Far-forward physics and instrumentation at EIC

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Outline

- Introduction to EIC and ePIC collaboration
- Overview of EIC science
- Far-forward physics and instrumentation
- Summary

Materials for slides come from various EIC community efforts: Yellow Report, EIC Project, detector proposals, ePIC collaboration, etc
Many thanks to all collaborators,
especially to Elke-Caroline Aschenauer, Rolf Ent, Alex Jentsch!

EIC Design Overview

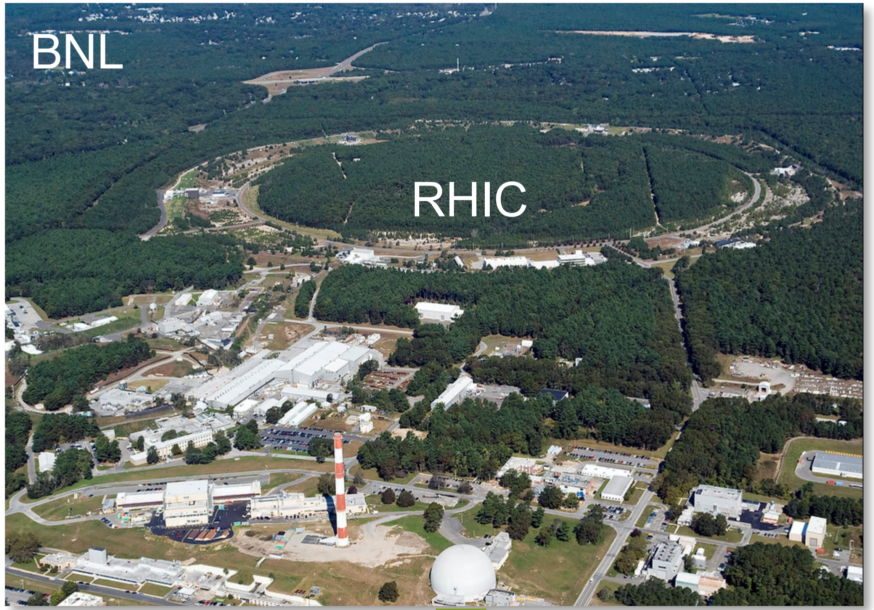
Exploiting existing Hadron complex RHIC (BNL) with its
- superconducting magnets, 275 GeV protons
- its large accelerator tunnel and
- its long straight sections
- its existing Hadron injector complex

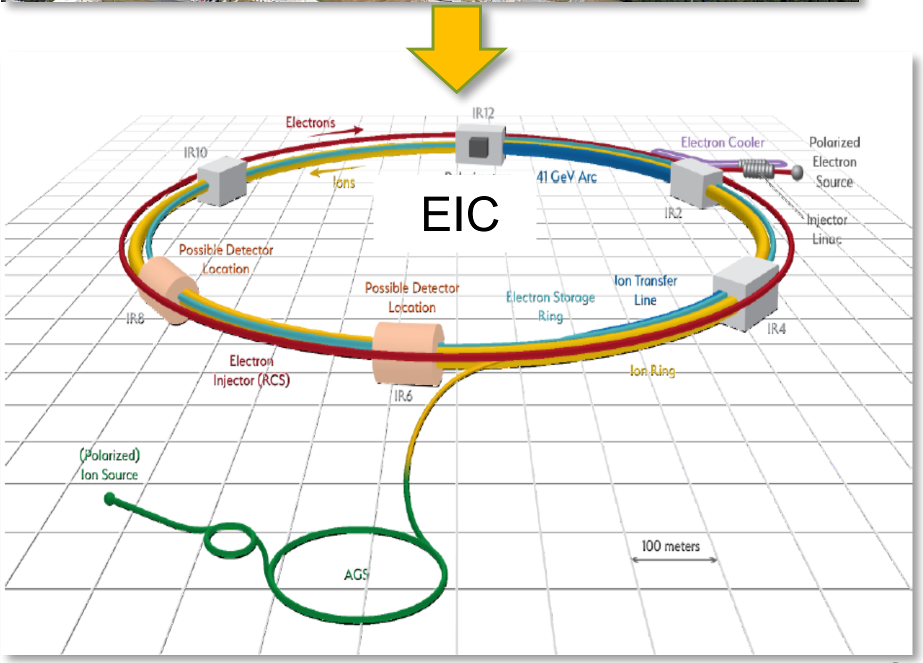
Adding an electron accelerator in the <u>same</u> tunnel

-> achieve high luminosity electron-Hadron collisions over a large range of CM Energies

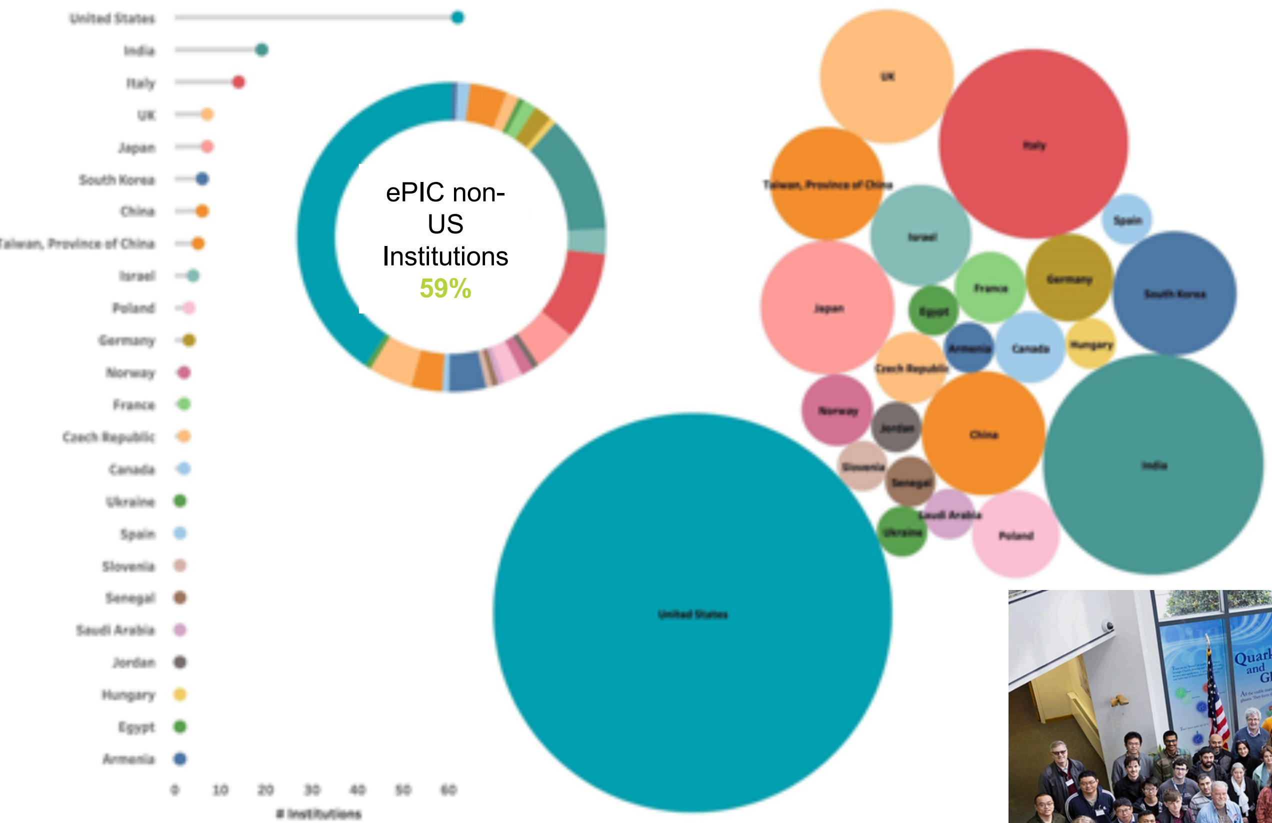
- 25 mrad crossing angle with crab cavities
- IP6 (location of STAR)
- Forward hadron instrumentation

e-: 5- 18 GeV
p : 40-275 GeV
$\sqrt{s}$: **30- 140 GeV**
Luminosity upto 10^{34} $cm^{-2}s^{-1}$





The ePIC detector Collaboration

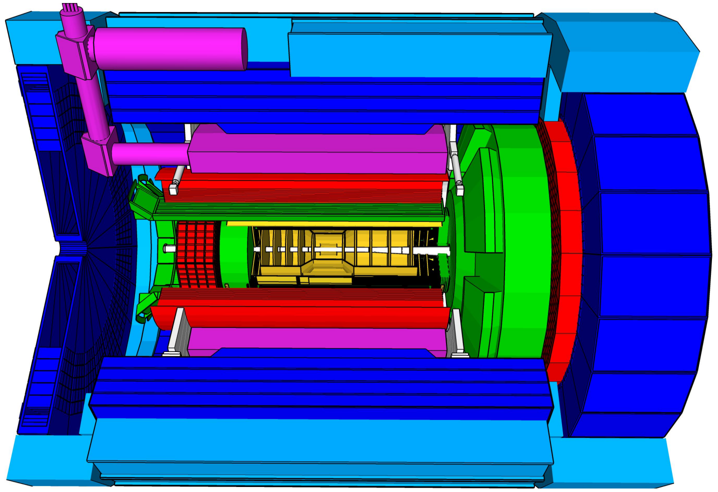


The ePIC collaboration is formed a year ago.

ePIC is now 171 institutions (including 11 new institutions that joined this July 2023)

Representing 24 countries and 500+ participants

ePIC Spokesperson: John Lajoie (Iowa State)
ePIC Deputy Spokesperson: Silvia Dalla Torre (INFN Trieste)



History

The science and requirements for an EIC were built over two decades

2002 2007 2009 2010 2012 2013 2015 2018 2021

arXiv:2103.05419

2002: "…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

2007: "We recommend the allocation of resources … to lay the foundation for a polarized Electron-Ion Collider…"

2009: "..a new dedicated facility will be essential for answering some of the most central questions."

2012: "The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider.."

2013: Electron-Ion Collider..*absolutely central* to the nuclear science program of the next decade.

2015: "a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."

2018: The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today."

2021: Science Requirements and Detector Concepts for the EIC – Drives the requirements of EIC detectors

We are ready to probe a femto-world!

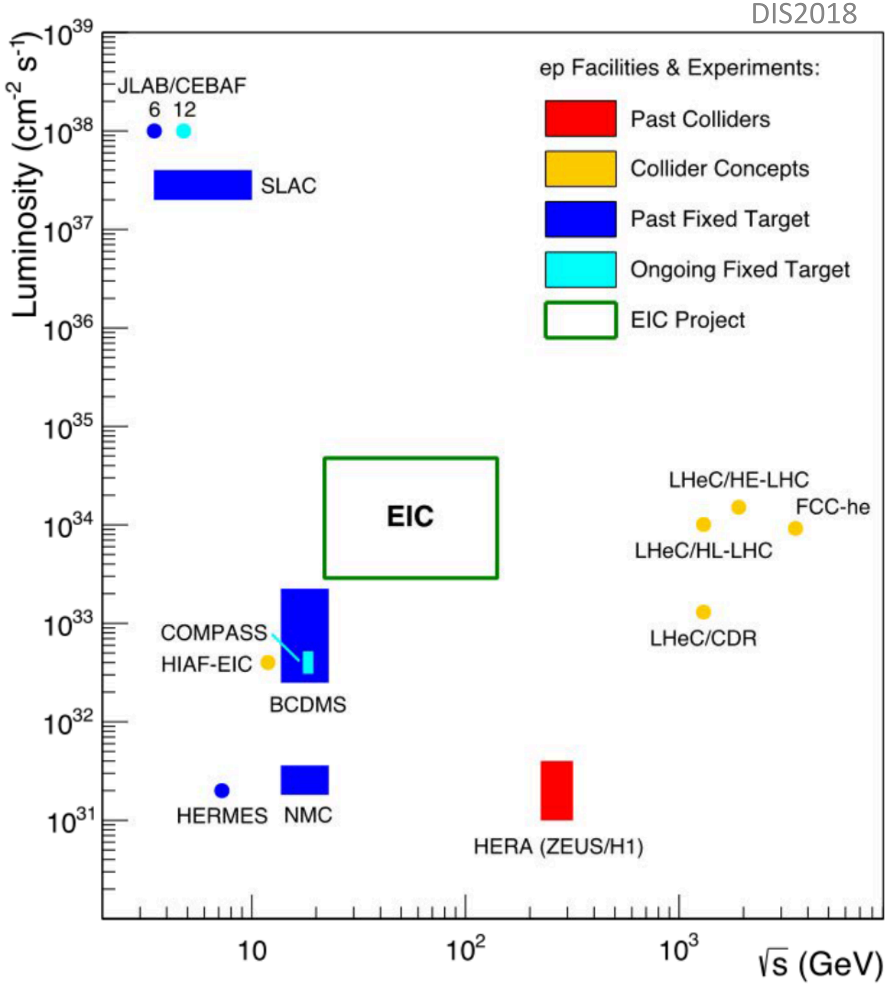
EIC is a "Cold" QCD facility to study a structure and dynamics of matter

- ✓ Property of Hadrons (Mass, Spin)
- ✓ Structure or Imaging of Hadrons (PDF, TMD, GPD)
- ✓ QCD at Extreme Parton Densities
- ✓ Emergence of hadrons

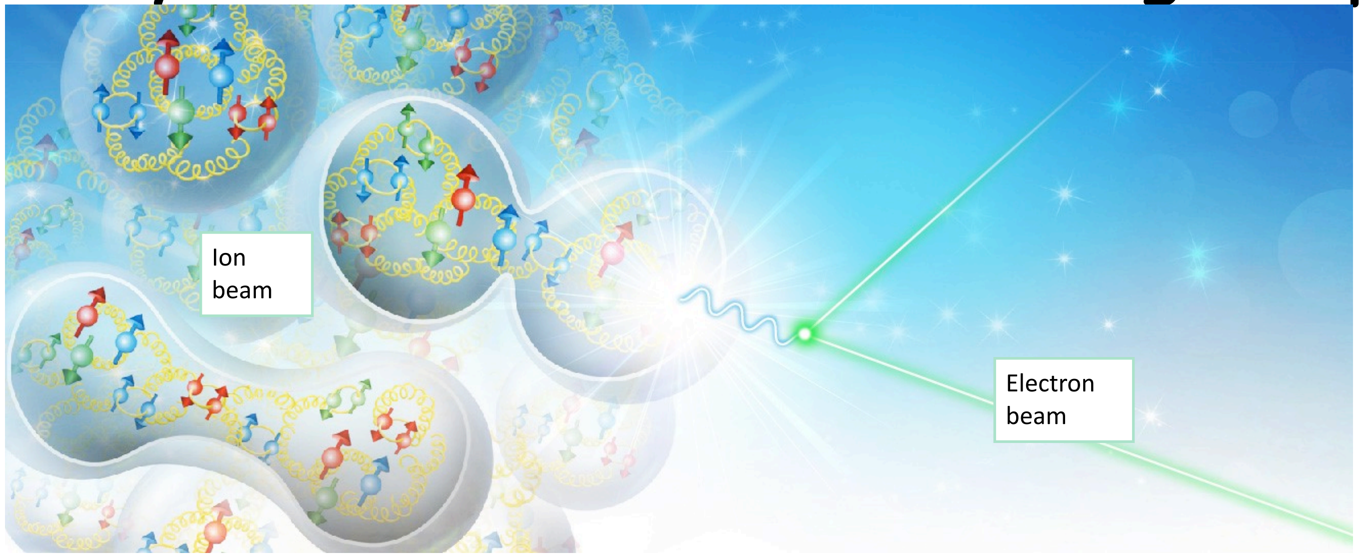
The EIC will be a unique facility:

- ➢ high luminosity & wide reach in √s
- ➢ polarized lepton & hadron beams
- ➢ nuclear beams

Past, existing and proposed DIS facilities



Why Electron- Ion scattering is special?



A giant "Microscope" – "see" quarks and gluons by looking/breaking the hadron

Many complementary probes at one facility:

Inclusive events e+ p/A —> e' +X

Detect only the scattered electron (Modern Rutherford experiment)

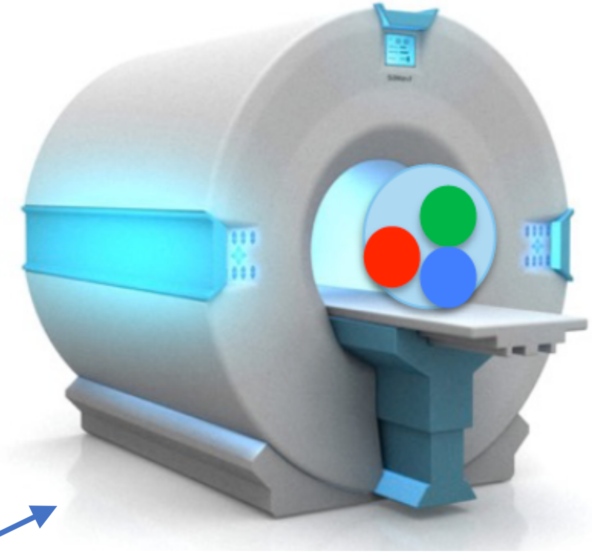
Semi-inclusive events: e+p/A —> e' + h (π, K, p, jet) +X

Detect the scattered electron in coincidence with hadrons/jets (initial hadron is broken -cleaner than h-h collisions)

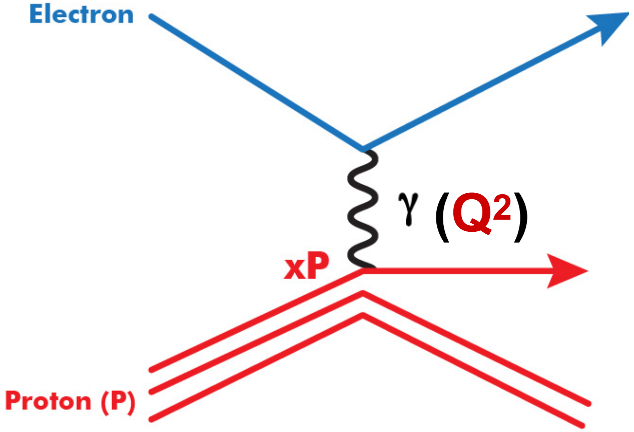
Exclusive events e+p/A —> e' + p'/A' + h (π, K, p, jet)

Detect everything, including scattered proton/nucleus (or its fragments)

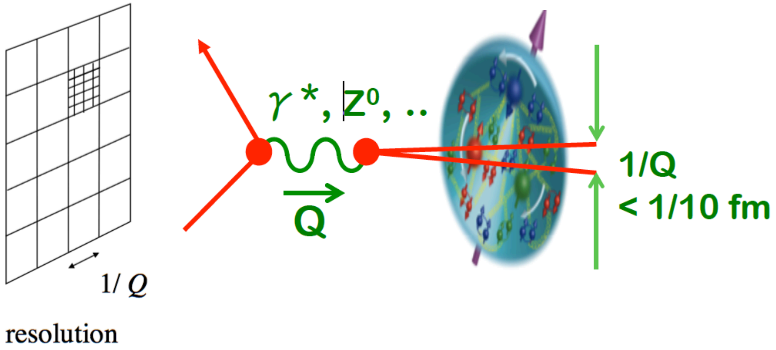
Initial hadron is NOT broken - tomography - almost impossible for h-h collisions



Electron-proton scattering



Ability to change **Q²** changes the resolution scale



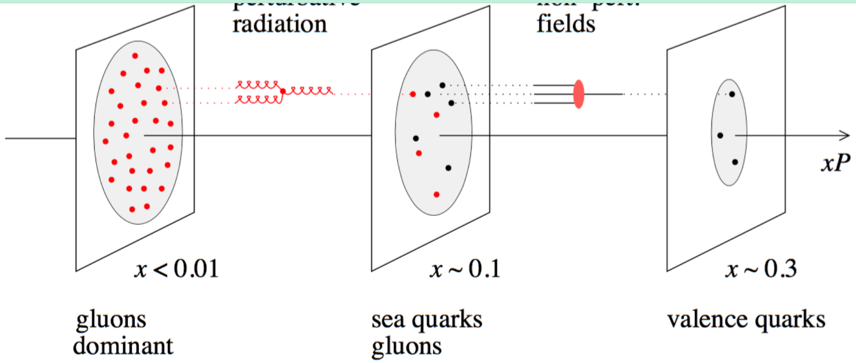
Transition area from DIS to Photoproduction (Q^2<5GeV)

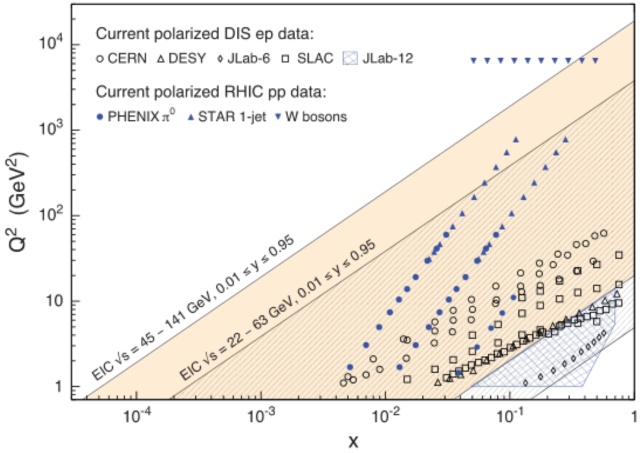
$$Q^2_{\mathrm{EM}} = 2E_eE_{e'}\,(1+\cos\theta_{e'})\,,$$

$$y_{\mathrm{EM}} = 1 - \frac{E_{e'}}{2E_e}(1-\cos\theta_{e'})\,,$$

$$x = \frac{Q^2}{4E_eE_{\mathrm{ion}}}\frac{1}{y}$$

Ability to change **x** projects out different configurations where different dynamics dominate



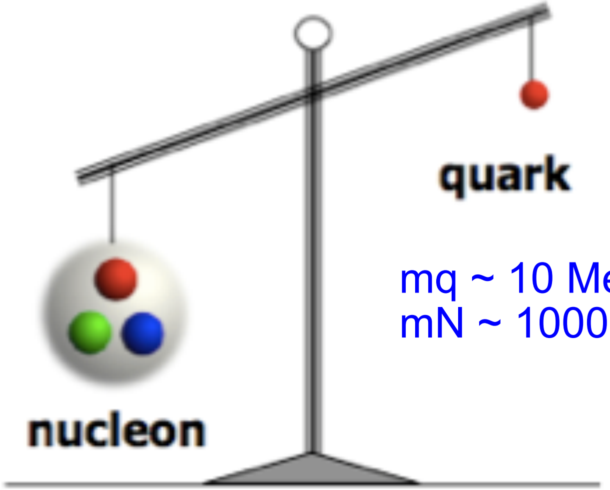


Q²=-q² : 4-momentum transfer squared

x (0<x<1) - fraction of proton momentum carried by the struck quark

y (0<y<1)=(Ee-Ee')/Ee - fractional energy transfer

Mass of the Proton, Pion, Kaon

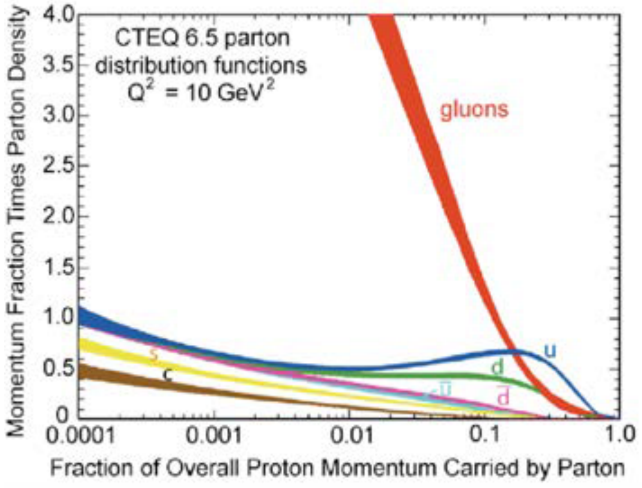


mq ~ 10 MeV
mN ~ 1000 MeV

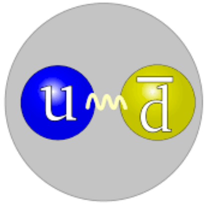
Visible world: *mainly made of light quarks*
Higgs mechanism

Protons:
Quark structure: uud
Mass ~ 940 MeV (~1 GeV)
Mass of quarks : ~ 10 MeV
Gluon rise discovered by HERA e-p

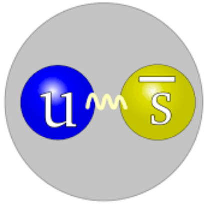
Density of quarks or gluons inside the proton



Pion
Quark structure: $u\bar{d}$
Mass ~ 140 MeV
Empty or full of gluons?

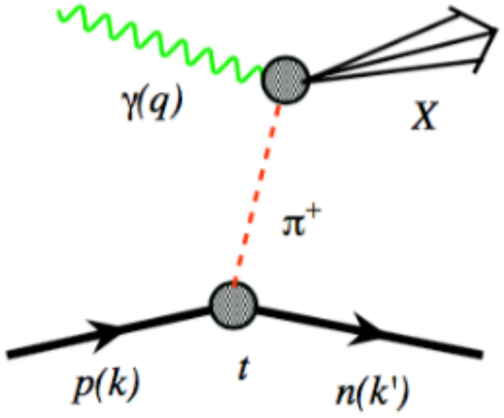


Kaon
Quark structure: $u\bar{s}$
Mass ~ 490 MeV
More or less gluons than in pion?



Meson structure

For the pion and the kaon the EIC will allow determination of the quark and gluon contributions to mass with the Sullivan process.



EIC physics goals: Spin

Proton spin =1/2

"Helicity sum rule"

$$\frac{1}{2}\hbar = \frac{1}{2}\Delta\Sigma + \Delta G + \sum_q L_q^z + L_g^z$$

quark contribution ~ 30%

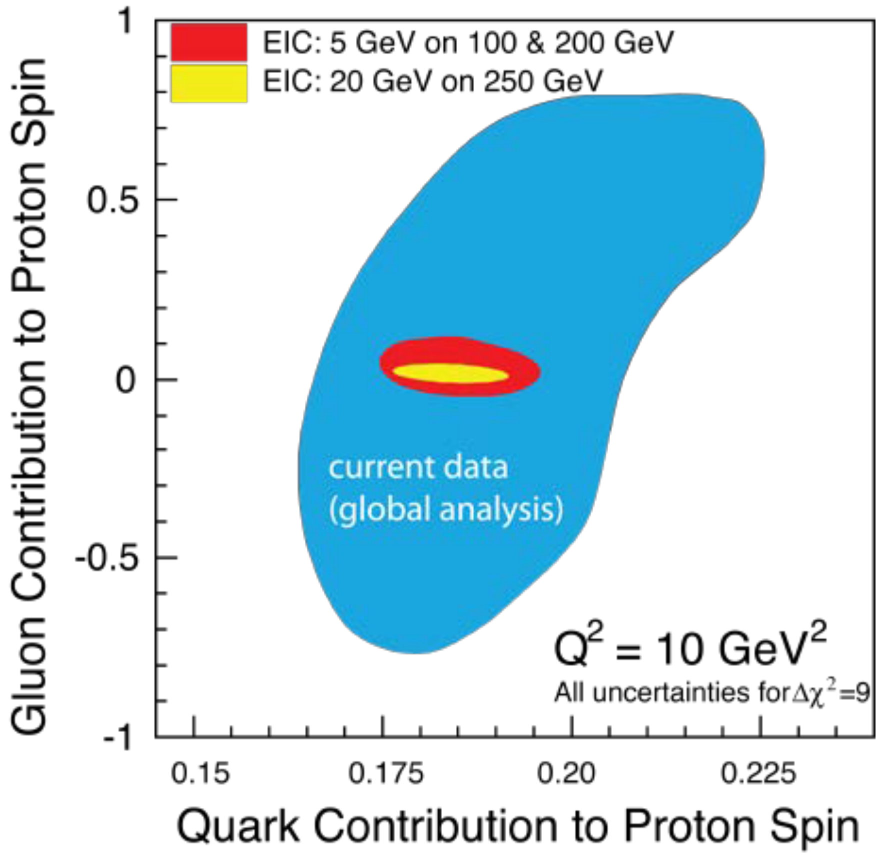
gluon contribution ~ 40%

orbital angular momentum ~?

EMC found:

$\Delta\Sigma =$ 0.12 ± 0.17 ~ 30%

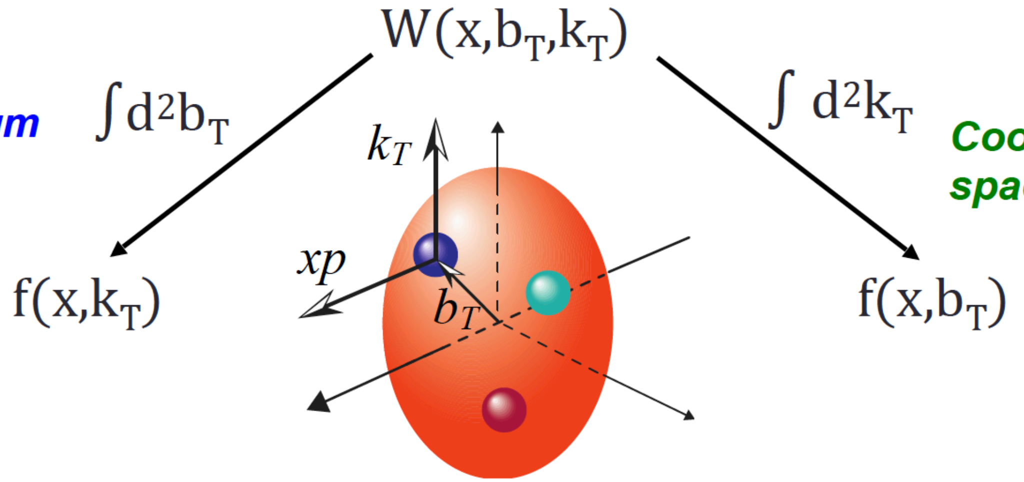
If we do not understand proton mass & spin, we do not understand QCD!

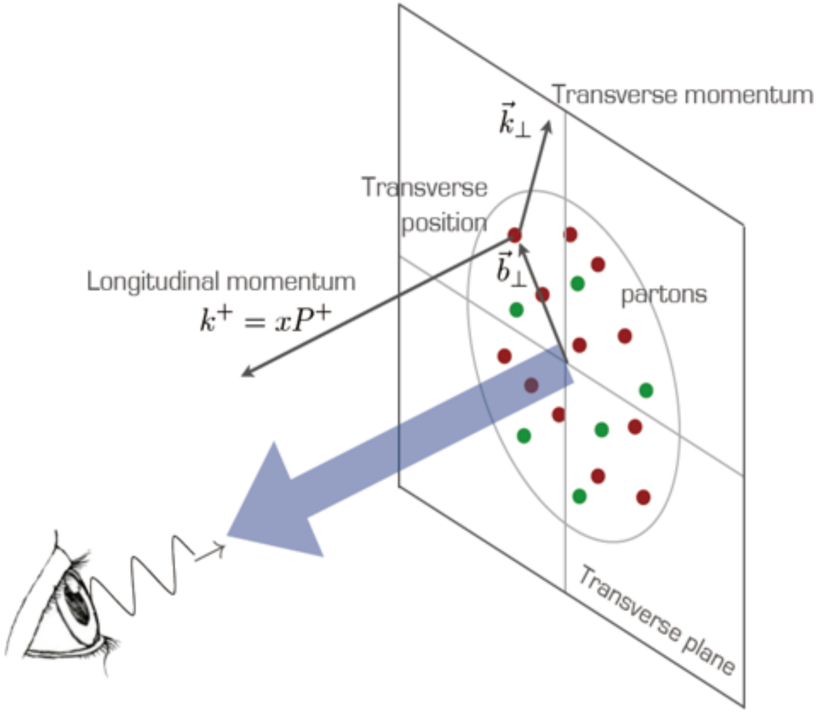


EIC physics goals: 3-Dimentional imaging

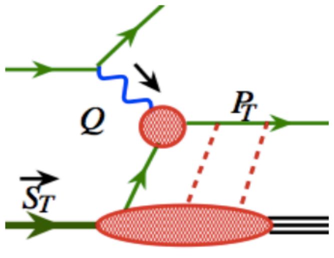
Wigner functions $W(x,b_T,k_T)$

offer unprecedented insight into confinement and chiral symmetry breaking.





✧ **Semi-inclusive DIS:**

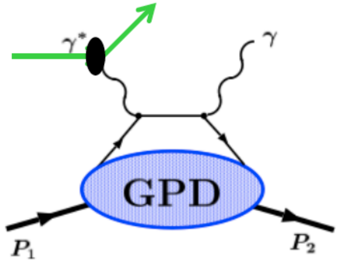


+ …

SIDIS: $Q \gg P_T$

Parton's confined motion encoded into TMDs

✧ **Exclusive DIS:**



+ …

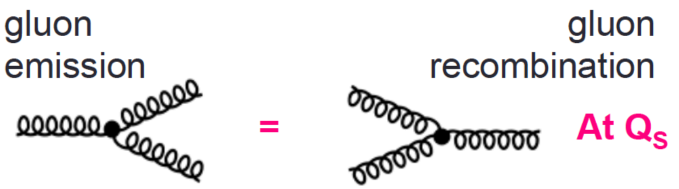
DVCS: $Q^2 \gg |t|$

Parton's spatial imaging from Fourier transform of GPDs' t-dependence

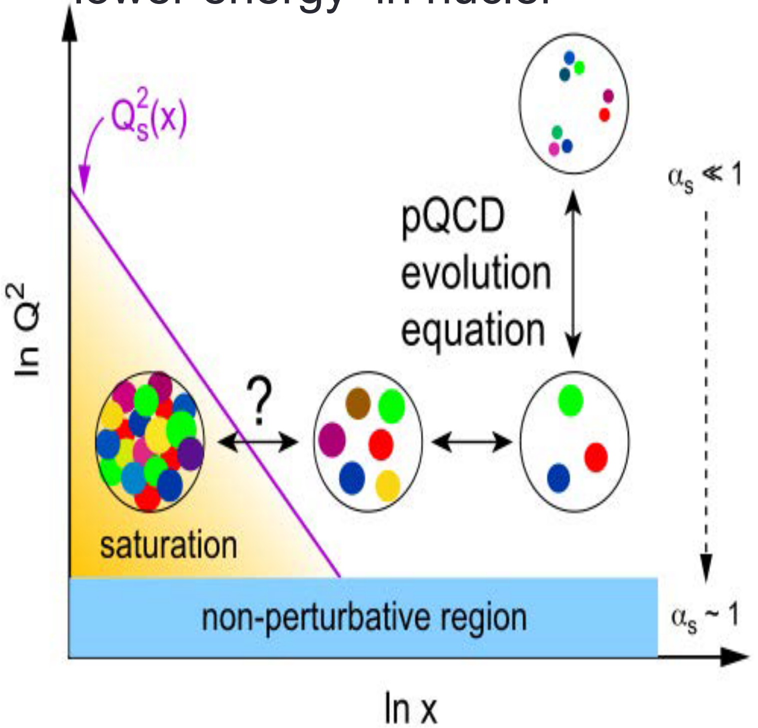
EIC physics goals: Extreme Parton Densities

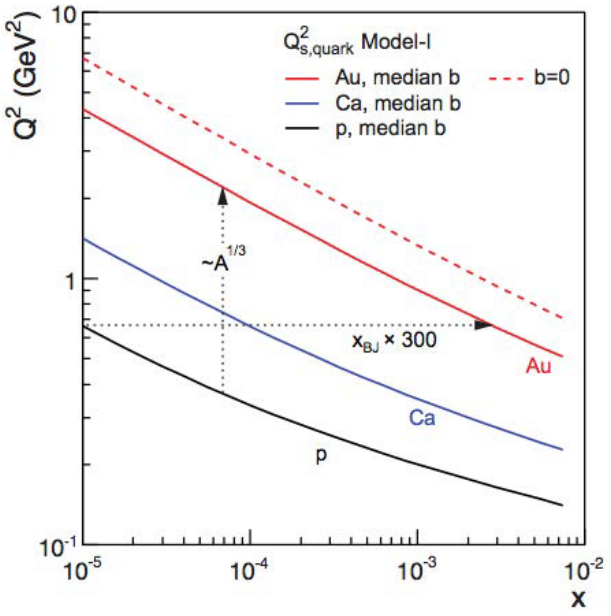
Low-x

At very low x, cross-section will saturate.
could be investigated in transition region

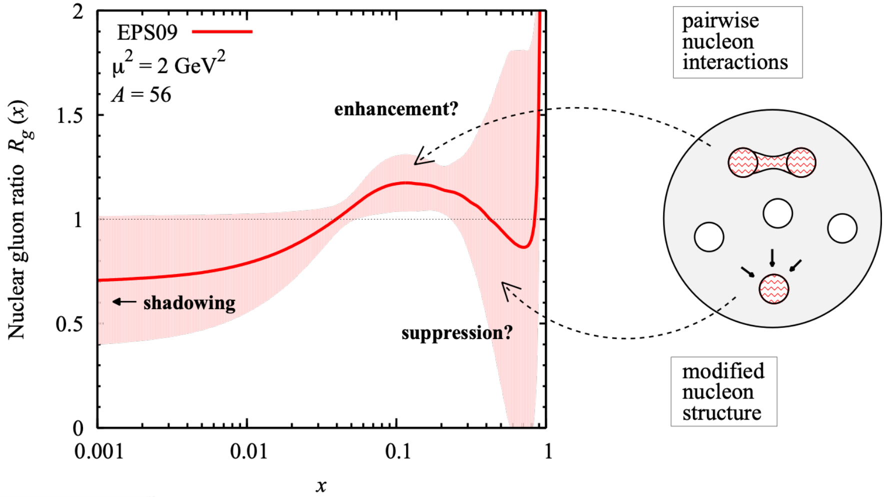


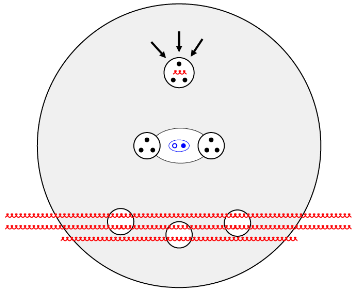
Saturation regime reached at significantly lower energy in nuclei





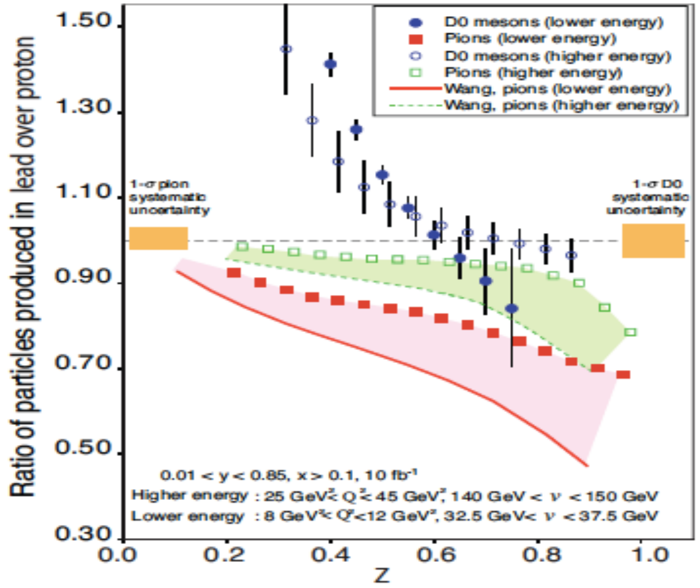
High-x





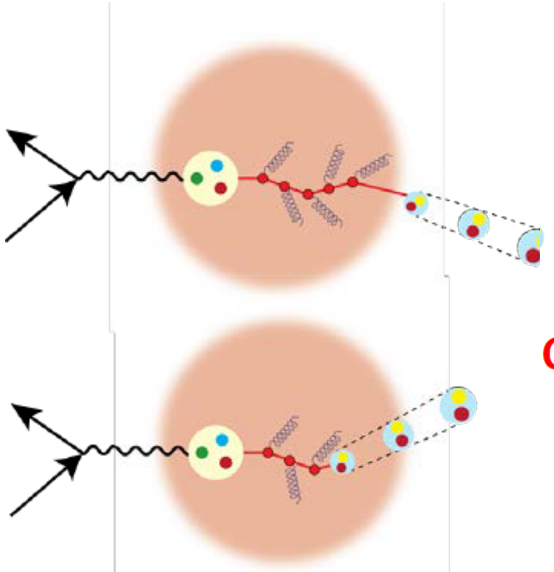
0.3 < x < 0.8	Suppression? EMC effect	Interactions at short distances cf. short-range NN correlations	JLab 6/12 GeV
0.05 < x < 0.2	Enhancement? Antishadowing	Interactions at average distances	
x ≪ 0.1	Shadowing	Coherent interactions enabled by diffraction Observed in J/PSI photoproduction on nuclei	Gribov 70s ALICE, CMS

EIC physics goals: Emergence of Hadrons



- EIC as Femtometer sized detector:

(colored) Quark passing through cold QCD matter emerges as color-neutral hadron.



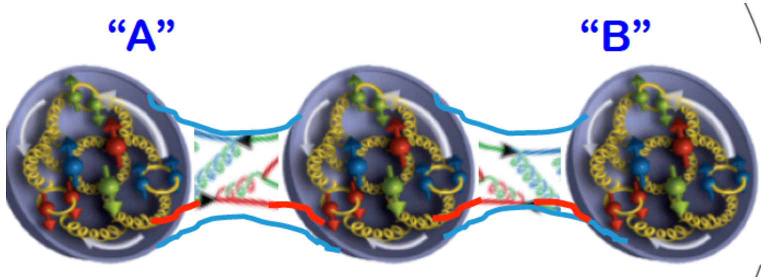
$$\nu = \frac{Q^2}{2mx}$$

Control of ν and medium length!

Understand energy loss of light vs. heavy quarks traversing the cold nuclear matter: Connect to energy loss in Hot QCD

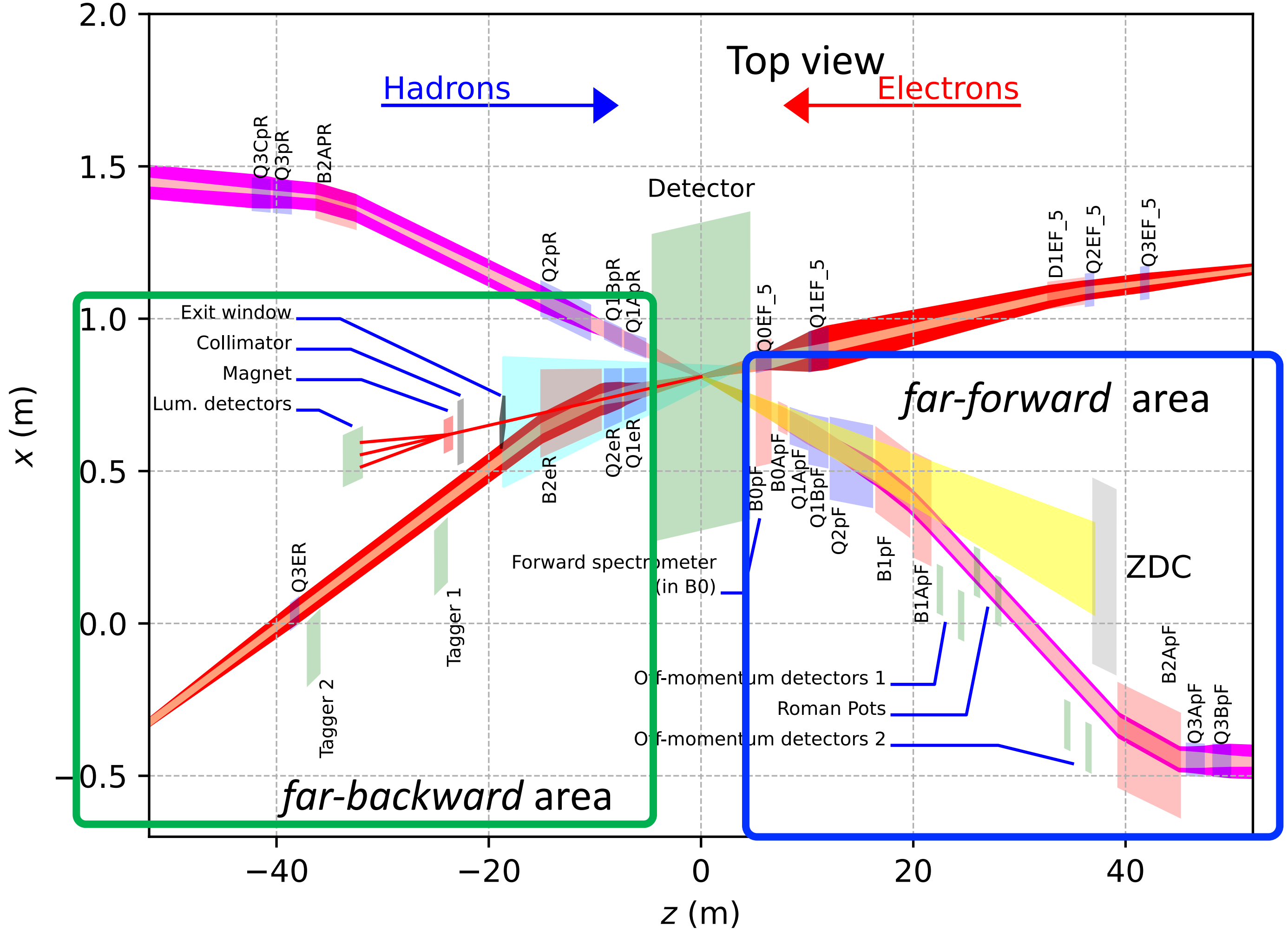
- What does a nucleus look like?

Does the color of "A" know the color of "B"?

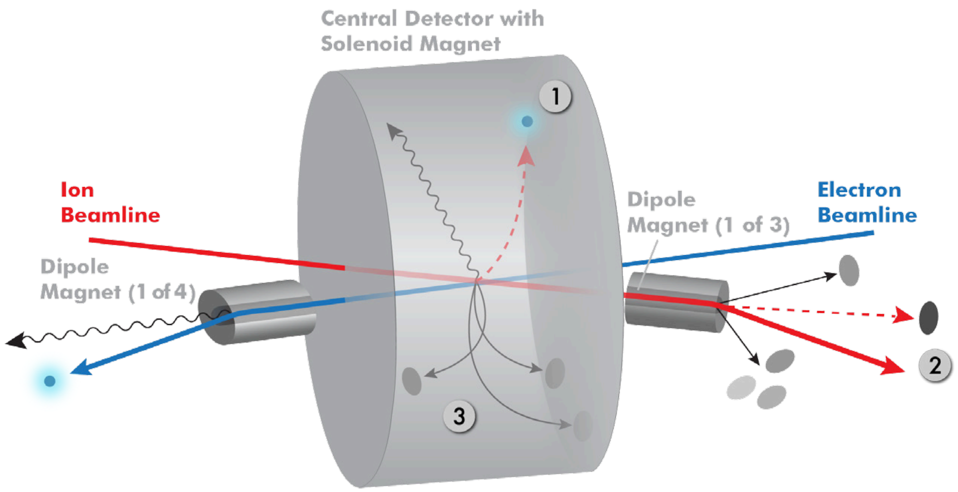


Need the collider energy of EIC and its control on parton kinematics!

EIC interaction region layout (IP6)



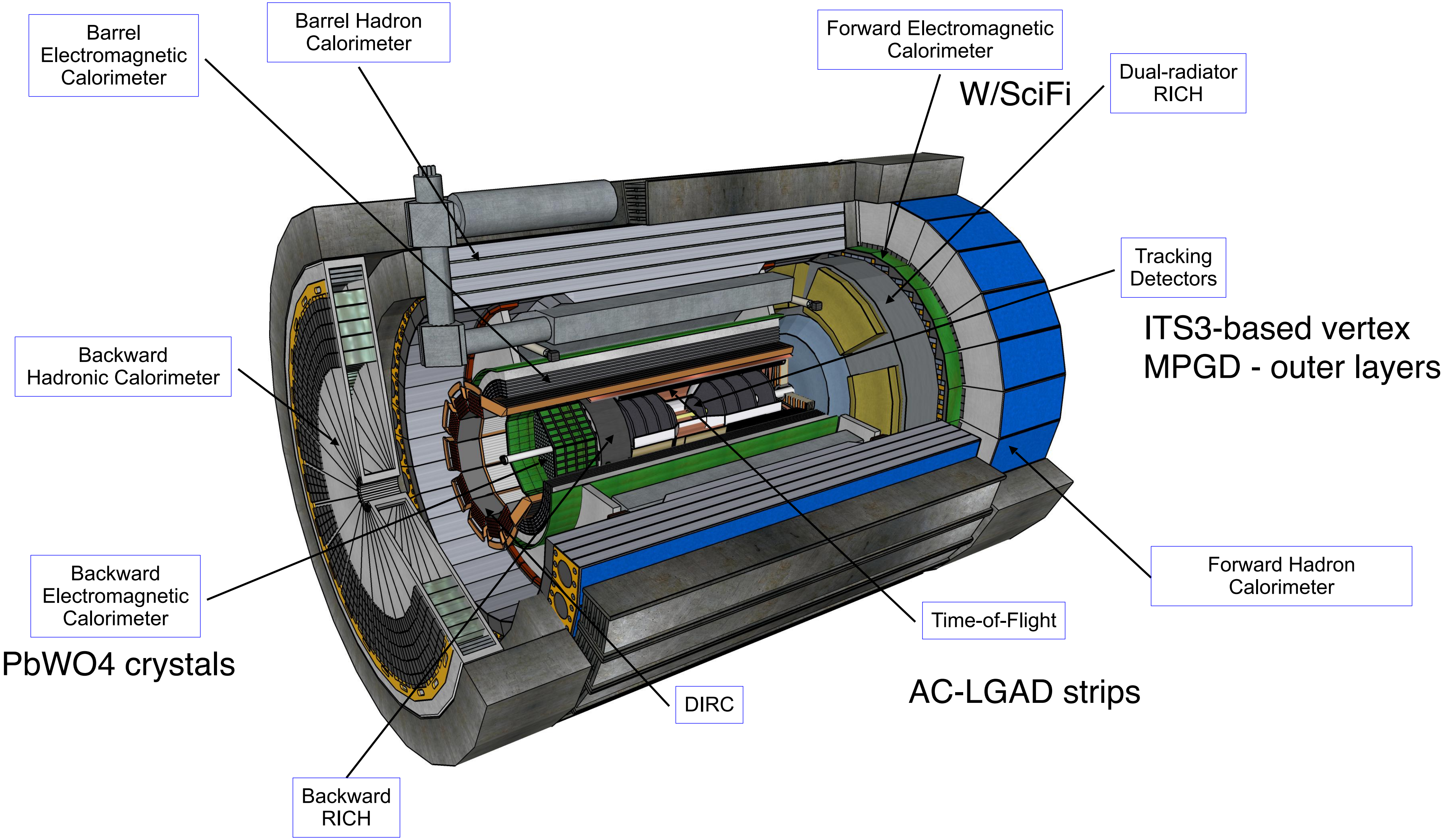
- ~9.5 m around the IP is reserved for the *central* detector
- Crossing angle provides beam separation and space for detector placements
- Apertures of FFQs and dipoles are designed to allow forward going particles to go through



- *Far forward* and *far backward* detector components are distributed along the beam line within ±40 m
- Design should be able to operate **with different beam energy and high luminosity**
- We are keeping a full detector integration in sync with the accelerator design from the early stages on

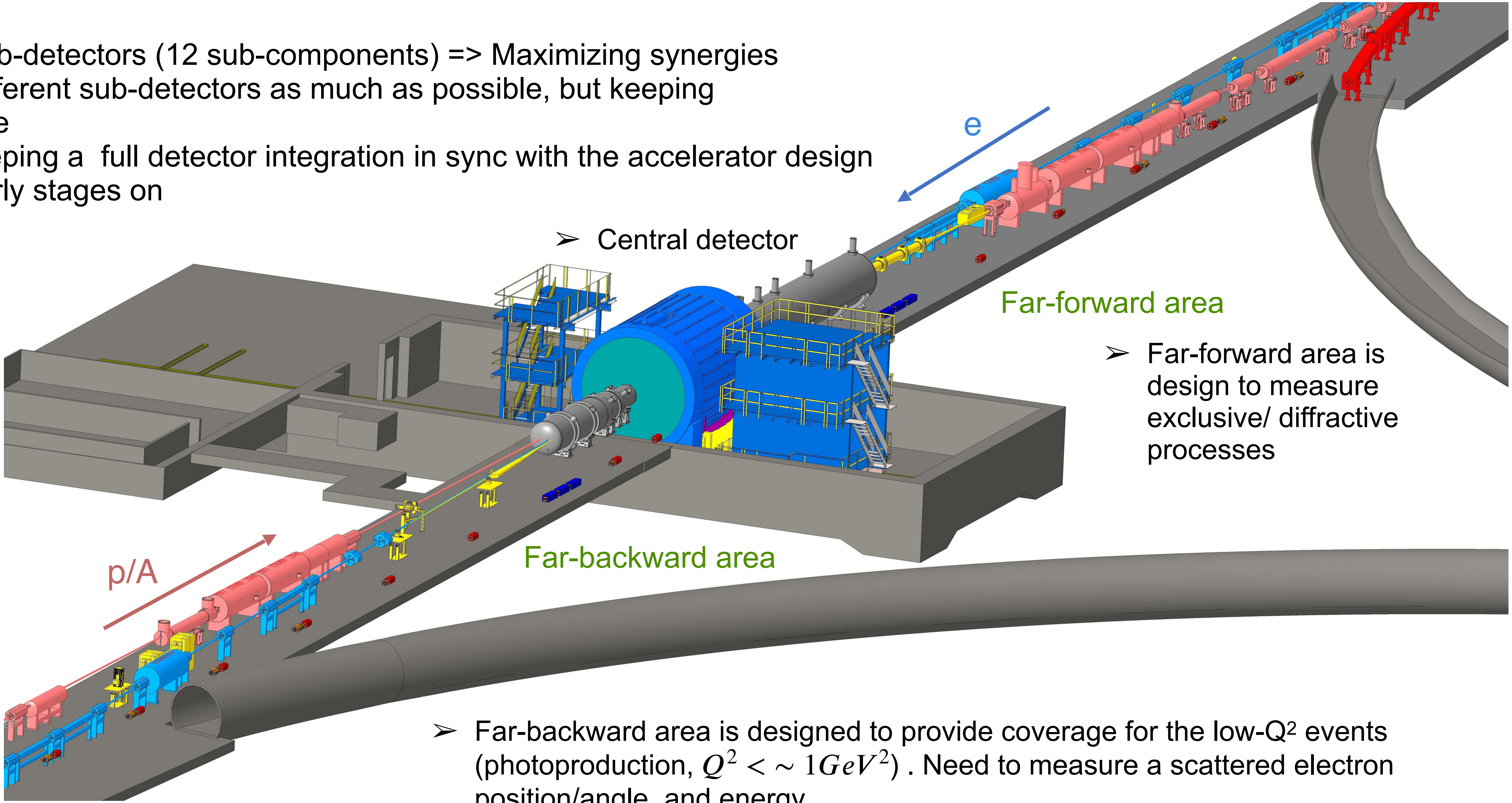
Central Detector

General purpose detector
Coverage: $-4 < \eta < 4$
PID: DIRC, dual-radiator RICH,pfRICH



3D View

- ❑ In total 7 sub-detectors (12 sub-components) => Maximizing synergies between different sub-detectors as much as possible, but keeping performance
- ❑ We are keeping a full detector integration in sync with the accelerator design from the early stages on



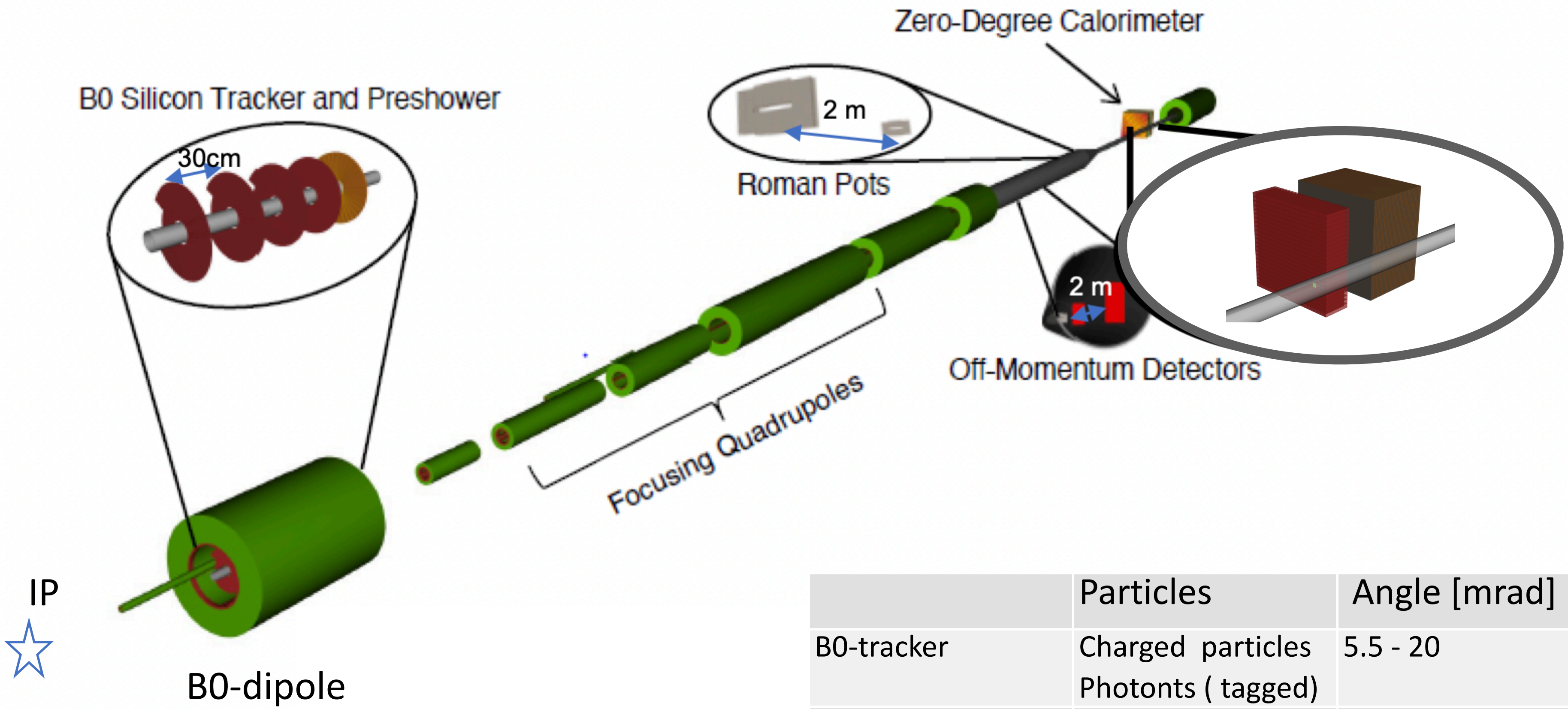
- ➢ Central detector

- ➢ Far-forward area is design to measure exclusive/ diffractive processes

- ➢ Far-backward area is designed to provide coverage for the low-Q^2 events (photoproduction, $Q^2 < \sim 1GeV^2$) . Need to measure a scattered electron position/angle and energy
- ➢ And luminosity detector (ep -> e'pγ bremsstrahlung photons)

Far-forward detectors (hadron-going)

Geant4 implementation of IP6 Far-forward area



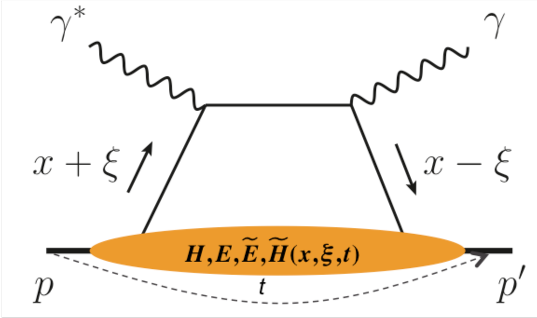
	Particles	Angle [mrad]	$p/p_{beam}(x_L)$
B0-tracker	Charged particles Photonts (tagged)	5.5 - 20	
Off-momentum	Charged particles	0-5.0	0.4< xL< 0.65
Roman Pots	Protons Light nuclei	0 * - 5.0 $(*)10\sigma\ cut$	0.6 < xL< 0.95
ZDC	Neutrons Photons	0-4.0 (5.5)	

Exclusive Reactions: DVCS

Parton tomography

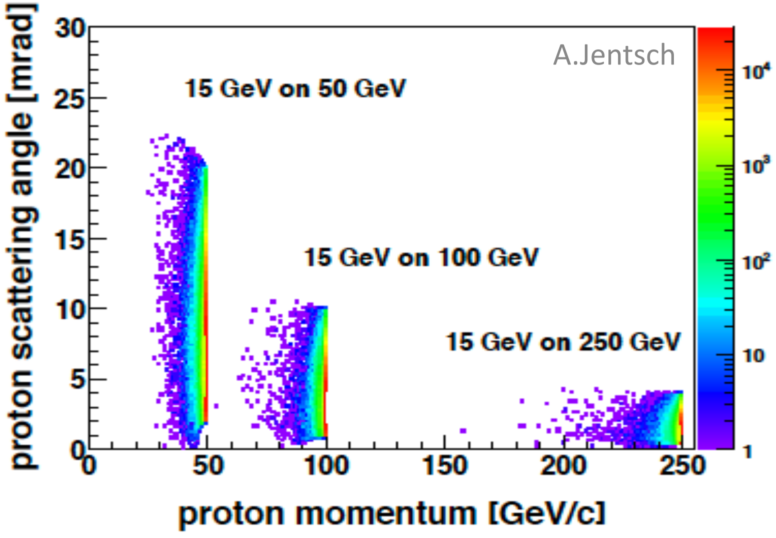
In addition to the central detector + Far-Forward proton tagger (Roman Pots) :

- ➢ Dedicated detector(s) close to the beam line is required
- ➢ Need to cover at least $0.18<p_T<1.3$ GeV/c
- ➢ Integration in the Interaction Region is critical
- ➢ Exclusiveness => hermetic coverage from central to far-forward



$$e + p \rightarrow e' + \gamma + p'$$

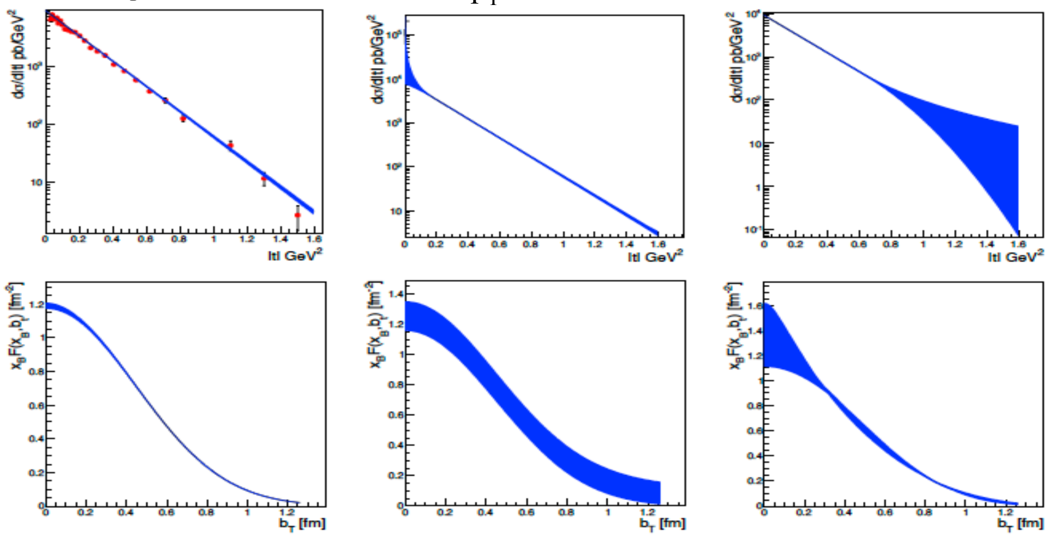
Need to detect a **scattered proton**



Fourier Transform

DVCS σ(t)

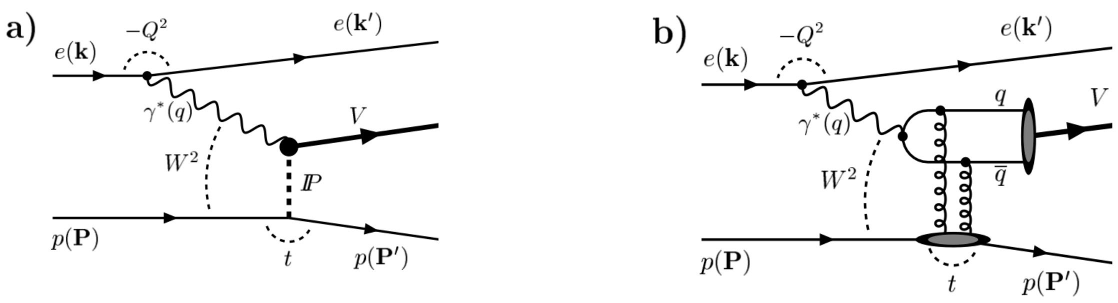
PDF(b_T)



Exclusive reactions: Vector Meson production

arXiv:2108.01694v2

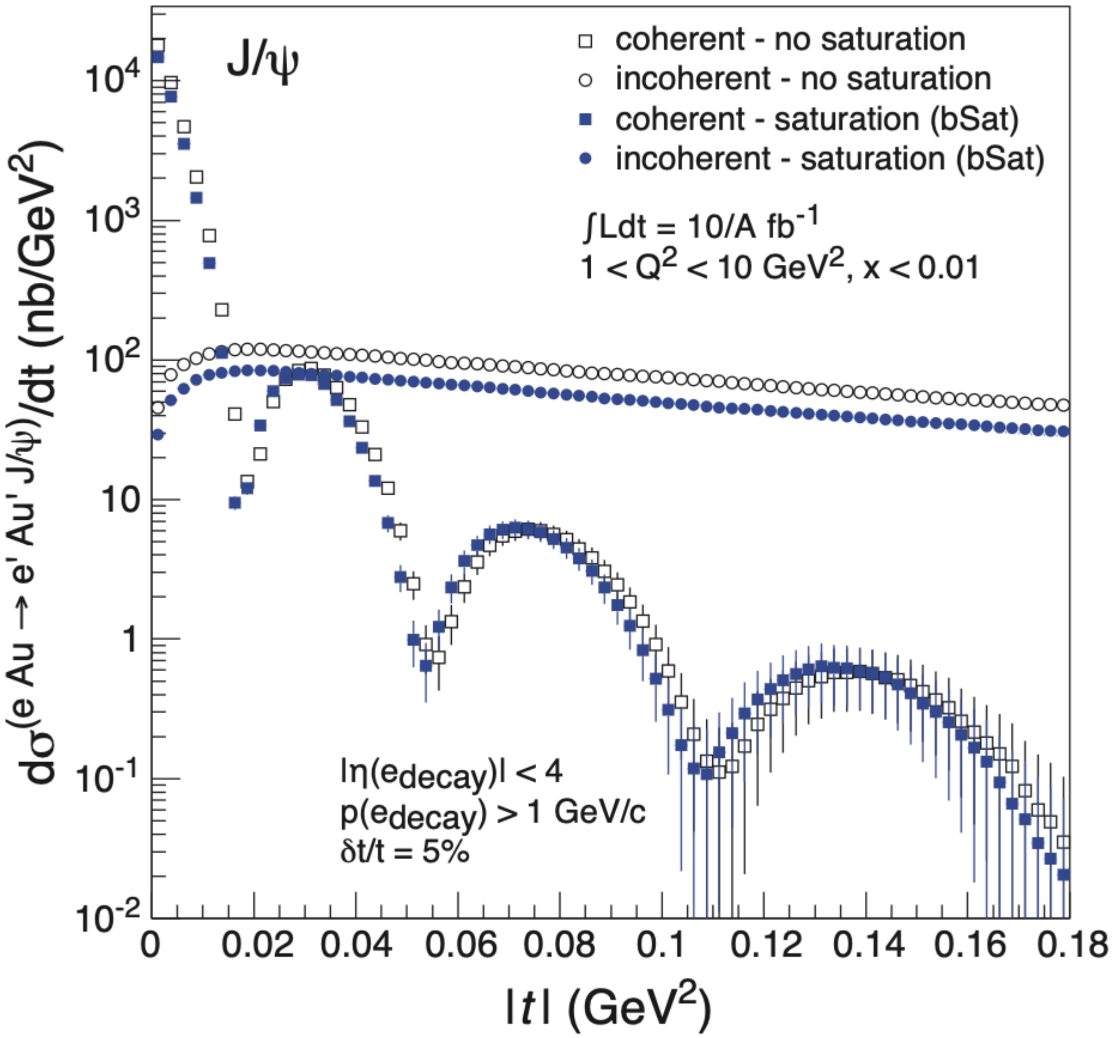
$$e + p \rightarrow e' + J/\Psi(e^+e^-, \mu^+\mu^-) + p'$$



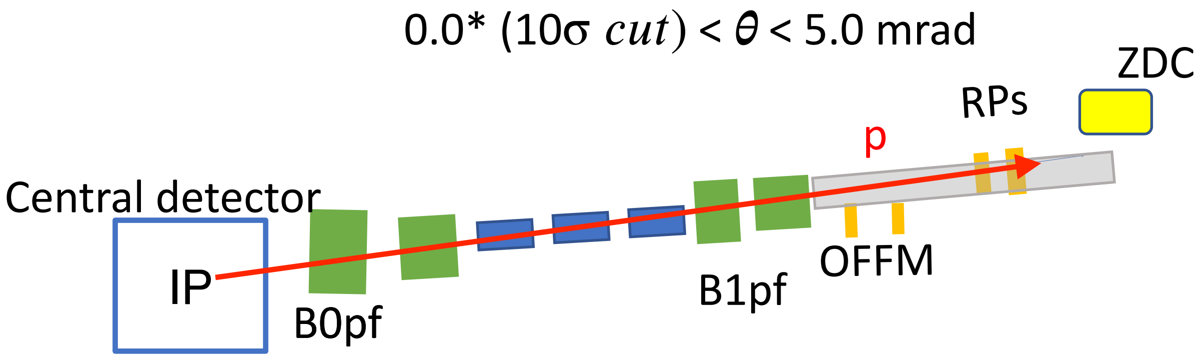
Elastic vector meson production described by (a) Regge theory and (b) perturbative quantum chromodynamics

- Need to detect a **scattered proton**
- **Photoproduction**

Coherent and incoherent J/Psi as a probe of saturation

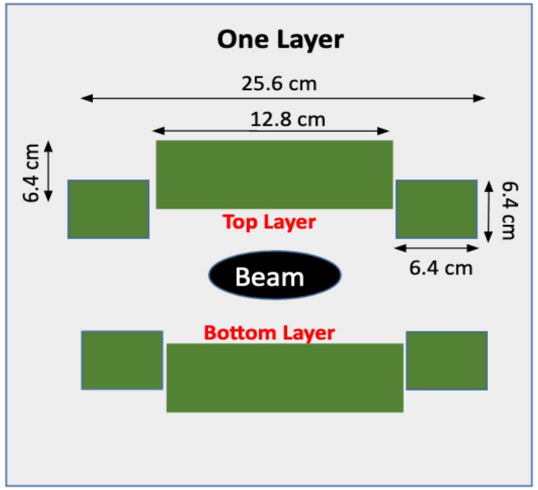


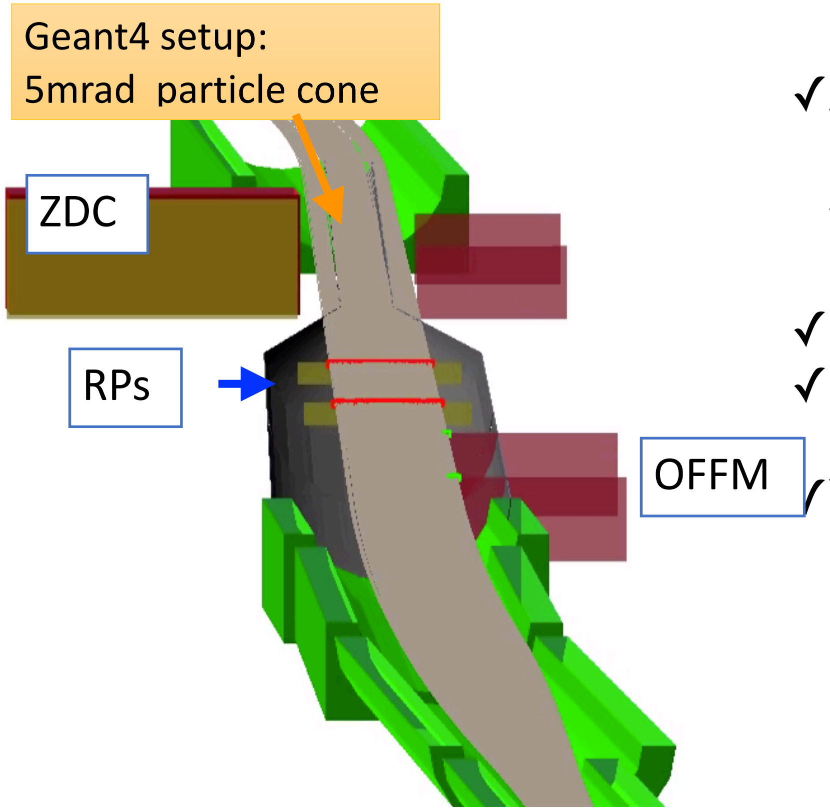
Roman-Pots



$$\sigma(z) = \sqrt{\varepsilon \bullet \beta(z))}$$

$\sigma(z)$ is the Gaussian width of the beam, $\beta(z)$ is the RMS transverse beam size. ε is the emittance.





- ✓**Movable** (as close as 10σ away from the beam (depends on beam energy and beam configuration: high divergence or high acceptance).
- ✓AC-LGADs with 500um pixel pitch. With charge-sharing can achieve **spatial resolution < 20μm per hit** . **Timing resolution < 35ps** (helps with unfolding of vertex to eliminate beam smearing effect)

- ✓RPs needs to be **integrated into the vacuum system , RF shielding**
- ✓Insertion from top and bottom - need to minimize space in front of ZDC.

- ✓**Very close contact with accelerator** to avoid negative impacts on the machine operation

Roman Pots resolution and beam effects

- The various contributions add in quadrature (this was checked empirically, measuring each effect independently).

$$\Delta p_{t,total} = \sqrt{(\Delta p_{t,AD})^2 + (\Delta p_{t,CC})^2 + (\Delta p_{t,pxl})^2}$$

Angular divergence

Primary vertex smearing from crab cavity rotation.

Smearing from finite pixel size.

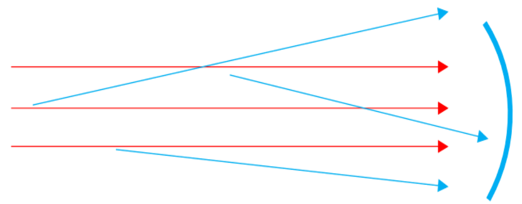
These studies based on the "ultimate" machine performance with strong hadron cooling.

A.Jentsch

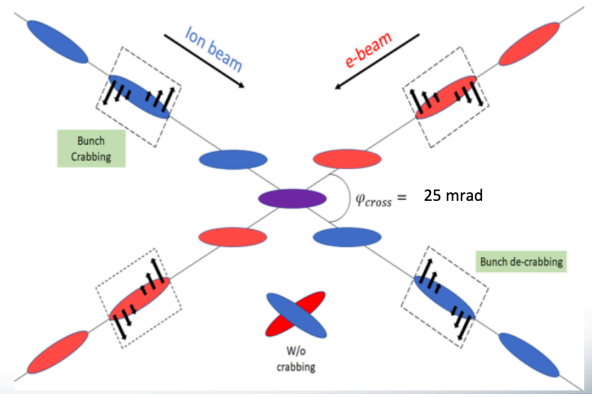
	Ang Div. (HD)	Ang Div. (HA)	Vtx Smear	250um pxl	500um pxl	1.3mm pxl
$\Delta p_{t,total}$ [MeV/c] - 275 GeV	40	28*	20	6	11	26
$\Delta p_{t,total}$ [MeV/c] - 100 GeV	22	11	9	9	11	16
$\Delta p_{t,total}$ [MeV/c] - 41 GeV	14	-	10	9	10	12

- **Beam angular divergence**
  - Beam property, can't correct for it – sets the lower bound of smearing.
  - Subject to change (i.e. get better) – beam parameters not yet set in stone
    - *using symmetric divergence parameters in x and y at 100urad.
- **Vertex smearing from crab rotation**
  - Correctable with good timing (~35ps).
  - With timing of ~70ps, effective bunch length is 2cm ->.25mm vertex smearing (~7 MeV/c)

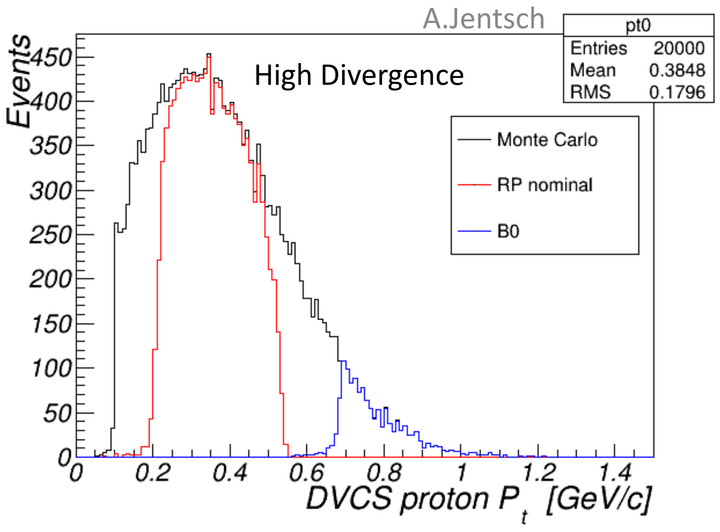
Angular divergence

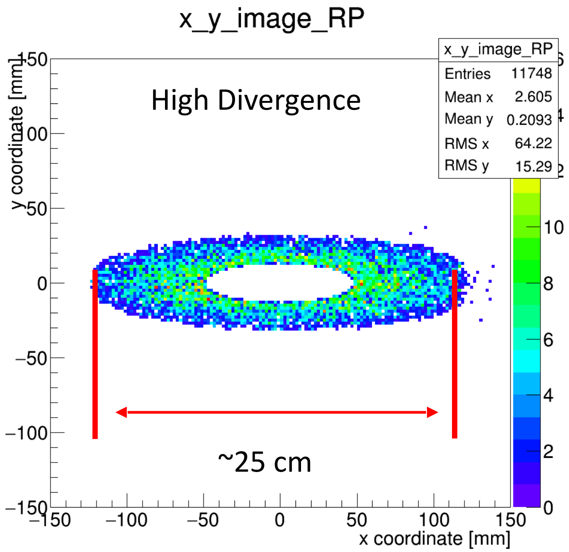


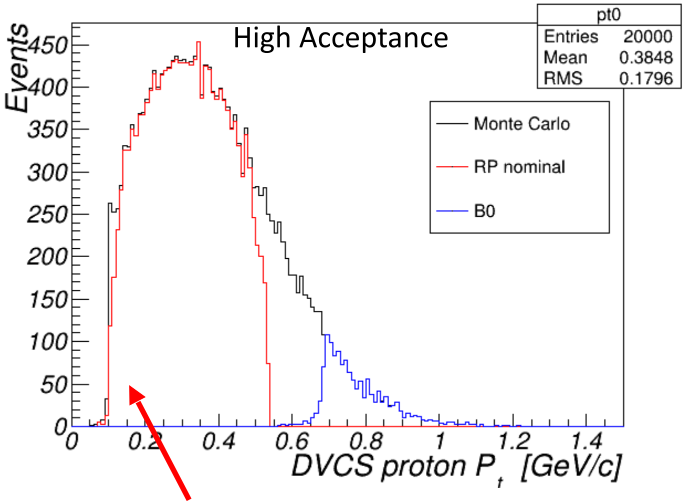
Primary vertex smearing from crab cavity rotation



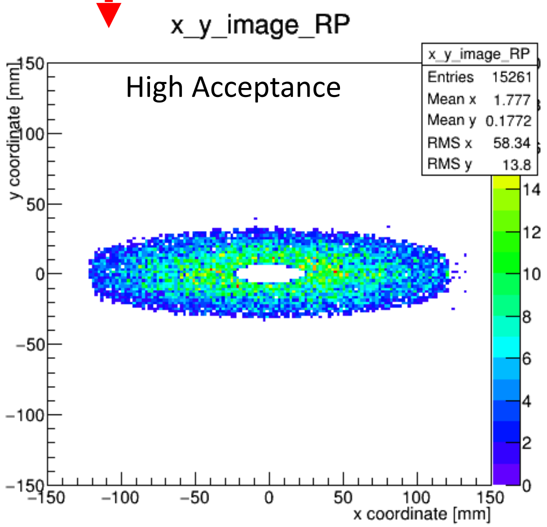
100 GeV DVCS protons







Improves low p_t acceptance.



$$\sigma(z) = \sqrt{\varepsilon \bullet \beta(z)}$$

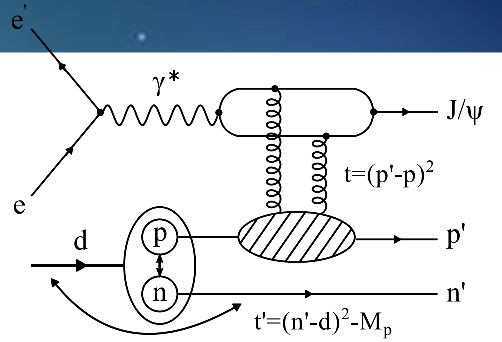
$\sigma(z)$ is the Gaussian width of the beam,
$\beta(z)$ is the RMS transverse beam size.
ε is the emittance.

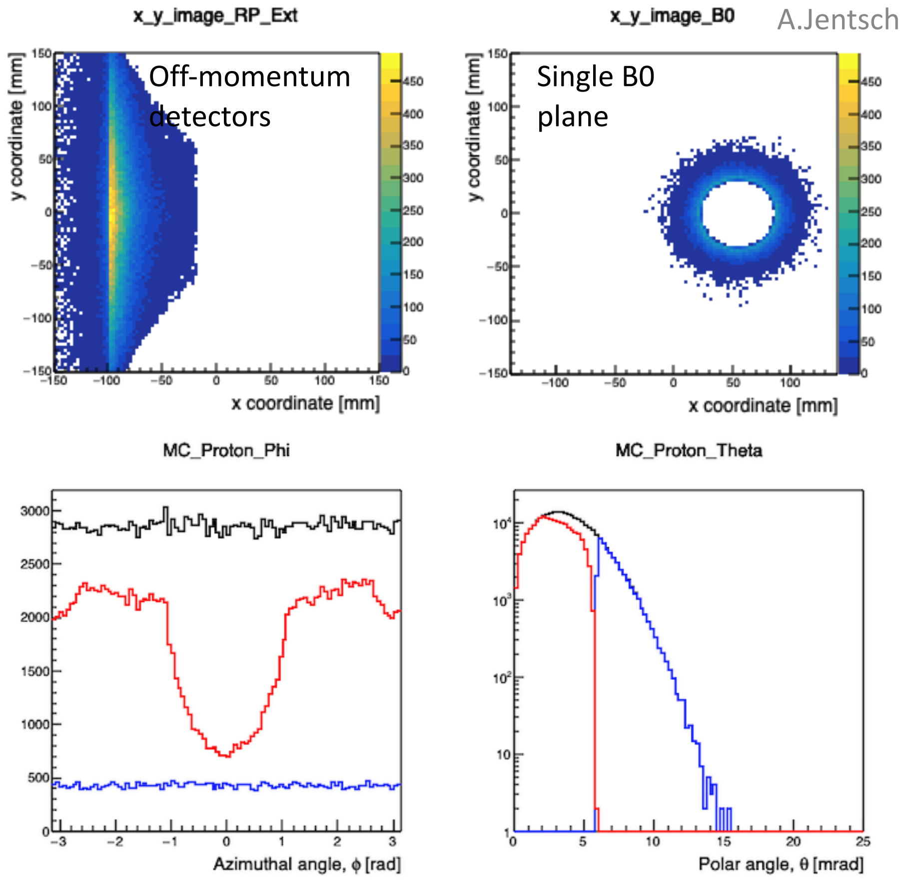
High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

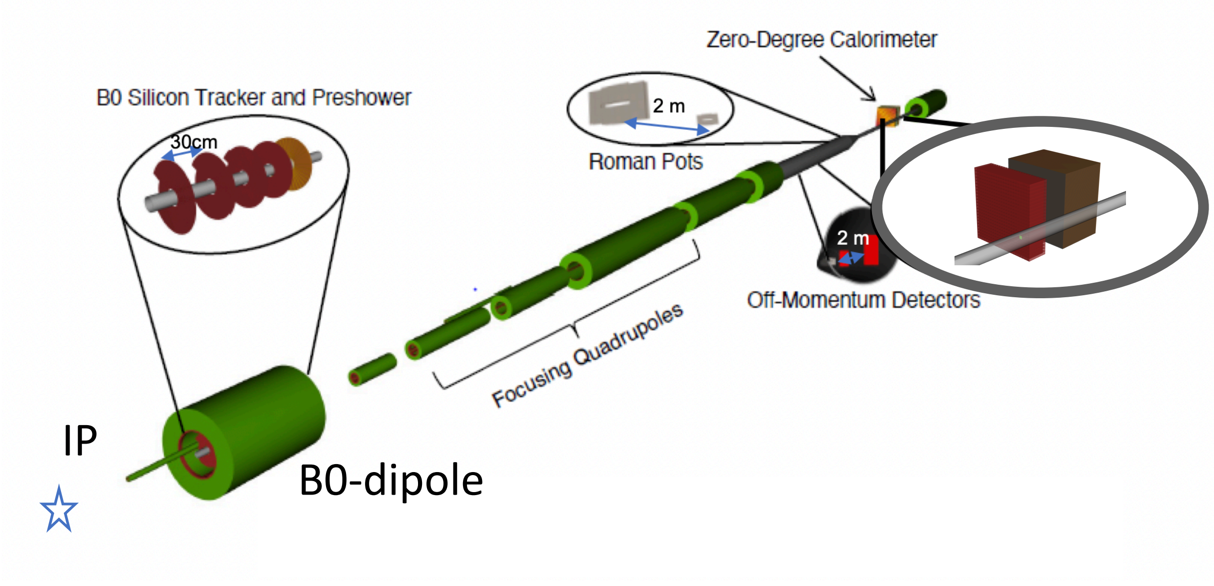
High Acceptance: larger β^* at IP, smaller $\beta(z = 30m)$ -> lower lumi., smaller beam at RP

B0- detectors

- ✓ Full p_T coverage for forward-going protons is critical for EIC physics, but the high p_T-acceptance in RPOTs is limited by magnet's apertures
- ✓ B0-system shall provide theta coverage in the range **5.5 < θ < 20.0 mrad** (4.6 < η < 5.9) with respect to the hadron beam line.
- ✓ And Off-Momentum detectors for particles with
- ✓ Need to provide measurements of forward photons and pi0: $\gamma + \gamma$ from π^0 separation to clearly isolate u-channel DVCS
- ✓ Must be resistant to extreme background conditions, high neutron flux in particular



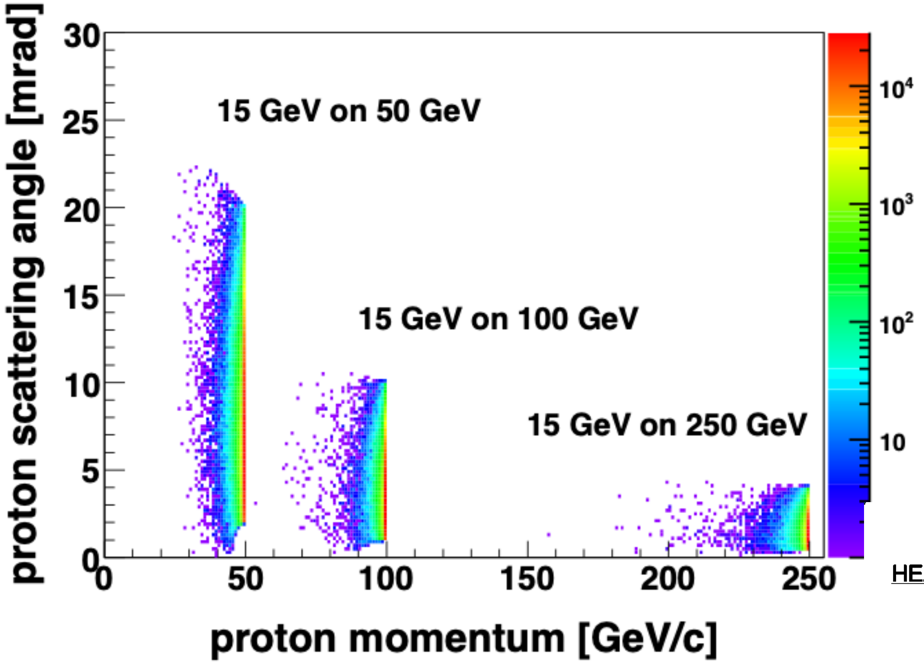




Neutron spectator/leading proton case.
ed (18x110GeV)

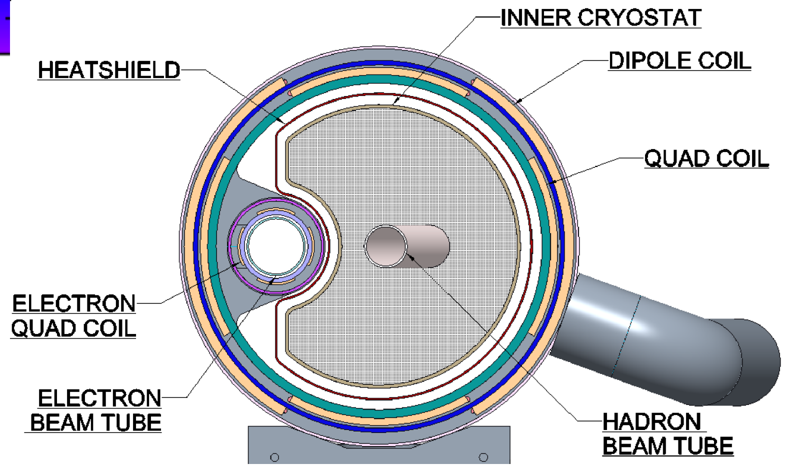
B0- detectors

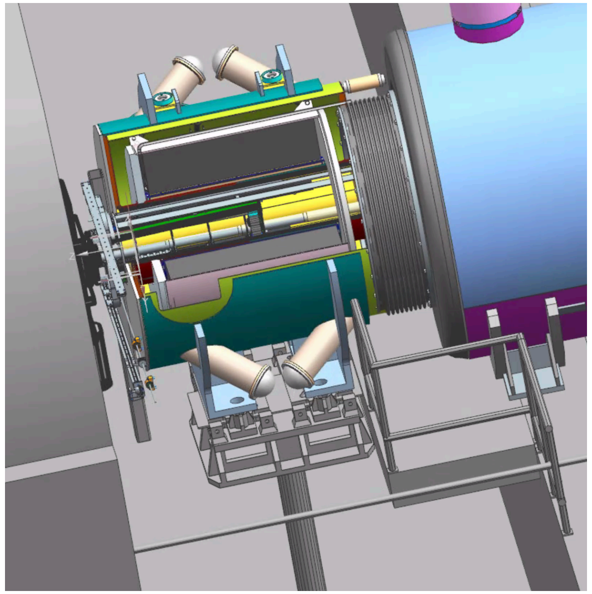
✓ B0 detectors are specially important for the low-energy operation



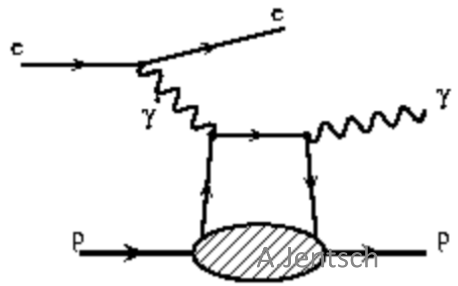
Placement:

✓ **B0-dipole:** length is ca 1.5m, field 1.3T for momentum reconstruction, ~20cm inner bore (design is on the way)
✓ Zero field line at electron beam axis.
✓ Warm space for detector package insert located inside a vacuum vessel to isolate from insulating vacuum.
✓ Beams are separating into two independent beam-pipes in front of B0;   Vacuum pump in front
  ➡ crossing angle: unequal space between beam-pipes
✓ Limited space:access to B0-detectors only from one side (after opening HCAL) ~ 15cm

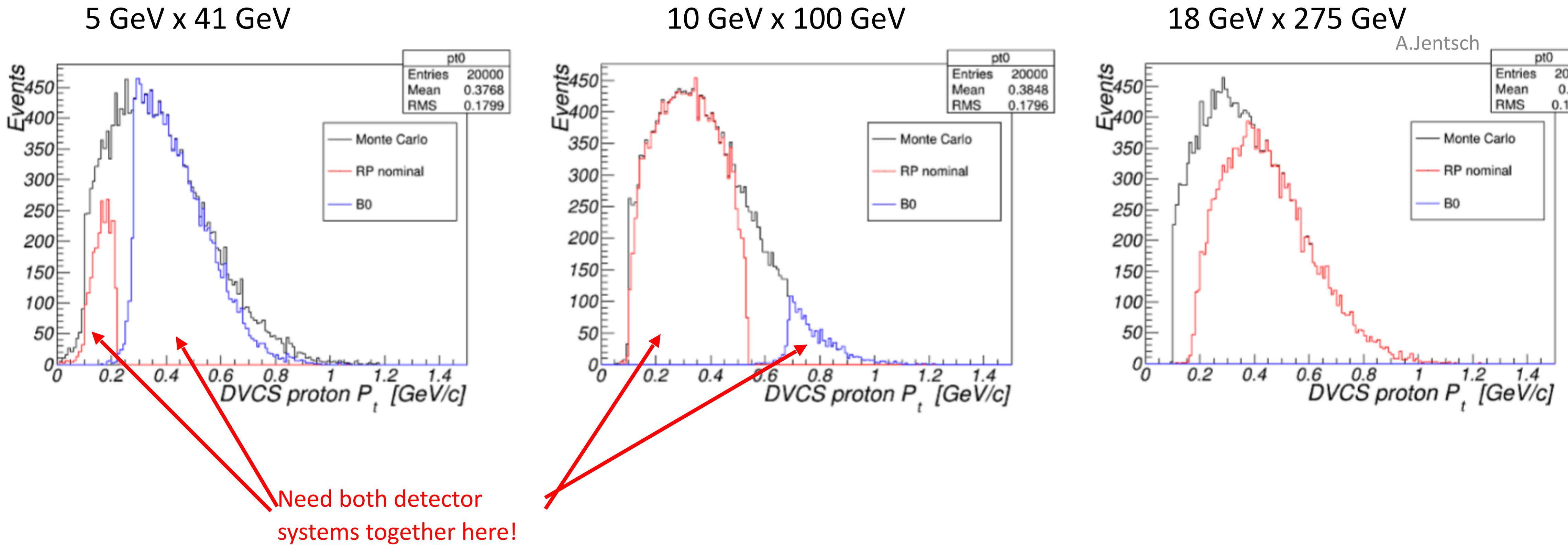




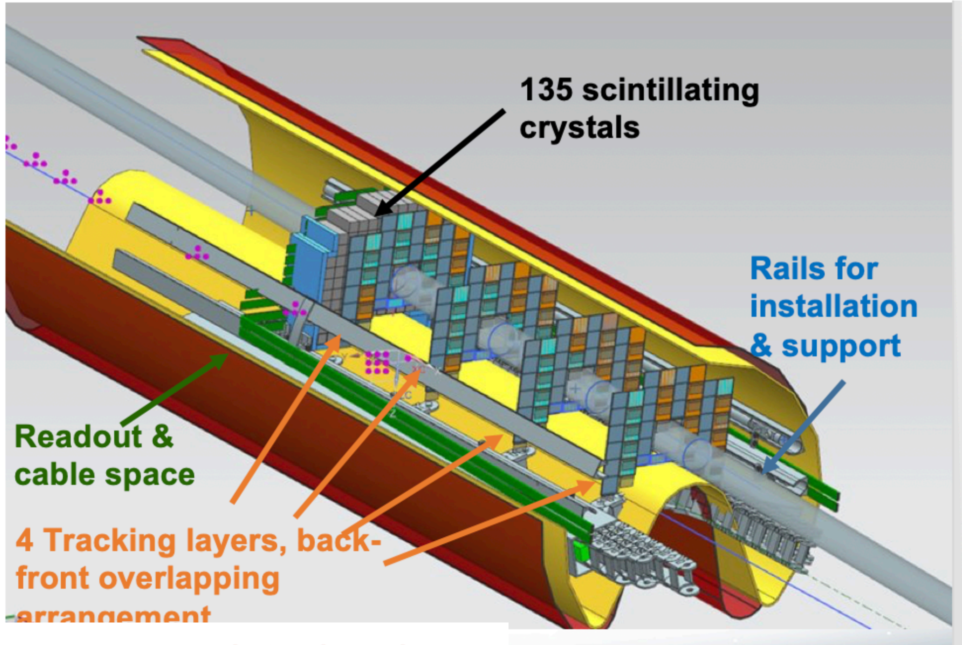
Forward Proton Acceptance



- ✓ Full p_T coverage for forward-going protons is critical for EIC physics, but the high p_T-acceptance in RPOTs is limited by magnet's apertures
- ✓ B0-system shall provide theta coverage in the range **5.5 < θ < 20.0 mrad** (4.6 < η < 5.9) with respect to the hadron beam line.

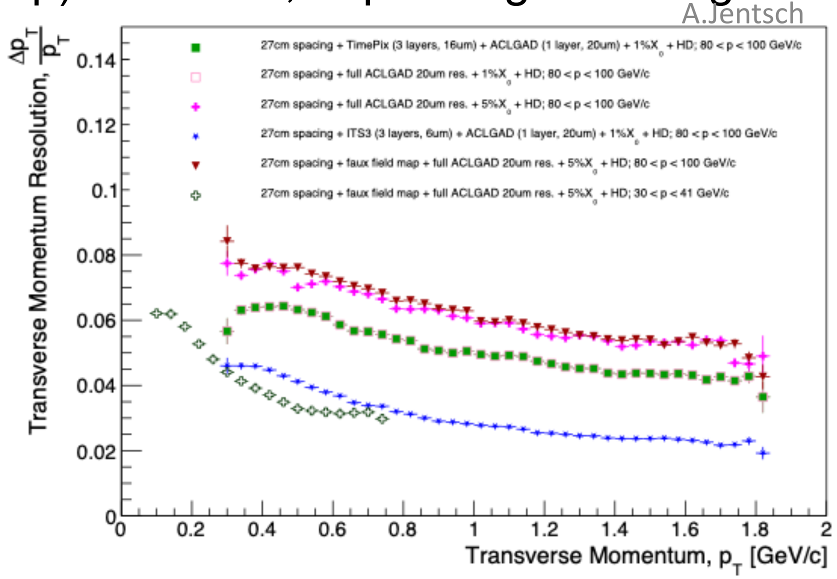


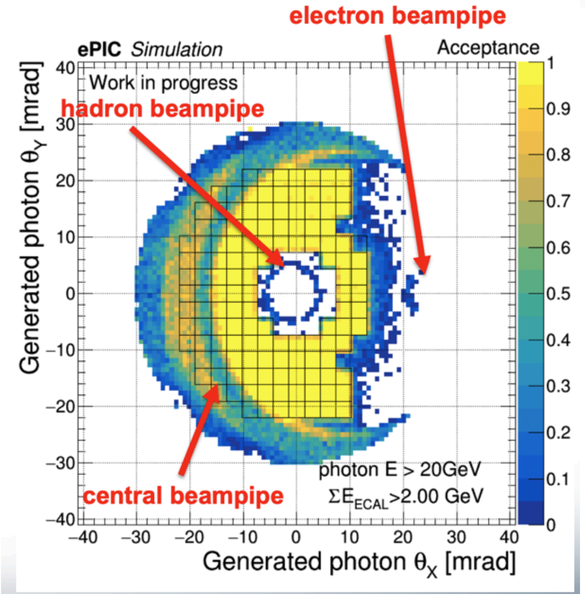
B0-detectors

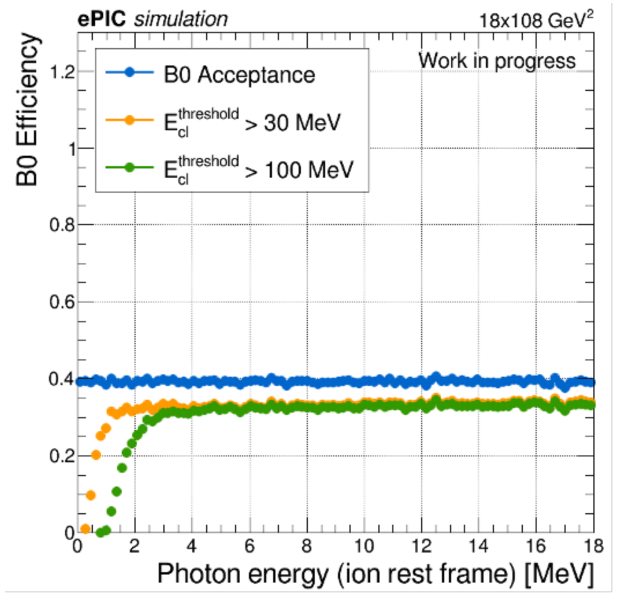


- ✓ **Tracker**: 4 layers of AC-LGADs (500 μm pixels) - ca 25-30 cm space between layers
  - ➡ synergies with other detectors(RPs, etc)
- ✓ **Calorimeter:** $PbWO_4$ 2x2x7 cm³ - synergies with backward EMCAL and ZDC EMCAL

For charged particles: momentum resolution (dp/p) is ~2-4%, depending on configuration.





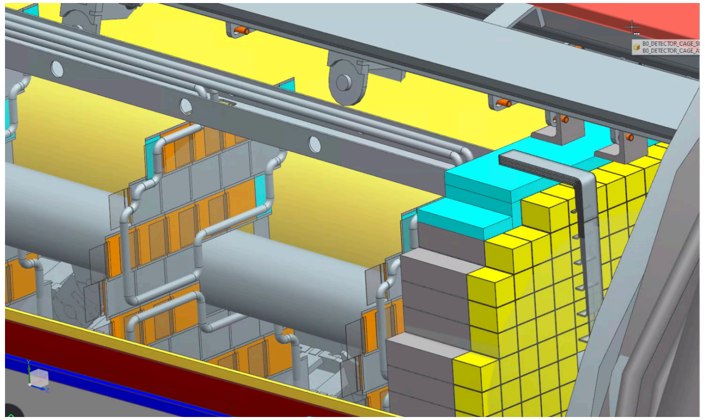


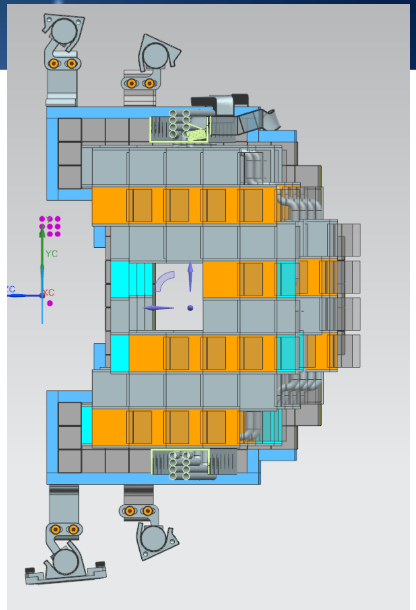
For photons:

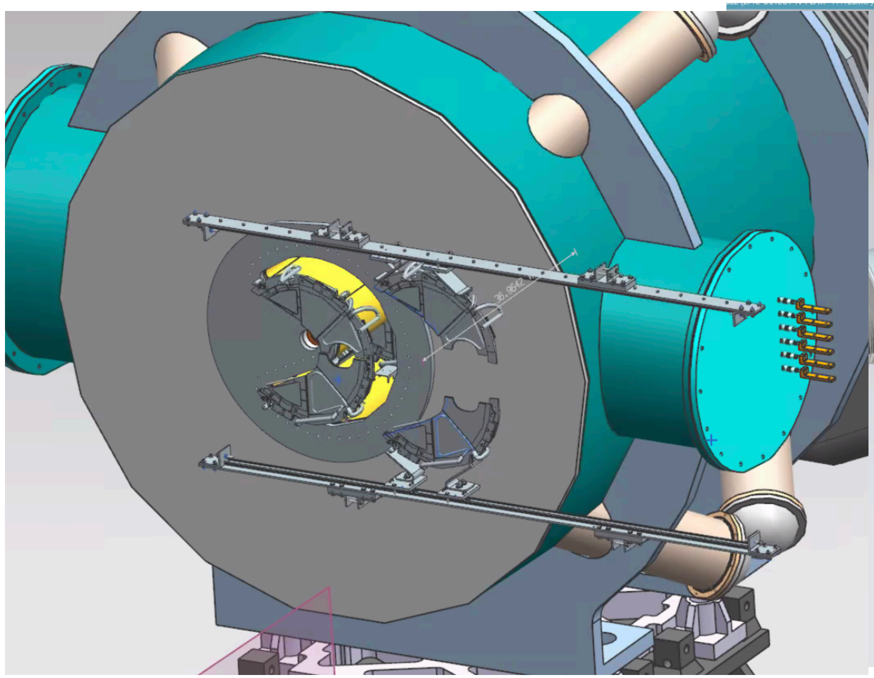
- ➢High acceptance in a broad energy range (> 100s MeV), including ~MeV de-excitation photons
- ➢Energy resolution of 6-7%
- ➢Position resolution of ~3 mm

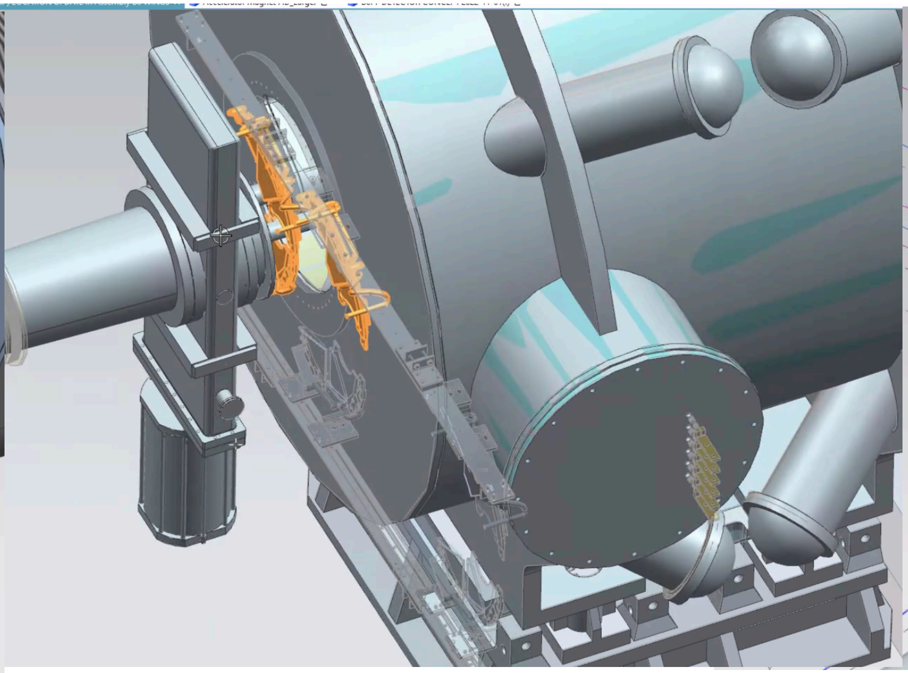
B0-detectors- integration

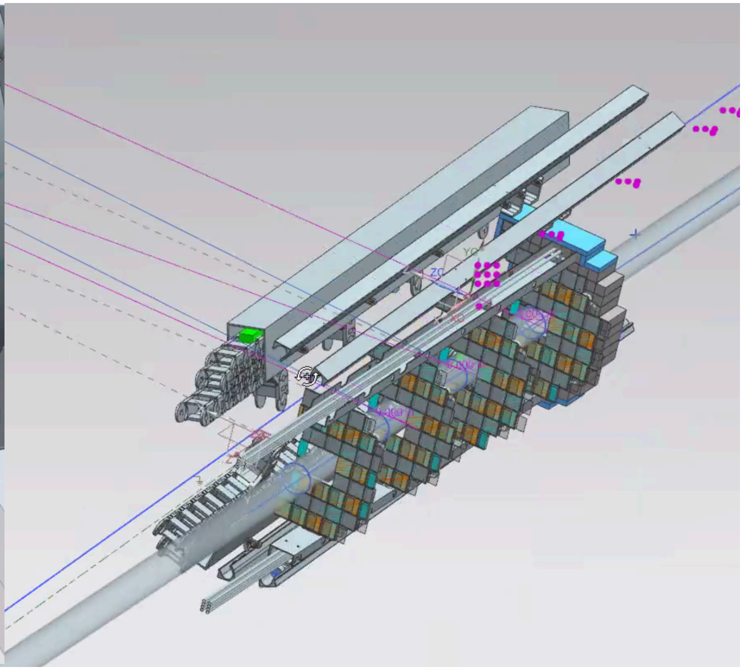
- Mechanical integration
- Installation and maintenance
- Cooling/cabling





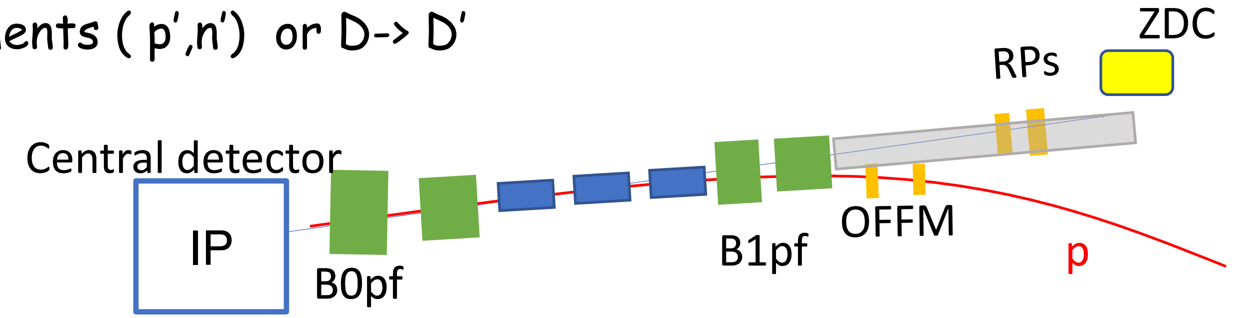


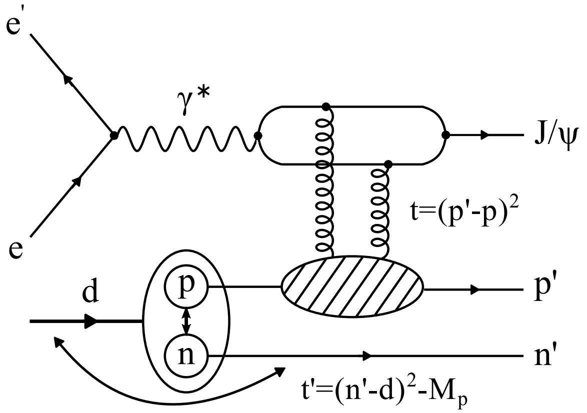




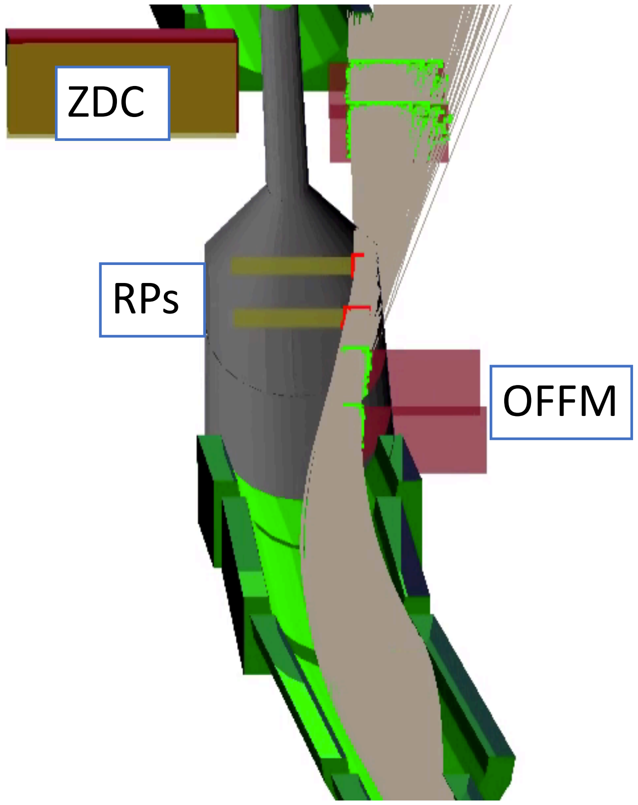
Exclusive reactions: eD/eA

- D-> fragments (p',n') or D-> D'



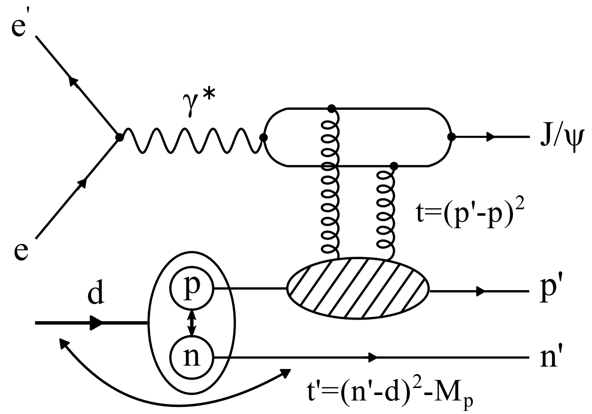


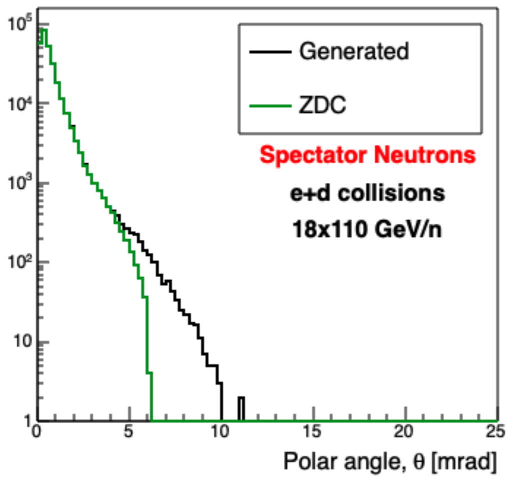
- Protons that come from nuclear breakup have a different magnetic rigidity than their respective nuclear beam (x_L<1)
- This means the protons experience more bending in the dipoles.
- As a result, small angle (θ < 5mrad) protons from these events will not make it to the Roman Pots, and will instead exit the beam pipe after the last dipole.
- Detecting these requires "off-momentum detectors".
- Movable, beam pipe integration.

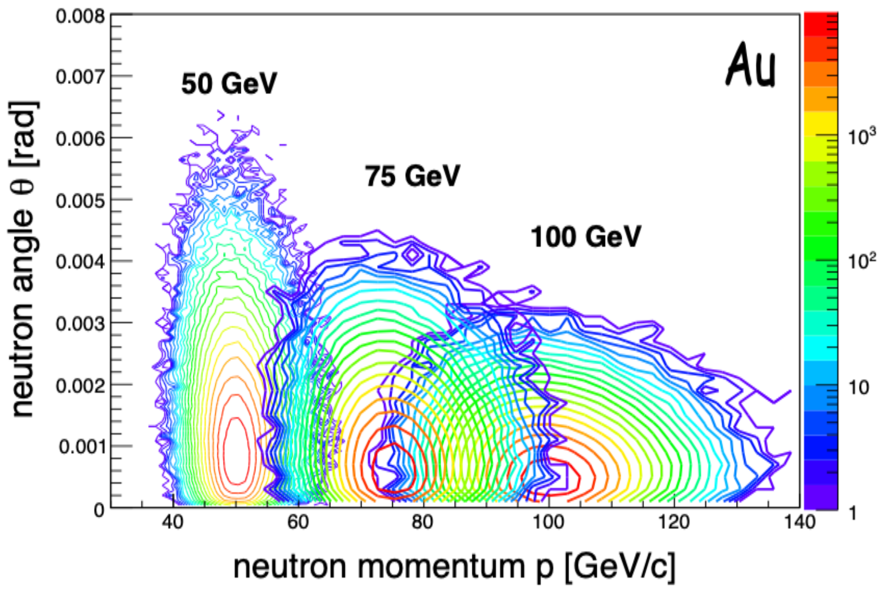


Detection of Neutrons

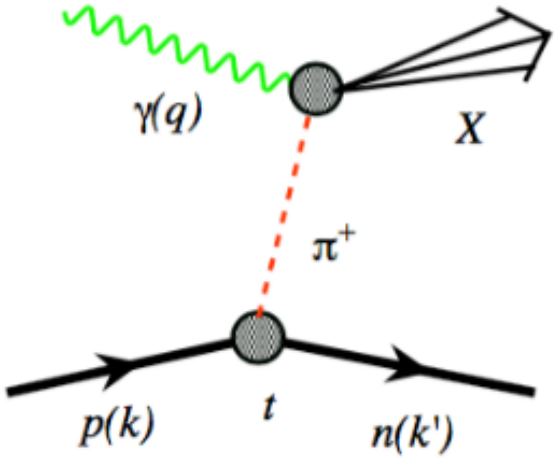
- Spectator neutrons



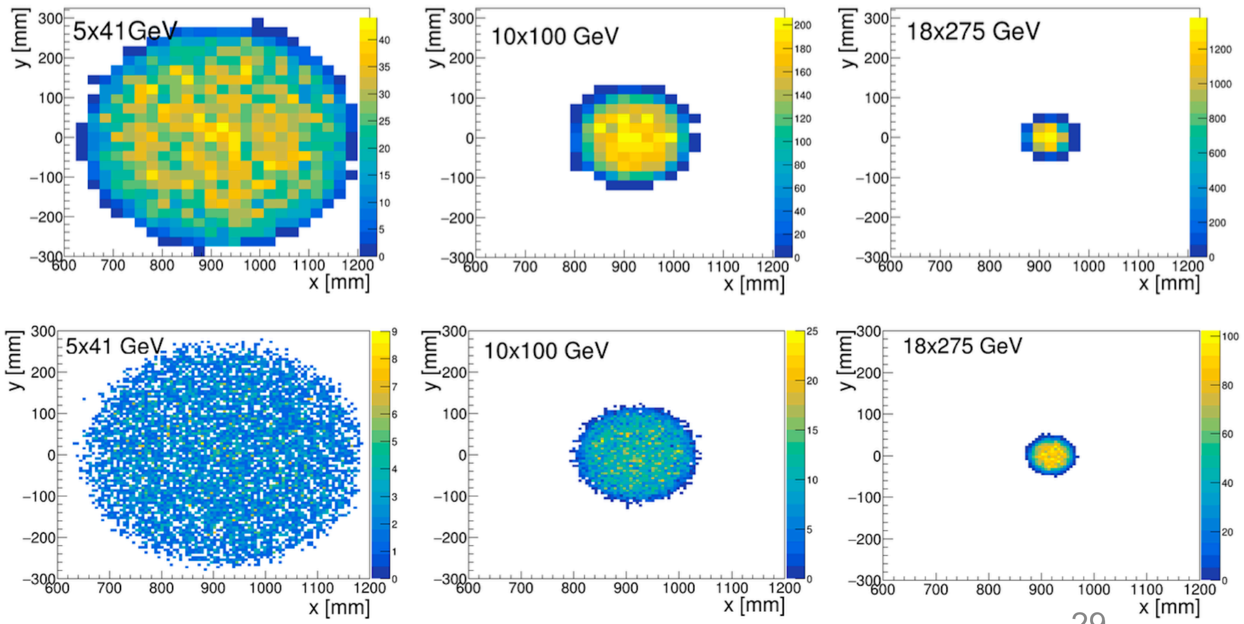




➢ Scattering of pions : Meson structure (ep → (π) → e' n X) .



For the *pion and the kaon* *the EIC will allow determination of the quark and gluon contributions to mass with the Sullivan process.*



Zero Degree Calorimeter

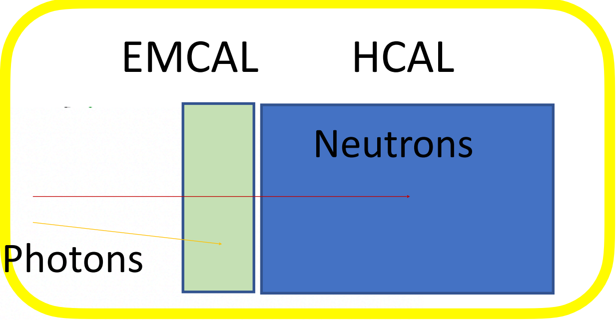
- ✓ The Zero Degree Calorimeter should provide measurements of neutral particles (**neutrons and photons**).
- ✓ need **+/- 4 mrad** coverage => beam element free cone before the zero degree calorimeter to detect the breakup neutrons from heavy Ions
- ✓ For neutrons: provide good angular resolution and energy measurements (<50%/$\sqrt{E}$+5%)
- ✓ For photons: provide photon measurements down to 100 MeV (nuclear excitation)

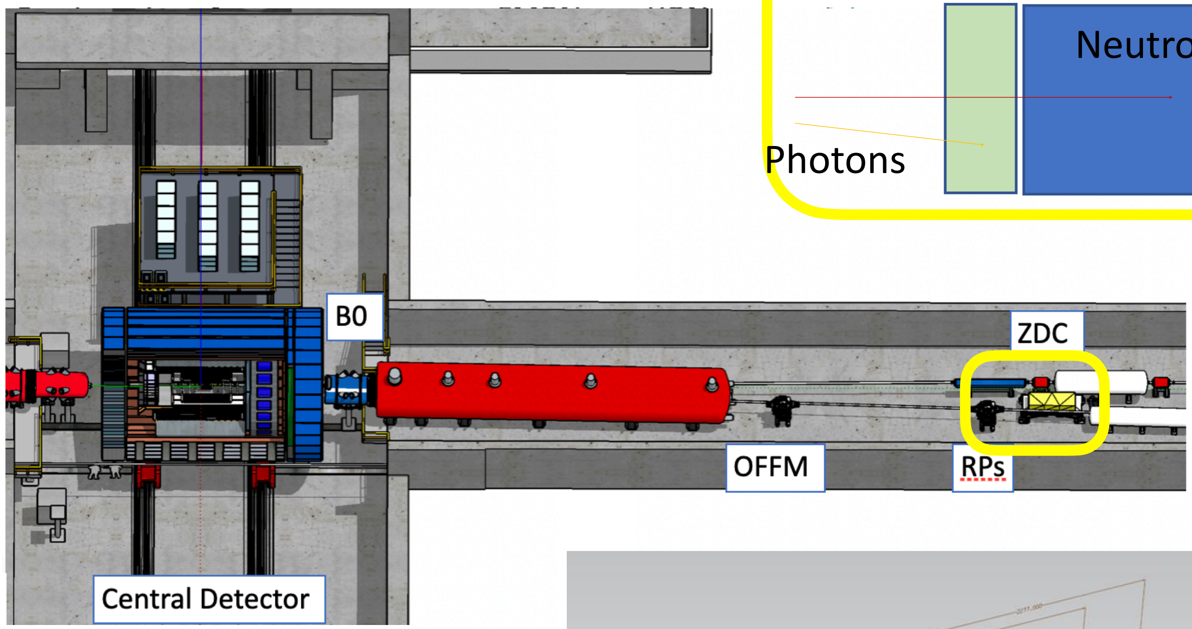
Technology (60cm x 60cm x 200 cm):
VETO: Si -layer in front for charged particle veto
EMCAL :

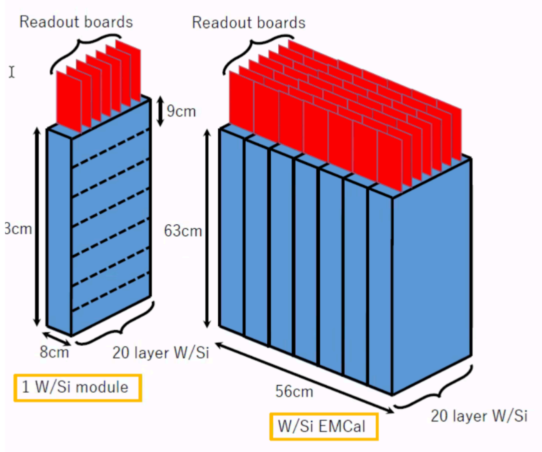
- PbWO4 crystals blocks
- **W/Si sampling calorimeter (imaging calorimeter) similar to ALICE FoCAL**

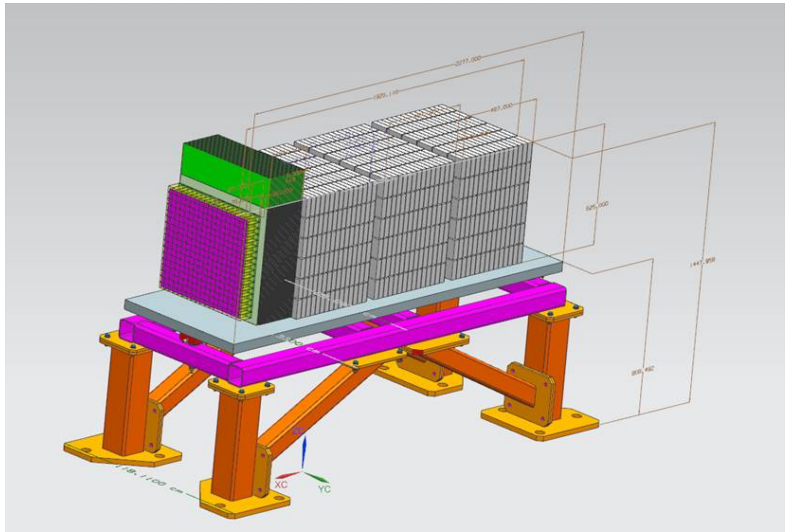
HCAL:

- Pb/Sci. sampling calorimeter.

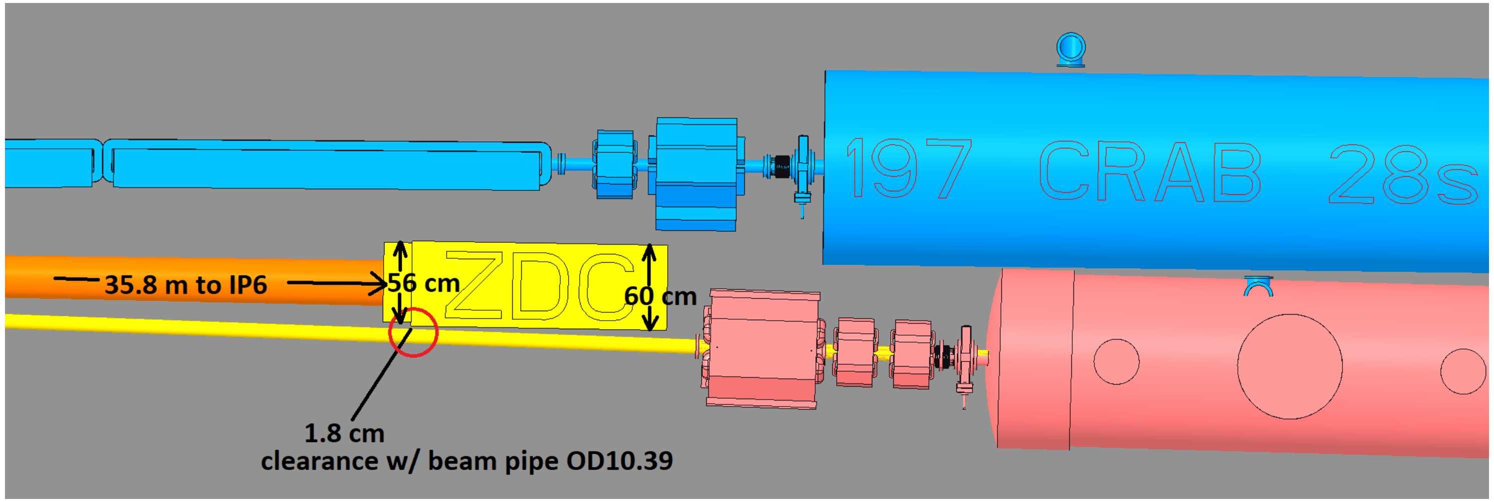








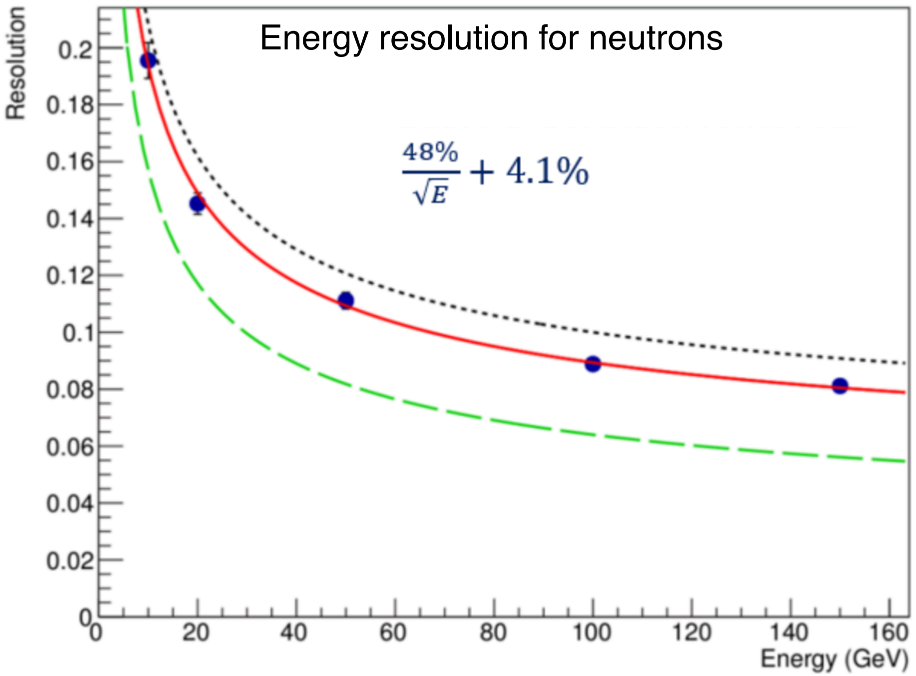
ZDC integration with lattice, resolution



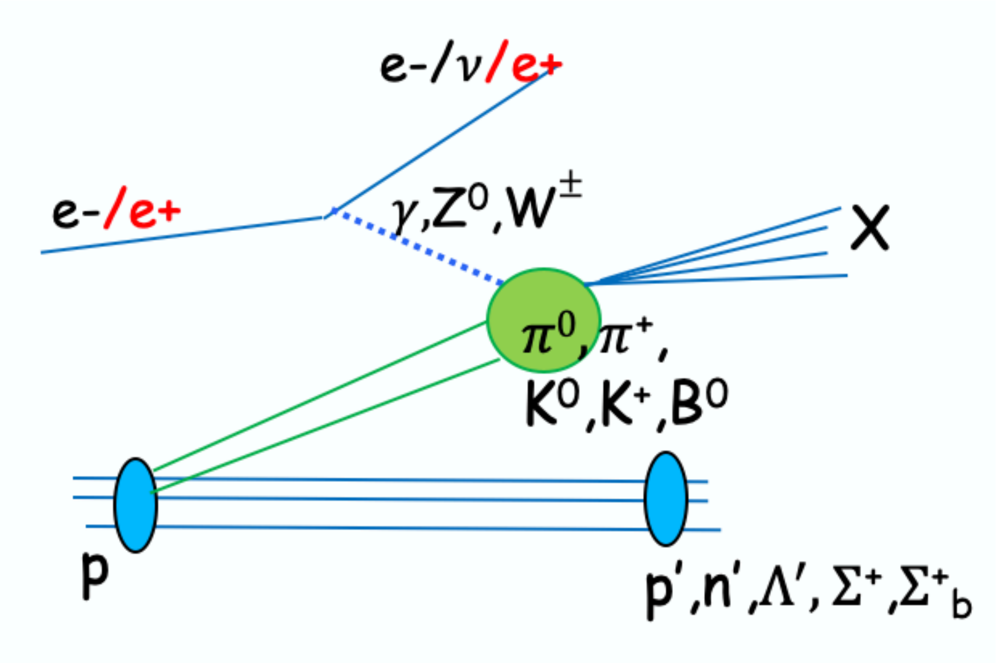
ZDC integration with accelerator lattice:
z-location 35.8 m,
stay-clear zone around the hadron beam-pipe

Should provide good energy and angular resolution to provide a proper p_T (-t) measurements

Po-Ju Lin



Meson structure

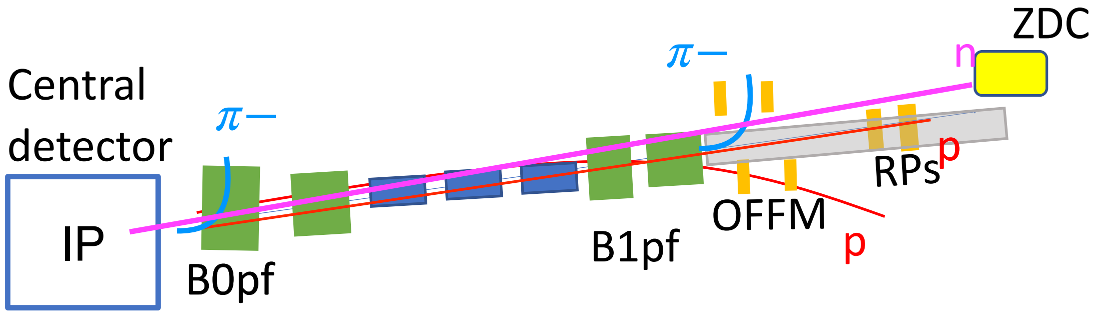


e p -> (K) -> e′ + Λ + X

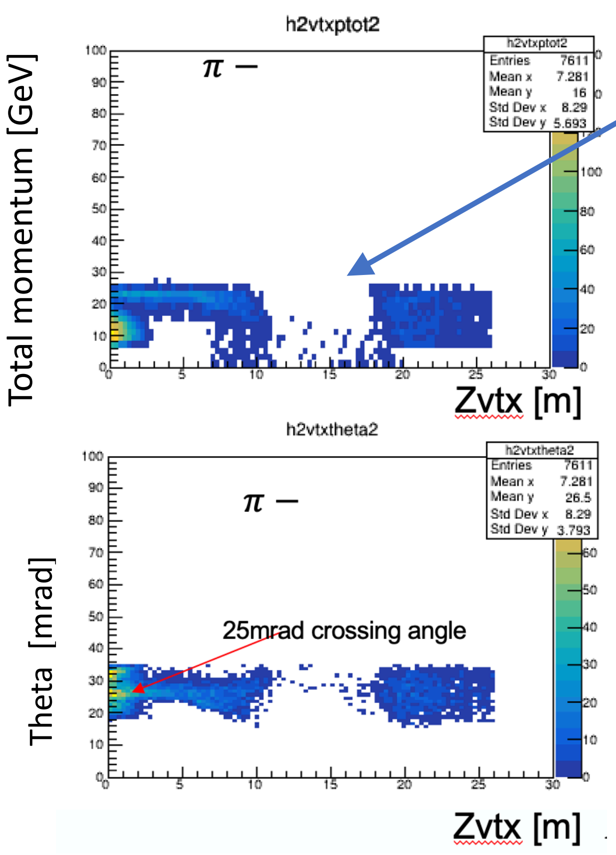
↳ p + $\pi-$(Br~64%)

↳ n+ $\pi0$ (Br ~36%)

- ➢ Detecting **Lambda's decays in the target fragmentation** area is very hard, due to a very large decay length (meters).
- ➢ Would require in addition detection of negative charged particles (pi-) at the OFF-momentum detector location



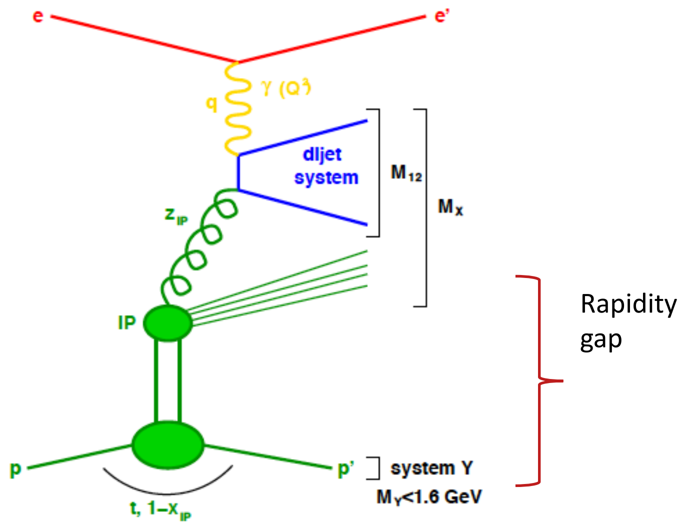
$$e + p \rightarrow e' + X + \Lambda$$ (for K structure)

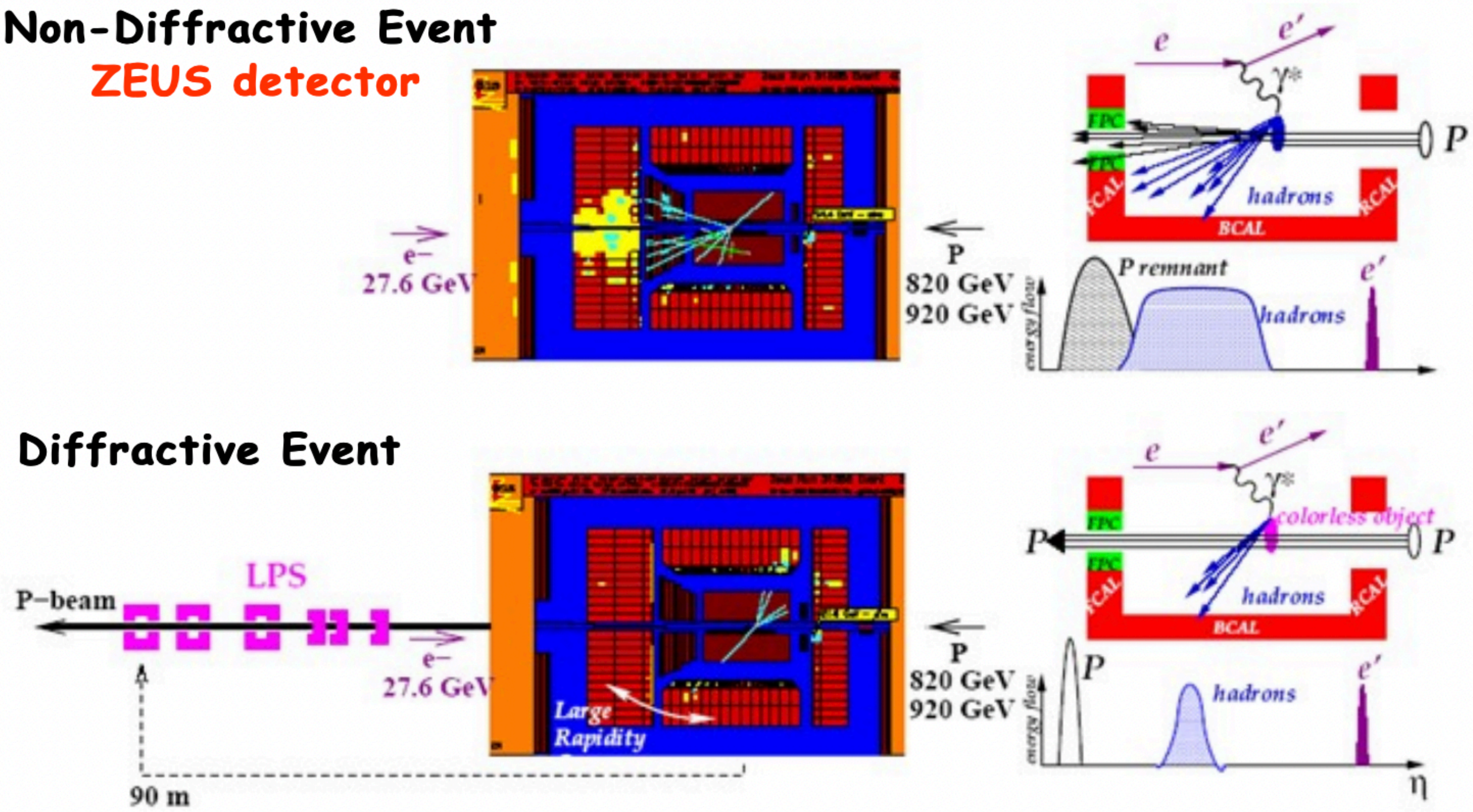


Example (10x100 GeV): ~100% detection for protons from Lambda. Significant loss $\pi-$ along the beam line (FFQs) due to low momentum of those pions (no instrumentation in this area)

Exclusive reactions: diffraction

Example from HERA/ZEUS





- Rapidity gap
- Hermetic coverage from central to far-forward region

M_X - invariant mass of all particles seen in the central detector
t - momentum transfer to the diffractively scattered proton
t - conjugate variable to the impact parameter

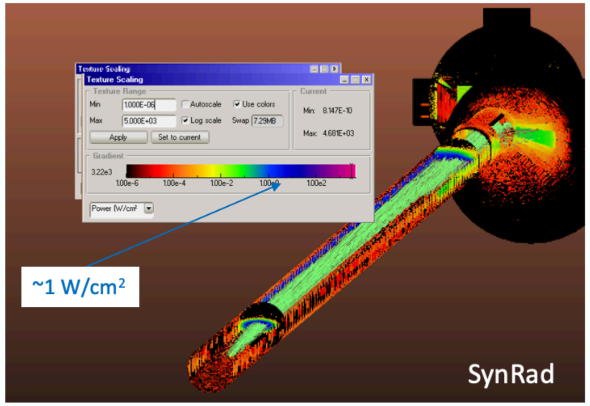
Background/radiation

- The HERA and KEK experience show that having backgrounds under control is crucial for the EIC detector performance

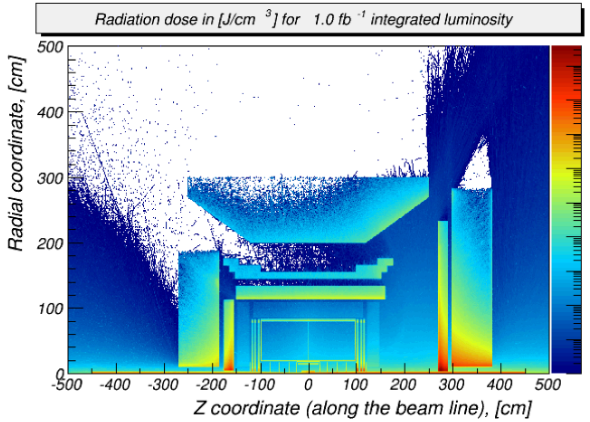
- There are several background/radiation sources :
  - ❖ primary collisions
  - ❖ beam-gas induced
  - ❖ synchrotron radiation

- The design of absorbers and masks must be modeled thoroughly

Synchrotron rad.

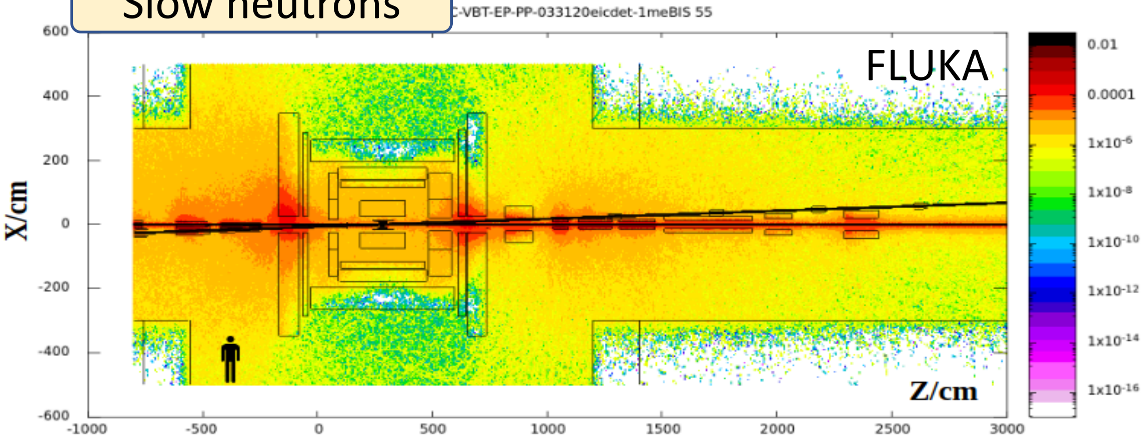


Primary collisions/ionizing radiation

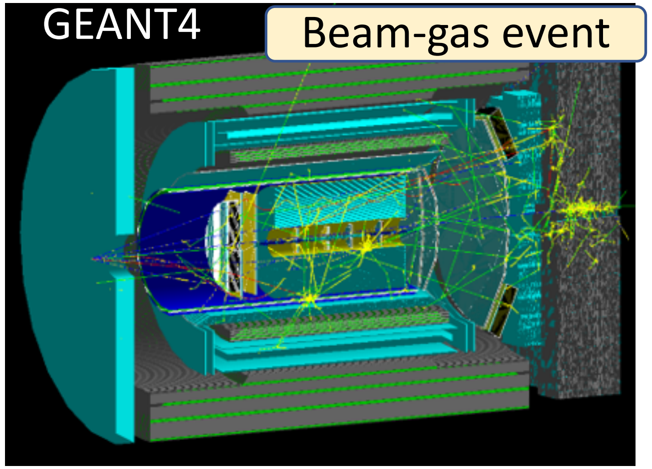


-> backward EmCal: ~250 rad/year (at a "nominal" luminosity ~10^{33} cm^{-2} s^{-1})

Slow neutrons

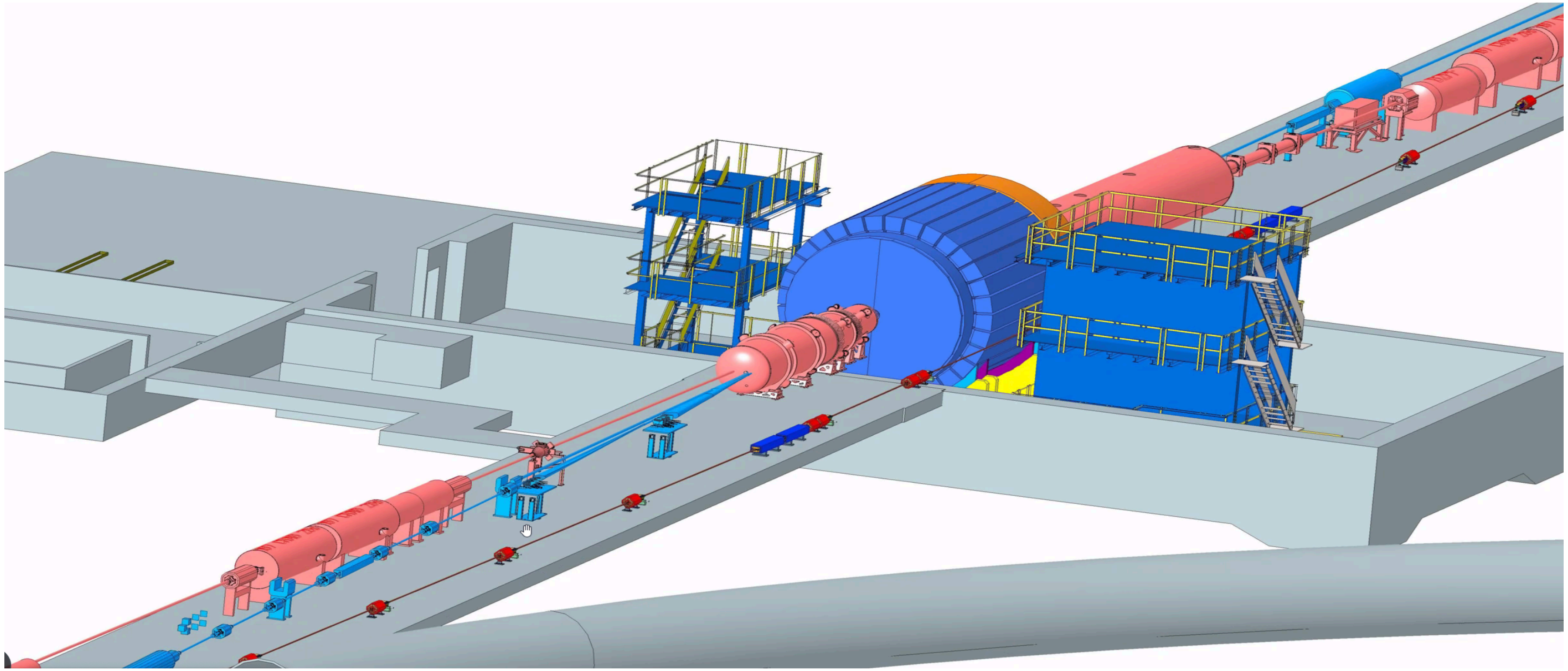


Beam-gas event



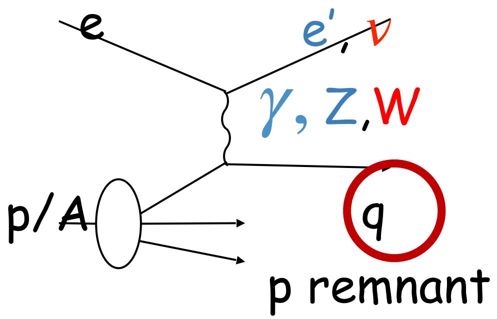
Summary

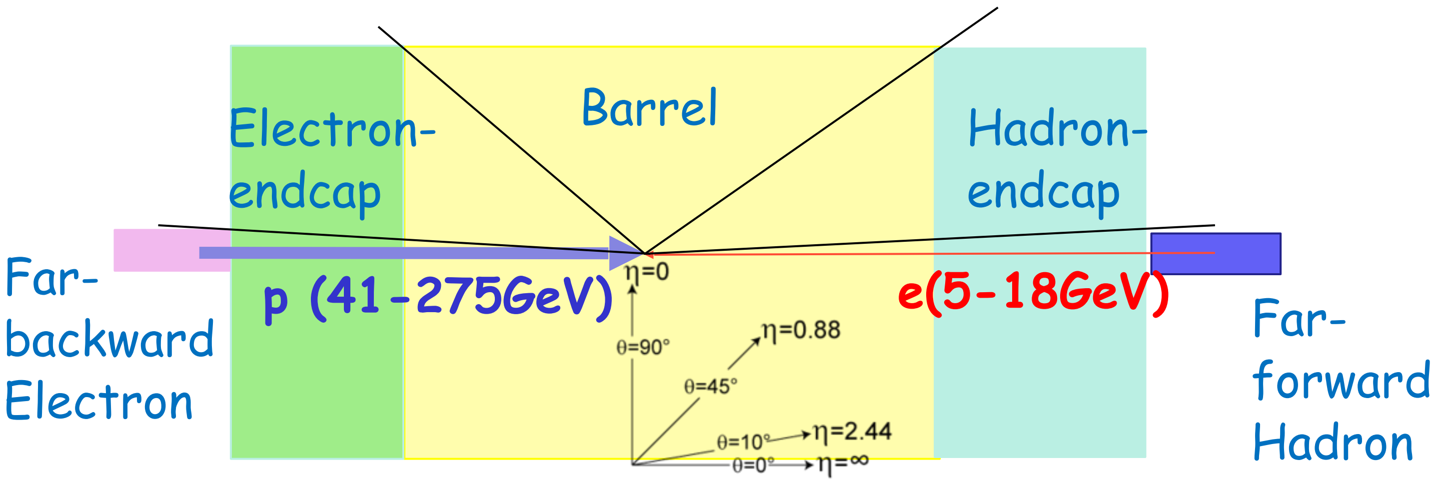
- ➢ Physics requirements drive the design of Far-forward region and the current configuration satisfies the requirements.
- ➢ There is lots of interest in the EIC community in studying this far-forward physics (imaging, meson structure, diffraction and tagging, etc.)
- ➢ The detailed detector layout and configuration are driven by the ongoing EIC community efforts and will be further improved. Keeping a close contact with the EIC accelerator group.
- ➢ Looking forward to collaborate with ALICE/LHC!

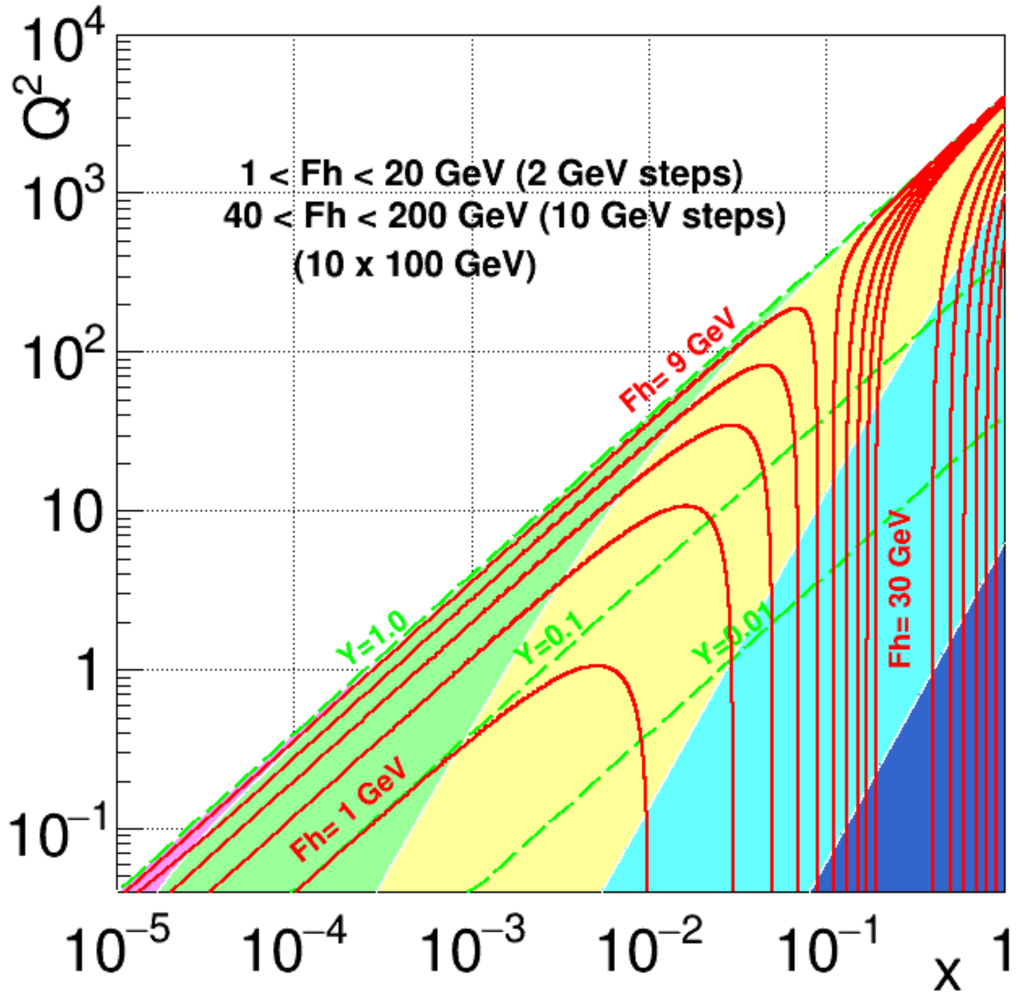


Backup

Why endcaps and forward areas are important at EIC?

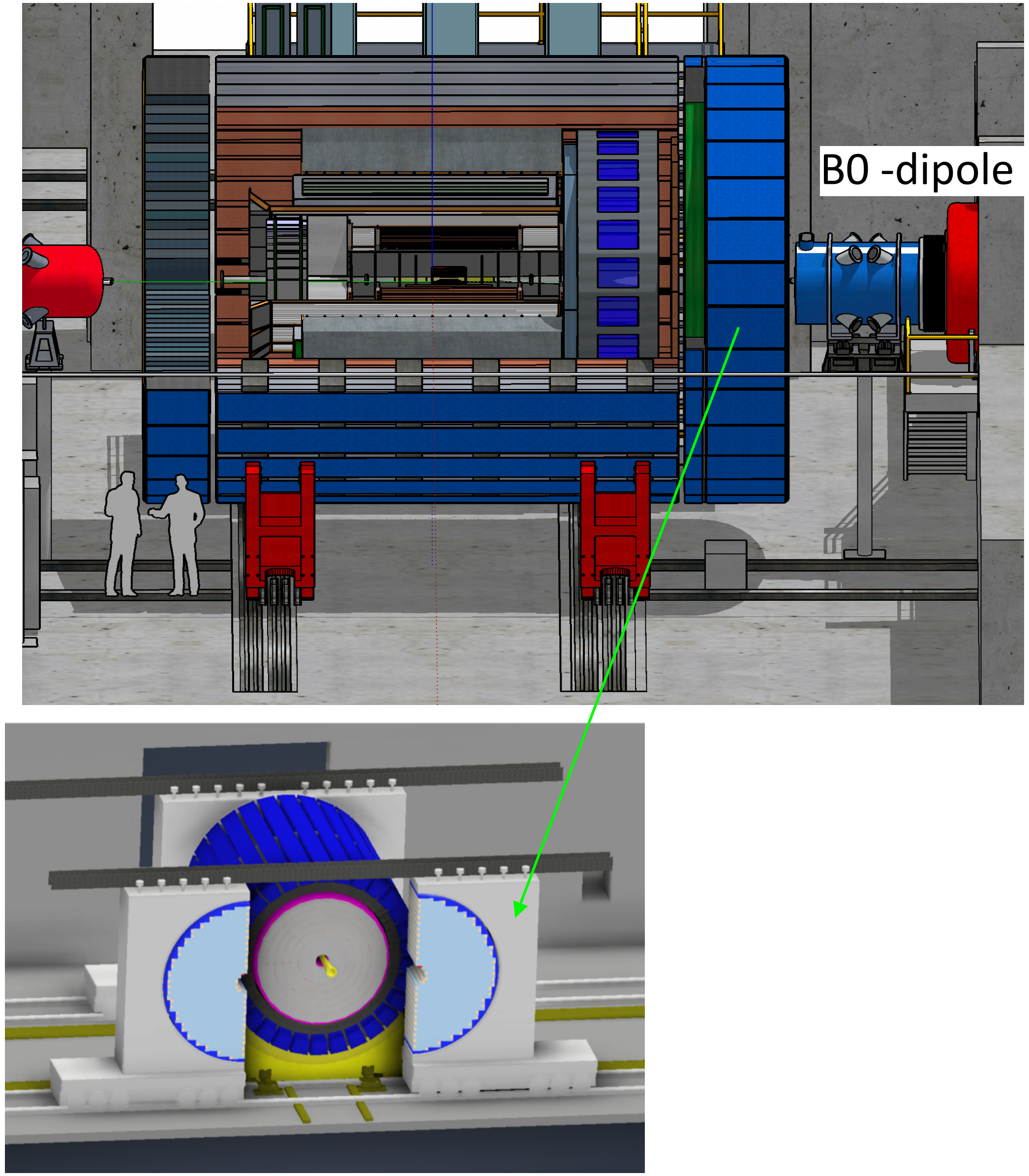


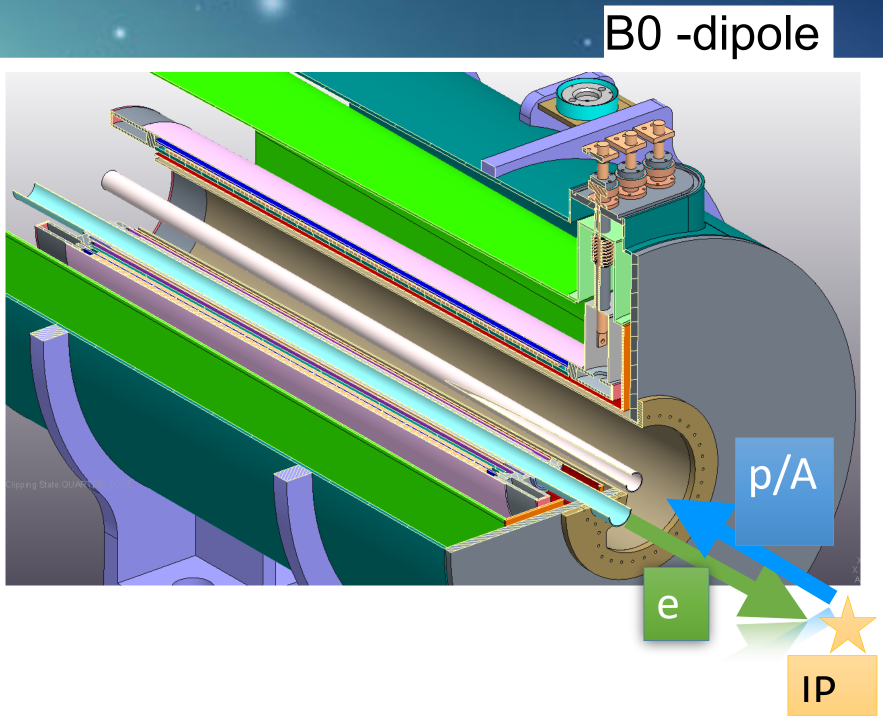




- All hadrons are boosted towards hadron-endcap due to asymmetric beam energies
- Proton/Ion Remnant
- Diffractive/exclusive physics in the Far-forward area

B0-detectors





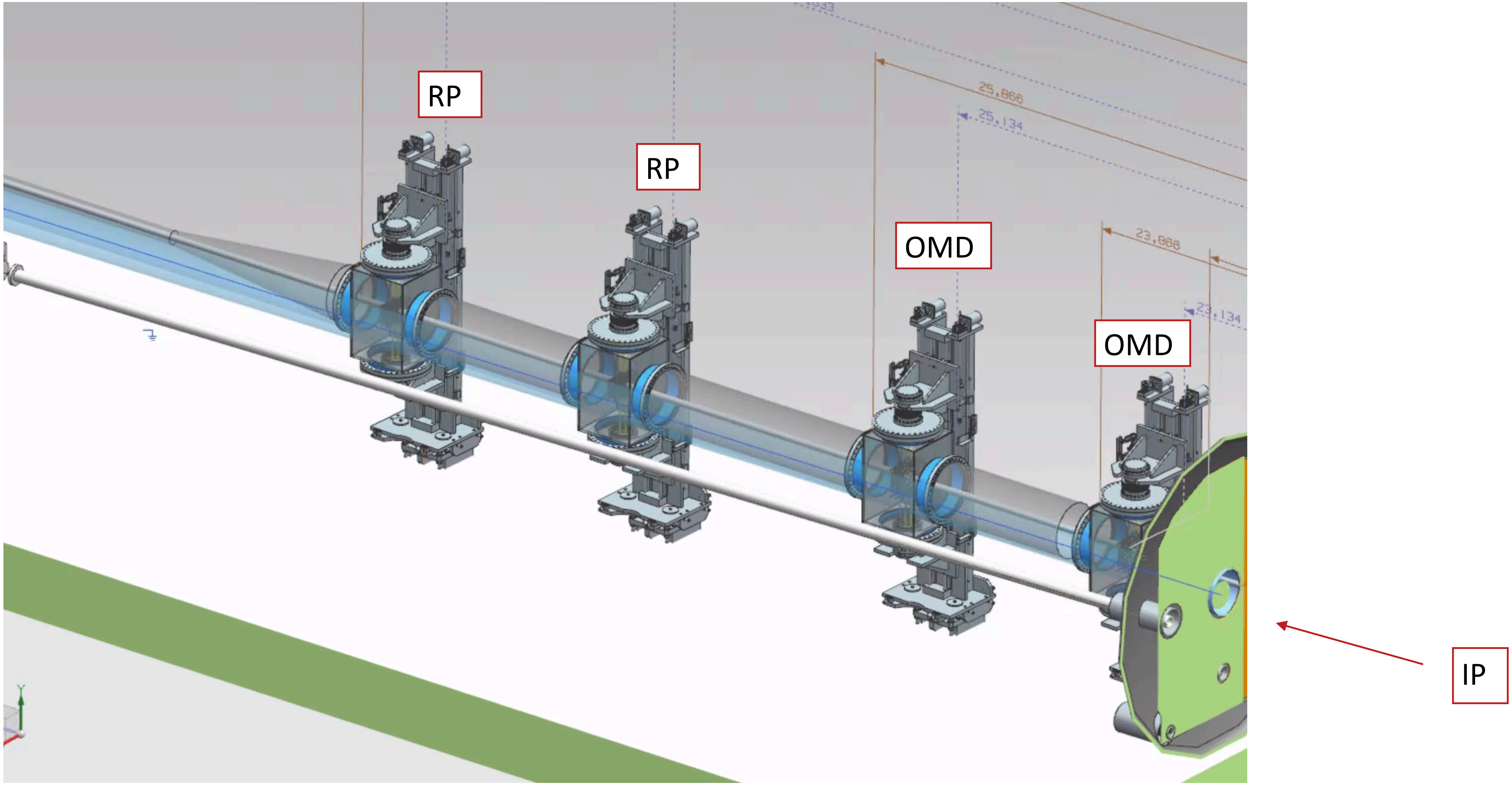
➡Dipole field 1.3T: for momentum reconstruction. Design still ongoing (most likely B0 will be shorter 1.8m -> ~1.5m)

➡B0 placement - after HCAL

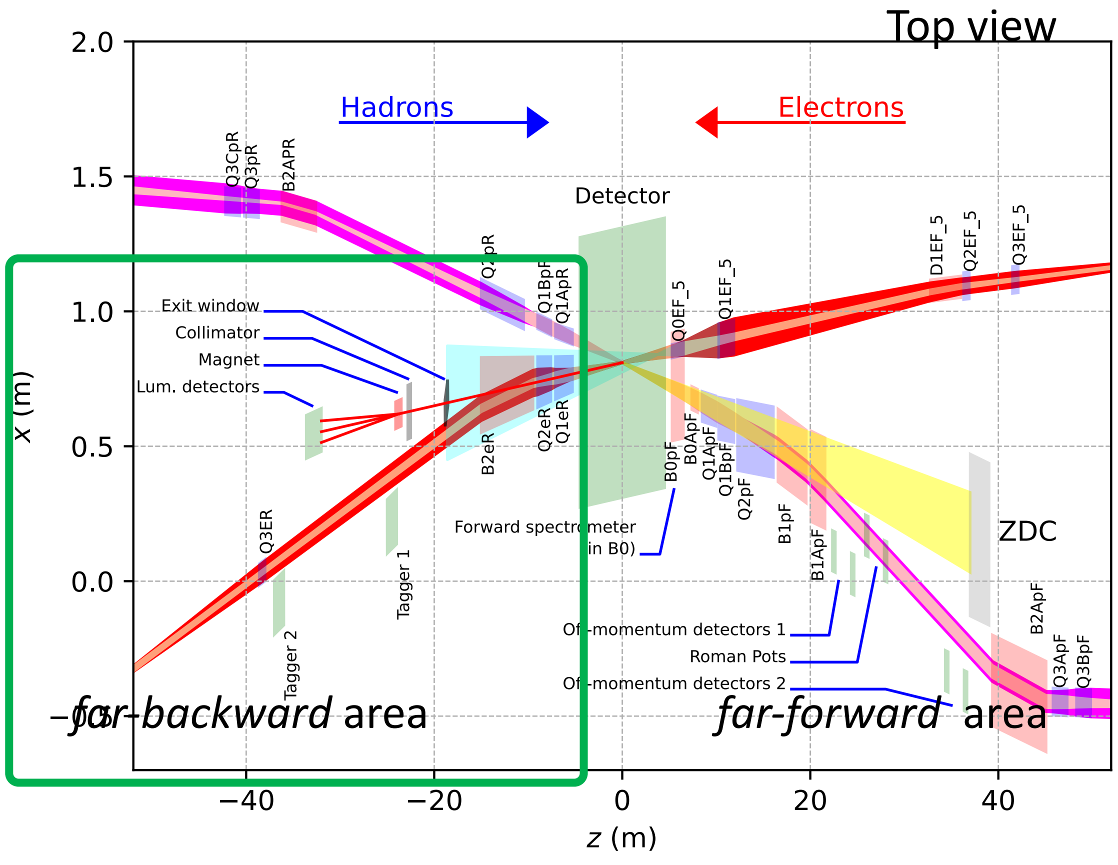
- ✦ Limited space
- ✦ Access to B0-detectors only from one side (after opening HCAL)
- ✦ Vacuum pumps
- ✦ Beam-pipes: crossing angle

➢ B0 placement: high background area => high granularity detectors needed in this area

Roman Pots/ OMDs integration



Far-backward (electron-going) region



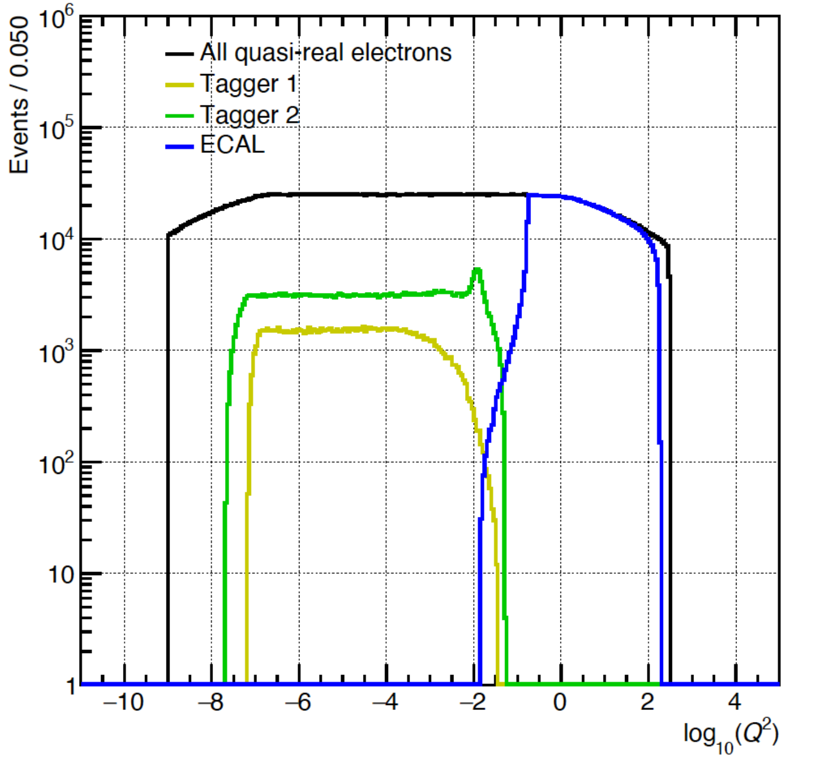
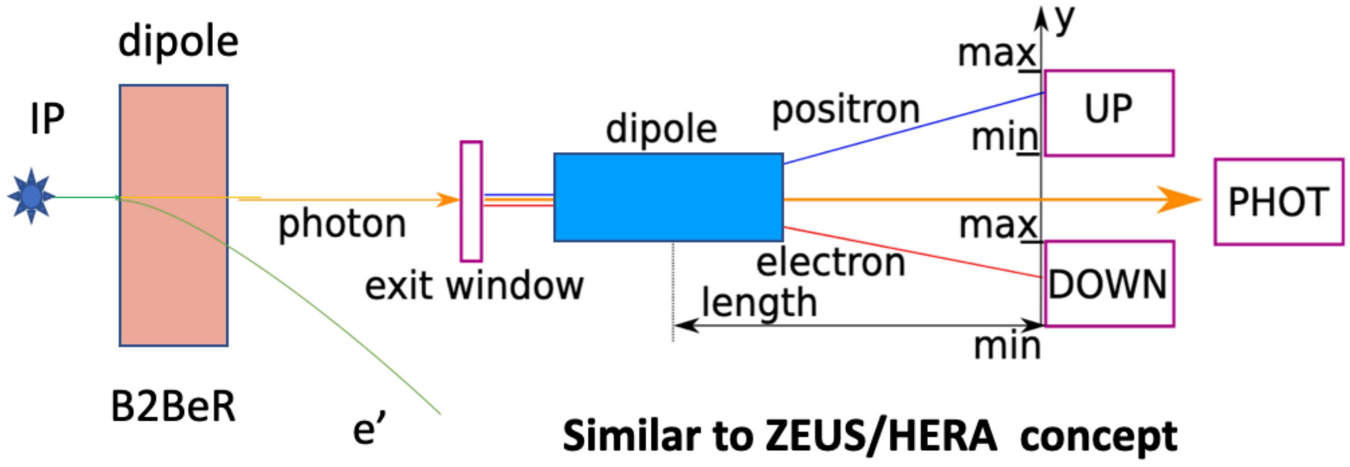
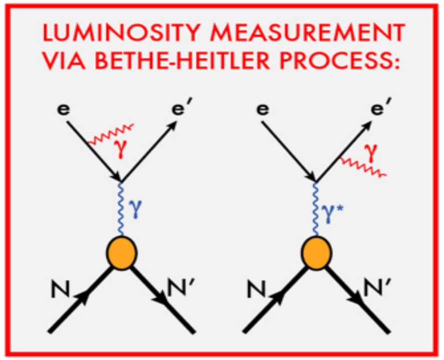


FIG. 16: Coverage in Q^2 for tagger detectors and ECAL.

- ➢ This area is designed to provide coverage for the low-Q² events (photoproduction, $Q^2 < \sim 1GeV^2$). Need to measure the scattered electron position/angle and energy.
- ➢ And luminosity detector (ep -> e'pγ bremsstrahlung photons)
- ➢ Beam-pipe design ongoing

Luminosity monitor





Goals for Luminosity Measurement:
Integrated luminosity with precision δL/L< 1%

- Luminosity measurements via Bethe-Heitler process
- Photons from IP collinear to e-beam
- First dipole bends electrons
- Photon conversion to e-/e+ pair
- Pair-spectrometer
- Synchrotron photons collimation scheme needs to be further refined