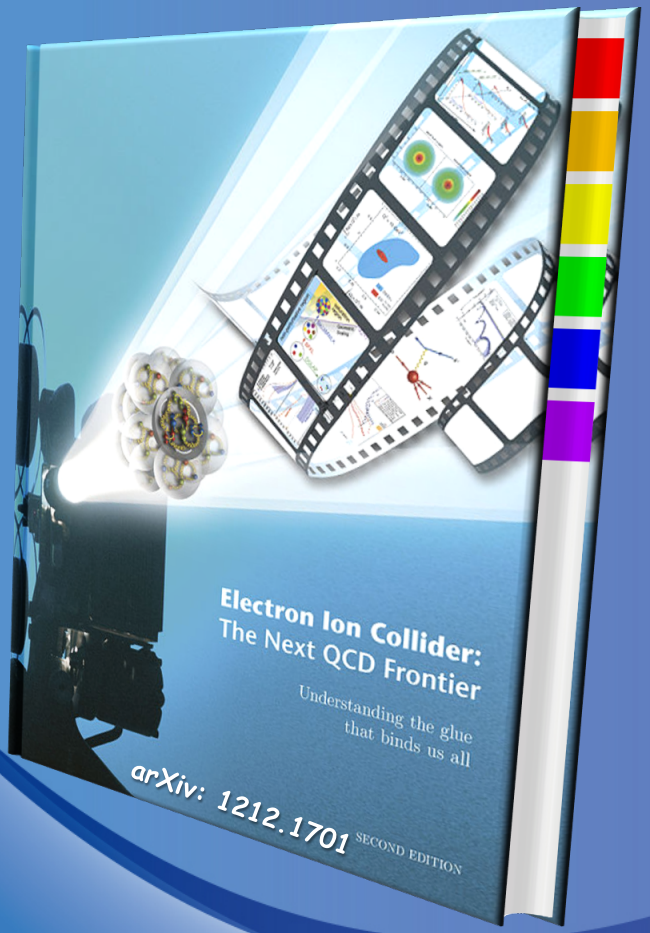
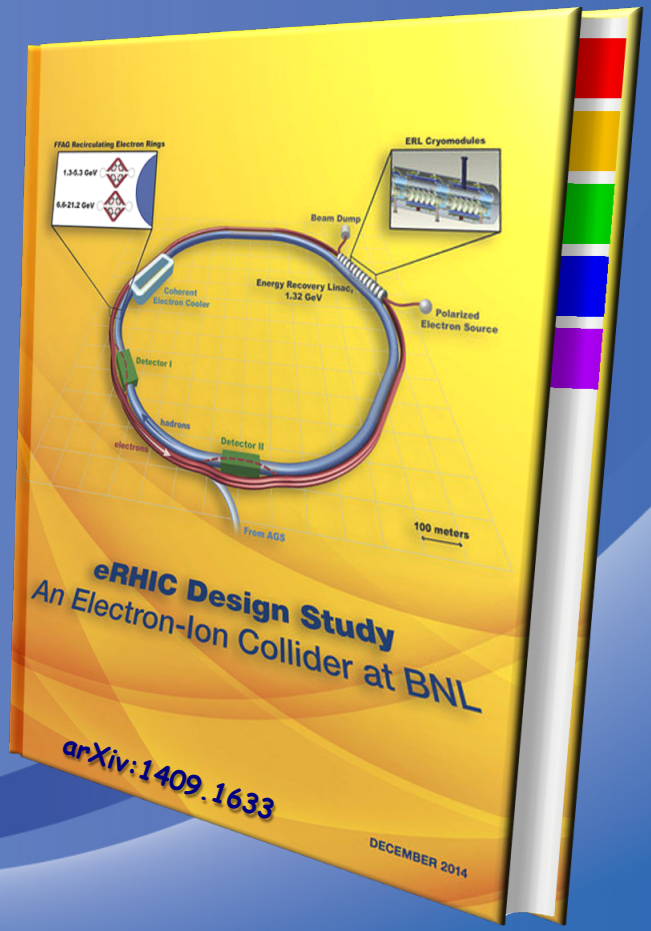
EIC Main and Auxiliary Detector Requirements

E.C. Aschenauer, A. Kiselev and R. Petti





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a passion for discovery

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GLOBAL REQUIREMENTS

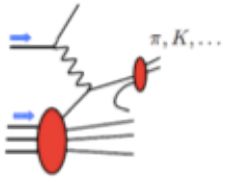
Requirements from Physics:

- High Luminosity > 10^{33} $cm^{-2}s^{-1}$ and higher → nucleon/nuclei imaging
- Flexible center of mass energy → wide kinematic reach
- Electrons (0.8) and protons/light nuclei (0.7) highly polarized → study spin
- Wide range of nuclear beams (D to U) → high gluon densities
- room for a wide acceptance detector with good PID (e/h and π, K, p)
- wide acceptance for protons from elastic reactions and neutrons from nuclear breakup

WHAT IS NEEDED TO REALIZE EIC PROGRAM

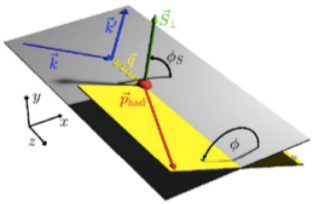
experimental program to address these questions:

prerequisites



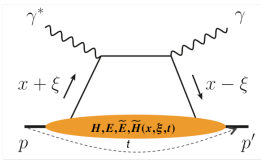
inclusive and semi-inclusive DIS

longitudinal motion of spinning quarks and gluons



azimuthal asymmetries in DIS

adds their transverse momentum dependence



exclusive processes

adds their transverse position

machine & detector requirements

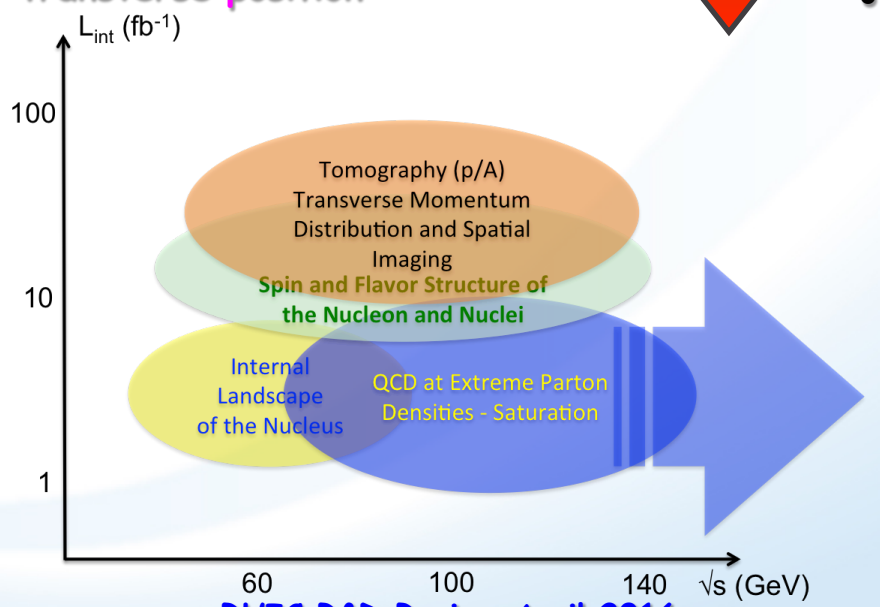
all need $\sqrt{s_{ep}}$ > 50 GeV

to access x < 10^{-3} where sea quarks and gluons dominate

L ≈ 10 fb^{-1}

L ≈ 10 - 100 fb^{-1}

- multi-dimensional binning → x, Q^2, z, p_T (or t), Θ
- to reach p_T > 1 GeV
- to reach |t| > 1 GeV^2



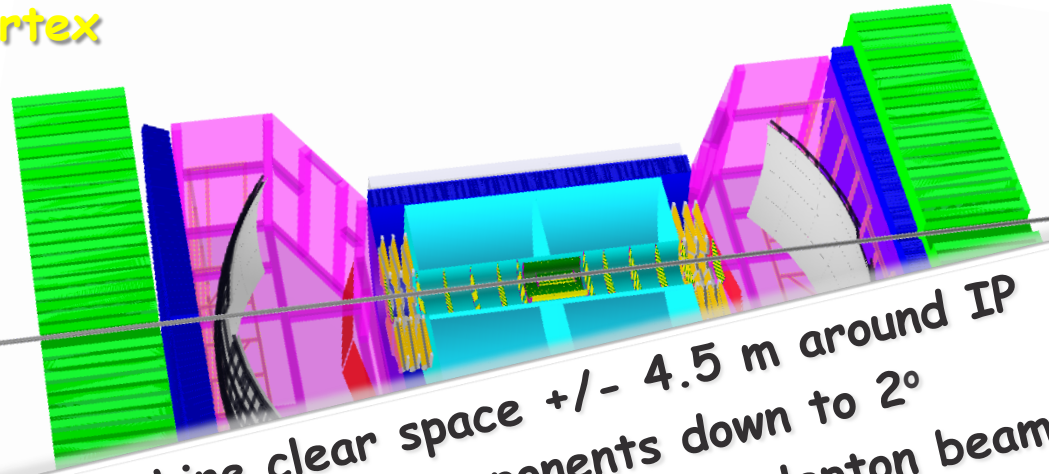
THE MODEL DETECTOR

fully model in Geant

Hcal μ-vertex

Ecal GEM

RICH TPC



low Q^2 tagger and luminosity detector

To Roman Pots

Machine clear space +/- 4.5 m around IP

detector components down to 2°

Detector magnet aligned with lepton beam

backgrounds due to synchrotron and beam gas events

have to be kept at a minimum

hadron beam → +η

H

- ... RICH + TPC: dE/dx

1 < ... radiator RICH

Lepton-ID:

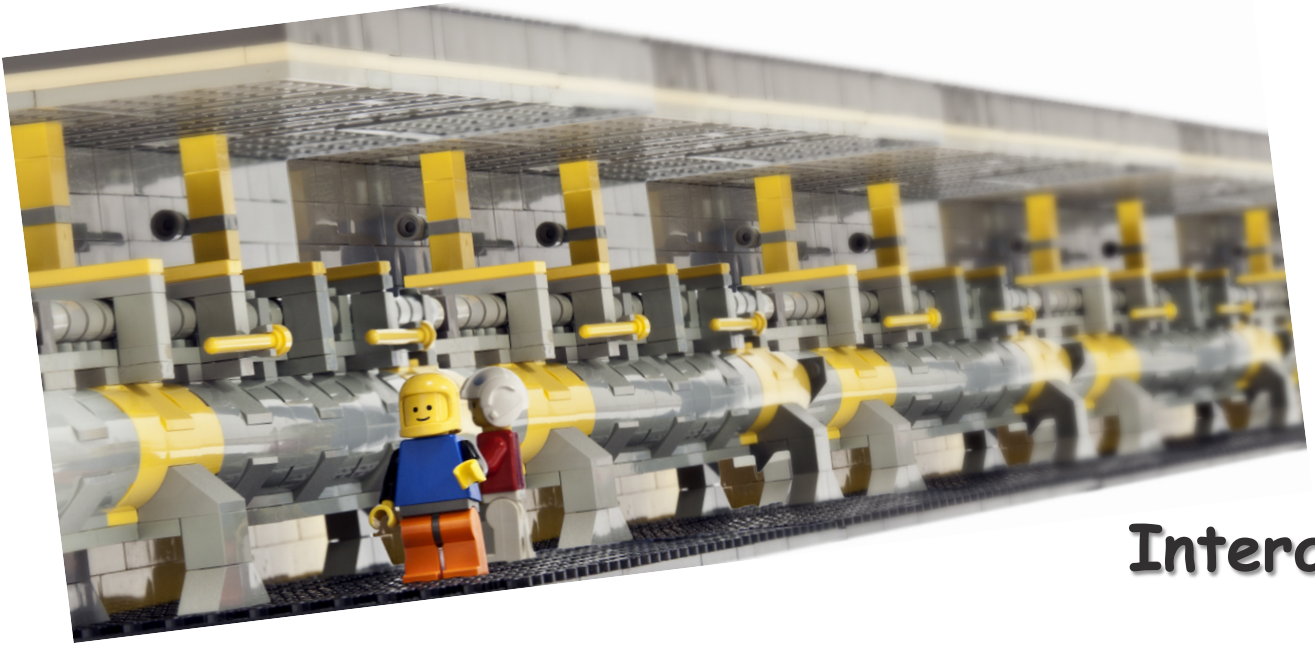
-3 <η< 3: e/p

1<|η|<3: in addition Hcal response & γ suppression via tracking

|η|>3: ECal+Hcal response & γ suppression via tracking

-4<η<4: Tracking (TPC+GEM+MAPS)

MAPS: CMOS Monolithic Active Pixel Sensors



EIC:

Interaction Region
and
ancillary detector systems:

hadron and lepton polarimeters
luminosity detector
low Q^2 tagger
ZDC and Roman Pot systems

all needed from the beginning

REQUIREMENTS FROM PHYSICS ON IR

Summarized at:
https://wiki.bnl.gov/eic/index.php/IR_Design_Requirements

Hadron Beam:

1. the detection of neutrons of nuclear break up in the outgoing hadron beam direction
   → location/acceptance of ZDC
2. the detection of the scattered [illegible] reaction in the [illegible]
   → [illegible]
3. space [illegible]

Lepton [illegible]

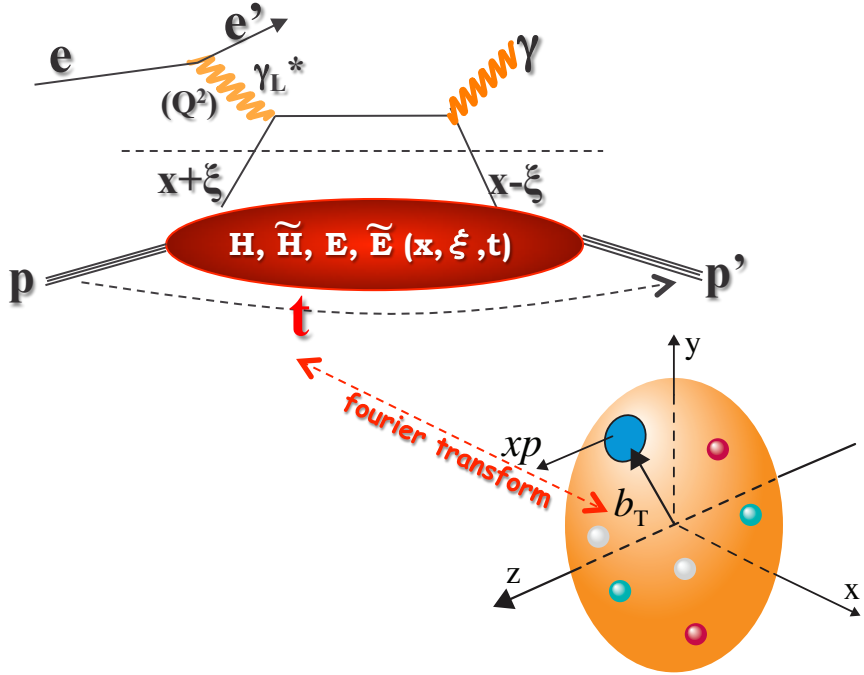
1. minimize impact of detector magnetic field on lepton beam
   → synchrotron radiation
2. space for low Q^2 scattered lepton detection
3. space for the luminosity monitor in the outgoing lepton beam direction
4. space for lepton polarimetry

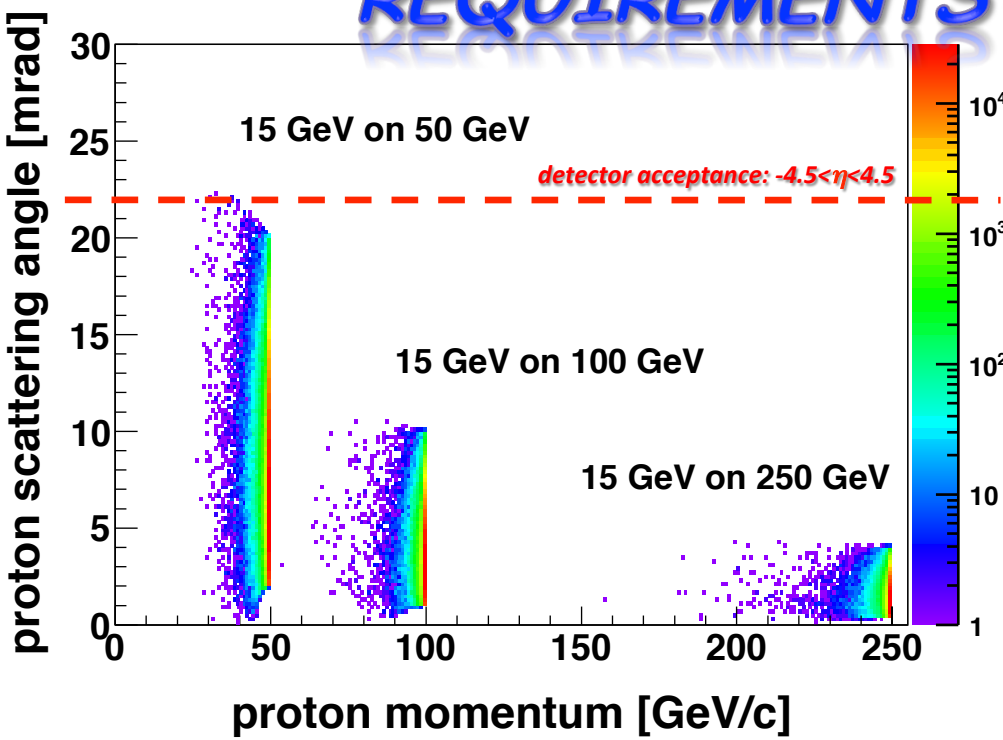
Important

EIC is a high luminosity machine 10^{33-34} $cm^{-2}s^{-1}$
such controlling systematics becomes crucial
→ luminosity measurement
→ lepton and hadron polarization measurement

Hadron Beam:
Requirements for forward going scattered protons and neutrons

REQUIREMENTS





This is the kinematics spectrum of protons from exclusive reactions → DVCS

→ the physics variable we are interested is t

→ Fourier transform of t → b_T spatial coordinate inside proton

→ t directly correlated to p_t of the proton → $t \sim p_t^2$

→ $p_t = p \sin\Theta$

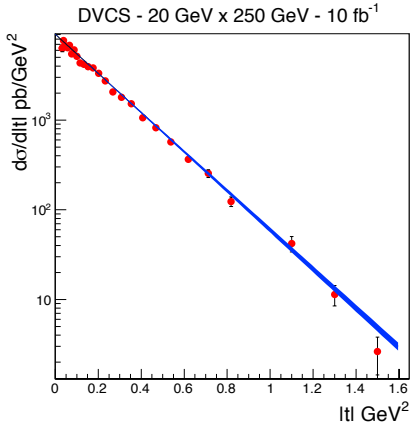
→ for physics we need

$0.17\ \text{GeV} < p_t < 1.3\ \text{GeV} \leftrightarrow 0.03\ \text{GeV}^2 < t < 1.6\ \text{GeV}^2$

→ Common Assumption:

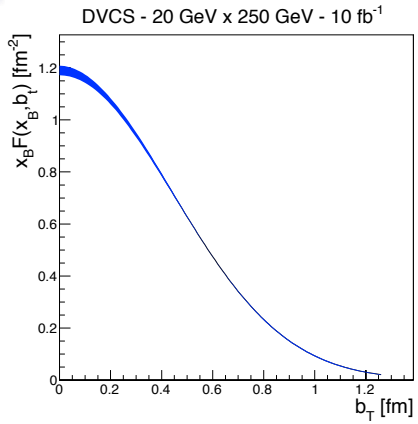
→ Use Romon Pots to detect the protons (LHC, RHIC, HERA, Tevatron) assume 10σ distance of the RP to the core of the beam

IMPACT OF REDUCED ACCEPTANCE



Plots from EIC WP:

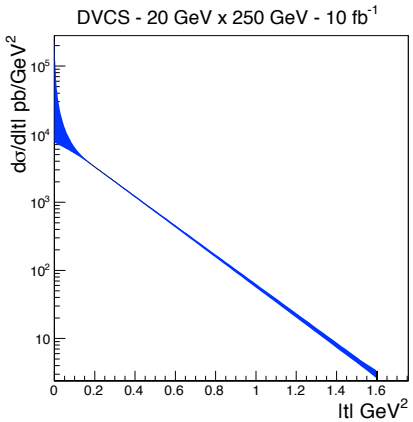
Fourier Transform



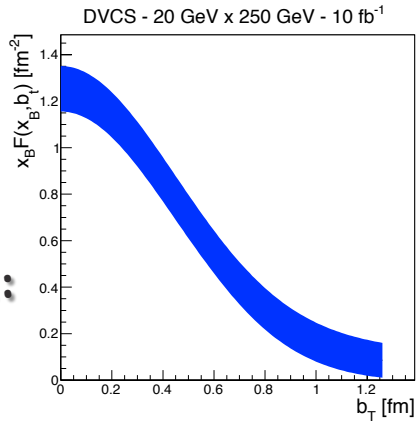
eRHIC with 20x250 GeV^2 and $\int L = 10 fb^{-1}$

$0.18 < p_t$ (GeV) < 1.3

$0.03 < |t|$ (GeV^2) < 1.6

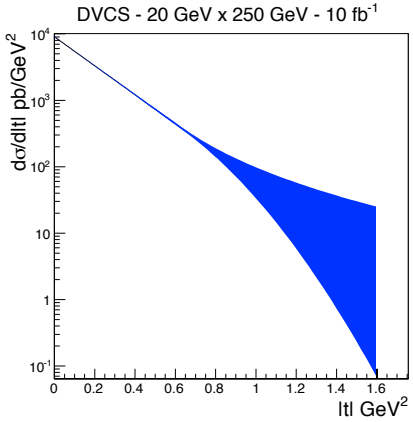


Plots with reduced lower p_t-acceptance:

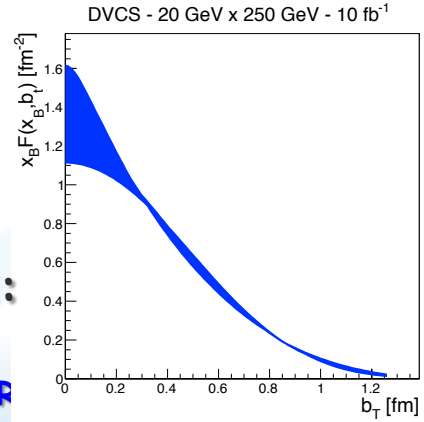


eRHIC with 20x250 GeV^2 and $\int L = 10 fb^{-1}$

$0.44 < |p_t|$ (GeV) < 1.3



Plots with reduced high p_t-acceptance:



eRHIC with 20x250 GeV^2 and $\int L = 10 fb^{-1}$

$0.18 < |p_t|$ (GeV) < 0.8

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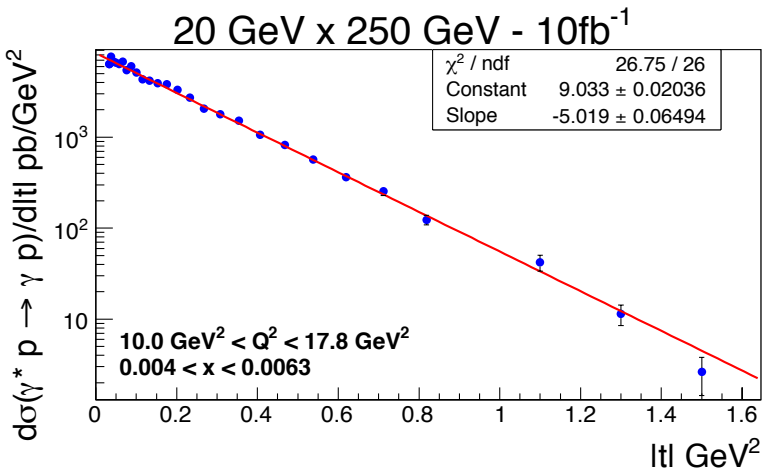
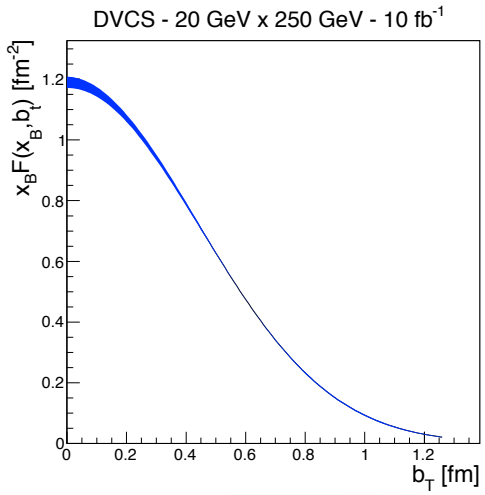
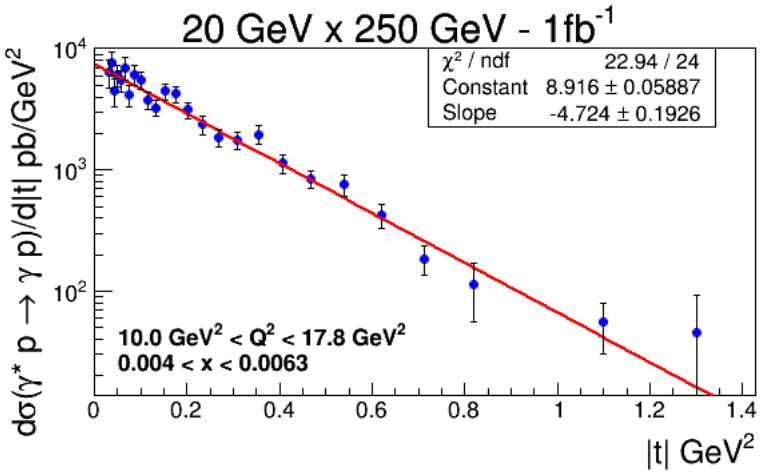
IMPACT OF REDUCED LUMINOSITY

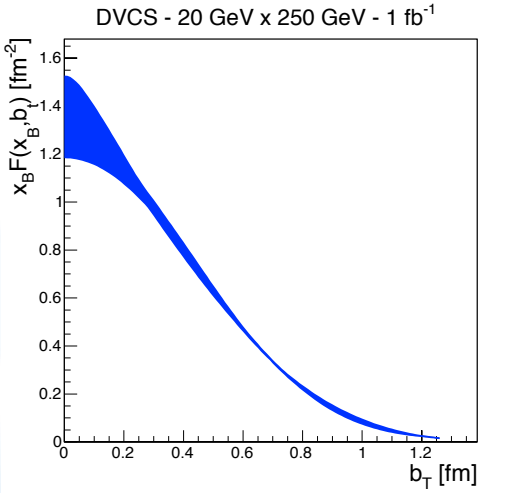
10 fb^{-1} → 1 fb^{-1}

0.18 < $|p_t|$ (GeV) < 1.3







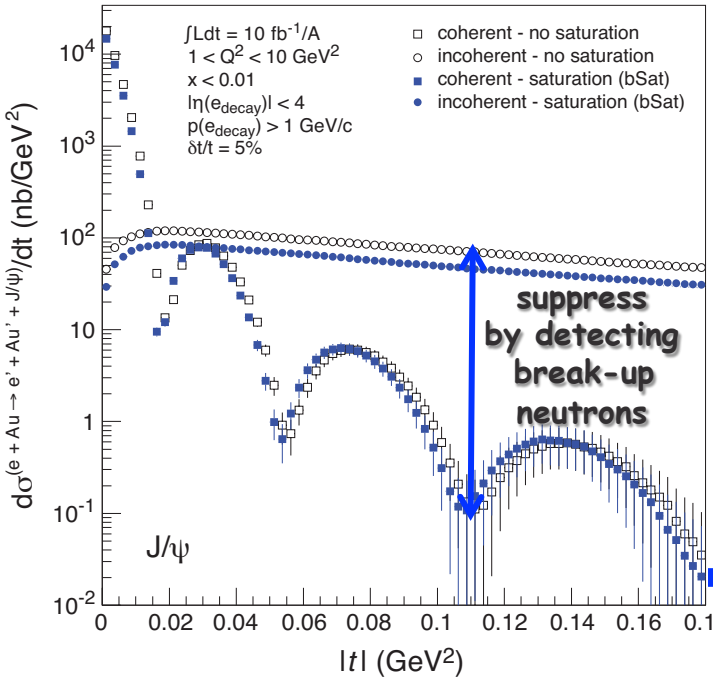


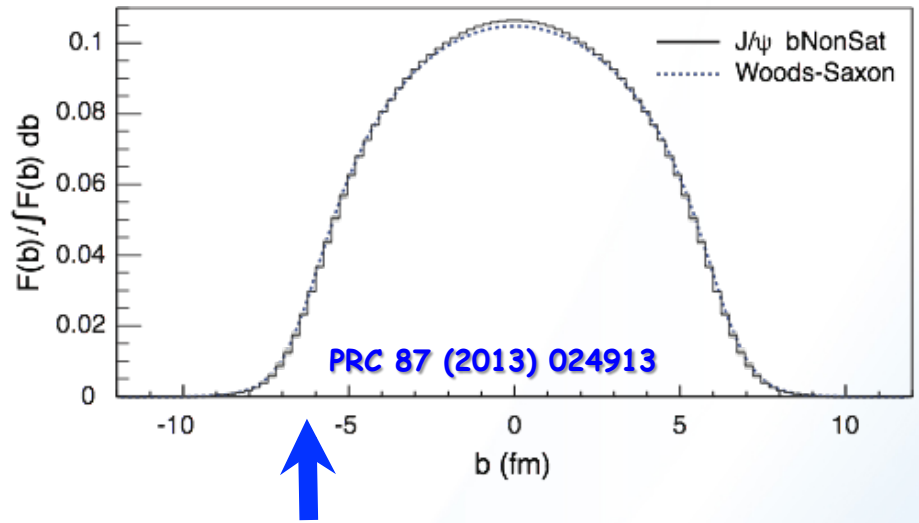
Why is Neutron Detection Critical

Measure spatial gluon distribution in nuclei

How: Diffractive vector meson production: $e + Au \rightarrow e' + Au' + J/\psi, \phi, \rho$

→ Momentum transfer $t = |p_{Au} - p_{Au'}|^2$ conjugate to b_T

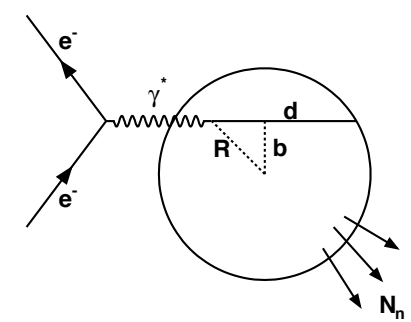


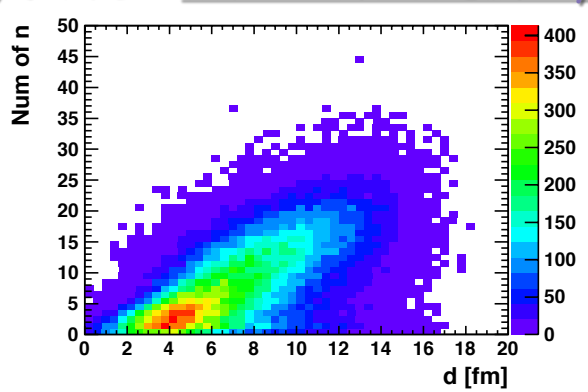


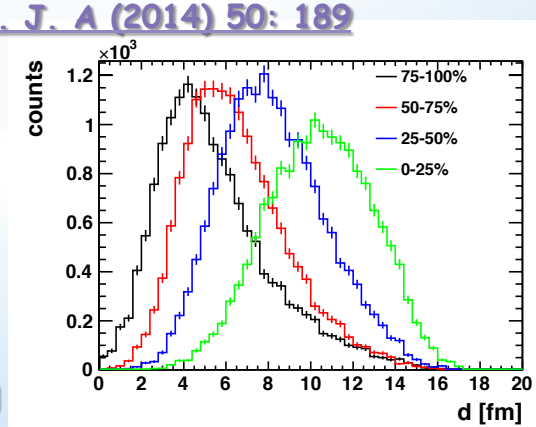
Fourier Transform

Reconstruct the eA collision geometry:

for details see L. Zheng, ECA, J-H. Lee arXiv:1407.8055 Eur. Phys. J. A (2014) 50: 189







MODELED NUCLEAR BREAKUP

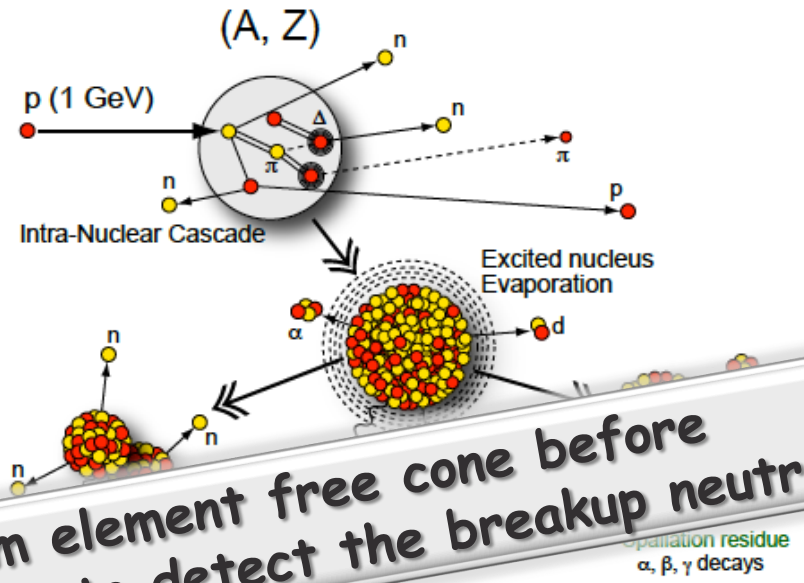
Traditional modeling done in pA:

Intra-Nuclear Cascade

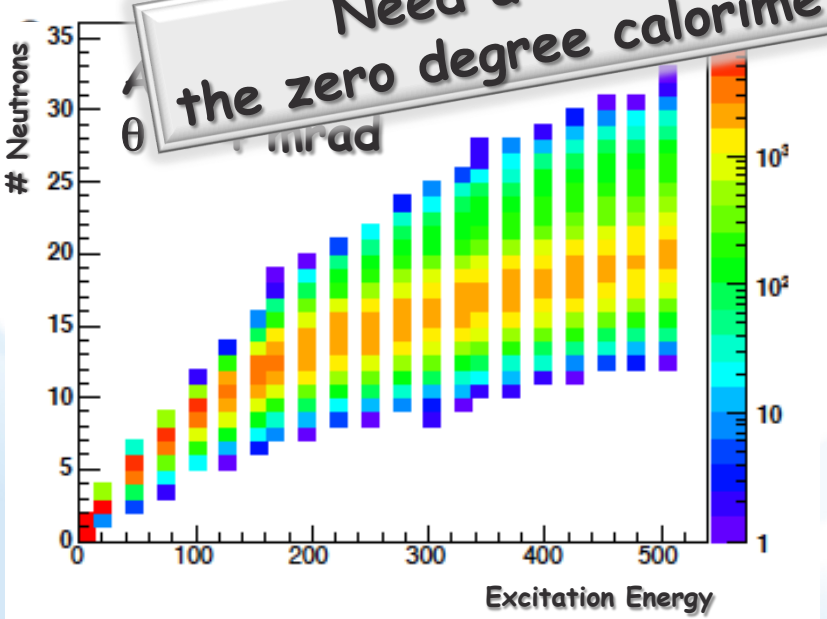
- Particle production
- Remnant Nucleus (A, Z, E*, ...)
- ISABEL, INCL4

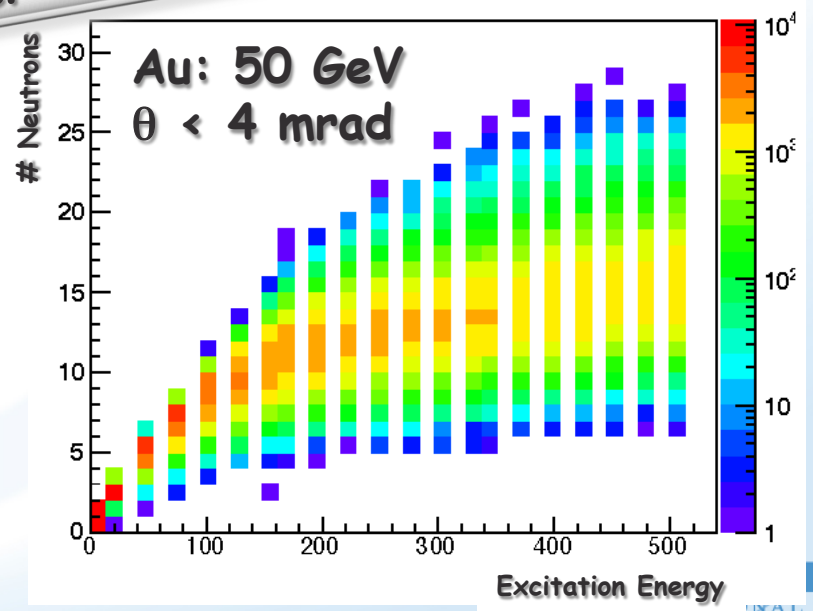
De-Excitation

- Evaporation
- Fission
- Residual Nuclei
- Gemini++, SMM, ABLA (all no γ)

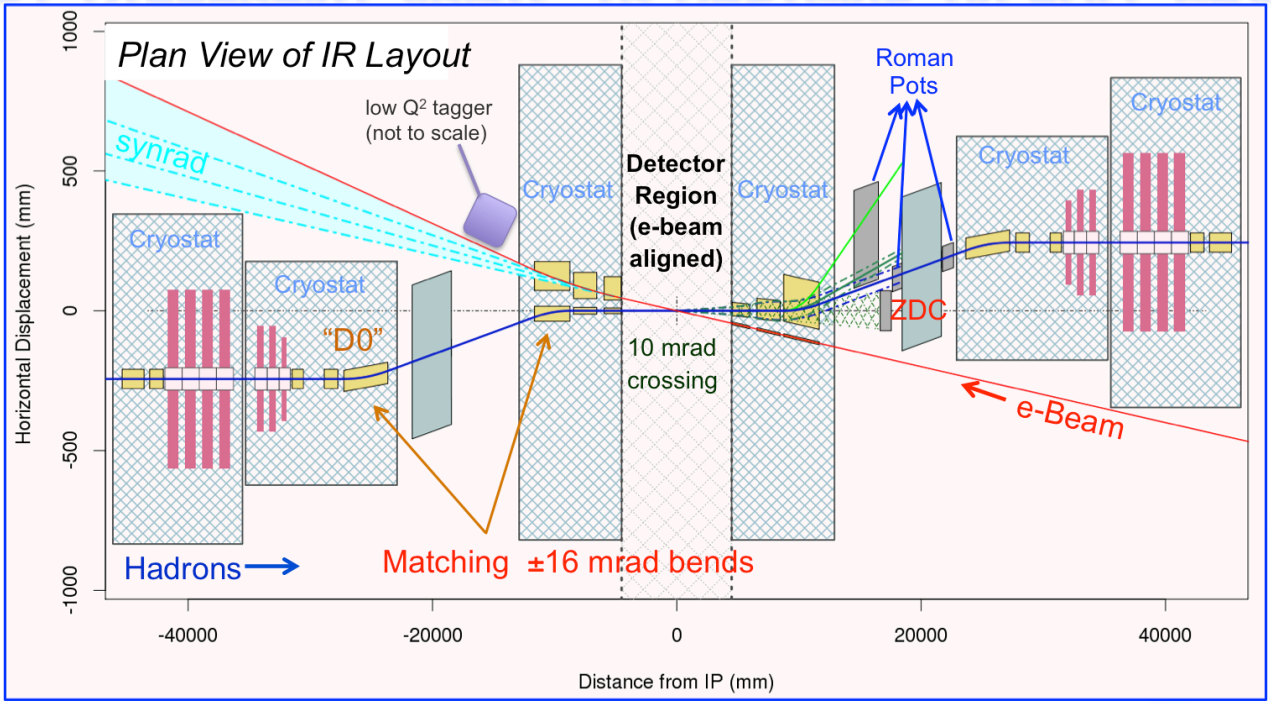


Need a 4 mrad beam element free cone before the zero degree calorimeter to detect the breakup neutrons





TEST DIFFERENT eRHIC-IR DESIGNS IN FULL GEANT SIMULATIONS

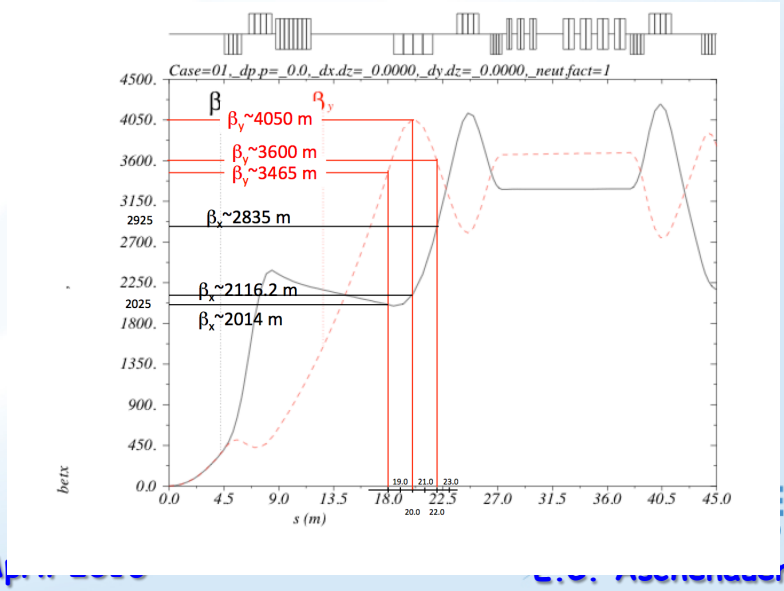


Linac Ring v2.1 most complete one as both e + p side are designed.

- expected beam width calculation $\sigma_{x,y} = \sqrt{\frac{\beta_{x,y}\varepsilon}{\gamma}}$
- from table 3.1 in eRHIC design report and the attached figure of the beta function
  - β_x = 2014m (at z=18m)
  - β_y = 3465m (at z=18m)
  - ε (normalized) = $0.2e^{-6}$m
  - γ = 270 (for 250 GeV protons)

  10 σ_x = 1.2 cm

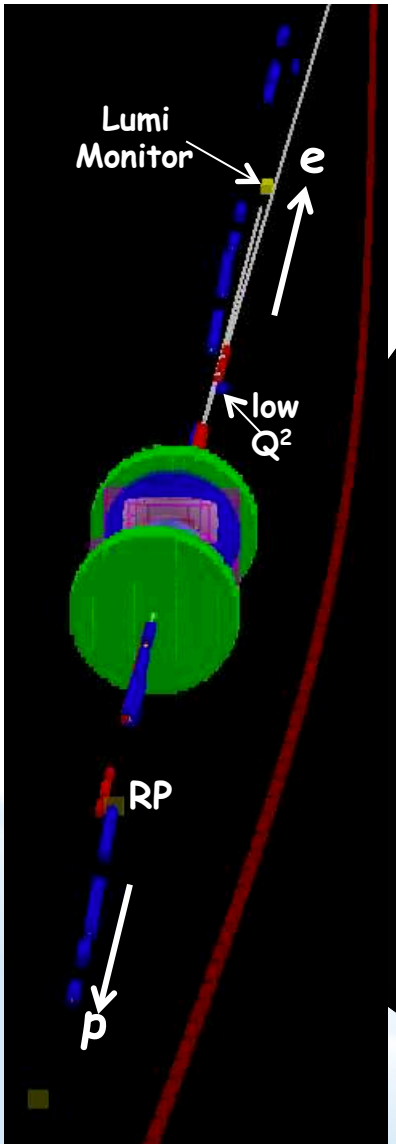
  10 σ_y = 1.6 cm



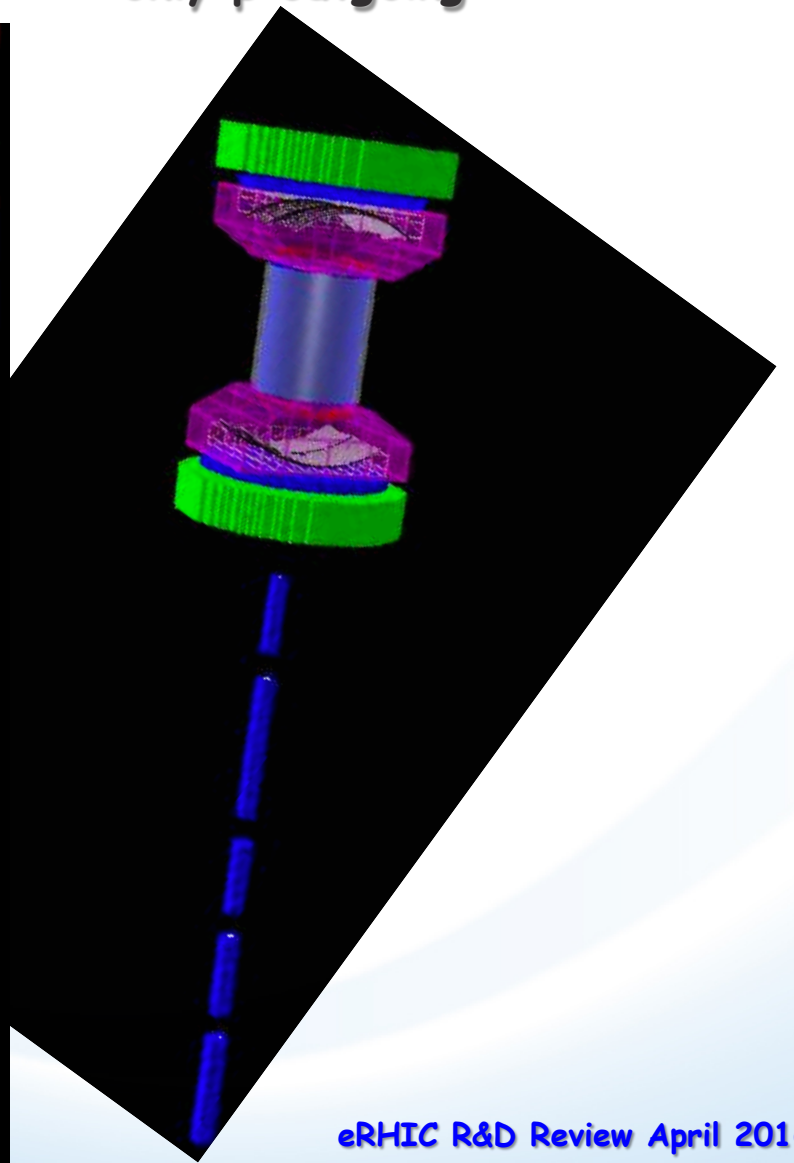
GEANT SIMULATIONS OF DIFFERENT IR-DESIGNS

Linac-Ring

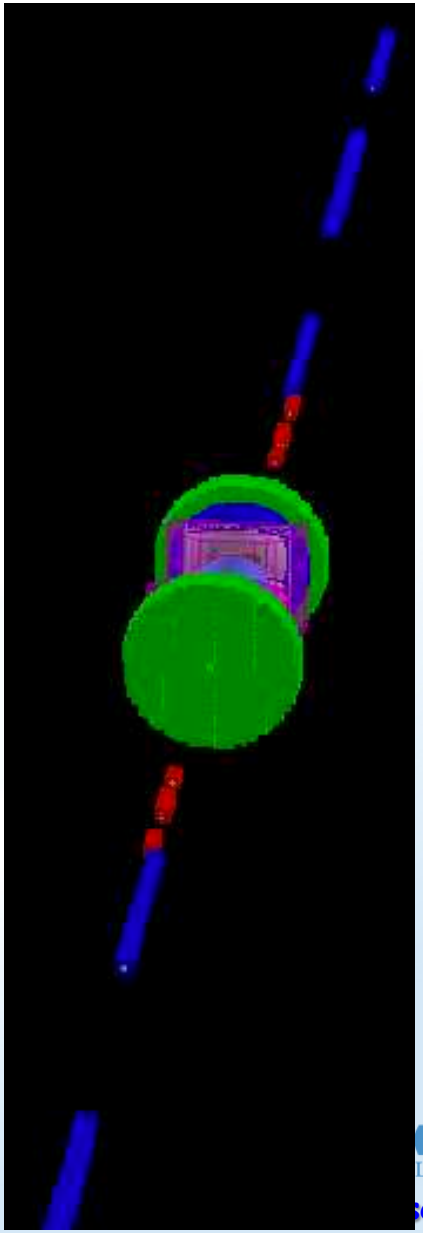
V2.1
most complete



V3.0
only p outgoing

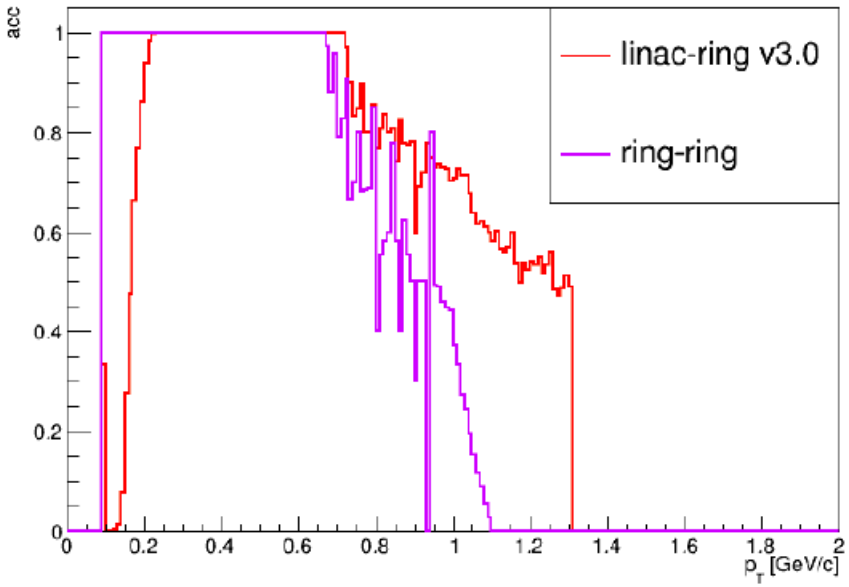


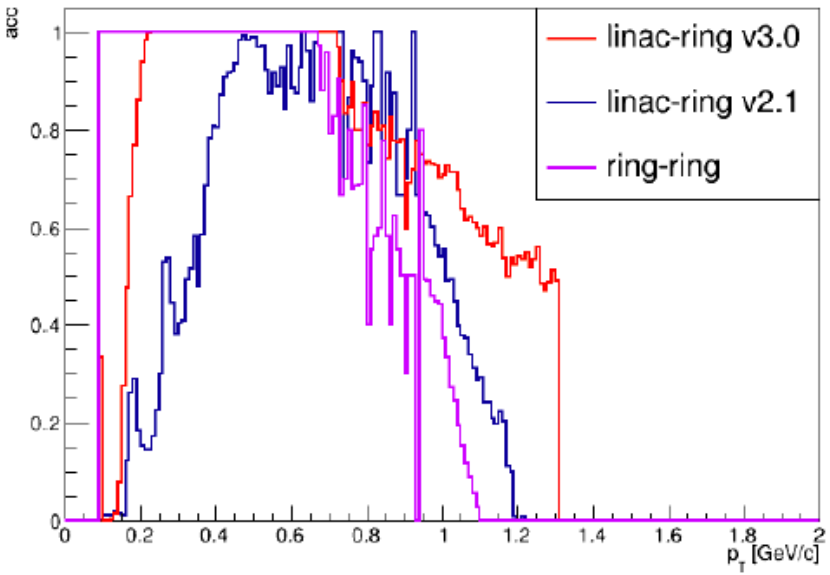
Ring-Ring



ACCEPTANCE FOR FORWARD GOING PROTONS

Ring-Ring and Linac-Ring Comparison 20 GeV x 250 GeV:

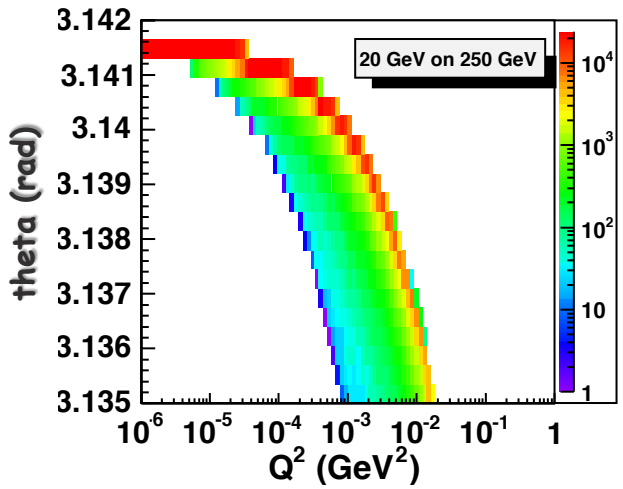


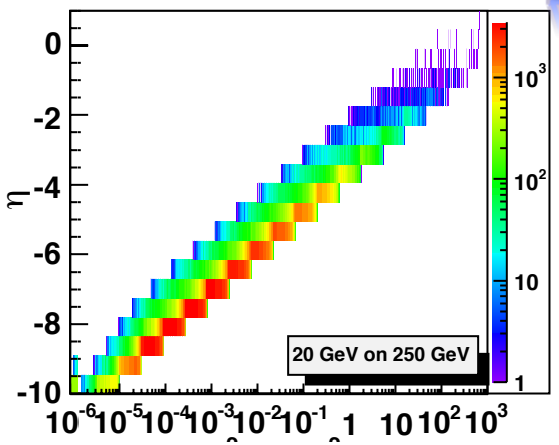


linac-ring v3.0 has a nice acceptance for forward going protons and neutrons

Low Q^2 tagger
Luminosity Detector

LOW Q2-TAGGER



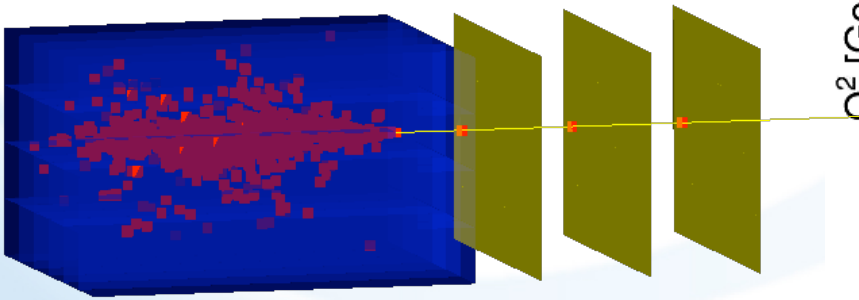


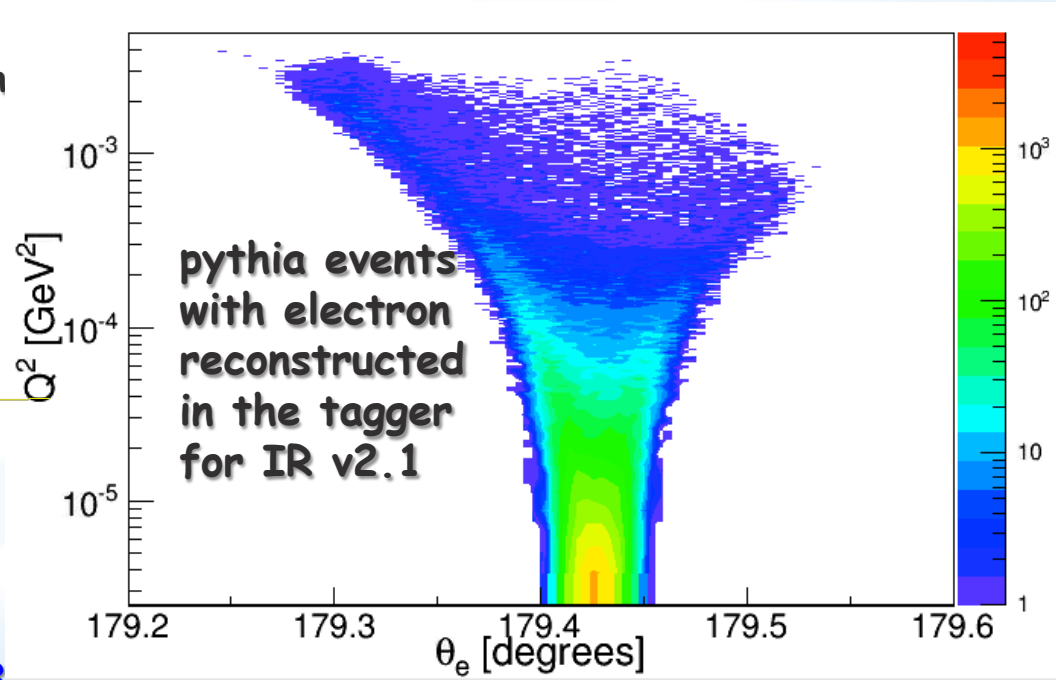
lepton beam energy

scattered lepton more and more at $-\eta$

- → main detector: $-4.5 < \eta < 4.5$
- → $\eta < -4.5$: scattered lepton needs to be detected in dedicated low-Q^2 tagger
- → kinematic coverage in Q^2-x-η critical for physics
- → low Q^2 physics:
  - → (un)polarised photon structure
  - → constrain internal radiative correction
  - → .....

Calorimeter with tracking planes





REQUIREMENTS: POLARIZATION AND LUMINOSITY MEASUREMENTS

Need high beam polarization → statistical uncertainty of spin asymmetries $\delta A_{LL} \sim \frac{1}{P_e P_p \sqrt{L_{\text{int}}}}$

→ electron beam polarization: 0.8 hadron beam polarization: 0.7

Dominant systematics for double spin asymmetries:

Luminosity Measurement → Relative Luminosity

$$A_{LL} = \frac{1}{P_e P_p}\left(\frac{N^{++/--} - R N^{+-/-+}}{N^{++/--} + R N^{+-/-+}}\right); \text{ with } \underbrace{R = \frac{L^{++/--}}{L^{+-/-+}}}_{\text{relative luminosity}}$$

→ R needs to be controlled better then A_{LL}~10^{-4} at low x → RHIC: 2.-4.x10^{-4} @ 500 GeV

→ need to run many different spin patterns to balance L^{++}, L^{--}, L^{+-}, L^{-+}

→ reduce any time dependences

→ RHIC is a perfect example: every bunch can have a different spin orientation

Spin patterns combinations of:

1: +-+--+-++-+- 2: -+-++-+--+-+ 3: ++--++--++-- 4: --++--++--++

→ flexible spin orientation bunch-by-bunch for both lepton and hadron beam

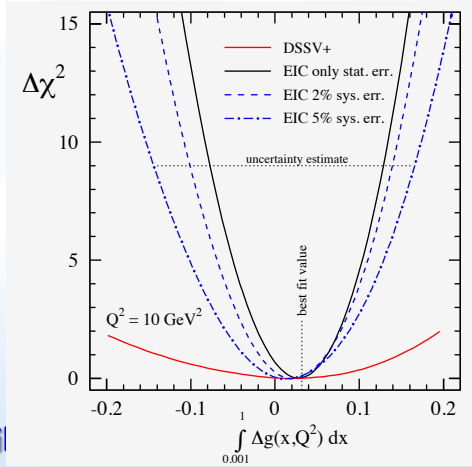
Need also an excellent Luminosity measurement

→ coupling of polarization and luminosity measurement

$$\sigma_{Brems.} = \sigma_o (1 + a P_e P_p)$$

→ Need overall systematics ≤ 2%

arXiv: 1206.6014



LUMINOSITY MEASUREMENT

Concept:

Use Bremsstrahlung ep → epγ as reference cross section

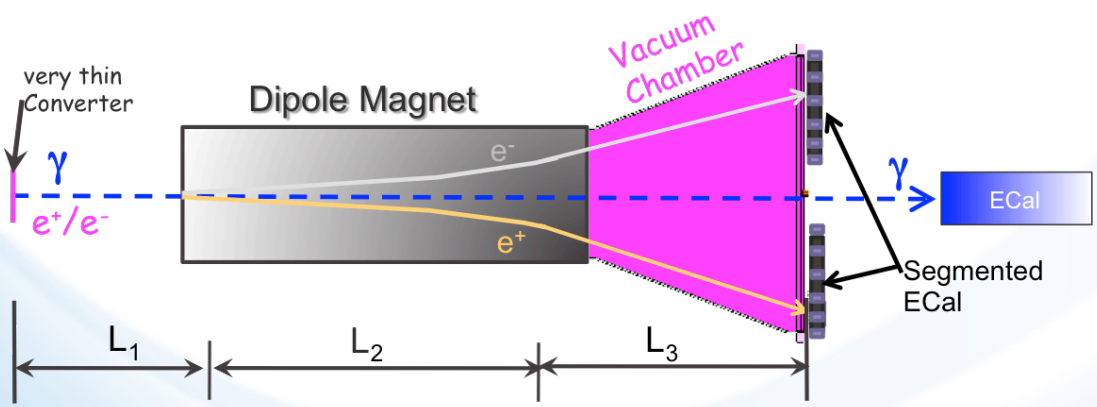
- different methods:
  - Bethe Heitler, QED Compton, Pair Production
- Hera: reached 1-2% systematic uncertainty

Goals for Luminosity Measurement:

- Integrated luminosity with precision $\delta L/L < 1\%$
- Measurement of relative luminosity: physics-asymmetry/10 → $\sim 10^{-4} - 10^{-5}$

EIC challenges:

- with 10^{33} $cm^{-2}s^{-1}$ one gets on average
  23 bremsstrahlungs photons/bunch for proton beam
  → A-beam Z^2-dependence
- this will challenge single photon measurement under 0°



zero degree photon calorimeter

high rate

- measured energy proportional to # photons
- subject to synchrotron radiation

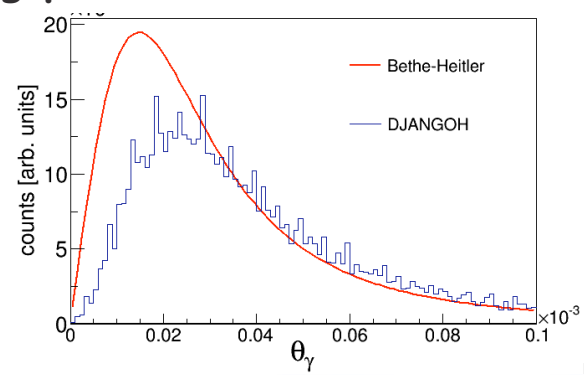
additional pair spectrometer

low rate

- The calorimeters are outside of the primary synchrotron radiation fan
- The spectrometer geometry
  → low energy cutoff in the photon spectrum,
  → depends on dipole field and calorimeter transverse location

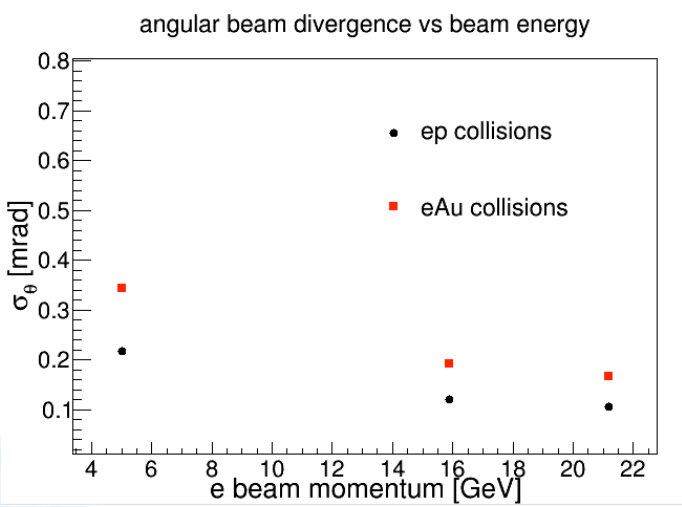
LUMINOSITY MONITOR STUDY

- The expected angular distribution of Bremsstrahlung photons
  - Bethe-Heitler calculation $\frac{d\sigma}{d\Theta_\gamma} \approx \frac{\Theta_\gamma}{\left((m_e/E_e)^2 + \Theta_\gamma^2\right)^2}$
  - typical angle emission less than 0.03 mrad though there is a fairly long tail to the distribution
  - → what is the beam divergence contribution 0.1 mrad for 20 GeV x 250 GeV



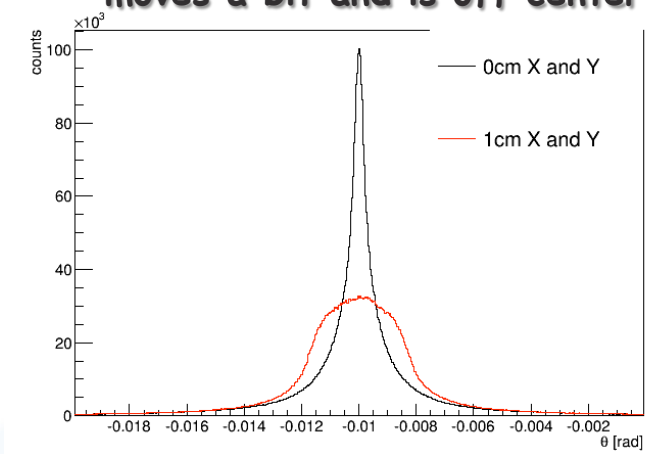
$$\sigma_\theta = \sqrt{\frac{\varepsilon}{\beta^* \gamma}}$$

σ_θ = angular beam divergence
ε = (normalized) emittance
γ = lorentz factor
β^* = beam optics parameter at IP



Large contribution:
critical to be considered in the design

considering the added effect if the IP moves a bit and is off center



both curves include crossing angle and angular beam divergence and a flat z vertex spread of +/- 2.5cm
→ black has all events at (0,0) (x,y) vertex
→ red has events with (x,y) vertex distributed flat with +/- 0.5 cm

Hadron and Electron Polarimeters

EIC HADRON POLARIMETRY

Polarized hydrogen Jet Polarimeter (HJet)

- Source of absolute polarization (normalization for other polarimeters)
- Slow (low rates ⇒ needs looong time to get precise measure

Proton-Carbon Polarimeter

- Very fast

All the equipment used since many years at RHIC

eRHIC:

same equipment needed to measure polarization

but with improved performance

need polarimeters for polarized He-3 beam

Local

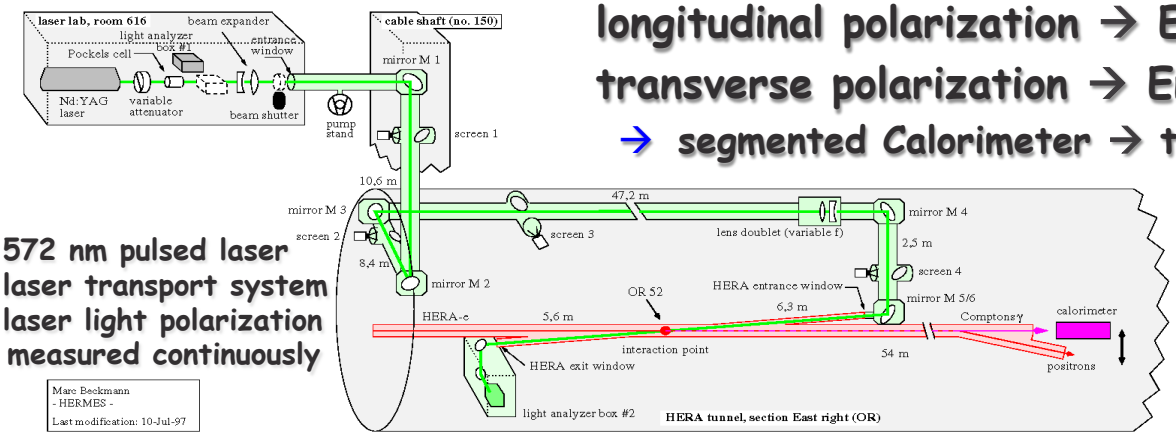
- sit spin rotators
- Critical to define spin direction at experiments
- → can use the concept of pC
- → asymmetry vanishes for longitudinal polarisation

All of these systems are necessary for the hadron beam polarization measurements and monitoring

ELECTRON POLARIMETER

$$A_{exp} = P_e P_\gamma A_\ell$$

- Method: Compton backscattering
  longitudinal polarization → Energy asymmetry
  transverse polarization → Energy dependent position asym.
  → segmented Calorimeter → to measure both components

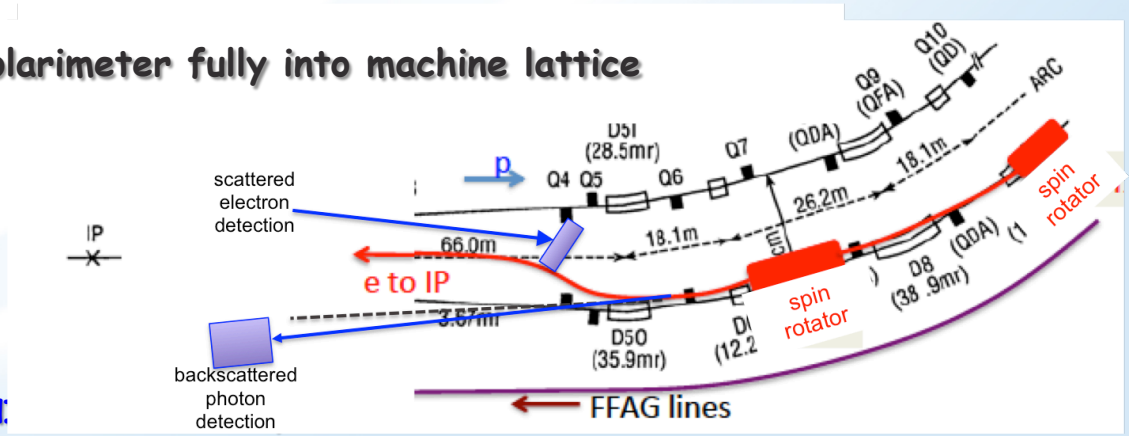


- 572 nm pulsed laser
- laser transport system
- laser light polarization measured continuously

HERA LPol:
achieved systematic uncertainty 1.4%

Considerations:

- Measure Polarization as close to IP as possible
  → location should have bremsstrahlungs and synchrotron radiation contamination minimized
- Polarimeter needs to measure both longitudinal and transverse component
  → important for systematics
- Polarimeter technology needs to allow to have precise polarisation measurements as function of all depolarizing effects,
  → feedback to collider
  → requires to integrate electron polarimeter fully into machine lattice



SUMMARY

- Requirements for detector and IR clearly defined and documented in different documents and actively maintained web-pages
- We [illegible] in and au[illegible]ry

	Hadron	Lepton
Polarization	0.7	0.8
Bunch spin orientation	flexible from bunch to bunch	flexible from bunch to bunch
scattered neutron acc.	+/- 4 mrad	
scattered proton acc.	+/- 5 mrad @ 250 GeV $0.18 < p_t$ (GeV) < 1.3	
Machine free region	+/- 4.5 m for detector	
Luminosity	$> 10^{33}$ cm^{-2}s^{-1}	
Luminosity monitor acc.		+/- 1-2 mrad $\delta L/L < 1\%$
Relative Luminosity	$L^{++/--}/L^{+-/-+} \sim 10^{-4}$ to 10^{-5}	
wide kinematic range	$\sqrt{s}$: 45 (30) to 140 GeV	
wide range of nuclei	p to Uranium	

BACKUP

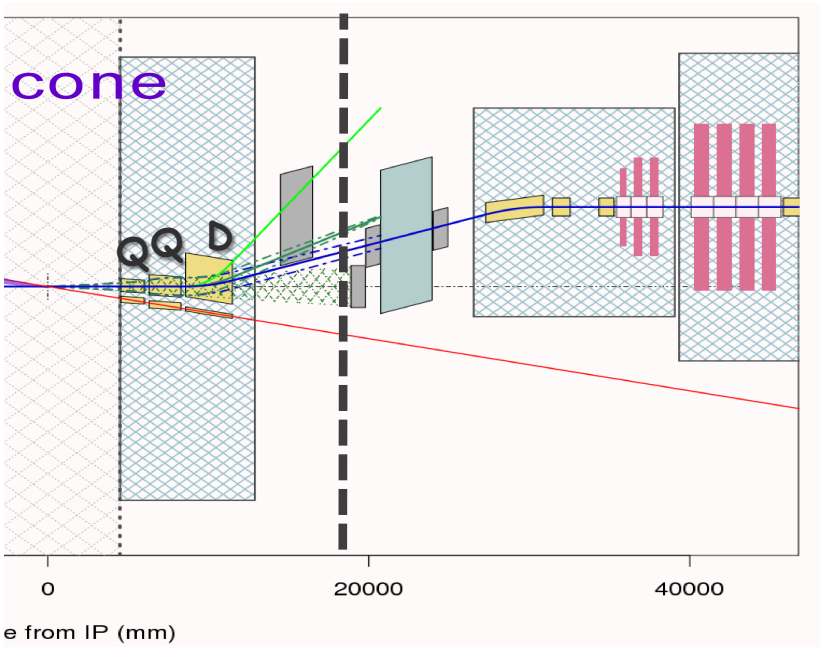
EXPERIMENTAL IMPACT SUMMARY FOR DIPOLE-IR

- A standard DIS detector design is impossible with scenario 3, the impacts on realizing the physics program described in [2].
- The DID design impacts the possible technology choices for the main tracker and the particle ID. To have not all technologies available increases the risk of the detector to reach the performance needed for the physics program. As example not having PID at small momenta is exactly the kinematic regime where saturation is studied. In general compromising on PID impacts all SIDIS measurements planned for ep and eA physics at an EIC. To not have the possibility to have a TPC as central tracker will significantly compromise the material budget in the detector as any other solution providing comparable momentum resolutions will have more material. More material will automatically lead to a worse scattered lepton reconstruction and therefore the event kinematics.
- The large size of the synchrotron radiation fan through the detector does impact how close the μ-vertex tracker can go to the IR. The coverage will be asymmetric, as the fan has different dimensions in y than x.
- All low Q2 (Q2 < 0.1 GeV2) physics will become impossible having no low Q2 tagger. It is absolutely critical to make sure the synchrotron radiation does not prevent a luminosity measurement with < 1% systematic uncertainty.

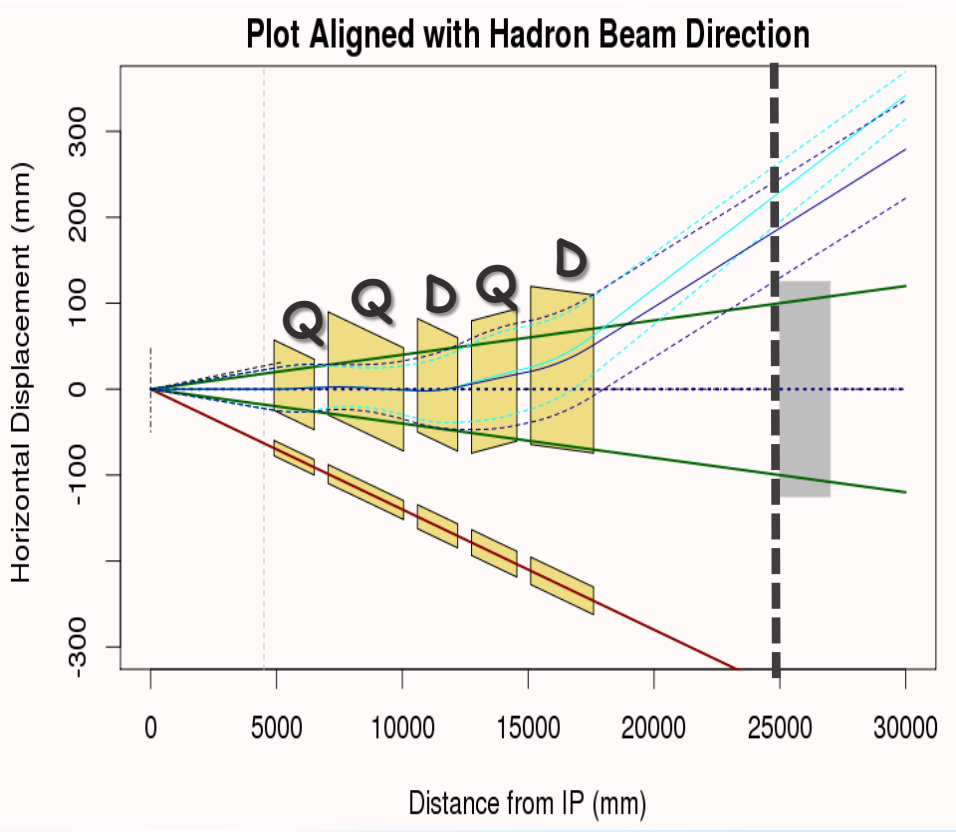
For Details see:
https://www.dropbox.com/s/q70yjruetsxxchc/SepDipoleWriteup.v5.pdf?dl=0

LINAC-RING LAYOUT

v2.1



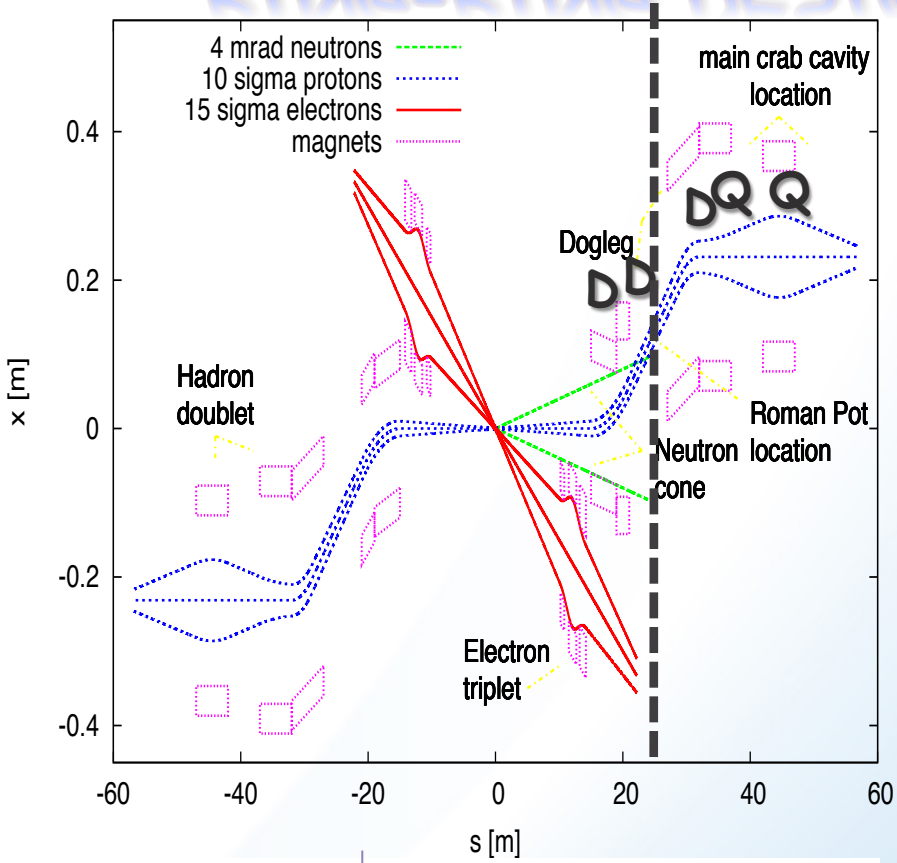
v3.0

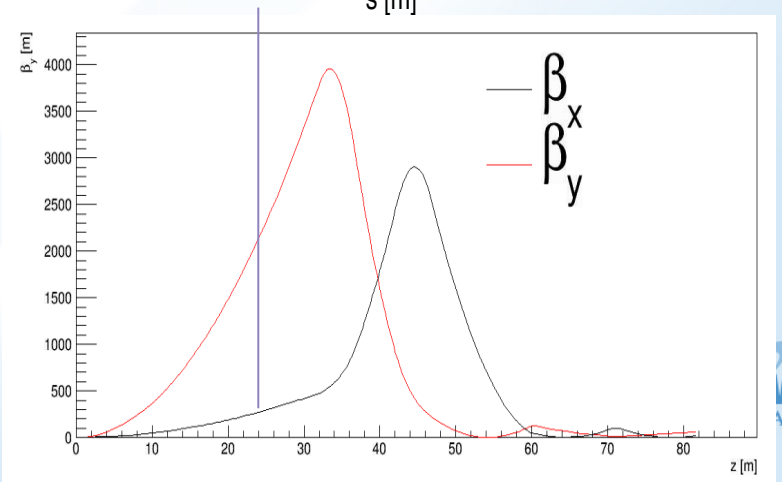


BROOKHAVEN NATIONAL LABORATORY

RING-RING DESIGN

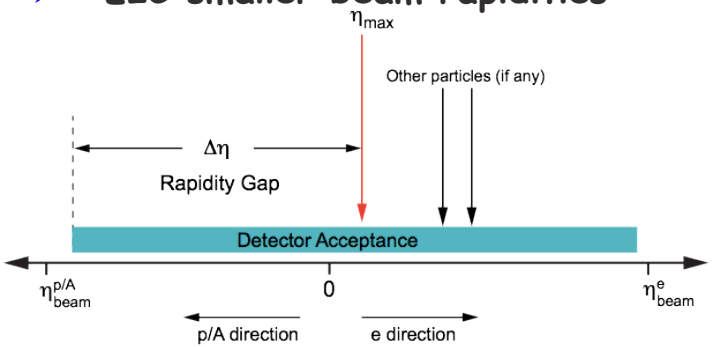
- Design by Christoph Montag
- One notable difference is that the hadron magnets are pushed back much farther from the IP (at ~15m compared to ~5m in linac-ring)
- Also beta function is much smaller in the location of the roman pots for this design
- Robert Palmer working on alternative design



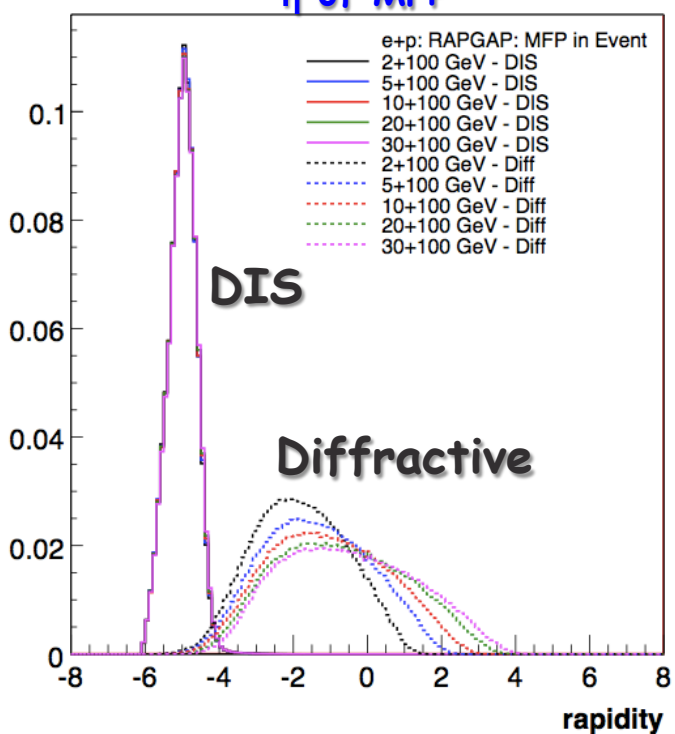


LARGE RAPIDITY GAP METHOD

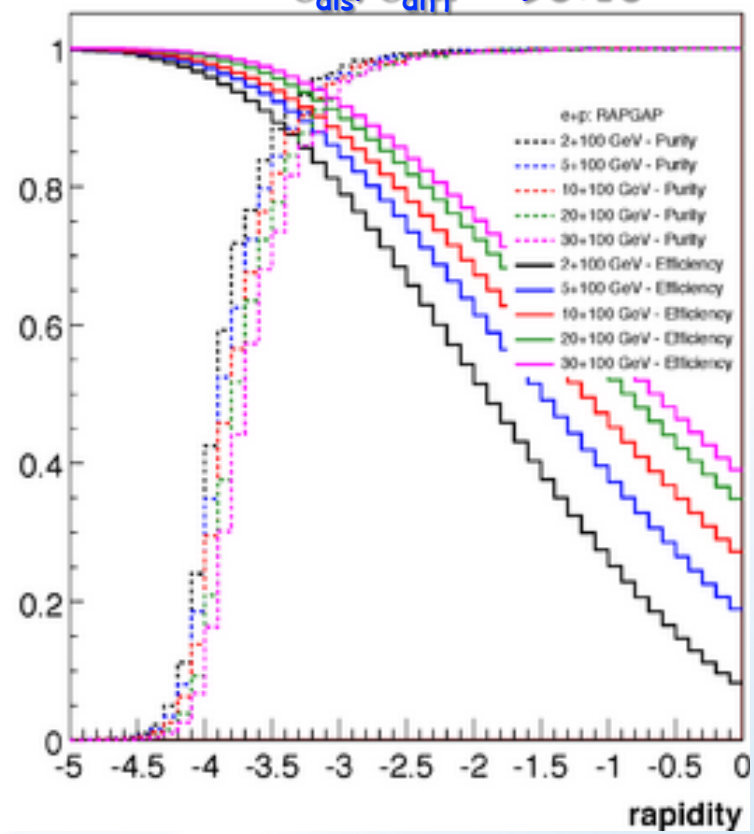
- Identify **Most Forward Going Particle (MFP)**
  - Works at HERA but at higher √s
  - EIC smaller beam rapidities



Diffractive ρ^0 production at EIC: η of MFP



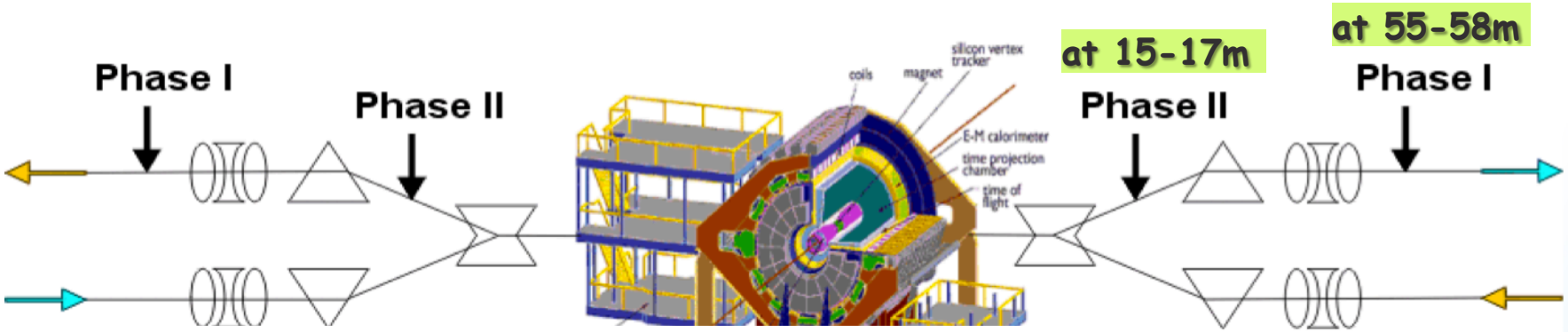
$\sigma_{dis}/\sigma_{diff}$ = 90:10

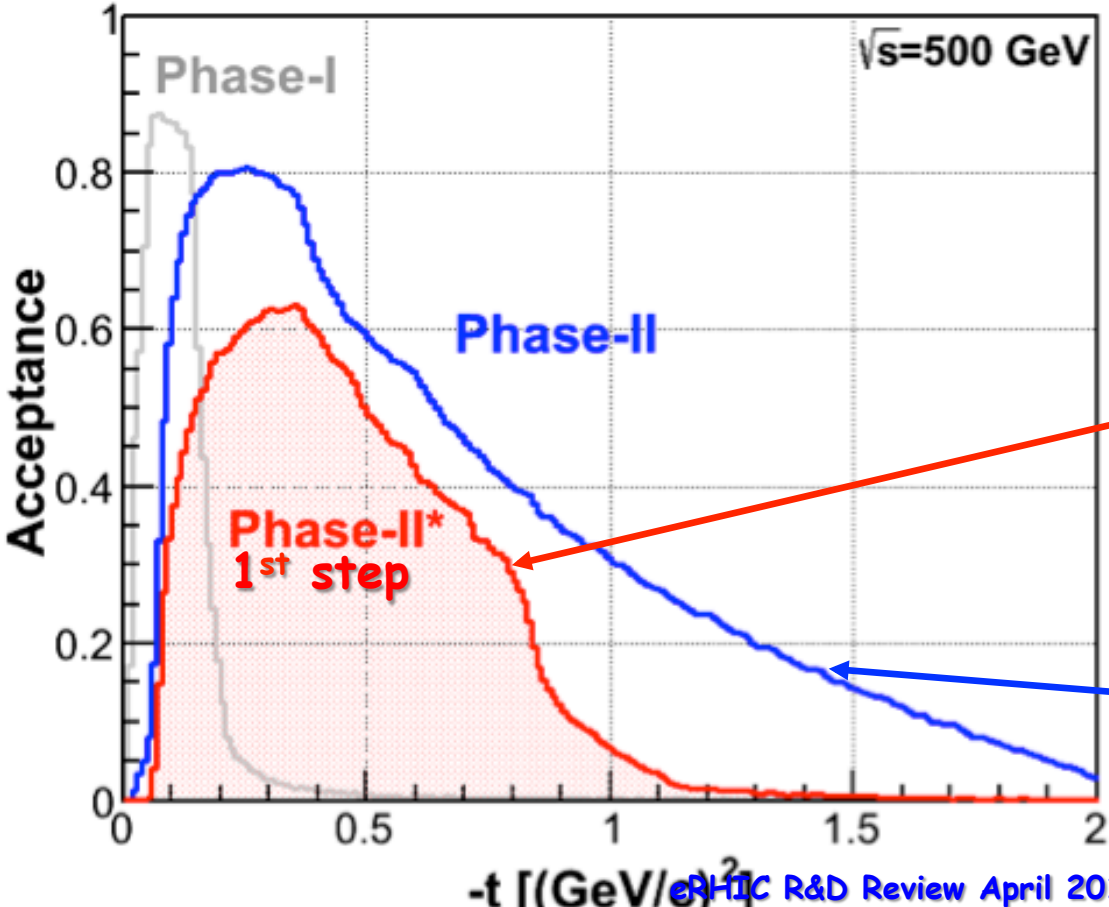


Hermeticity requirement:

- needs just detector to be present → $-4 < \eta < 2$
- does not need momentum or PID
- simulations: no show stopper for EIC √s
  (can achieve <10% contamination, 90% efficiency)

STAR RPs IN RHIC

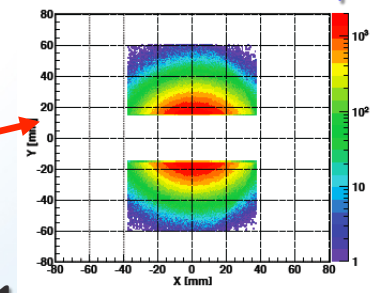




run pp2pp@STAR with

ny more

Phase-II: 1st step



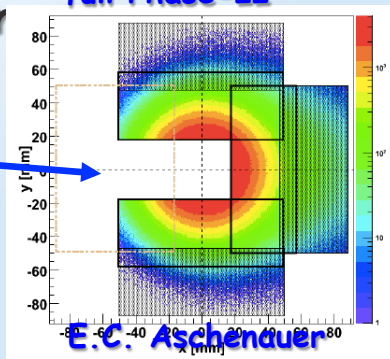
Run-2015+2017)

n x-direction

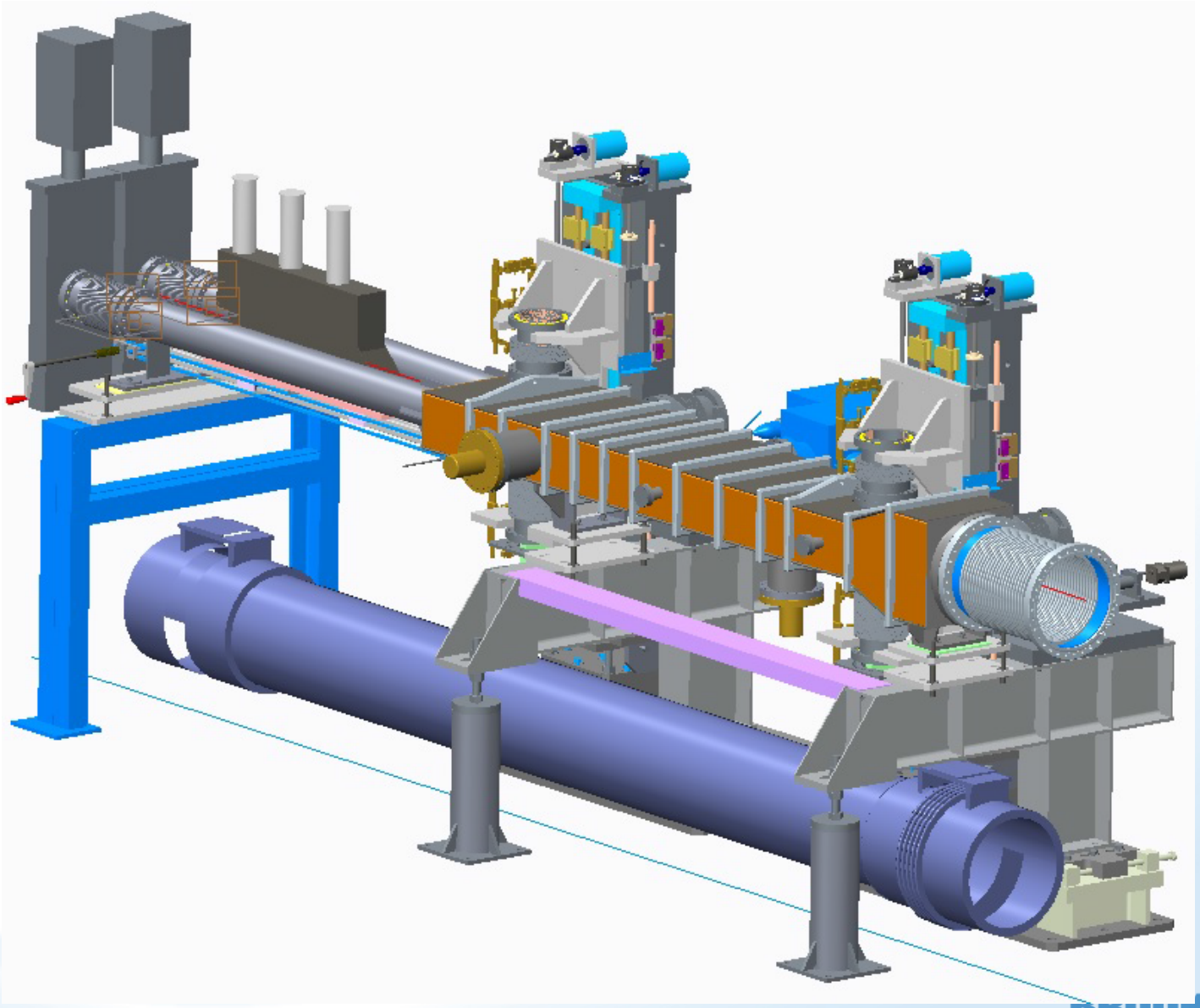
nstraints

protons

full Phase-II



STAR RPs IN RHIC

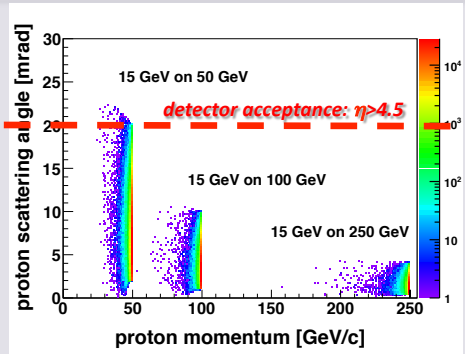


EXCLUSIVE REACTIONS

two methods: to select events

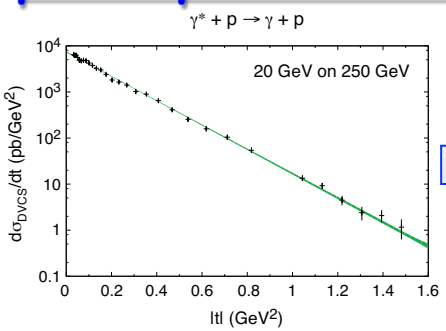
proton/neutron tag method

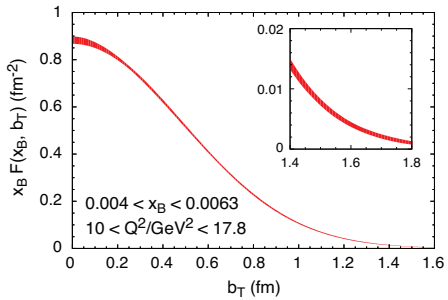
- Measurement of t
- Free of p-diss background
- Higher M_X range
- to have high acceptance for Roman Pots / ZDC challenging → IR design



Need for Roman Pots (RP) and Zero Degree Calorimeter (ZDC)

p' acceptance critical:

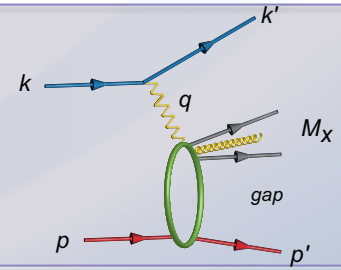




- t (~p_t^2) reach influences b_T uncertainty
  t_{min}~ 0.175 GeV² → 300 GeV² $\delta F/F$ > 50%

Large Rapidiy Gap method

- M_X system and e' measured
- Proton dissociation background
- High acceptance in η for detector



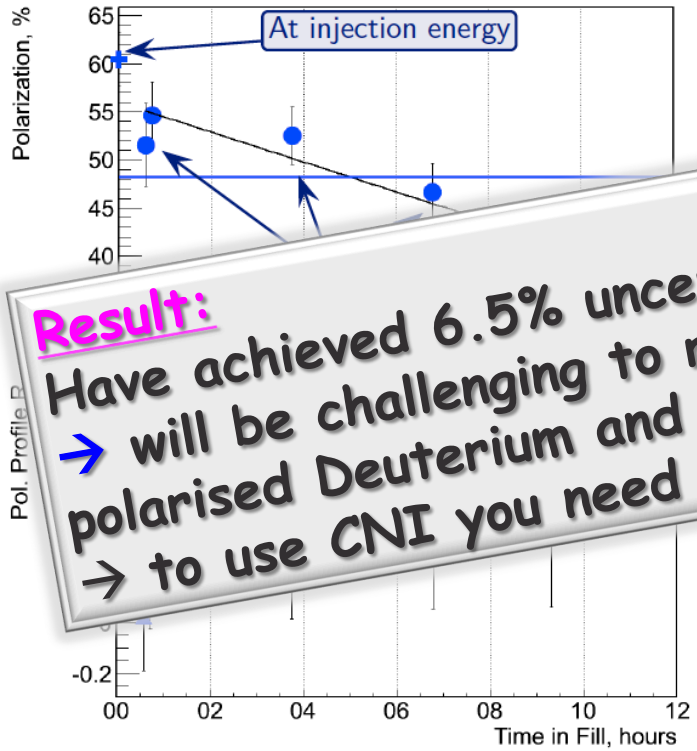
Need for HCal in the forward region

RHIC HADRON POLARISATION

Account for
beam polarization decay through fill → $P(t)=P_0\exp(-t/\tau_p)$
growth of beam polarization profile R through fill

pCarbon polarimeter

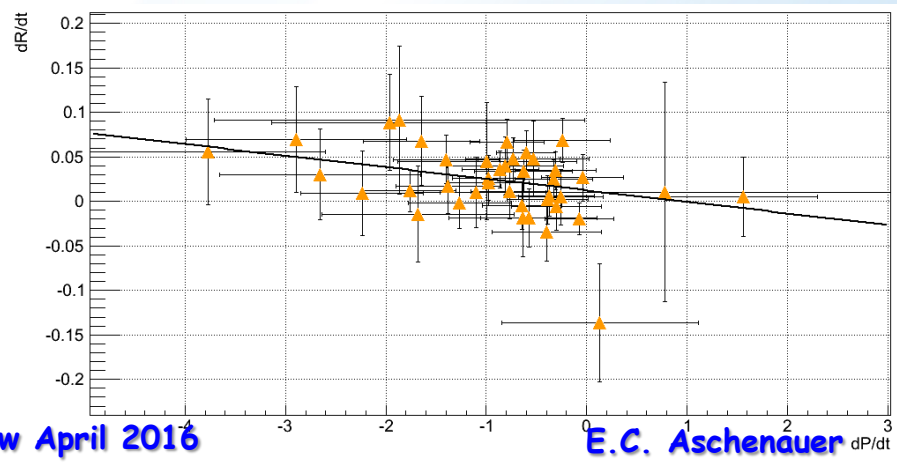
Collider



Result:
Have achieved 6.5% uncertainty for DSA and 3.4 for SSA
→ will be challenging to reduce to 1-2%
polarised Deuterium and He-3 polarimetry will be challenging
→ to use CNI you need to make sure D and He-3 does not break up

$$R = \frac{\sigma_I^2}{\sigma_P^2}$$

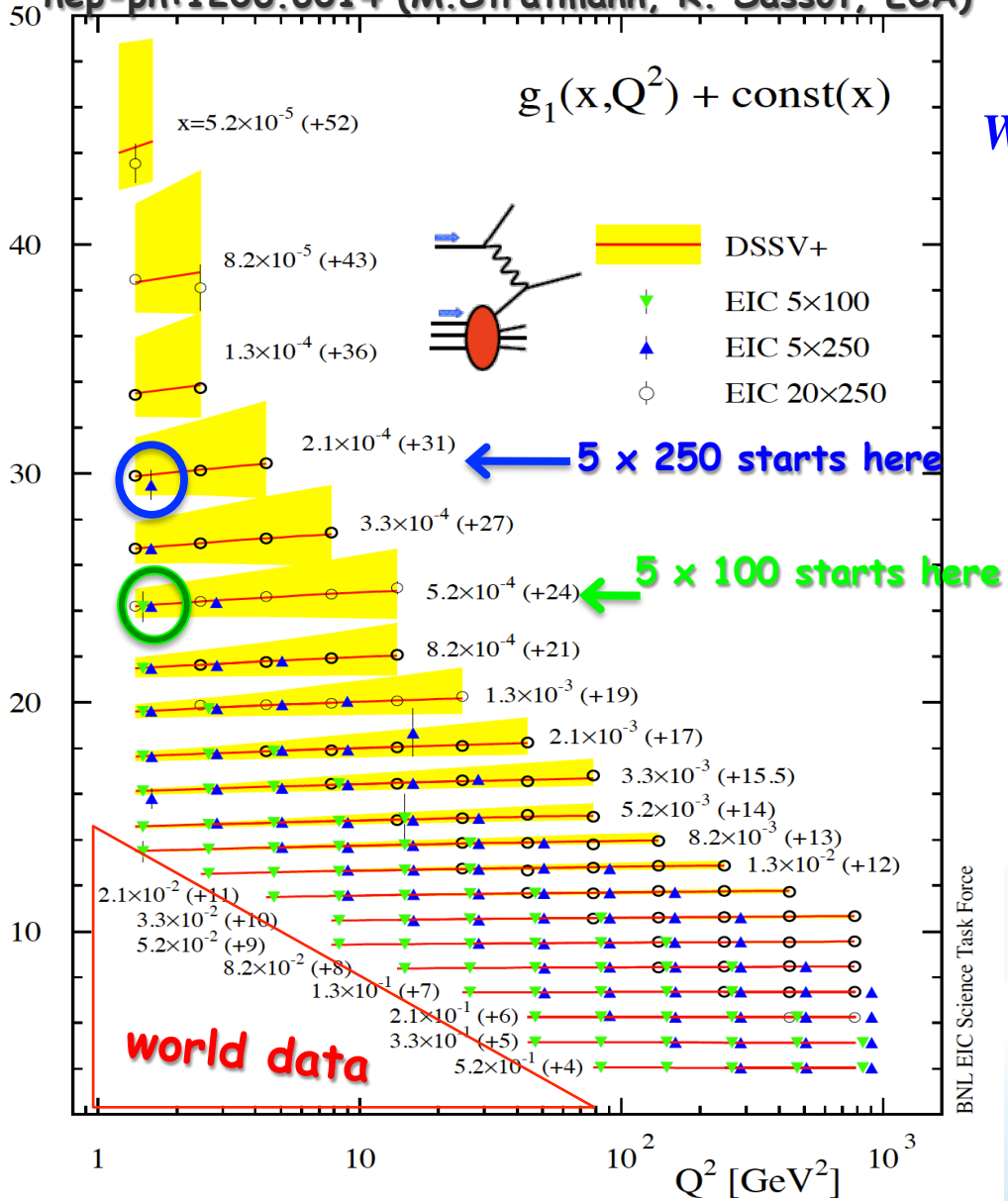
all 2012 fills
at 250 GeV



Polarization lifetime has consequences for physics analysis
→ different physics triggers mix over fill
→ different <P>

g_1^p THE WAY TO FIND THE SPIN

hep-ph:1206.6014 (M.Stratmann, R. Sassot, ECA)



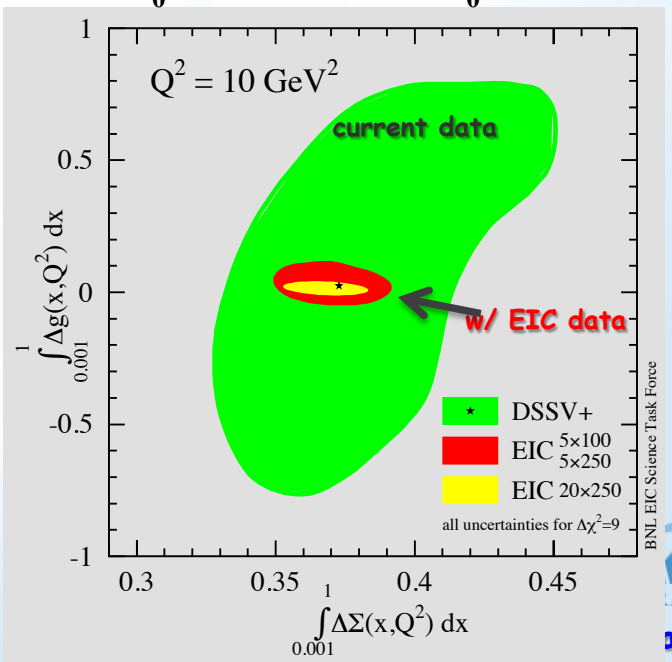
cross section: $\frac{d^2\sigma}{d\Omega dE'} \sim L_{\mu\nu} W^{\mu\nu}$

$$W^{\mu\nu} = -g^{\mu\nu} F_1 - \frac{p^\mu p^\nu}{\nu} F_2 + \frac{i}{\nu}\varepsilon^{\mu\nu\lambda\sigma} q^\lambda s^\sigma g_1 + \frac{i}{\nu^2}\varepsilon^{\mu\nu\lambda\sigma} q^\lambda \left(p\bullet q s^\sigma - s\bullet q p\sigma\right) g_2$$

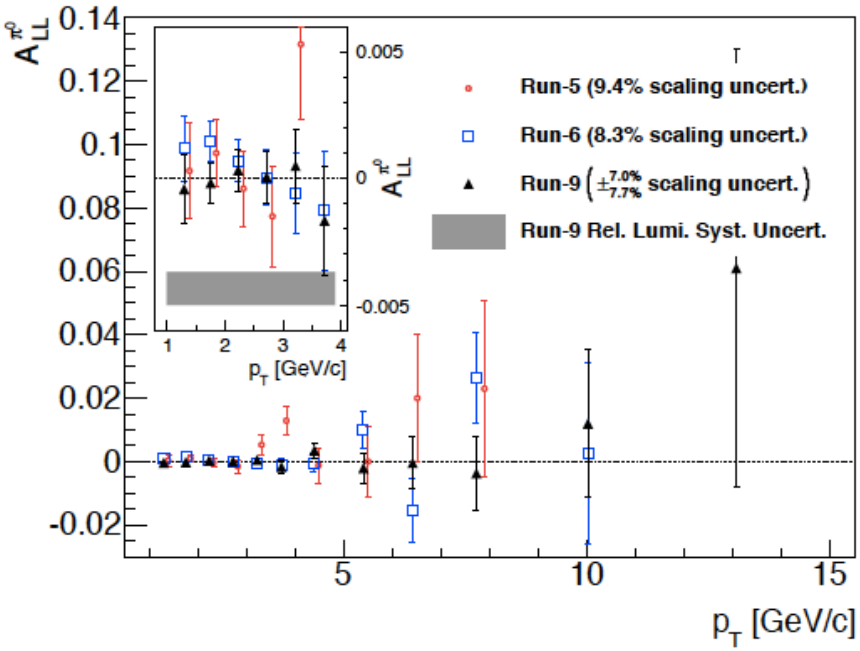
pQCD scaling violations

$$\frac{dg_1}{d\log(Q^2)} \sim -\Delta g(x,Q^2)$$

$$\Delta\Sigma(Q^2) = \int_0^1 g_1(x,Q^2)\,dx = \int_0^1 \Delta q_f(x,Q^2)\,dx$$



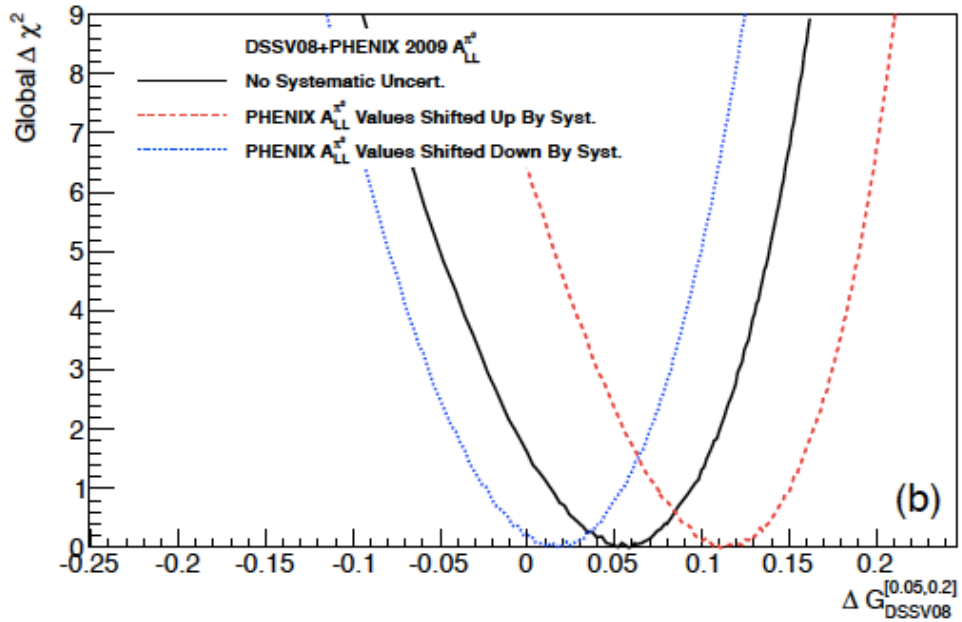
IMPACT ON CORRELATED SYSTEMATIC UNCERTAINTY IN p+p π^0 A_{LL} ON ΔG



arXiv:1402.6296

$$A_{LL} = \frac{1}{P_B P_Y}\left(\frac{N^{++/--} - RN^{+-/-+}}{N^{++/--} + RN^{+-/-+}}\right); \text{ with } \underbrace{R = \frac{L^{++/--}}{L^{+-/-+}}}_{\text{relative luminosity}}$$

2009: Relative Luminosity uncertainty same size as physics asymmetry

$R = 1.18\times10^{-3} + 0.21\times10^{-3}$

$A_{LL} = 0.4 - 4 \times 10^{-3}$