New opportunities with Jefferson Lab at 22 GeV

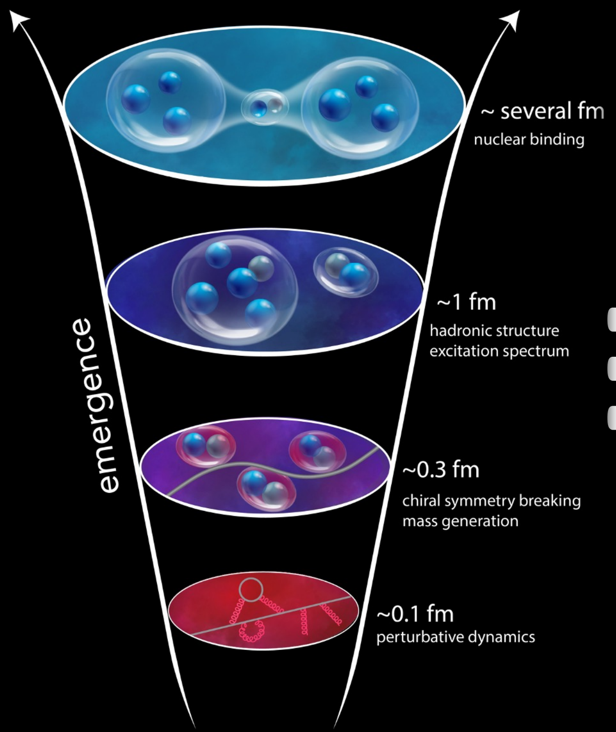
- Why?
- How?
- When?

Patrizia Rossi

HADRON2023

Genova (Italy), June 5-9, 2023

- **Emergence of hadron structure & dynamics in the non-pQCD regime**
  - **Complex and multifaced problem requiring multiple observables**



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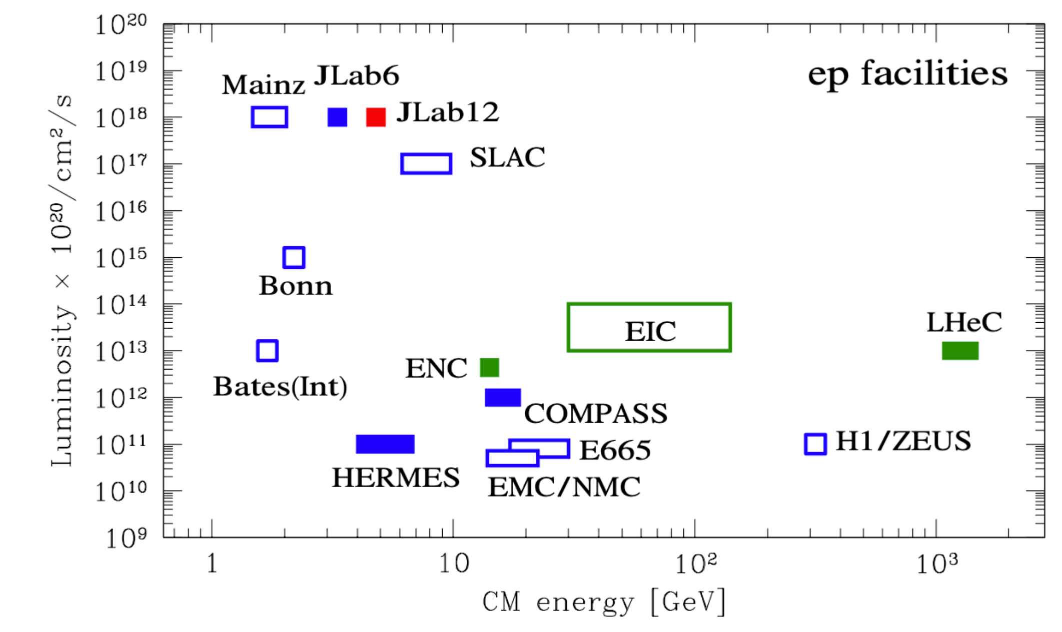
- **Precision measurements → LUMINOSITY**



The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe." -- *More is different*, P. W. Anderson [Science 177, 393 (1972)].

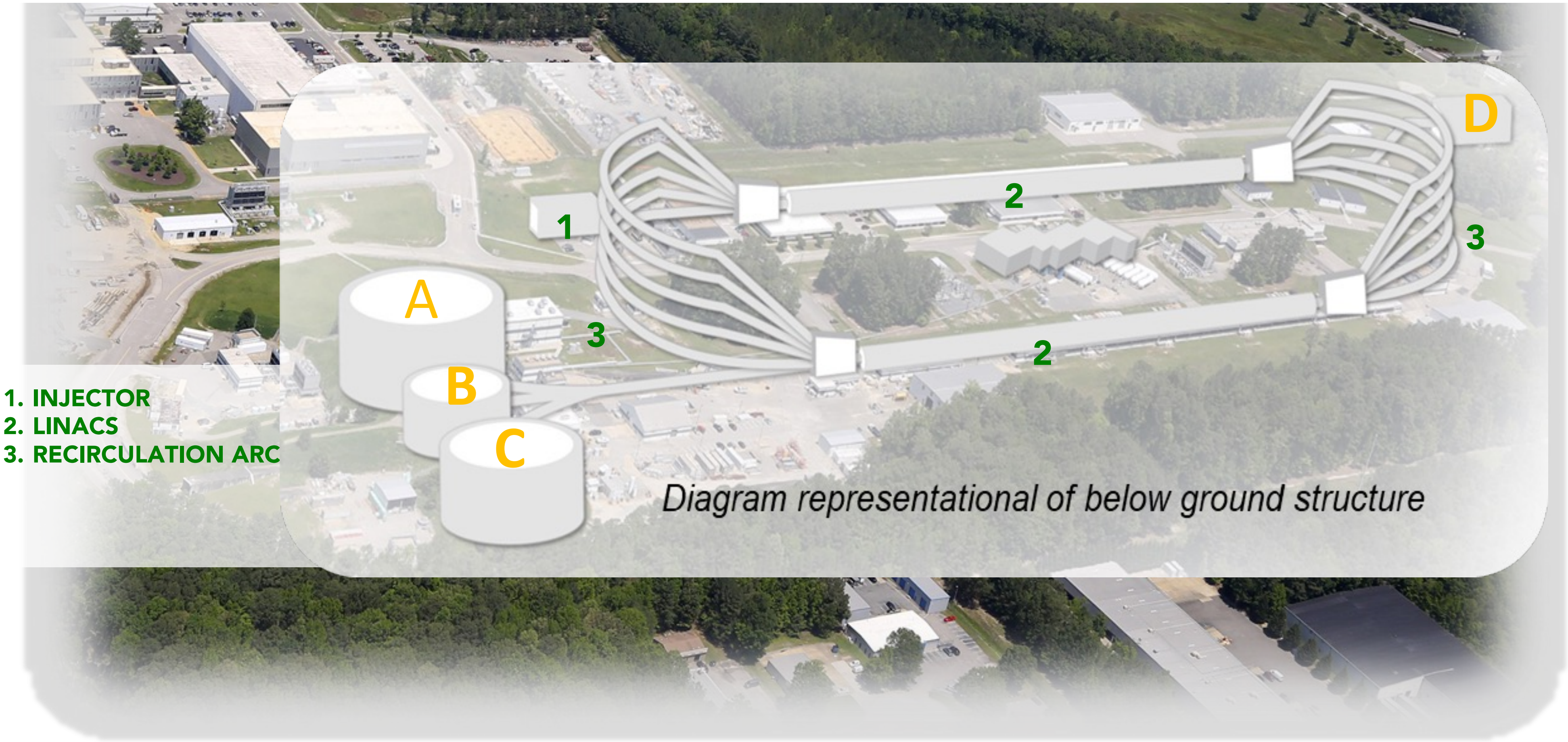
Jefferson Lab and CEBAF

- **CW electron beam, E_{max} = 12 GeV, Pol_{max} ~ 90%**
- **High intensity linearly polarized photon beam at 9 GeV**
- Range of beam energies & currents delivered to multiple exp. halls simultaneously

Fixed target experiments at the "luminosity frontier"
(up to 10^{39} e-N /cm^2/ s)

Jefferson Lab

Jefferson Lab and CEBAF



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Jefferson Lab

Jefferson Lab Physics Program

- **Program @ 12 GeV started in 2017**
- **~ 1 decade to complete the already approved experimental program**

Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
Hadron spectra as probes of QCD	0	3	1	4	0	**8**
Transverse structure of the hadrons	7	4	1	1	0	**13**
Longitudinal structure of the hadrons	1	3	12	1	0	**17**
3D structure of the hadrons	7	9	8	0	0	**24**
Hadrons and cold nuclear matter	9	6	8	1	1	**25**
Low-energy tests of the Standard Model and Fundamental Symmetries	3	2	0	1	2	**8**
Total	**27**	**27**	**30**	**8**	**3**	**95**
Total Completed	**11**	**11**	**8**	**3**	**0**	**33**
Experiments Removed by Jeopardy	**4**	**4**	**3**	**0**	**0**	**11**
Total Experiments Remaining	**12**	**12**	**19**	**5**	**3**	**51**

What a 22 GeV Upgrade will bring?

- **A NEW territory to explore → cross the critical threshold into the region where $c\bar{c}$ states can be produced in large quantities, and with additional light quark degrees of freedom.**
- **A BETTER (and needed) insight into our current program → enhancement of the phase space**
- **A BRIDGE between JLab @ 12 GeV and EIC → test and validation of our theory from lower to higher energy and with high precision**

The physics program will:

- **Leverage on the uniqueness of CEBAF HIGH LUMINOSITY**
- **Utilize largely existing or already-planned Hall equipment**
- **Take advantage of recent novel advances in accelerator technology**

Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at JLab

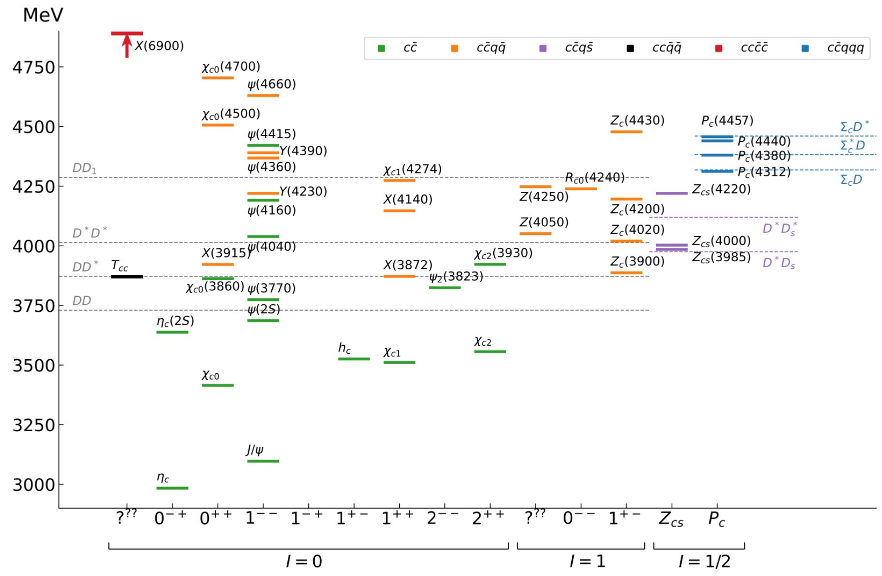
https://drive.google.com/file/d/1VQelVEu6Sz6Z9cxWV4nkrYMX7NzO1rUP

Contents

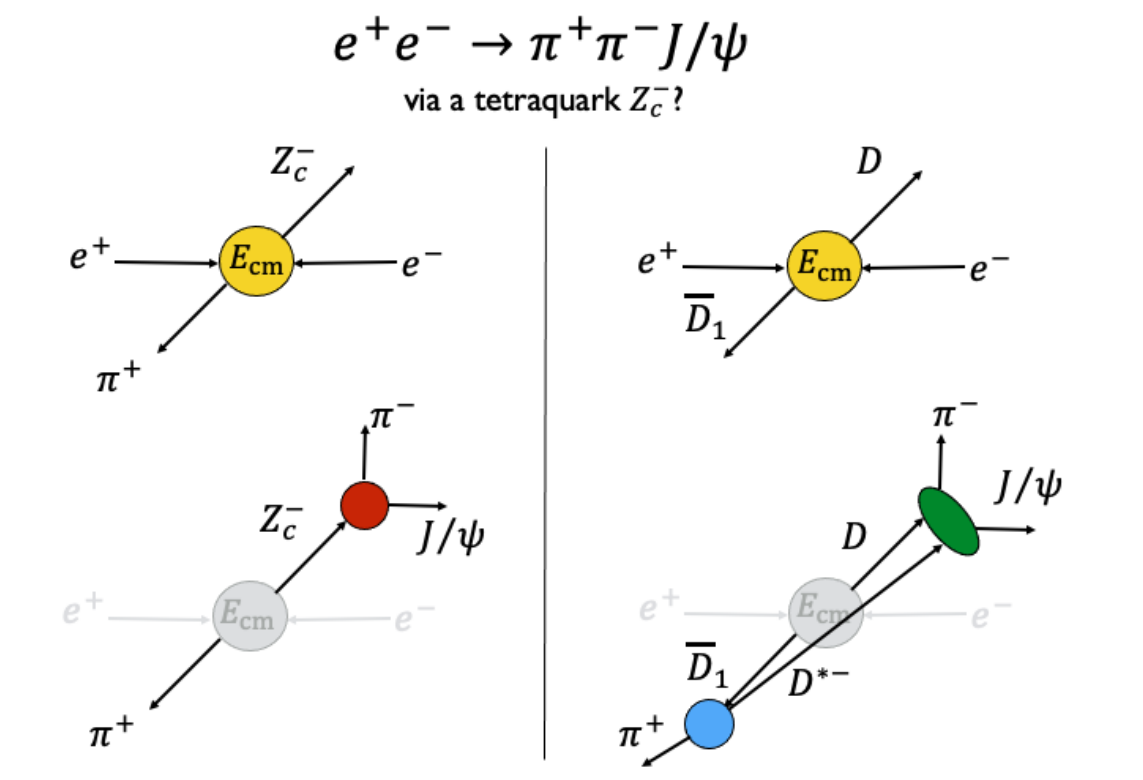
- White Paper on ArXiv by the end of this week
- It will be presented at the US LRP of NP

Photoproduction of Hadrons with Charm Quarks

Potentially decisive information about the **nature of some 5-quark and 4-quark (XYZ)** candidates



- **Many "XYZ" states observed in B decays, e^+e^- colliders**
- **Scarce consistency between various production mechanisms**
- **Significant theoretical interest and progress, but internal structure not understood yet**

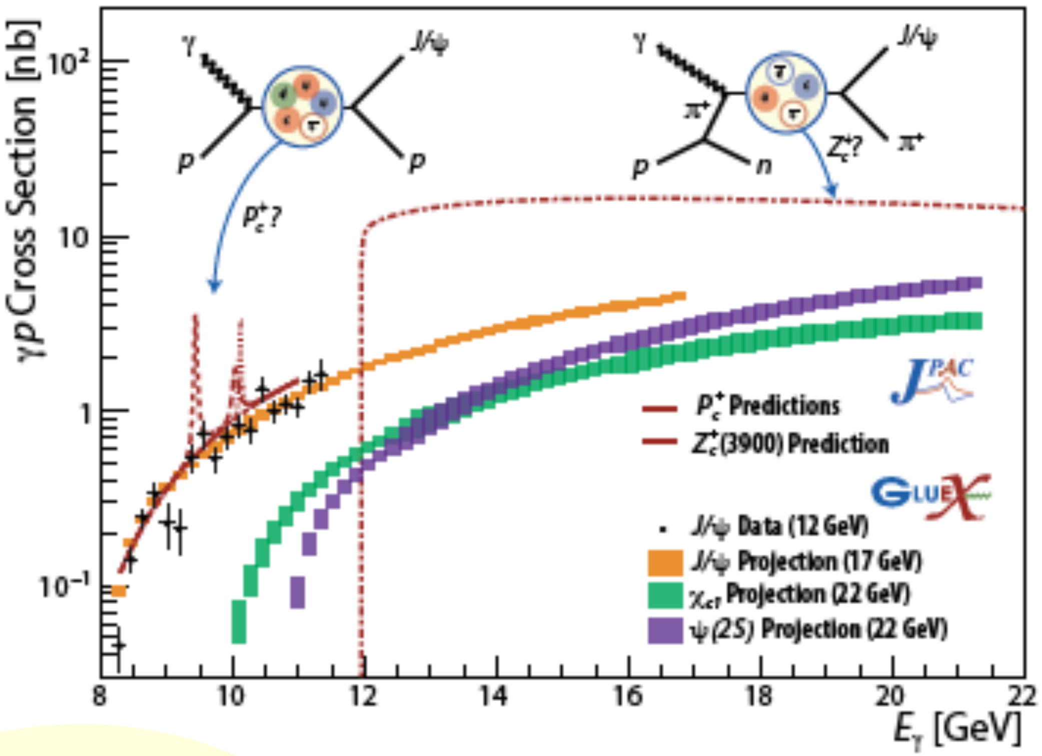


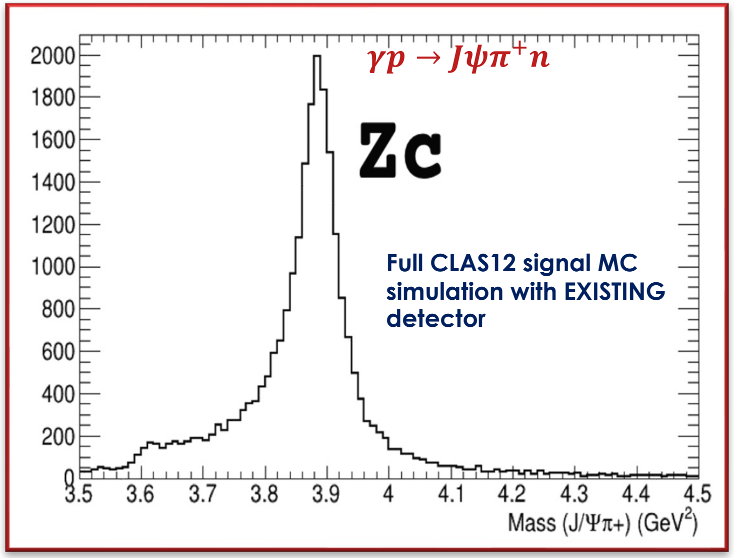
Interpretation of data is complicated by nonresonant $D^{*-}D \to J/\psi\pi^-$ scattering that can produce peaks in invariant mass spectra for certain choices of E_{cm} and π^+ momentum that result in a $D^{*-}D$ interaction. These peaks are effects of initial state kinematics and do not require a resonance in $\pi^- J/\psi$.

Spectroscopy of Exotic States with $c\bar{c}$

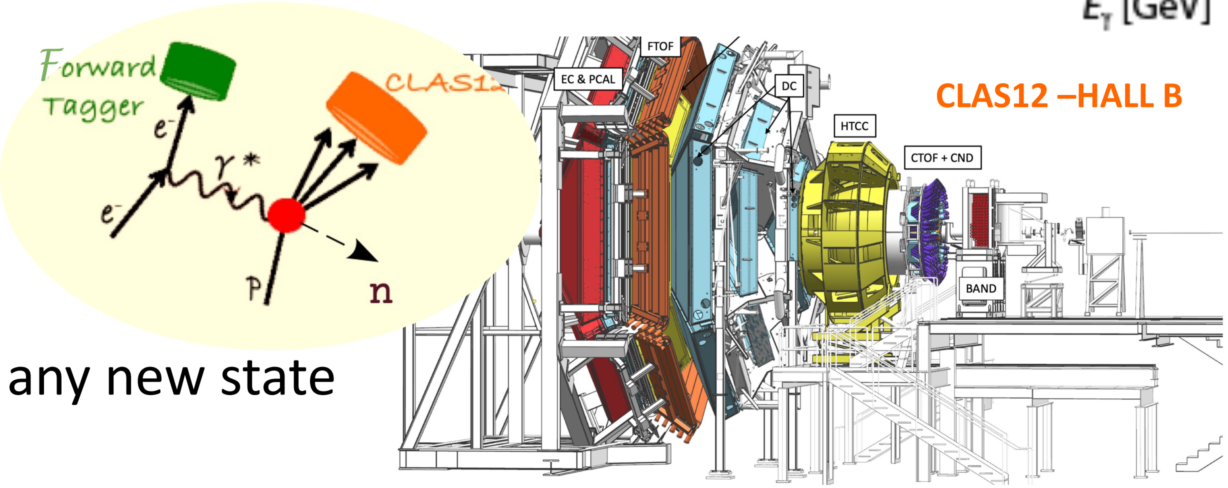
- **Never direcly produced using γ/lepton beam**
- Direct probe of the $Z_c \rightarrow J/\psi\pi$ coupling without re-scattering effects
- **Photoproduction** tool already used to validate the existence of **charmed 5quark**.
- With an energy upgraded CEBAF, this line of investigation can be **extended to other exotic candidates.**

GlueX-Hall D





e⁻ 2.5-4.5° →
Q^2<0.03 (GeV/c)²



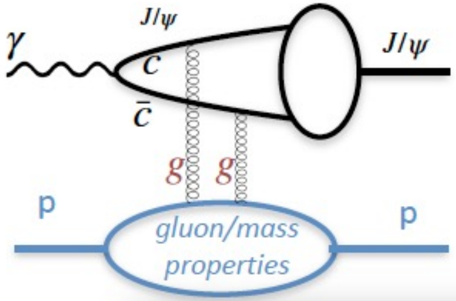
CLAS12 –HALL B

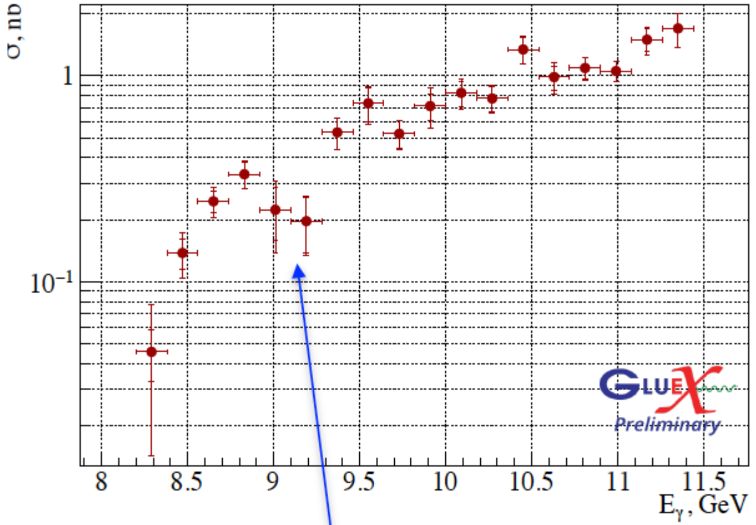
- **Q^2 evolution** of any new state produced

J/ψ photoproduction near threshold

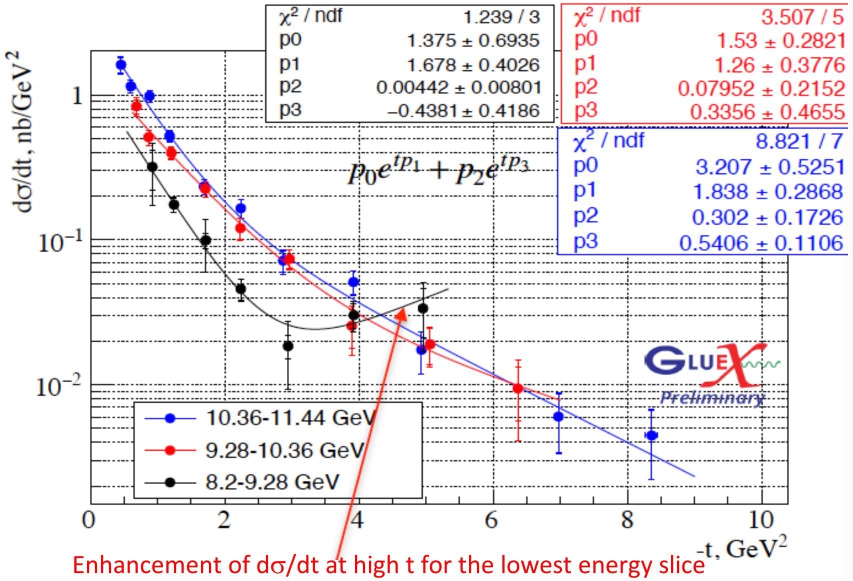
- **Near-threshold J/ψ photoproduction:**
  a tool to access the gluonic content of the nucleon
  (mass radius, nucleon mass, gravitational FFs, etc)

..based on some assumptions (mainly gluon exchange)

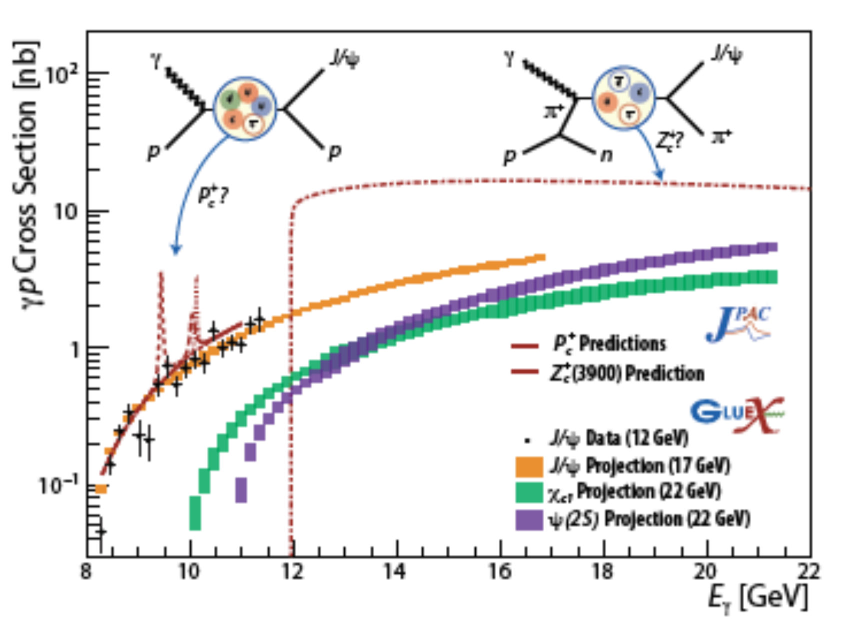




Possible structure at $\Lambda_c\bar{D}^{(*)}$ threshold σ(8.6-9.6) GeV



Enhancement of dσ/dt at high t for the lowest energy slice



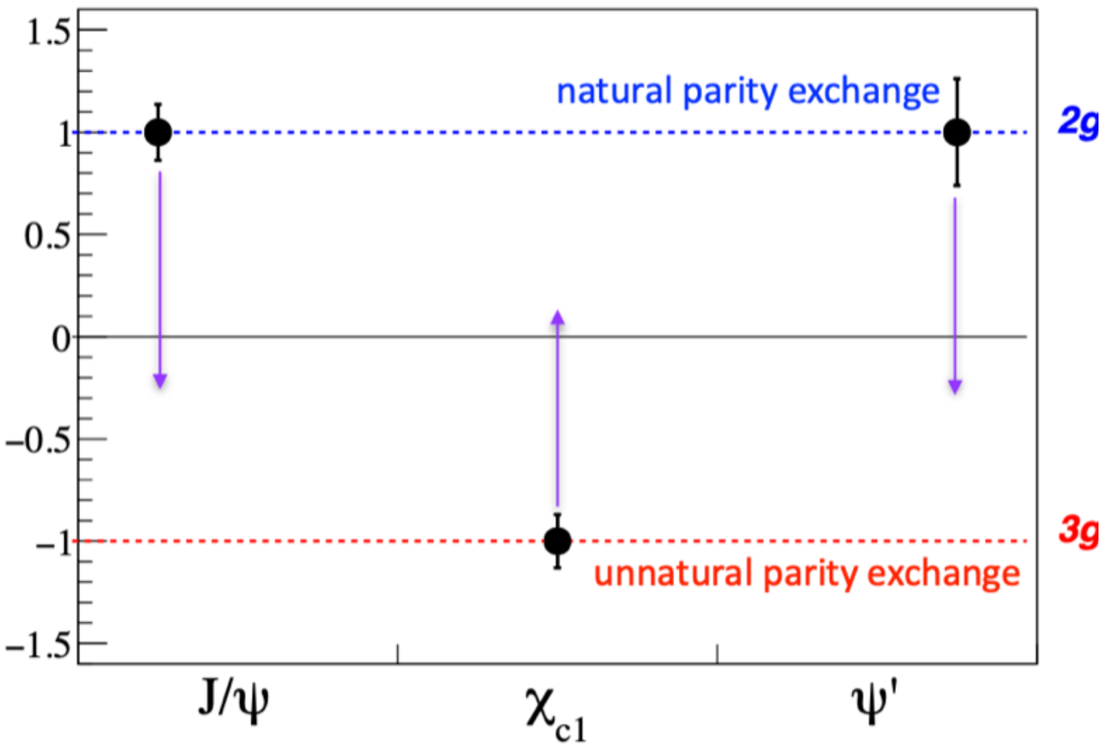
- In general, consistent with the t-channel production via gluon-exchange but current experimental precision is not sufficient to completely rule out alternative interpretation of the data.

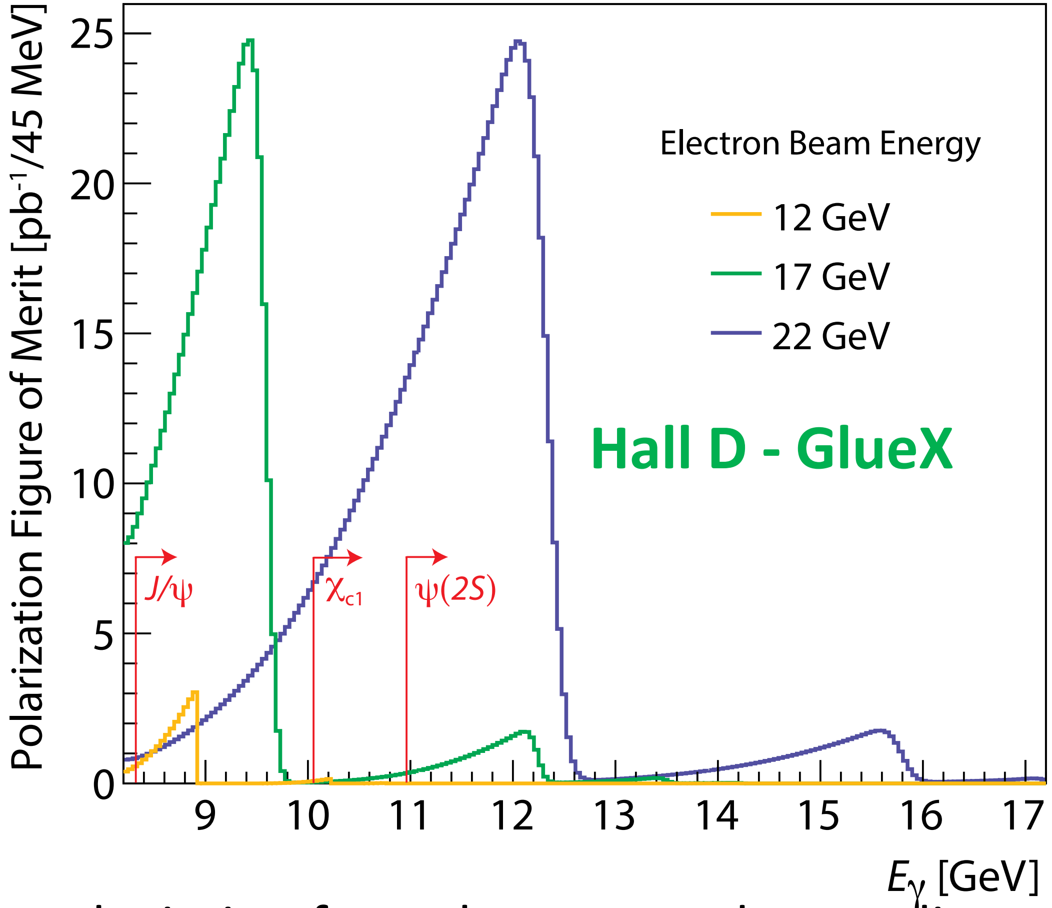
- Similar precision with the SoLID detector in Hall A

J/ψ Photoproduction – Polarization

- Energy upgrade gives significant increase of polarization FOM, allowing unique studies of the gluon exchange for J/ψ and higher charmonium states

$$naturality \times (-1)^J = P$$

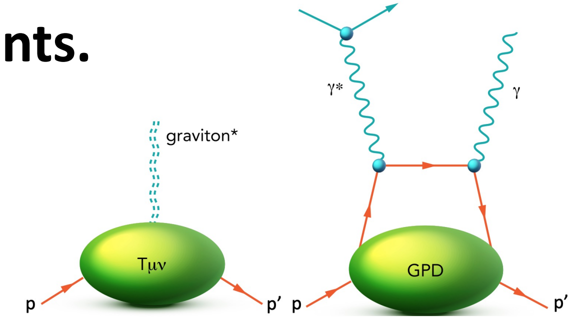




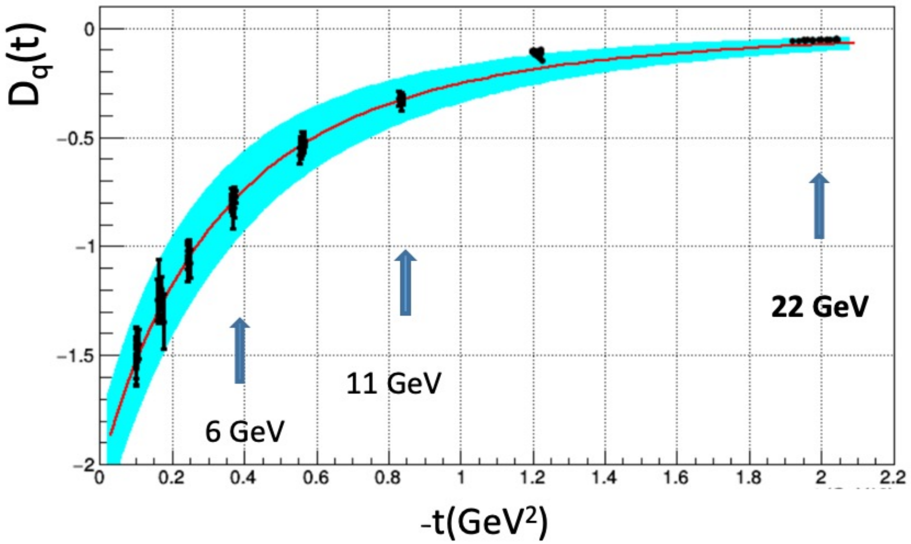
Any deviation from the expected naturality (+ or -1) indicates contribution of mechanism different from what is needed to study mass properties of the proton

Mechanical Properties of the Proton

GFFs : describe how energy, spin, and various mechanical properties of hadrons are carried by quark and gluon constituents.

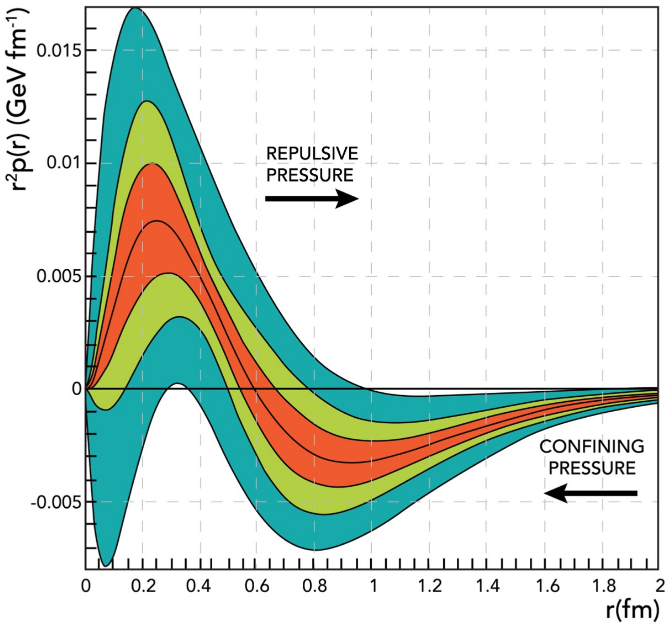


A massless spin-2 field would couple to the stress–energy tensor in the same way that gravitational interactions do

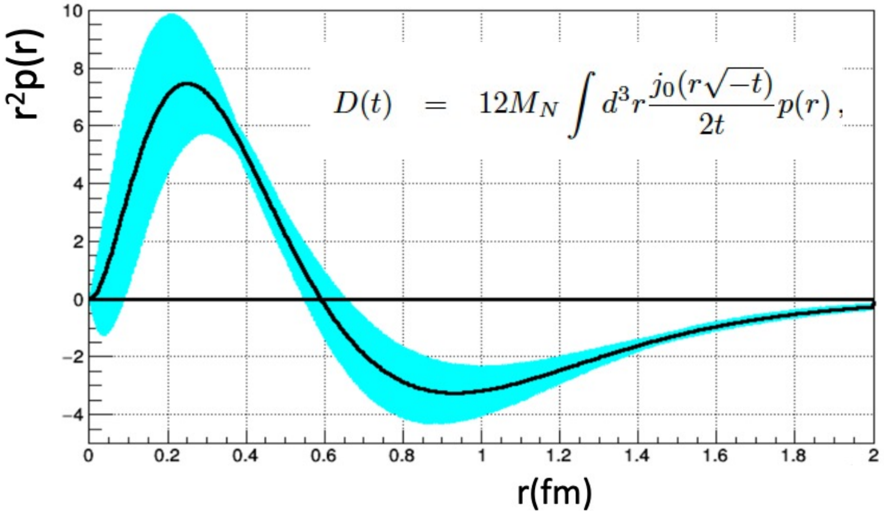


GFF D(t): describes the pressure distribution in the nucleon, accessible through measurements of the CFFs of DVCS

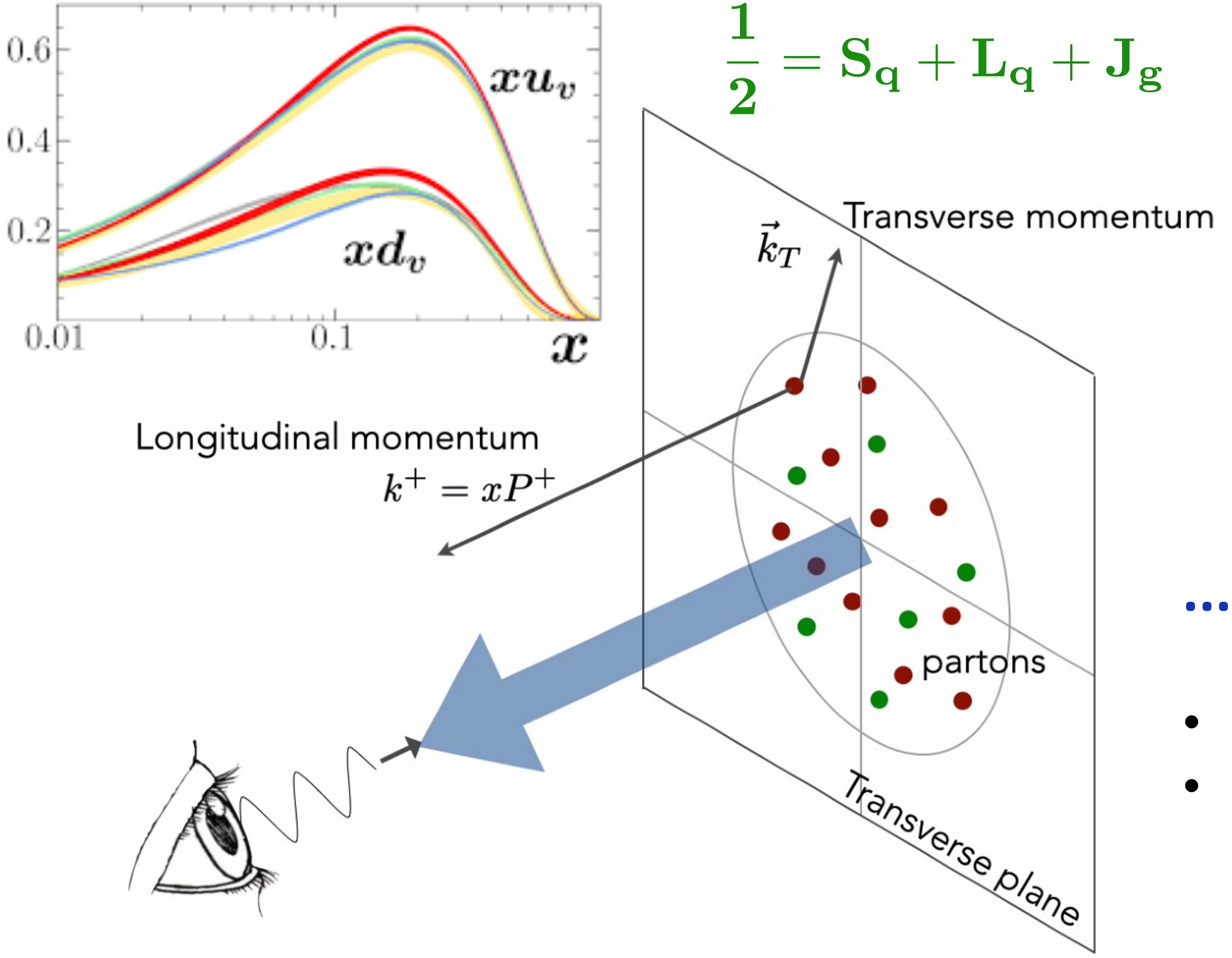
- **A large -t range is required to perform the Fourier transform with controlled uncertainties → high luminosity**



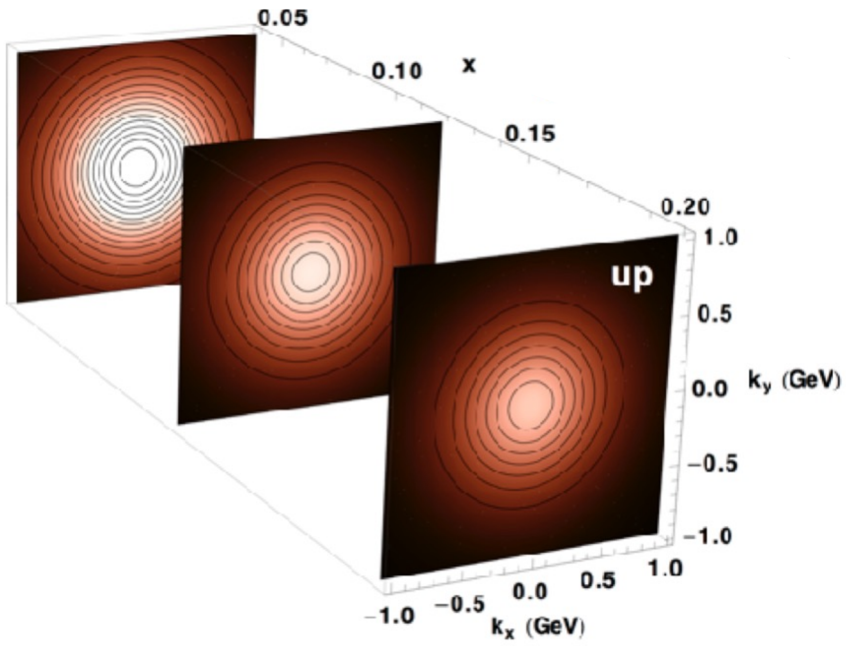
- First experimental extraction of the D(t) term and the determination of the pressure distribution inside the proton obtained with JLab-CLAS DVCS data @ 6 GeV



3D Picture of the Nucleon in Momentum Space (TMD)



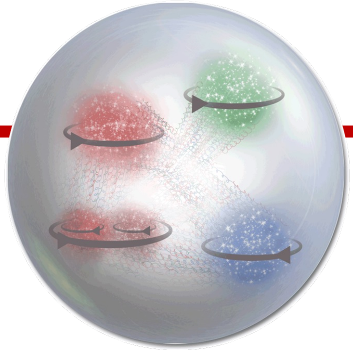
$$\frac{1}{2} = \mathbf{S_q} + \mathbf{L_q} + \mathbf{J_g}$$



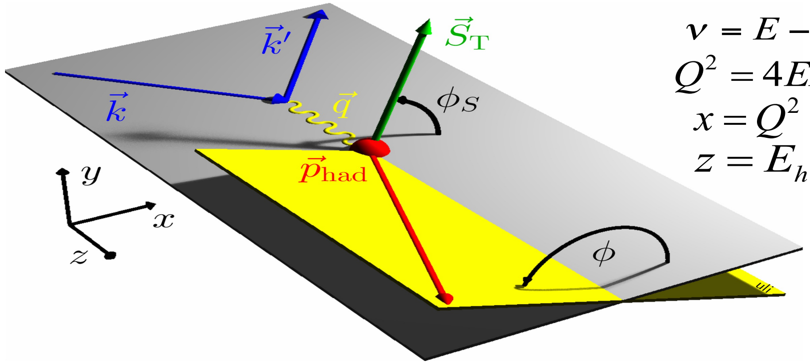
....but there is no free lunch

- More functions in the x-section
- More variables for each function
  - → Complexity in the extraction
  - → High statistics required

The Nucleon Structure in 3D



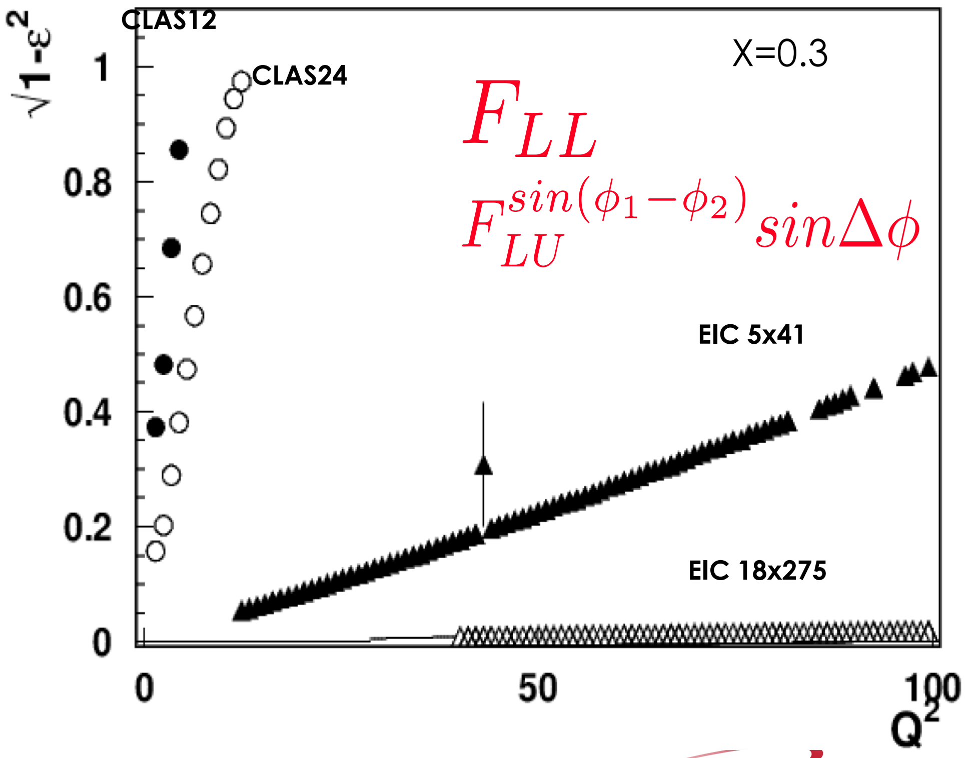
$\sigma = f(x, Q^2, z, P_T)$



$$\nu = E - E'$$
$$Q^2 = 4EE'\sin(\theta/2)$$
$$x = Q^2/2M\nu$$
$$z = E_h/\nu$$

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

ε = ratio of longitudinal and transverse photon flux

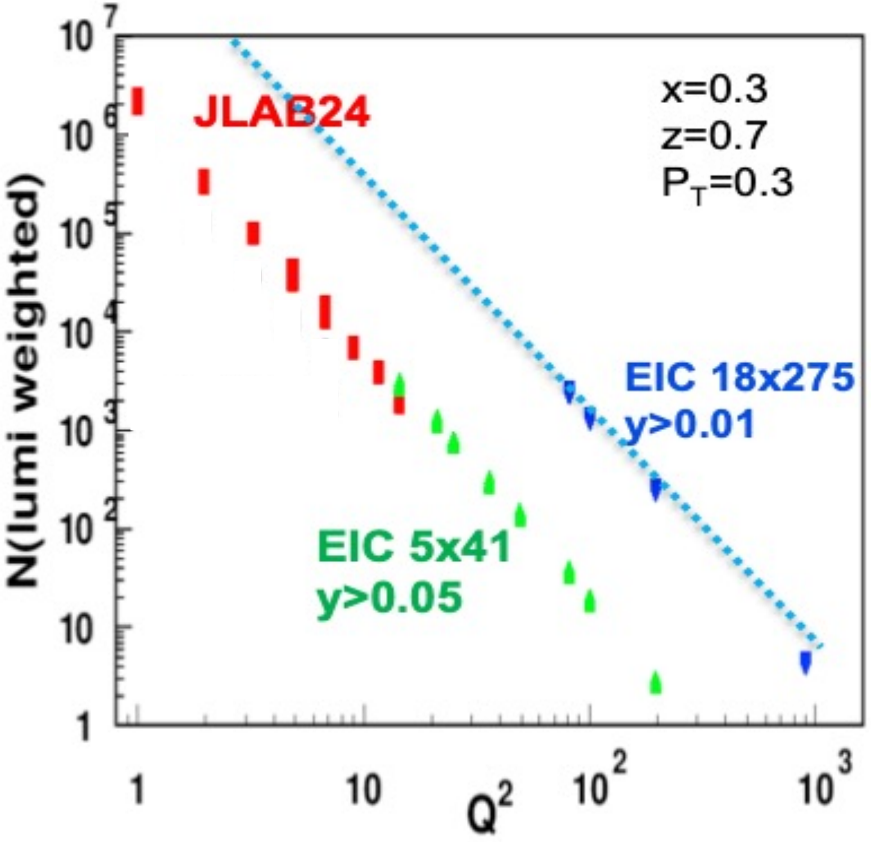


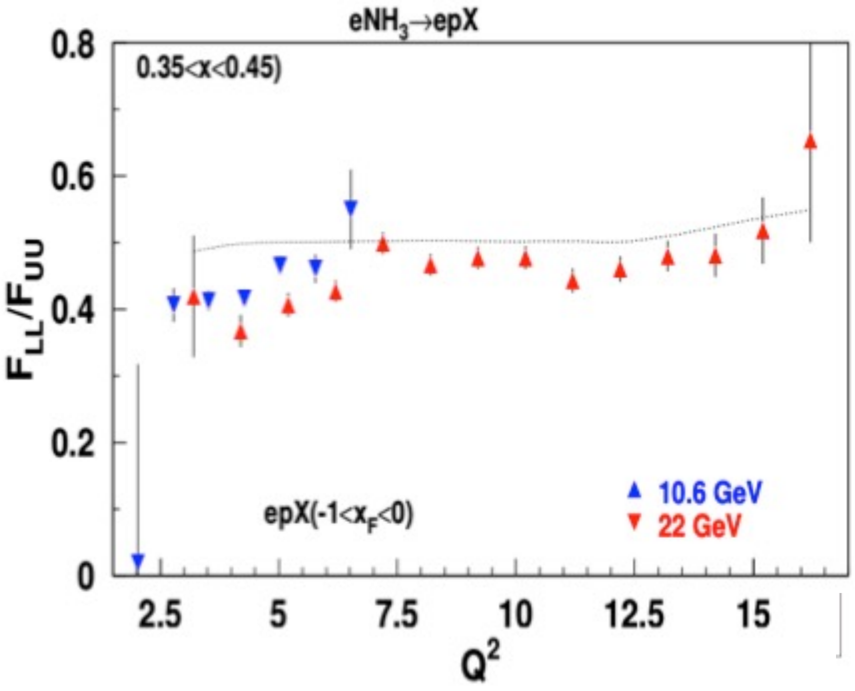
- **At large x fixed target experiments are sensitive to ALL Structure Functions**

Jefferson Lab

SIDIS Phase Space @ 22 GeV

- **Complementarity with EIC**

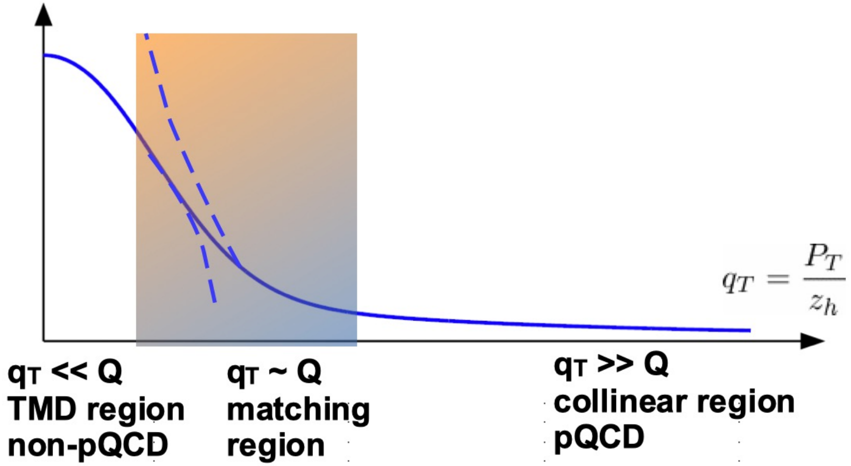


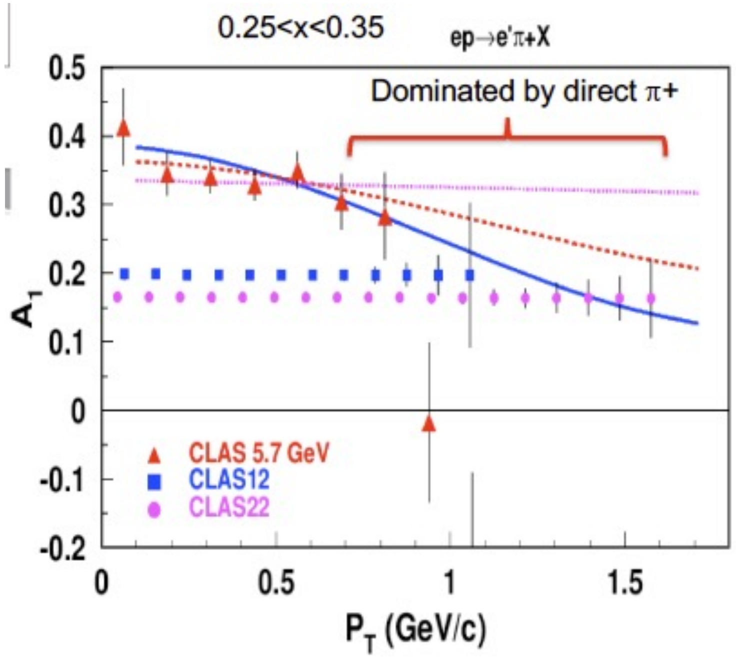


- **Q^2 evolution studies possible**

QCD predicts only the Q^2 dependence

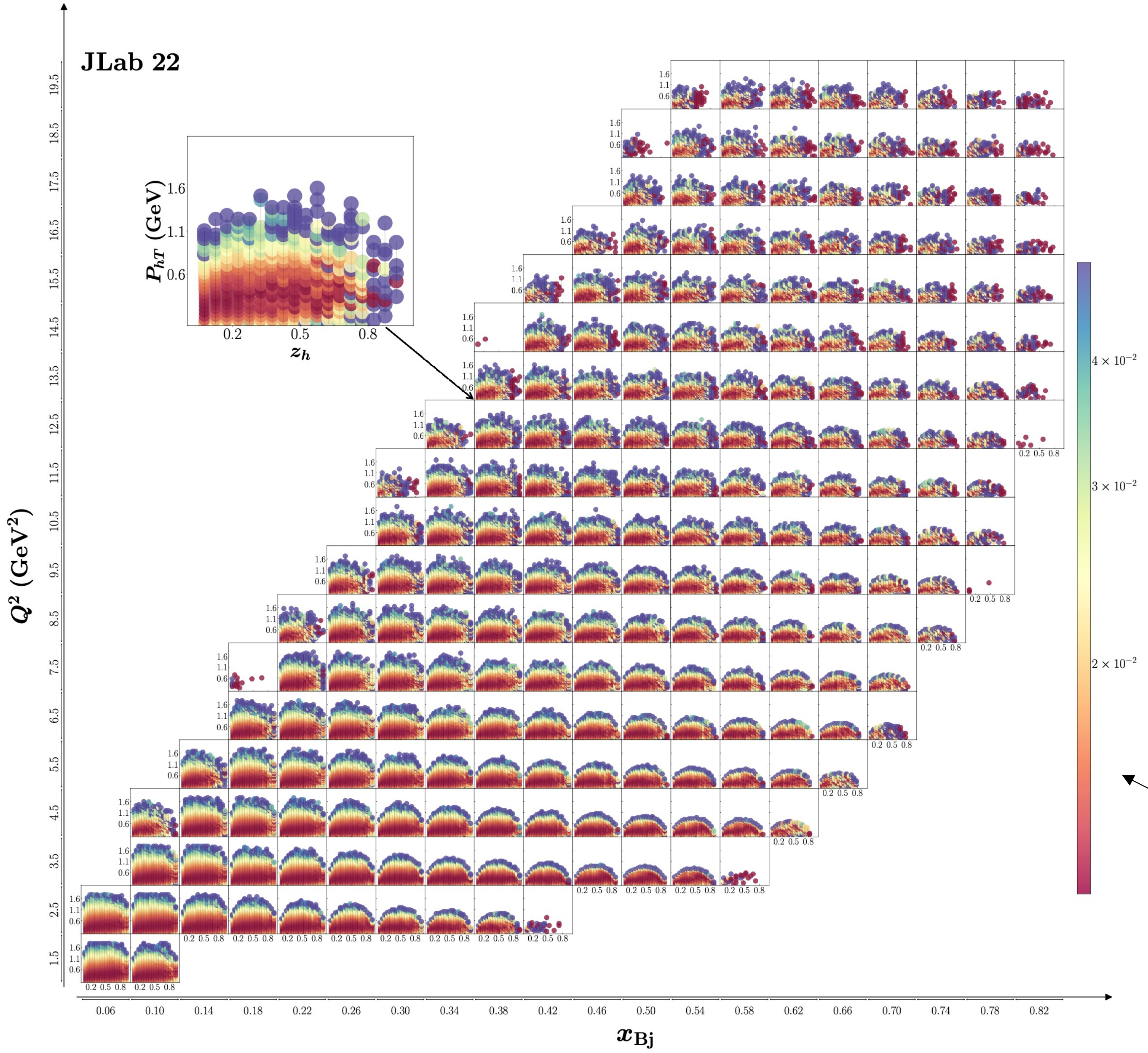
Increase significant the range of high Q^2 to validate/test the theory/phenomenology





- **How does QCD manifest itself in the "matching region"?**

Multi-D phase space at 22 GeV kinematics



- Multi-dimensional coverage of P_T access give access to fine binning of all observables
- Projections using the existing CLAS12 simulation/reconstruction chain for 100 days of running with L= 10^{35} cm^{-2}s−1

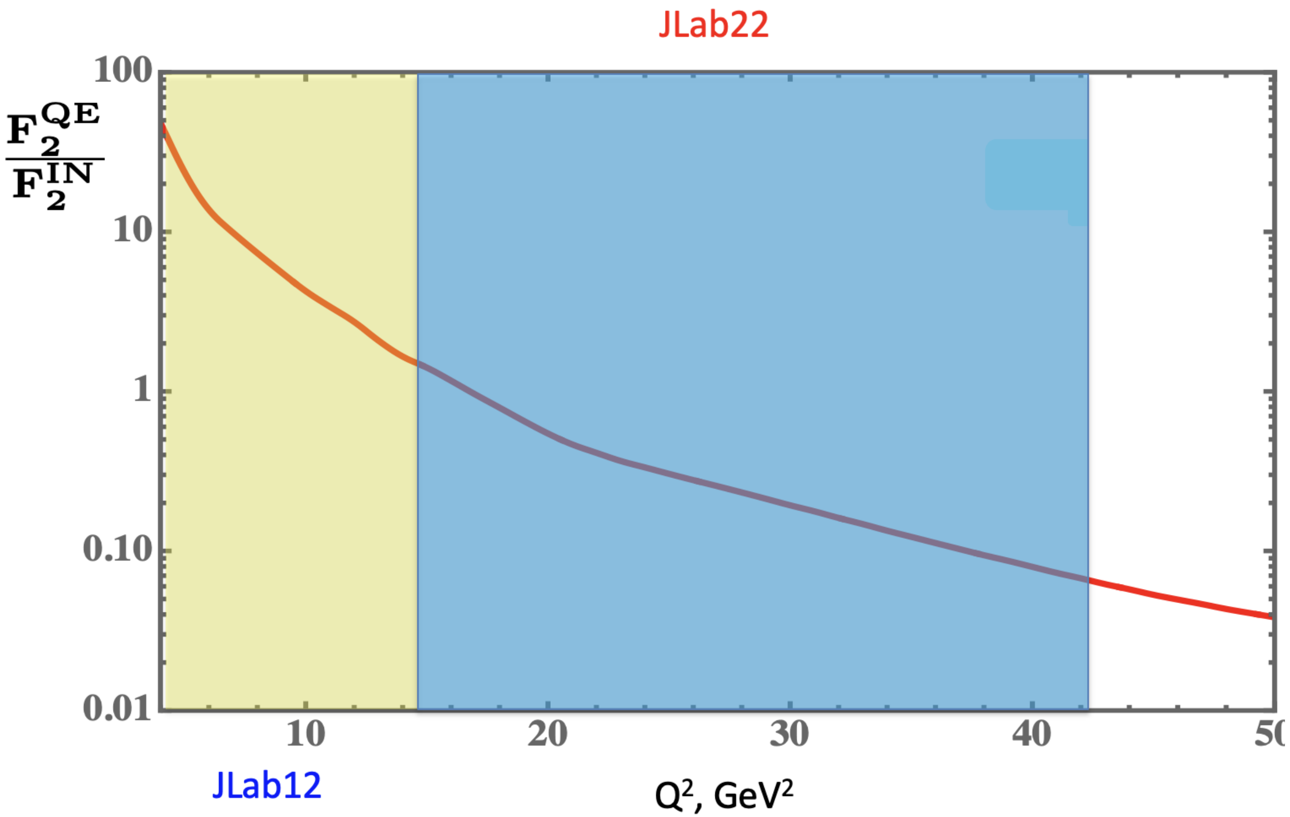
Expected uncertainties for SIDIS cross sections in 4D bins

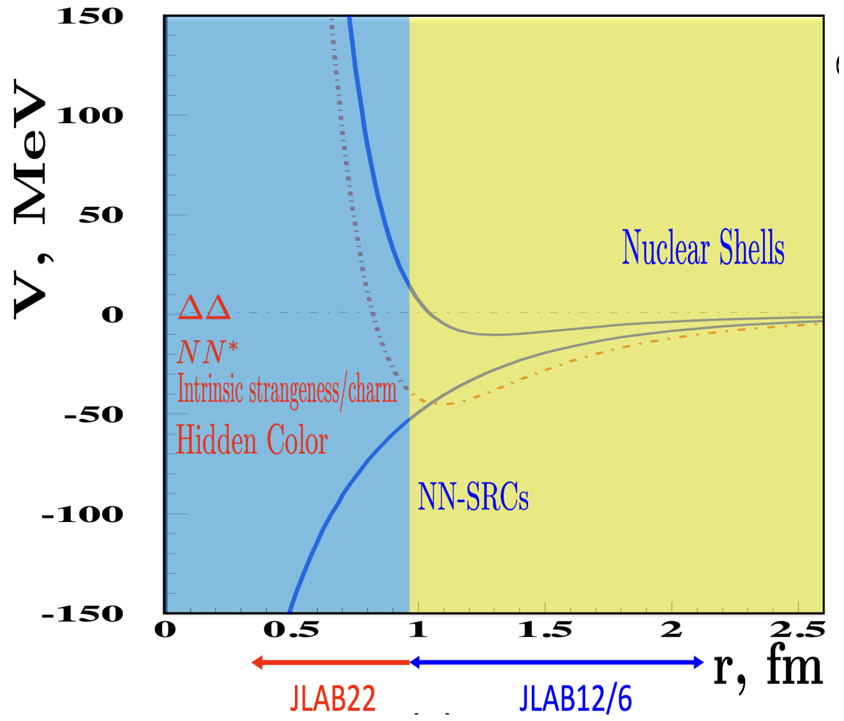
Nuclear Dynamics at Extreme Conditions

The dynamics of the nuclear repulsive core is still poorly understood

- Crucial for understanding the dynamics of transition between hadronic to quark-gluon phases of matter
  - ➔ **evolution of the universe**
  - ➔ **dynamics of superdense matter at the cores of neutron stars**

A 22 GeV upgrade will provide reach to the nuclear forces dominated by nuclear repulsion



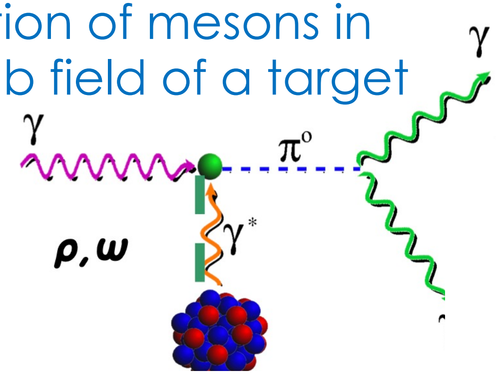


- **Superfast Quarks**

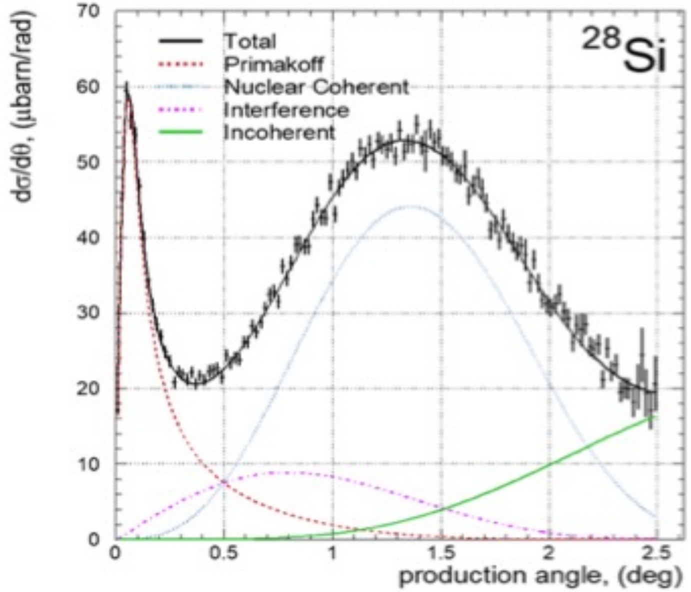
  The high Q^2 reach will allow
  - the suppression of quasi-elastic contributions,
  - the first-ever direct study of nuclear DIS structure function at Bjorken x > 1.2 (r~ 0.5 fm,)

QCD Confinement and Fundamental Symmetries

- γ/e-production of mesons in the Coulomb field of a target



PrimEx-II: $\gamma + {}^{28}Si \rightarrow \pi^0 + {}^{28}Si$



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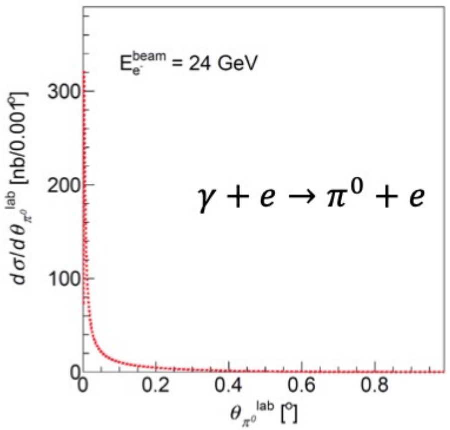
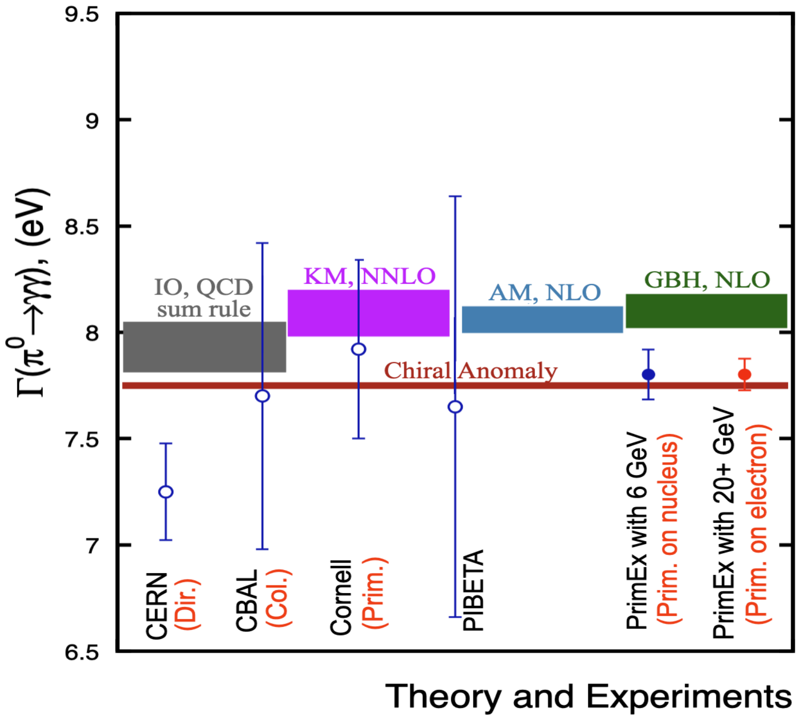
- **π^0 Primakoff production off an electron target**



Measurement	Reaction	E_{th} (GeV)
$\Gamma(\pi^0 \rightarrow \gamma\gamma)$	$\gamma + e \rightarrow \pi^0 + e$	18.0
$F(\pi^0 \rightarrow \gamma^*\gamma)$	$e + e \rightarrow \pi^0 + e + e$	18.1

π^0 Primakoff off an e- target: eliminate nuclear bkg

- **π^0 radiative decay width**: can be predicted at ≈ 1% precision in the low energy QCD



CEBAF FFA Upgrade – Baseline under Study

- Starting with 12 GeV CEBAF
- NO new SRF (1.1 GeV per linac)
- New 650 MeV recirculating injector
- Remove the highest recirculation pass (Arc 9 & A) and replace them with two FFA arcs including time-of-flight chicanes
- Recirculate 4 + **6.5** times to get to **22 GeV**

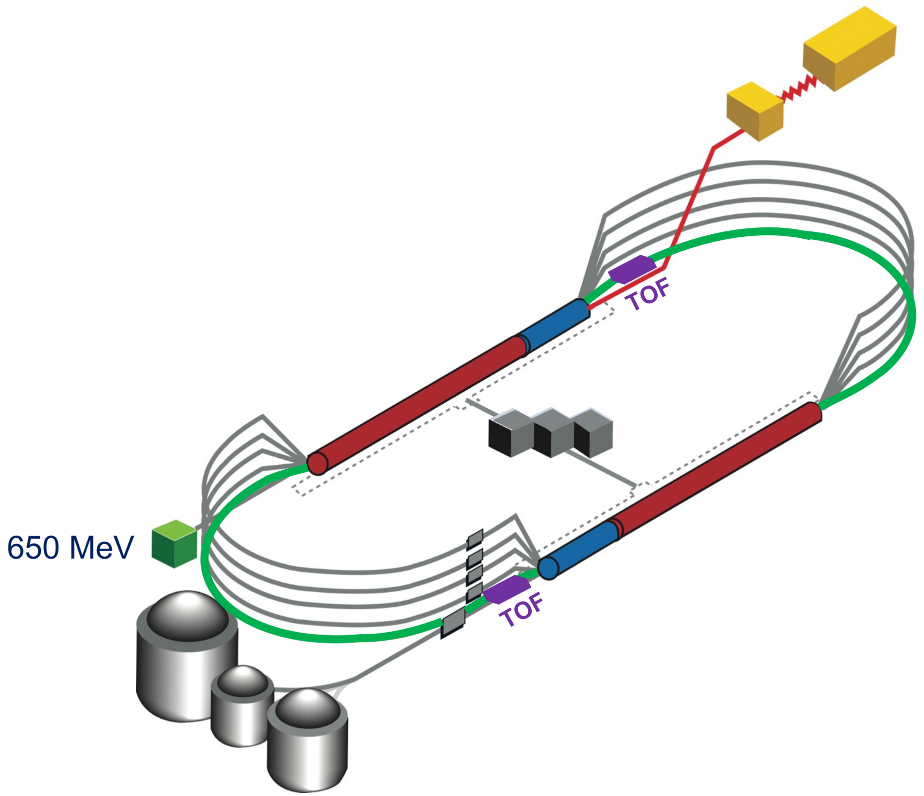
Pass Arithmetic: **5** -1 + **6.5** = **10.5**

Synchrotron Radiation impact on beam quality

Net transverse emittance dilution (normalized): **150μm**

Net natural energy spread: **2×10^{-3}**

Net synchrotron radiated energy: **1 GeV**

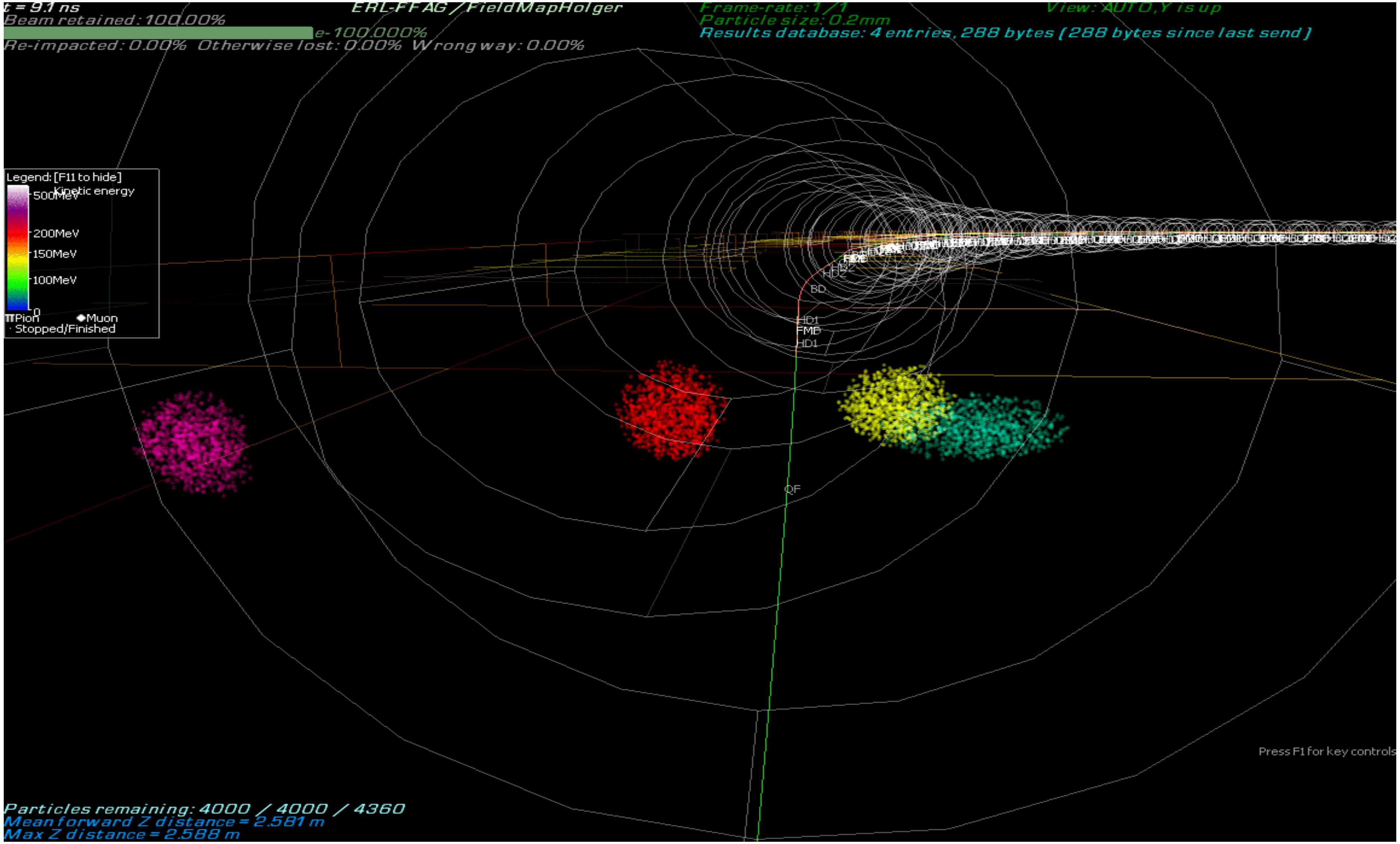


Enabling Technology:

Novel permanent magnets, CBETA-like used for power and cost savings

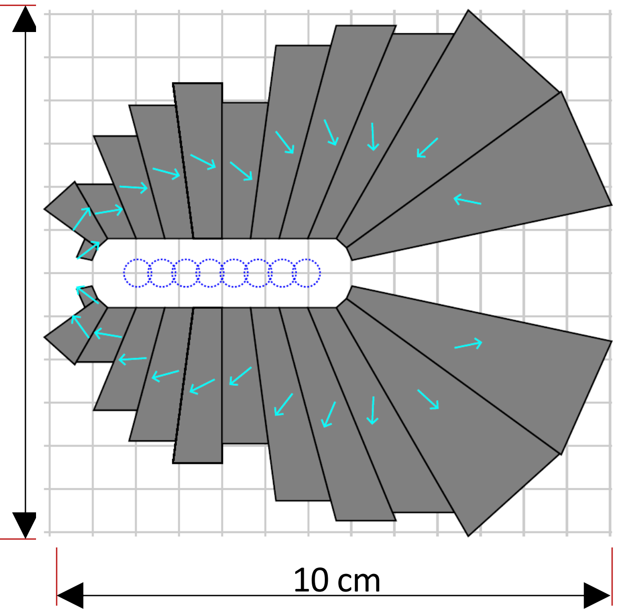
Courtesy A. Bogacz

Multi-Bunch Dynamics in CBETA FFA Arc



 Courtesy A. Bogacz

Permanent Magnet Design – Open Mid-plane Geometry

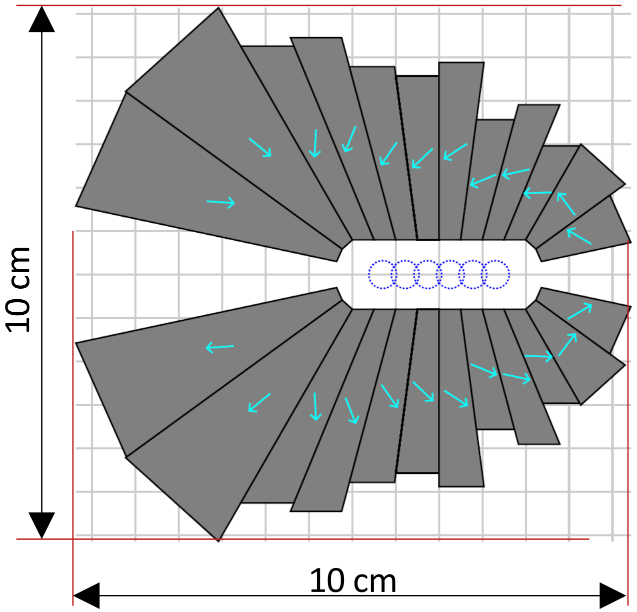


Focusing Magnet BF

G_F= -41.13 T/m

L_{QF}= 1.67 m

B_F= -0.812 T

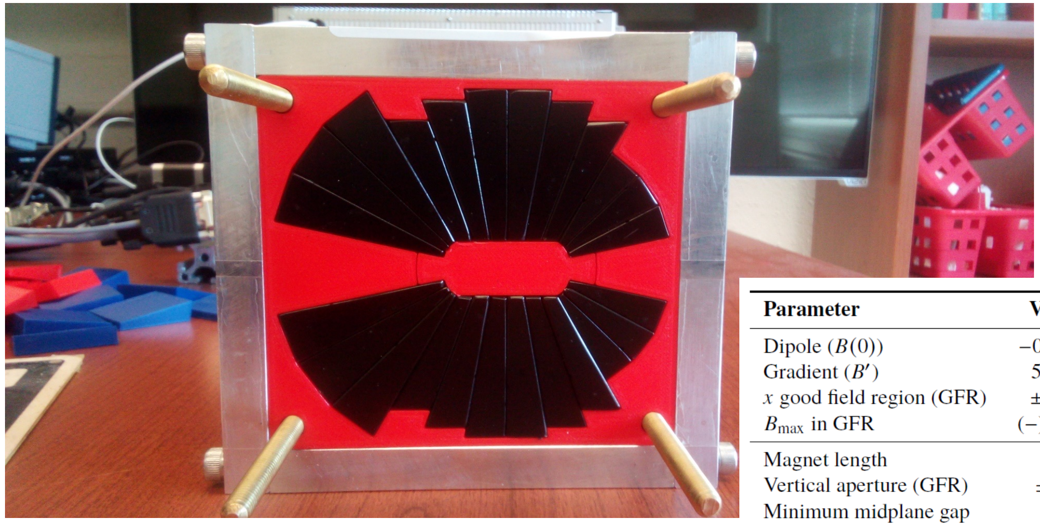


Defocusing Magnet BD

G_D= 43.44 T/m

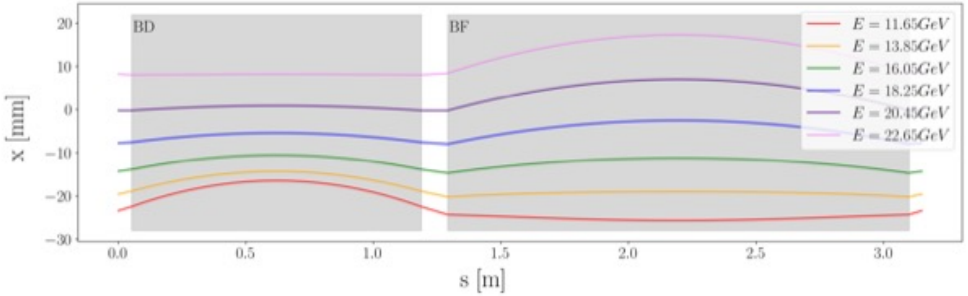
L_{BD}= 1.24 m

B_D= -0.593 T



Courtesy A. Bogacz

Parameter	Value	Unit
Dipole ($B(0)$)	−0.9512	T
Gradient (B')	55.54	T/m
x good field region (GFR)	±10.5	mm
B_{max} in GFR	(−)1.536	T
Magnet length	45	mm
Vertical aperture (GFR)	±7.5	mm
Minimum midplane gap	±3	mm
Material	NdFeB	
Grade	N42EH	
B_r	1.28–1.33	T
$\mu_0 H_{cJ}$	2.9	T



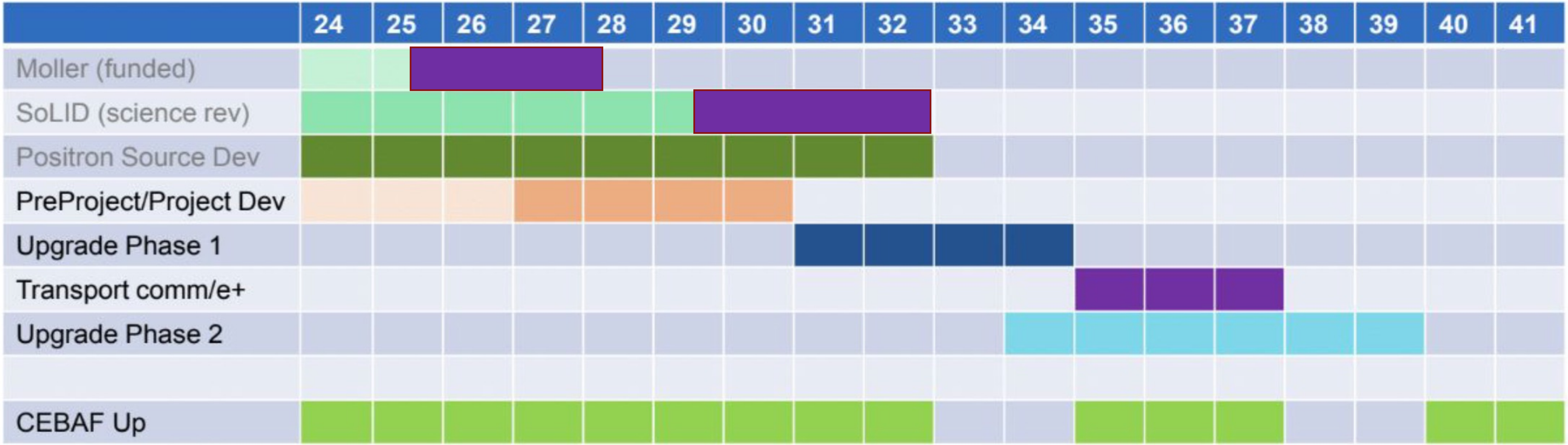
orbits

- **Each cell: 1 BF +1 BD, total length = 3.15 m**
- **Each arc: 70 cells**

- **A prototype open midplane BF magnet was built and evaluated for mechanical integrity.**
- **Magnetic measurement confirmed a robust design with >1.5 Tesla in good field region, 10^{-3} field accuracy.**
- **Radiation resilience tests will be carried out at CEBAF**

VERY ROUGH Timeline

Gantt chart to give a rough idea when these project could become a reality.



Phase 1 includes building the positron source and the tunnel & beamline connecting the source to main machine.
Phase 2 includes the new permanent magnets to allow 22 GeV within current CEBAF footprint.

NOTE: Plan was formulated so that these projects are ramping up as the EIC project cost is ramping down.

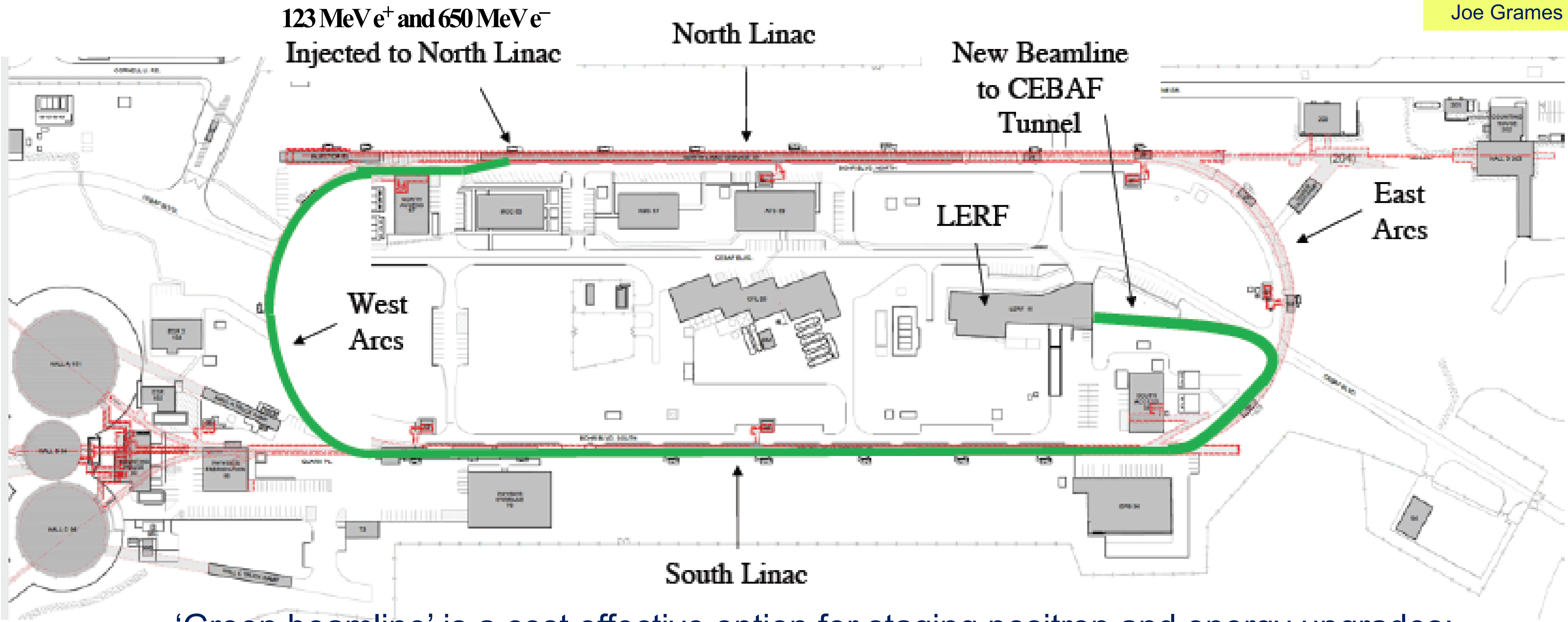
Conclusions and Outlook

- Understanding the strong interaction dynamics of non-pQCD and ``how'' hadrons/nuclei emerge from fundamental QCD principles, is a complex problem
- This complexity requires to observe the chromodynamic fields ``at work'' through multiple observables using different approaches and measurements
- With CEBAF at higher energy some important thresholds would be crossed and an energy window which sits between JLab @ 12 GeV and EIC would be available. This, together with CEBAF uniqueness to run electron scattering experiment at the luminosity frontier **can provide a unique insight into the non-pQCD dynamics.**
- A strong science case for such an upgrade is emerging and it will be presented at the LRP

Backup

Electron/positron injector vault is required for 12 GeV e+ and 22 GeV e-

Joe Grames



'Green beamline' is a cost effective option for staging positron and energy upgrades:

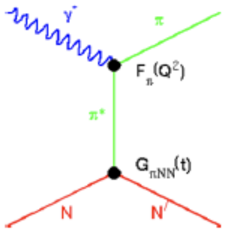
123 MeV e^+ for 12 GeV CEBAF

650 MeV e^- for 22 GeV CEBAF Energy Upgrade

Pion Structure Studies with Exclusive Measurements

- 1) Determine the pion form factor, F_π to high Q^2
- F_π is a key QCD observable
- Measure F_π indirectly using pion cloud of the proton via $p(e, e'\pi^+)n$

$$|p\rangle = |p\rangle_0 + |n\pi^+\rangle + \ldots$$

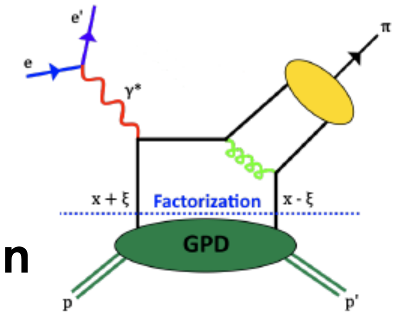


- Pion FF good observable for study of interplay between hard and soft physics in QCD

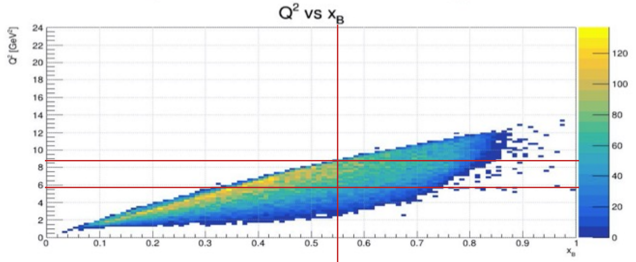
F_π asymptotic behavior rigorously calculable in pQCD
F_π Q^2<0.3 measured

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)} g^2_{\pi NN}(t) F_\pi^2(Q^2,t)$$

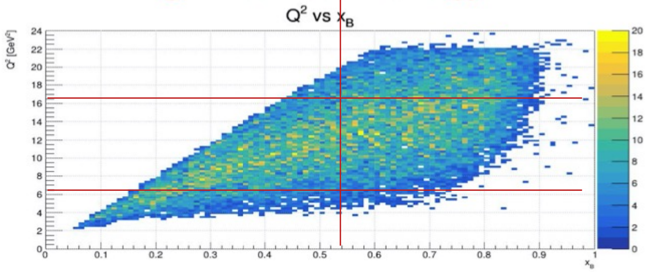
- 2) Study the hard-soft factorisation regime
- Determine region of validity of hard-exclusive reaction mechanism
- Can only extract GPDs where factorisation applies



@ 10.6 GeV beam energy



@ 22 GeV beam energy



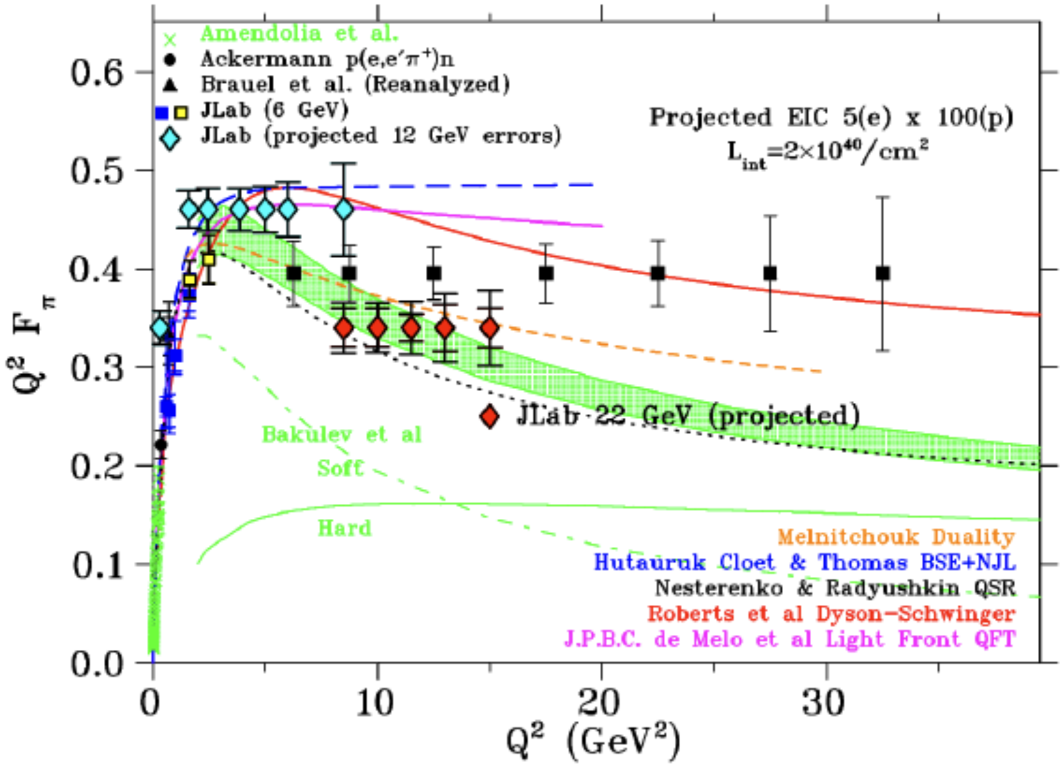
One of the most stringent tests of factorization is the x-section Q^2 dependence

- σ_L scales to leading order as Q^{-6}
- σ_T expectation as Q^{-8}
- As Q^2 becomes large: $\sigma_L >> \sigma_T$

All these studies require σ_L/σ_T separation

JLab22 F_π Data in the EIC Era

- L-T separations not possible at the EIC
- JLab will remain **only** source of quality L-T separated data!
- Phase 2 with upgraded HMS (VHMS)
  - Extends region of high quality F_π values to $Q^2 = 13\ GeV^2$
  - Larger error point at $Q^2 = 15\ GeV^2$



- JLab energy upgrade and Hall C upgrade provides much improved overlap of F_π data between JLab and EIC

Talk by S. Kay
APS GHP 2023
14/04/23

Jefferson Lab

Partonic Structure and Spin

Nucleon Strangeness

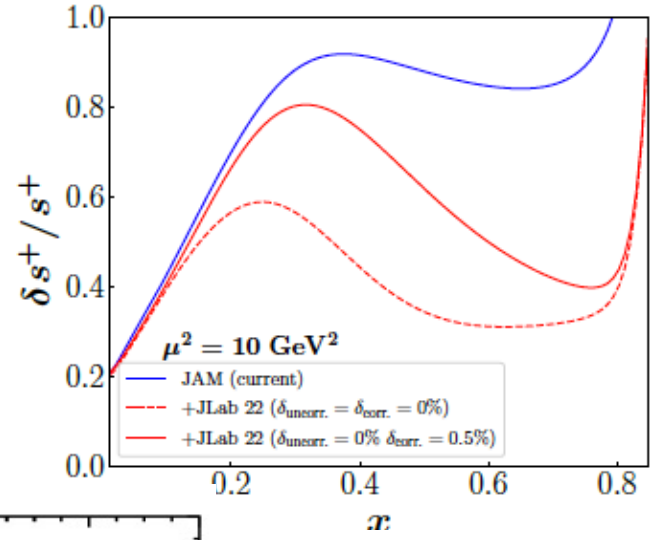
- The nucleon strange sector is largely unexplored with an up to 80% uncertainty in the $s^+ = s + \bar{s}$ PDF

Substantial improvement with a reduction in the s+ uncertainty that can reach more than a factor two at large-x

- **Precision extraction of $\sin^2\theta_W$**

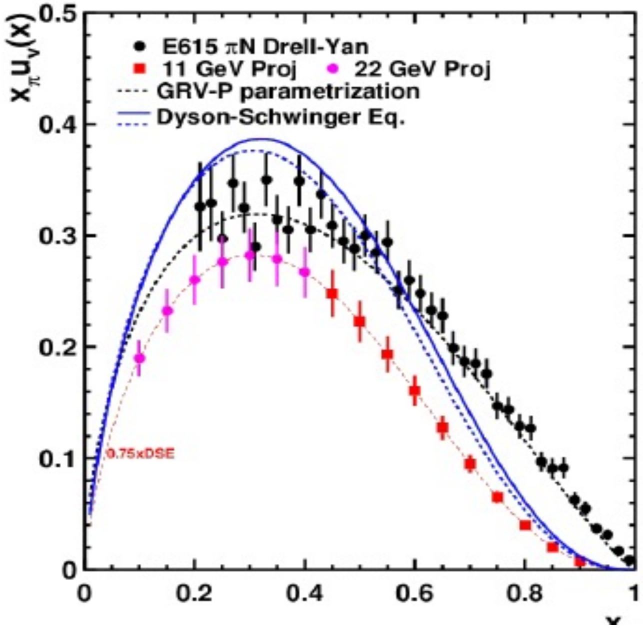
PVDIS @ 22 GeV with the SoLID

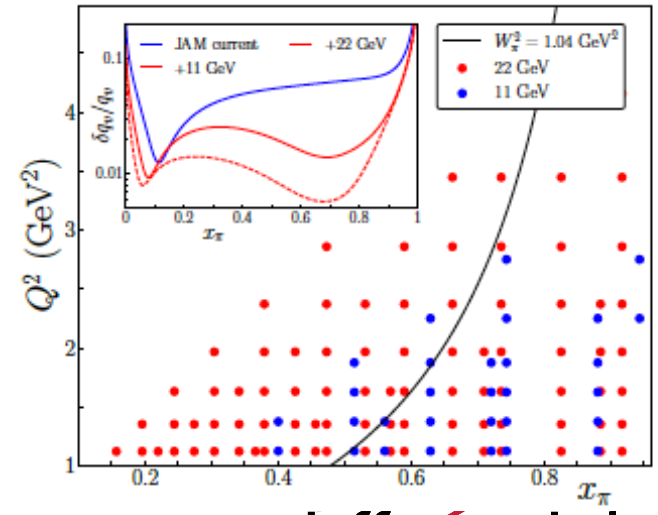
~100 days, 40 μA beam split between 40 cm D and H targets



Meson structure

- Available phase space significantly increased
  ➔ large improvement in the determination of the valence structure of the pion
  ➔ kin. coverage to smaller x_π region to probe the sea content of mesons
- Overlap the existing π induced DY data
  ➔ test the universality of PDFs in the mid to large x_π region





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CEBAF @ 22 GeV

Pass number	Beam Energy [GeV]	ϵ_N^x [mm mrad]	$\sigma_{\frac{\Delta E}{E}}$ [%]
1	2.8	1.0	0.01
2	5.0	2	0.02
3	7.2	4	0.02
4	9.4	12	0.03
5	11.5	20	0.03
6	13.7	21	0.04
7	15.8	23	0.05
8	17.9	26	0.06
9	19.9	34	0.08
10	21.9	49	0.11
10.5	22.9	61	0.12

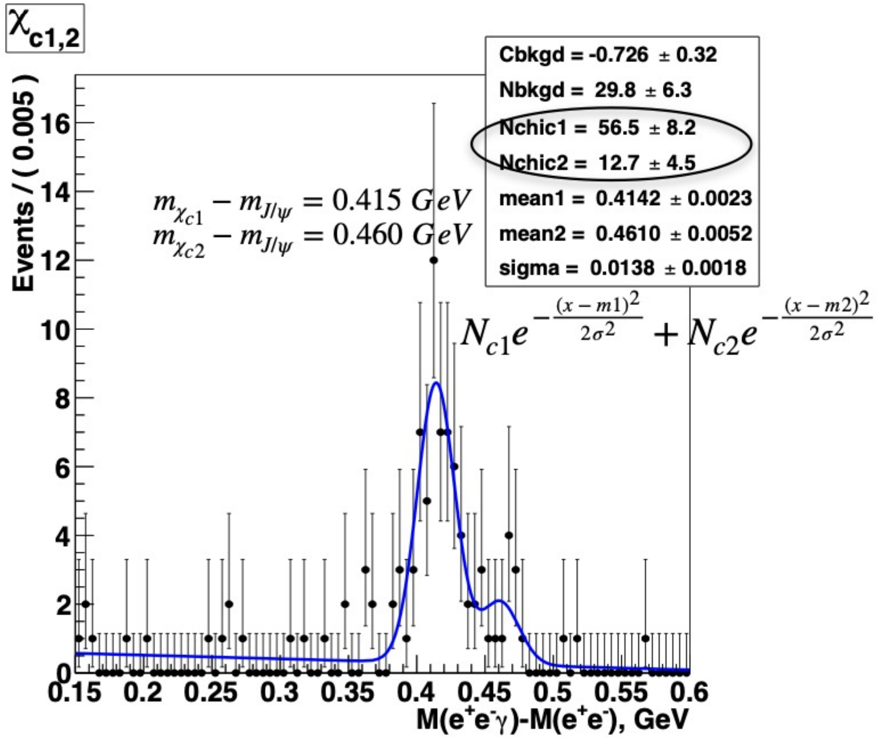
Table 1: The horizontal and longitudinal emittances diluted by synchroton radiation as delivered at various passes. Here, $\sigma_{\frac{\Delta E}{E}} = \sqrt{\frac{\Delta\epsilon_E^2}{E^2}}$.

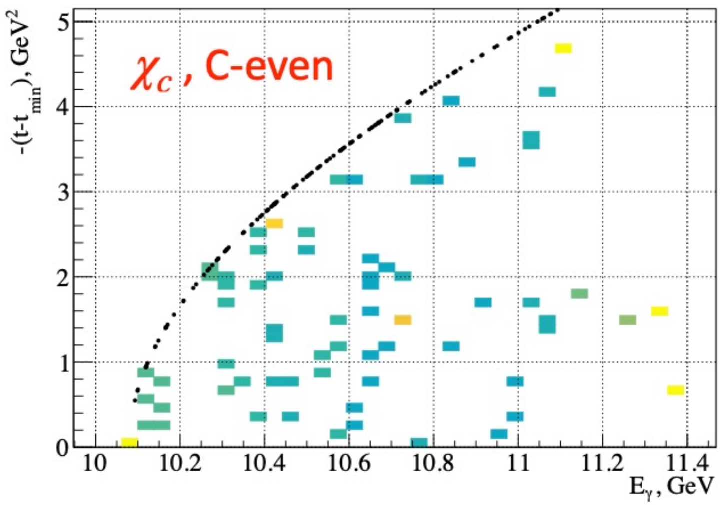
Synchrotron Radiation impact on beam quality

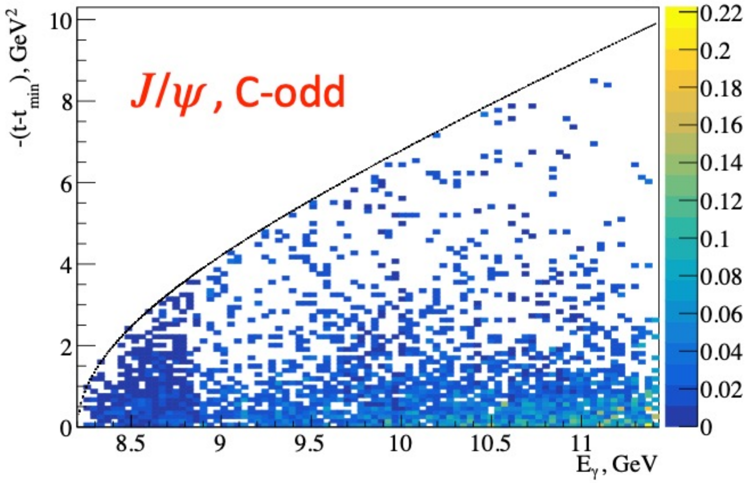
- Net transverse emittance dilution (normalized): **150μm**
- Net natural energy spread: **2×10^{-3}**
- Net synchrotron radiated energy: **1 GeV**

Higher Charmonium States, χ_c and ψ' with GlueX

$$\gamma p \rightarrow \chi_c p \rightarrow (J/\psi\gamma)p \rightarrow (e^+e^-\gamma)p$$







$$weight = \frac{1}{L(E_\gamma)}$$

- $\chi_{c1}(3511)$ and $\chi_{c2}(3556)$, 1^{++} and 2^{++} $(1P)$, $E_\gamma^{thr} = 10.1$ GeV
- C-even charmonium states require 3g-exchange
- Dramatic difference in (E_γ, t) distribution w.r.t J/ψ

- GlueX has observed also a small number of $\psi'(3686)$ $(2S)$ states in $\gamma p \rightarrow \psi' p \rightarrow (e^+e^-)p, \quad E_\gamma^{thr} = 10.9$ GeV