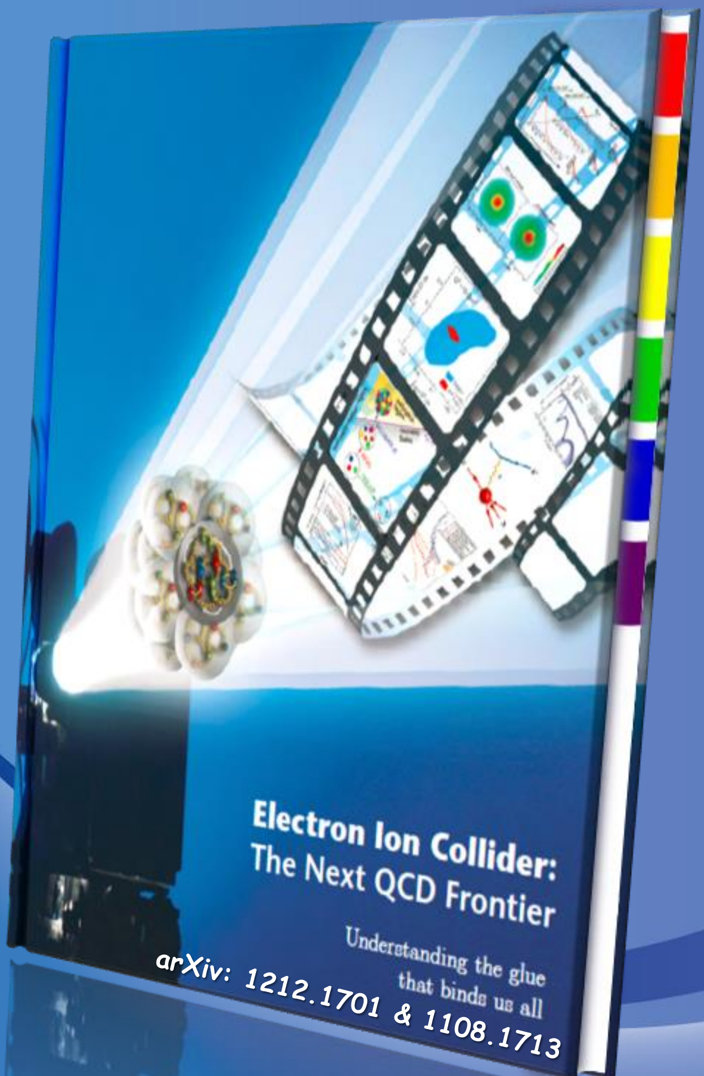
eRHIC:

NEW SCIENTIFIC AND TECHNOLOGY FRONTIERS TO DO PARTON FEMTOSCOPY



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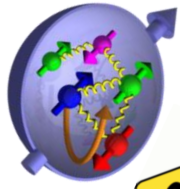
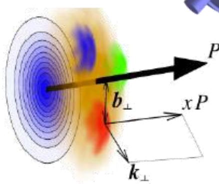
a passion for discovery
U.S. DEPARTMENT OF ENERGY | Office of Science

MOST COMPELLING SCIENCE QUESTIONS

How are sea quarks and gluons and their spin distributed in space and momentum inside the nucleon?

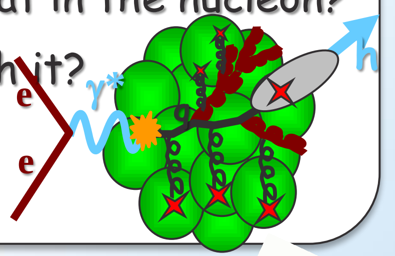


- How are these quark and gluon distributions correlated with the over all nucleon properties, such as spin direction?
- What is the role of the motion of sea quarks and gluons in building the nucleon spin?

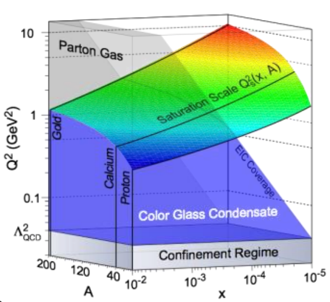


How does the nuclear environment affect the distribution of quarks and gluons and their interaction in nuclei?

- How does the transverse spatial distribution of gluons compare to that in the nucleon?
- How does matter respond to fast moving color charge passing through it? Is this response different for light and heavy quarks?



Where does the saturation of gluon densities set in?

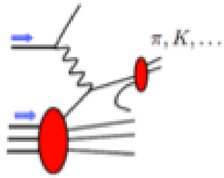


- Is there a simple boundary that separates the region from more dilute quark gluon matter? If so how do the distributions of quarks and gluons change as one crosses the boundary?
- Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

REQUIREMENTS TO REALIZE THE PROGRAM

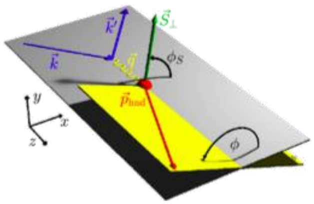
WHAT IS NEEDED TO REALIZE THIS PROGRAM

experimental program to address these questions:



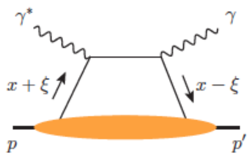
inclusive and semi-inclusive DIS

longitudinal motion of spinning quarks and gluons



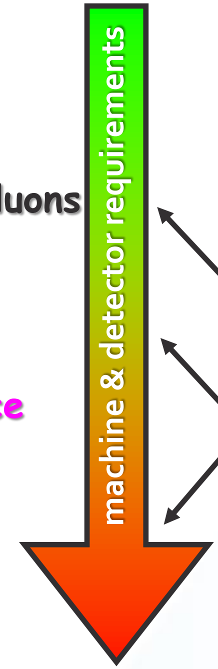
azimuthal asymmetries in DIS

adds their transverse momentum dependence



exclusive processes

adds their transverse position



prerequisites

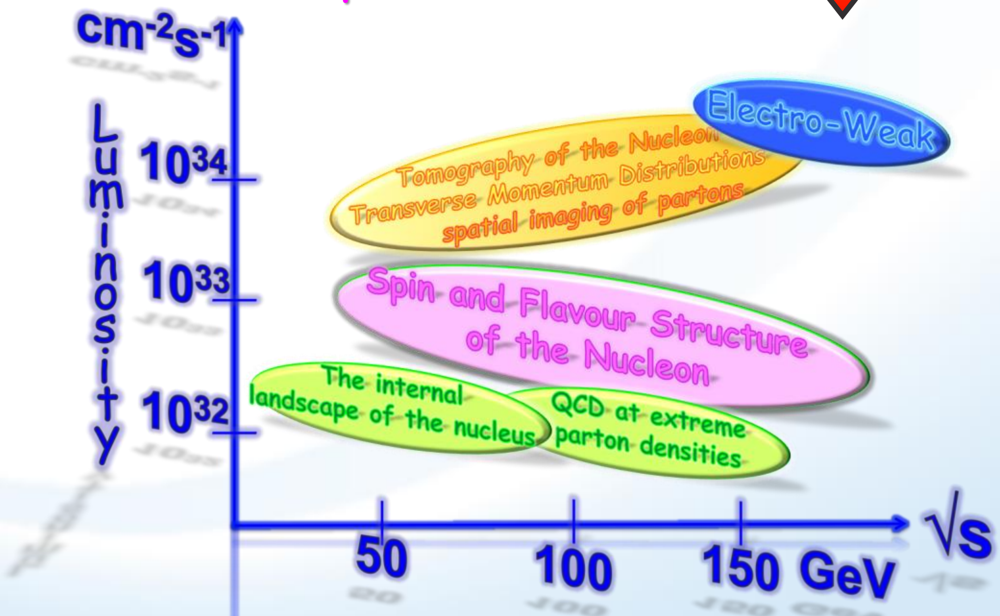
all need $\sqrt{s_{ep}} > 50$ GeV

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

$\mathcal{L} \simeq 10\,\mathrm{fb}^{-1}$

$\mathcal{L} = 10 \div 100\,\mathrm{fb}^{-1}$

- multi-dimensional binning
- to reach $k_T > 1$ GeV
- to reach $|t| > 1$ GeV²



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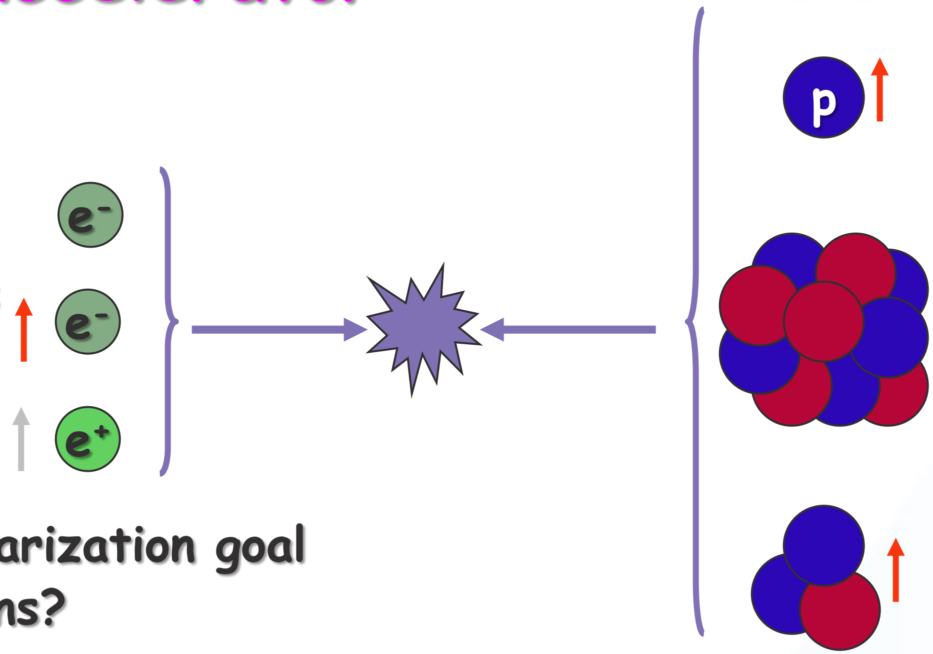
Electron accelerator

to be build

Unpolarized and polarized leptons 5-20 (30) GeV

RHIC

Existing = $2B



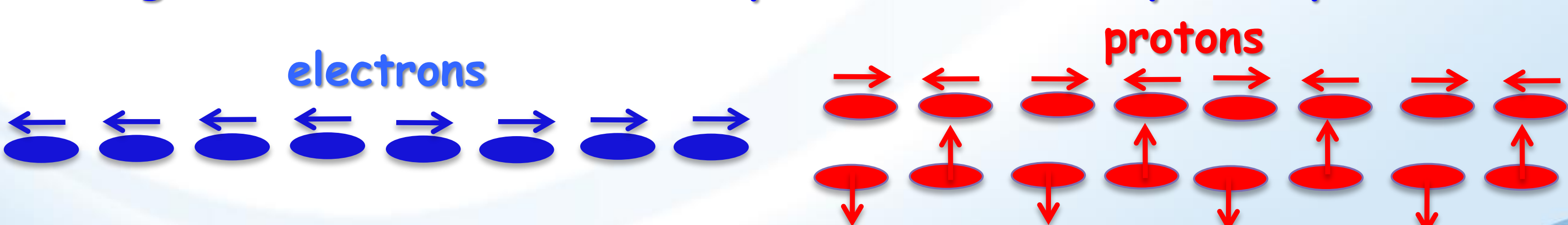
Polarized protons 50-250 GeV

Light ions (d,Si,Cu)
Heavy ions (Au,U)
50-100 GeV/u

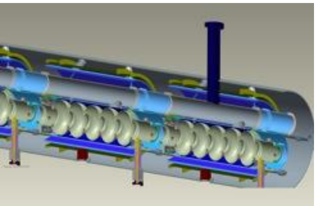
Polarized light ions
He^3 166 GeV/u

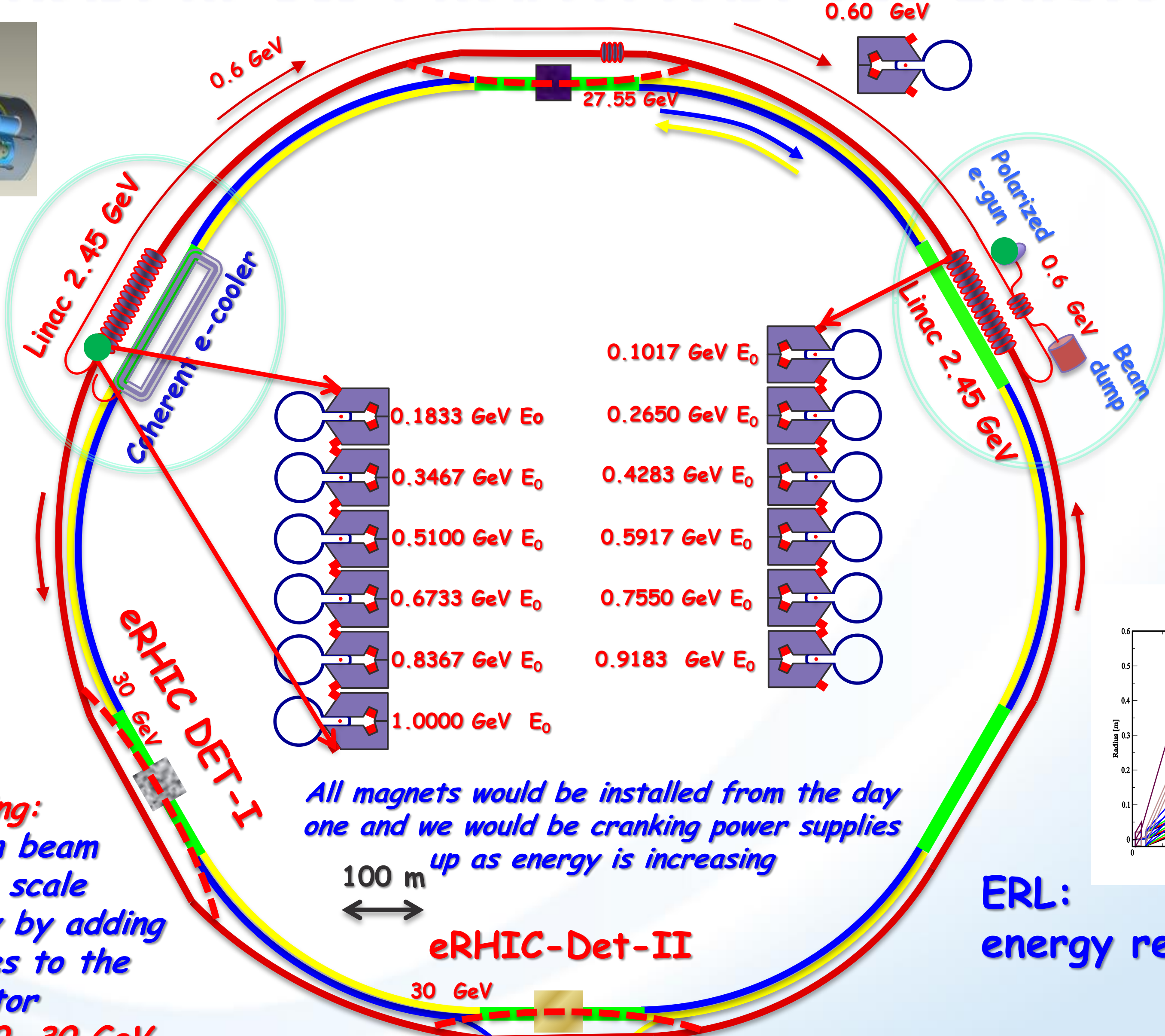
70% e^- beam polarization goal
polarized positrons?

Center mass energy range: $\sqrt{s}$=30-200 GeV; L~100-1000xHera
longitudinal and transverse polarization for p/He^3 possible

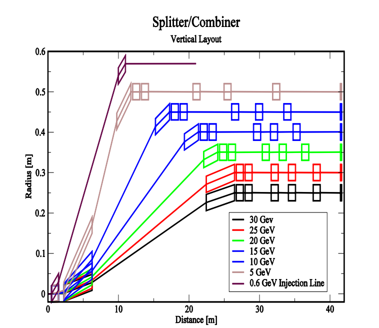


ELECTRON BEAM EVOLUTION IN eRHIC'S ERL





E/Eo
0.0200
0.1017
0.1833
0.2650
0.3467
0.4283
0.5100
0.5917
0.6733
0.7550
0.8367
0.9183
1.0000



All magnets would be installed from the day one and we would be cranking power supplies up as energy is increasing

Staging:

All lepton beam energies scale proportionally by adding SRF cavities to the injector

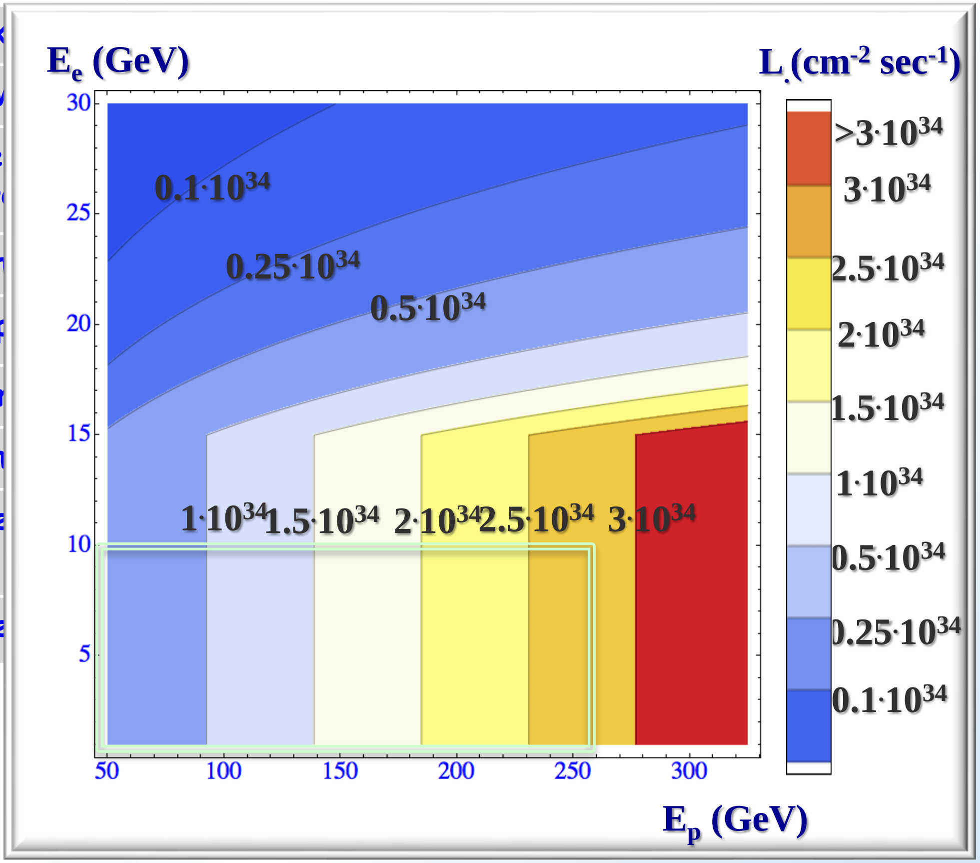
E_o=5, 10, 20, 30 GeV

ERL:
energy recovery linac

Animation is by N. Tsoupas

eRHIC R&D HIGHLIGHTS AND LUMINOSITY

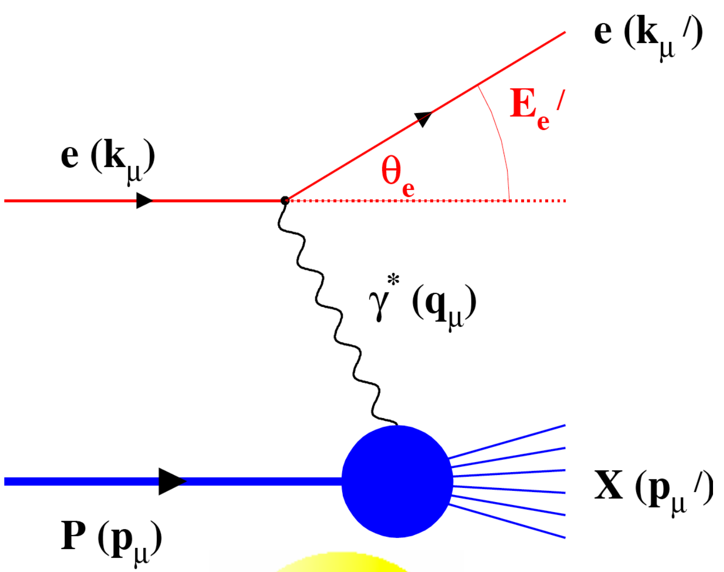
Challenge	Increase/reduction beyond the state of the art
Polarized electron gun	10 x
Coherent Electron Cooling	New
Multi-pass SRF ERL	5 x incre 30 x incr
Crab crossing	New for h
Understanding beam-beam effects	New typ
β*=5 cm	5x r
Multi-pass SRF ERL	2-3 x in
Feedback for kink instability suppression	Nove
Space charge effect compensation	Nove



- Hourglass the pinch effects are included. Space charge effects are compensated.
- Energy of electrons can be selected at any desirable value at or below 30 GeV
- The luminosity does not depend on the electron beam energy below or at 20 GeV
- The luminosity falls as E_e^{-4} at energies above 20 GeV
- The luminosity is proportional to the hadron beam energy: $L \sim E_h/E_{top}$

DEEP INELASTIC SCATTERING

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 2E_e E'_e(1 - \cos\Theta_{e'})$$

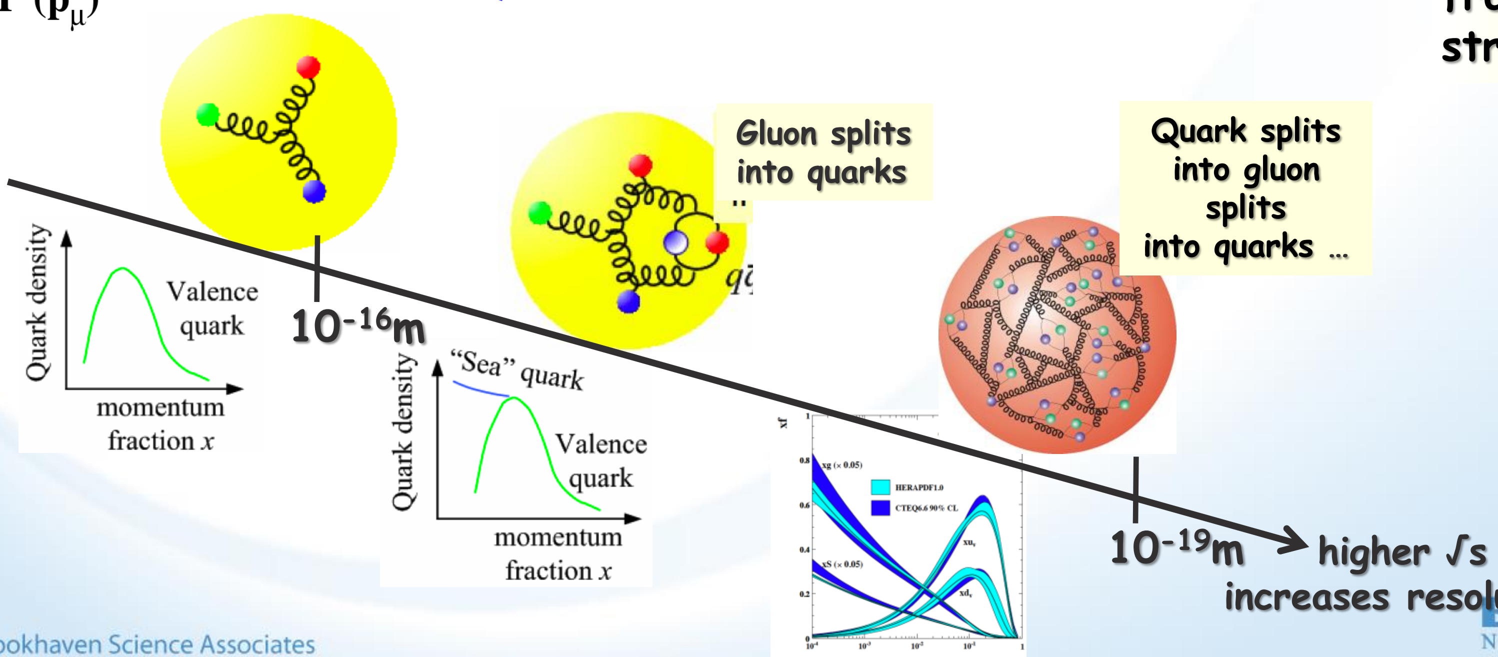
Measure of resolution power

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

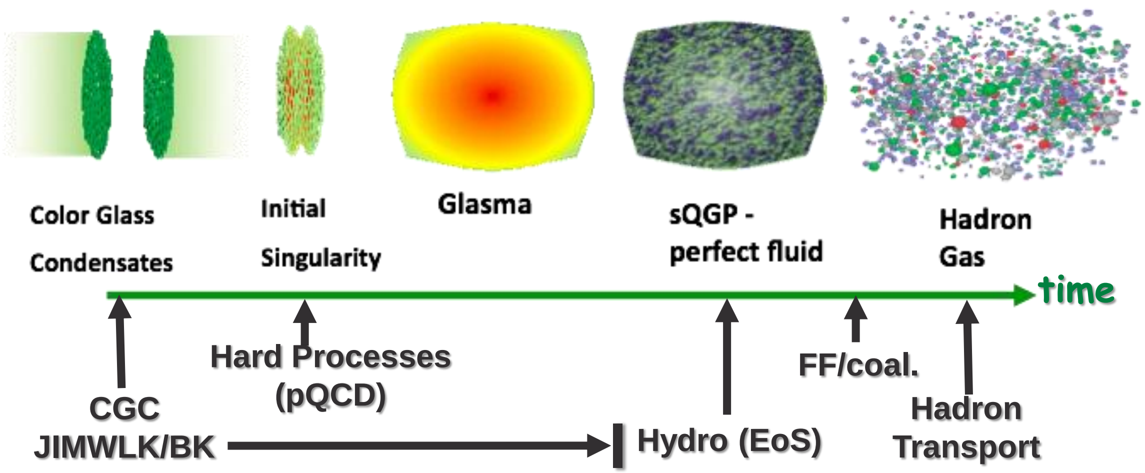
Measure of inelasticity

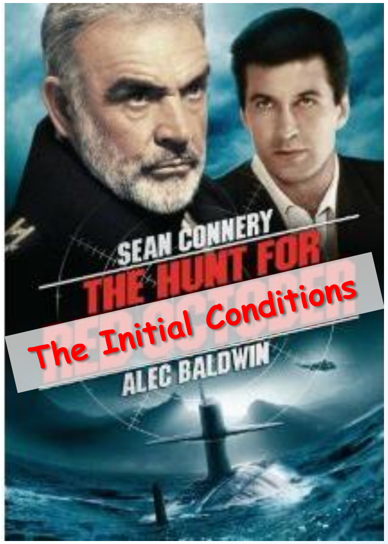
$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark



THE eA PHYSICS PROGRAM





Our understanding of some **fundamental** properties of the Glasma, sQGP and Hadron Gas depend **strongly** on our knowledge of the initial state!

3 conundrums of the initial state:

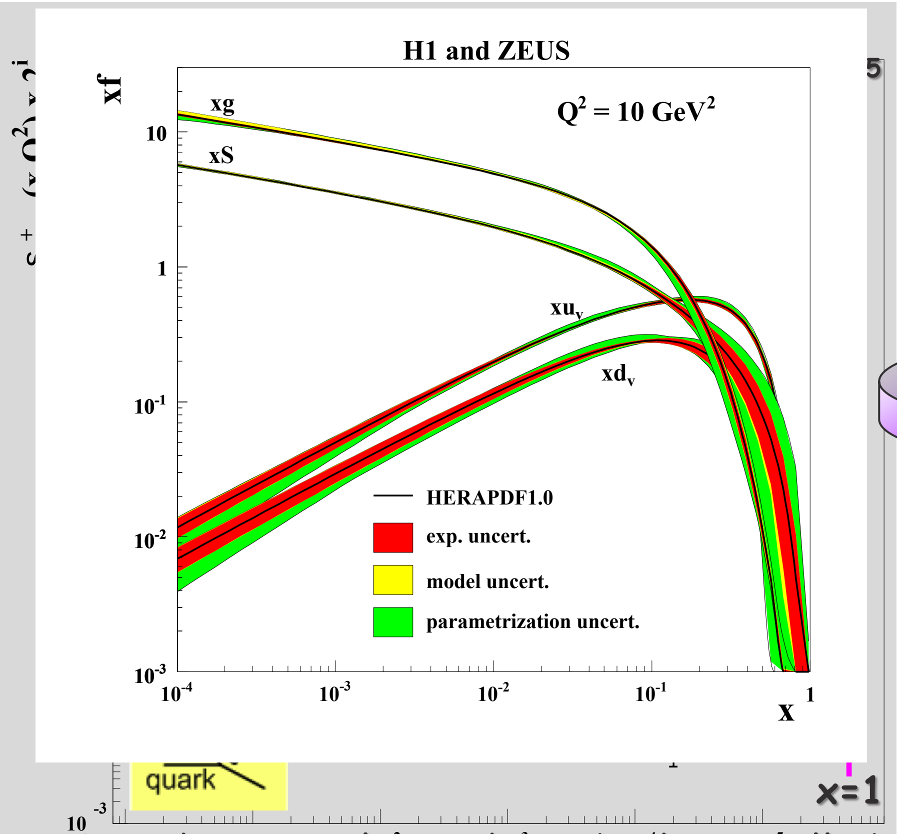
1. What is the spatial transverse distributions of nucleons and gluons?
2. How much does the spatial distribution fluctuate? Lumpiness, hot-spots etc.
3. How saturated is the initial state of the nucleus?
   → unambiguously see saturation

Advantage over p(d)A:

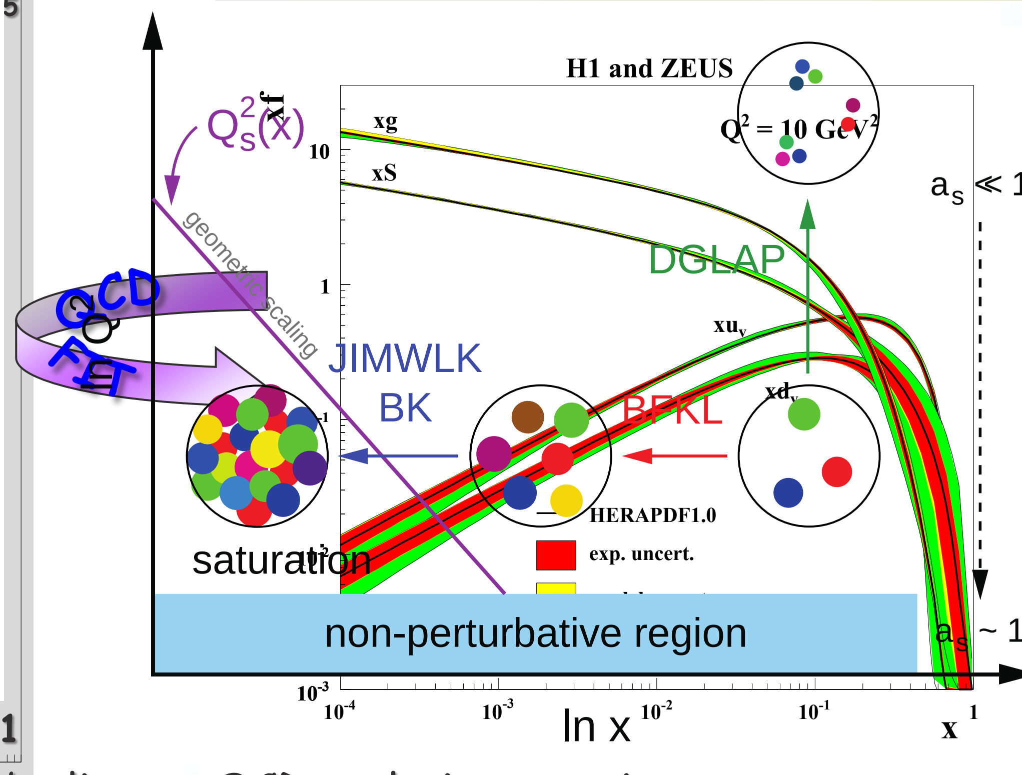
- eA experimentally much cleaner
  - ✓ no "spectator" background to subtract
- Access to the parton kinematics through scattered lepton (x, Q^2)
- initial and final state effects can be disentangled cleanly
- Saturation:
  - ✓ no alternative explanations, i.e. no hydro in eA

WHAT DO WE KNOW

Gluon density dominates at x<0.1

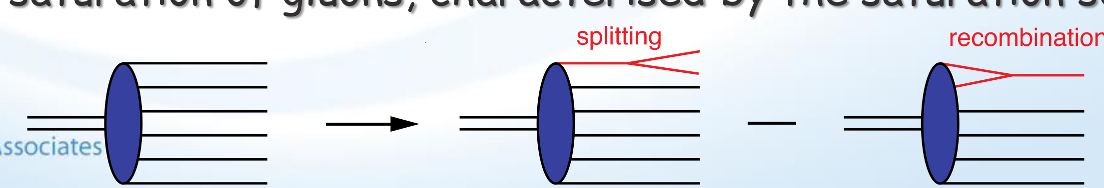


Gluon density dominates at x<0.1



- Rapid rise in gluons described naturally by linear pQCD evolution equations
- This rise cannot increase forever - limits on the cross-section

→ non-linear pQCD evolution equations provide a natural way to tame this growth and lead to a saturation of gluons, characterised by the saturation scale $Q^2_s(x)$



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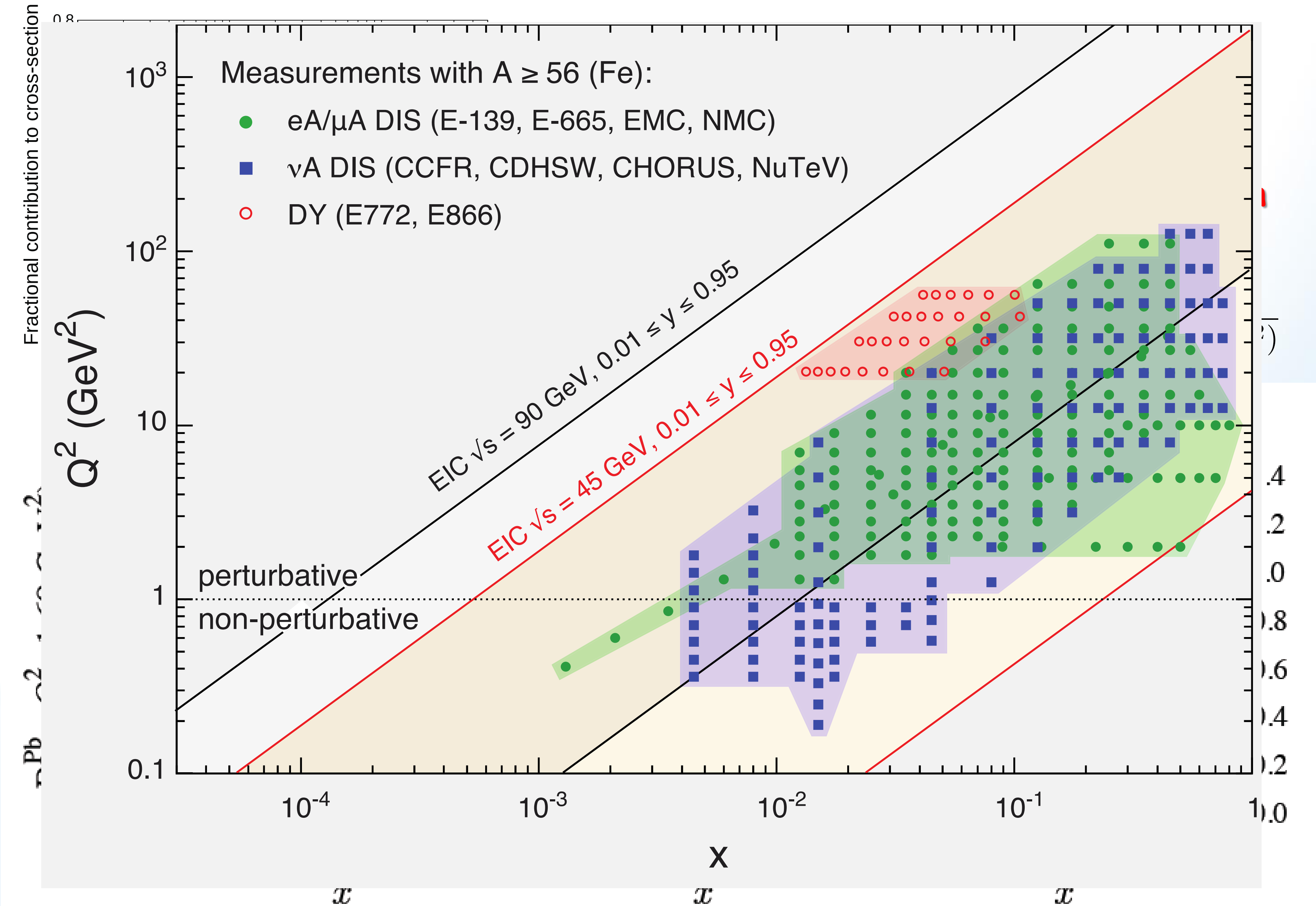
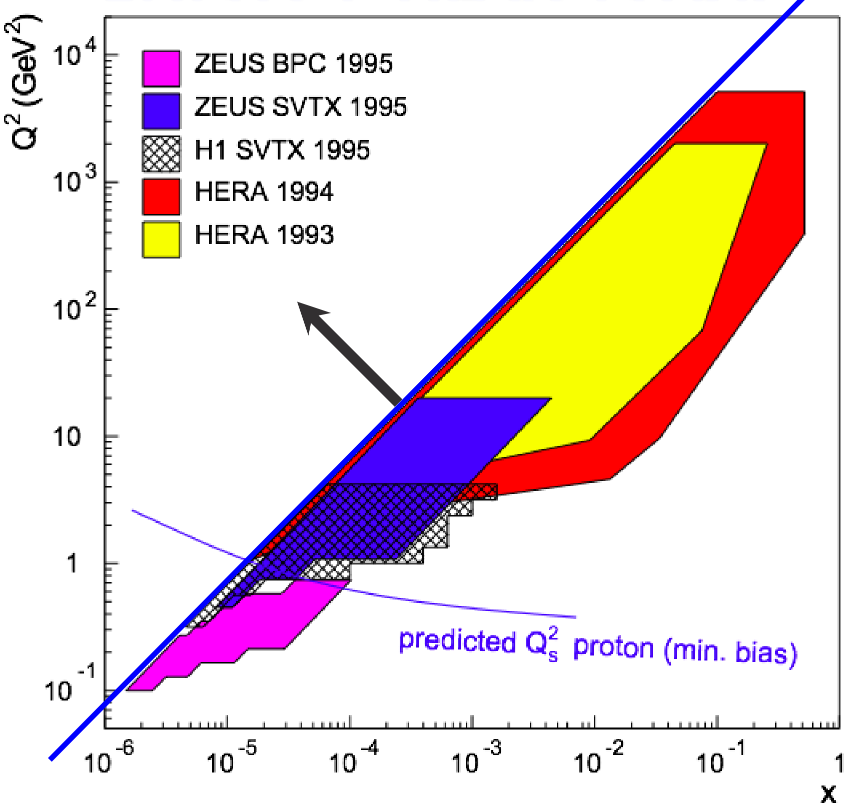
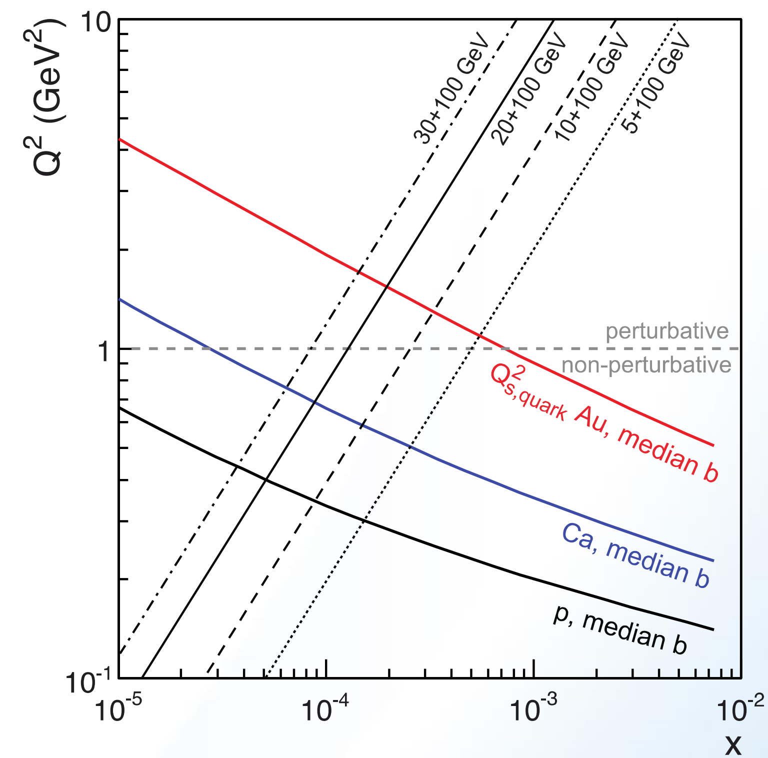
WHAT DO WE KNOW ABOUT xG IN NUCLEI?



eRHIC: REACHING THE SATURATION REGION





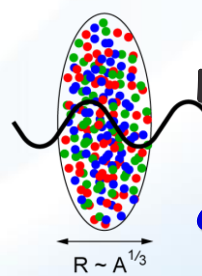
HERA (ep):

Despite high energy range:

- F_2, $G_p(x, Q^2)$ outside the saturation regime
- **Need also Q^2 lever arm!**
- Only way in ep is to increase $\sqrt{s}$
- Would require an ep collider at $\sqrt{s} \sim$ 1-2 TeV → LHeC

eRHIC (eA):

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



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

Probe interacts

coherently with all nucleons

Gold: 197 times smaller effective *x* !

MEASURING F_L WITH THE EIC (I)

$$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark momentum distributions

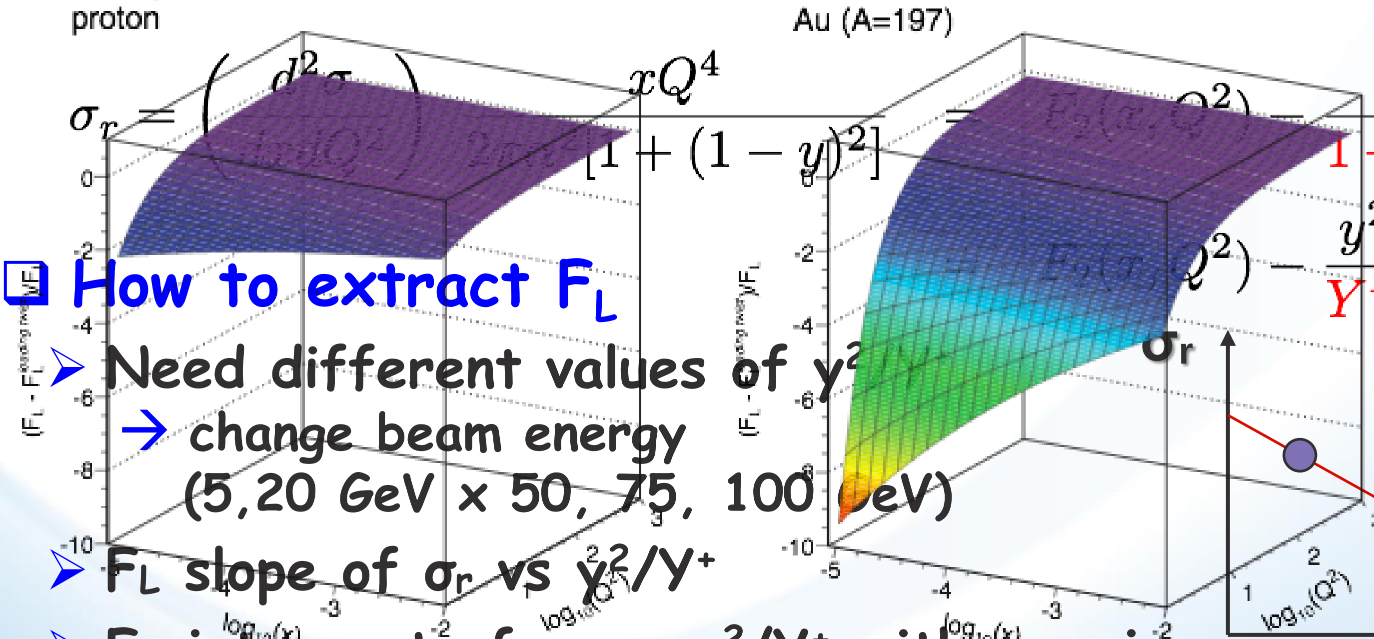
gluon momentum distribution

- Expect strong non-linear effects in F_L

In practice use reduced cross-section:

$$\sigma_r = \left(\frac{d^2\sigma}{dxdQ^2}\right)\frac{xQ^4}{2\pi\alpha^2[1+(1-y)^2]} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$

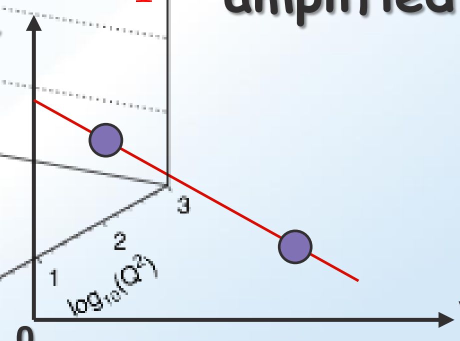
$$= F_2(x,Q^2) - \frac{y^2}{Y^+}F_L(x,Q^2)$$



Relative contributions of higher twist effects to F_L amplified in eA

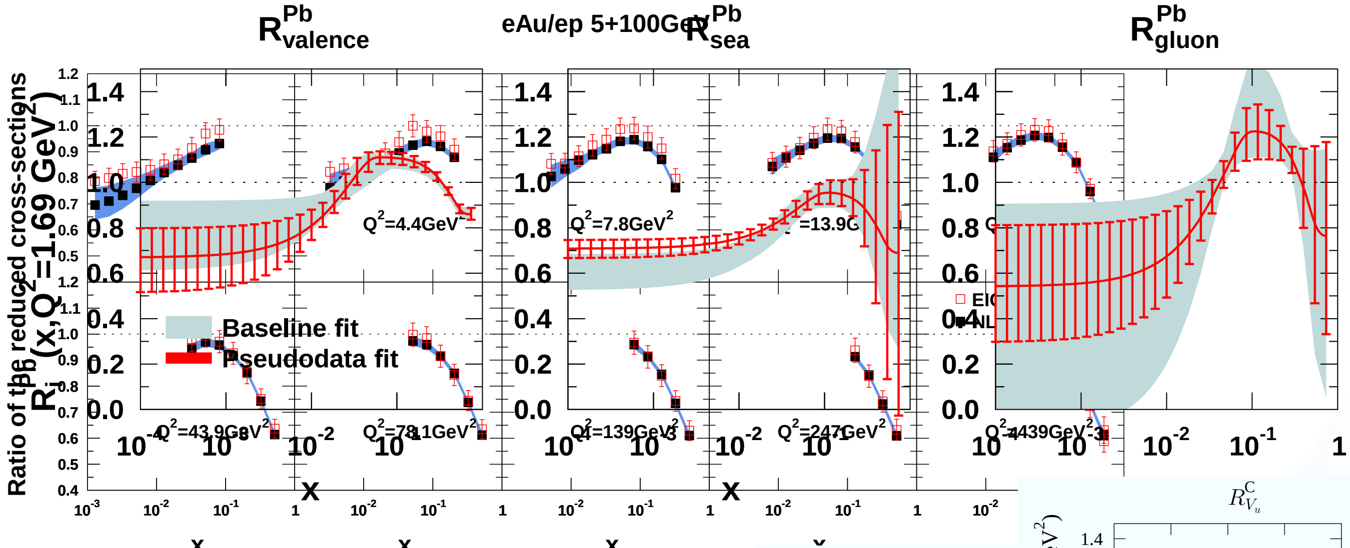
Dipole model (J. Bartels et al.)

- How to extract F_L
  - Need different values of y^2/Y^+
    - → change beam energy (5,20 GeV x 50, 75, 100 GeV)
  - F_L slope of σ_r vs y^2/Y^+
  - F_2 intercept of σ_r vs y^2/Y^+ with y-axis



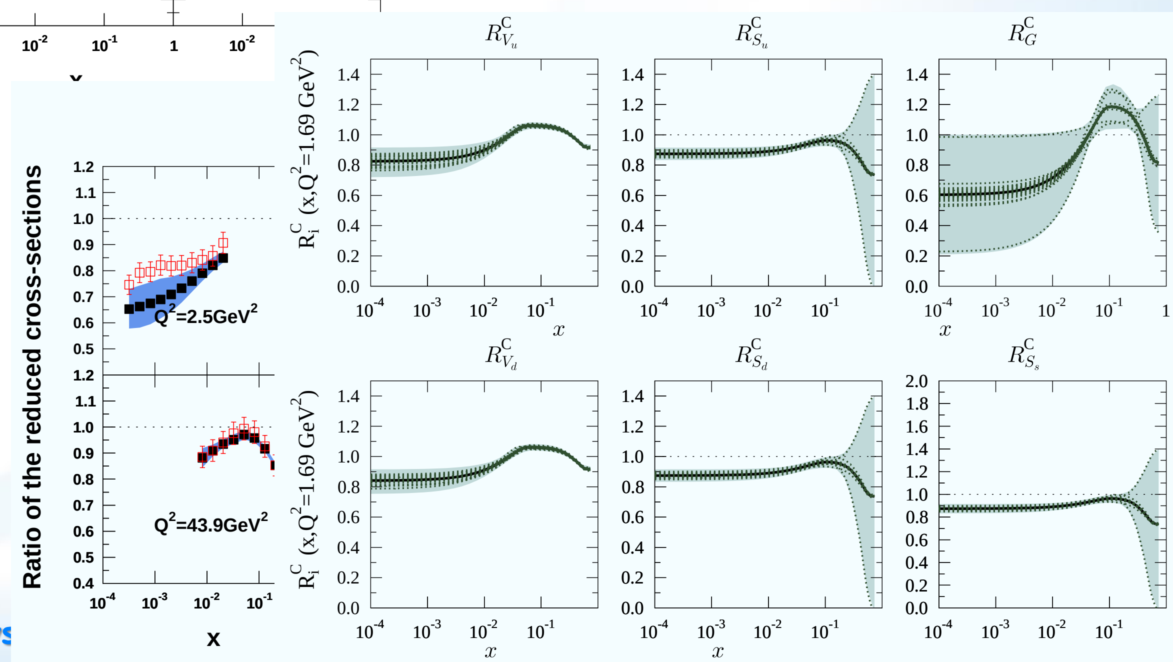
IMPACT ON EPS nPDFs

- Take the generated Pseudo-data and include it in a global fit
  - Only 20x100 and 5x100 included in these plots
    - More data will constrain this further



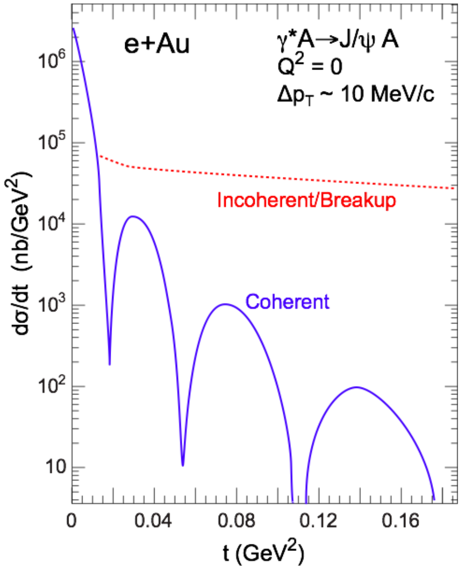
F_2^C and F_L^C will improve gluon further

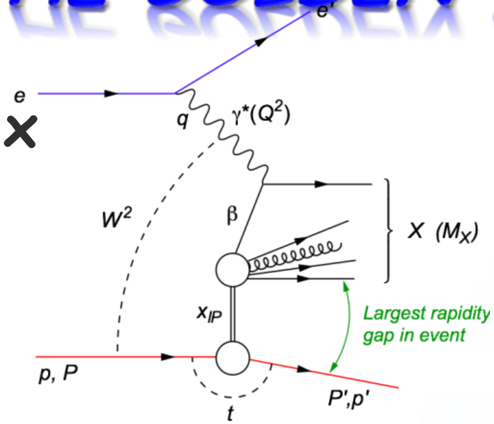
big impact even with limited part of generated pseudo data



SATURATION: THE GOLDEN CHANNEL

- Hard diffraction in DIS at small x





Why is diffraction so important

- Sensitive to **spatial** gluon distribution

$$\frac{ds}{dt} \text{ o } \frac{\text{Fourier Transformation}}{\text{of Source Density } r_g(\text{b})}$$

  - Hot topic:
    - Lumpiness?
    - Just Wood-Saxon+nucleon g(b)
  - Incoherent case: measure fluctuations/lumpiness in g_A(b)
- VM: Sensitive to gluon momentum distributions
  - $\sigma \sim g(x,Q^2)^2$

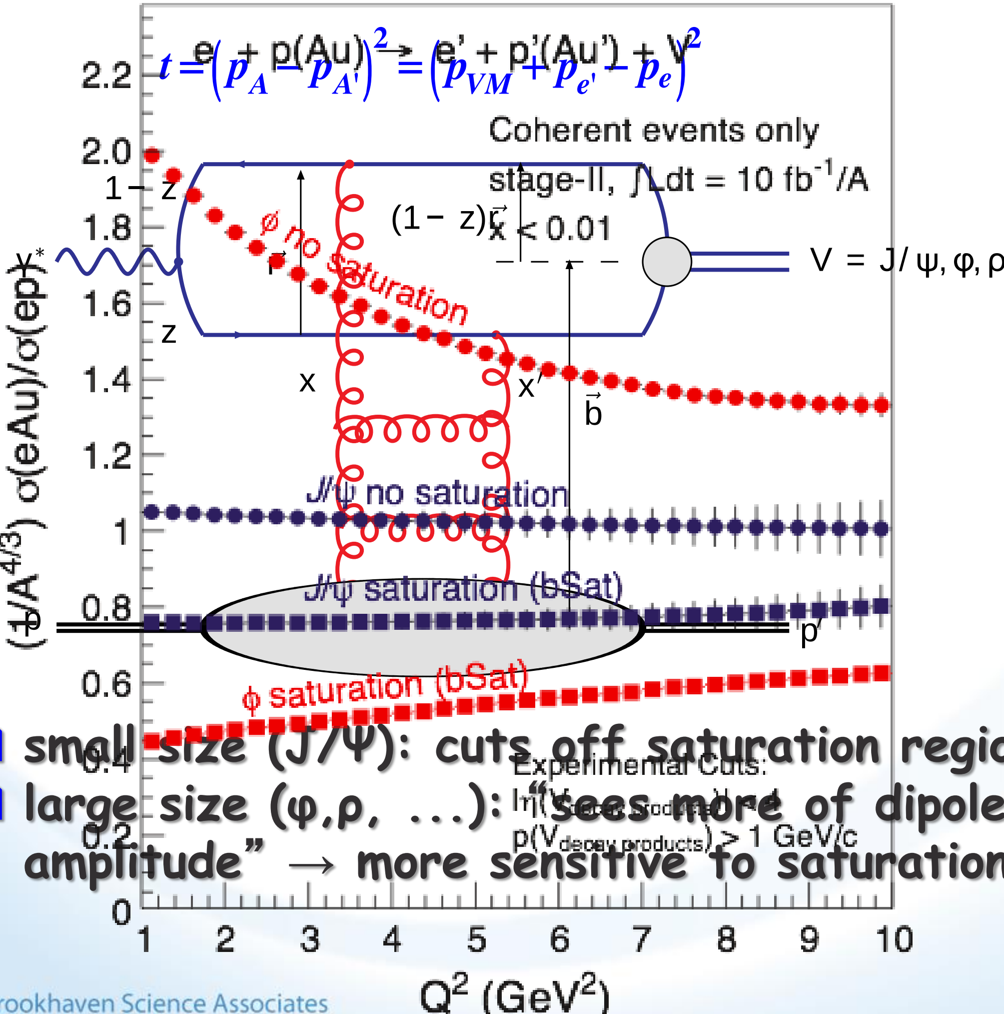
- Diffraction in e+A:
  - coherent diffraction (nuclei intact)
  - breakup into nucleons (nucleons intact)
  - incoherent diffraction

Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%

HERA: 15% of all events are hard diffractive

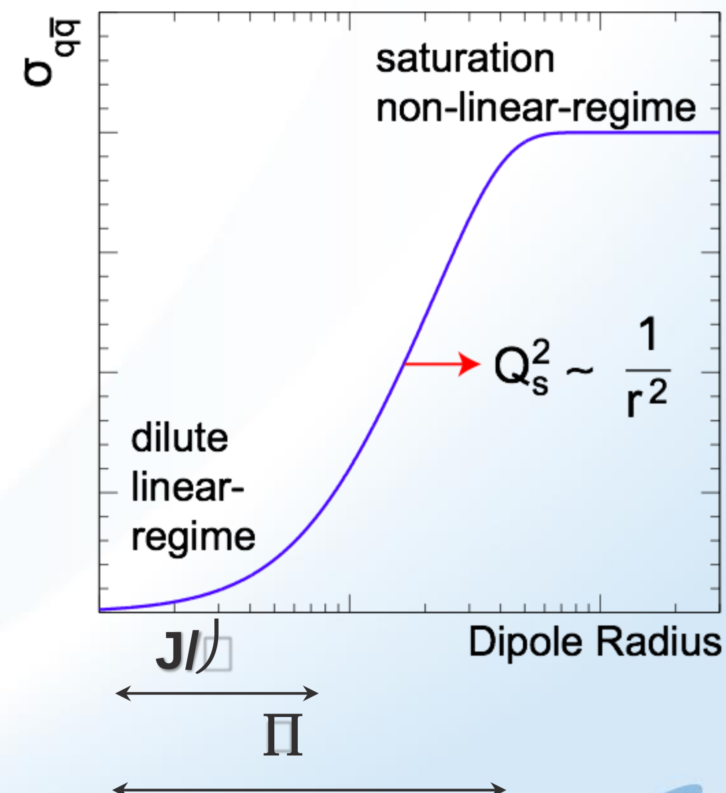
EXCLUSIVE VECTOR MESON PRODUCTION

- Unique probe - allows to measure momentum transfer t in eA diffraction
  - → in general, one cannot detect the outgoing nucleus and its momentum



- small size (J/Ψ): cuts off saturation region
- large size (φ,ρ, ...): "sees more of dipole amplitude" → more sensitive to saturation

Dipole Cross-Section:

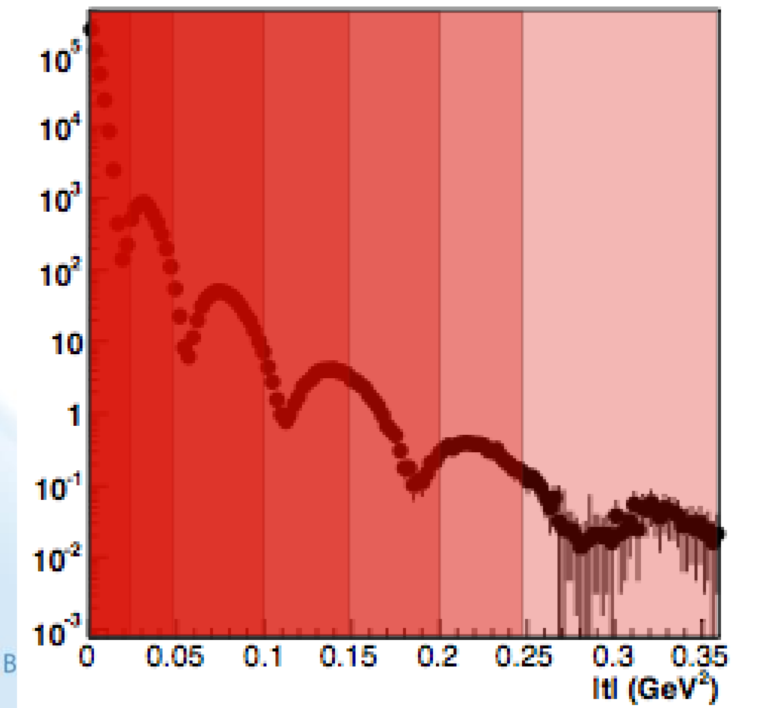


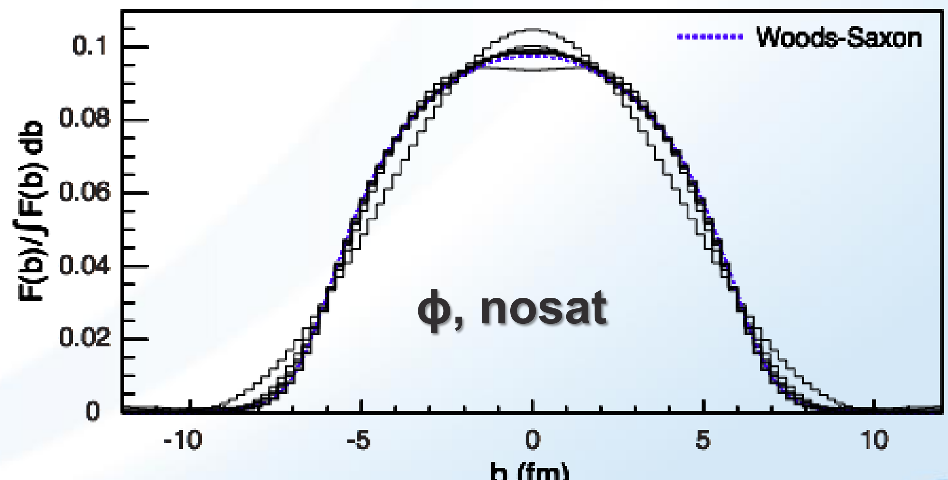
SPATIAL GLUON DISTRIBUTION THROUGH DIFFRACTION

- Idea: momentum transfer t conjugate to transverse position (b_T)
  - coherent part probes "shape of black disc"
  - incoherent part (dominant at large t) sensitive to "lumpiness" of the source (fluctuations, hot spots, ...)

Spatial source distribution: $$F(b) \sim \frac{1}{2\pi}\int_0^\infty d\Delta \Delta J_o(\Delta b)\sqrt{\frac{d\sigma}{dt}}$$

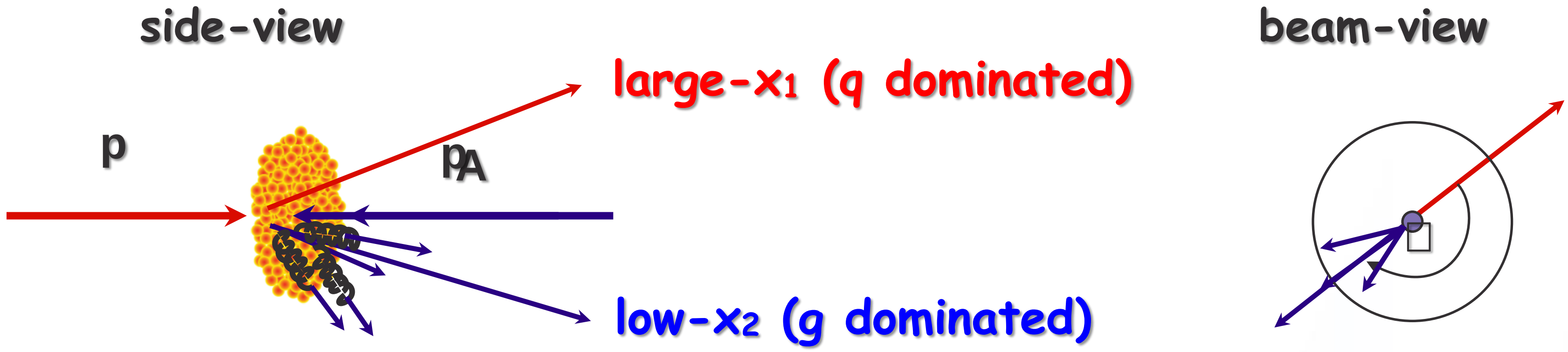
$$t = \Delta^2/(1-x) \approx \Delta^2 \quad \text{(for small x)}$$





Golden eA measurement for eRHIC

h-h FORWARD CORRELATION IN p(d)A AT RHIC



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

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

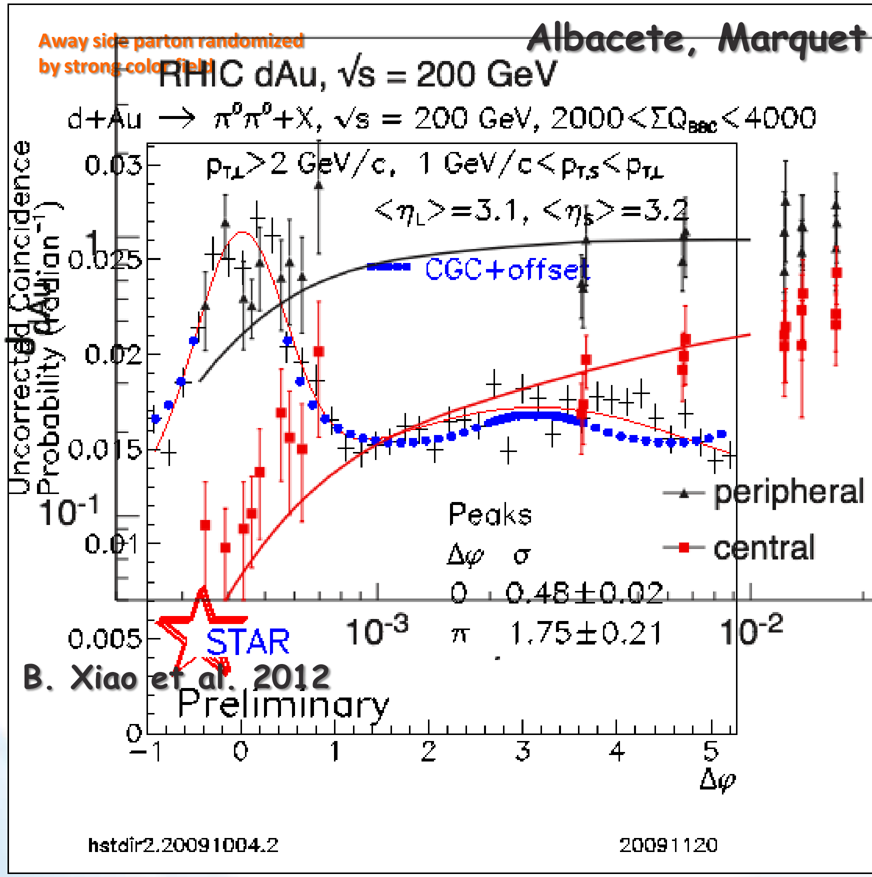
- Small-x evolution ↔ multiple emissions
- Multiple emissions → broadening
- Back-to-back jets (= leading hadrons) may get broadening in p_T with a spread of the order of Q_S

Advantage of eA over p(d)A:
- eA experimentally much cleaner
- no "spectator" background to subtract
- Access to the exact kinematics of the DIS process (x, Q^2)

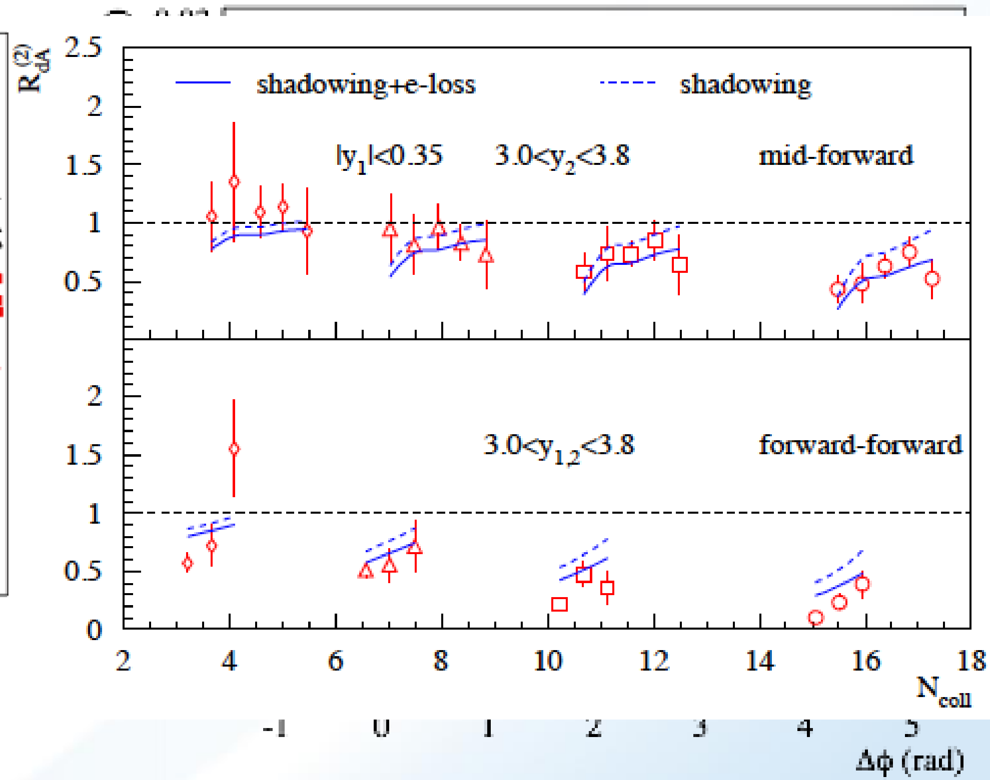
FORWARD CORRELATIONS IN dA AT RHIC

1 question, 2 answers

Initial state saturation model



"Non-initial state" shadowing model



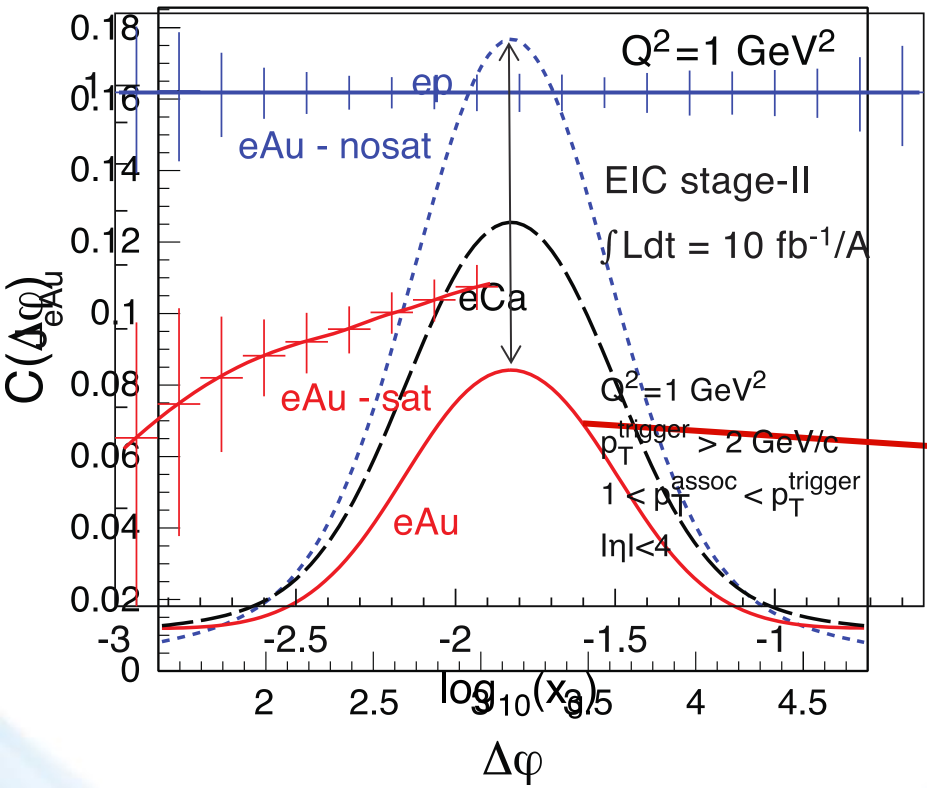
$$\left\langle q_\perp^2 \right\rangle_{dAu} = \left\langle q_\perp^2 \right\rangle_{pp} + \Delta \left\langle q_\perp^2 \right\rangle$$

How saturated is the initial state?

eA DIHADRON CORRELATIONS STUDIES

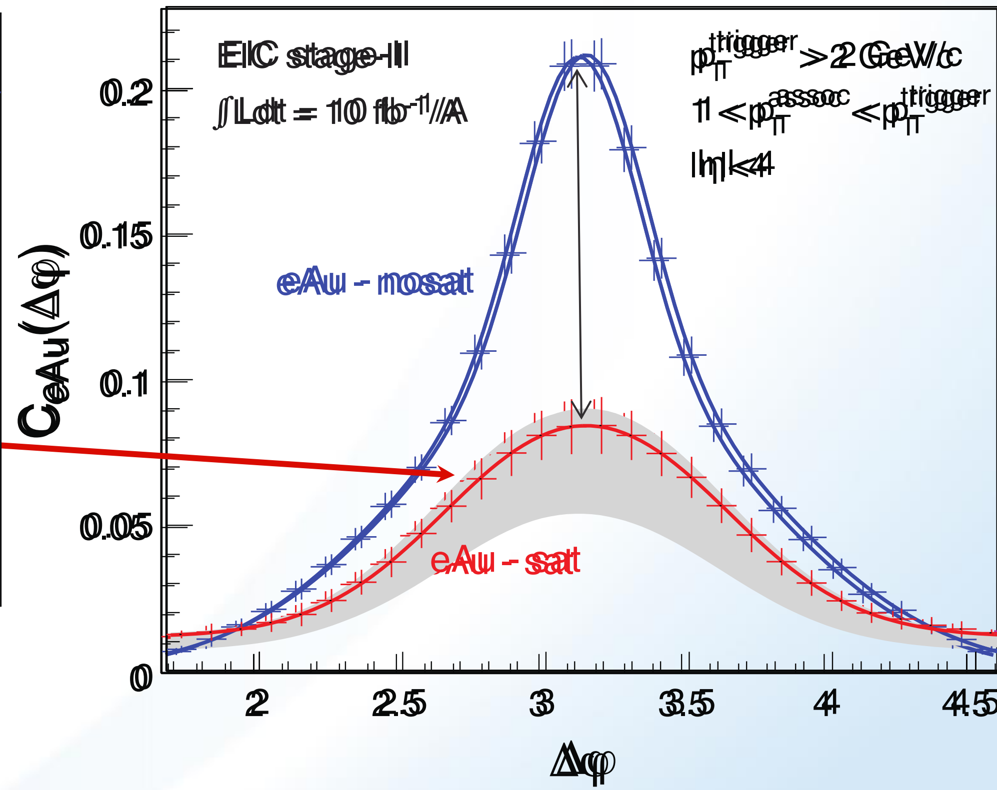
Theory: Saturation

Dominguez, Xiao, Yuan, Lee, Zheng '11/12



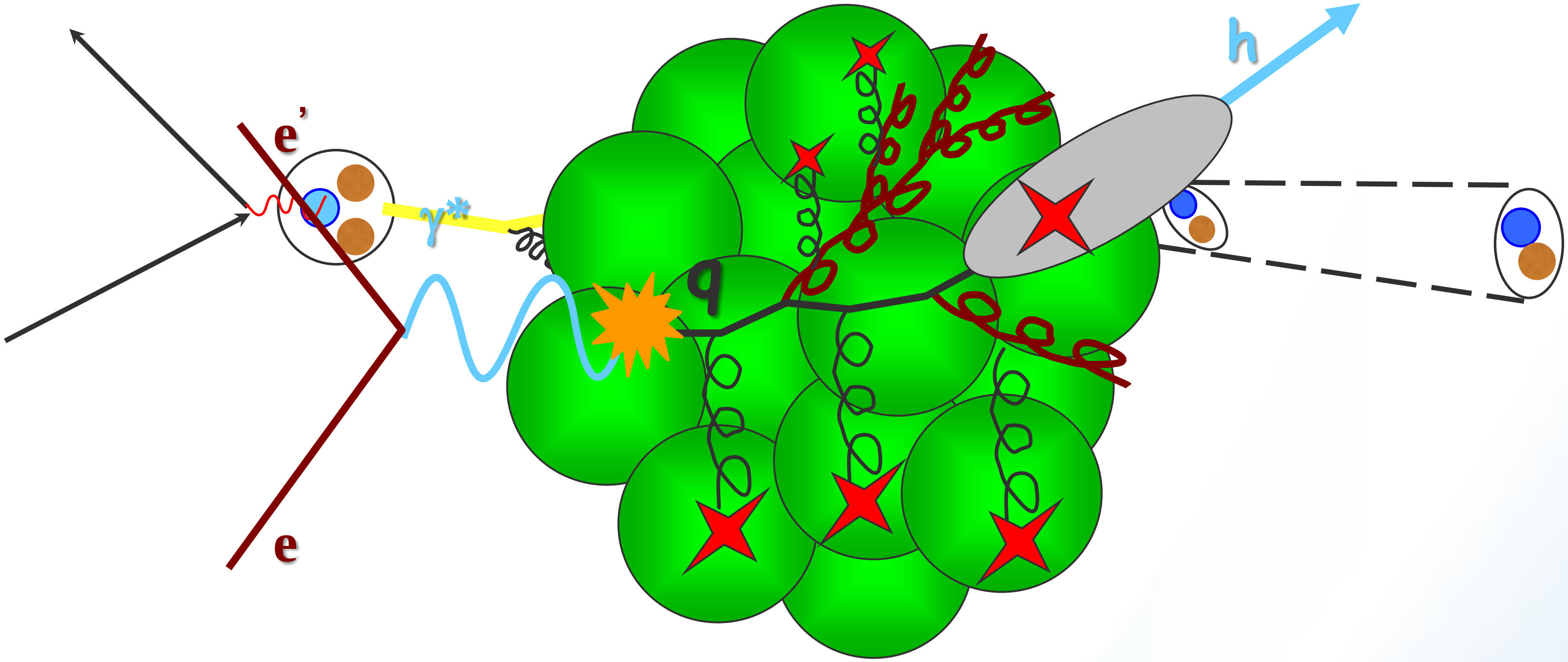
Exp: Saturation versus "conventional" scenario

J.H. Lee, L. Zheng (CCNU) '11/12



- eA-MC: Pythia6.4 + nPDF (EPS09) + nuclear geometry from DPMJetIII without PS
- Here for 10 fb^{-1}/A (~ 20 weeks), std. experimental cuts
- Clear signal, pronounced differences between sat and no-sat

DEEP INELASTIC SCATTERING - VACUUM



What happens if we add a nuclear medium

Observables:

Broadening: Δp_t^2 linked directly with saturation scale $\Delta p_t^2 = \langle p_t^2 \rangle_A - \langle p_t^2 \rangle_p$

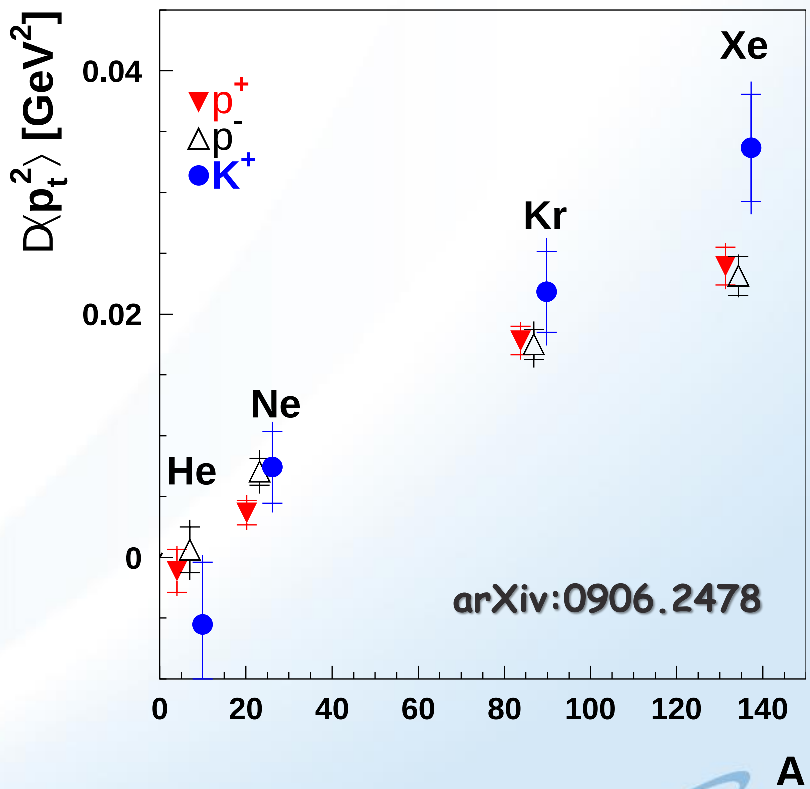
Attenuation: ratio of hadron production in A to d $R_A^h(Q^2, x, z, p_t, \Theta)$
modifications of nPDF cancel out

FRAGMENTATION IN NUCLEAR MEDIUM

$$R_A^h(z,\nu,p_t,Q^2) = \frac{\left.\dfrac{N_h(z,\nu,p_t,Q^2)}{N_{DIS}}\right|_A}{\left.\dfrac{N_h(z,\nu,p_t,Q^2)}{N_{DIS}}\right|_D} = \frac{\left.\dfrac{1}{\sigma_{DIS}}\dfrac{d^2\sigma_h}{dz\,d\nu\,dp_t\,dQ^2}\right|_A}{\left.\dfrac{1}{\sigma_{DIS}}\dfrac{d^2\sigma_h}{dz\,d\nu\,dp_t\,dQ^2}\right|_D} = \frac{\left.\dfrac{\sum e_f^2 q_f(x,Q^2,k_t)\,D_f^h(z,p_t,Q^2)}{\sum e_f^2 q_f(x,Q^2,k_t)}\right|_A}{\left.\dfrac{\sum e_f^2 q_f(x,Q^2,k_t)\,D_f^h(z,p_t,Q^2)}{\sum e_f^2 q_f(x,Q^2,k_t)}\right|_D}$$

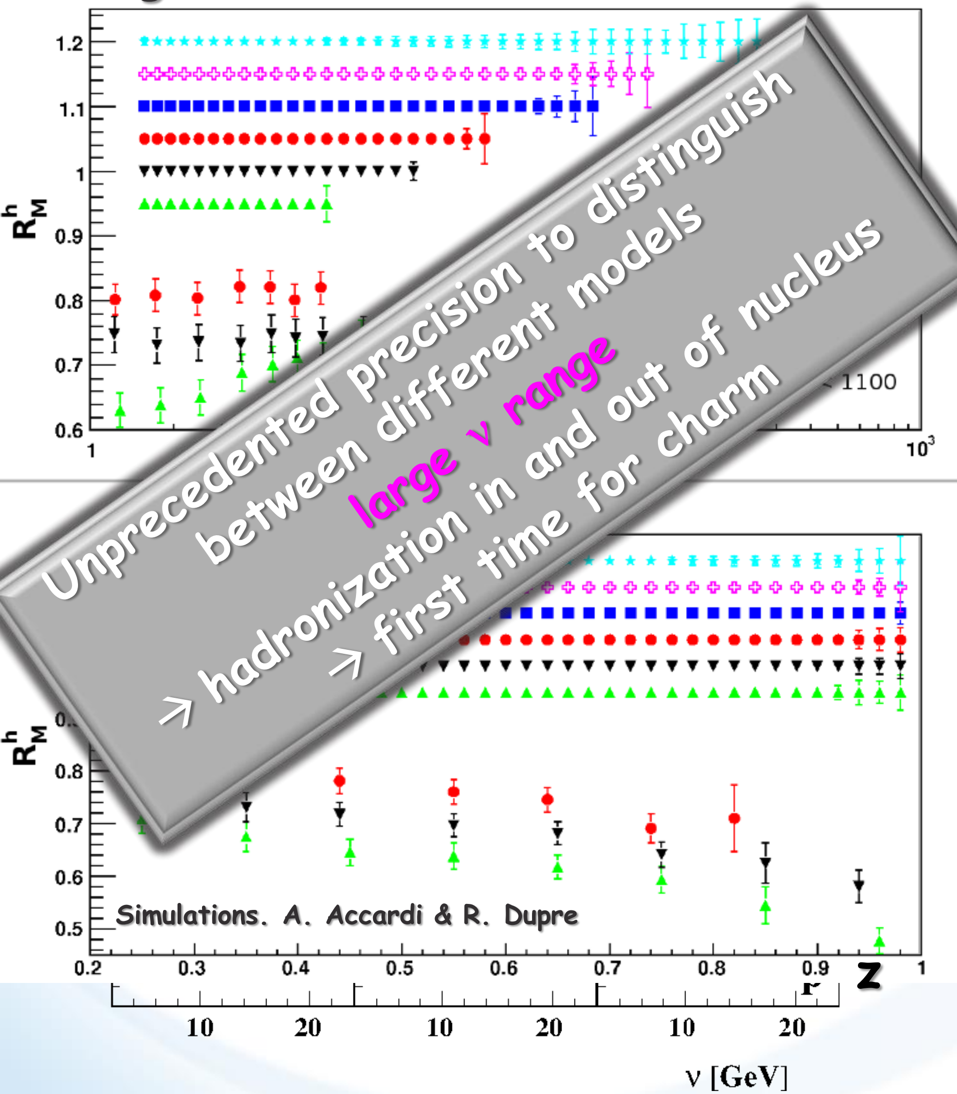
Advantage over p(d)A:

- eA experimentally much cleaner
  - ✓ no "spectator" background to subtract
- Access to the parton kinematics through scattered lepton (x, Q^2)
- initial and final state effects can be disentangled cleanly
- important to test universality with pA
- Saturation:
  - ✓ no alternative explanations, i.e. no hydro in eA

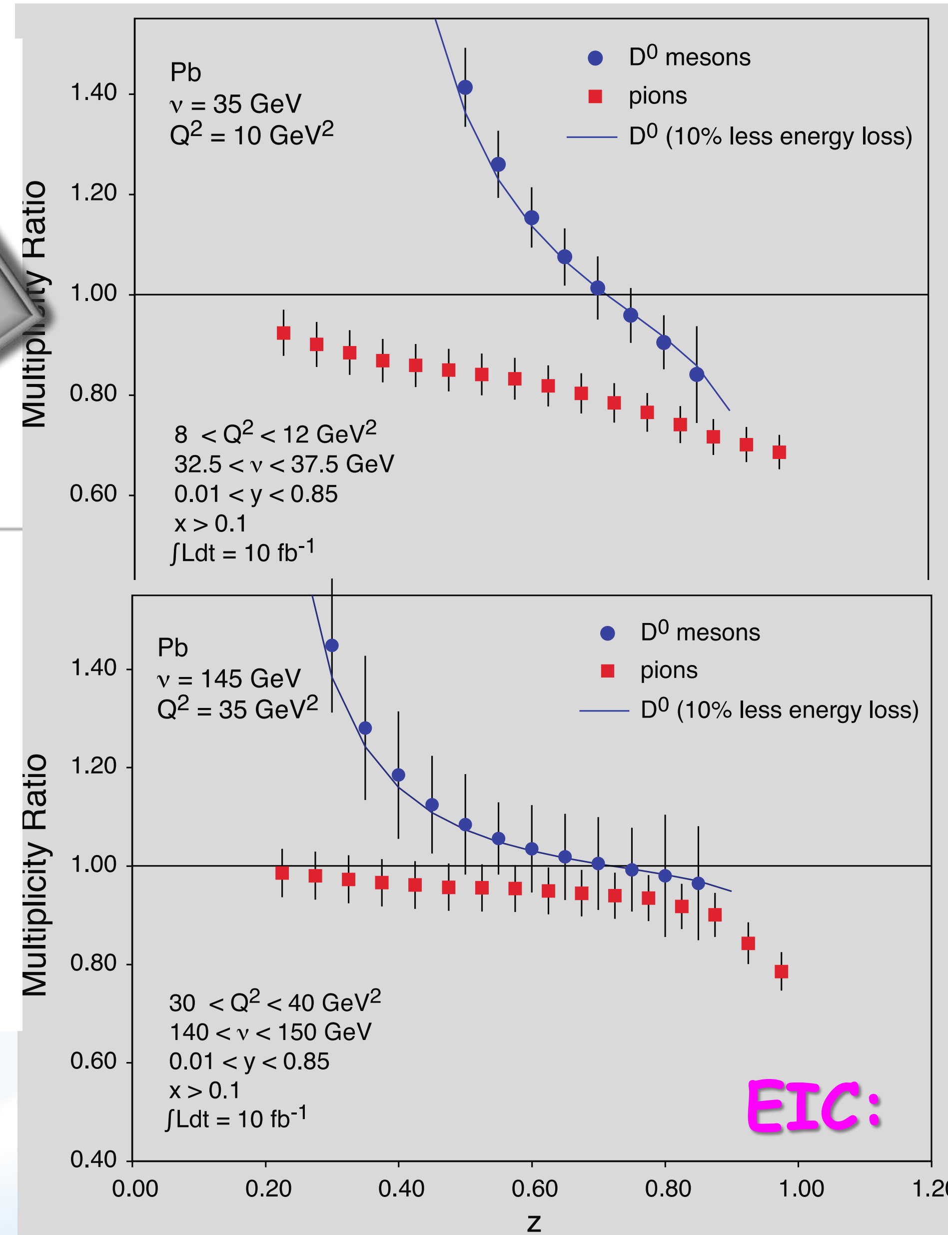


WHAT DO WE KNOW AND WHAT CAN EIC DO

- light hadrons

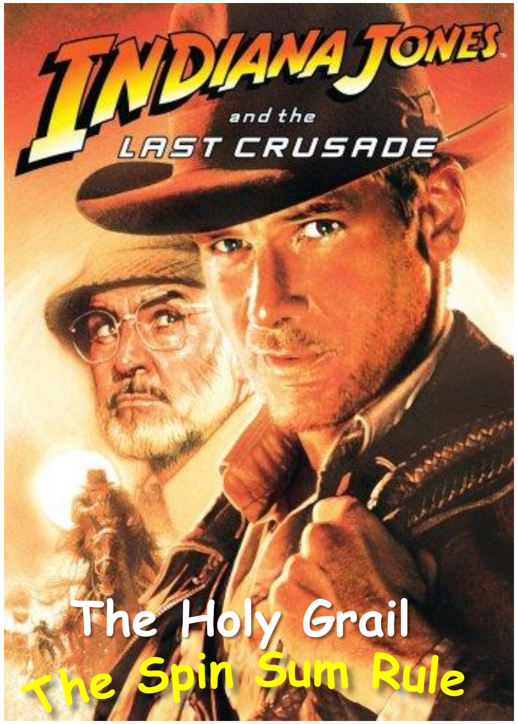


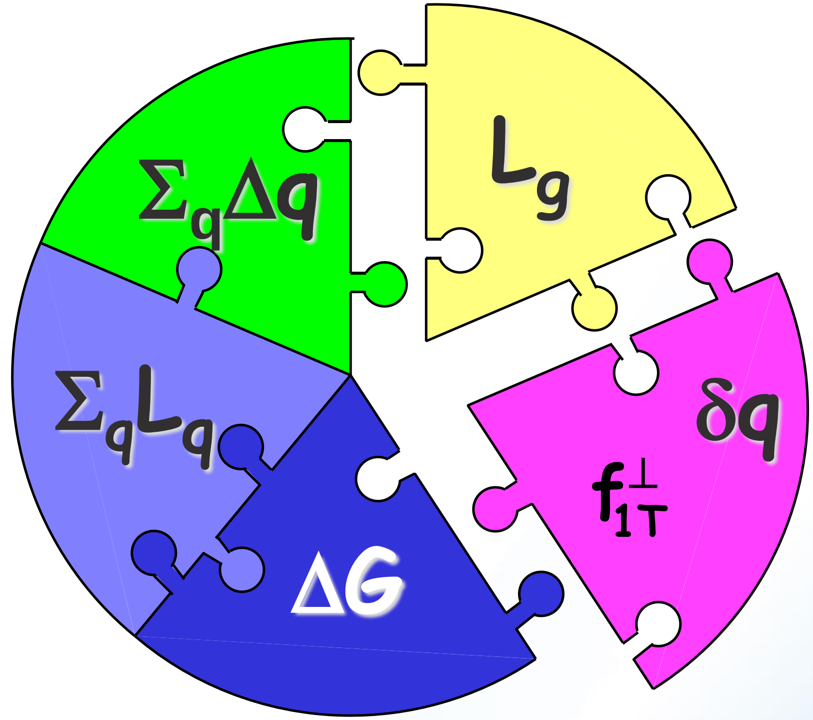
Unprecedented precision to distinguish between different models
large ν range
→ hadronization in and out of nucleus
→ first time for charm



EIC:

WHAT COMPOSES THE SPIN OF THE PROTON





"Helicity sum rule"

$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2} \middle| J^z_{QCD} \middle| P,\frac{1}{2}\right\rangle = \underbrace{\sum_q \frac{1}{2} S^z_q}_{\text{total u+d+s quark spin}} + \overbrace{S^z_g}^{\text{gluon spin}} + \underbrace{\sum_q L^z_q + L^z_g}_{\text{angular momentum}}$$

gluon spin

total u+d+s quark spin

angular momentum

Can an eRHIC give the final answer?

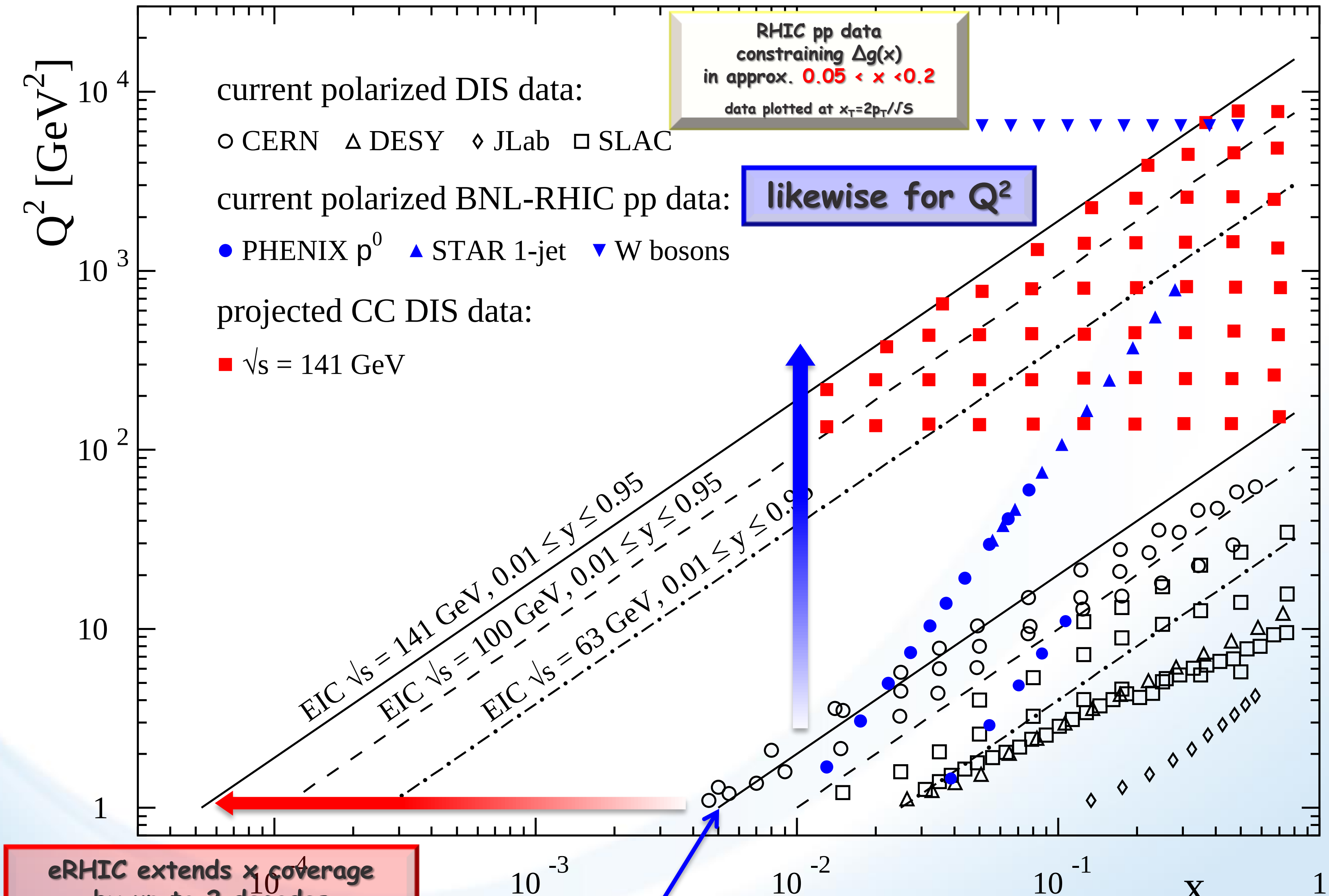
Contribution to proton spin to date:

Gluon: 20% (RHIC)

Quarks: 30% (DIS)

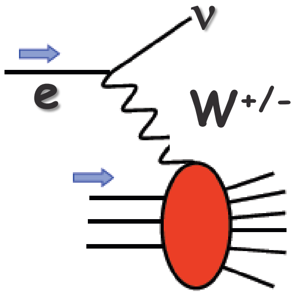
MISS 50% → low x

PRESENT VS eRHIC KINEMATIC COVERAGE



eRHIC extends x coverage by up to 2 decades (at Q^2=1 GeV^2)

lowest x so far 4.6 x10^{-3} COMPASS



$$A_L^{W^-,N} = \frac{d^2\Delta\sigma^{W^-,N}/dxdy}{d^2\sigma^{W^-,N}/dxdy}$$

POLARIZED EW PHYSICS

Complementary to SIDIS:

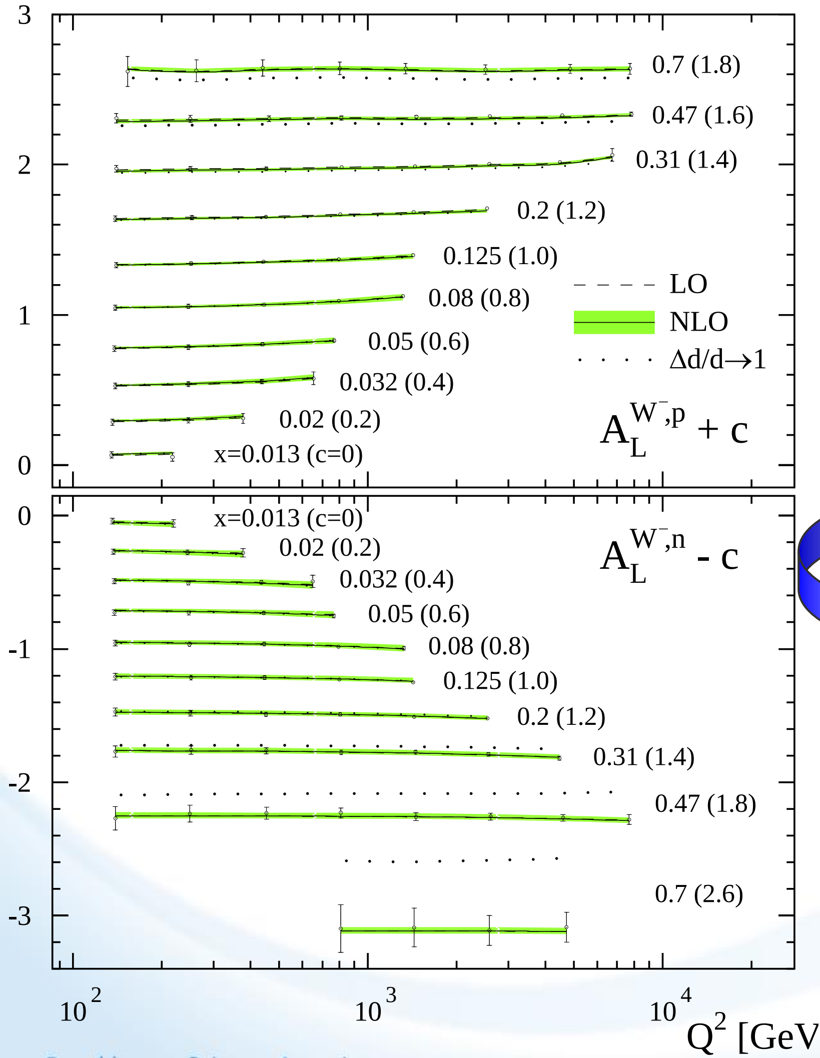
very high Q2-scale

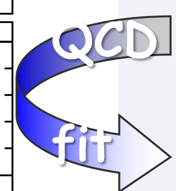
extremely clean theoretically

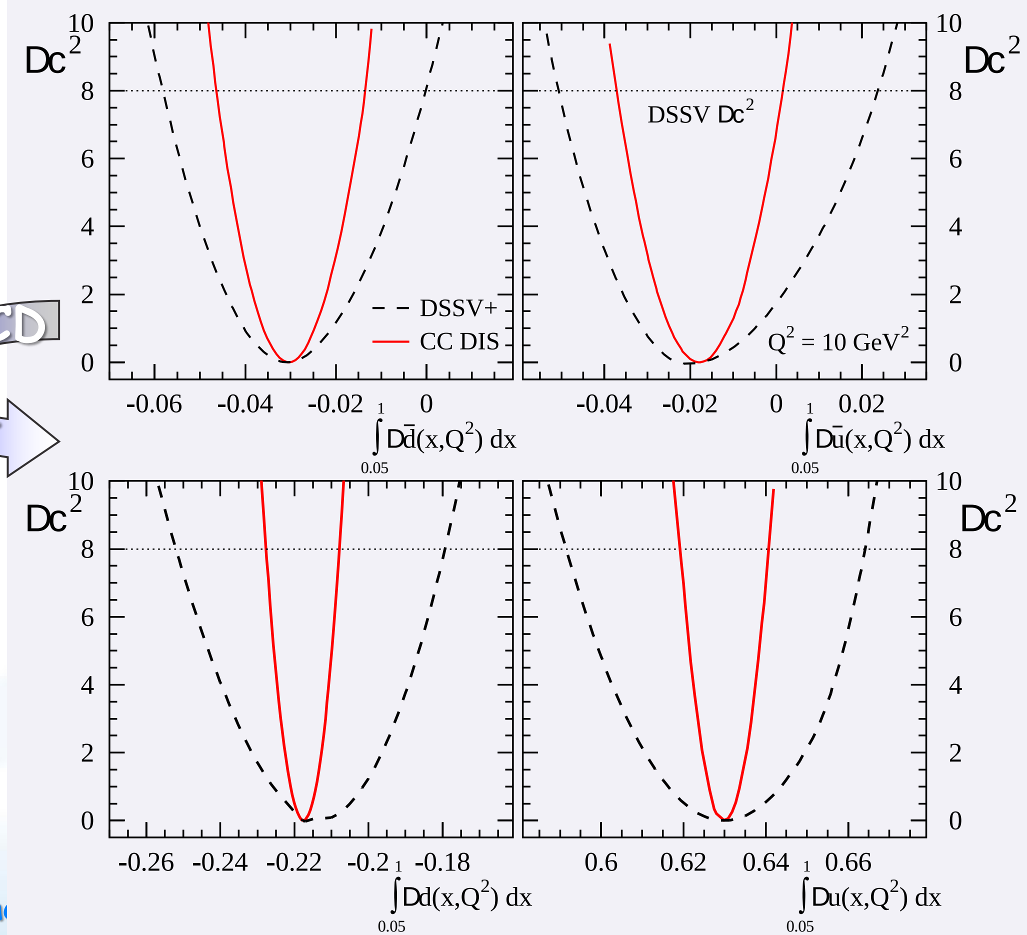
No Fragmentation function

best way to measure at very high x

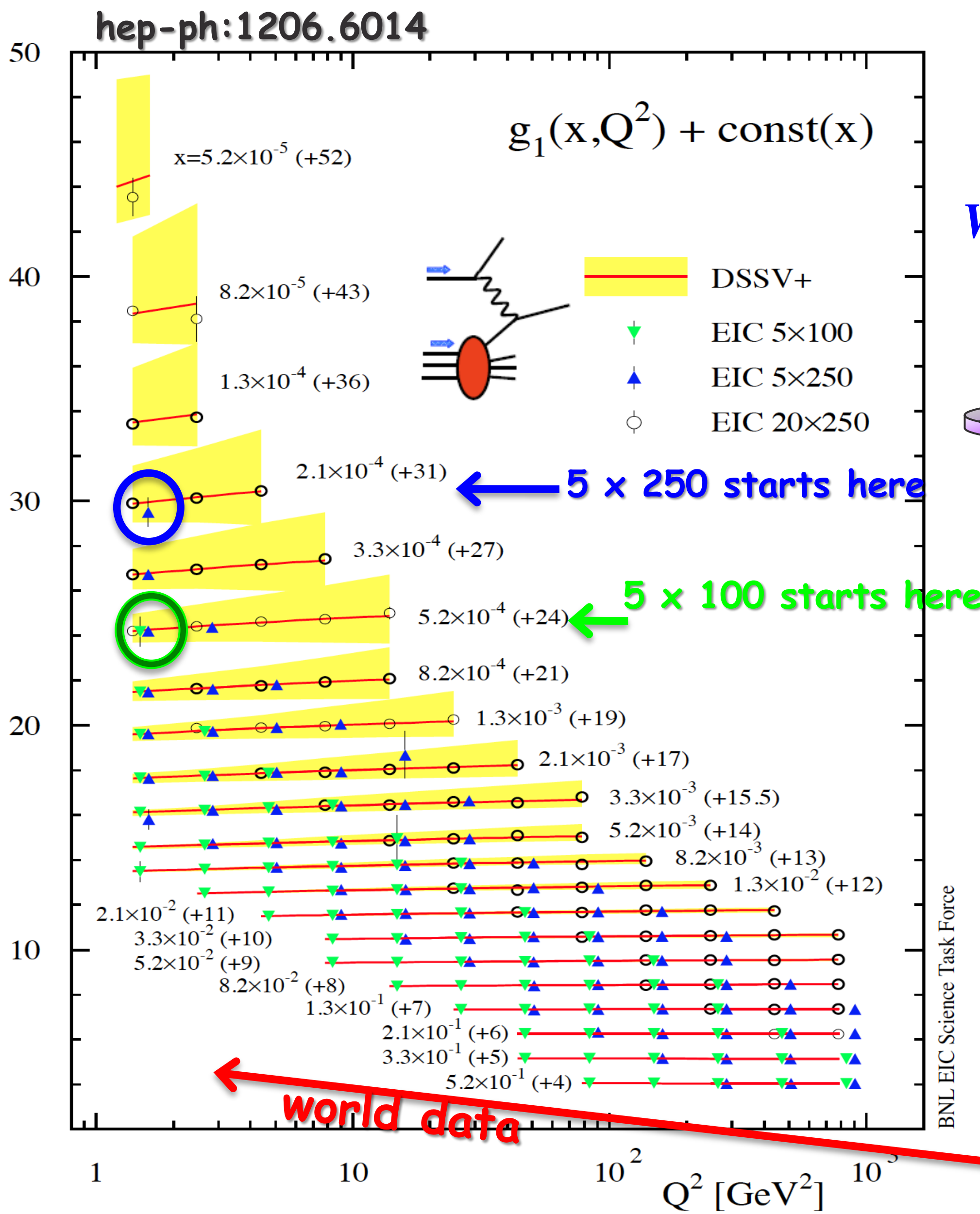
$$g_1^{W^-,p}(x) = \Delta u(x) + \Delta\bar{d}(x) + \Delta c(x) + \Delta\bar{s}(x)$$







g_1^p THE WAY TO FIND THE SPIN



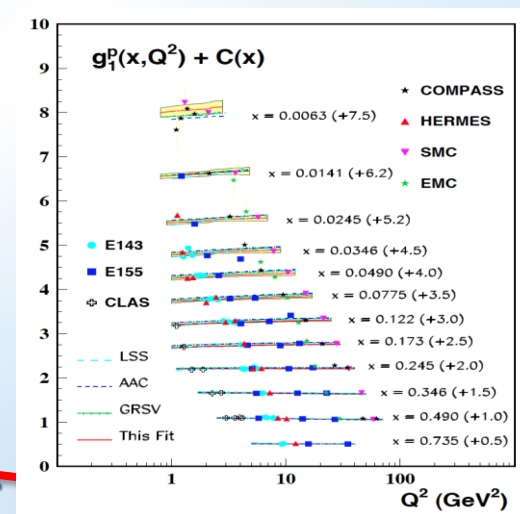
cross section: $\frac{d^2\sigma}{d\Omega dE'} \sim L_{\mu\nu} W^{\mu\nu}$

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

pQCD scaling violations

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

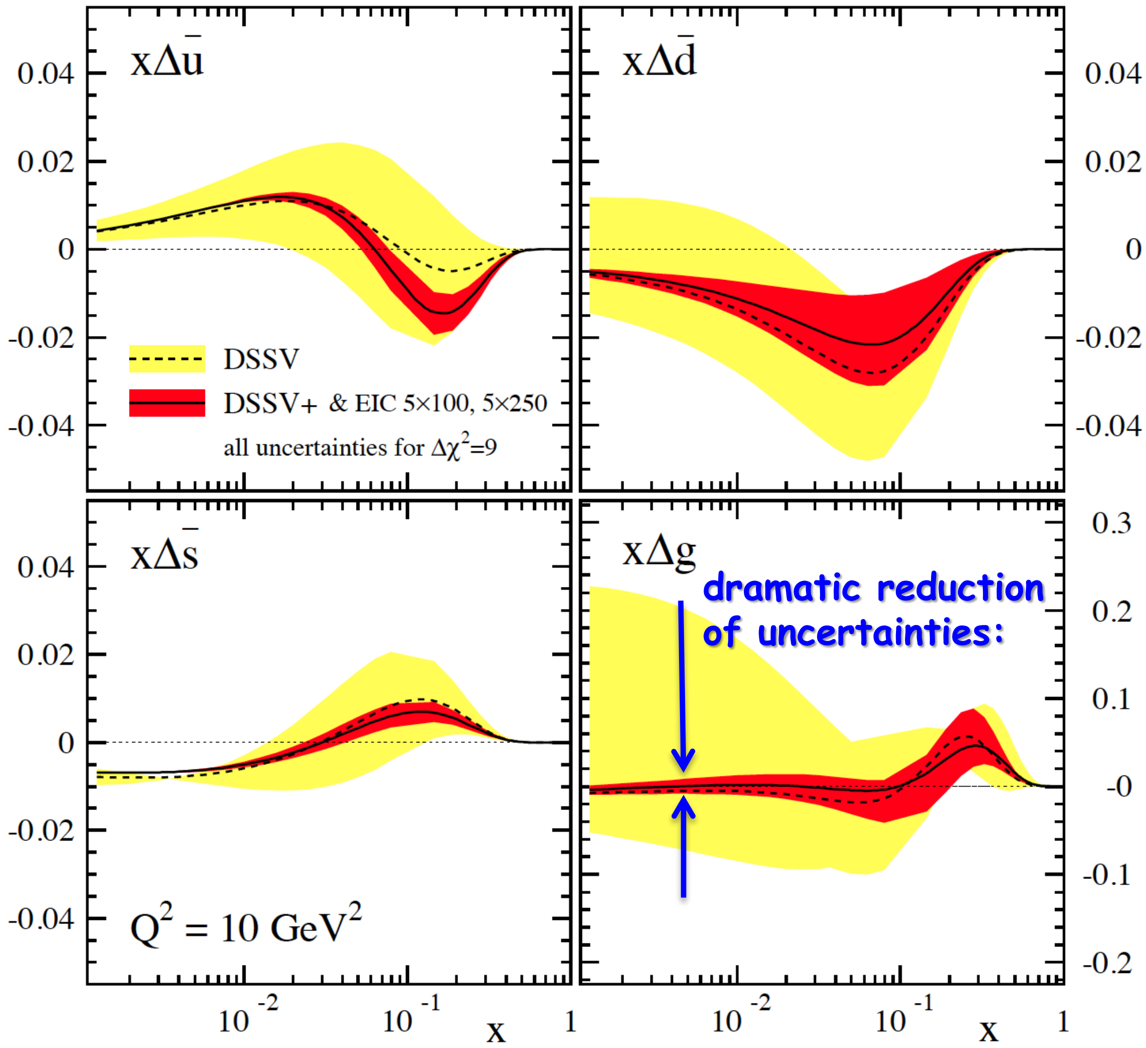
$$\Delta\Sigma(Q^2) = \int_0^1 g_1(x,Q^2)\,dx = \int_0^1 \Delta q_f(x,Q^2)\,dx$$



IMPACT OF eRHIC DATA ON HELICITY PDFs

DIS scaling violations mainly determine Δg at small x

in addition, SIDIS data provide detailed **flavor separation of quark sea**



yet, small x behavior completely unconstrained
→ determines x-integral, which enters proton spin sum

- includes only "stage-1 data"
- can be pushed to $x=10^{-4}$ with 20 x 250 GeV data

"issues":

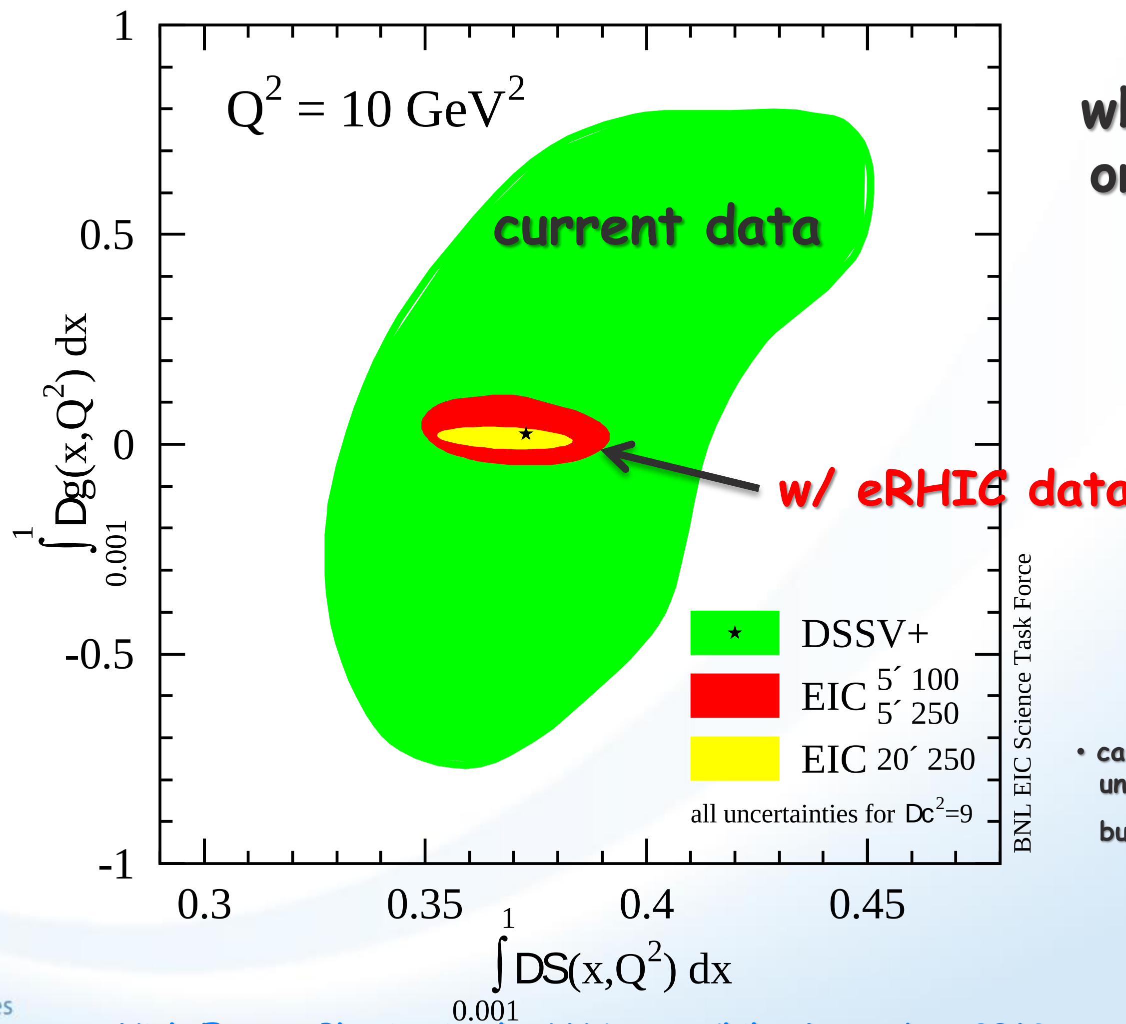
- (SI)DIS @ eRHIC limited by systematic uncertainties
  need to control rel. lumi, polarimetry, detector performance, … very well

CAN WE SOLVE THE SPIN SUM RULE ?

$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}\left| J^z_{QCD} \right| P,\frac{1}{2}\right\rangle = \sum_q \underbrace{\frac{1}{2}S^z_q}_{\text{total quark spin } \Delta\Sigma} + \overbrace{S^z_g}^{\text{gluon spin } \Delta g} + \sum_q \left(L^z_q + L^z_g\right)$$

gluon spin Δg ✔

total quark spin ΔΣ ✔



what about the orbital angular momentum?

- can expect approx. 5-10% uncertainties on ΔΣ and Δg

  but need to control systematics

QUANTUM TOMOGRAPHY OF THE NUCLEON

Join the real
3D experience !!

TMDs

GPDs

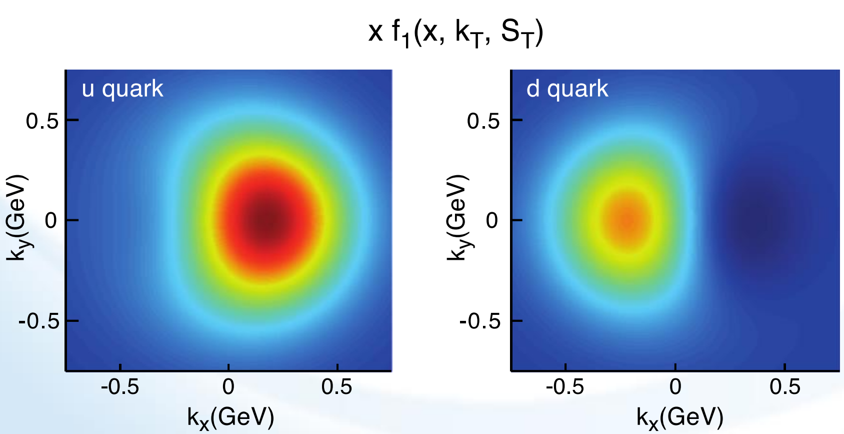
Spin as vehicle to do tomography of the nucleon
We do this daily in medicine

2D+1 picture in momentum space

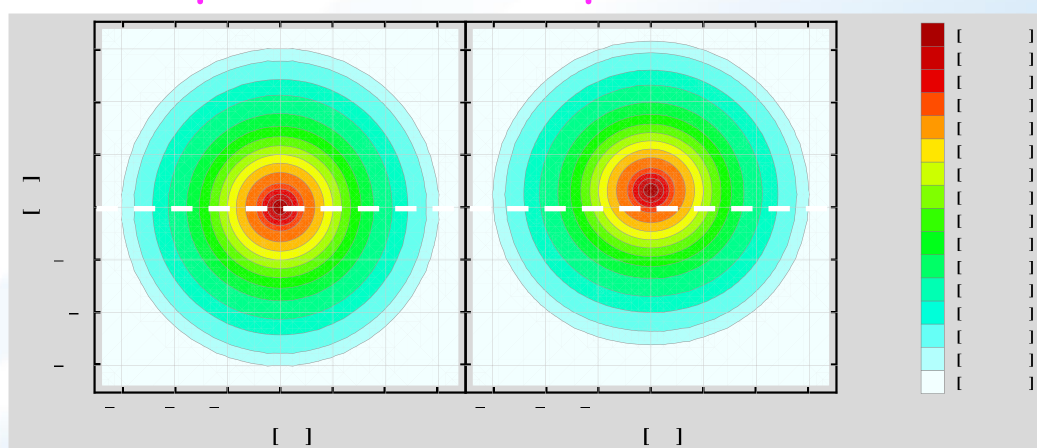
transverse momentum
dependent distributions

2D+1 picture in coordinate space

generalized parton distributions
→ exclusive reaction like DVCS

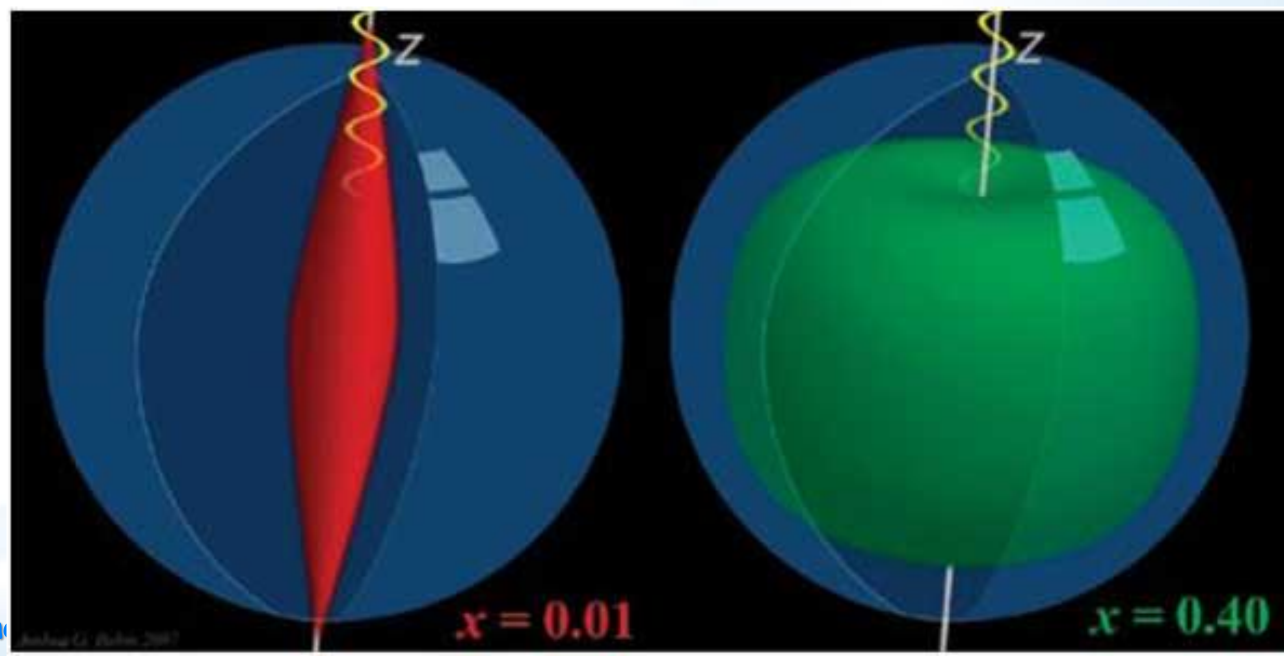


Quarks
unpolarised polarised



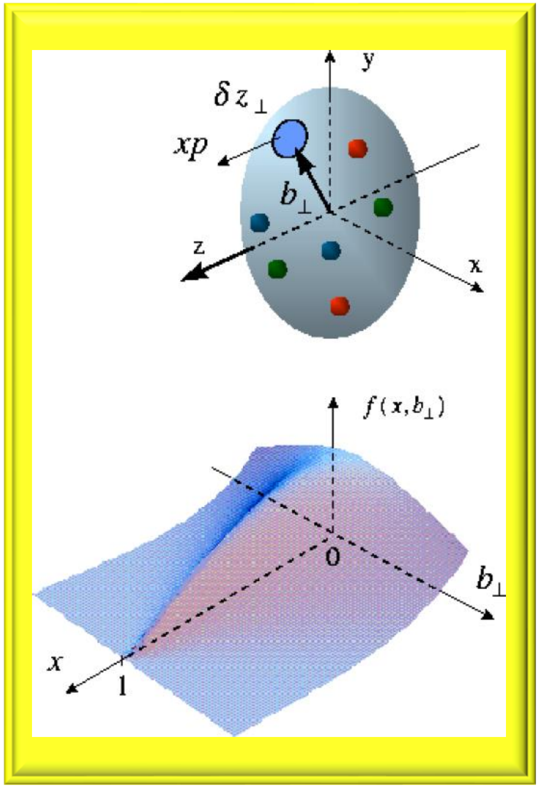
GENERALIZED PARTON DISTRIBUTIONS (GPDs)

or



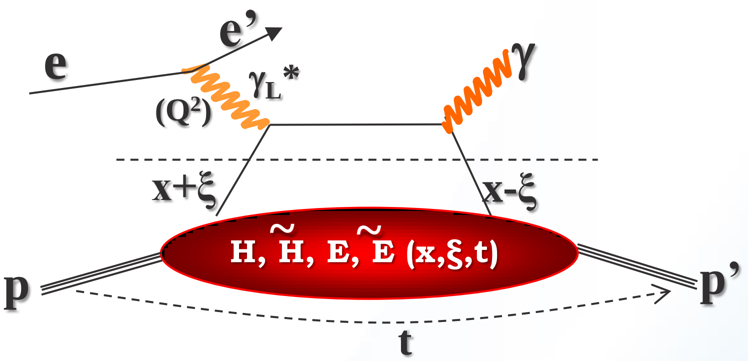
GENERALIZED PARTON DISTRIBUTIONS

the way to 3d imaging of the proton and the orbital angular momentum L_q & L_g



GPDs:
Correlated quark momentum and helicity distributions in **transverse space**

Measure them through exclusive reactions
golden channel: **DVCS**



Spin-Sum-Rule in PRF:

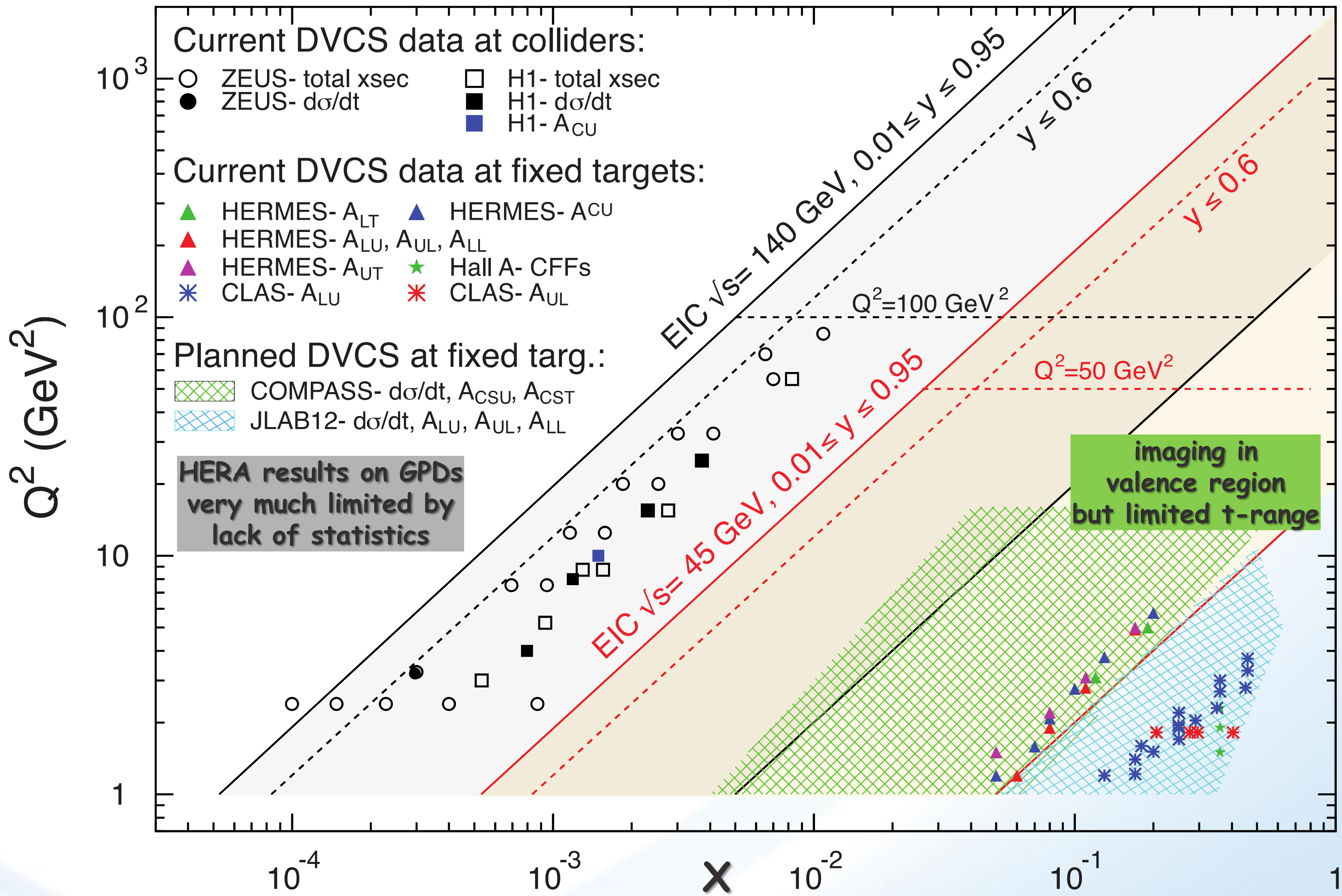
from g_1

$$\frac{1}{2} = J_q^z + J_g^z = \frac{1}{2}\Delta\Sigma + \sum_q \mathcal{L}_q^z + J_g^z$$

$$J_{q,g}^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx\left(H^{q,g} + E^{q,q}\right)\right)_{t\to 0}$$

responsible for orbital angular momentum

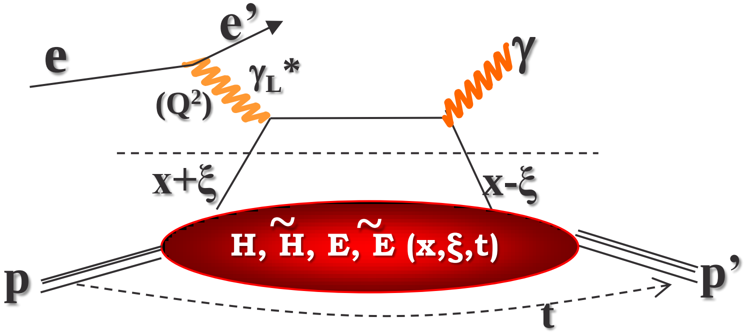
THE DVCS PHASE SPACE



quantum numbers of final state → selects different GPD

DVCS: wide range of observables (σ, A_{UT}, A_{LU}, A_{UL}, A_C) to disentangle GPDs

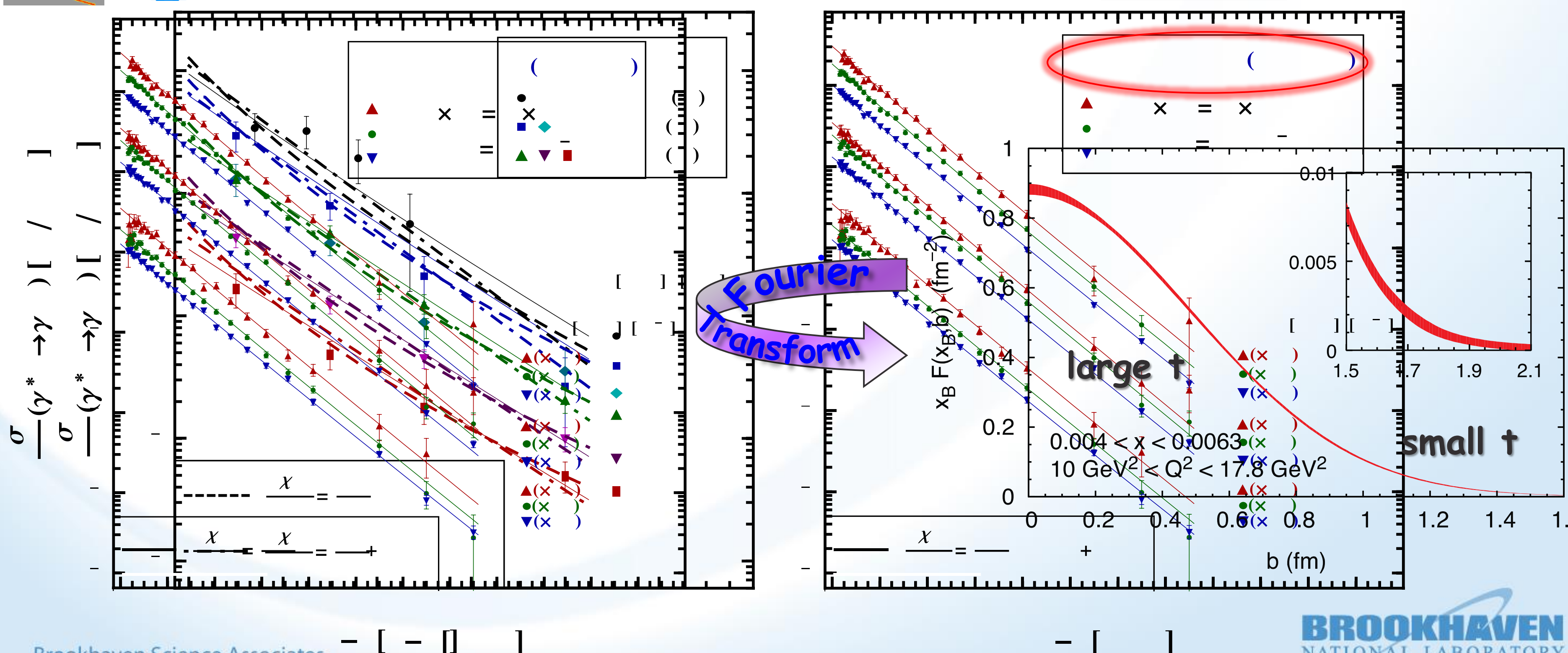
DVCS AT eRHIC



DVCS: Golden channel
theoretically clean
wide range of observables
(σ, A_{UT}, A_{LU}, A_{UL}, A_C)
to disentangle different GPDs

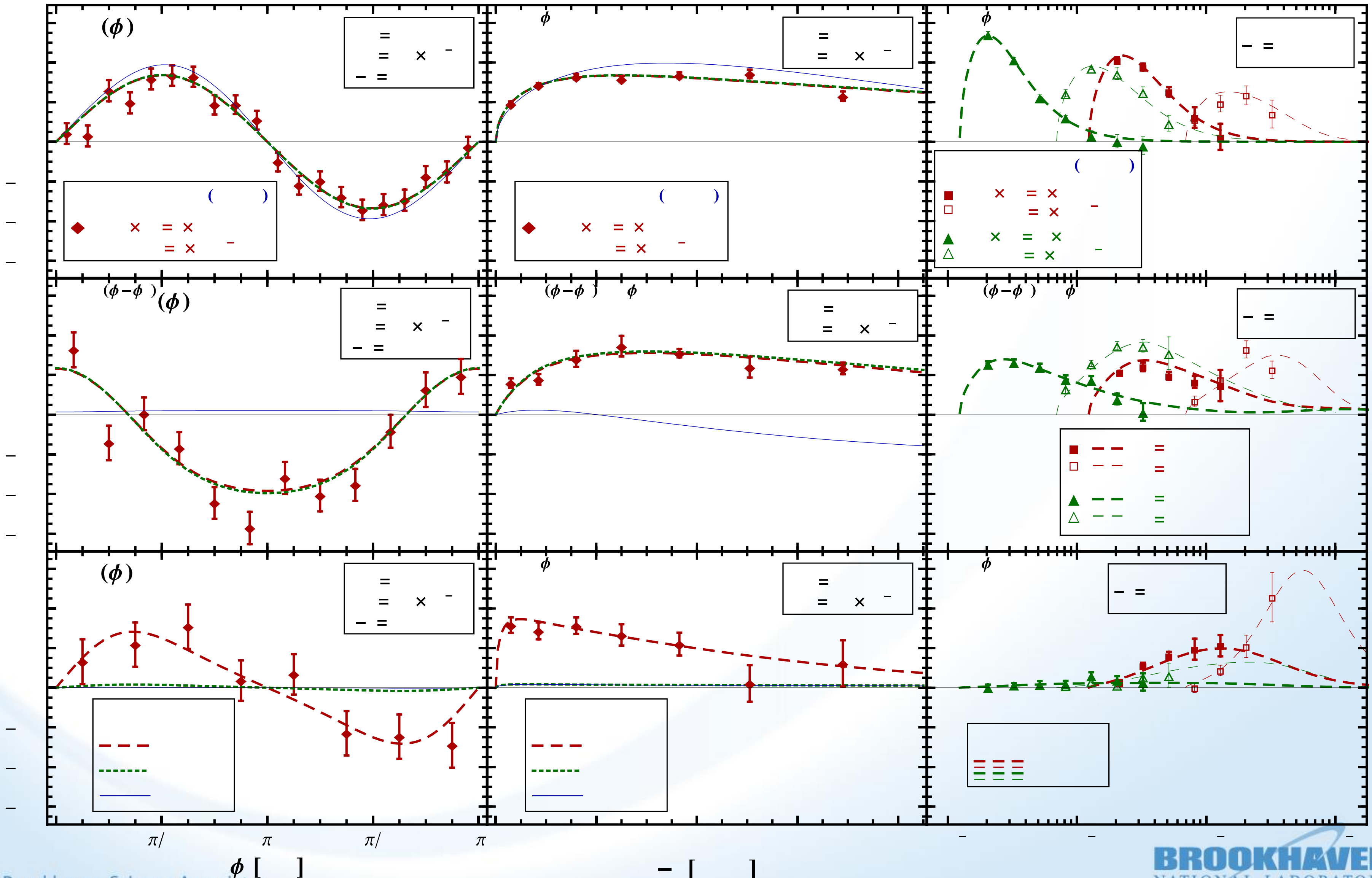
DVCS data at end of HERA

D. Mueller, K. Kumericki
S. Fazio, and ECA
arXiv:1304.0077



DIFFERENT DVCS ASYMMETRIES

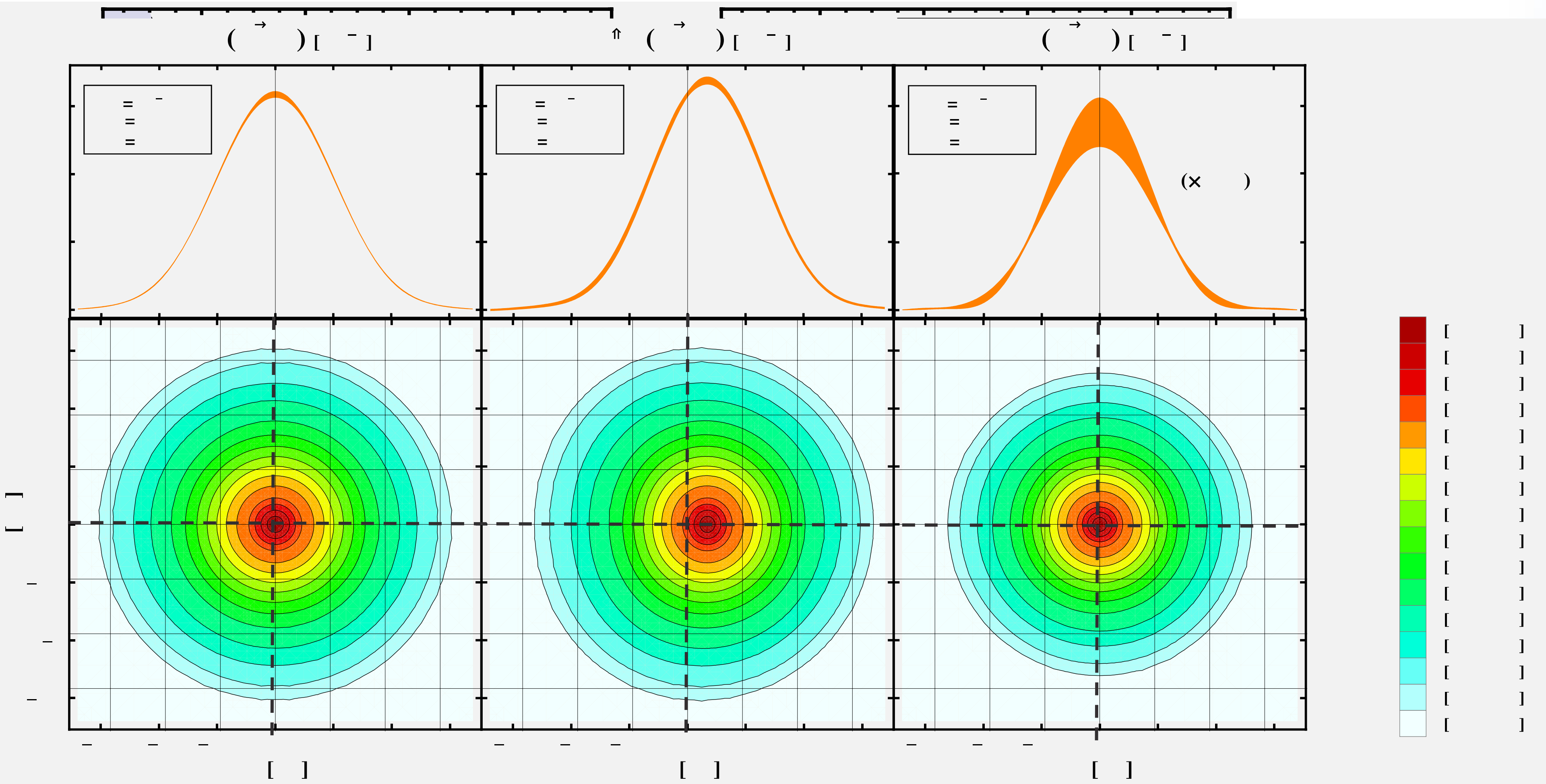
arXiv:1304.0077



WHAT WILL WE LEARN ABOUT 2D+1 STRUCTURE OF THE PROTON

GPD H and E as function of t, x and Q^2

GPD H and E 1d+1



GPD H and E 2d+1 structure for sea-quarks and gluons

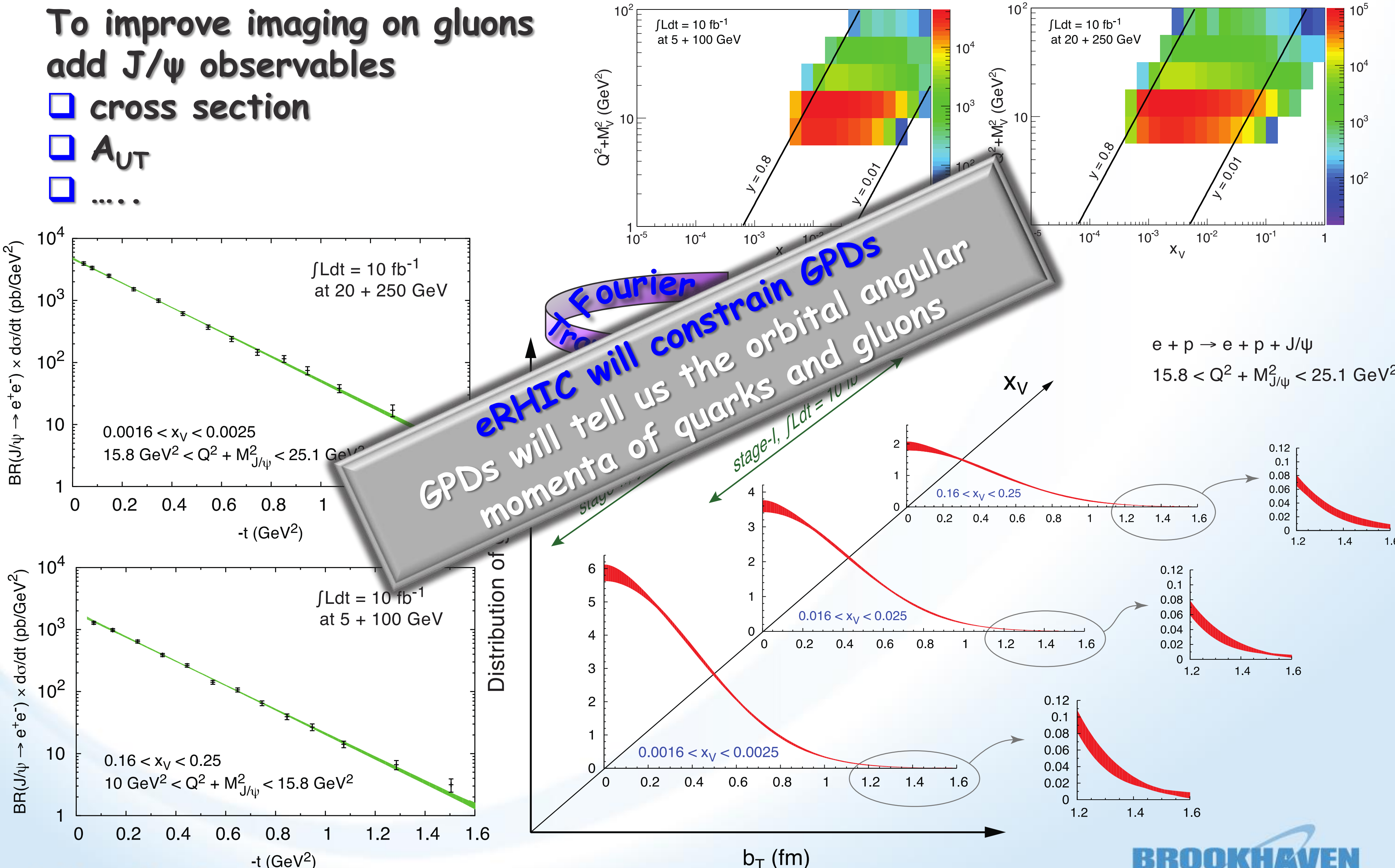
- Excellent reconstruction of H^{sea}, H^{sea} and good reconstruction of H^{g} (from $d\sigma/dt$)

GPD H^g: J/Ψ

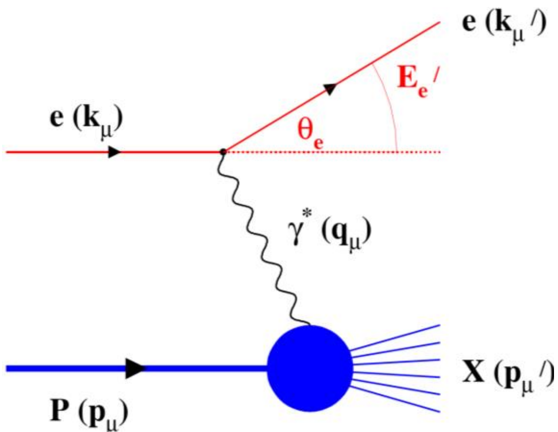
M. Diehl & ECA

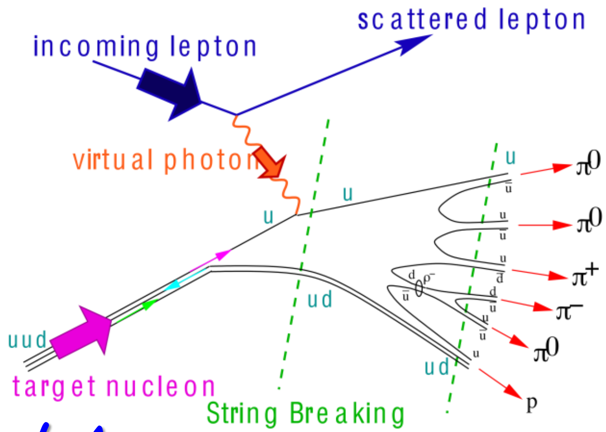
To improve imaging on gluons add J/ψ observables

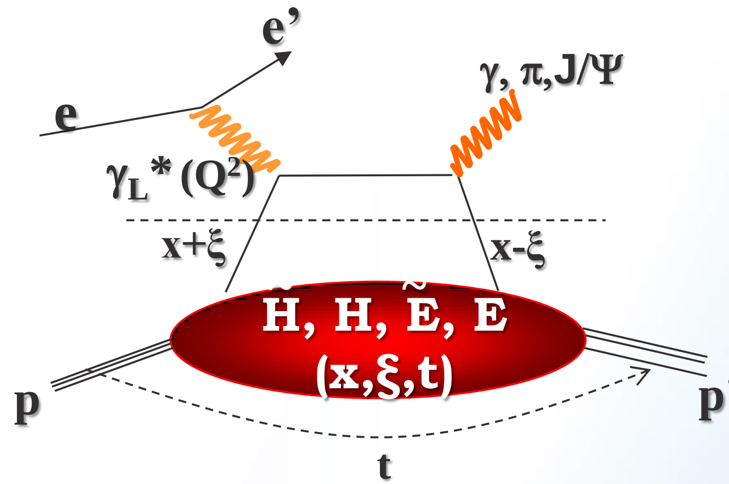
- cross section
- A_{UT}
- …..



WHAT NEEDS TO BE COVERED BY THE DETECTOR







Inclusive Reactions in ep/eA:

- Physics: Structure Fcts.: g_1, F_2, F_L
- Very good electron id → find scattered lepton
- Momentum/energy and angular resolution of e' critical
- scattered lepton → kinematics

Semi-inclusive Reactions in ep/eA:

- Physics: TMDs, Helicity PDFs → flavor separation, dihadron-corr.,…
  → Kaon asymmetries, cross sections
- Excellent particle ID: $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$ separation over a wide range in η
- full Φ-coverage around γ^*
- Excellent vertex resolution → Charm, Bottom identification

Exclusive Reactions in ep/eA:

- Physics: GPDs, proton/nucleus imaging, DVCS, excl. VM/PS prod.
- Exclusivity → large rapidity coverage → rapidity gap events
- ↘ reconstruction of all particles in event
- high resolution in t → Roman pots

THE eRHIC DETECTOR CONCEPT

Extremely wide physics program puts stringent requirements on detector performance

- high acceptance -5 < η < 5
- good PID (π,K,p and lepton) and vertex resolution
- same rapidity coverage for tracking and calorimeter
  → good momentum resolution, lepton PID
- low material density because of low scattered lepton p
  → minimal multiple scattering and brems-strahlung
- very forward electron and proton/neutron detection
- Fully integrated in machine IR design

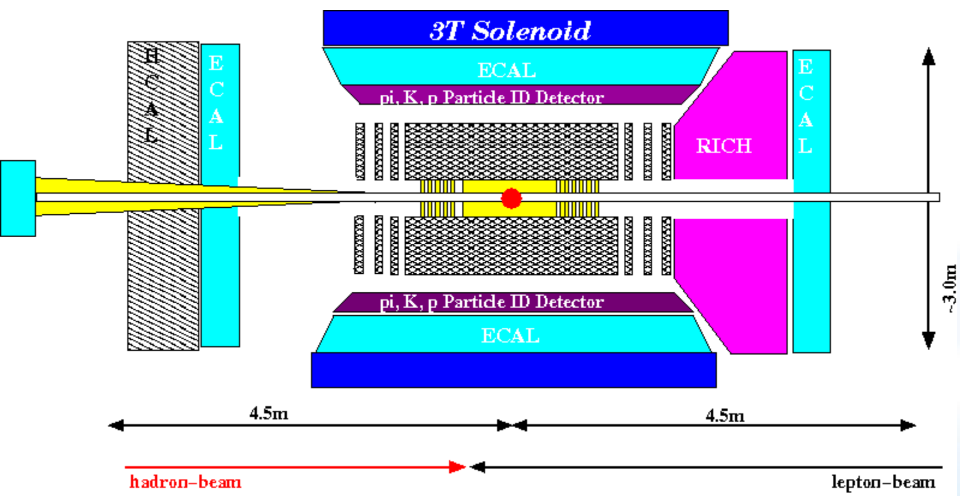
Summary:

Full Geant Model based on Generic EIC R&D detector concepts

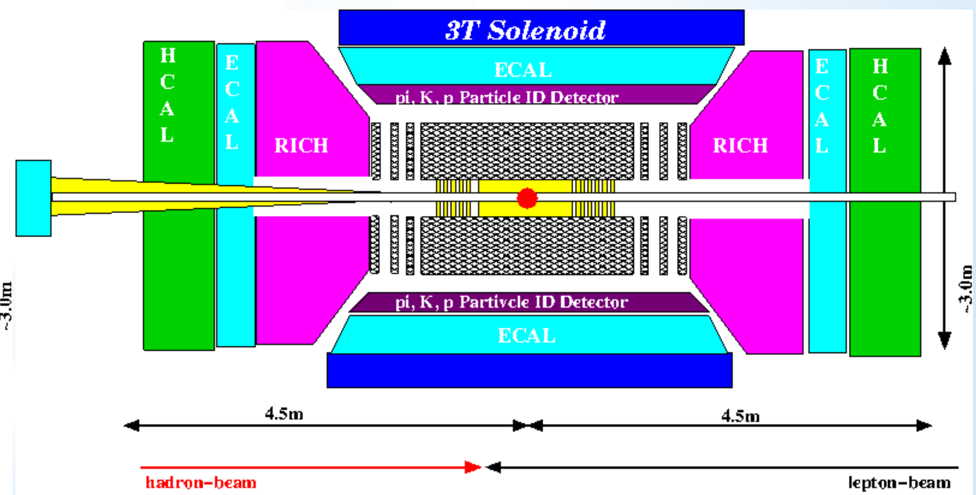
https://wiki.bnl.gov/eic/index.php/DIS:_What_is_important

https://wiki.bnl.gov/eic/index.php/ERHIC_Dedicated_Detector_Design

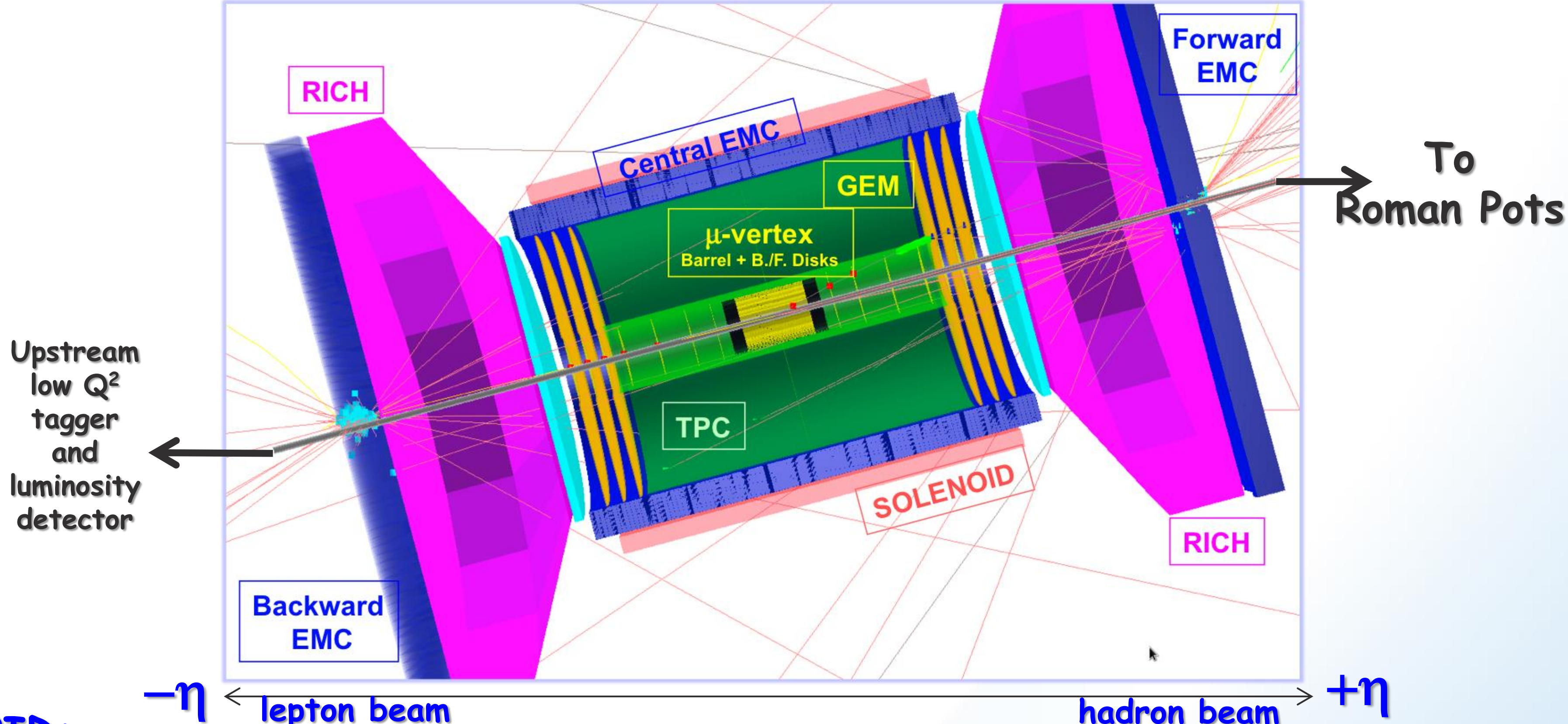
Phase-I (5 - 10 GeV):



Phase-II (>10 GeV):



BNL: 1ST DETECTOR DESIGN CONCEPT



PID:

$-1<\eta<1$: DIRC or proximity focusing Aerogel-RICH + TPC: dE/dx

$1<|\eta|<3$: RICH

Lepton-ID:

$-3 <\eta< 3$: e/p

$1<|\eta|<3$: in addition Hcal response & γ suppression via tracking

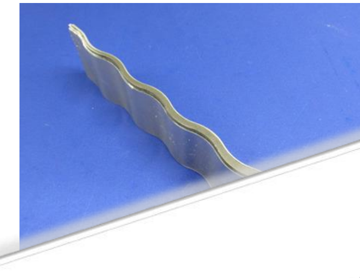
$|\eta|>3$: ECal+Hcal response & γ suppression via tracking

$-5<\eta<5$: Tracking (TPC+GEM+MAPS)

VIBRANT DETECTOR R&D PROGRAM

- Calorimetry
  - W-Scintillator & W-Si
    - compact and high resolution
  - Crystal calorimeters PbW & BGO

BNL, Indiana University, Penn State Univ., UCLA, USTC, TAM



- Pre-Shower
  - W-Si
  - LYSO pixel array with readout via X-Y WLS fi...

Univ. Tecnica Valparaiso

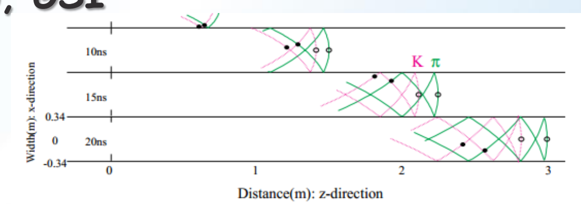
...W plates, ~500μ Si pads

More Info on EIC-Detector R&D:
https://wiki.bnl.gov/conferences/index.php/EIC_R%25D

- PID via Ceren...
  - DI...
  - ...readout
  - ...based TRD → eSTAR

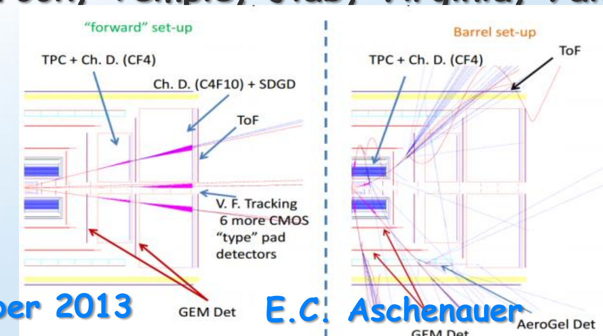
...ion, South Carolina, JLab, GSI

...diana Univ., USTC, VECC, ANL



- Tracking

BNL, Florida Inst. Of Technology, Iowa State, LBNL, MIT, Stony Brook, Temple, Jlab, Virginia, Yale
  - μ-Vertex: central and forward based on MAPS
  - Central: TPC/HBD provides low mass, good momentum, dE/dx, eID
    Fast Layer: μ-Megas or PImMS
  - Forward: Planar GEM detectors



TAKE AWAY MESSAGE

entire science program uniquely tied to a future high energy polarized electron ion collider

never been measured before & never without

The … impact … CD … luminosity … ep collisions

a dedicated …

… WP

We would like to invite everybody to join and work with us on the eRHIC PHYSICS case and DETECTOR design

… machine design ambitious, but will push collider technologies in several regions

BACKUP

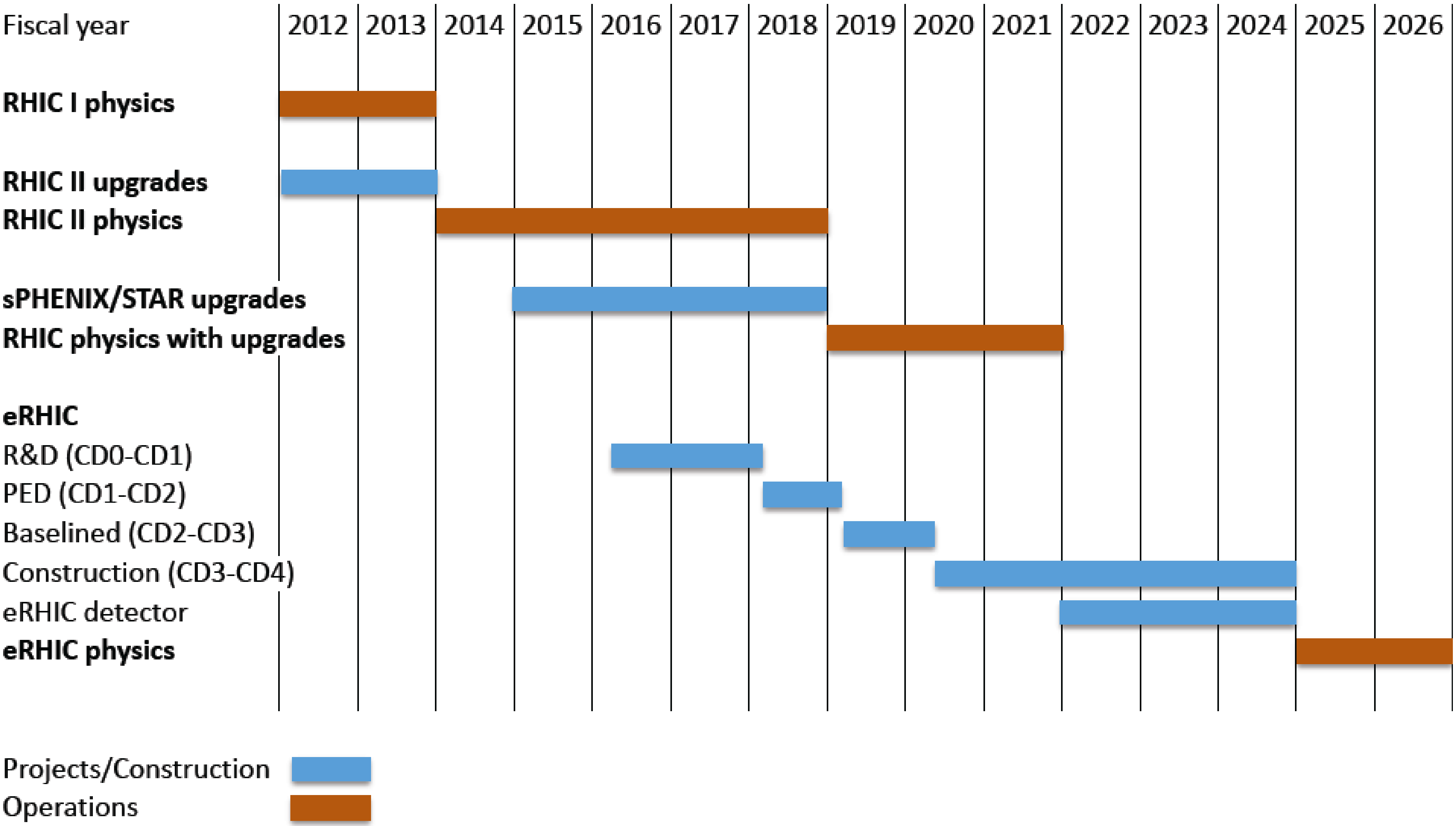
Electron-"Ion" colliders in the past and future:

	HERA@DESY	LHeC@CERN	eRHIC@BNL	MEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	45-175	12-140	12 → 65	14
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-5}	5×10^{-5}	7×10^{-3} →3×10^{-4}	5×10^{-3}
ion	p	p to Pb	p to U	p to Pb	p to U	p to ~ ^{40}Ca
polarization	-	-	p, ^{3}He	p, d, ^{3}He (^{6}Li)	p, d, ^{3}He	p,d
L [cm^{-2} s^{-1}]	2×10^{31}	10^{33}	10^{33-34}	10^{33-34}	10^{32-33} → 10^{35}	10^{32}
IP	2	1	2+	2+	1	1
Year	1992-2007	2022 (?)	2022	Post-12 GeV	2019 → 2030	upgrade to FAIR

Requirements:

- High Luminosity > 10^{33} $cm^{-2}s^{-1}$
- Flexible center of mass energies
- Electrons and protons/light nuclei polarised
- Wide range of nuclear beams
- 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

POSSIBLE SCHEDULE TO REALIZE eRHIC

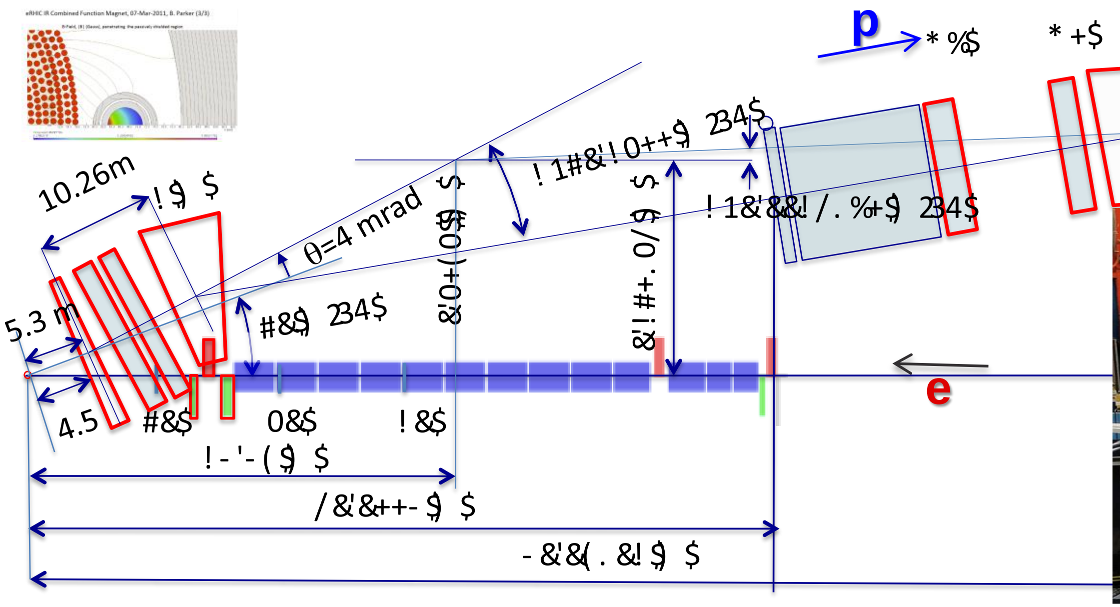


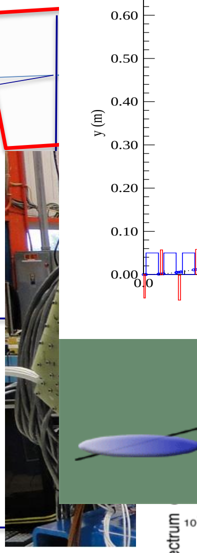
eRHIC: design luminosity

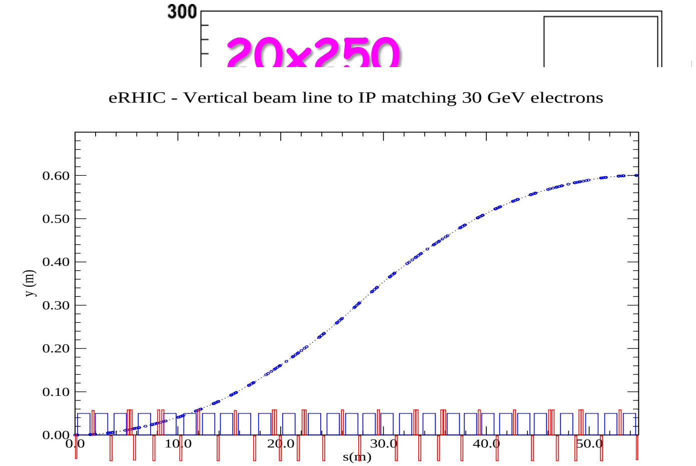
	e	p	$^2He^3$	$^{79}Au^{197}$	$^{92}U^{238}$
Energy, GeV	20	250	167	100	100
CM energy, GeV		100	82	63	63
Number of bunches/distance between bunches	107 nsec	111	111	111	111
Bunch intensity (nucleons) ,10^{11}	0.36	4	6	6	6
Bunch charge, nC	5.8	64	60	39	40
Beam current, mA	50	556	556	335	338
Normalized emittance of hadrons , 95% , mm mrad		1.2	1.2	1.2	1.2
Normalized emittance of electrons, rms, mm mrad		16	24	40	40
Polarization, %	80	70	70	none	none
rms bunch length, cm	0.2	5	5	5	5
β^*, cm	5	5	5	5	5
Luminosity per nucleon, x 10^{34} $cm^{-2}s^{-1}$		2.7	2.7	1.6	1.7

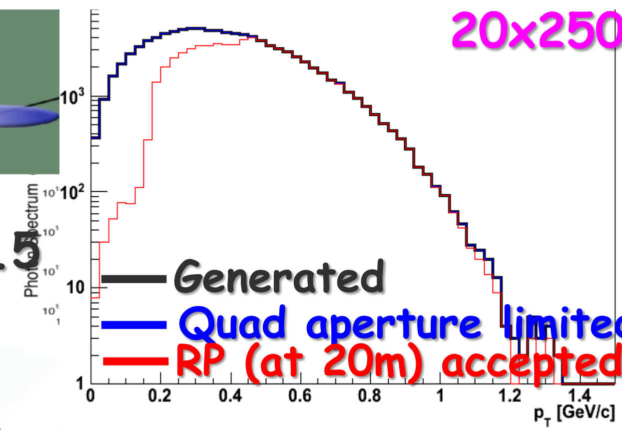
Hourglass the pinch effects are included. Space charge effects are compensated.
Energy of electrons can be selected at any desirable value at or below 30 GeV
The luminosity does not depend on the electron beam energy below or at 20 GeV
The luminosity falls as E_e^{-4} at energies above 20 GeV
The luminosity is proportional to the hadron beam energy: $L \sim E_h/E_{top}$

eRHIC: HIGH-LUMINOSITY IR









eRHIC - Geometry high-lumi IR with β*=5 cm, l*=4.5 and 10 mrad crossing angle → 10^{34} cm^{-2} s^{-1}

- 10 mrad crossing angle and crab-crossing
- High gradient (200 T/m) large aperture Nb_3Sn focusing magnets
- Arranged free-field electron pass through the hadron triplet magnets
- Integration with the detector: efficient separation and registration of low angle collision products
- Gentle bending of the electrons to avoid SR impact in the detector

MODELING THE DETECTOR IN GEANT

μ-vertex detector:

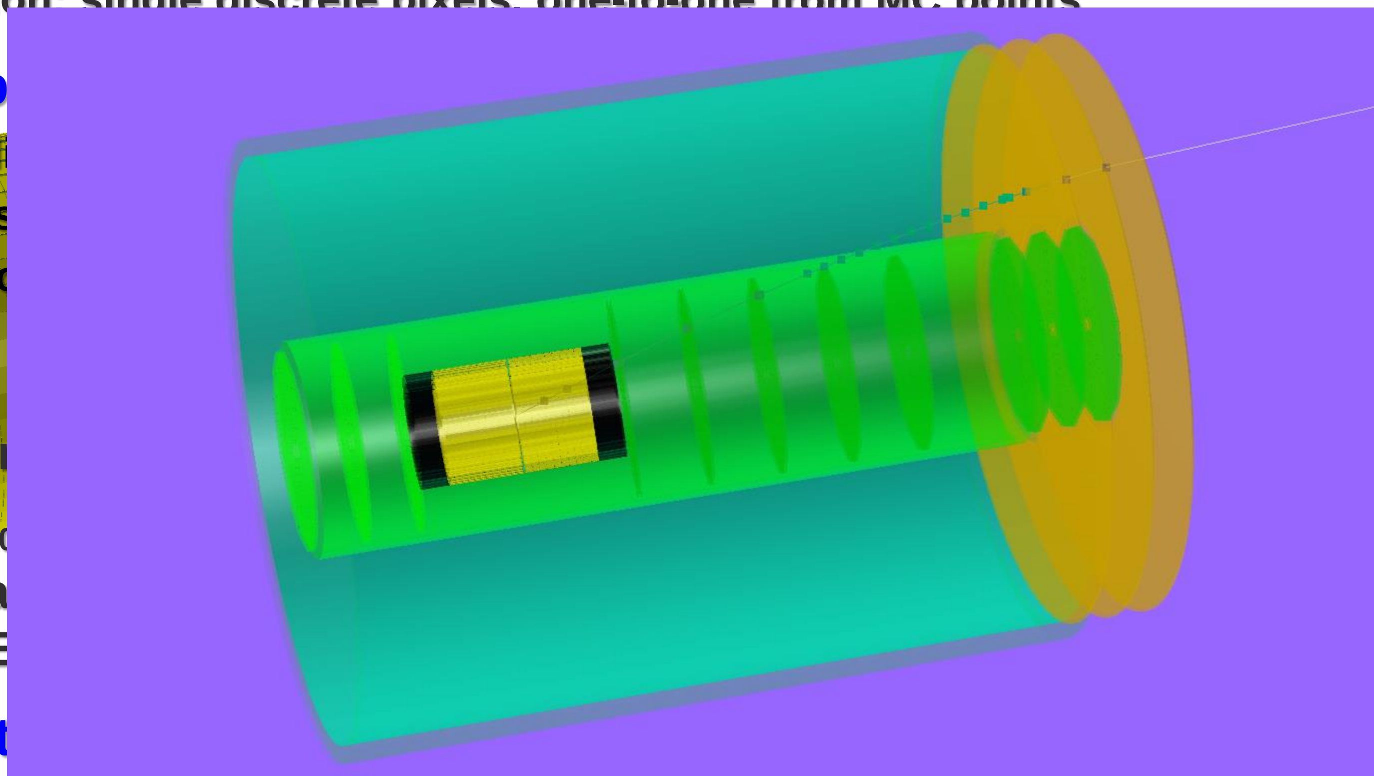
- 6 layers with [30..160] mm radius
- 0.37% X_0 in acceptance per layer simulated precisely;
- digitization: single discrete pixels, one-to-one from MC points

Forward/b

- 3+5+3 sili
- N sectors
- digitizatio

TPC

- ~2m lo
- 1.2% X_0
- digitiza … nd 1x5 mm GE



Forward t

- 3 disks behind the TPC endcap
- rather precise START FGT design implemente
- digitization: 100 μm resolution in X&Y; gaussi

barrel silicon tracker:

- MAPS technology; ~20x20mm^2 chips, ~20 μm 2D pixels
- 6 layers at [30..160] mm radius
- 0.37% X_0 in acceptance per layer simulated precisely;
- digitization: single discrete pixels, one-to-one from MC points

forward/backward silicon trackers:

- 2x7 disks with up to 280 mm radius
- N sectors per disk; 200 μm silicon-equivalent thickness
- digitization: discrete ~20x20 μm^2 pixels

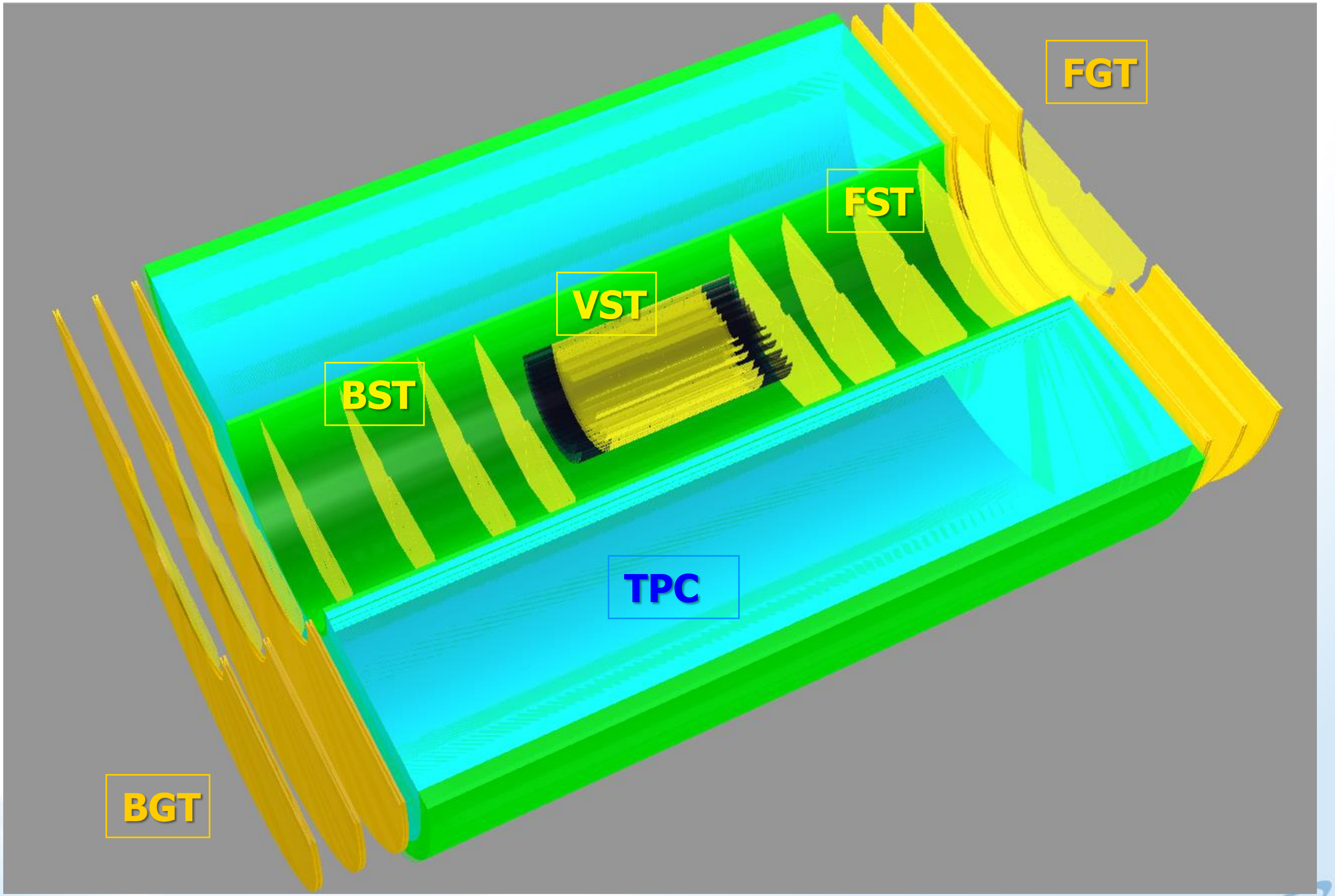
TPC:

- ~2m long; gas volume radius [300..800] mm
- 1.2% X_0 IFC, 4.0% X_0 OFC; 15.0% X_0 aluminum endcaps
- digitization: idealized, assume 1x5 mm GEM pads

GEM trackers:

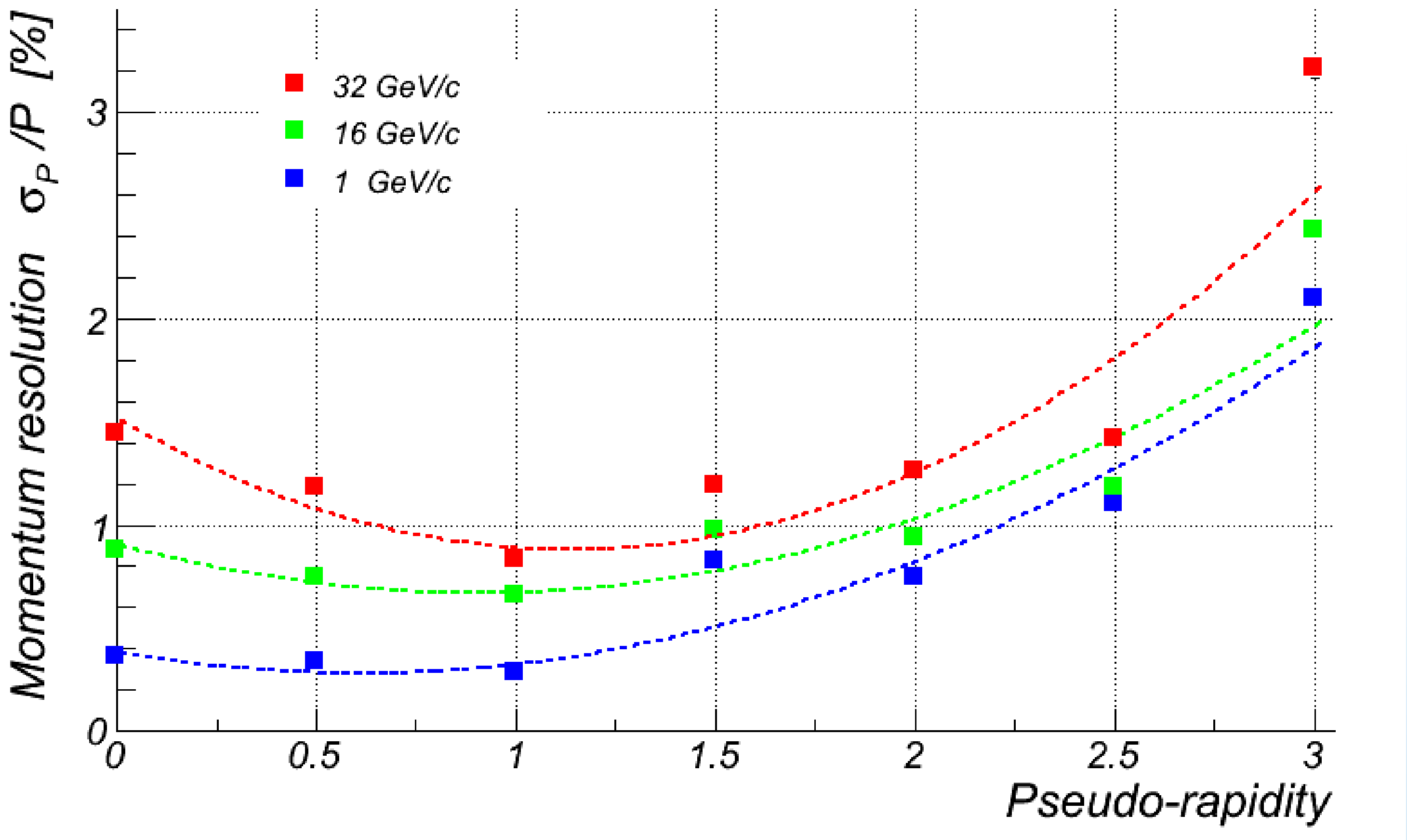
- 3 disks behind the TPC endcap
- STAR FGT design
- digitization: 100 mm resolution in X&Y; gaussian smearing

TRACKER ZOOMED VIEW



MOMENTUM RESOLUTION STUDY (1)

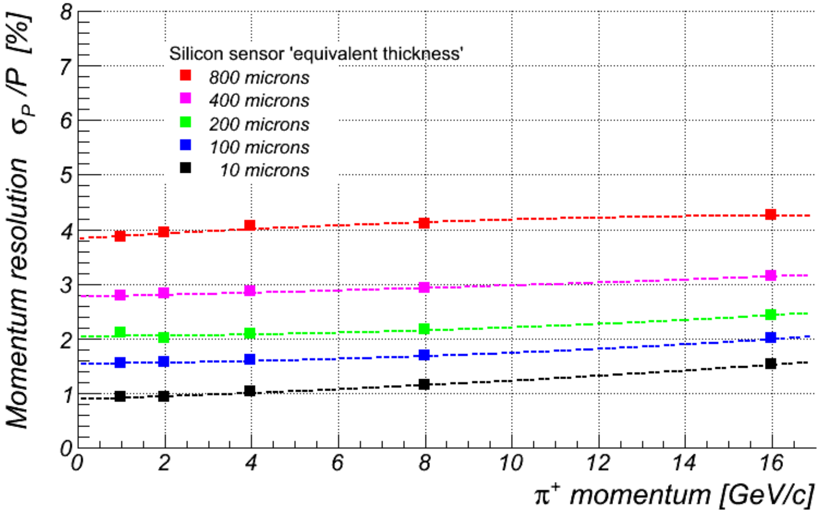
π^+ track momentum resolution vs. pseudo-rapidity



-> expect 2% or better momentum resolution in the whole kinematic range

MOMENTUM RESOLUTION STUDY (2)

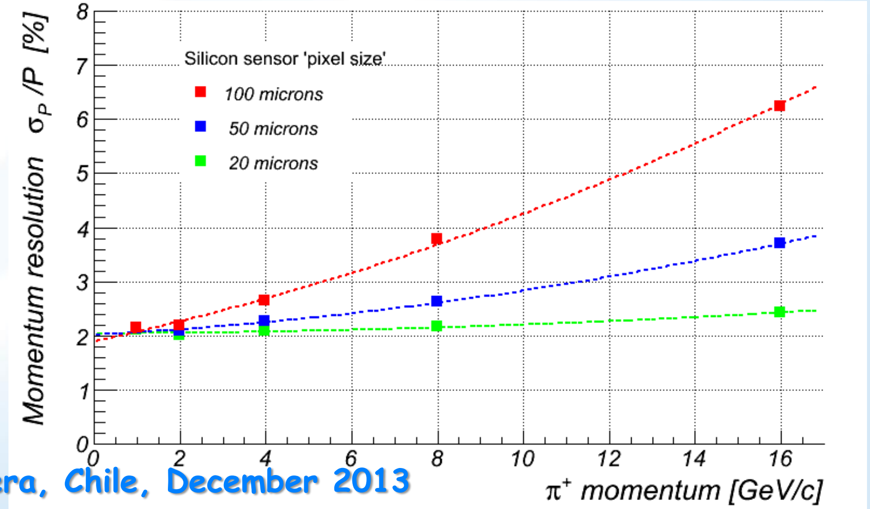
π^+ track momentum resolution at η = 3.0 vs. Silicon thickness



-> ~flat over inspected momentum range because of very small Si pixel size

π^+ track momentum resolution at η = 3.0 vs. Silicon pixel size

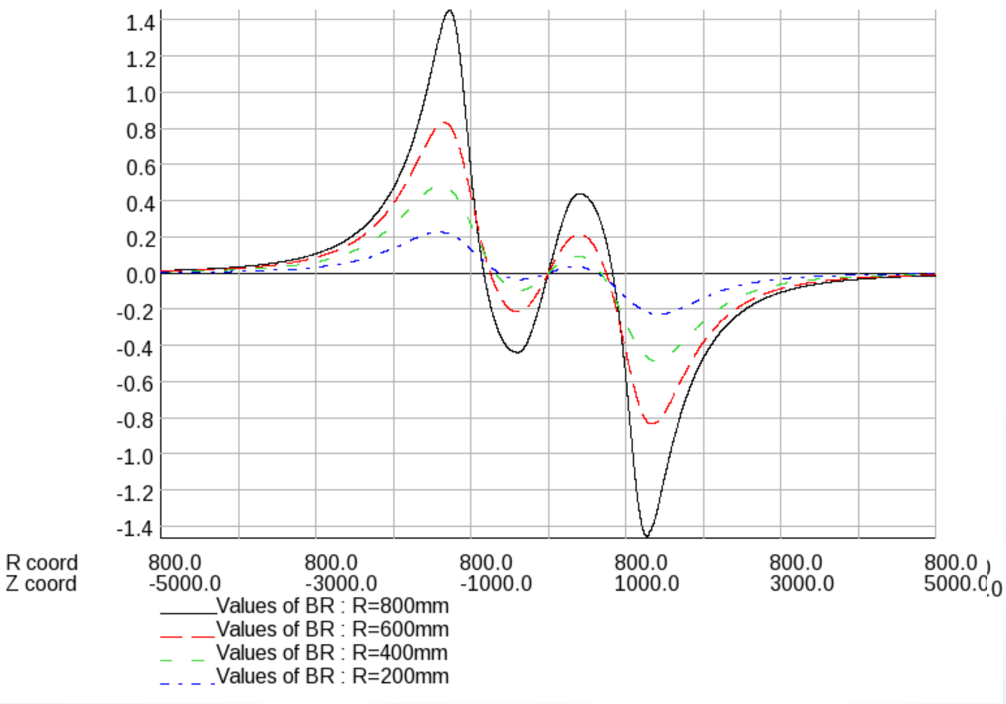
-> 20 micron pixel size is essential to maintain good momentum resolution



EIC SOLENOID MODELING

main requirements:

- Yield large enough bending for charged tracks at large η
- Keep field inside TPC volume as homogeneous as possible
- Keep magnetic field inside RICH volume(s) small

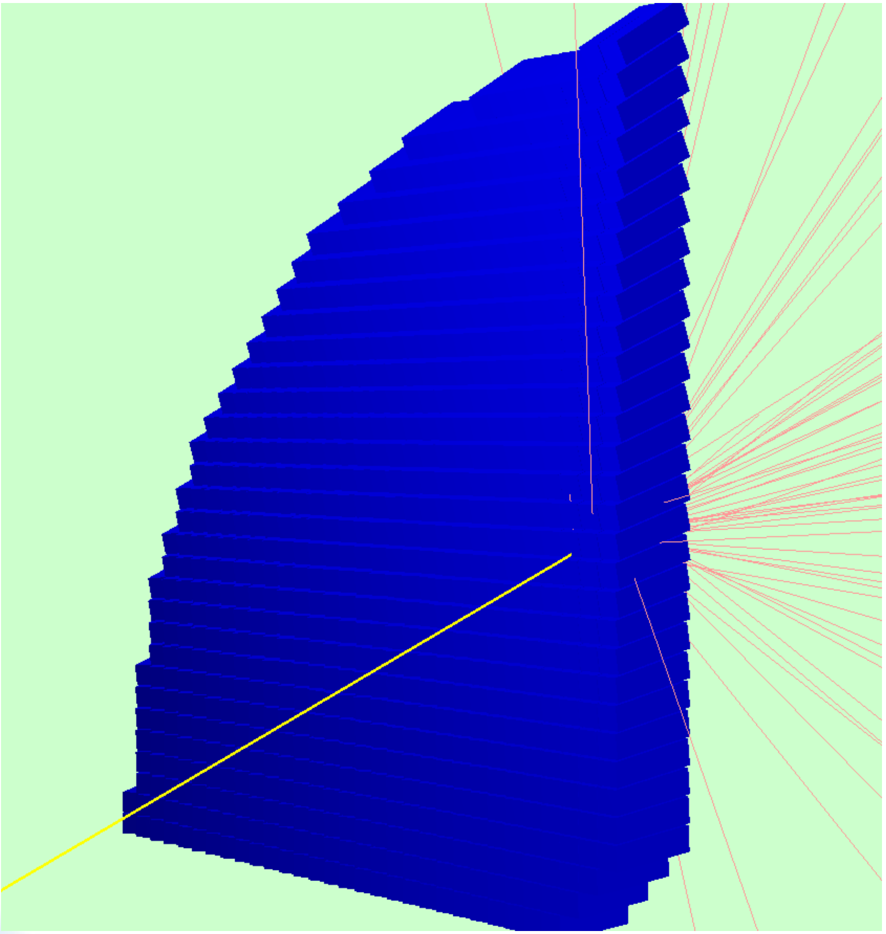


-> use OPERA-3D/2D software

Presently used design: MRS-B1

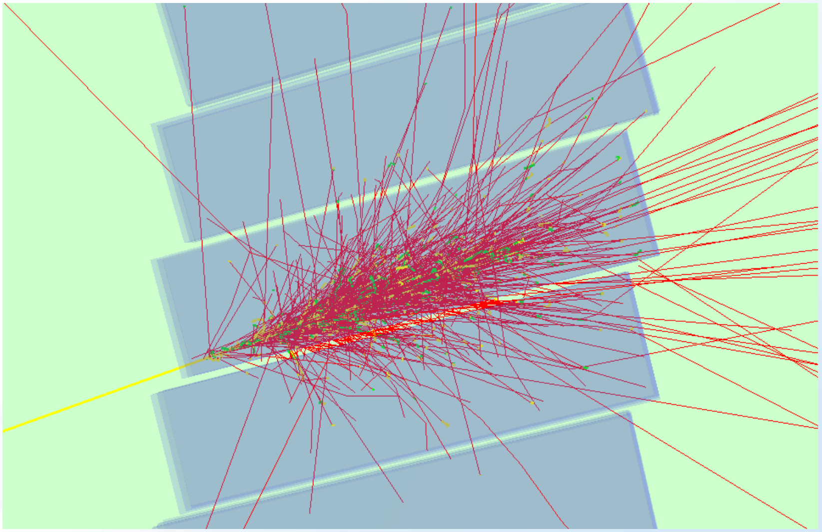
Total Length	:	2.4 m
Inner Radius	:	1.0 m
Outer Radius	:	1.1 m
Central B field	:	3.0 T

BACKWARD EM CALORIMETER (BEMC)



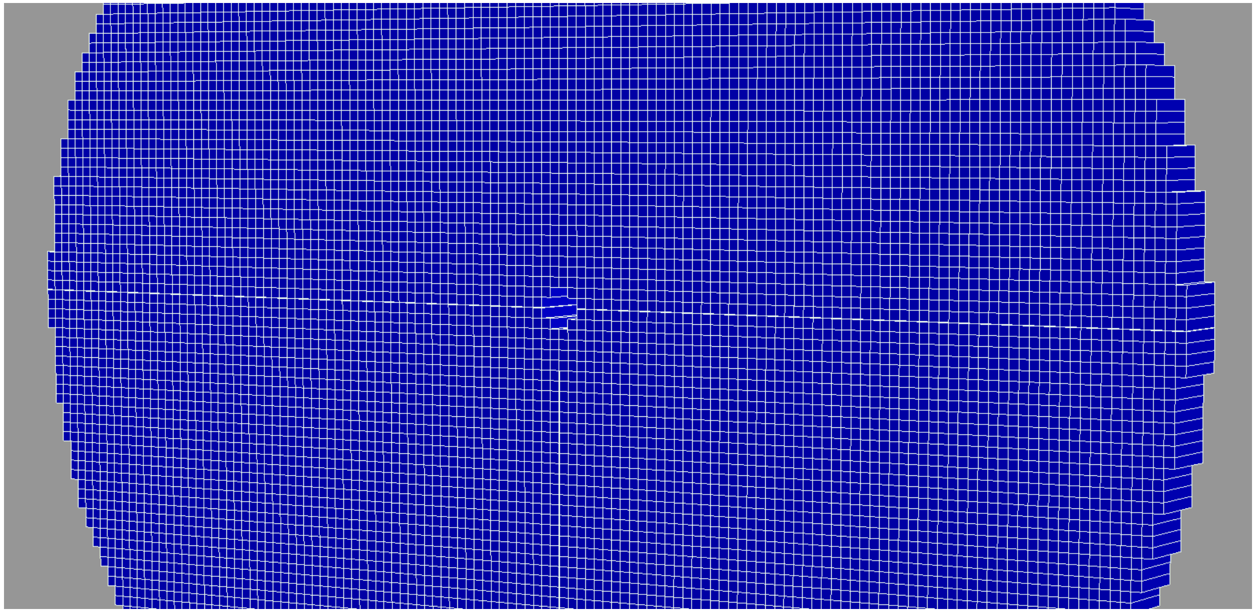
10 GeV/c electron hitting one of the four BEMC quadrants

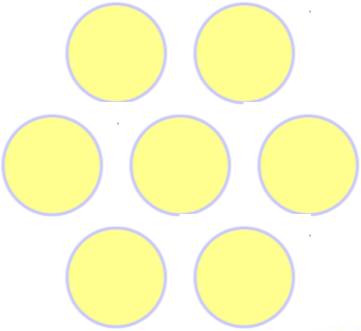
- PWO-II, layout a la CMS & PANDA
- -2500mm from the IP
- both projective and non-projective geometry implemented
- digitization based on PANDA R&D

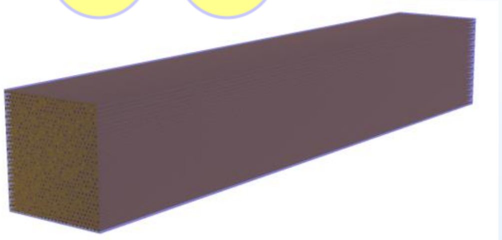


Same event (details of shower development)

FORWARD EM CALORIMETER (FEMC)





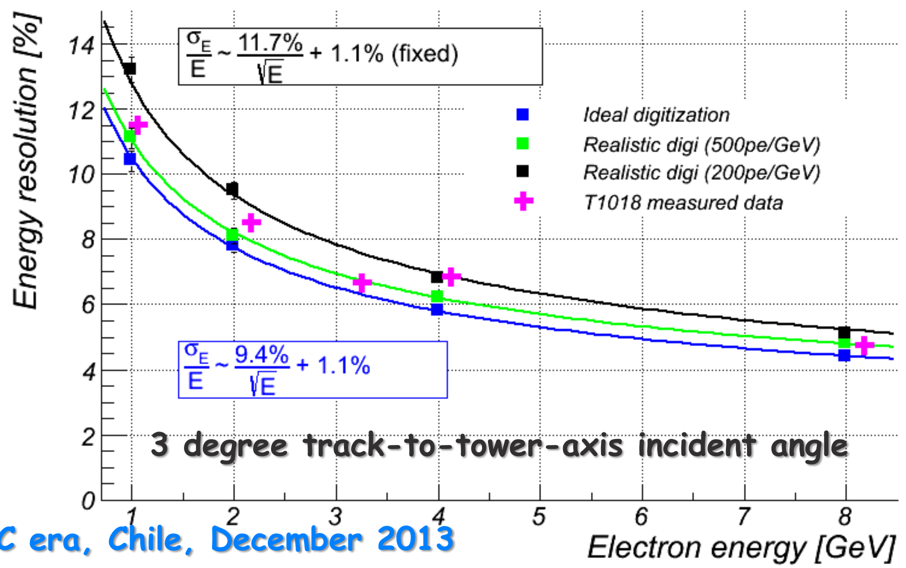


tower (and fiber) geometry described precisely

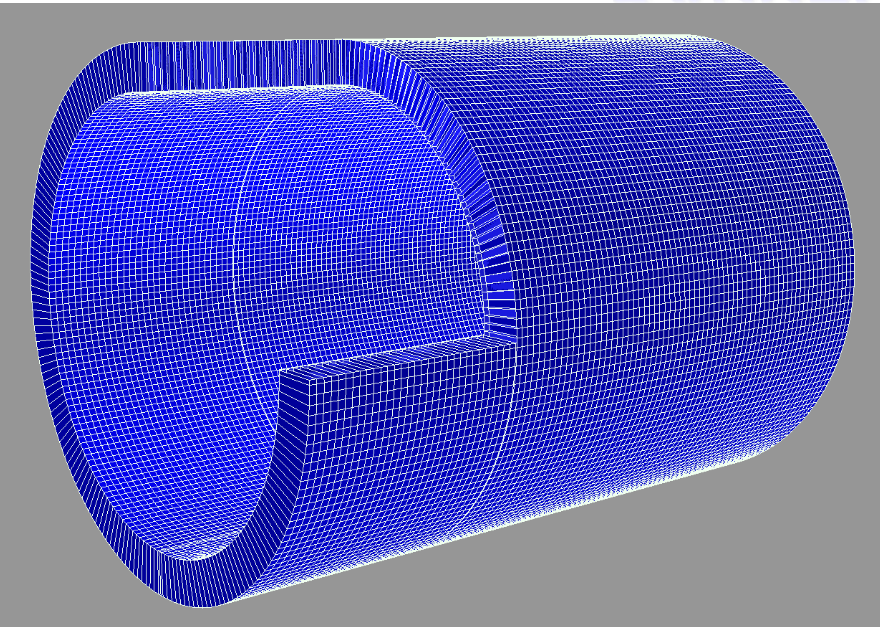
- tungsten powder scintillating fiber sampling calorimeter technology
- +2500mm from the IP; non-projective geometry
- sampling fraction for e/m showers ~2.6%
- "medium speed" simulation (up to energy deposit in fiber cores)
- reasonably detailed digitization; "ideal" clustering code

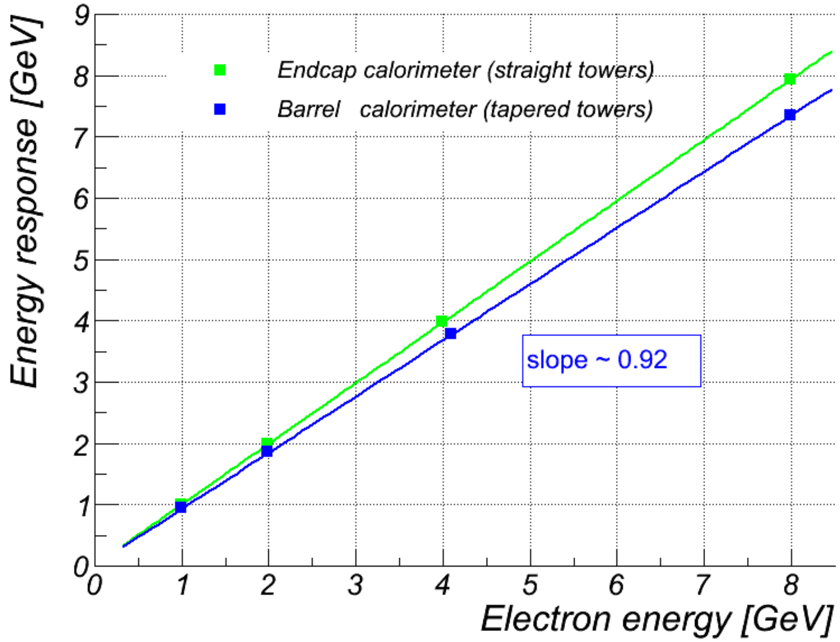
- "Realistic" digitization: 40MHz SiPM noise in 50ns gate;
- 4m attenuation length; 5 pixel single tower threshold;
- 70% light reflection on upstream fiber end;

-> good agreement with original MC studies and measured data



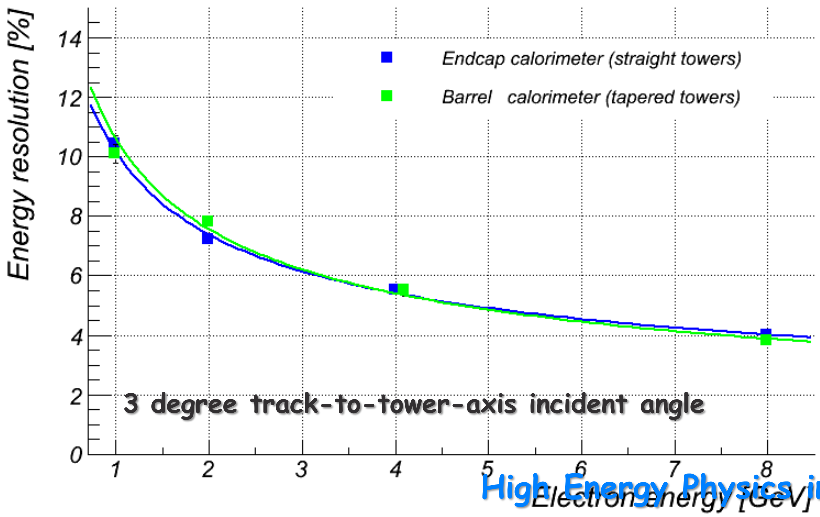
BARREL EM CALORIMETER (CEMC)





- same tungsten powder + fibers technology as FEMC, …
- … but towers are tapered
- non-projective

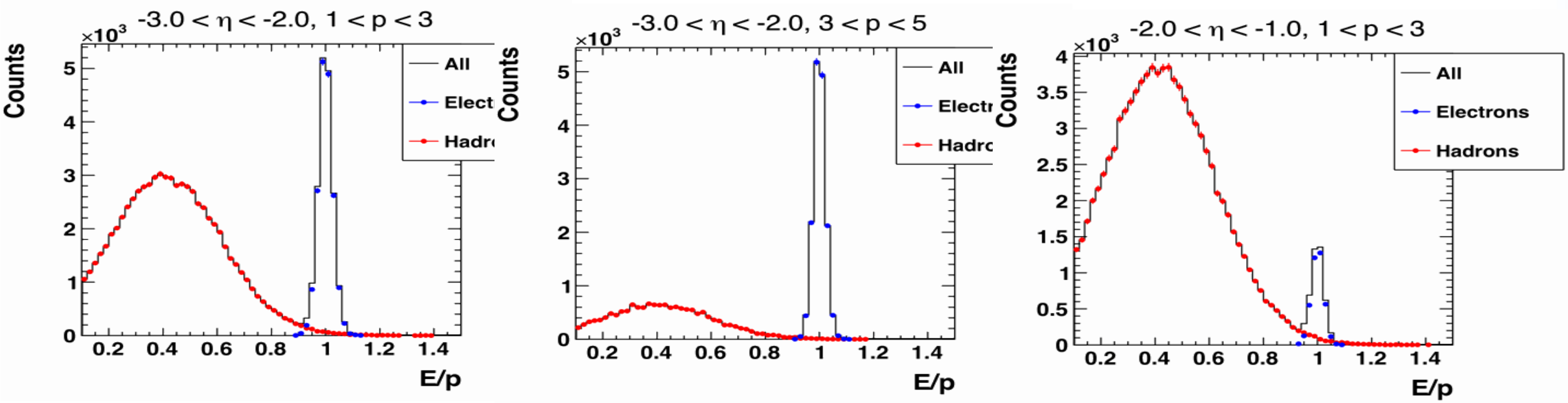
-> barrel calorimeter collects less light, but response (at a fixed 3° angle) is perfectly linear



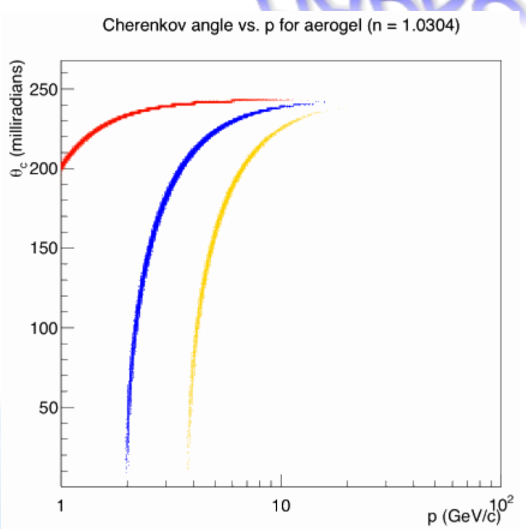
-> simulation does not show any noticeable difference in energy resolution between straight and tapered tower calorimeters

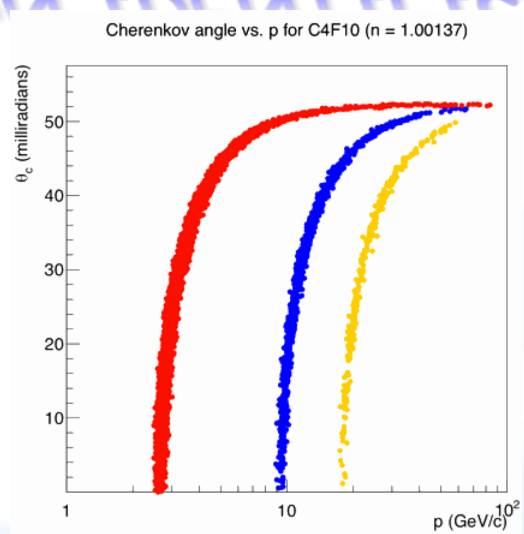
LEPTON-HADRON SEPARATION VIA E/P

all plots: 10GeV x 100GeV beams



HADRON IDENTIFICATION WITH RICH



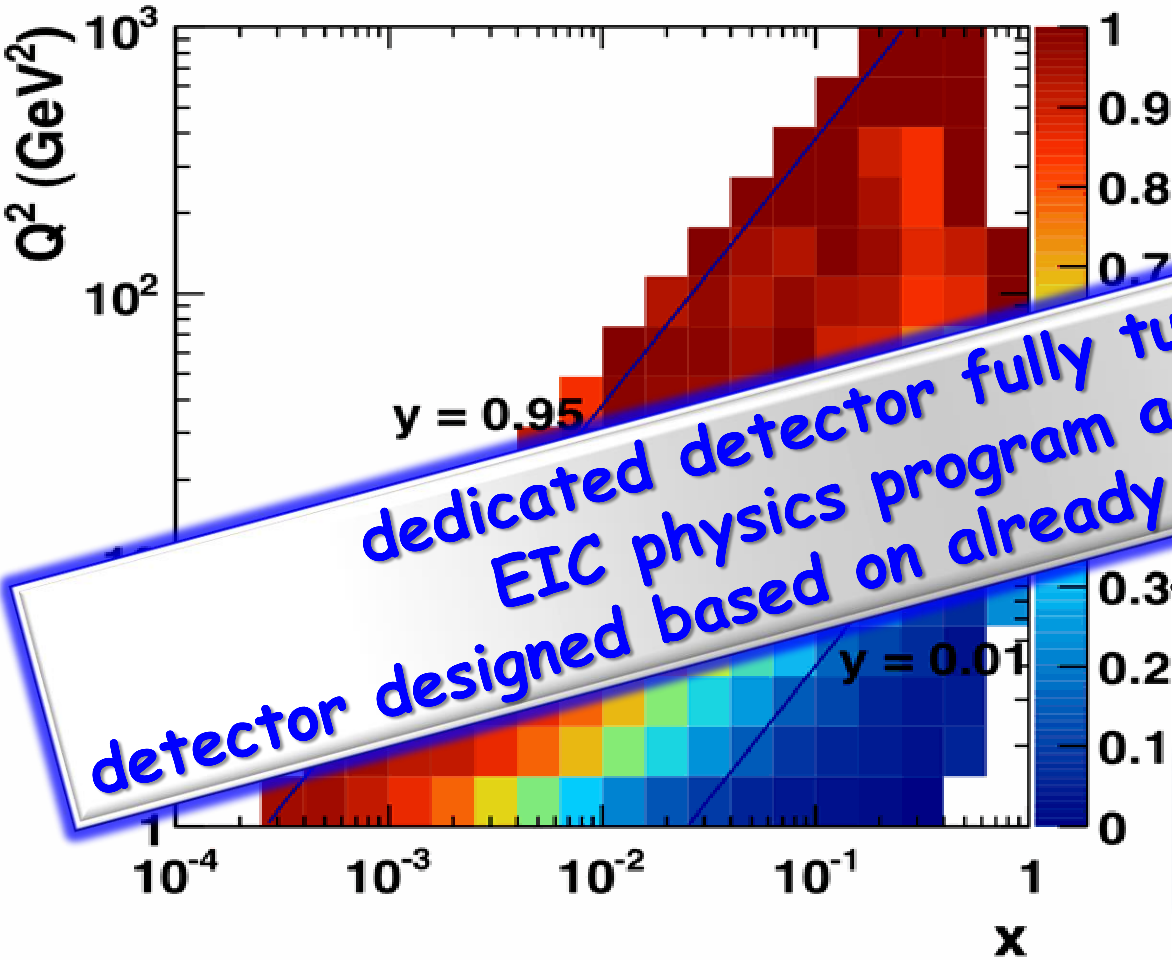


consider hadrons in pseudo-rapidity range ~[1.0 .. 3.0]

-> pion/kaon/proton identification should be possible up to momenta ~40 GeV/c

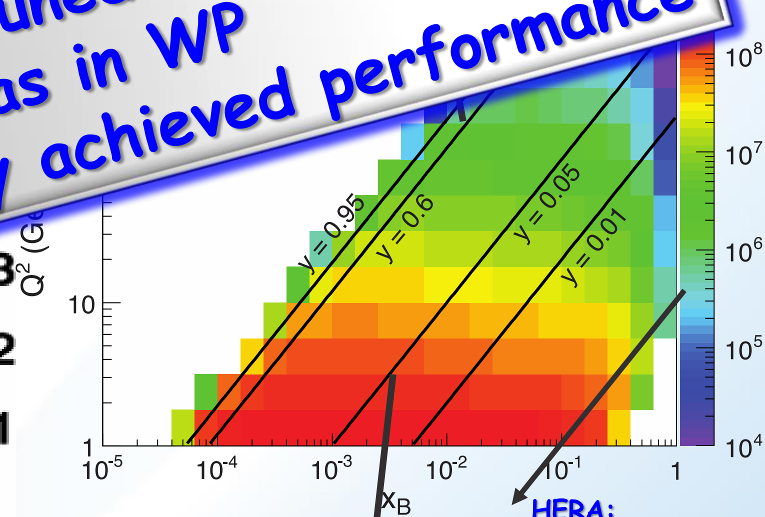
MIGRATION IN (X,Q²) BINS

10 GeV x 100 GeV beams



dedicated detector fully tuned to do
EIC physics program as in WP
detector designed based on already achieved performance

high y limited by
radiative co...

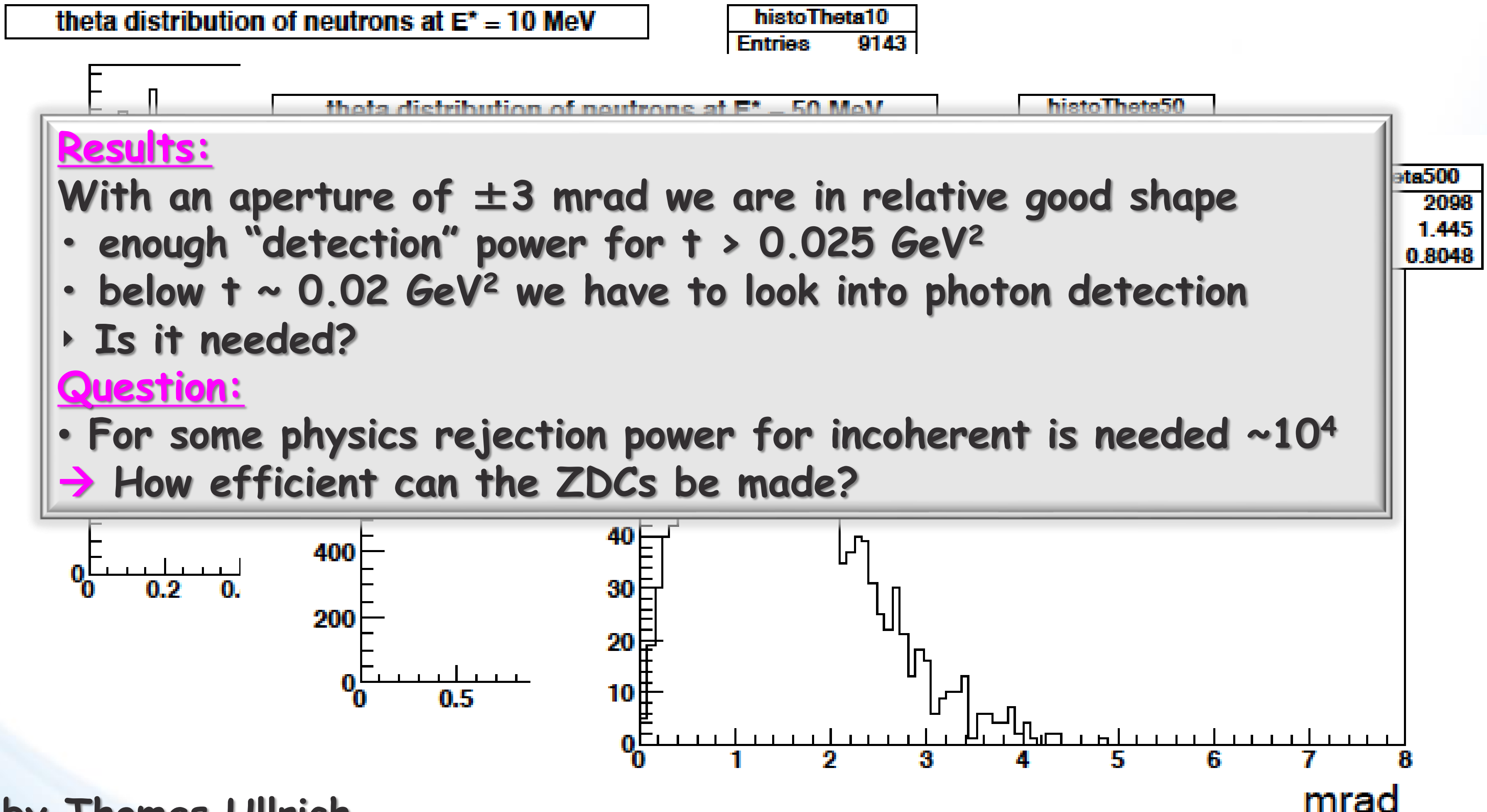


HERA:
y>0.005

low y-coverage:
limited by E'_e resolution
→ hadron method
→ or change beam energy

-> "survival probability" is above ~80% in the region, where tracking has superior resolution

Results from GEMINI++ for 50 GeV Au



Results:

With an aperture of ±3 mrad we are in relative good shape

- enough "detection" power for $t > 0.025\ GeV^2$
- below $t \sim 0.02\ GeV^2$ we have to look into photon detection
- Is it needed?

Question:

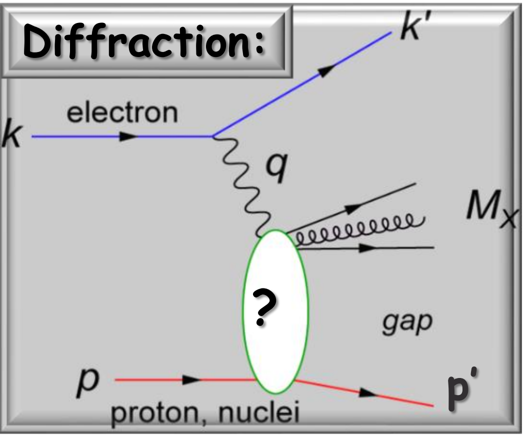
- For some physics rejection power for incoherent is needed $\sim 10^4$

→ How efficient can the ZDCs be made?

by Thomas Ullrich

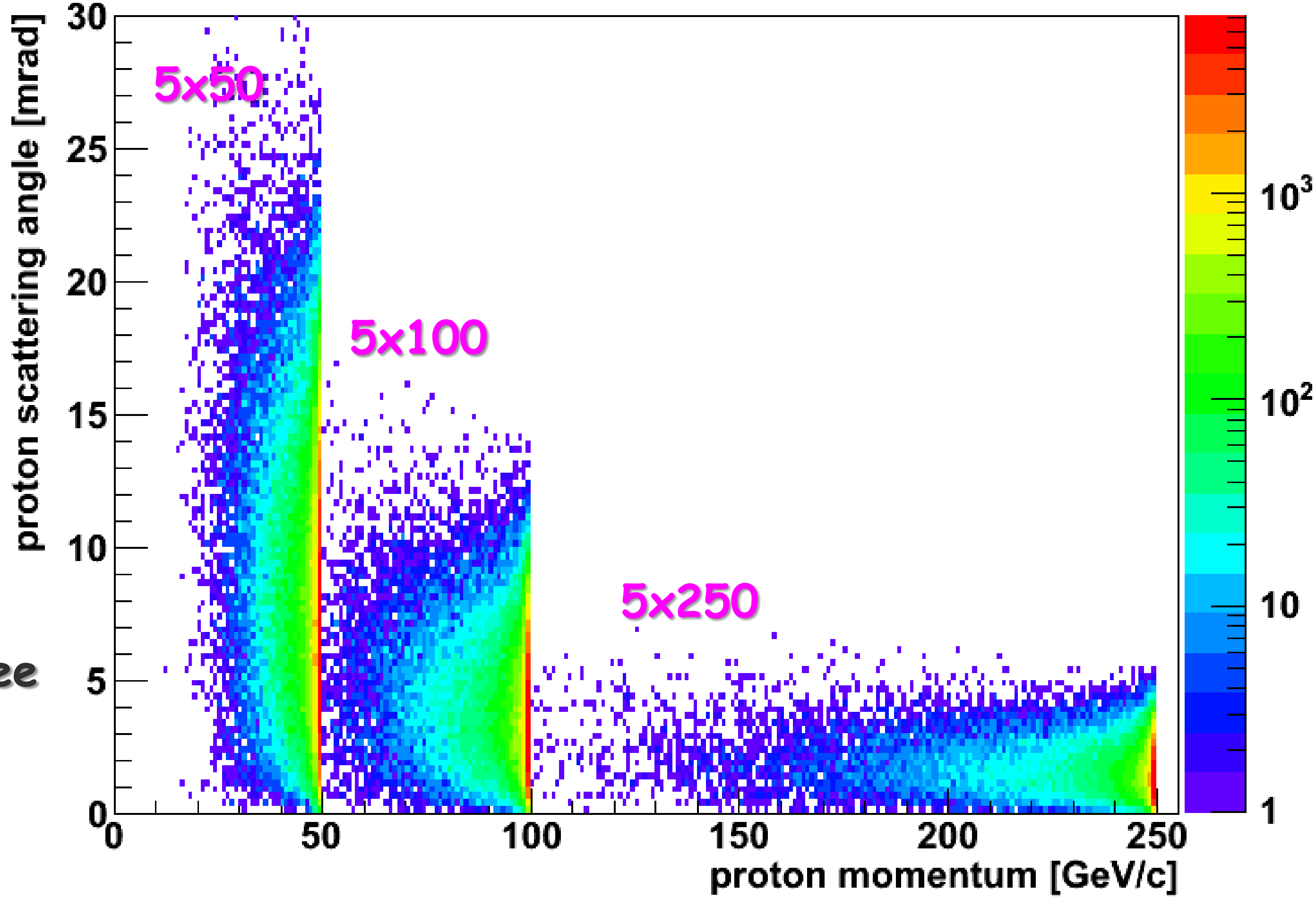
→ +/-5mrad acceptance seems sufficient

DIFFRACTIVE PHYSICS: P' KINEMATICS



$t=(p_4-p_2)^2 = 2[(m_p^{in}.m_p^{out})-(E^{in}E^{out} - p_z^{in}p_z^{out})]$

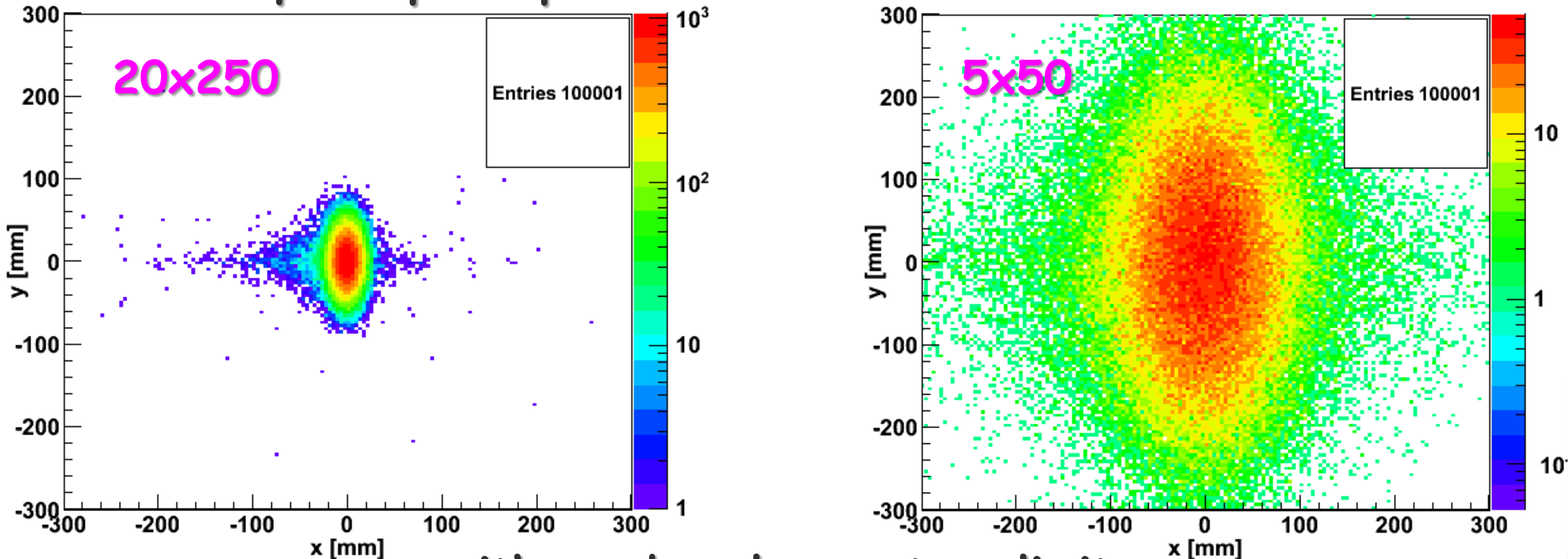
→ " Roman Pots" acceptance studies see later



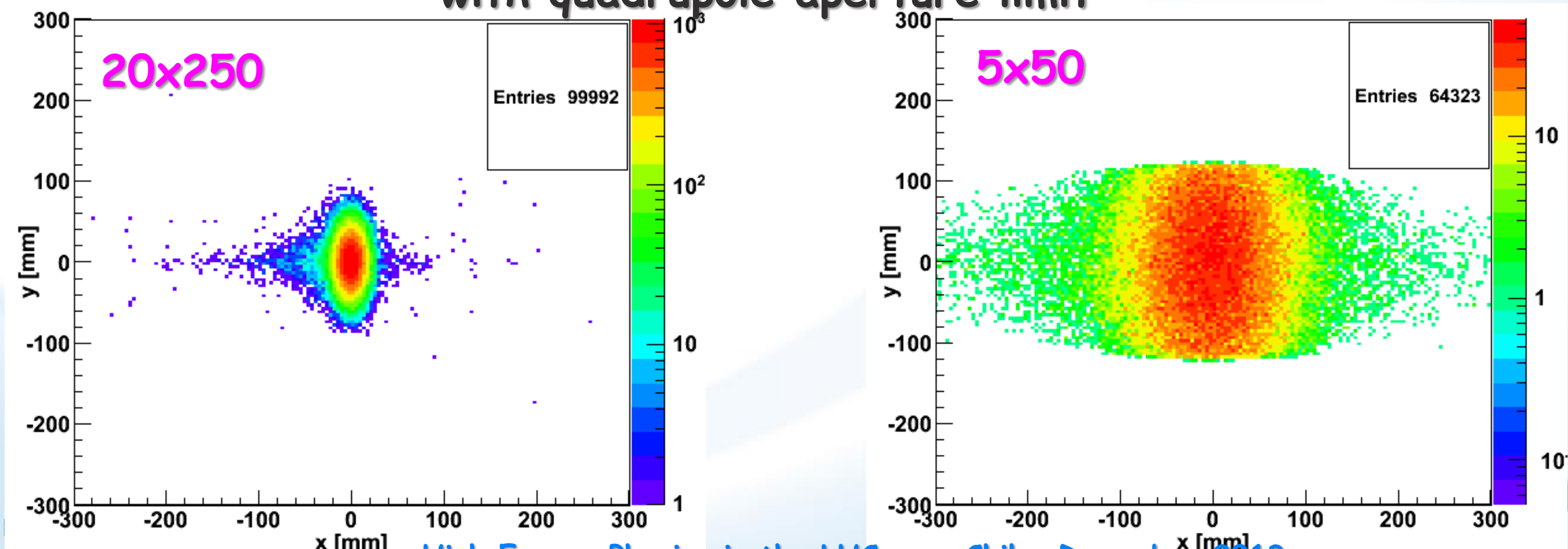
Simulations by J.H Lee

PROTON DISTRIBUTION IN Y VS X AT S=20 M

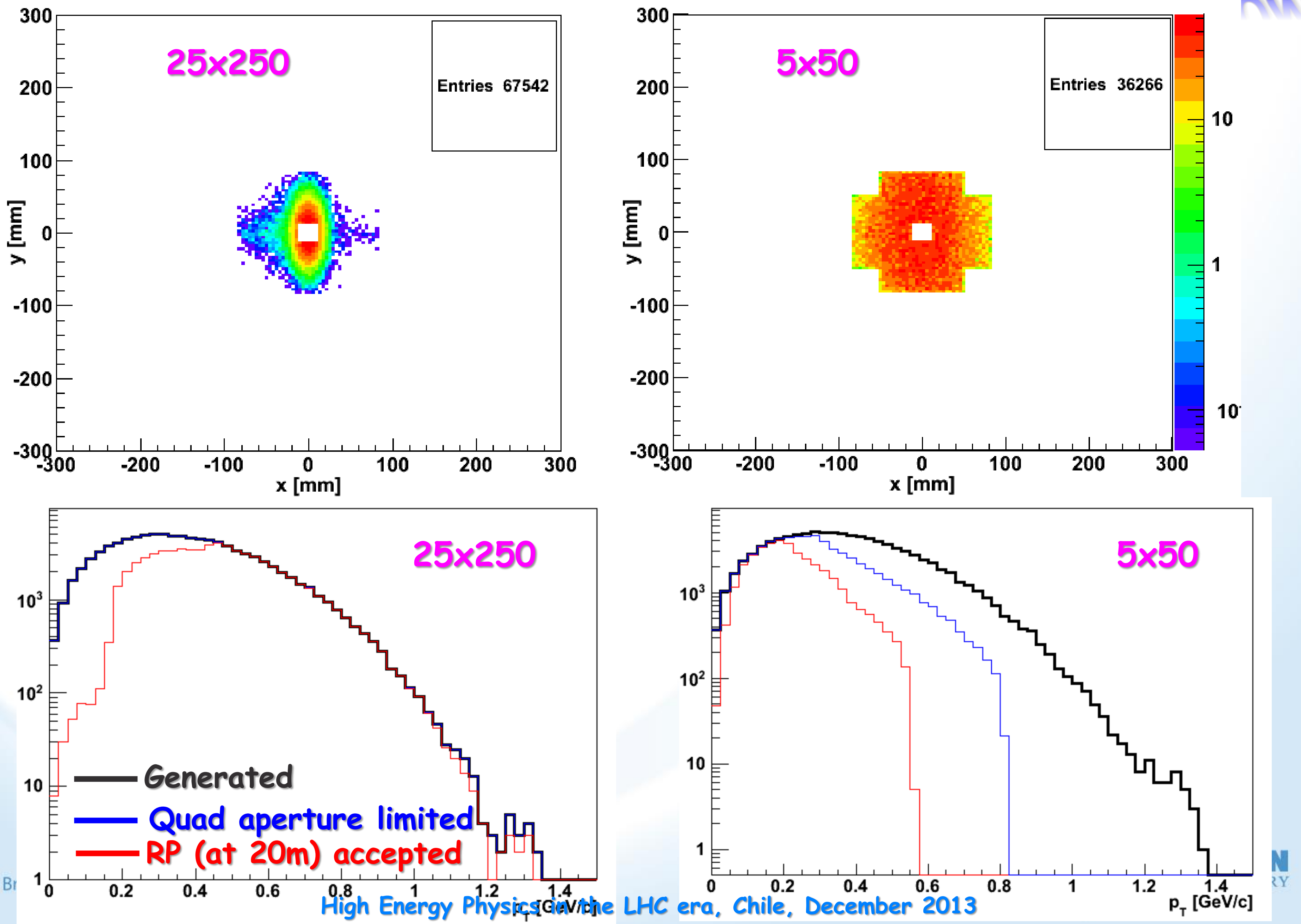
without quadrupole aperture limit



with quadrupole aperture limit

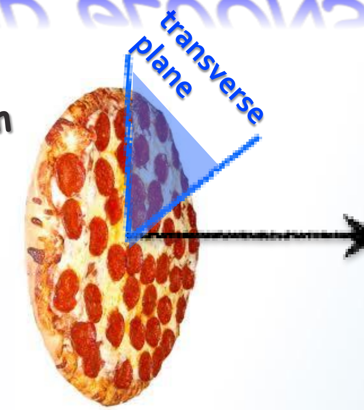


ACCEPTED IN "ROMAN POT" (EXAMPLE) AT S=20M



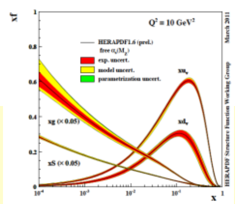
THE PATH TO IMAGING QUARKS AND GLUONS

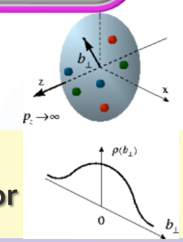
- PDFs do not resolve transverse momenta or positions in the nucleon
- fast moving nucleon turns into a `pizza' but transverse size remains about 1 fm



compelling questions
- how are quarks and gluons spatially distributed
- how do they move in the transverse plane
- do they orbit and do we have access to spin-orbit correlations

→ required set of measurements & theoretical concepts





1-D

$\mathbf{f(x)}$ parton densities

$\mathbf{F(t)}$ form factor

2+1-D

$\int d^2k_T$ (from $f(x, k_T)$ to $f(x)$)

$\int d^2b_T$ (from $f(x, b_T)$ to $f(x)$)

$\int dx$ (from $H(x,0,t)$ to $F(t)$)

$\mathbf{f(x, k_T)}$ transv. mom. dep. PDF — *semi-inclusive DIS*

← not related by Fourier transf. →

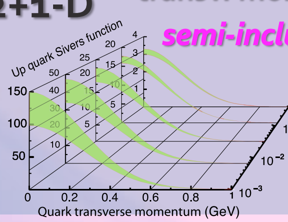
$\mathbf{f(x, b_T)}$ impact par. dep. PDF

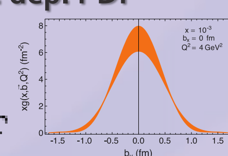
$b \leftrightarrow t$

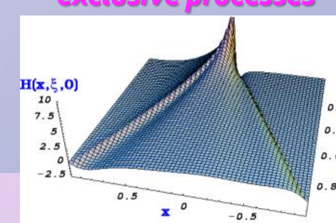
$\mathbf{H(x, 0, t)}$

$\xi \to 0$

$\mathbf{H(x, \xi, t)}$ generalized PDF — *exclusive processes*







$\int d^2b_T$ (from W to $f(x, k_T)$)

$\int d^2k_T$ (from W to $f(x, b_T)$)

4+1-D

Wigner function

$\mathbf{W(x, k_T, b_T)}$

high-level connection

measurable ?

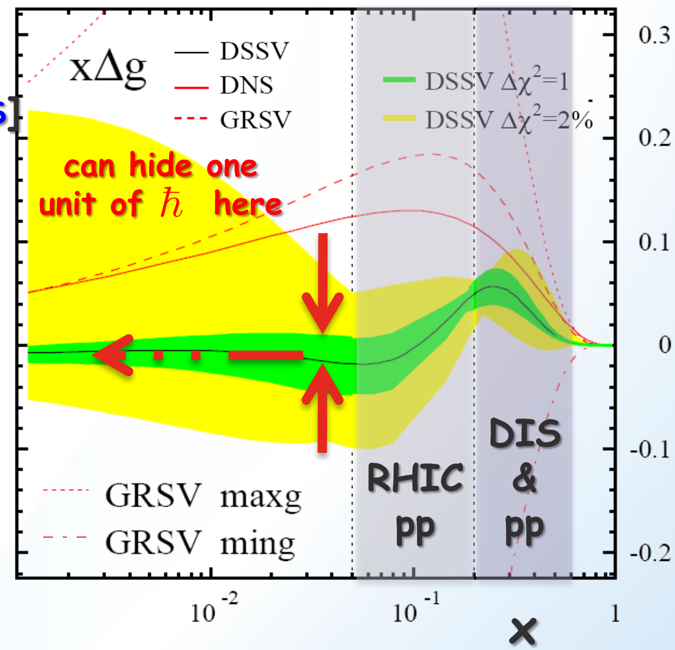
important in other branches of Physics

HELICITY STRUCTURE - OPEN QUESTIONS

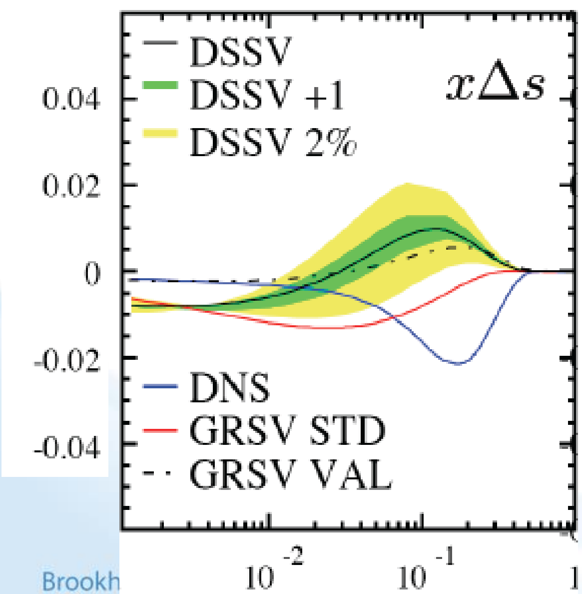
significant experimental and theoretical progress in past 25+ years, yet many unknows …

$\Delta g(x,Q^2)$

- found to be small at 0.05 < x < 0.2 [RHIC, COMPASS, HERMES]
- RHIC can slightly extend x range & reduce uncertainties [500 GeV running & particle correlations]



yet, full 1st moment [proton spin sum] will remain to have significant uncertainties from unmeasured small x region

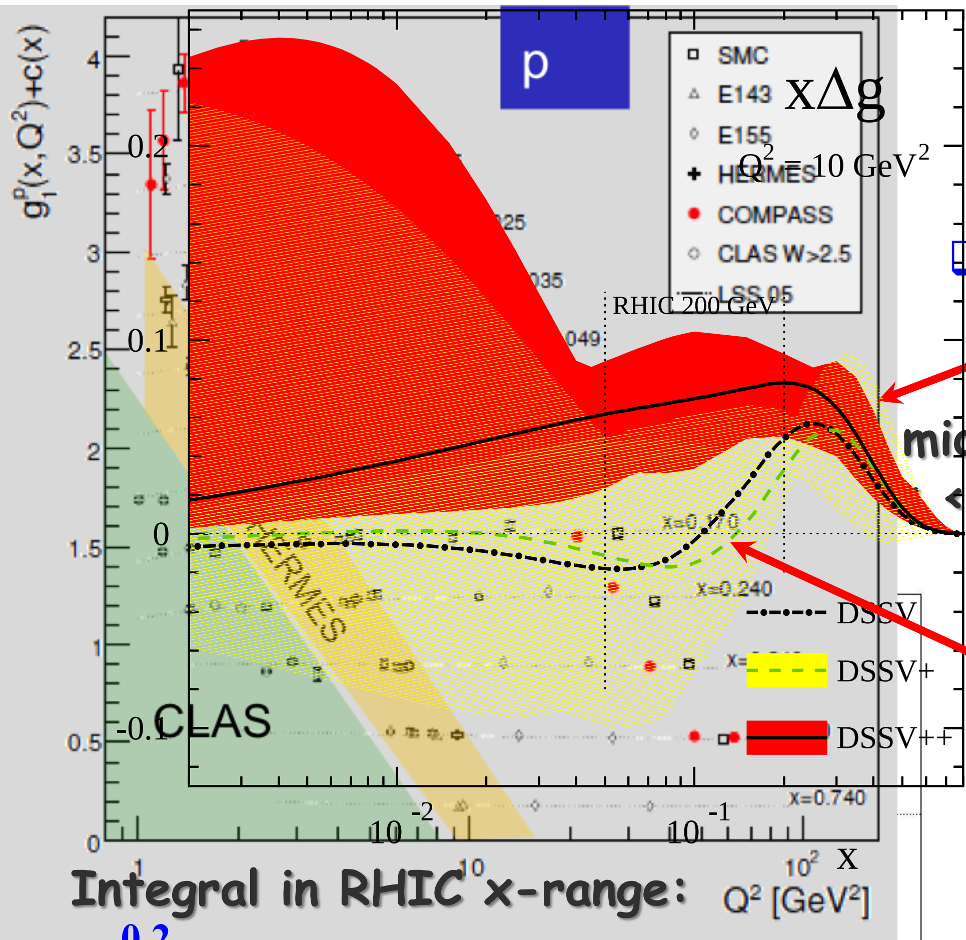


Δq's (x,Q^2)

- known: quarks contribute much less to proton spin than expected from quark models
  large uncertainties in $\Delta\Sigma$ from unmeasured small x
- surprisingly small/positive Δs from SIDIS: large SU(3) breaking?
- flavor separation not well known, e.g., $\Delta\bar{u} - \Delta\bar{d}$

WHAT DO WE KNOW NOW ON $\Delta g(x)$

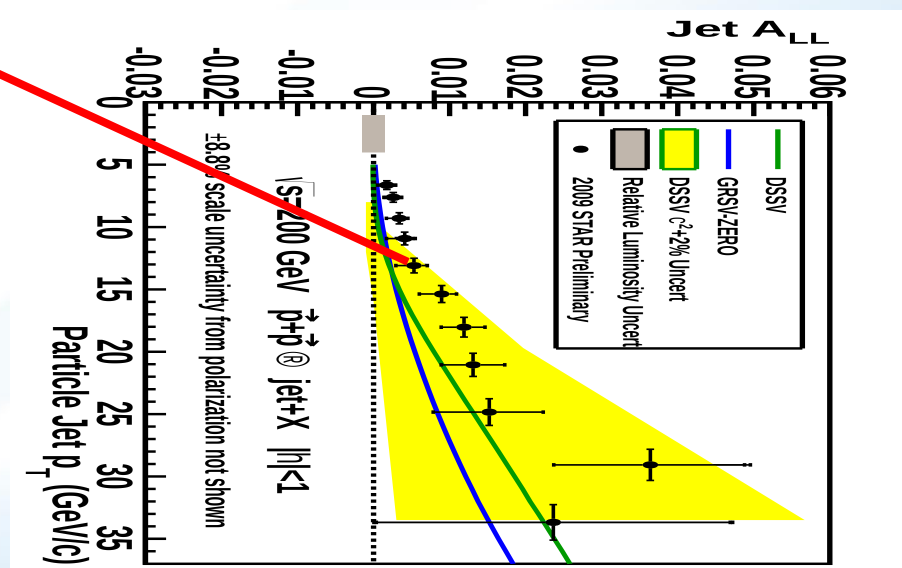
$$\frac{dg_1}{d\log(Q^2)} \sim -\Delta g(x,Q^2)$$



- Scaling violations of g_1 (Q^2-dependence) give indirect access to the gluon distribution via DGLAP evolution.

midrapidity: direct access to gluons (gg,qg)

< 0.2



Integral in RHIC x-range:

$$\int_{0.05}^{0.2} dx\Delta g \sim 0.1^{+0.06}_{-0.07} \;@\; 10\text{ GeV}^2$$

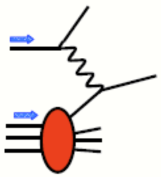
Contribution to proton spin to date:

Gluon: 20% Quarks: 30%

PREPARATION OF DIS AND SIDIS MOCK DATA

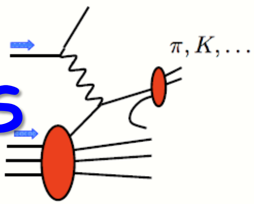
- PEPSI MC to generate σ^{++} and σ^{+-} with LO GRSV PDFs

DIS



inclusive final-state

SIDIS



identified charged pions and kaons

assume modest 10 fb^{-1} for each energy, 70% beam polarizations

$Q^2 > 1$ GeV^2, $0.01 < y < 0.95$, invariant mass $W^2 > 10$ GeV^2

depolarization factor of virtual photon $D(y,Q^2) > 0.1$ (cuts on small y)

scattered lepton: $1^o < \theta_{elec} < 179^o$ and $p_{elec} > 0.5$ GeV

hadron: $p_{hadr} > 1$ GeV, $0.2 < z < 0.9$,
$1^0 < \theta_{hadr} < 179^o$

- use rel. uncertainties of data to generate mock data by randomizing around DSSV+ by 1-σ
- SIDIS: incl. typical 5% (10%) uncertainty for pion (kaon) frag. fcts (from DSS analysis)

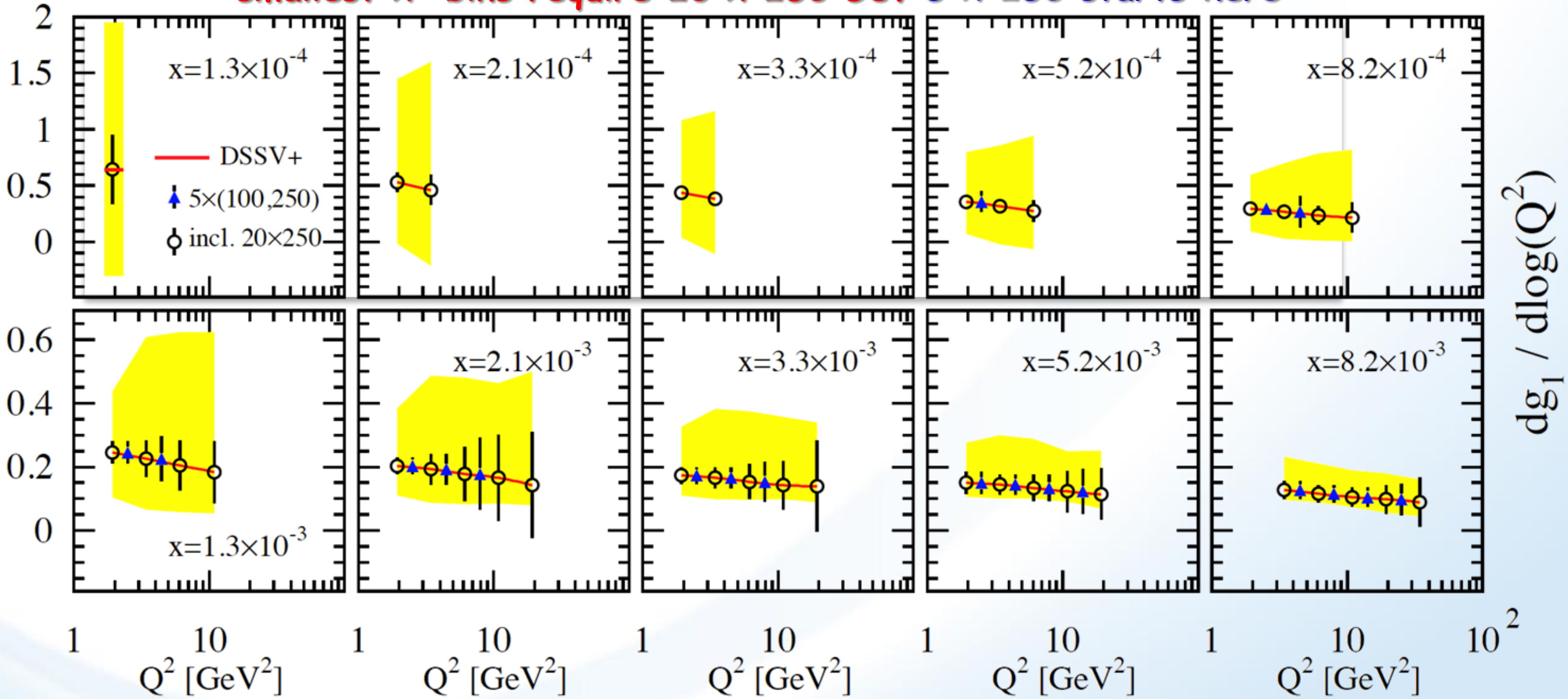
rough small-x approximation to Q^2-evolution:

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

spread in $\Delta g(x,Q^2)$ translates into spread of scaling violations for $g_1(x,Q^2)$

- need x-bins with a least two Q^2 values to compute derivative (limits x reach somewhat)

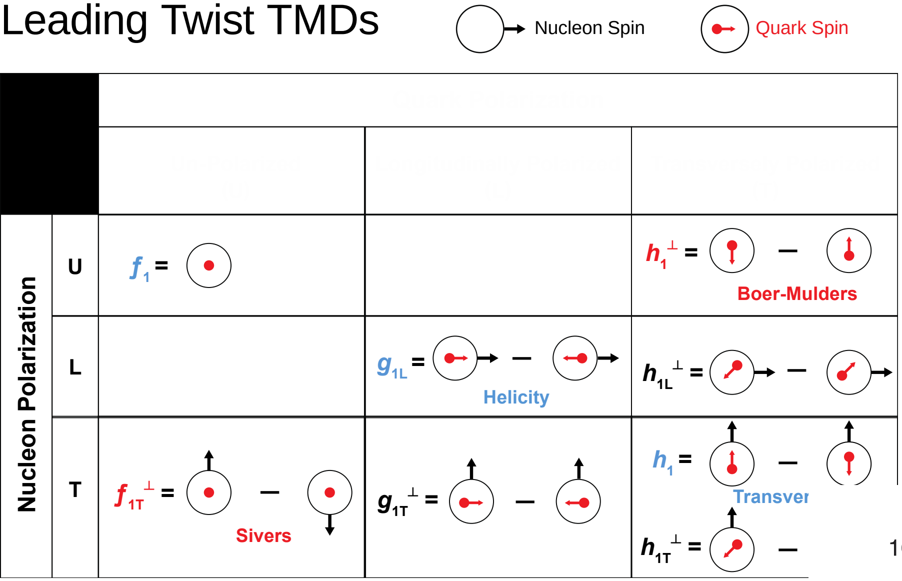
smallest x bins require 20 x 250 GeV 5 x 250 starts here



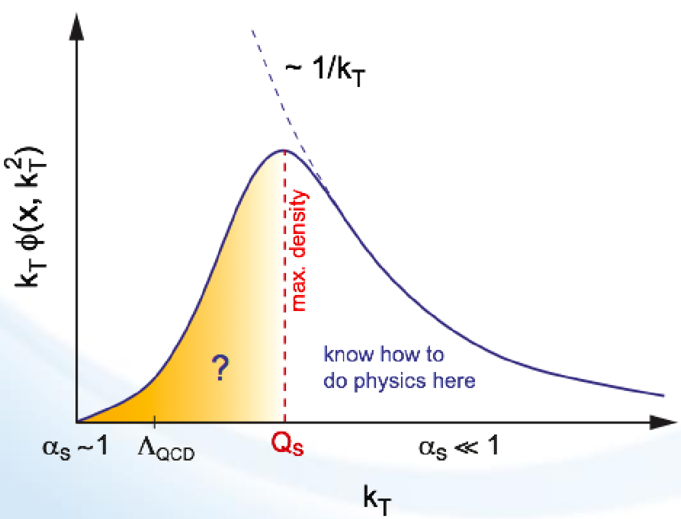
- error bars for moderate $10 fb^{-1}$ per c.m.s. energy; bands parameterize current DSSV+ uncertainties

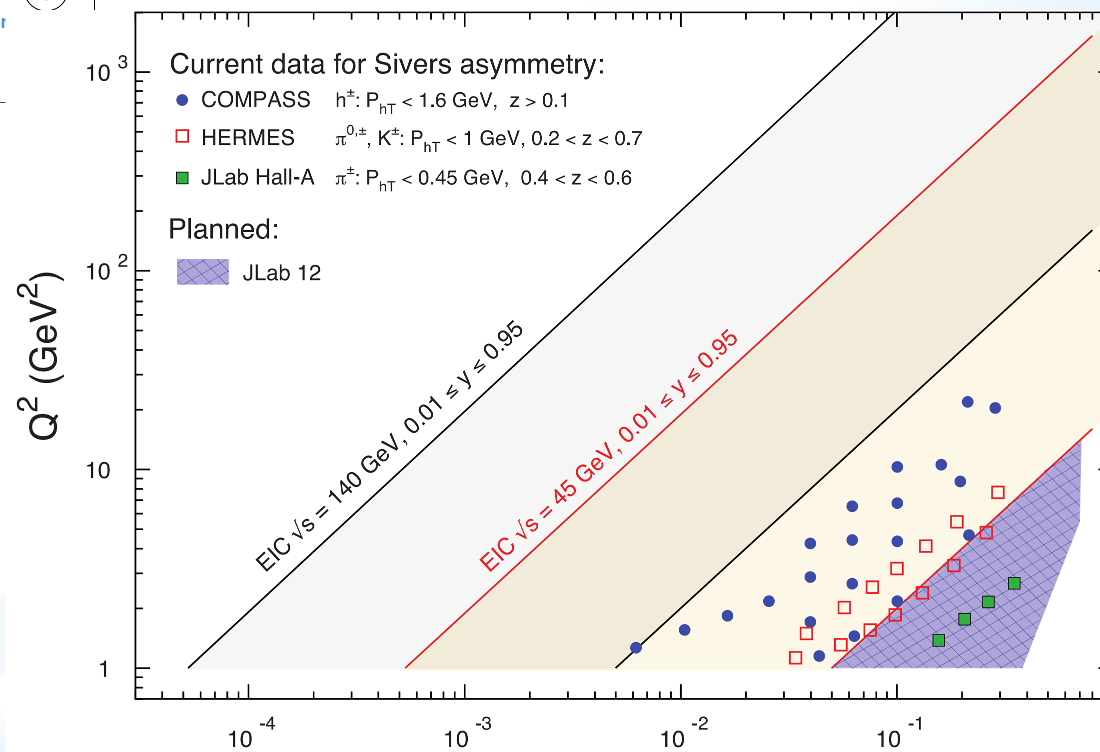
MORE INSIGHTS TO THE PROTON: TMDs

Leading Twist TMDs

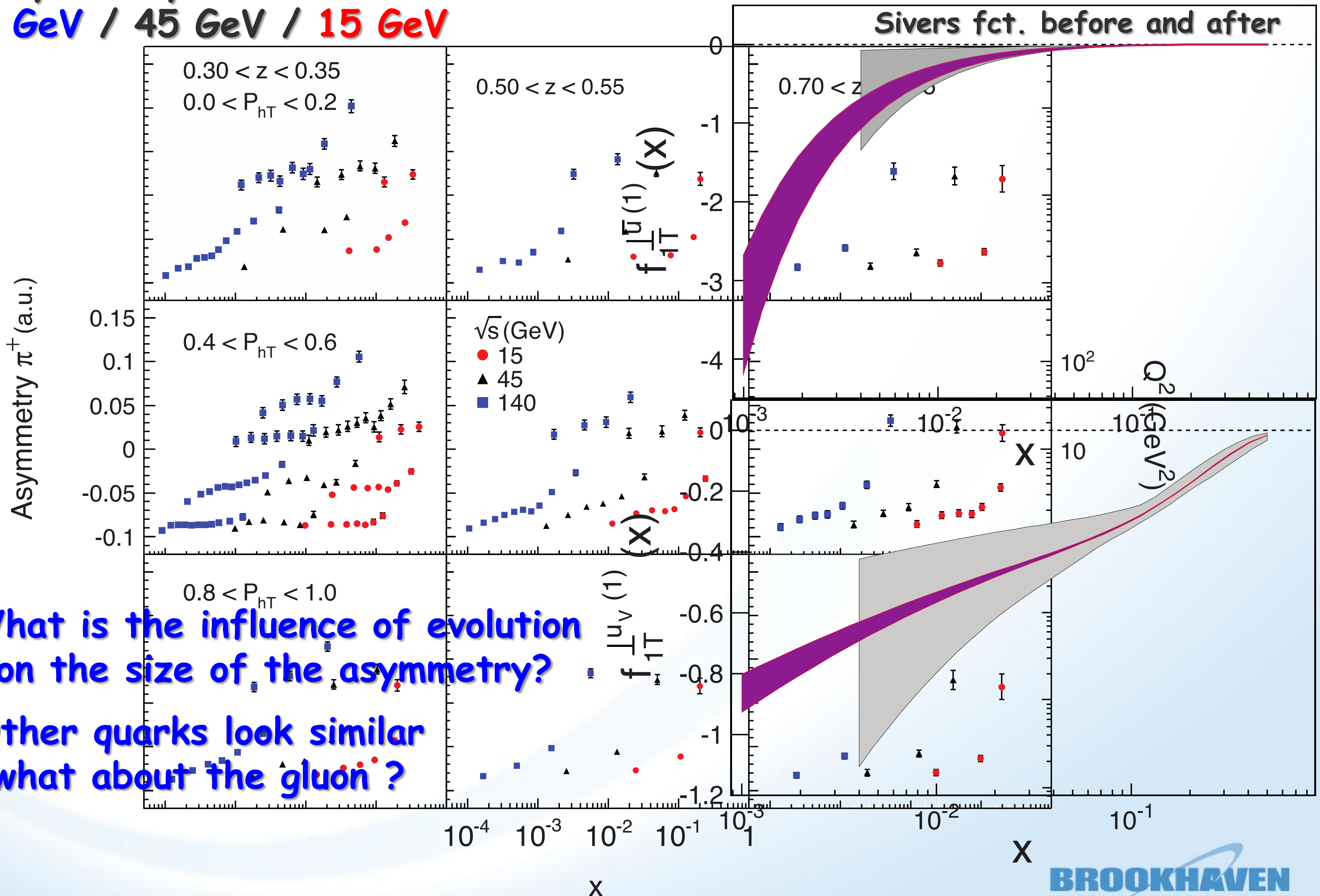


Similar for gluons





Sivers asymmetry for π+:
√s=140 GeV / 45 GeV / 15 GeV

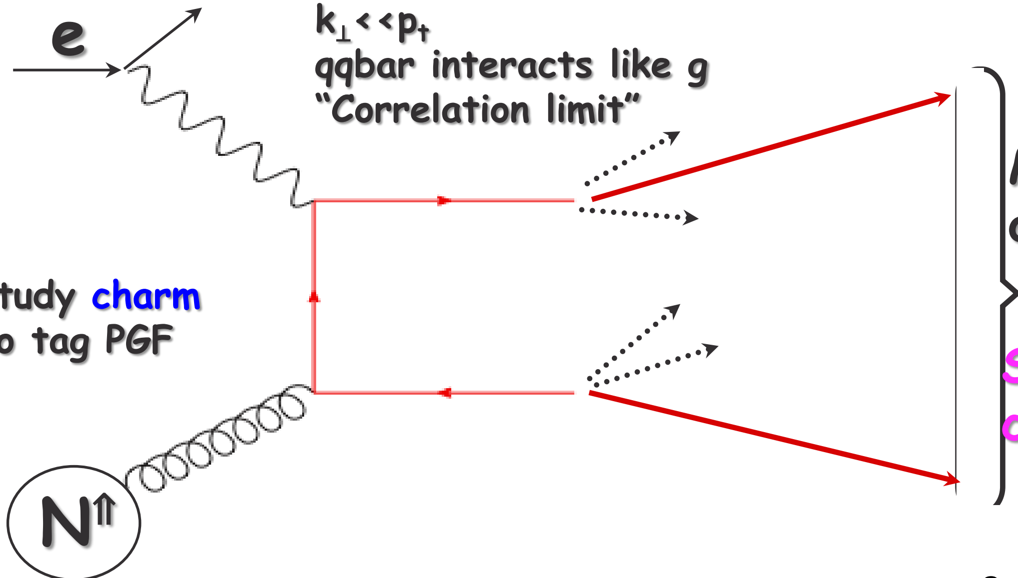


What is the influence of evolution on the size of the asymmetry?

Other quarks look similar
what about the gluon ?

The Gluon Sivers Function: $\gamma^* N^{\Uparrow} \rightarrow h+h+X$

$k_\perp << p_t$
qqbar interacts like g
"Correlation limit"



study **charm** to tag PGF

Measure a pair of **D** mesons

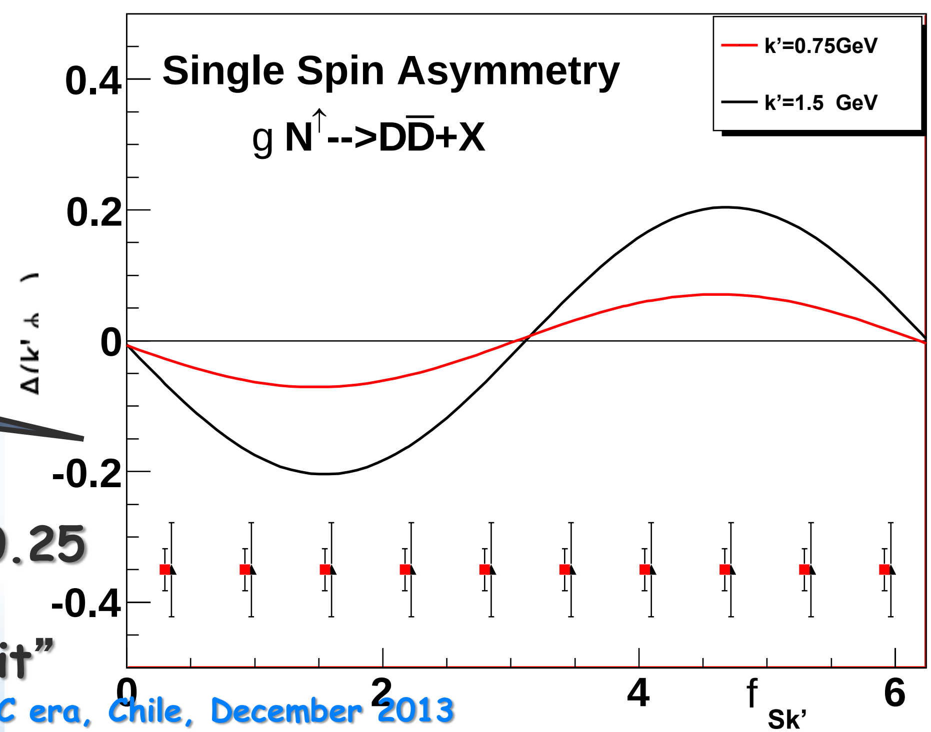
$k_\perp = |k_{1T} + k_{2T}|$

$P_T = (k_{1T} - k_{2T}) / 2$

Statistically challenging

$$A(k'_\perp, \phi_{Sk'}) = \frac{d\sigma(k'_\perp, \phi_{Sk'}) - d\sigma(k'_\perp, \phi_{Sk'} + \pi)}{d\sigma(k'_\perp, \phi_{Sk'}) + d\sigma(k'_\perp, \phi_{Sk'} + \pi)}$$

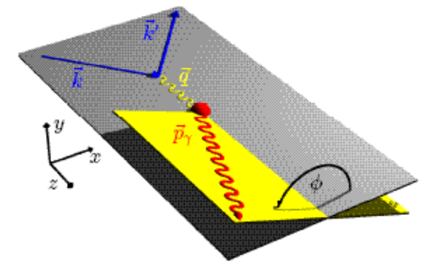
~8 months with 50% efficiency and $L = 10^{34} cm^2 s^{-1}$



- Beam Energies: 20 GeV x 250 GeV
- Q^2: 1 – 10 GeV^2, y: 0.01 – 0.95, z>0.25
- no cut on $k_\perp$ and p_t, but on $k_\perp/p_t$ < 0.5 for "correlation limit"

DVCS ASYMMETRIES

$$d\sigma \sim \left(\tau^{*}_{BH}\tau_{DVCS} + \tau^{*}_{DVCS}\tau_{BH}\right) + |\tau_{BH}|^{2} + |\tau_{DVCS}|^{2}$$



→ different charges: e^{+} e^{-}:

$$\Delta\sigma_{C} \sim \cos\phi \cdot \mathrm{Re}\{ H + \xi\tilde{H} + \ldots \} \Rightarrow H$$

→ polarization observables:

$$\Delta\sigma_{LU} \sim \sin\phi \cdot \mathrm{Im}\{ H + \xi\tilde{H} + kE \} \Rightarrow H$$

$$\Delta\sigma_{UL} \sim \sin\phi \cdot \mathrm{Im}\{ \tilde{H} + \xi H + \ldots \} \Rightarrow \tilde{H}$$

$\Delta\sigma_{UT}$ ↙ beam ↘ target

$$\Delta\sigma_{UT} \sim \sin\phi \cdot \mathrm{Im}\{ k(H - E) + \ldots \} \Rightarrow H, E$$

$\xi = x_B/(2-x_B)$ $k = t/4M^2$ kinematically suppressed

CONSTRAIN J_q VIA GPD E

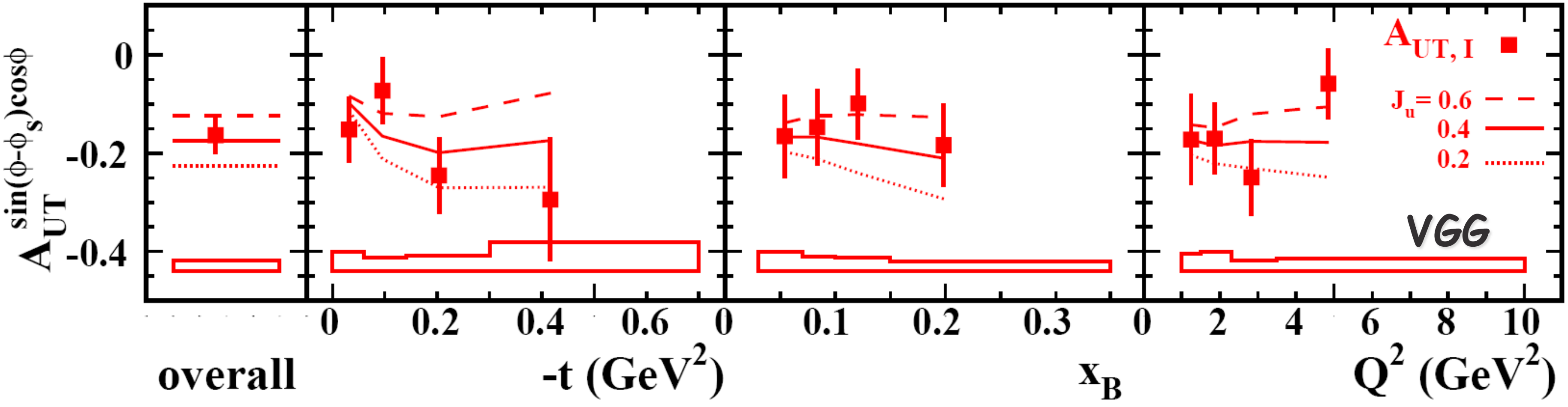
observables sensitive to E:

(J_q input parameter in ansatz for E)

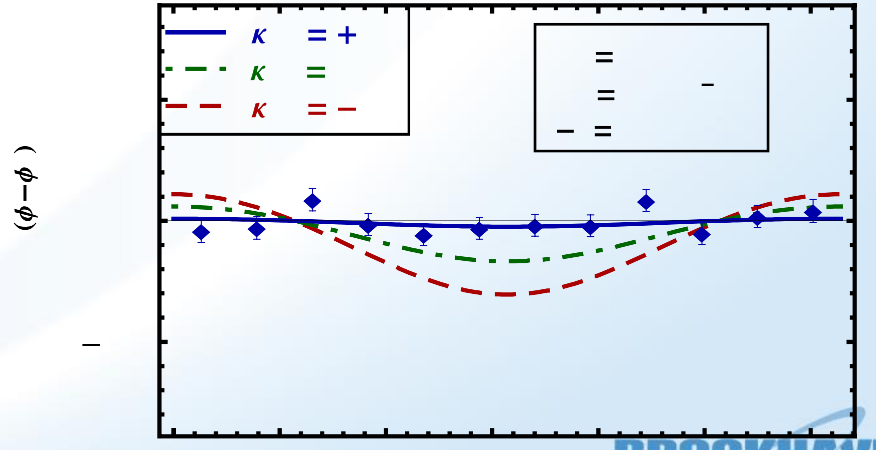
- DVCS A_{UT} : HERMES
- nDVCS A_{LU} : Hall A

Hermes DVCS-TTSA [arXiv: 0802.2499]:

$$A_{UT}^{\sin(\phi-\phi_T)\cos\phi} \sim \mathrm{Im}(F_2 H - F_1 E)$$



eRHIC:
HERMES like A_{UT}
20 GeV x 250 GeV
Lumi: 2x50fb^{-1}



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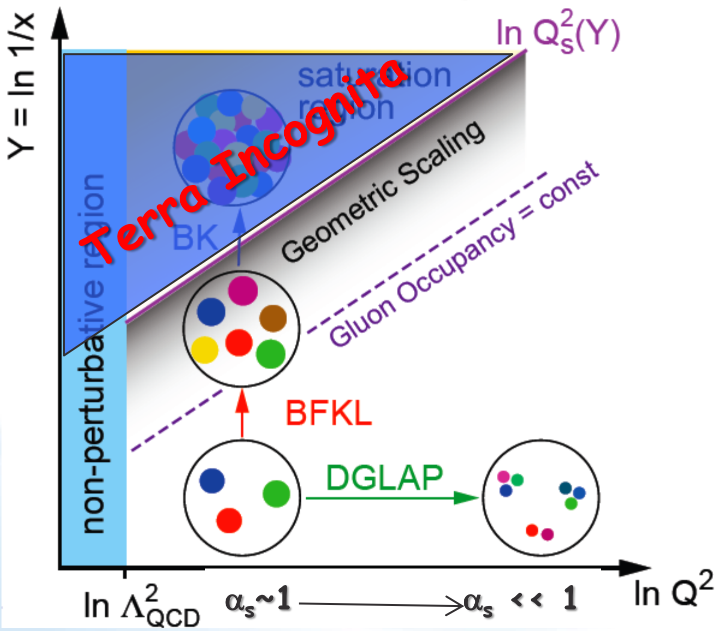
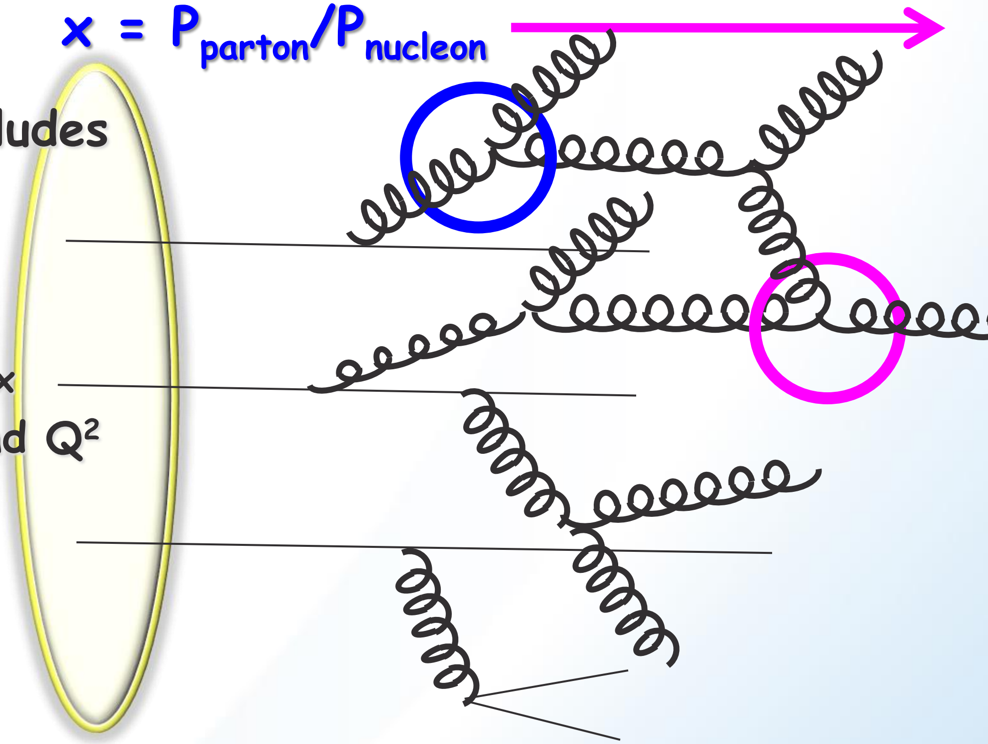
HOW MANY GLUONS HAVE SPACE IN A PROTON?

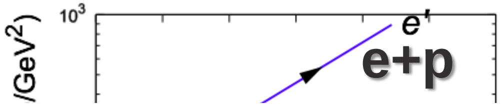
- at small x linear evolution gives strongly rising g(x)
  - cannot go on forever
- BK/JIMWLK **non-linear** evolution includes **recombination** effects → **saturation**
  - Dynamically generated scale
    Saturation Scale: $Q^2_s(x)$
    - Increases with energy or decreasing x
  - Scale with $Q^2/Q^2_s(x)$ instead of x and Q^2

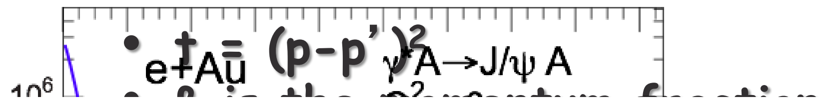




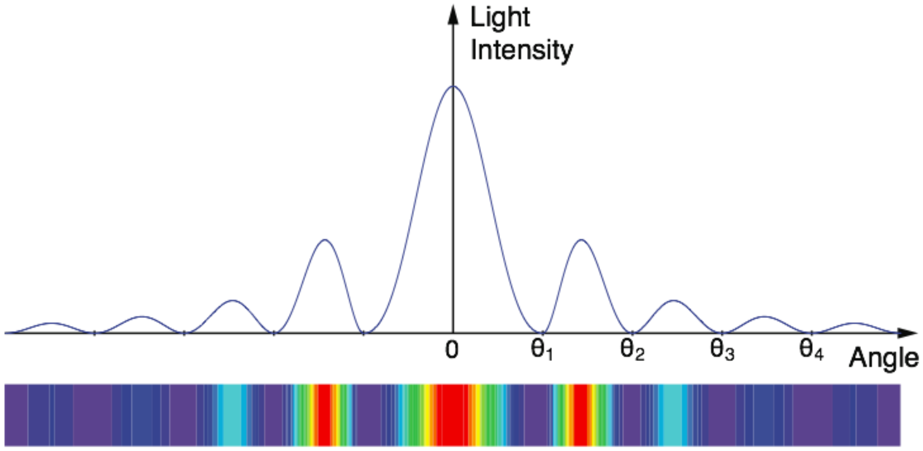
Saturation must set in at low x → high occupancy

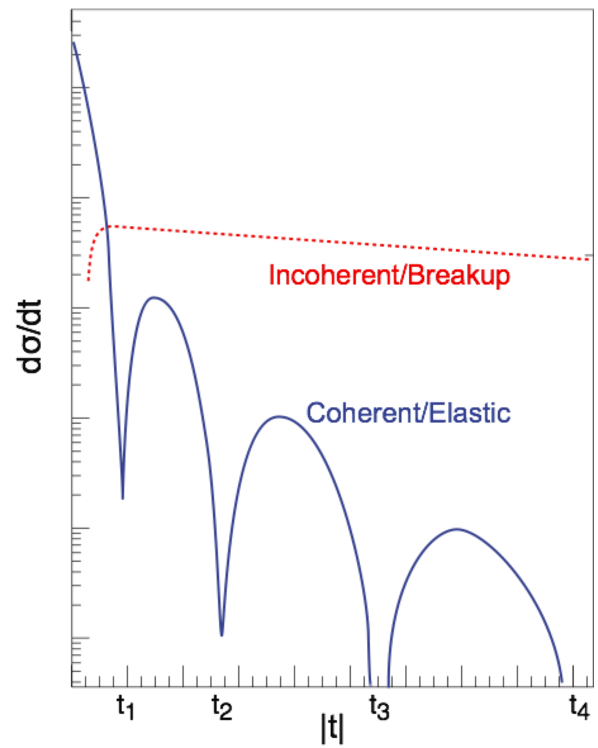
HARD DIFFRACTION IN DIS AT SMALL X





Diffraction Analogy: plane monochromatic wave incident on a circular screen of radius R

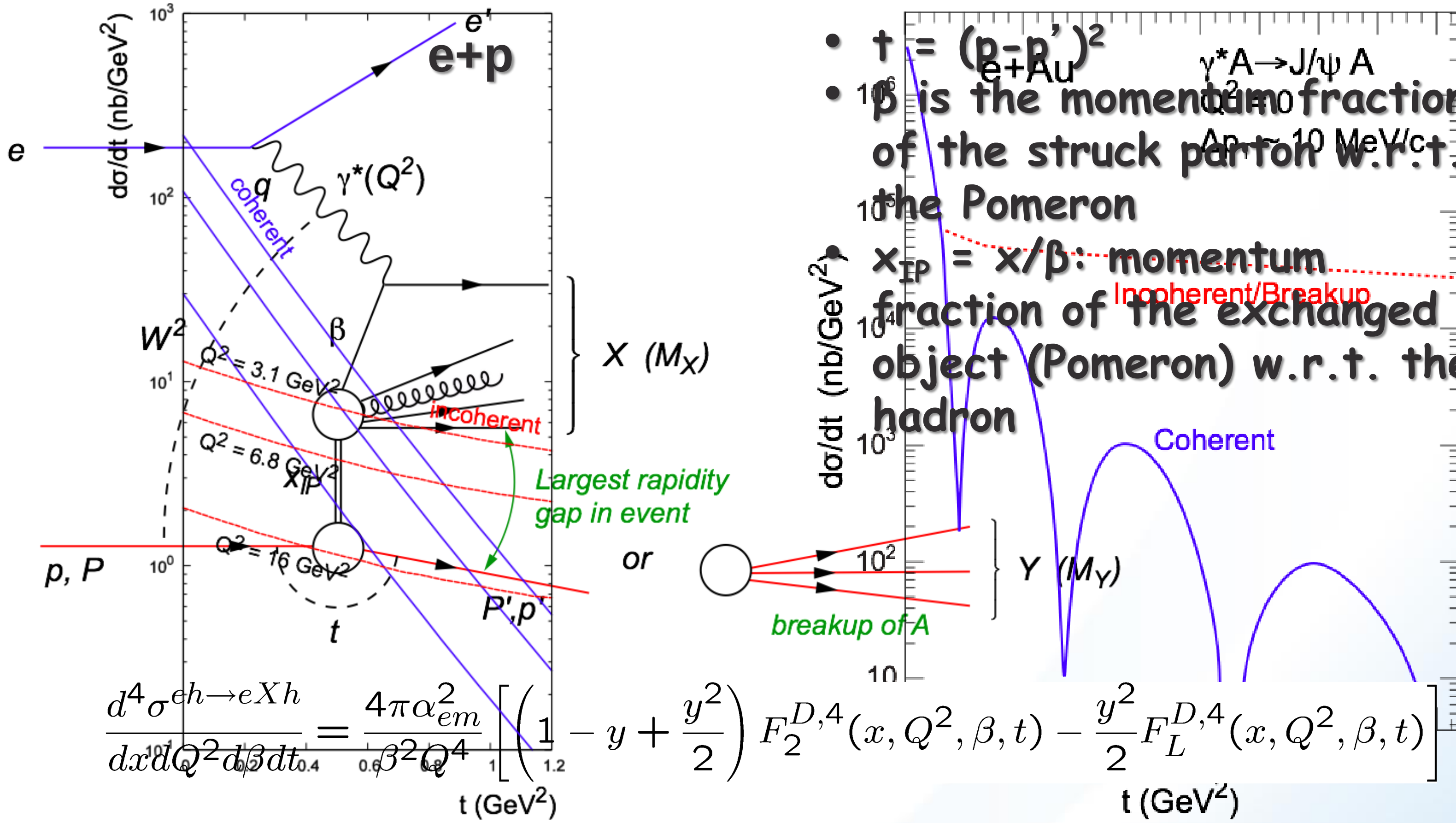




- incoherent ⇔ breakup of p
- HERA: 15% of all events are hard diffractive

- breakup into nucleons (nucleons intact)
- incoherent diffraction
- Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%

HARD DIFFRACTION IN DIS AT SMALL X



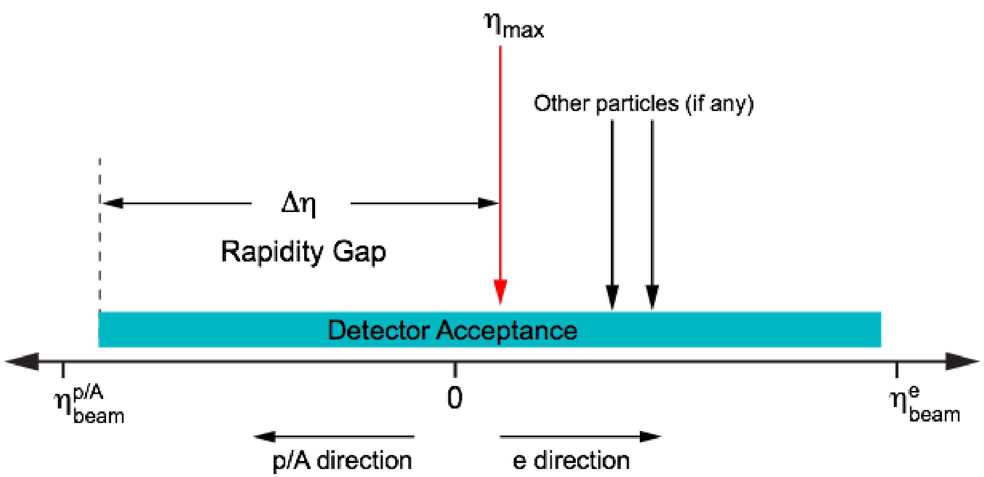
- $t = (p-p')^2$
- β is the momentum fraction of the struck parton w.r.t. the Pomeron
- $x_{IP} = x/\beta$: momentum fraction of the exchanged object (Pomeron) w.r.t. the hadron

$$\frac{d^4\sigma^{eh\to eXh}}{dx\,dQ^2\,d\beta\,dt} = \frac{4\pi\alpha_{em}^2}{\beta^2 Q^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2^{D,4}(x,Q^2,\beta,t) - \frac{y^2}{2}F_L^{D,4}(x,Q^2,\beta,t)\right]$$

- Diffraction in e+p:
  - coherent ⇔ p intact
  - incoherent ⇔ breakup of p
  - HERA: 15% of all events are hard diffractive
- Diffraction in e+A:
  - coherent diffraction (nuclei intact)
  - breakup into nucleons (nucleons intact)
  - incoherent diffraction
  - Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%

LARGE RAPIDITY GAP METHOD (LRG)

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

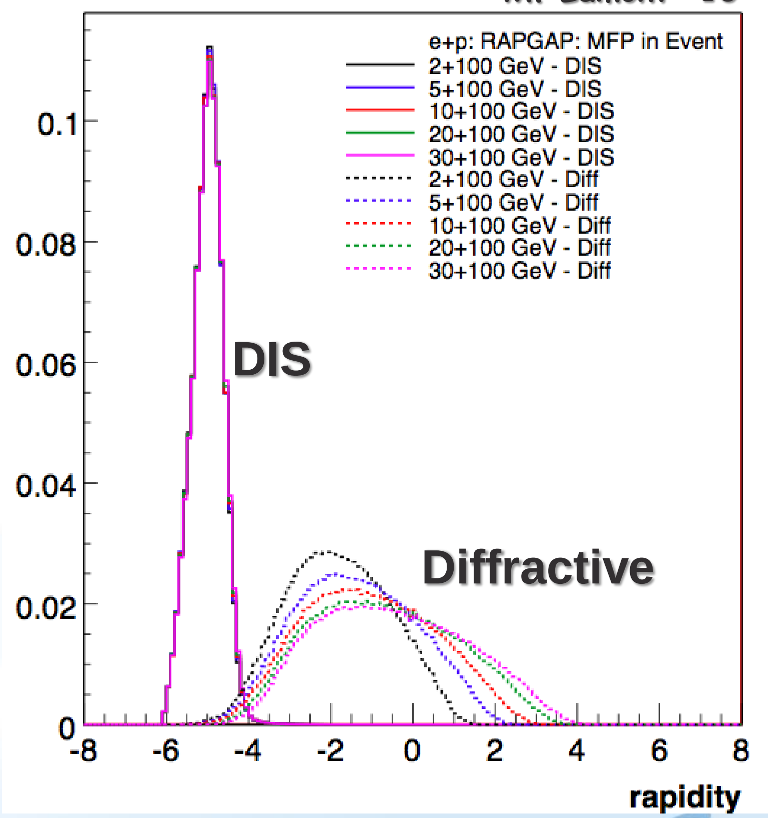


Hermeticity requirement:

- needs just to detector presence
- does not need momentum or PID
- simulations: √s not a show stopper for EIC **(can achieve 1% contamination, 80% efficiency)**

Diffractive ρ^0 production at EIC: **η of MFP**

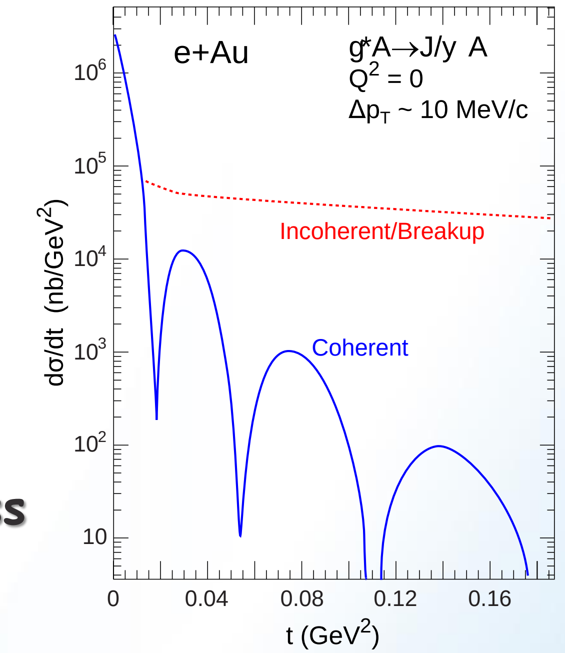
M. Lamont '10



- Sensitive to **spatial** gluon distribution

$$\frac{ds}{dt} \; \text{o} \; \frac{\text{Fourier Transformation}}{\text{of Source Density } r_g(\text{b})}$$

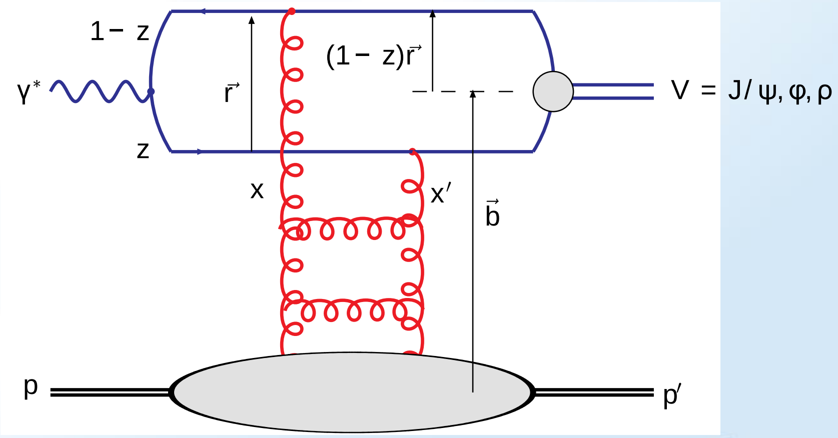
  - Hot topic:
    - Lumpiness?
    - Just Wood-Saxon+nucleon g(b)
  - Incoherent case: measure fluctuations/lumpiness in g_A(b)



- Sensitive to gluon momentum distributions
  - $\sigma \sim g(x,Q^2)^2$

$$\frac{d\sigma^{\gamma^* p \to pV}}{dt} \sim \left| \int \Psi_V^* \frac{d\sigma_{q\bar{q}}}{d^2b} \Psi e^{-ib\Delta} \right|^2$$

$$\frac{d\sigma_{q\bar{q}}}{d^2b} \sim r^2 \alpha_s x g(x,\mu^2) T(b)$$



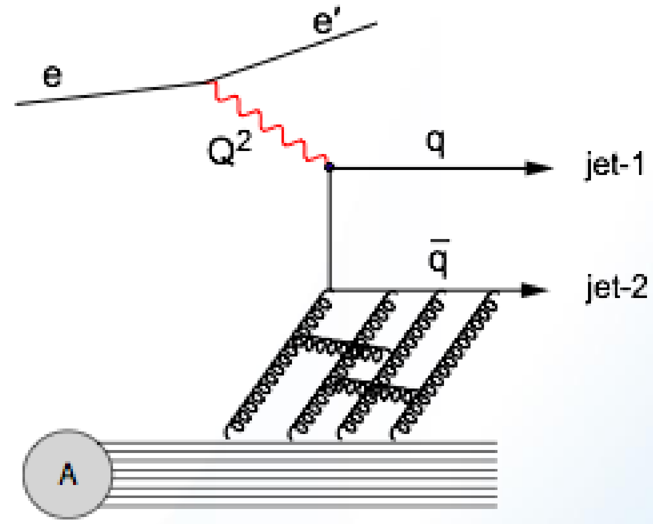
EIC:

- Extract the spatial multi-gluon correlations and study their non-linear evolution
  - essential for understanding the transition from a deconfined into a confined state.

Advantage over p(d)A:

- eA experimentally much cleaner
  - no "spectator" background to subtract
  - Access to the exact kinematics of the DIS process (x, Q^2)

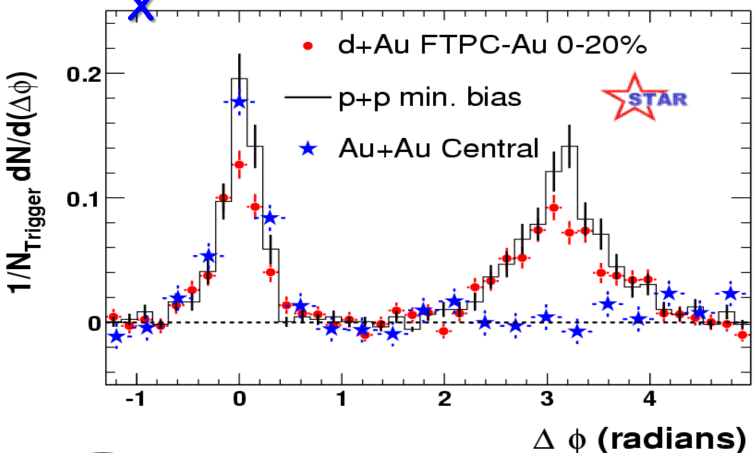
Perfect saturation signature:



Either jets or use leading hadrons from jets (dihadrons)

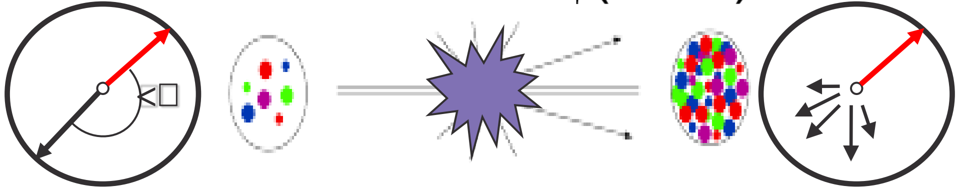
DI-HADRON CORRELATIONS IN dA

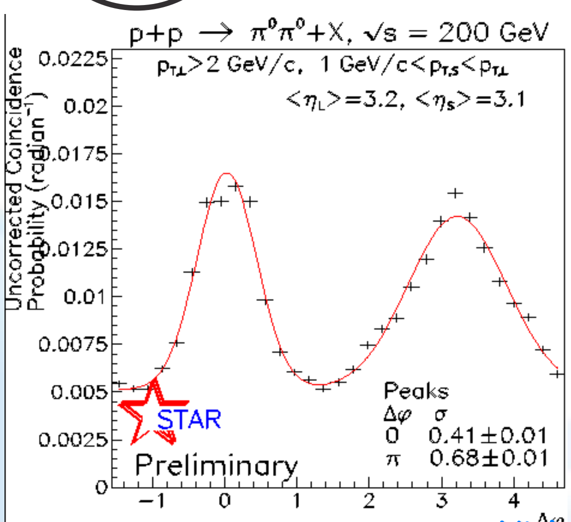
comparisons between d+Au → h_1 h_2 X (or p+Au → h_1 h_2 X) and p+p → h_1 h_2 X

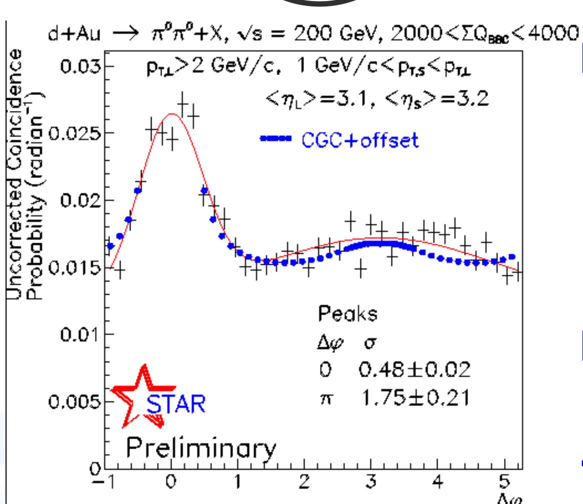


- At y=0, suppression of away-side jet is observed in A+A collisions
- No suppression in p+p or d+A → x~10^{-2}

$$x_A = \frac{k_1 e^{-y_1} + k_2 e^{-y_2}}{\sqrt{s}} << 1$$







- However, at forward rapidities (y ~ 3.1), an away-side suppression is observed in dAu
- Away-side peak also much wider in d+Au compared to pp

→ x ~ 10^{-3}

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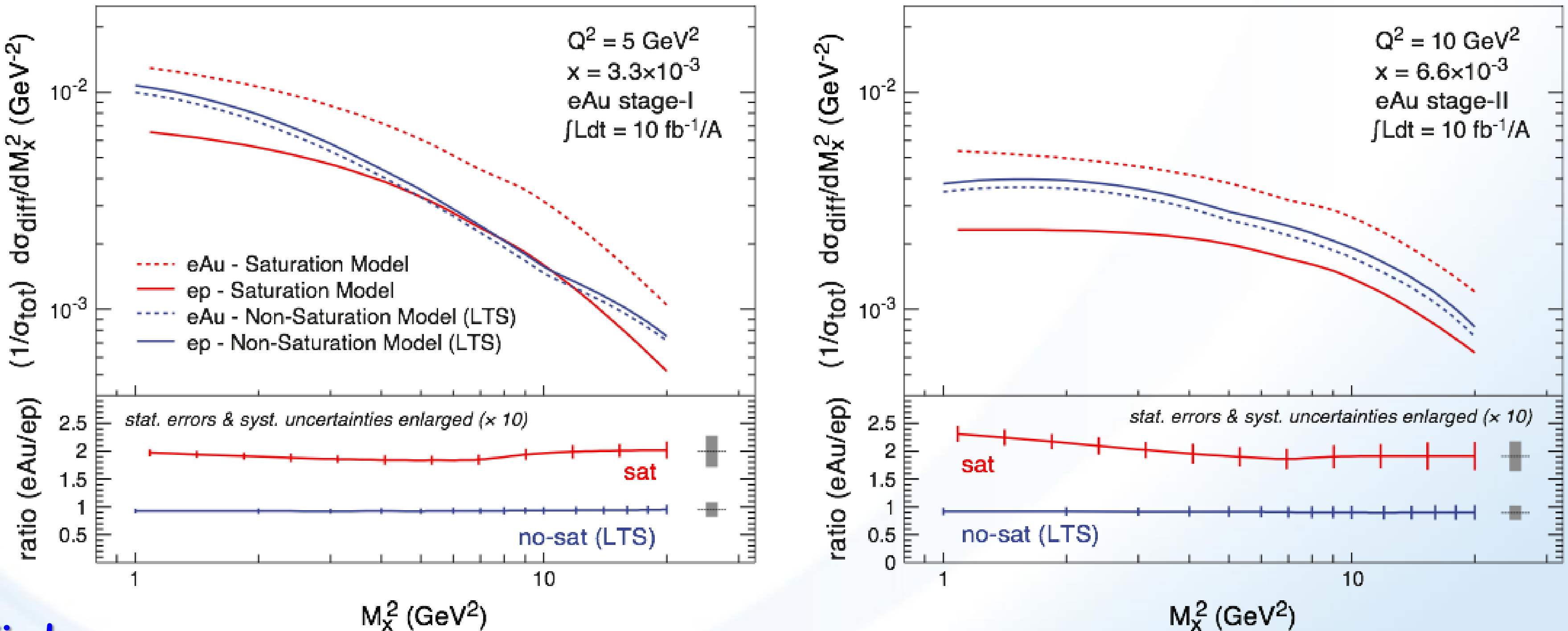
RATIO OF DIFFRACTIVE TO TOTAL CROSS-SECTION

- Black disc limit characterized by $\sigma_{diff}/\sigma_{tot}$ = 1/2 (Hera sees 1/7)
- Large fraction of diffractive event is **unambiguous** signature for reaching the **saturated limit**

Fraction of low-mass coherent diffraction in ep and eA at eRHIC:

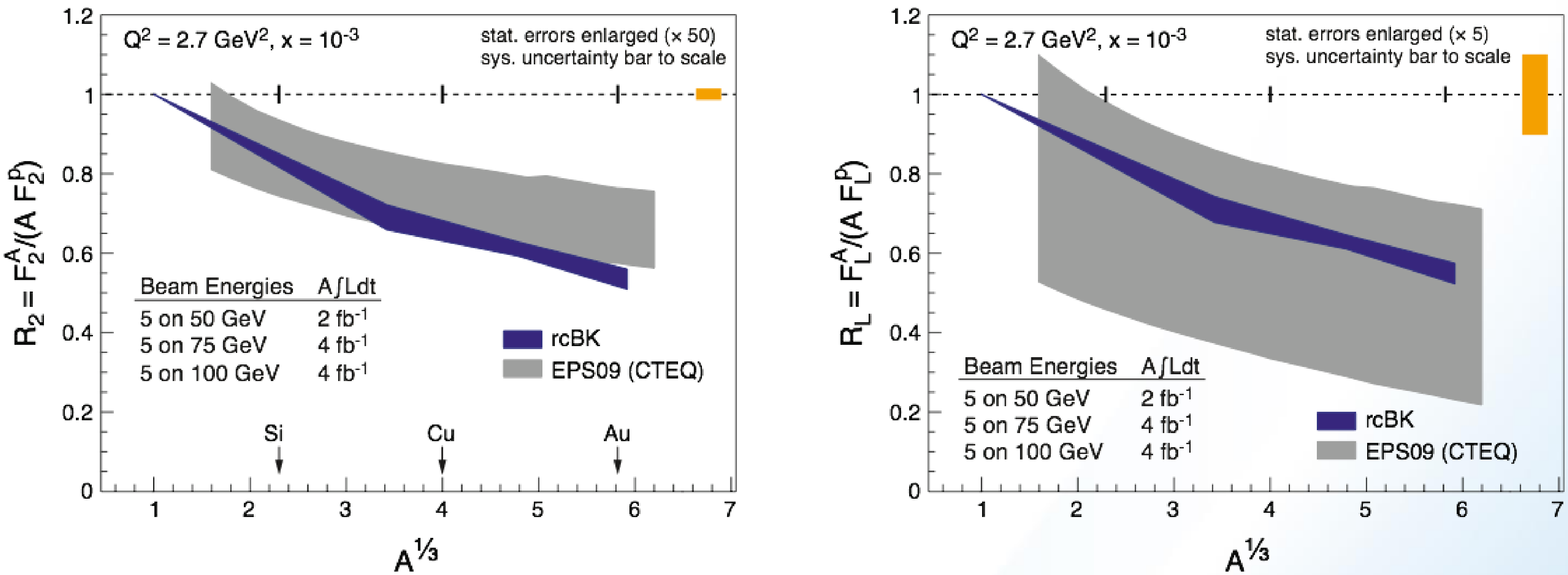


Find:

- w/o non-linear effects eA/ep ratio stays roughly one
- non-linear effects enhance σ_{diff} in eA scattering

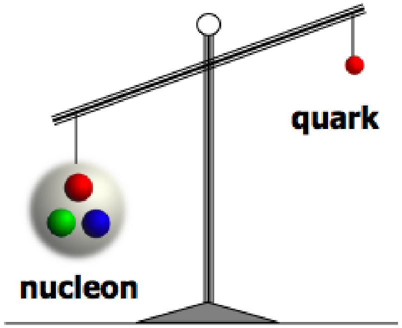
Day-1 signature for Saturation

INCLUSIVE DIS IN EA: NUCLEAR PDFS



- measurement of F_L requires running at different □s
- F_2, F_L: negligible stat. error, systematics dominated
- A dependence helps to discriminate between linear and non-linear (saturation) models
- Precision nPDF: Huge impact on pA, AA programs

THE HADRONIC MASS PUZZLE

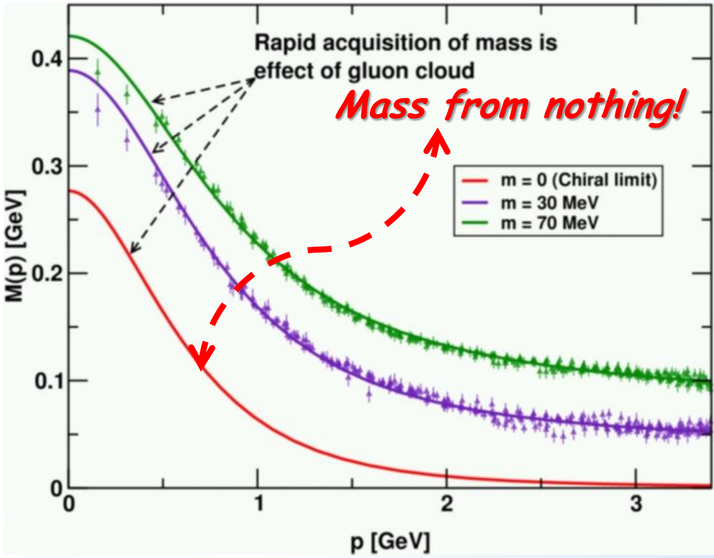


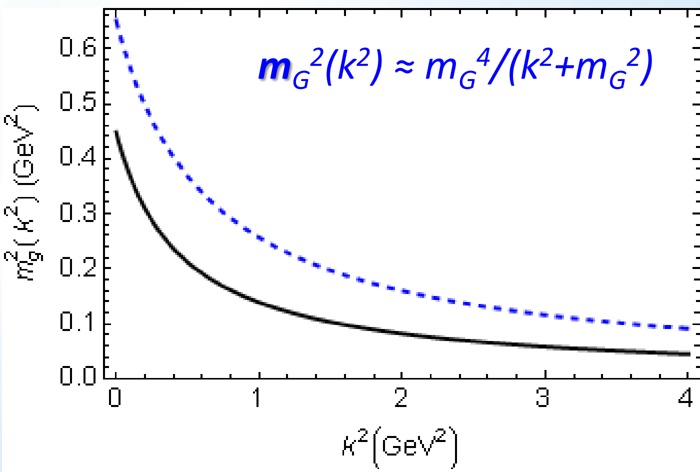
- In QCD, all "constants" of quantum mechanics are actually strongly momentum dependent: couplings, number density, mass, etc.
- So, a quark's mass depends on its momentum.
- Mass function can calculated and is depicted here.

in agreement: the vast bulk of the light-quark mass comes from a cloud of gluons, dragged along by the quark as it propagates.

- Continuum- and Lattice-QCD
- Running gluon mass
  - Gluon is massless in UV, in agreement with pQCD
  - Massive in infrared
    - $m_G(0)$ = 0.67-0.81 GeV
    - $m_G(m_G^2)$ = 0.53-0.64 GeV
- DSE prediction confirmed by numerical simulations of lattice-regularised QCD

C.D. Roberts, Prog. Part. Nucl. Phys. 61 (2008) 50
M. Bhagwat & P.C. Tandy, AIP Conf.Proc. 842 (2006) 225-227





Qin et al., Phys. Rev. C 84 042202 (Rapid Comm.)