From PHENIX to an EIC Detector

Built Around the BaBar Magnet and sPHENIX Calorimetry

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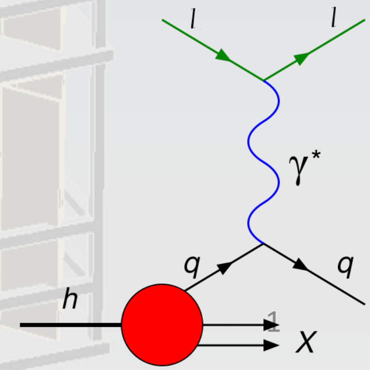
For PHENIX Collaboration

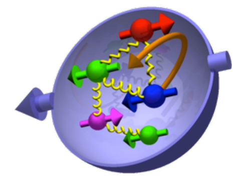
October 20-24, 2014, Beijing, China



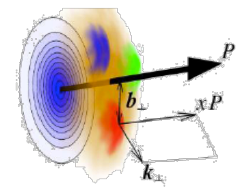
EIC Physics

Well developed and summarized in:
INT EIC report: arXiv:1108.1713
EIC White Paper: arXiv:1212.1701

Distribution of quarks and gluons and their spins in space and momentum inside the nucleon

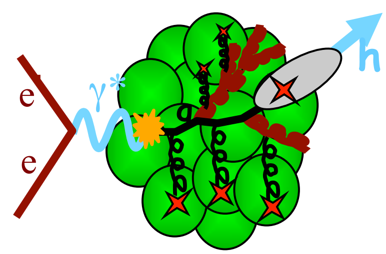


- Nucleon helicity structure
- Parton transverse motion in the nucleon
- Spatial distribution of partons and parton orbital angular momentum



QCD in nuclei

- Nuclear modification of parton distributions
- Gluon saturation
- Propagation/Hadronization in nuclear matter



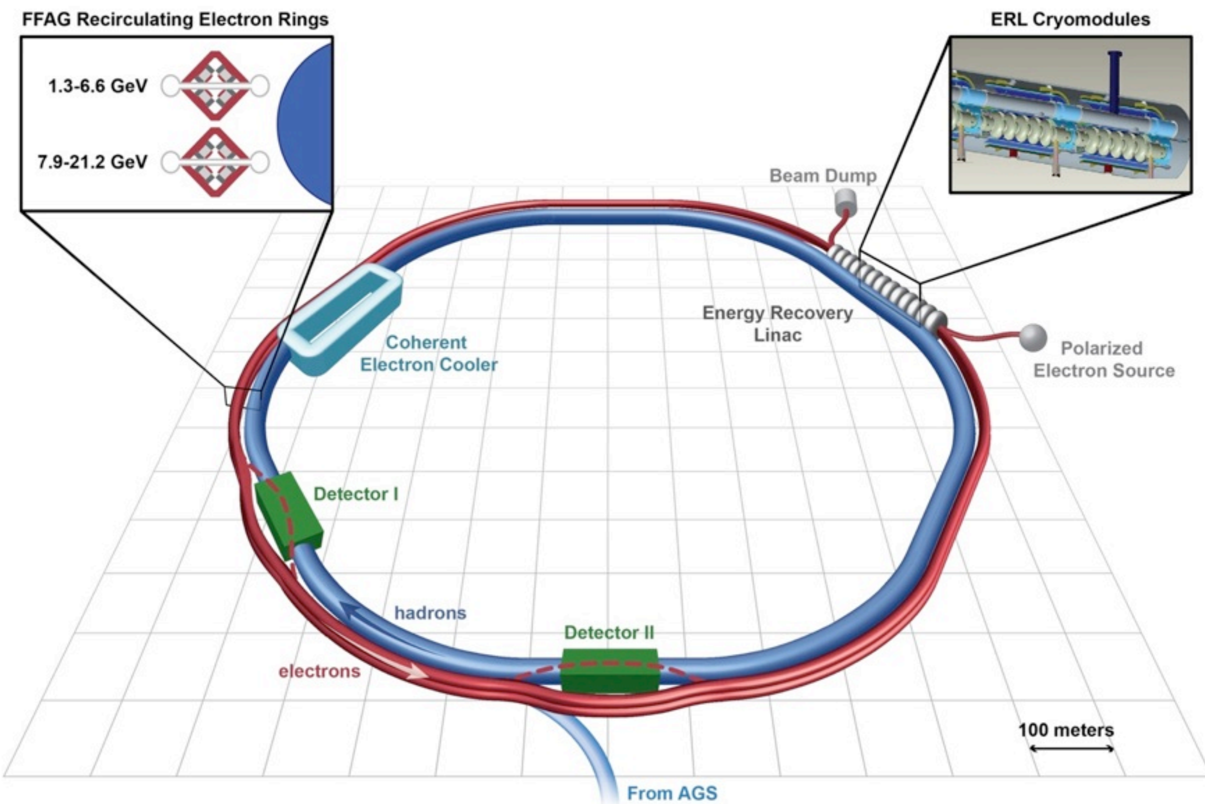
~~Weak interactions & beyond standard model~~

- Require highest energy and lum. -> not for stage-1

eRHIC (BNL, USA)

See M.Bai talk

ep/eA



In current design:

Energy:

- Electron: 6.6–21.2 GeV
- Proton: 25–250 GeV
- Ions: 10–100 GeV
- $\sqrt{s}$: up to 145 GeV

Polarization:

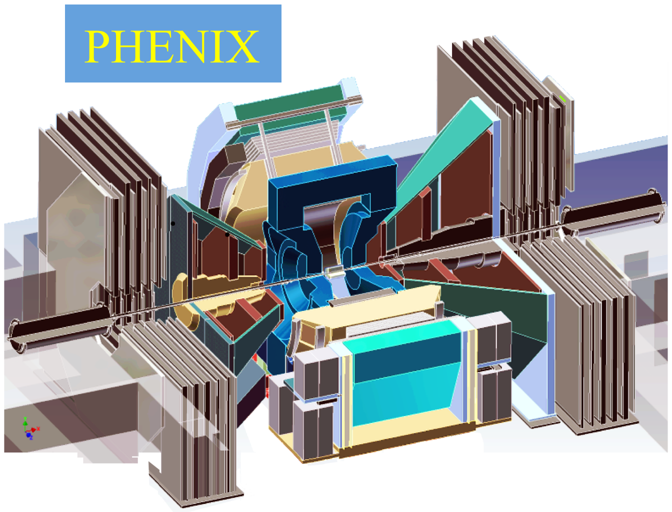
- Electrons: 80%
- Protons and He3: 70%

Luminocity:

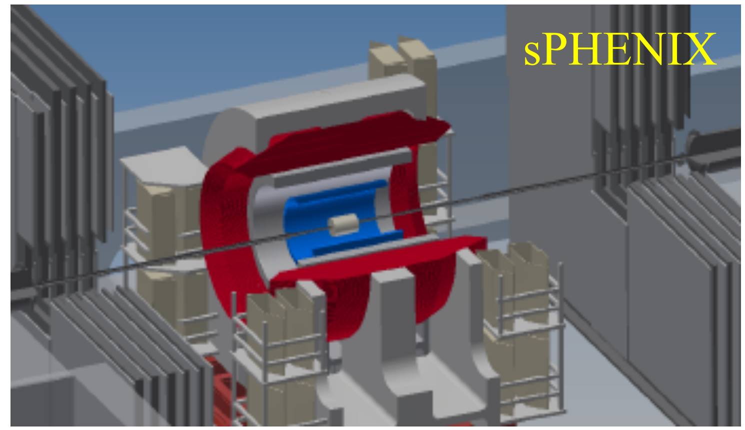
- $>10^{33}$ cm^{-2} s^{-1}

… Still evolving

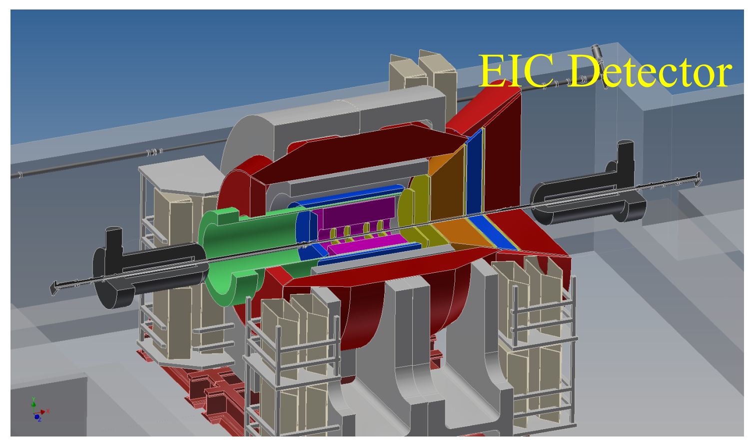
PHENIX -> EIC Detector Path



~2021



By ~2025



Evolve sPHENIX (pp and HI detector) to EIC Detector (ep and eA detector)

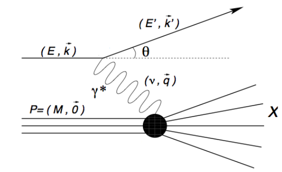
- To utilize e and p (A) beams at eRHIC with *e*-energy up to 15 GeV and *p*(*A*)-energy up to 250 GeV (100 GeV/n)
- *e*, *p*, *He*3 polarized
- Stage-1 luminosity ~10^{33} cm^{-2} s^{-1} (~$1 fb^{-1}$ /month)

General Detector Concept

Inclusive DIS and scattered electron measurements

With focus in e-going direction and barrel

High resolution EMCal and tracking; minimal material budget

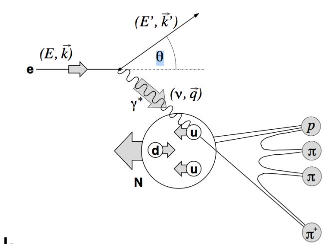


Semi-inclusive DIS and hadron ID

With focus in h-going direction and barrel

Barrel: DIRC for p_h<4 GeV/c

h-going direction: aerogel for lower p_h and gas RICH for higher p_h

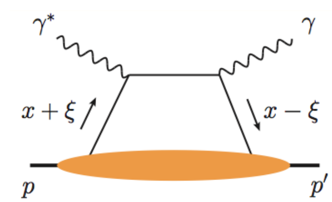


Exclusive DIS (DVCS etc.)

EMCal and tracking coverage in -4<η<4

High granularity EMCal in e-going direction

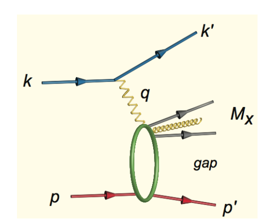
Roman Pots in h-going direction



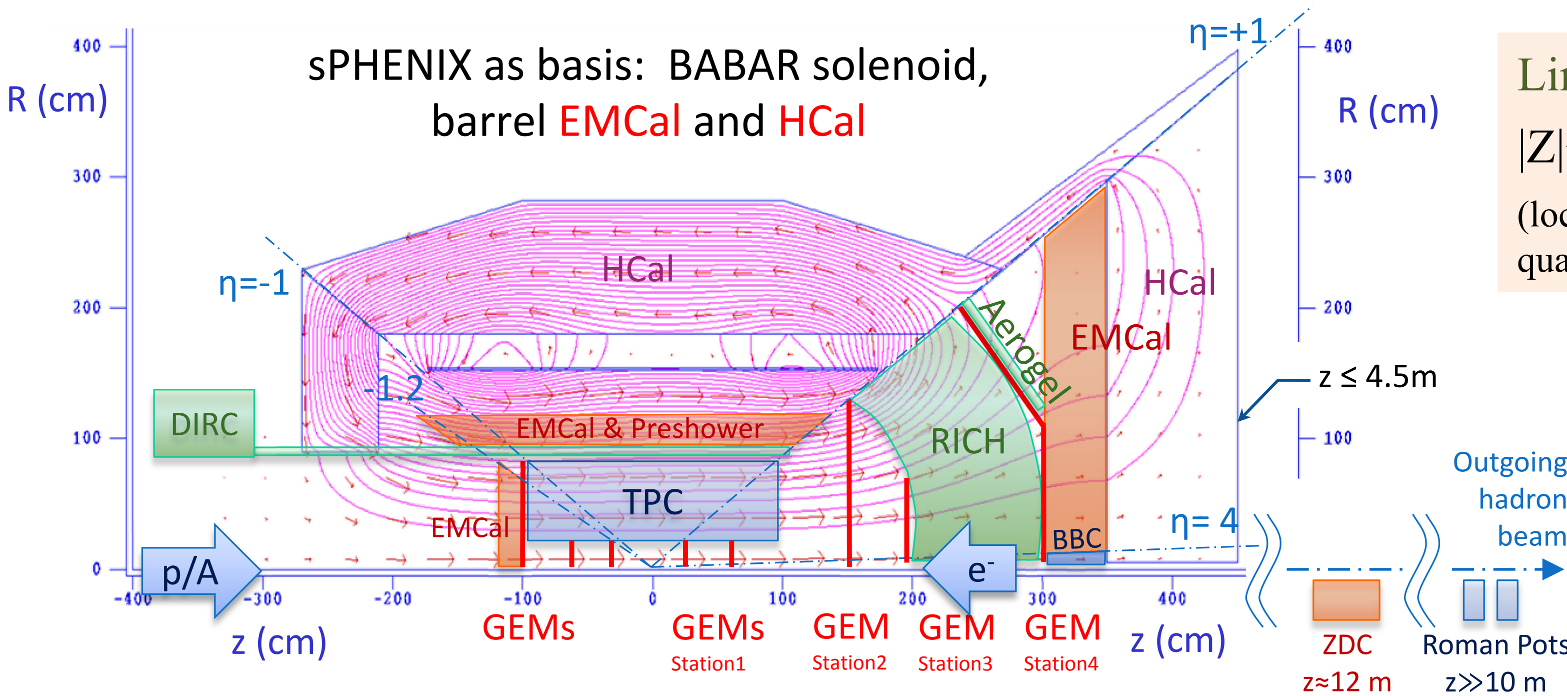
Diffractive

Rapidity gap measurements: HCal in -1<η<5; EMCal in -4<η<4

ZDC in h-going direction



EIC Detector Proposal



Limitation:

|Z|<4.5m

(location of focusing quadrupoles)

- -4<η<-1 (e-going):
  - Crystal calorimeter with high energy and position resolution
  - GEM Trackers
- -1<η<1 (barrel):
  - Add Compact-TPC and DIRC
- 1<η<4 (h-going):
  - HCal & EMCal (1<η<5)
  - GEM Trackers
  - Aerogel RICH (1<η<2)
  - Gas RICH
- Far Forward (h-going)
  - ZDC and Roman Pots

BaBar Magnet

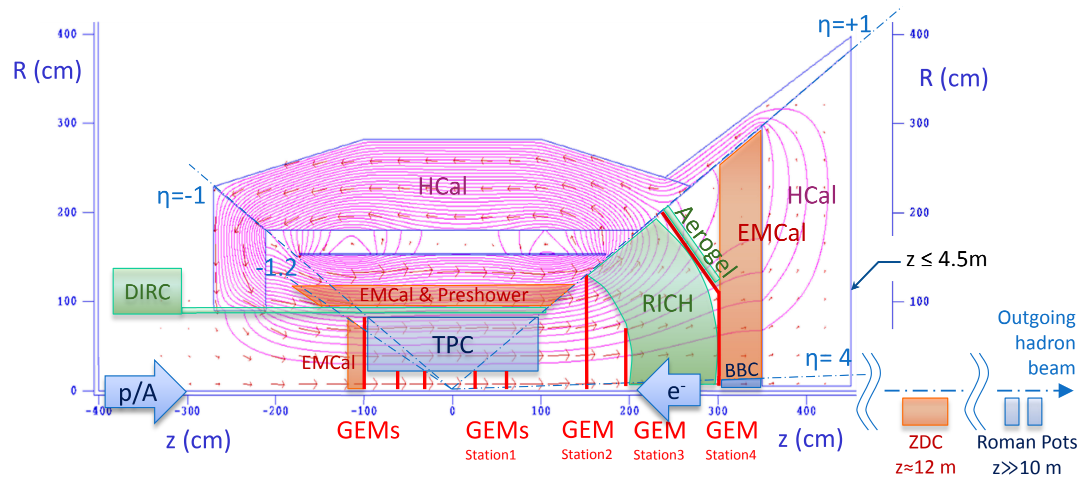
Major Parameters:

- ✓ Superconducting Solenoid
- ✓ Field: 1.5T
- ✓ Inner radius: 140 cm
- ✓ Outer radius: 173 cm
- ✓ Length: 385 cm

Higher current density at magnet ends and field shaping in forward angles provide high analyzing power for momentum determination in e-going and h-going directions

Flux return and field shaping:

Forward HCal
Steel lapmshade
Barrel HCal
Steel endcup

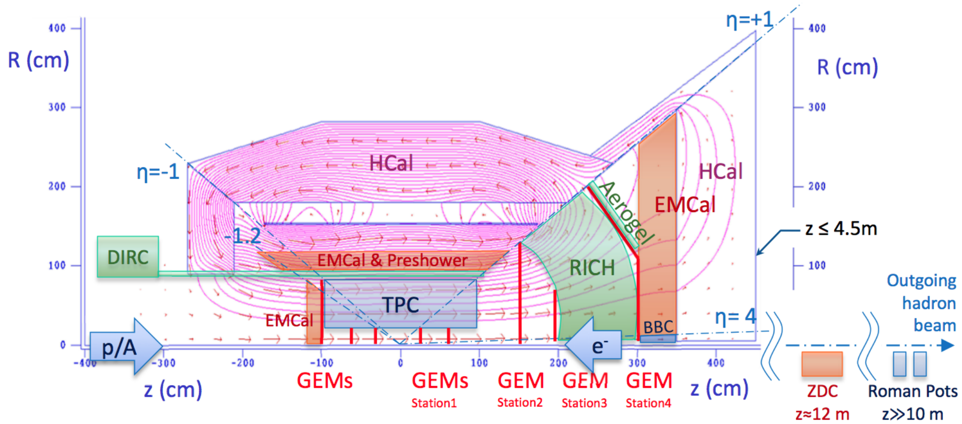


Main space limitation observed: |z|<4.5m
(due to focusing magnet location)

Tracking

$-3<\eta<4$

TPC in barrel (15<r<80 cm, |z|<95 cm)
GEMs in forward and backward



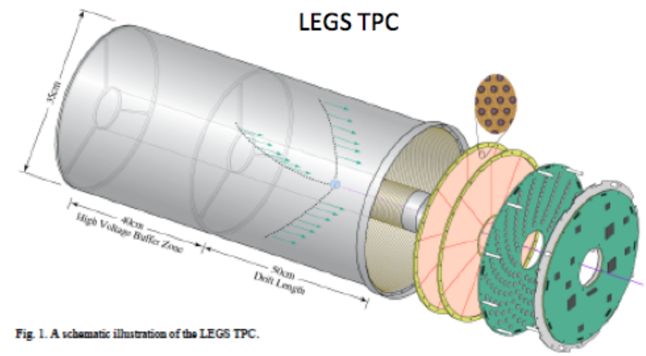
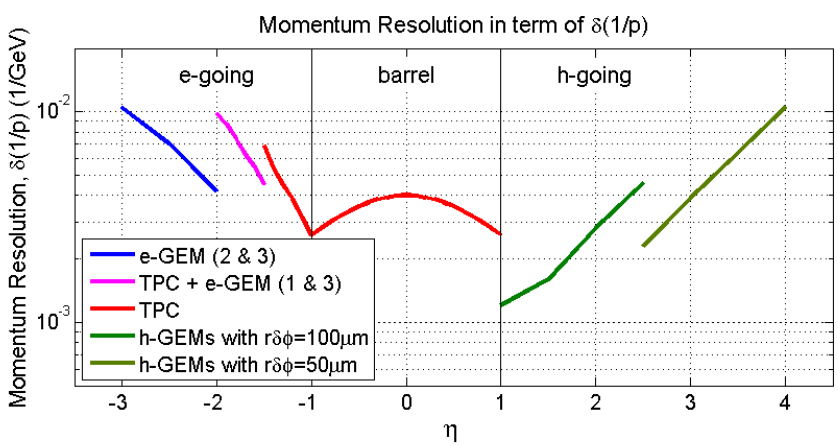


Fig. 1. A schematic illustration of the LEGS TPC.



Good resolution over full acceptance

e-going: electron ID (E/p)

Barrel: low mom. measurements (<10 GeV/c)

h-going: needed for PID

EM Calorimetry

-4<η<4

Endcap EMCal:

$\sigma_E/E \sim 1.5\%/\sqrt{E}$

$\sigma_X < 3mm/\sqrt{E}$

$PbWO_4$ crystal

Similar to PANDA endcap design

Barrel EMCal:

$\sigma_E/E \sim 12\%/\sqrt{E}$

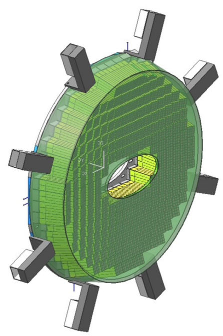
sPHENIX EMCal

Tungsten-fiber

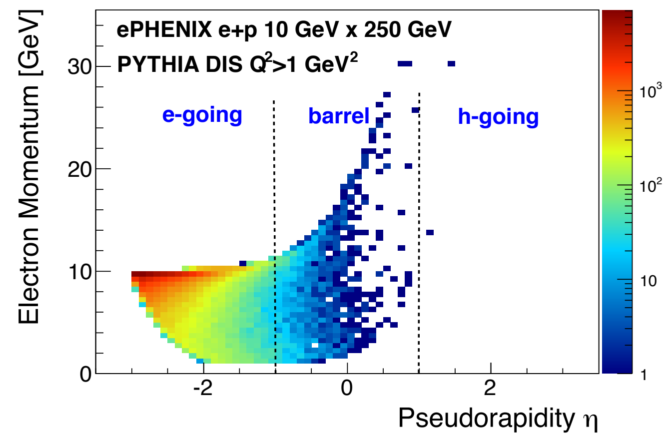
Forward EMCal:

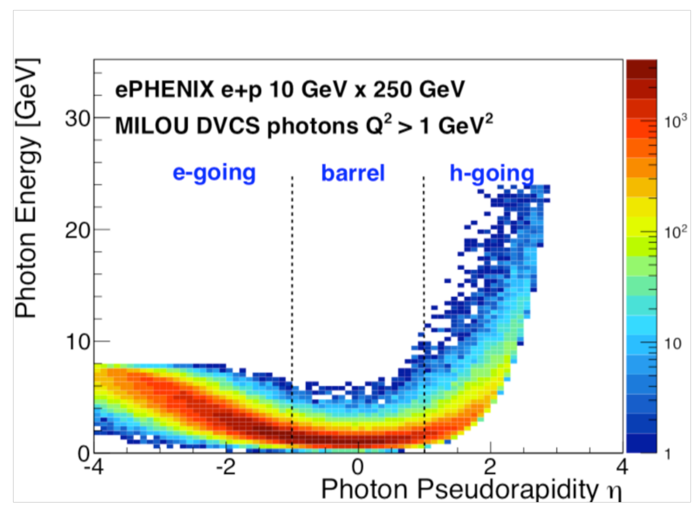
$\sigma_E/E \sim 12\%/\sqrt{E}$

Pb-fiber



TDR for PANDA
arXiv:0810.1216





- ➢ Scattered electron measurements

  High resolutions in e-going direction required

- ➢ Vector meson and photon measurements

  Wide coverage required

Hadron Calorimetry

$-1<\eta<5$

Barrel HCal:

$\sigma_E/E \sim 100\%/\sqrt{E}$

Steel & Scintillator

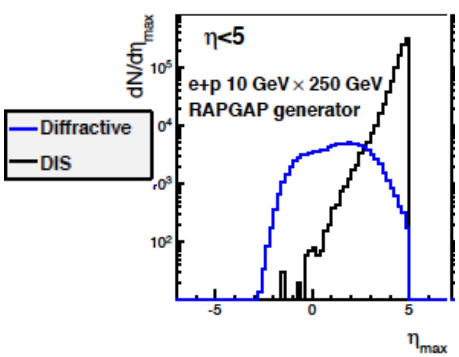
sPHENIX EMCal

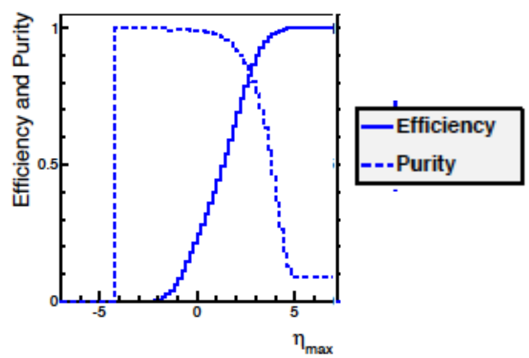
Forward HCal:

$\sigma_E/E \sim 100\%/\sqrt{E}$

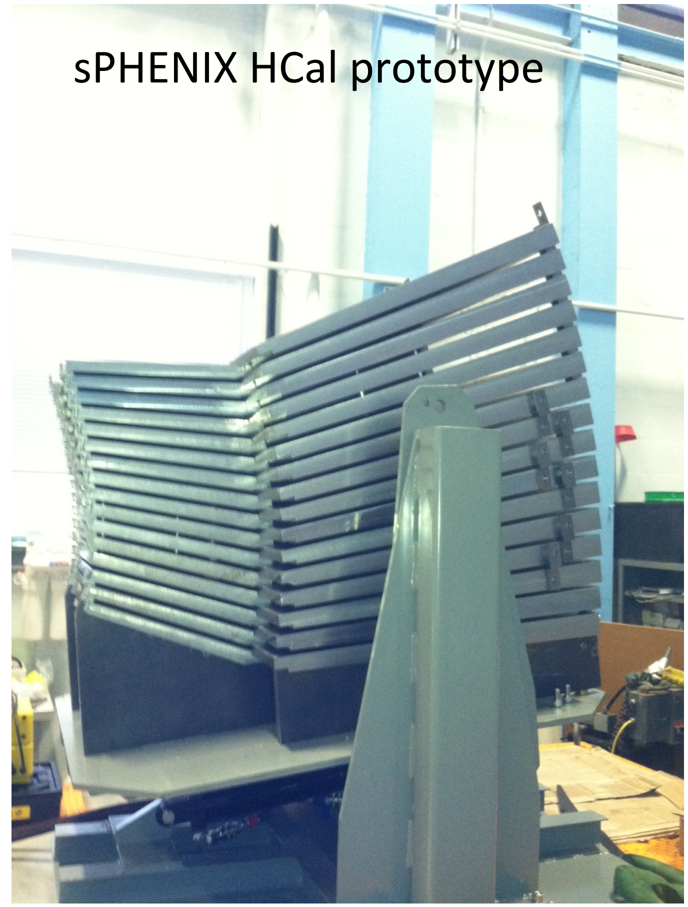
Steel & Scintillator

Same as barrel



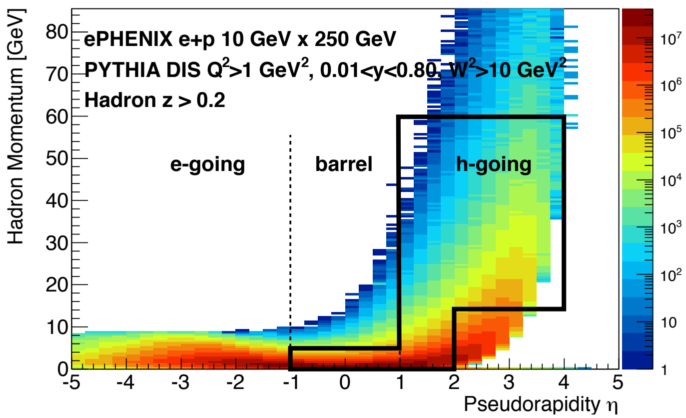


- Rapidity Gap for Diffractive
- Assist to PID and high momentum hadron measurements

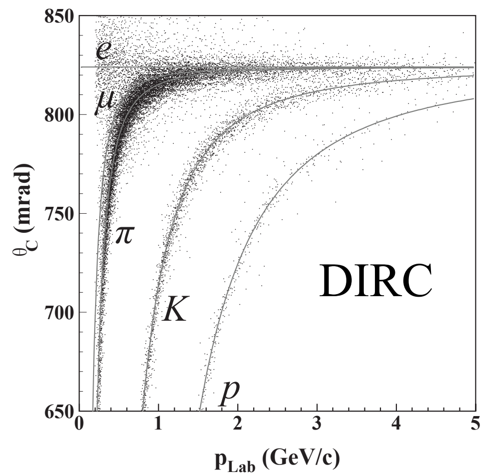


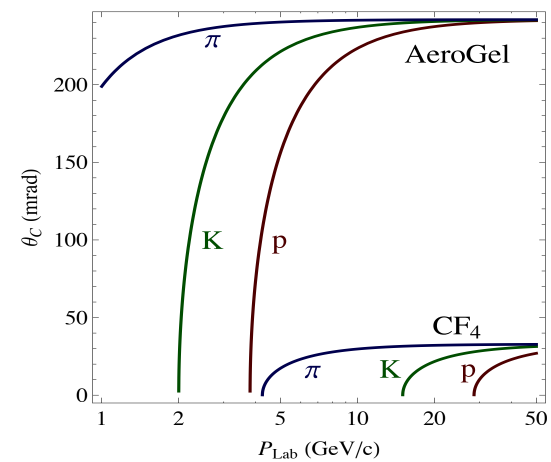
Hadron PID

-1<η<4



Focus on h-going direction and barrel





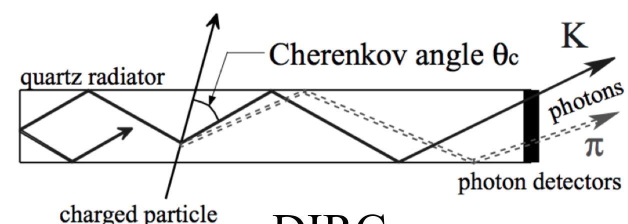
DIRC:
-1<η<1
PID at <4 GeV/c

Aerogel:
1<η<2
PID at <15 GeV/c

Gas RICH (CF4):
1<η<4
PID at <60 GeV/c

- **Quark Helicity, TMDs, Hadronization**

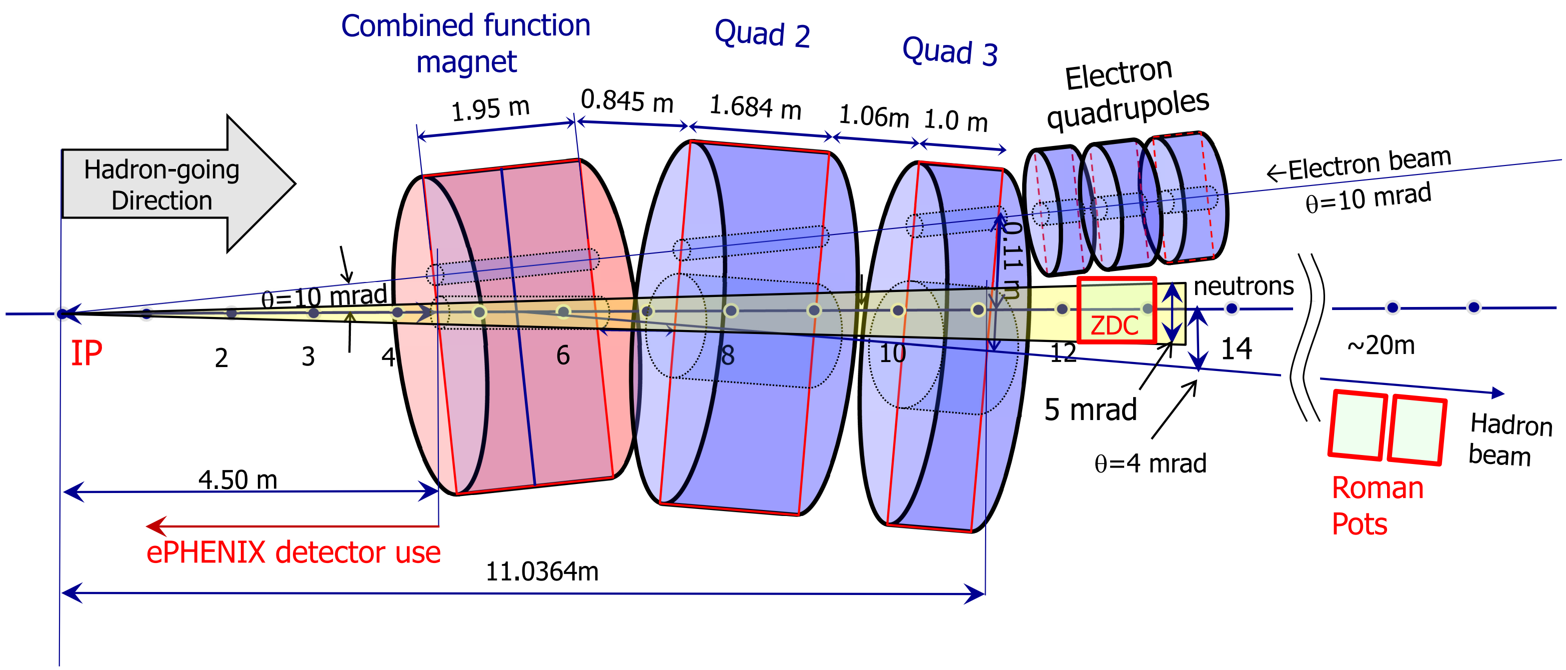
  Tightly coupled to high resolution momentum measurements in forward



DIRC

Beamline Detectors

Similar to all eRHIC detectors, being designed in parallel with IR design



ZDC

12 m downstream

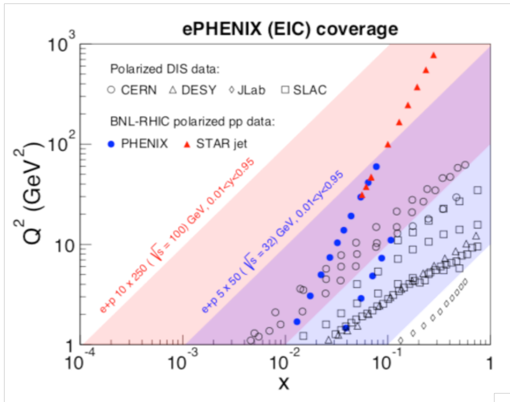
5 mrad cone opening of the IP is available from ePHENIX and IP design

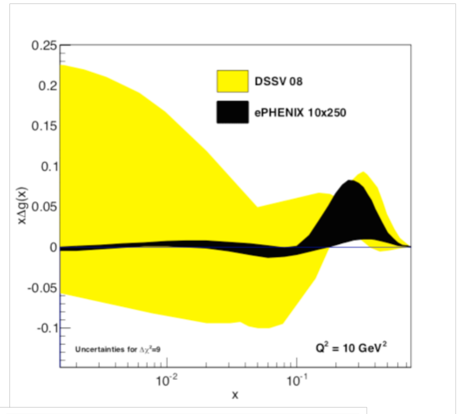
Roman Pots

>20 m downstream

Similar to STAR design

Physics Expectations





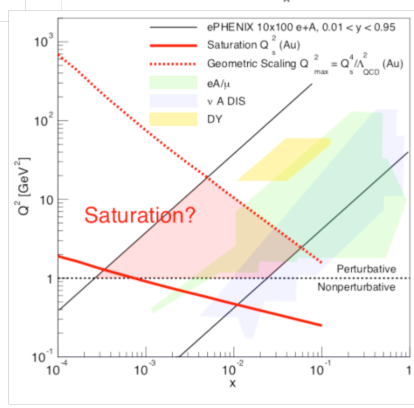
Proton Helicity Structure

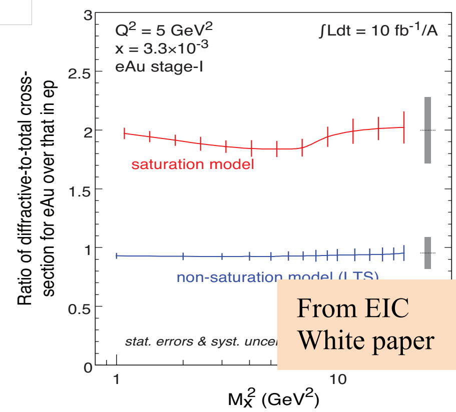
Also:

TMD (motion of confined partons)

GPD (Proton tomography)

Gluon saturation

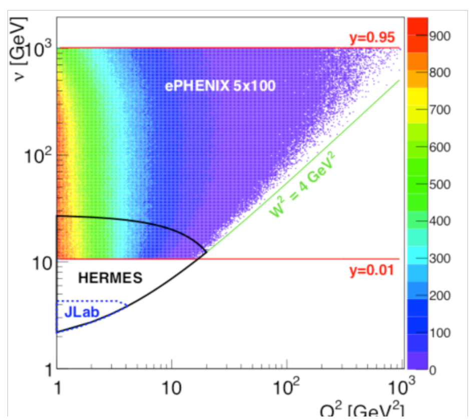


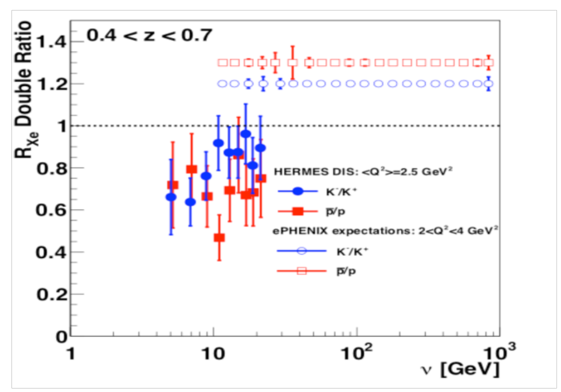


From EIC White paper

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

Propagation and hadronozation





Summary

PHENIX → sPHENIX (2021) → EIC Detector (2025)

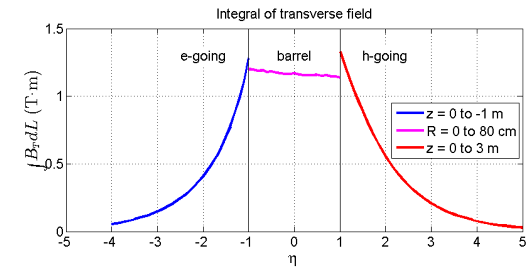
- sPHENIX Science and Cost&Schedule Review in July 2014
- EIC Detector Concept Review, Jan 10, 2014

Proposed EIC Detector is a comprehensive detector to address a broad range of EIC physics

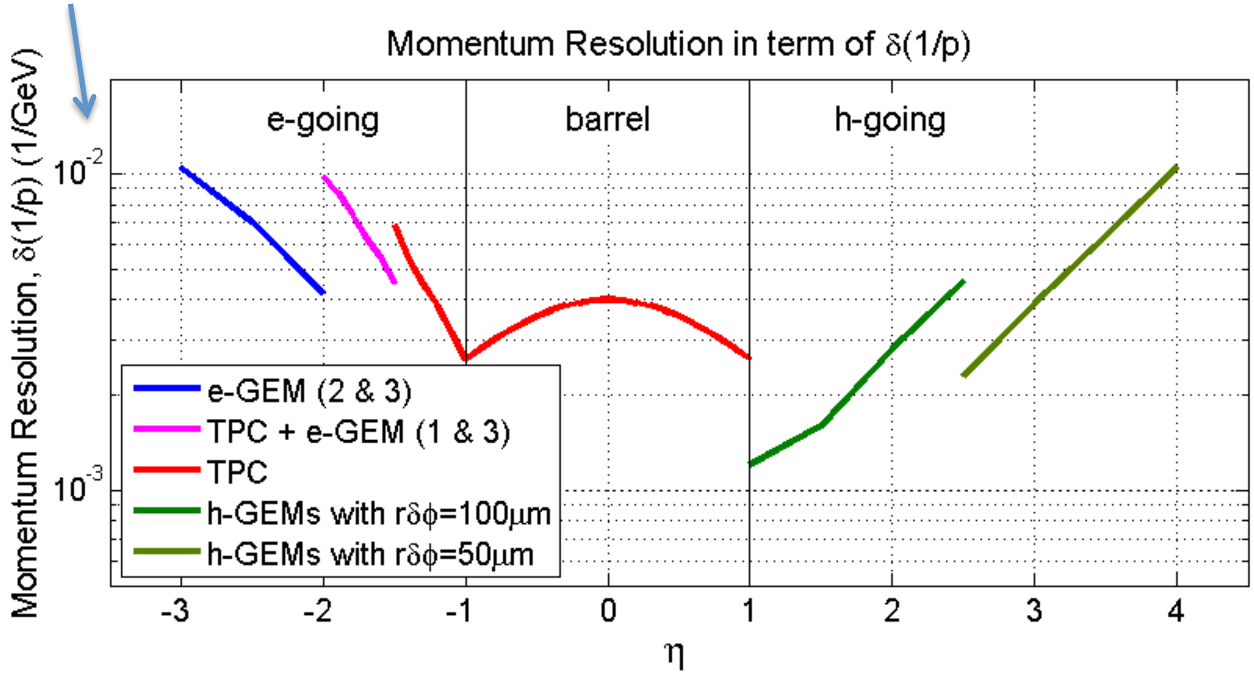
- Summarized in Letter of Intent: arXiv:1402.1209
- To be evolved from sPHENIX → sPHENIX upgrade is consistent with EIC detector plans
- New collaboration to be formed with a lot of opportunities in detector design, physics program development and scientific leadership

Backup

Momentum Resolution



$\delta p/p \sim a \times p$

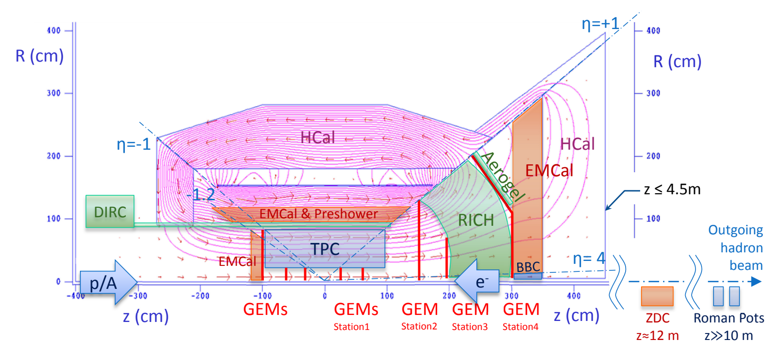


Good resolution over full tracking acceptance ($-3<\eta<4$):

e-going, $\sigma_p/p \sim (0.4\text{-}1.0\%)\times p$: primarily needed for electron ID (E/p)

barrel, $\sigma_p/p < 0.4\%\times p$: hadron momentum, electron momentum at p<10 GeV/c

h-going, $\sigma_p/p \sim (0.1\text{-}1.0\%)\times p$: crucial for PID



Inclusive DIS and Kinematics

Resolutions for (x,Q²)

$$\frac{\sigma_{Q^2}}{Q^2} = \frac{\sigma_{E'}}{E'} \qquad \frac{\sigma_x}{x} = \frac{1}{y}\frac{\sigma_{E'}}{E'}$$

Angle resolution provided by EMCal position resolution doesn't affect (x,Q^2) resolution

Defines the precision of unfolding technique to correct for smearing due to detector effects

Results in statistics migration from bin to bin –> bin survival probability

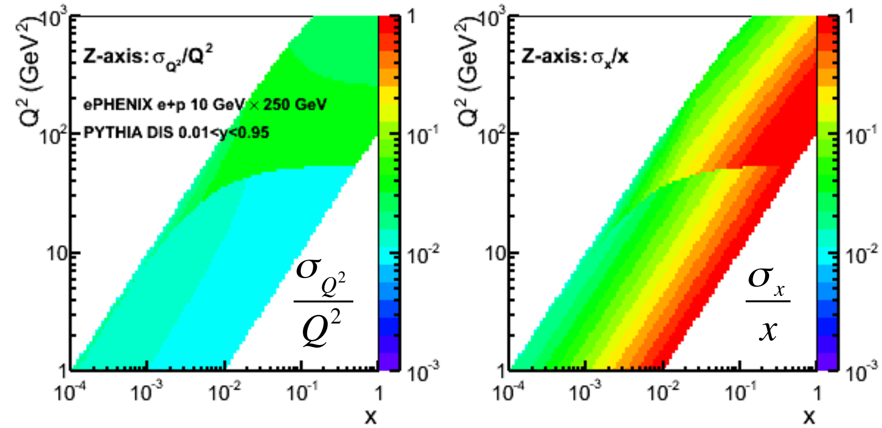
From HERMES experience: ~80% needed

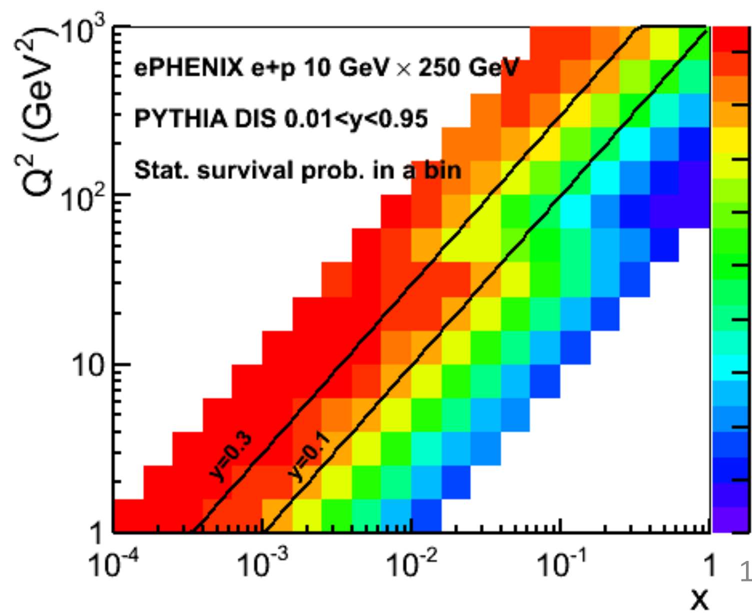
Jacqet-Blondel method (with hadronic final state) will help at lower y and higher Q^2

Bremsstrahlung radiation: no sizable effect

Minimal material

GEANT4: 3-7% impurity for y=0.5-0.95





Inclusive DIS and Kinematics

eID and background rejection

Hadron rejection:

EMCal energy response and E/p

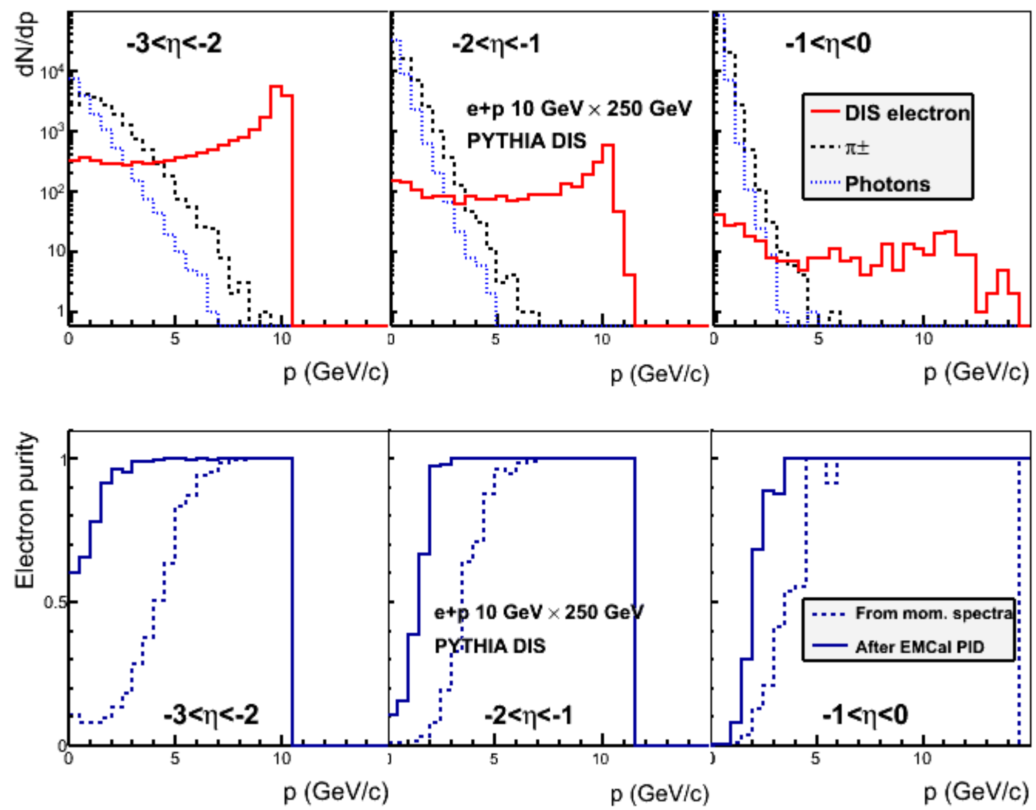
- ×20-30 at 1 GeV/c
- ×100 at 3 GeV/c

EMCal shower profile

- Expect ×3-10
- Not yet included in plots

EMCal long. segmentation and/or preshower

- For future considerations



Photon rejection ($\gamma \rightarrow e^+e^-$)

Minimal material

GEANT4 studies:

- >3 GeV/c: background negligible
- <3 GeV/c: rejected with tracking+EMCal

Reliable eID down to

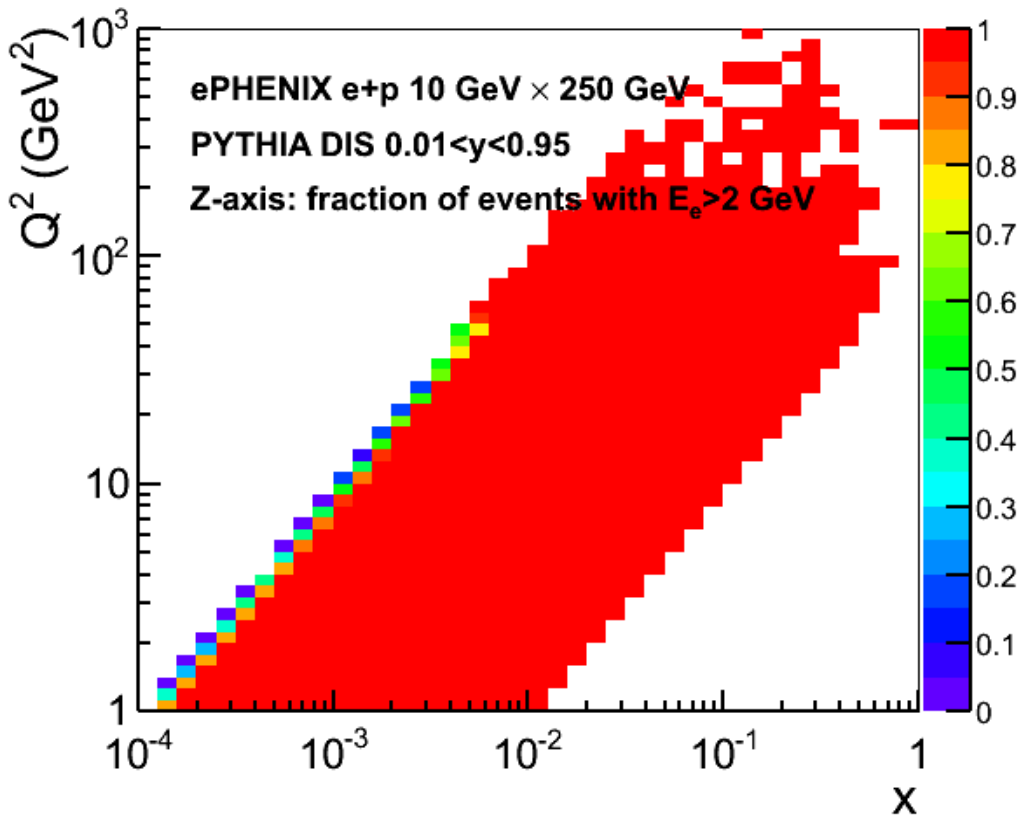
- p=2 GeV/c for 10 GeV e-beam
- p=1 GeV/c for 5 GeV e-beam

Negligible effect on the probed (x,Q^2) space

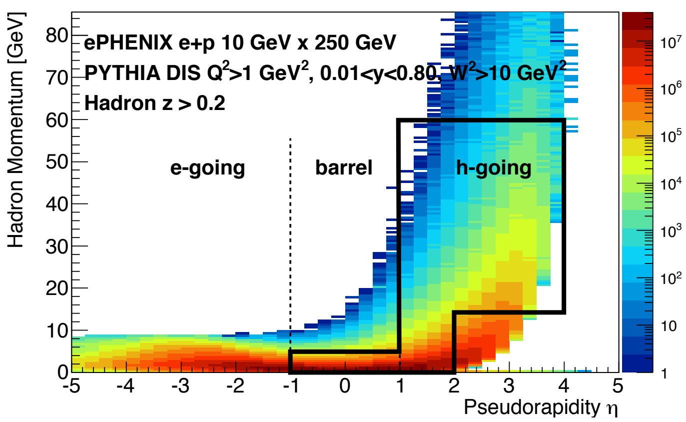
Inclusive DIS and Kinematics

What if poor eID at <2 GeV/c

Don't lose much of the (x,Q^2) space



Hadron ID with gas RICH

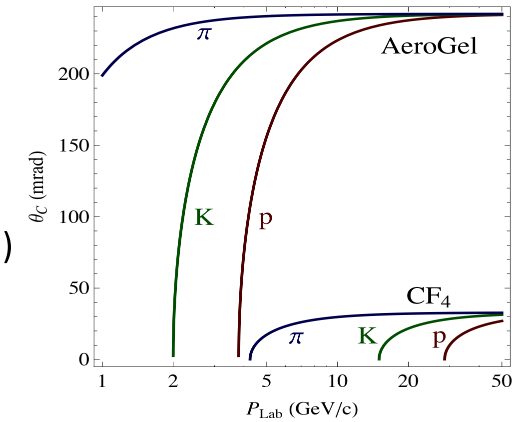


Gas RICH (CF4): 1<η<4

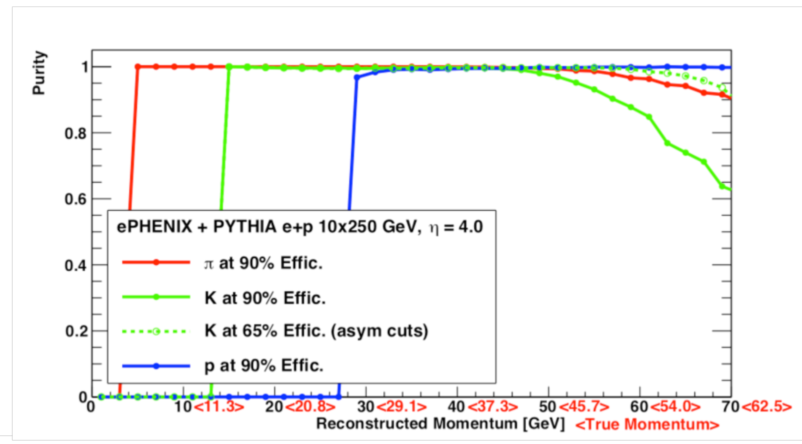
Highest momentum measurements require:

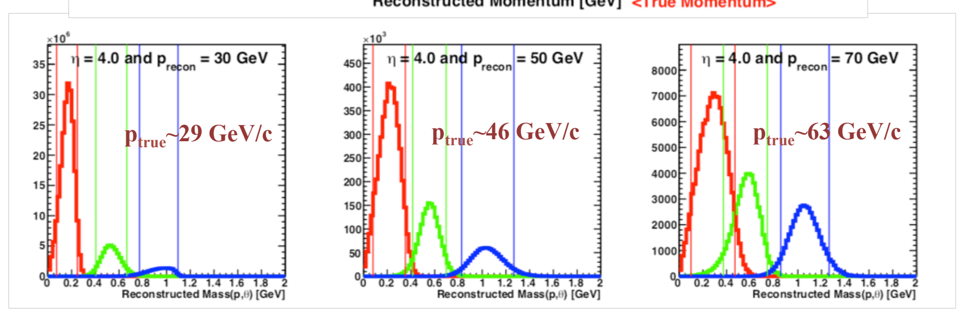
- Good momentum resolution (combination of tracking and HCal)
- Good ring resolution

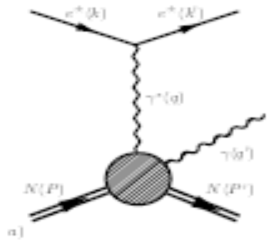
Need to balance efficiency and purity to get best measurement



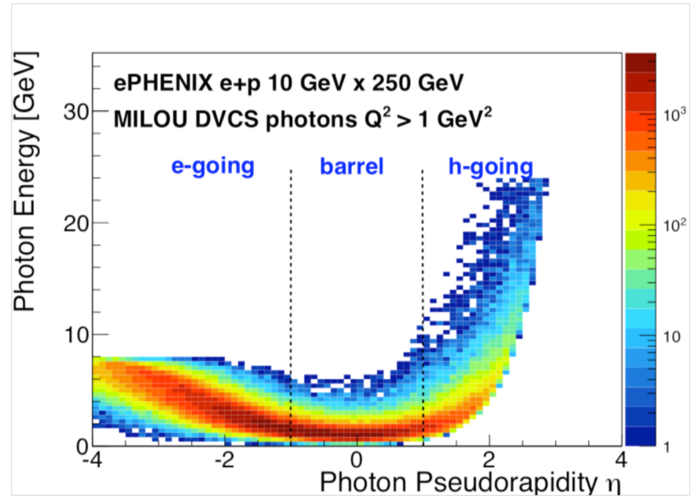
- PID up to ~60 GeV/c
- Currently limited by ring resolution (2.5% per photon - the current feedback from EIC R&D)
- Much smaller smearing due to magnetic field and off-center-vertex tracks







Exclusive Measurements



DVCS:

Wide coverage for photon measurements

EMCal and tracking in |η|<4

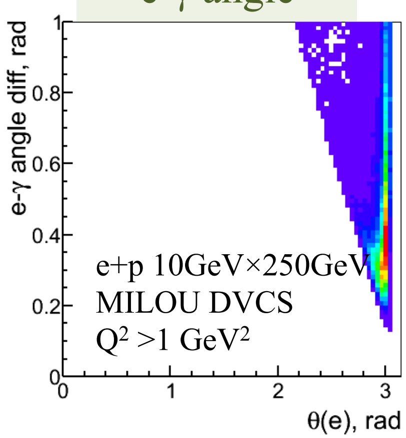
Separation of e-γ in EMCal

0.02×0.02 EMCal granularity is sufficient

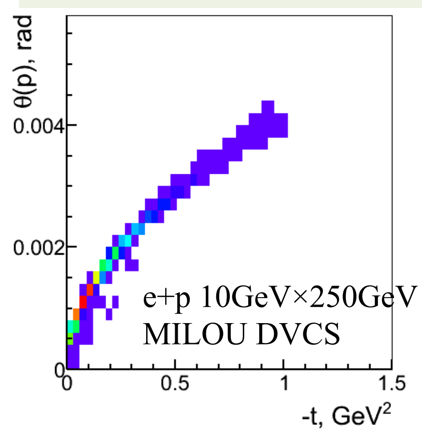
Intact proton detection is highly desirable

Roman Pots

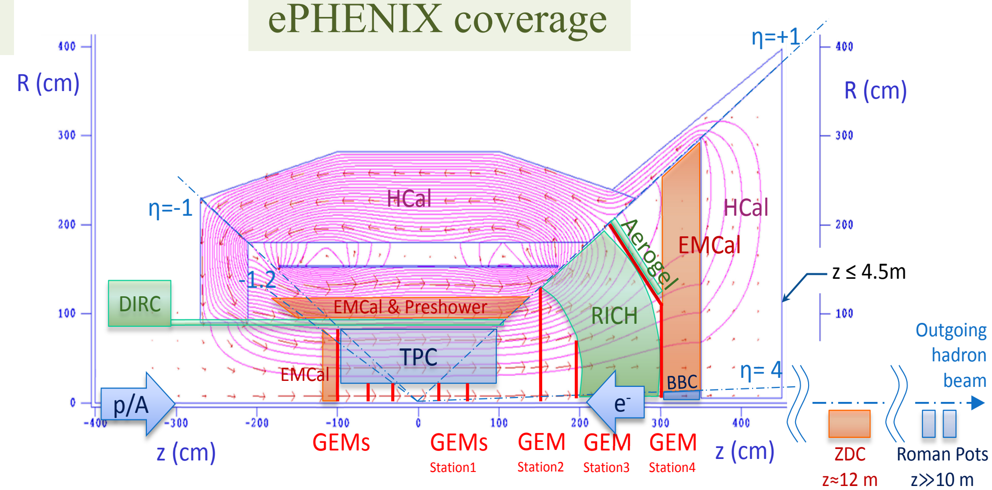
e-γ angle



Proton scattering angle



ePHENIX coverage

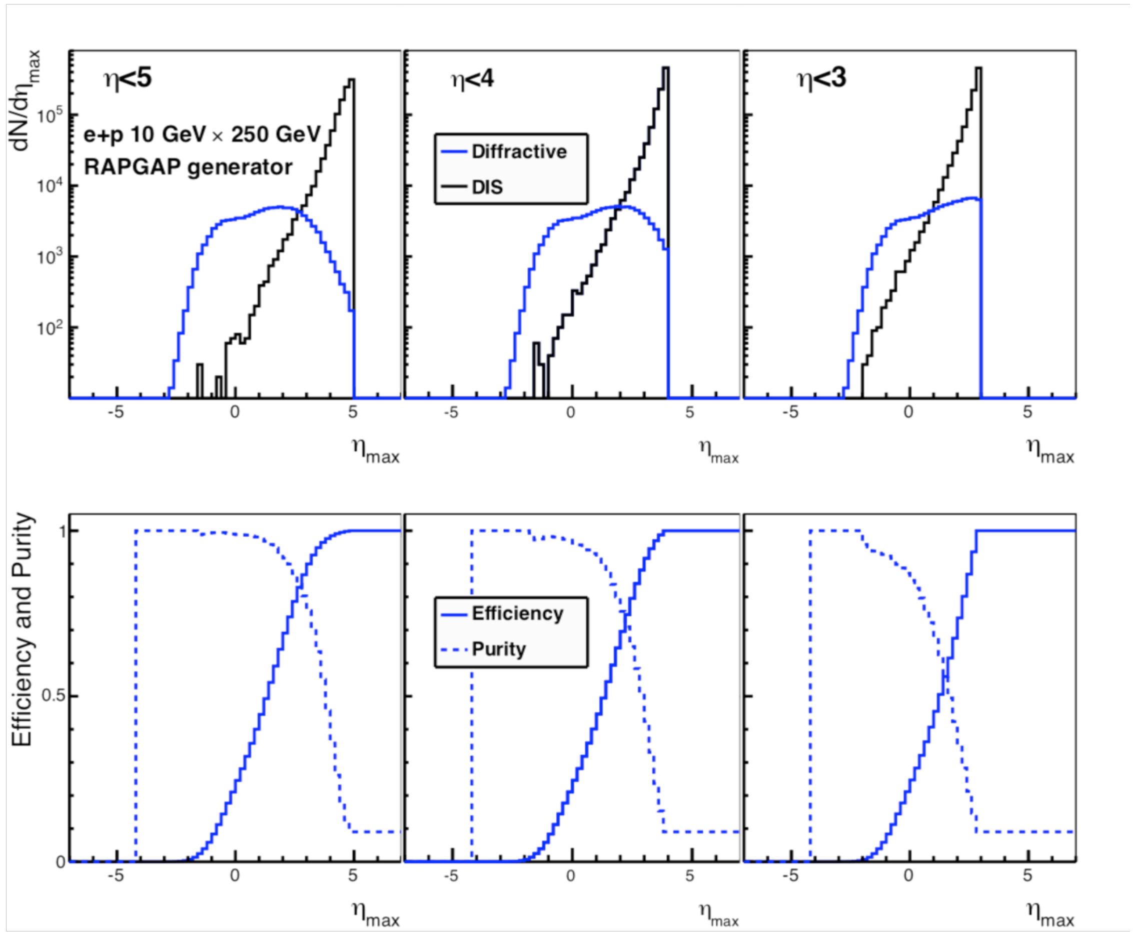


Diffractive Measurements

- Measure most forward going particle, to determine rapidity gap

  HCal with -1<η<5 and EMCal with -4<η<4 are excellent in separation of DIS and diffractive

- ZDC to measure nucleus breakup



TPC

LEGS TPC

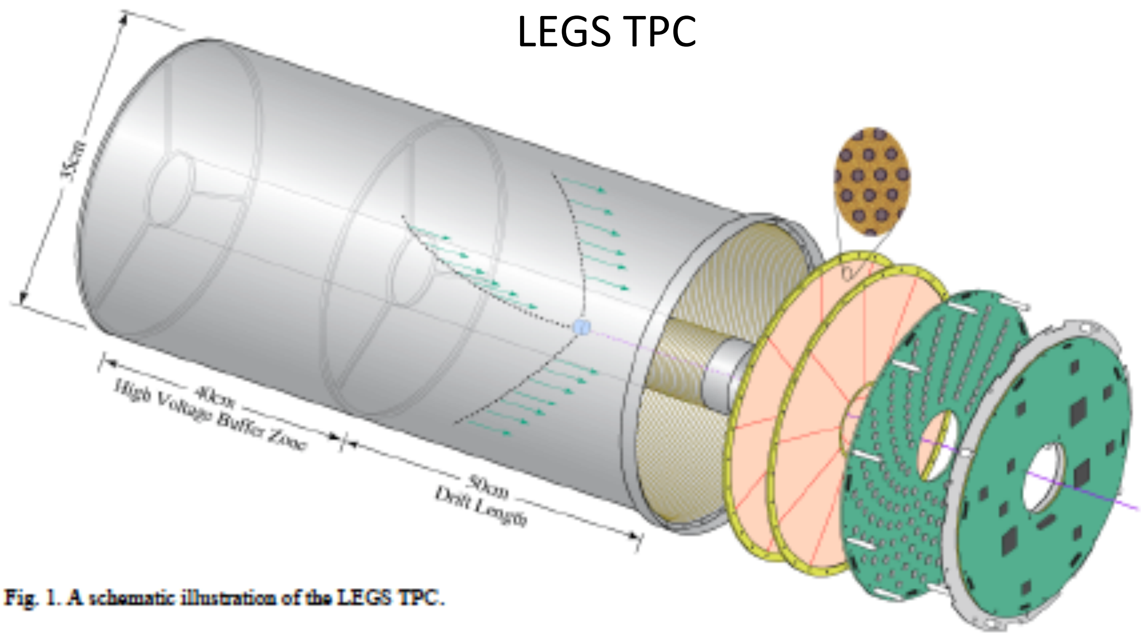
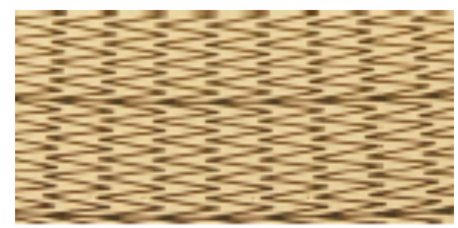


Fig. 1. A schematic illustration of the LEGS TPC.

Chevron-type readout pattern with a pad size 2mm × 5mm

Achieved pos. res. 200 μm



ePHENIX TPC:

R=15-80cm, |z|<95cm

Gas mixture with fast drift time: 80% Ar, 10% CF4, 10% CO2

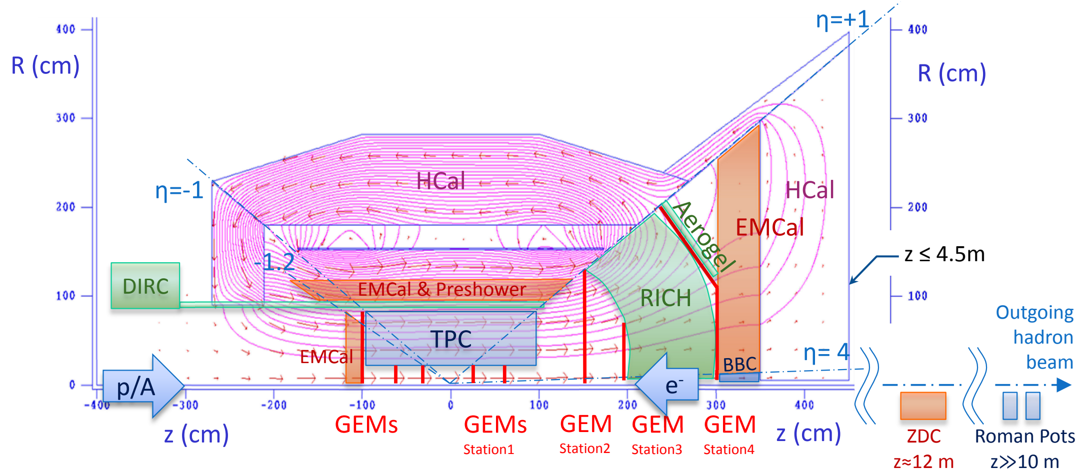
For 650 V/m -> 10cm/μs -> Drift time 10 μs

2×10mm pads –> 180k pads (both ends readout)

Pos. resolution 300 μm (twice longer drift distance tha LEGS) and 40 readout rows => $\sigma_p/p \sim 0.4\% \times p$

Tracking with GEM

Improved pos. res. with mini-drift GEM



e-going direction

Station 1-2: z=30, 55cm r=2-15cm
Station 3: z=98 cm
-3<η<-2: 50μm with 1mm pad
-2<η<-1: 100μm with 2mm pad
Δr=1cm for St1-2 and Δr=10cm for St3

h-going direction

Station 1: z=17 and 60cm with r=2-15cm
Station 2-4: z=150, 200, 300 cm, 1<η<4
2.5<η<4: 50μm with 1mm pad
1<η<2.5: 100μm with 2mm pad
Δr=1-10cm

Collision vertex is necessary in e-going direction:

BBC: η=4-5, z=3m, σ_t=30ps (with MRPC or MCP) -> σ_z=5mm -> const term in σ_p/p~2%

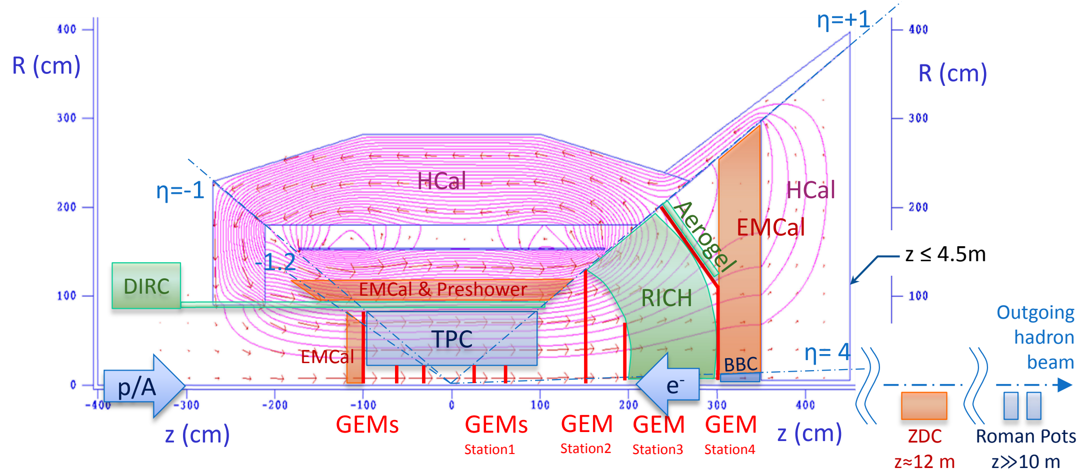
Total channel count: 217k

Large area GEMs are being developed in CERN for CMS (needed for our St 2-4)

Calorimetry

EMCal coverage -4<η<4
HCal coverage -1<η<5

Readout: SiPM



e-going direction

Crystall EMCal:

2cm×2cm

5k towers

$\sigma_E/E \sim 1.5\%/\sqrt{E}$

$\sigma_x \sim 3mm/\sqrt{E}$

Barrel (sPHENIX)

Tungsten-fiber EMCal:

2cm×2cm

25k towers

$\sigma_E/E \sim 12\%/\sqrt{E}$

Steel-Sc HCal:

10cm×10cm

3k towers

$\sigma_E/E \sim 100\%/\sqrt{E}$

h-going direction

Pb-fiber EMCal:

3cm×3cm

26k towers

$\sigma_E/E \sim 12\%/\sqrt{E}$

Steel-Sc HCal:

10cm×10cm

3k towers

$\sigma_E/E \sim 100\%/\sqrt{E}$

Hadron PID

DIRC

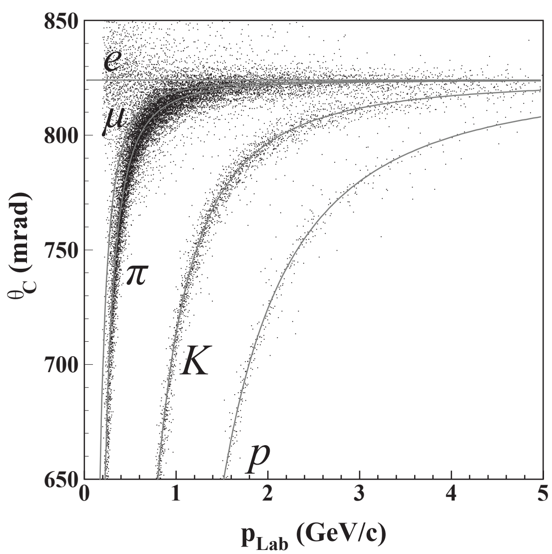
-1<η<1
Mirror focusing
Threshold for π/K/p:
 0.2/0.7/1.5 GeV

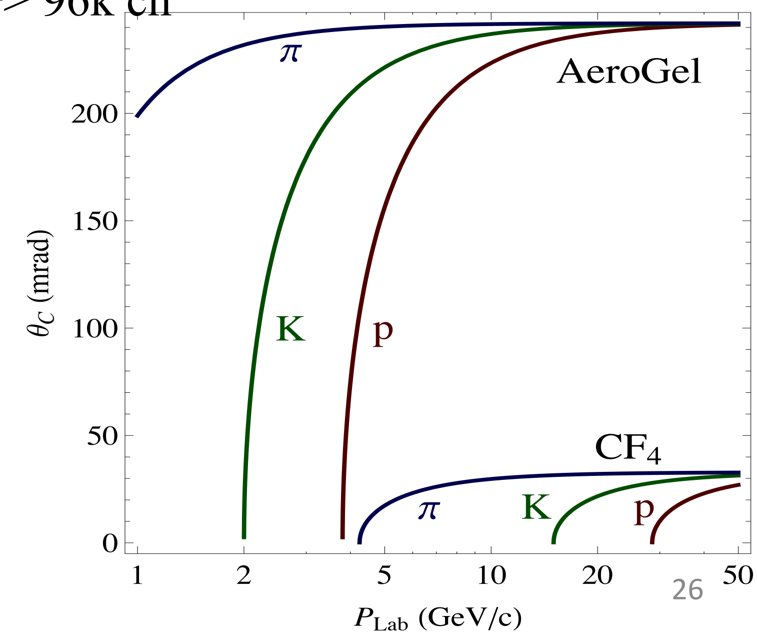
Gas RICH (CF4)

1<η<4
Mirror focusing
Threshold for π/K/p:
 4/15/29 GeV
6 azimuthal segments
Photodetection: GEM with CsI
 Area 6×0.3m² –> 96k ch
 In gas volume!

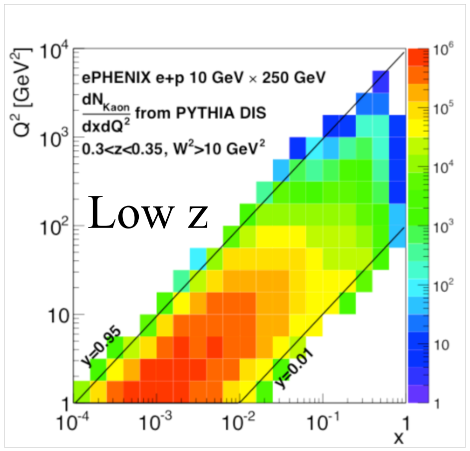
Aerogel

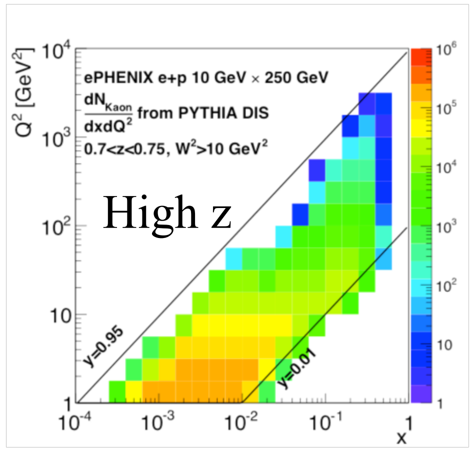
1<η<2
Proximity focused
Threshold for π/K/p:
 0.6/2/4 GeV





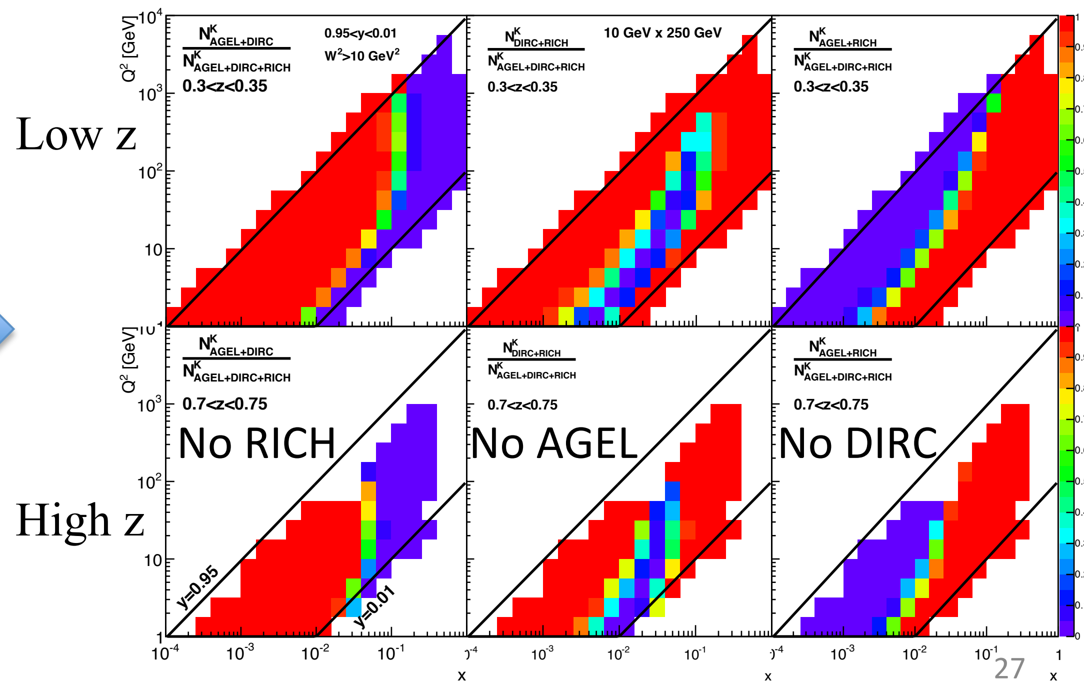
Semi-inclusive DIS and hadron ID





(x,Q^2) coverage with K

(x,Q^2) loss if not have given detector



All three detectors are important

Hadron PID: gas RICH

CF4 (n=1.00062)

Ring resolution

Ring radius resolution: 2.5%/$\sqrt{N_\gamma}$

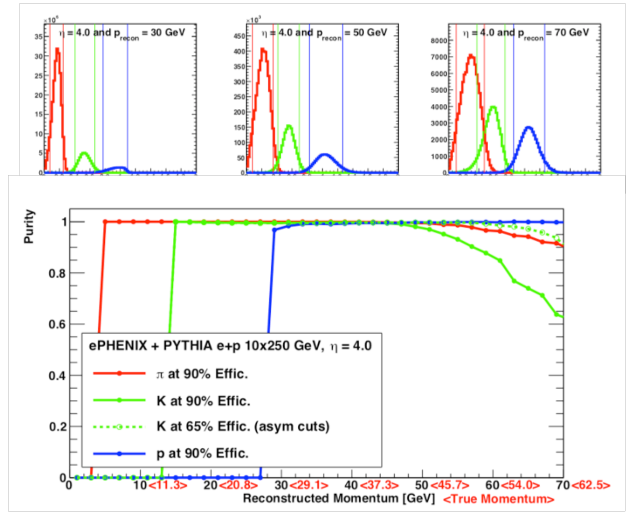
- From current EIC R&D studies
- LHCb and COMPASS claimed 1% per photon

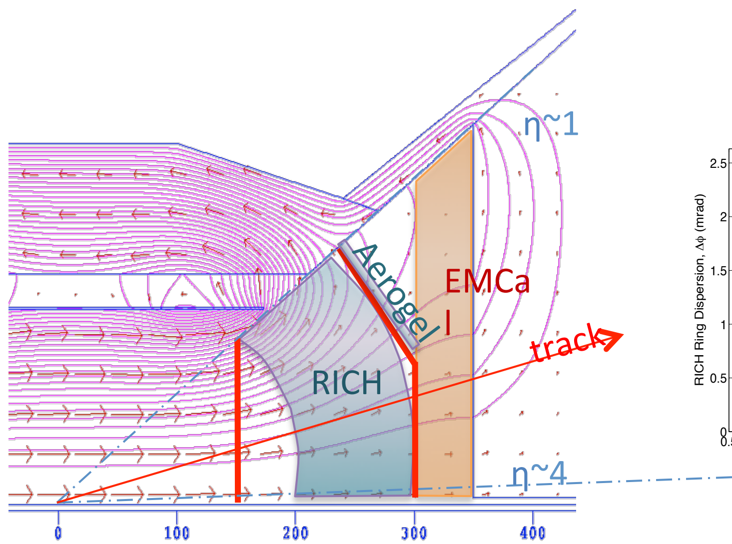
Residual magnetic field (~0.5 T) bends tracks radiating photons => ring smearing

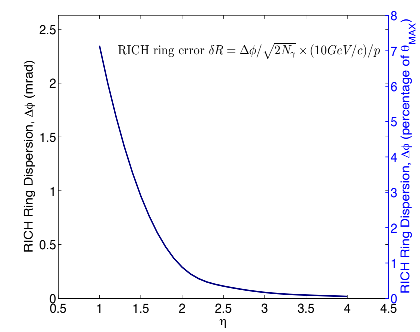
- Since field is near parallel to tracks the effect is minimal

Off-center vertex tracks have shifted focal plane => ring smearing

- For η=1 and z=40cm => ring dispersion 5%/$\sqrt{N_\gamma}$×(10 GeV/c) / p
- For larger η effect is smaller







Ring resolution limits PID at higher p

Hadron measurements with HCal and Tracking

At very forward rapidity (η~4) HCal energy resolution for single tracks may considerably exceed tracking momentum resolution

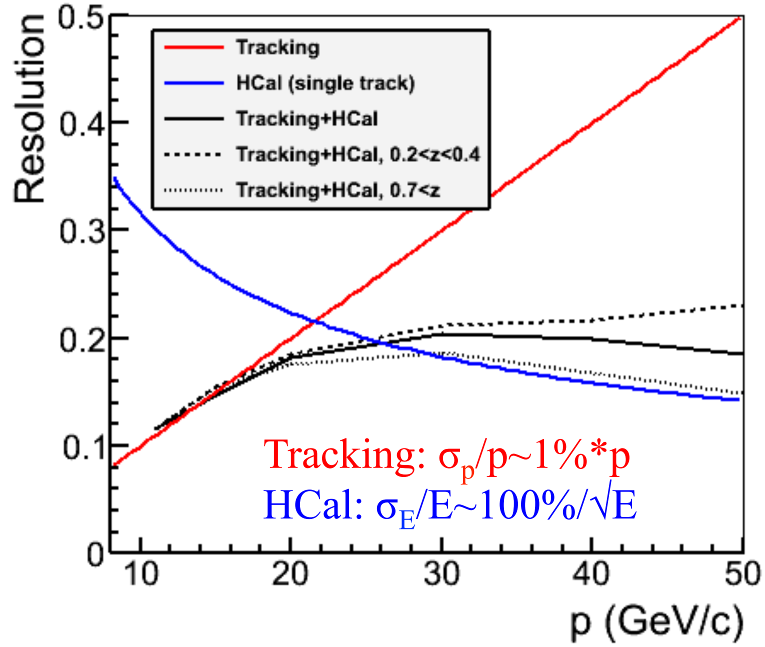
Can HCal be used to measure energy (momentum) of high momentum tracks ?

The main concern is that the energy depositions of tracks in vicinity of a given track are merged in a single cluster in HCal (non-separable in HCal)

<u>The idea:</u>

> Usual event structure is that there is one high momentum leading particle with a few lower momentum particles;
> Low momentum particles are supposed to be well reconstructed with tracking, so their contribution in HCal can be evaluated and subtracted to calculate the energy deposition of the leading high momentum particle.

PYTHIA simulation

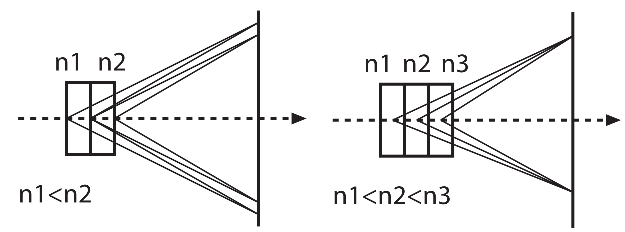


Full GEANT4 simulation is ongoing
The main impact is expected from tracking eff. and ghost (high momentum) tracks

Hadron PID: Aerogel

Allows to identify K for 3<p<10 GeV

Focusing



Challenges:

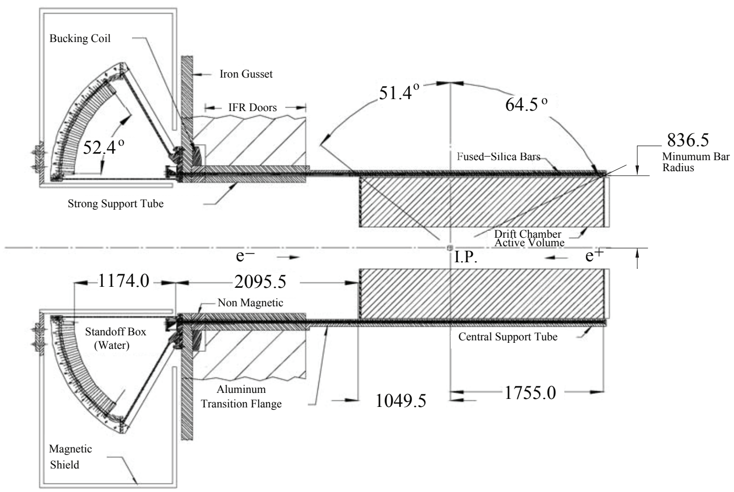
- Fringe field
- Low light output
- Visible wavelength range
- Limited space for light focusing

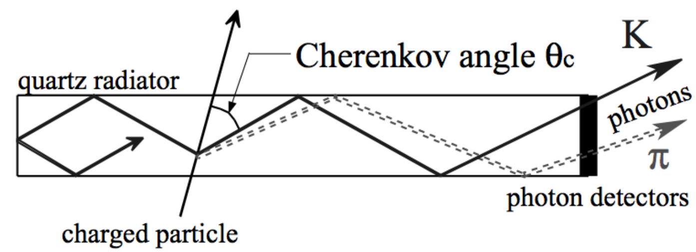
Photon detection:

Microchannel Plate Detector

- Multi-alkali photocathode
- Also ToF with σ=20-30ps
- Being developed by LAPPD Collaboration

Hadron PID: DIRC





BaBar DIRC

Quartz radiator bars, Cerenkov light internally reflected

No focusing => Large water filled expansion volume

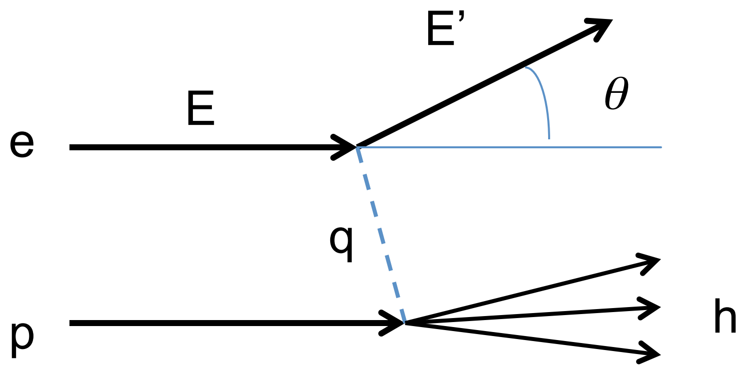
PMT for readout

ePHENIX DIRC

Mirror Focusing to avoid large expansion region

Pixelated multi-anode PMT for readout

Ring resolution limits PID at higher p



Electron vs Jacquet-Blondel

Electron

$$Q^2 = 4EE'\sin^2\left(\frac{\theta}{2}\right)$$

$$y = 1 - \frac{E'}{E}\cos^2\left(\frac{\theta}{2}\right)$$

$$x = \frac{Q^2}{sy}$$

JB

$$Q^2_{JB} = \frac{p^2_{T,h}}{1-y_{JB}} \qquad p^2_{T,h} = \left(\sum_h p_{x,h}\right)^2 + \left(\sum_h p_{y,h}\right)^2$$

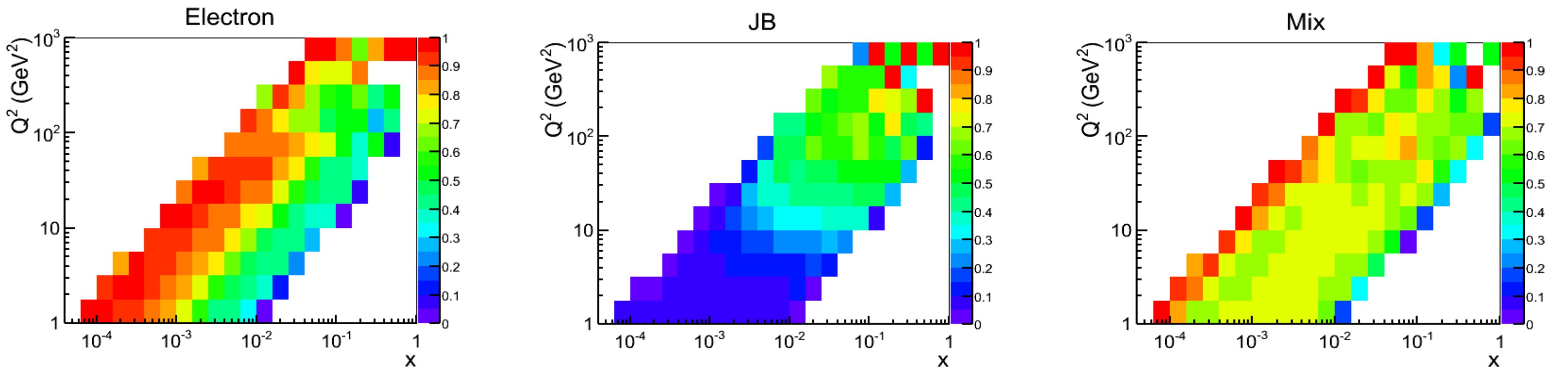
$$y_{JB} = \frac{(E-p_z)_h}{2E_e} \qquad (E-p_z)_h = \sum_h (E_h - p_{z,h})$$

$$x_{JB} = \frac{Q^2_{JB}}{sy_{JB}}$$

$y \to 0$: $\sigma_y/y \sim 1/y$

$y \to 0$: $\sigma_y/y \sim$ const

Electron vs JB vs Mix

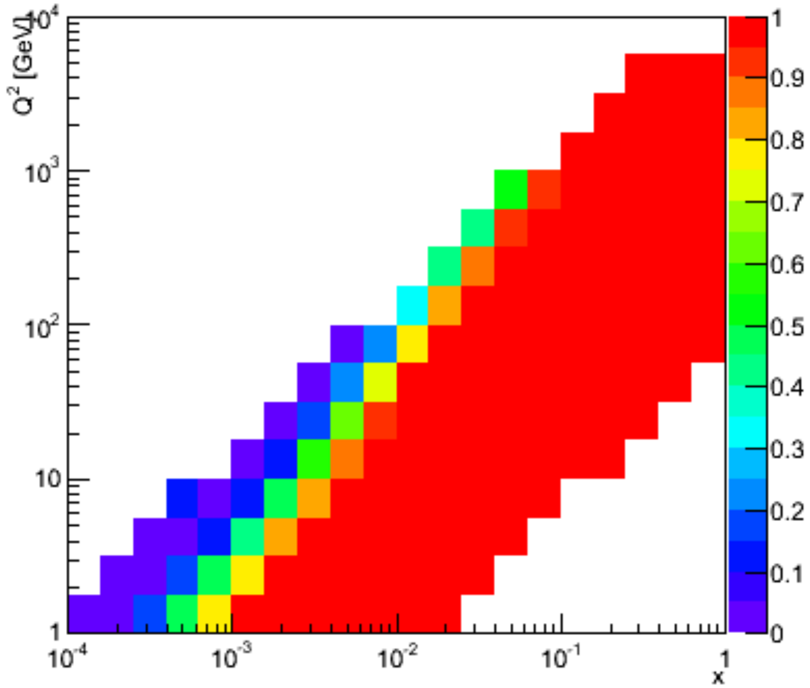


For 15 GeV × 250 GeV beam energy configuration, event purity in (x,Q^2) bins, defined by the likelihood of an event to remain in its true (x,Q^2) bin after resolutions smearing; left – for electron method, middle – for Jacquet-Blondel method, and right – for "Mixed" method, when Q^2 is defined from electron method, y is defined from Jacquet-Blondel method, and $x=Q^2/(sy)$.

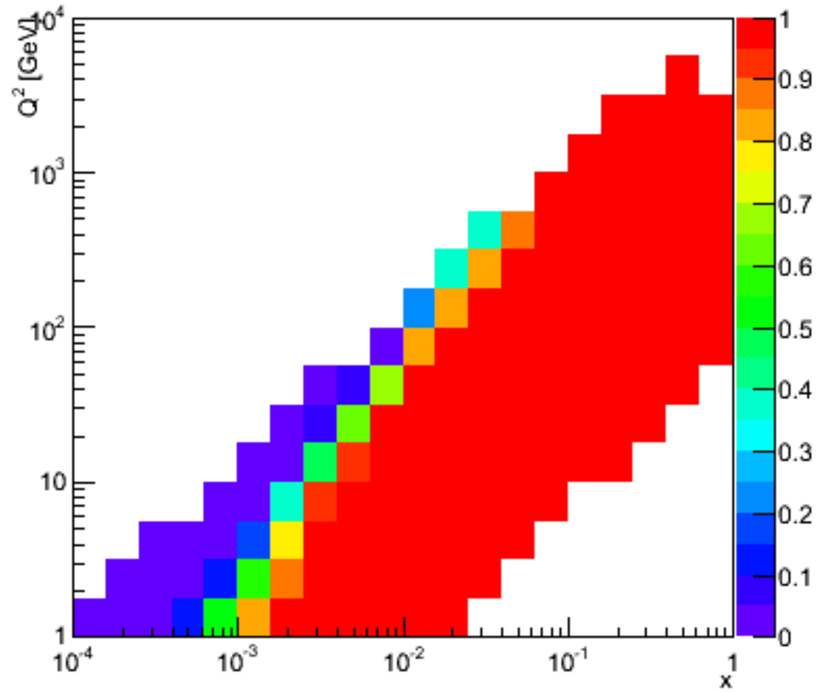
(x,Q2) loss due to no ePID in e-going direction

e+p 10 GeV × 250 GeV
PYTHIA DIS 0.01<y<0.95 W^2>10 GeV^2

0.30<z<0.35



0.70<z<0.75



If better DIRC?

e+p 10 GeV × 250 GeV
PYTHIA DIS $0.01<y<0.95$ $W^2>10\ GeV^2$

"Normal" DIRC: pi/K separation up to 3.5 GeV/c
Improved DIRC: pi/K separation up to 6 GeV/c