ERHIC:

NEW SCIENTIFIC AND TECHNOLOGY FRONTIERS TO DO PARTON FEMTOSCOPY

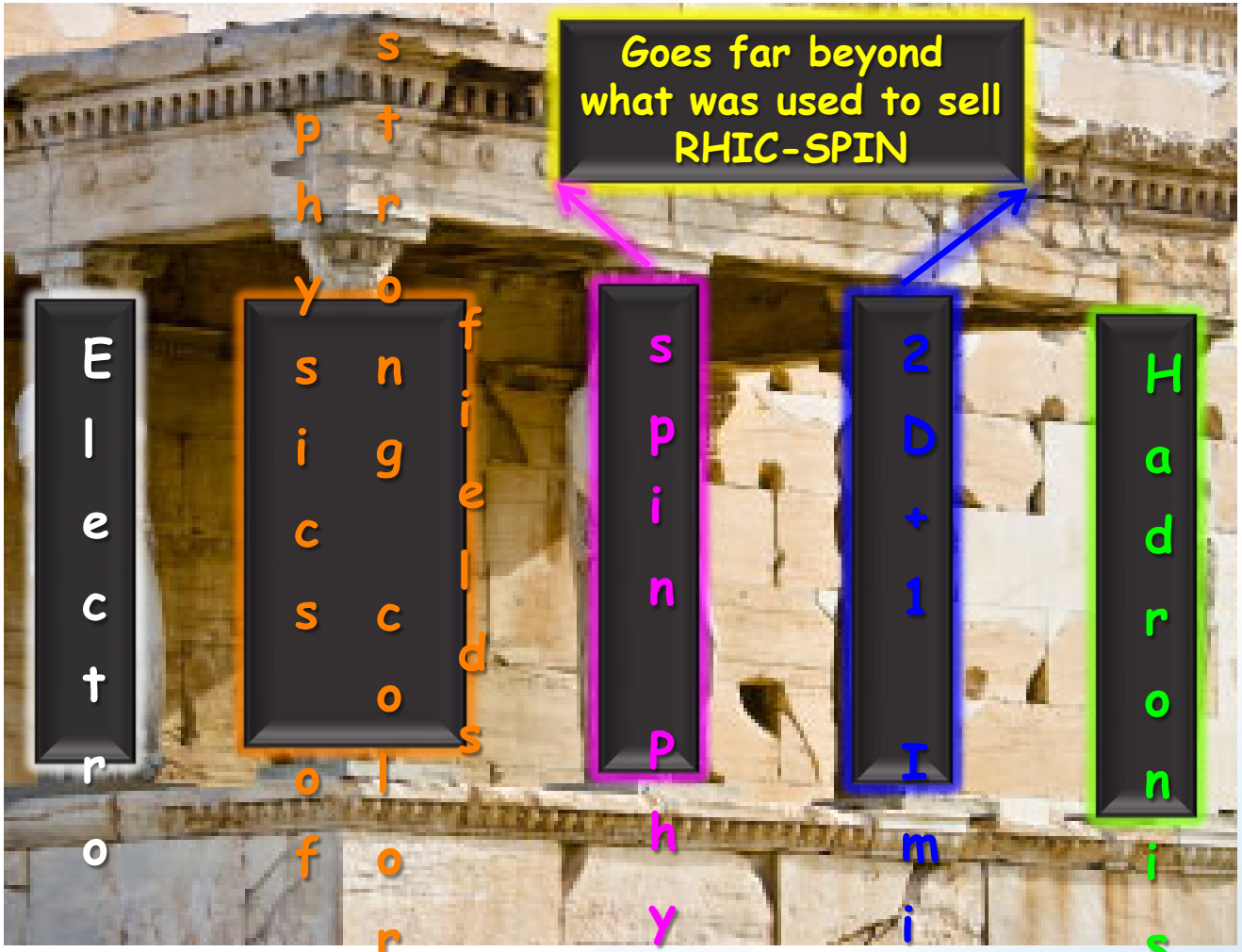
THANKS TO TOM B., THOMAS, RAMIRO, SALVATORE, MATT, DIETER, HUBERT, MARCO, ANDERS, WILL, LIANG, JH, TOM H, CRAIG, KLAUS AND eRHIC -CAD-TEAM

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

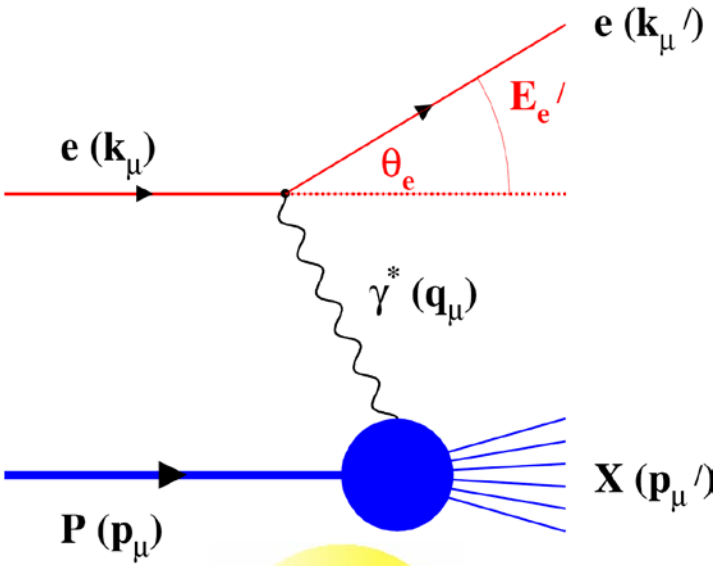
THE PILLARS OF THE eRHIC PHYSICS PROGRAM



Wide physics program with high requirements on detector and machine performance

DEEP INELASTIC SCATTERING

Kinematics:



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

Measure of resolution power

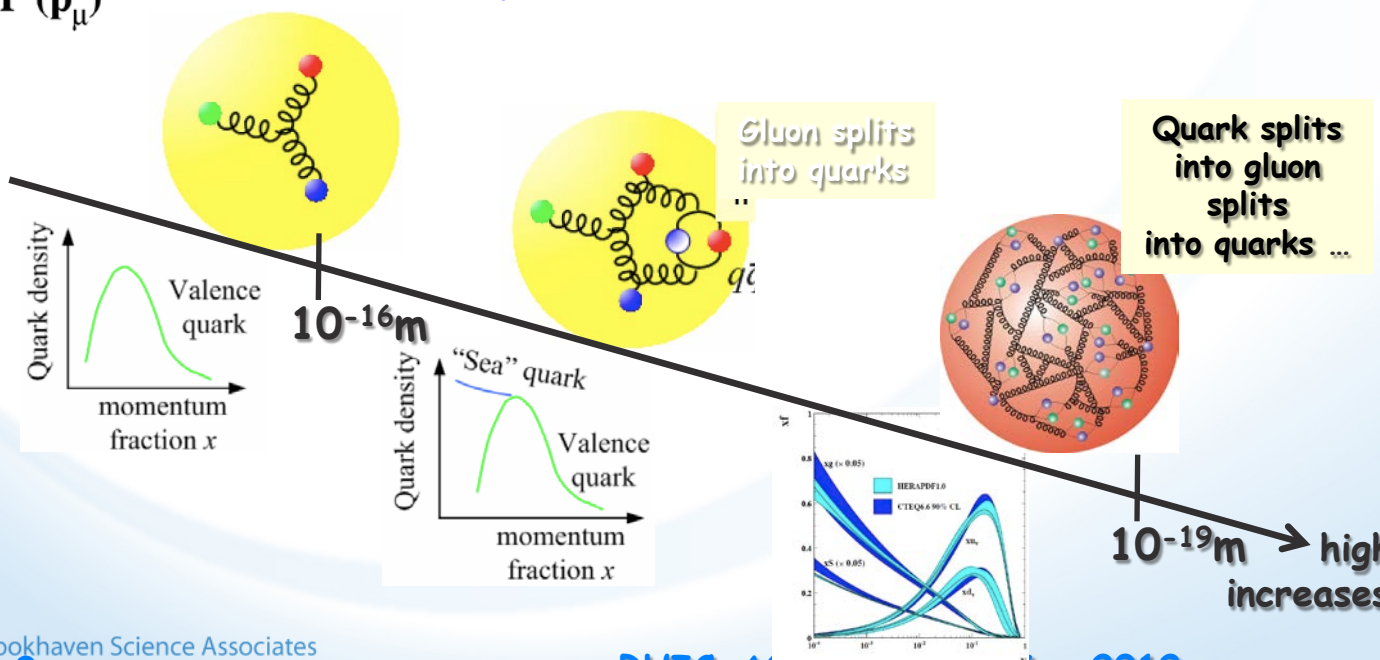
$$Q^2 = 2E_e E'_e (1 - \cos\Theta_{e'})$$

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

Measure of inelasticity

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

Measure of momentum fraction of struck quark

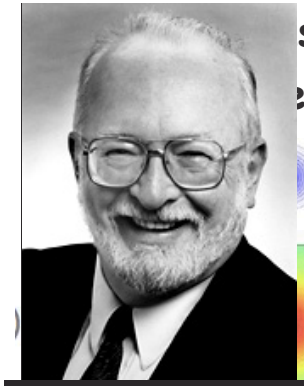


QUANTUM TOMOGRAPHY OF THE NUCLEON

Join the real
3D experience !!

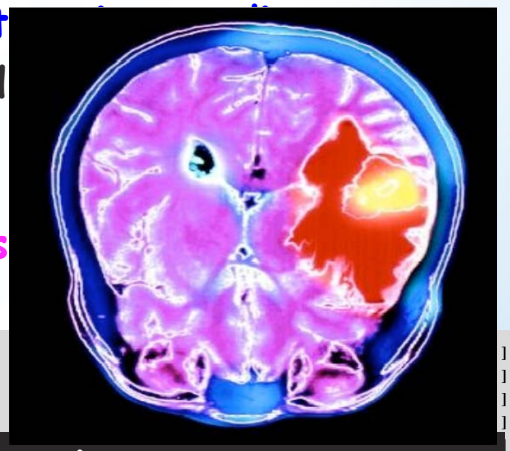
Spin as vehicle to do tomography of the nucleon
We do this daily in medicine

2D+1 picture in momentum s

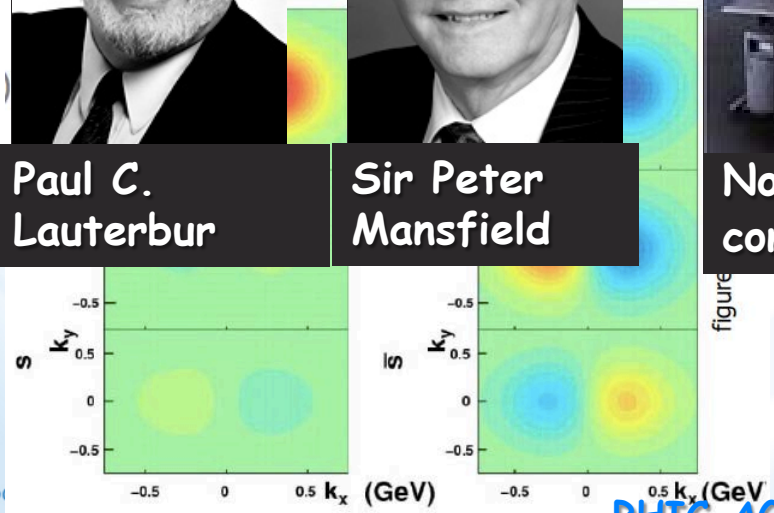


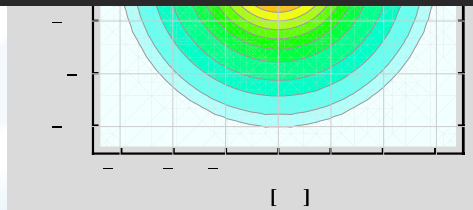
Paul C. Lauterbur

Sir Peter Mansfield



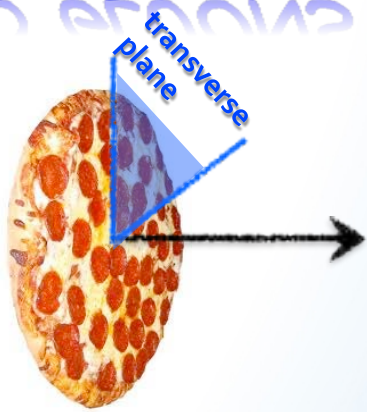
Nobel Prize, 2003: "for their discoveries concerning magnetic resonance imaging"





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

2+1-D $\mathbf{f(x, k_T)}$

transv. mom. dep. PDF

semi-inclusive DIS

$\int d^2 k_T$

1-D $\mathbf{f(x)}$

parton densities

THE PATH TO IMAGING QUARKS AND GLUONS

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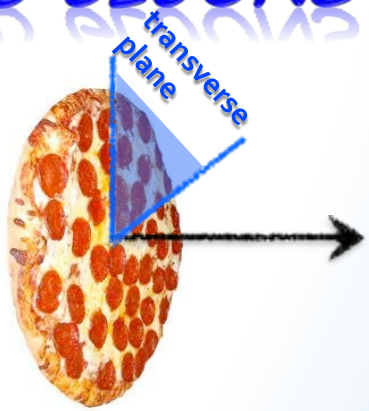

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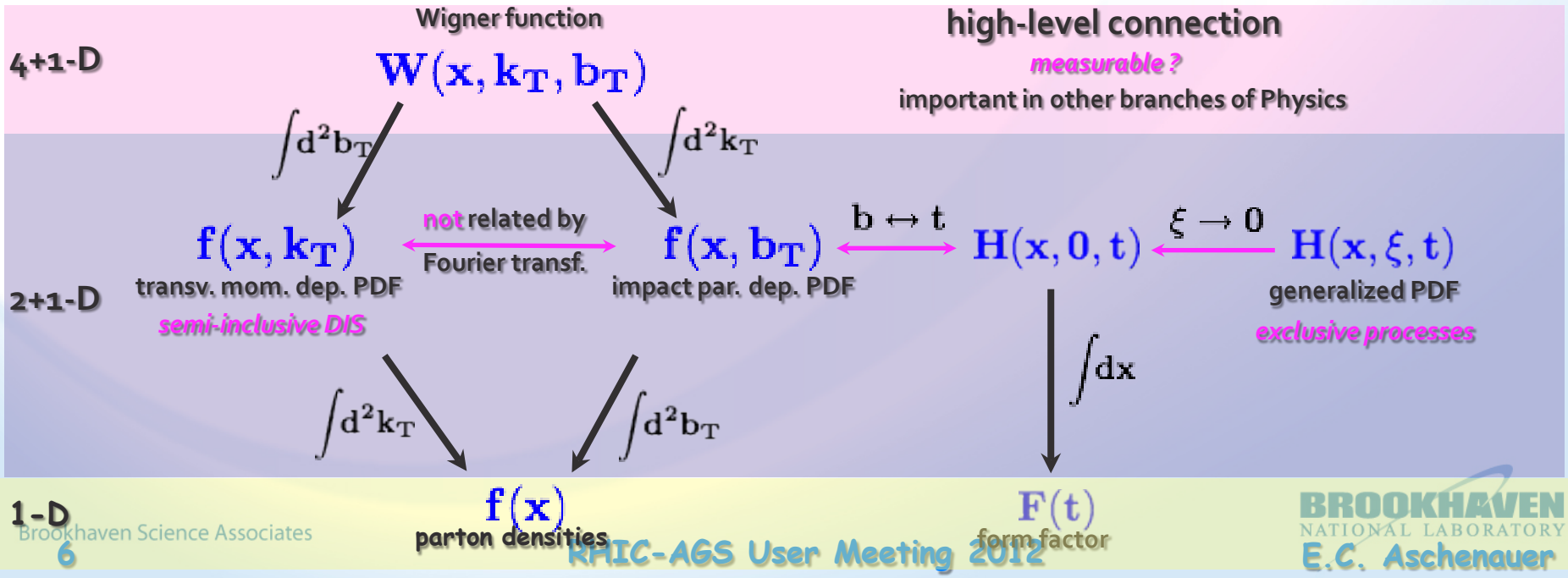
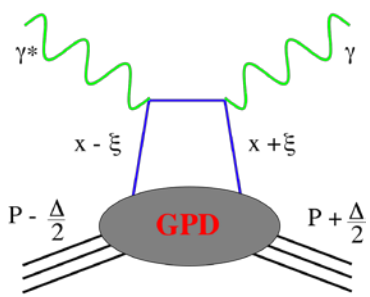


SMALL GPD PRIMER

How are GPDs characterized?

unpolarized	polarized	
$H^q(x,\xi,t)$	$\tilde{H}^q(x,\xi,t)$	conserve nucleon helicity $H^q(x,0,0)=q, \tilde{H}^q(x,0,0)=\Delta q$
$E^q(x,\xi,t)$	$\tilde{E}^q(x,\xi,t)$	flip nucleon helicity not accessible in DIS

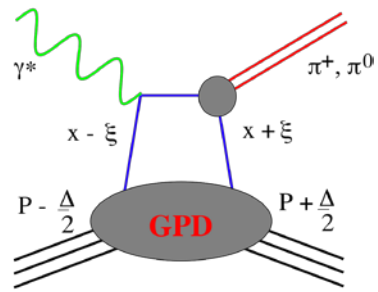
quantum numbers of final state ⟹ select different GPD



DVCS

$H^q \quad E^q \quad \tilde{H}^q \quad \tilde{E}^q$

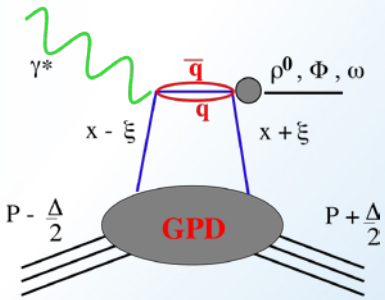
- $Q^2 = 2E_eE_e'(1-\cos\theta_{e'})$
- $x_B = Q^2/2M\nu \quad \nu = E_e - E_{e'}$
- $x+\xi$, $x-\xi$ long. mom. fract.
- $t = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$



pseudo-scaler mesons

$\tilde{H}^q, \tilde{E}^q$

π^0	$2\Delta u+\Delta d$
η	$2\Delta u-\Delta d$

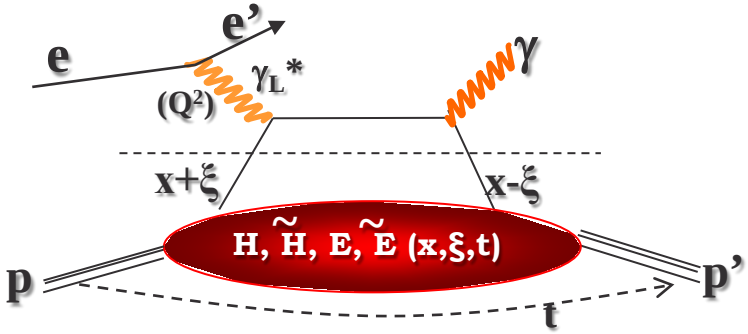


vector mesons

H^q, E^q

ρ^0	2u+d, 9g/4
ω	2u–d, 3g/4
ϕ	s, g
ρ^+	u–d
J/ψ	g

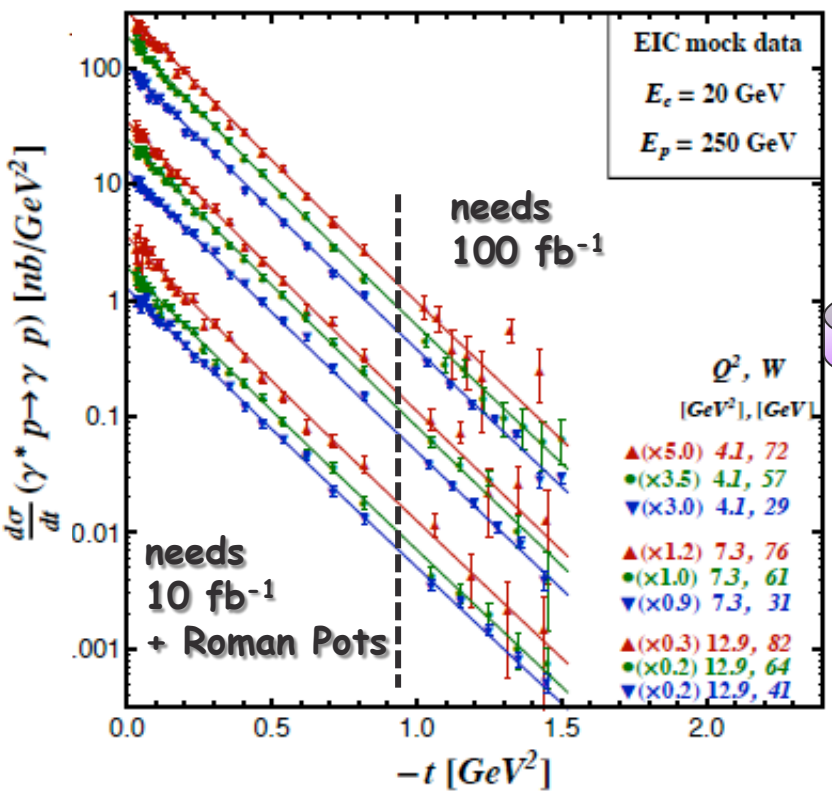
DVCS AT eRHIC



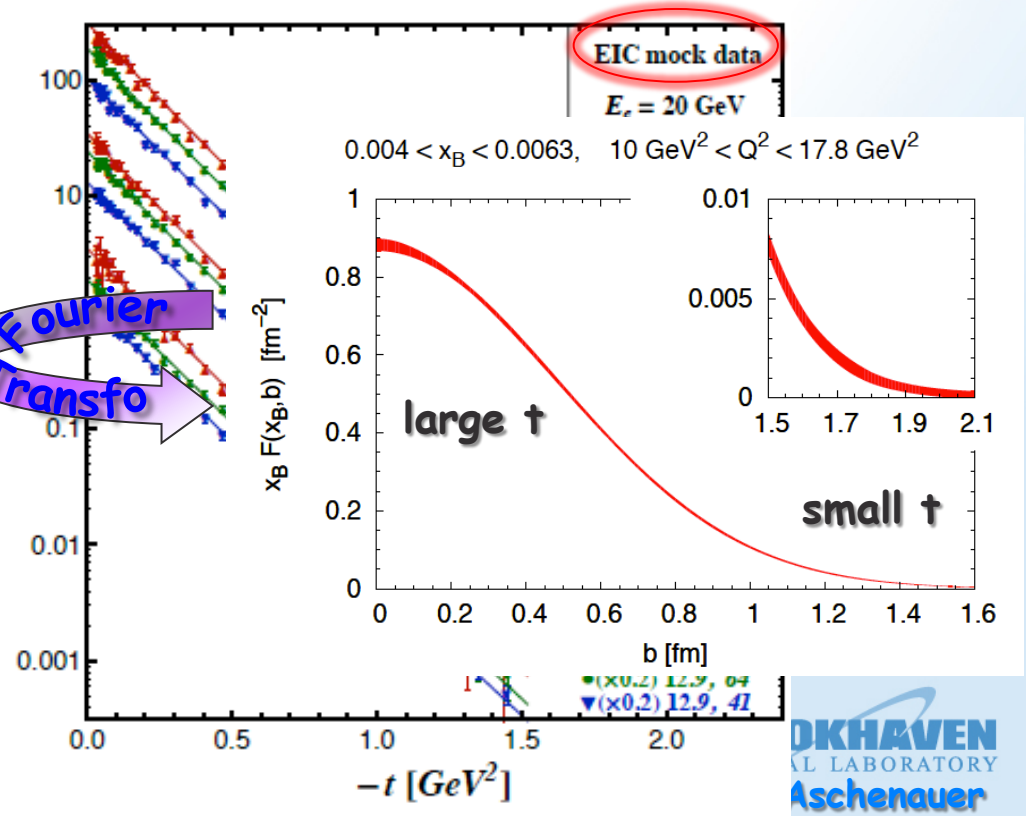
DVCS: Golden channel
theoretically clean
wide range of observables
(σ, A_{UT}, A_{LU}, A_{UL}, A_C)
to disentangle different GPDs

DVCS data at end of HERA

D. Mueller, K. Kumericki
S. Fazio, M. Diehl and ECA

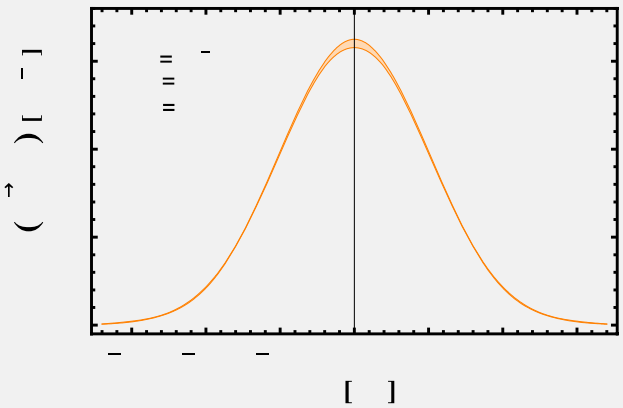


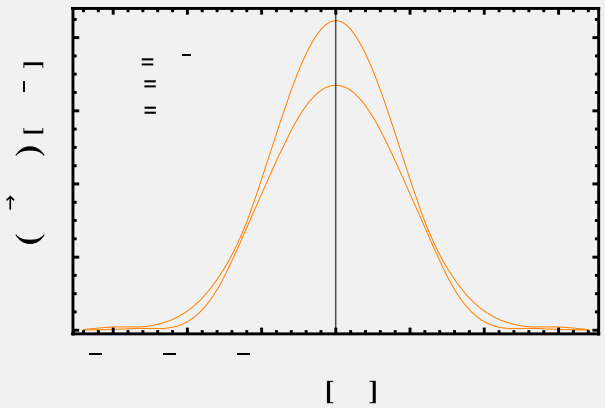
Fourier Transfo



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

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

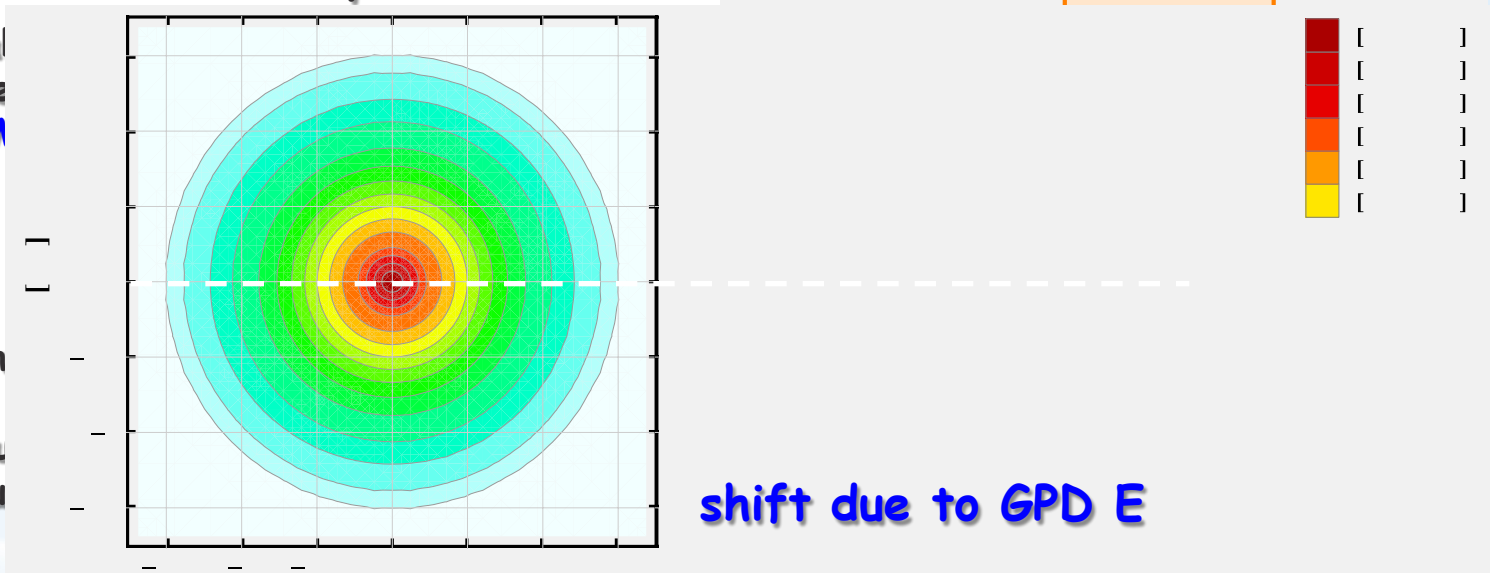




Plots from D. Mueller

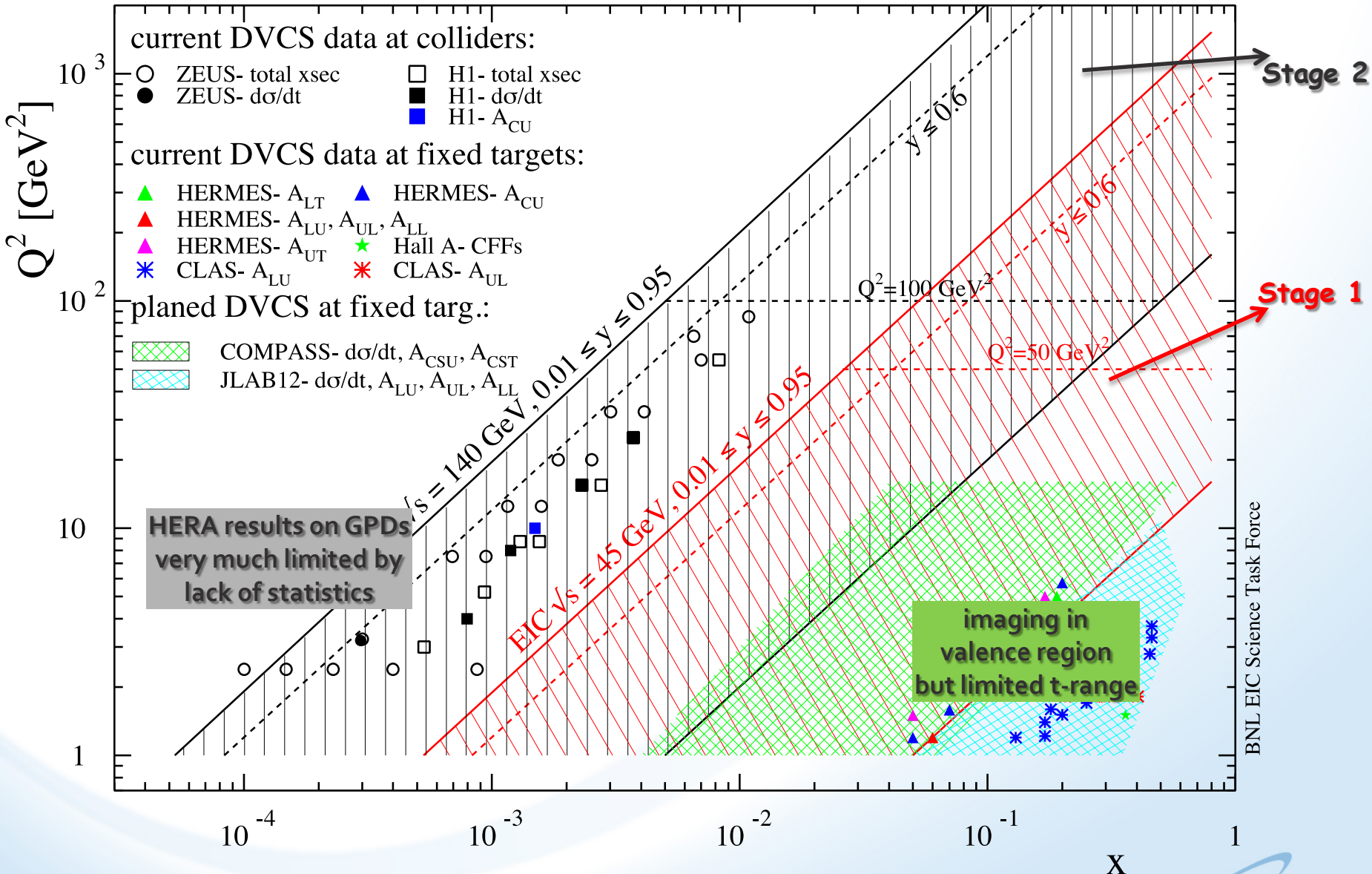
GPD H and E 2d structure for quarks

- A global fit over al
  done, based on the
  [K. Kumerički, D M
  Kumerički 2007]
- Known values *q(x)*,
  for H^q, H^g (at =0,
  E^q, E^g are unknown
- Excellent reconstru
  and good reconstru
  dσ/dt)



shift due to GPD E

THE DVCS PHASE SPACE



WHAT ELSE CAN BE DONE

The Holy Grail

PRESENT VS EIC KINEMATIC COVERAGE

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

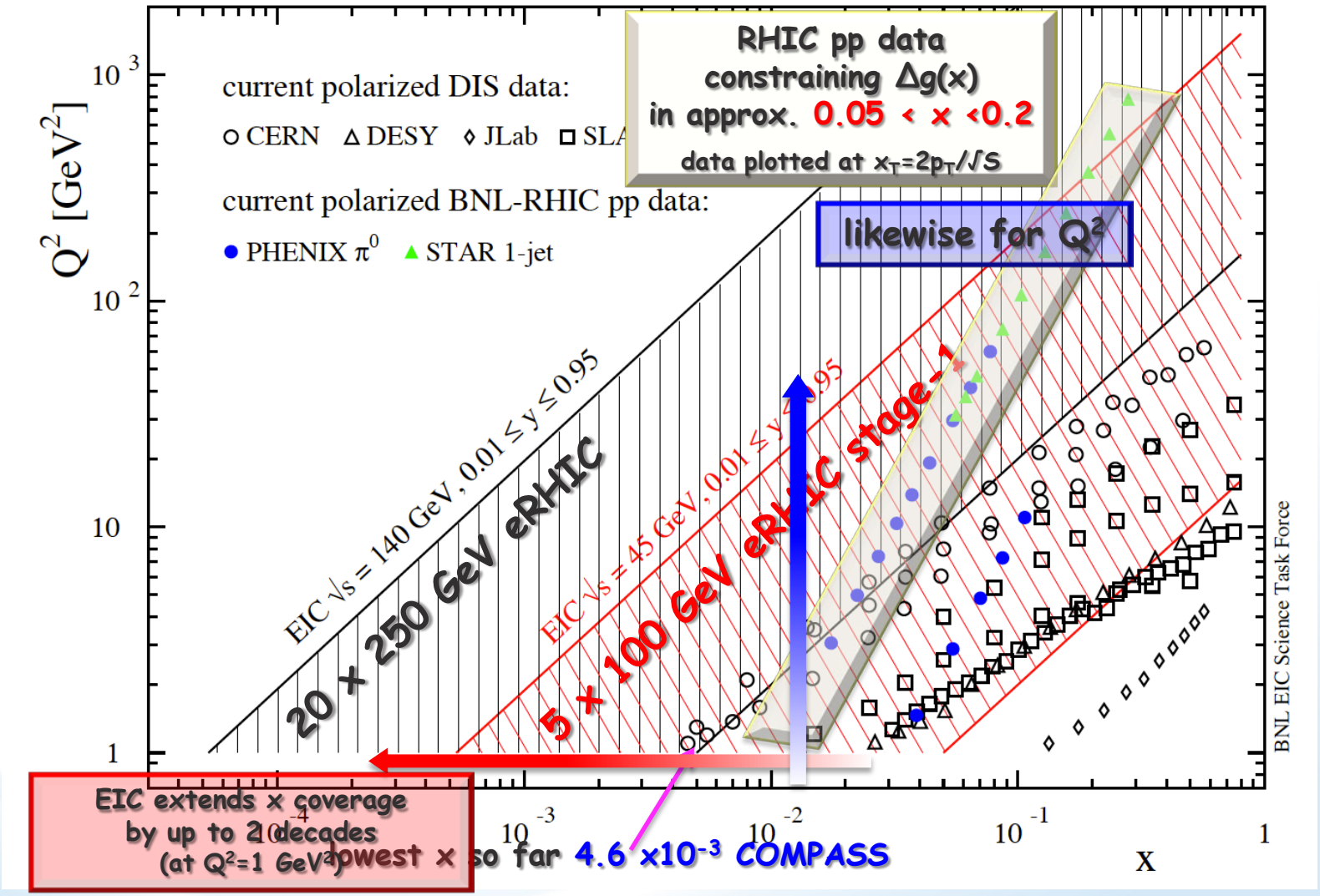
$$W^{\mu\nu} = -g^{\mu\nu} F_1 - \frac{p^\mu p^\nu}{\nu} F_2 + \frac{i}{\nu}\varepsilon^{\mu\nu\lambda\sigma} q^\lambda s^\sigma g_1 + \frac{i}{\nu^2}\varepsilon^{\mu\nu\lambda\sigma} q^\lambda (p\cdot q s^\sigma - s\cdot q p^\sigma) g_2$$

pQCD scaling violations

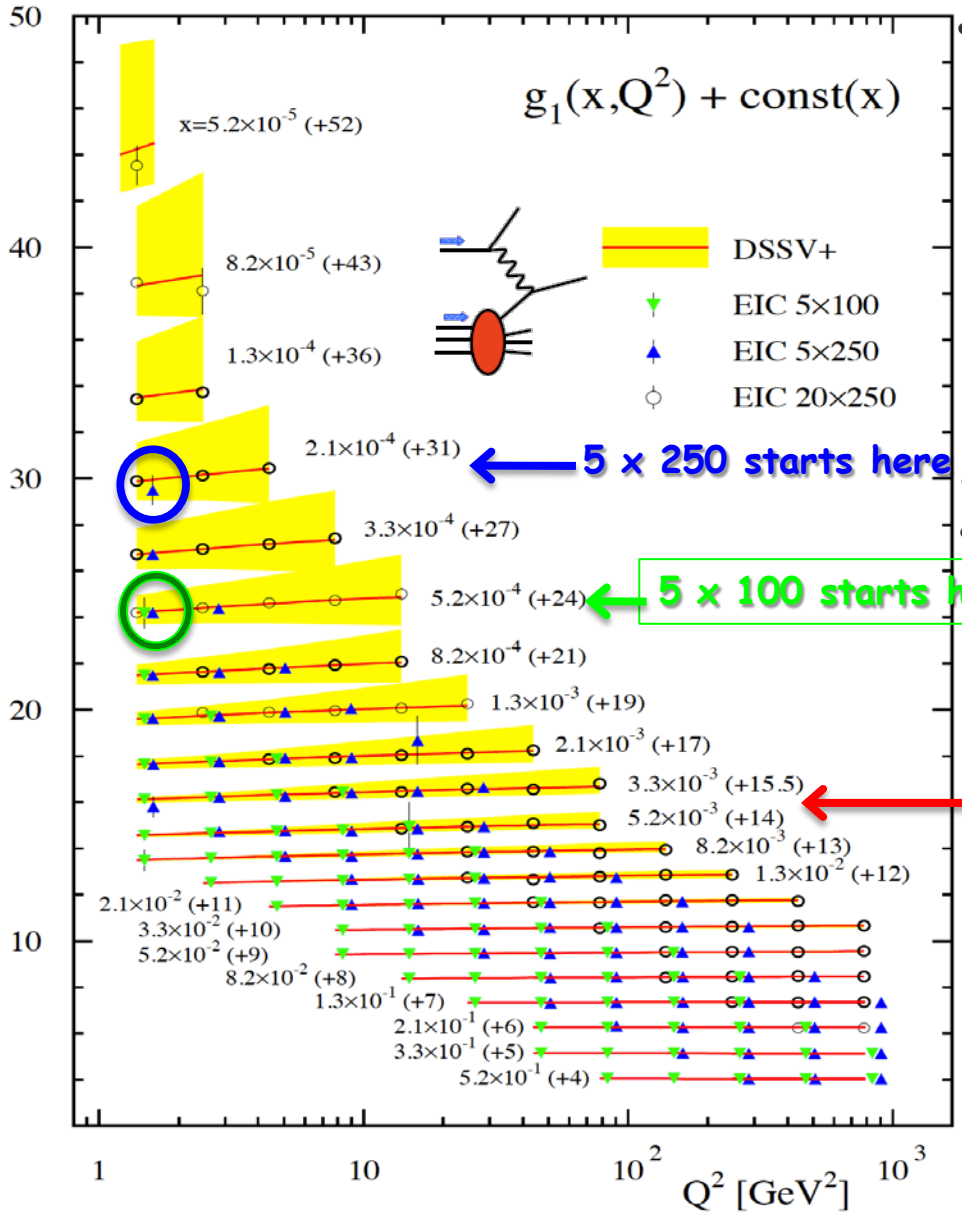
$$\frac{dg_1}{d\log(Q^2)} \sim -\Delta g(x,Q^2)$$

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

PRESENT VS EIC KINEMATIC COVERAGE



EXAMPLE: PROJECTED DIS DATA FOR g_1^p

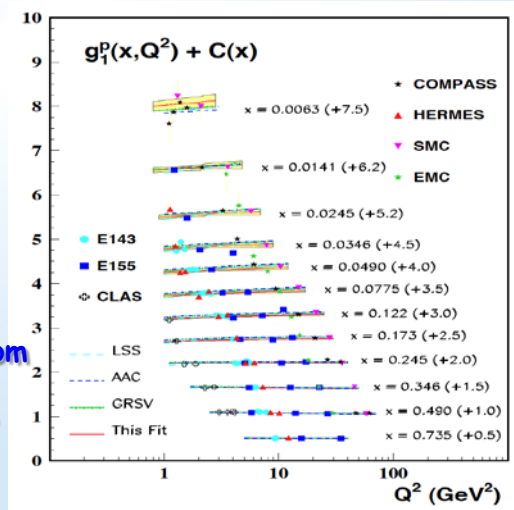


- 3 sets of [eRHIC] energy settings studied:

$E_e \times E_p$ [GeV]	$\sqrt{s}$ [GeV]	x_{min} for y_{max} = 0.95 and Q^2 = 1 GeV^2	Q^2 = 2 GeV^2
5 x 100	44.7	5.3 x 10^{-4}	1.1 x 10^{-3}
5 x 250	70.7	2.1 x 10^{-4}	4.2 x 10^{-4}
20 x 250	141.4	5.3 x 10^{-5}	1.1 x 10^{-4}

- 4 [5] bins/decade in Q^2 [x] (spaced logarithmical
- bands reflect current uncertainties on g_1^p DSSV+ estimate

COMPASS data start here



taken from Blumlein, Bottcher

IMPACT OF EIC DATA ON HELICITY PDFS

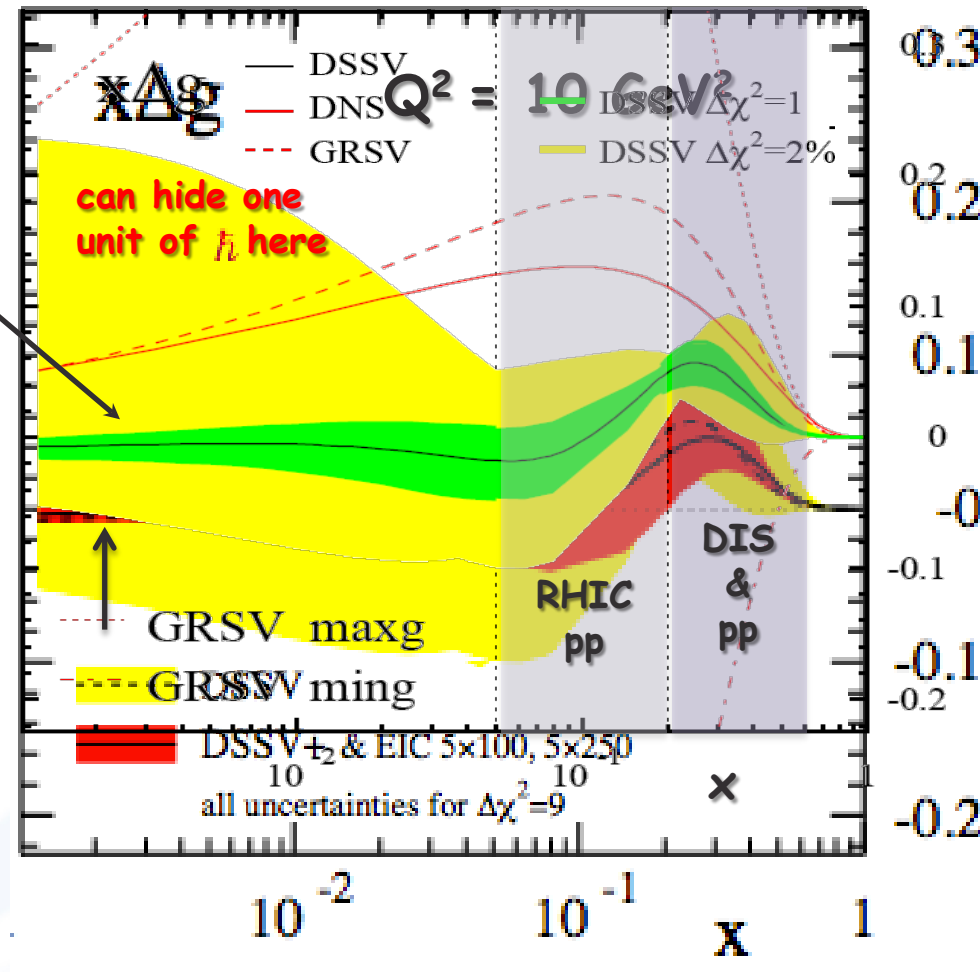
EIC: DIS scaling violations mainly determine Δg at small x

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

dramatic reduction of uncertainties:

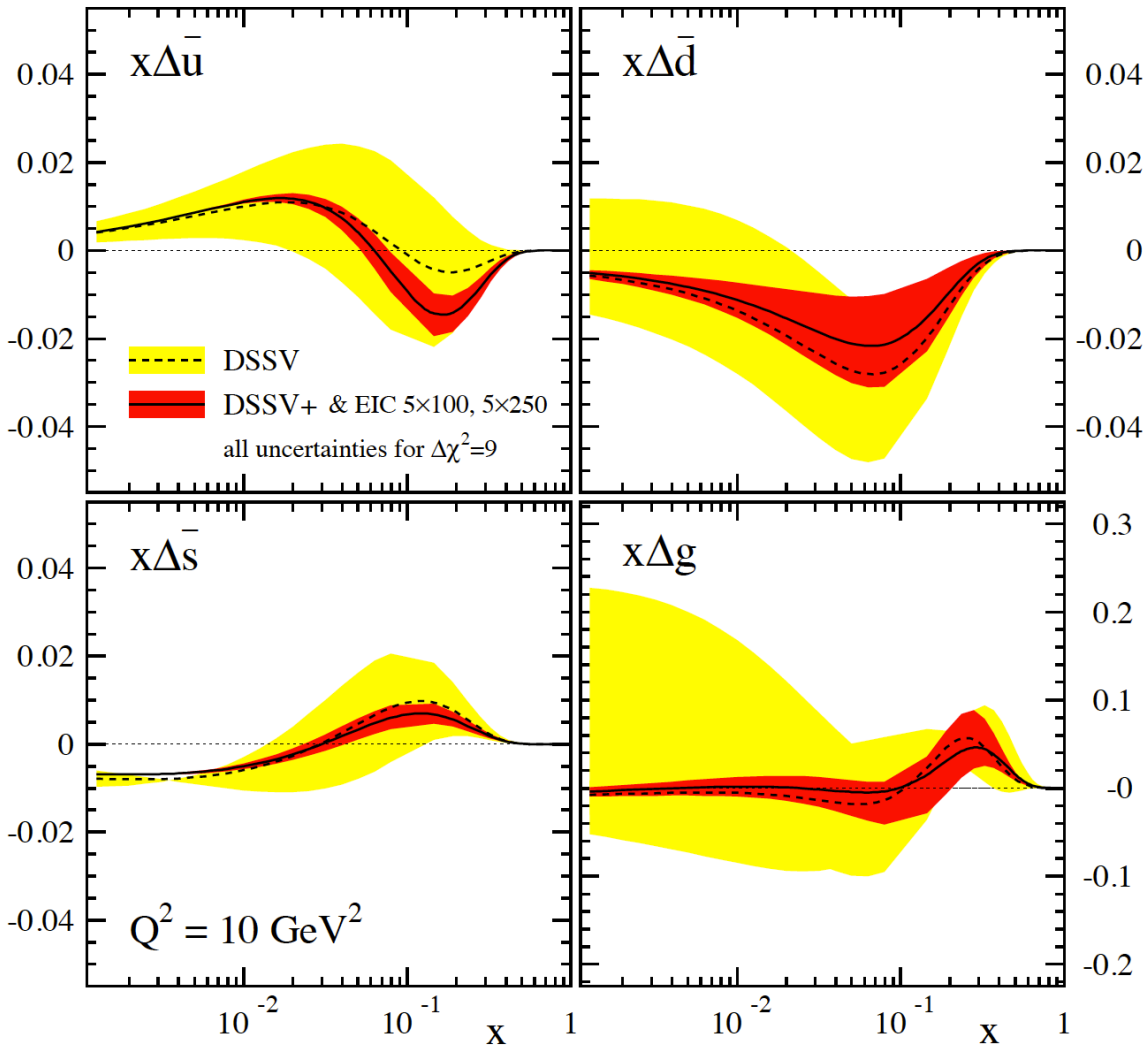
"before"

"after"



IMPACT OF EIC DATA ON HELICITY PDFs

DIS scaling violations mainly determine Δg at small x
(SIDIS scaling violations add to this)
in addition, SIDIS data provide detailed flavor separation of quark sea



- includes only "stage-1 data"
  [even then Q^2_{min} can be 2-3 GeV^2]
- can be pushed to $x=10^{-4}$ with 20 x 250 GeV data
  [still one can play with Q^2_{min}]
- uncertainties determined with both Lagrange mult. & Hessian

"issues":

- (SI)DIS @ EIC limited by systematic uncertainties
  need to control rel. lumi, polarimetr
  detector performance, … very well
- QED radiative corrections
  need to "unfold" true x,Q^2
  well known problem (HERA)
  BNL-LDRD project to sharpen tools

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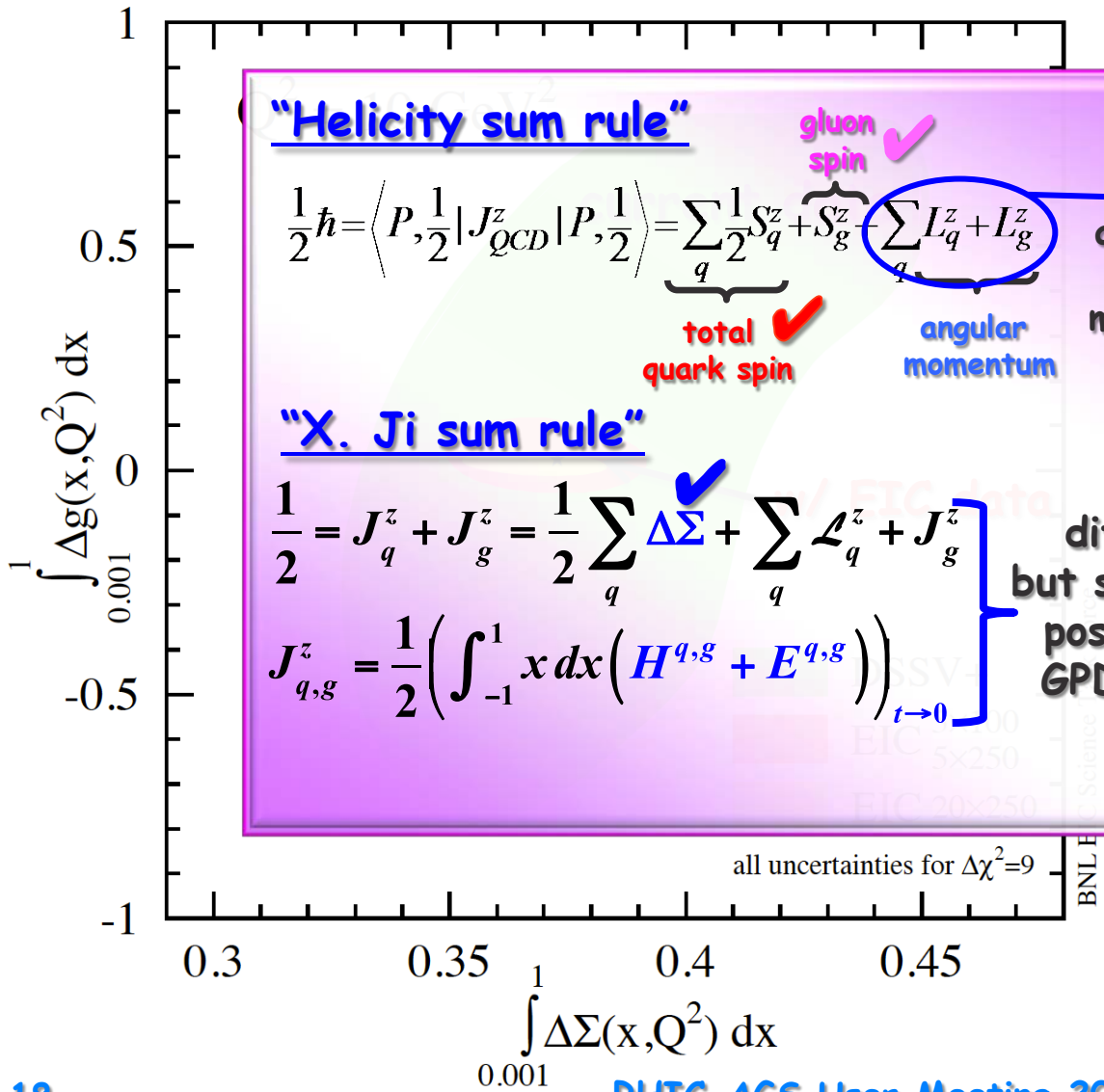
PROGRESS TOWARDS SPIN SUM RULE

- combined correlated uncertainties for $\Delta\Sigma$ and Δg



"Helicity sum rule"

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

access through Twist-3 GPDs
more theoretical work needed

"X. Ji sum rule"

$$\frac{1}{2} = J^z_q + J^z_g = \frac{1}{2}\sum_q \Delta\Sigma + \sum_q \mathcal{L}^z_q + J^z_g$$

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

difficult, but should be possible in GPD models

tained with two
multipliers
ethod consistent

rovement
1-1 moments
250 GeV data

t approx. 5-10%
ies on $\Delta\Sigma$ and Δg
but need to control systematic

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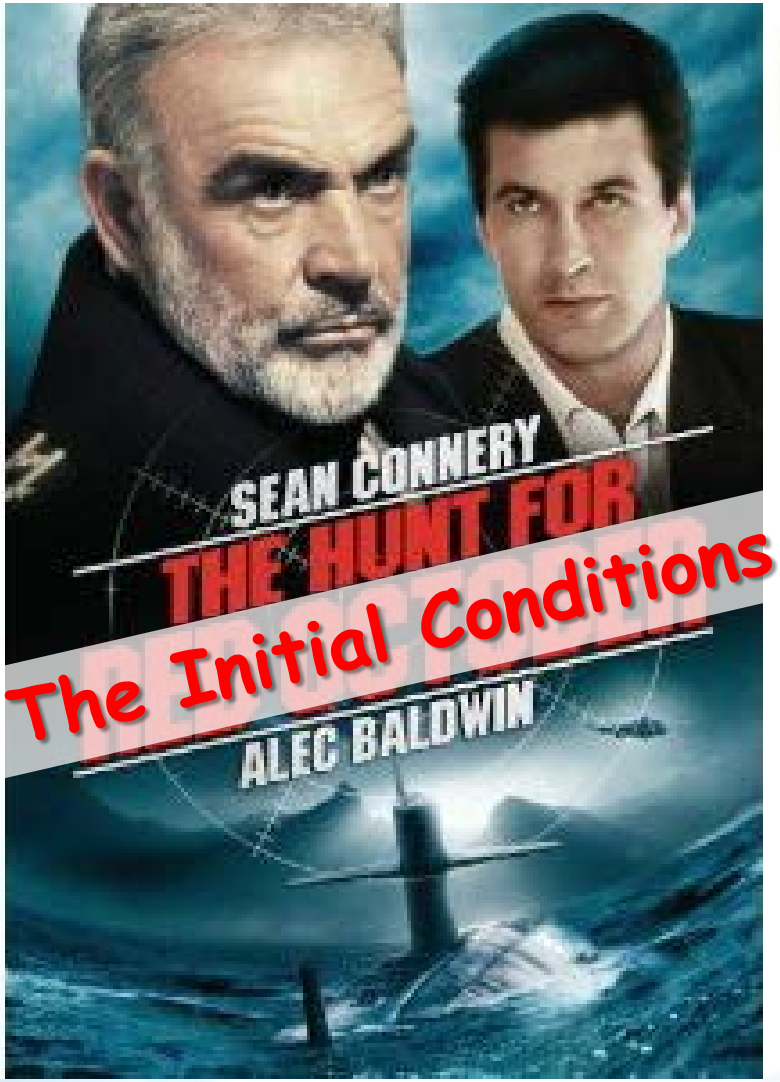
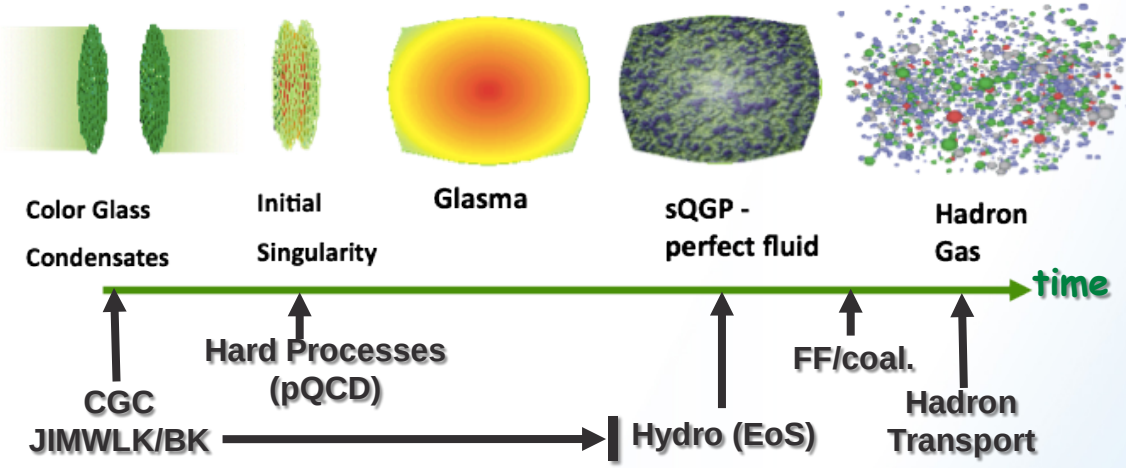
THE eA PHYSICS PROGRAM





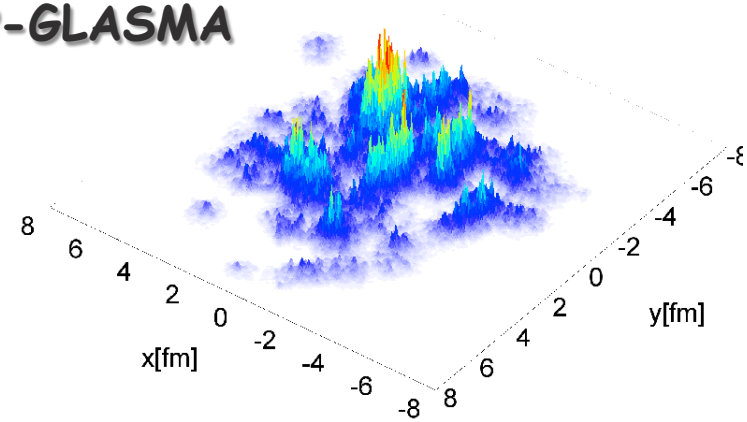
Our understanding of some fundamental properties of the Glasma, sQGP and Hadron Gas depend strongly on our knowledge of the initial state!

3 conundrums of the initial state:

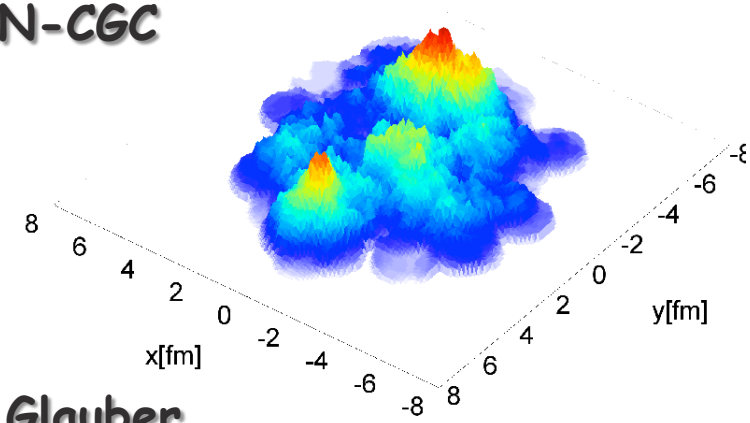
1. What is the spatial transverse distributions of nucleons and gluons?
2. How much does the spatial distribution fluctuate? Lumpiness, hot-spots etc.
3. How saturated is the initial state of the nucleus?

IS THE sQGP A PERFECT FLUID?

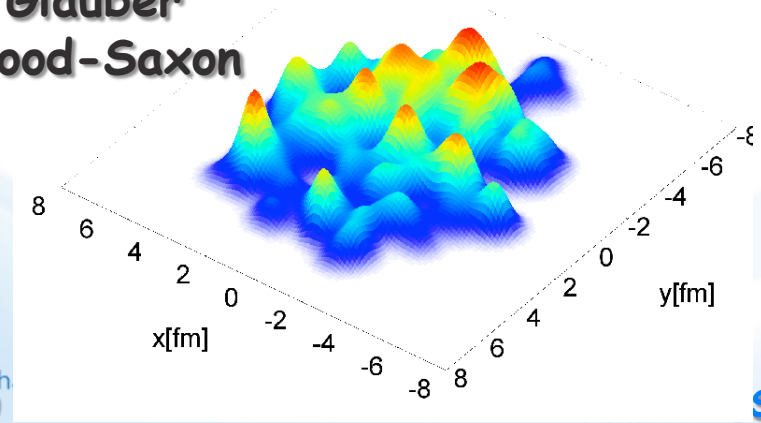
IP-GLASMA



KLN-CGC

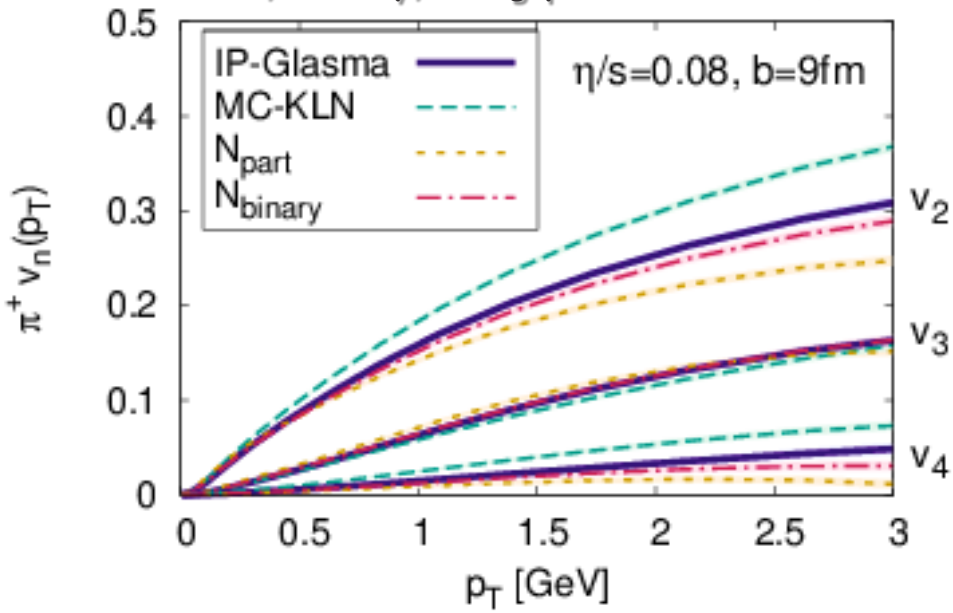


Glauber
Wood-Saxon



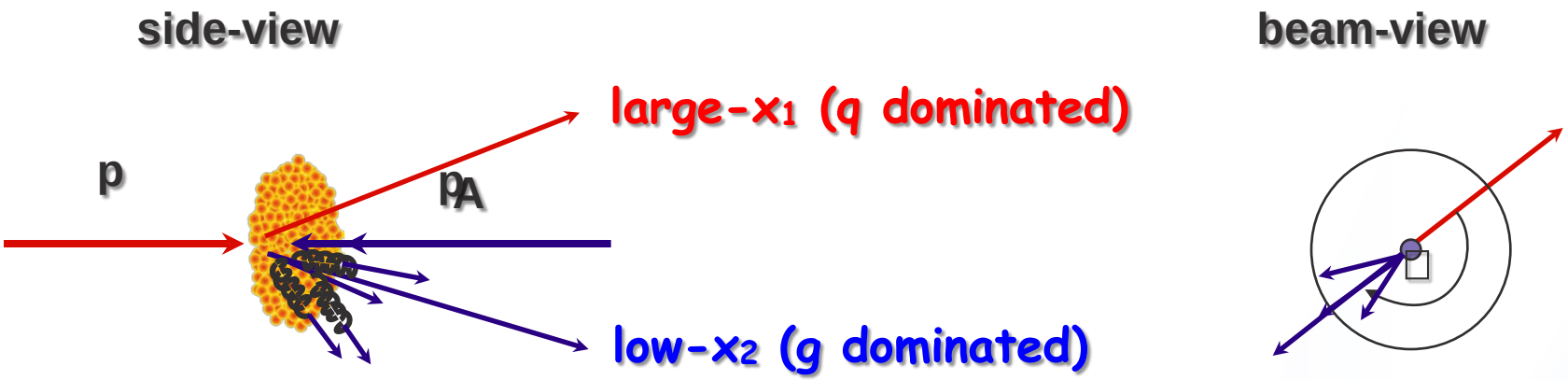
AdS/CFT predicts for a perfect fluid:
$\eta/s = 1/(4\pi) \sim 0.08$

Schenke, Tribedy, Venugopalan arXiv:1202.6646



Different initial states =
different fluctuation scales

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

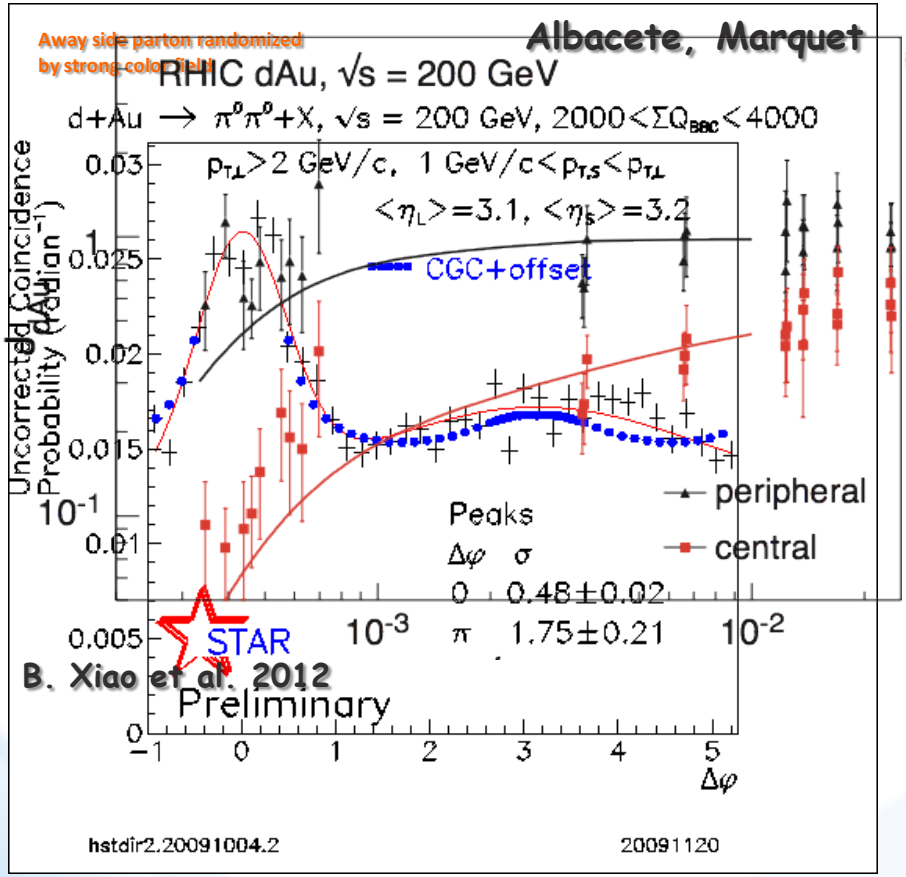
- Small-x evolution ↔ multiple emissions
- Multiple emissions → broadening
- Back-to-back jets (here leading hadrons) may get broadening in p_T with a spread of the order of Q_S

First prediction by: C. Marquet ('07)
Latest review: Stasto, Xiao, Yuan arXiv:1109.1817 (Sep. '11)

FORWARD CORRELATIONS IN dA AT RHIC

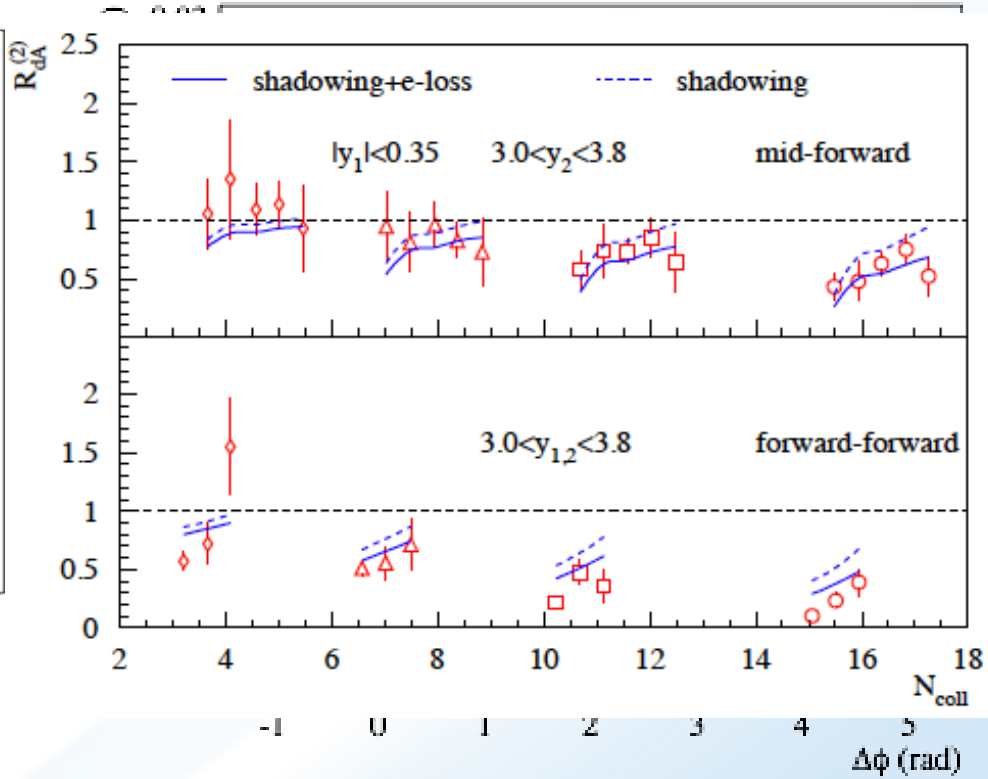
1 question, 2 answers

Initial state saturation model



B. Xiao et al. 2012

"Non-initial state" shadowing model



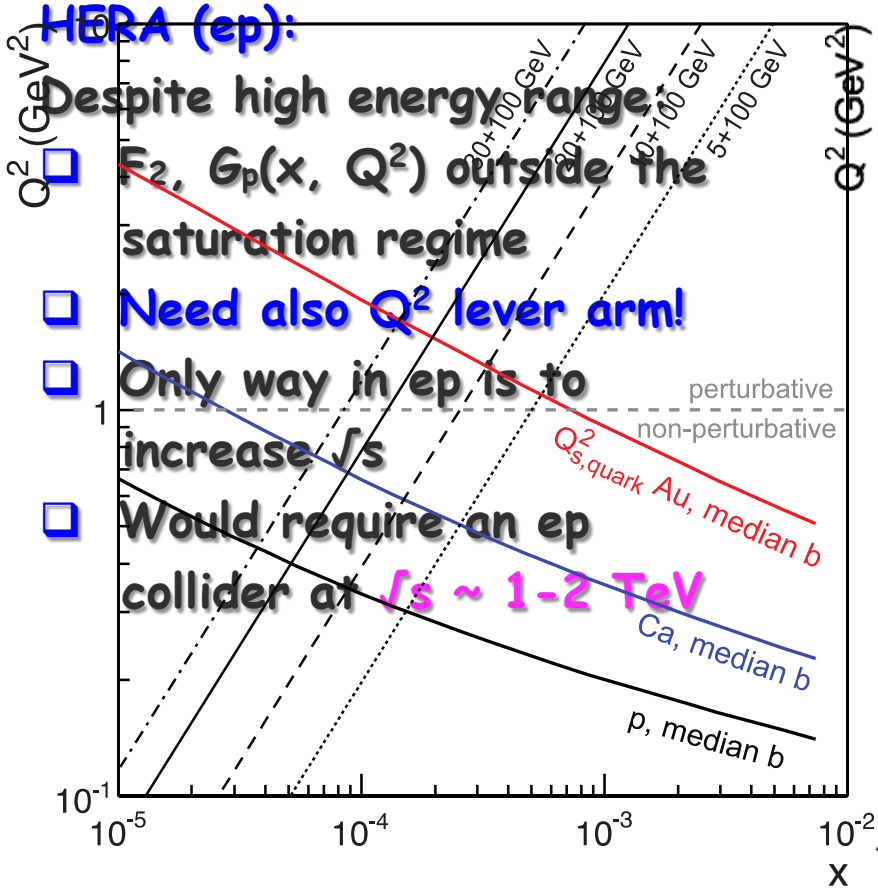
$$\langle q_\perp^2 \rangle_{dAu} = \langle q_\perp^2 \rangle_{pp} + \Delta \langle q_\perp^2 \rangle$$

How saturated is the initial state?

eRHIC: REACHING THE SATURATION REGION

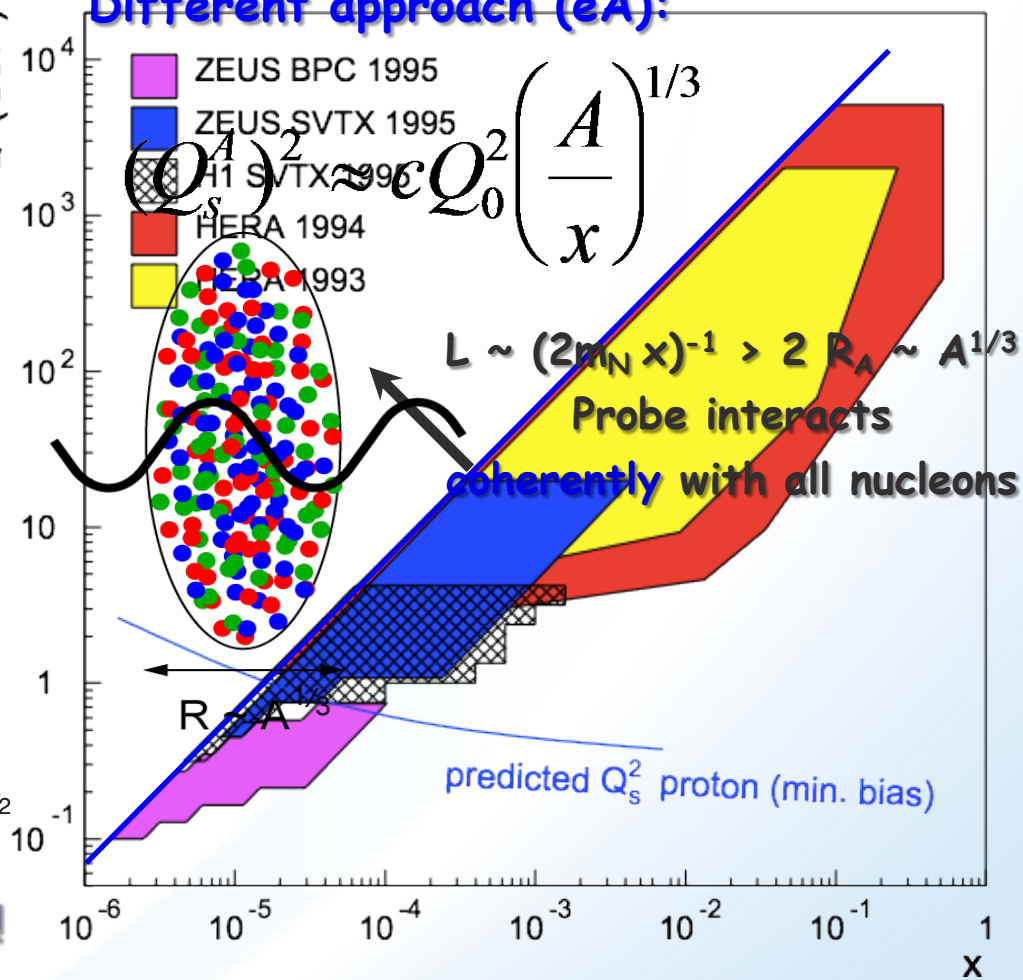
HERA (ep):

- 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 $\sqrt{s}$ ~ 1-2 TeV



Gold: A=197, x 197 times smaller!

Different approach (eA):



DIHADRON CORRELATIONS IN eA AT EIC

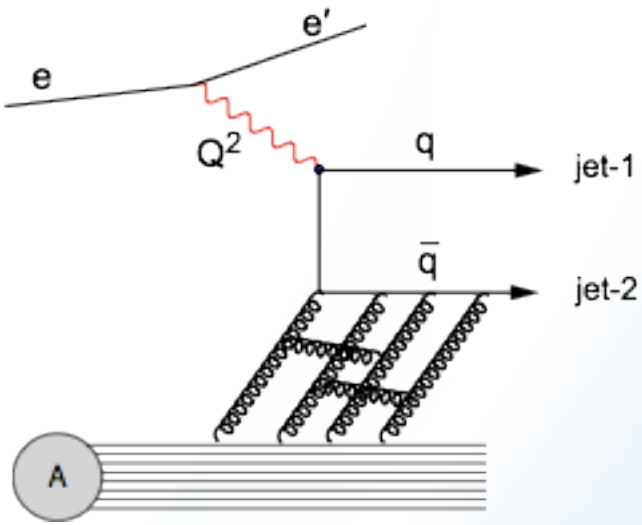
EIC:

- 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:

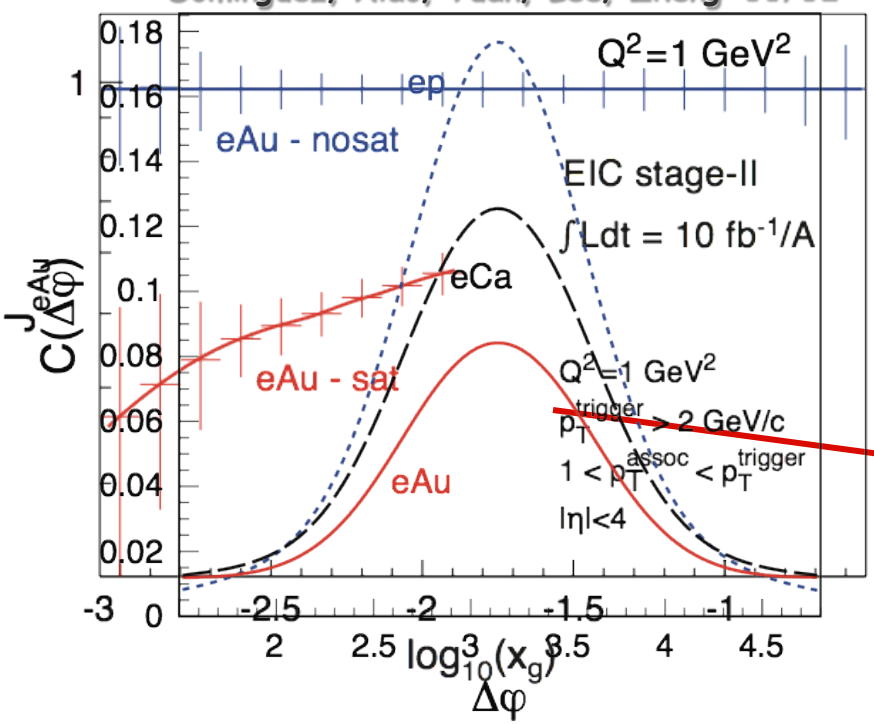


Either jets or use leading hadrons from jets (dihadrons)

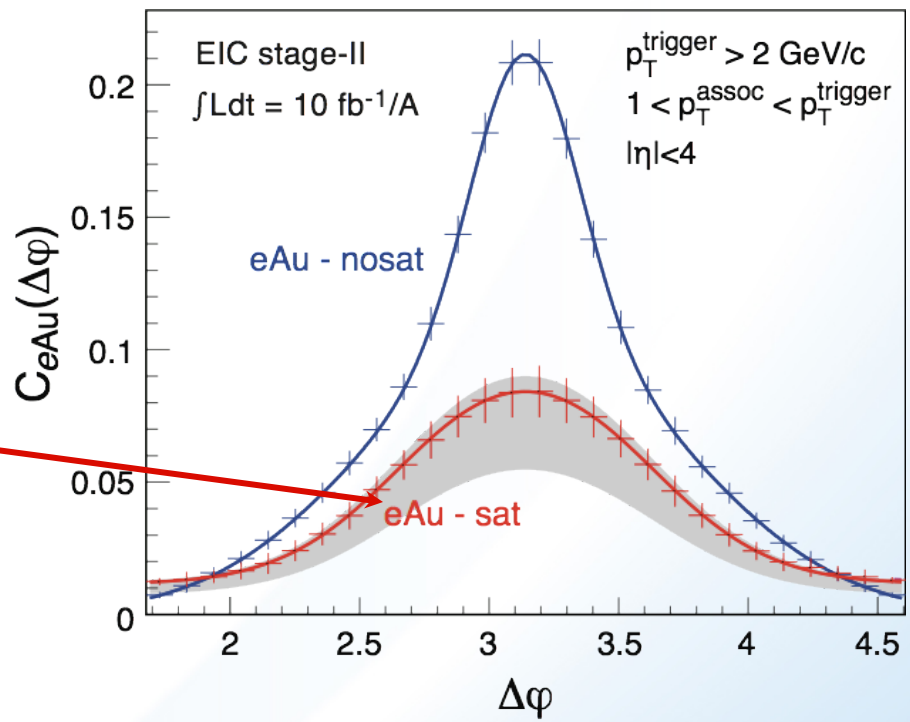
EIC: eA DIHADRON CORRELATIONS STUDIES

Theory: Saturation

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

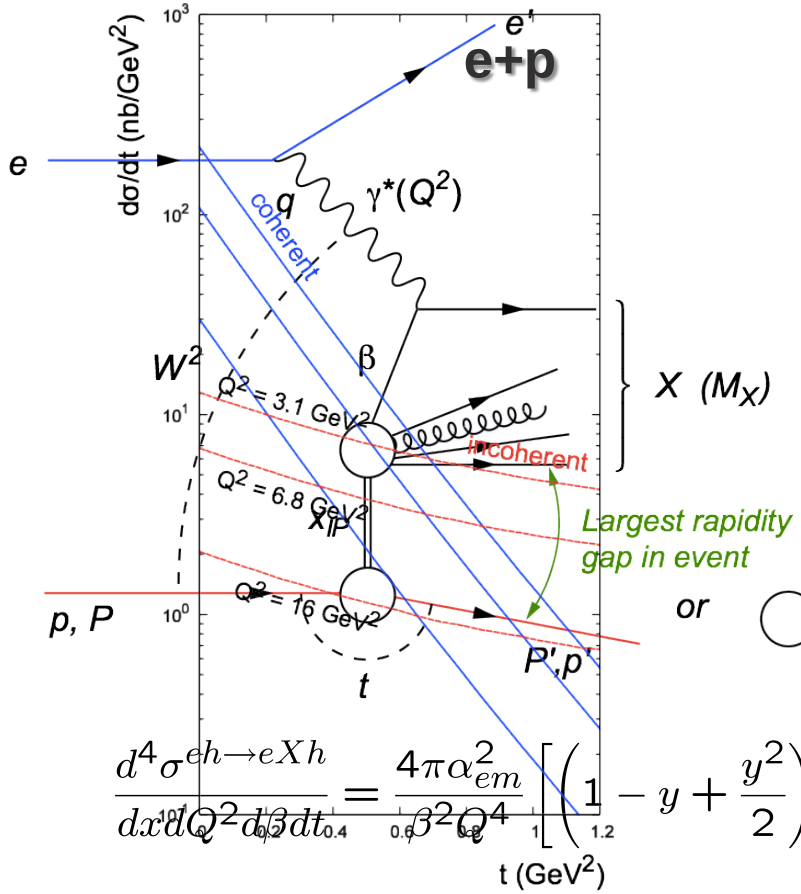


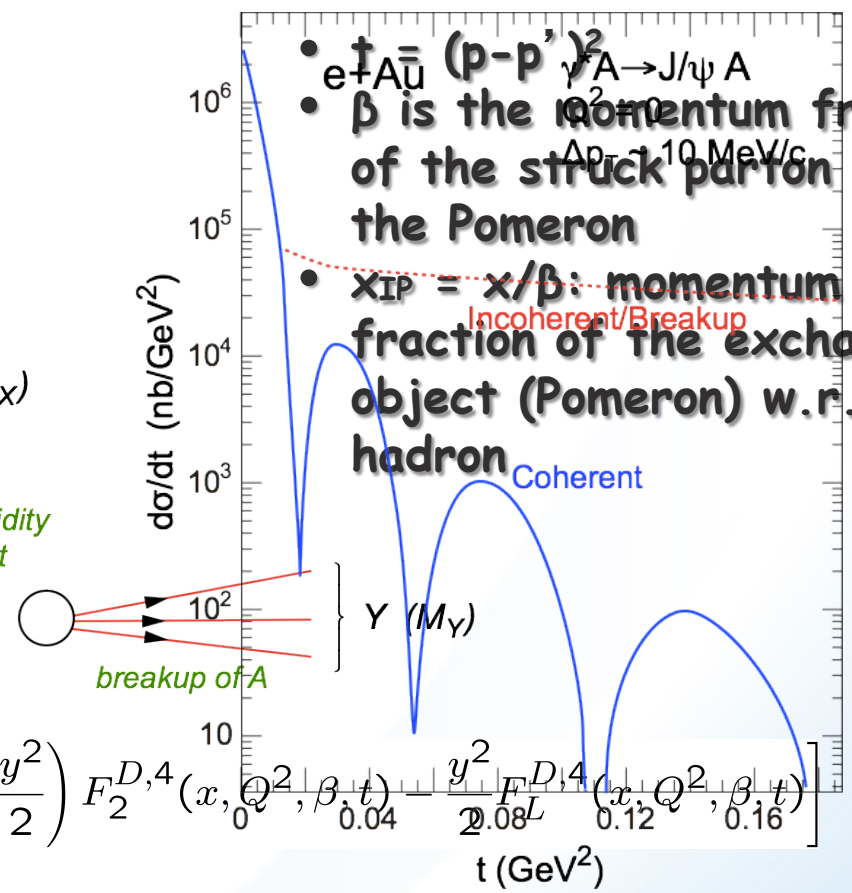
Exp: Saturation versus "conventional" scenario



- 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

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

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

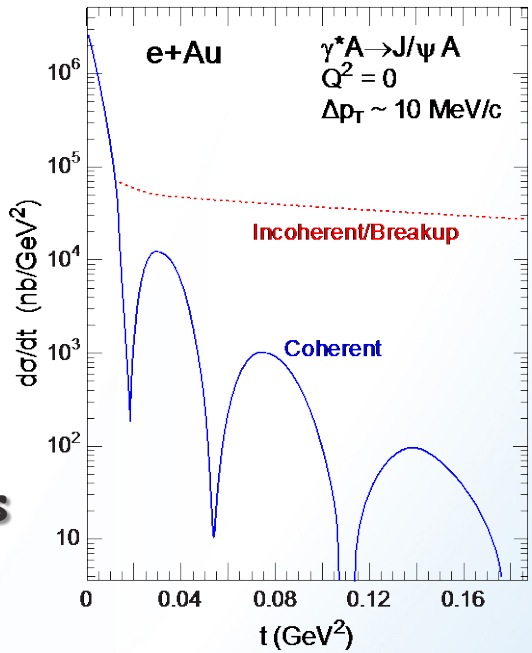
- Diffraction in e+p:
  - coherent ⇔ p intact
  - incoherent ⇔ breakup of p
  - HERA: 15% of all events are hard diffractive
- Diffraction in e+A:
  - coherent diffraction (nuclei intact)
  - breakup into nucleons (nucleons intact)
  - incoherent diffraction
  - Predictions: $\sigma_{diff}/\sigma_{tot}$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

WHY IS DIFFRACTION SO IMPORTANT

- Sensitive to spatial gluon distribution

$$\frac{d\sigma}{dt}$$

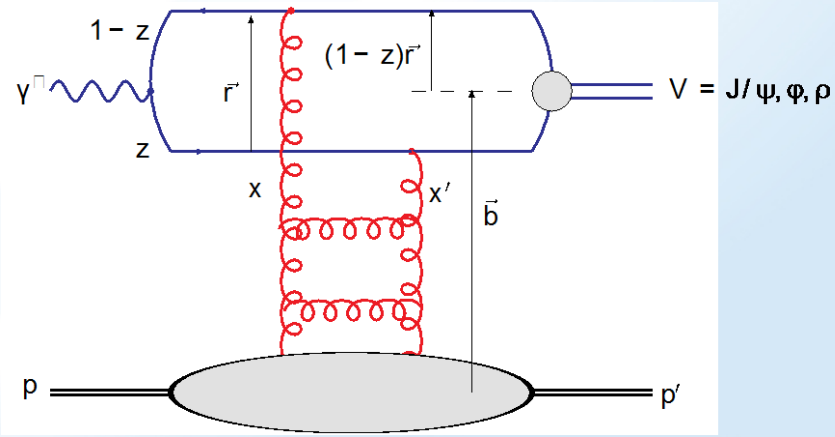
  - Hot topic:
    - Lumpiness?
    - Just Wood-Saxon+nucleon g(b)
  - Incoherent case: measure fluctuations/lumpiness in $g_A(b)$



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

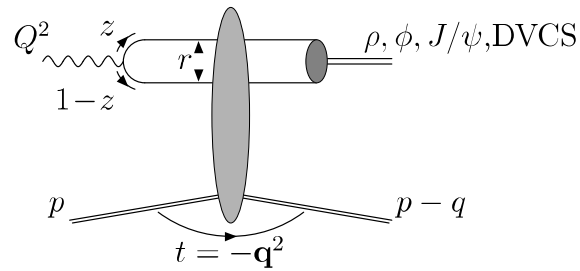
$$\frac{d\sigma^{\gamma^* p \to pV}}{dt} \sim \left| \int \Psi_V^* \frac{d\sigma_{q\bar{q}}}{d^2b} \Psi e^{-ib\Delta} \right|^2$$

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

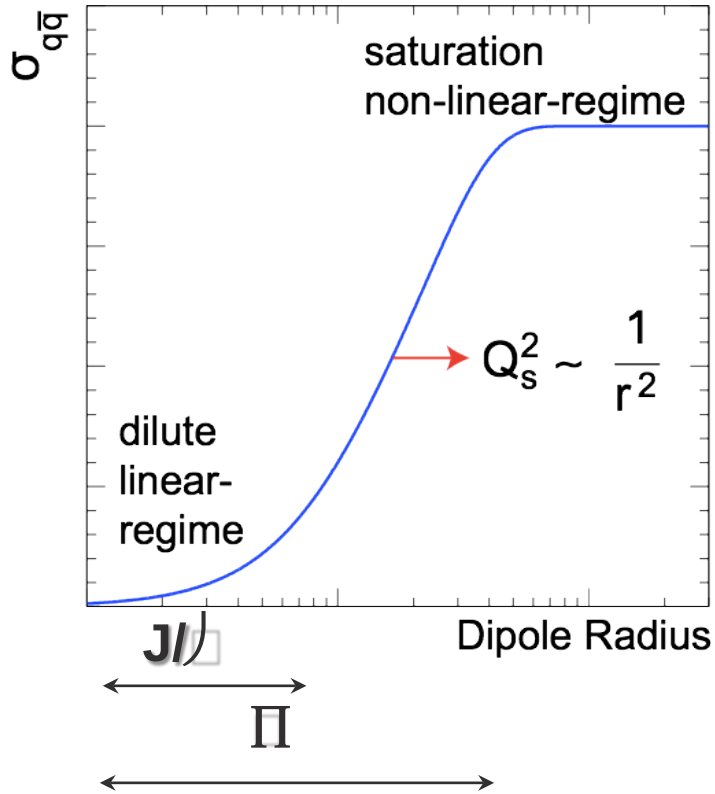


EXCLUSIVE VECTOR MESON PRODUCTION

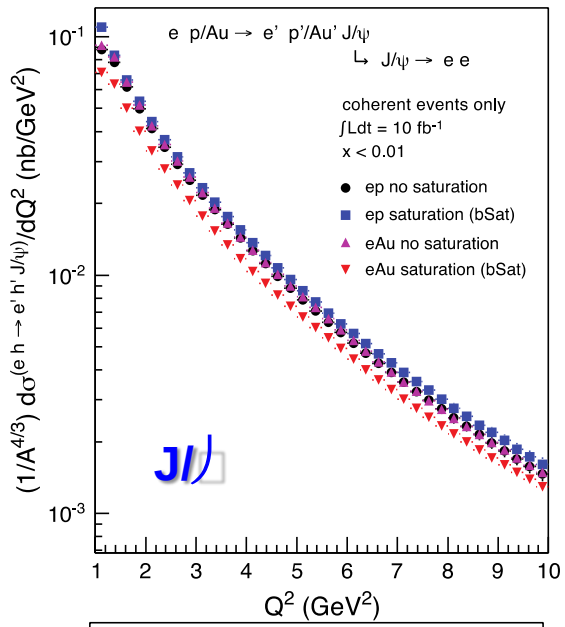
- Golden channel: e + A → e' + A' + VM
  - C
    f
  - D
    b
    f

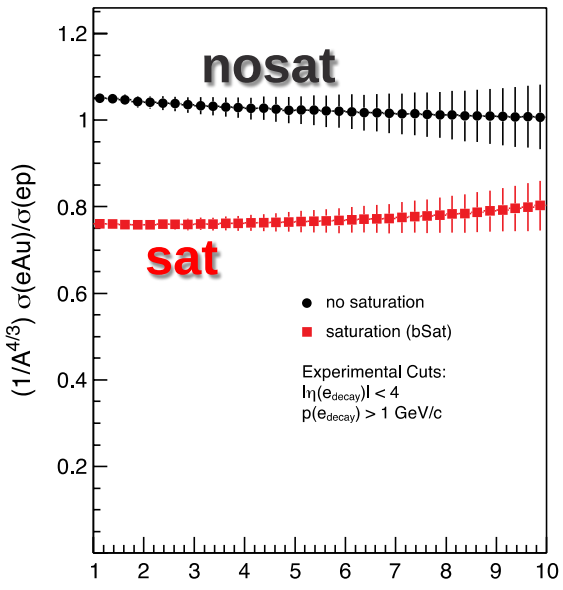


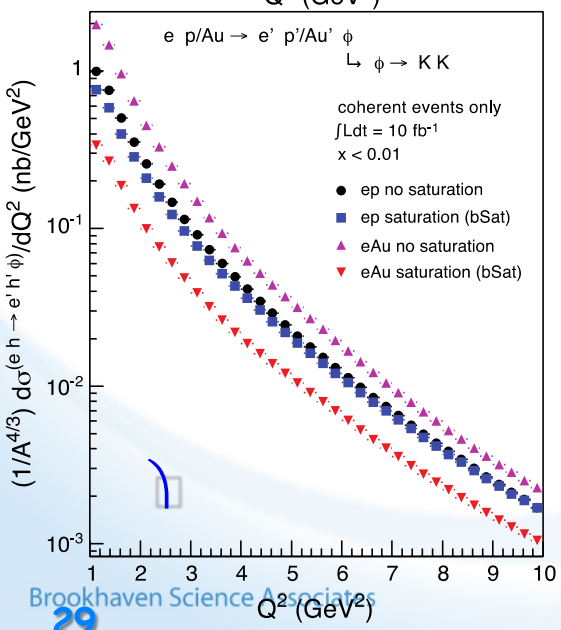
Dipole Cross-Section:

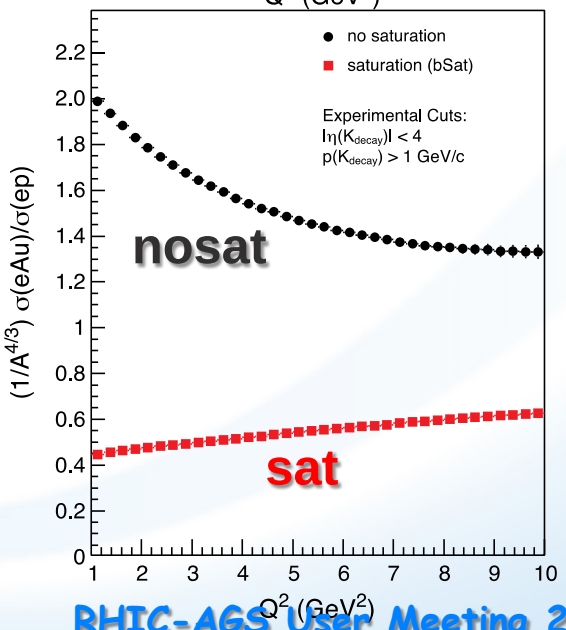


DIFFRACTION SENSITIVE TO SATURATION



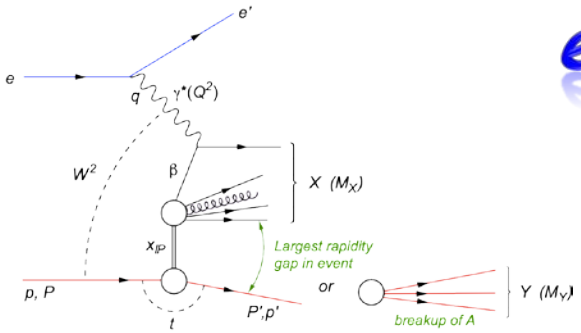


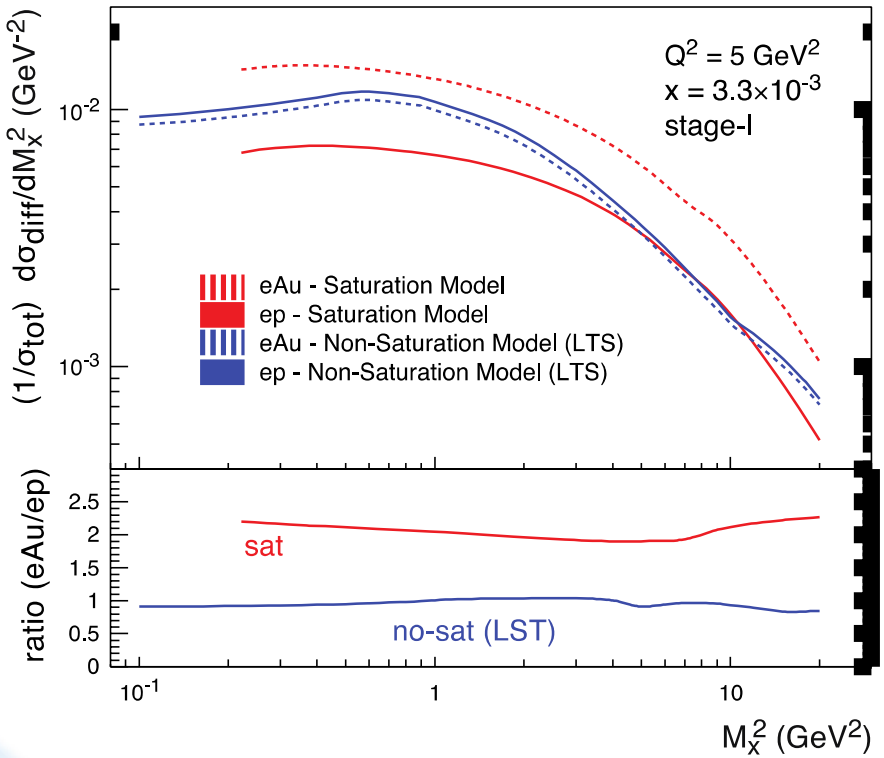


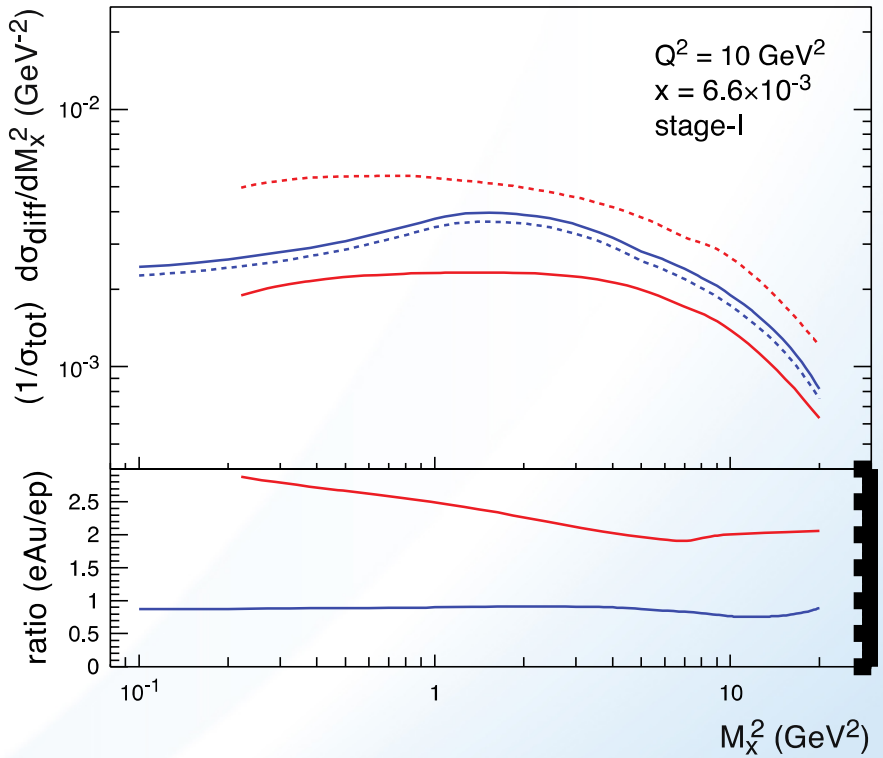


- Simple but effective Measurement:
  - $\int_{Diff(eA)}/\sigma_{Diff(ep)}/A^{4/3}$ as fct. of Q^2
  - Coherent events only scale with $A^{4/3}$ for large Q^2
  - Sartre event generator based on dipole model
    - o describes HERA data
  - nosat: dipole cross-section linearized
- Clear difference in model prediction between sat and nosat

eRHIC: INCLUSIVE DIFFRACTION





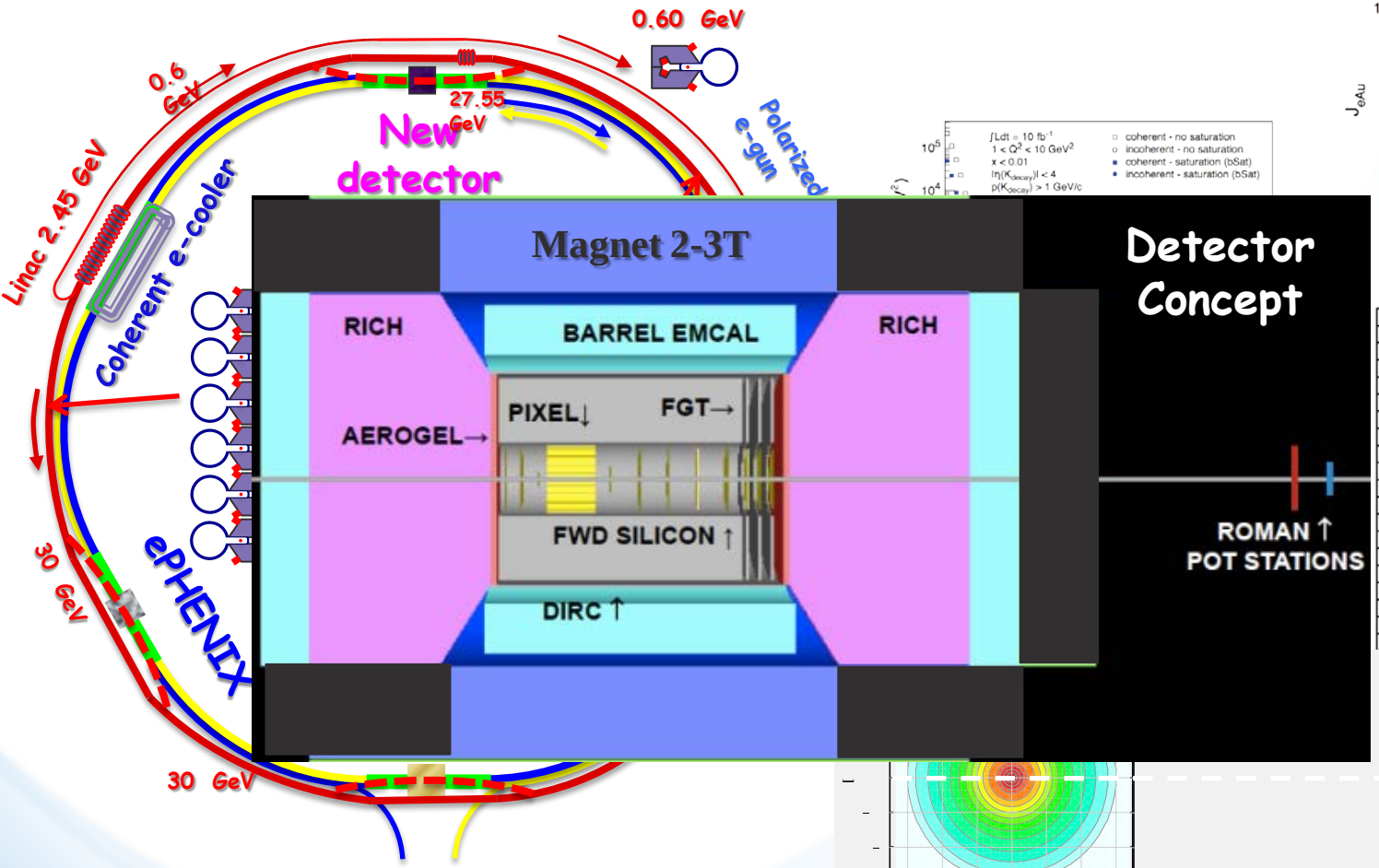


Can constrain models a lot with a few months of running!

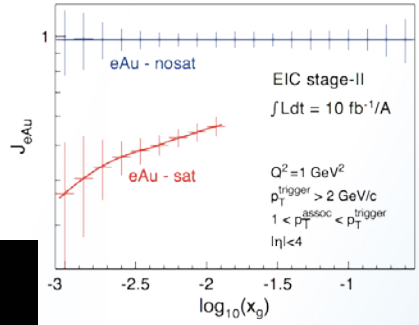
Already in Stage 1!

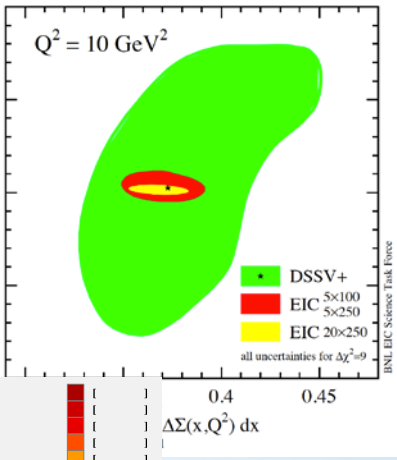
WHAT ELSE DO WE NEED?

Innovative Machine Design

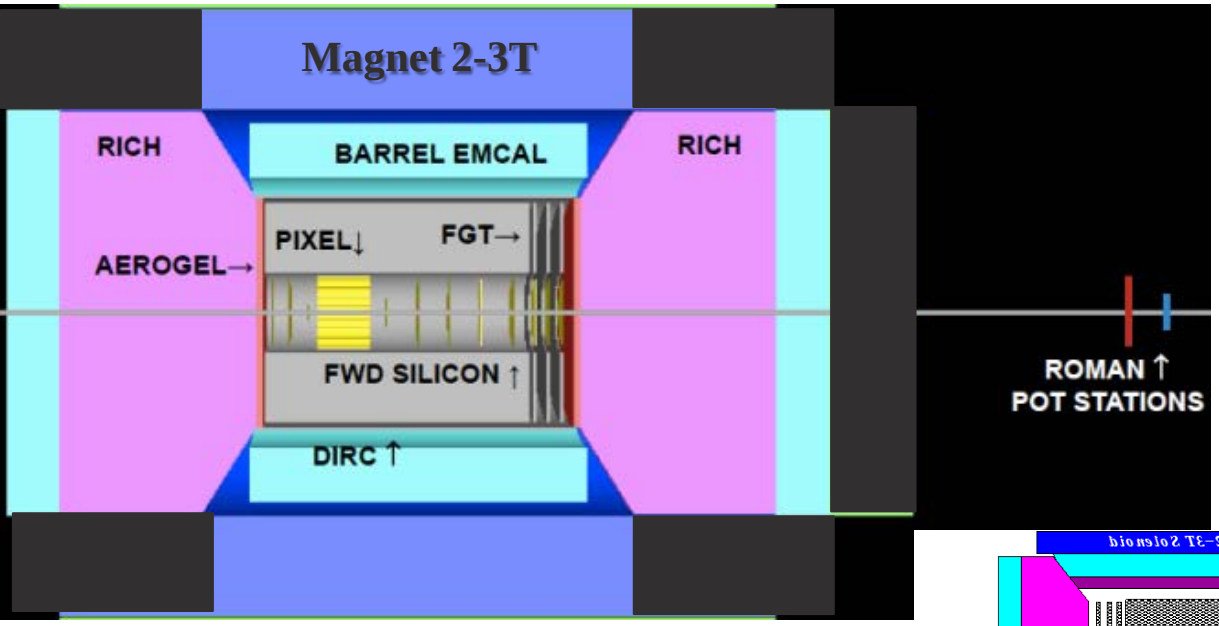


Very Novel Physics Program

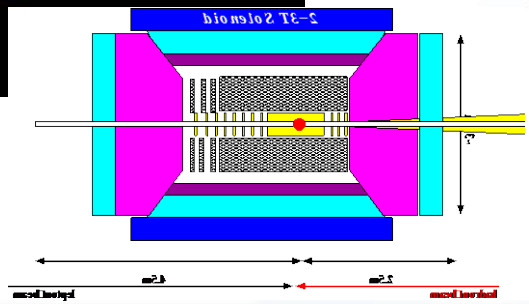


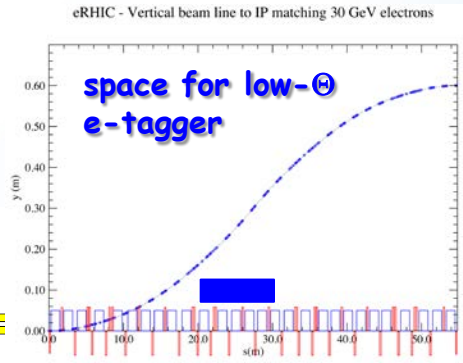


EMERGING DETECTOR CONCEPT



Backward Spectrometer
For very low Q^2-electrons:





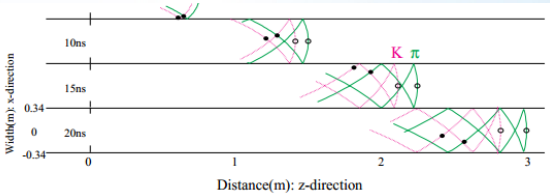
high acceptance $-5 < \eta < 5$ central detector
good PID (π,K,p and lepton) and vertex resolution (< 5μm)
tracking and calorimeter coverage the same → good momentum resolution, lepton PID
low material density → minimal multiple scattering and brems-strahlung
Magnetic field extremely critical to get good tracking resolution in forward direction
very forward electron and proton/neutron detection → Roman Pots, ZDC, low e-tagger
Integration of detector in IR design

VIBRANT DETECTOR R&D PROGRAM STARTED

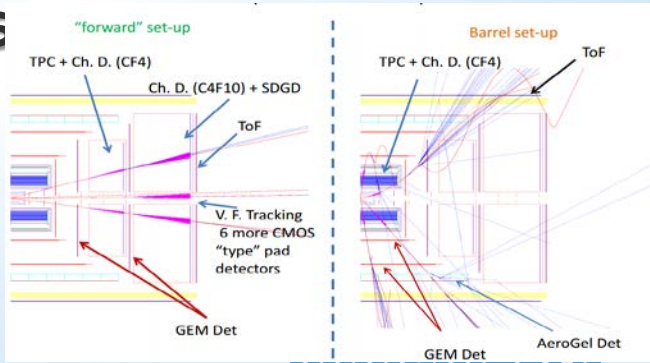
- W-Calorimetry
  - compact and high resolution

- Pre-Shower
  - W-Si
  - LYSO pixel array with cartesian readout via X-Y WLS fibers

- PID via Cerenkov
  - DIRC and timing info
  - RICH based on GEM readout



- Tracking
  - 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 (MAPS+ timing)
  - Forward: Planar GEM detectors



Details: https://wiki.bnl.gov/conferences/index.php/EIC_R%25D

SUMMARY

ep /eA Data from an EIC

will provide answers to many questions

- What are the spatial transverse distributions of nucleons and gluons?
- How much does the spatial distribution fluctuate? Lumpiness, hot-spots etc.
- How saturated is the initial state of the nucleus?

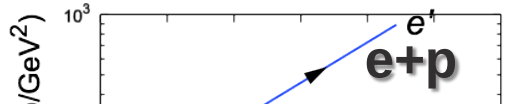
- 2d +1 imaging in transverse momentum and impact parameter space of the partons in the proton
- will determine the quark and gluon contribution to the spin and get a shot on the orbital contribution

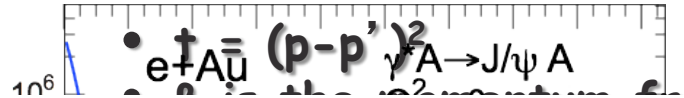
- and many things not mentioned

using a novel accelerator and a 21st century detector

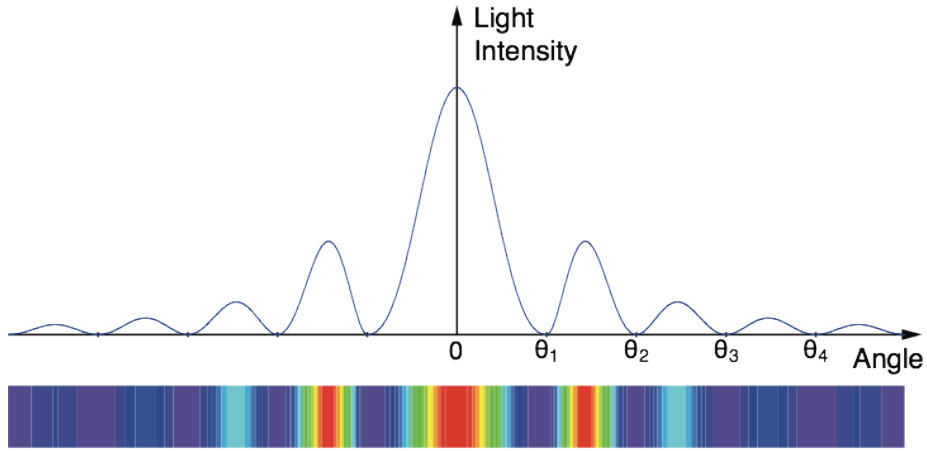
BACKUP

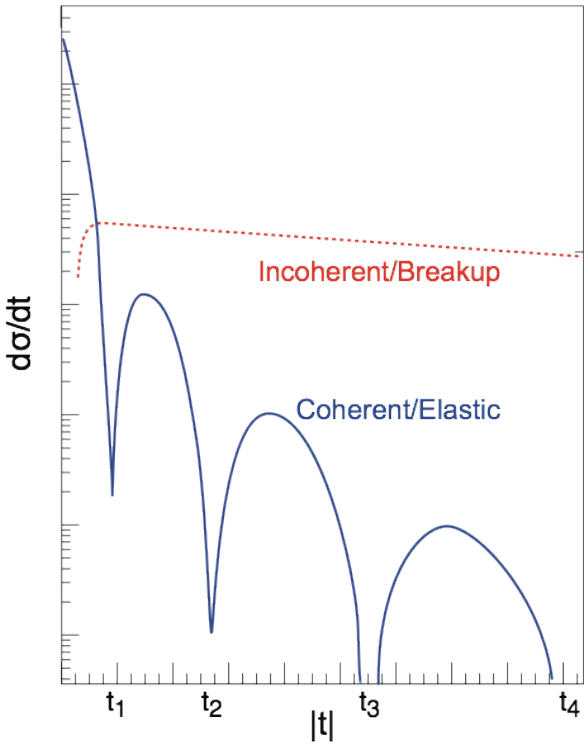
HARD DIFFRACTION IN DIS AT SMALL X





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





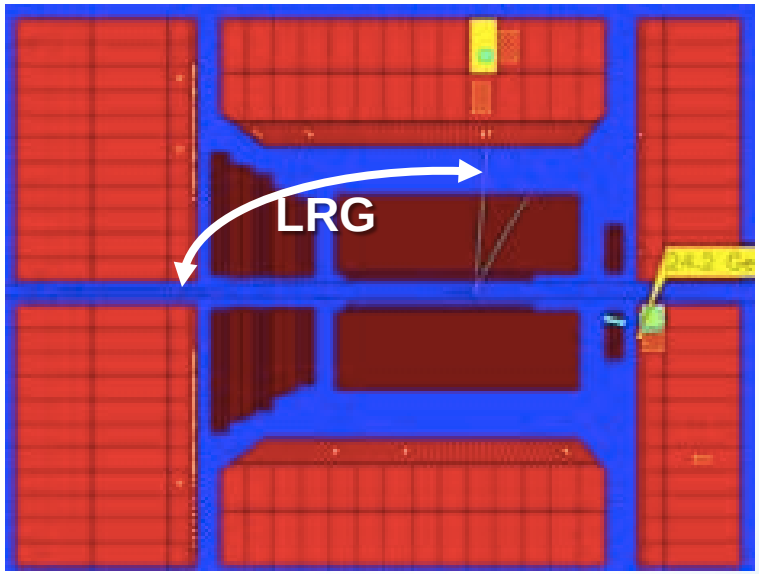
- incoherent ⇔ breakup of p
- HERA: 15% of all events are hard diffractive

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

WHY IS DIFFRACTION SO DIFFICULT?

- Key in identifying diffraction is **rapidity gap**
  - requires hermetic detector
  - does not allow separation of coherent from incoherent

- Measuring the scattered nucleus with Forward Spectrometer (Roman Pots)
  - coherent → cannot separate from beam
  - incoherent → cannot reconstruct all fragments to get p'



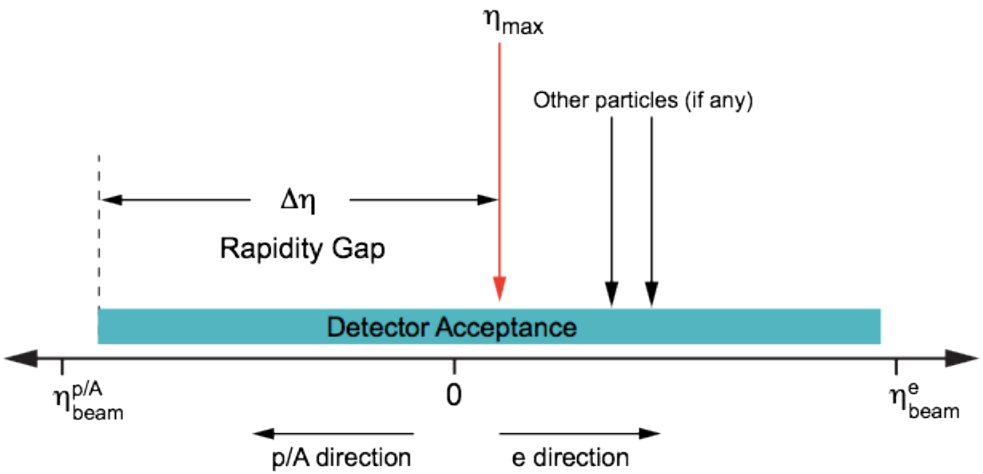
- Cannot measure t in eA **except** in **exclusive vector meson production**, e.g.:

$$e + A \rightarrow e' + J/\psi + A'$$

- Lack of t not a big issue for measurements of F_2^D, F_L^D and hence $G(x,Q^2)$

LARGE RAPIDITY GAP METHOD (LRG)

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

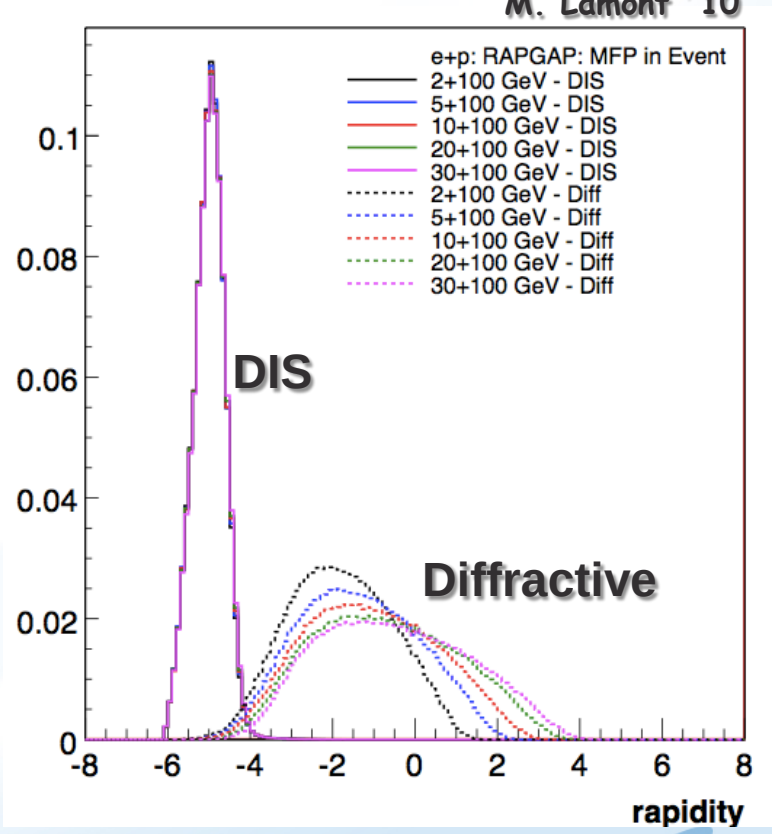


Hermeticity requirement:

- 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



EIC eA KEY MEASUREMENTS

- Key Measurements: Small set of measurements whose ability to extract novel physics is beyond question.

Low x:

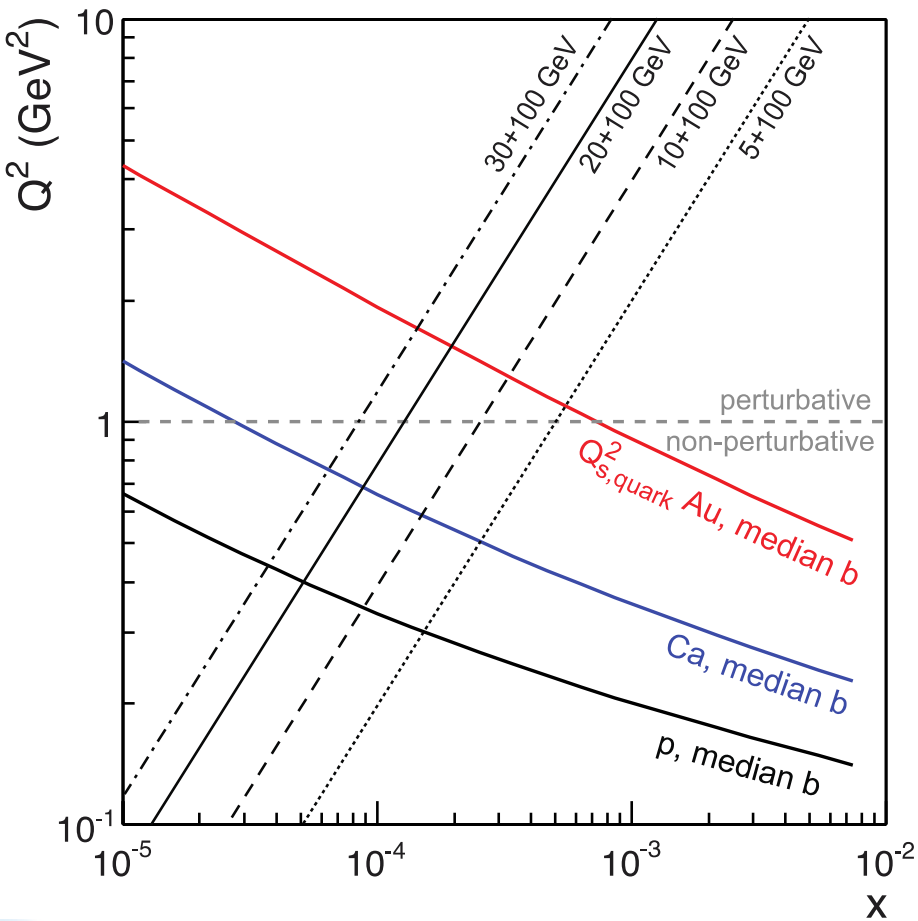
EIC INT-Report: arXiv:1108.1713v1

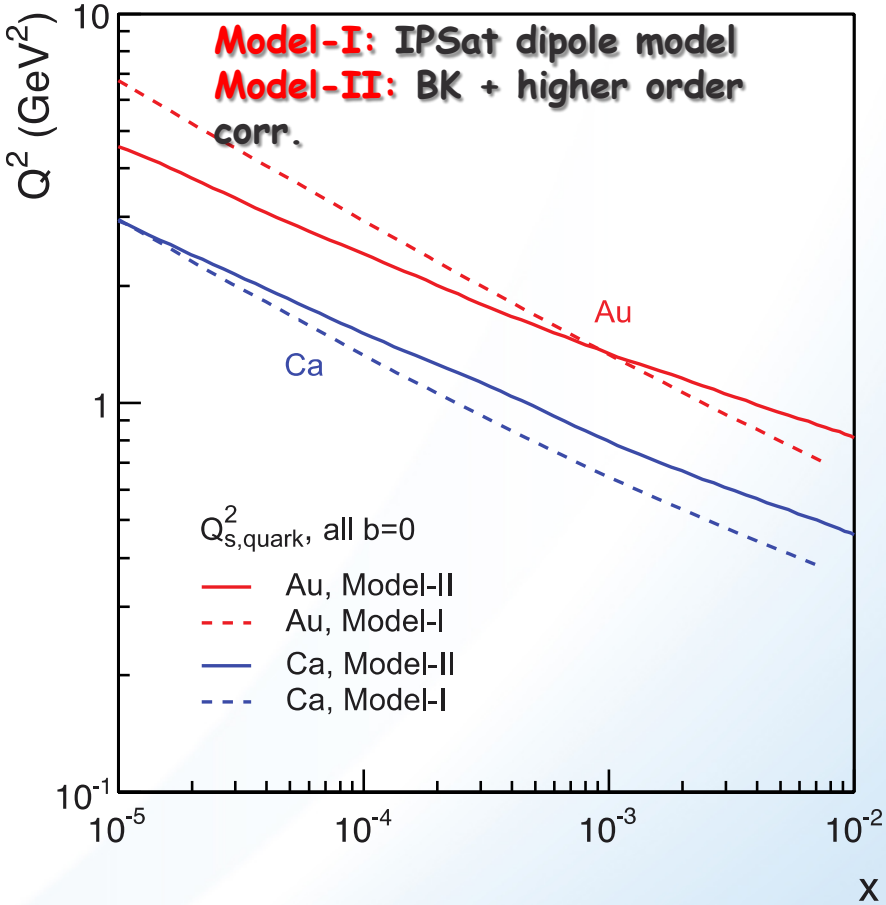
Deliverables	Observables	What we learn	Stage-I	Stage-II
Integrated gluon momentum distributions	$F_{2,L}$	Nuclear wave function; saturation, Q_s	Gluons at $10^{-3} \lesssim x \lesssim 1$	Exploration of saturation regime
k_T-dependent gluons; gluon correlations	Di-hadron correlations	Non-linear QCD evolution/ universality	Onset of saturation; Q_s	Nonlinear small-x evolution
Spatial gluon distributions; gluon correlations	Diffractive vector mesons and DVCS	Nonlinear small-x evolution; saturation dynamics	Moderate x with nuclei	Smaller x, saturation

Large x:

transp. coefficients in cold matter	large-x SIDIS; jets	parton energy loss, shower evolution; energy loss mech.	light flavors, charm bottom; jets	precision rare probes; large-x gluons

BEST KNOWLEDGE OF Q_S IN eA



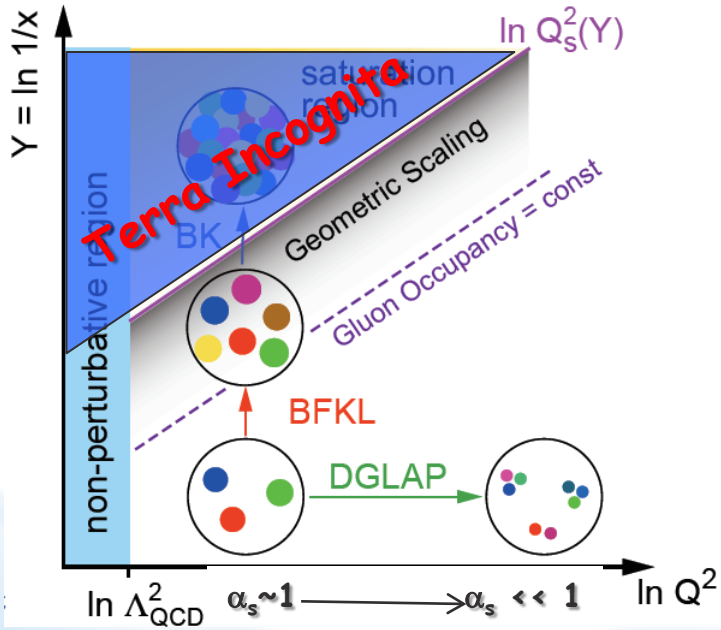


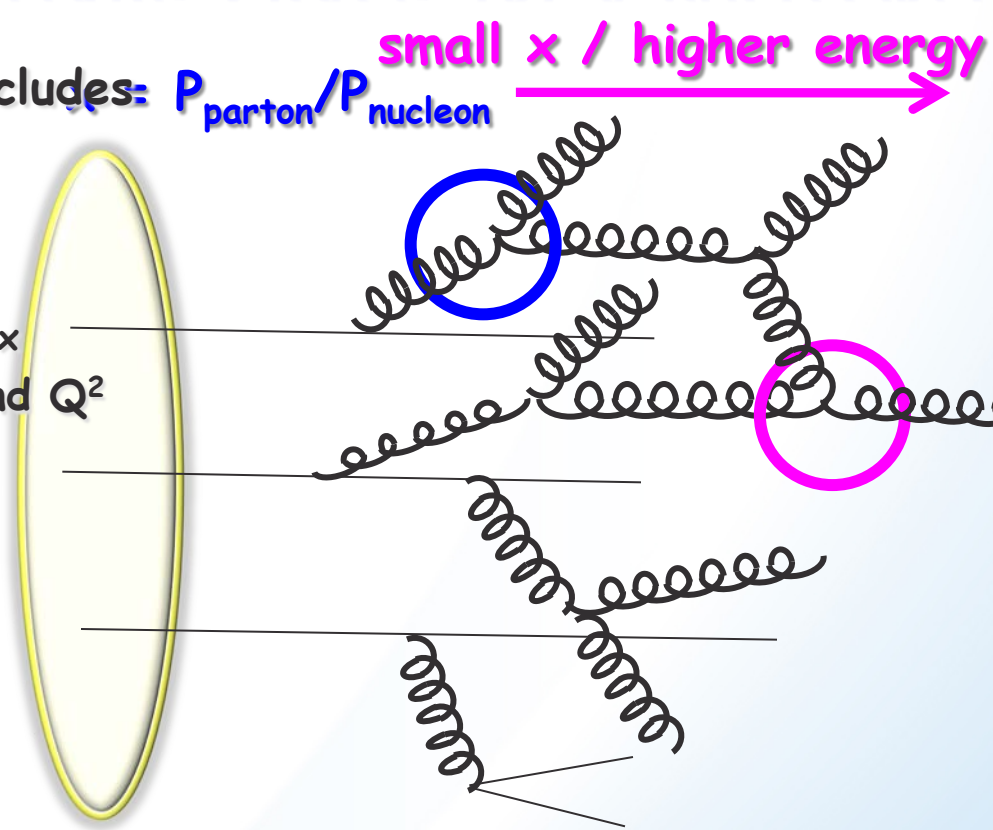
Enhancement of Q_S with A

⇒ saturation regime reached at significantly lower energy in nuclei

HOW MANY GLUONS HAVE SPACE IN A PROTON?

- 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



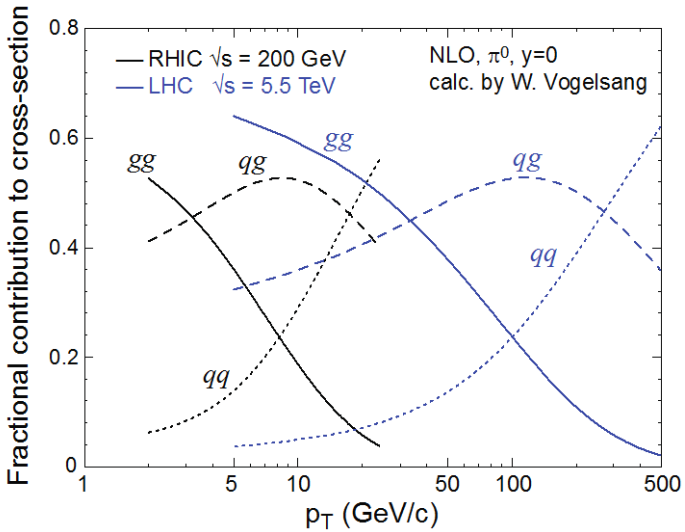


Bremsstrahlung $\sim \alpha_s \ln(1/x)$

Recombination $\sim \alpha_s \rho$

Saturation must set in at low x → high occupancy

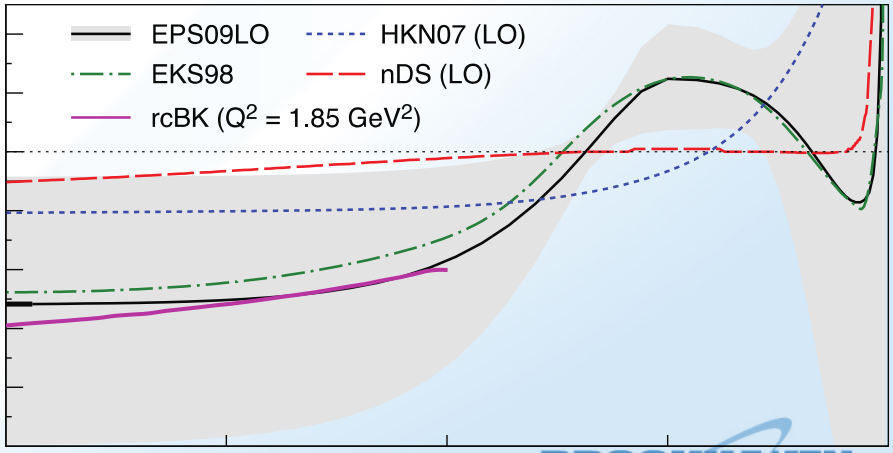
WHAT DO WE KNOW ABOUT xG IN NUCLEI?



99% of all $h^{\pm}$ have p_t < 2 GeV/c
"Bulk Matter" → x < 0.01

Other than in p:
$G(x,Q^2)$ for nuclei is little known
Key: $F_L(x,Q^2) \sim xG(x,Q^2)$

$$R_L(x,Q^2) \equiv \frac{F_L^A(x,Q^2)}{A\ F_L^p(x,Q^2)} \approx \frac{G_A(x,Q^2)}{A\ G_p(x,Q^2)}$$



MEASURING F_L WITH THE EIC (I)

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

quark+anti-quark momentum distributions

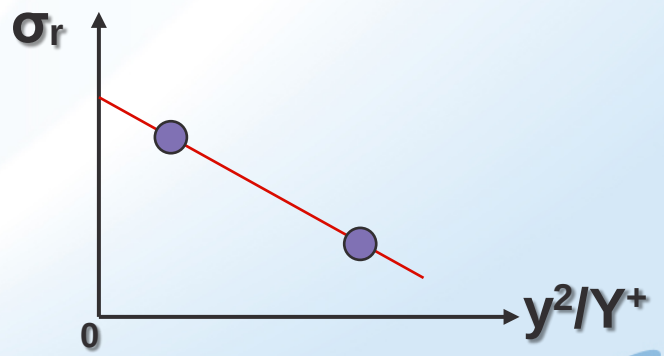
gluon momentum distribution

In practice use reduced cross-section:

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

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

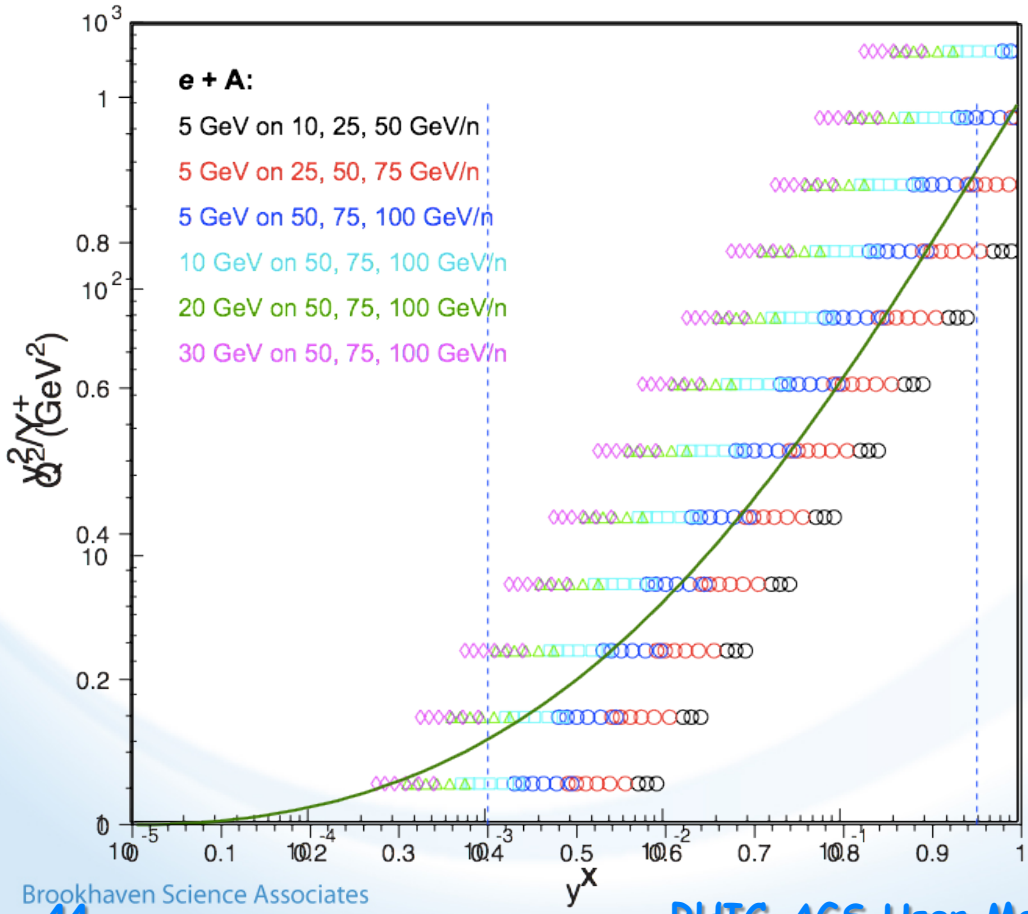
- How to extract F_L
  - Need different values of y^2/Y^+
  - F_L slope of σ_r vs y^2/Y^+
  - F_2 intercept of σ_r vs y^2/Y^+ with y-axis



MEASURING F_L WITH THE EIC (II)

In order to extract F_L one needs **at least two measurements** of the inclusive cross section with "wide" span in inelasticity parameter y ($Q^2 = sxy$)

F_L requires runs at various $\sqrt{s}$ ⇒ longer program



EIC studies:

- Statistical error is negligible in essentially whole range
- Systematical Error
  - Calibration
  - Normalization
  - Experiment
  - Radiative Corrections

AN ELECTRON ION COLLIDER IN THE US

Requirements:

- High Luminosity > 10^{33} $cm^{-2}s^{-1}$
- Flexible center of mass energy
- 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

All energies scale

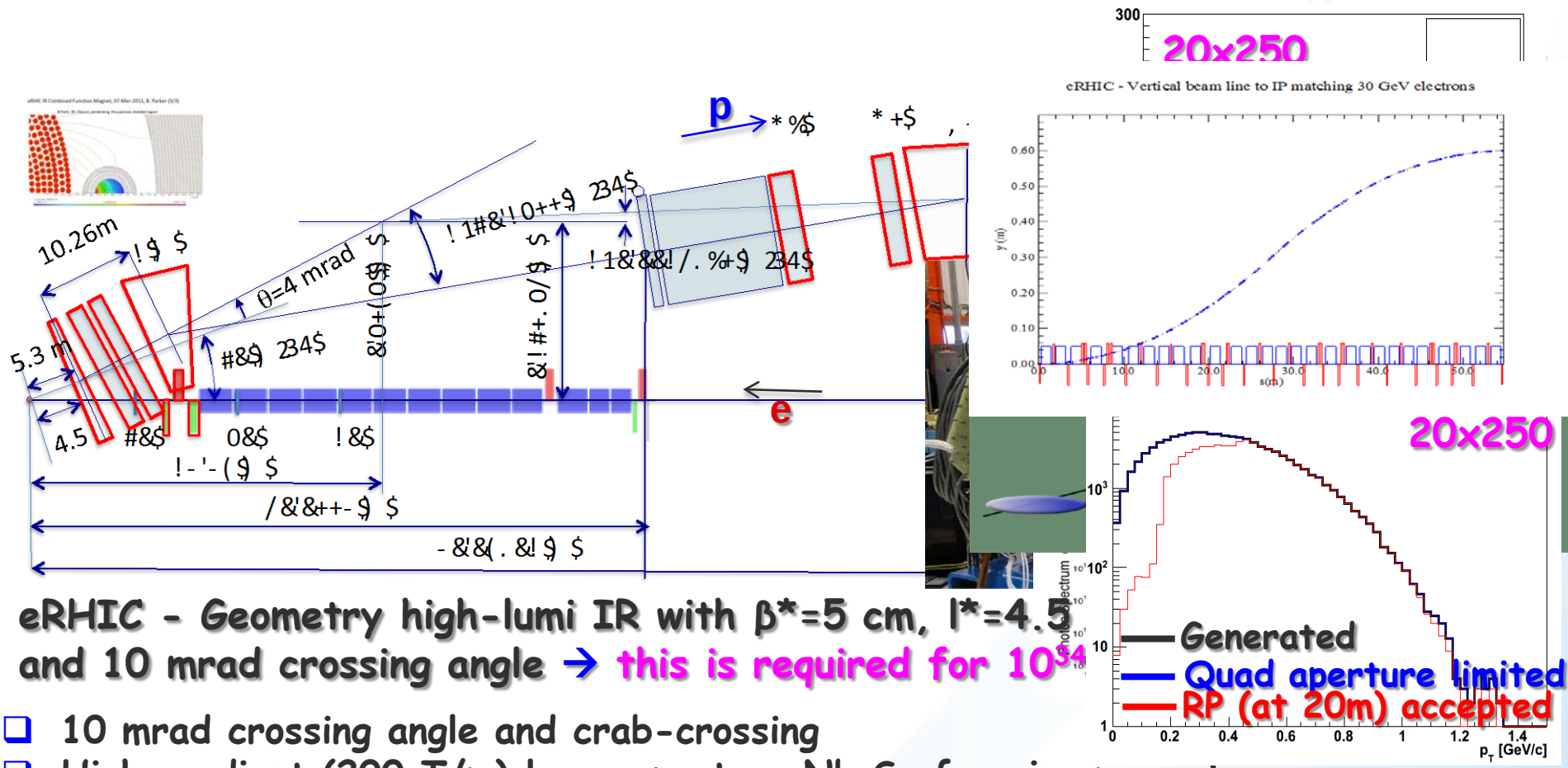
Main Accelerator Challenges

In red –increase/reduction beyond the state of the art

Polarized electron gun – 10x increase	
Coherent Electron Cooling – New concept	
Multi-pass SRF ERL 5x increase in current 30x increase in energy	
Crab crossing New for hadrons	
Polarized ^{3}He production	
Understanding of beam-beam affects New type of collider	
β*=5 cm 5x reduction	
Multi-pass SRF ERL 3-4x in # of passes	
Feedback for kink instability suppression Novel concept	

$^{92}U^{238}$
100
89
166
0.83
5.2
67
1.2
80
none
8.3
5
0.41

eRHIC HIGH-LUMINOSITY IR WITH β*=5 CM



eRHIC - Geometry high-lumi IR with β*=5 cm, l*=4.5 and 10 mrad crossing angle → this is required for 10^{34}

- 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

© D.Trbojevic, B.Parker, S. Tepikian, J. Beebe-Wang

SCALING VIOLATIONS AT SMALL X

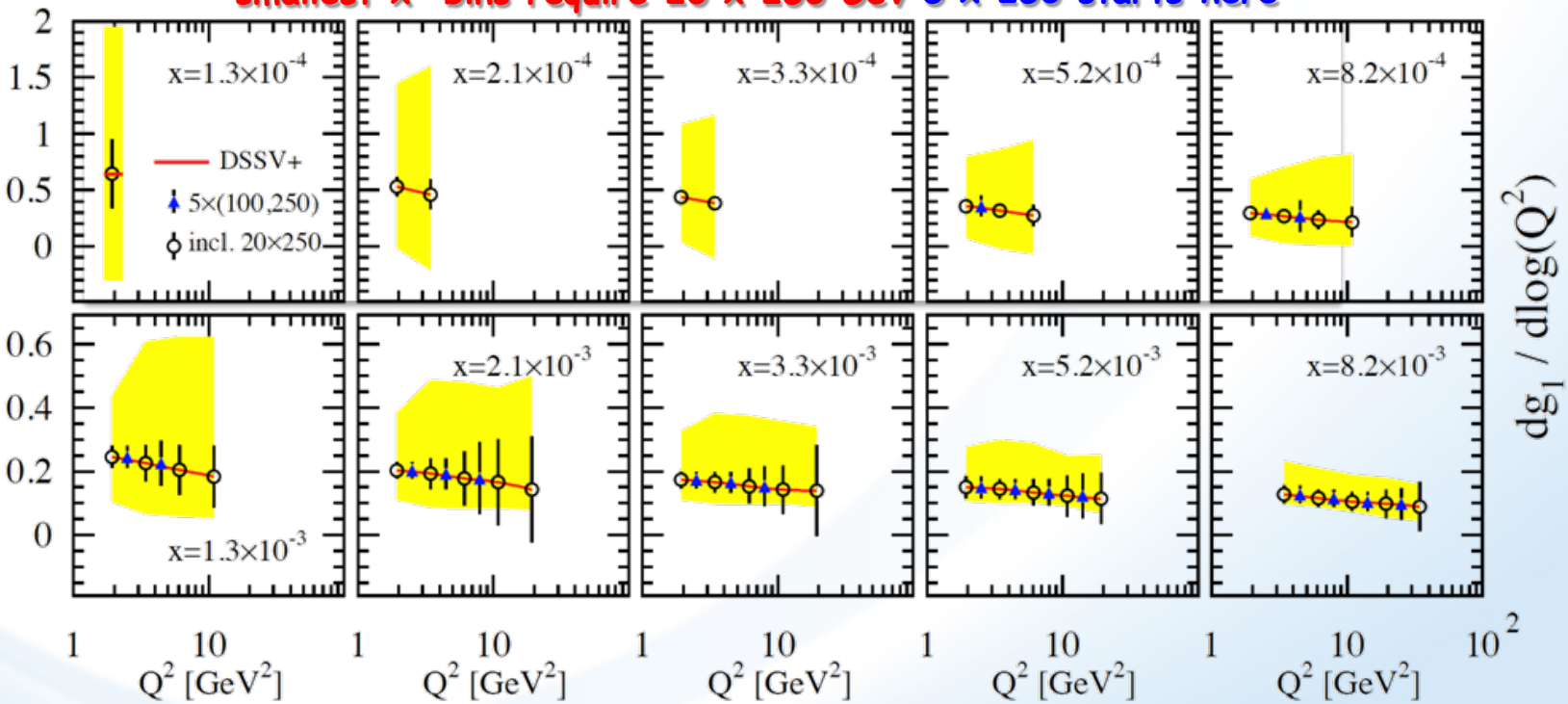
rough small-x approximation to Q^2-evolution:

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

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

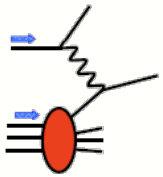


- error bars for moderate $10fb^{-1}$ per c.m.s. energy; bands parameterize current DSSV+ uncertainties

PREPARATION OF DIS AND SIDIS MOCK DATA

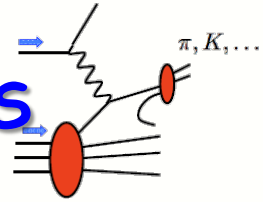
- PEPSI MC to generate σ^{++} and σ^{+-} with LO GRSV PDFs

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)

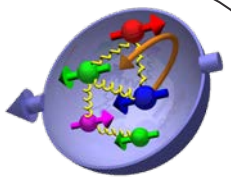
scattered lepton: $1^o < \theta_{elec} < 179^o$ and $p_{elec} > 0.5\ GeV$

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)

MOST COMPELLING PHYSICS QUESTIONS

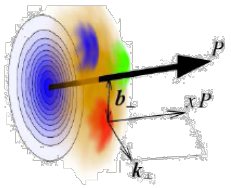
spin physics



- what is the polarization of gluons at small x where they are most abundant
- what is the flavor decomposition of the polarized sea depending on x

determine quark and gluon contributions to the proton spin at last

imaging

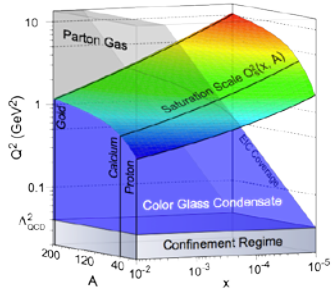


- what is the spatial distribution of quarks and gluons in nucleons/nuclei
- understand deep aspects of gauge theories revealed by k_T dep. distr'n

possible window to orbital angular momentum

physics of strong color fields

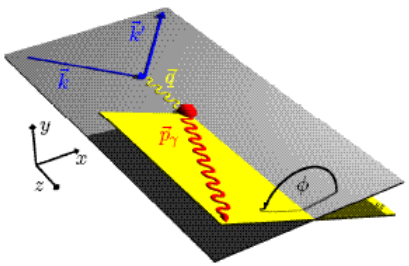
quantitatively probe the universality of strong color fields in AA, pA, and eA



- understand in detail the transition to the non-linear regime of strong gluon fields and the physics of saturation
- how do hard probes in eA interact with the medium

DVCS ASYMMETRIES

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



→ different charges: $e^+ e^-$:

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

→ polarization observables:

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

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

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

$\Delta\sigma_{UT}$ → beam, target

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

MC SIMULATION

Written by E. Perez, L Schoeffel, L. Favart [arXiv:hep-ph/0411389v1]

The code MILOU is based on GPD convolution by:
A. Freund and M. McDermott [All ref.s in: http://durpdg.dur.ac.uk/hepdata/dvcs.html]

- ✓GPDs, evolved at NLO by an independent code which provides tables of CFF
  - at LO, the CFFs are just a convolution of GPDs:

$$\mathscr{H}(\xi,Q^2,t)=\sum_{u,d,s}\int_{-1}^{1}\left[\frac{e_i^2}{1-x/\xi-i\varepsilon}\pm\{\xi\to-\xi\}\right]H_i\left(x,\xi,Q^2,t\right)dx$$

- ✓provide the real and imaginary parts of Compton form factors (CFFs), used to calculate cross sections for DVCS and DVCS-BH interference.

$$\frac{d\sigma}{dxdyd|t|d\phi d\varphi}=\frac{\alpha^3 x_B y}{16\pi^2 Q^2\sqrt{1+\varepsilon^2}}\left|\frac{\mathcal{I}}{e^3}\right|$$

$$\phi=\phi_N-\phi_l$$

$$\varphi=\Phi_T-\phi_N$$

$$\varepsilon\equiv 2x\frac{m_N}{Q}$$

$$\left|\mathcal{I}_{\mathcal{BH}}\right|^2=\frac{e^6}{x^2y^2(1+\varepsilon^2)^2\Delta^2\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left\{c_0^{BH}+\sum_{n=1}^{2}c_n^{BH}\cos(n\phi)+s_1^{BH}\sin(\phi)\right\}$$

$$\left|\mathcal{I}_{\mathcal{DVCS}}\right|^2=\frac{e^6}{y^2Q^2}\left\{c_0^{DVCS}+\sum_{n=1}^{2}\left[c_n^{DVCS}\cos(n\phi)+s_n^{DVCS}\sin(n\phi)\right]\right\}$$

$$\left|\mathcal{I}\right|^2=\frac{\pm e^6}{xy^3\Delta^2\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left\{c_0^{I}+\sum_{n=1}^{3}c_n^{I}\cos(n\phi)+s_1^{I}\sin(\phi)\right\}$$

- ✓ $\frac{d\sigma}{d|t|}=\exp\left(B\left(Q^2\right)t\right)$ -> The B slope is allowed to be constant or to vary with Q^2:
- ✓Proton dissociation ($ep\to e\gamma Y$) can be included
- ✓Other non-GPD based models are implemented like FFS, DD

DATA SIMULATION AND SELECTION

Acceptance criteria

- for Roman pots: $0.03 < |t| < 0.88$ GeV^2
- for $|t| > 1$GeV2 detect recoil proton in main detector
- $0.01 < y < 0.85$ GeV^2
- $\eta < 5$

- BH rejection criteria (applied to x-sec. measurements)
  - $y < 0.6$
  - $(\theta_{el}-\theta_{\gamma}) > 0$
  - $E\gamma > 1$GeV^2; $E_e > 1$GeV^2

- Events smeared for expected resolution in t, Q2, x
- Systematic uncertainty assumed to be ~5% (having in mind experience from HERA)
- Overall systematic uncertainty from luminosity measurement not taken into account

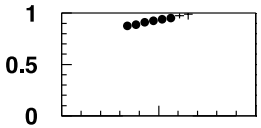
$0.01 < |t| < 0.85$ GeV^2
(Low-|t| sample)
- Very high statistics
- Systematics will dominate!
- Within Roman pots acceptance

$1.0 < |t| < 2.0$ GeV^2
(Large-|t| sample)
- Xsec goes down exponentially
- requires a year of data taking @ 20x250 GeV (stage 2)
- Main detector can be used in measuring |t|

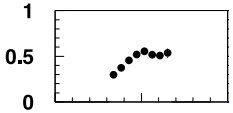
eRHIC-Stage 1: 5 X 100 GeV → ~10 fb^{-1} (~ a year)

eRHIC-Stage 2: 20 X 250 GeV → ~100 fb^{-1} (~ a year)

BH FRACTION



5 GeV x 100 GeV
BH subtraction will be relevant in stage 1, at large y, depending on the x-Q^2 bin



<2.51,3.98>

<3.98,6.31>

<6.31,10>

<10,15.8>

<15.8,25.1>

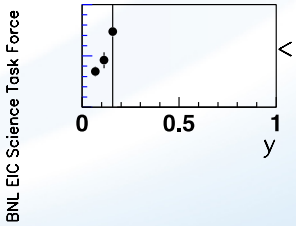
<25.1,39.8>

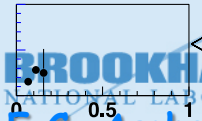
<39.8,63.1>

<63.1,100>

BUT…

5 GeV x 100 GeV
and
5 GeV x 250 GeV
are overlapping:
x-sec. measurements at 5x250 at low-y can crosscheck the BH subtrac. made for 5x100





20 GeV x 250 GeV
BH subtraction will be not an issue for y<0.6

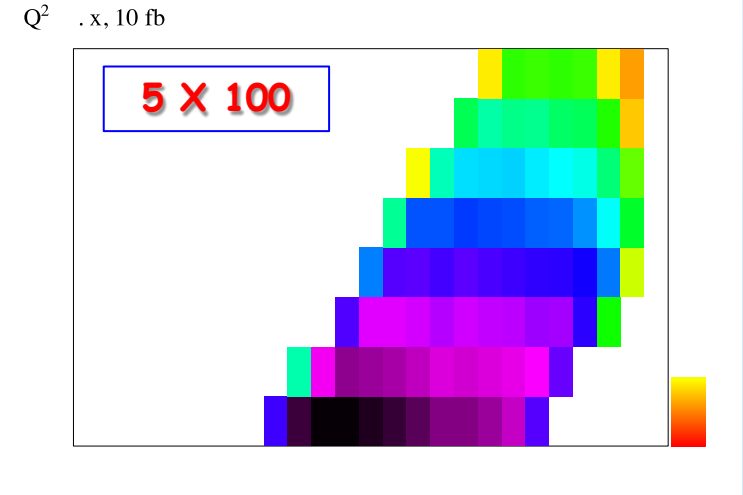
GPDs: DVCS@eRHIC

$$\frac{d\sigma}{d|t|} = \frac{\#evt}{\Delta_{bin} \bullet A \bullet \mathcal{L}} \qquad \sim e^{-bt}$$

b=5.6

Specifications:

- Statistical error down to 1%
- It uses smeared t values (5% momentum resol.)
- |t|-binning -> 3 * resolution (or higher)

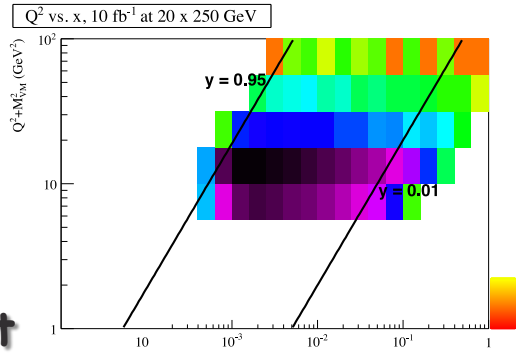


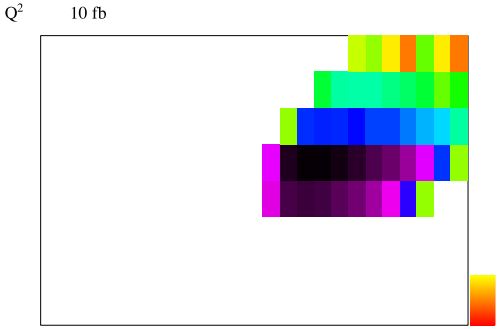
GPD H: J/Ψ

To improve imaging on gluons add J/ψ observables

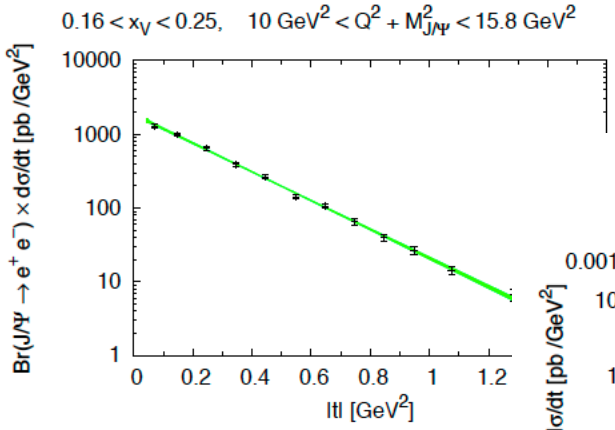
- cross section
- A_{UT}
- ……

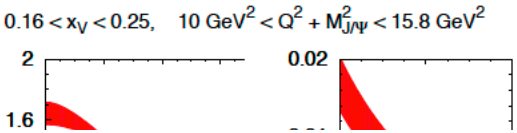
→ need still to do combined fit in Dieter's model



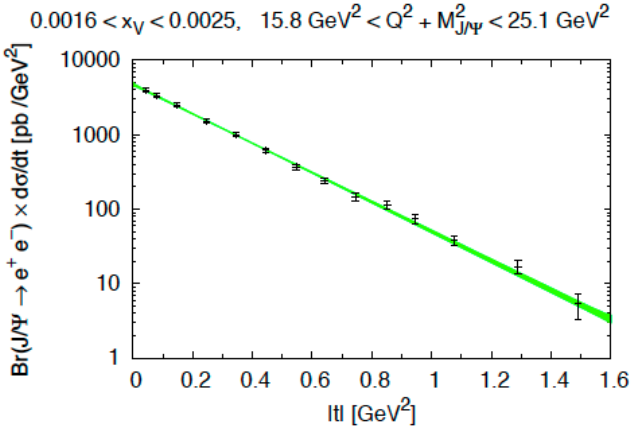


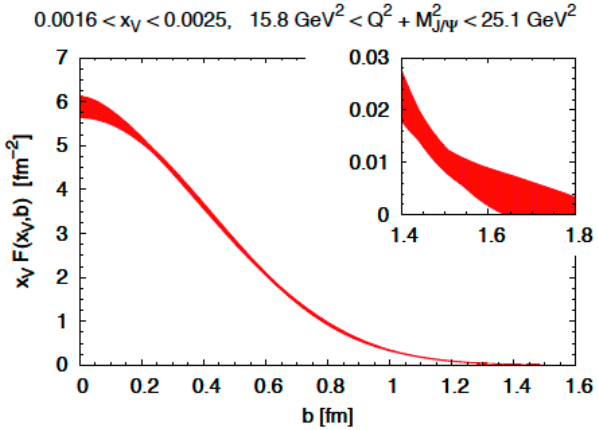
$E_e = 10\,\mathrm{GeV},\ E_p = 100\,\mathrm{GeV}$ with $10\,\mathrm{fb}^{-1}$





$E_e = 20\,\mathrm{GeV},\ E_p = 250\,\mathrm{GeV}$ with $10\,\mathrm{fb}^{-1}$

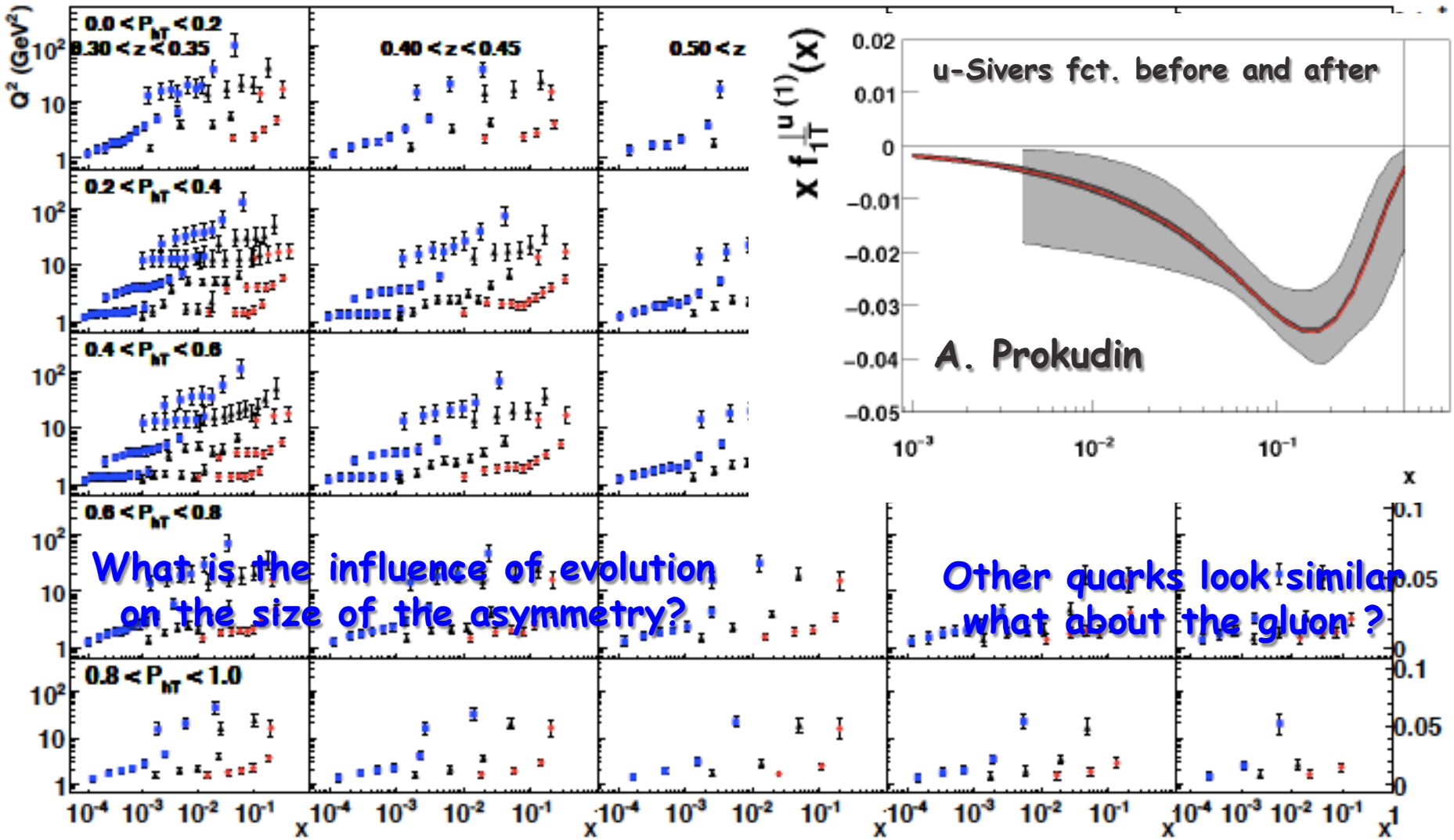




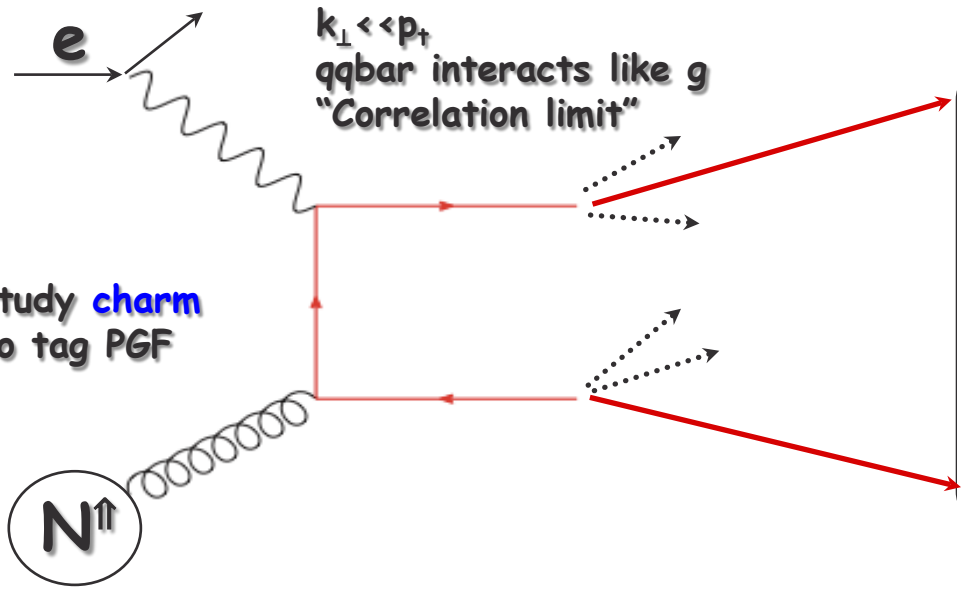
Plots: M. Diehl

QUARK TMDs @ EIC

Sivers asymmetry for π+:
$\sqrt{s}$=140 GeV / 45 GeV / 15 GeV



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



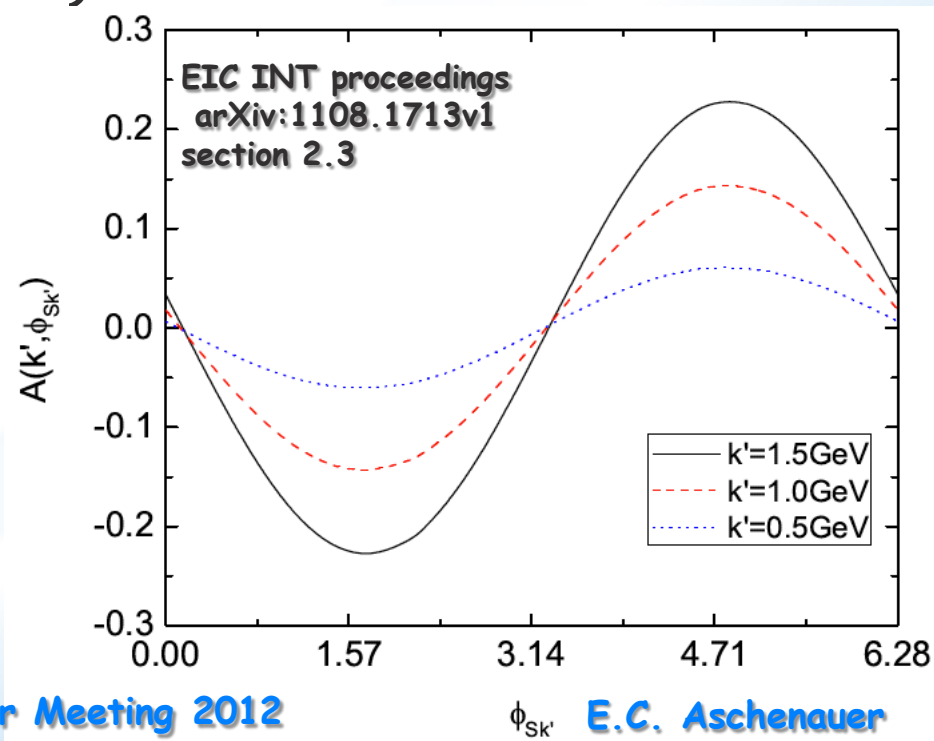
Measure a pair of D mesons

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

Statistically challenging

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

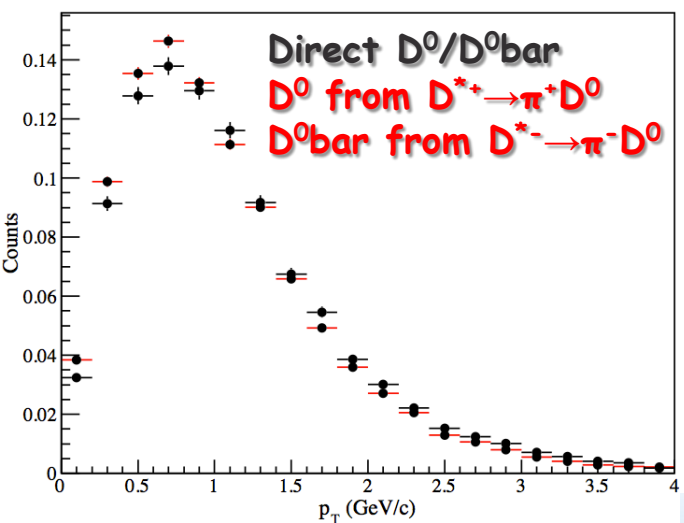
$$A(k'_\perp, \phi_{Sk'}) = \frac{d\sigma(k'_\perp, \phi_{Sk'}) - d\sigma(k'_\perp, \phi_{Sk'} + \pi)}{d\sigma(k'_\perp, \phi_{Sk'}) + d\sigma(k'_\perp, \phi_{Sk'} + \pi)}$$

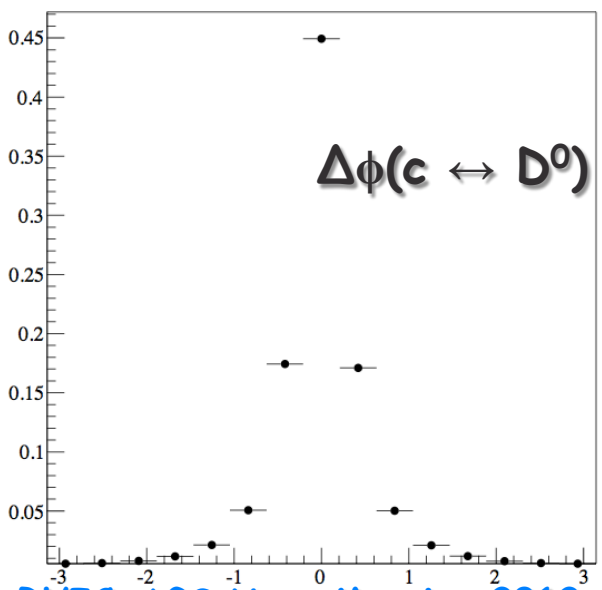


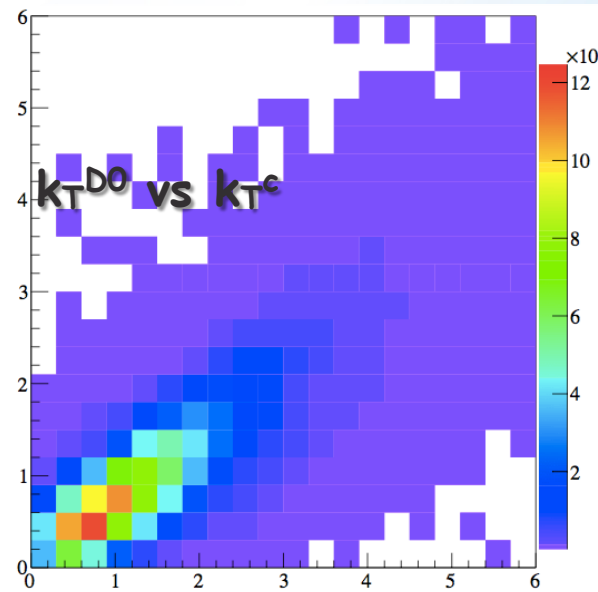
SIMULATION ASSUMPTIONS

Pythia:

- unpolarised with CEQT 10 PDF
- 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"
- Both D0 and D0-bar → π K
  - Easily reconstructed
  - Branching ratio 3.87%
  - Are down feeds from different Mesons an issue?
  - Is the charm Meson a good proxy for the charm quark

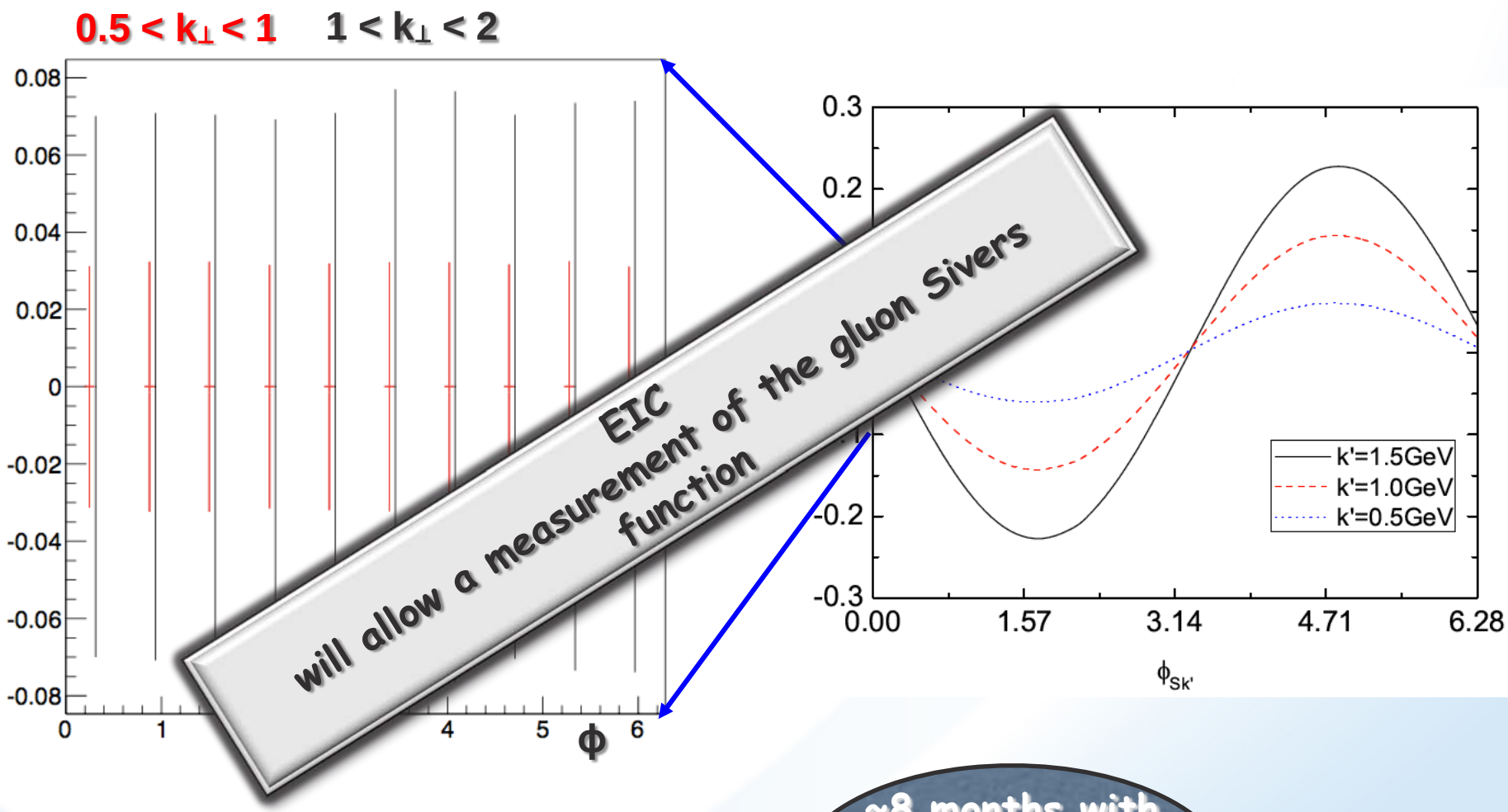






BROOKHAVEN NATIONAL LABORATORY
E.C. Aschenauer

SIMULATION RESULT

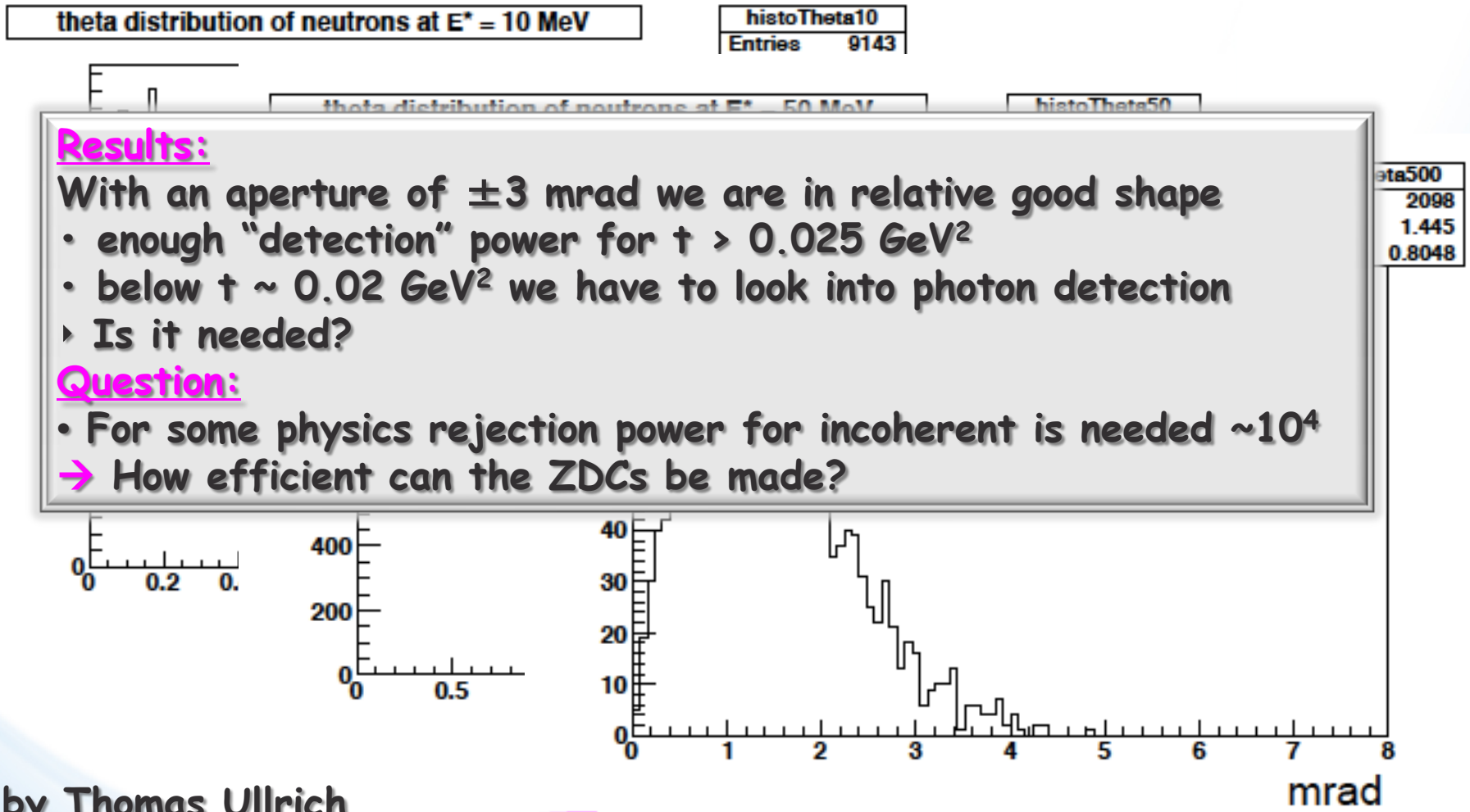


- 1/sqrt(N) error per (ϕ, $k_\perp$) bin, scaled for
  - 70% beam polarisation
  - 100 fb^{-1} integrated luminosity

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

KINEMATICS OF BREAKUP NEUTRONS

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 ~ 0.02 GeV^2 we have to look into photon detection
  - Is it needed?

Question:

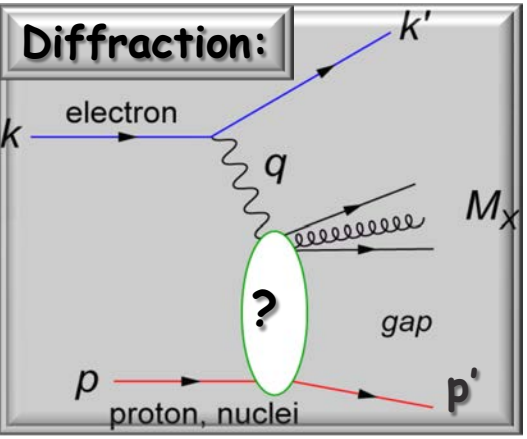
- For some physics rejection power for incoherent is needed ~10^4

→ How efficient can the ZDCs be made?

by Thomas Ullrich

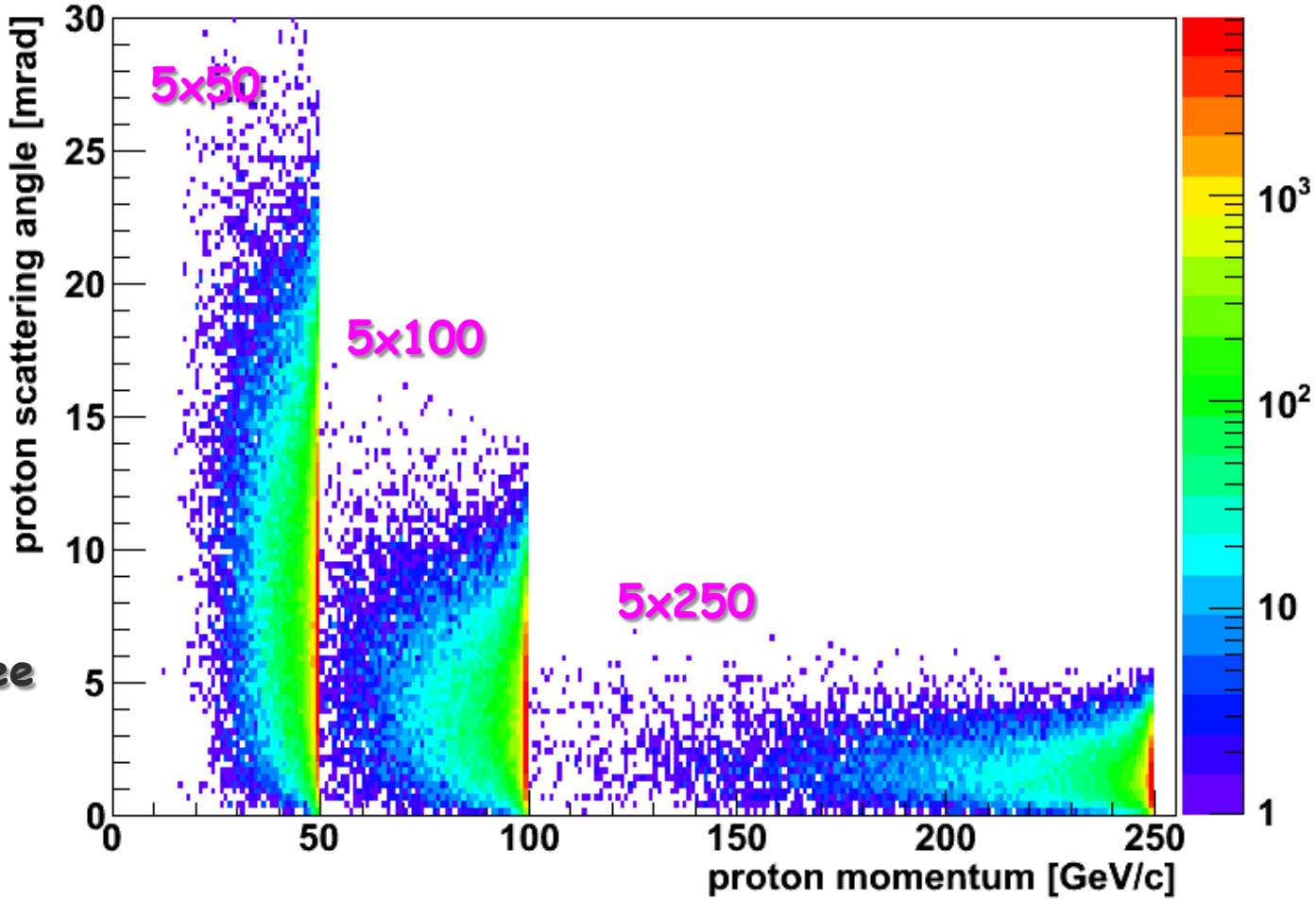
⇒ +/-5mrad acceptance seems sufficient

DIFFRACTIVE PHYSICS: P' KINEMATICS



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

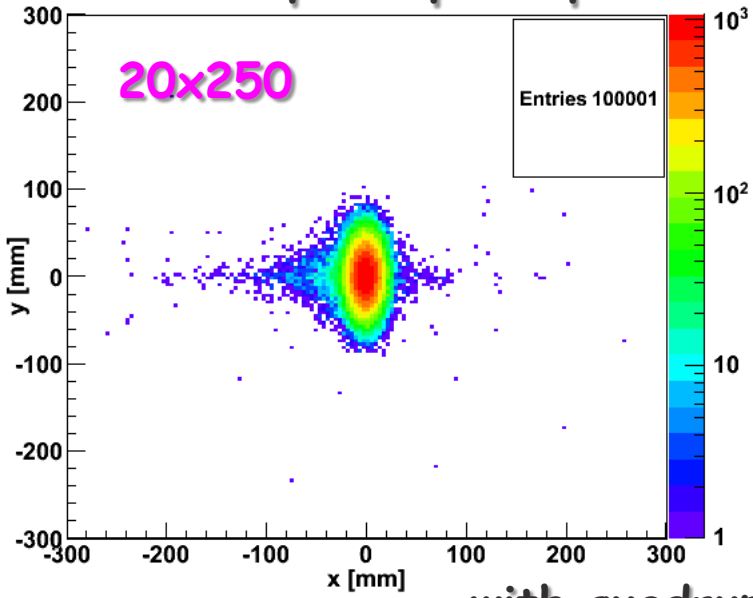
→ " Roman Pots" acceptance studies see later

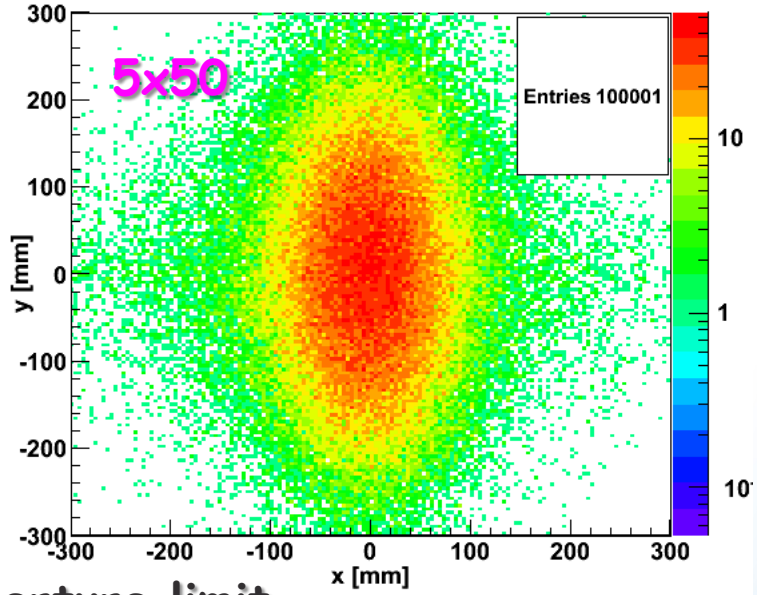


Simulations by J.H Lee

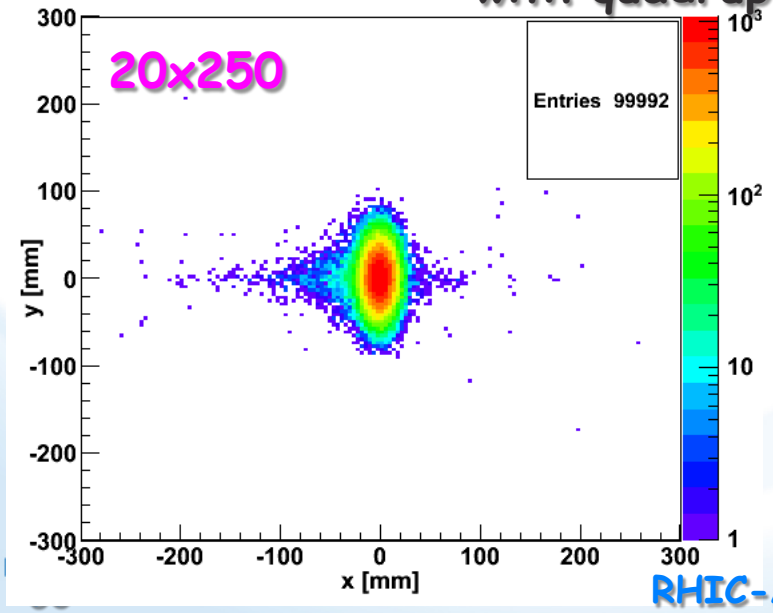
PROTON DISTRIBUTION IN Y VS X AT S=20 M

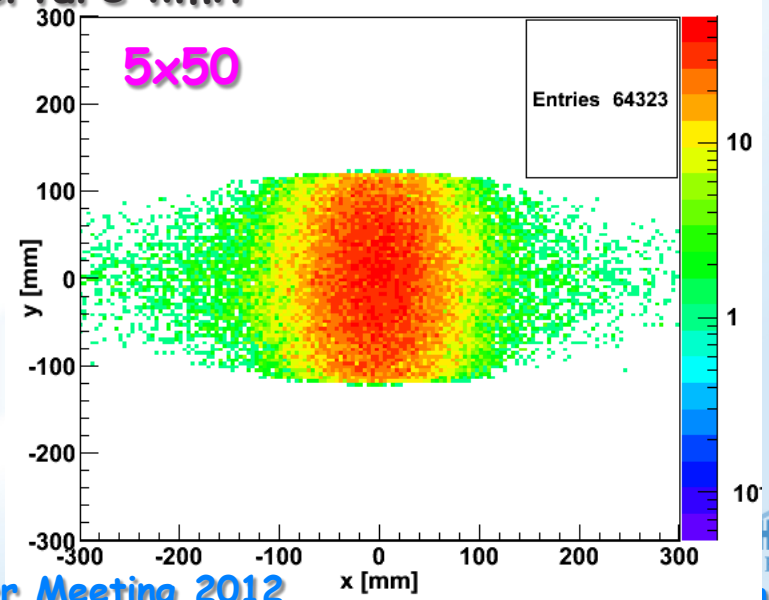
without quadrupole aperture limit



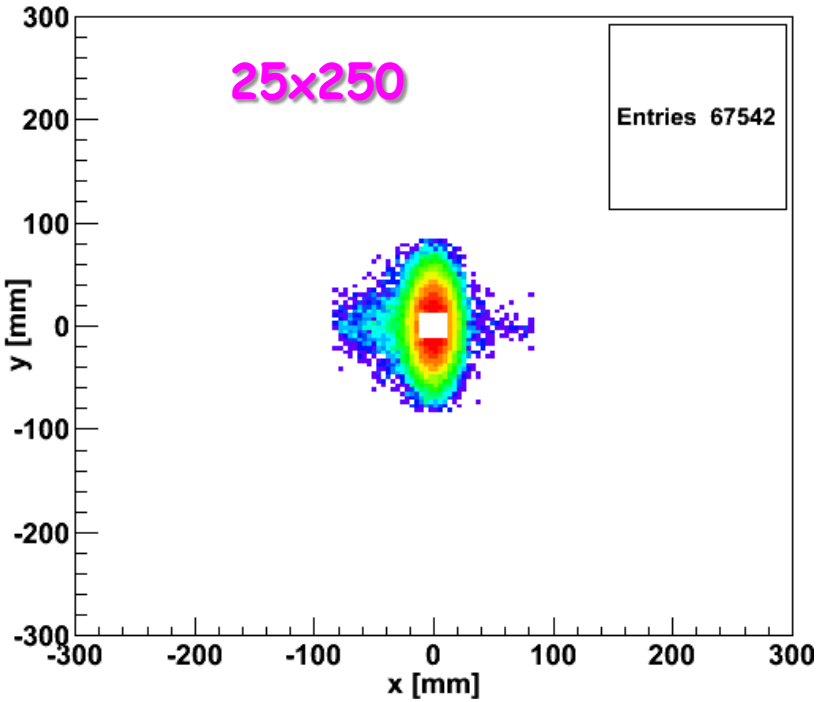


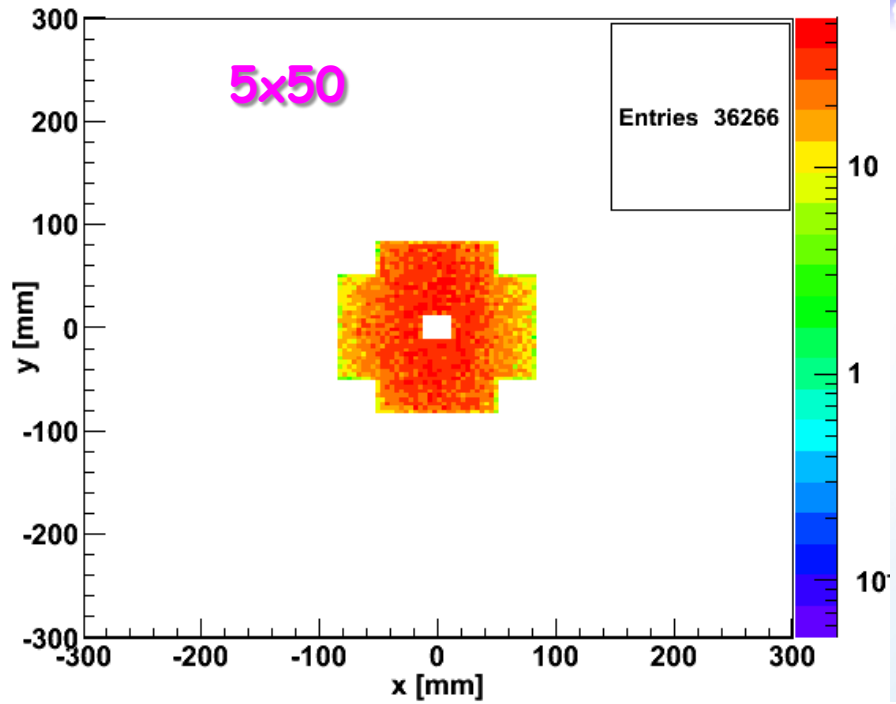
with quadrupole aperture limit

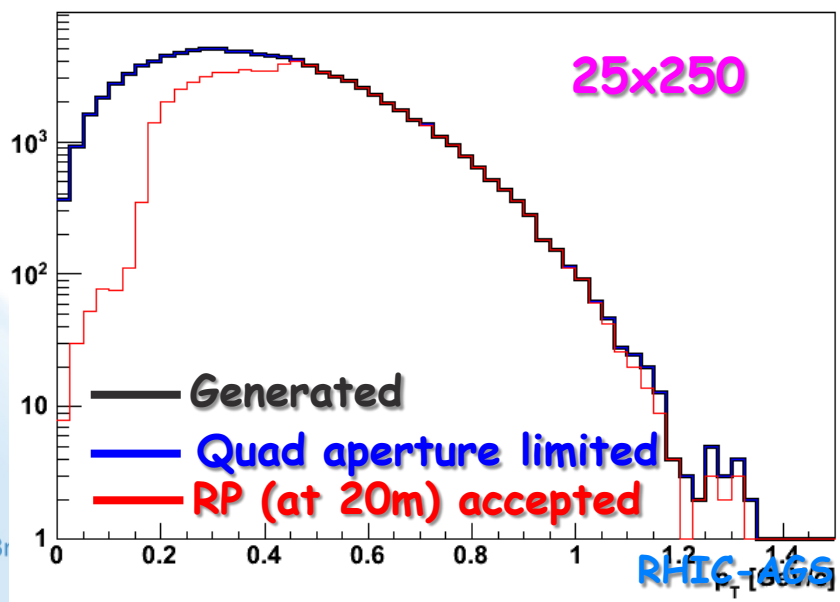


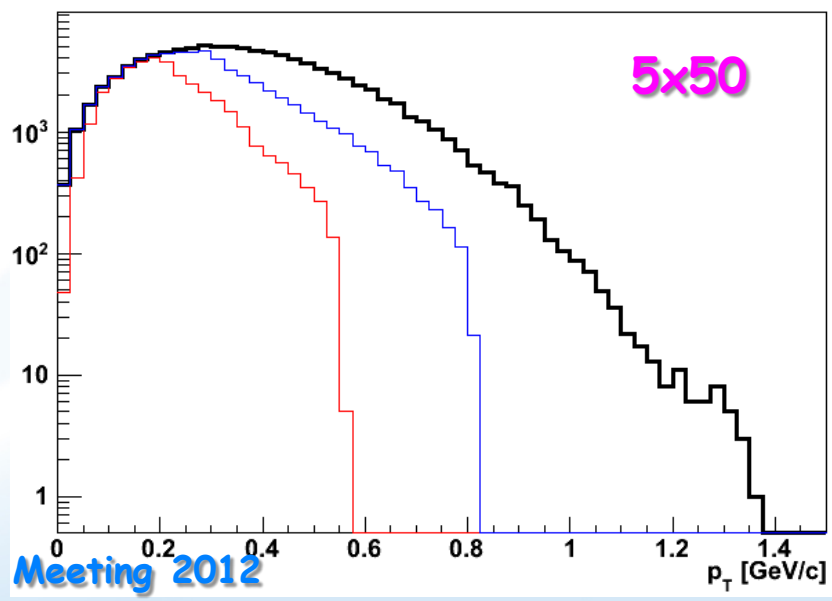


ACCEPTED IN "ROMAN POT" (EXAMPLE) AT S=20M

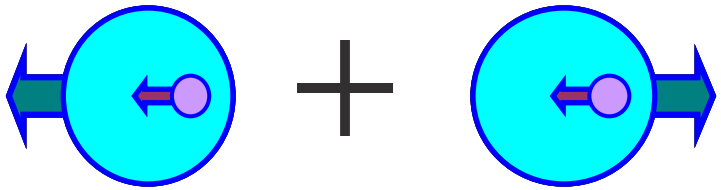








MORE INSIGHTS TO THE PROTON



Unpolarized distribution function q(x), G(x)

Transversity distribution function $\delta q(x)$

Correlation between $\vec{s}_\perp^{\,q}$ and $\vec{S}_\perp^{N}$

beyond collinear picture

Explore spin orbit correlations

Helicity distribution function $\Delta q(x)$, $\Delta G(x)$

Boer-Mulders distribution function $h_1^\perp$

Correlation between $\vec{s}_\perp^{\,q}$ and $\vec{k}_\perp^{\,q}$

Sivers distribution function $f_{1T}^\perp$

Correlation between $\vec{S}_\perp^{N}$ and $\vec{k}_\perp^{\,q}$

Single Spin Asymmetries

peculiarities of $f^\perp_{1T}$

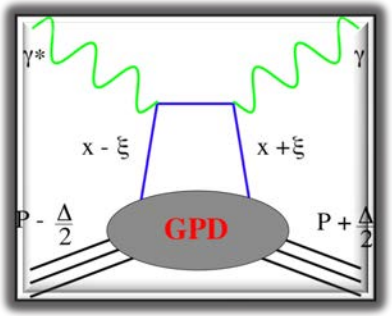
chiral even naïve T-odd DF
related to parton orbital angular momentum
violates naïve universality of PDFs
QCD-prediction: $f^\perp_{1T,DY} = -f^\perp_{1T,DIS}$

GPDS INTRODUCTION

How are GPDs characterized?

unpolarized	polarized	
$H^q(x,\xi,t)$	$\tilde{H}^q(x,\xi,t)$	conserve nucleon helicity $H^q(x,0,0)=q, \tilde{H}^q(x,0,0)=\Delta q$
$E^q(x,\xi,t)$	$\tilde{E}^q(x,\xi,t)$	flip nucleon helicity not accessible in DIS

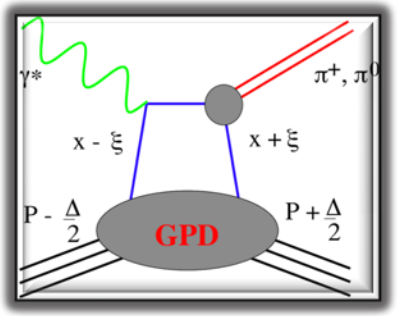
quantum numbers of final state ⟹ select different GPD



DVCS

$H^q \quad E^q \quad \tilde{H}^q \quad \tilde{E}^q$

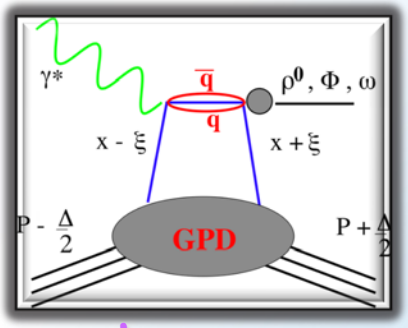
- x+ξ, x-ξ long. mom. fract.
- $t = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$



pseudo-scaler mesons

$\tilde{H}^q, \tilde{E}^q$

π^0	$2\Delta u+\Delta d$
η	$2\Delta u-\Delta d$

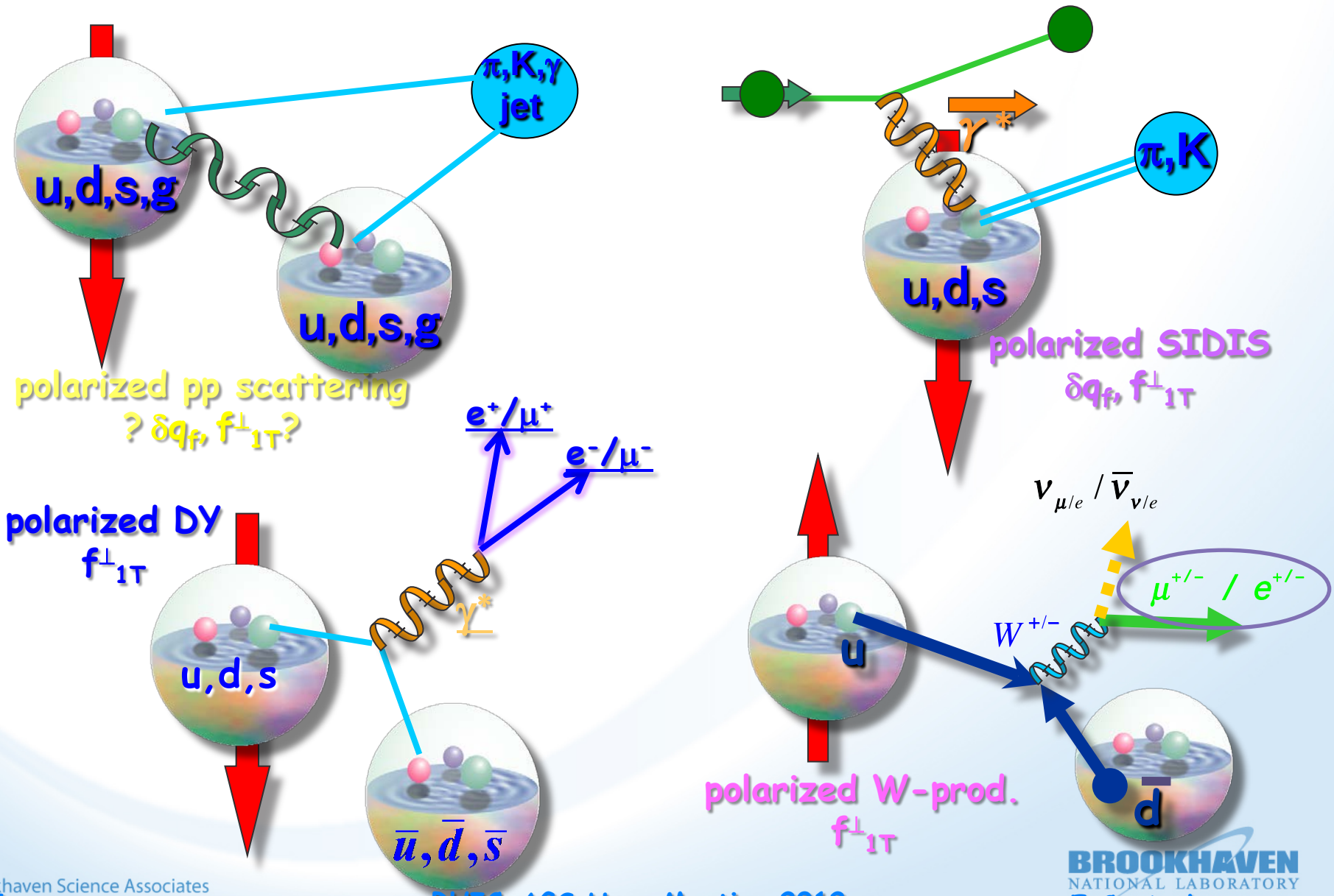


vector mesons

H^q, E^q

ρ^0	2u+d, 9g/4
ω	2u–d, 3g/4
ϕ	s, g
ρ^+	u–d
J/ψ	g

PROCESSES TO STUDY SINGLE SPIN ASYMMETRIES

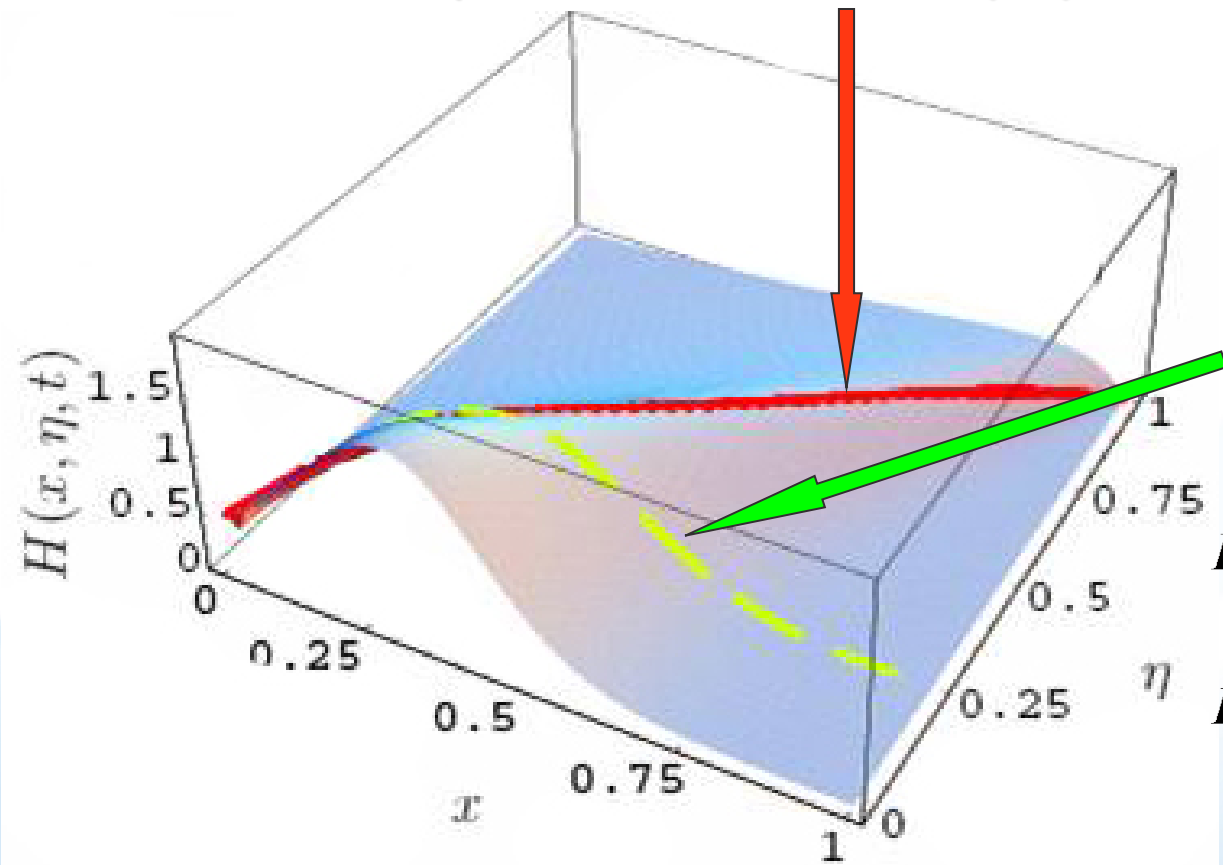


GPD MODELING AND EVOLUTION

outer region governs the evolution at the cross-over trajectory

$$\mu^2 \frac{d}{d\mu^2} H(x,x,t,\mu^2) = \int_x^1 \frac{dy}{x} V(1, x/y, \alpha_s(\mu)) H(x,y,\mu^2)$$

GPD at $\eta = x$ is `measurable' (LO)



net contribution of outer + central region is governed by a sum rule:

$$PV \int_0^1 dx \frac{2x}{\eta^2 - x^2} H^-(x,\eta,t) =$$

$$PV \int_0^1 dx \frac{2x}{\eta^2 - x^2} H^-(x,x,t) + C(t)$$

SUMMARY

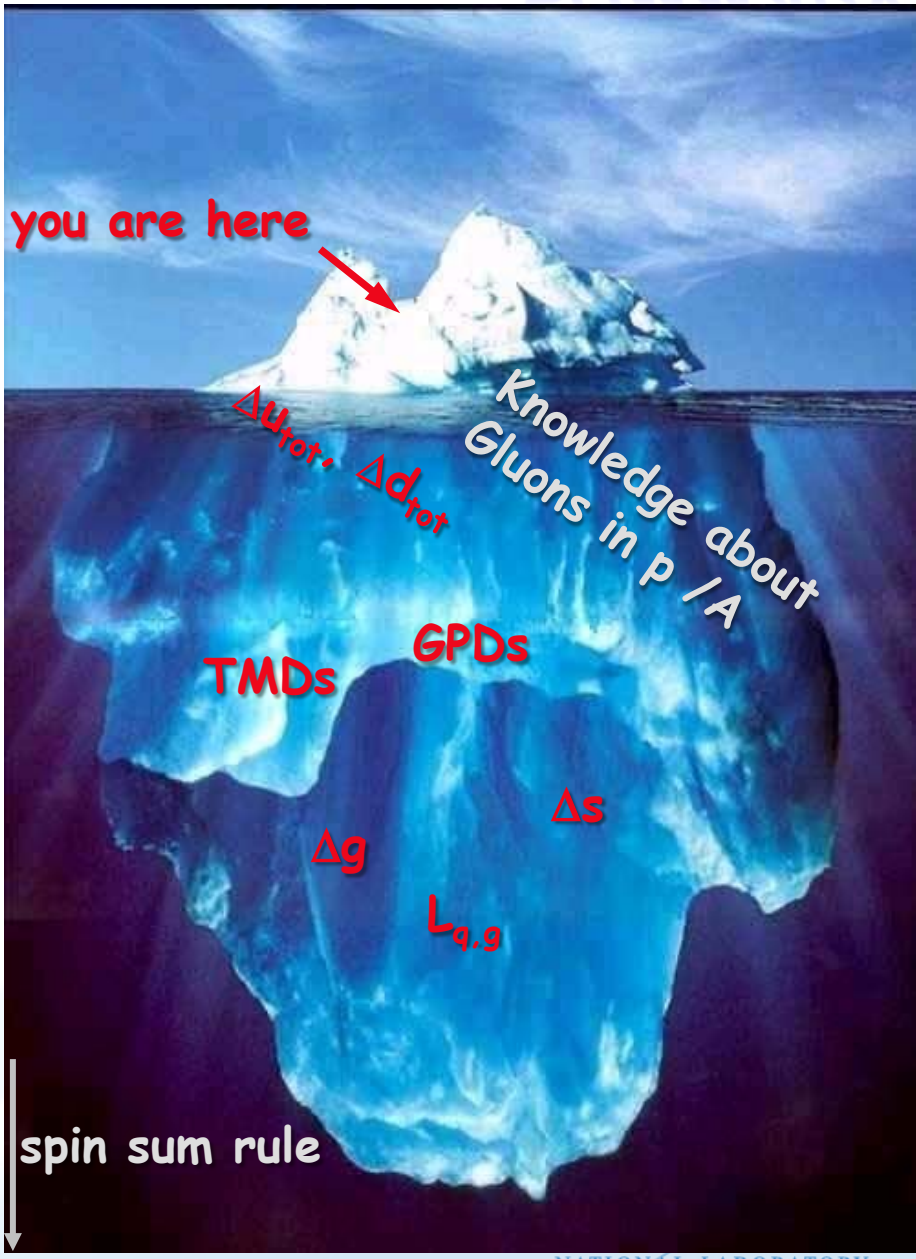
without EIC
we will just be able to
explored the
tip of the iceberg
to understand gluons
and sea quarks

EIC
will be a quantum step to
provide the answers to many
of our questions

⇒

why WE have mass
protons spin
"understand" non linear effects
initial conditions for AA

.....



Physics Case: http://arXiv.org/pdf/1108.1713