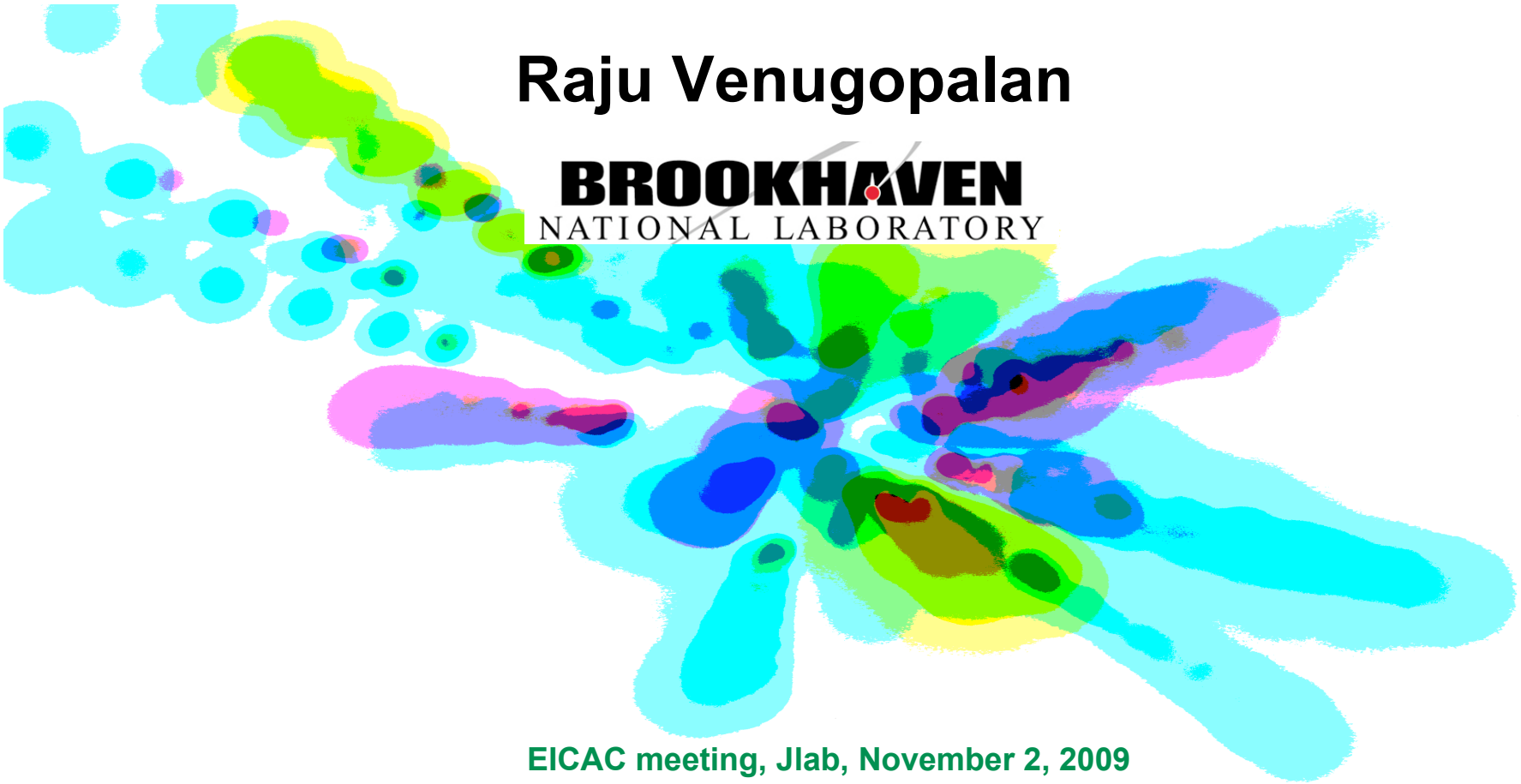
Summary of the Joint BNL/JLAB/INT workshop:

"Physics of a High Energy Electron Ion Collider"



Raju Venugopalan

BROOKHAVEN
NATIONAL LABORATORY

EICAC meeting, Jlab, November 2, 2009

INT workshop (Oct. 19 - 23, 2009)

- Organizers: D. Boer (Groningen)
  M. Diehl (DESY)
  R. Venugopalan (BNL)
  W. Vogelsang (Tubingen)

- Attendance: ~ 50 participants from US, Europe and Japan
  Strong participation from BNL and Jlab communities
  - including Hugh Montgomery and Steve Vigdor

- Excellent talks on the wide range of physics topics relevant to an EIC

- Several discussion sessions on physics / staging options / "golden measurements"

- Nice "warm up" to the INT 10 week long program next year: Sept. 14 - Nov. 19, 2010. Organizers as above + Richard Milner (MIT)

Thanks to David Kaplan and INT Staff !!

Physics Agenda of Talks-I

Talks online at: http://www.int.washington.edu/talks/WorkShops/int_09_43W/

- ✓ **QCD overview:** Sterman
- ✓ **Overview of physics measurements:** Aschenauer, Horn
- ✓ **Accelerator issues:** Bogacz (Jlab), Ptitsyn (BNL)
- ✓ **Detector Issues:** Lamont
- ✓ **EIC in context of current and planned facilities:** Weiss (Jlab 12 GeV), Ullrich (RHIC+LHC Heavy Ions), Sichtermann (RHIC spin), Gradl (ENC@FAIR), Cole (LHeC)
- ✓ **Parton Distribution Functions (pdfs):** Blumlein, Kumano, Pisano, Stratmann
- ✓ **Leading Twist vs Higher Twist effects:** Qiu, Strikman

Physics Agenda of Talks-II

- ✓ **Semi-inclusive final states: Accardi, Kopeliovich, Qiu, Yuan**
- ✓ **Diffractive and Exclusive final states: Degli Atti, Kowalski, Lappi, Marquet, Tuchin**
- ✓ **Generalized Parton Distributions: Burkardt, Guzey, D. Muller**
- ✓ **Hadronization, Fragmentation, Energy Loss: Accardi, Brooks, Stratmann, Wang**
- ✓ **Transverse Momentum Dependent Distributions (TMDs): Chen, Gamberg, Metz, Yuan**
- ✓ **Electroweak Physics: Kumar, Marciano, Ramsey-Musolf**
- ✓ **Factorization, Universality, low x Theory: Bartels, Gelis, Kopeliovich, Kovchegov, Sterman**

Physics Agenda of Talks-III

Discussion Sessions:

Staged EIC-prospects and physics goals
(Discussion Leaders: Montgomery/Vigdor)

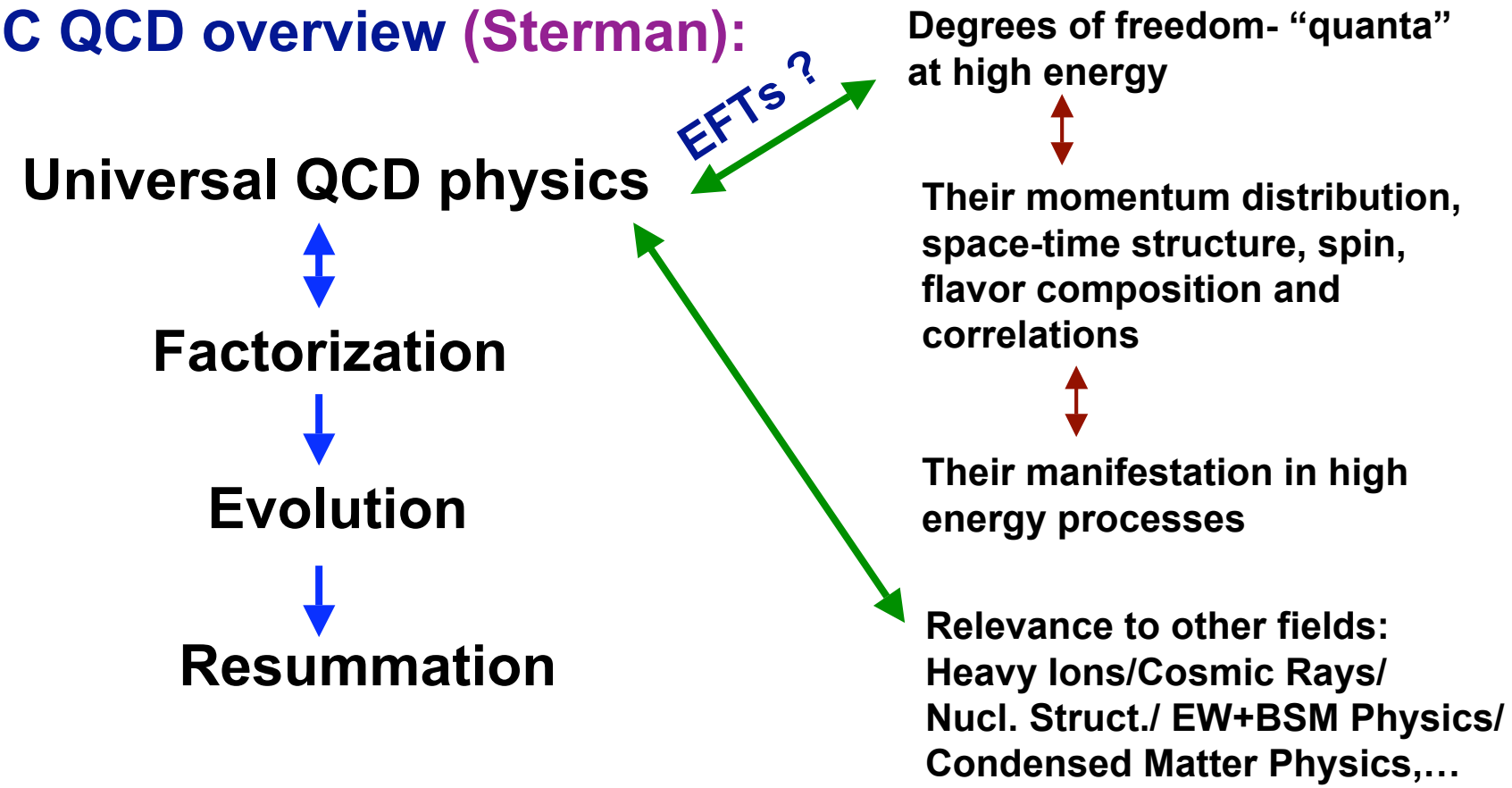
EIC Science Goals and Measurements
(Discussion Leader: Rolf Ent)

Generalized Parton Distributions
(Discussion Leader: Markus Diehl)

Summary Discussion and Future Organization:

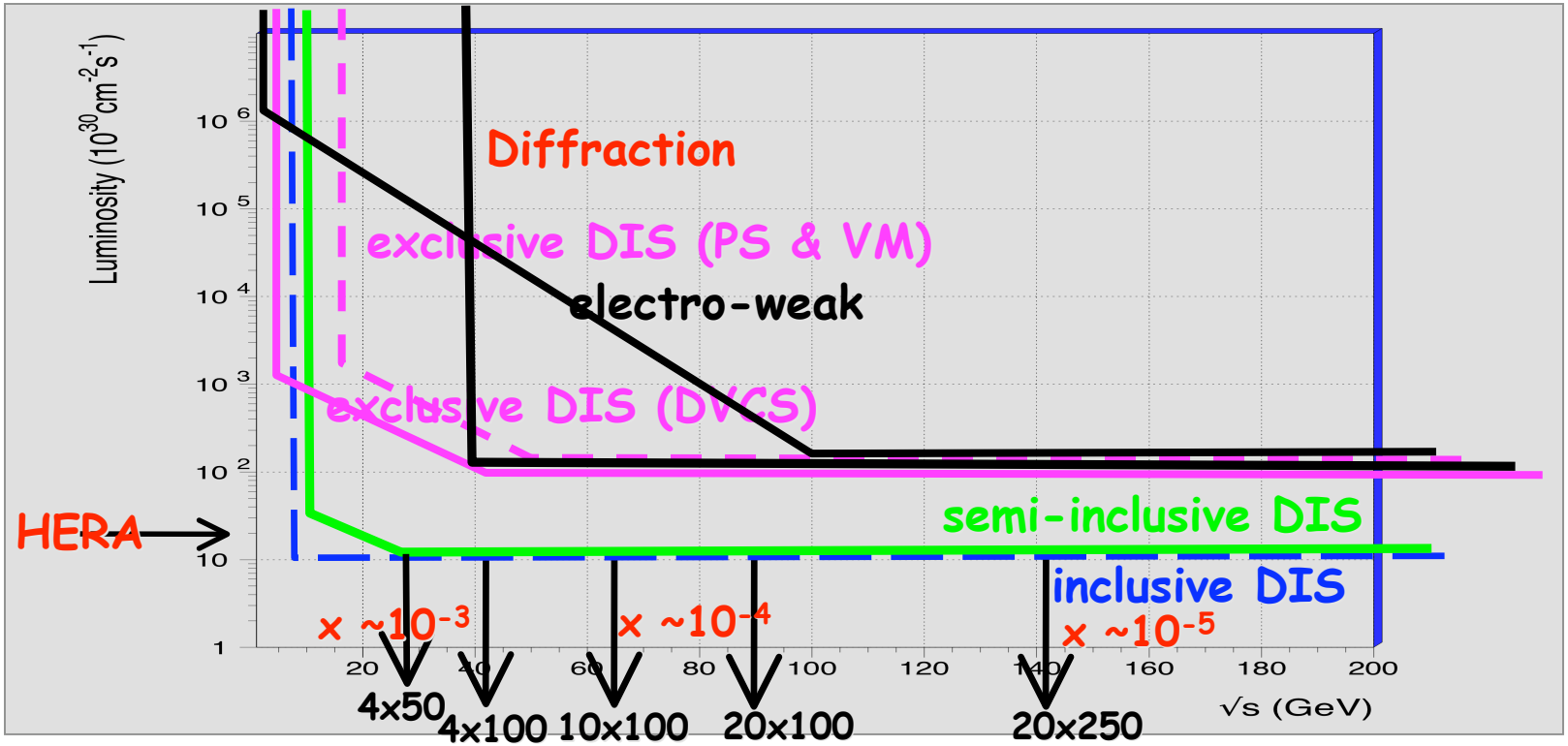
(Discussion Leader: Deshpande)

EIC QCD overview (Sterman):



- Detailed questions about origins of "bright matter" in the universe require high luminosity.
- Extracting universal physics reliably requires high energy, multiple facilities,…

Physics measurements: (Aschenauer,Horn)



- Both collider options can study "low" energies. Me.eRHIC can access higher energies as well. Many first measurements!
- Me.ELIC push for high luminosity ~ 10^{34}.
- Exclusive processes need high luminosity. But reliable extraction (read: factorization+ evolution) of relevant physics requires wide kinematic reach as well; detailed simulations underway

Pdfs: (Blumlein,Stratmann,Kumano,Pisano)

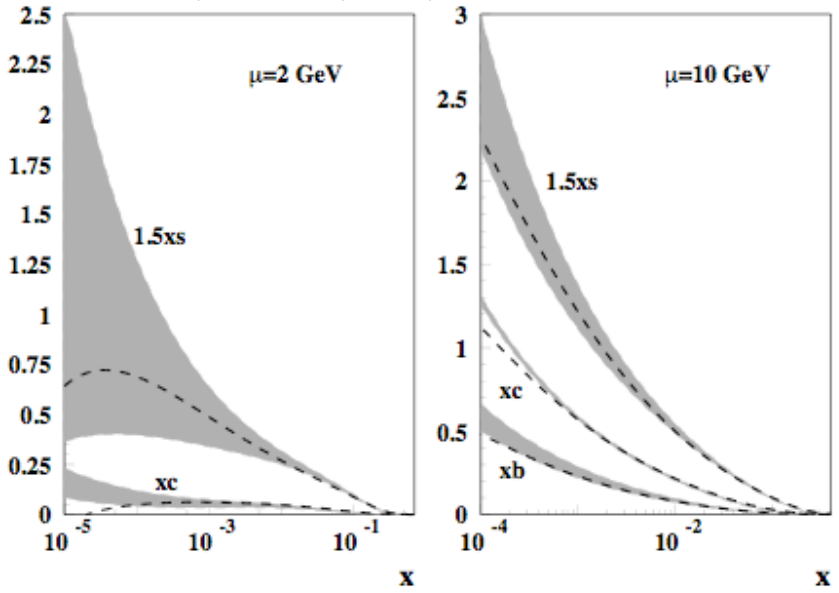
Status of Highest Order Calculations

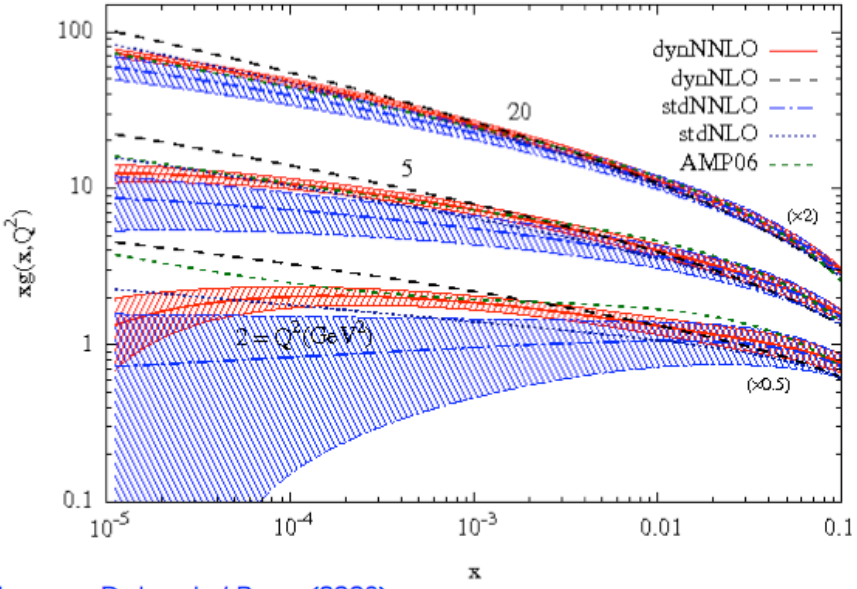
- Running α_s: $O(\alpha_s^4)$ Larin, van Ritbergen, Vermaseren 1997
- Unpol. anomalous dimensions and Wilson coefficients: $O(\alpha_s^3)$ **Blumlein**
  Moch, Vermaseren, Vogt 2004/05
- Unpol. NS anomalous dimension 2nd Moment: $O(\alpha_s^4)$ Baikov, Chetyrkin 2006
- Pol. anomalous dimension: $O(\alpha_s^2)$; Mertig, van Neerven, 1995; Vogelsang 1995;
  $\Delta P^{qq} \Delta P_{qG}$: $O(\alpha_s^3)$ Moch, Rogal, Vermaseren, Vogt 2008
- Pol. Wilson coefficients: $O(\alpha_s^2)$; $\Delta C_{NS}^{qq}, \Delta C_{qG}$: van Neerven, Zijlstra 1994
- Transversity: $O(\alpha_s^2)$, some moments anom. dim.: $O(\alpha_s^3)$, Hayashigaki, Kanazawa, Koike;
  Kumano, Miyama; Vogelsang; 1997; Gracey 2006, HQ: JB, S.Klein, B. Tödtli 2008
- Unpol. Heavy Flavor Wilson Coefficients: $O(\alpha_s^2)$ Laenen, van Neerven, Riemersma, Smith, 1993
  Fast Mellin Space code: Blümlein & Alekhin, 2003
- Pol. Heavy Flavor Wilson Coefficients: $O(\alpha_s^1)$ Watson 1982
- $Q^2 \gg m^2$ Unpol. Heavy Flavor Wilson Coefficient F_L: $O(\alpha_s^3)$
  Blümlein, De Freitas, van Neerven, S. Klein 2005
- $Q^2 \gg m^2$ Pol. Heavy Flavor Wilson Coefficient : $O(\alpha_s^2)$ van Neerven, Smith et al. 1996,
  Bierenbaum, Blümlein & Klein 2007
- $Q^2 \gg m^2$ Unpol. Heavy Flavor Wilson Coefficient F_2: $O(\alpha_s^2 \varepsilon)$: all operators
  (also polarized), Bierenbaum, Blümlein, Klein, Schneider, 2008; $O(\alpha_s^3)$: Moments 2–10(12,14)
  of the operator matrix elements, HQ Wilson coeff. Bierenbaum, Blümlein, Klein, 2008

= done at DESY (or in DESY collab.).

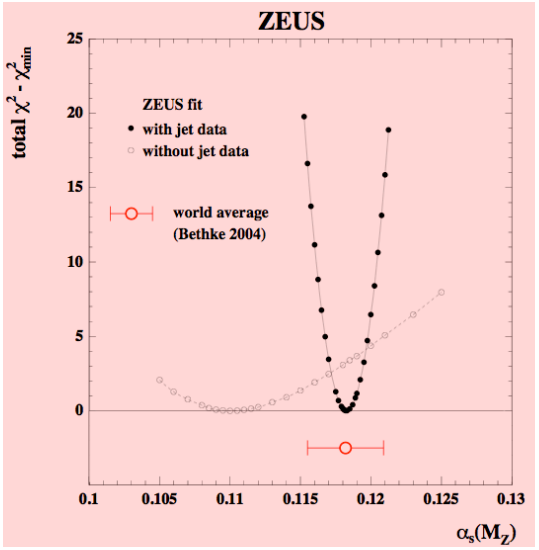
Heavy quarks and glue in the proton (NNLO)

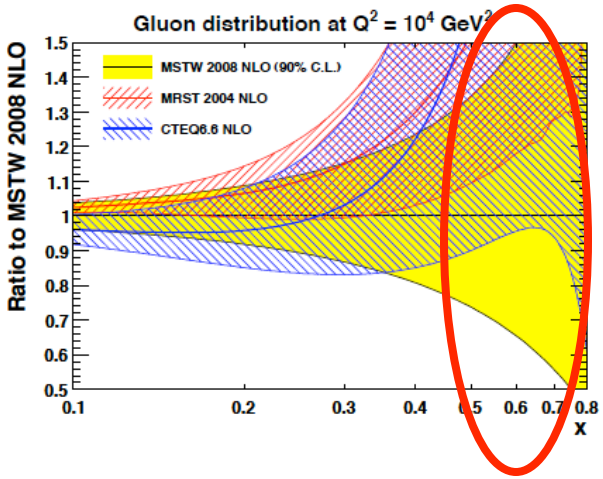
Alekhin,Blumlein,Klein,Moch

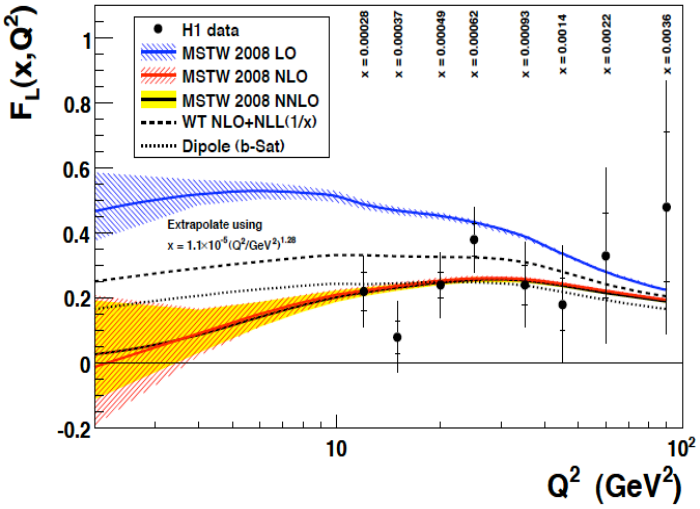




Jimenez-Delgado/ Reya (2008)





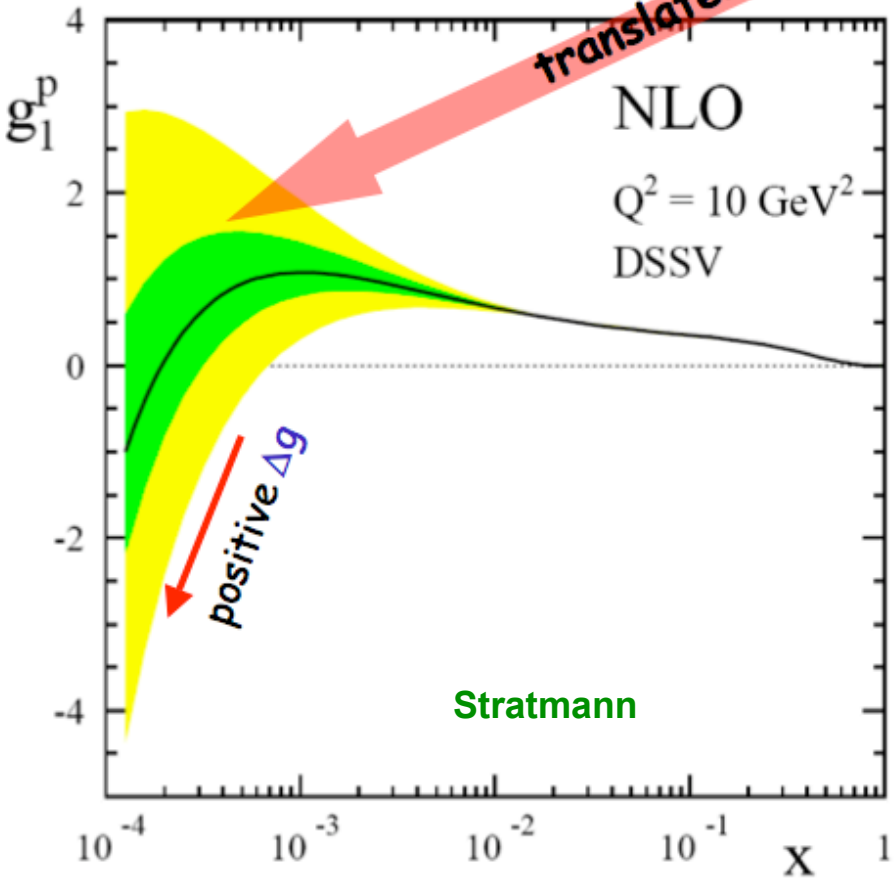


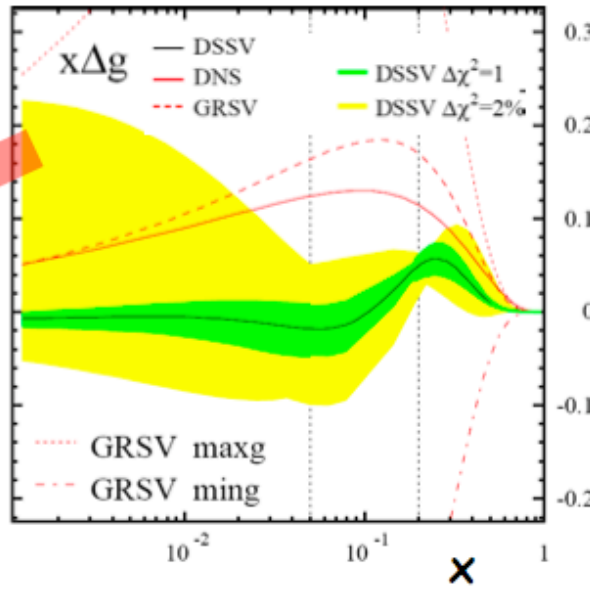
Proton Helicity Distributions

- small x uncertainty from **DSSV**

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

translates into





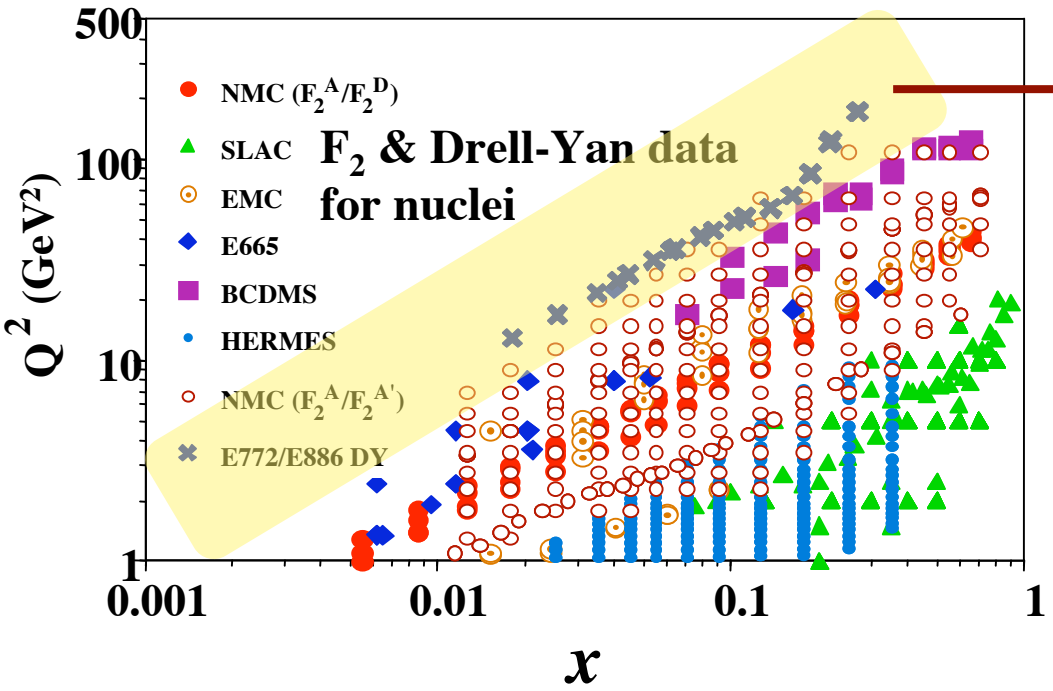
QCD theory progress:
NNLO kernels on the horizon
Vogt, Moch, Rogal, Vermaseren

important exercise to be done:
global QCD fit with projected EIC data to quantify their impact

studies already under way

- **Photon content of nucleon and its evolution (Pisano)**

Nuclear pdfs (Kumano)

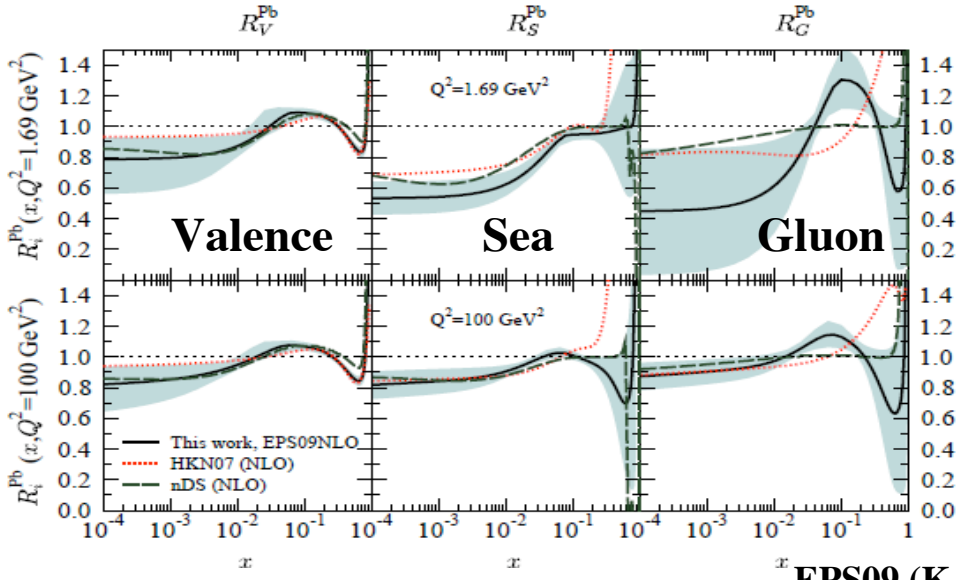


Stage-I EIC coverage

First measurements of gluon distribution In nuclei

$Q^2 = 1.69$ GeV^2

$Q^2 = 100$ GeV^2



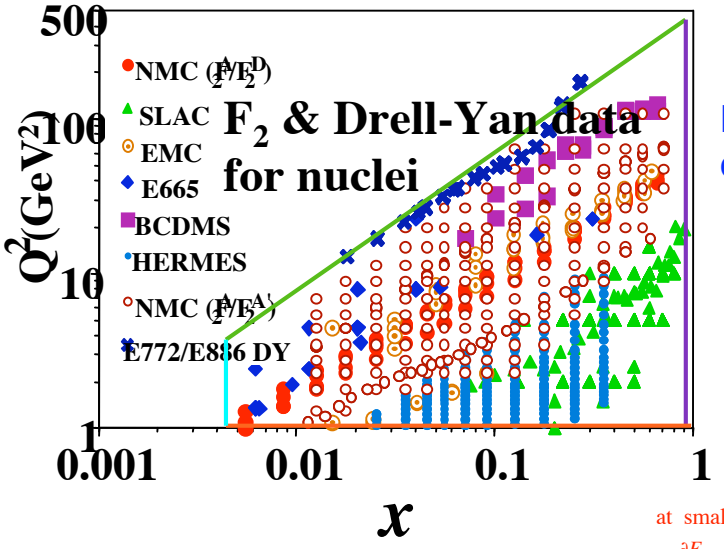
EPS09

HKN07

DS04

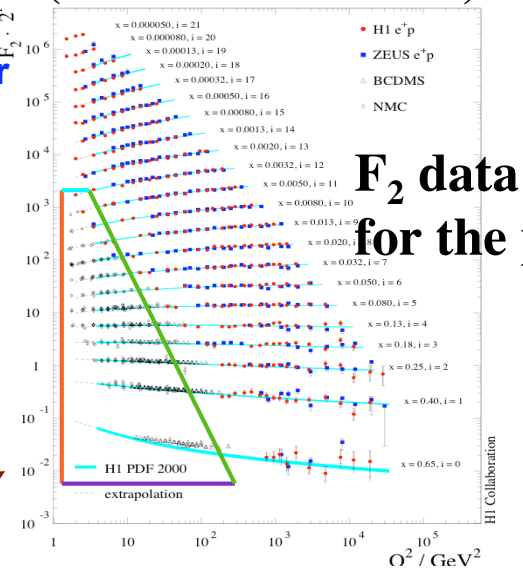
EPS09 (K. J. Eskola *et al.*), JHEP 04 (2009) 065

Leading Twist / Higher Twist (Kumano,Strikman,Qiu)



No window for evolution!

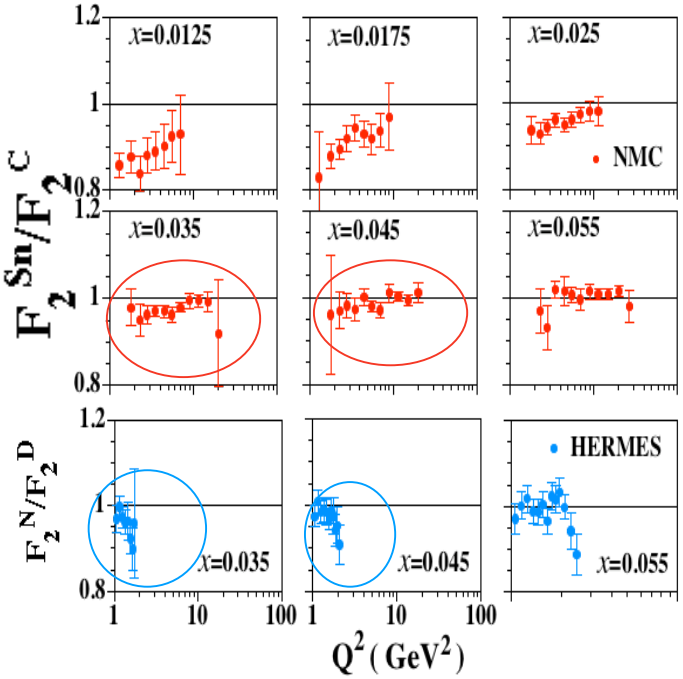
(from H1 and ZEUS, hep-ex/0502008)

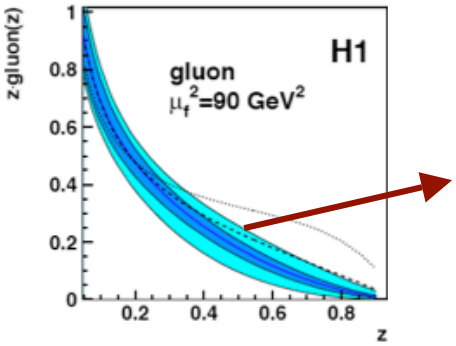


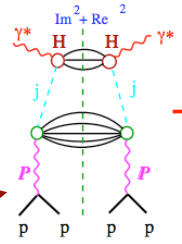
F_2 data for the proton

at small x

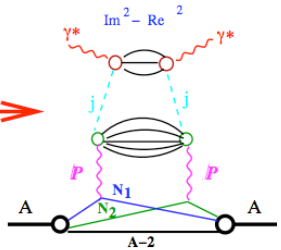
$$\frac{\partial F_2}{\partial(\ln Q^2)} \approx \frac{20\,\alpha_s}{27\pi} xg$$







Hard diffraction off parton "j"



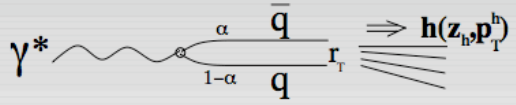
Leading twist contribution to the nuclear shadowing for structure function $f_j(x,Q^2)$

Strikman: diff. pdfs from HERA can constrain LT shadowing in nuclei-search for HT effects

Qiu: particular class of HT effects
-window of applicability small compared to "dipole" approach

Semi-inclusive final states (Kopeliovich,Yuan)

Experimentally known is $z_h = \frac{p_h^+}{q_{\gamma^*}^+}$

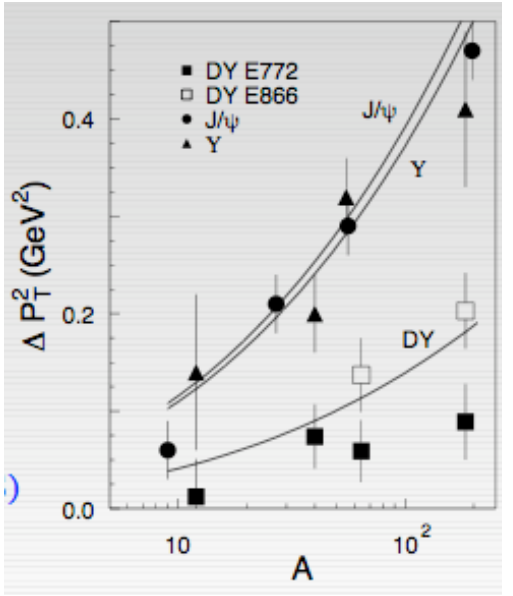


$$\Delta(p_T^h)^2 = \frac{z_h^2 \Delta p_T^2}{\int d^2r_T \int_0^1 d\alpha |\Psi_{\gamma^*}(r_T,\alpha)|^2 \sigma_{dip}(r_T,x)}$$

$$\times \int d^2r_T \left\{ \int_{z_h}^{1} \frac{d\alpha}{\alpha^2} |\Psi_{\gamma^*}(r_T,\alpha,Q^2)|^2 \sigma_{dip}(r_T,x) D_{h/q}\left(\frac{z_h}{\alpha},Q^2\right) \right.$$

$$\left. + \int_0^{1-z_h} \frac{d\alpha}{(1-\alpha)^2} |\Psi_{\gamma^*}(r_T,\alpha,Q^2)|^2 \sigma_{dip}(r_T,x) D_{h/q}\left(\frac{z_h}{1-\alpha},Q^2\right) \right\}$$

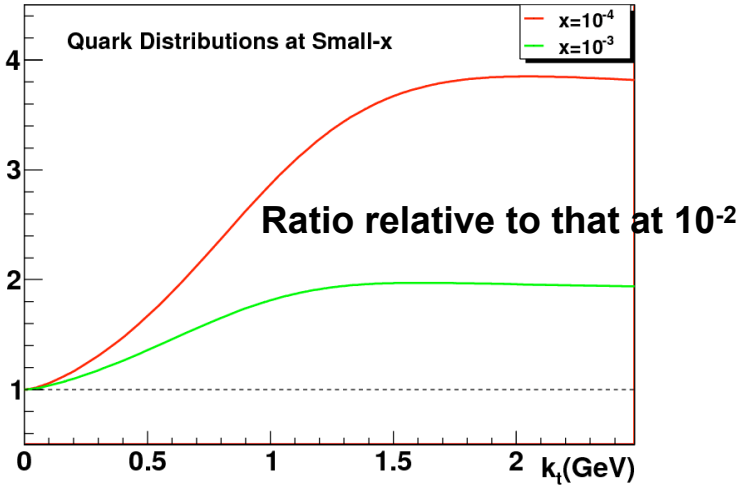
Ψ_{γ^*} is known from pQCD; σ_{dip}, $D_{h/q}$ from phenomenology.



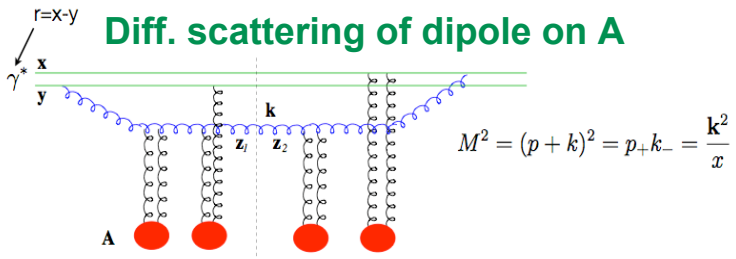
Extract saturation scale from pT broadening in SIDIS in dipole picture (Kopeliovich)

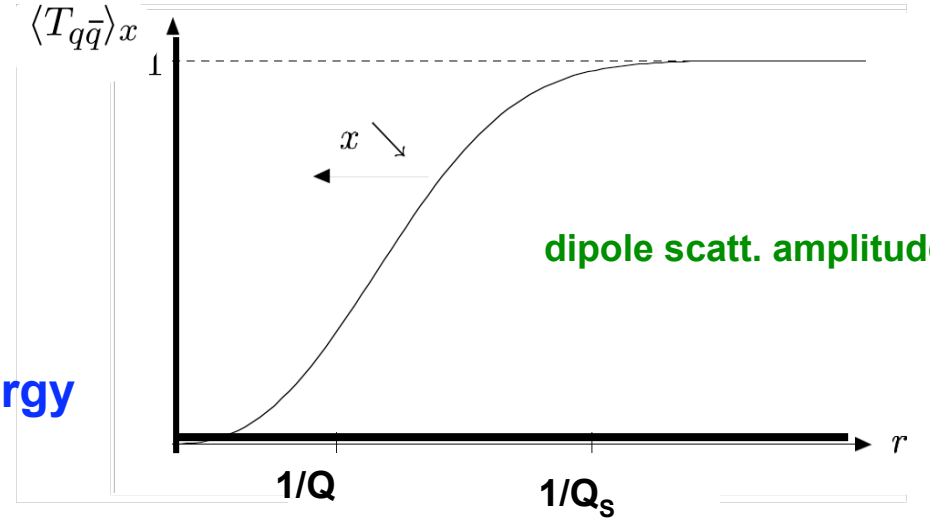
SIDIS in TMD approach (Yuan)

At small x,
identical to dipole approach
-sensitive to saturation effects…



Coherent+Incoherent Diffraction (Strikman,Lappi,Marquet, Tuchin)



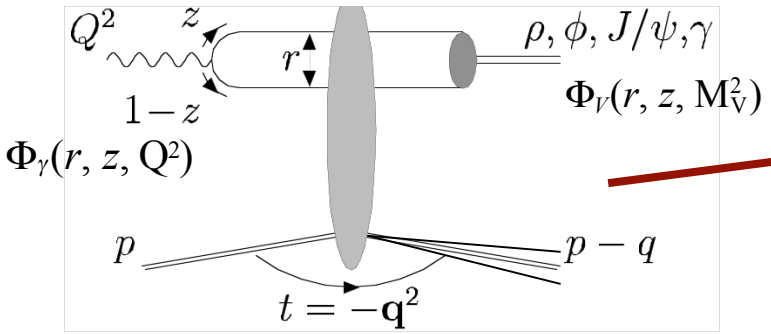


- diffraction directly sensitive to HT / saturation with increasing energy

σ_{DIS} dominated by relatively hard sizes $1/Q < r < 1/Q_S$

σ_{DDIS} dominated by semi-hard sizes $r \sim 1/Q_S$

- Ratio: Incoherent / Coherent = sensitive to color fluctuations → 0 (s→∞, A >>1)



Marquet: Detailed studies of exclusive VM production sensitive to QCD evolution of multi-parton correlations

(Bartels,Gelis,Kovchegov)

Coherent vs. incoherent in practice

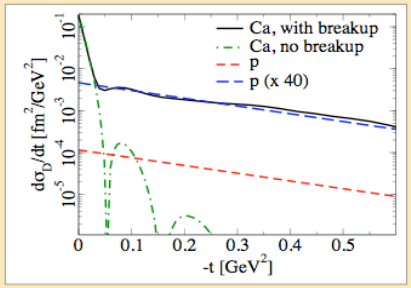
Coherent: $\langle \sigma_{\rm dip}(\boldsymbol{\Delta}_T)\rangle_N$ smooth
▶ FT at small scale $-t \sim 1/R_A^2$
radially symmetric in $\mathbf{b}_T$

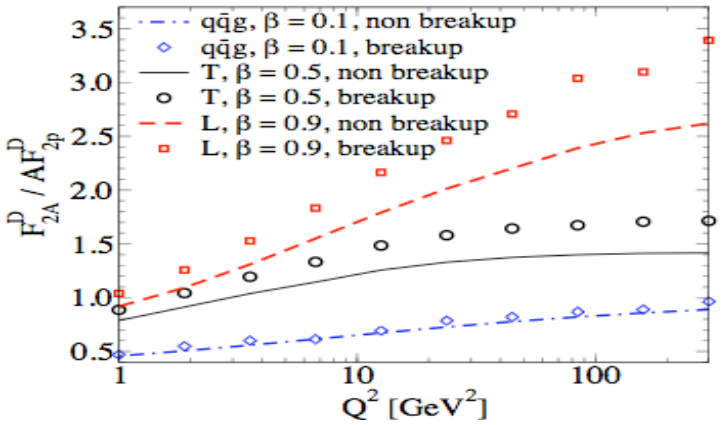
Incoherent: FT $\sigma_{\rm dip}(\boldsymbol{\Delta}_T)$ **before** $\langle\cdot\rangle_N$
▶ lumpy, larger $-t \sim 1/R_p^2$

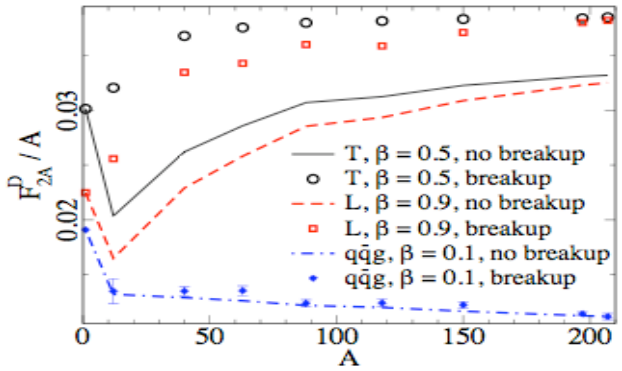
$(t = -\boldsymbol{\Delta}_T{}^2)$

Result: t-distributions

Really 2d integral in $\mathbf{b}_T$

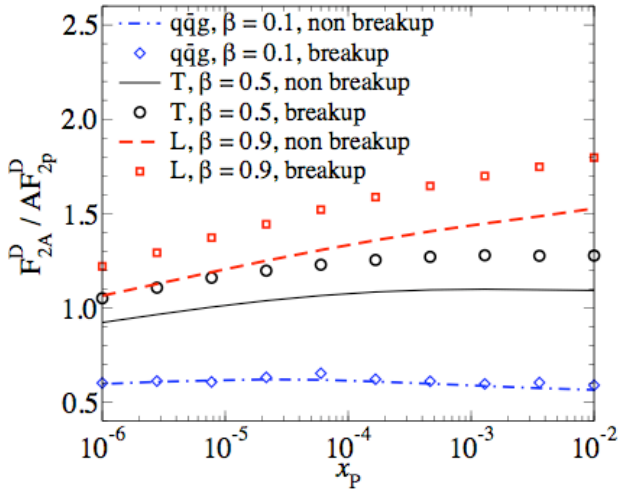


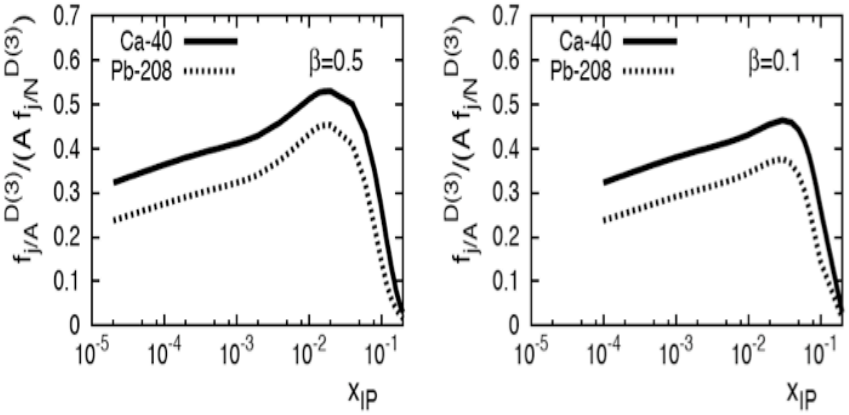




Lappi: striking pattern of enhancement/ suppression of diff. structure fns.

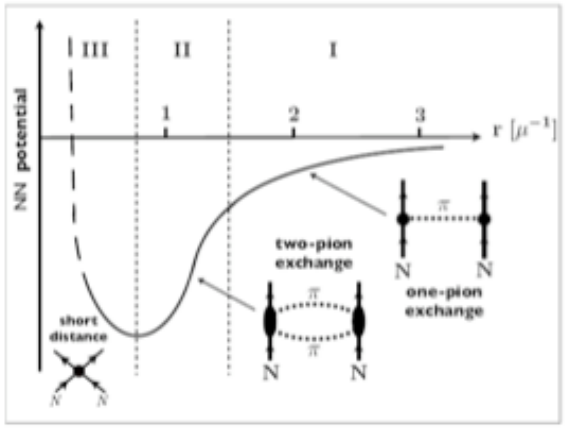
Breakup= Coherent+Incoherent
Non-Breakup= Incoherent

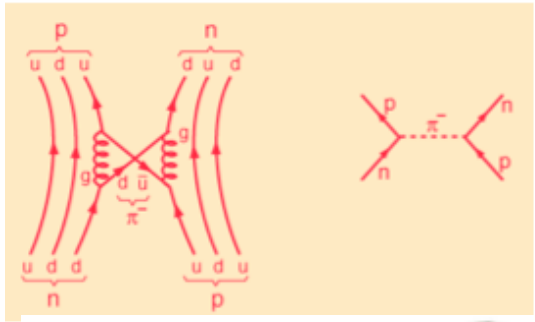


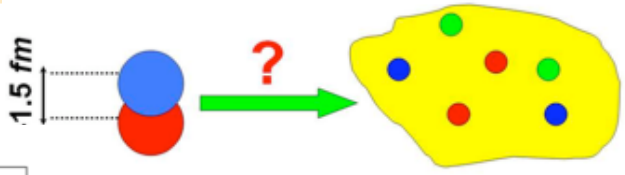


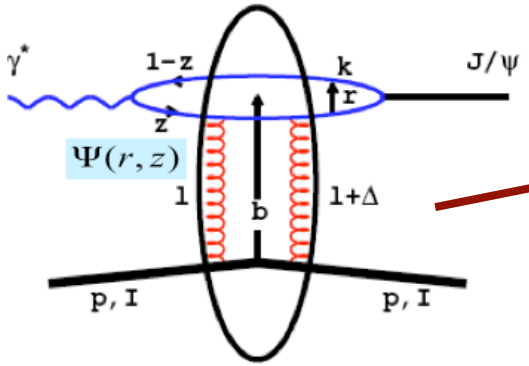
Strikman:LT prediction- however initial conditions are “dipole like”

Probing partonic structure of short range nuclear Forces (Kowalski,Degli Atti)









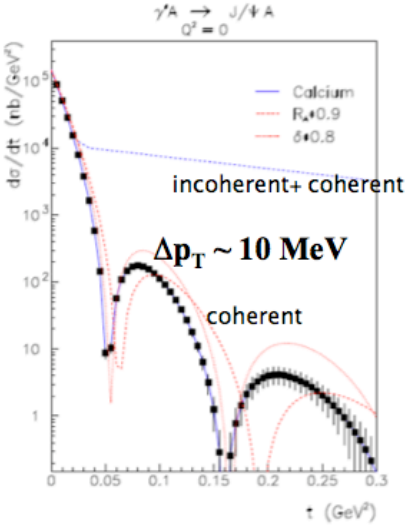


Photo-production off J/ψ sensitive to parton correlations at small t

Caldwell-Kowalski

$$\sum_{n\neq 0}\frac{d\sigma^{q\bar{q}}_{A_0\to A_n}}{dt}=\frac{\sigma_p^2}{16\pi}e^{-B_p\Delta^2}\int d^2\vec{b}_1 d^2\vec{b}_2\left\{A\left(T_A(b_1)T_A(b_2)-T_A^{(2)}(\vec{b}_1,\vec{b}_2)e^{-i(\vec{b}_1-\vec{b}_2)\cdot\vec{\Delta}}\right)\right.$$
$$\left.+\;A^2\left(T_A^{(2)}(\vec{b}_1,\vec{b}_2)-T_A(b_1)T_A(b_2)\right)e^{-i(\vec{b}_1-\vec{b}_2)\cdot\vec{\Delta}}\right\}$$

Generalized Parton Distributions (Muller,Burkardt,Guzey)

Generalized parton distributions and elastic scattering. Difficult, but important opportunities given the how fundamental these are. Sterman

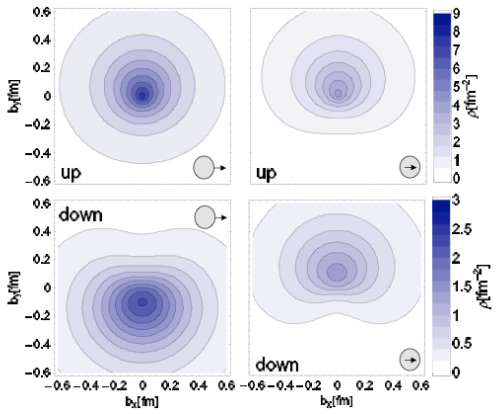
$$\int \frac{dx^-}{2\pi} e^{ix^-\bar{p}^+x} \left\langle p' \left| \bar{q}\left(-\frac{x^-}{2}\right)\gamma^+ q\left(\frac{x^-}{2}\right)\right| p\right\rangle = H(x,\xi,\Delta^2)\bar{u}(p')\gamma^+u(p) + E(x,\xi,\Delta^2)\bar{u}(p')\frac{i\sigma^{+\nu}\Delta_\nu}{2M}u(p)$$

Impact parameter dependent dists.

$$q(x,\mathbf{b}_\perp) = \int \frac{d^2\boldsymbol{\Delta}_\perp}{(2\pi)^2} e^{i\boldsymbol{\Delta}_\perp\cdot\mathbf{b}_\perp} H(x,0,-\boldsymbol{\Delta}_\perp^2)$$

$$\Delta q(x,\mathbf{b}_\perp) = \int \frac{d^2\boldsymbol{\Delta}_\perp}{(2\pi)^2} e^{i\boldsymbol{\Delta}_\perp\cdot\mathbf{b}_\perp} \tilde{H}(x,0,-\boldsymbol{\Delta}_\perp^2)$$

- lowest moment of distribution $q(x,\mathbf{b}_\perp)$ for unpol. quarks in $\perp$ pol. proton (left) and of $\perp$ pol. quarks in unpol. proton (right):



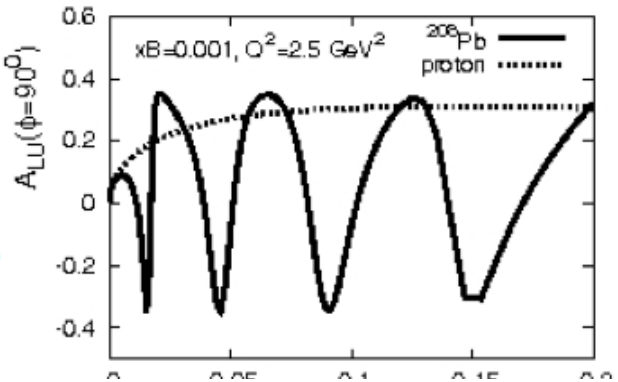
Hagler et al

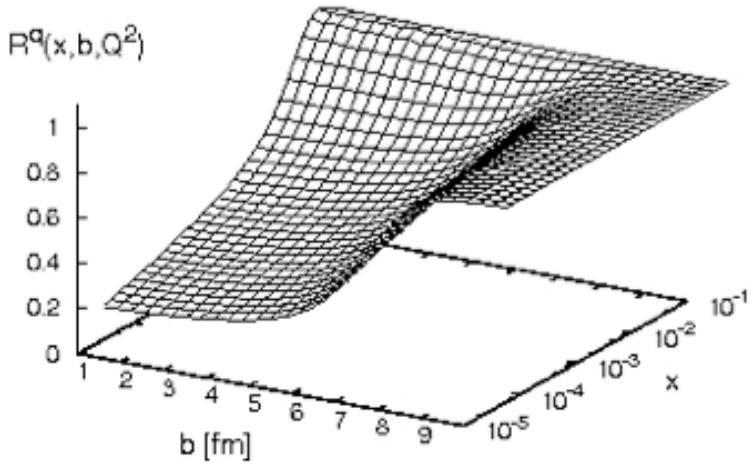
Impact parameter dists. in $\perp$ pol. nucleon deformed compared to long. pol. nucleon

$E(x,0,-\Delta_\perp^2)$ **measure of deformation**

Nuclear GPDs (Guzey)

$$R^q(x,b) = \frac{H_A^q(x,\xi=0,b)}{AT_A(b)H_N^q(x,\xi=0,b)}$$



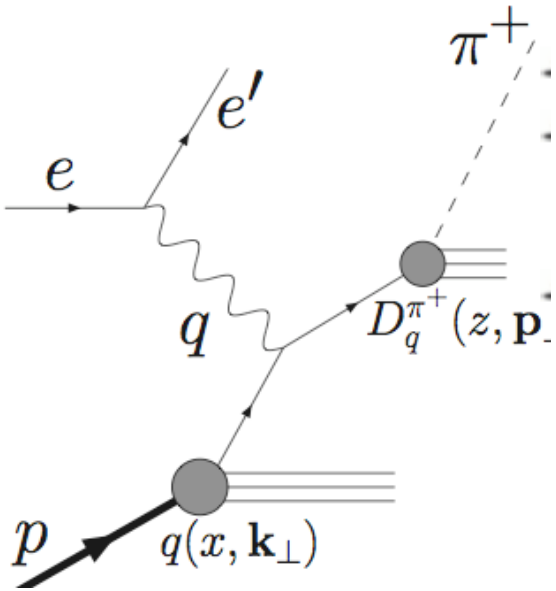


- The beam-spin DVCS asymmetry

The reason for the oscillations is shadowing, position of nodes measures the strength of shadowing

Discussion: How does one go beyond models? EFT ?
What is the predictive power-can information from GPDs provide insight into hadronic scattering?

Transverse Momentum Dependent Distributions (TMDs)
(Burkardt,Chen,Metz,Gamberg,Yuan)



Sivers effect

$$f_{q/p^\uparrow}(x, \mathbf{k}_\perp) = f_1^q(x, \mathbf{k}_\perp^2) - f_{1T}^{\perp q}(x, \mathbf{k}_\perp^2) \frac{(\hat{\mathbf{P}} \times \mathbf{k}_\perp) \cdot S}{M}$$

Non-zero only with final state interactions (FSI)

FSI transforms position space distortion of quarks into momentum space asymmetries

Boer-Mulders effect

$$f_{q^\uparrow/p}(x, \mathbf{k}_\perp) = \frac{1}{2}\left[f_1^q(x, \mathbf{k}_\perp^2) - h_1^{\perp q}(x, \mathbf{k}_\perp^2) \frac{(\hat{\mathbf{P}} \times \mathbf{k}_\perp) \cdot S_q}{M} \right]$$

Lots of interesting information on spin-orbit, spatial correlations-is this universal ?
How do factorization/evolution/resummation work?

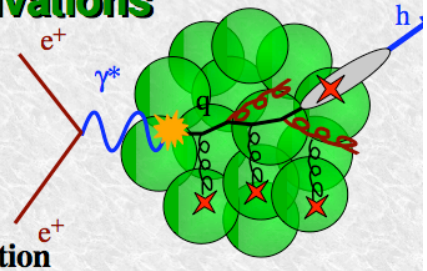
Gluon TMDs → EIC

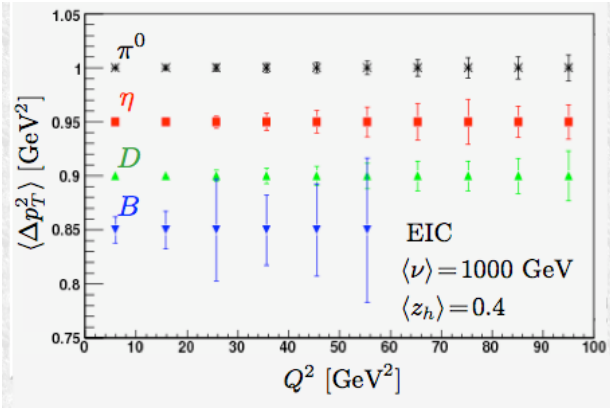
Fragmentation,Hadronization,Energy Loss (Accardi,Brooks,Stratmann,Wang)

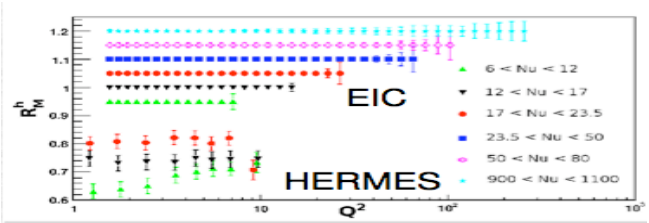
Physics motivations

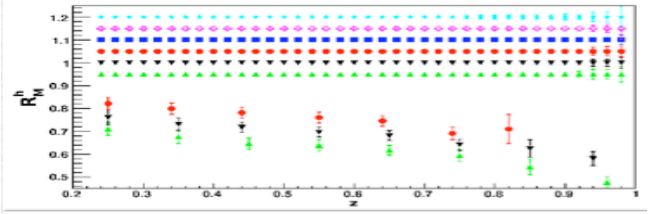
Accardi

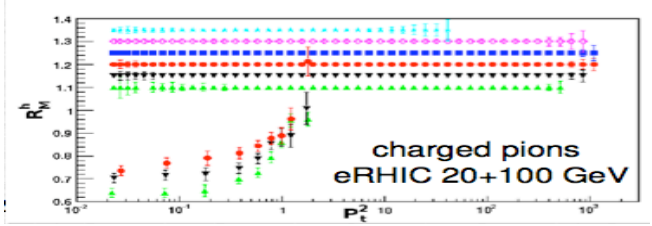
- **Nuclei as space-time analyzers**
  - nucleons as femto-detectors
  - medium rather well known
  - low final-state multiplicity
- **Non perturbative aspects of hadronization**
  - approaching microscopic understanding of Fragmentation Functions
  - how do partons dress up? Space-time evolution of hadronization
  - color confinement dynamics
- **Parton propagation in perturbative QCD**
  - QCD energy loss: basic pQCD, only indirectly tested so far
  - DGLAP parton showers
- **Connection to other fields**
  - Calibration of jet-quenching in A+A ⇒ properties of QGP
  - Tuning of parton showers in Monte-Carlo generators
  - Hadron attenuation corrections for ν-oscillation experiments





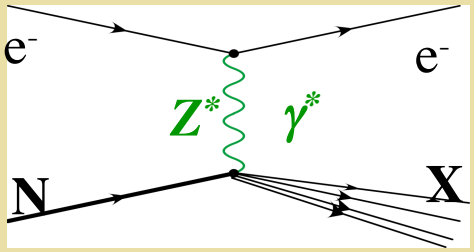




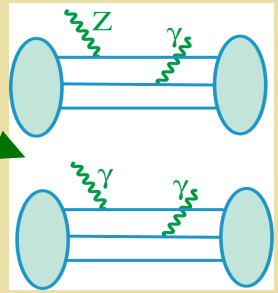


Extensive physics program -including first measurements of Jets in nuclear DIS!

Electroweak+Beyond Standard Model
(Kumar,Marciano,Ramsey-Musolf)



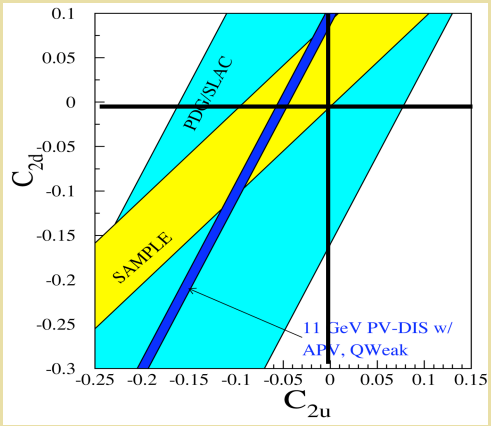
Higher Twist: qq and qqg correlations

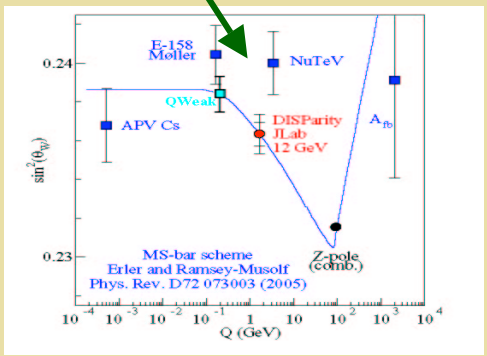


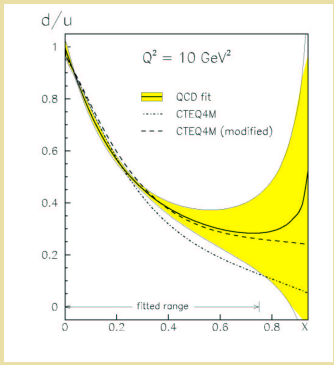
Charge sym in pdfs

$$u^p(x) = d^n(x)\,?$$

$$d^p(x) = u^n(x)\,?$$







Musolf

Electroweak test: e-q couplings & $\sin^2\theta_W$

d(x)/u(x): large x

Kumar: extract parity violating structure functions from

e^- scattering on polarized hydrogen, deuterium & ^{3}He

Lepton # violation $e^- + p \to \mu^+ + X \qquad e^- + p \to \tau^+ + X$

Exciting potential: to be explored!

Summary

- Talks suggest rich physics program

- Few detailed studies - especially for less than fully inclusive final states

- Topical working groups - to present results at dedicated workshop at end of INT program?