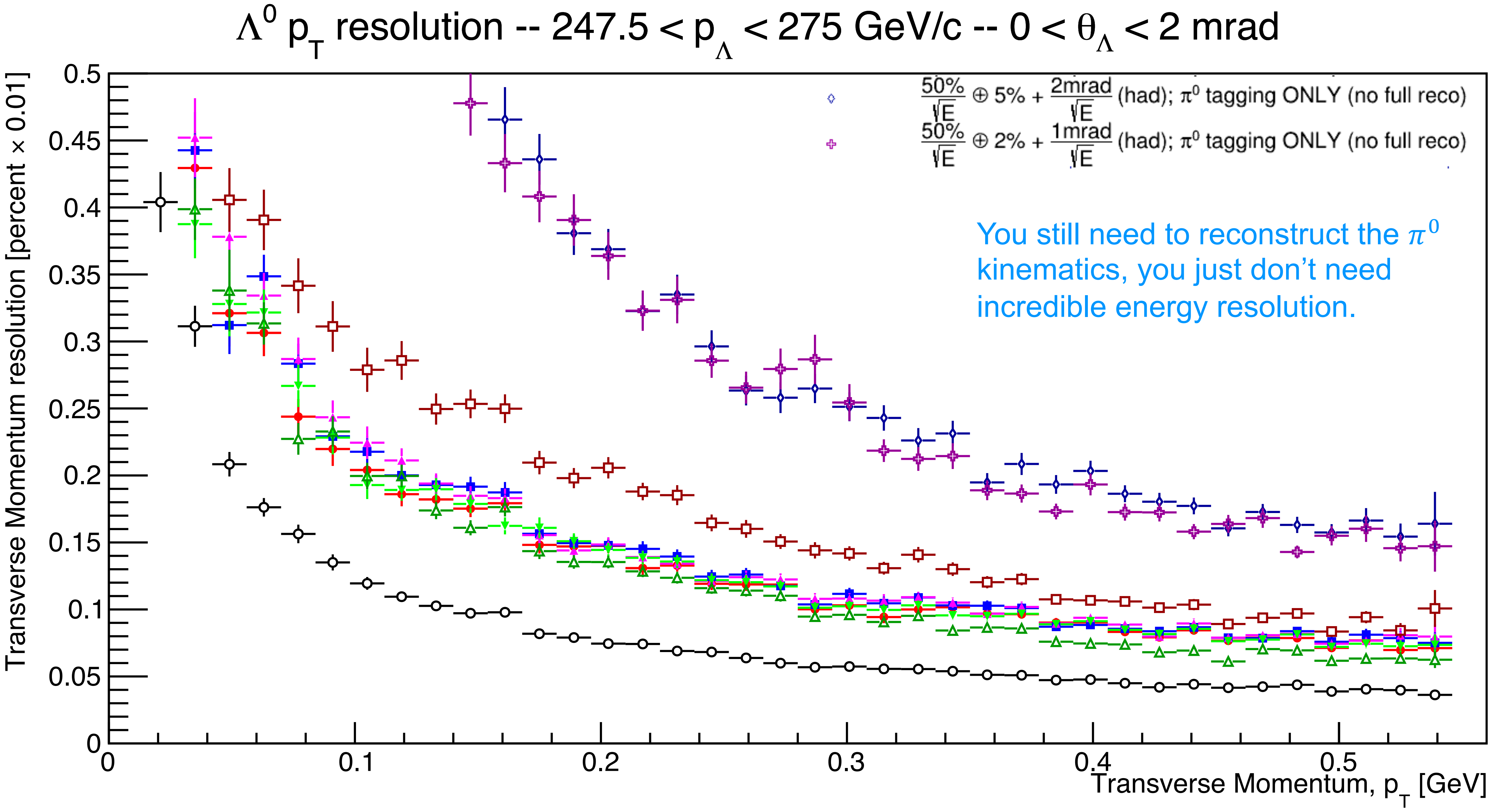
$\frac{35\%}{\sqrt{E}} \oplus 2\% + \frac{3mrad}{\sqrt{E}}$ (had); $\frac{20\%}{\sqrt{E}} \oplus 2\% + \frac{1mrad}{\sqrt{E}}$ (EM)
$\frac{35\%}{\sqrt{E}} \oplus 2\% + \frac{2mrad}{\sqrt{E}}$ (had); $\frac{20\%}{\sqrt{E}} \oplus 2\% + \frac{1mrad}{\sqrt{E}}$ (EM)
HCAL

Results



You still need to reconstruct the π^0 kinematics, you just don't need incredible energy resolution.

Initial Conclusions

- Performance for neutron reconstruction plays the **dominant** role in Λ^0 reconstruction.
  - Results do not indicate that 20cm long PbWO4/LYSO crystals are *needed* for reconstruction of the Λ^0 (via the $\pi^0 \rightarrow \gamma\gamma$).
- Angular resolution plays the dominant role in p_T reconstruction.
  - This is clear from the results on the neutron, where the angular resolution is more-important than the energy resolution (in the limit that E resolution is already quite good for an HCAL).
- You still need to **reconstruct** the kinematics of the $\pi^0 \rightarrow \gamma\gamma$ decay.

Important Discussion/Considerations

- *How* do we carry-out the reconstruction?
  - We *do not* a priori know the vertex for the Λ^0 decay → this causes a problem for reconstructing the π^0.
    - **For crystals:** We will know the positions with ~1-2mm resolution, but we will ***not*** have the angular information needed to measure the 4-vector (cannot assume photons originate at IP).
    - **For imaging via SiPM-on-Tile:** We have enough information about the spatial extent of the showers to extract the incident angle of the photons on the EMCAL → this will enable full 4-vector reconstruction of the π^0 **(but how good will it be??).**

Some options to consider

1. **20cm long crystals + SiPM-on-Tile:**
   - E-resolution is very good, but we lose the benefit of the SiPM-on-Tile for the shower angles for photons.
   - This study indicates very high energy resolution for photons *not required.*
   - 20cm long crystals mean ~ full absorption of photon energy, and loss of angular information needed to fully reconstruct the π^0, and therefore to fully reconstruct the Λ^0.

PbWO4 radiation length: ~ 0.92cm
LYSO radiation length: ~ 1.1cm

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2. **~10cm long crystals + SiPM-on-Tile:**
   - Crystals can act as a sort of "pre-shower", while still enabling usage of the information in the SiPM-on-Tile.
   - Crystals still usable to tag events with low-energy photons (e.g. e+A incoherent).
   - **How well will this really work? A study is needed here!**

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Some options to consider

1. 20cm long crystals + SiPM-on-Tile:

- E-resolution is very good, but we lose the benefit of the SiPM-on-Tile for the shower angles for photons.
- This study indicates very high energy resolution for photons *not required.*
- 20cm long crystals mean ~ full absorption of photon energy, and loss of angular information needed to fully reconstruct the π^0, and therefore to fully reconstruct the Λ^0.

2. ~10cm long crystals + SiPM-on-Tile:

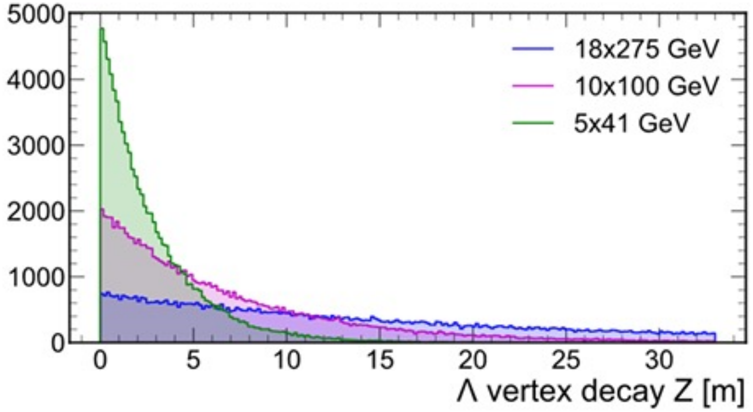
- Crystals can act as a sort of “pre-shower”, while still enabling usage of the information in the SiPM-on-Tile.
- Crystals still usable to tag events with low-energy photons (e.g. e+A incoherent).
- **How well will this really work? A study is needed here!**

3. SiPM-on-Tile ONLY:

- Allows best option for angular reconstruction of shower.
- *Might* lose low-E photon capability (need to show it works with SiPM-on-Tile **only**).
- Potentially more-difficult hadronic/EM shower separation.

PbWO4 radiation length: ~ 0.92cm
LYSO radiation length: ~ 1.1cm

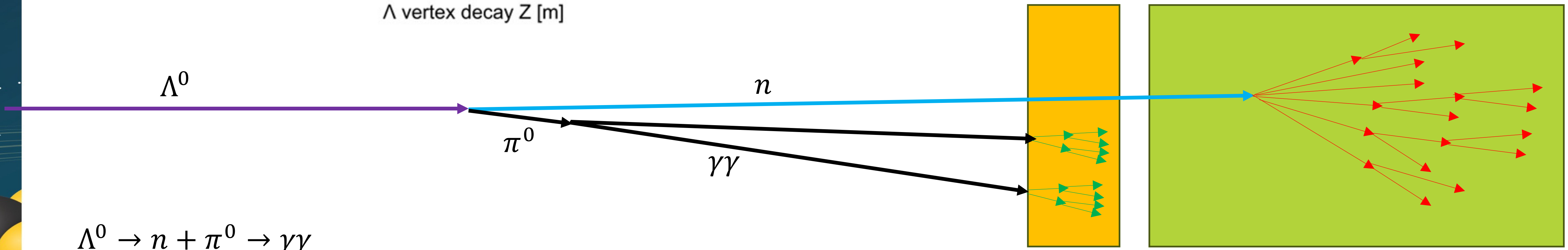
Pictorial view of neutral decay into ZDC



From: J Arrington *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* **48** 075106

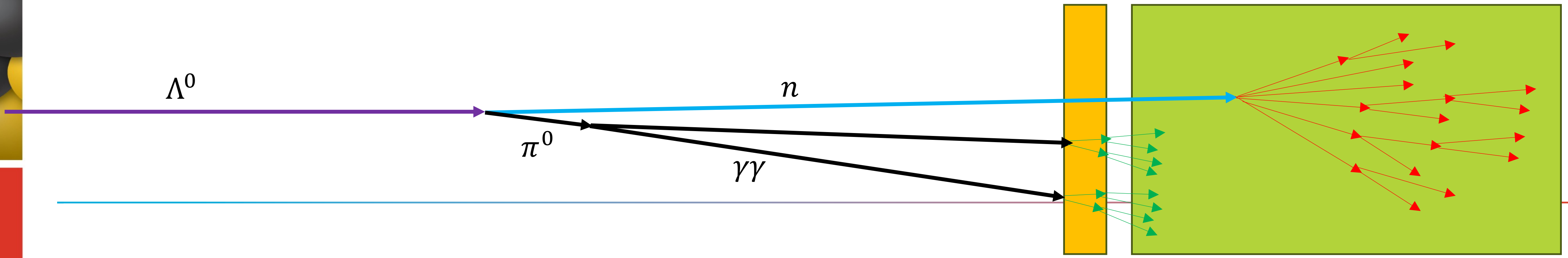
Yellow: crystal EMCAL
Blue: SiPM-on-Tile

Current configuration



$\Lambda^0 \rightarrow n + \pi^0 \rightarrow \gamma\gamma$

Shorter crystals

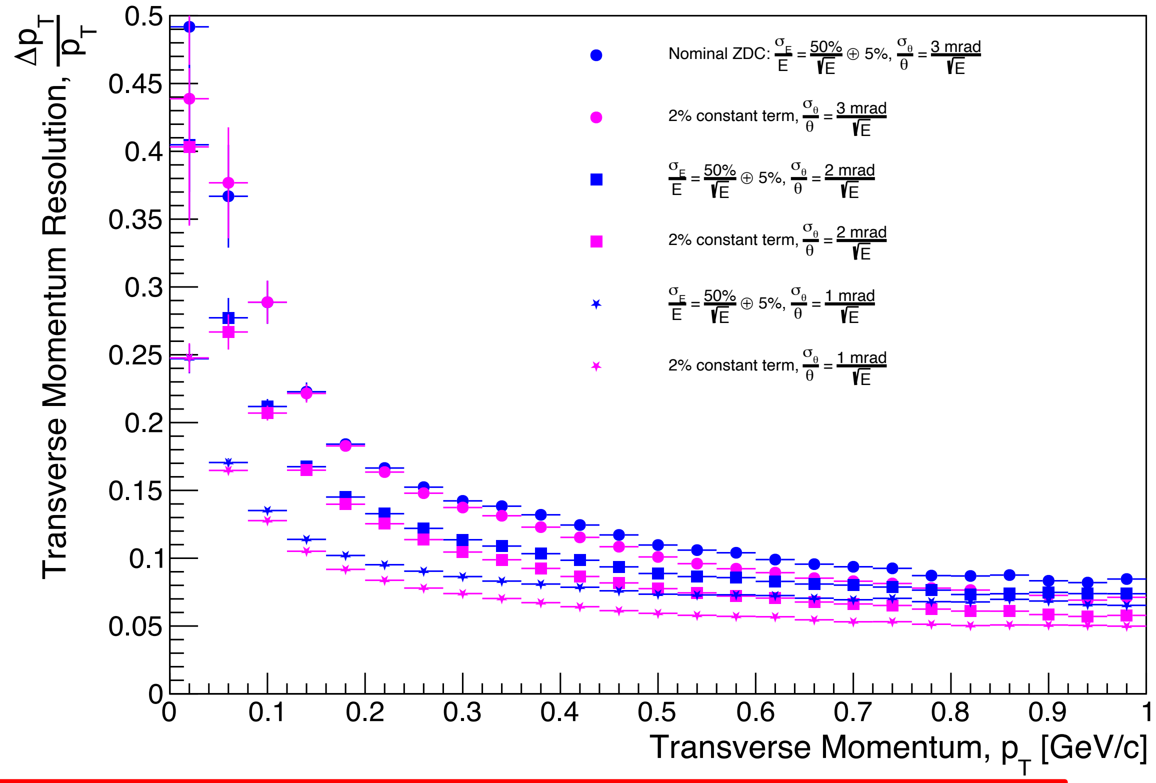


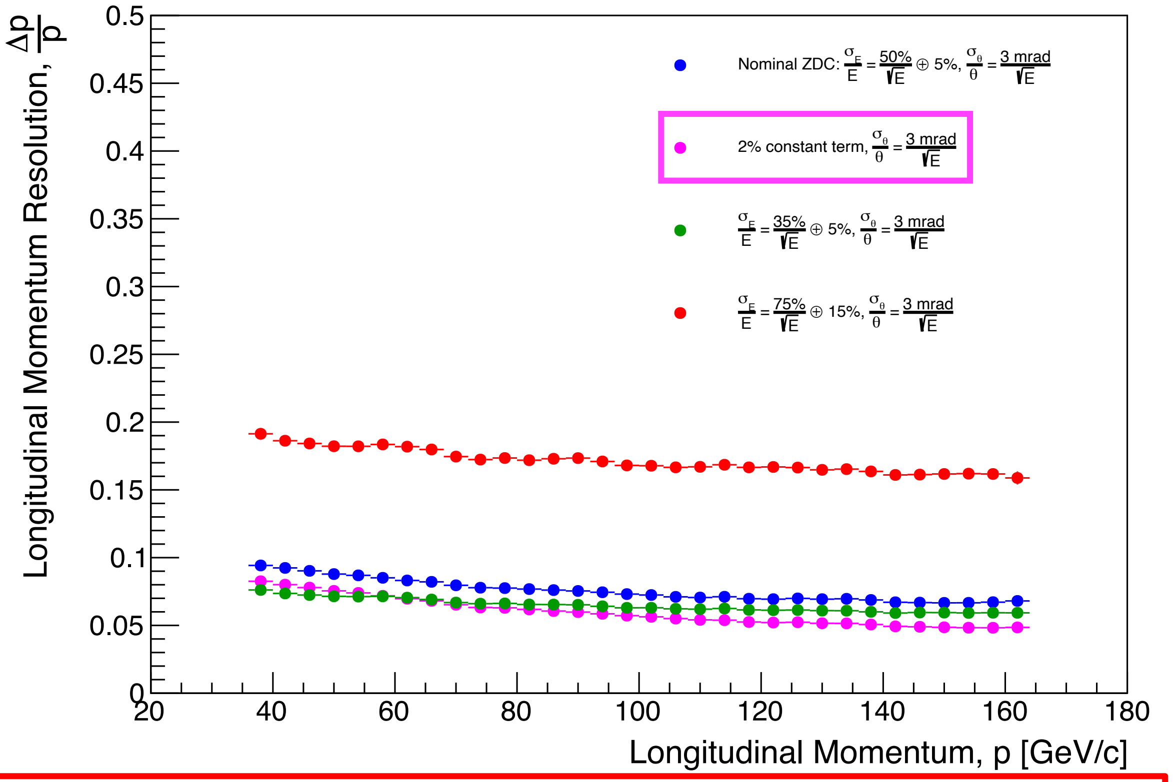
Conclusions

- ZDC requirements have evolved as understanding and priority of measurements has solidified.
  - High energy resolution **better** than $\frac{\sigma_E}{E} \leq \frac{50\%}{\sqrt{E}} \oplus 5\%$ always assumed.
- Dynamic range of EMCAL a clear challenge → ~100 MeV photons from e+A "quasi-coherent" reactions; ~ 10-100 GeV photons possible from other exclusive processes (lambda decay, u-channel DVCS)
- **ZDC implementation would benefit from a creative approach** – potentially non-static configuration which can be "changed" for different running conditions.
  - **Crystal EMCAL need depends on physics channel – some level of conflict in the final states & associated requirements.**
  - Having the ability to bring the EMCAL in/out of configuration, as needed, would provide clear benefit to specific physics needs.
- **Angular resolution** is a common thread – this was less-emphasized early-on, an **absolute requirement for successful exclusive physics program**.

Backup

Single Neutrons (better constant term)





- If energy resolution is too poor, better spatial/angular resolution does very little to improve pT-resolution.
  - **Need minimum $\frac{\sigma_E}{E} \leq \frac{50\%}{\sqrt{E}} \oplus 5\%$**

To get pT resolution competitive with the tagged-proton case would require $\frac{\sigma_\theta}{\theta} \leq \frac{2\ mrad}{\sqrt{E}}$

Very little difference between $\frac{\sigma_E}{E} \leq \frac{50\%}{\sqrt{E}} \oplus 5\%$ and $\frac{\sigma_E}{E} \leq \frac{35\%}{\sqrt{E}} \oplus 5\%$ → Improved constant term has small effect.