CFNS Workshop on a Second EIC Detector
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Stony Brook University

Exclusive Scattering on Nuclei

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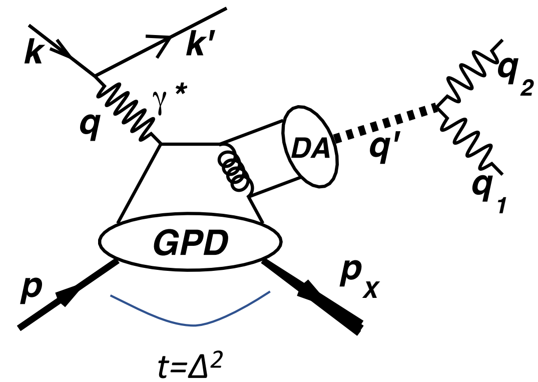
Spatial Properties of the Nucleon



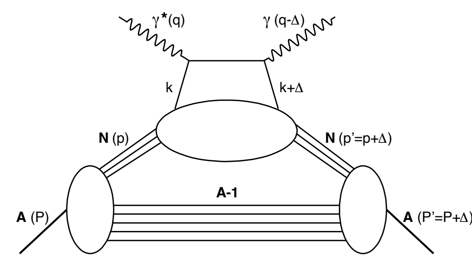
- 1+2 dimensional tomography
  - $q(x,b) - \bar{q}(x,b)$,
  - $q(x,b) + \bar{q}(x,b)$,
  - $G(x,b)$
- Longitudinal momentum *x* determined by (e,e') kinematics
- Transverse momentum transfer $\Delta_\perp$ Fourier-conjugate to impact parameter **b**
- No reason to suppose common spatial distributions
  - Pion cloud concept implies $q + \bar{q}$, spatially broader than $q - \bar{q}$
  - Gluon radius of proton?
  - "Proton radius = $\sqrt{\int b^2[q(x,b) - \bar{q}(x,b)]dx}$

Exclusive scattering on the Nucleon

- $eN \rightarrow eN\gamma$
- $eN \rightarrow eNV$, $V = \rho^0, \phi, J/\Psi$, …etc.
- No direct measurement of q(x,**b**), but strong constraints, (dispersive integrals, etc.)
- Flavor sensitivity (u,d,s) from
  - $ep \rightarrow ep\gamma$ vs. $en \rightarrow en\gamma$
  - $ep \rightarrow ep\,\rho^0$ vs. $ep \rightarrow en\rho^+$ or $ep \rightarrow ep\omega$
  - $ep \rightarrow eK^+\Lambda$
- Quark vs. Gluon sensitivity
  - $ep \rightarrow ep\gamma$,
  - $ep \rightarrow ep\phi$,
  - $ep \rightarrow ep\, J/\Psi$

Exclusive Scattering on Nuclei

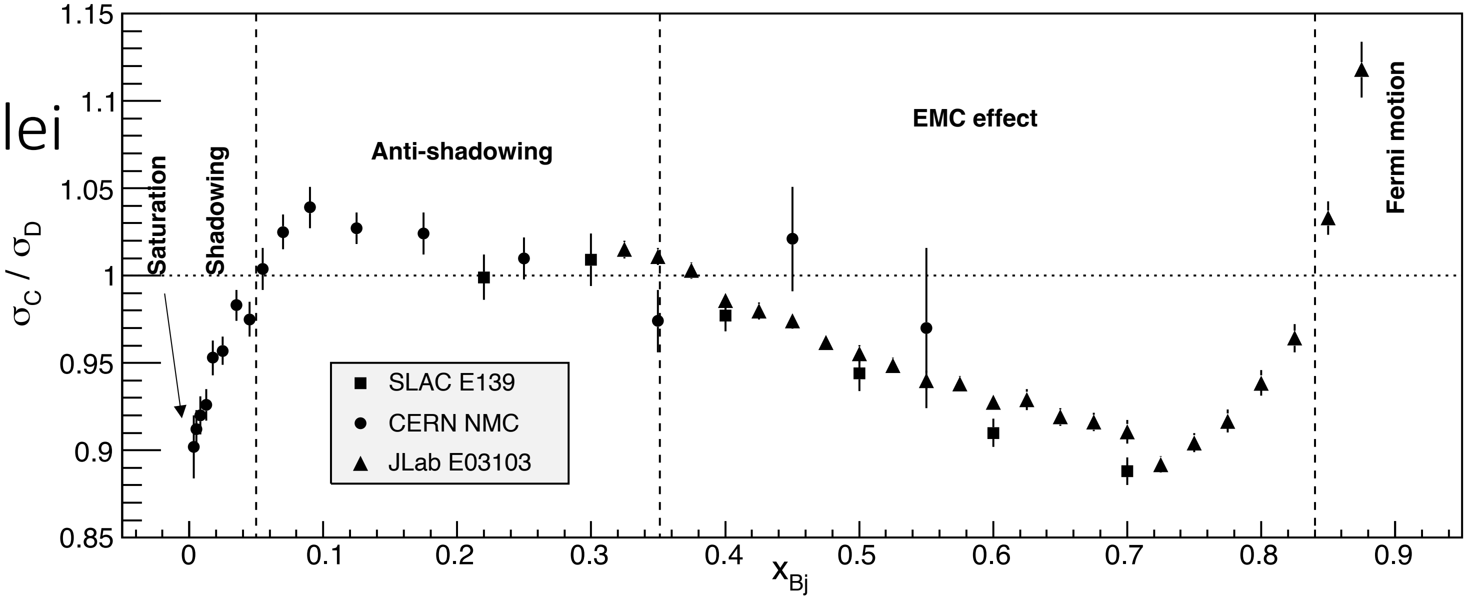
- $e\,{}^{Z}A \rightarrow e\,{}^{Z}A\gamma$, $e\,{}^{Z}A \rightarrow e\,{}^{Z}A\phi$, $e\,{}^{Z}A \rightarrow e\,{}^{Z}AJ/\Psi$, *etc.*
- Convolution of nucleon spectral functions in nuclei with nucleon GPDs
  - R.Dupre, S.Scopetta EPJA **52** (2016) 159 →
  - S.Fucini, S.Scopetta, M. Viviani, PRC **98** (2016) 015203
    - TOPEG Event generator
  - S. Liuti, S. Taneja, PRC **72** (2005) 034902.
  - V. Guzey, arXiv.org:0907.4124 [hep-ph]



Nuclei as quark-gluon structures

- Effects are not necessarily small
- Nuclear Hadrodynamics:
  - Relativistic N, ρ, ω, σ, π fields;
  - Proton mass modified in nuclear medium by ≈ factor of 2!
- Nuclear Effects vary with flavor (q, g) and with momentum (x).
  - Some non-nucleon dynamics in S. Liuti, S. Taneja, PRC **72** (2005) 034902

Quark-Gluon Structure of Nuclei



- EMC, Anti-shadowing, Shadowing, Saturation to be studied at EIC with Jets, SIDIS, TMDs, etc
  - Phenomenology suggest anti-shadowing is primarily glue.
- Exclusive scattering has an important role to play
- Shadowing is the reference against which we must assess signals of Saturation.
- Spectator tagging on *d,* ^{3}He, *etc* provides a reference "nearly on-shell" neutron, **and** enables the study of medium effects in those same nuclei

Challenges of Exclusive Scattering

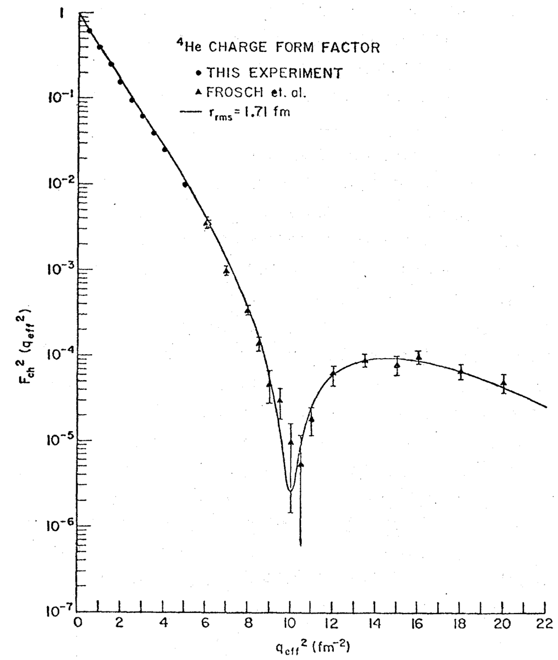
- Exclusivity
  - Recoil nucleus lost in 10σ beam envelope
  - Need near hermetic veto on inelastic/break-up channels
    - Forward p, n, even γ
      - 3-layer ZDC: High resolution PreCAL of ~$5X_0$ for photons < 100 MeV
      - $20X_0$ EMCal for high energy gammas,
      - HCal for neutrons
    - Daughter nuclei: Rigidity $K = P_A/Q_A$
      - Secondary focus extends tag/veto to $|1-K'/K_0| \geq 0.01$
        Resolves $\Delta A \geq 1$ up to Zr and $\Delta A \geq 2$ up to Pb.
- Momentum transfer Δ^μ resolution
  - Nuclear size $\sim$ (1 fm) $A^{1/3}$ ➔ Diffractive minima at $\sim 0.2\text{GeV}/A^{1/3}$
  - Medium to heavy nuclei, beam momentum spread is $\geq 0.2\text{GeV}/A^{1/3}$

Exclusivity Tagging or Inclusive Veto?

- Proton, 275 GeV
  - Maximal luminosity tune
    - Beam rms $p_{\perp}$ at IP = 0.040 GeV/c
    - 10σ beam envelope = 0.400 GeV/c
  - Maximal acceptance tune
    - 10σ beam envelope ≈ 0.200 GeV/c
  - IP-6 Acceptance for exclusivity tag of final state proton:
    - $p_{\perp} \geq 0$ for $x_B \geq 0.1$
    - $p_{\perp} \geq (87\%)(10\sigma)$ for $x_B \geq 0.05$
    - $p_{\perp} \geq (97\%)(10\sigma)$ for $x_B \geq 0.025$
  - IP-8 with secondary focus: factor of 10 improvement vs x_B
    - $p_{\perp} \geq 0$ for $x_B \geq 0.01$
    - $p_{\perp} \geq (87\%)(10\sigma)$ for $x_B \geq 0.005$
    - $p_{\perp} \geq (97\%)(10\sigma)$ for $x_B \geq 0.0025$

Nuclear Exclusivity

- 4He P = 137.5 GeV per nucleon
  - Beam envelope: *10σ in $P_\perp$(He) ≈ 1.2* GeV/*c*
  - First Diffractive minimum in ^{4}He ≈ 0.6 GeV/c
- Veto breakup channels in all nuclei ≥ ^{4}He

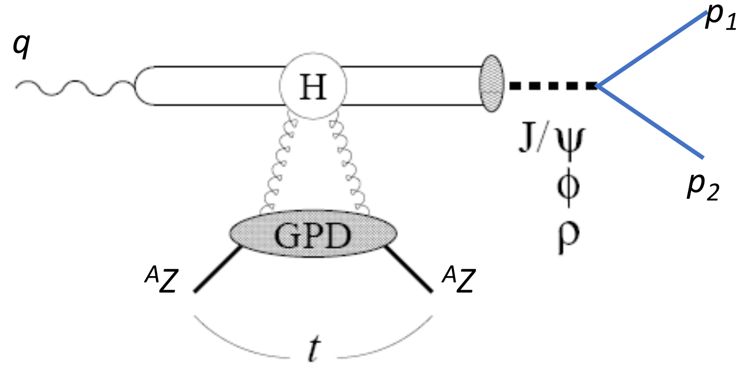


Incoherent / Inelastic tag/veto

- Ejected nucleons, nuclear fragments, residual nuclei
- Spectator or "active" nucleons ejected in incoherent $ep \rightarrow epV$ reactions in nuclei detected in "off-momentum" detectors and ZDC.
  - Approx 20% of nucleons in nuclei have intrinsic momenta > $p_F \approx 0.27$ *GeV/c*
  - In a heavy nucleus with P = 110 GeV/c, this is an emission cone > 2.7 mrad
    - Start to lose acceptance in far-forward trackers and ZDC
- Tag the residual nuclei !
  - Nuclear magnetic rigidity K = (ZP_0) A/Z. (P_0 = storage ring setting for proton)
  - Daughter nucleus $^{A'}Z'$ ➔ K' = (ZP_0) A'/Z'
  - ^{16}O to ^{90}Zr, A-1 daughter nuclei:
    - 1%<|K-K'|/K < 7%
    - **100% tagging with secondary focus proposed for IR-8, 0% tagging in IR-6**

Resolving momentum transfer to nucleus

- Must measure independent of ion beam momentum spread
  - $t = \Delta^2$
  - Measure
    $\Delta^\mu = (q\text{-}q')^\mu = (q - p_1 - p_2)^\mu$

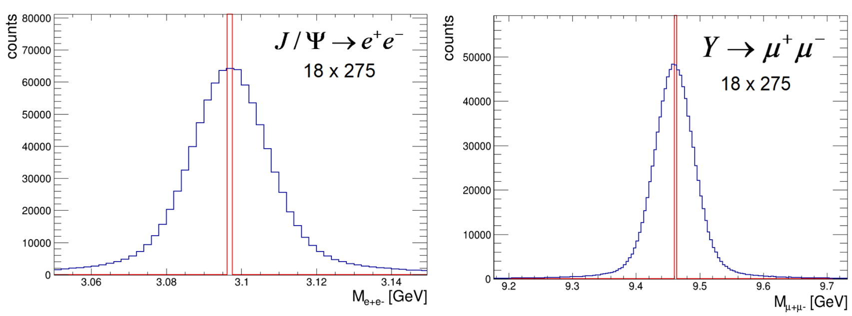


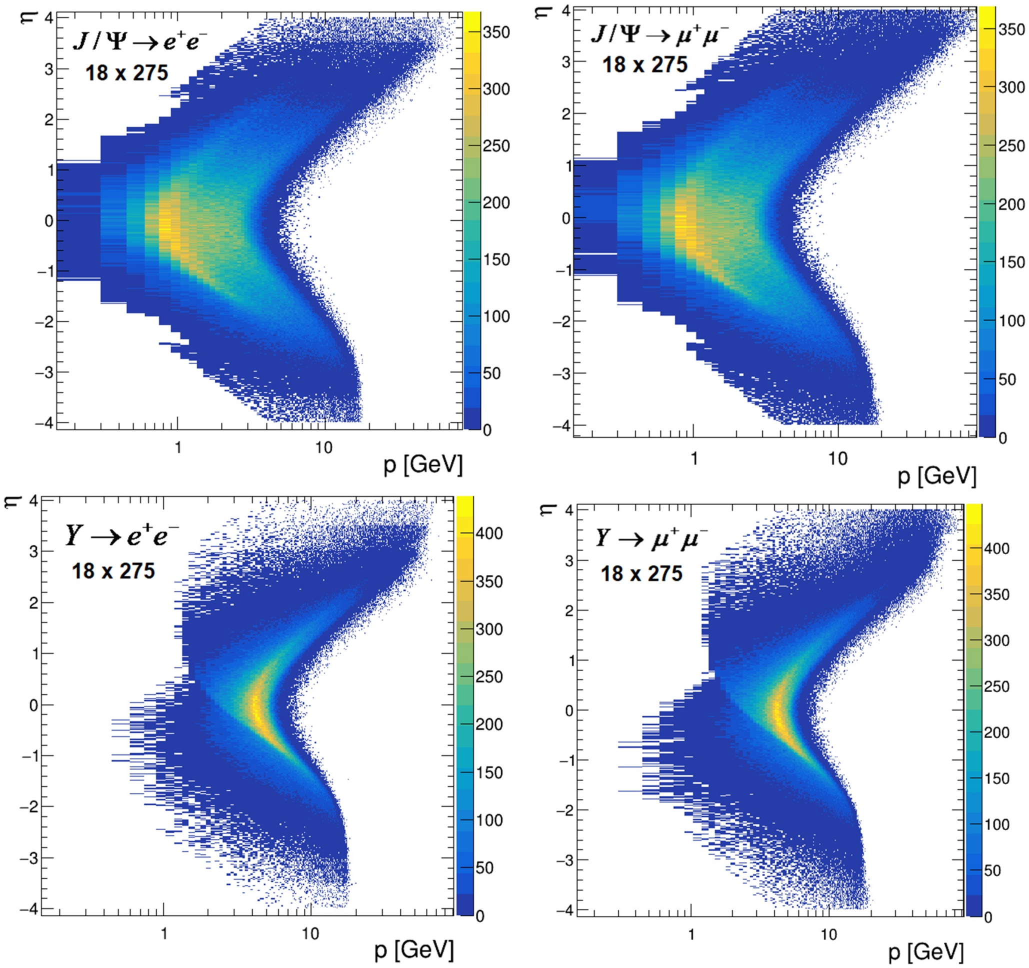
- Vector Mesons
  - Charged particle decays
  - Resolution from tracking.
- Neutral channels require high-resolution EMCal
  - $e\,{}^{Z}A \rightarrow e\,{}^{Z}A\,\gamma$
  - $e\,{}^{Z}A \rightarrow e\,{}^{Z}A\,\omega$

J/Ψ, Υ Production

- STARLIGHT generator: $ep \rightarrow epV$
  - *Cf talk for* Stefan Diehl
- $\mu^{+}\mu^{-}$ channel
  - Doubles statistics;
  - Different systematics;
  - Enables DDVCS without scattered electron coherent interference
    - Cross sections grow at low-x_B

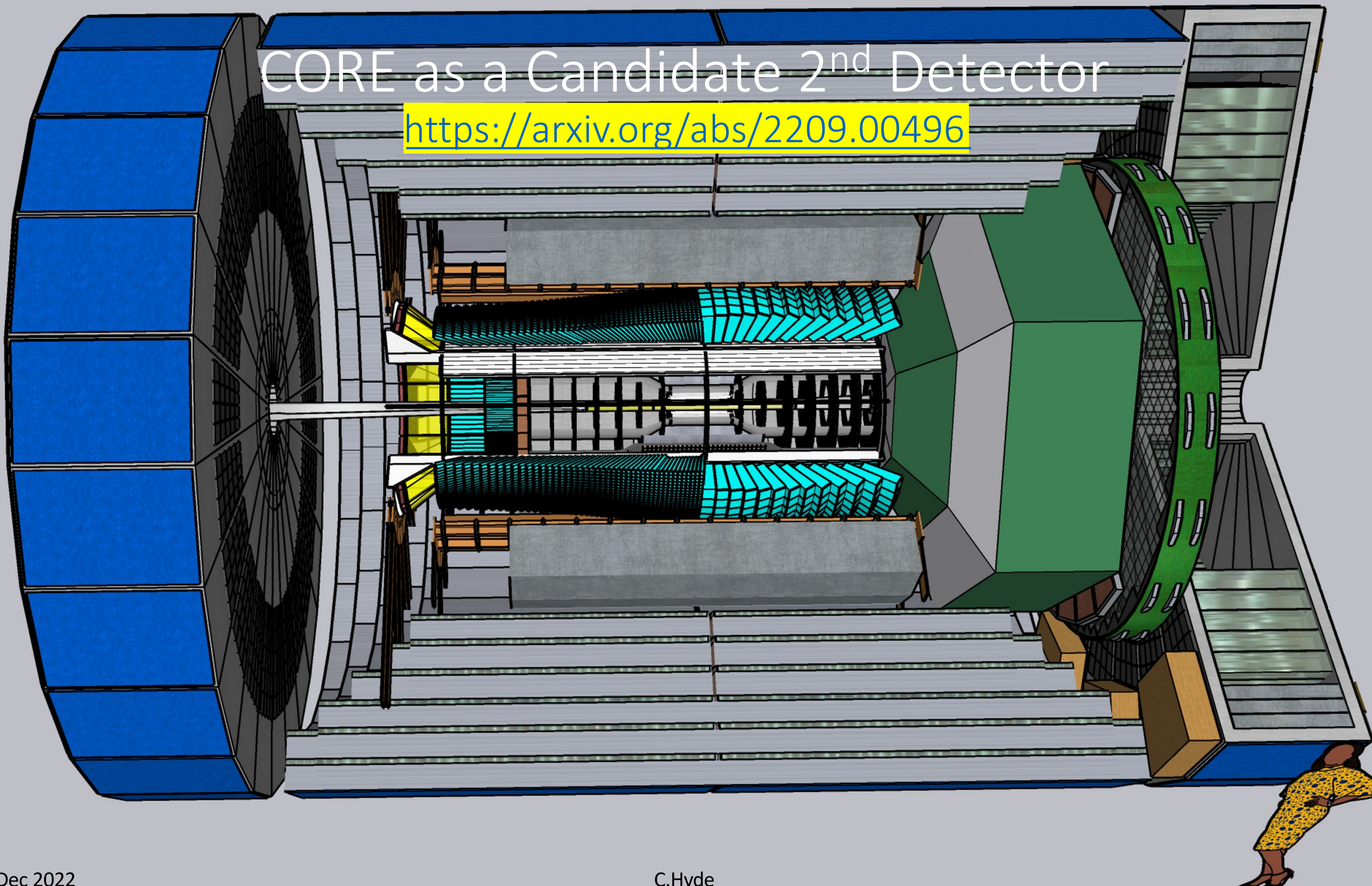
Resolution in CORE





CORE as a Candidate 2nd Detector

https://arxiv.org/abs/2209.00496



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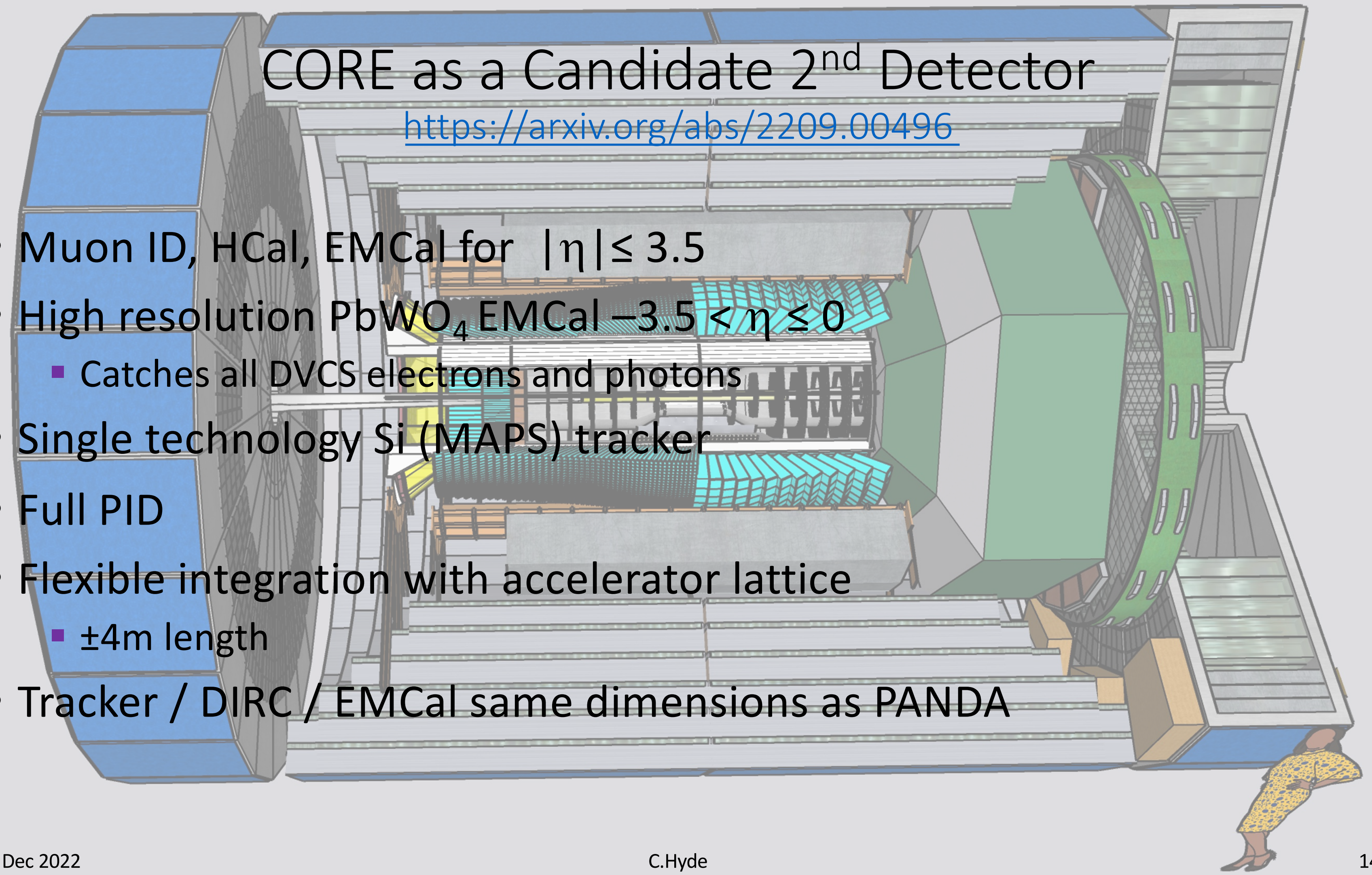
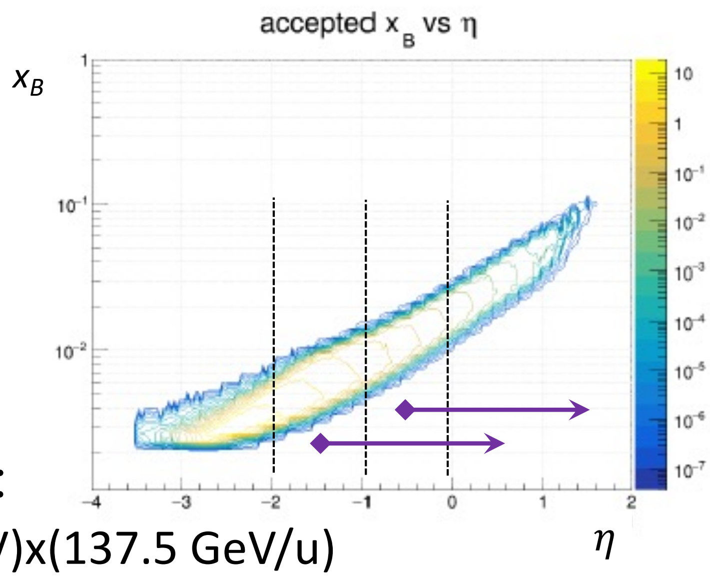
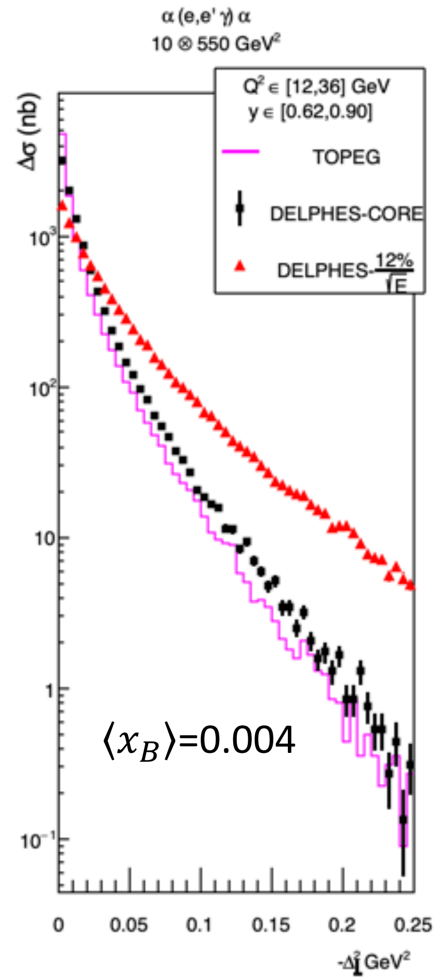


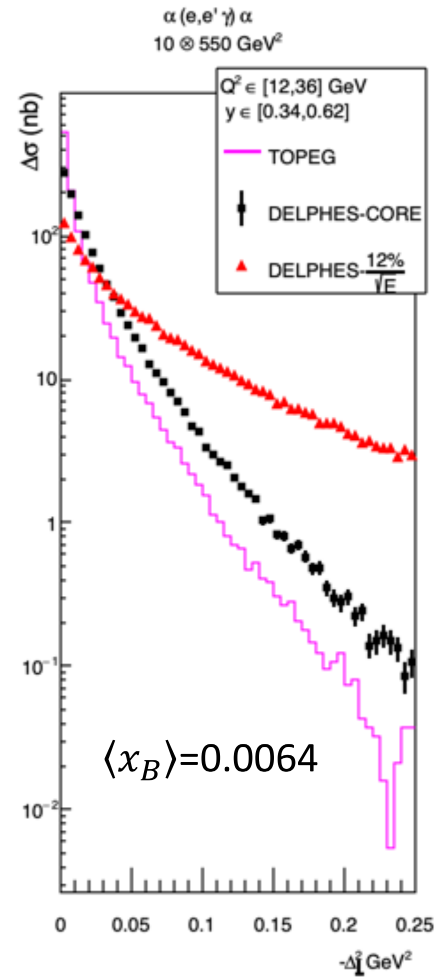
- Muon ID, HCal, EMCal for $|\eta| \leq 3.5$
- High resolution $PbWO_4$ EMCal $-3.5 < \eta \leq 0$
  - Catches all DVCS electrons and photons
- Single technology Si (MAPS) tracker
- Full PID
- Flexible integration with accelerator lattice
  - ±4m length
- Tracker / DIRC / EMCal same dimensions as PANDA

DVCS Bin Migration Comparison



- α(e,e'γ)α:
  - (10 GeV)x(137.5 GeV/u)
  - $Q^2 \in [12,36]$ GeV²
  - Orsay-Perugia (TOPEG) Generator:
    - Event generation by P. Simmerling, UConn
  - $PbWO_4$: $1\% \oplus \frac{2\%}{\sqrt{E}} \oplus \frac{1\%}{E}$
  - EMCal: $\frac{12\%}{\sqrt{E}}$ = Yellow Report
- Bin Migration strongly depends on EMCal resolution.

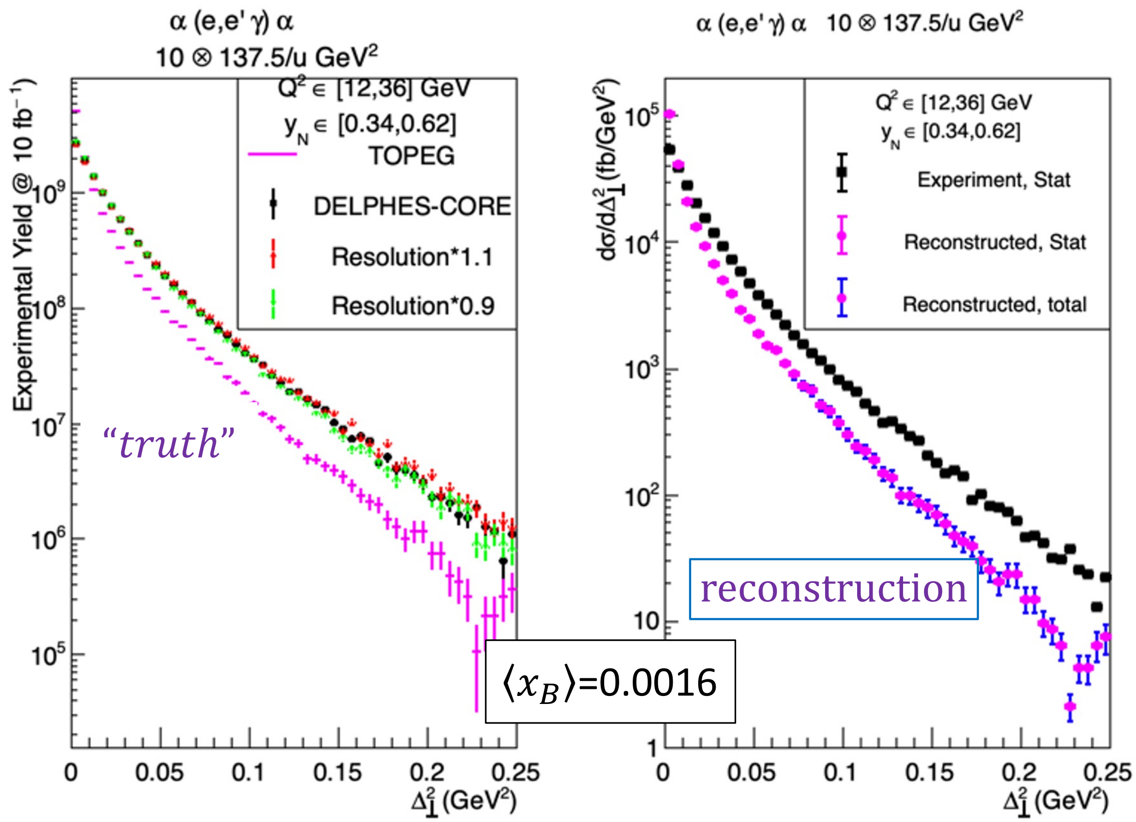




Coherent DVCS on light nuclei. Unfolding the Bin Migration

TOPEG event generator
DELPHES FastMC

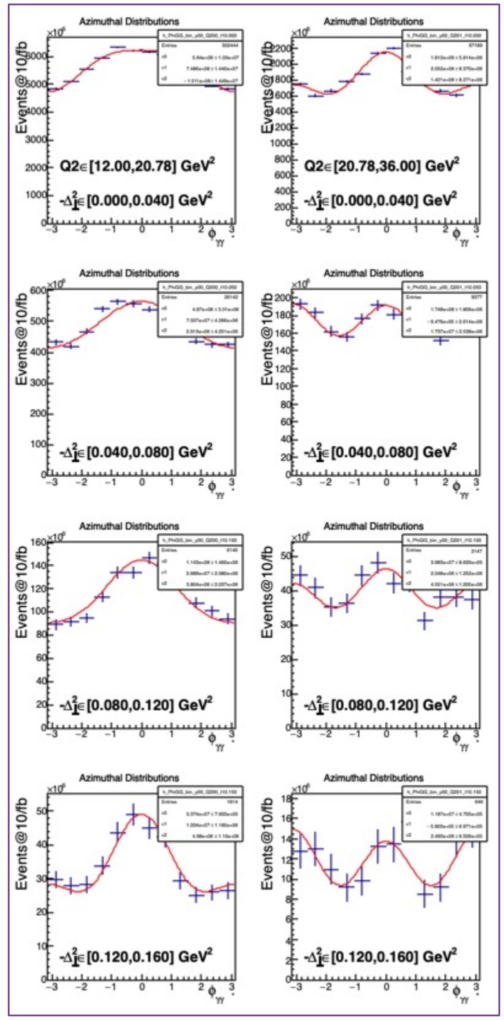
- Systematic uncertainty in reconstructed cross section estimated by varying $PbWO_4$ resolution event-by-event ±10%
- Error bars from uncertainty of bin-migration remain small.



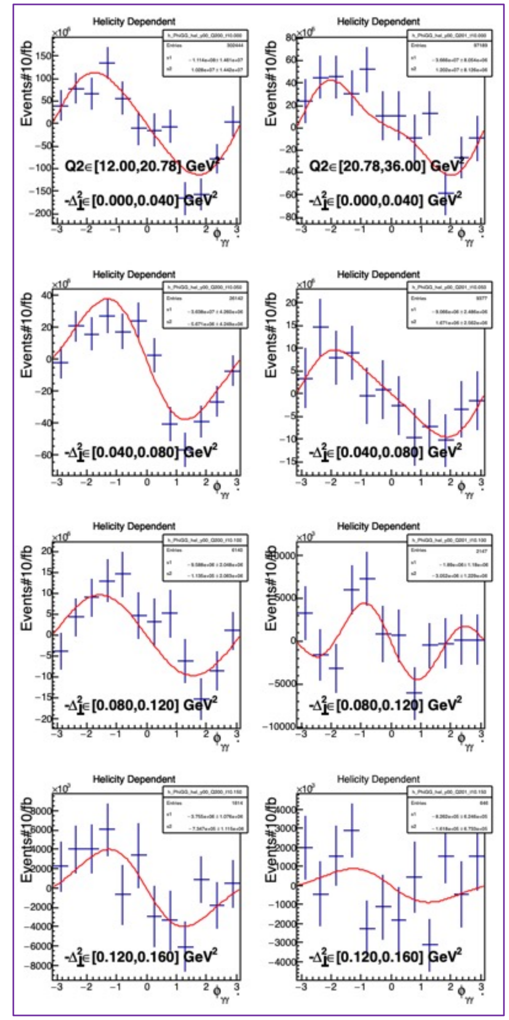
Example Azimuthal Distributions: $\alpha(e, e'\lambda)\alpha$

- (10 GeV)x(137.5 GeV/u)
- $y \in [0.62,0.90]$
- $\langle x_B \rangle \approx 0.004$
- Projected counts at 10/fb/nucleus
- Error bars are MC, (not data) statistics!
- Fits are simple Fourier, not |BH+DVCS|^2

$\sigma(+) + \sigma(-)$



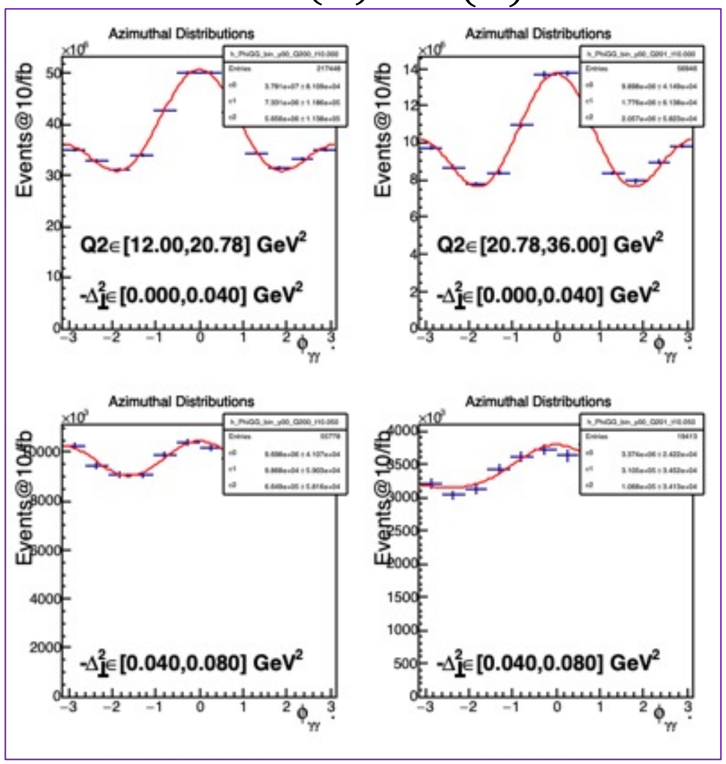
$\sigma(+) - \sigma(-)$



Example Azimuthal Distributions: $\alpha(e, e'\lambda)\alpha$

- Repeat
- (10 GeV)x(137.5 GeV/u)
- $y \in [0.06, 0.32]$
- $\langle x_B \rangle \approx 0.012$
- Projected counts at 10/fb/nucleus
- Error bars are MC, (not data) statistics!
- Fits are simple Fourier, not |BH+DVCS|^2

$\sigma(+) + \sigma(-)$



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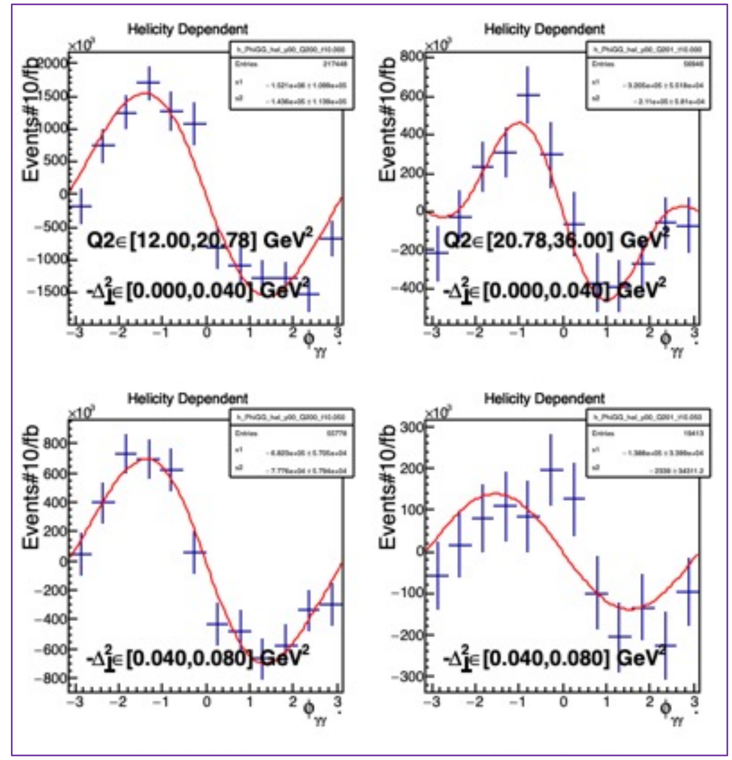


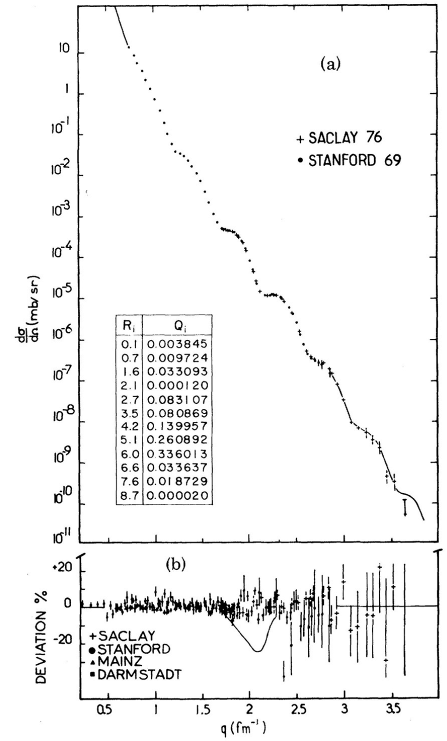
Conclusions

- IR-8 High-Dispersion focus in downstream ion beam line enables 100% tagging of break-up nuclei ≤ A-1 up to ${}^{90}_{40}Zr$
  - Tagging of ≤ A-2 daughter nuclei beyond Zr in IR-8
  - Region from ${}^{16}_{8}O$ to ${}^{90}_{40}Zr$ not accessible for A-1 in IR-6
- Muon Detection above 1 GeV/c will enhance Deep Virtual Vector Meson measurements and enable DDVCS—expecting counting rates to be sufficient at low-x
- Event generators for DVCS and DVMP for a broader range of nuclei are urgently needed.
- High Resolution EMCal in entire η<0 hemisphere is an enabling technology for precision DVCS on nuclei

Additional Slides

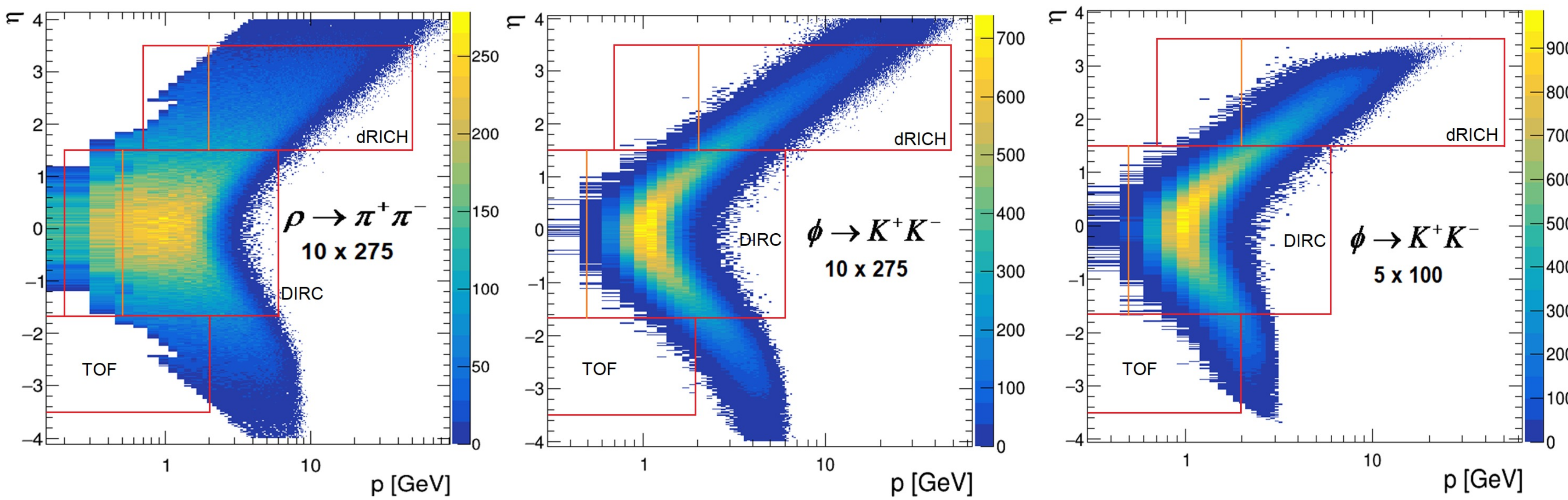
Comment on Diffractive Minima in Nuclear DVCS

- Sharp diffractive minima in (e,e') Form Factors
  - In heavy nuclei, these minima are smoothed out in the (e,e') cross section by Coulomb effects in the Dirac Equation (DWBA, not PWBA).
- DVCS & BH amplitudes interfere in Z(e,e'γ)Z
  - Even for light nuclei, the diffractive patterns have different minima: Charge distribution ≠ Mass distribution: $q - \overline{q} \neq q + \overline{q}$
  - Diffractive minima will wash out in phi-averaged cross sections.
  - Diffractive minima of both BH & DVCS amplitudes should be visible in DVCS*BH interference terms, such as electron helicity difference $\overrightarrow{d\sigma} - \overleftarrow{d\sigma}$



Particle ID Requirements (exclusive vector meson)

- π/K separation up to 6 GeV in central region covers full kinematics in high luminosity configuration.



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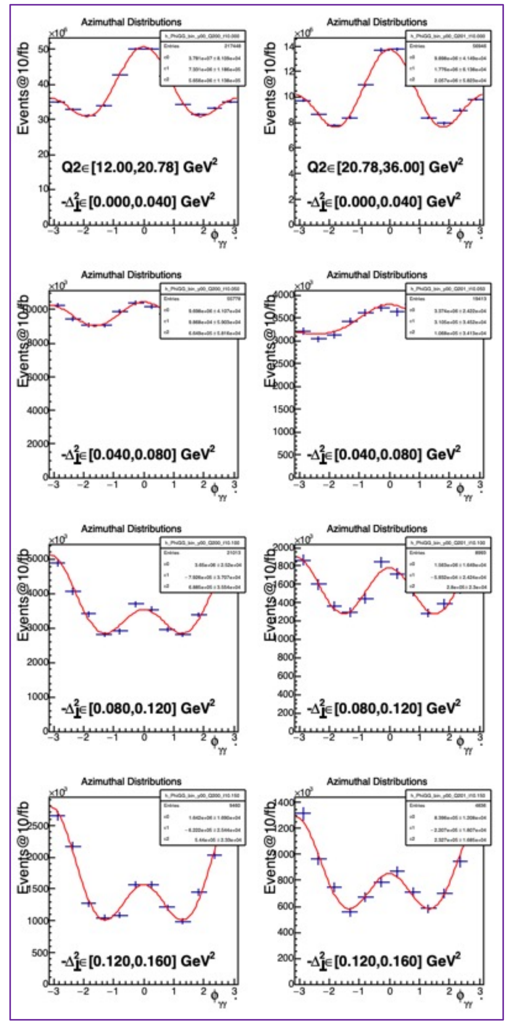

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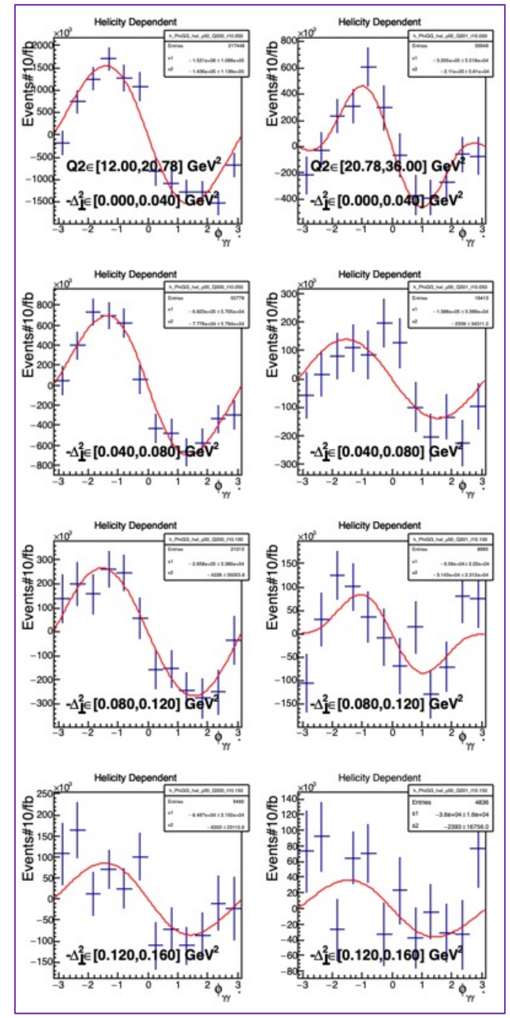
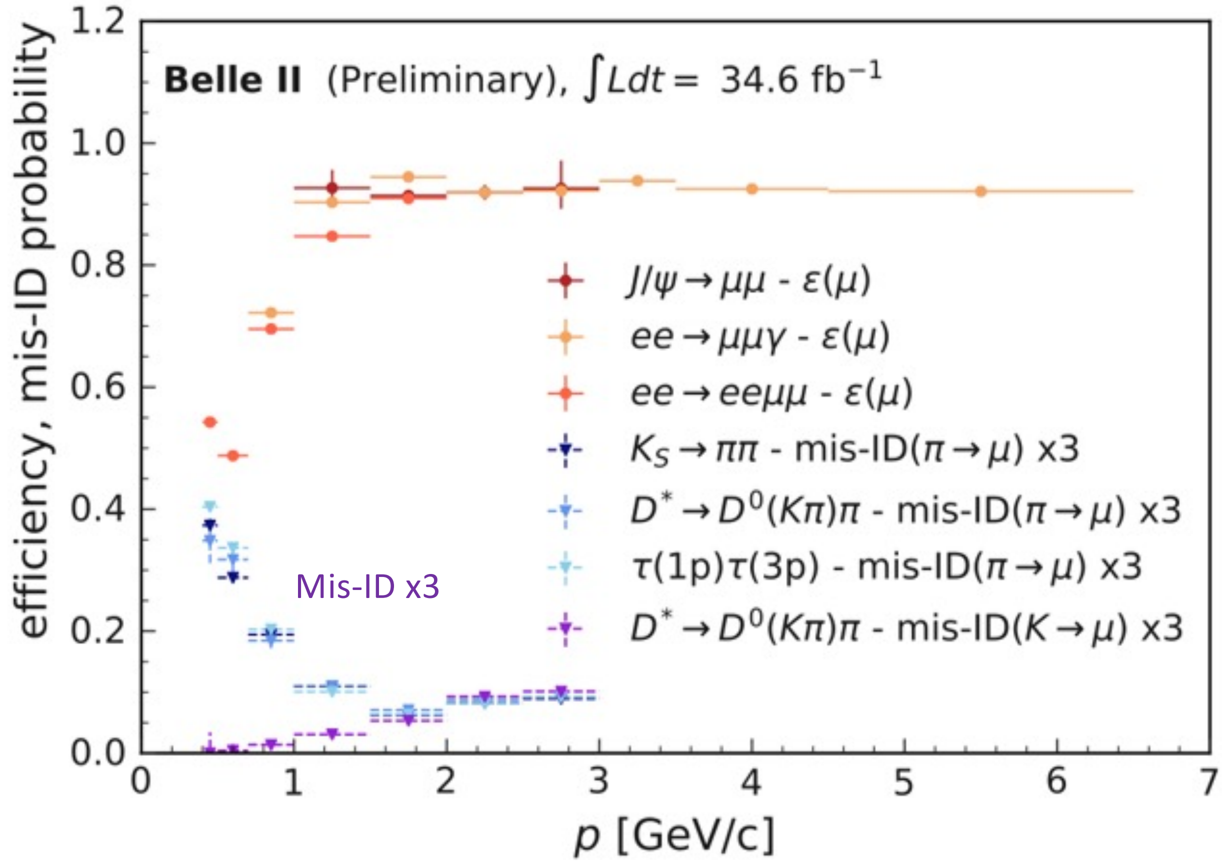


Muon Detection with KLM (BELLE I & II)

- Belle II full results expected soon.



Neutral Hadron detection with KLM

- K_L