Measurements of mesons at ePIC

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UNIVERSITÀ DELLA CALABRIA
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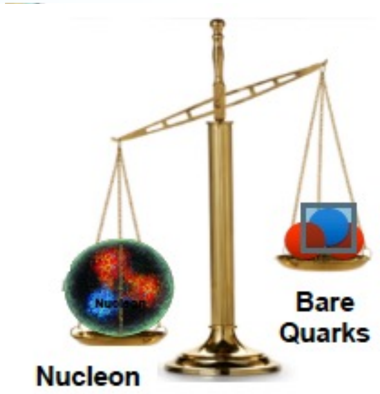
Istituto Nazionale di Fisica Nucleare

Workshop on: "Synergies between LHC and EIC for quarkonium physics"

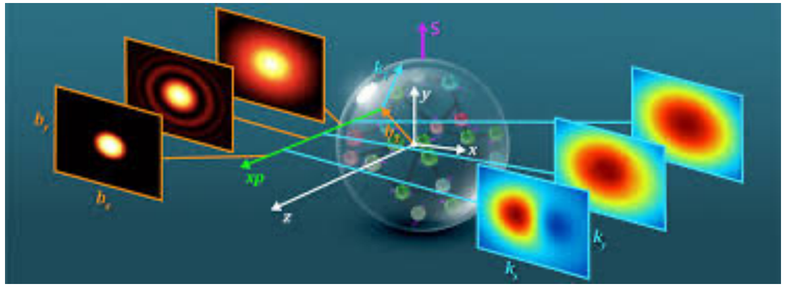
ECT*, Trento (Italy) – July 8-12, 2024

Most compelling physics GOALS

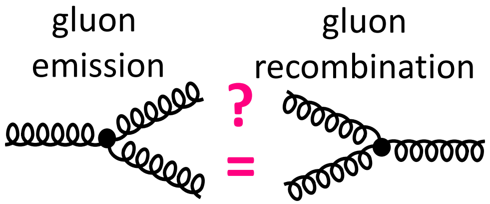


Origin of hadron mass

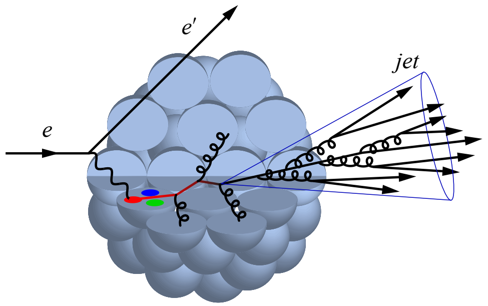
Origin of proton spin



3D structure of hadrons (tomography)

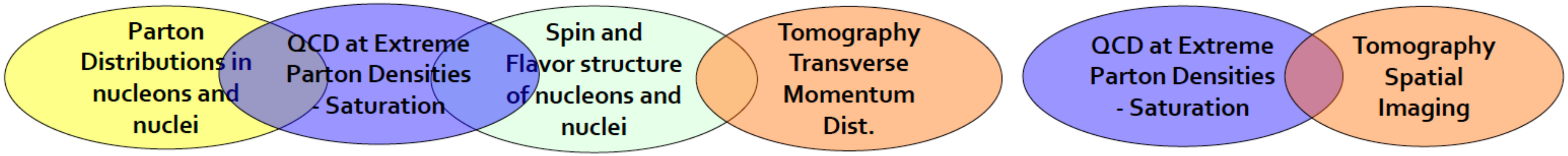


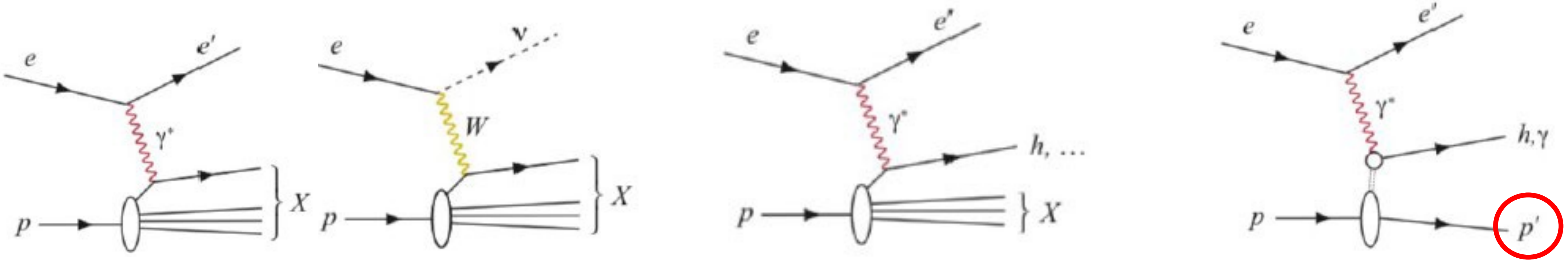
Gluon saturation



Nuclear effects

What process must be measured?



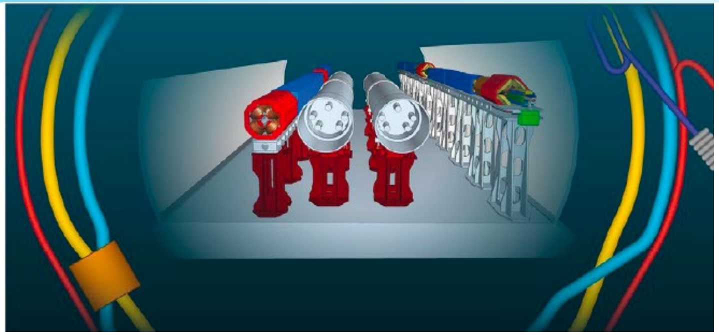


NC & CC Inclusive DIS | **Semi-Inclusive DIS** | **Exclusive Reactions**

$\int \mathcal{L}dt$: $\sim 1\ \mathrm{fb}^{-1}$ | $\sim 10\ \mathrm{fb}^{-1}$ | $\sim 100\ \mathrm{fb}^{-1}$

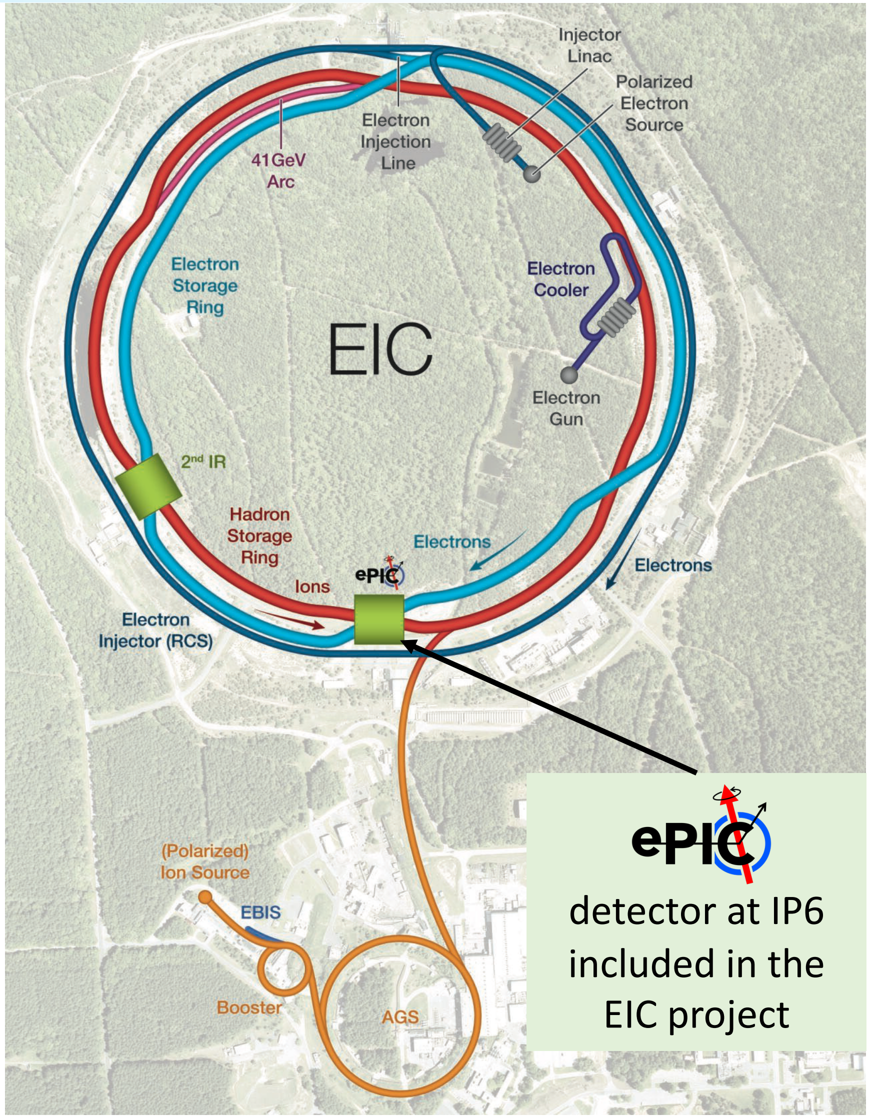
The Electron-Ion Collider

A DOE approved project!
Could be the only new collider
in the coming ~20-30 years



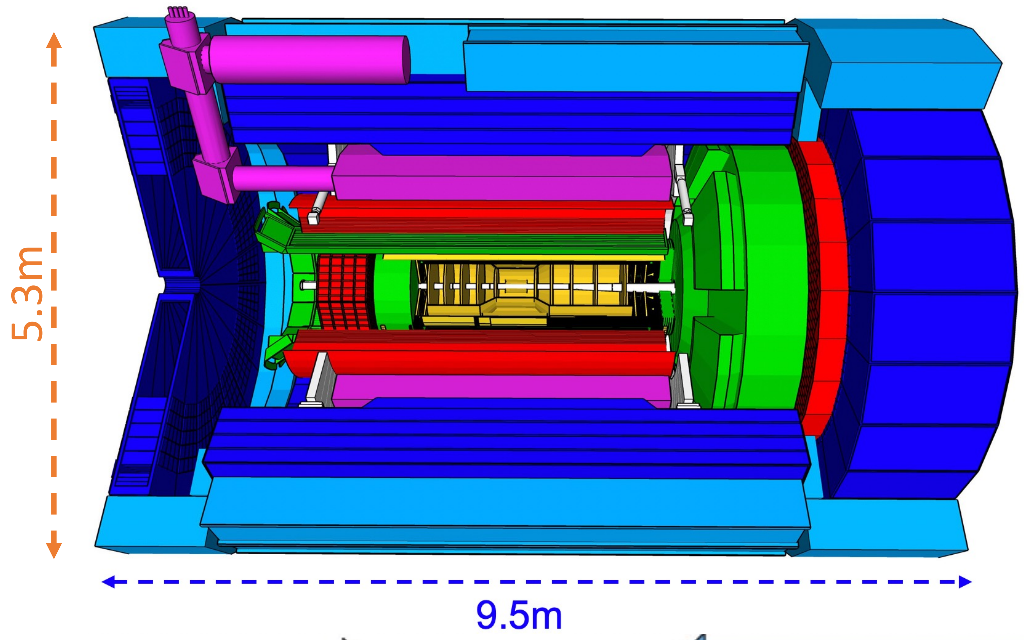
- ✓ Add a 5 to 18 GeV electron storage ring (same tunnel) & its injector complex to the RHIC facility
- ✓ Two interaction regions, IP6 and IP8
- ✓ High Luminosity: 10^{33} -10^{34} $cm^{-2}s^{-1}$ (~10^2-10^3 times HERA)
- ✓ Flexible $\sqrt{s}$ = 29-141 GeV (per nucleon)
- ✓ Highly polarized (~70%) $e^{\uparrow}, p^{\uparrow}, d^{\uparrow}, He^{\uparrow}$, flexible spin pattern
- ✓ Wide variety of nuclear beams: (D to U)

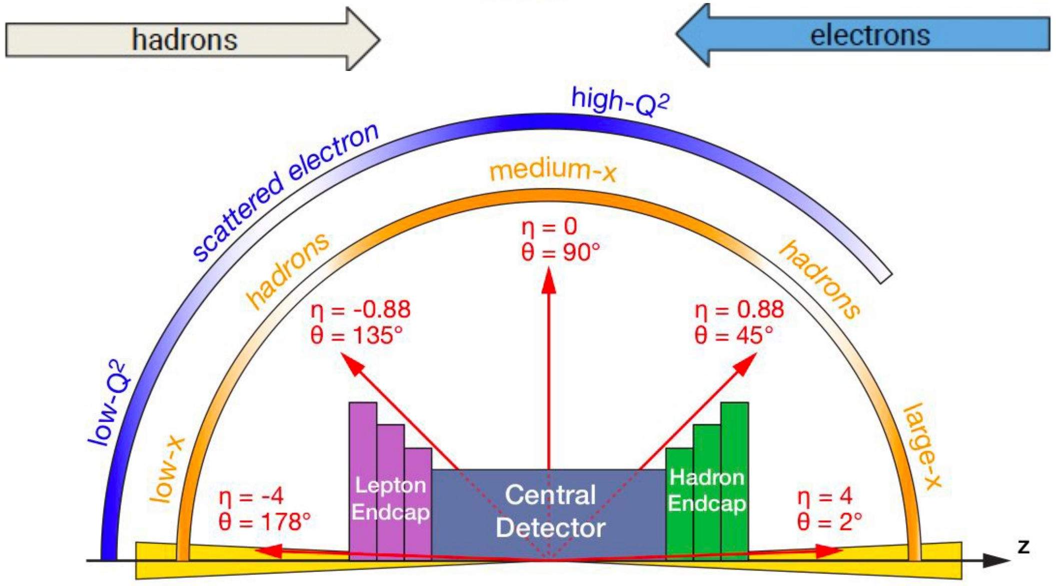
World's first Polarized electron-proton/light ion and electron-Nucleus collider



ePIC detector at IP6 included in the EIC project

The ePIC detector





Tracking

- New 1.7 T solenoid
- Si MAPS (vertex, barrel, forward, backward disks)
- MPGDs (μRWELL/μMegas) (barrel, forward, backward disks)

Particle identification

- High performance DIRC (barrel)
- Dual radiator (aerogel+gas) RICH (forward)
- Proximity focusing RICH (aerogel) (backward)
- TOF (~30ps): AC-LGAD (barrel and forward)

E.M. Calorimetry

- Imaging EMCAL (barrel)
- W-powder/ScFi (forward)
- $PbWO_4$ crystals (backward)

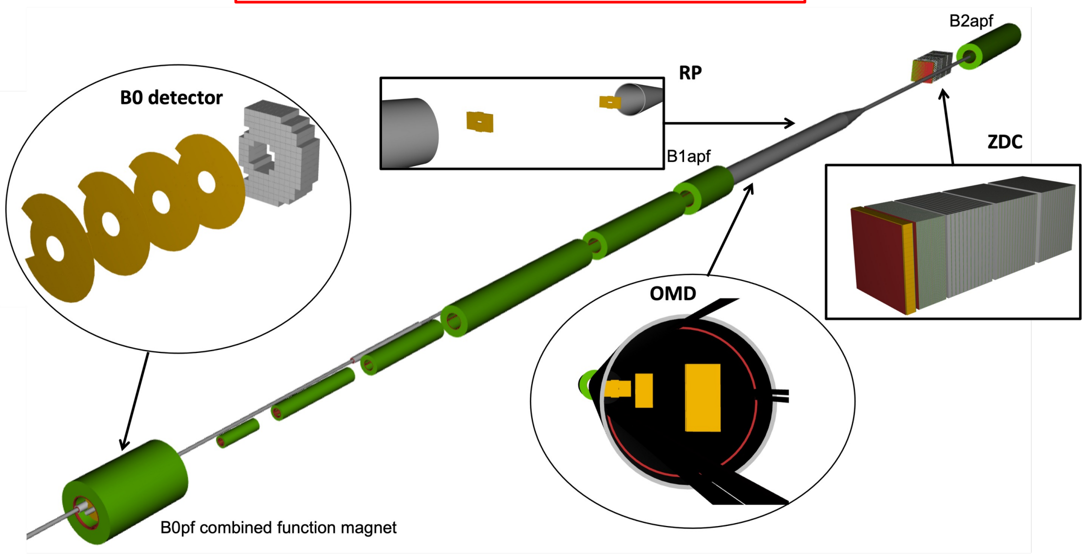
Hadronic Calorimetry

- Fe/Scint reuse from sPHENIX (barrel)
- Steel/Scint - W/Scint (backwards/forward)

DAQ: streaming/triggerless with AI

Far forward/backwards detectors

Far Forward spectrometers



Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	θ < 5.5 mrad (η > 6)
Roman Pots (2 stations)	0.0 < θ < 5.0 mrad (η > 6)
Off-Momentum Detectors (2 stations)	θ < 5.0 mrad (η > 6)
B0 Detector	5.5 < θ < 20.0 mrad (4.6 < η < 5.9)

The impact parameter information encoded in $t = (p' - p)^2$

- Scattered protons measured by
  - Roman Pots (low t)
  - B0 (higher t)

Far Backwards detectors

Figure: Low-Q^2 taggers

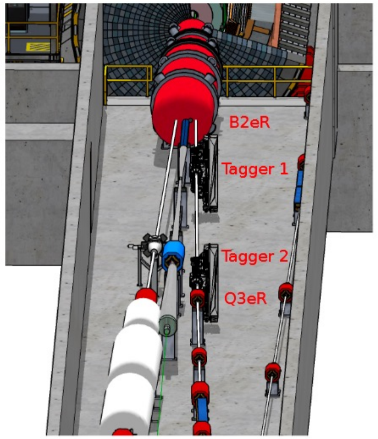
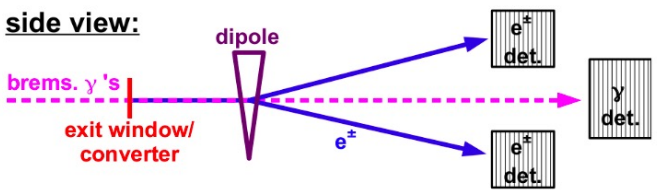
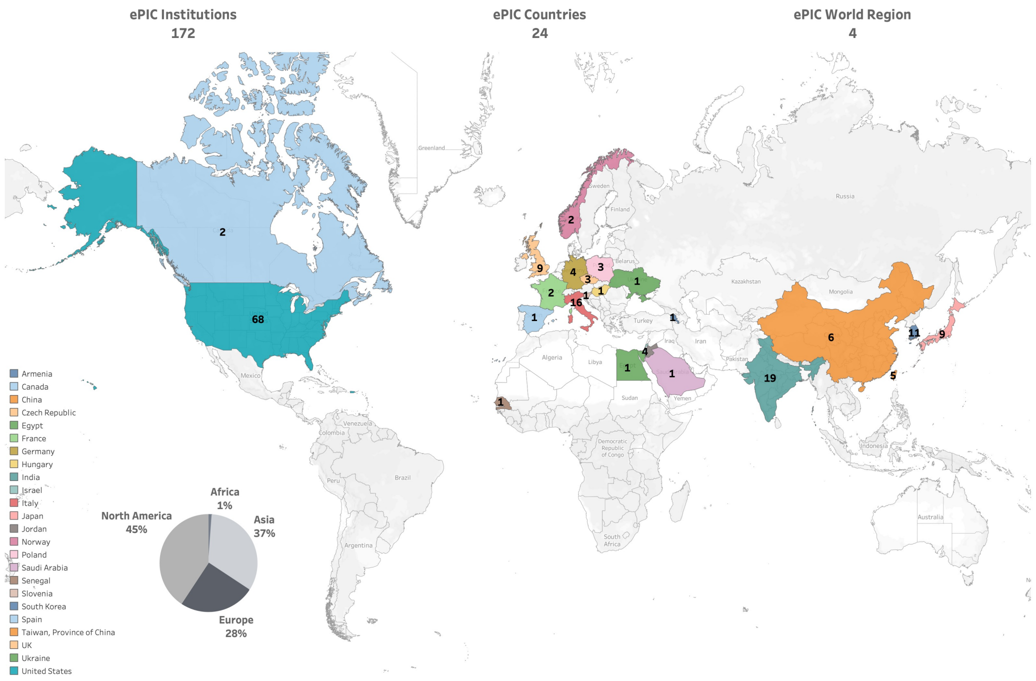


Figure: Luminosity detector



- High precision luminosity measurement at 1% level for absolute luminosity and 0.01% for relative luminosity measurement using several methods based on the Bremsstrahlung process:
- Low Q2 taggers - PHP tagger

The ePIC Collaboration



A truly global pursuit for a new experiment at the EIC

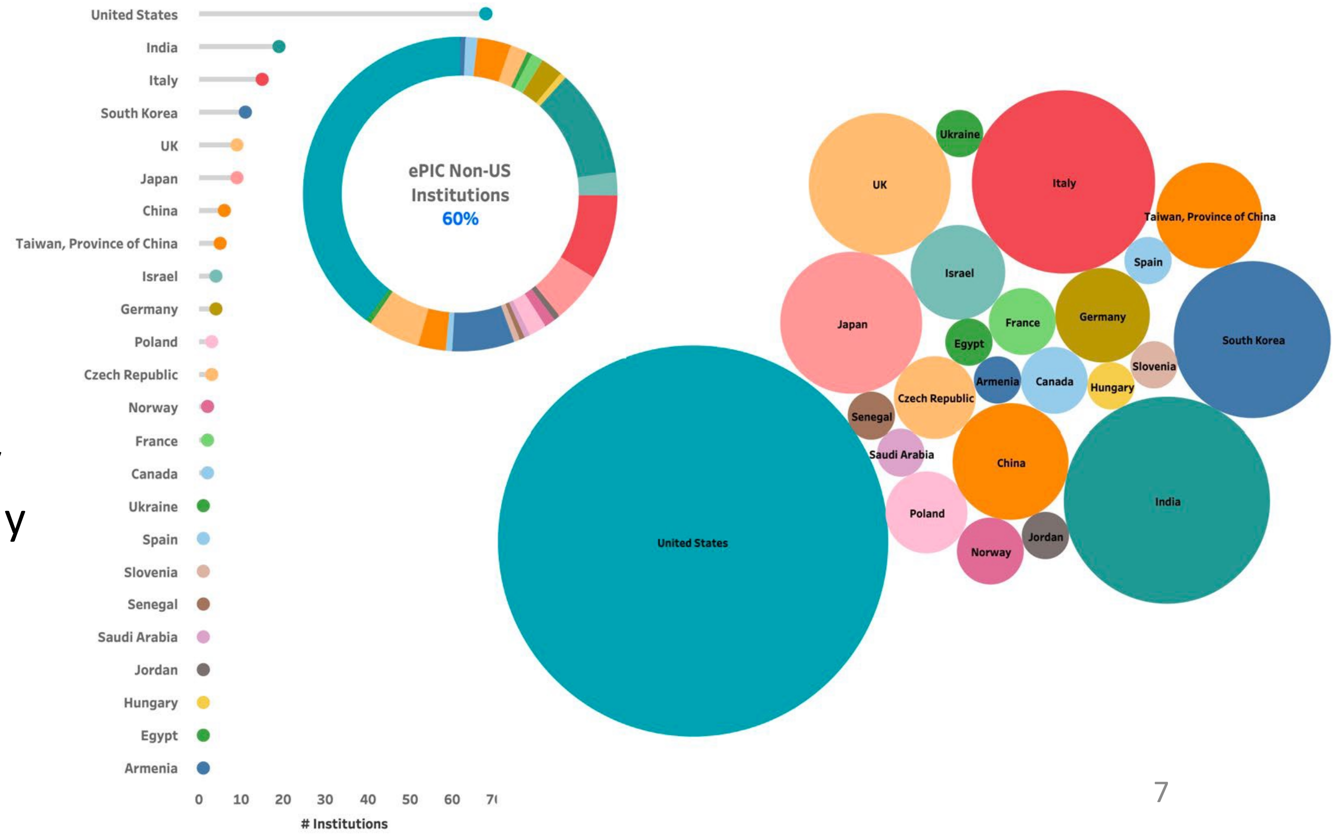
(Official statistics at November 2023)

24 Countries; 173 Institutions and counting!

500+ scientists and counting!

Pathway:

- Detector down in ~6 y
- Operations start in ~7 y



Structure of the ePIC Physics Working Groups

ANALYSIS COORDINATORS
Salvatore Fazio (Cosenza)
Rosi Reed (Lehigh)

- Each PWG convener is for a two-years term
  - Rotations in each PWG are staggered every year
- Conveners in blue are ending their term after Lehigh meeting

INCLUSIVE PHYSICS
Tyler Kutz (MIT)
Claire Gwenlan (Oxford)

Meeting time: Mondays (biweekly) at 12pm ET
Mailing list: eic-projdet-Inclusive-l@lists.bnl.gov
Indico: https://indico.bnl.gov/category/417/

SEMI-INCLUSIVE PHYSICS
Charlotte Van Hulse (Alcala)
Stefan Diehl (UConn)

Meeting time: Tuesdays (biweekly) at 8:30am ET
Mailing list: eic-projdet-semiincl-l@lists.bnl.gov
Indico: https://indico.bnl.gov/category/418/

JETS AND HEAVY FLAVOR
Brian Page (BNL)
Olga Evdokimov (UIC)

Meeting time: Wednesdays (biweekly) at 12:00pm ET
Mailing list: eic-projdet-jethf-l@lists.bnl.gov
Indico: https://indico.bnl.gov/category/420/

EXCLUSIVE, DIFFRACTION AND TAGGING
Raphael Dupre (Orsay)
Rachel Montgomery (Glasgow)

Meeting time: Mondays (biweekly) at 12pm ET
Mailing list: eic-projdet-excldiff-l@lists.bnl.gov
Indico: https://indico.bnl.gov/category/419/

BSM AND PRECISION EW
Ciprian Gal (JLab)
Michael Nycz (Virginia)

Meeting time: Tuesdays (biweekly) at 8:30am ET (together with Inclusive PWG)
Mailing list: eic-projdet-semiincl-l@lists.bnl.gov
Indico: https://indico.bnl.gov/category/421/

ePIC Technical Design Report and paper on physics

Technical Design Report (TDR) is our current top priority

pre–TDR (60% design completion) ⟹ early 2025

TDR (90% design completion) ⟹ ~ early 2026

TDRs will have a chapter on of detector performance for physics

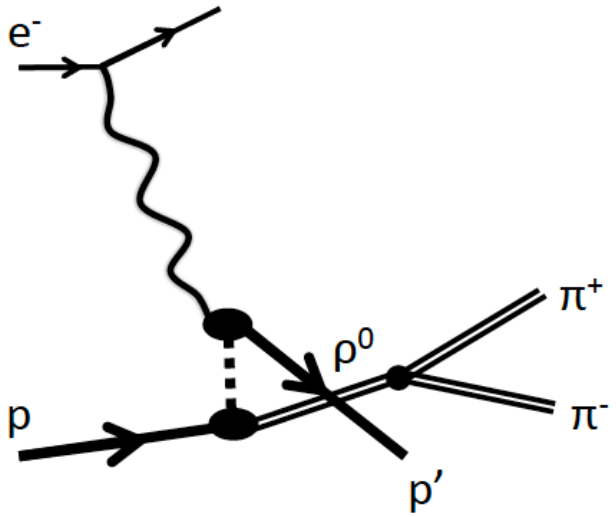
- Extended paper on ePIC's Physics on a peer-reviewed journal
  - **Extended description** of the physics performance and science reach at ePIC
    - Holistic detector performance
    - Physics and science reach
  - Gives full details on physics studies and performance plots
  - Includes physics impact studies (extraction of physics, e.g. PDFs, GPDs, TMDs)

❖ Spin-off papers can also be published by individual study groups **(theorists included)**

Science content - Outlook

- Show a bunch of ongoing studies on meson production
  - Priority to processes challenging the detector
  - All are based on full GEANT simulation
  - All are sensitive to the reconstruction: still crude but quickly improving by the day
- I am a listener here
  - During discussion we would love to here from this community
    - What can ePIC do for quarkonia?
    - New projects we should look at?
    - Opportunities for closer collaboration?

u-Channel ρ^0

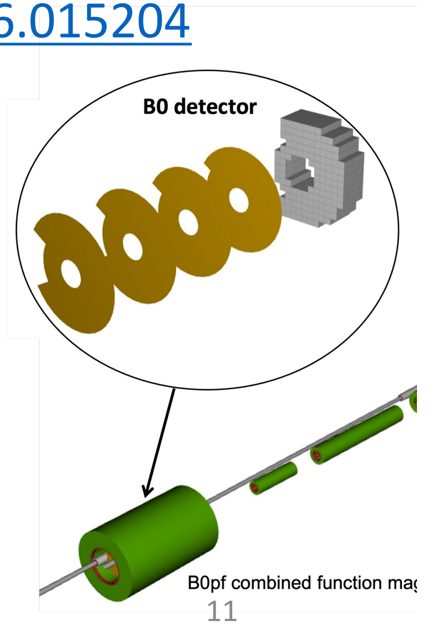


u-channel $\rho^0 \rightarrow \pi^+\pi^-$

- Low Mandelstam *u*, high *t*
- Backwards (*u*-channel) physics → nucleon/nuclear tomography
- Forward (*t*-channel) cross-sections → parton tomography via GPDs
- Backwards cross-sections → quark clusters and baryon number distributions in transverse plane via Transition Distribution Amplitudes (TDAs)
- See published paper: https://journals.aps.org/prc/abstract/10.1103/PhysRevC.106.015204

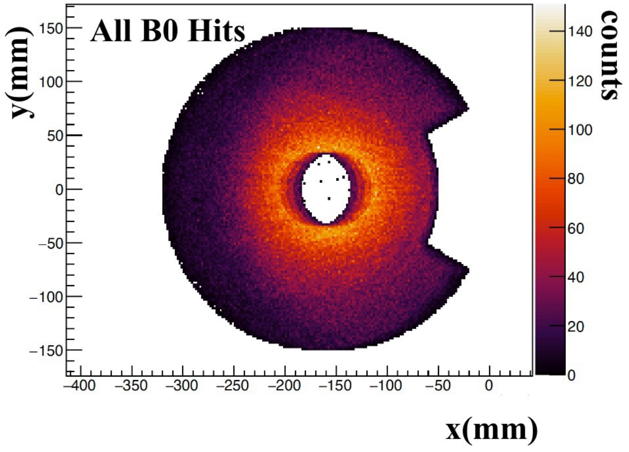
In ePIC:

- Produced VM takes most of momentum of struck nucleon → goes to the far-forward region
  - B0 spectrometer critical for measuring $\rho^0 \rightarrow \pi^+\pi^-$
- Struck nucleon shifts of several units in rapidity → ends up in mid-rapidity
- Simulation studies based on an edited version of the eSTARlight generator

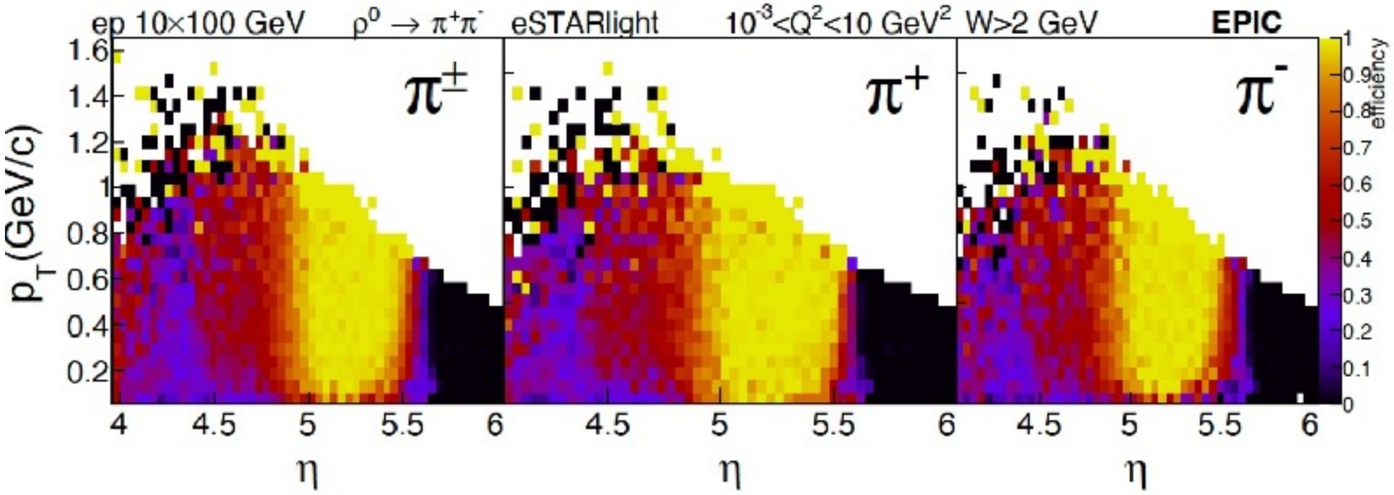


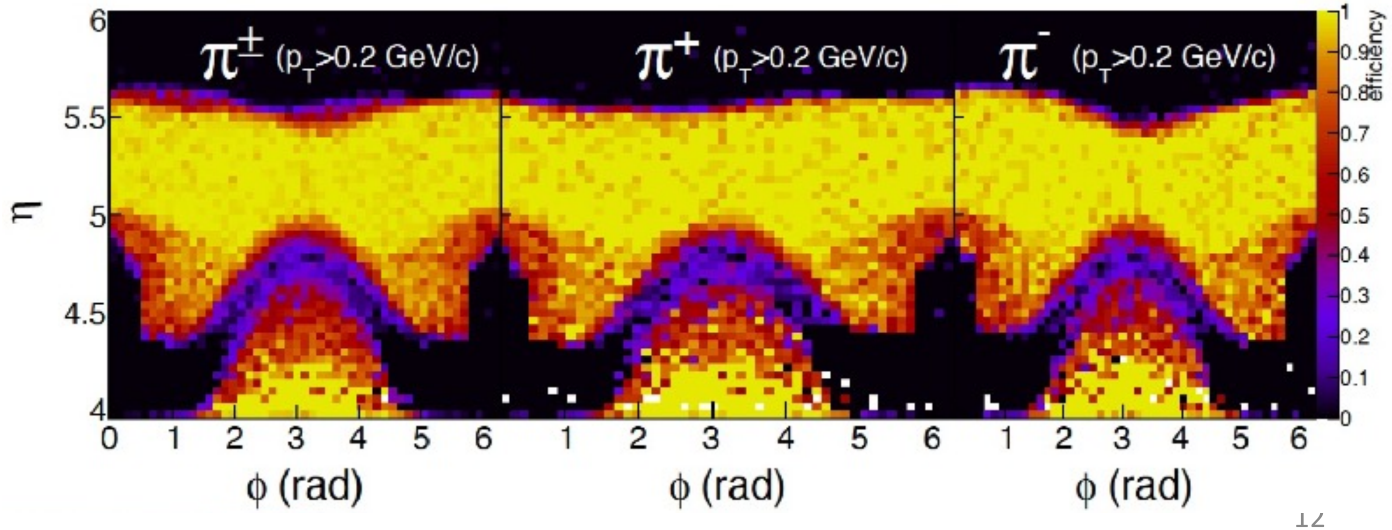
u-Channel ρ^0

$\rho^0 \rightarrow \pi^+\pi^-$ in the B0

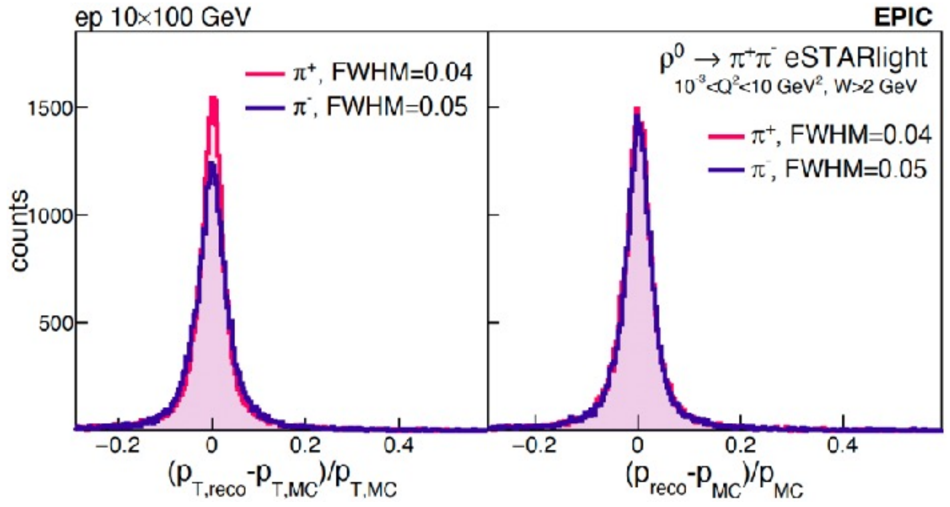


$\pi^+\pi^-$ reconstruction efficiency



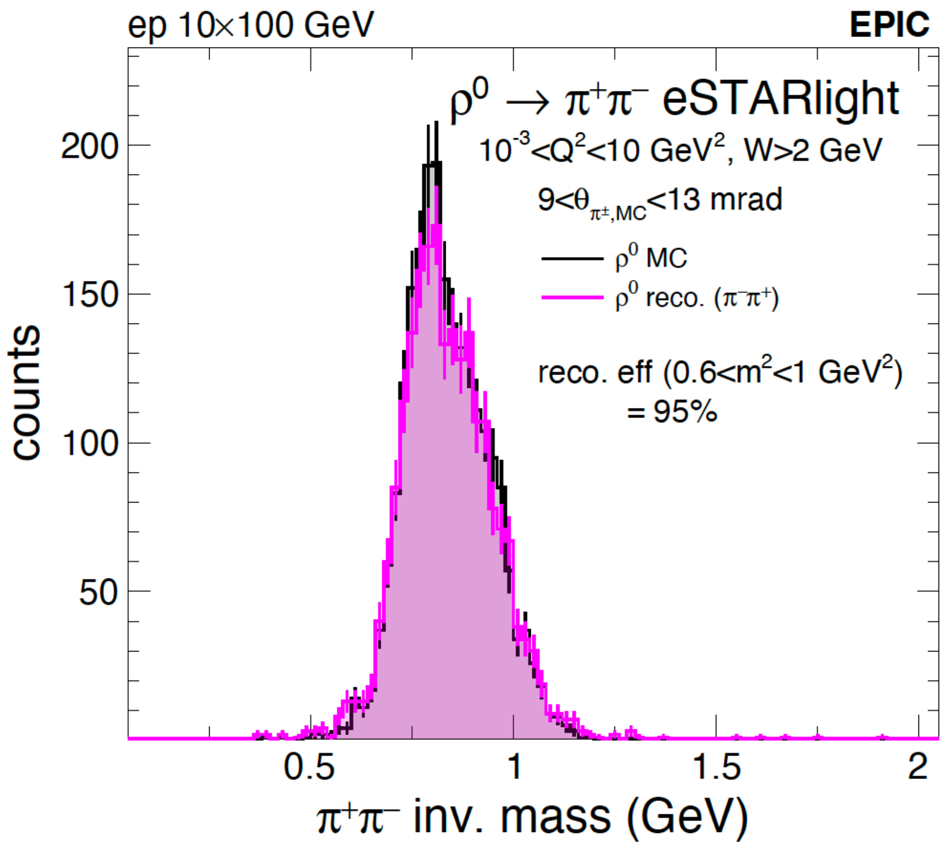


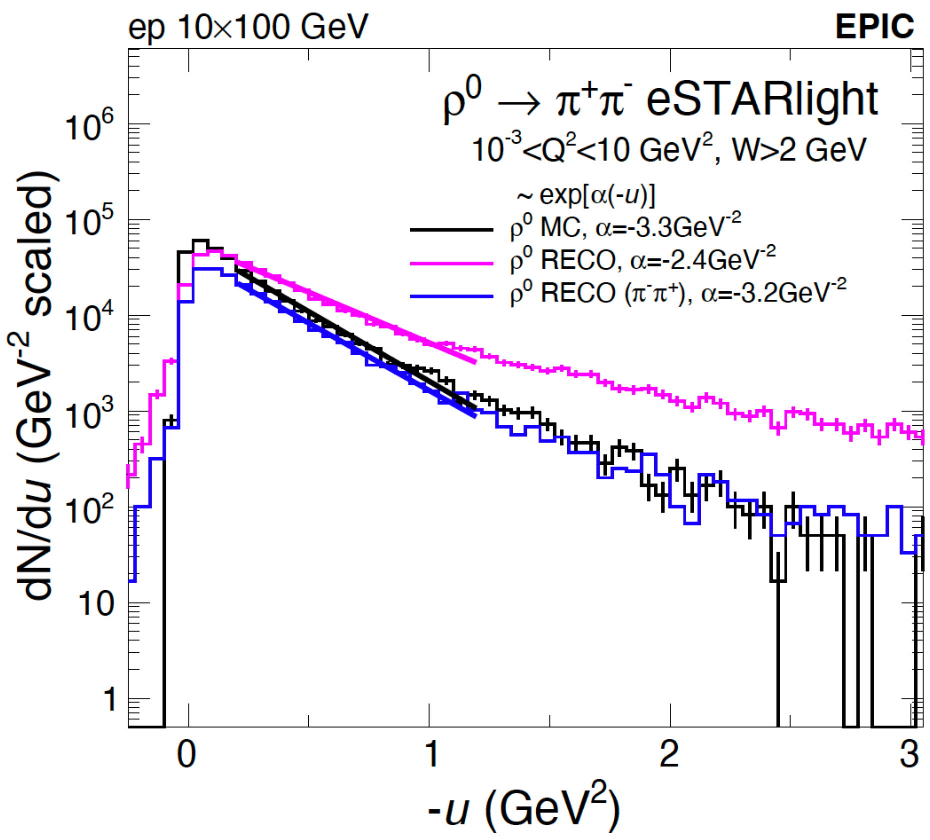
$\pi^+\pi^-$ reconstruction resolution (%)



Plots: Z. Sweger (UCDavis)

u-Channel ρ^0





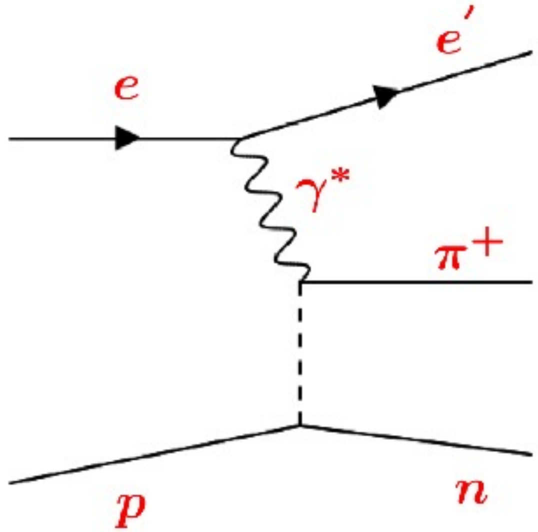
Invariant mass reconstruction

- Reco. efficiency = 95%
  - flagged bad if <90%

u-channel ρ^0 cross section slope reconstruction

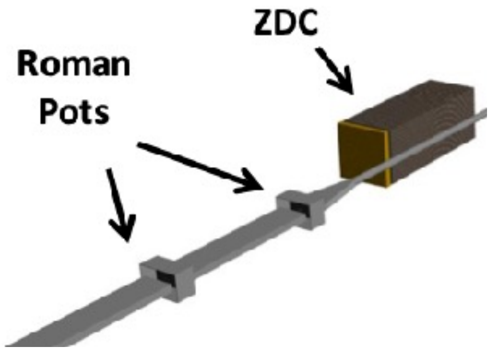
Plots: Z. Sweger (UCDavis)

Meson form factors



$$ep \rightarrow e'\pi^+n$$

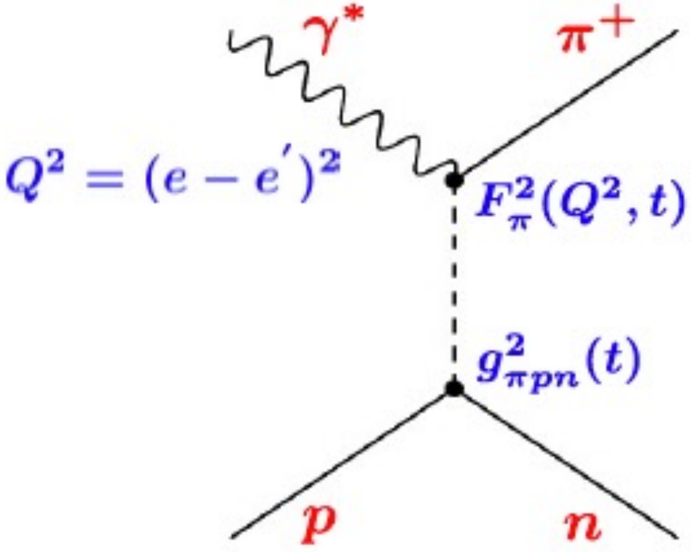
- Enigma of emergent hadronic mass
- Pion form factor under study, all final state particles reconstructed
  - e' and π^+ in central detector
  - n in FF region (mainly ZDC)
- At small $-t$, the pion pole process dominates σ_L



- In the Born model [In practice one uses a more sophisticated model], F_π^2 appears as

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)^2} g_{\pi pn}^2(t) F_\pi^2(Q^2,t)$$

- Q^2 and $-t$ reconstruction resolution is crucial for extracting F_π^2 from the measured cross section



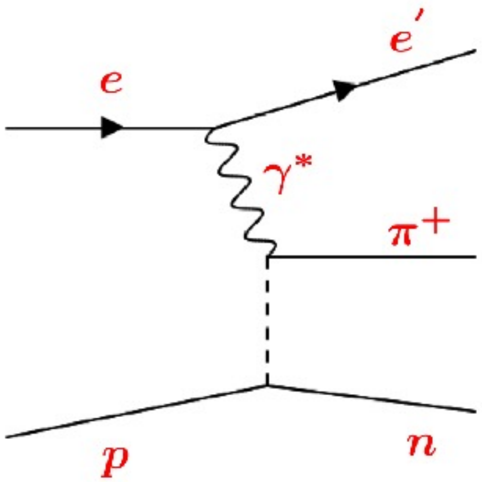
Plots: L. Preet (Regina)

Meson form factors

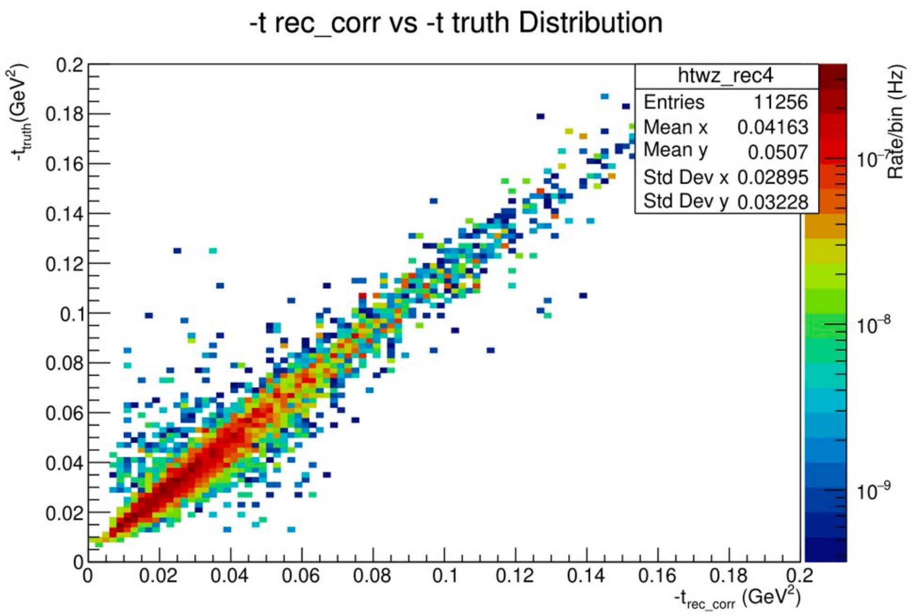
- **Best method:** $-t$ reconstruction using corrected *n* track
  - See paper: https://www.sciencedirect.com/science/article/abs/pii/S0168900223002280
  - n_{corr} is constructed using missing momentum information:

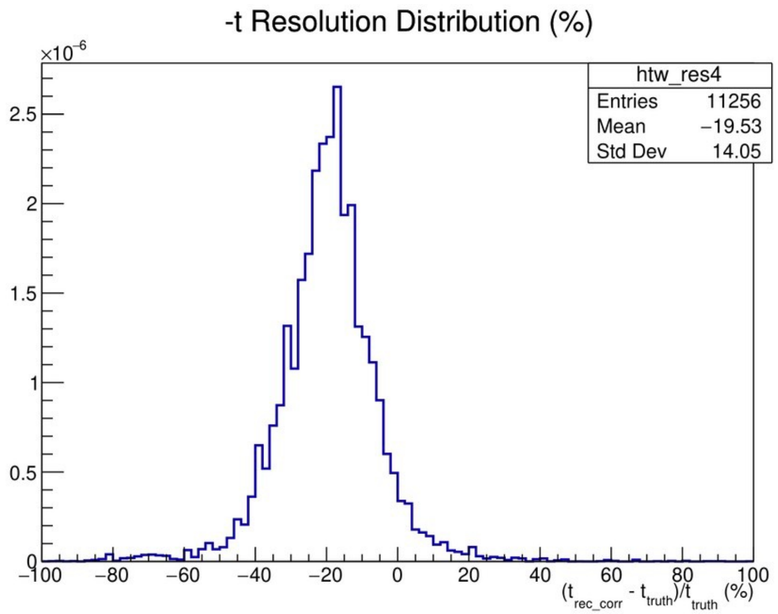
$$p_{miss} = |\vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}|$$

  - And replacing $\theta_{Miss}, \phi_{Miss}$ with θ_{ZDC}, ϕ_{ZDC}, and fixing the neutron mass



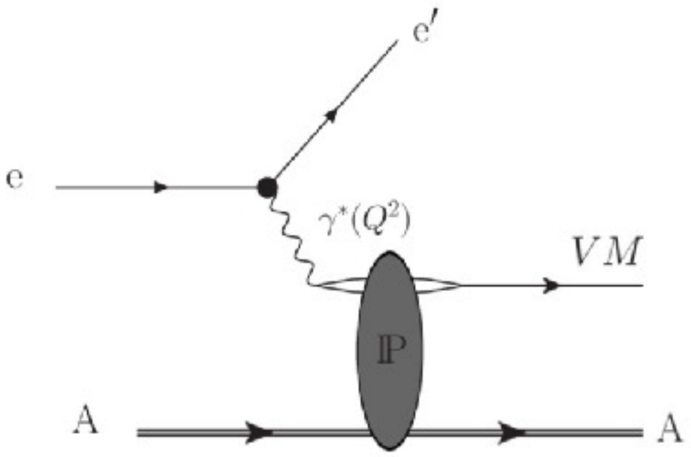
$$-t_{truth} = -(\gamma^* - \pi^+)^2 \qquad -t_{rec\_corr} = -(p - n_{corr})^2$$



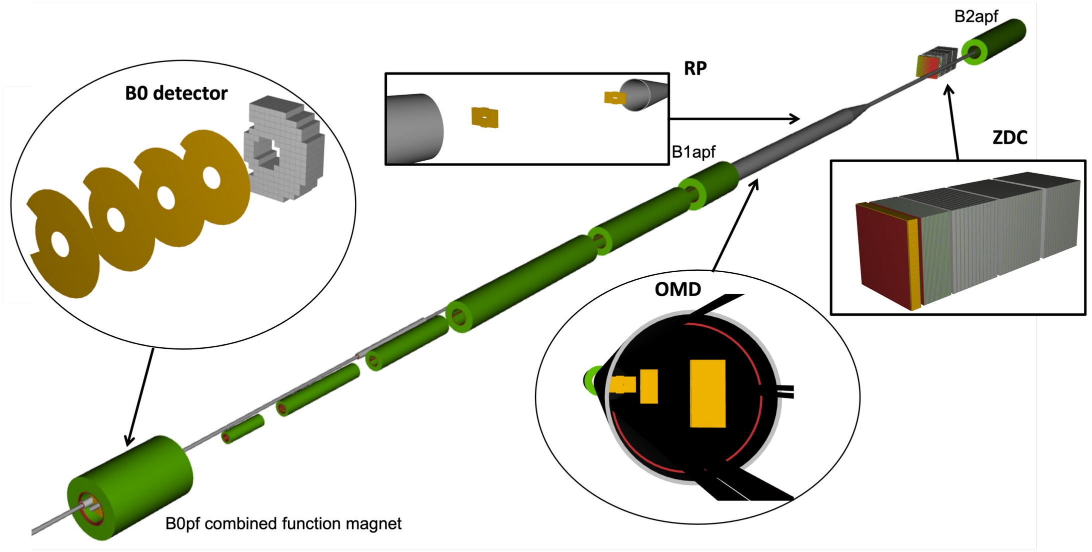


Plots: L. Preet (Regina)

Diffractive vector meson production in eA (J/ψ)



- Probe low-*x* structure
- Sensitivity to gluon distributions in nucleon/nuclei
- Probe spatial parton structure of nuclei
- Challenges: veto incoherent background, *t*-reconstruction

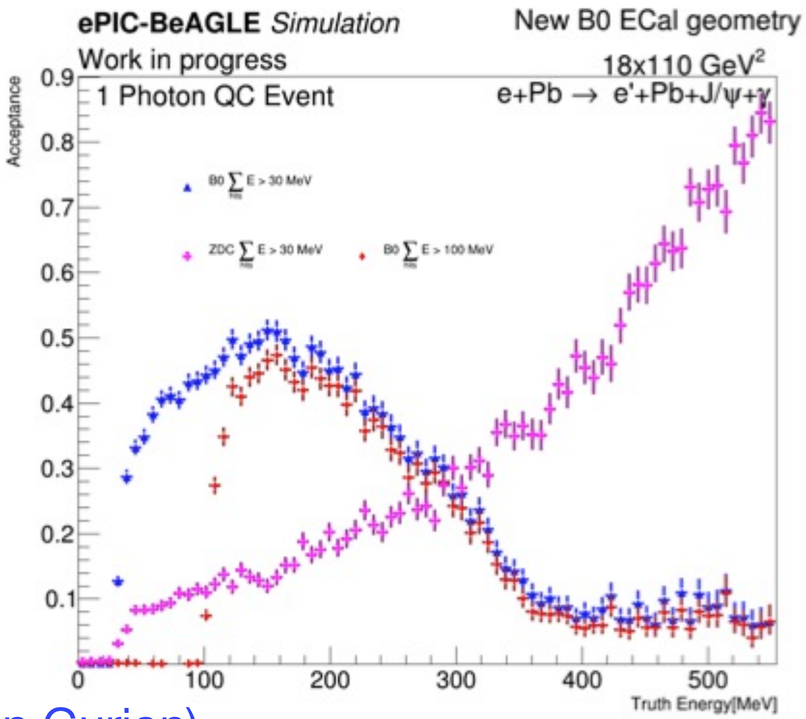


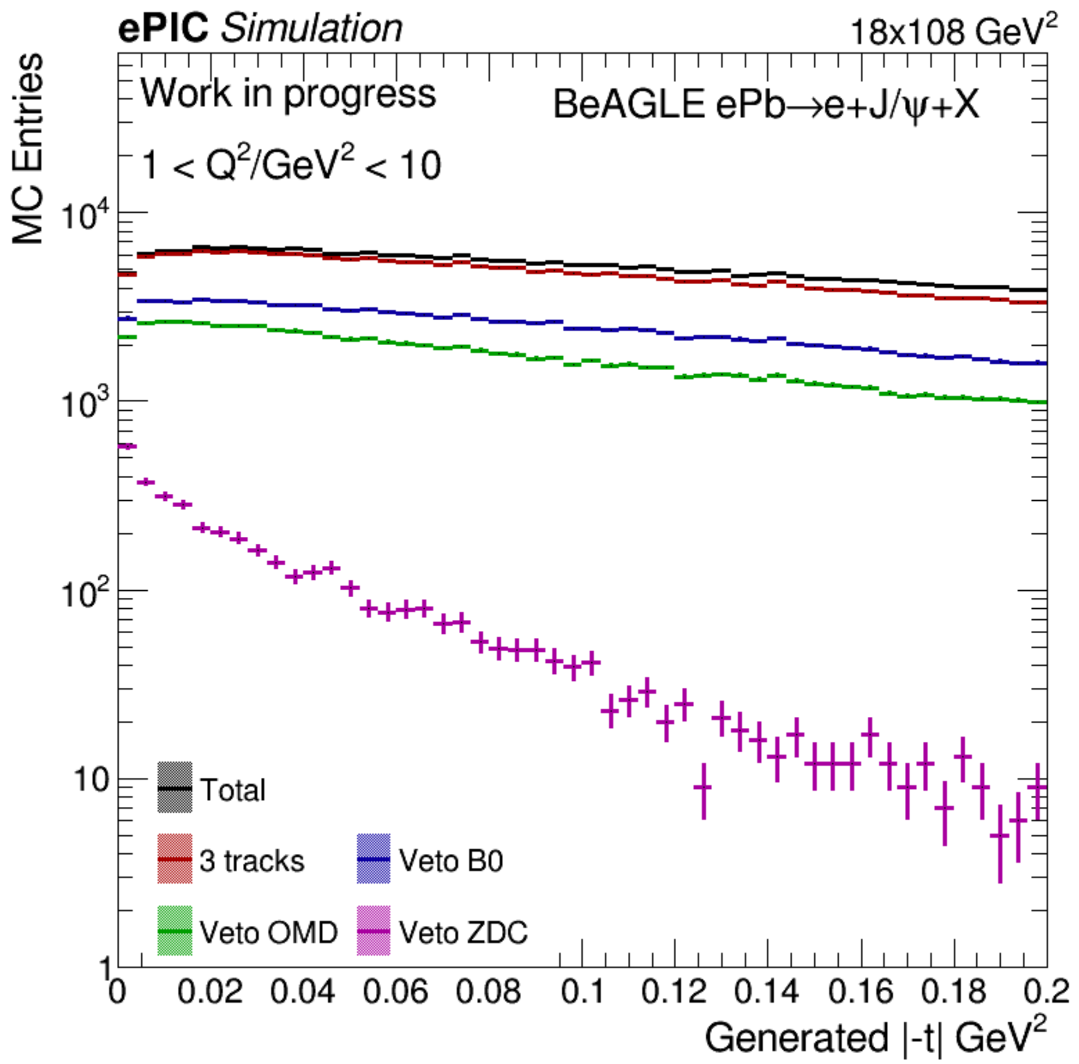
Coherent event Selection (J/ψ)

- 3 track events (at least two tracks in main detector)
- J/psi mass window of 0.4 GeV (no PID)
- Veto activity in forward region (reco/hits):
  - B0 tracks, B0 clusters, Hits in OMD/RPs, Ecal and Hcal ZDC Clusters

Diffractive vector meson production in eA (J/ψ)

- Veto of incoherent events: promising veto performance
  - Majority of remaining background is photons from quasi-coherent events (J/Psi+Pb+photon)
    - Good sensitivity to those events in B0/ZDC
    - Some work still needed on clustering for photons in B0/ZDC to allow check of energy resolution



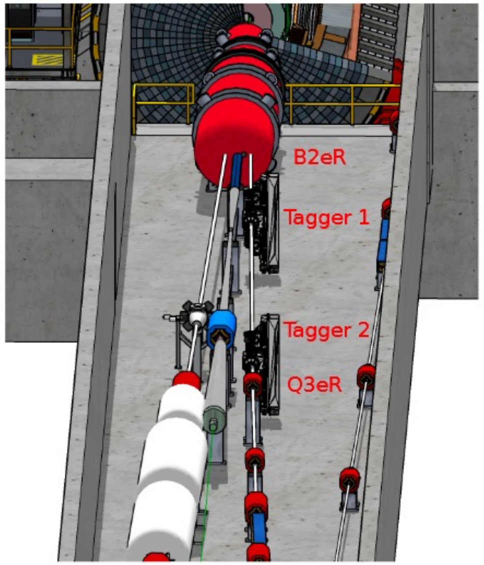


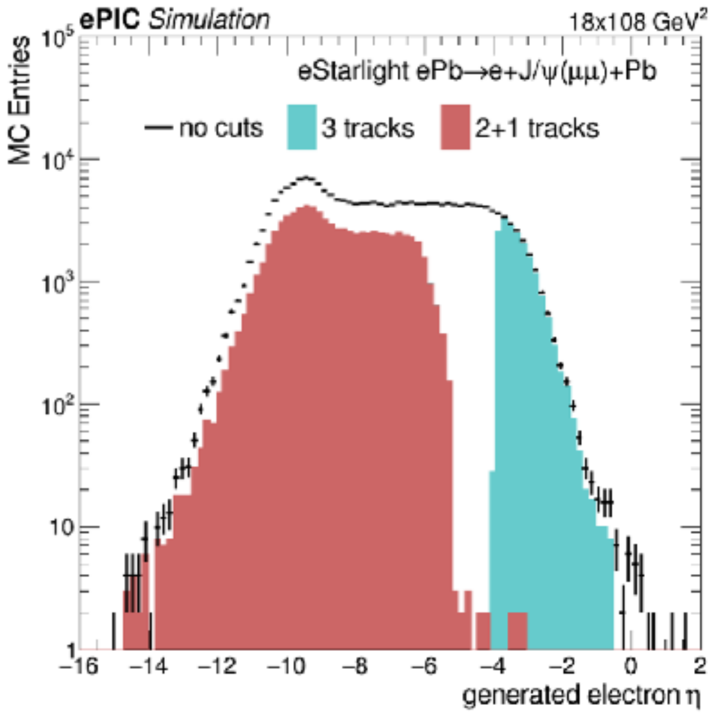
Plots: M. Pitt (Ben Gurion)

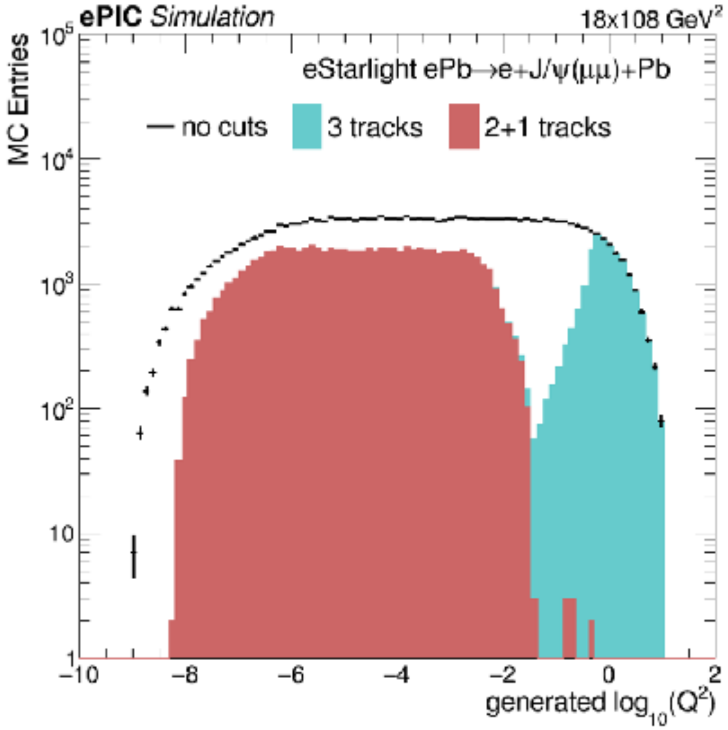
Diffractive vector meson production in eA (J/ψ)

- Phase space can be extended by use of low Q^2 tagger
  - Increases statistics and reduces uncertainty on e', can eventually help t-reconstruction

Figure: Low-Q^2 taggers





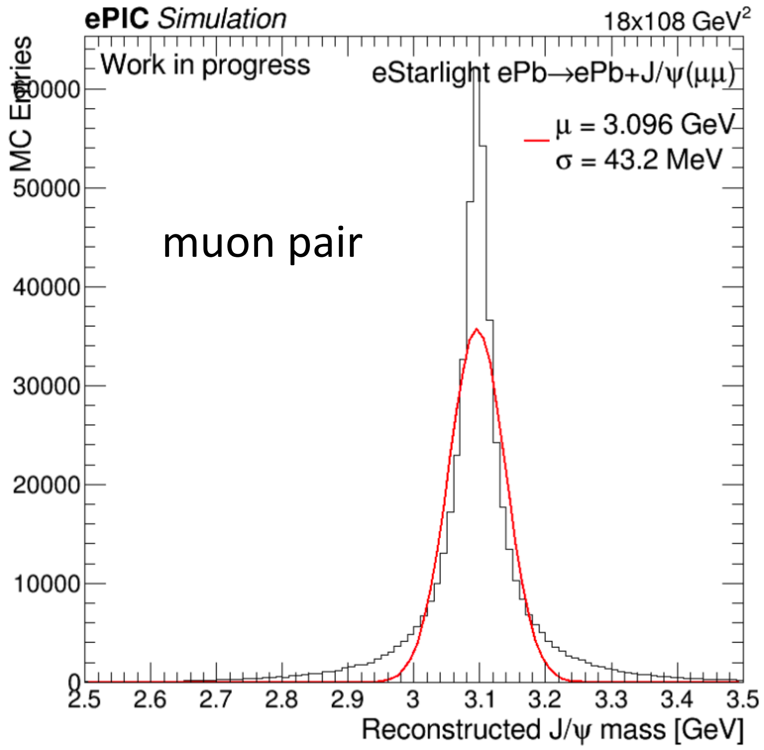


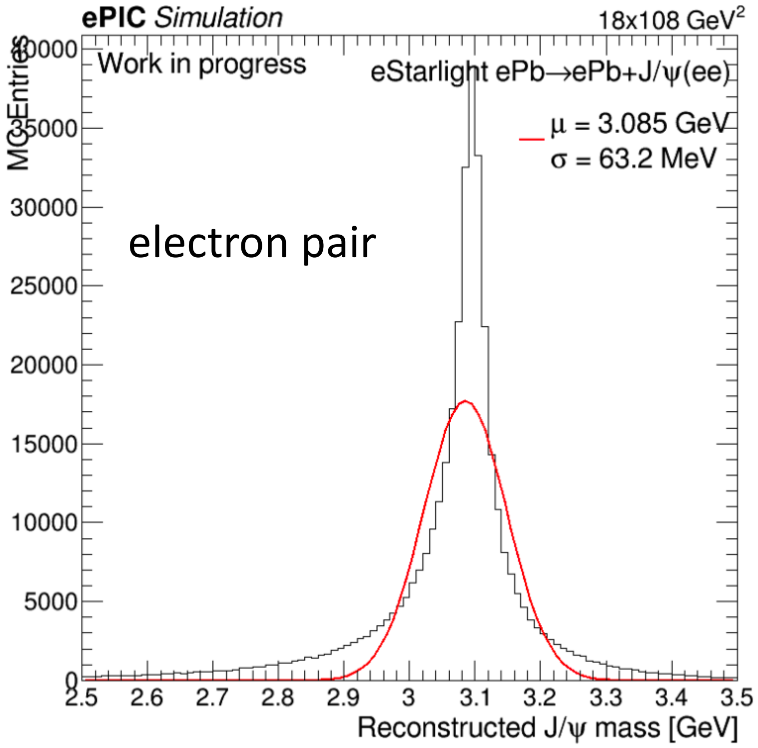
Acceptance of low-Q taggers and **Acceptance in central detector**

Plots: M. Pitt (Ben Gurion)

Diffractive vector meson production in eA (J/ψ)

J/psi invariant mass reconstruction



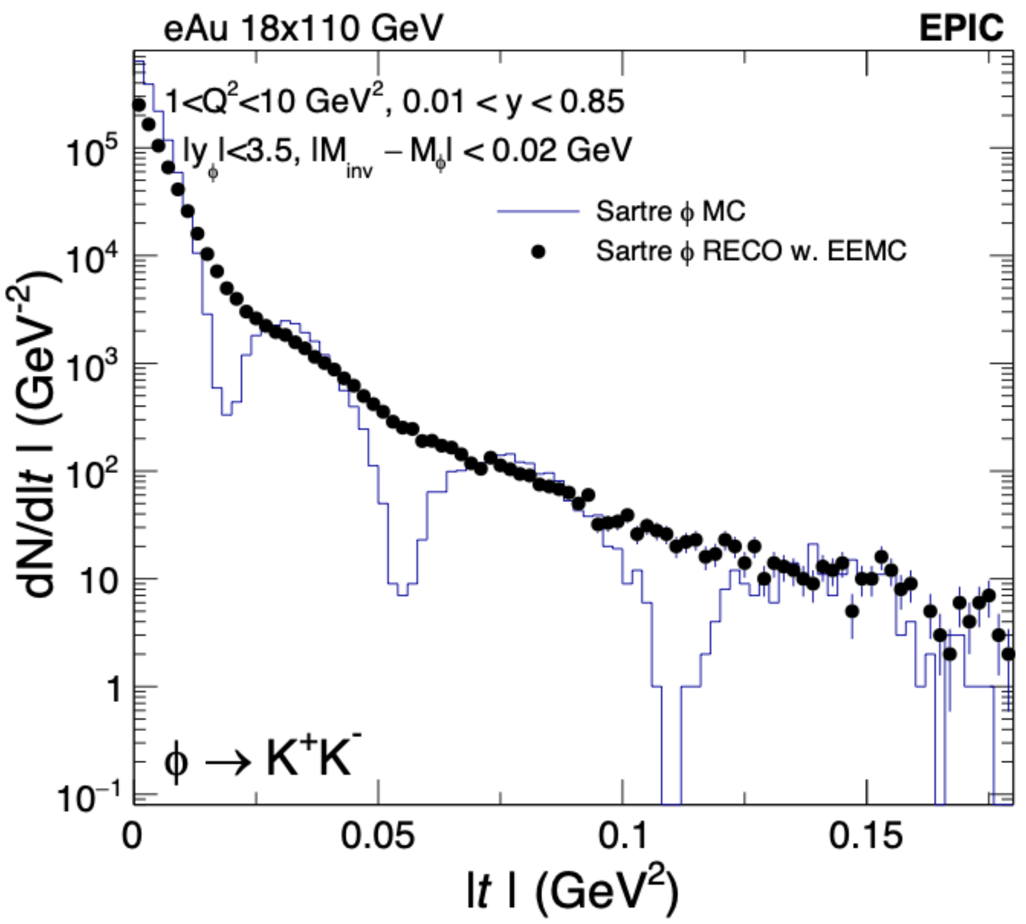


Signal efficiency for different lepton flavours in various Q^2 regions:

	electrons			Muons		
Cut	Q^2<0.001	0.001<Q^2<0.03	1 <Q^2 < 10	Q^2<0.001	0.001<Q^2<0.03	1 <Q^2 < 10
3 tracks	0.565585	0.338035	0.973705	0.566175	0.337	0.97383
VM mass cut	0.495305	0.29898	0.838785	0.52959	0.317285	0.898815
Veto FFD	0.495305	0.29897	0.838745	0.52959	0.31727	0.898795

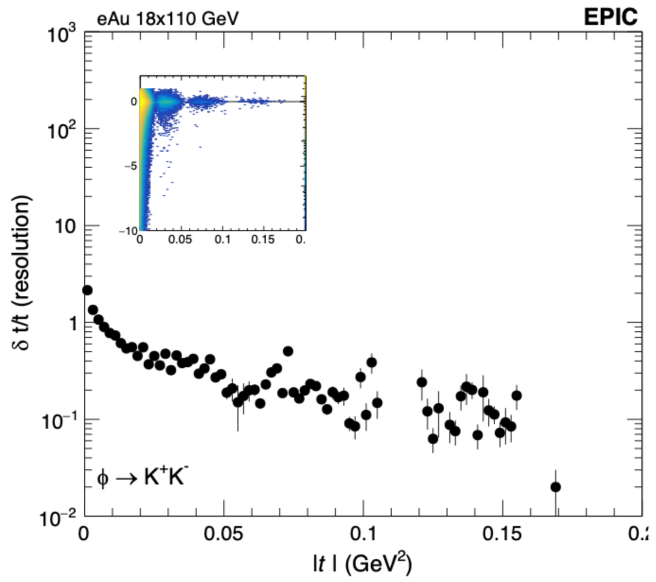
Plots: M. Pitt (Ben Gurion)

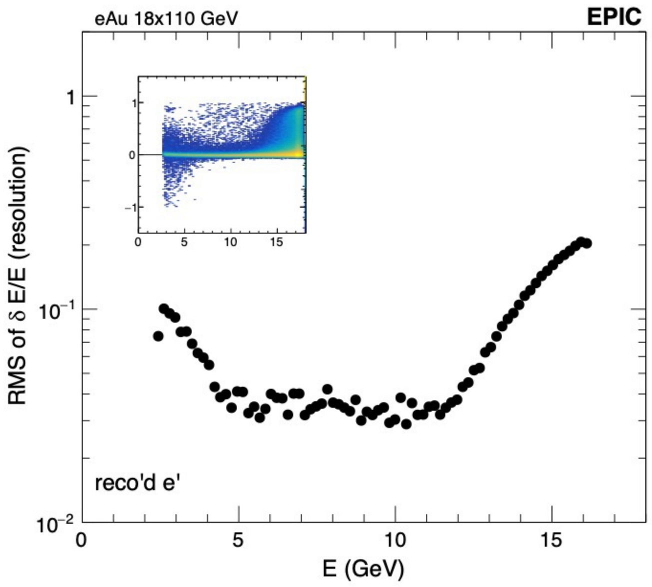
Diffractive vector meson production in eA (ϕ)



$$eAu \rightarrow \phi \rightarrow K^{+}K^{-}$$

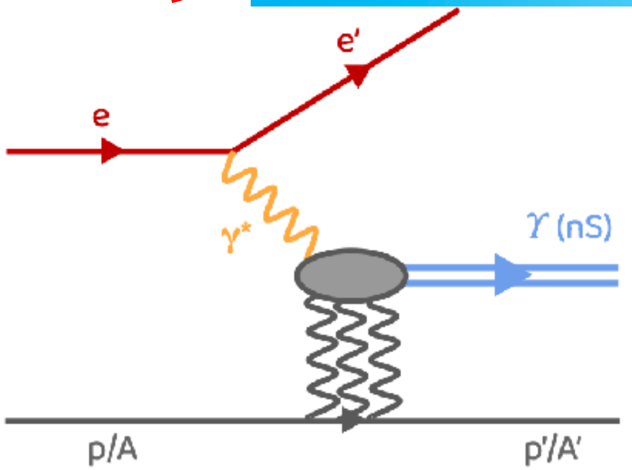
- Coherent electroproduction of ϕ meson in eA
- Sensitivity to gluon saturation
- Challenges: PID and FF detectors crucial to measure the decay kaons, reconstruct $|t|$ and veto the incoherent part





Plots: Kong Tu (BNL)

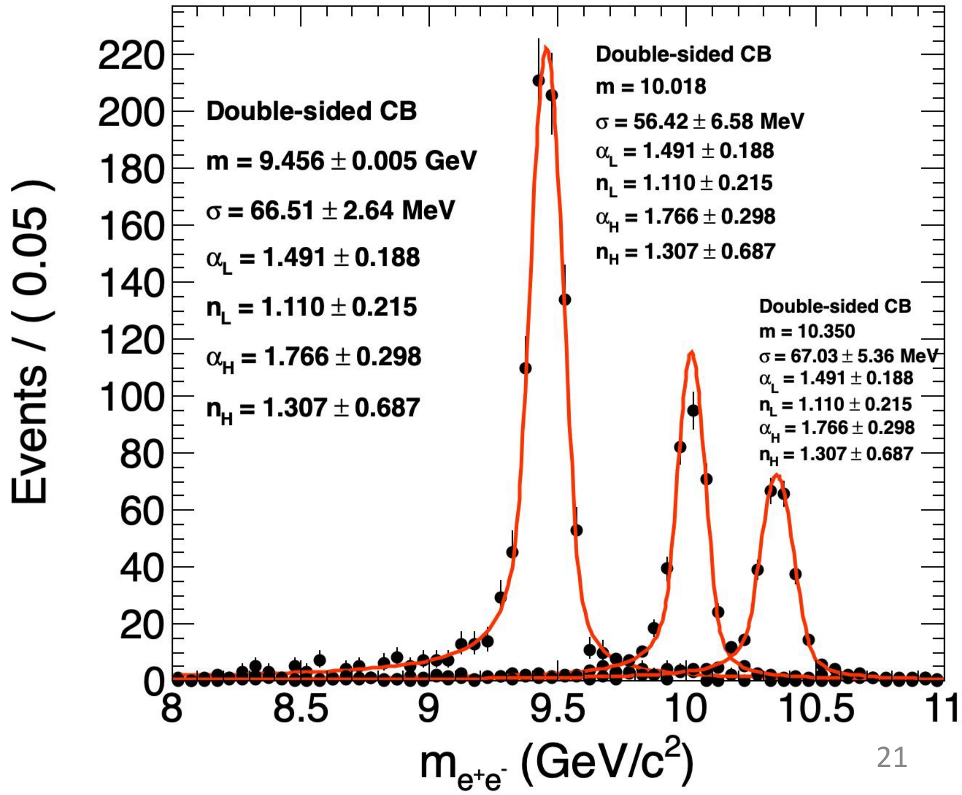
Υ production



$$\Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \rightarrow e^+e^-$$

- Sensitivity to gluon distributions
- Near threshold production → origin of mass
- Challenges: tracking resolution is crucial
- First studies at low Q^2

- Used Ratio yields 1 : 0.45 : 0.33 from STARlight paper
- Fitted with the **Double-Sided Crystal Ball function**
- $m_{\Upsilon nS} = m_{\Upsilon 1S} \frac{\text{PDGmass}_{nS}}{\text{PDGmass}_{1S}}$
- Resolution of each peak:
  - $\sigma_{1S} = 66.5 \pm 2.6$ MeV
  - $\sigma_{2S} = 56.4 \pm 6.6$ MeV
  - $\sigma_{3S} = 67.5 \pm 2.6$ MeV
- Need to reobtain values using a larger sample size



Plots: S. Yoo (Berkeley)

Summary

- ✓ The EIC provides an unprecedented opportunity for the ultimate understanding of QCD
  - ❖ It might be the only new collider in the world for the next decades
- ✓ The ePIC experimental Collaboration was formed in Spring 2022
  - ❖ ePIC is approved as part of the EIC project, and progressing according to schedule

Physics studies at ePIC - quarkonia

- TDR and companion physics paper our current top priority
- Several studies on VM production in ep and eA are being done or initiated
- Event reconstruction at the ePIC experiment being finalized & novel analysis tools being developed
  - Opportunity for new, more realistic, impact studies
- We welcome suggestions for new studies from this community
  - It is NOW the right time to join the efforts and get involved!

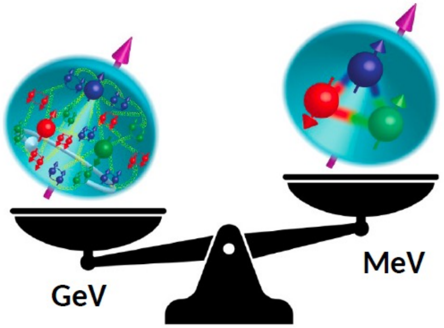

BACKUP

Scientific goals: origin of the mass of visible matter

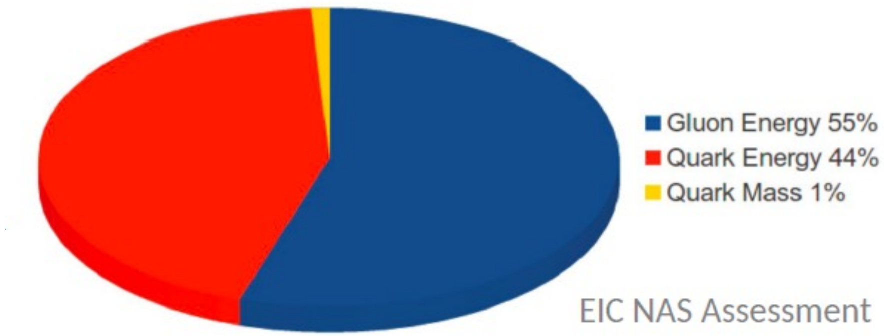
- Gluons have no mass and quarks are very light, but nucleons and nuclei are heavy, making up for most of the visible mass in the Universe
- Visible matter only made of constituents of light mass: masses emerge from quark-gluon dynamics

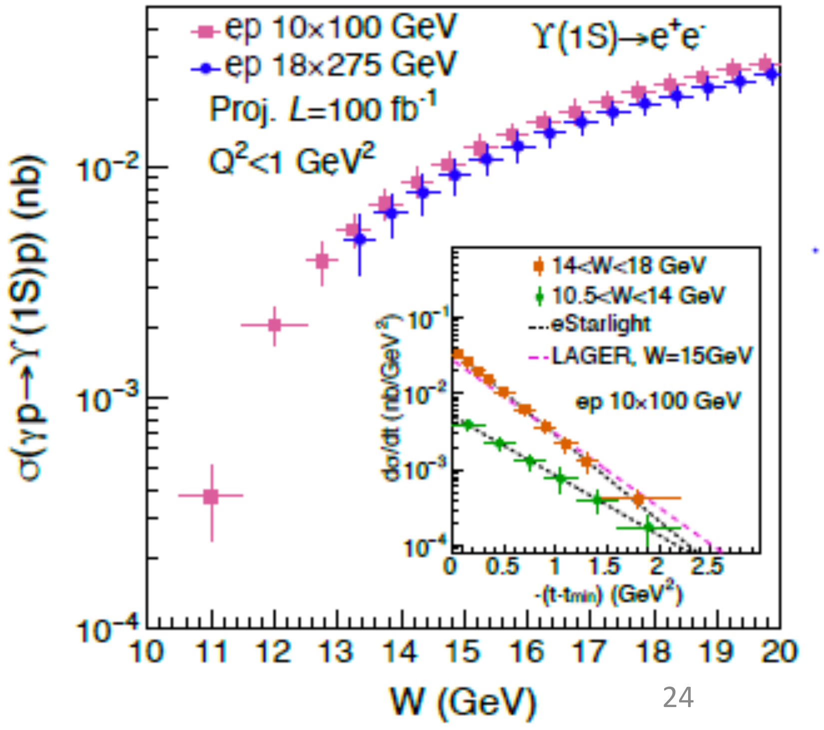
Proton (valence quarks: uud) → $m_p = 940$ MeV

- The mass is dominated by the energy of highly relativistic gluonic field
- EIC can determine an important contribution term to the proton mass, the so-called "QCD trace anomaly" ⟼ accessible in exclusive reactions (e.g. Υ photoproduction near threshold)



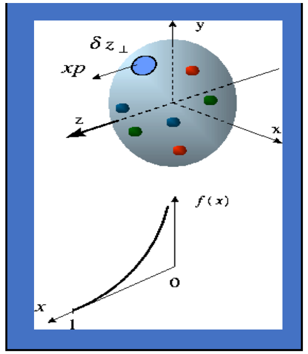
Contributions to the total mass of the nucleon





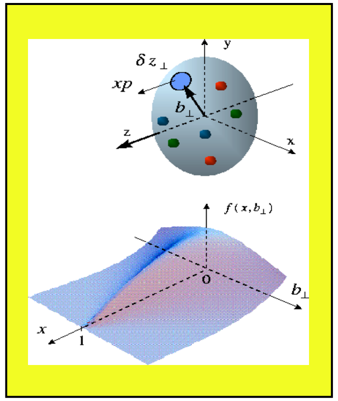
Scientific goals: GPDs

Longitudinal momentum & helicity distributions



$f(x)$

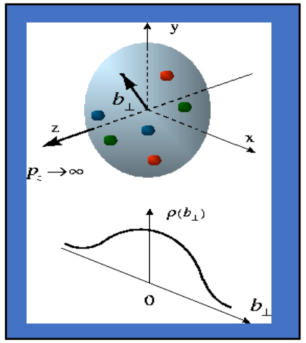
parton densities



$H(x,\xi,t)$

GPDs

transverse charge & current densities



$F(t)$

form factors

N / q	U	L	T
U	H		E_T
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T \quad \tilde{H}_T$

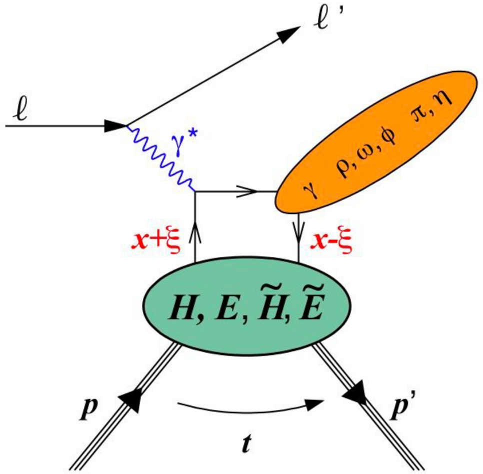
Spin-½ hadron: **4 chiral-even** (H, E and their polarized-hadron versions $\widetilde{H}$, $\tilde{E}$) and **4 chiral-odd** ($H_T, E_T, \widetilde{H}_T, \tilde{E}_T$) quark and gluon **GPDs at leading twist**

Like usual PDFs, GPDs are non-perturbative functions **defined via the matrix elements of parton operators**:

$$F^q = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ix\bar{P}^+z^-} \langle p'|\bar{q}(-\frac{1}{2}z)\gamma^+ q(\frac{1}{2}z)|p\rangle|_{z^+=0,\mathbf{z}=0}$$
$$= \frac{1}{2\bar{P}^+}\left[H^q(x,\xi,t,\mu^2)\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t,\mu^2)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m_N}u(p)\right]$$

- Experimental access to GPDs via Compton Form Factors (CFFs)

$$\mathcal{H}(\xi,t) = \sum_q e_q^2 \int_{-1}^{1} dx\, H^q(x,\xi,t)\left(\frac{1}{\xi - x - i\varepsilon} - \frac{1}{\xi + x - i\varepsilon}\right)$$



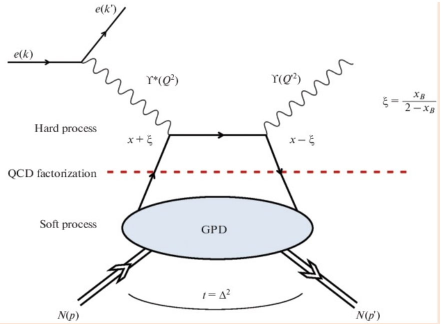
Connection to the **proton spin**: $J_q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} dx\, x[H^q(x,\xi,t) + E^q(x,\xi,t)]$ $\quad J_q = \frac{1}{2}\Delta\Sigma + L_q$

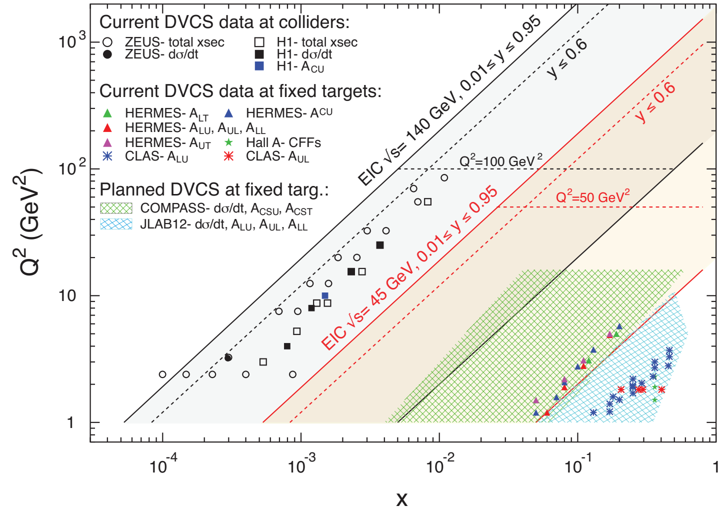
[X.D. Ji, Phys. Rev. Lett. 78, 610 (1997)]

Accessing GPDs in exclusive processes

Real photon (DVCS):

- Very clean experimental signature
- No VM wave-function uncertainty
- Hard scale provided by Q^2
- Access to the whole set of GPDs
- Sensitive to both quarks and gluons [via Q^2 dependence of xsec (scaling violation)]





Only possible at EIC: from valence quark region, deep into the sea!

Hard Exclusive Meson Production (HEMP):

- Uncertainty of wave function
- Hard scale provided by $Q^2 + M^2$
- J/Psi, Υ → direct access to gluons, $c\bar{c}$, or $b\bar{b}$ pairs produced via $q(g) - g$ fusion
- Light VMs → quark-flavor separation
- Psedoscalars → helicity-flip GPDs

$H^q \; E^q$

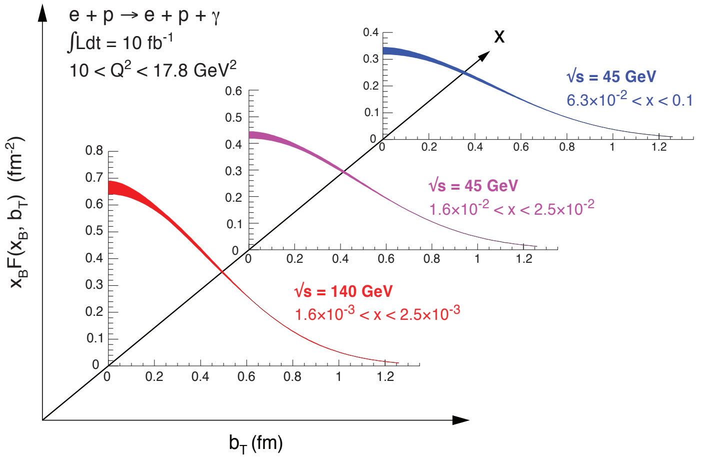
ρ⁰	2u+d, 9g/4
ω	2u–d, 3g/4
ϕ	s, g
ρ⁺	u–d
J/ψ, Υ	g

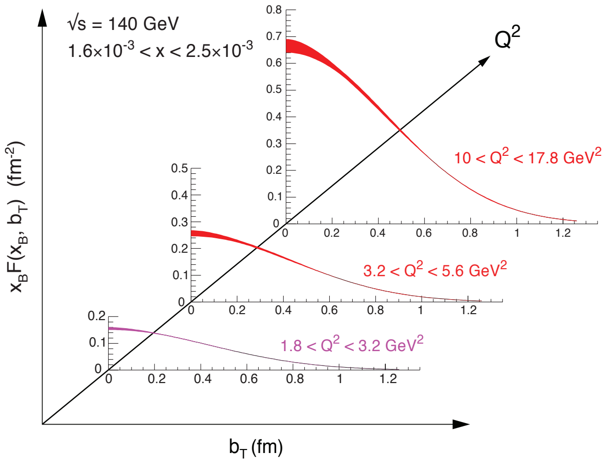
$\widetilde{H^q} \; \widetilde{E^q}$

π⁰	2Δu+Δd
η	2Δu–Δd

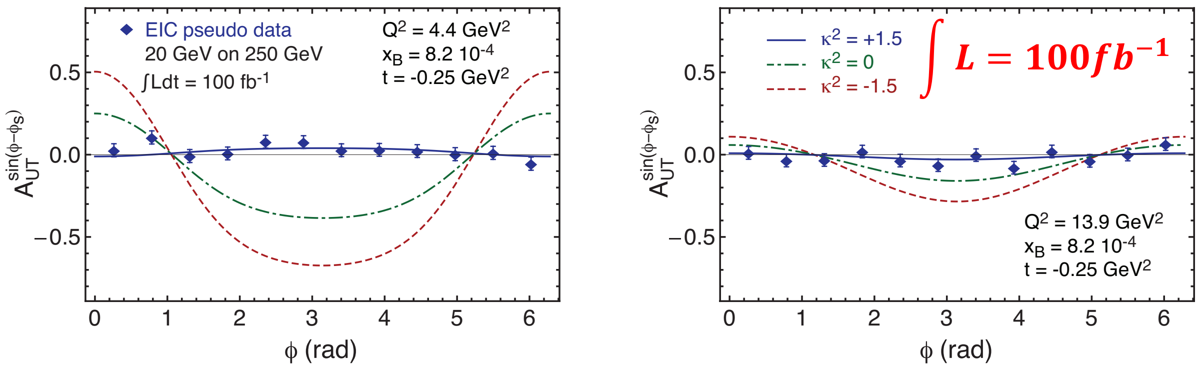
Accessing GPDs in exclusive processes

DVCS: $ep \to \gamma$



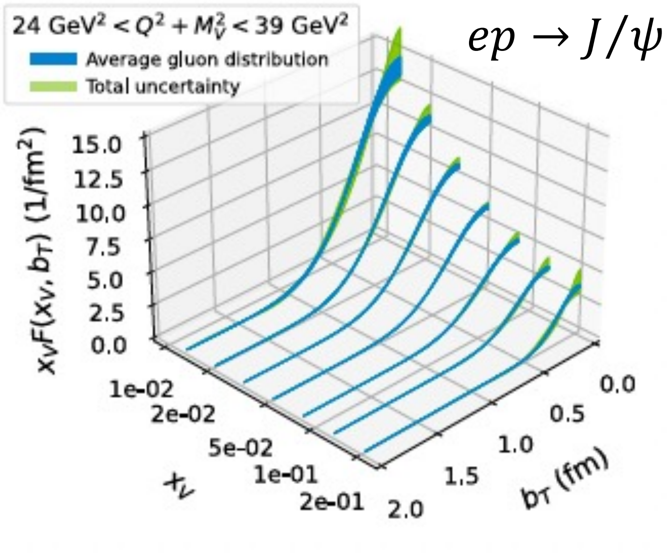


E.C. Aschenauer, S. F., K. Kumerički, D. Müller [JHEP09(2013)093]

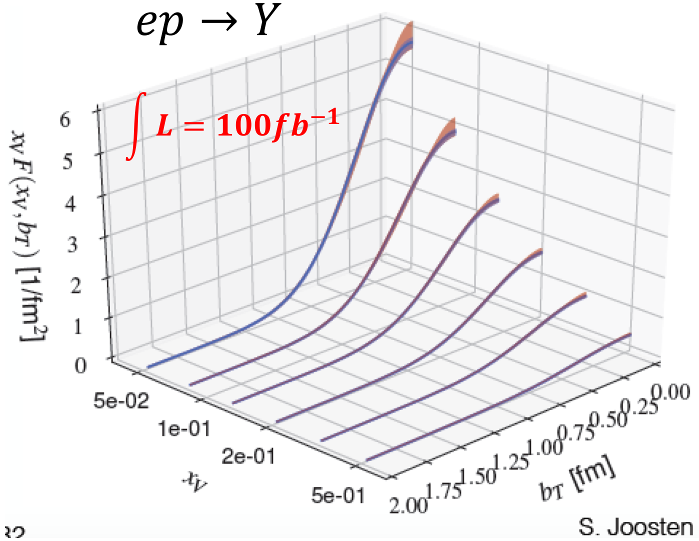


Theory curves show different assumptions for E

$ep \to J/\psi$



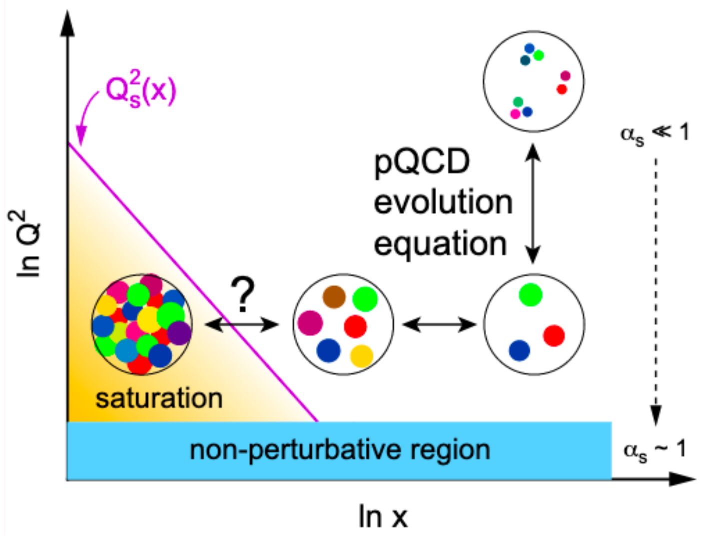
$ep \to \Upsilon$

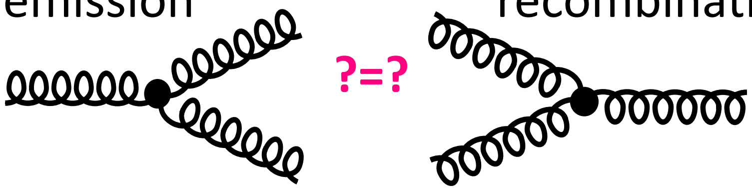


Key detector performance:

- γ/π^0 separation in ECAL for DVCS
- Acceptance and low material for VM decay leptons
- Resolution of lepton pair inv. mass
- Muon id
- Scattered electrons over full kinem.
- t- lever arm in FF spectrometers

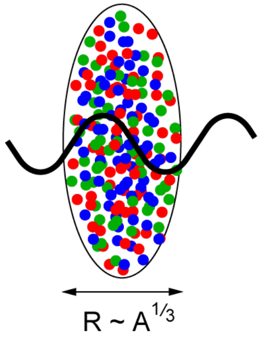
A window into the Gluon Saturation regime





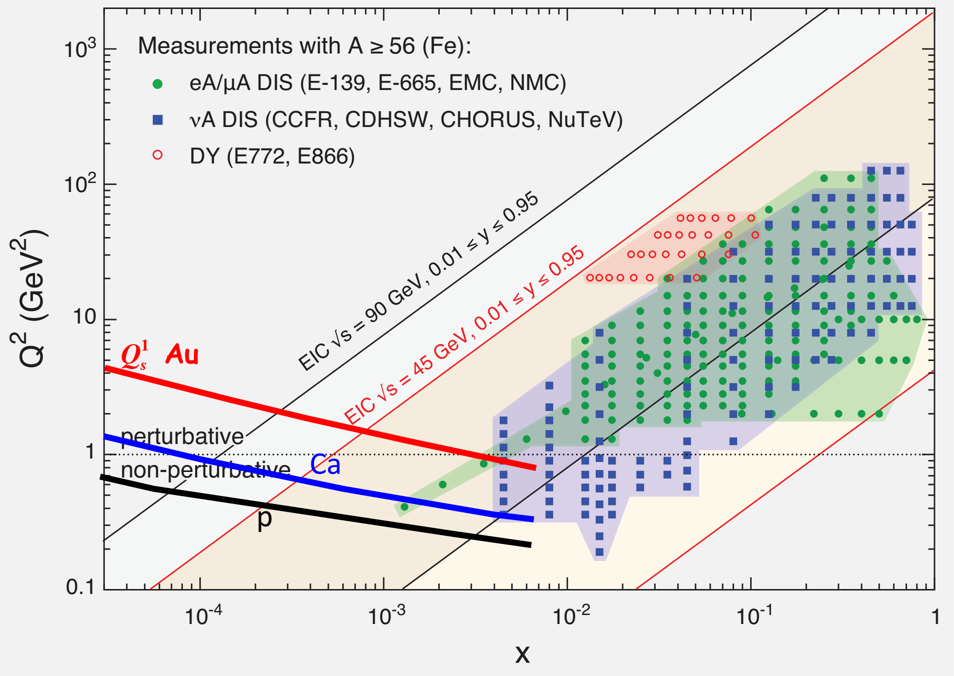
$$(Q_s^A)^2 \sim cQ_o^2\left(\frac{A}{x}\right)^{1/3}$$

$L \sim (2m_N x)^{-1} > 2 R_A \sim A^{1/3}$



Probe interacts coherently with all nucleons

Gold: 197 times smaller effective *x* !



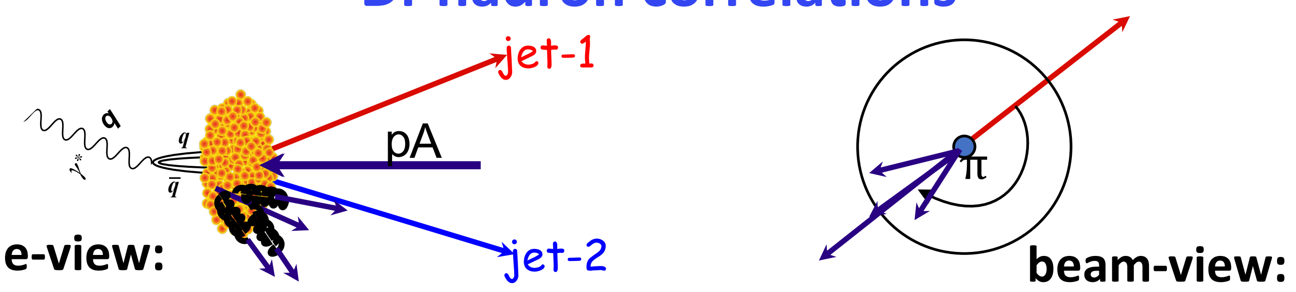
→ EIC will map the transition between a non-saturated and a saturated regime with high precision, by making use of a large range of nuclei and spin

→ With its flexible ion source, we will be able to measure the A-dependence of the saturation scale $Q_s(x)$

→ a fundamental landmark of QCD

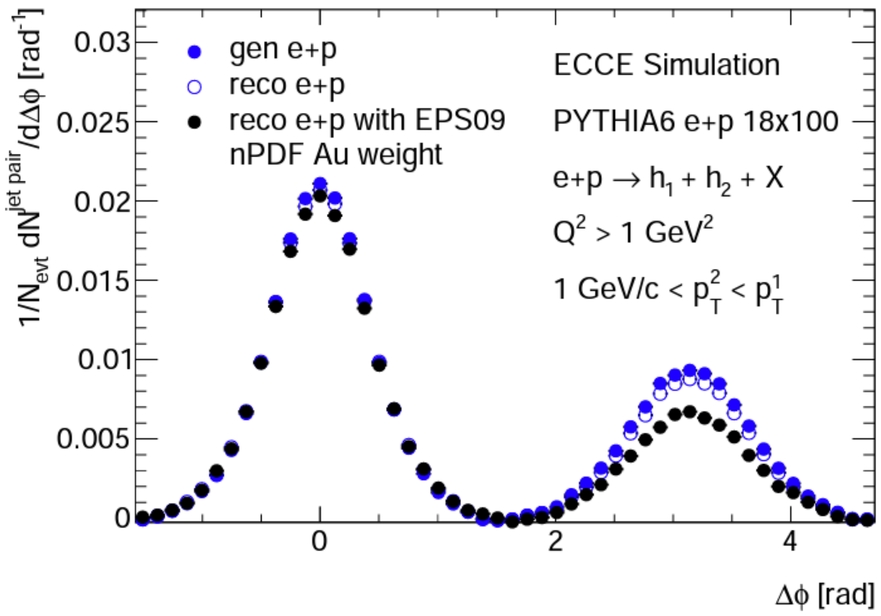
Scientific goals: gluon saturation

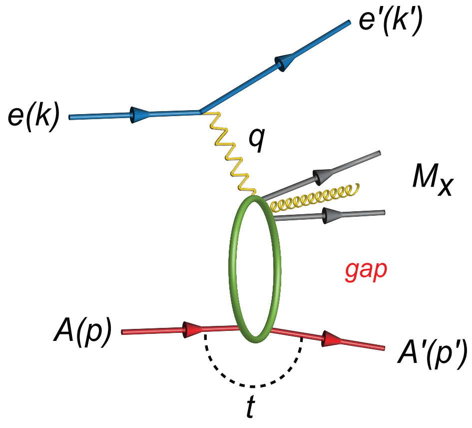
Di-hadron correlations



Low gluon density (ep):
pQCD predicts 2→2 process
⇒ back-to-back di-jet

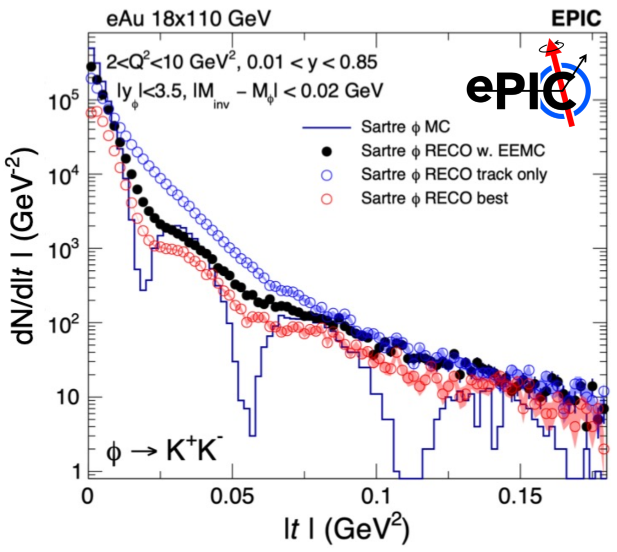
High gluon density (eA):
2 → many process
⇒ expect broadening of away-side





Diffraction

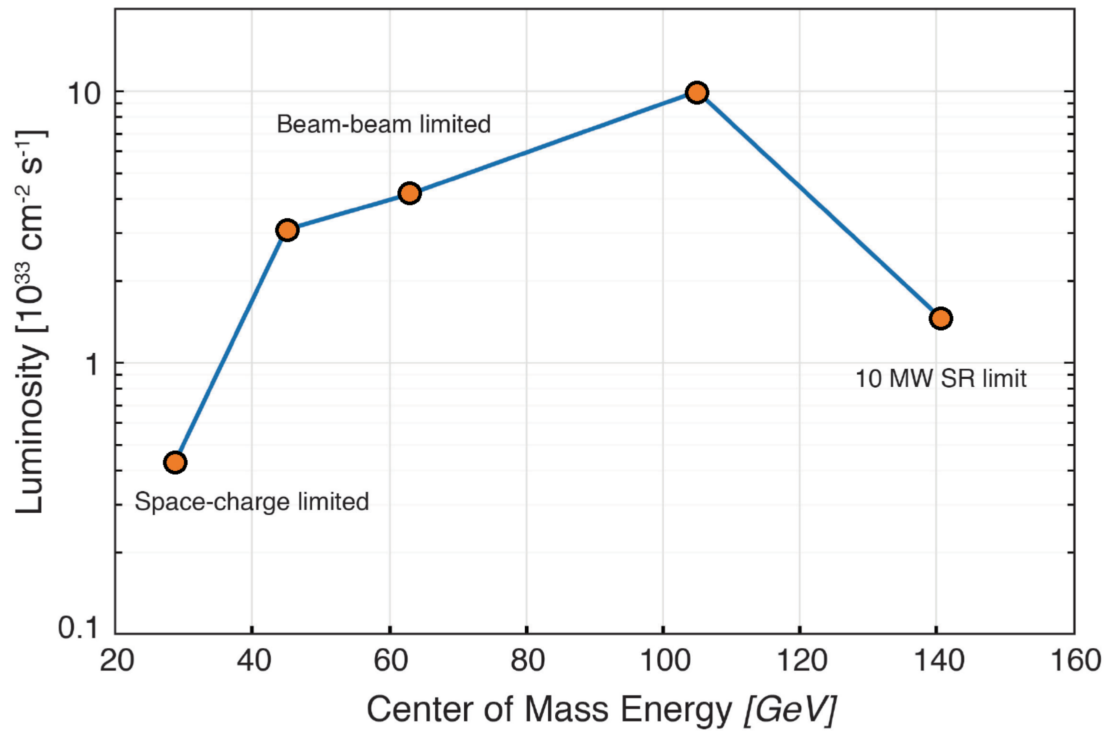
High sensitivity to gluon density in linear regime $\sigma \sim [g(x,Q^2)]^2$

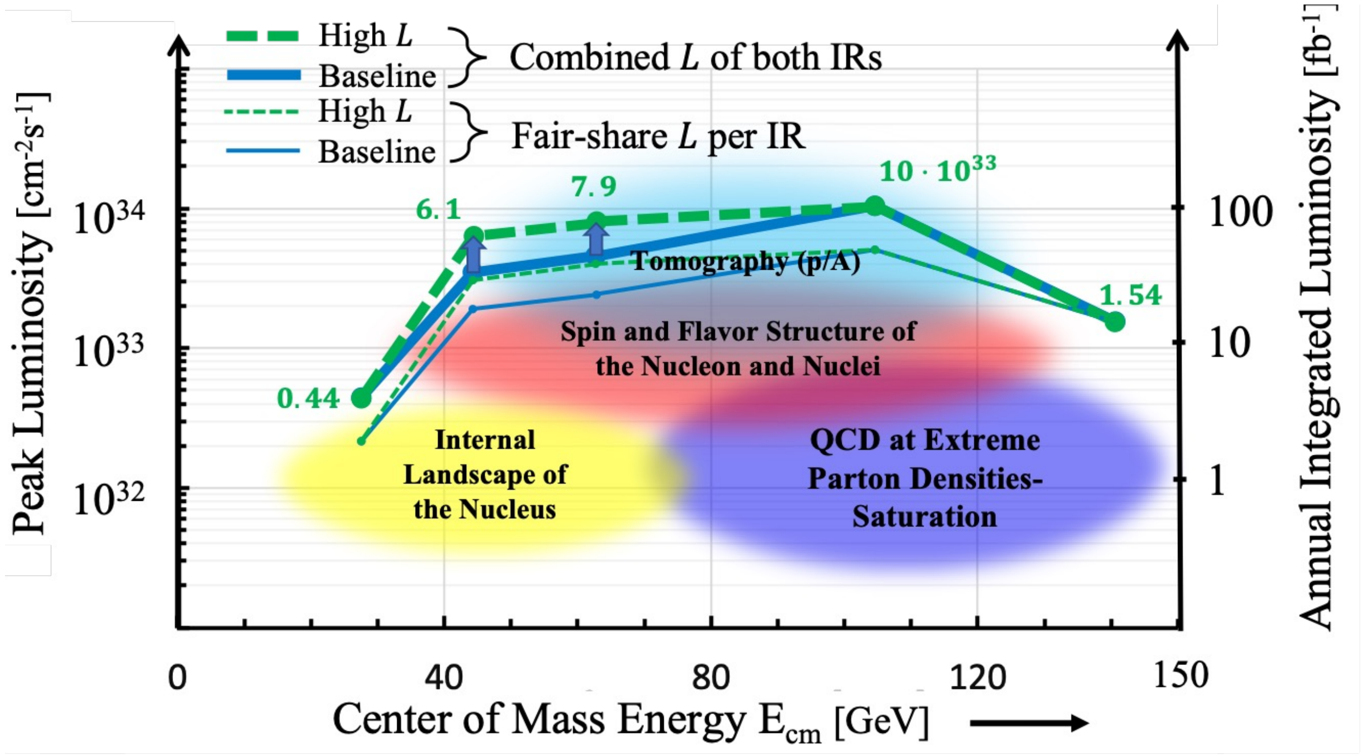


Key detector performance:

- Quality of detection at mid rapidity
- Reconstruction of dijets (dihadron)
- Particle ID

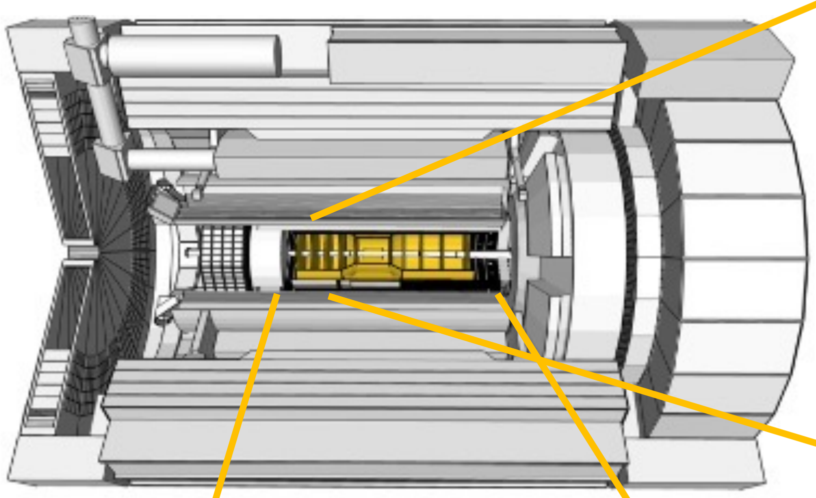
The EIC Luminosity

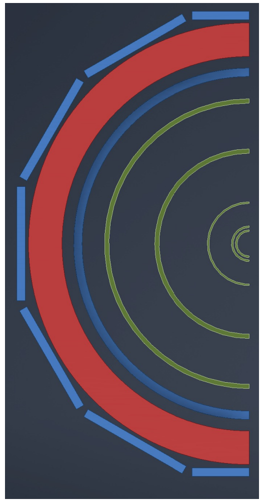




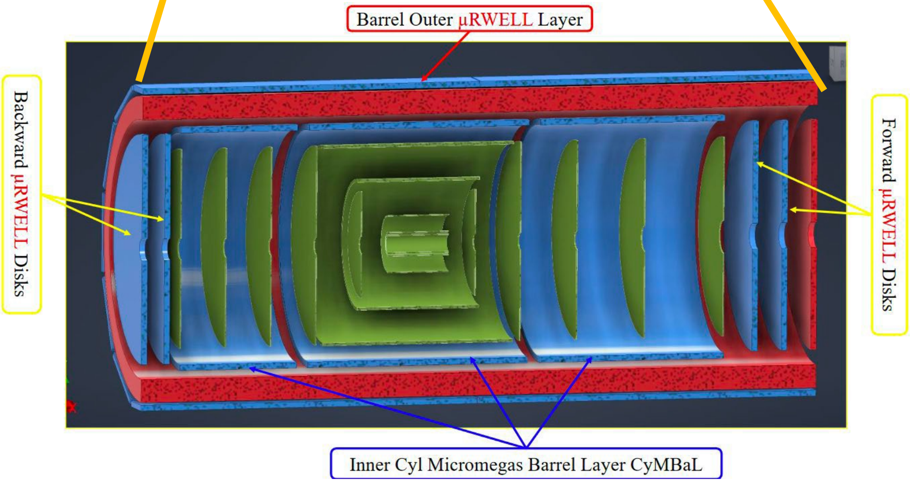
- $e-p$ collisions luminosity vs center-of-mass energy
  - achieves expected physics needs
- $e-A$ collisions luminosity is similar within a factor of ~2 to 3

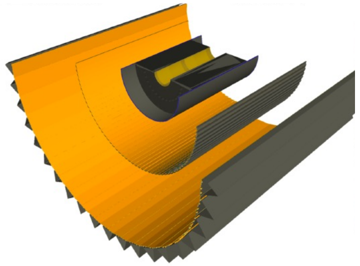
Tracking

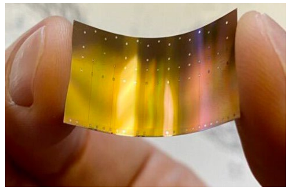




- MAPS Barrel + Disks
- MPGD Barrels + Disks
- AC-LGAD based ToF

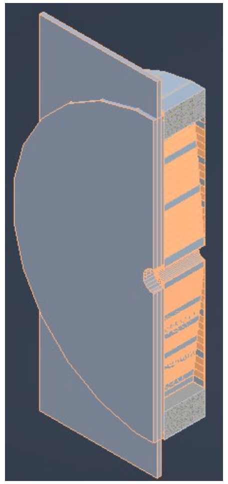




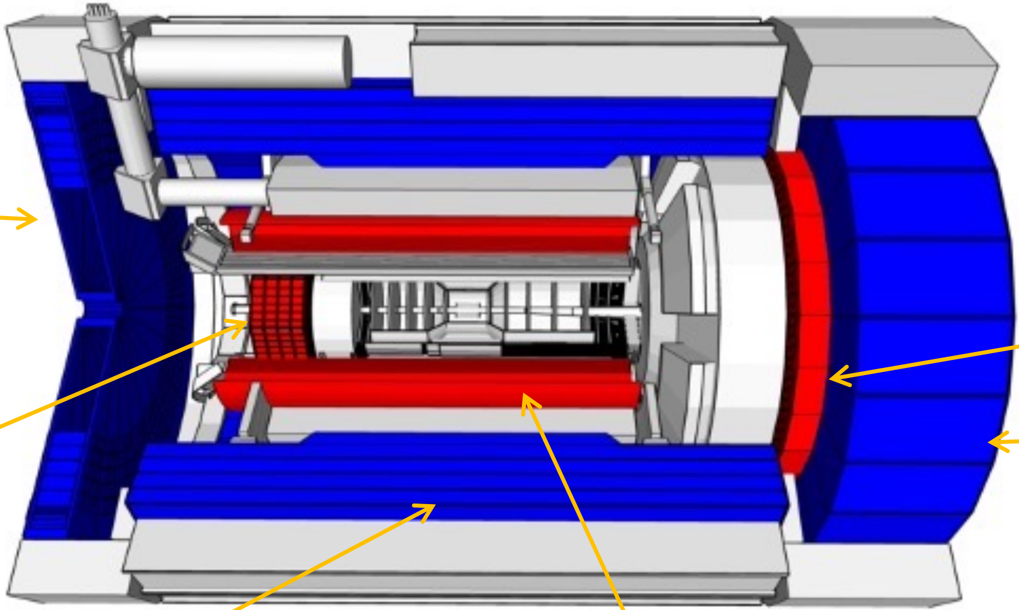


- MAPS Tracker:
  - Small pixels (20 µm), low power consumption (<20 mW/cm^2) and low material budget (0.05% to 0.55% X/X_0) per layer
  - Based on ALICE ITS3 development
  - Vertex layers optimized for beam pipe bake-out and ITS-3 sensor size
  - Forward and backward disks
- MPGD Layers:
  - Provide timing and pattern recognition
  - Cylindrical µMEGAs
  - Planar µRWell's before hpDIRC - Impact point and direction for ring seeding
- AC-LGAD TOF and AstroPix (BECAL):
  - Additional space point for pattern recognition / redundancy
  - Fast hit point / Low p PID

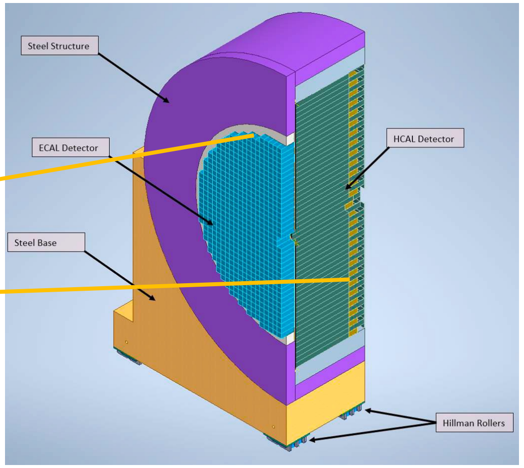
Calorimetry



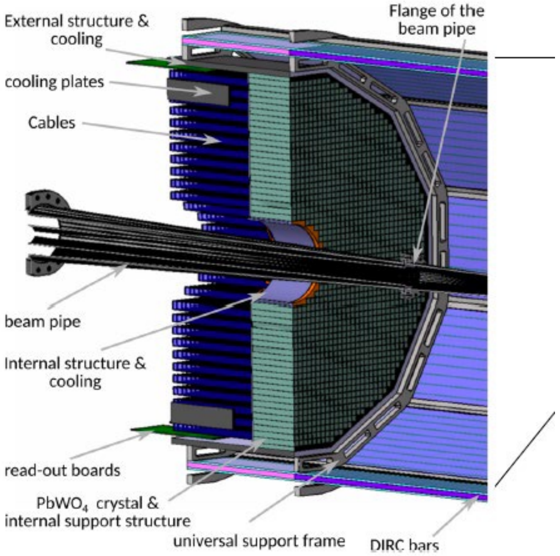
Backwards HCal
Steel/Sc
Sandwich
tail catcher



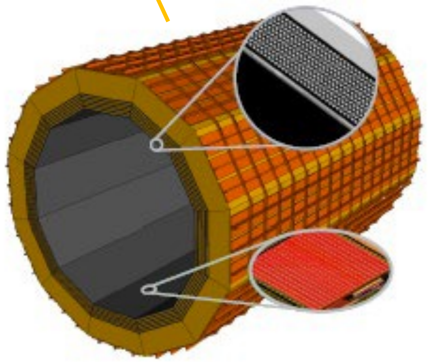
Forward EMCal
High granularity W/SciFi
a unique technology allowing to achieve
e/h ~1 (response to hadrons)



Backwards EMCal
PbW04 crystals, SiPM photosensors

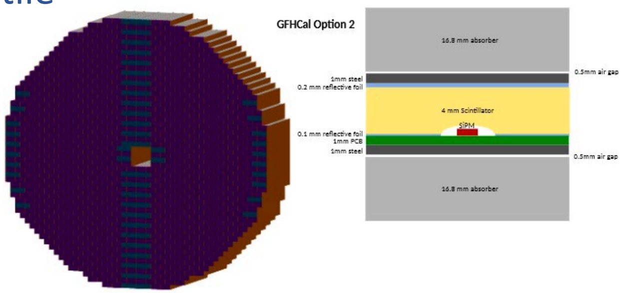


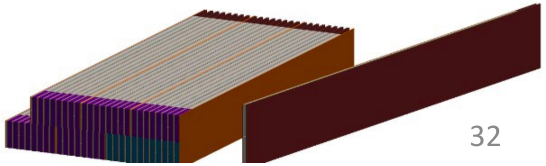
Barrel HCAL
Fe/Sc sandwich, ~3.5λ
(sPHENIX re-use)



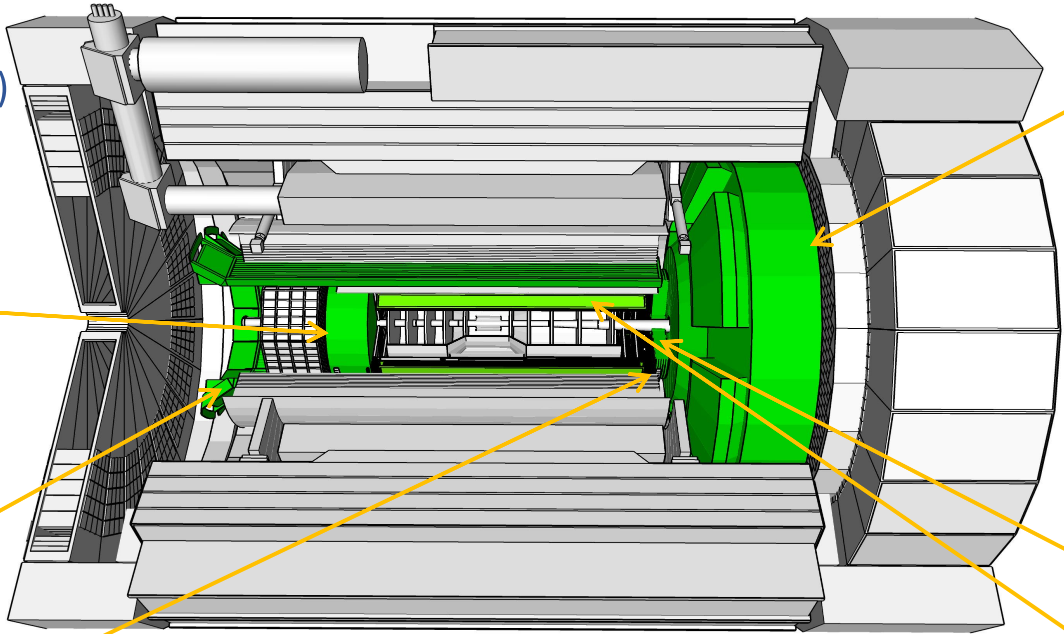
Barrel EMCAL
4 (6) layers of imaging calorimetry
by Astropix MAPS,
and sampling calorimetry by Pb/SciFi

Forward Hcal
SiPMs on tile



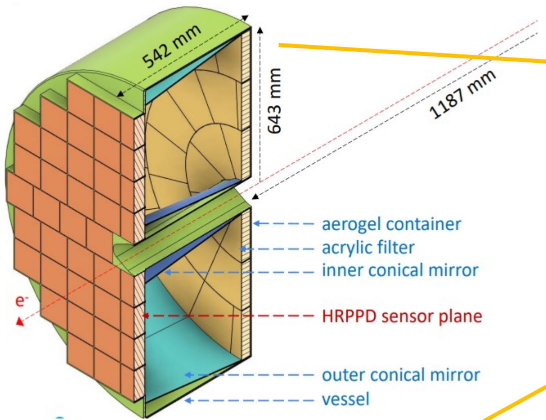


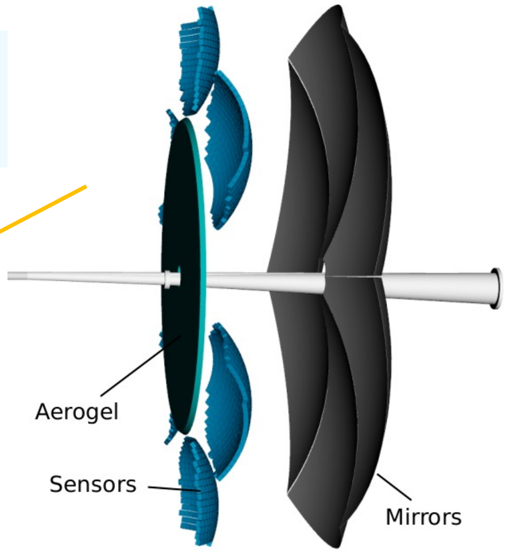
Particle ID



Proximity Focused (pfRICH)

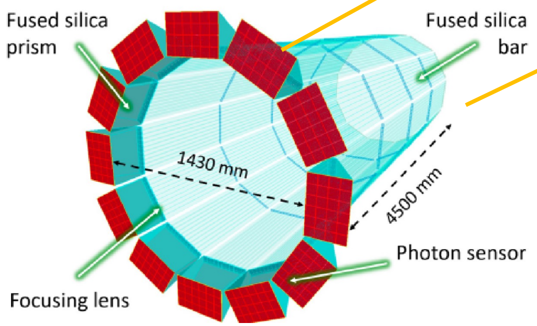
- Aerogel with Long proximity gap (~40 cm)
- Sensor: HRPPDs
- 3σ π/K sep. up to 9 GeV/c





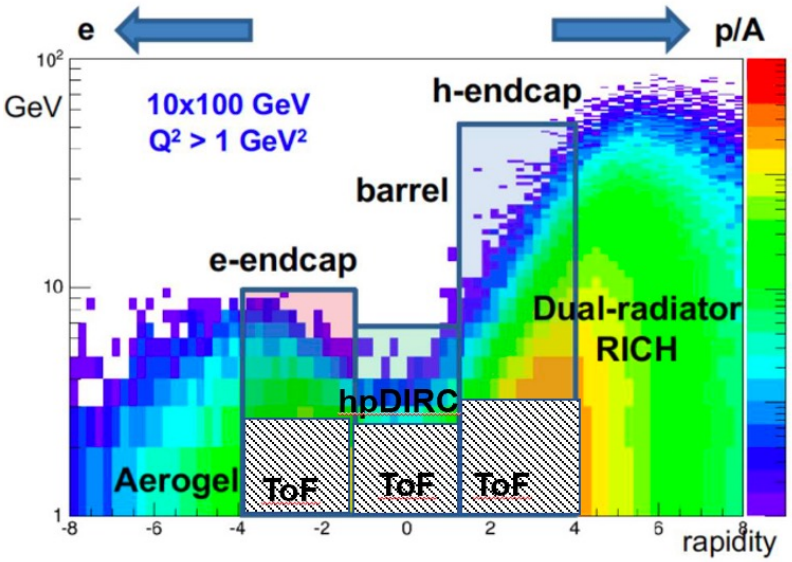
Dual-Radiator RICH (dRICH)

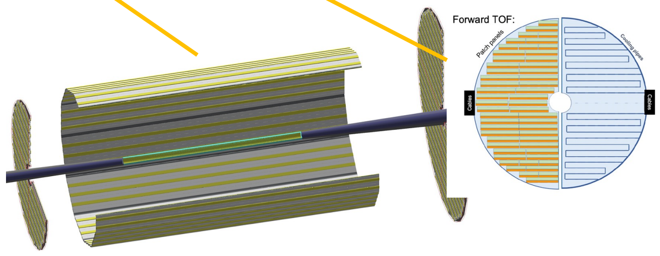
- C_2F_6 Gas Volume and Aerogel
- Single photon sensors (SiPMs)
- π/K 3σ sep. at 50 GeV/c



High-Performance DIRC

- Quartz bar radiator (BaBAR bars) light detection with MCP-PMTs
- 3σ π/K sep. at 6 GeV/c

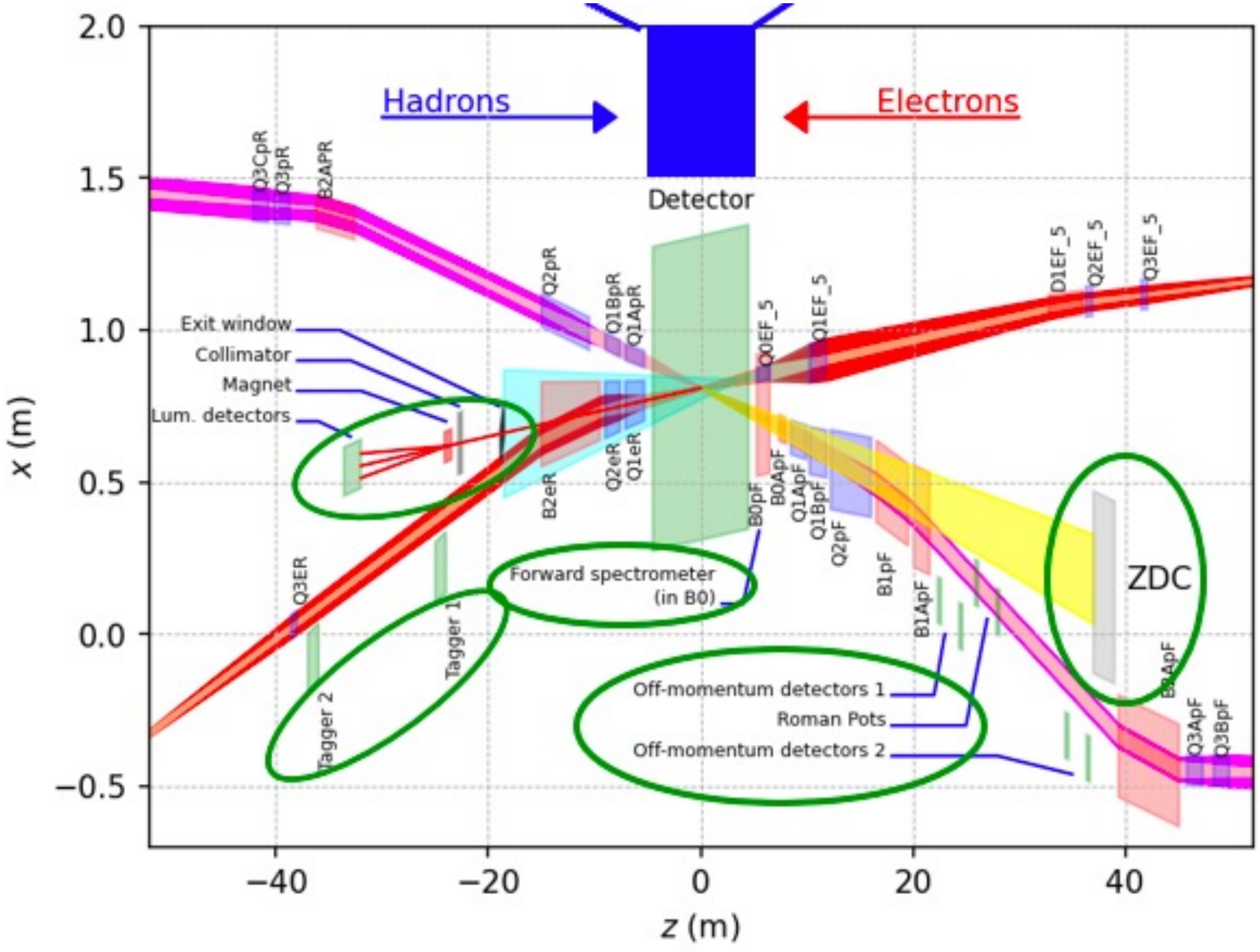




AC-LGAD TOF (~30ps)

- Accurate space point for tracking / Low p PID
- Forward disk and central barrel

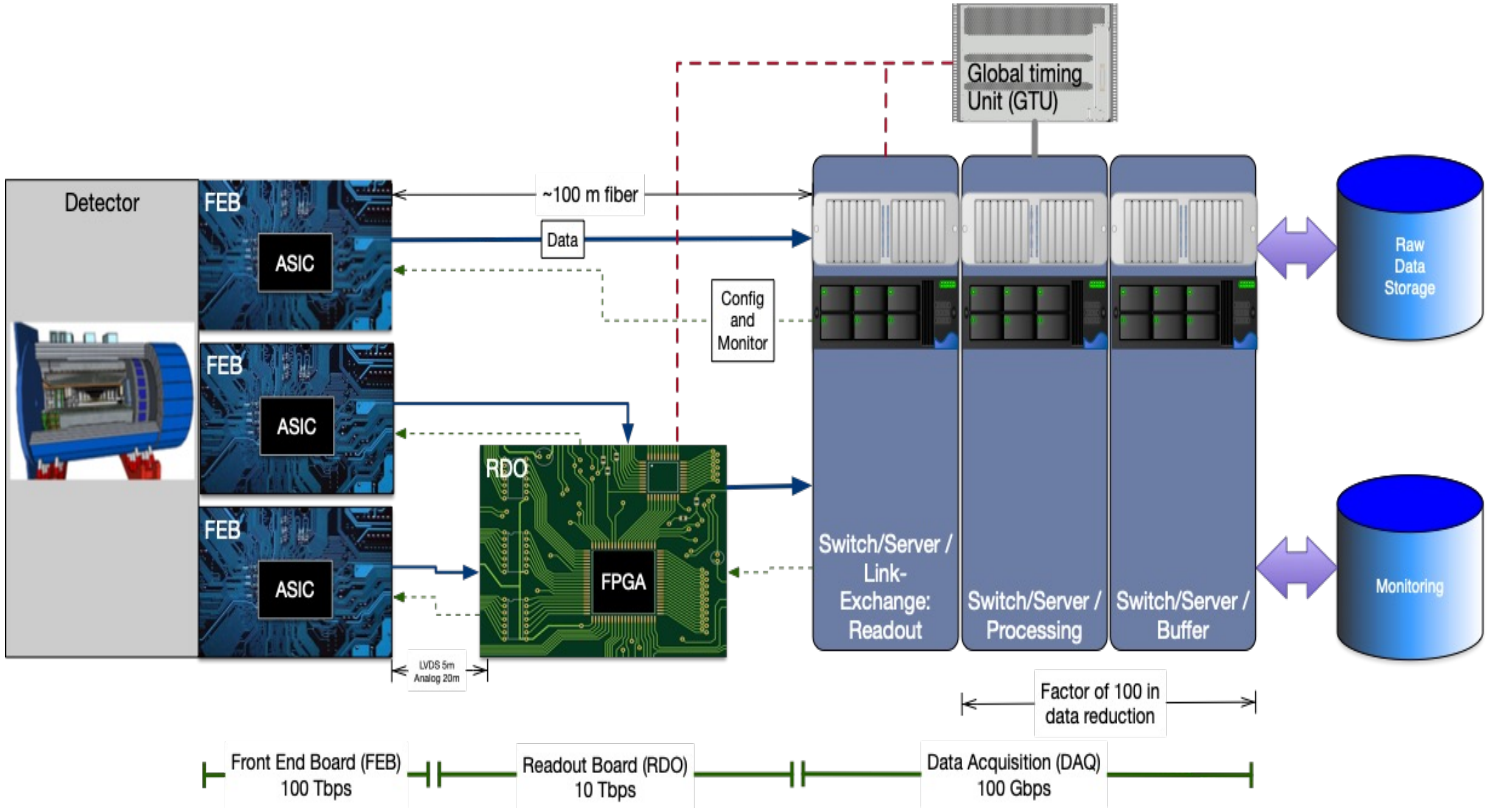
Auxiliary detectors



Needed to tag particles with very small scattering angles both in the outgoing lepton and hadron beam direction

- B0-Taggers
- Off-momentum taggers
- Roman Pots
- Zero-degree Calorimeter
- low Q2-tagger
- Luminosity detector

Streaming DAQ



- No External trigger
- All collision data digitized, but zero suppressed at FEB
- Low / zero dead-time
- Event selection can be based on full data from all detectors (in real-time, or later)
- Collision data flow is independent and unidirectional

  → no global latency requirements
- Avoiding hardware triggers avoids complex custom hardware and firmware