EIC@JLab - a medium energy collider taking nucleon structure beyond the valence region

– Implementation

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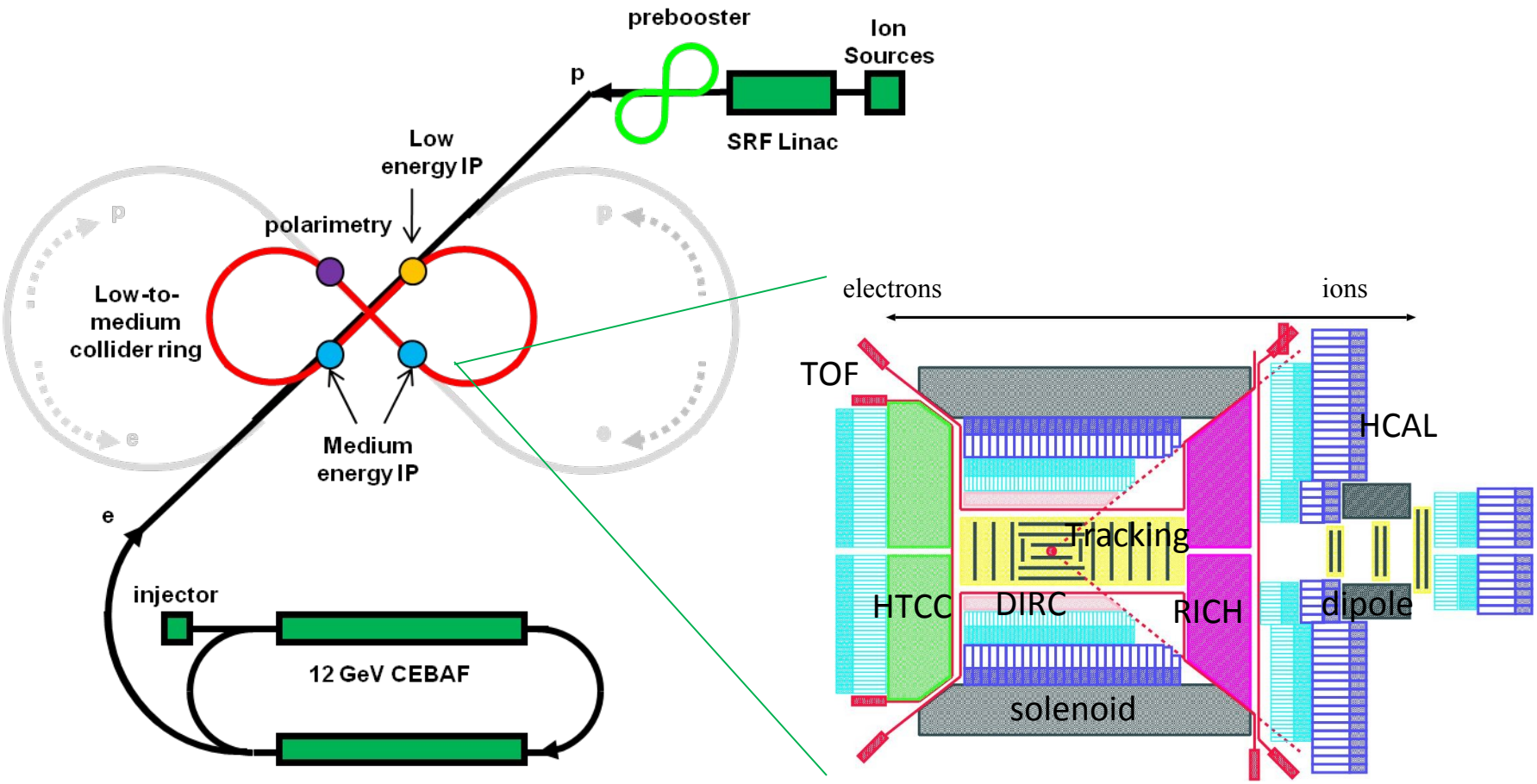
EIC@Jlab – overview



EIC@JLab – main features

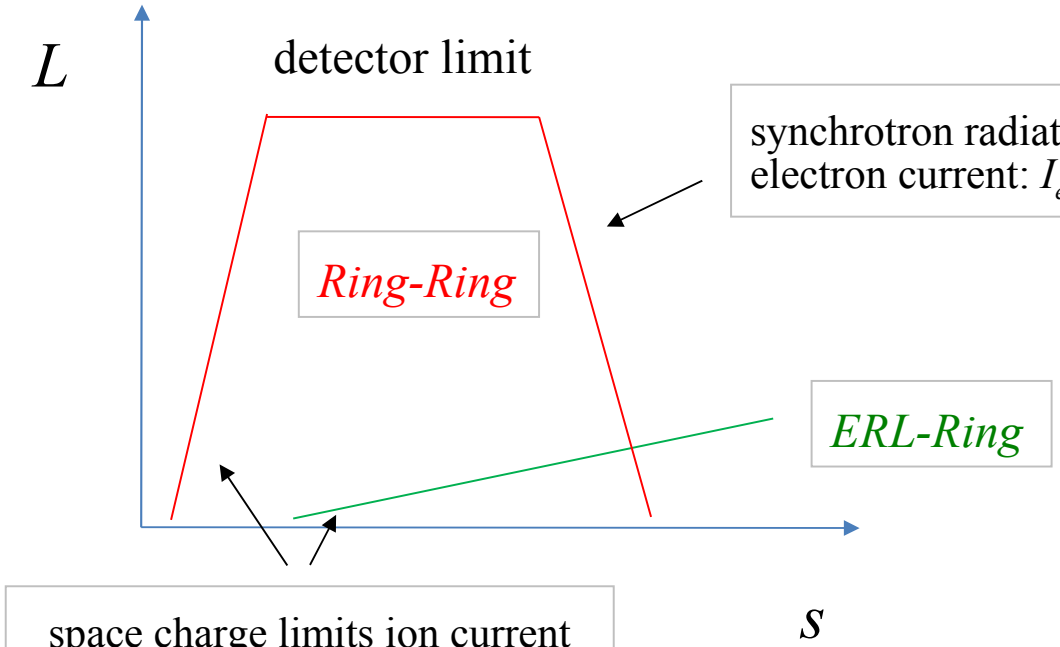
- High luminosity (few x 10^{34} cm^{-2} s^{-1})
  - not only at max ion energy

- Excellent polarization
  - electrons (no source issues as for ERL)
  - light ions (figure-8)
    - in particular: transverse ion polarization

- Large dynamic range
  - ion energies from 12 to 60 GeV (> factor two in beam size)

- Close to symmetric kinematics, where low lab momenta improve
  - momentum resolution
  - particle identification
  - detector acceptance (hermeticity)

Luminosity



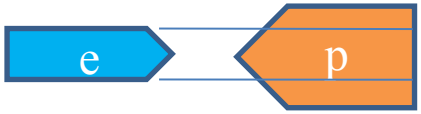
synchrotron radiation limits electron current: $I_e \sim R/p_e^4$

$$\text{Luminosity} \propto I_e I_p \frac{p_p}{\varepsilon_p m_p}$$

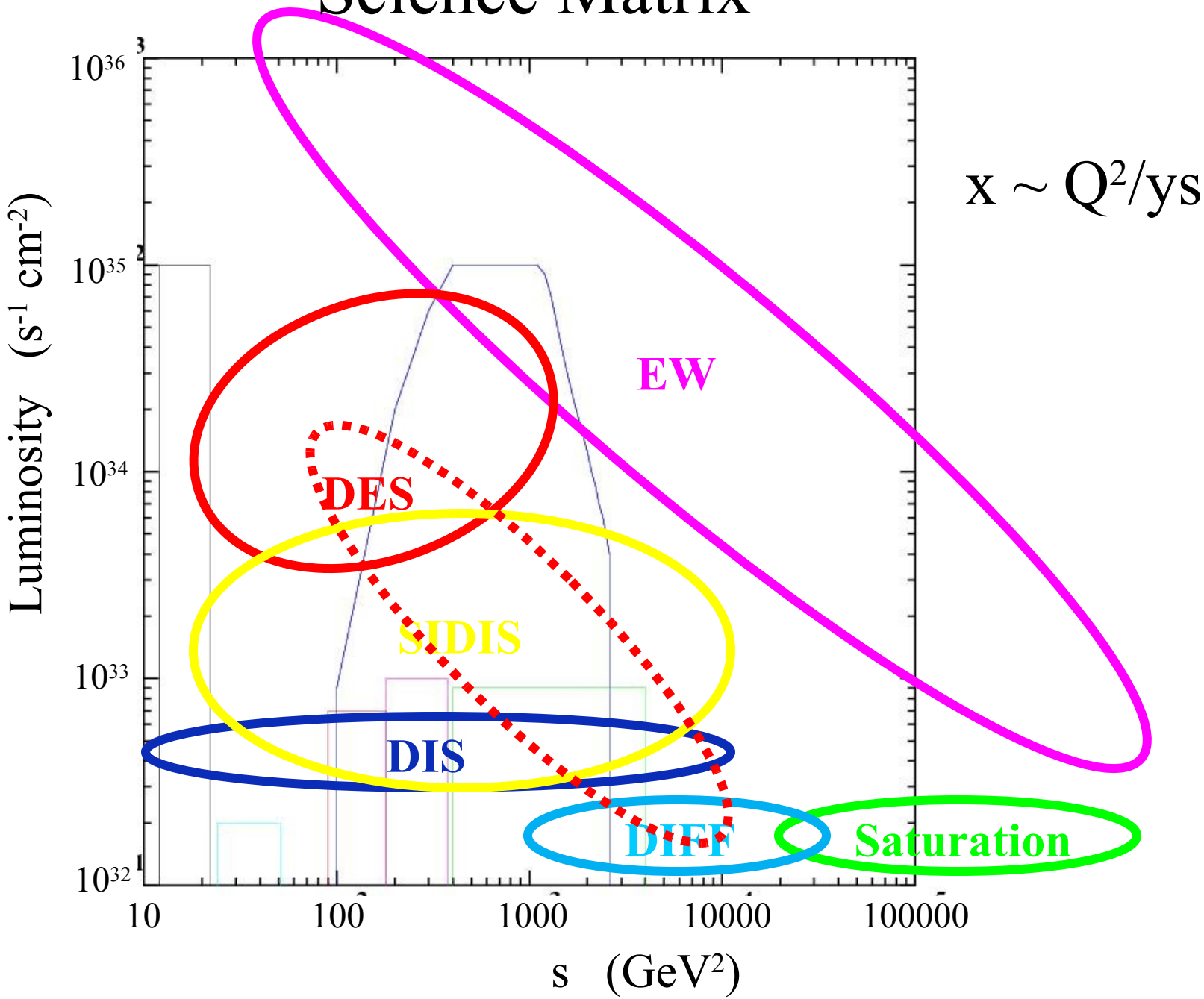
space charge limits ion current
L ~ 1/(ring circumference)

Luminosity scales with ion momentum *if* cooling can shrink the ion beam (ε_p): cooling efficiency ~ $1/p_p^2$

A medium-energy ring-ring collider provides a high luminosity over a wide range in *s, not only at the end point*



Science Matrix

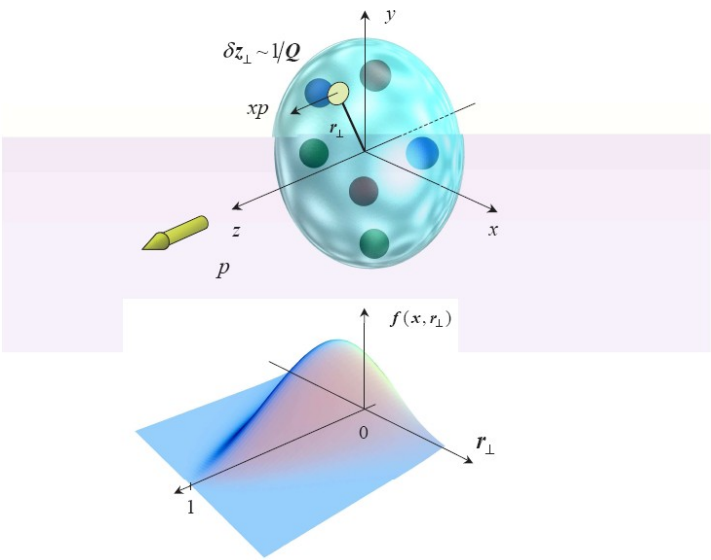


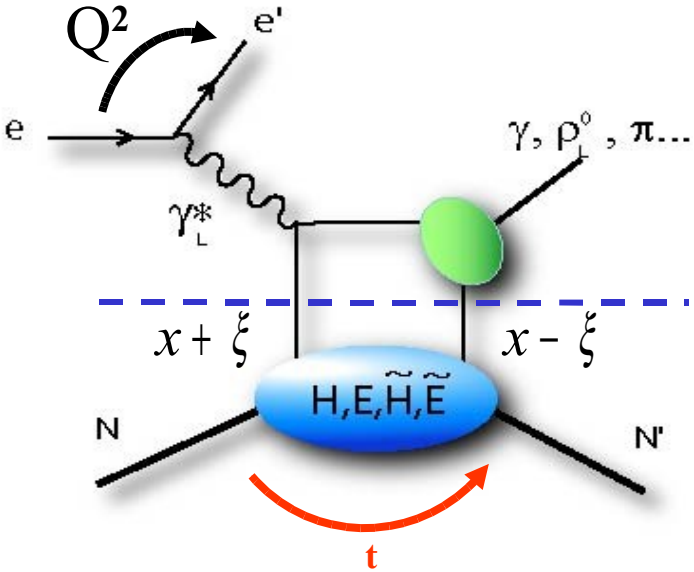
Planned program (examples)

- Inclusive DIS
  - Unpolarized: EMC effect, gluons in nuclei
  - Polarized: ΔG, Δq
- Semi-Inclusive DIS
  - Unpolarized: flavor decomposition of sea, strangeness
  - Polarized: orbital angular momentum in TMDs, flavor separation of Δq
- Exclusive (GPDs: transverse spatial distributions, orbital angular momentum)
  - Diffractive: gluons from DVCS and J/ψ; DVCS on nuclei
  - Non-diffractive: sea quarks from light mesons

Experimental requirements

GPDs – deep exclusive reactions

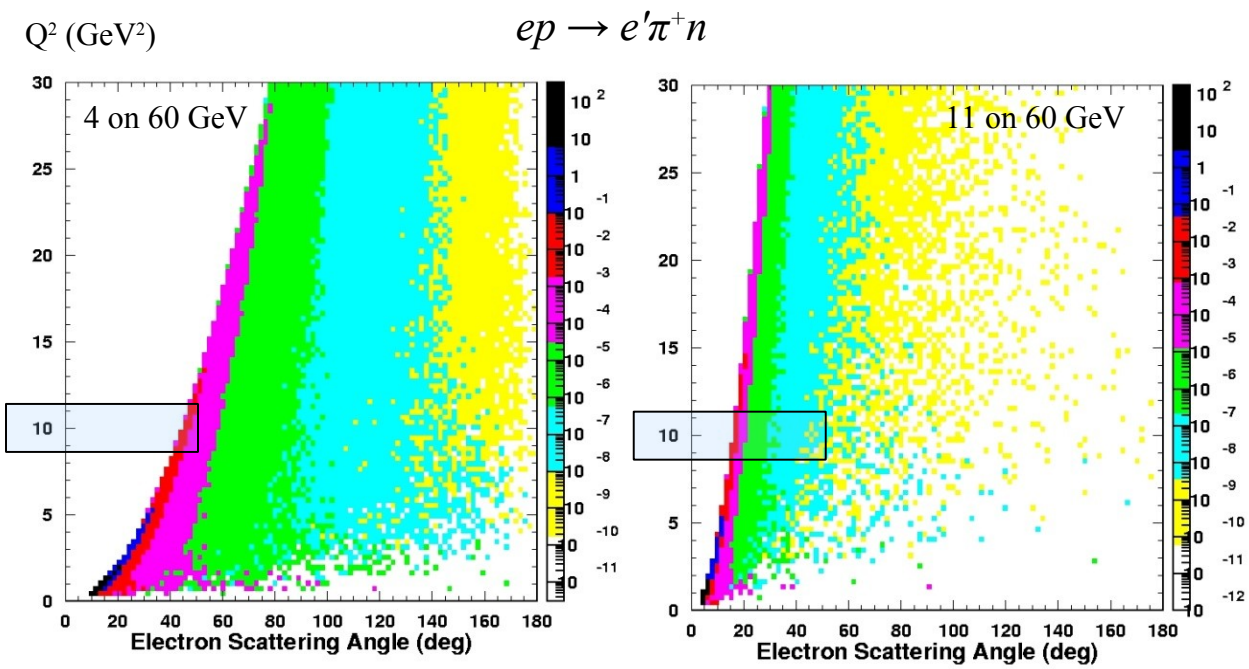




- Experimental requirements
  - High luminosity (non-diffractive)
  - Good momentum resolution
  - Good particle identification
  - Good low -*t* coverage

- Pion production provides a good illustration of collider kinematics

Deep exclusive – electron kinematics

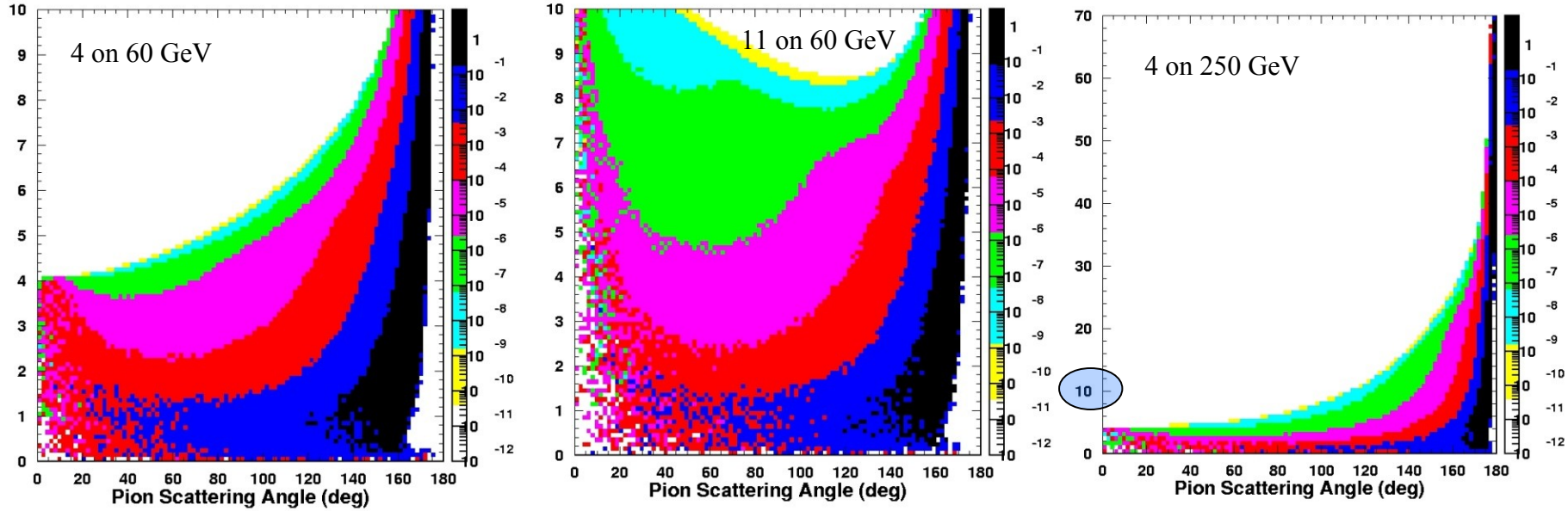


(T. Horn)

- Electrons scattering angles are large compared with fixed-target kinematics.
- Large *e-p* momentum asymmetry would require e/π discrimination at large angles in order to reach $Q^2 \sim 10$ GeV^2 (ensuring factorization).
- Small-angle coverage only needed for symmetric collisions and photoproduction.

Deep exclusive - meson kinematics

$ep \rightarrow e'\pi^{+}n$



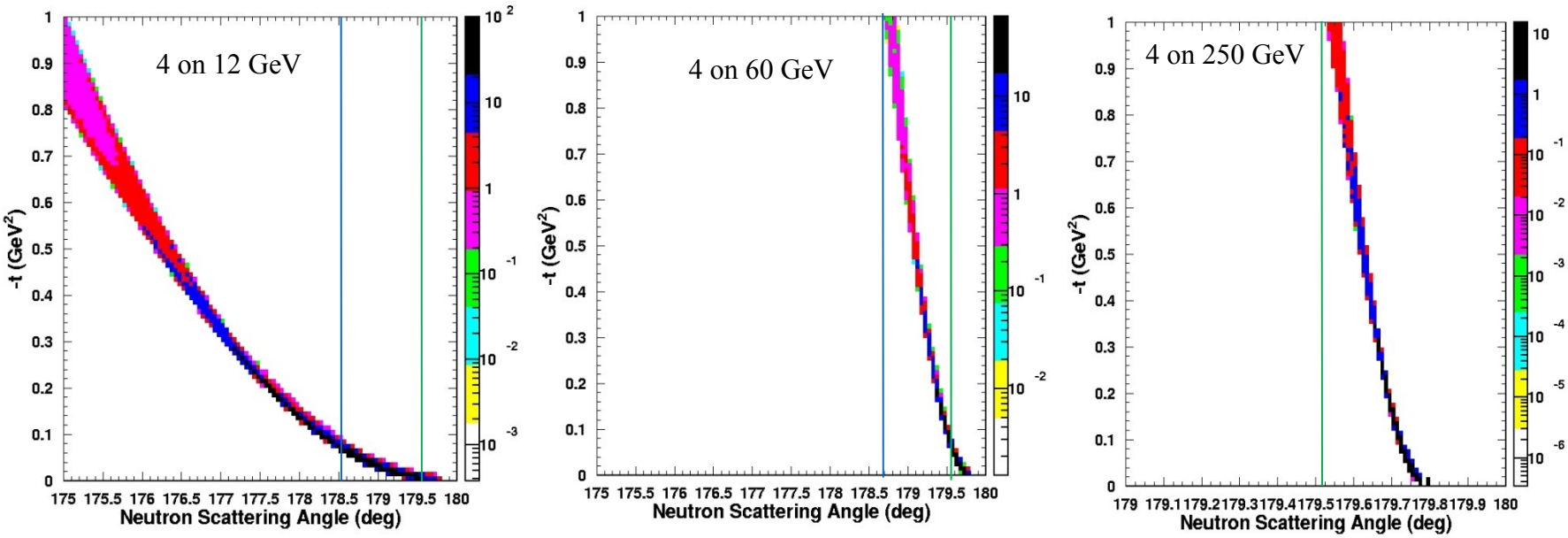
(T. Horn)

- Large boost in asymmetric *e-p* collisions
  - hadrons produced in narrow cone with large lab momenta

- More symmetric kinematics improve detector *acceptance (hermeticity)*, *particle identification*, and *resolution (momentum and angular)*.

Deep exclusive – recoil baryon kinematics

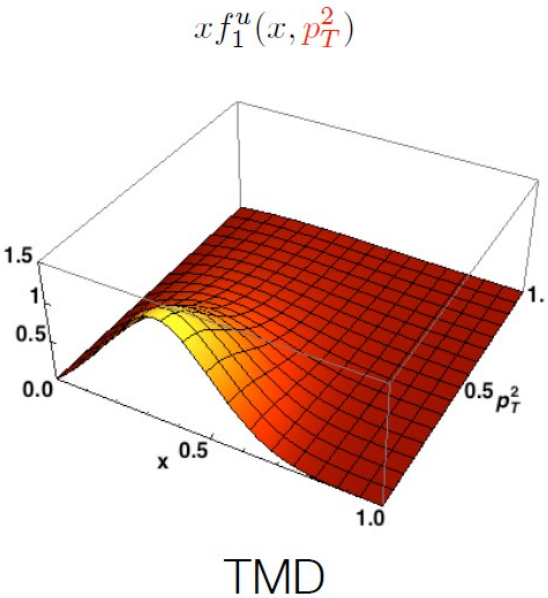
$ep \rightarrow e'\pi^+ n$



(T. Horn)

- Symmetric kinematics greatly improve *acceptance* (*t*-coverage)
- Forward detection needed to reach very low -*t*
  - Long magnet free space between IP and first beam quad (9 m)
  - Spreader magnet for recoil protons (dipole, toroid?)
  - Calorimeter for recoil neutrons (angular information only)

Semi-Inclusive DIS – TMDs



(A. Bacchetta)

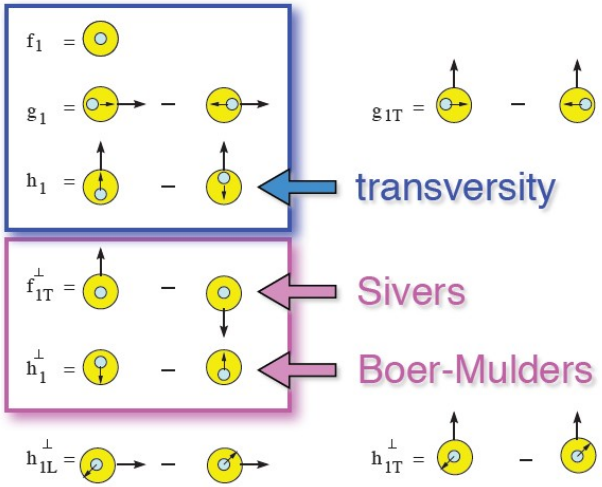
$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&\quad + S_L\,\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&\quad + S_T\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\quad\quad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\quad\quad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] + S_T\,\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\quad\quad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\}
\end{aligned}
$$

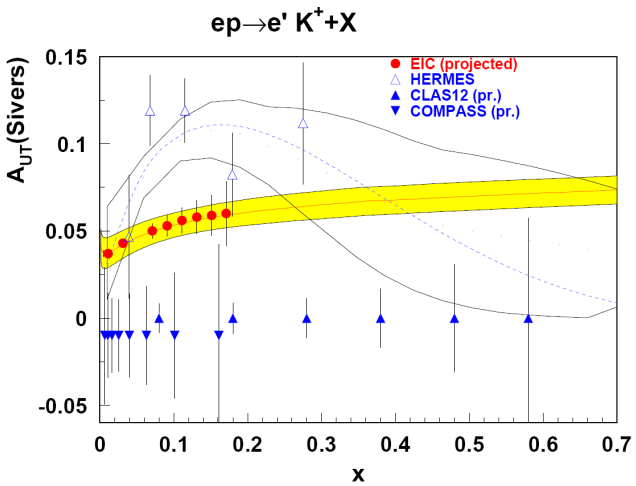
18 structure functions

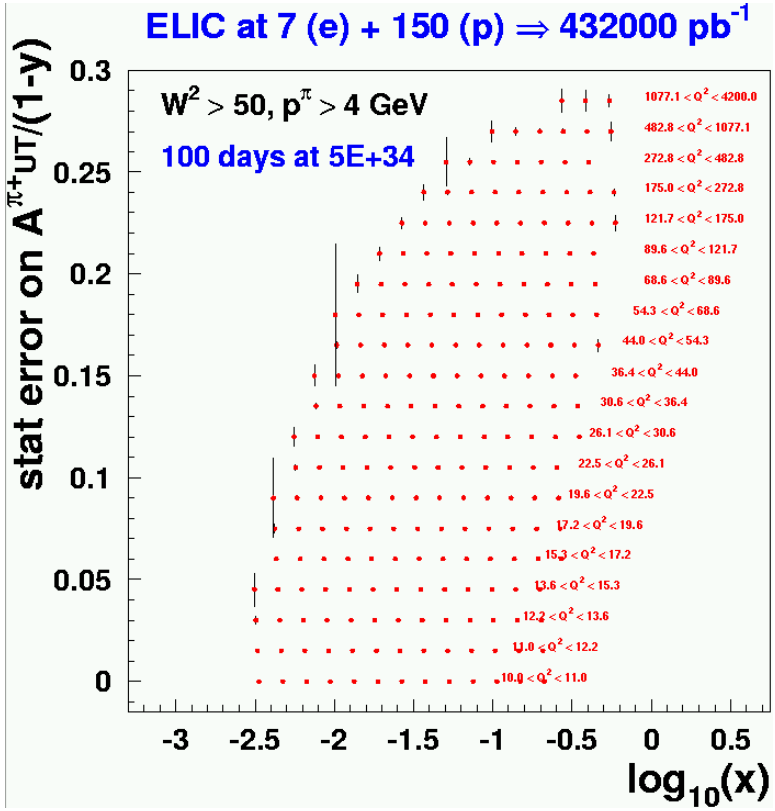
- GPDs combine longitudinal momentum and transverse spatial distributions
- TMDs combine transverse and longitudinal momentum (PDF) information
- Cross section can be expressed in terms of 18 structure functions

TMDs – simulations

Transverse Momentum Distributions (TMDs)







Transversity, pions (N. Makins *et al.*)

Sivers, kaons (H. Avakian)

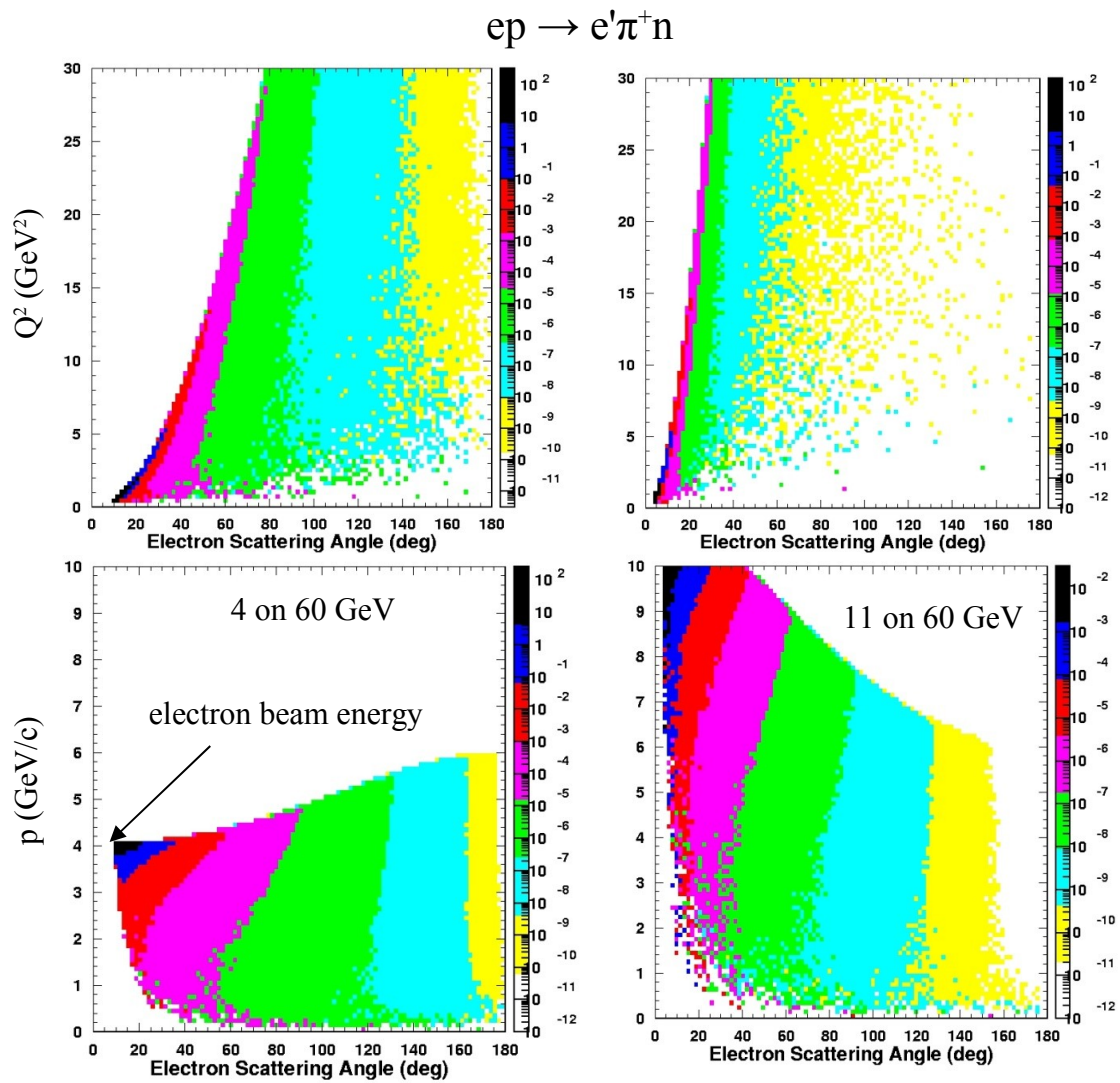
Polarized Transverse Momentum Distributions (TMDs)

– will greatly benefit from collider

- Particle identification at higher cm energies
  - favors symmetric kinematics (low lab momenta)
- Transverse “target” in collider has exceptional figure of merit
  - no beam current limitations (or holding fields)
  - no dilution (low background)
  - high transverse polarization

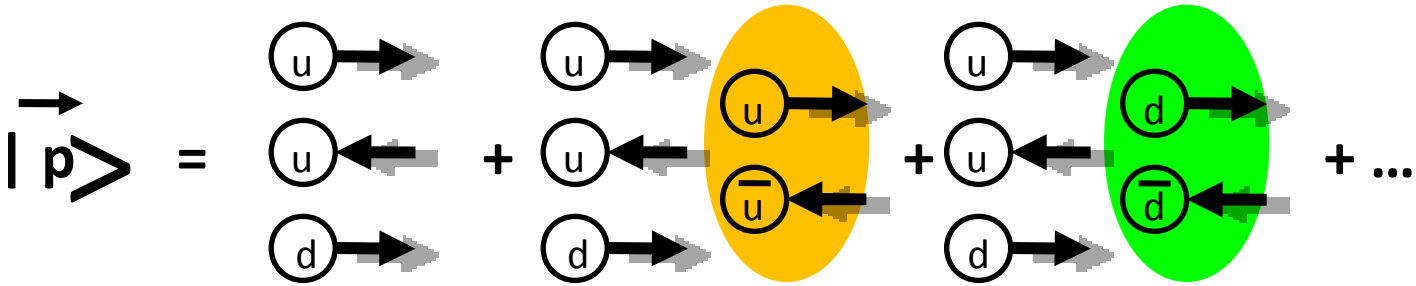
DIS – kinematics

- symmetric kinematics gives access to higher Q^2 at smaller scattering angles
  - Cerenkov coverage
  - better PID in SIDIS
- asymmetric kinematics provide lower momenta at small scattering angles
  - better resolution
- A medium energy collider allows optimization of kinematics for each experiment.



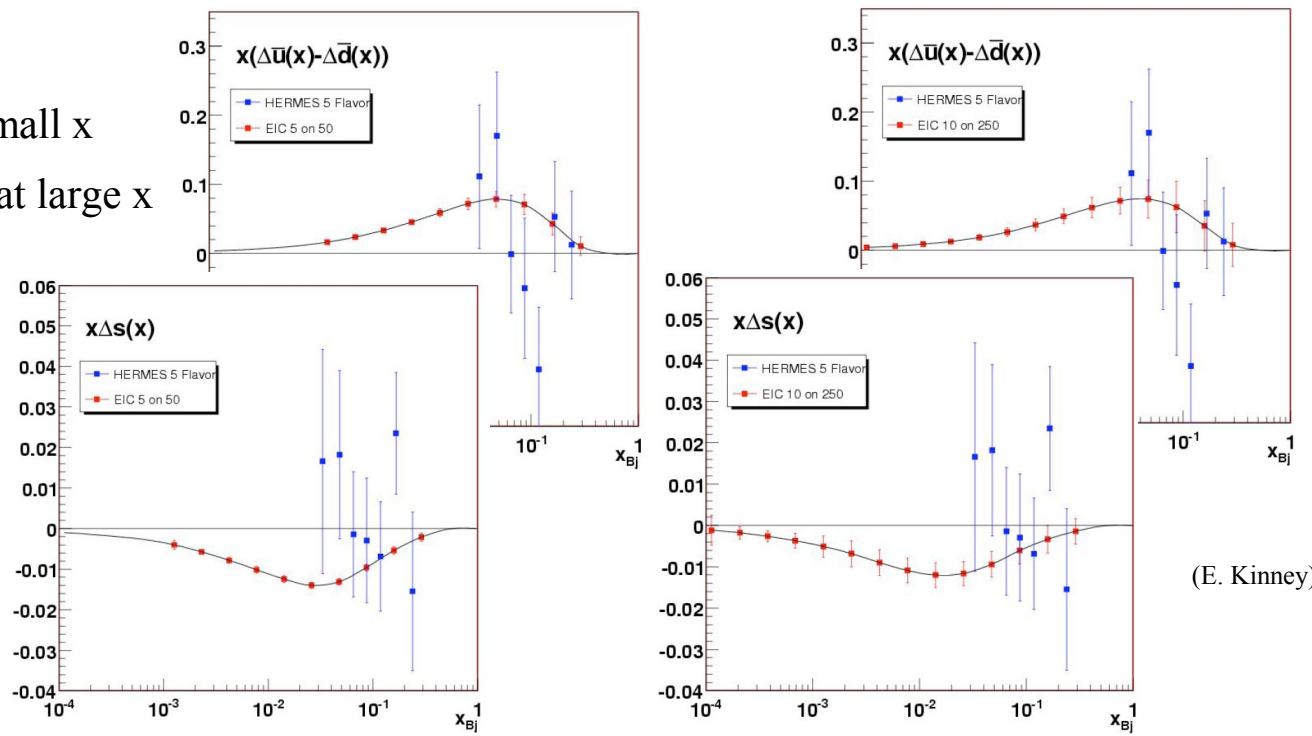
(T. Horn)

SIDIS – flavor decomposition



- Higher cm energies give
  - better coverage at small x
  - larger uncertainties at large x

- Also interesting are spatial correlations in the vacuum (nucleon sea). *See previous talk.*

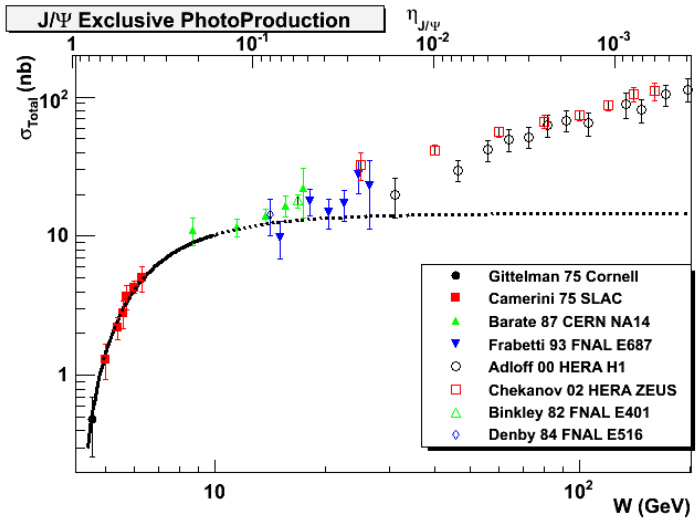


(E. Kinney)

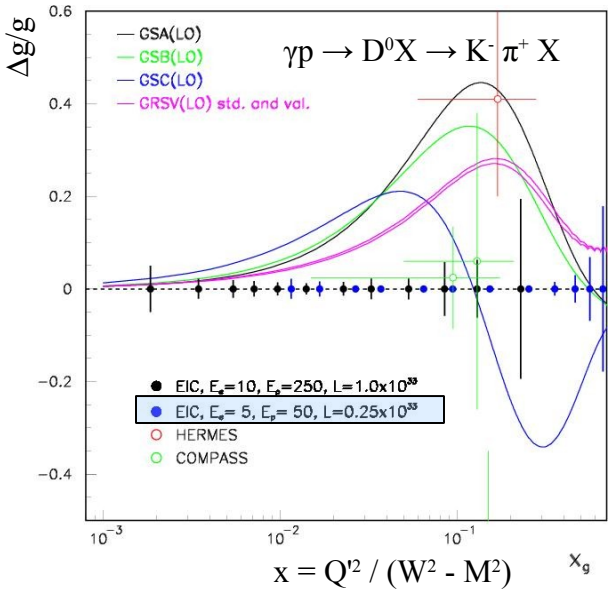
100 days at 10^{33} cm^{-2} s^{-1} shown, curves are GRSV

Charm photoproduction

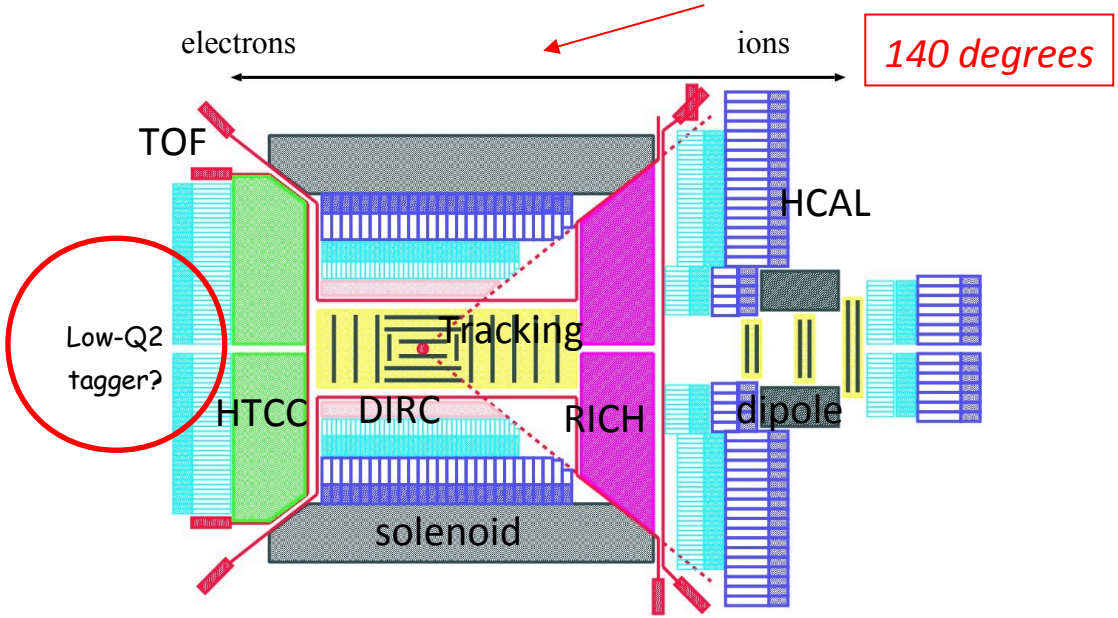
- J/ψ : transverse spatial gluon imaging
- Mass (Q') is large
  - perturbative at $Q'^2 = 0$
- High-x (low-W) requires high luminosity.
- Shown low-W data usually lack *t*-distrubutions



- $D^0 \rightarrow K^- \pi^+$ photoproduction can measure gluon contribution to proton spin (ΔG) at $Q'^2 \sim 10$ GeV^2
- uncertainties in $x\Delta g < 0.01$



Photoproduction – low-Q^2 tagger



- Advantages
  - No Moller electrons from target ions
  - Low tagging rates compared with real-photon taggers (Hall B/D)

- Small-angle electron backgrounds need to be investigated in detail

Electron Trigger

- A selective electron trigger is essential for a high luminosity *e-p* collider.
  - high particle multiplicities and hadronic backgrounds.
- Development of the advanced CLAS12 trigger and the high rate GlueX trigger puts JLab at the forefront of this technology.
- Features could include vertex determination from simple tracking, calorimeter shower shape analysis, and geometric matching with Cerenkov.

Summary

- The EIC@JLab is well suited for taking JLab beyond 12 GeV.
- It offers high *luminosity*, excellent *polarization*, and benefits from more *symmetric* collision kinematics.
- A medium energy collider is particularly appealing for measurements requiring *transverse targets* as well as good *resolution* and *particle id* (*e.g.*, TMDs, GPDs).
- Great opportunity for the user community to participate!

Backup

EIC physics

Nucleon structure

Builds on JLab 12 GeV and RHIC spin

QCD at high gluon density

Discovery or precision measurement?

e - *p*: not seen at HERA
p - *p*: will be observed in ultraperipheral collisions at LHC *before* EIC is built?

e - *A*: do we understand the postulated nuclear *oomph* sufficiently well to use it as a substitute for a high energy *e* - *p* machine?

EIC implementation choices

Nucleon structure machine

- optimized performance
- simpler R&D
- energy upgrade possible

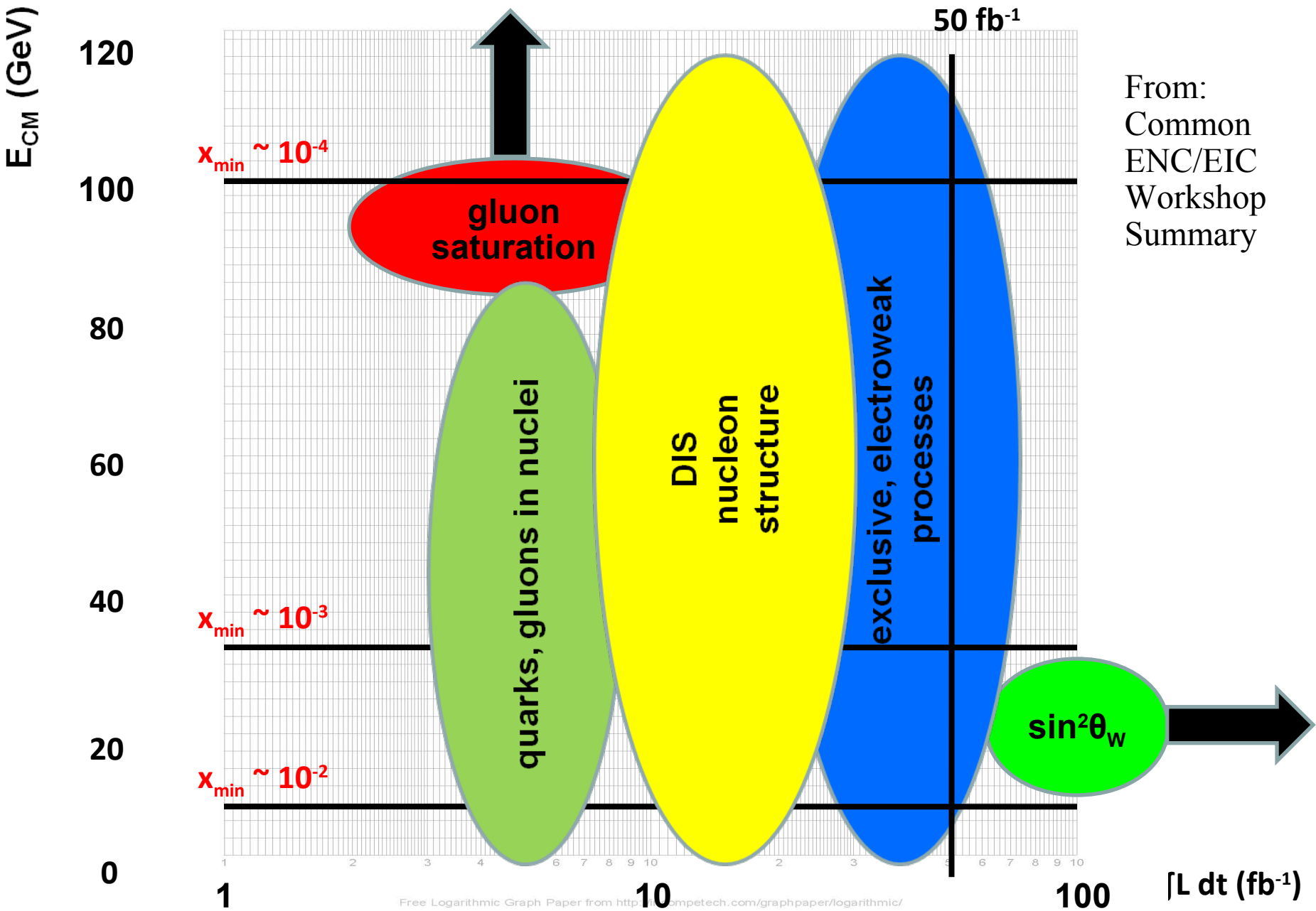
EIC@JLab:
- s up to 2640 GeV^2
- high luminosity at *medium* energy
- excellent spin characteristics
- more symmetric kinematics

High-energy, low-x machine

- performance compromises
- technical challenges (cooling)
- physics motivation for staging?

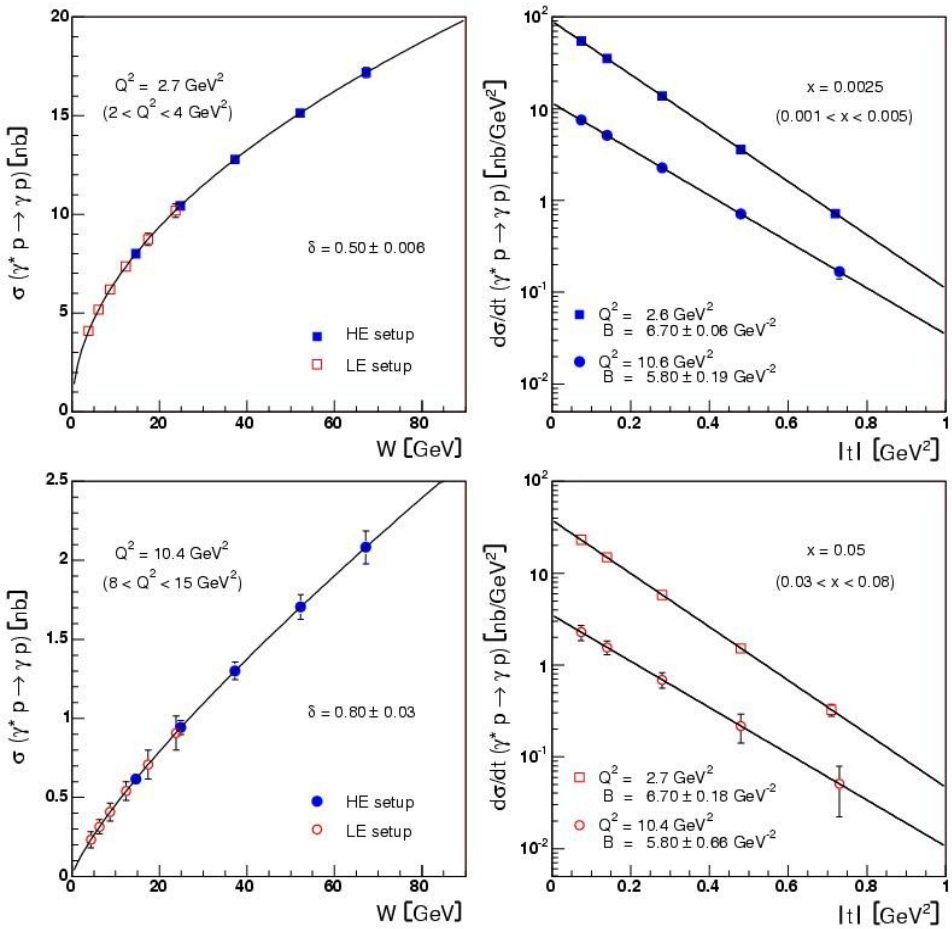
staged eRHIC:
- s up to 4000 GeV^2
- lower luminosity even at max energy
- electron polarization? (0.42 A source)

Science reach as function of E_{CM} and integrated luminosity



From: Common ENC/EIC Workshop Summary

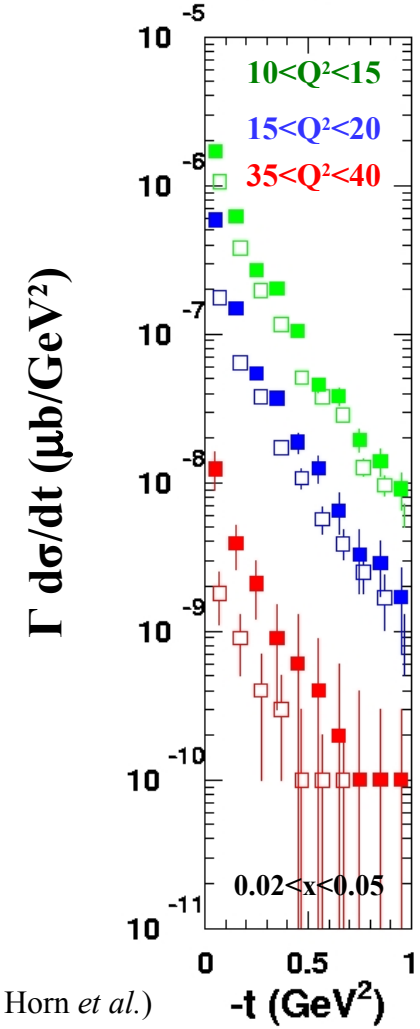
GPDs – DVCS


Q² = 2.7 GeV²
(2 < Q² < 4 GeV²)
δ = 0.50 ± 0.006
HE setup
LE setup
σ (γ* p → γ p) [nb]
W [GeV]
x = 0.0025
(0.001 < x < 0.005)
Q² = 2.6 GeV²
B = 6.70 ± 0.06 GeV⁻²
Q² = 10.6 GeV²
B = 5.80 ± 0.19 GeV⁻²
dσ/dt (γ* p → γ p) [nb/GeV²]
|t| [GeV²]
Q² = 10.4 GeV²
(8 < Q² < 15 GeV²)
δ = 0.80 ± 0.03
HE setup
LE setup
x = 0.05
(0.03 < x < 0.08)
Q² = 2.7 GeV²
B = 6.70 ± 0.18 GeV⁻²
Q² = 10.4 GeV²
B = 5.80 ± 0.66 GeV⁻²

GPDs – pion production

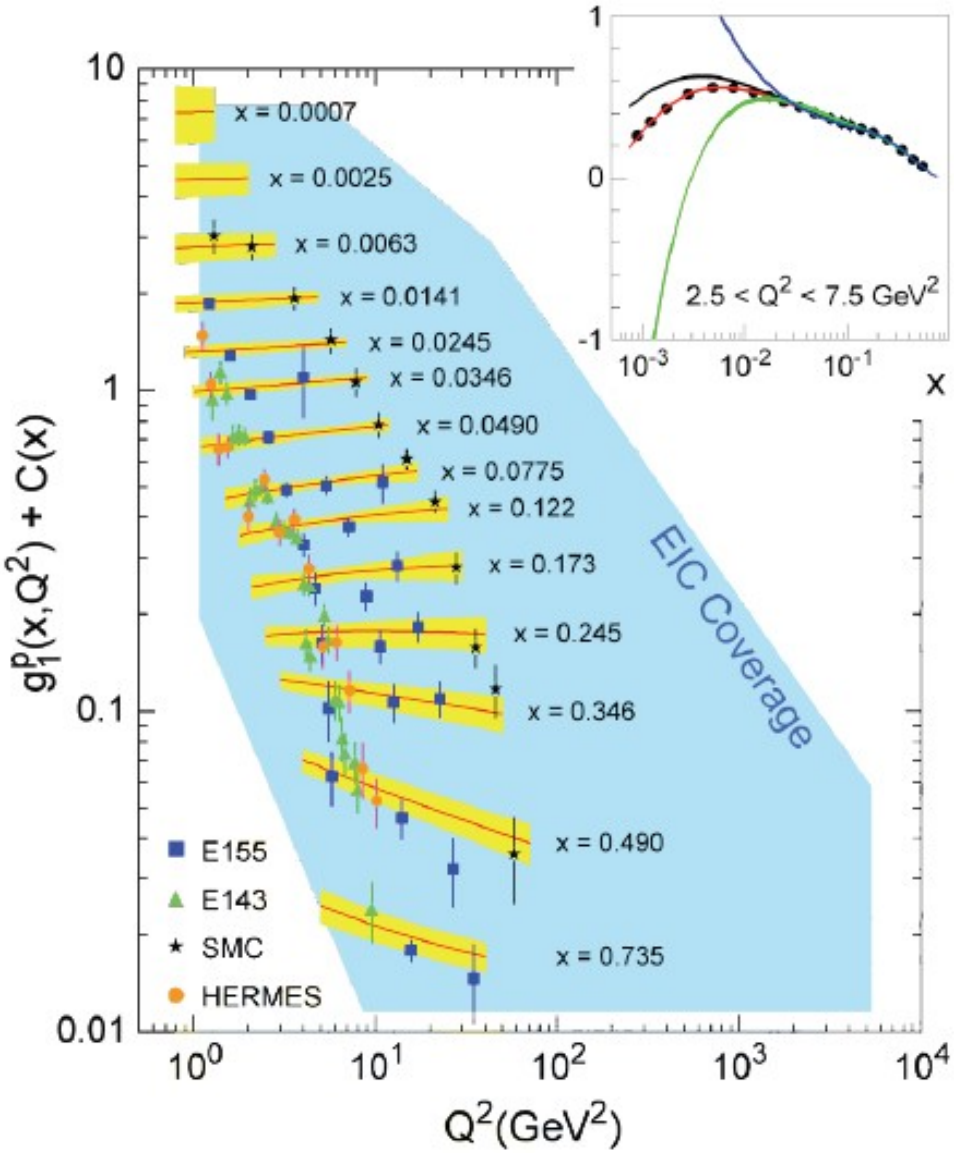
- Non-diffractive channels are essential for probing the spin/flavor structure of quark GPDs
  - Highest luminosity requirement

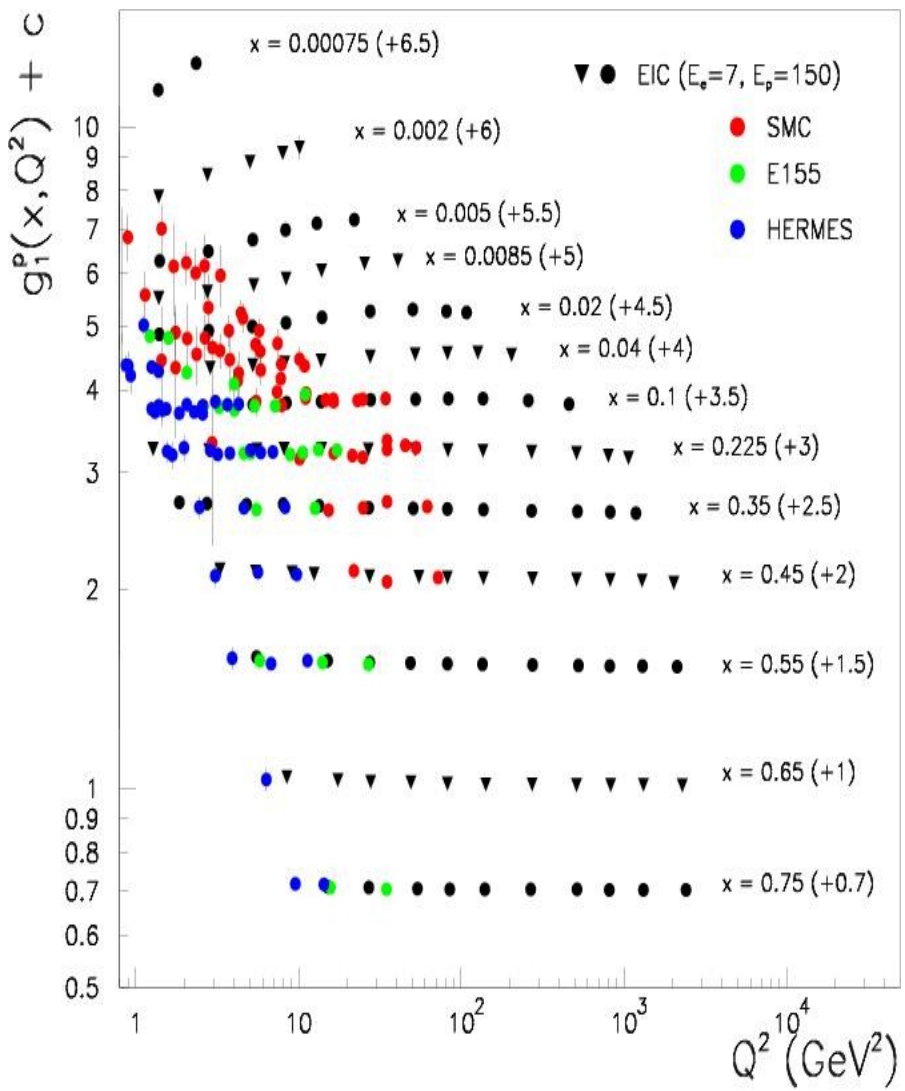
- Uncertainties in shown π+ simulation assume a luminosity of 10^{34} cm^2 s^{-1} for 100 days, using
  - C. Weiss: Regge model
  - T. Horn: empirical parameterization



(T. Horn *et al.*)

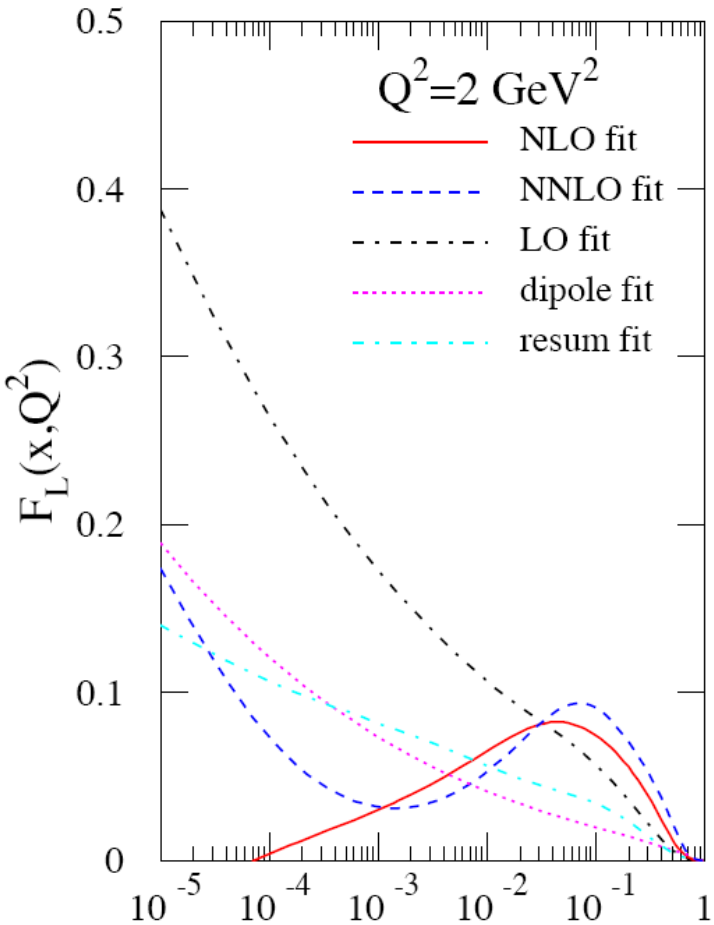
Plot produced for 7 GeV on 150 GeV

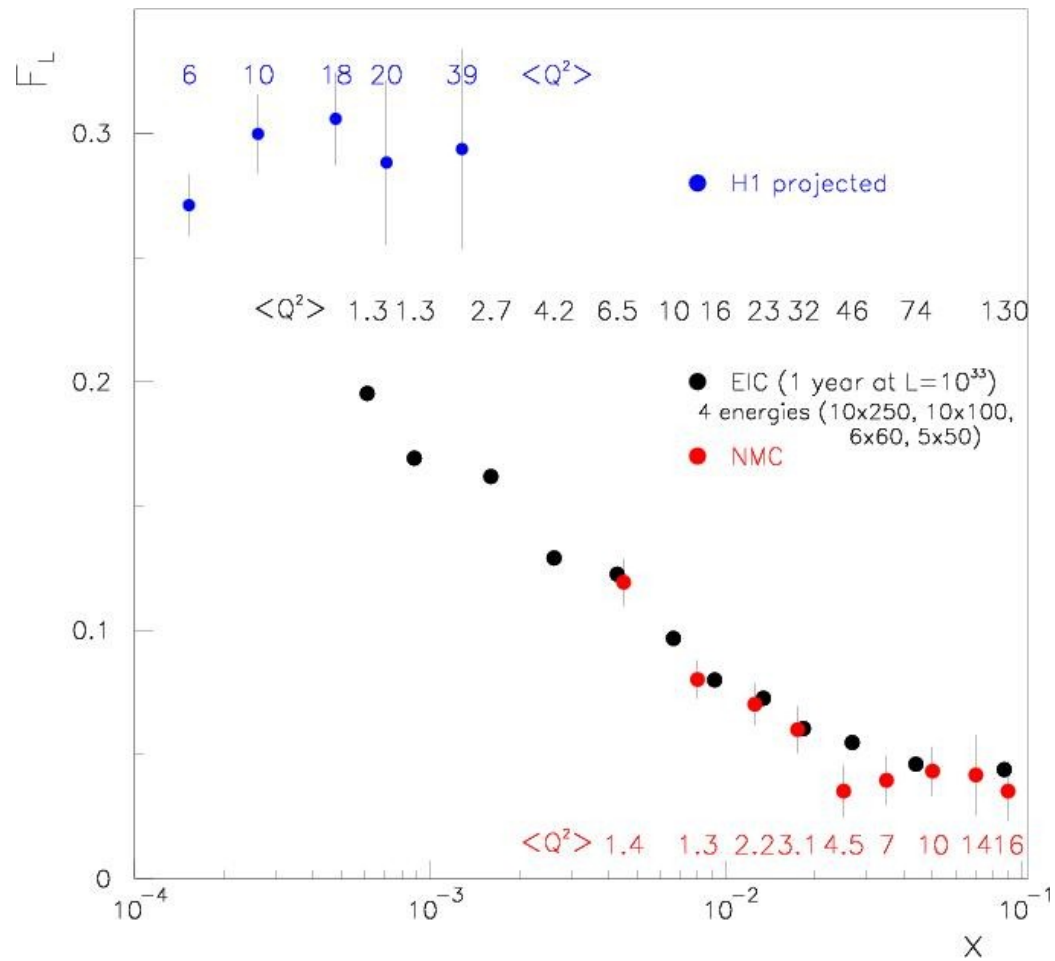




Gluons in the Nucleon – Low x and Q^2

$$F_L \propto \frac{\alpha_s}{2\pi} x \int_x^1 \frac{d\xi}{\xi} \xi(1-\xi)\, g\left(\frac{x}{\xi}, Q^2\right) + \ldots$$





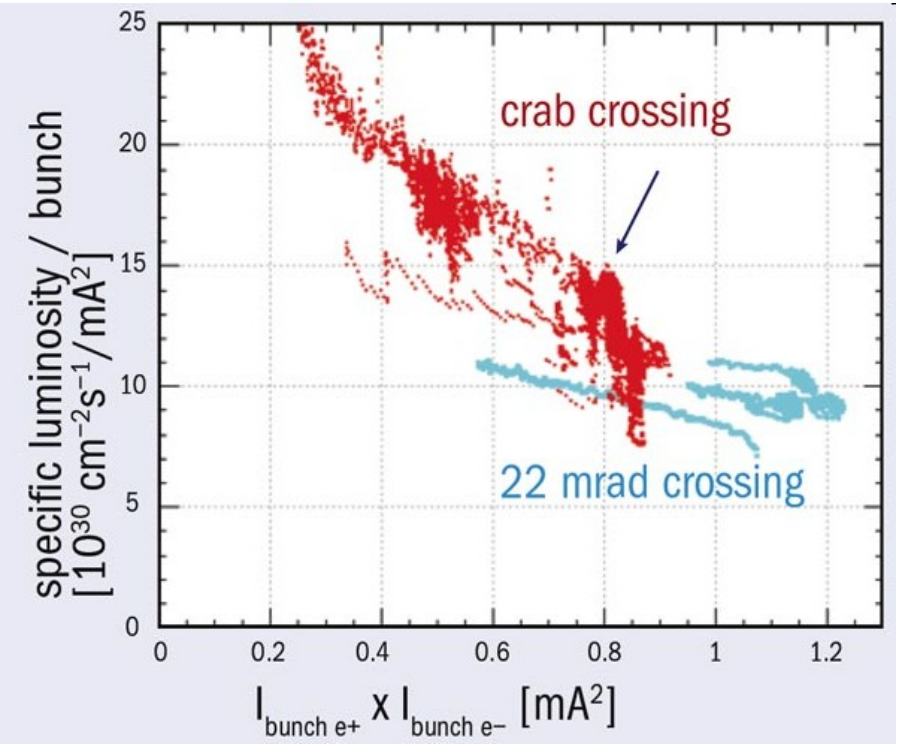
Great News From KEK

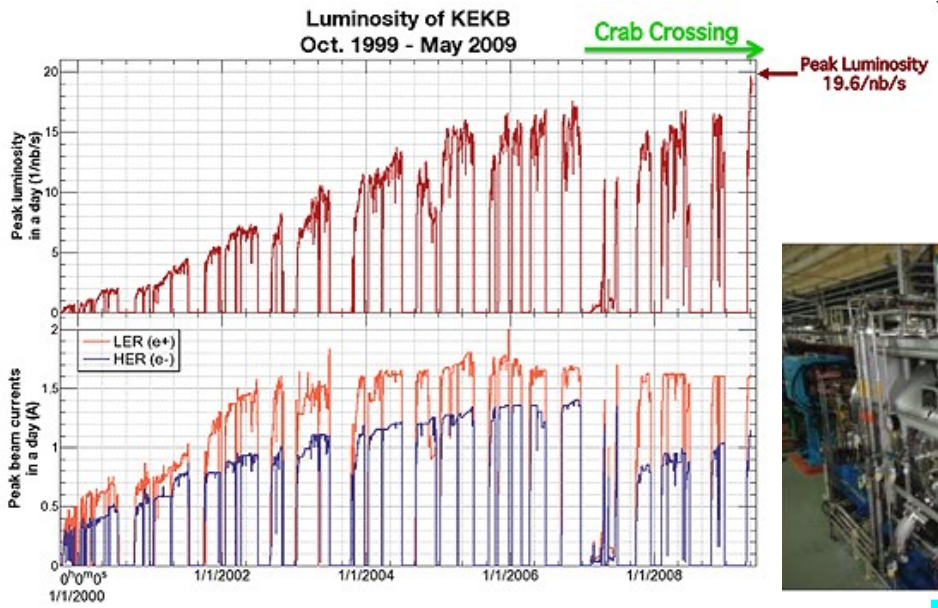
KEK Press Release (05/11/09)

"Using Crab Cavities, KEKB Breaks Luminosity World Record"

Symmetry*Breaking* (05/11/09)

"Record luminosity collisions due to "crab" crossing,





Trick: 28 skew sextupoles