

# eSTAR Lol

*Ernst Sichtermann, LBNL  
for the STAR Collaboration*

$\sim 10^{-10}$  m  
 $\sim$ keV

$\sim 10^{-14}$  m  
 $\sim$ MeV

$\sim 10^{-15}$  m  
 $\sim$ GeV

$< 10^{-18}$  m



# Electron Ion Colliders

Past

Possible Future

	HERA @ DESY	LHeC @ CERN	HIAF @ CAS	ENC @ GSI	MEIC/ELIC @ JLab	eRHIC @ BNL
$\sqrt{s}$ [GeV]	320	800 - 1300	12 - 65	14	20 - 140	78 - 145
proton $x_{min}$	$1 \times 10^{-5}$	$5 \times 10^{-7}$	$7 \times 10^{-3} - 3 \times 10^{-4}$	$5 \times 10^{-3}$	$1 \times 10^{-4}$	$5 \times 10^{-5}$
ion	p	p to Pb	p to U	p to $\sim^{40}\text{Ca}$	p to Pb	p to U
polarization	-	-	p, d, $^3\text{He}$	p, d	p, d, $^3\text{He}$ ( $^6\text{Li}$ )	p, $^3\text{He}$
L [ $\text{cm}^{-2}\text{s}^{-1}$ ]	$2 \times 10^{31}$	$10^{34}$	$10^{32-33} - 10^{35}$	$10^{32}$	$10^{33-34}$	$10^{33}$
Interaction Points	2	1 (?)	1	1	2+	1-2
Year	1992 - 2007	post ALICE	2019 - 2030	upgrade to FAIR	post 12 GeV	2025

High-Energy Physics

Nuclear Physics

World Wide Interest

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High-Energy Physics

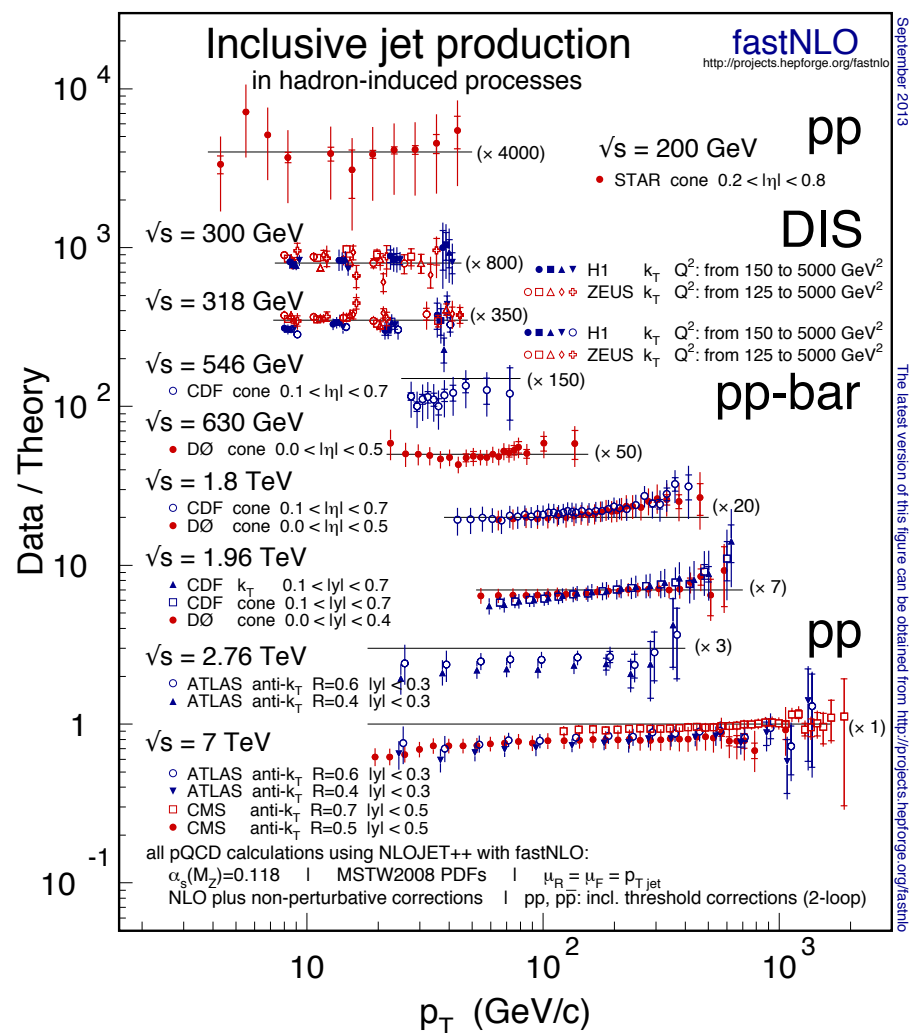
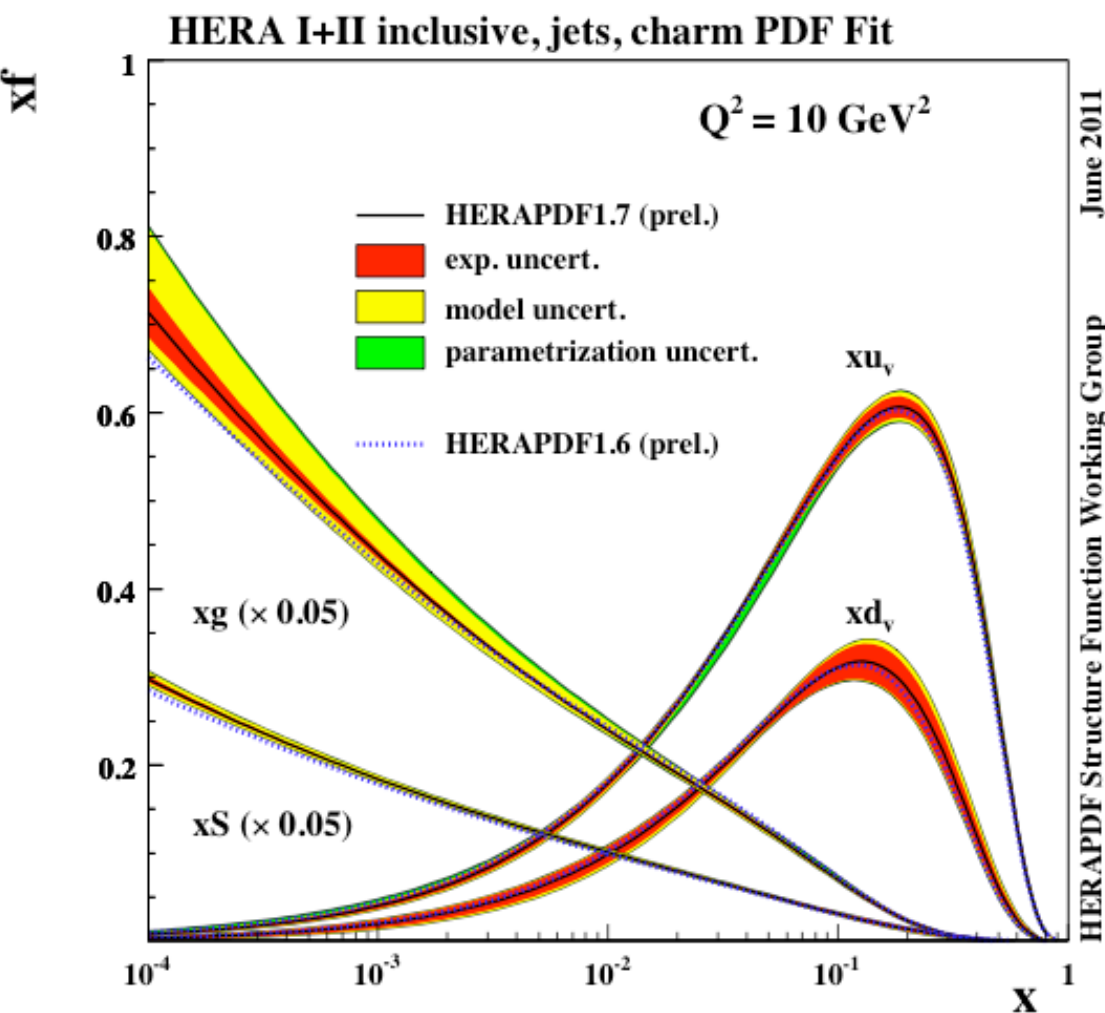
Nuclear Physics

World Wide Interest

# HERA's legacy

The proton in terms of gluons and quarks

pQCD at work...



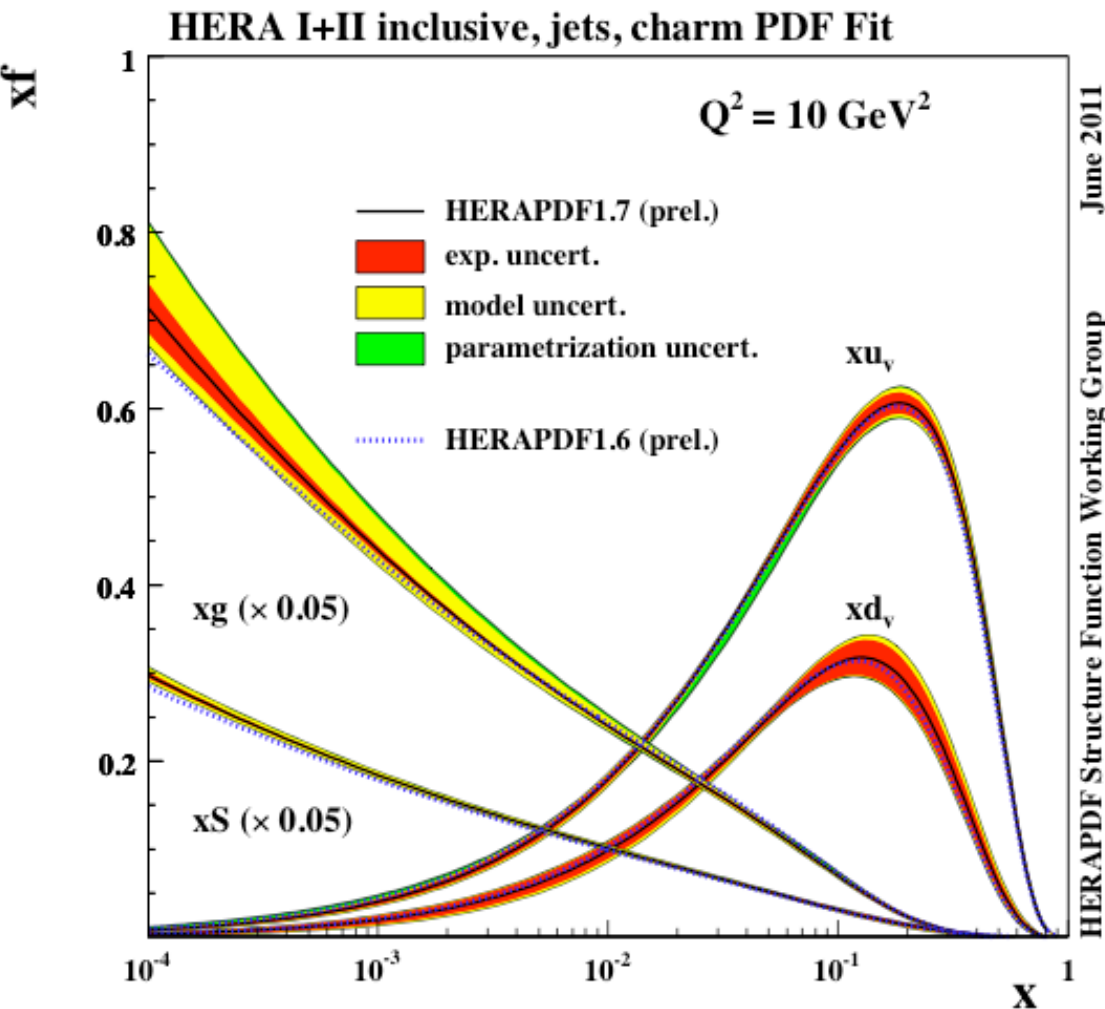


# HERA's legacy

The proton in terms of gluons and quarks

... and quite remarkable voids:

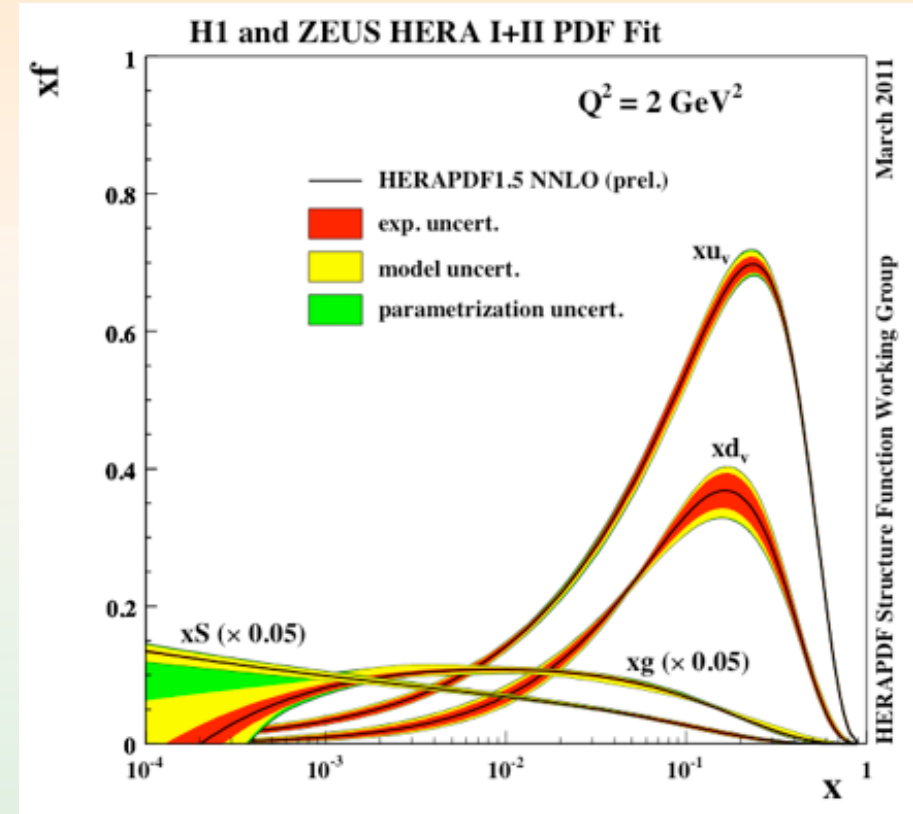
- Precision  $F_L$  - insufficient time,
- Test isospin, u-d, - no deuterons,
- d/u at large  $x$  - luminosity,
- Strange quark distributions - luminosity,
- Spin puzzle - no hadron beam polarization,
- Quark-gluon dynamics in nuclei - no nuclei,
- Saturation - insufficient  $\sqrt{s}$  / no nuclei,
- Fragmentation - limited particle-ID,
- ...



# HERA - RHIC

## Saturation:

- geometric scaling of the cross section,
- diffractive cross-section independent of  $W$  and  $Q^2$ ,
- hints of a negative gluon number distribution (at NLO),
- forward multiplicities and correlations at RHIC,



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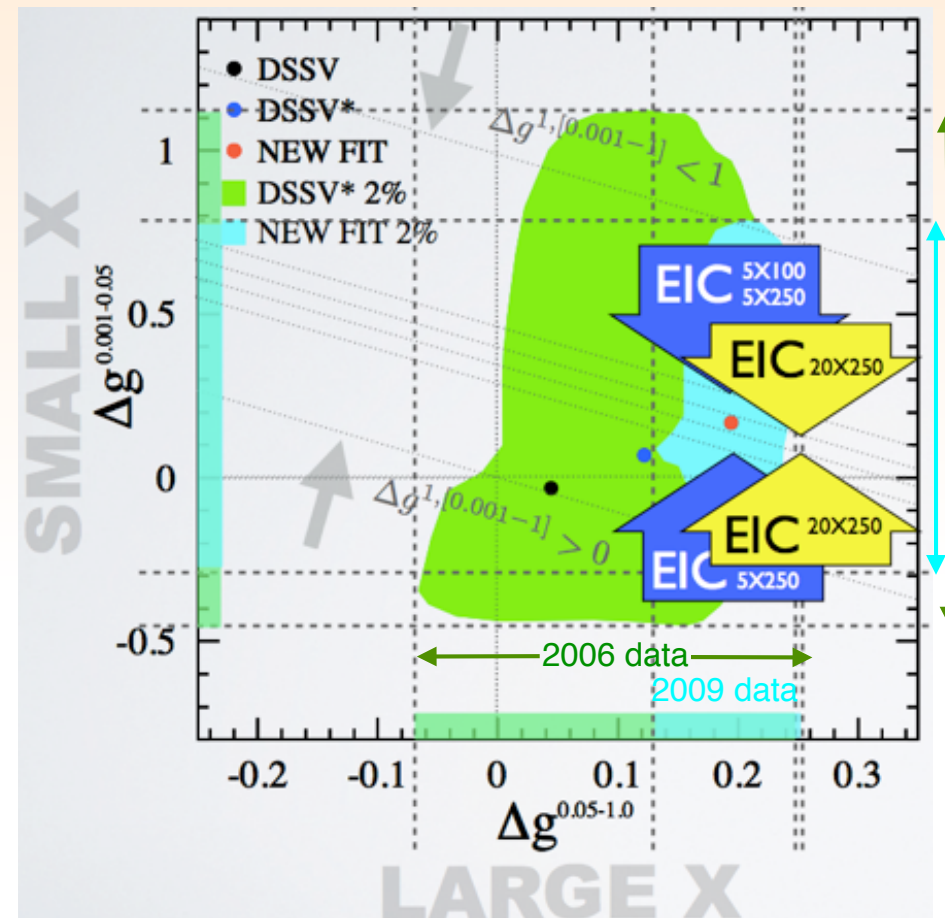
## Spin puzzle:

- defining constraint on  $\Delta G(x)$  for  $x > 0.05$ , smaller  $x$  is terra-icognita,
- fragmentation-free insight in  $\Delta u$ ,  $\Delta d$ ,  $\Delta \bar{u}$ ,  $\Delta \bar{d}$  strange (anti-)quarks?
- large forward transverse-spin phenomena origin?

Mid-term: forward upgrade(s) at RHIC

Longer-term: EIC

Rodolfo Sassot at 2013 Spin Summer Program



# HERA - RHIC, JLab

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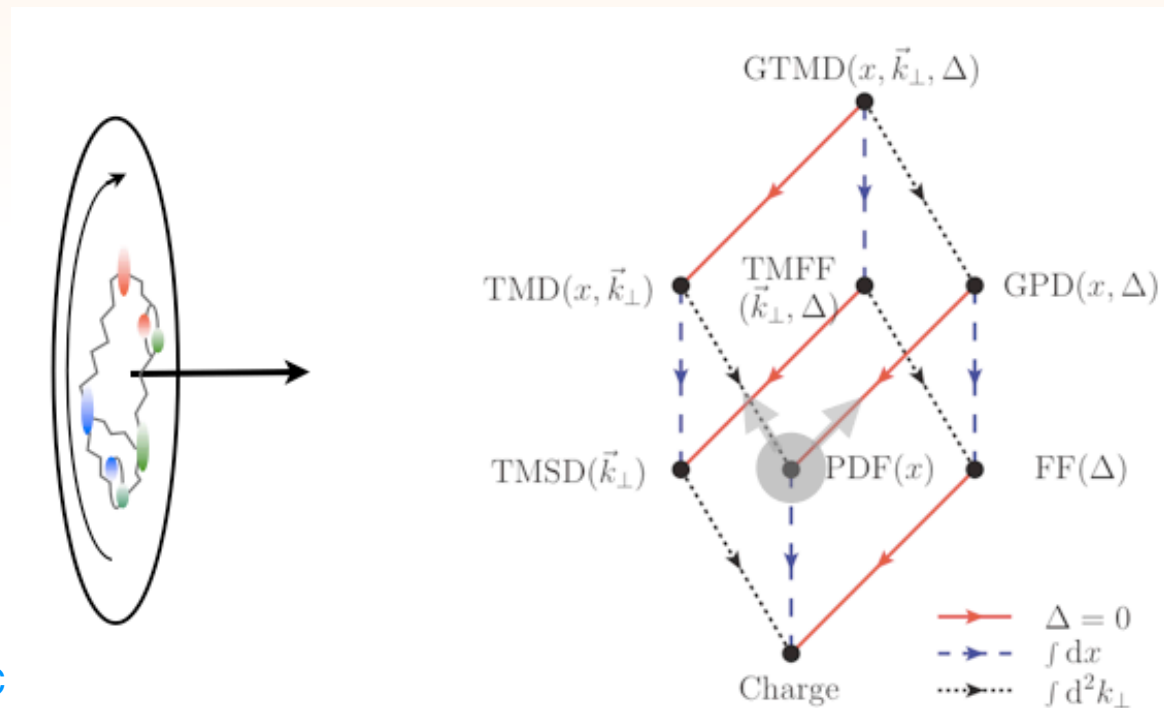
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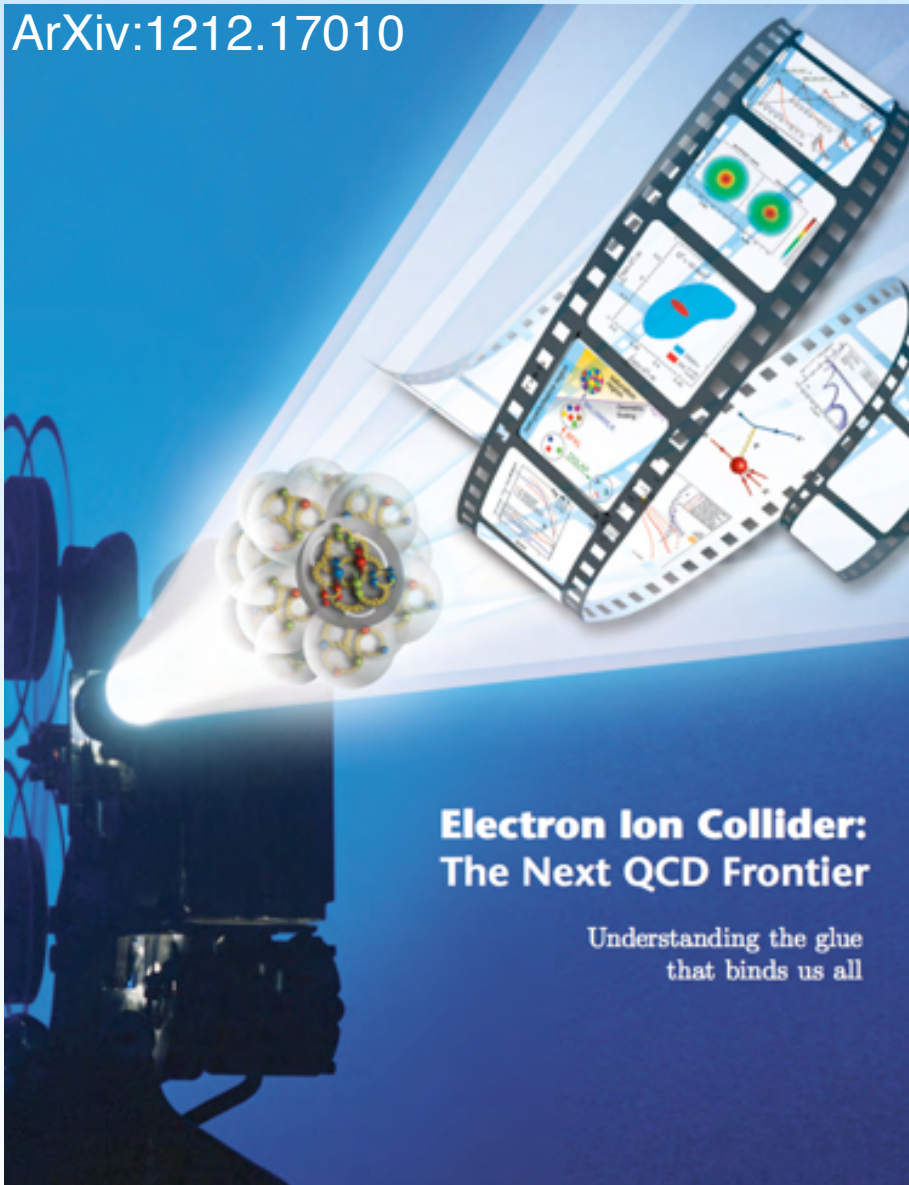
## Imaging / tomography:

- valence quark region at JLab,
- precision insight in the gluon region *requires* EIC



# U.S. EIC Key Science Questions

ArXiv:1212.17010

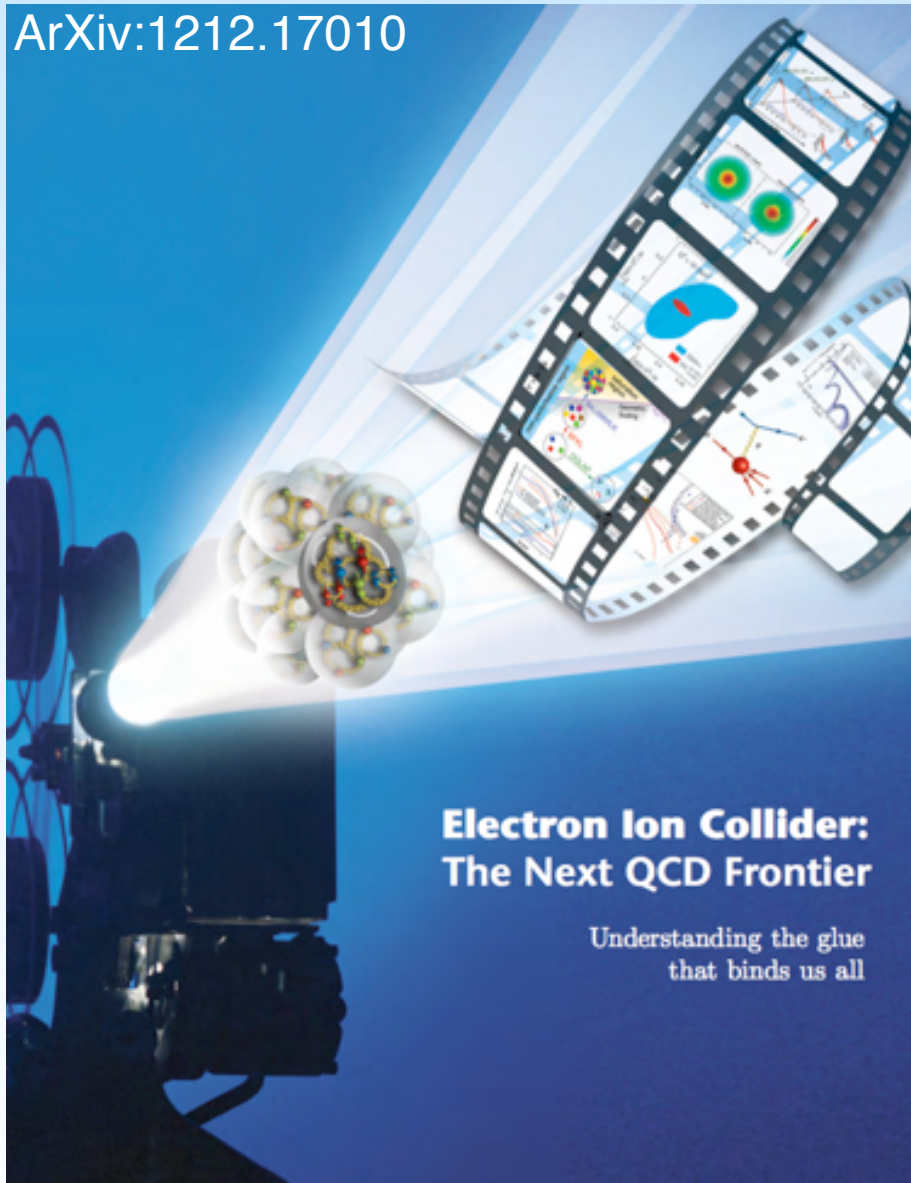


- *How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus?*
- *Where does the saturation of gluon densities set in?*
- *How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?*



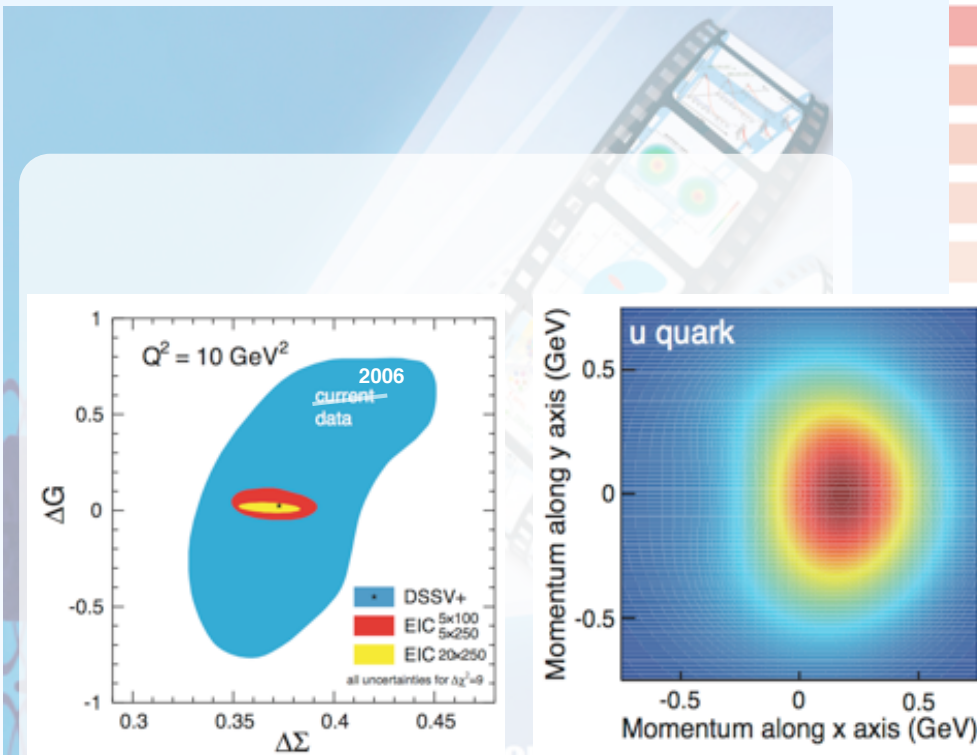
# U.S. EIC Necessary Capabilities

ArXiv:1212.17010



- *A collider to provide kinematic reach well into the gluon dominated regime,*
- *Electron beams provide the unmatched precision of the electromagnetic interaction as a probe,*
- *Polarized nucleon beams to determine the correlations of sea quark and gluon distributions with the nucleon spin,*
- *Heavy Ion beams to access the gluon-saturated regime and as a precise dial to study propagation of color charges in nuclear matter.*

# U.S. EIC Science Case and Measurements



## The Next QCD Frontier

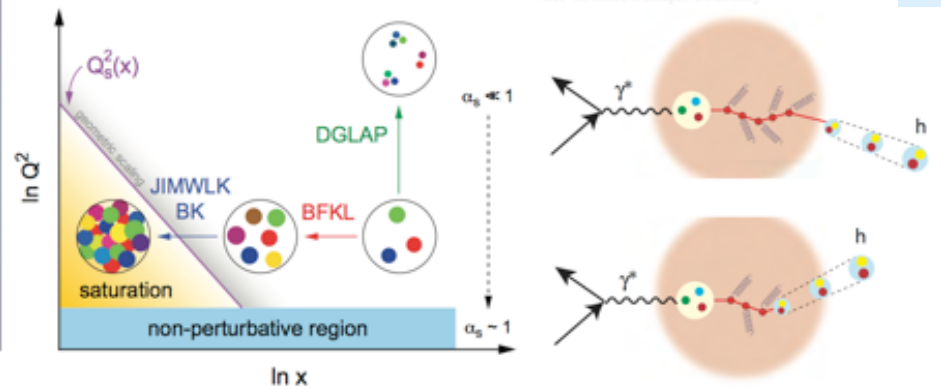
Understanding the glue that binds us all

coherent contributions from many nucleons effectively amplify the gluon density being probed.

The EIC was designated in the 2007 Nuclear Physics Long Range Plan as “embodying the vision for reaching the next QCD frontier” [1]. It would extend the QCD sci-

ence programs in the U.S. established at both the CEBAF accelerator at JLab and RHIC at BNL in dramatic and fundamentally important ways. The most intellectually pressing questions that an EIC will address that relate to our detailed and fundamental understanding of QCD in this frontier environment are:

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?
- Where does the saturation of gluon densities set in? Is there a simple boundary



correlations of sea quark and gluon distributions with the nucleon spin;

- Heavy ion beams are needed to provide precocious access to the regime of saturated gluon densities and offer a precise dial in the study of propagation-length for color charges in nuclear matter.

The EIC would be distinguished from all past, current, and contemplated facilities around the world by being at the intensity frontier with a versatile range of kinematics and beam polarizations, as well as beam species, allowing the above questions to be tackled at one facility. In particular, the EIC design exceeds the capabilities of HERA, the only electron-proton collider

to date, by adding a) polarized proton and heavy-ion beams; b) a wide variety of heavy-ion beams; c) two to three orders of magnitude increase in luminosity to facilitate tomographic imaging; and d) wide energy variability to enhance the sensitivity to gluon distributions. Achieving these challenging technical improvements in a single facility will extend U.S. leadership in accelerator sci-



# U.S. EIC Science Case and Measurements

## Key questions:

- *How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus?*
- *Where does the saturation of gluon densities set in?*
- *How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?*

## Key measurements:

- *Inclusive Deep-Inelastic Scattering,*
- *Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,*
- *Exclusive deep-inelastic scattering,*
- *Diffraction.*

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• How are the quarks and gluons, and their spins, distributed in space and momentum inside the nucleus? How are these quark and gluon distributions correlated with overall nucleus properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nucleus spin?

• Where does the saturation of gluon densities set in? Is there a simple boundary between the perturbative and non-perturbative regimes? If so, how does this saturation produce matter of universal properties in the nucleus and all nuclei viewed at nearly the speed of light?

• How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei? How does the transverse spatial distribution of quarks and gluons affect the distribution of quarks and gluons in the final state? Answers to these questions are essential for understanding the nature of visible matter.

An EIC is the ultimate machine to provide answers to these questions for the following reasons:

• A collider is needed to provide kinematic reach well into the gluon-dominated regime; a fixed-target machine is not sufficient because of the limited energy range of the electromagnetic interaction as a probe.

• Polarized nucleus beams are needed to determine the correlations of sea quark and gluon distributions with the nucleus spin.

• Heavy ion beams are needed to provide precious access to the regime of saturated gluon densities and offer a precise dial in the study of propagation-length for color fields in nuclear matter.

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# U.S. EIC Science Case and Measurements

## Key requirements:

- *Electron identification - scattered lepton*
- *Momentum and angular resolution -  $x, Q^2$*
- *$\pi^+, \pi^-, K^+, K^-, p^+, p^-, \dots$  identification, acceptance*
- *Rapidity coverage,  $t$ -resolution*

## Key measurements:

- *Inclusive Deep-Inelastic Scattering,*
- *Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,*
- *Exclusive deep-inelastic scattering,*
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## Electron Ion Collider: The New QCD Frontier

Understanding the glue that binds us all

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• How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei? How does the transverse spatial distribution of partons in nuclei affect the scattering process? Answers to these questions are essential for understanding the nature of visible matter.

An EIC is the ultimate machine to provide answers to these questions for the following reasons:

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• Polarized nucleon beams are needed to determine the correlations of sea quark and gluon distributions with the nucleon spin;

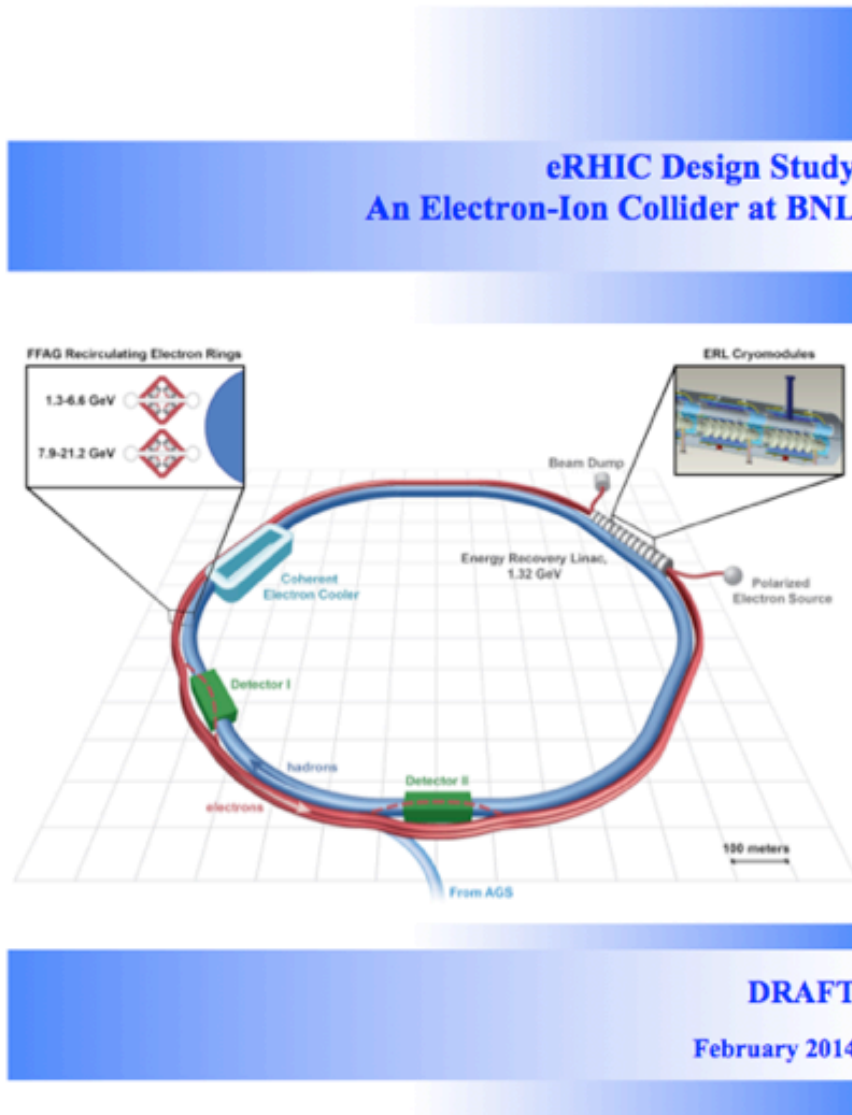
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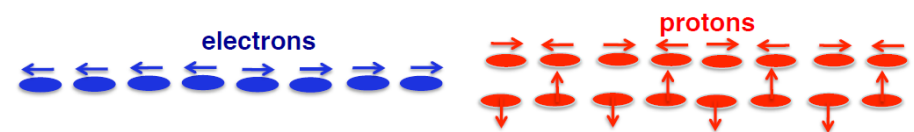
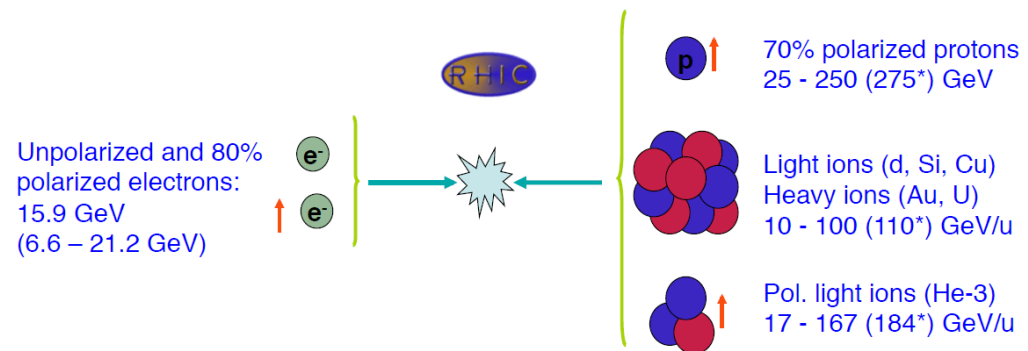
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# eRHIC: EIC at Brookhaven National Laboratory

c.f. Talk by Vadim Ptytsin, Thursday's plenary III



The eRHIC accelerator ... design adds a high-current, multi-pass Energy Recovery Linac (ERL) and electron recirculation rings to the existing RHIC hadron facility:



\* It is possible to increase RHIC ring energy by 10%

to provide a polarized electron beam with energy 15.9 GeV colliding with ion species ranging from polarized protons with a top energy of 250 GeV to fully stripped Uranium ions with energies up to 100 GeV/u, and e-nucleon luminosity of  $10^{33} \text{ cm}^{-2} \text{ sec}^{-2}$ .

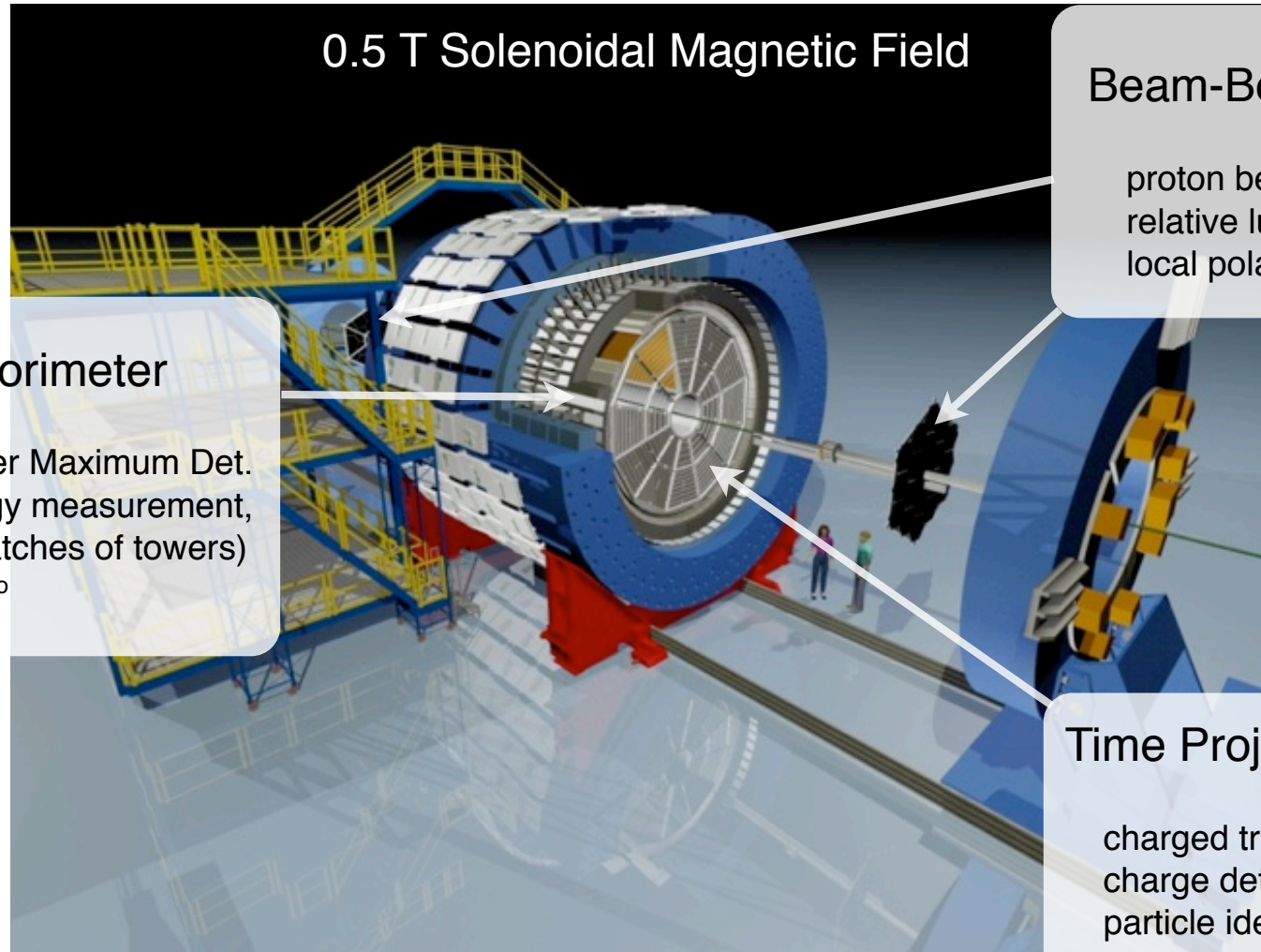
E.C. Aschenauer et al.

Numerous external contributions,

See talk by T. Roser at EIC-IAC meeting past February 28, 2014



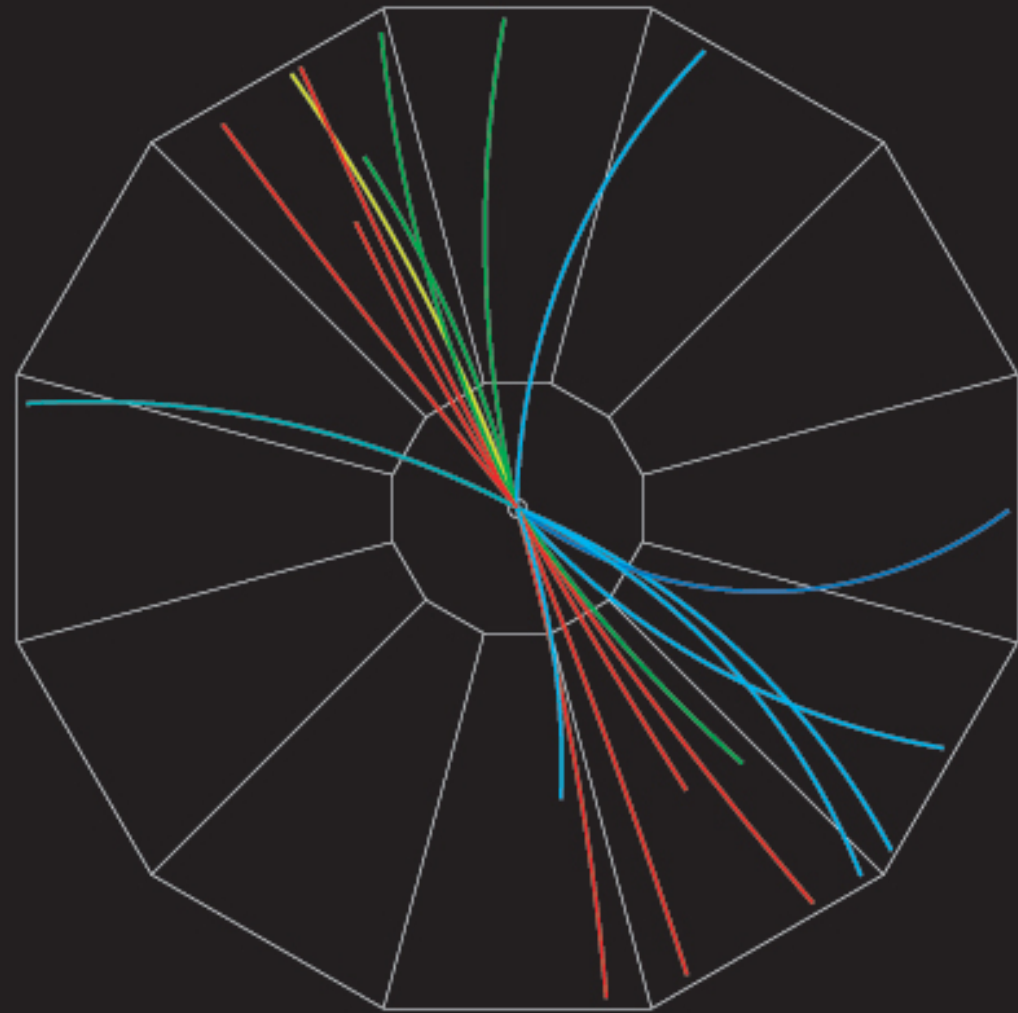
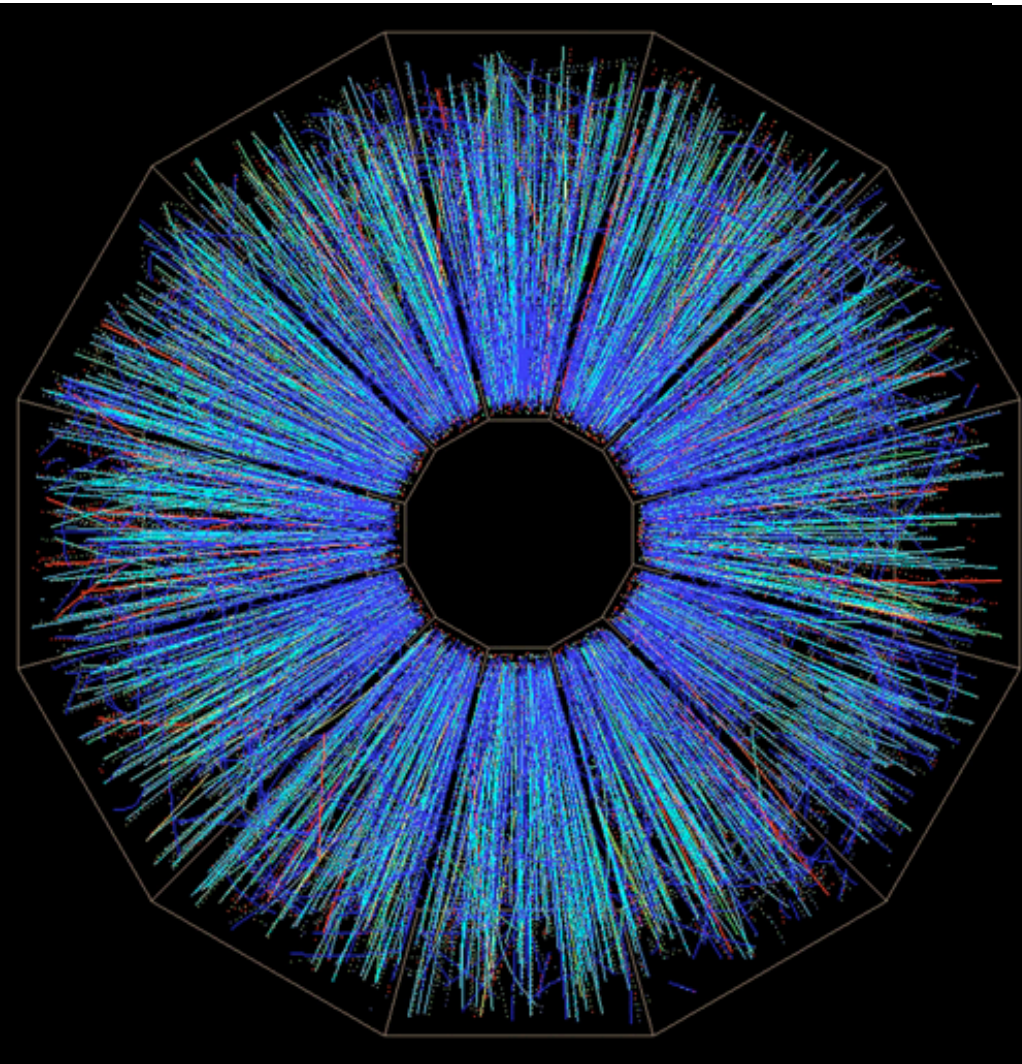
# STAR - Solenoidal Tracker at RHIC



Nucl. Instrum. Meth. A499, 624, 2003

Additional subsystems, e.g. DAQ-1000, ZDC, Time-of-Flight, EEMC, FGT (complete),  
Ongoing upgrades: Heavy Flavor Tracker, Muon-Telescope Detector  
Upgrade plans: Roman Pot system (phase IIa), Forward Calorimeter System, ...

# STAR - Solenoidal Tracker at RHIC



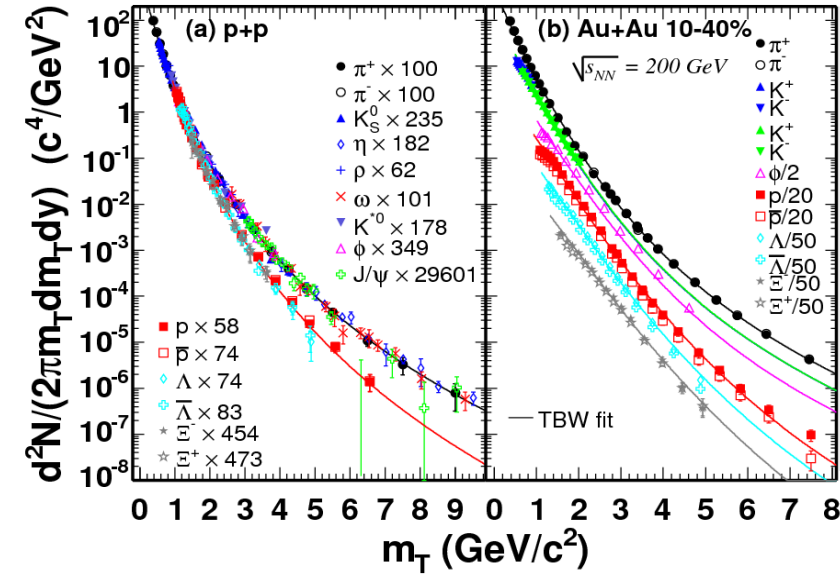
A versatile instrument to study QCD: Au+Au, d+Au, p+p,  $\sqrt{s} = 7.7 - 500$  GeV, polarization.  
key strengths: **Acceptance, low-mass, mid-rapidity Particle-Identification.**

Can it be adapted to eRHIC? If so, how? - *STAR Decadal Plan 2010-2020, eSTAR Lol.* 15

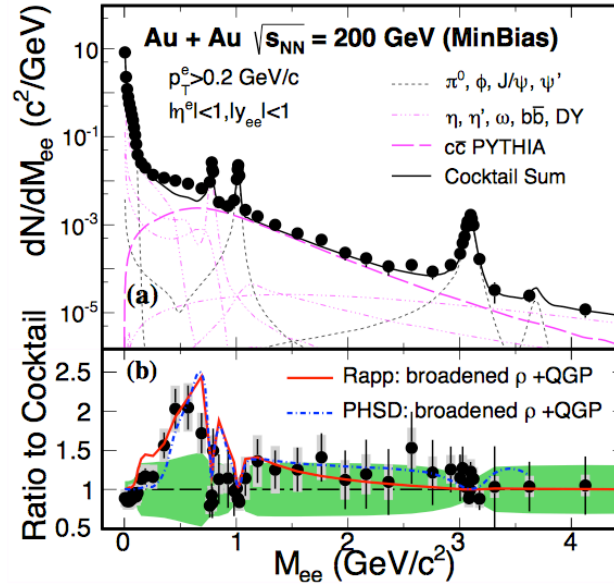


# The Future Evolves from the Present...

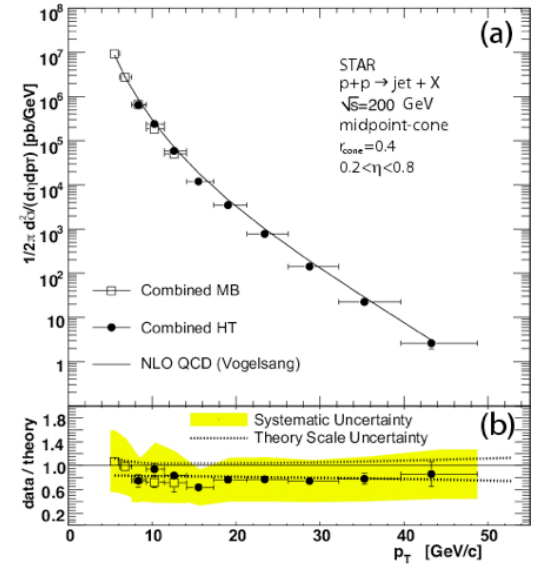
Z. Tang et al, ArXiv:1101.1912



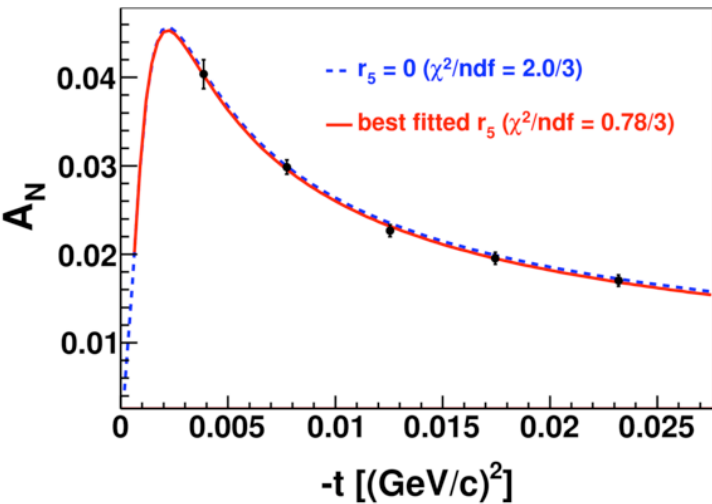
ArXiv: 1312.7379, accepted for publ. in PRL



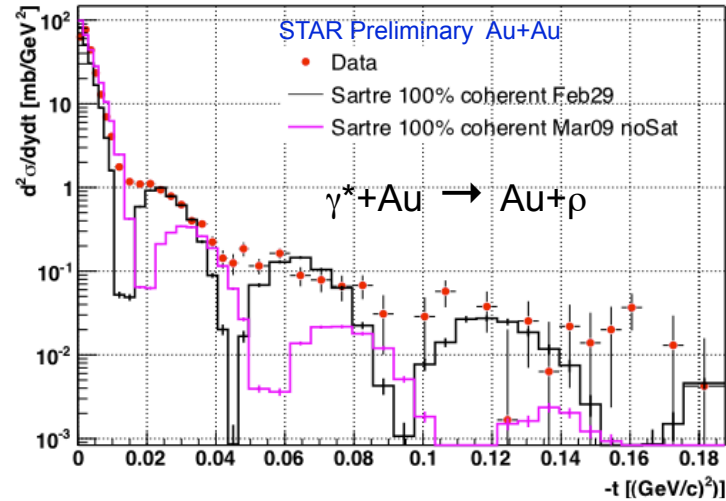
PRL 97 (2006) 252001



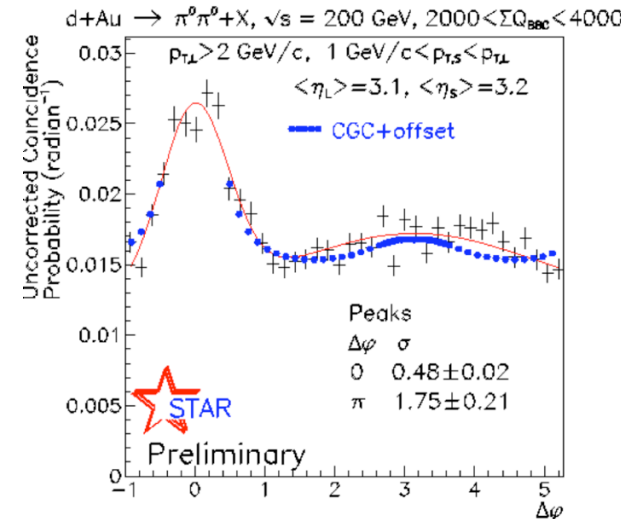
PLB 719 (2013) 62



R. Debbre for the STAR coll. WWND'12



E. Braidot for the STAR coll., QM'08



Berndt Müller's charge to Dave Morison, Jamie Nagle, Nu Xu, all (May 2013):

...

We now have an EIC White Paper with a comprehensive outline of the physics questions for an Electron Ion Collider, a rapidly maturing machine design for eRHIC, and a clearer view of a possible path to an early-stage eRHIC program leading to first measurements in the mid-2020s.

Therefore, the PHENIX and STAR Collaborations are now being asked to consider their role in a transition from RHIC to eRHIC on this time scale, and to provide specific plans (i.e. Letters of Intent) to upgrade/reconfigure the detectors from their present form to first-generation eRHIC detectors ...

In preparing these LOI the collaborations should assume an eRHIC machine with:

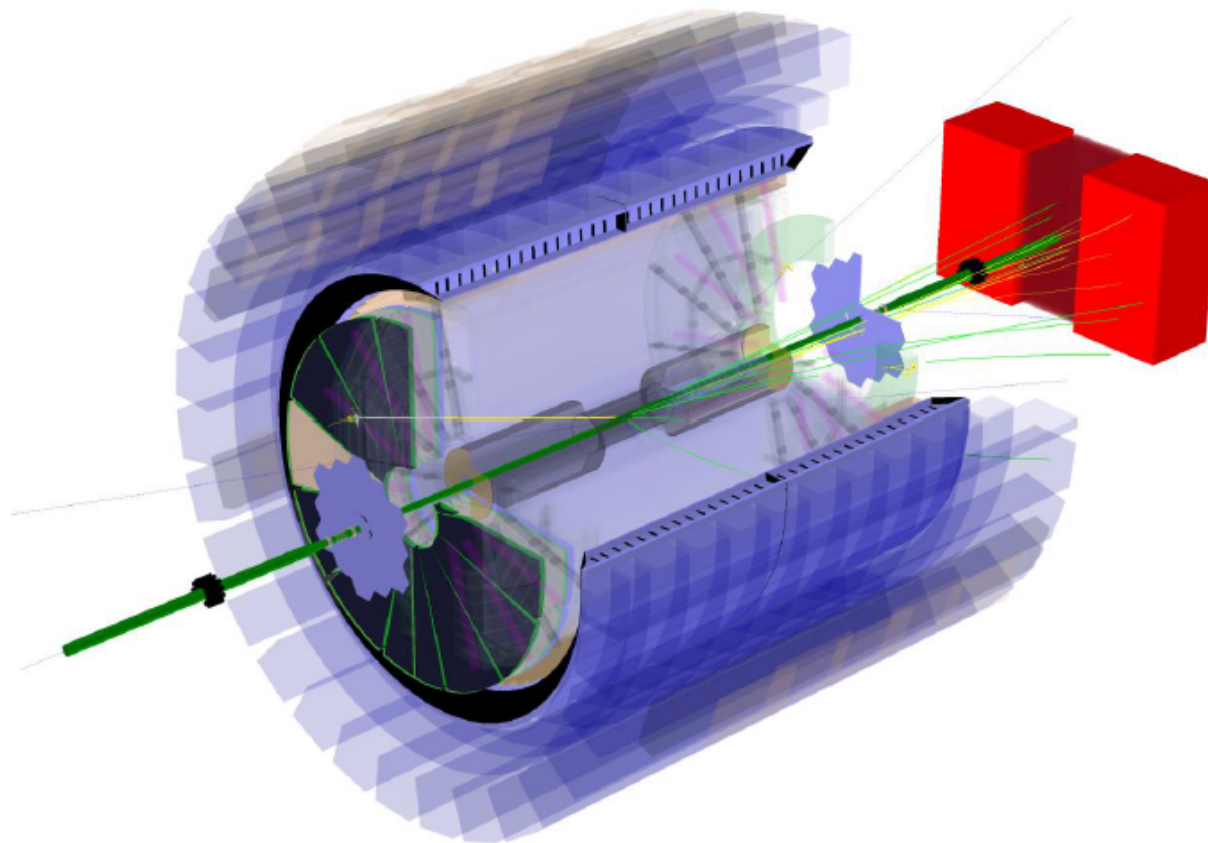
- an electron beam energy up to 10 GeV,
- hadron beam energies as provided by the current RHIC machine,
- design luminosities of  $10^{33} \text{ cm}^{-2}\text{s}^{-1}$  for 10 GeV on 255 GeV ep collisions and the equivalent of  $6 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$  for 10 GeV on 100 GeV/nucleon eA collisions.

... submitted by September 30, 2013



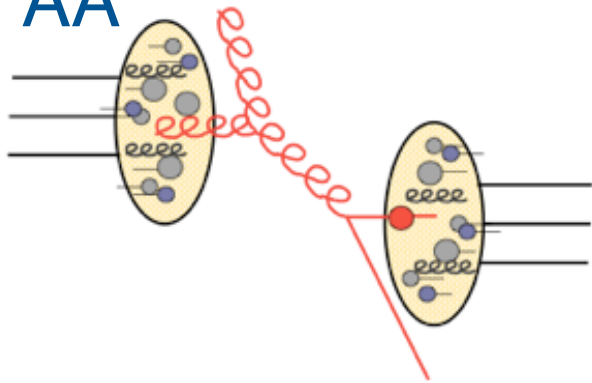
# eSTAR: A Letter of Intent

The STAR Collaboration

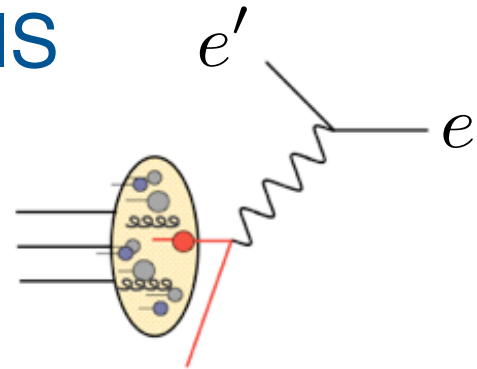


<https://drupal.star.bnl.gov/STAR/starnotes/public/sn0592>

pp, pA, AA



DIS



Relevant invariants:

$$s = (e + p)^2$$

Square of total c.m. energy

$$q = e - e' \quad Q^2 = -(e - e')^2$$

Square of (4-)momentum transfer

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

Bjorken-x, ~parton mom. fraction

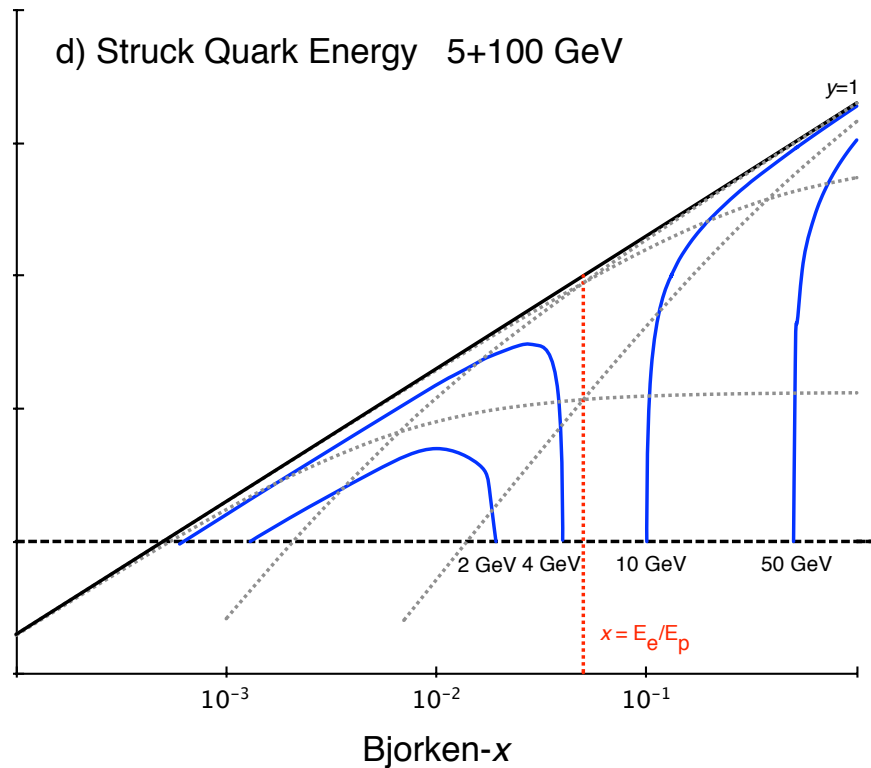
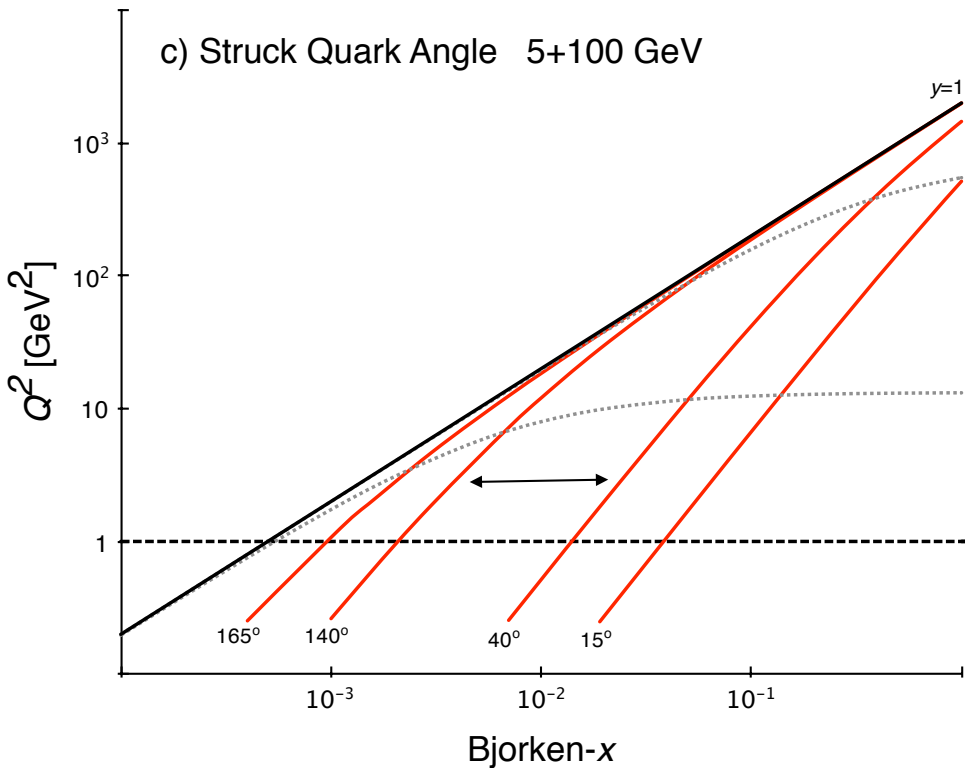
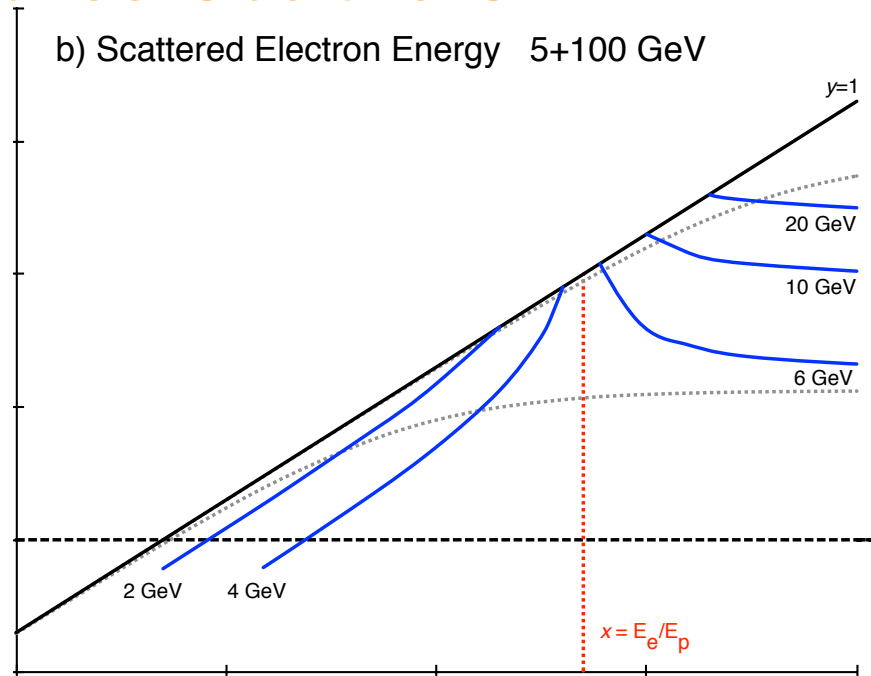
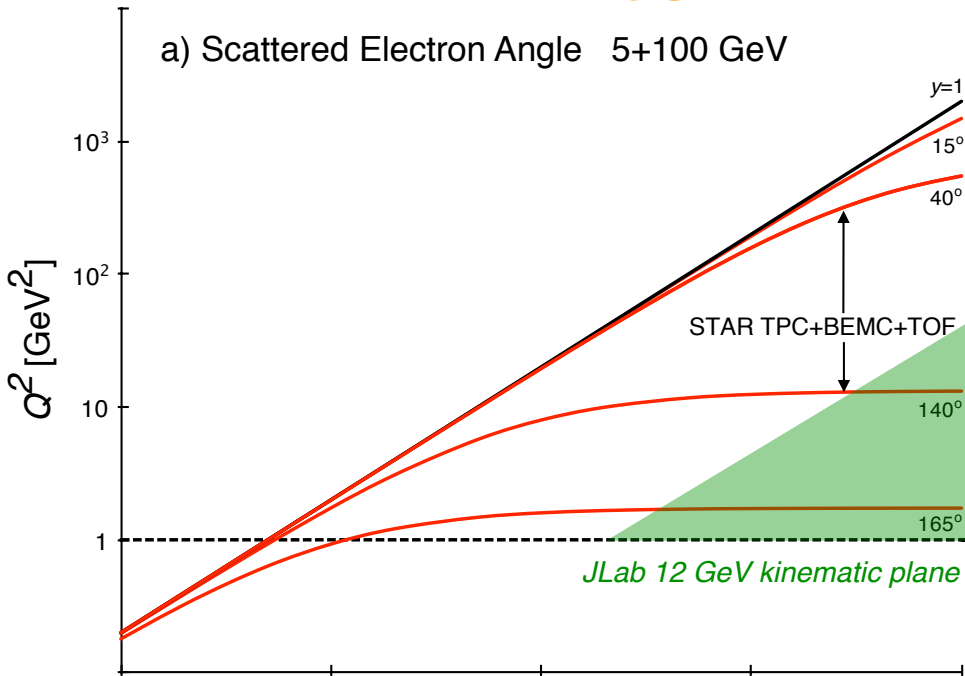
$$y = (q.p)/(e.p)$$

Fractional energy transfer

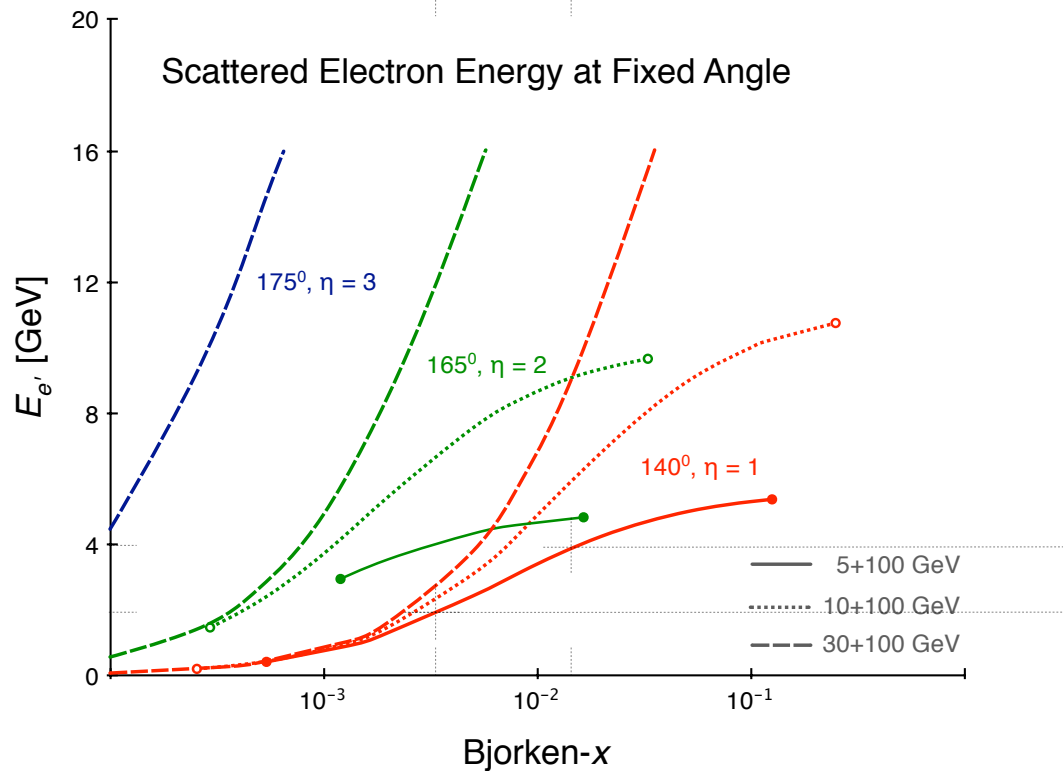
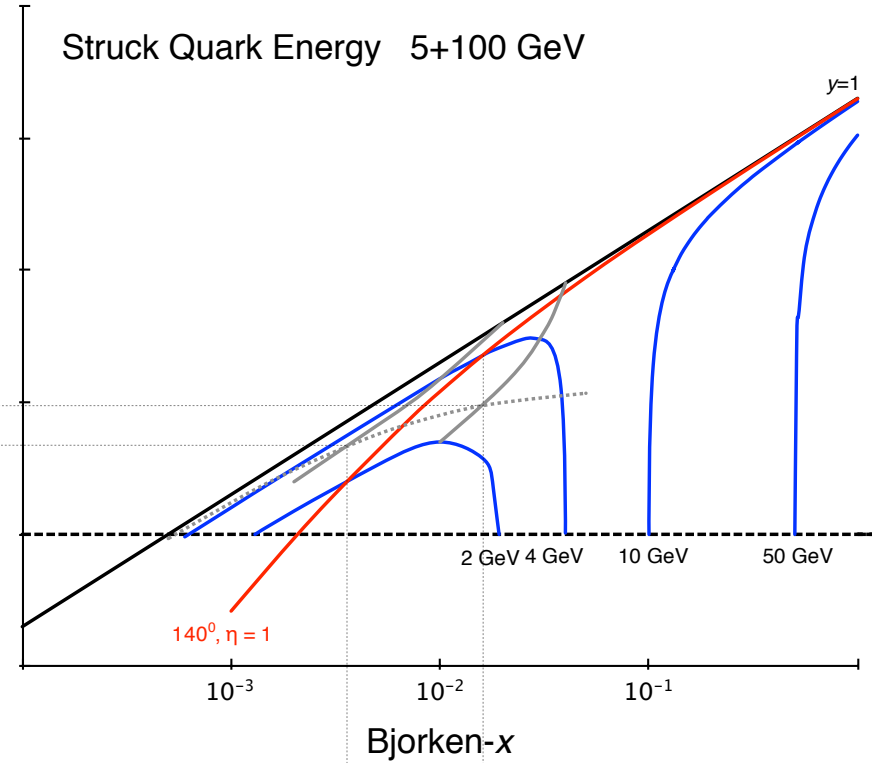
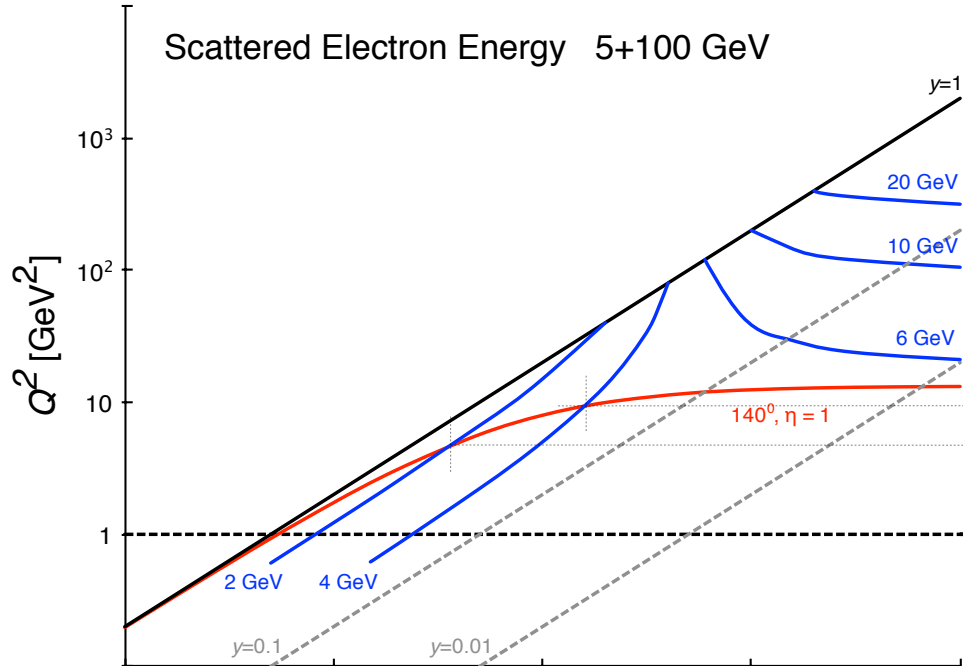
$x$ ,  $Q^2$  can be reconstructed from the scattered electron, the “current jet”, or hybrids.

Adopt HERA-convention; angles w.r.t. hadron beam.

# eSTAR - Initial Considerations



# eSTAR - Initial Considerations



Bending radii  $\sim m$ ,

Sagitta  $\sim \text{mm}$  (over 40cm),

At  $140^\circ$ ,  $dx/x \sim 2$  implies:

$$dE/E \sim 0.5 \text{ at } x \sim 10^{-3}$$

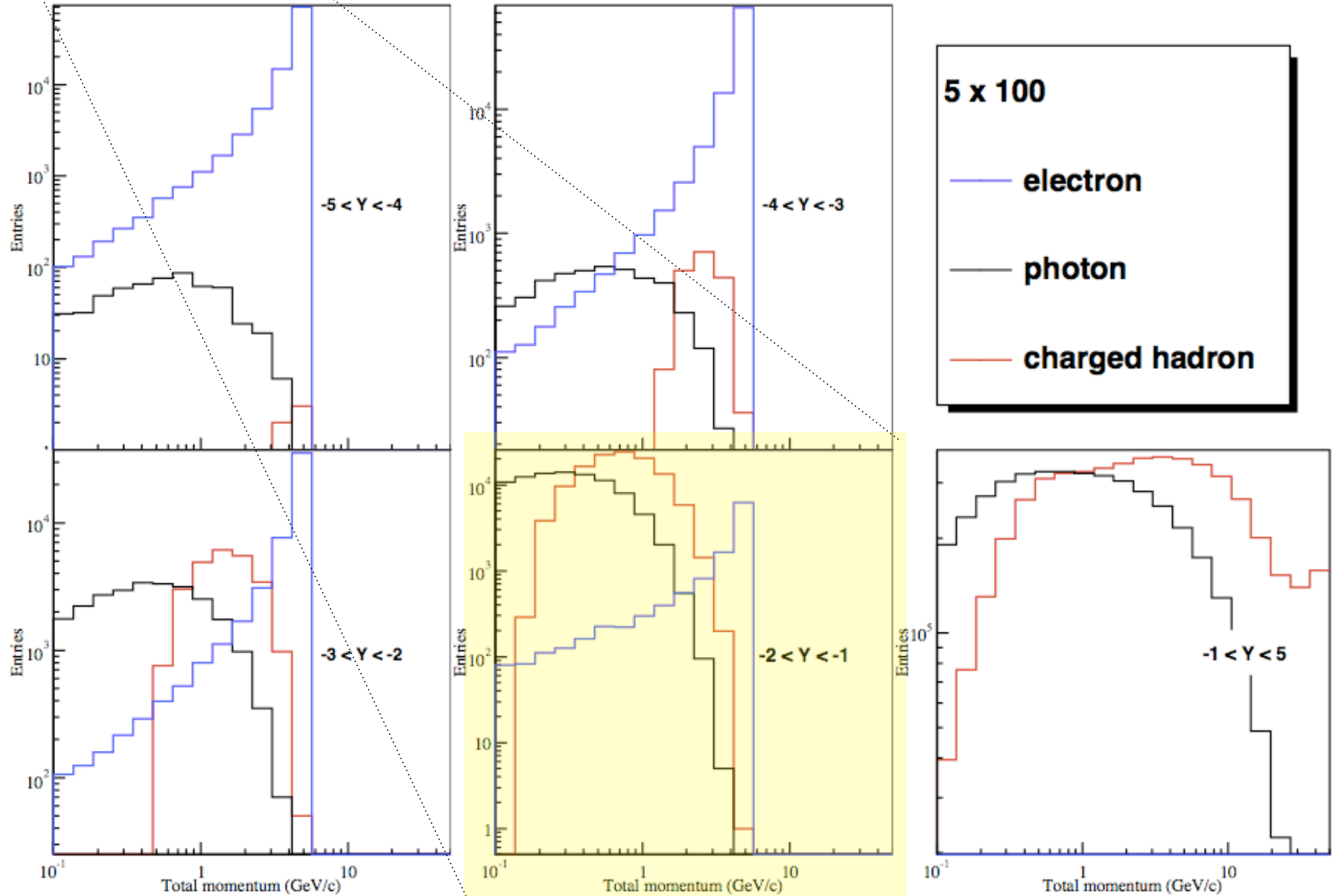
$$dE/E \sim 0.3 \text{ at } x \sim 10^{-2}$$

$$dE/E \sim 0.04 \text{ at } x \sim 10^{-1}$$

At  $165^\circ$ ,  $dx/x \sim 2$  implies  $dE/E \sim 0.09$  at  $5 \cdot 10^{-3}$

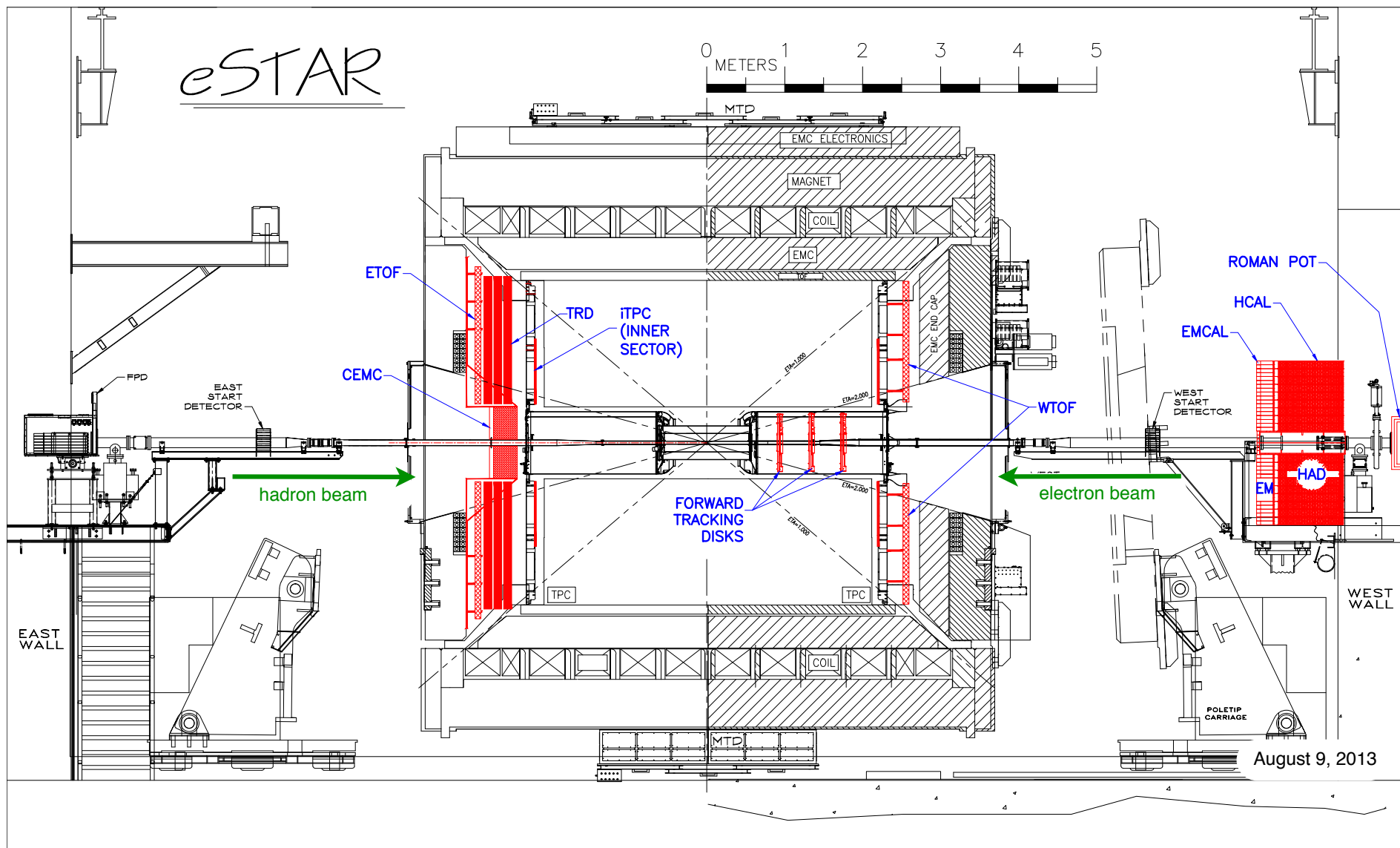
# eSTAR - Initial Considerations

Electron identification, from ArXiv 1108.1713v2:



# eSTAR - Concept

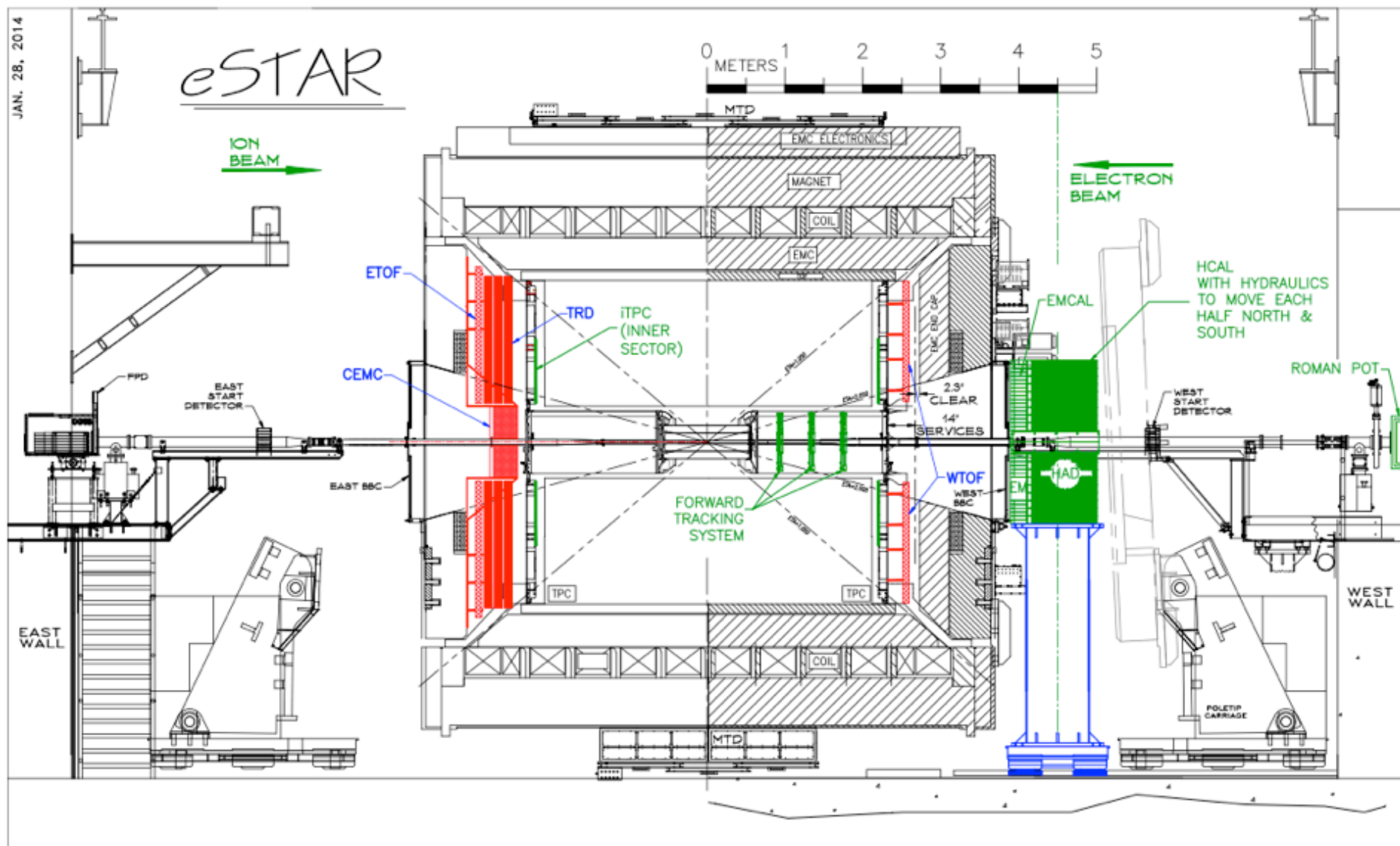
A modest evolution compared to the upgrade-plan outlined in the STAR Decadal Plan:



**Rough "DNA":** Forward Calorimeter(s), Roman Pots, Tracking essential to p+p, p+A,  
Complement with iTPC, TRD, ETOF and CEMC form the baseline of eSTAR.



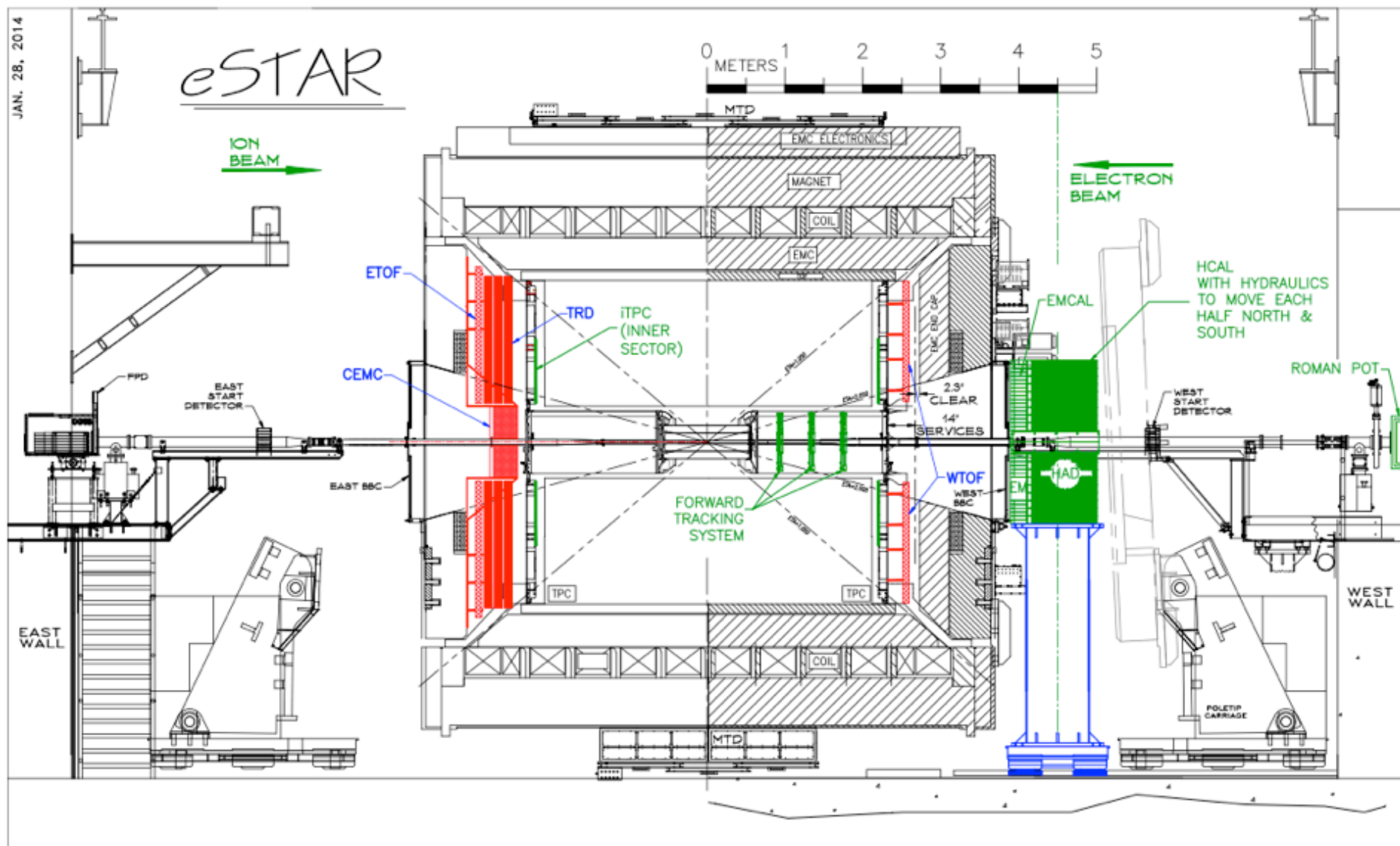
# eSTAR - Concept



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 Compactified.



# eSTAR - Concept

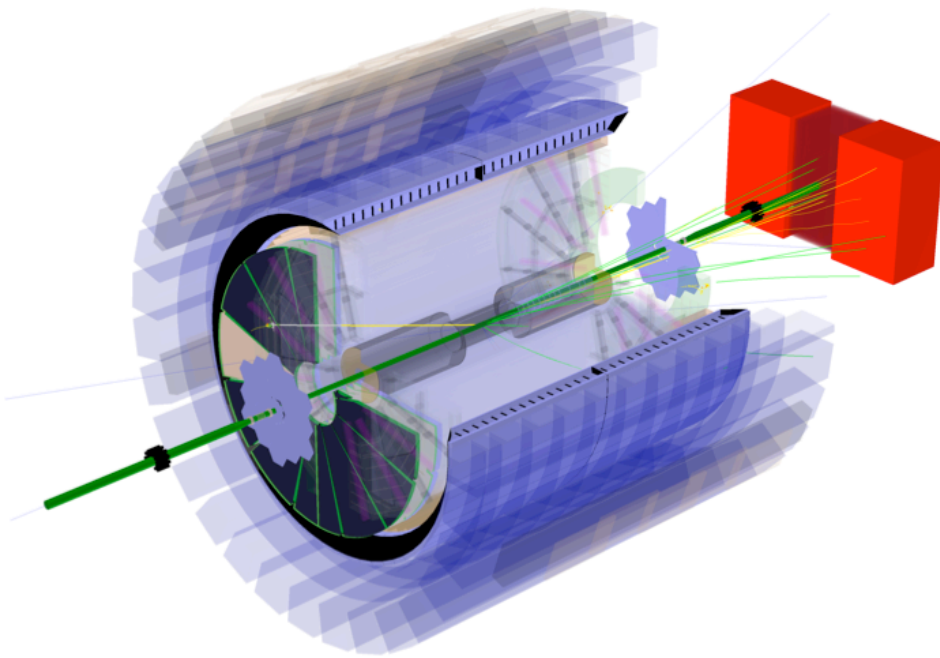


**Simulations:** a combination of GEANT3/4-based full response simulations and response parametrizations applied to event-generator outputs (Pythia, MILOU, Sartre, ...)

**R&D:** BNL-EIC R&D and STAR-specific R&D: CEMC, ETTIE, FCS, (FTS), iTPC

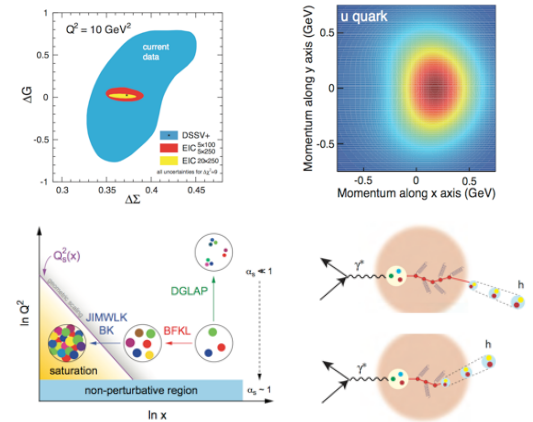
# eSTAR - Concept and Intent

## eSTAR: A Letter of Intent The STAR Collaboration



September 2013

- Adopts the U.S. EIC Science Case,

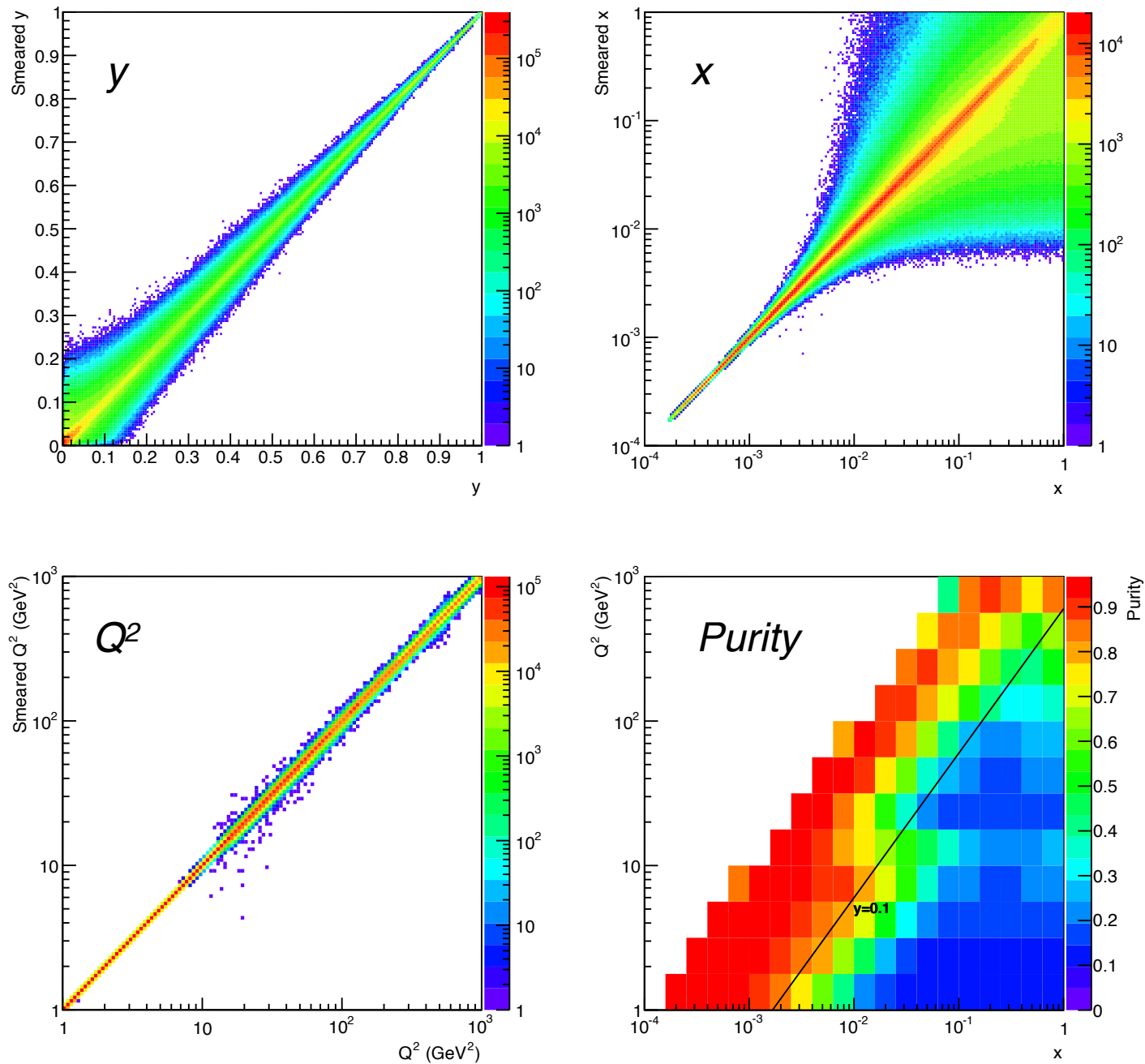


- Initial quantitative assessment of capabilities,

- Backed by simulations and R&D

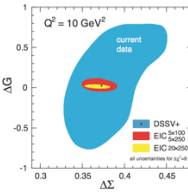
- Context: open collaboration with an instrument and a science-driven plan.

# eSTAR: A Letter of Intent - Scattered electron capability



15 GeV electron beam energy + 100 GeV hadron beam energy

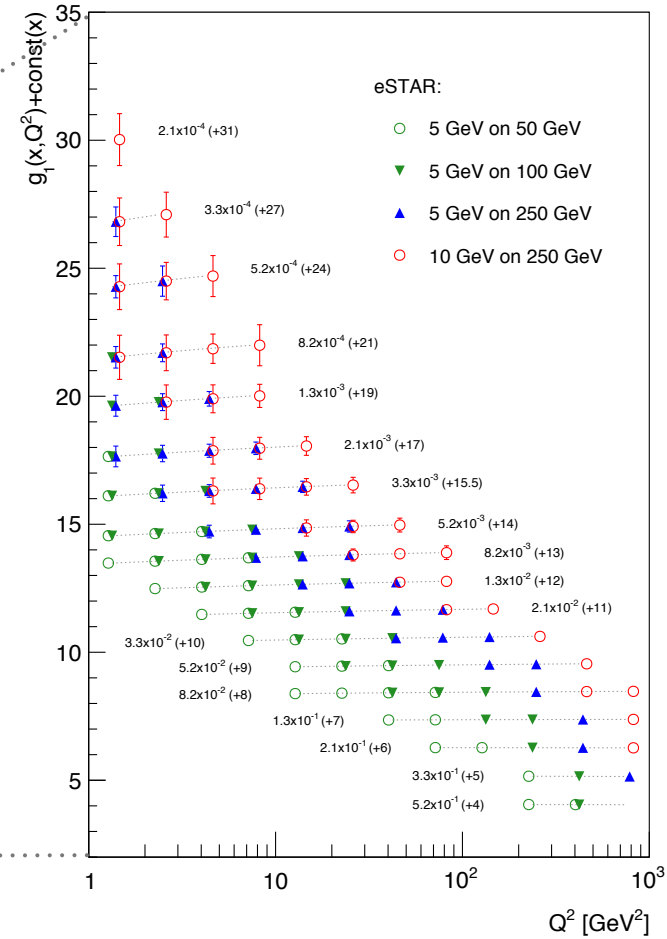
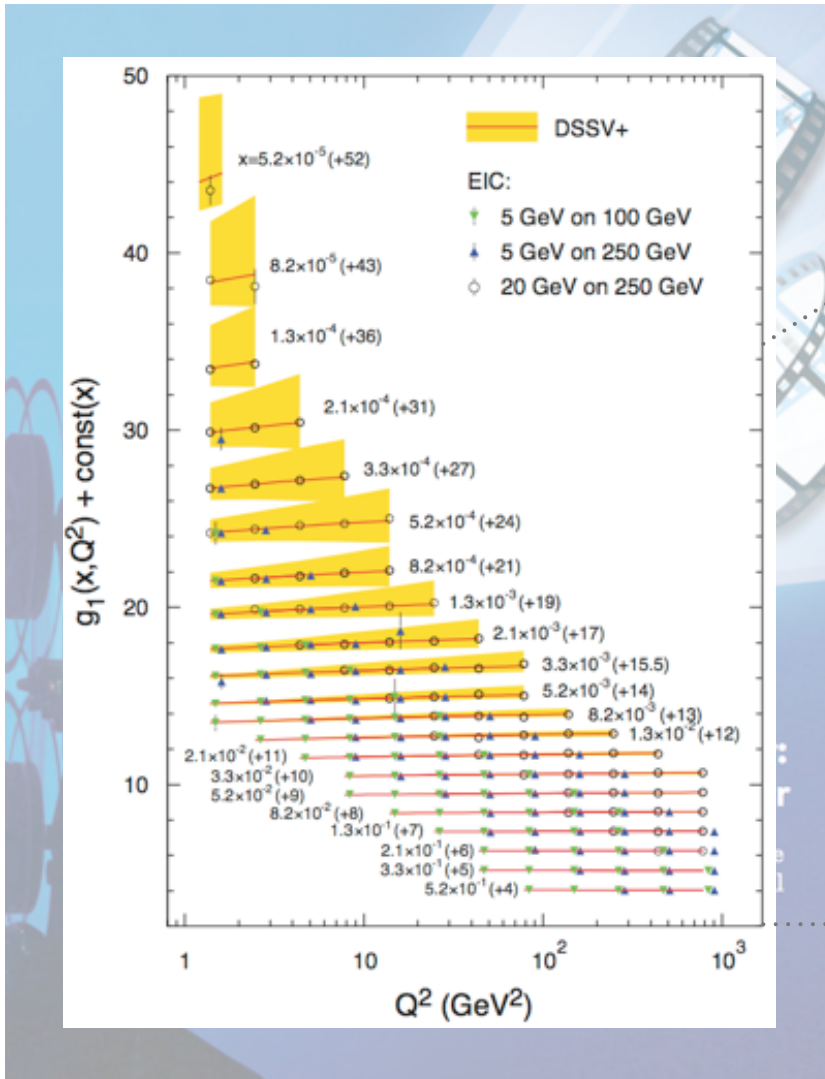
# eSTAR: A Letter of Intent - Inclusive Measurements



Full eRHIC, dedicated detector

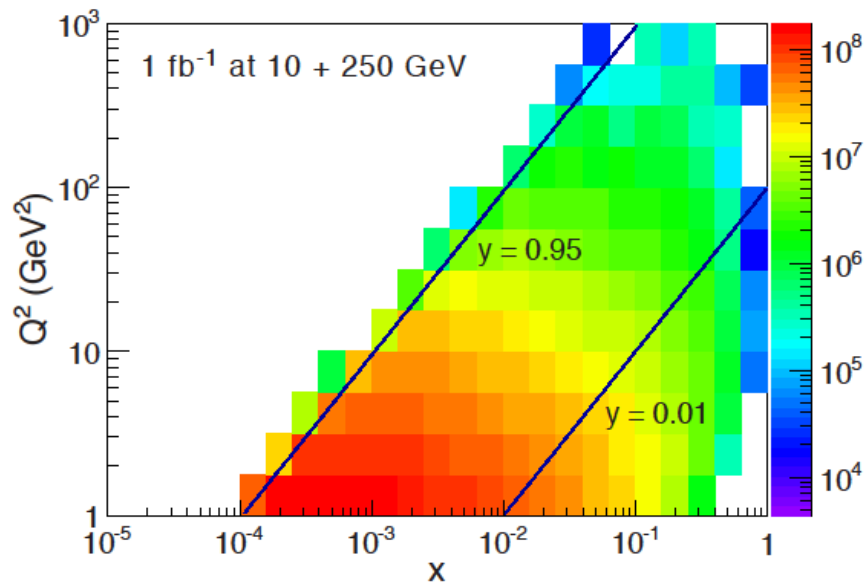


Initial stage eRHIC, eSTAR

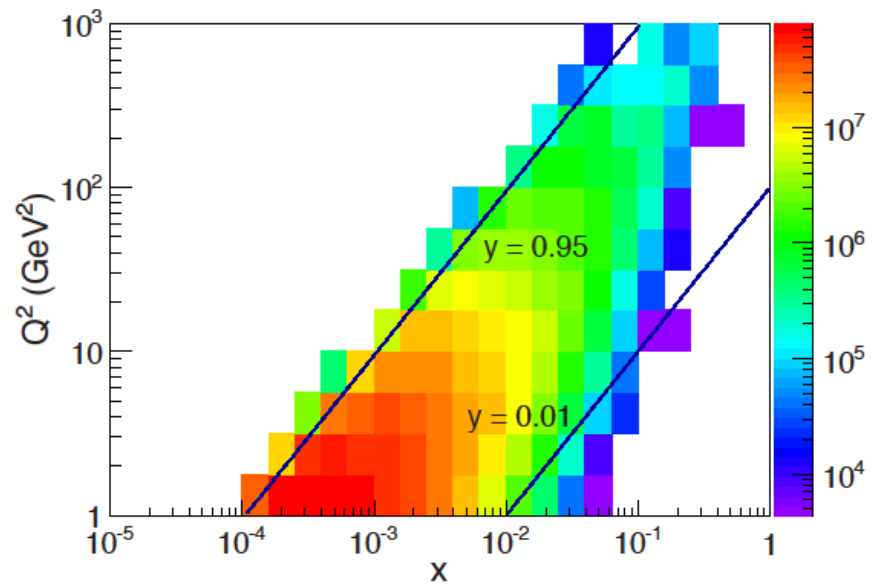


Significant measurement capability for the unpolarized and polarized inclusive structure functions.

# eSTAR: A Letter of Intent - PID capability

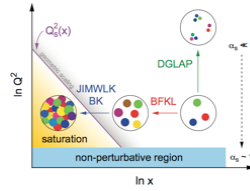


generator level



eSTAR charged pion response

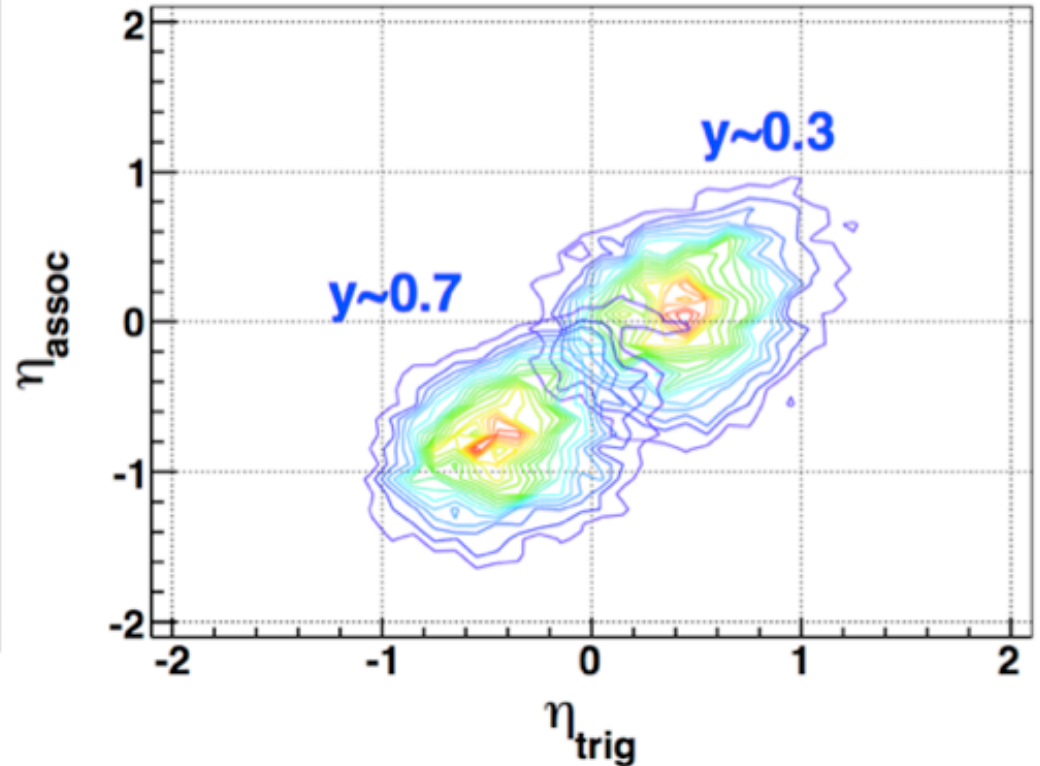
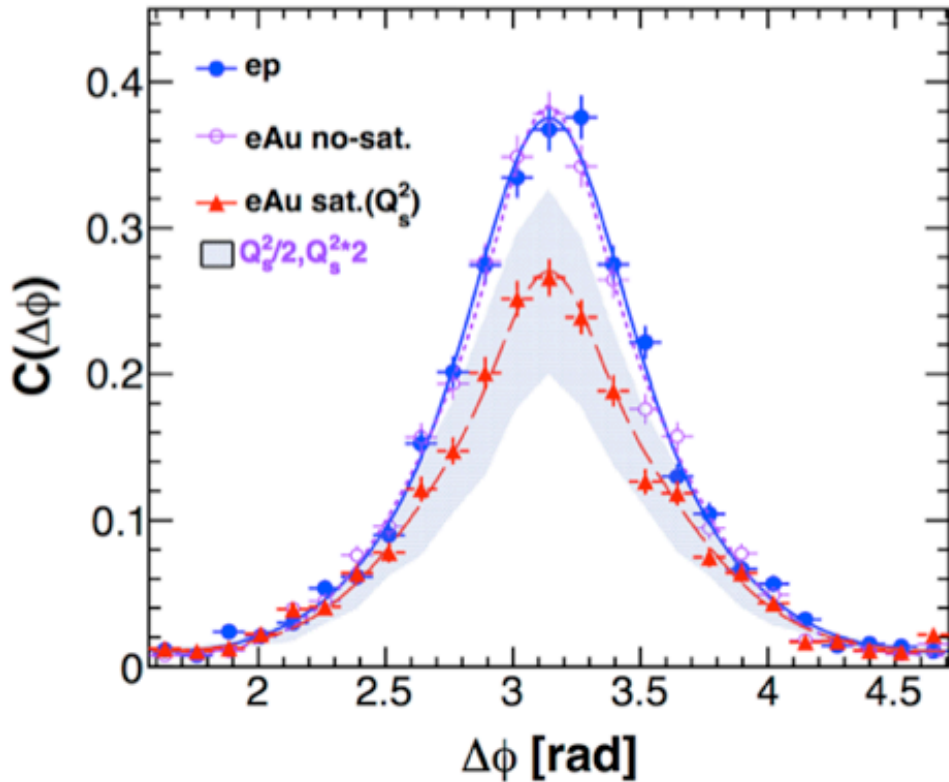
# eSTAR: A Letter of Intent - SIDIS



Azimuthal correlations in di-hadron (semi-inclusive deep-inelastic scattering) measurements,

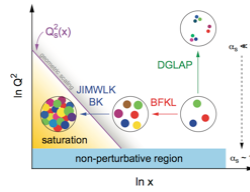
$$e + Au \longrightarrow e' + Au + h_1 + h_2 + X$$

provide sensitivity to gluons and have been proposed as a robust probe of saturation:

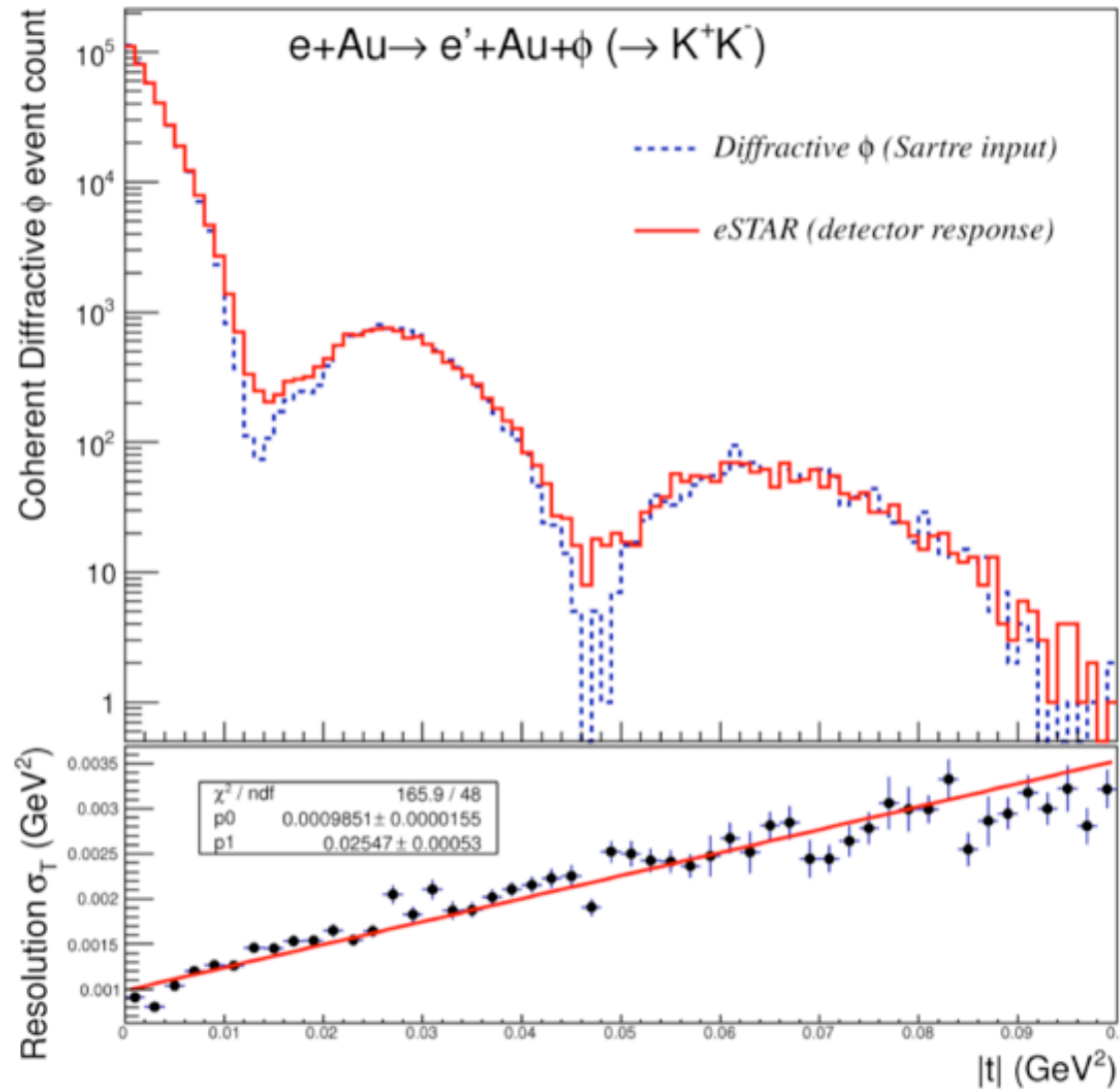


eSTAR projections for 10 GeV electrons scattering off 100 GeV/nucleon Au beams, 1 fb<sup>-1</sup>.

# eSTAR: A Letter of Intent - Exclusive VM



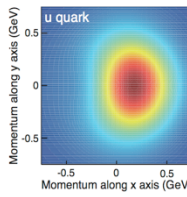
eSTAR projections for coherent diffractive production of phi-mesons



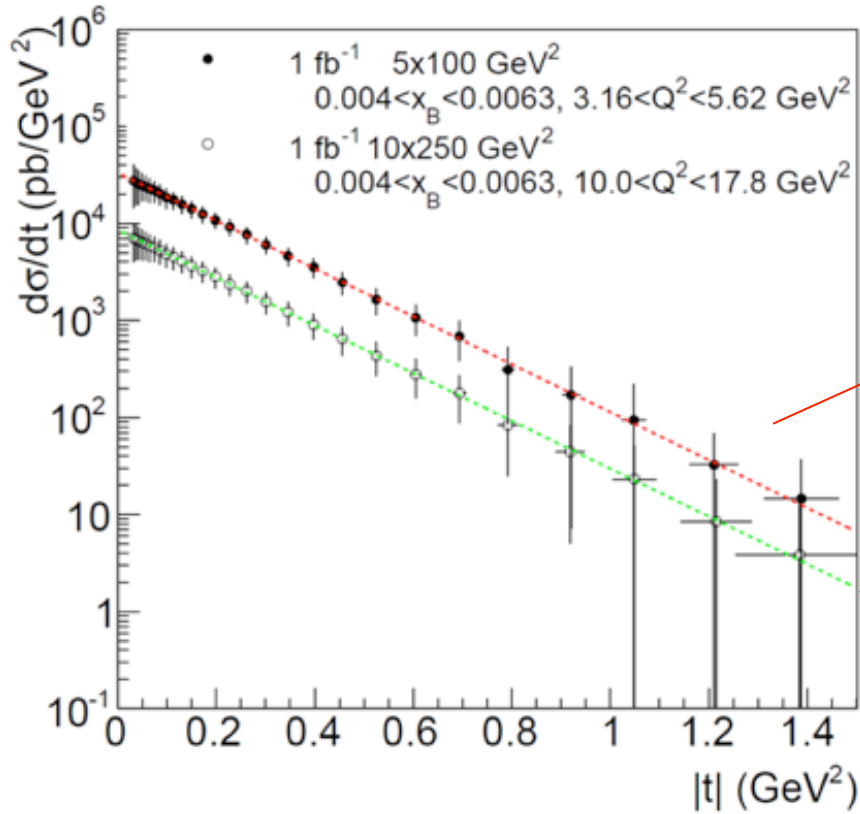
Plays well to STAR's mid-rapidity PID strengths, good resolution.



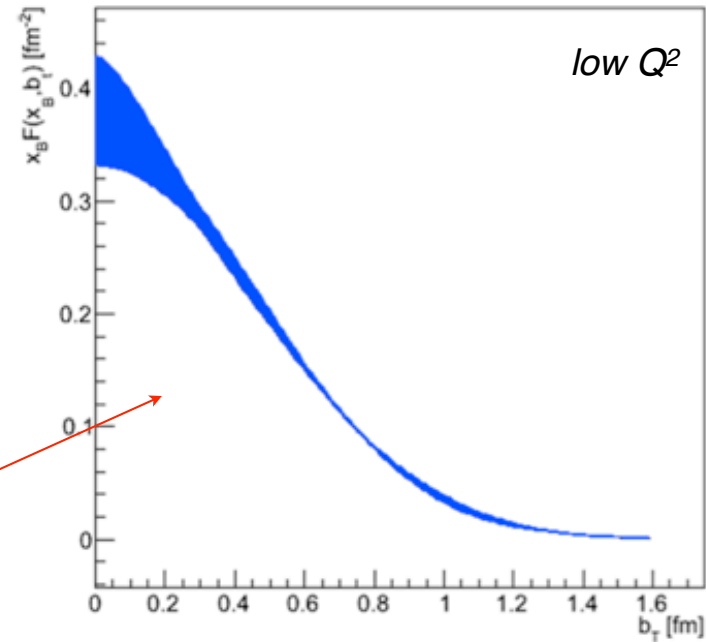
# eSTAR: A Letter of Intent - DVCS



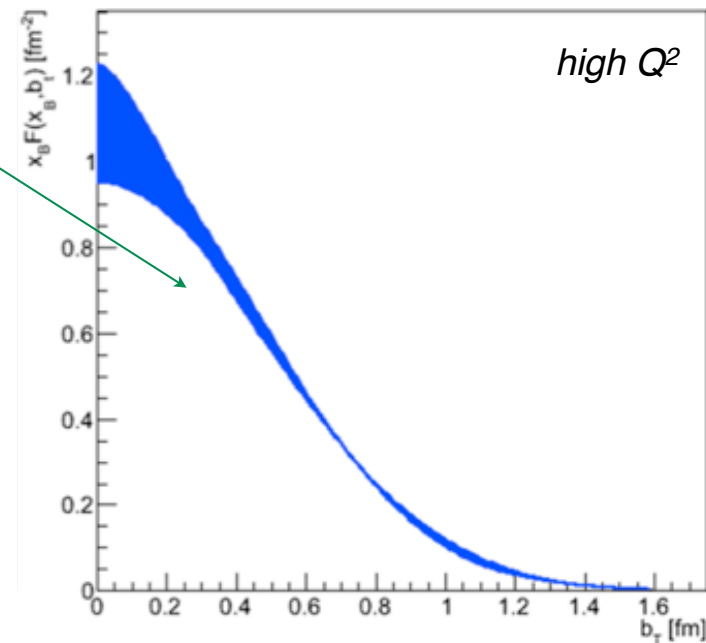
## Imaging



DVCS - parton distribution

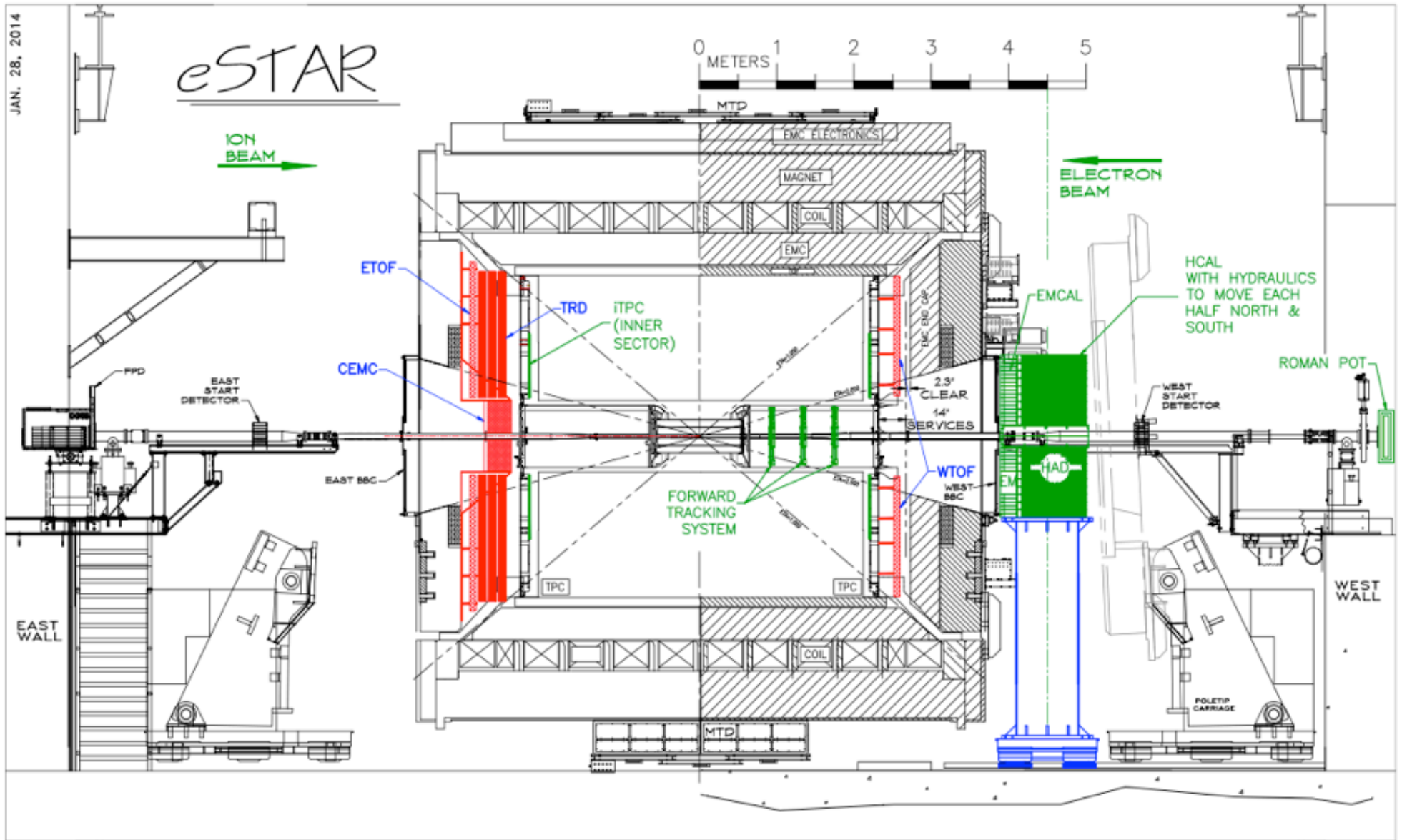


DVCS - parton distribution



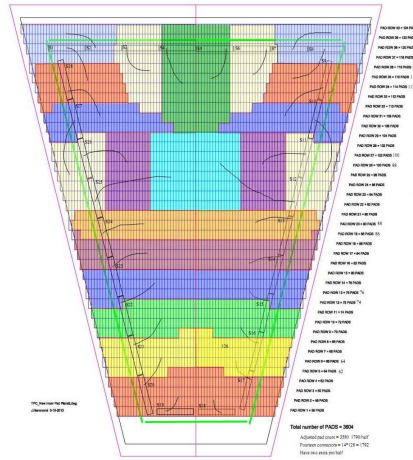
eSTAR projections for “DVCS”, Deeply-Virtual Compton Scattering / exclusive photon production, measurements

# eSTAR - (selected) R&D

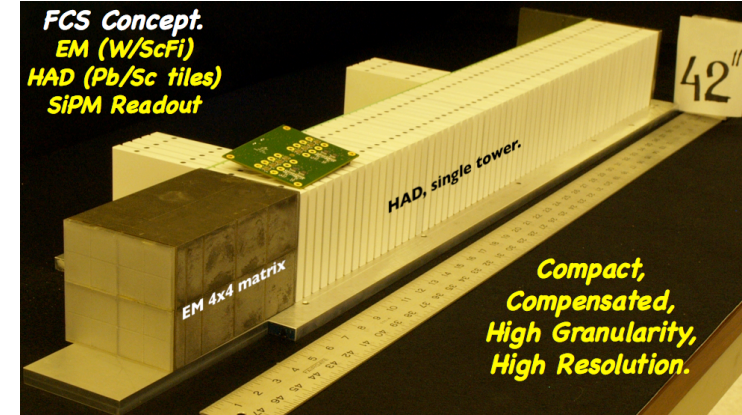


# eSTAR - (selected) R&D

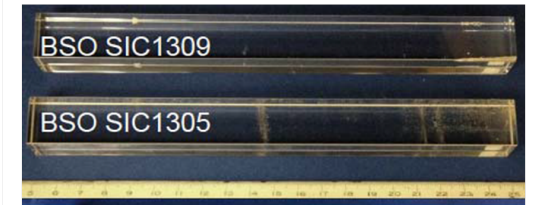
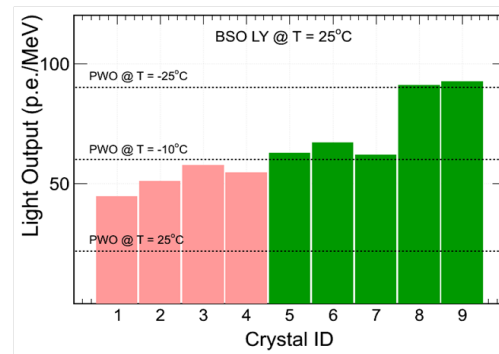
- inner TPC (iTPC) sector upgrade  
pad-row arrangement  
material reduction



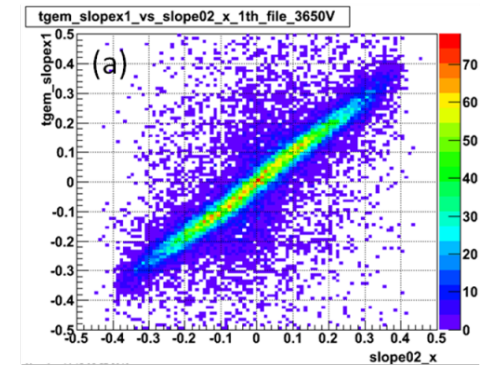
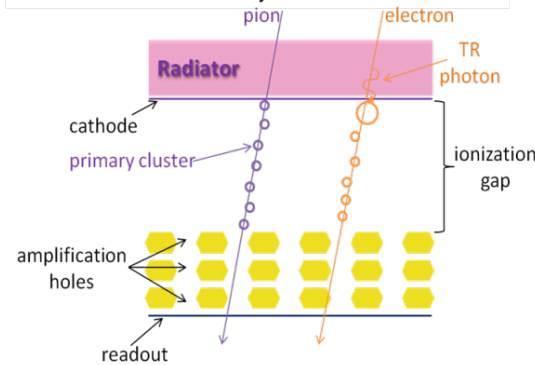
- Forward Calorimeter System (FCS)  
W-powder + Fiber



- Crystal EM Calorimeter (CEMC)  
new type of crystal



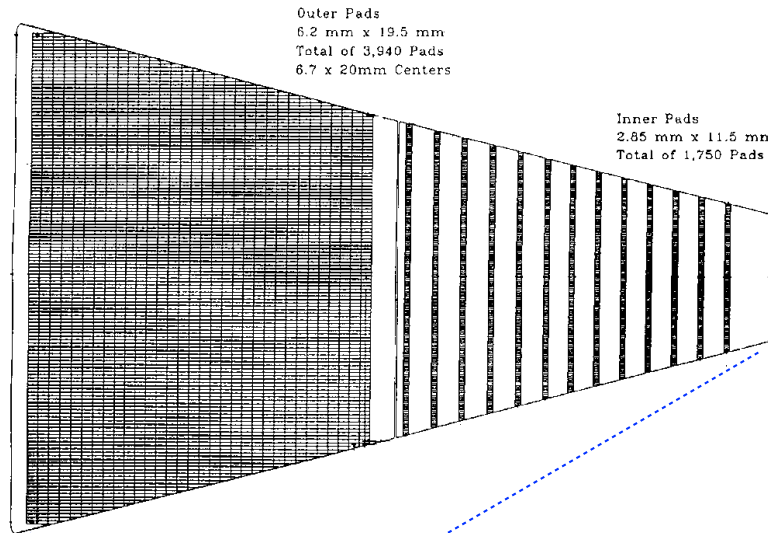
- GEM based TRD.





Multi motivation, Beam-Energy Scan - physics case for phase II → iTPC

STAR



Increase inner pad channel density by a factor two or more,

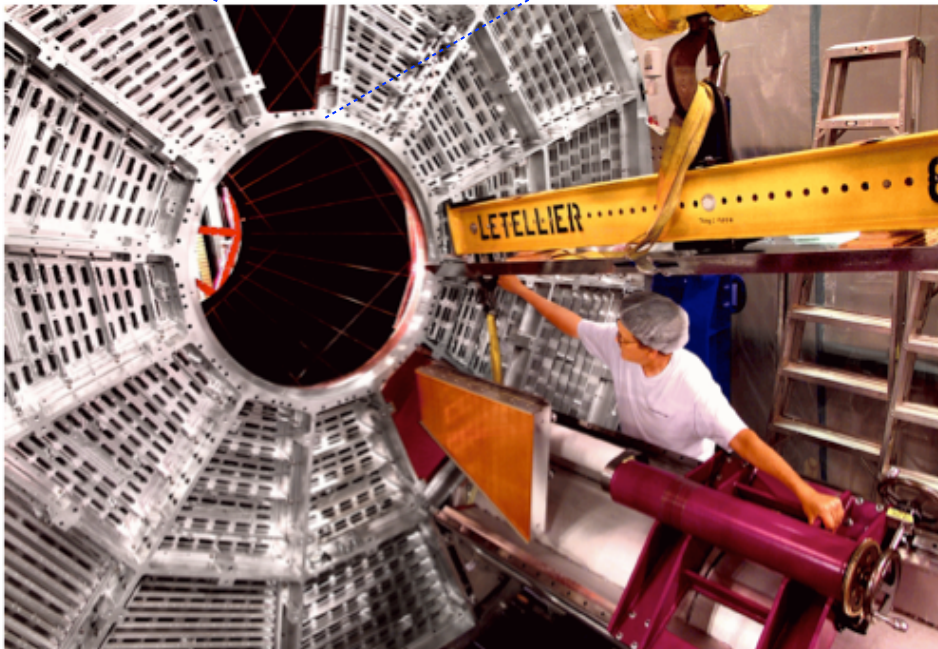
Benefits most STAR physics:

- Eliminate the concern about issues related to wire aging,
- Increase pseudo-rapidity coverage by  $\sim 0.5$  unit,
- Improve low- $p_T$  acceptance,
- Improve  $dE/dx$  resolution for particle identification,

Bridges HI and spin goals,

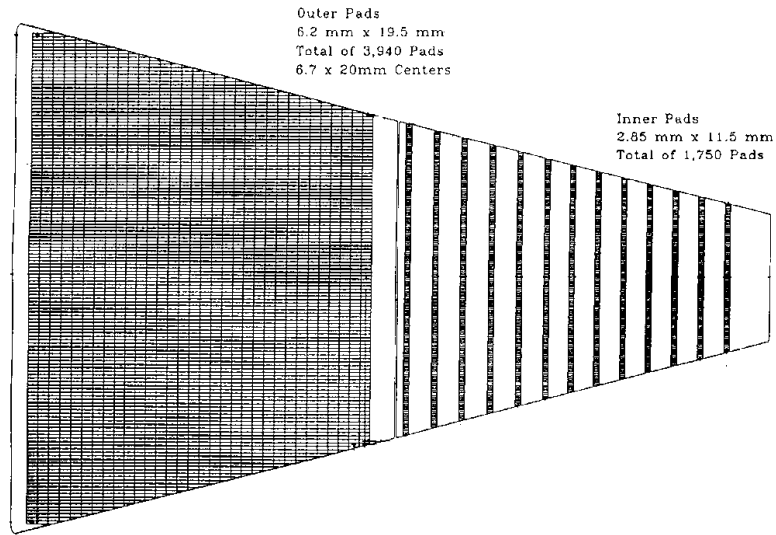
Status:

- many/most simulations in hand,
- MWPC (SDU/SINAP)
- Mechanics (LBL/BNL)
- Electronics (BNL/ALICE)
- Timeline: 3 years, 2017, cost estimate: 5M\$

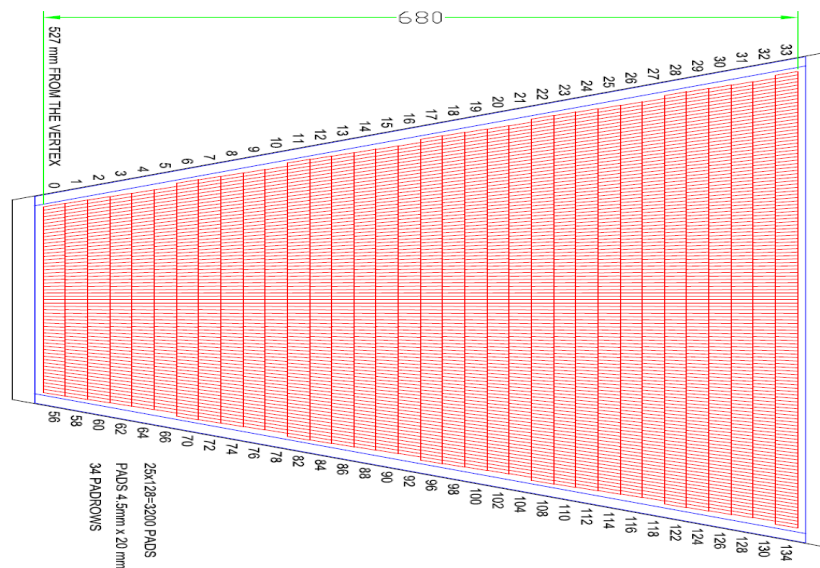


Multi-motivation, Beam-Energy Scan - physics case for phase II → iTPC

STAR



ALICE



Increase inner pad channel density by a factor two or more,

Benefits most STAR physics:

- Eliminate the concern about issues related to wire aging,
- Increase pseudo-rapidity coverage by  $\sim 0.5$  unit,
- Improve low- $p_T$  acceptance,
- Improve  $dE/dx$  resolution for particle identification,

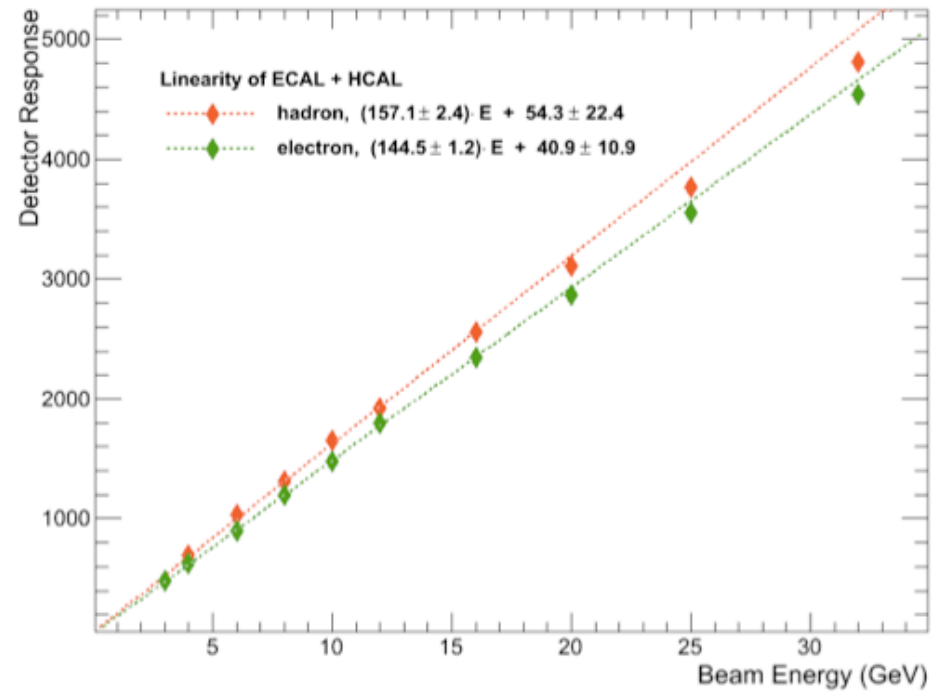
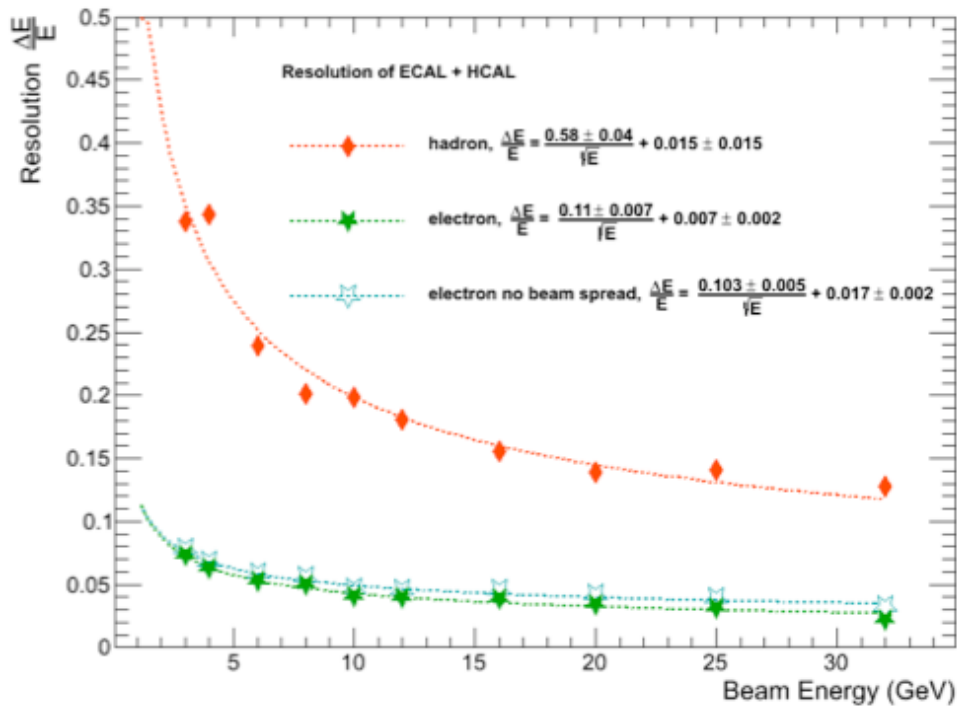
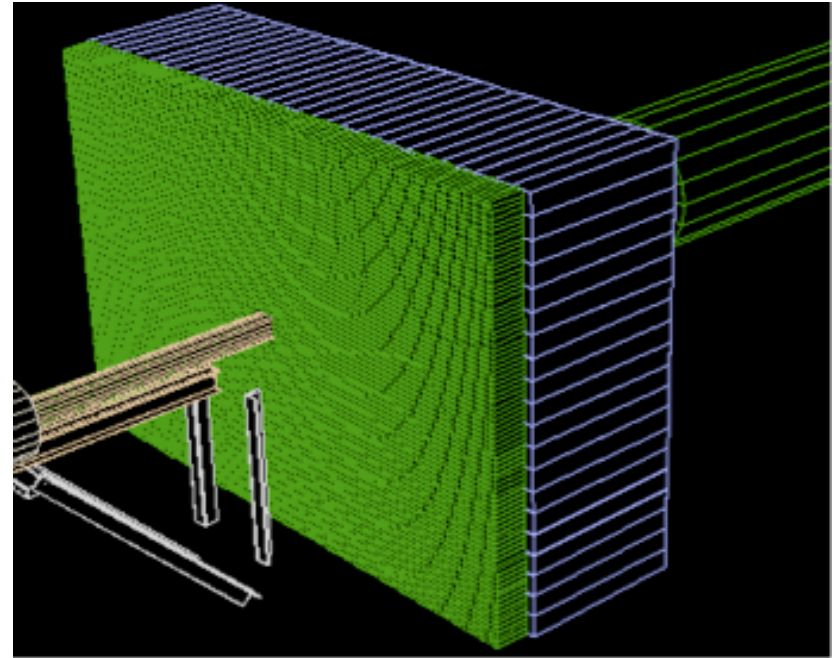
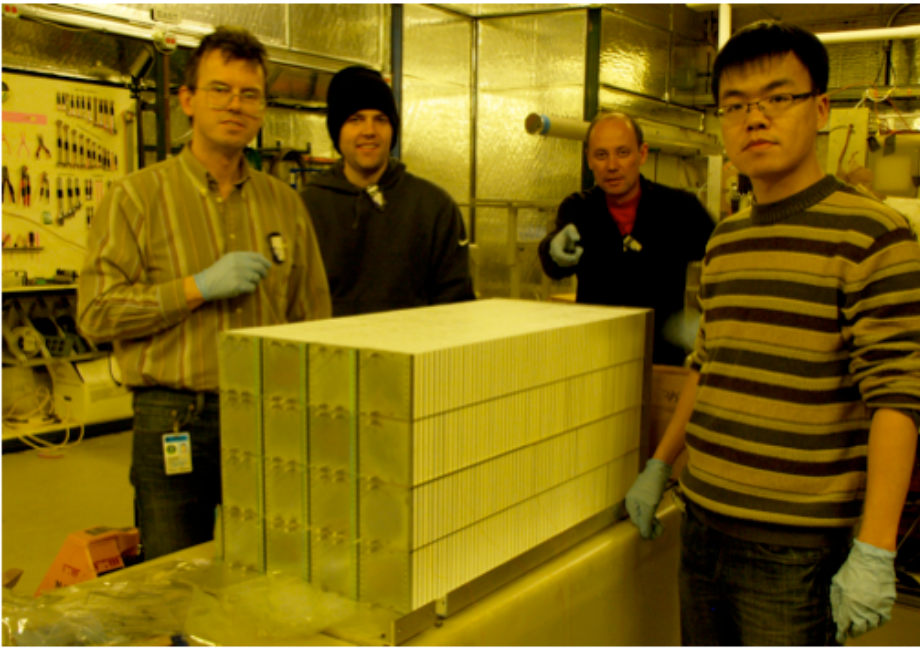
Bridges HI and spin goals,

Status:

- many/most simulations in hand,
- MWPC (SDU/SINAP)
- Mechanics (LBL/BNL)
- Electronics (BNL/ALICE)
- Timeline: 3 years, 2017, cost estimate: 5M\$



# (e)STAR - FCS Upgrade c.f. Oleg Tsai @ Calor 2014

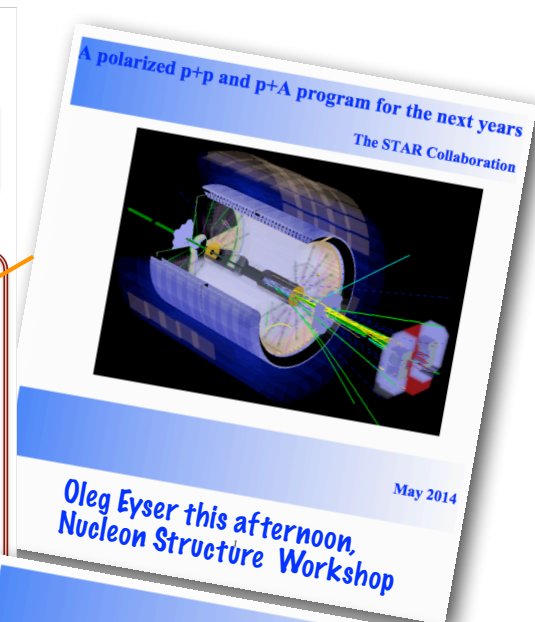
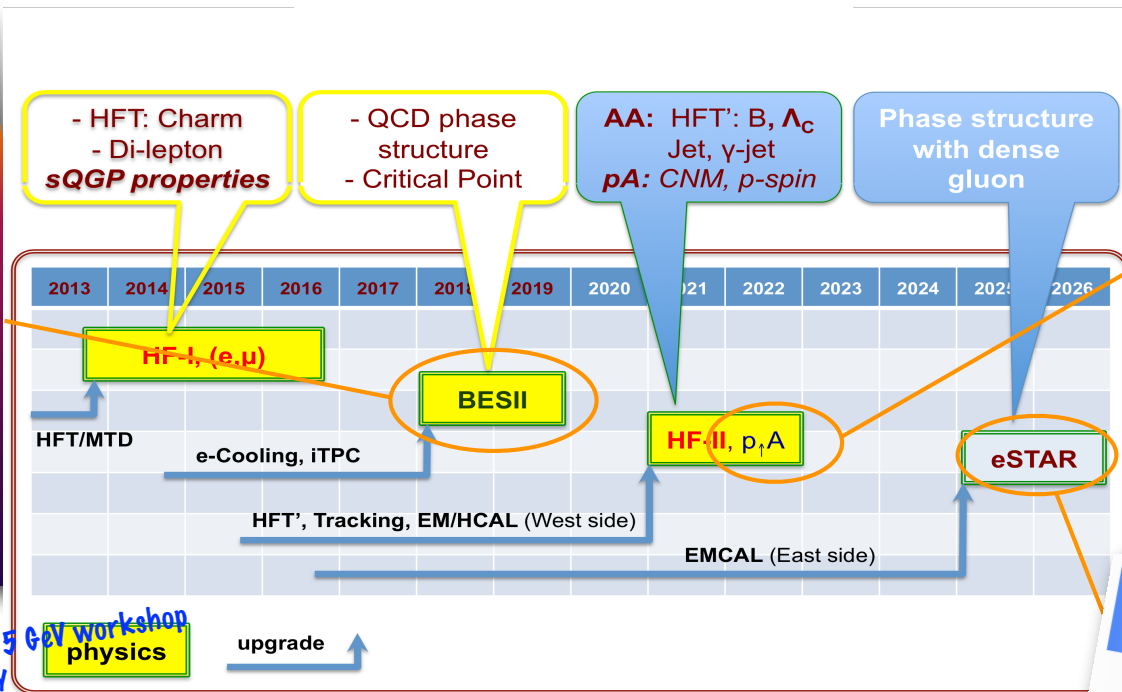


# eSTAR - A Detector for eRHIC

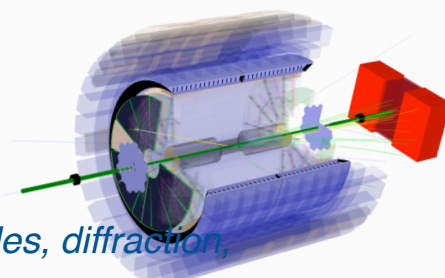
- Letter of Intent outlines a science-driven path to evolve STAR into a detector for eRHIC (initial stage):



Several talks at this mtg.  
Evan Sangaline - tomorrow's 19 GeV workshop  
Alex Schmah - Friday's plenary



Oleg Eysler this afternoon,  
Nucleon Structure Workshop



September 2013

- Baseline eSTAR plan has three components: Endcap TOF, GTRD, and CEMC

relies on: iTPC, FCS, FTS

- Significant measurement capabilities: inclusive DIS, SIDIS, exclusive observables, diffraction, key parts of EIC white-paper.

- Opportunity and lots of work ahead!

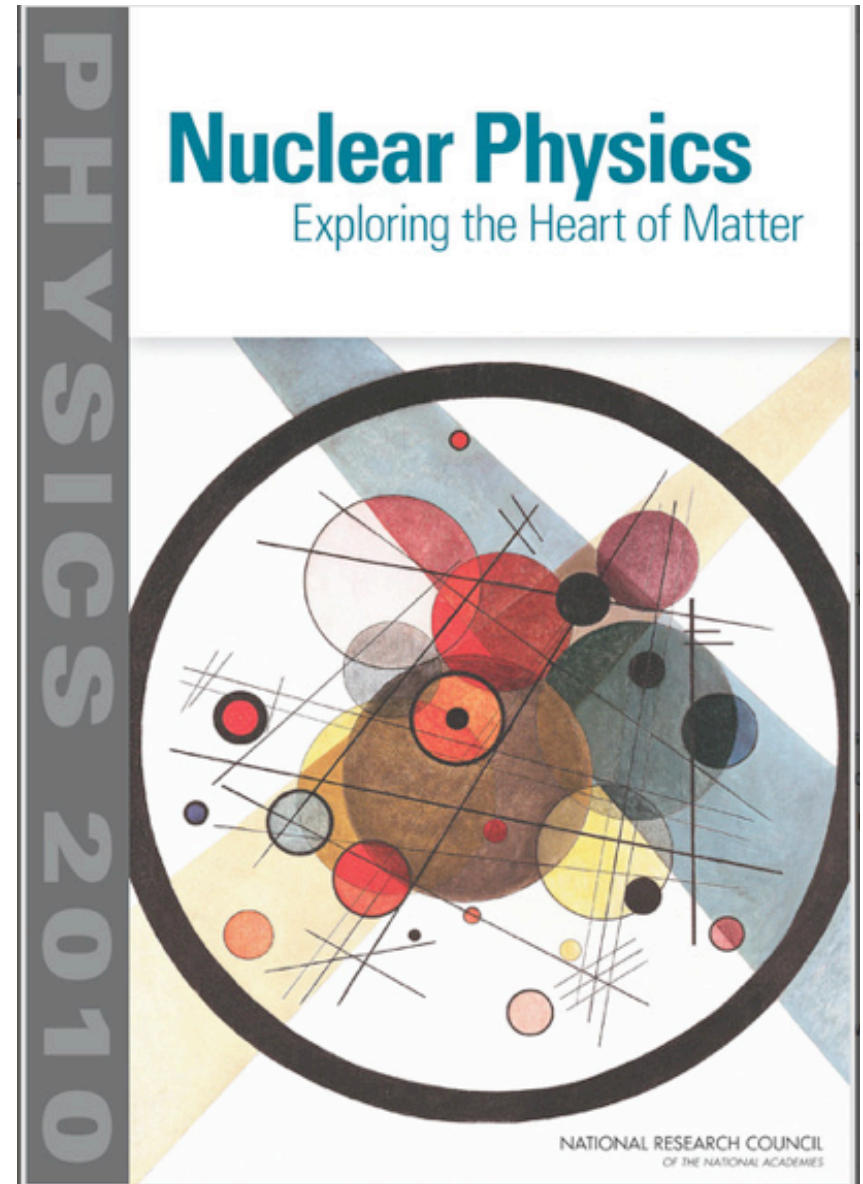
## Page 236 - Recommendations, Building a Foundation for the Future:

*Without gluons, there would be no neutrons or protons and no atomic nuclei. Gluon properties in matter remain largely unexplored and mysterious.*

**Finding:** An upgrade to an existing accelerator facility that enables the colliding of nuclei and electrons at forefront energies would be unique for studying new aspects of quantum chromodynamics. In particular, such an upgrade would yield new information on the role of gluons in protons and nuclei. An electron-ion collider is currently under scrutiny as a possible future facility.

**Recommendation:** Investment in accelerator and detector research and development for an electron-ion collider should continue. The science opportunities and the requirements for such a facility should be carefully evaluated in the next Nuclear Science Long Range Plan.

**No other facility finding or recommendation.**



National Research Council. *Nuclear Physics: Exploring the Heart of Matter*. Washington, DC: The National Academies Press, 2013.



# Concluding Remarks

QCD is, in many cases, still *far* from ab-initio calculations,

RHIC is a) a truly unique facility, b) online, and  
c) a timely path to a polarized high-energy EIC,

STAR capabilities, with continued suitable upgrades:

TPC inner-sectors,  
forward calorimetry,  
endcap TOF & TRD,  
crystal calorimeter,

...

match rather well to eRHIC with 5-15 GeV electron  
beams for inclusive, semi-inclusive, and exclusive /  
diffractive measurements - key measurements of the  
eRHIC science program,

Active groups, opportunities abound to take part, and lots  
of work ahead!

$\sim 10^{-10}$  m  
 $\sim$ keV

$< 10^{-18}$  m

$\sim 10^{-15}$  m  
 $\sim$ GeV

