Capabilities of the ATHENA detector proposal for small x physics

Spencer Klein, LBNL

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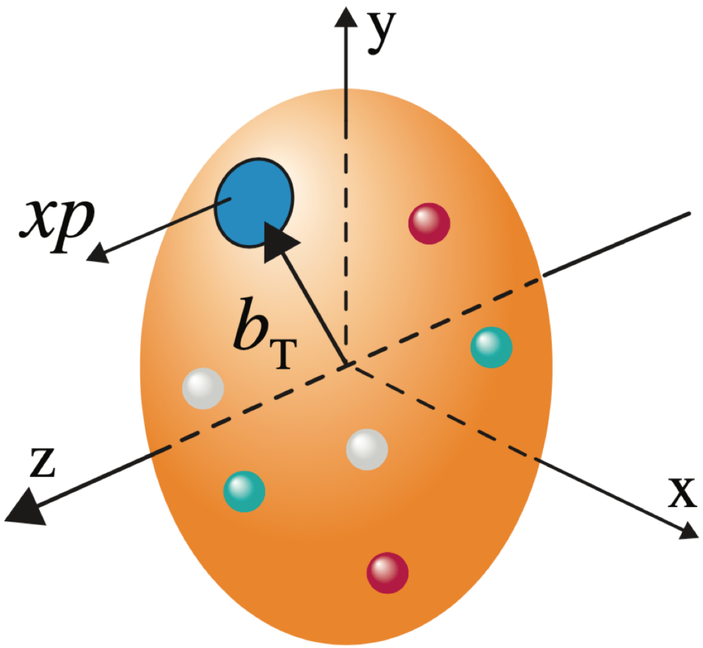
ATHENA

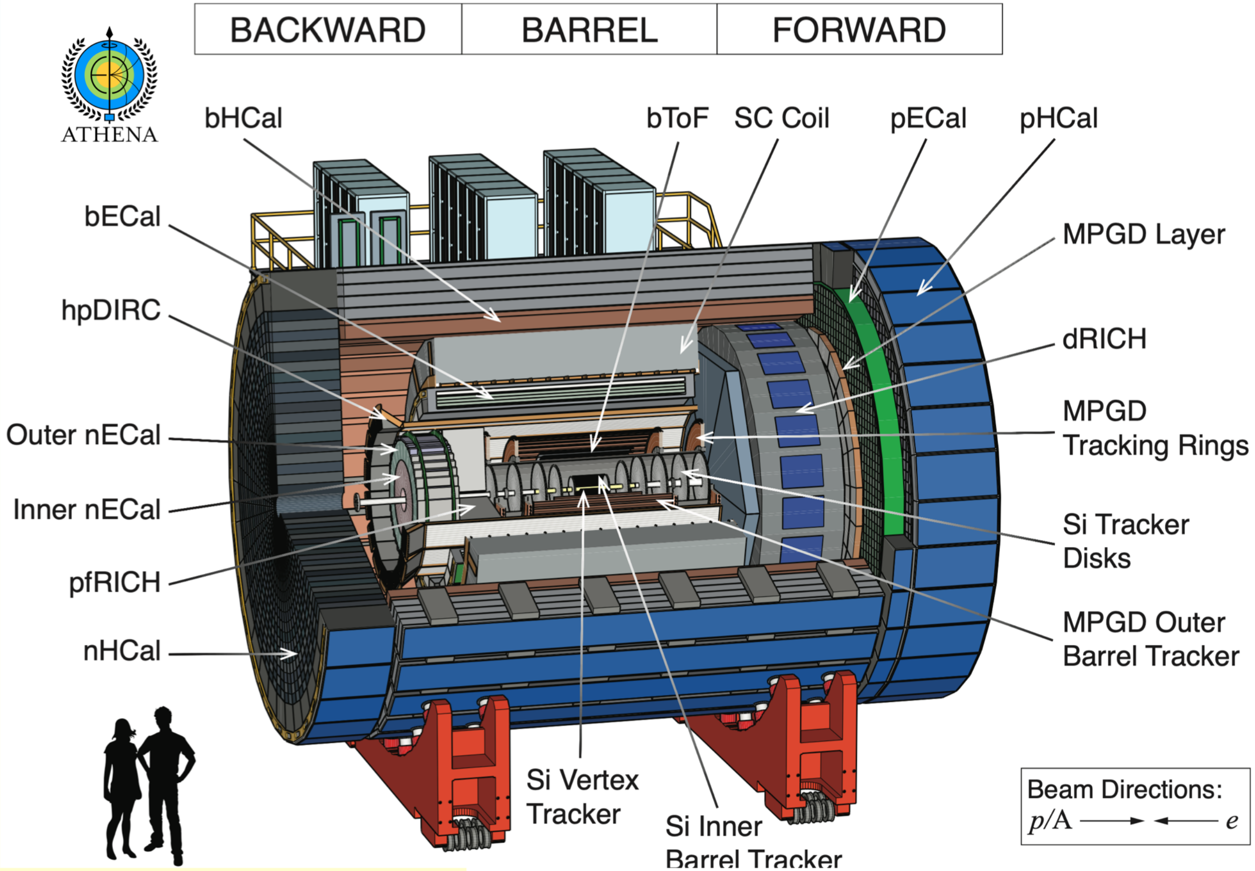
- ATHENA overview
- Quarks - DIS at low x
- SIDIS
- Gluons - Open Charm
- Gluons – Vector Mesons



"Material from ATHENA Proposal by the courtesy of the ATHENA Collaboration"

ATHENA

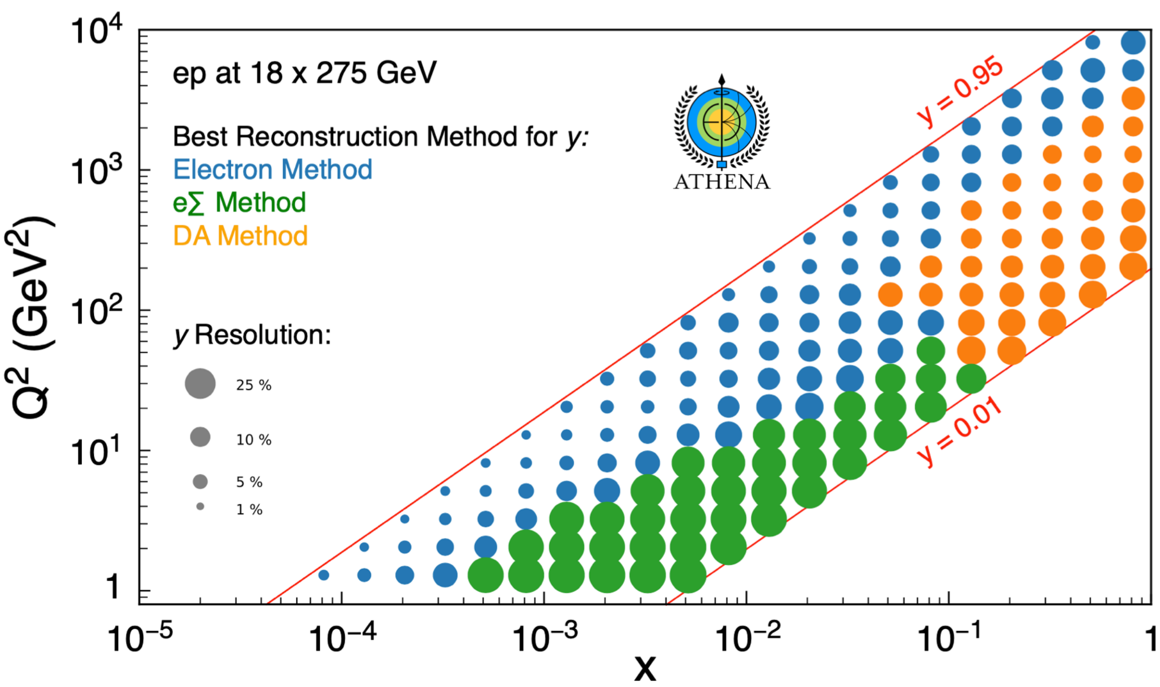
- Further development of the Yellow Report ‘reference’ detector
- 3 T solenoidal magnetic field
- ”Central” detector w/ backward, barrel and forward region
  - Much emphasis on particle identification (e/μ/π/K/p)
- Plus far forward (e-going) and far backward (h-going) detectors

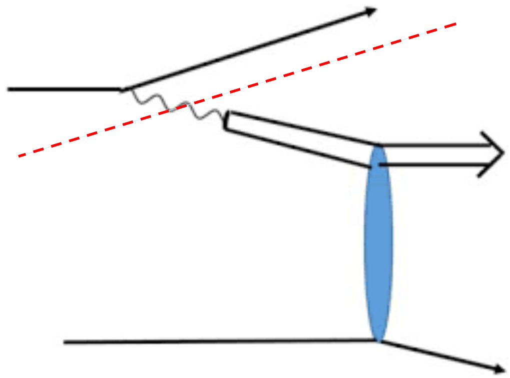


	Detector	Purpose	Technology	Acceptance	PID Range (GeV/c)
Forward (h-going)	Si-Tracker Disks	Tracking	6 disks of MAPS	$1.1 < \eta < 3.75$	
	Tracking Rings (MPGD)	Tracking	Planar GEMs with annular shape surrounding the Si-disks	$1.1 < \eta < 2.0$	
	dRICH	PID	Dual RICH with aerogel and gas	$1.2 < \eta < 3.7$	$3 < p < 60$ (K/π) $0.85 < p < 15$ (e/π)
	MPGD Layer	Tracking	Planar μRWell disk	$1.4 < \eta < 3.75$	
	pECal	e/m Calorimetry	W-Powder/SciFi calorimeter	$1.2 < \eta < 4.0$	
	pHCal	Hadron Calorimetry	Fe/Sci sandwich	$1 < \eta < 4.0$	
Barrel	Si Vertex-Tracker	Tracking and Vertexing	3-layer MAPS	$-2.2 < \eta < 2.2$	
	Si Barrel-Tracker	Tracking	2-layer MAPS	$-1.05 < \eta < 1.05$	
	bToF	PID and Tracking	AC-LGAD	$-1.05 < \eta < 1.05$ $p_T > 0.23$ GeV/c @ 3T	$p < 1.3$ (K/π) $p < 0.4$ (e/π)
	Barrel Tracker (MPGD)	Tracking	4 (2+2) layer cylindrical Micromegas	$-1.05 < \eta < 1.05$	
	hpDIRC	PID	DIRC with focusing elements and fine pixel readout	$-1.64 < \eta < 1.25$ $p_T > 0.45$ GeV/c @ 3T	$p < 6.5$ (K/π) $p < 1.2$ (e/π)
	bECal	e/m Calorimetry & Tracking	Hybrid with Astropix imaging layers alternated with Pb/SciFi layers followed by a set of Pb/SciFi layers	$-1.5 < \eta < 1.2$	
	bHCal	Hadron Calorimetry	Fe/Sci sandwich	$-1.0 < \eta < 1.0$	
Backward (e-going)	Si-Tracker Disks	Tracking	5 disks of MAPS	$-1.1 > \eta > -3.8$	
	Tracking Rings (MPGD)	Tracking	Planar GEMs with annular shape surrounding the Si-disks	$-1.1 > \eta > -1.8$	
	pfRICH	PID	Proximity focusing RICH with aerogel	$-1.5 > \eta > -3.8$	$3 < p < 11$ (K/π) $0.85 < p < 3$ (e/π)
	Inner nECal	e/m Calorimetry	$PbWO_4$	$-2.3 > \eta > -4.0$	
	Outer nECal	e/m Calorimetry	SciGlass	$-1.5 > \eta > -2.3$	
	nHCal	Hadron Calorimetry	Fe/Sci sandwich	$-1 > \eta > -4$	

Kinematic Range and reconstruction

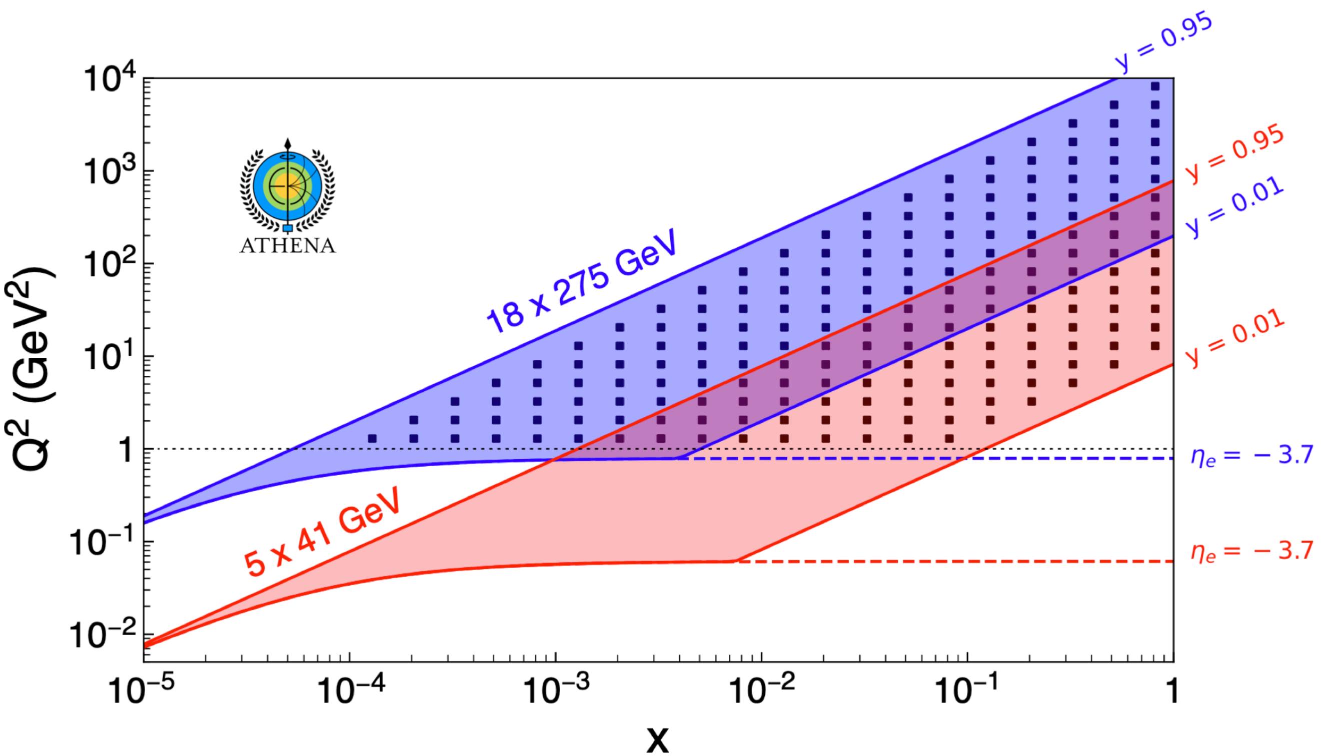
- Key variables: x, Q^2
  - y=inelasticity; $Q^2 \sim sxy$
- x,Q^2 determinable by observing scattered electron
  - Best over most of kinematic range, except at low y
  - Alternately, reconstruct x,Q^2 from hadronic final state
    - Double-angle method uses hadronic system + electron angles
    - Σ method uses hadronic final state





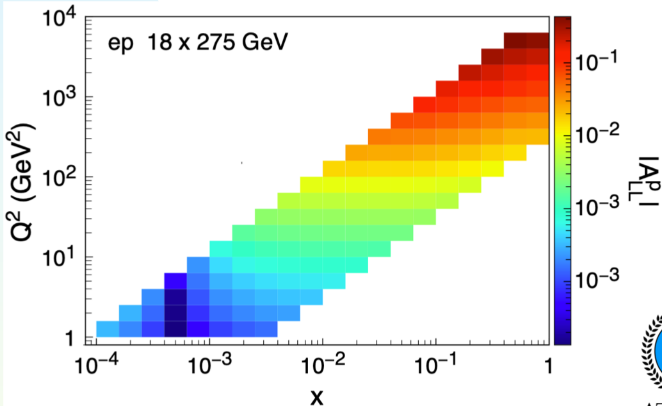
ATHENA Running Conditions

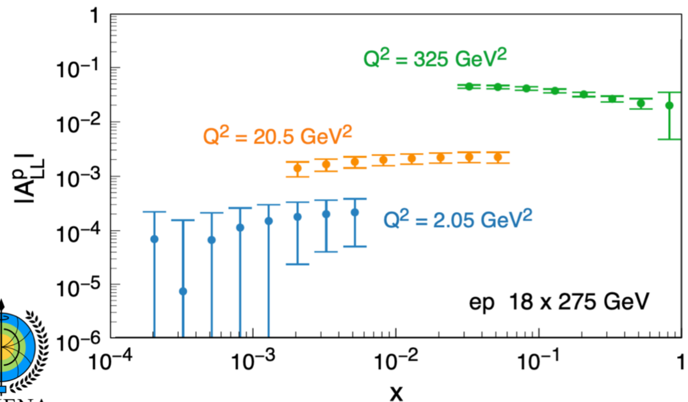
- ep, eAu plus intermediate ions
- Lower beam energies advantageous for many topics
  - Multiple beam energies
- Some topics benefit from lower magnetic fields
  - Better acceptance for low p_T particles



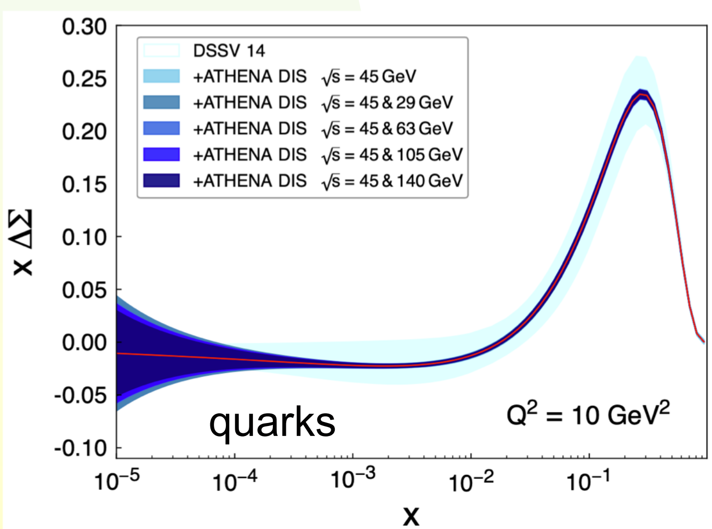
Spin PDFs at low x

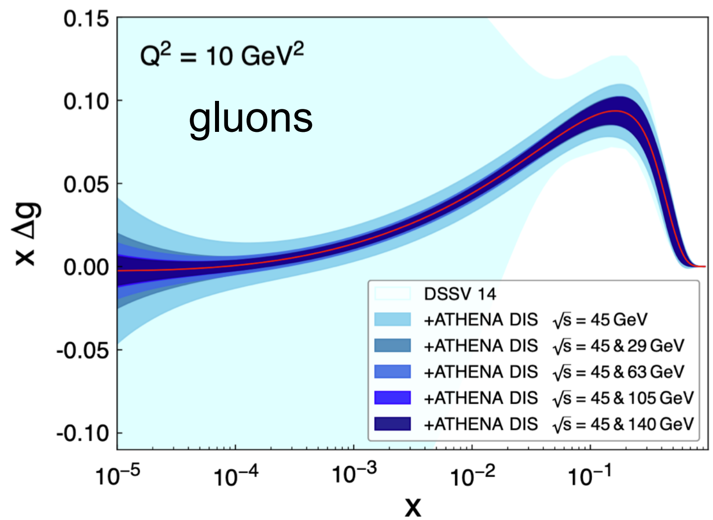
- Highly polarized electrons and protons (& light ions)
- Accurate measurements of double-spin asymmetries
- Constrain polarized parton distributions (gluons from evolution…)
- Strange quarks via kaon semi-inclusive DIS





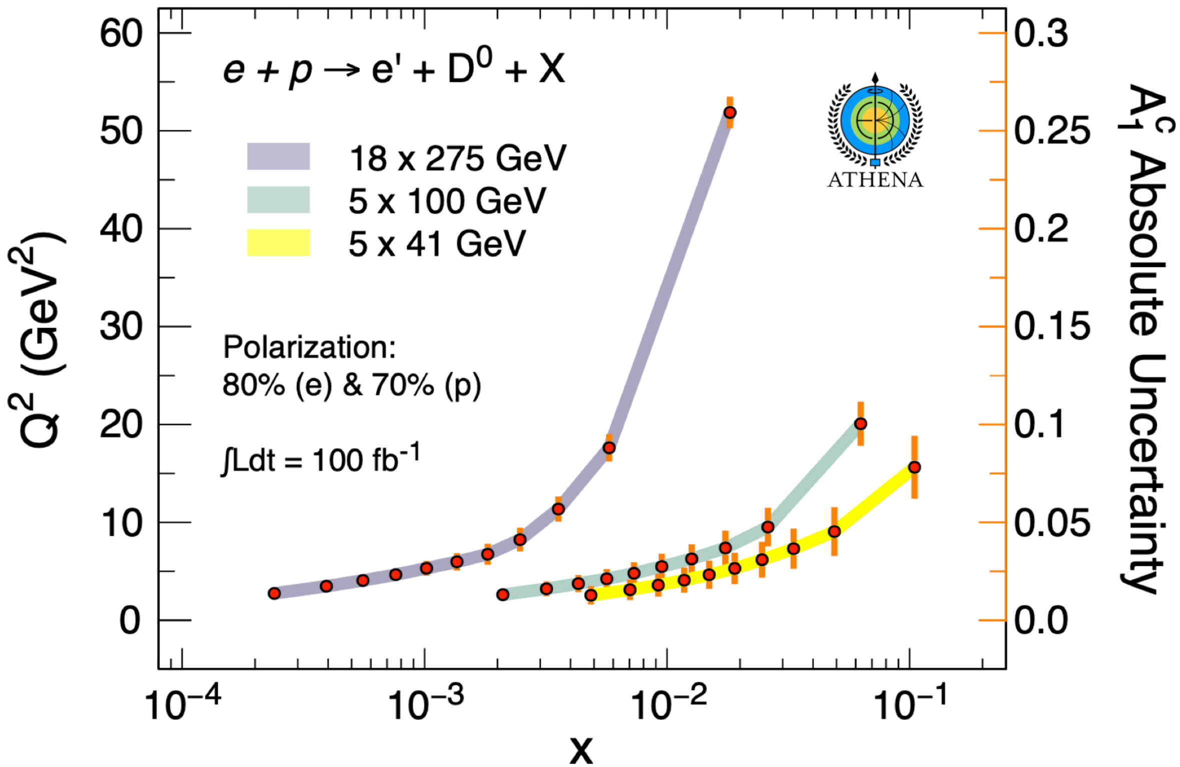
ATHENA





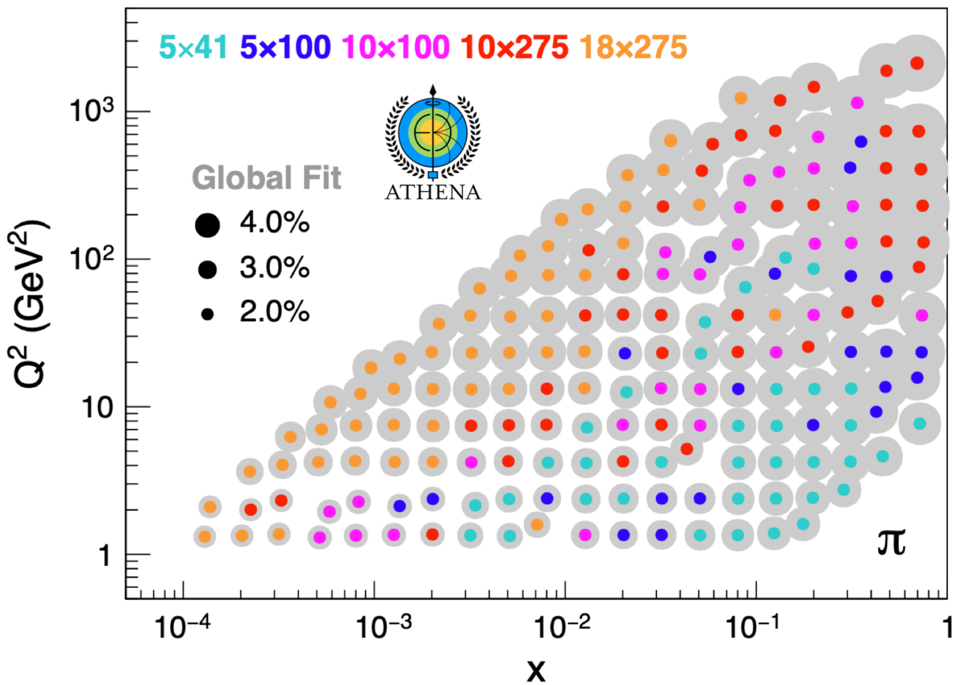
More direct access to the gluons

- Photoproduction of open charm and dijets
  - γ + g -> ccbar (or qqbar-> dijets)
    - Jets are tricky at low energy (i. e. low x)
- $Q^2 = Q^2_{photon} + Q^2_{pair} = Q^2_{photon} + (M_{finalstate}/2)^2$
- Polarized and unpolarized measurements in ep



Transverse Momentum Distributions from Semi- Inclusive DIS (SIDIS)

- Measure DIS + a high momentum π/K..
  - PID is critical
- Polarized and unpolarized…
- High-precision measurements expected



SIDIS π production cross-sections from ATHENA, compared with PV17 TMD extraction (grey dots). In many areas, the measurements are dominated by systematic errors.

Exclusive production, gluon shadowing & hotspots

- Study γ^*p, A -> V p,A over full range of
  - Bjorken-x
  - Q^2 - the low Q^2 region is also important!
  - Transverse and longitudinal polarization
  - Different vector mesons and photons for DVCS

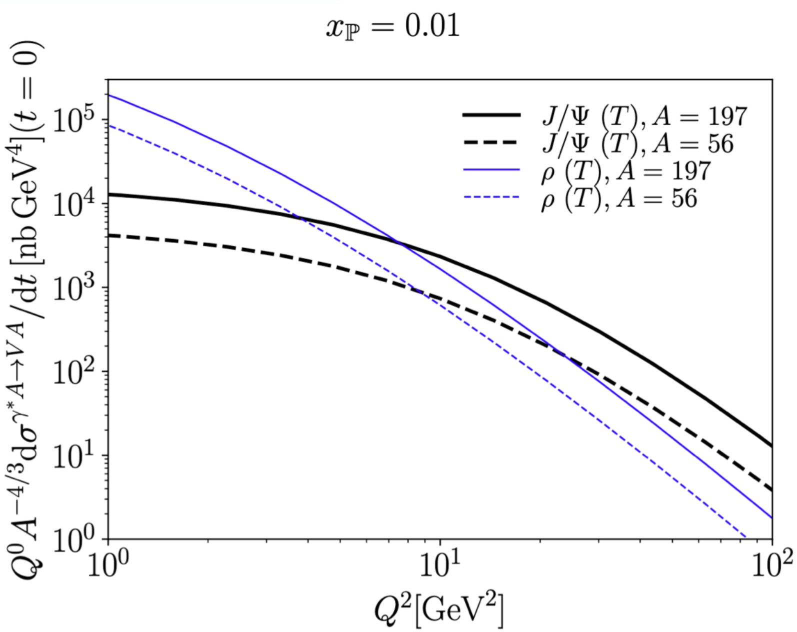


FIG. 6: The cross-section for coherent transverse vector meson production production at $t = 0$. It is Q^2 independent at low Q^2. The cross-section is scaled in A by the asymptotic analytical expectation $\approx A^{4/3}$.

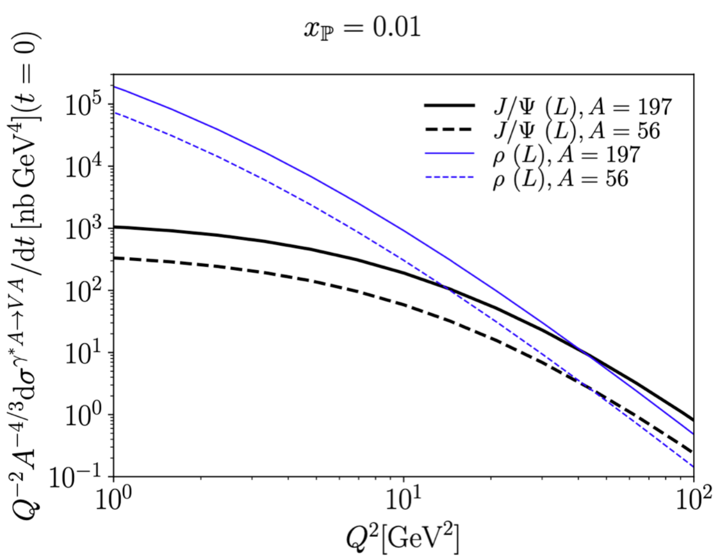


FIG. 5: The cross-section for coherent longitudinal vector meson production at $t = 0$. At low Q, the cross-section is flat at low Q^2 when scaled by Q^{-2}. For ρ, this behavior is only obtained at asymptotically small Q^2 values where our model is not applicable.The cross-section is scaled in A by the analytical asymptotical expectation $\approx A^{4/3}$. Our result here shows that the scaling is not exact for realistic kinematics.

H. Mantysaari and R. Venugopalan, Phys. Lett. B781, 664 (2018)

Spatial Imaging and GPDs (and hot spots)

- In the Good-Walker paradigm the coherent and incoherent $d\sigma/dt$ are related to the average nuclear structure and event-by-event fluctuations respectively.
  - Photoproduction, DVCS, anything coherent

$$\frac{\mathrm{d}\sigma_{\mathrm{tot}}}{\mathrm{d}t} = \frac{1}{16\pi}\left\langle \left|A(K,\Omega)\right|^2 \right\rangle$$ Average cross-sections (Ω)

$$\frac{\mathrm{d}\sigma_{\mathrm{coh}}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\langle A(K,\Omega)\rangle\right|^2$$ Average amplitudes (Ω)

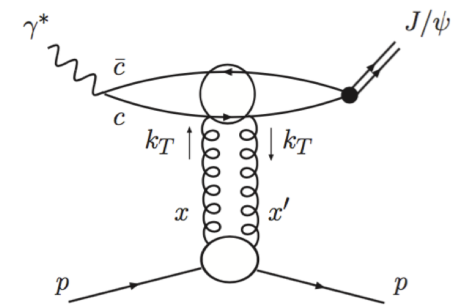
$$\frac{\mathrm{d}\sigma_{\mathrm{inc}}}{\mathrm{d}t} = \frac{1}{16\pi}\left(\left\langle \left|A(K,\Omega)\right|^2 \right\rangle - \left|\langle A(K,\Omega)\rangle\right|^2\right)$$ Incoherent is difference

  - K is the kinematic factors of the reaction (s,t,…)
  - Ω is nuclear configuration –nucleon positions, gluonic hot spots….
    - Assumed to be fixed throughout the interaction
- $d\sigma_{coherent}/dt$ can be used to image the nucleus
- $d\sigma_{incoherent}/dt$ probes event-by-event fluctuations in nuclear config.
- Requires good coherent/incoherent separation

Coherent photoproduction of hadronic final states

- Coherent production proceeds vs. Pomeron exchange
  - Two gluons, to lowest order

$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\, p)\Big|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} x g(x,\bar{Q}^2)\right]^2 \left(1+\frac{Q^2}{M_{J/\psi}^2}\right).$$



  - With $\bar{Q}^2 = (Q^2 + M_{J/\psi}^2)/4, \qquad x = (Q^2 + M_{J/\psi}^2)/(W^2 + Q^2)$
  - Caveats
    - pQCD factorization does not strictly hold
      - Two gluons have different x values (with x' ≪ x ≪ 1)
        - Use generalized (skewed) gluon distributions – smallish correction.
        - Can do exactly with Shuvaev transform
    - Photon is not pure $q\bar{q}$ dipole
    - Choice of scale μ
- NLO calculation for σ_L in CGC/ dipole picture
  - not (yet) for pure pQCD, but hopefully close
- More naturally treated with GPDs

SP Jones *et al.,* J. Phys. G**44**, 03LT01 (2017); H. Mantysaari and J. Penttala, arXiv:2104.02349
SK & Heikki Mantysaari, Nat. Phys. Rev. **1**, 662 (2019)

Imaging the target with coherent production

- b (impact parameter) and p_T are conjugate variables, so the 2-d Fourier transform of $d\sigma/dp_T$ gives $d\sigma/db$, i. e. the transverse positions of the interactions in a target
- $\sigma_{coherent} = |\Sigma_i A_i k \exp(ikb)|^2$
- Two approaches to selecting coherent interactions
  - High detection efficiency for nuclear breakup products
    - Still not clear if this is enough by itself
  - Measure $d\sigma/dt_{incoherent}$ at large t, extrapolate to zero and subtract
    - Used for ultra-peripheral collisions
- Exponential exp(ikb) encodes information about the transverse locations of the interactions
  - without shadowing, this is the shape of the nucleus
- Fourier transform to get 2-d interaction density F(b)

$$F(b) \propto \frac{1}{2\pi} \int_0^\infty dp_T p_T J_0(b p_T) \sqrt{\frac{d\sigma}{dt}}$$

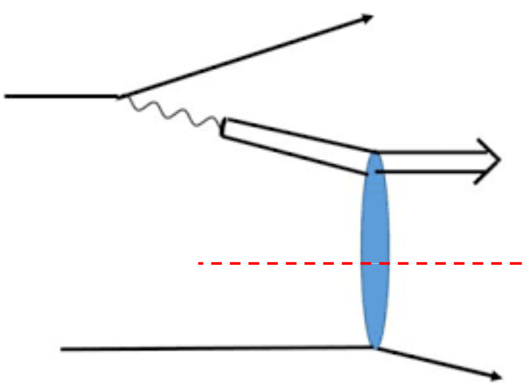
* = flips sign after each minimum

Toll & Ullrich, Phys. Rev. **C87**, 024913 (2013), STAR, Phys. Rev. **C96**, 054904 (2017); SK DIS18

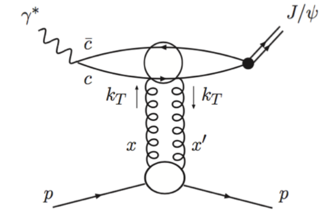
Experimental aspects of imaging

$$F(b) \propto \frac{1}{2\pi}\int_0^\infty dp_T\, p_T J_0(bp_T)\sqrt{\frac{d\sigma}{dt}}$$

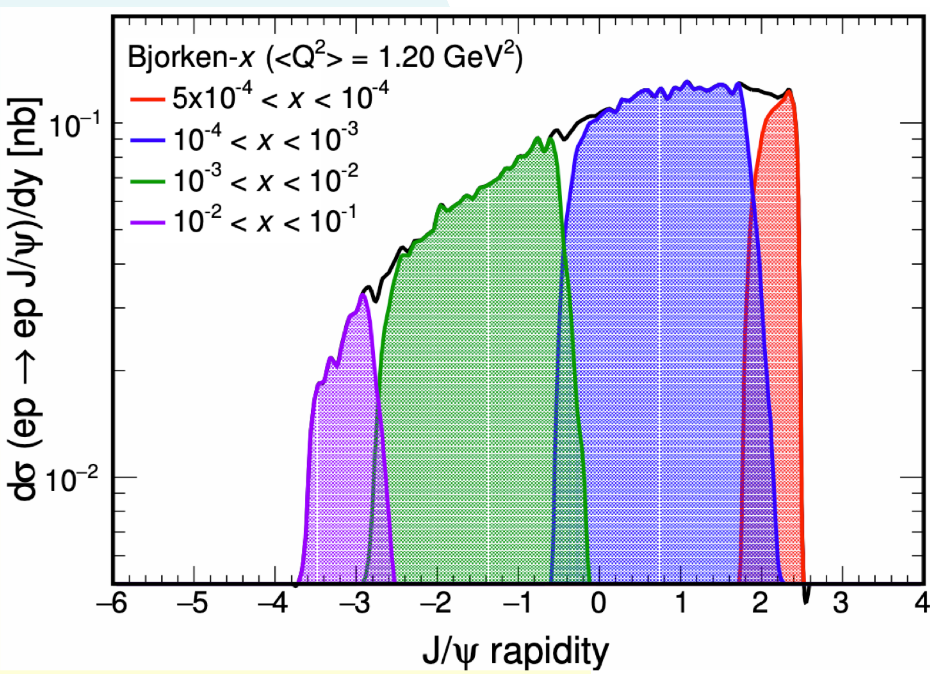
- This integral goes from 0 to infinity, but data has a maximum p_T
  - This introduces a 'window' (box) from 0 to p_{Tmax}, which is unavoidable convoluted with the signal
  - Need to go to large p_T to minimize windowing
    - ~ to the third minimum
- Find t via scattered p/ion, or e + hadrons
  - Scattered ion only visible for protons/light ions
- Need to remove resolution via deconvolution
  - Including beam energy & momentum spreads
    - Most important when electron energy loss is small

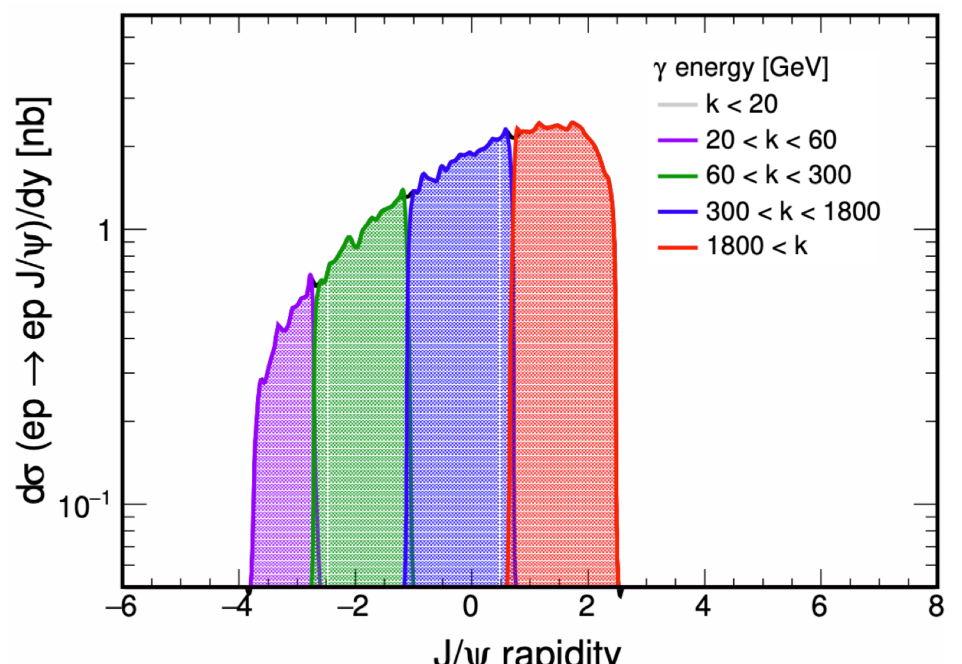


Coherent production – practical aspects



- Bjorken-x is mapped from rapidity:
  - $x = M_F/2\gamma_P Mp \exp(y)$
    - M_F = final state mass, γ_p = ion Lorentz boost, and M_p = proton mass
    - Modified for photons with high Q^2
- Broad coverage in Bjorken-x requires broad coverage in rapidity





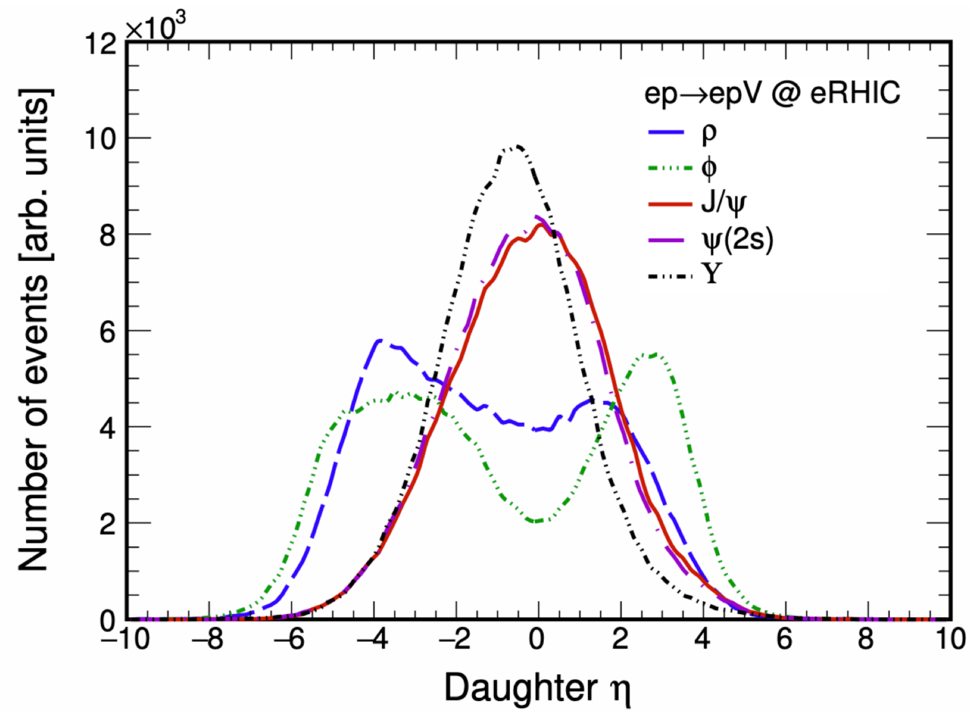
(Flipped Rapidity Convention)

M. Lomnitz & SK, eSTARlight, Phys. Rev. C**99**, 015203 (2019)

Coherent VM production in ATHENA: x, Q^2 range

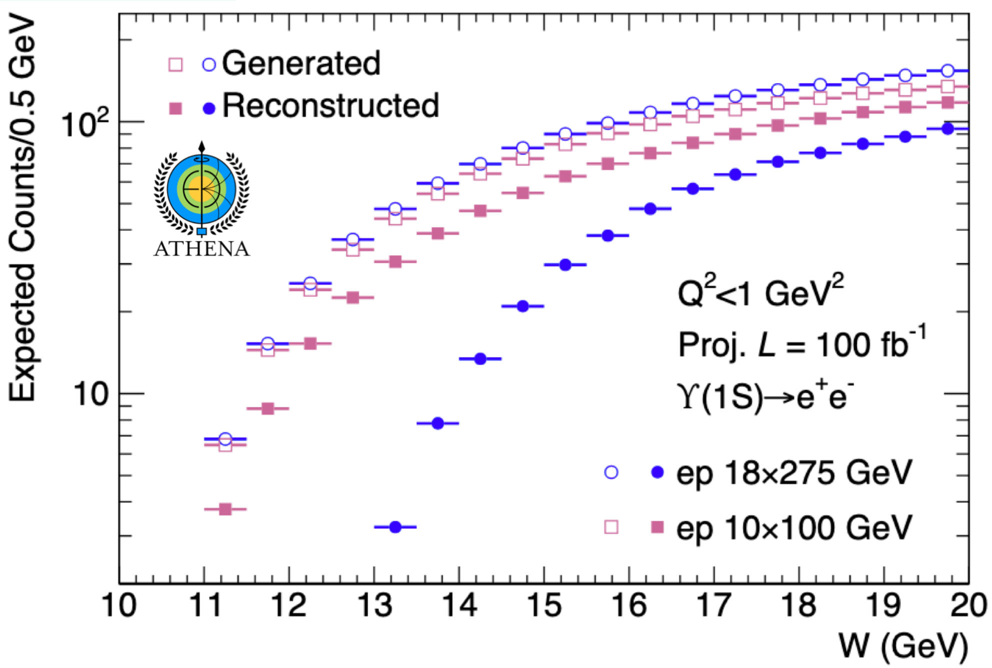
- x depends on rapidity range of central tracker
- Roughly, tracking a vector meson out to rapidity $|y_{max}|$ with good efficiency requires tracking daughters out to $|\eta_{max}|= |y_{max}| +1$
  - Not fully satisfied in ATHENA (or any other EIC detector)
  - Loss of efficiency for x~1 or $x \sim x_{minimum}$
- Rapidity distribution depends on decay Clebsch-Gordon coefficients

M. Lomnitz & SK, eSTARlight, Phys. Rev. C**99**, 015203 (2019)



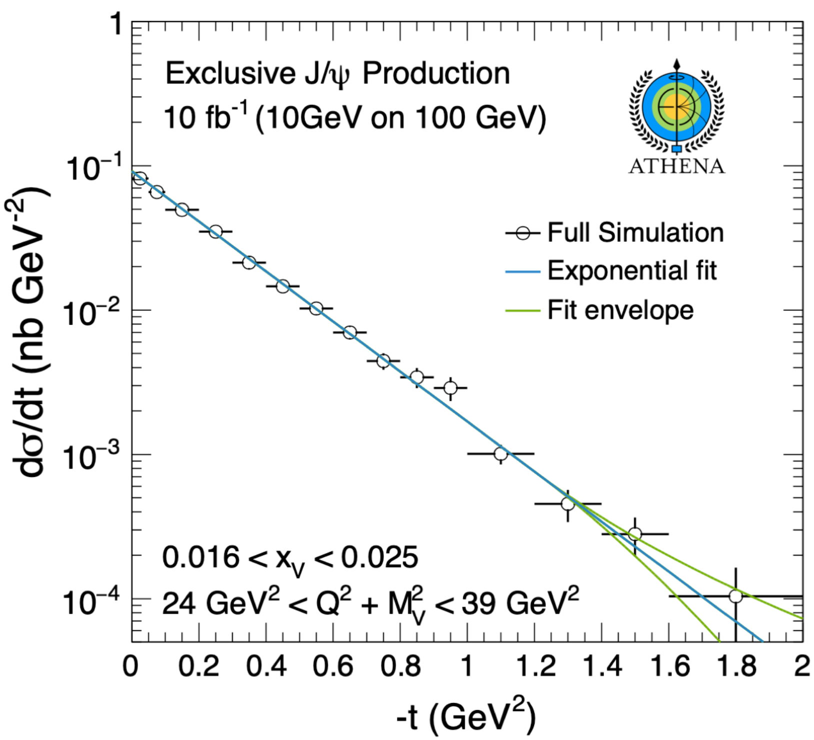
Example: near-threshold Υ

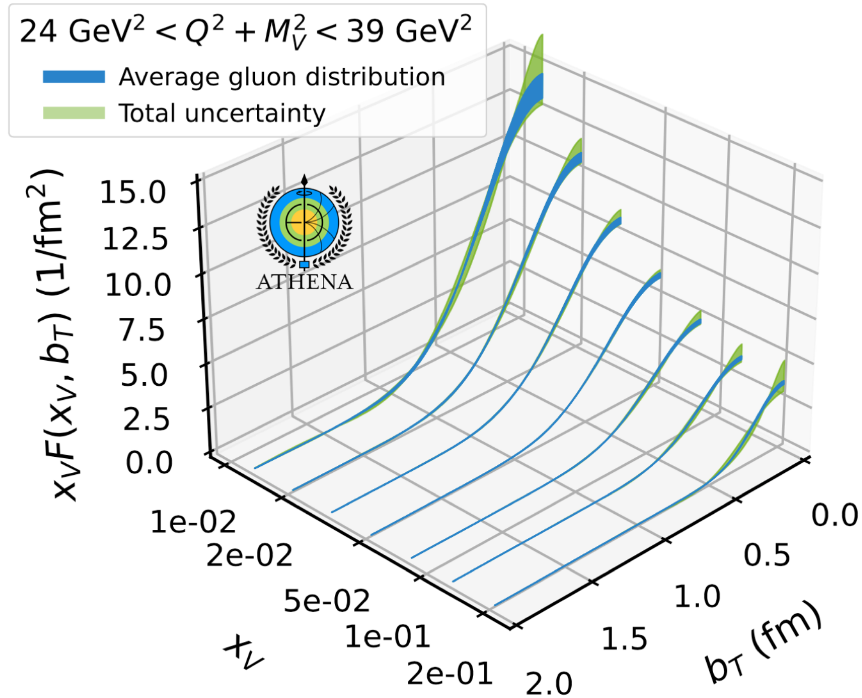
- At full beam energy (18 x 275 GeV^2), near-threshold U production is at/beyond the edge of the detector acceptance
- Solution: run at lower beam energy (10 x100 GeV^2), which shifts the threshold to near mid-rapidity
  - Total Υ rate is much lower, but the near-threshold rates are the same
  - Unfortunately, this does not work at low x



ATHENA gluon tomography of the proton using coherent J/ψ production

- In ep, so t comes from scattered proton
- Gluon distribution is Fourier transform of dσ/dt



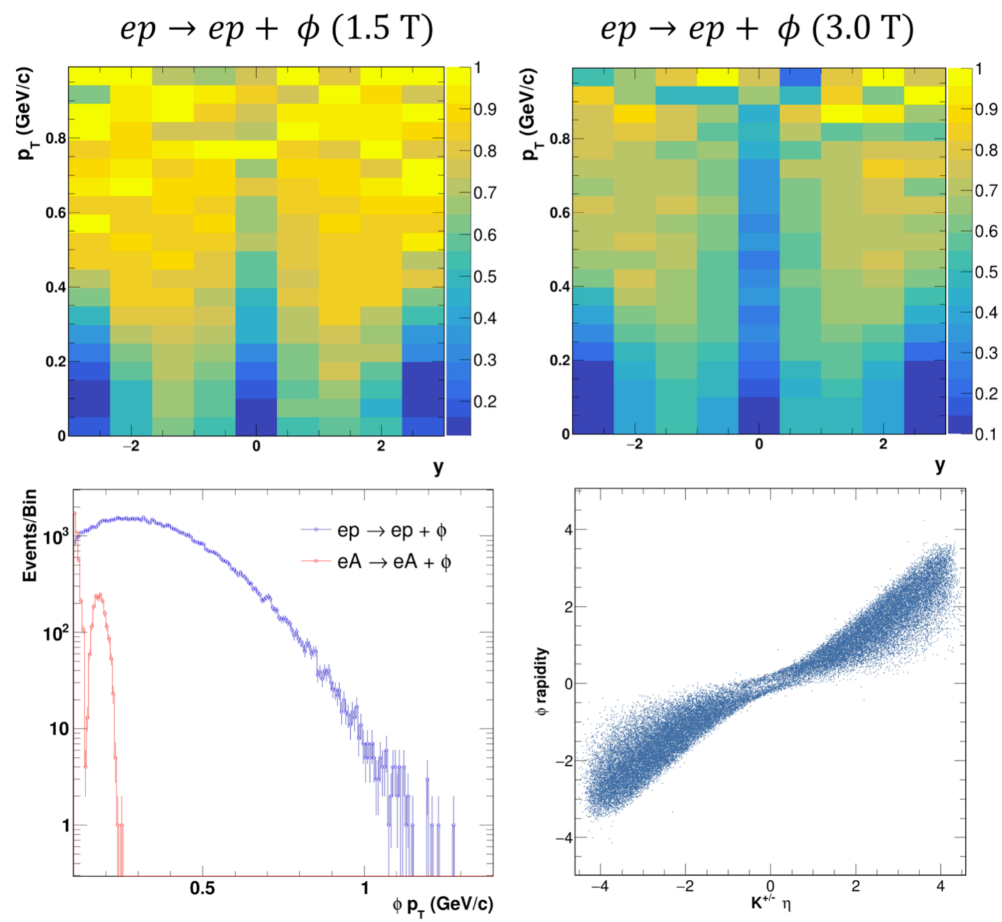


Challenges in exclusive ϕ production

- ϕ was highlighted in EIC White Paper
- $K^{\pm}$ from ϕ decay have 135 MeV/c in ϕ rest frame
  - Other decay channels are impractical
- ϕ w/o longitudinal (|y|>0) or transverse (large Q^2) boost are hard to reconstruct
  - Limited range in x,Q^2 space
- Background from $\rho \rightarrow \pi^+\pi^-$
- The ρ is much easier
  - Usable for theory?

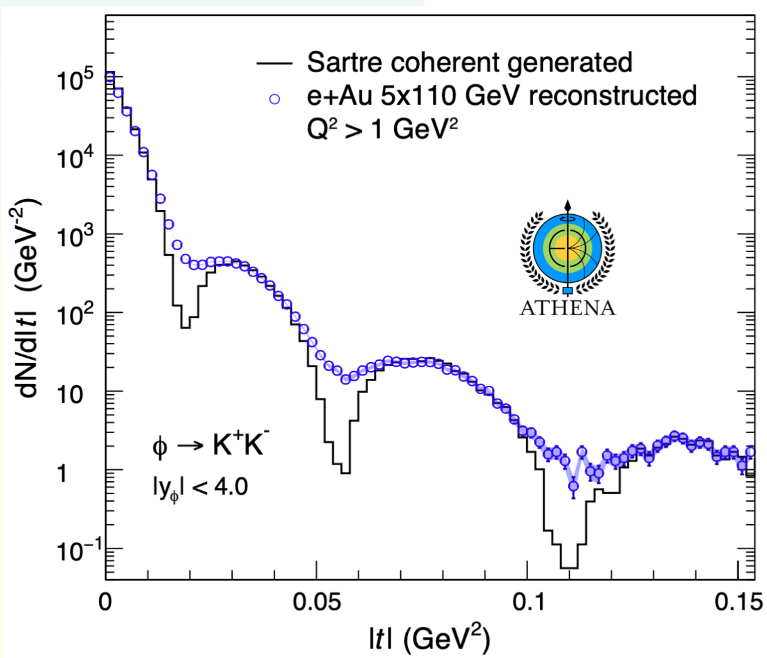
J. Arrington et al.
arXiv:2102.08337

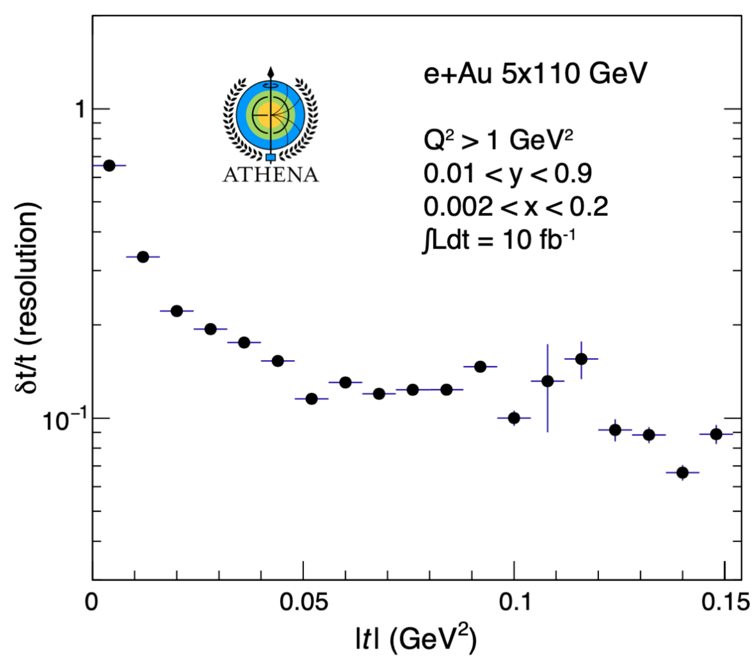
An ATHENA-like silicon detector



Low-x ϕ production in eA

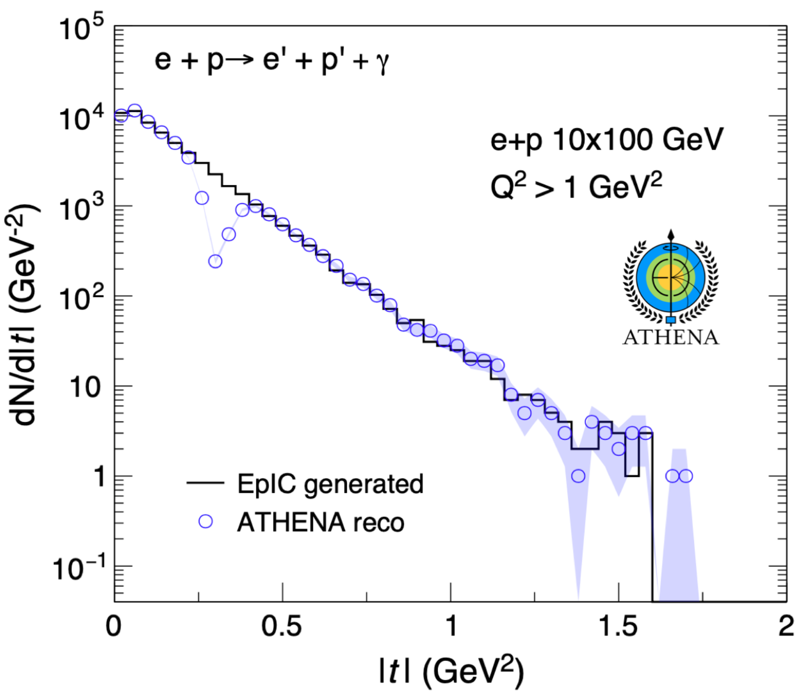
- Must reconstruct t using scattered electron + ϕ
  - Difference between two large numbers
    - Initial electron momentum, with beam spread
    - Scattered electron momentum
- Good resolution at lower electron energy
- Tradeoff between narrower x range and good t resolution
  - Large Q^2 helps, so electron is at smaller |y|

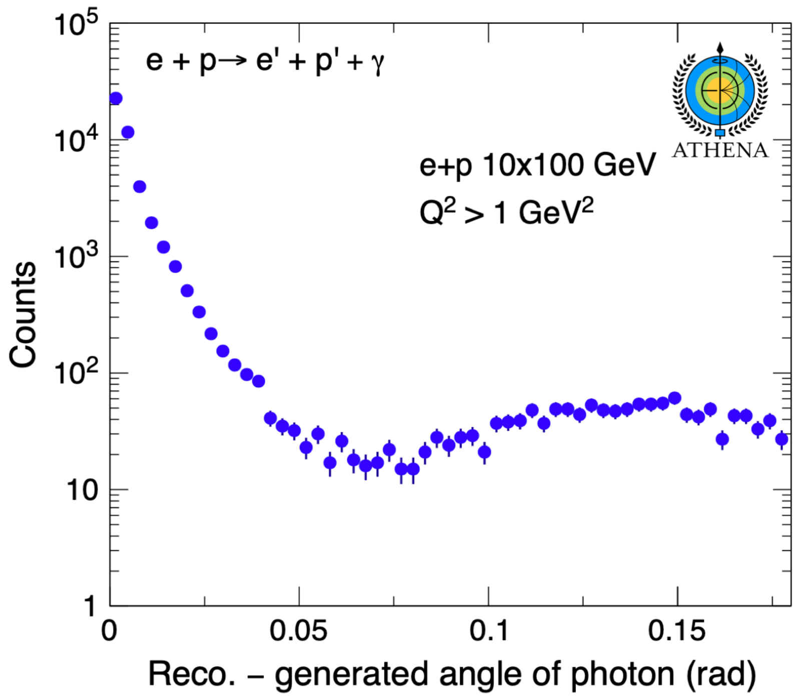




Deeply Virtual Compton Scattering

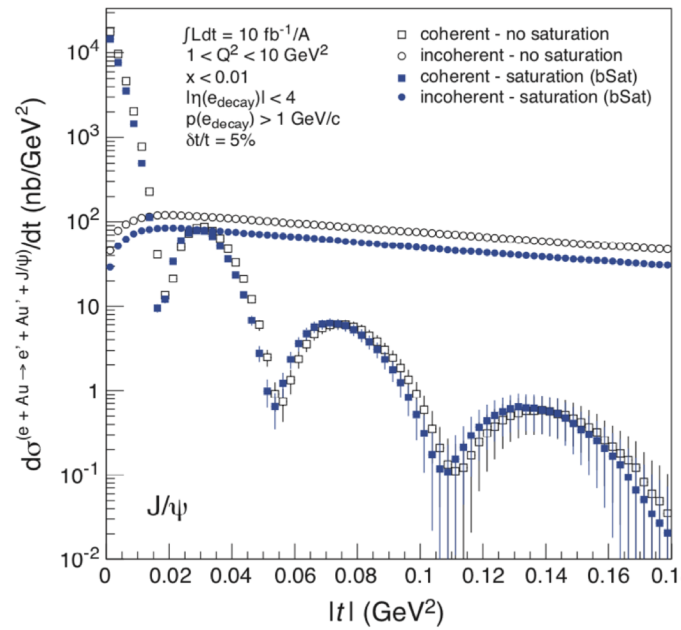
- Good photon detection from $-3.5 < \eta < 3.5$
- In ep, t is measured using scattered proton
  - Roman pots + B0 spectrometer
    - Tagging 'gap' visible for $|t|=0.3$ GeV^2 below
- Main background is exclusive π^0 production
  - Photon resolution is good enough to insure good π^0 rejection



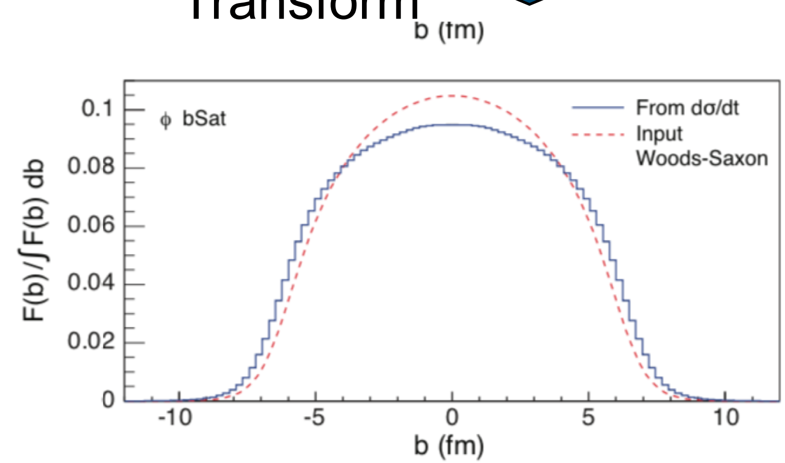


How good a coherent/incoherent separation is needed?

- Wide |t| range required for coherent photoproduction to measure GPDs
  - Parton distributions as a function of transverse position within the nucleus
  - Fourier transform dσ/dt to F(b)
  - Accurate Fourier transform requires $0 < |t| < \sim 0.18$ GeV^2 range for eAu
- Need ~500:1 rejection of incoherent production to observe coherent production with $|t| > \sim 0.1$ GeV^2
- Need 100:1 rejection of coherent production to observe incoherent production at small |t|



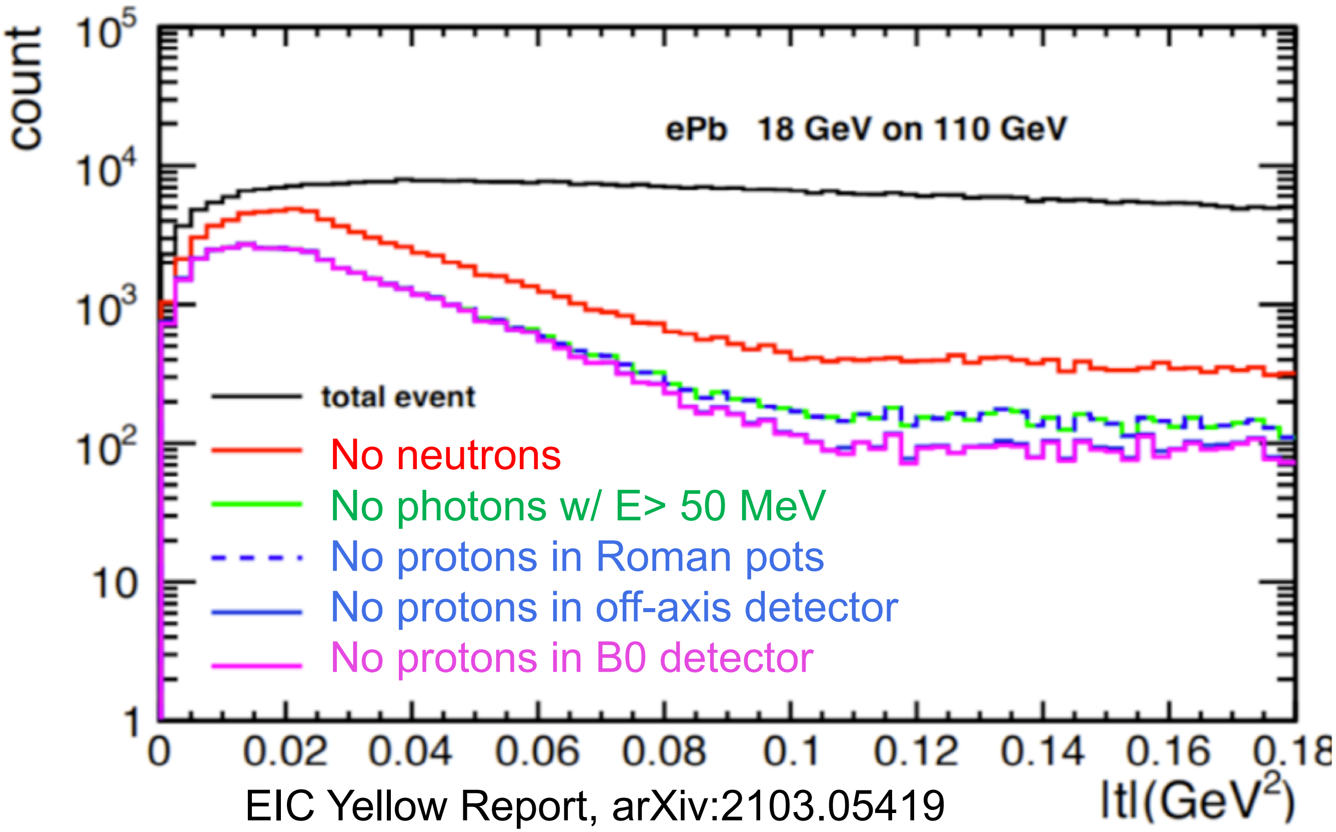
Fourier Transform



Discussed in Yellow Report; Plots from EIC White Paper

Separating coherent and incoherent production with heavy ion targets

- Nuclear breakup via neutron, proton or photon emission
  - Mixture depends on t, since reactions are exothermic
  - Significant theoretical uncertainties in branching ratios



EIC Yellow Report, arXiv:2103.05419

Detecting photonic deexcitation

- For excitation energy < 1-5 MeV, the final state is well defined
  - Shell model state with fixed energy, spin, parity
- Relationship between E and t depends on mass of recoiling state
  - STAR ρ^0 photoproduction data supports single-nucleon recoil fits
    - Fit is in range 0.45 $GeV^2 > t > 0.2$ GeV^2
- Lab-frame energy depends on Lorentz boost & angle
- For ^{208}Pb, the lowest lying excited state is at 2.6 MeV
  - Incoherent production impossible below this threshold
  - $J^\pi=3^-$, so production is marginal, due to angular momentum
  - In the single nucleon paradigm (questionable here), with maximum boost, p_{min} ~ 70 MeV/c, t_{min} ~ 0.005 GeV^2
- For ^{197}Au, the lowest lying excited state is at 77 keV
  - τ=1.9 nsec, so the excited nucleus escapes the detector
  - Next lowest states are at 269 keV and 279 keV
- Lead is preferred for coherent production studies

Theory needs

- From Raju “we would appreciate in addition your perspective on the challenges (in particular those that could benefit from such a collaboration) for what you see as key small x measurements at the EIC and their discovery potential.”

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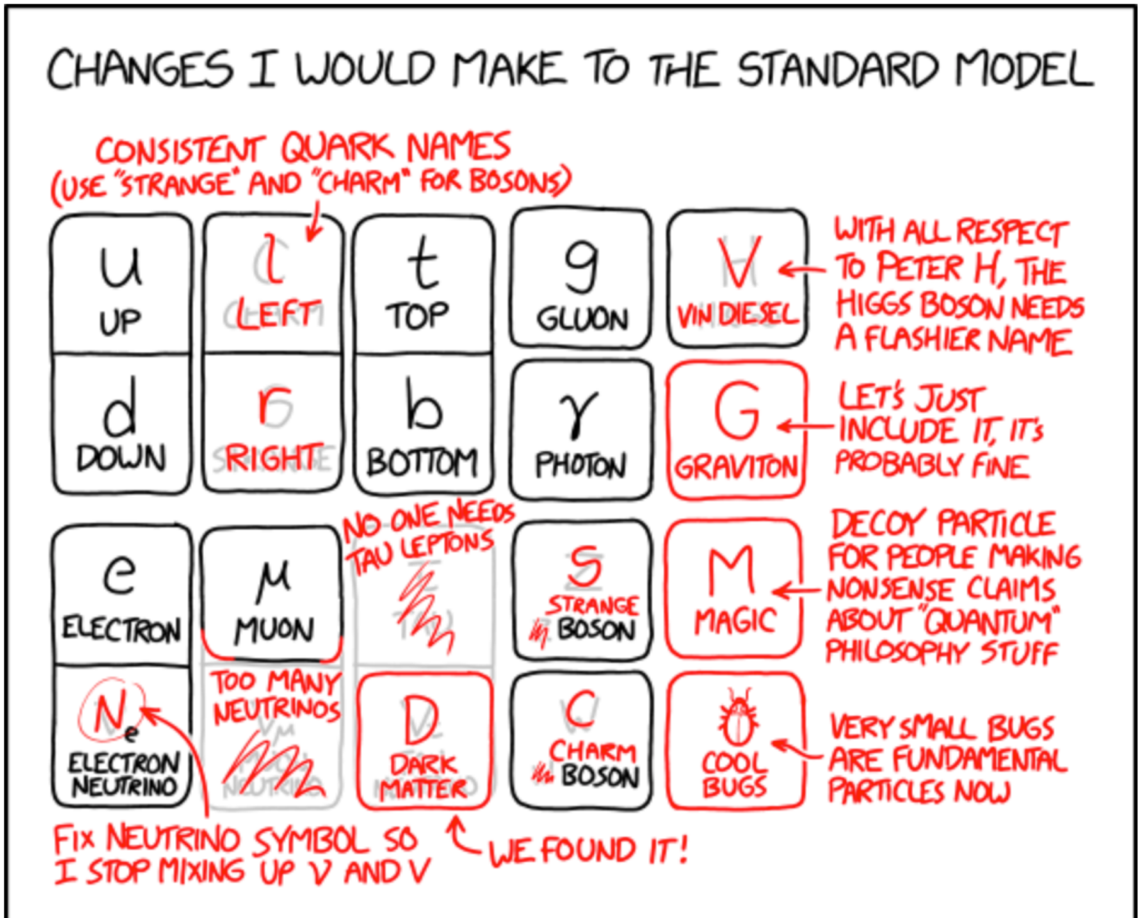


Thanks to xkcd.com

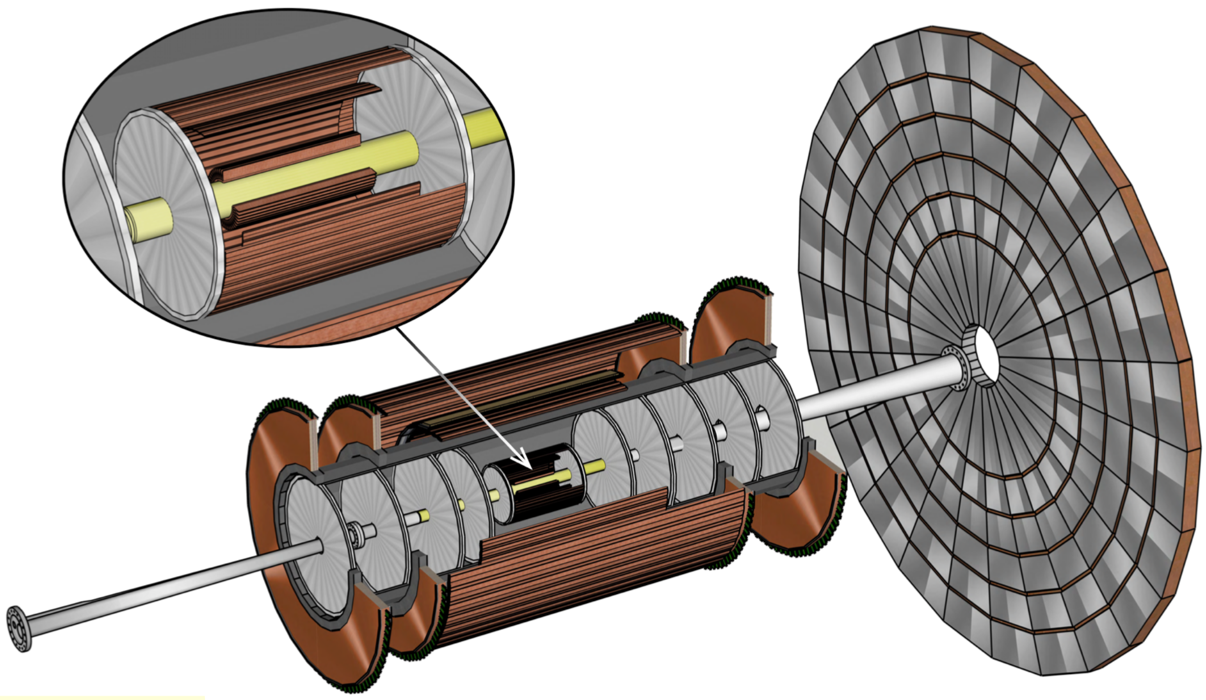
Conclusions

- ATHENA is well suited to studying low-x physics at the EIC.
  - A broad program is planned, including DIS, SIDIS with different hadrons and coherent production of a variety of mesons
  - Some limitations are common to all proposals:
    - Limited rapidity coverage -> limited Bjorken-x coverage
    - Separating coherent and incoherent interactions of heavier ions
- There are many places where more theory work is needed
  - Full NLO calculation of exclusive vector meson production
  - Better understanding what products are emitted when nuclei break up, as a function of t
  - Understanding if/how ρ^0 photoproduction can replace the ϕ

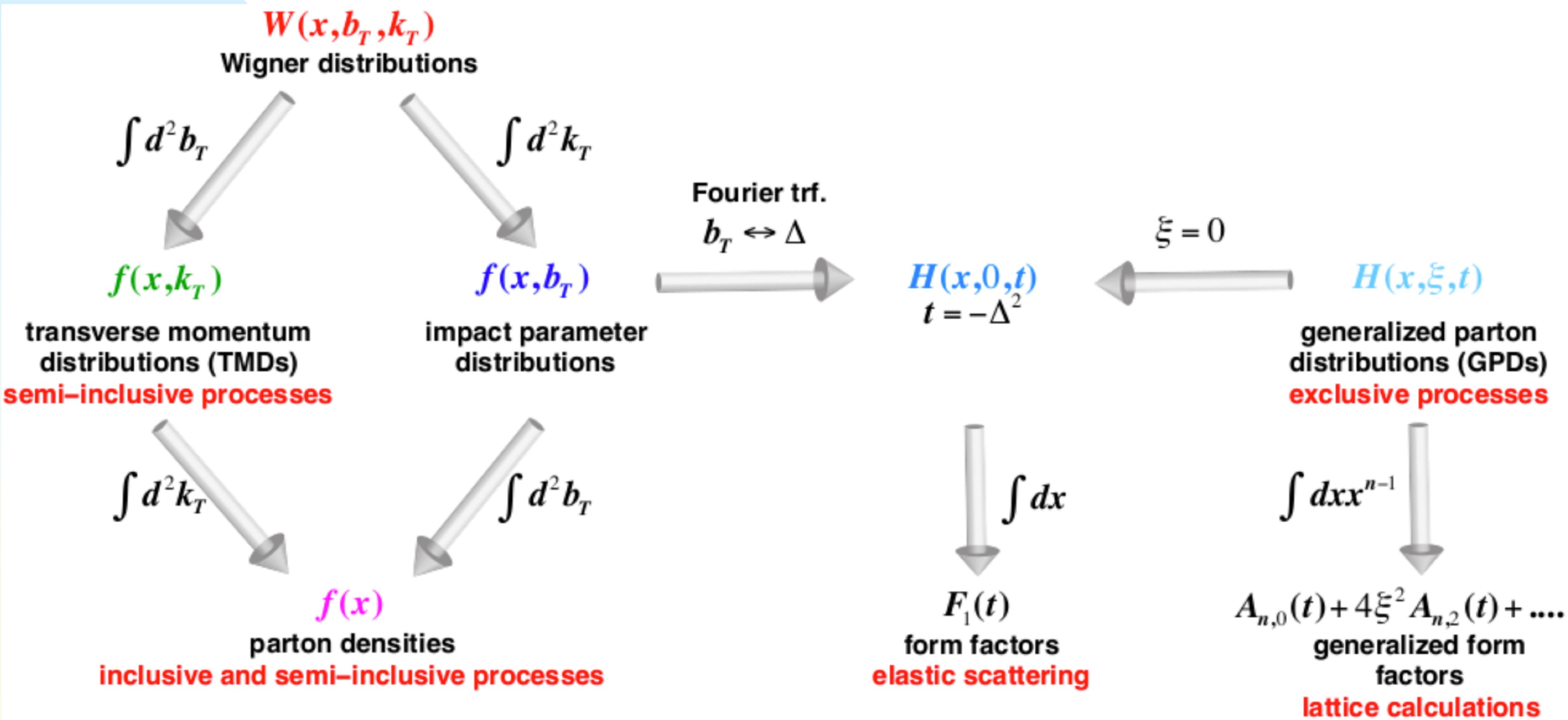
Backup

ATHENA baseline tracking

- Silicon vertex detector using 65 nm CMOS
  - 6 forward disks, 5 layer barrel, 5 backward disks
- MPGD forward disk and barrel layer



Full information – the Wigner distribution



From the EIC White Paper

Experimental requirements for ep/A-> ep/AVX

- Most studied VM are 2-prong decays:
  - J/ψ, $\psi(2S)$, $\Upsilon(1S)\to l^+l^-$, $\Upsilon(2S)\to l^+l^-$, $\Upsilon(3S)\to l^+l^-$
  - $\rho\to\pi^+\pi^-$, $\Phi\to K^+K^-$
  - Higher Ψ and Υ are of interest, but have had much less attention
- Reconstruct full final state?
  - Can get by without electron at low Q^2
    - HERA shows this works
    - Scattered protons somewhat accessible; scatter heavy ions are not
      - Detection of light ions highly desirable, but difficult
- Acceptance to cover full Bjorken-x range
  - For photoproduction, photon energy $k = M_V/2 \exp(-y)$
  - $x_{BJ}= M_V/(2\gamma m_p) \exp(y)$; γ is ion Lorentz boost
    - For Υ, rapidity range is roughly $-3 < y < 3$
      - Threshold corresponds to $y \sim 3.1$
- Need to determine if the target nucleon/nucleus broke up

Vector meson rates in 10 fb^{-1}/A

Accelerator	σ					Number of events				
	ρ^0	ϕ	J/ψ	ψ'	$\Upsilon(1S)$	ρ^0	ϕ	J/ψ	ψ'	$\Upsilon(1S)$
eRHIC - *ep*	5.0 μb	230.0 nb	8.5 nb	1.4 nb	14.0 pb	50 giga	2.3 giga	85 mega	14 mega	140 kilo
eRHIC - *eA*	870.0 μb	55.0 μb	1.9 μb	320.0 nb	1.2 nb	44 giga	2.8 giga	100 mega	16 mega	60 kilo
JLEIC - *ep*	3.7 μb	160.0 nb	3.9 nb	600.0 pb	4.3 pb	37 giga	1.6 giga	39 mega	6.0 mega	43 kilo
JLEIC - *eA*	580.0 μb	33.0 μb	590.0 nb	82.0 nb	-	28 giga	1.6 giga	28 mega	3.9 mega	-
LHeC - *ep*	10.0 μb	560.0 nb	47.0 nb	7.8 nb	120.0 pb	100 giga	5.6 giga	470 mega	78 mega	1.2 mega
LHeC - *eA*	2.3 mb	170.0 μb	15.0 μb	2.9 μb	41.0 nb	110 giga	8.2 giga	720 mega	140 mega	2.0 mega
HERA - *ep*	7.9 μb	450.0 nb	40.0 nb	6.4 nb	85.0 pb	-	-	-	-	-

TABLE III. The cross-sections and rates for VM photoproduction ($Q^2 < 1$ GeV^2) at the proposed EICs, and at HERA.

Accelerator	σ					Number of events				
	ρ^0	ϕ	J/ψ	ψ'	$\Upsilon(1S)$	ρ^0	ϕ	J/ψ	ψ'	$\Upsilon(1S)$
eRHIC - *ep*	14.0 nb	1.7 nb	570.0 pb	120.0 pb	2.4 pb	140 mega	17 mega	5.7 mega	1.2 mega	24 kilo
eRHIC - *eA*	730.0 nb	110.0 nb	77.0 nb	19.0 nb	200.0 pb	37 mega	5.6 mega	3.9 mega	960 kilo	10 kilo
JLEIC - *ep*	10.0 nb	1.2 nb	270.0 pb	55.0 pb	790.0 fb	100.0 mega	12 mega	2.7 mega	550 kilo	7.9 kilo
JLEIC - *eA*	450.0 nb	67.0 nb	25.0 nb	5.1 nb	-	22 mega	3.2 mega	1.2 mega	250 kilo	-
LHeC - *ep*	26.0 nb	3.7 nb	2.9 nb	630.0 pb	18.0 pb	260 mega	37 mega	29 mega	6.3 mega	180 kilo
LHeC - *eA*	2.0 μb	340.0 nb	560.0 nb	150.0 nb	5.3 nb	100 mega	16 mega	27 mega	7.2 mega	250 kilo
HERA - *ep*	44.0 nb	6.4 nb	17.0 nb	3.6 nb	120.0 pb	-	-	-	-	-

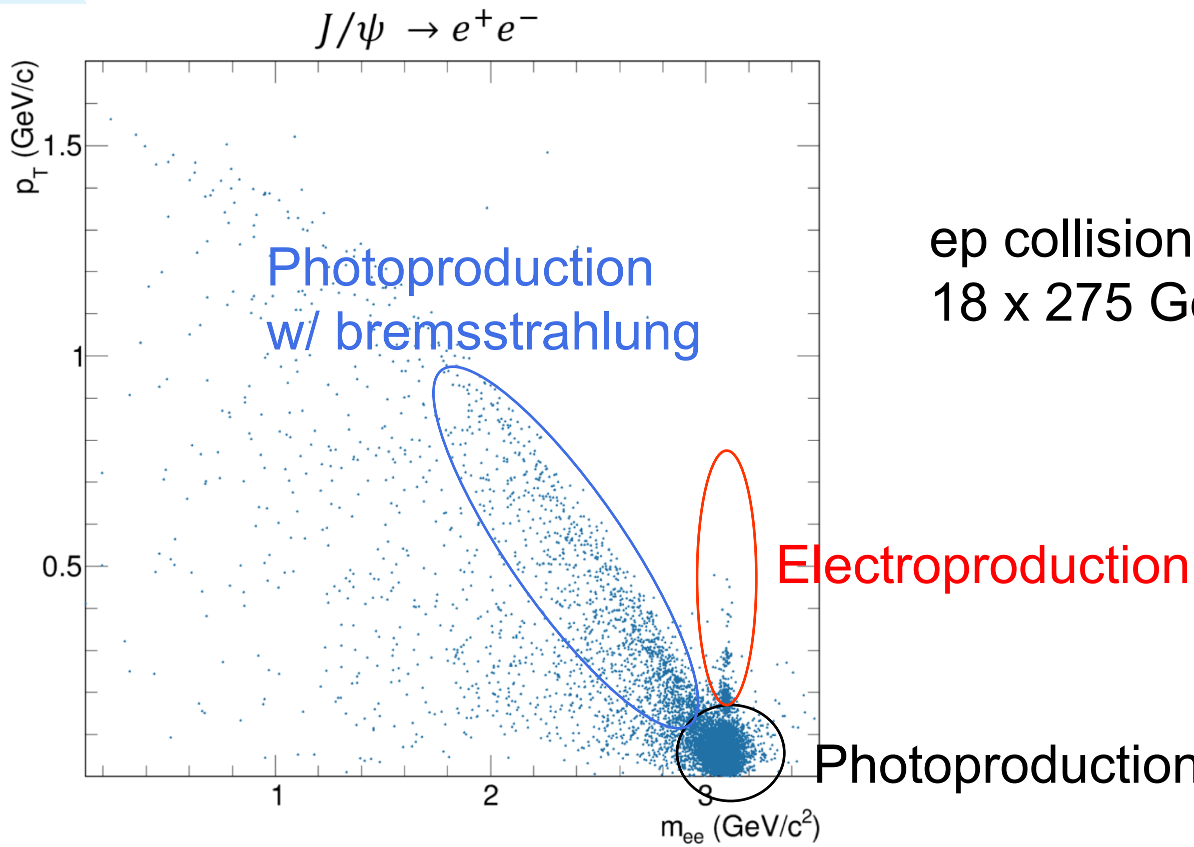
TABLE IV. The cross-sections and rates for VM electroproduction ($Q^2 > 1$ GeV^2) at the proposed EICs and at HERA.

$\Upsilon(2S)$ $\Upsilon(3S)$ somewhat lower than $\Upsilon(1S)$

From eSTARlight; M. Lomnitz and SK, Phys. Rev. C99, 015203 (2019)

Thin detectors required for J/ψ etc. ->e^+e^-

- Bremsstrahlung causes signal confusion
- There is also a background from γγ->e^+e^-
  - OK @ HERA, but larger in eA collisions

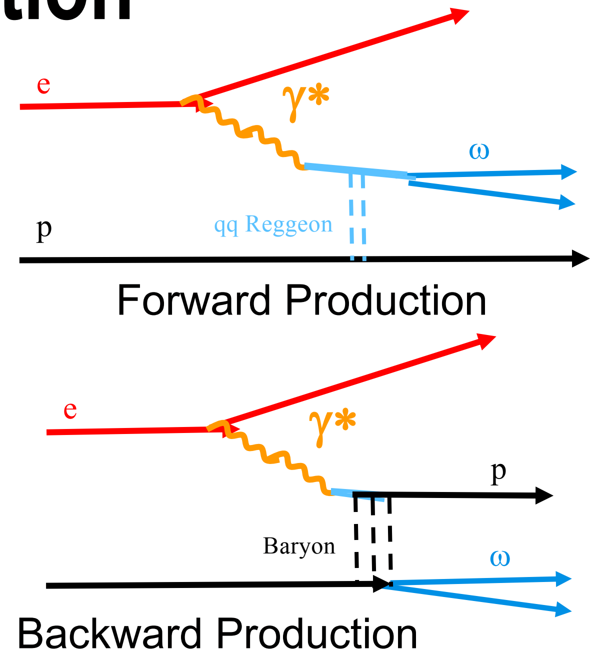


ep collisions
18 x 275 GeV

J. Arrington et al., arXiv:2103.08337 & YR

Backward (u-channel) J/ψ production

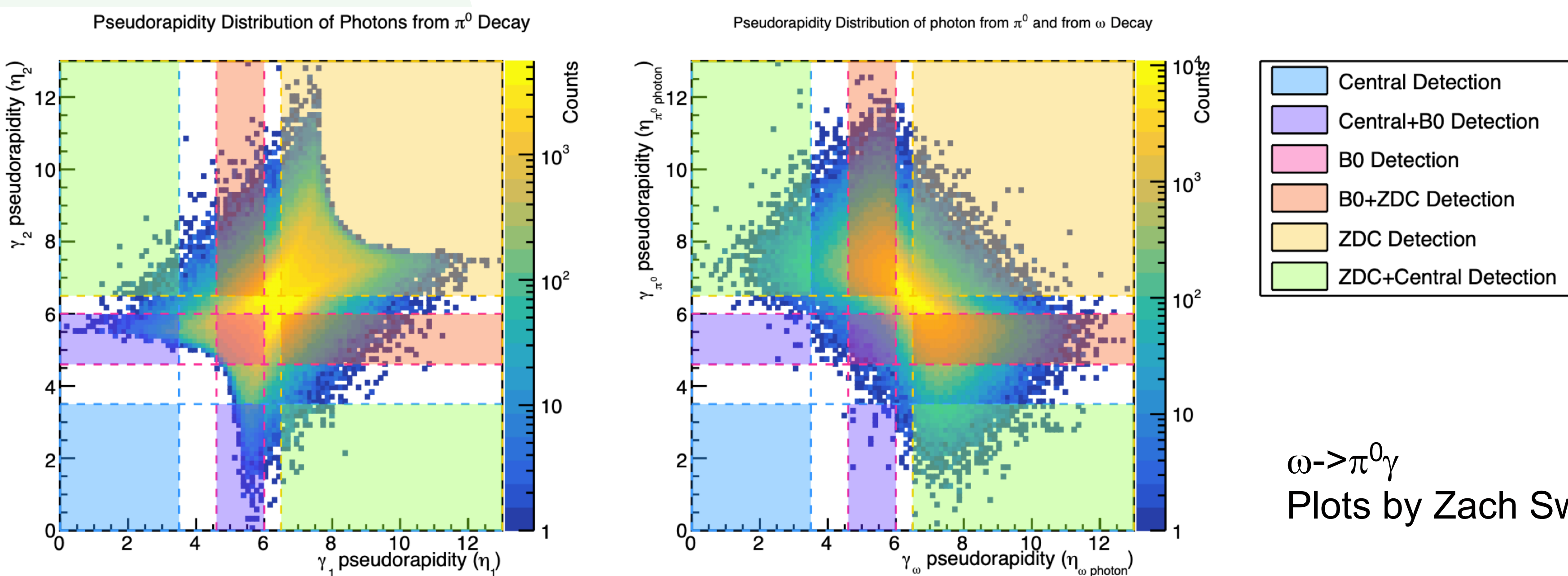
- t is large and u is small
  - In γp center-of-mass frame, meson and proton switch places
  - The meson is far-forward, while the proton is at mid-rapidity
- Studied at fixed target accelerators
  - Only light mesons
    - Proton and meson share quark flavors
    - Production models using Transition Distribution Amplitudes (TDA, like GPDs) or Regge trajectories involving baryons
- Cross-section parameterized for the ω
  - For ω, $d\sigma/du \sim 4.4\ \mu b/GeV^2\ (s/1GeV)^{-2.7}\ \exp(-21\ GeV^{-2}u)$
  - At EIC, backward ω rate is ~~~ few percent of forward ω rate
    - J/ψ rate 1,000-10,000 times lower????
      - If so, backward J/ψ are accessible



SK, Aaron Stanek, Sam Heppelman, Zach Sweger, et al., to appear
C. Ayerbe Gayoso et al., arXiv:2107.06748

Kinematics of backward production at the EIC

- Forward vector meson + mid-rapidity proton (+ electron for $Q^2>0$)
- Meson detection in central detector ($|\eta|<3.5$), B0 detector ($4.6 < \eta < 6.0$) and ZDC ($\eta>6.5$)
  - Different sensitive regions for charged and neutral products
- For light mesons:
  - 18 x 275 GeV beams -> some products in ZDC
  - 10 x 100 GeV beams -> products in B0
- Heavier mesons (like J/ψ) have smaller $<\eta>$
  - B0 and central detector



$\omega \to \pi^0\gamma$

Plots by Zach Sweger

Dissociation products

- For protons, p->Δ^+ -> nπ^+, pπ^0 is fairly easy to see
  - Pion carries substantial energy
- Heavy nuclei can emit, in order of decreasing likelihood
  - Neutrons
    - In LHC UPC production of J/ψ on lead, 7% of incoherent production does not include neutrons
    - Seen by Zero Degree Calorimeters, except at large p_T
  - Protons
    - Seen by off-axis spectrometer, B0 detector etc.
  - Photons
    - Seen in ZDC and B0 converter or calorimeter

M. Strikman et al, Phys. Lett. **B626**, 72 (2005)

Models of Incoherent production

- BEAGLE
  - qqbar dipole scatters from a single nucleon, which recoils
  - Recoil causes an intra-nuclear cascade, leading to dissociation.
    - Microscopic model.
  - At low energies, photonic excitations may appear
  - nucleon-free fraction depends on |t|
    - Expected – nuclear breakup depends on available energy
  - Rejection < ~ 1/50 at large |t|
- Sartre
  - Similar dipole to BEAGLE
  - Nucleus diffractively dissociates, with fragments ~ $1/M^2$
  - Nuclear breakup is from the GEMINI++ intranuclear cascade code
- Large theoretical uncertainties from intranuclear cascades

M. D. Baker, https://wiki.bnl.gov/conferences/images/f/f7/ERD17-2020-06-plus.pdf
T. Toll and T. Ullrich, *Comput.Phys.Commun.* **185** (2014) 1835-1853

Energy conservation and dσ/dt

- Nucleon emission from heavy nuclei is endothermic
  - Neutron emission requires 8.07 / 7.38 MeV for ^{197}Au/^{208}Pb
  - Proton emission requires 5.27 / 7.5 MeV for ^{197}Au/^{208}Pb
- Without this energy, nucleon emission is impossible
  - Nucleon emission disappears as t -> 0
- IF the Pomeron exchange leads to single nucleon recoil in the target (as in the Beagle model), then we can find the required momentum transfer
  - Single nucleon supported by STAR UPC ρ^0 photoproduction data
  - p_{min} ~ 100 MeV/c, so t_{min}~0.01 GeV^2
  - Nucleon emission is not possible at smaller t
- The nuclear final state must depend on t
  - We cannot measure at large t, and expect it to hold as t drops

STAR, Phys. Rev. C **96**, 054904 (2017)

Final states for photonic de-excitation

- For E< 1-5 MeV, the final state is a well defined shell-model state
  - Fixed energy, spin, parity
    - Better described with nuclear shells than using nucleon positions and momentum, which are known only probabilistically
  - At higher energies, multiple photons are emitted
- For photonic excitation, energy loss is quantized
- For ^{208}Pb, the lowest lying excited state is at 2.6 MeV
  - $J^{\pi}=3^{-}$, so production is marginal, due to angular momentum
  - In the single nucleon paradigm (questionable here), this corresponds to p_{min} ~ 70 MeV/c, t_{min} ~ 0.005 GeV^2
- For ^{197}Au, the lowest lying excited state is at 77 keV
  - τ=1.9 nsec, so the excited nucleus escapes the detector
    - These excitations are not detectable
  - Next lowest states are at 269 keV and 279 keV
- Lead is preferred for vector meson studies

Detecting excitation photons

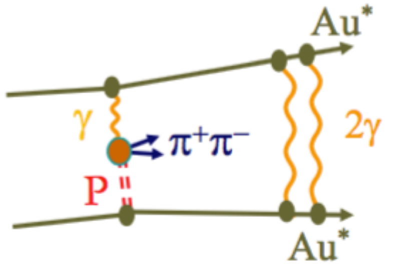
- The photons are Lorentz boosted
- Most hit the ZDC or B0 detector
- Maximum Lorentz boost is 2γ ~ 234 at full EIC ion energy
  - 600 MeV for 2.6 MeV lead photons
  - ~ 65 MeV for 270 keV gold photons
- Typical Lorentz boost is lower, and some photons are downshifted.
  - Lead is much easier than gold, even neglecting the long-lived 77 keV state

New approaches to calculation and experiment?

- An intranuclear cascade model could be used to find the final state in terms of nucleon positions, etc., and then the overlap with different final states, but this is not the natural approach
- It may be better to consider the final state directly from the matrix elements
  - $\sigma \sim |\langle A^*| \mathcal{P} |A\rangle|^2$, where $\mathcal{P}$ is the Pomeron excitation
- Relevant data would help!
  - Small downstream high-resolution EM calorimeter at RHIC/ LHC
    - E_γ ~ 1 MeV*Lorentz boost: 100 MeV (RHIC) 3 GeV (LHC)
      - Good resolution is required to resolve lines.
    - Also of interest to study Lows theorem & low-energy bremsstrahlung
  - HPGe detector at Jlab for vector meson photoproduction
    - Excitation γ-rays coincident with vector meson production
    - Caveat: t_{min} is pretty high since the beam energy is low
      - Study lighter mesons?

Cautions, questions and caveats

- Breakup into A>1 fragments is possible, but probably unlikely
- Can a recoiling nucleon emit bremsstrahlung γ w/o breakup?
  - eA->eVγA
    - Rate is probably low
- What are the real requirements for coherence?
  - Same initial and final state?
  - $\sigma = | \Sigma_i A_i \exp(ikx)|^2$
    - AA->A*A* V (ρ, ρ',J/ψ) still exhibits coherence
- Strictly speaking, Good-Walker applies only for stable final states.



Miettinen and Pumplin, Phys. Rev. Lett. 42, 204 (1979).

Caneschi and Schwimmer, Nucl. Phys. **B133**, 408 (1978).