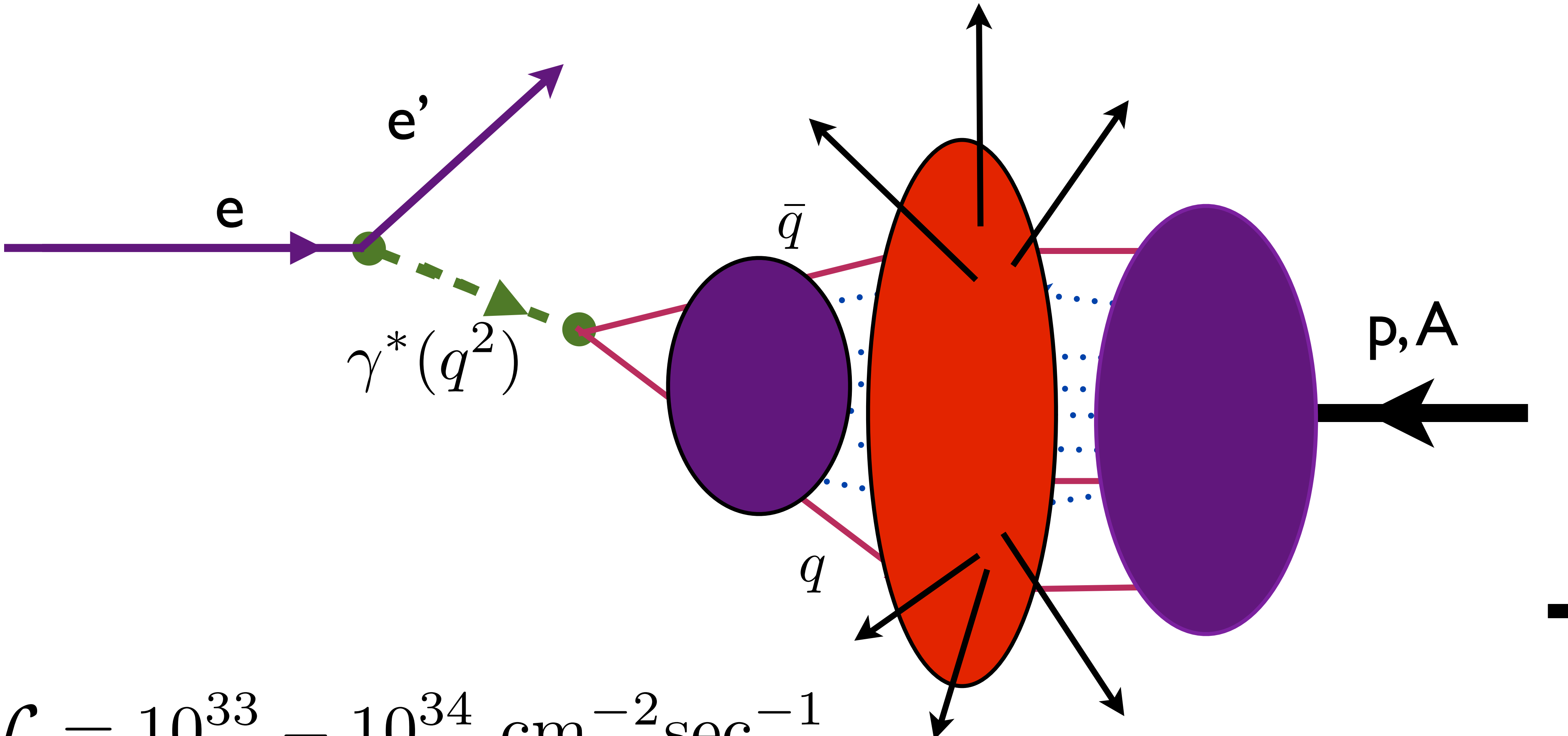
Novel EIC Physics

Perspective from the e-p collider frame



$$\mathcal{L} = 10^{33} - 10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$$

Pre-Town Meeting
August 13, 2014 JLab

Stan Brodsky, SLAC

Novel EIC Physics

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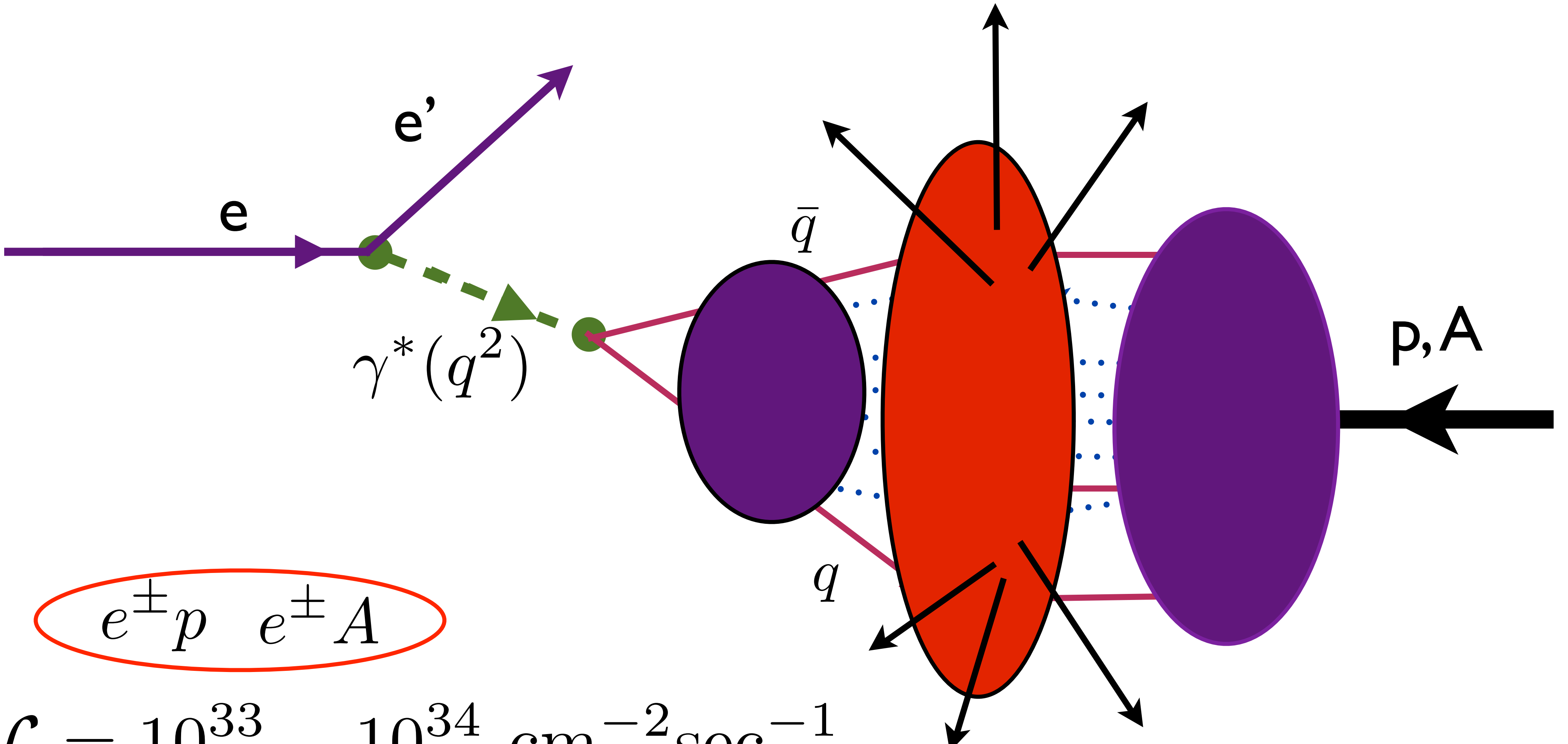


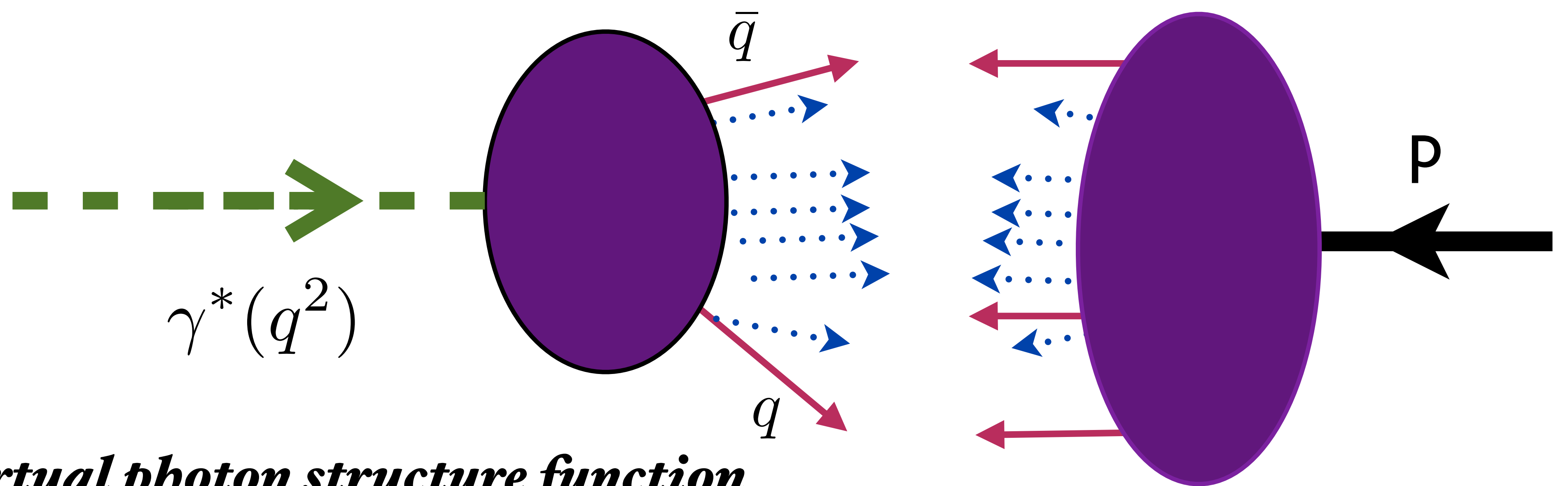
$e^{\pm}p \quad e^{\pm}A$

$$\mathcal{L} = 10^{33} - 10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$$

EIC: Virtual Photon-Proton Collider

Perspective from the photon-proton collider frame

QCD Factorization: Interactions of Light-Front Wavefunctions of photon and proton



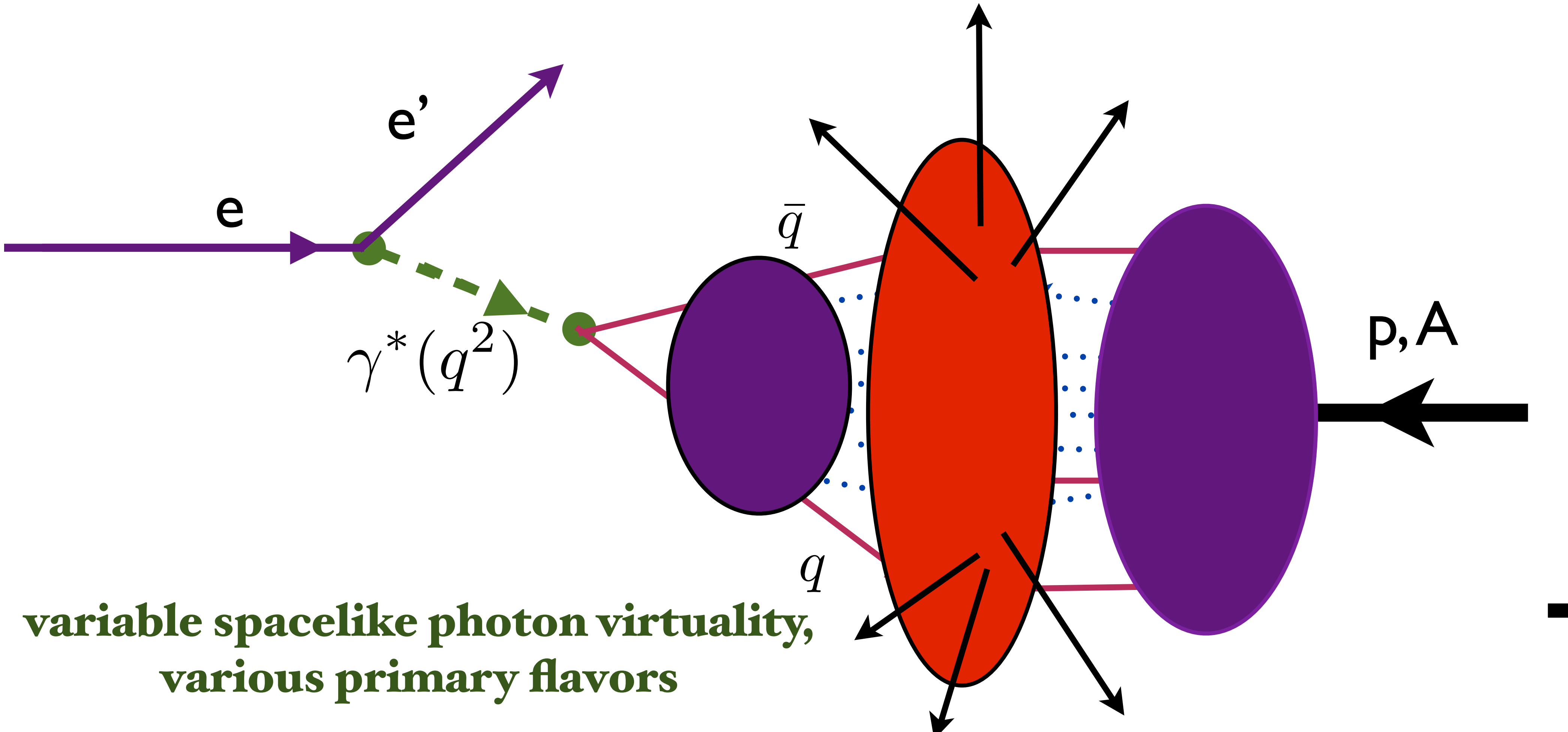
Virtual photon structure function

variable spacelike photon virtuality
various primary flavors

$q\,\bar{q}$ plane aligned with lepton scattering plane ~ $\cos^2\phi$

EIC: Virtual Photon-Proton Collider

Perspective from the e-p collider frame



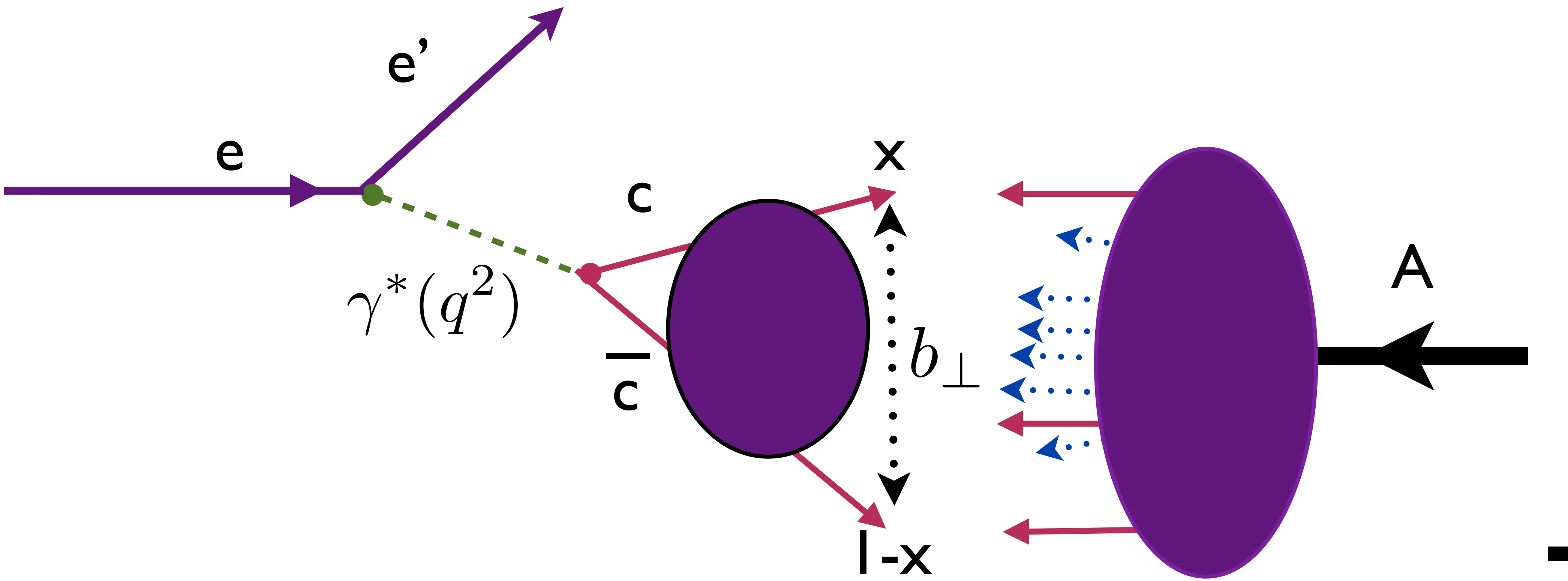
variable spacelike photon virtuality, various primary flavors

photon and proton/nuclear fragmentation vs. central regions

Saturation, nuclear shadowing, antishadowing

$c\,\bar{c}$ and γ^* virtuality act as a 'drill'

$$\langle b_\perp^2 \rangle \sim \frac{1}{Q^2 x(1-x) + M_t^2}$$

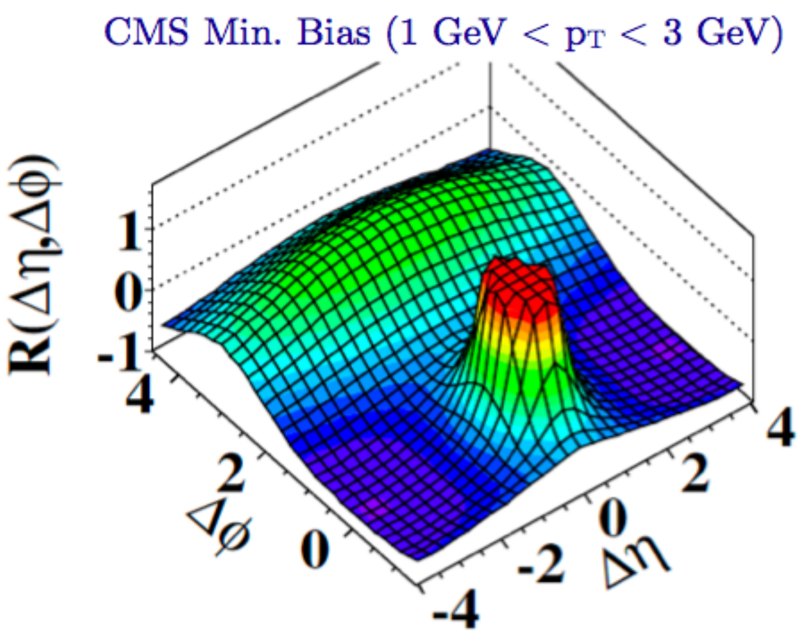


$$\text{Color transparency: } \sigma(\gamma^* p) \propto \pi\alpha\langle b_\perp^2 \rangle$$

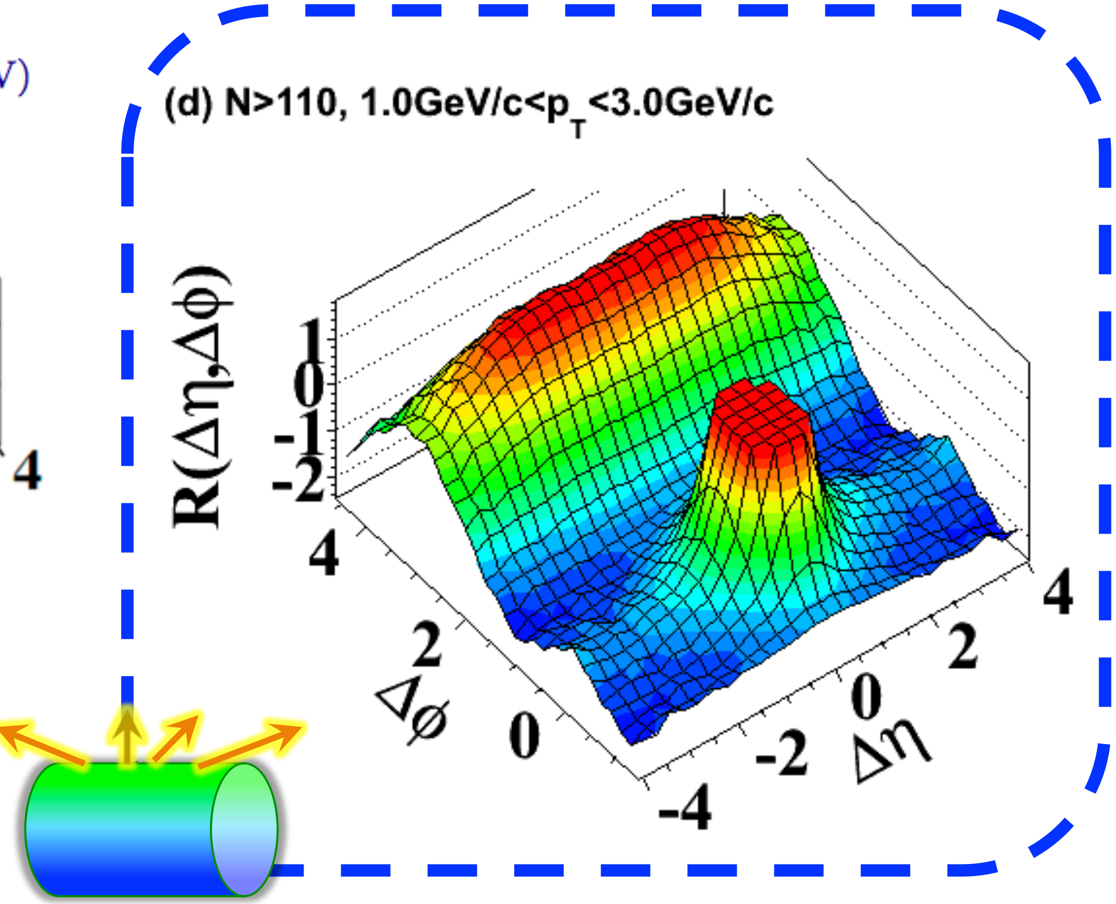
No nuclear shadowing at high Q^2 or M^2_Q

Ridge in p p collisions Raju Venugopalan

Two particle correlations: CMS results



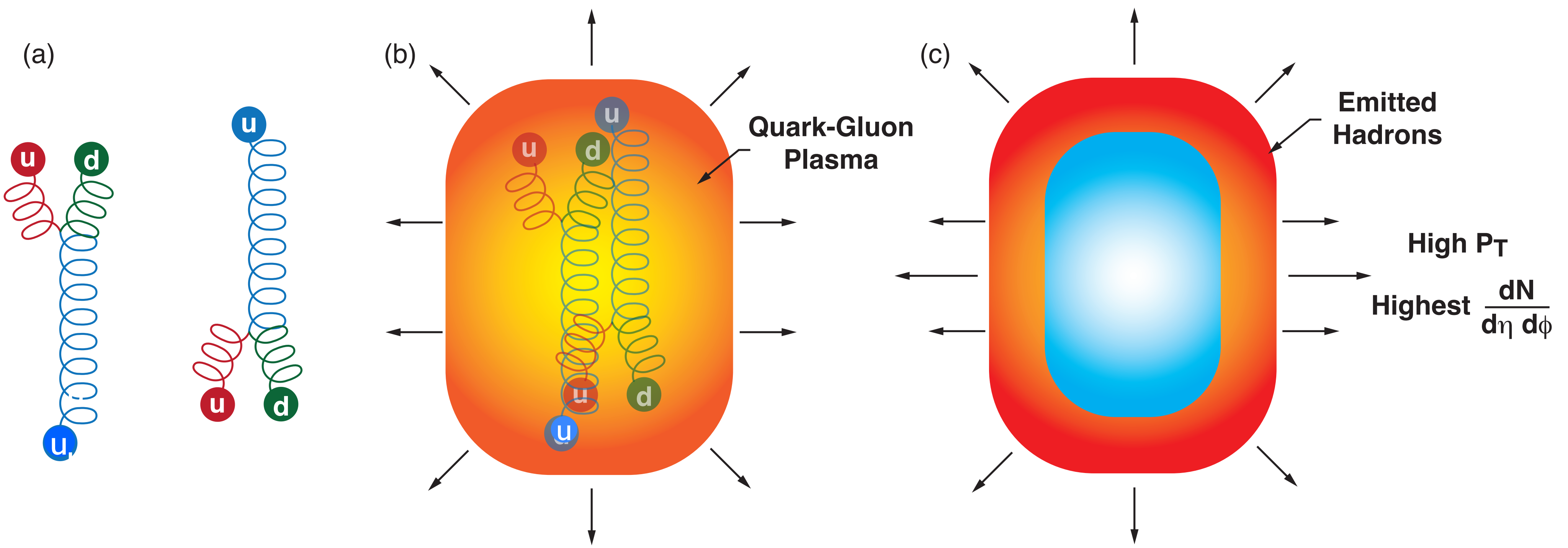
"Discovery"



- Ridge: Distinct long range correlation in η collimated around $\Delta\Phi \approx 0$ for two hadrons in the intermediate $1 < p_T, q_T < 3$ GeV

Possible origin of same-side CMS ridge in p p Collisions

Bjorken, Goldhaber, sjb



$$\vec{V} = \sum_{i=1}^{N} [\cos 2\phi_i \hat{x} + \sin 2\phi_i \hat{y}]$$

Bjorken, Goldhaber, sjb

Multiparticle ridge-like correlations in very high multiplicity proton-proton collisions

We suggest that this "ridge"-like correlations are a reflection of the rare events generated by the collision of aligned flux tubes connecting the valence quarks in the wave functions of the colliding protons.

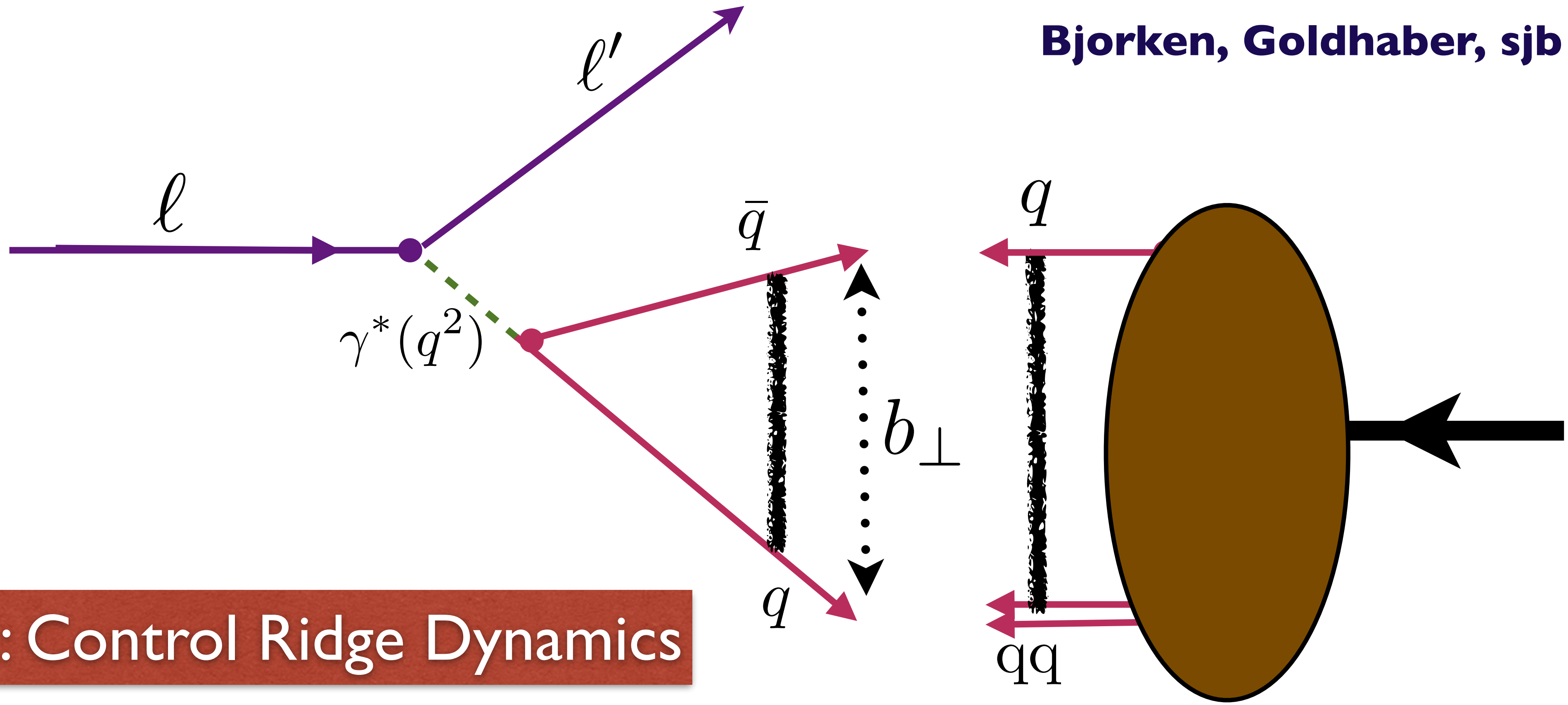
The "spray" of particles resulting from the approximate line source produced in such inelastic collisions then gives rise to events with a strong correlation between particles produced over a large range of both positive and negative rapidity.

EIC: Variable plane and virtual photon size: enhanced sensitivity to ridge mechanism

Scattered lepton produces flux-tube in lepton's scattering plane

Colliding flux-tubes produce opposite-side ridge of hadrons over full range of rapidity

Bjorken, Goldhaber, sjb



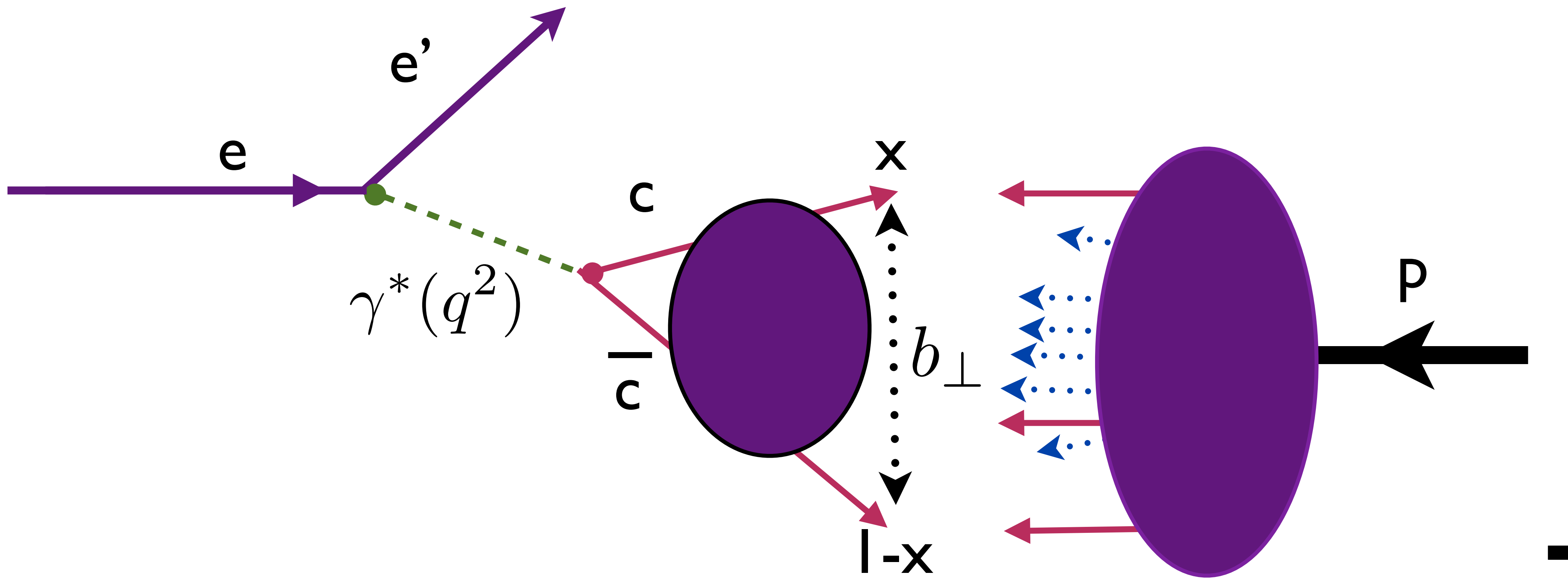
EIC: Control Ridge Dynamics

Ridge axes correlated with leptonic scattering plane

$$\langle b_\perp^2 \rangle \sim \frac{1}{Q^2 x(1-x) + M_t^2}$$

Small size domain activated

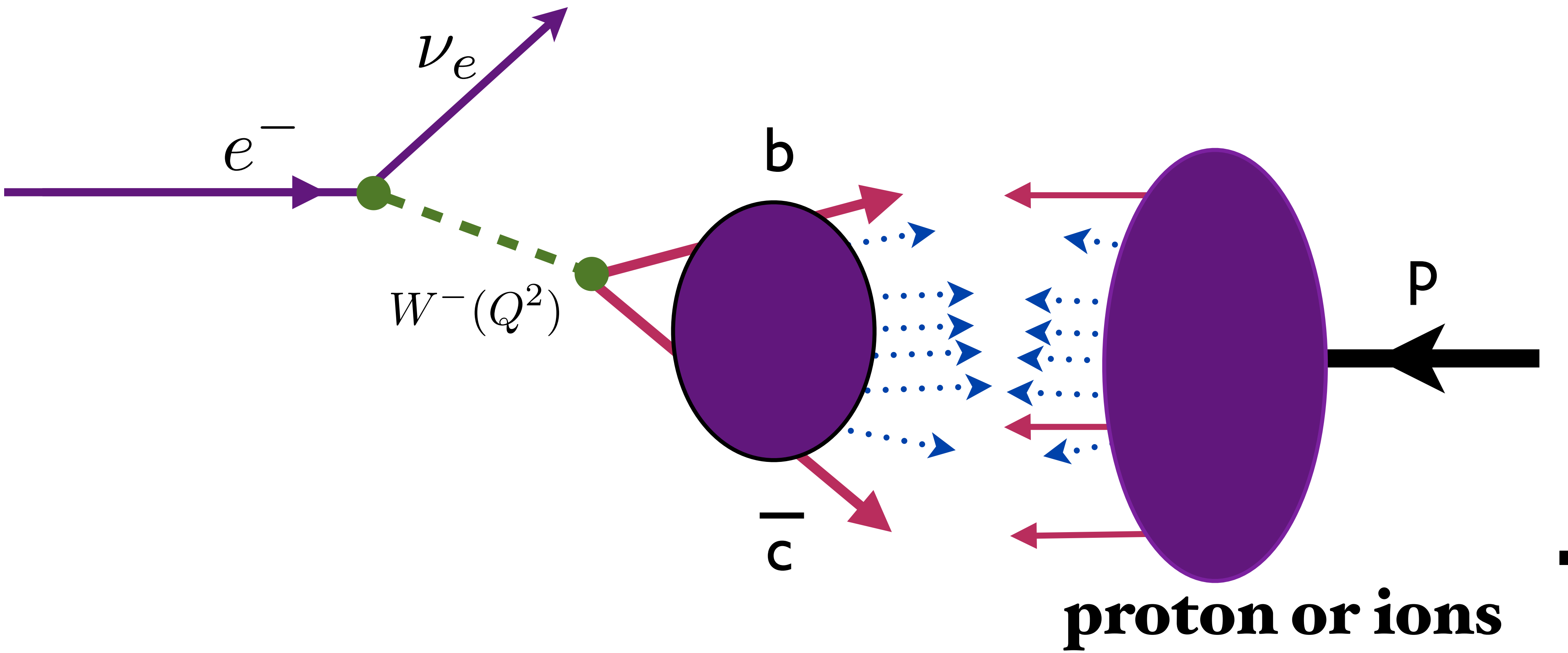
$$\langle b_\perp^2 \rangle \sim \frac{1}{Q^2 x(1-x) + M_t^2}$$



High Q^2, high M^2_Q virtual photon at LHeC acts as a precision, small bore, linearly oriented, flavor-dependent probe acting on a proton or nuclear target.

Study final-state hadron multiplicity distributions, ridges, nuclear dependence, etc.

EIC: "W-Proton Collider"



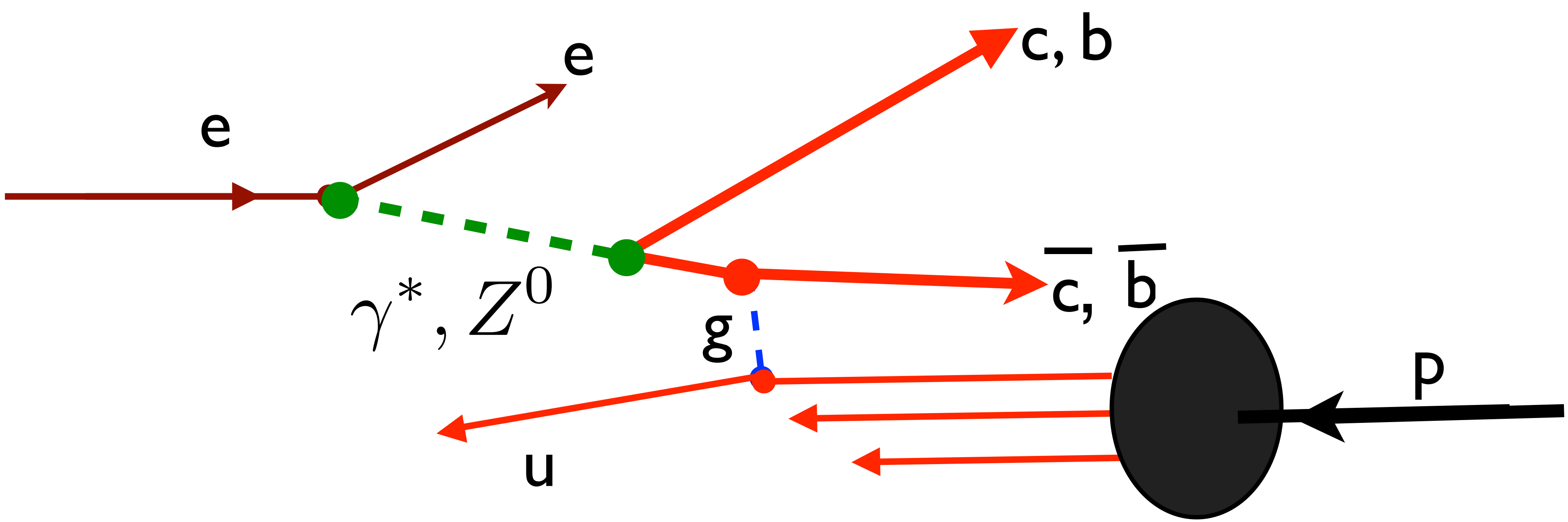
Only partially included by DGLAP in proton pdf

EIC: Virtual-Photon—Ion Collider

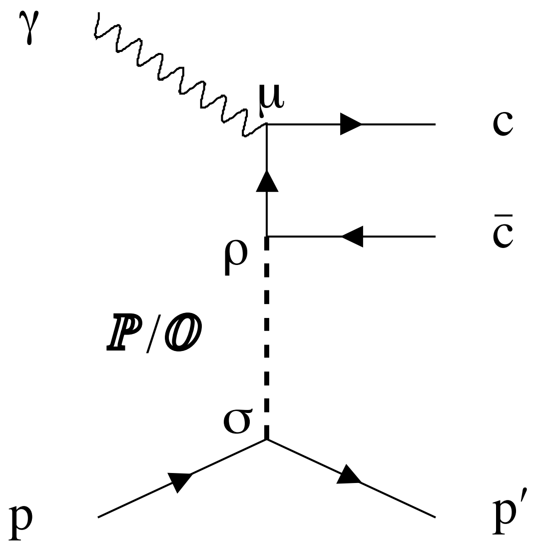
Inclusive c,b Electroproduction at the EIC

$c - \bar{c}$ asymmetry from $\gamma^* - Z^*$ or pomeron/odderon interference

Interpretation: Charm quark in photon vs. heavy sea quark in proton?

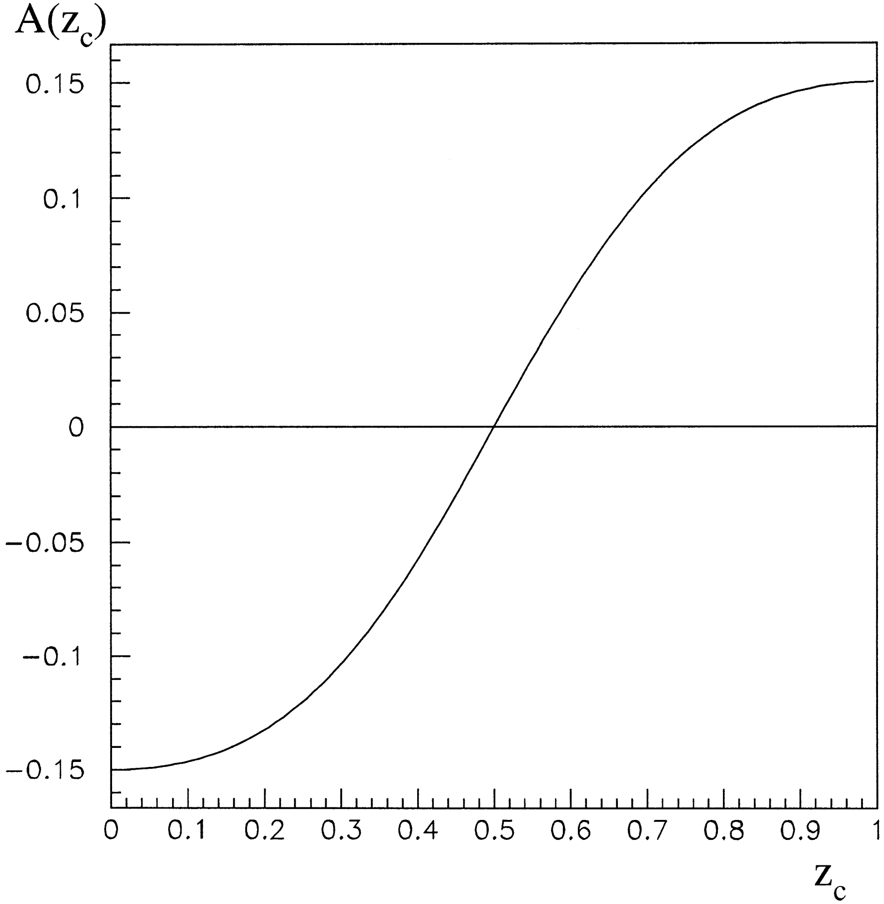


$Q\ \bar{Q}$ Plane correlated with Electron Scattering Plane



$$\gamma^* p \to c\bar{c}p$$

Odderon-Pomeron Interference!



$$\mathscr{A}\left(t \simeq 0, M_X^2, z_c\right) \simeq 0.45 \left(\frac{s_{\gamma p}}{M_X^2}\right)^{-0.25} \frac{2z_c - 1}{z_c^2 + (1 - z_c)^2}$$

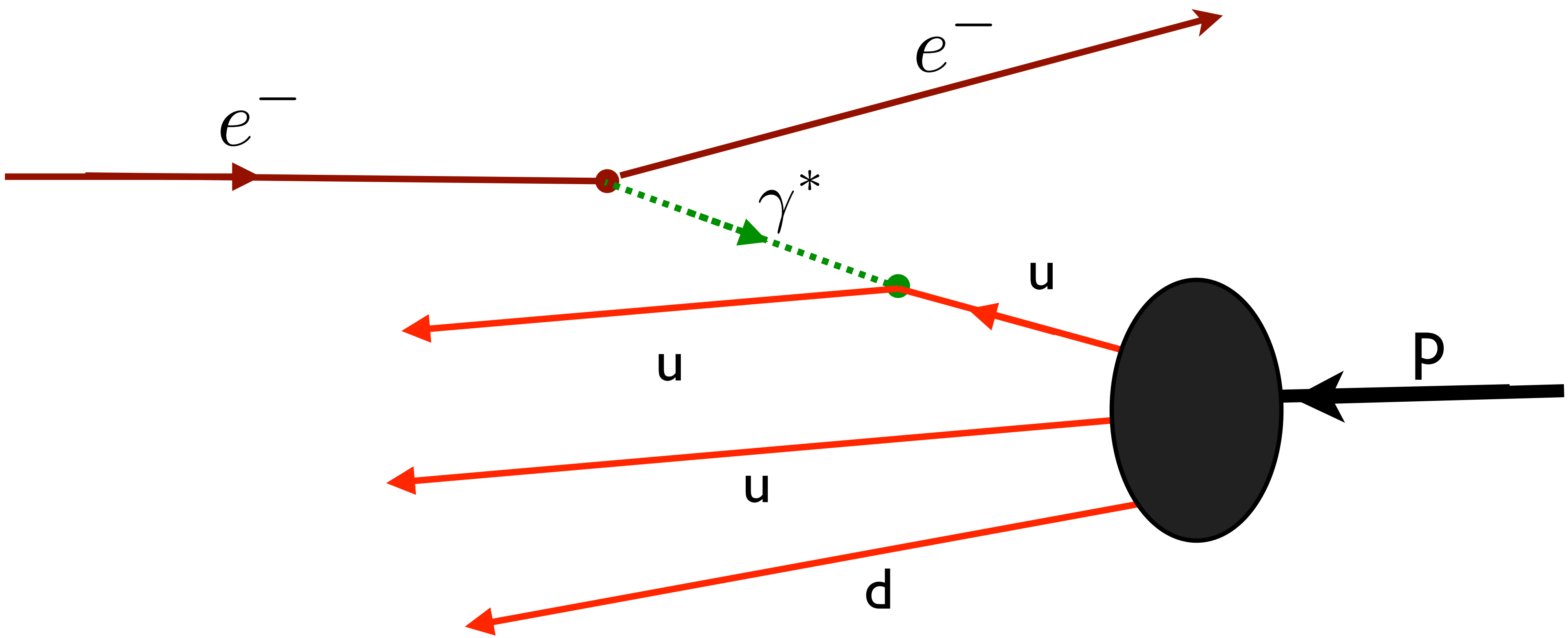
Measure charm asymmetry in photon fragmentation region

Merino, Rathsman, sjb

Coulomb Exchange analogous to diffractive excitation *Ashery, et al*

Electromagnetic Tri-Jet Excitation of Proton

$$ep \to e \text{ jet jet jet}$$



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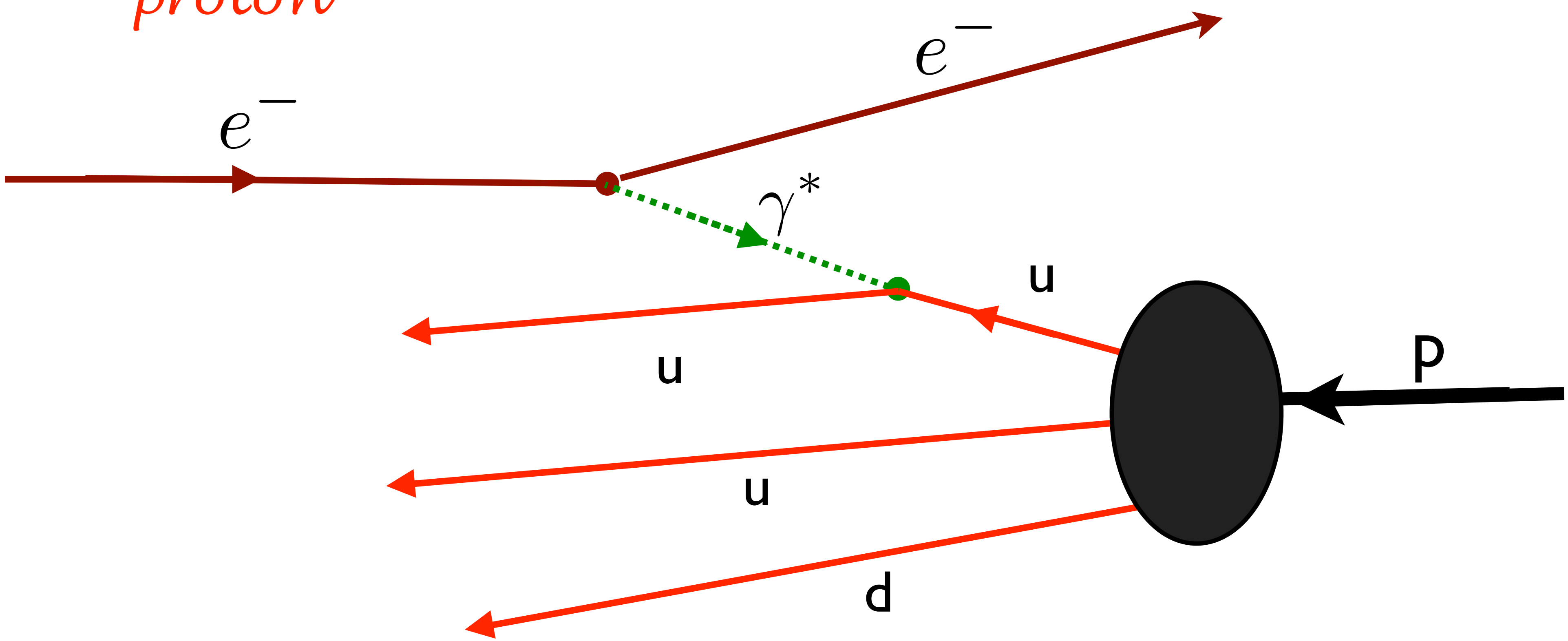
Measure light-front wavefunction of proton

$$\frac{\partial}{\partial k_\perp} \Psi^p_{n=3}(x_i, \vec{k}_{\perp i}, \lambda_i)$$



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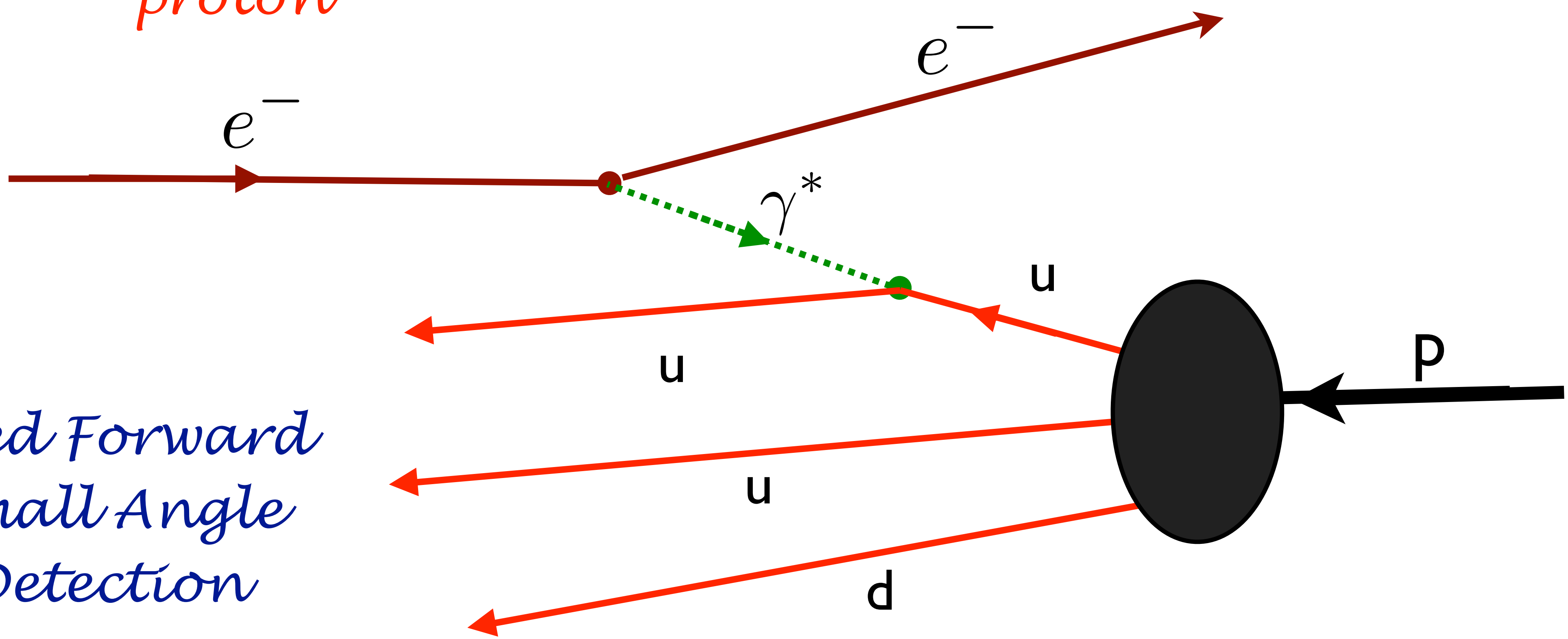
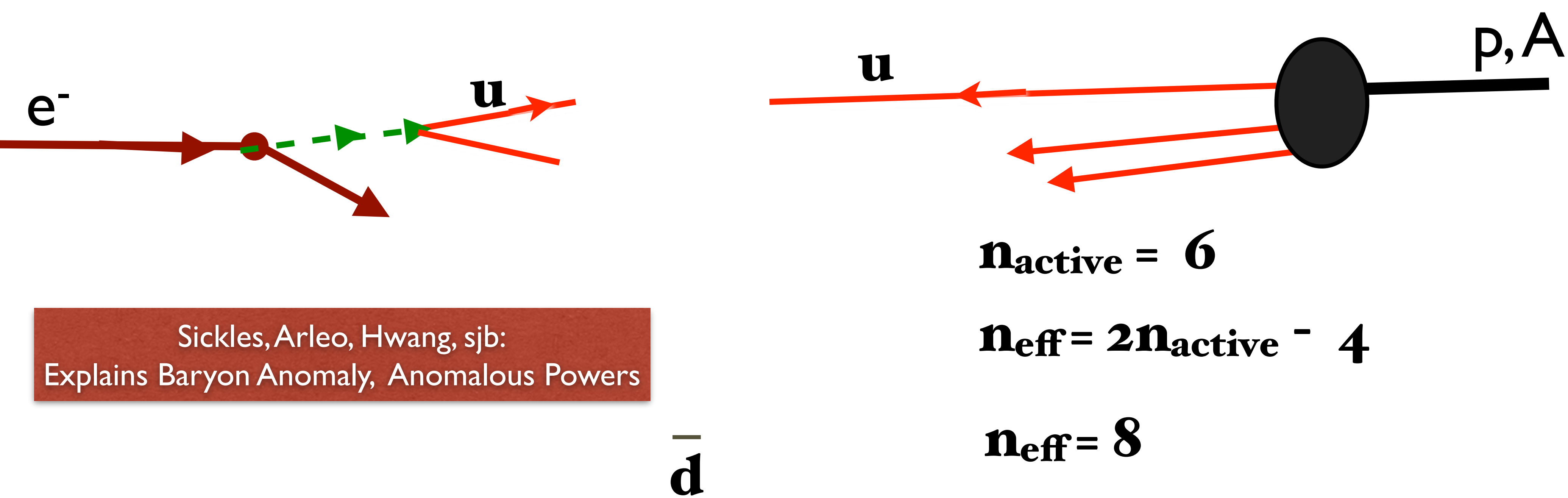


Need Forward Small Angle Detection

Baryon made directly within hard subprocess



$n_{active} = 6$

$n_{eff} = 2n_{active} - 4$

$n_{eff} = 8$

Sickles, Arleo, Hwang, sjb:
Explains Baryon Anomaly, Anomalous Powers

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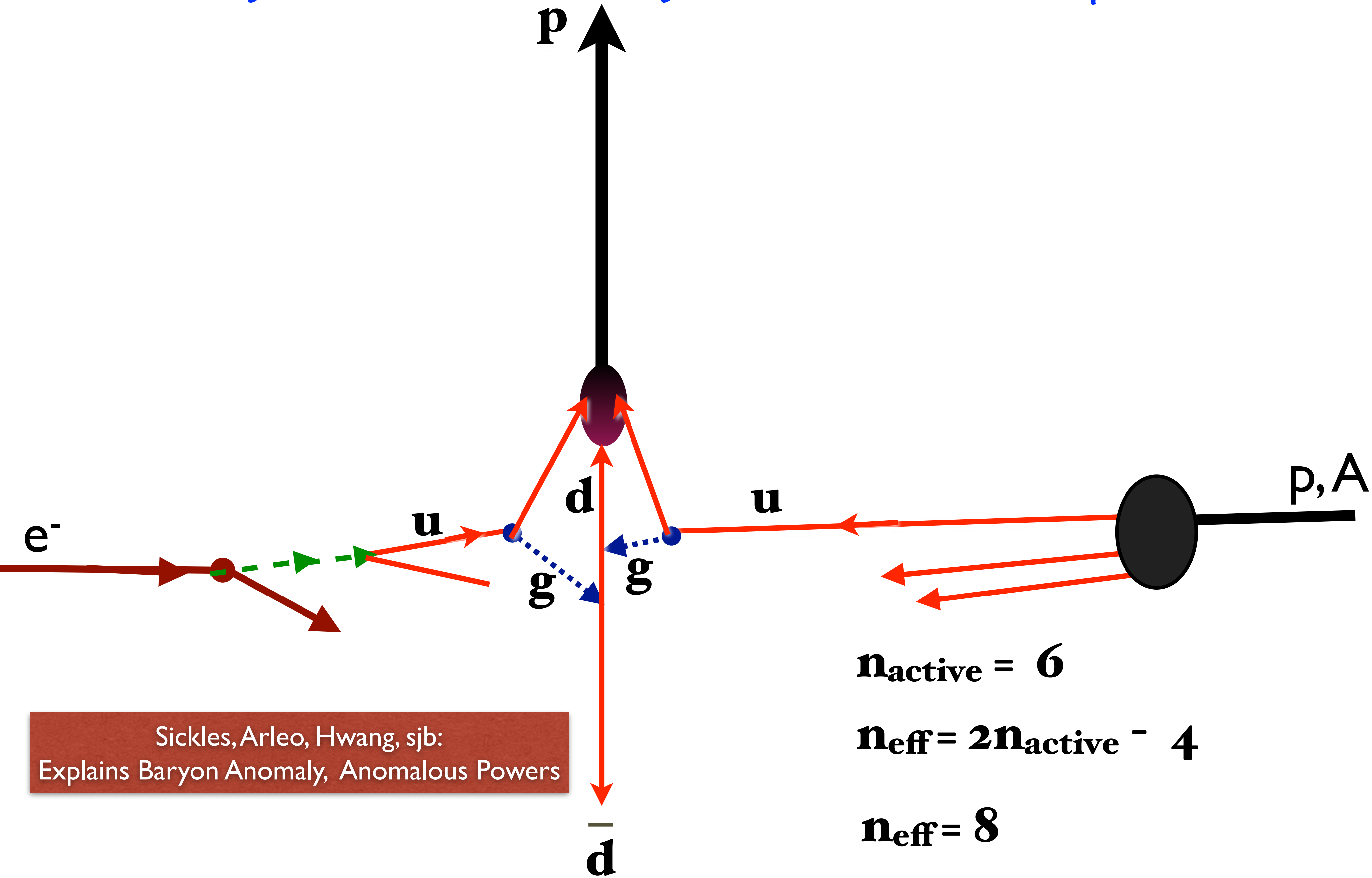

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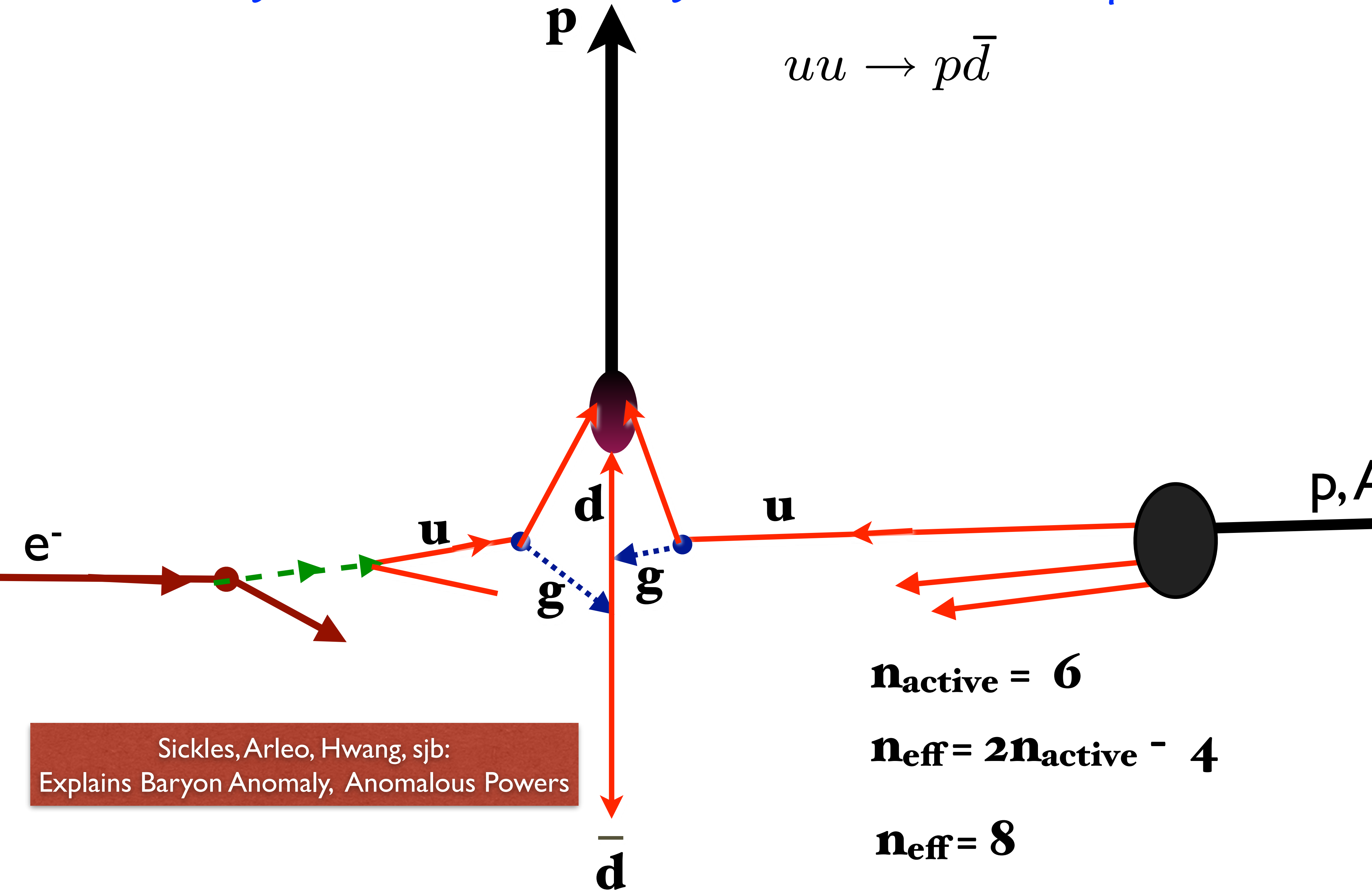
$uu \to p\bar{d}$



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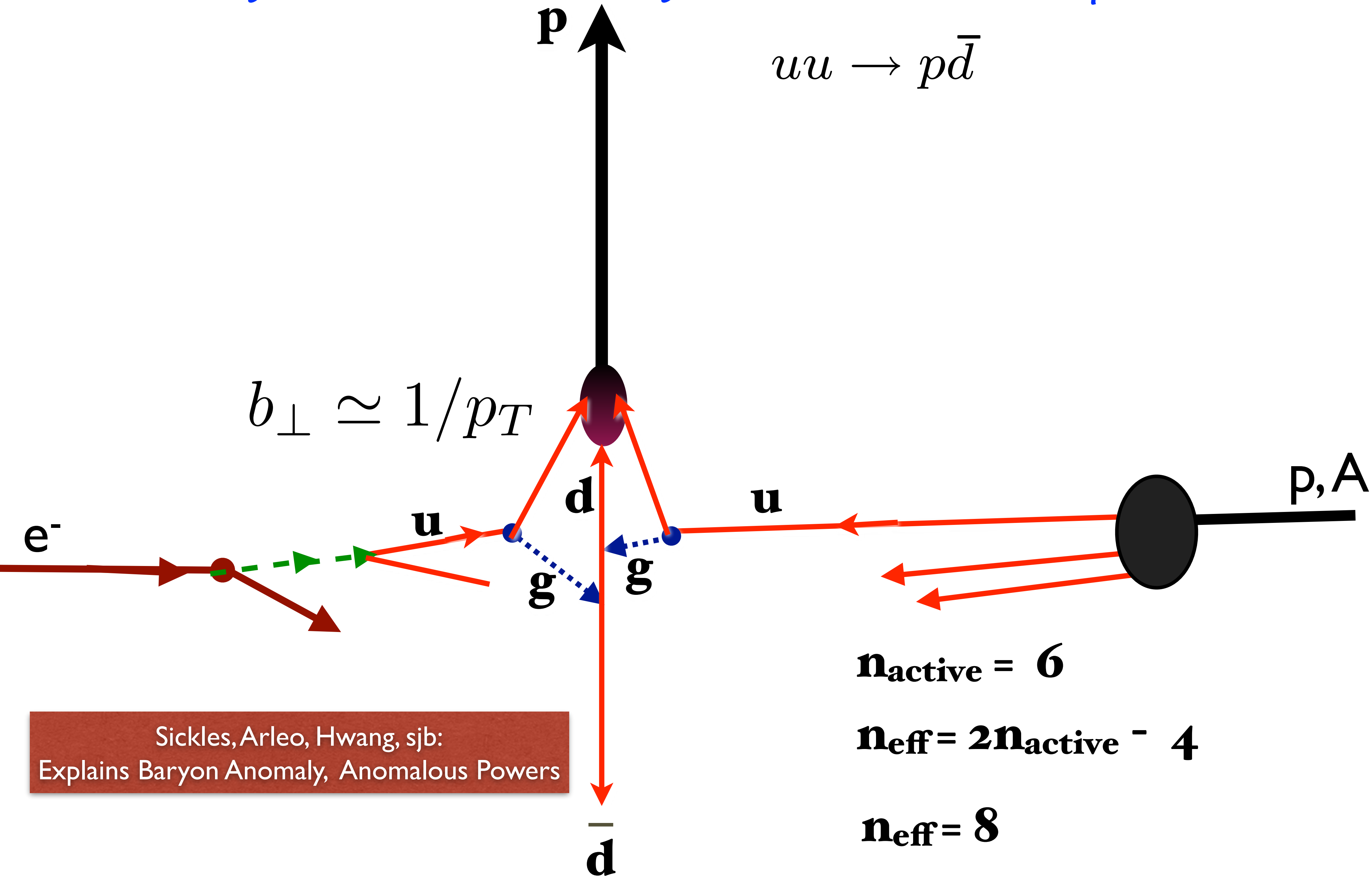

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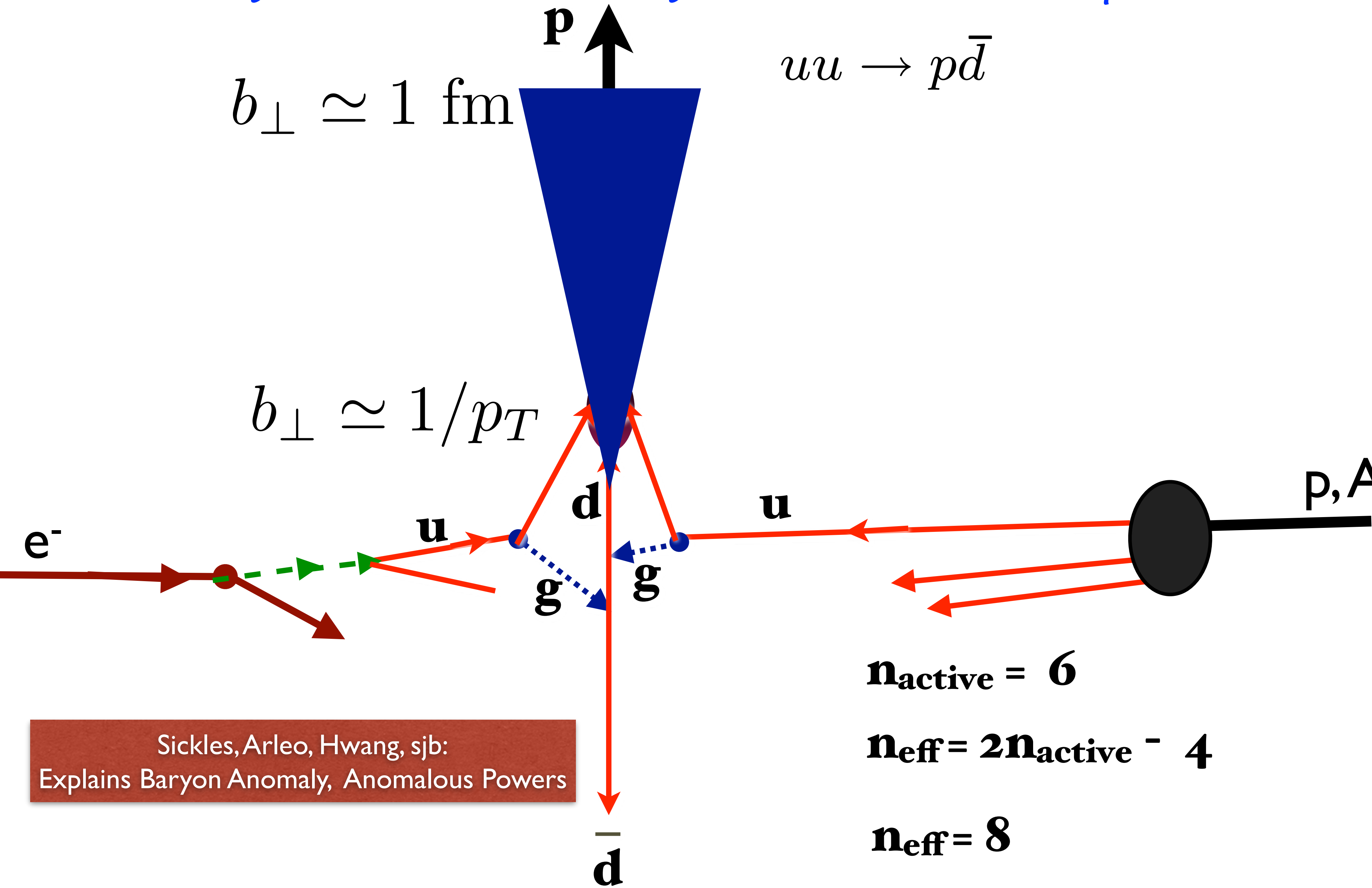

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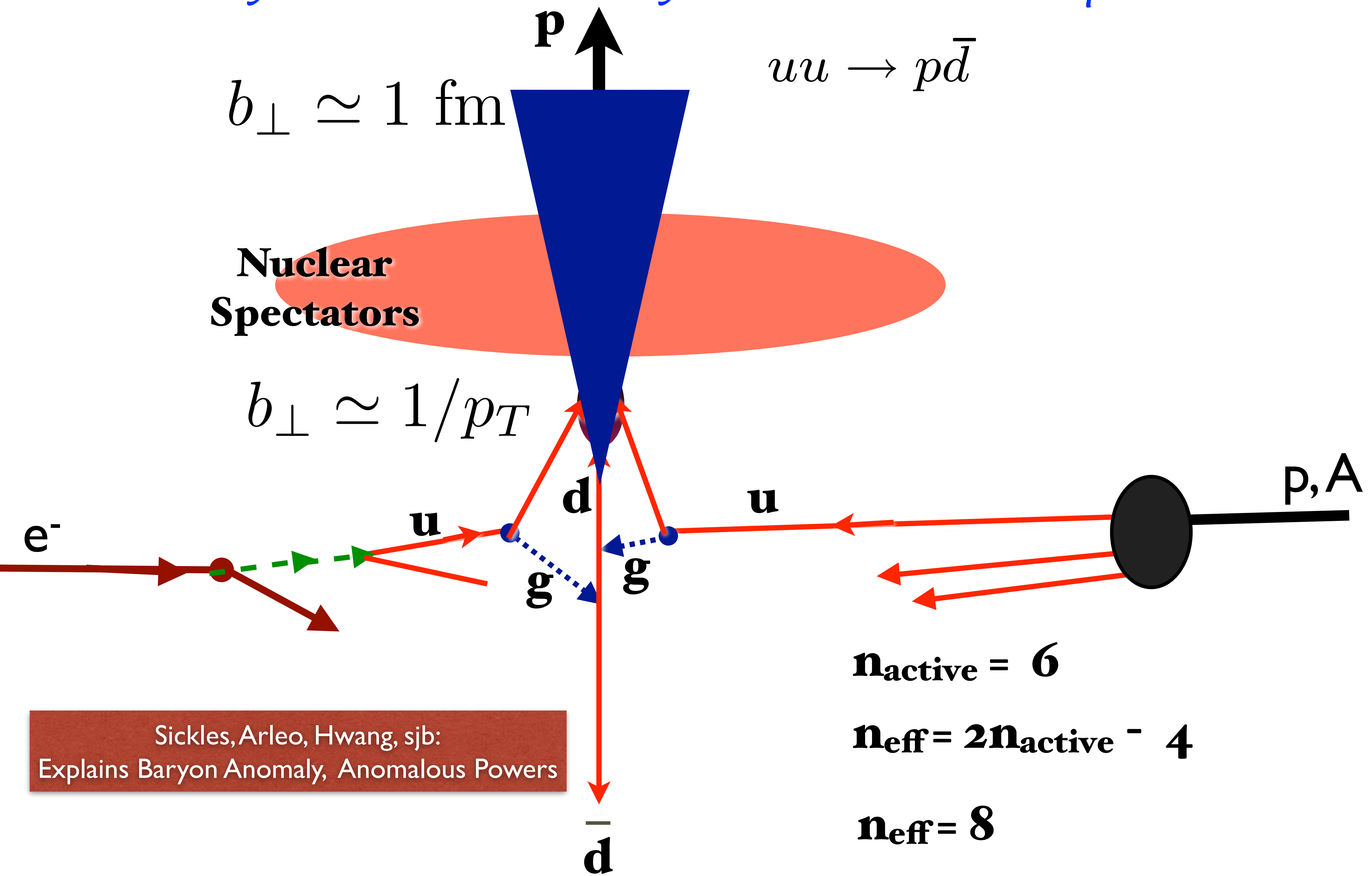

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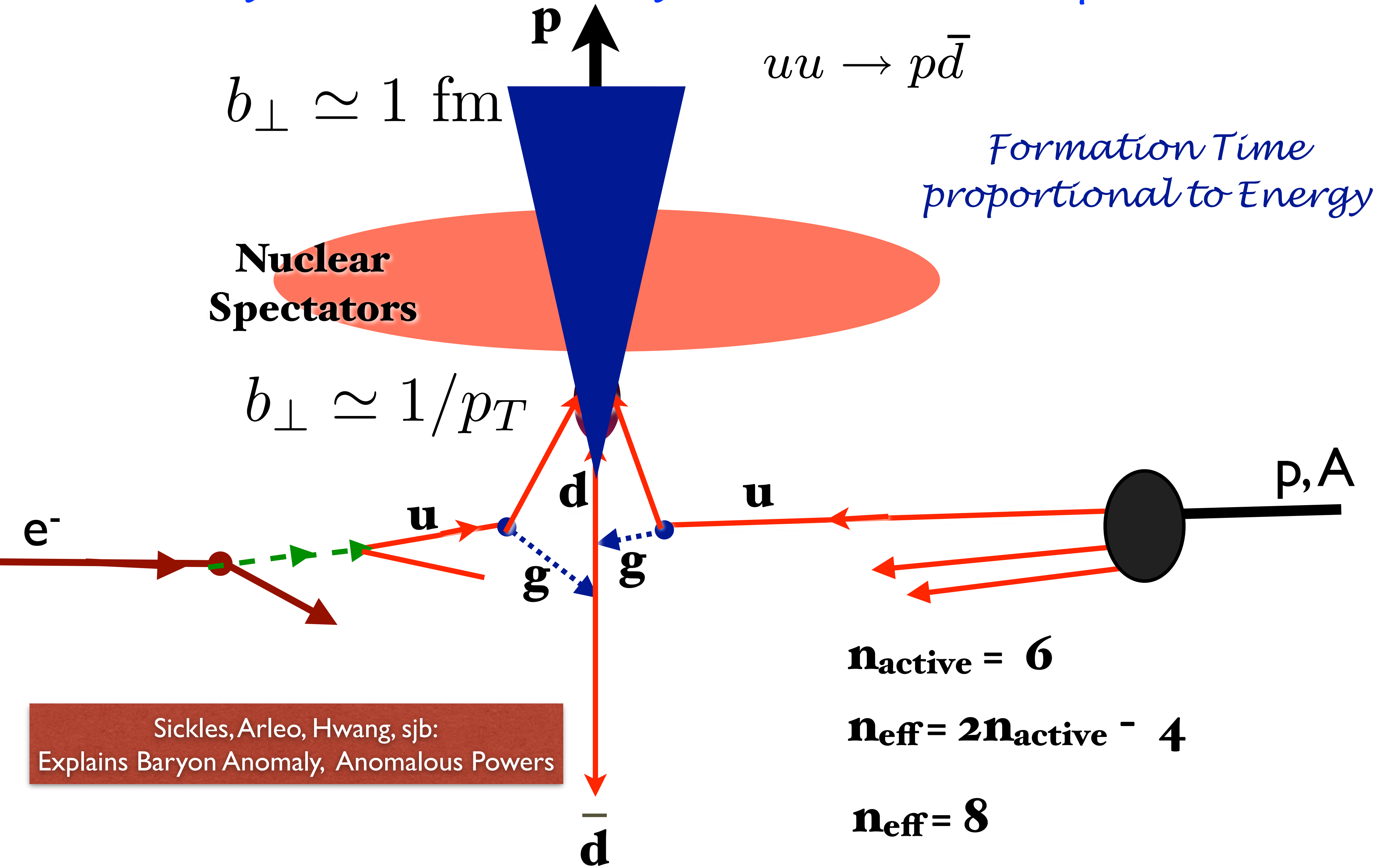

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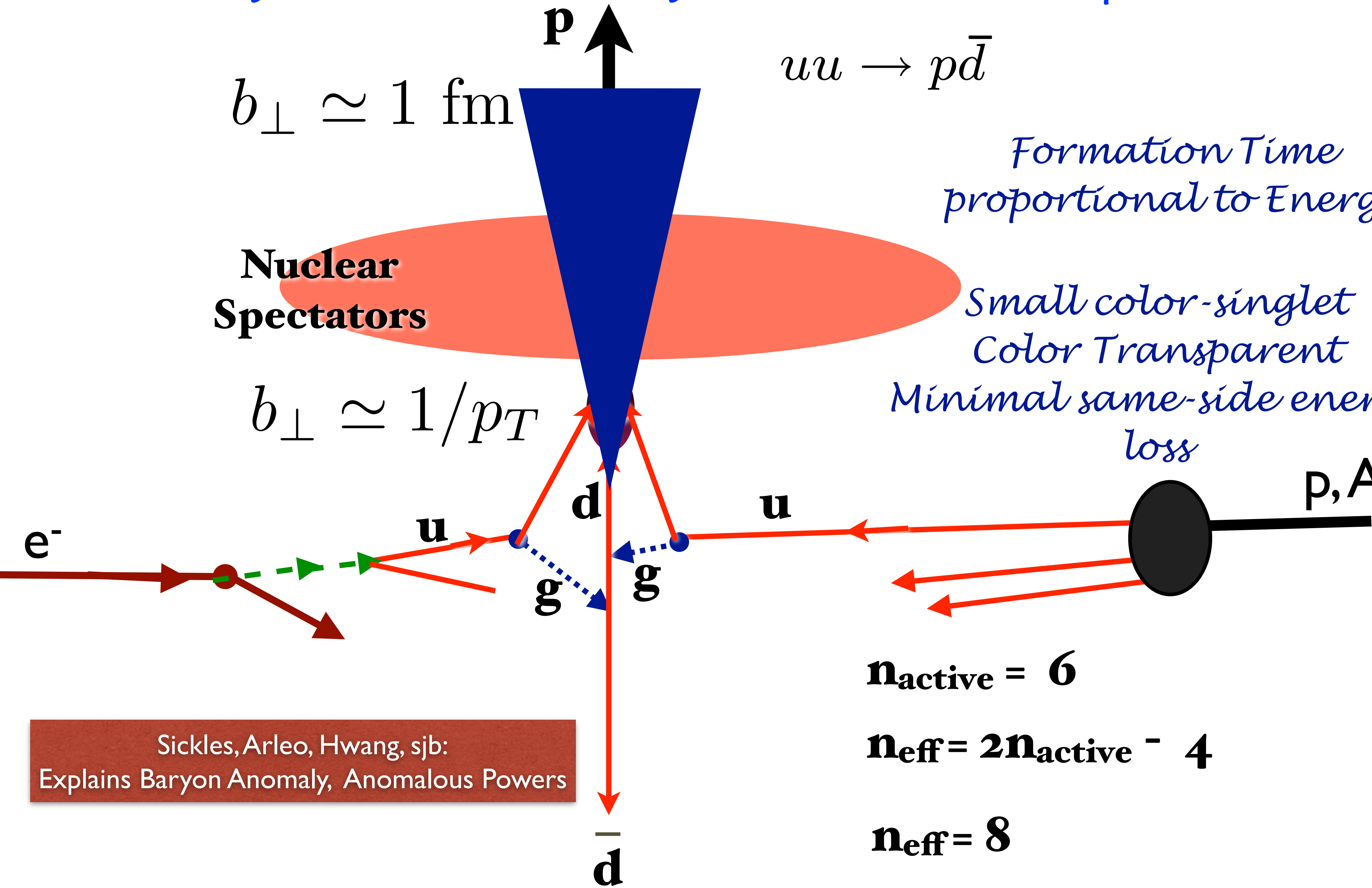

Formation Time proportional to Energy

Small color-singlet
Color Transparent
Minimal same-side energy loss

$n_{active} = 6$

$n_{eff} = 2n_{active} - 4$

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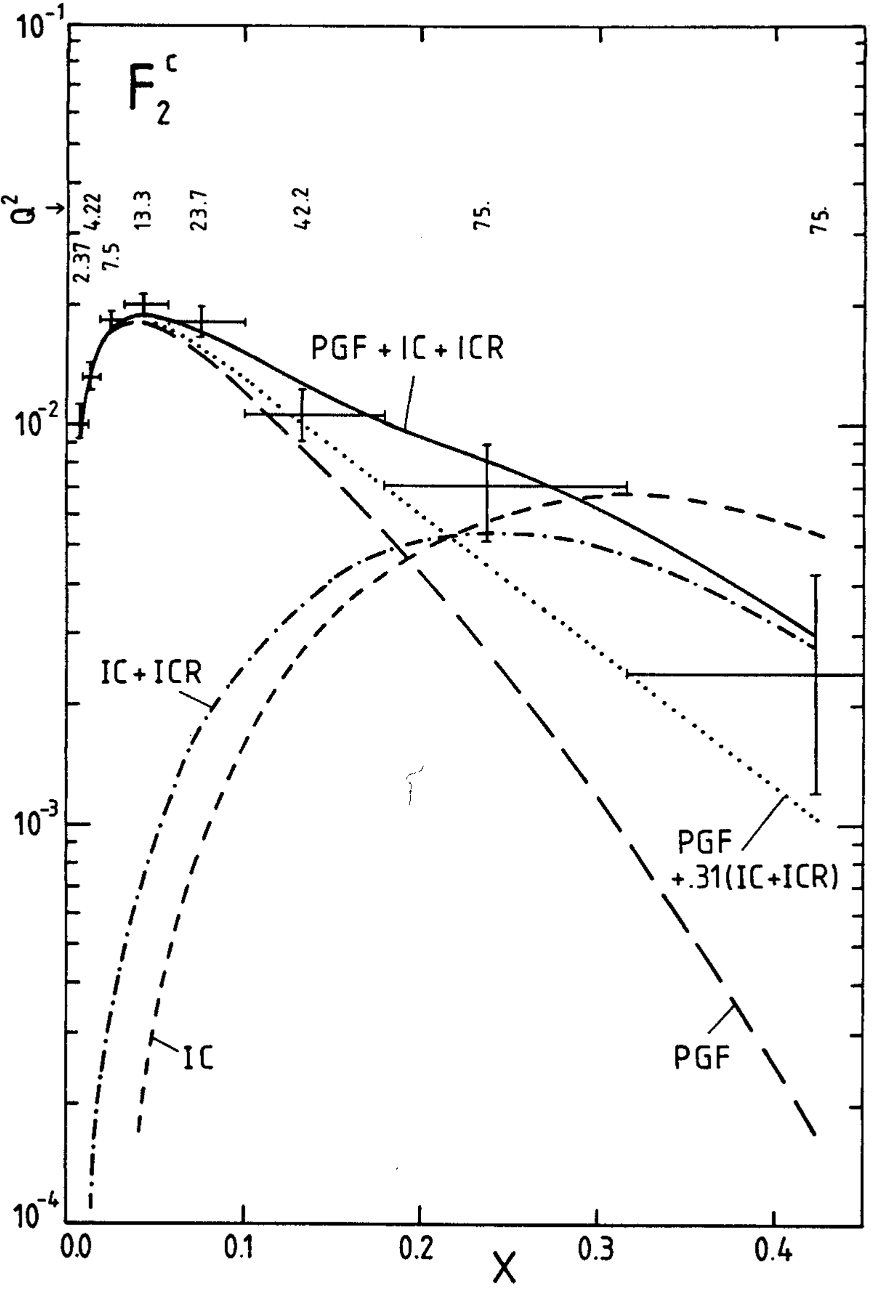

Measurement of Charm Structure Function

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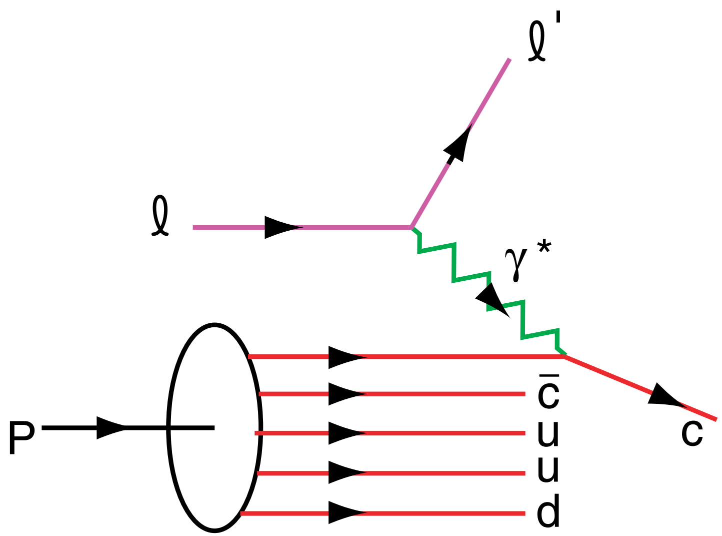
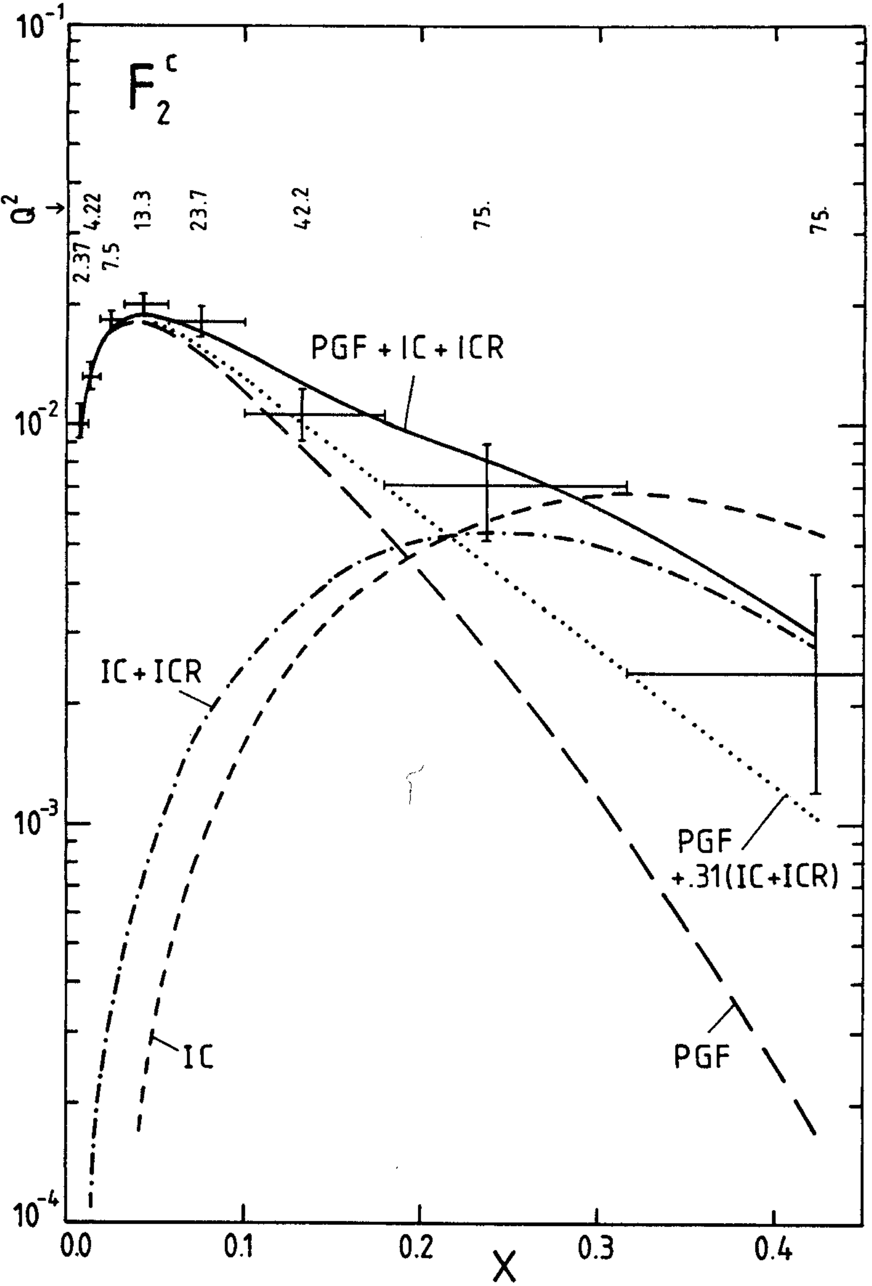
First Evidence for Intrinsic Charm





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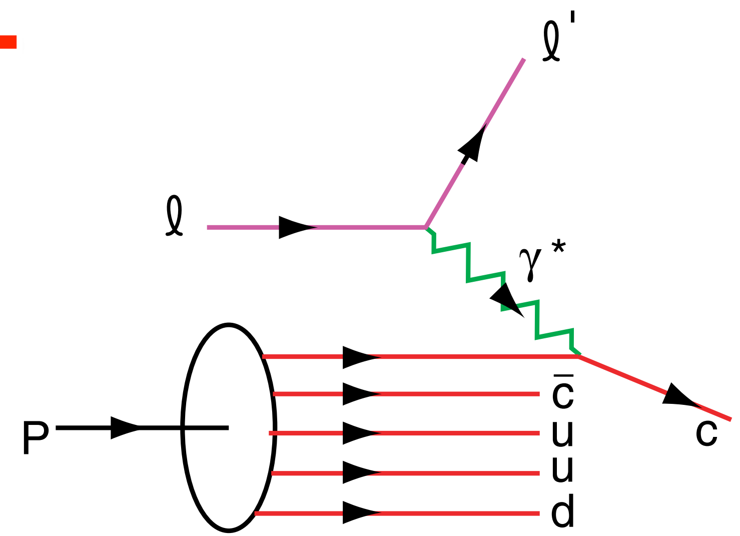

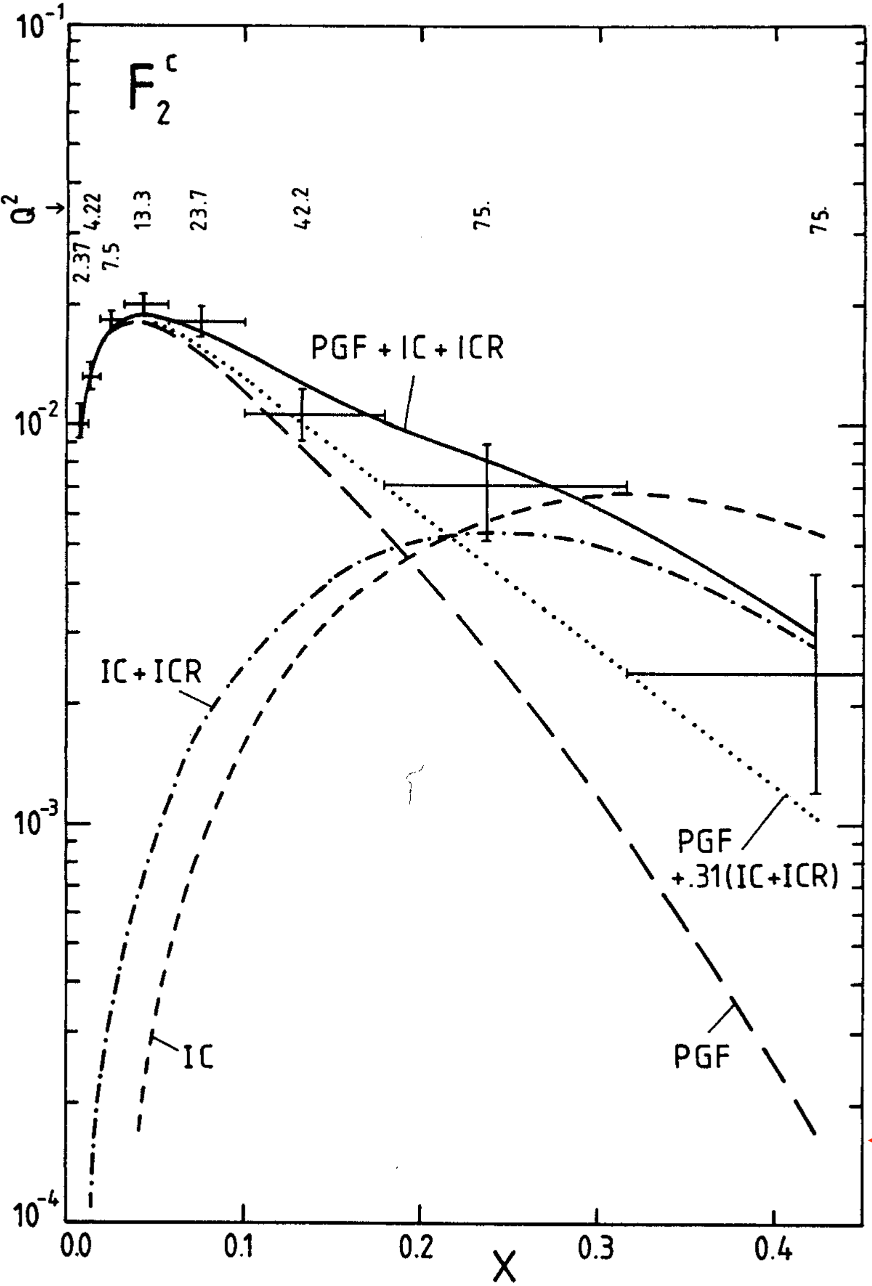

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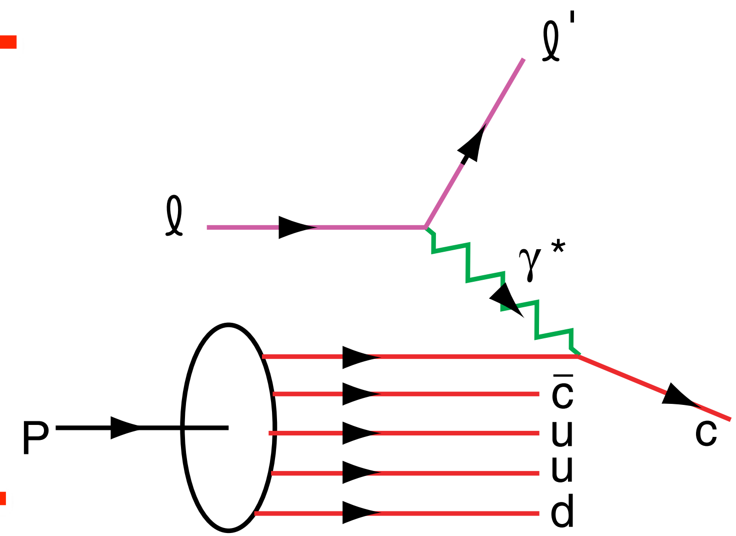

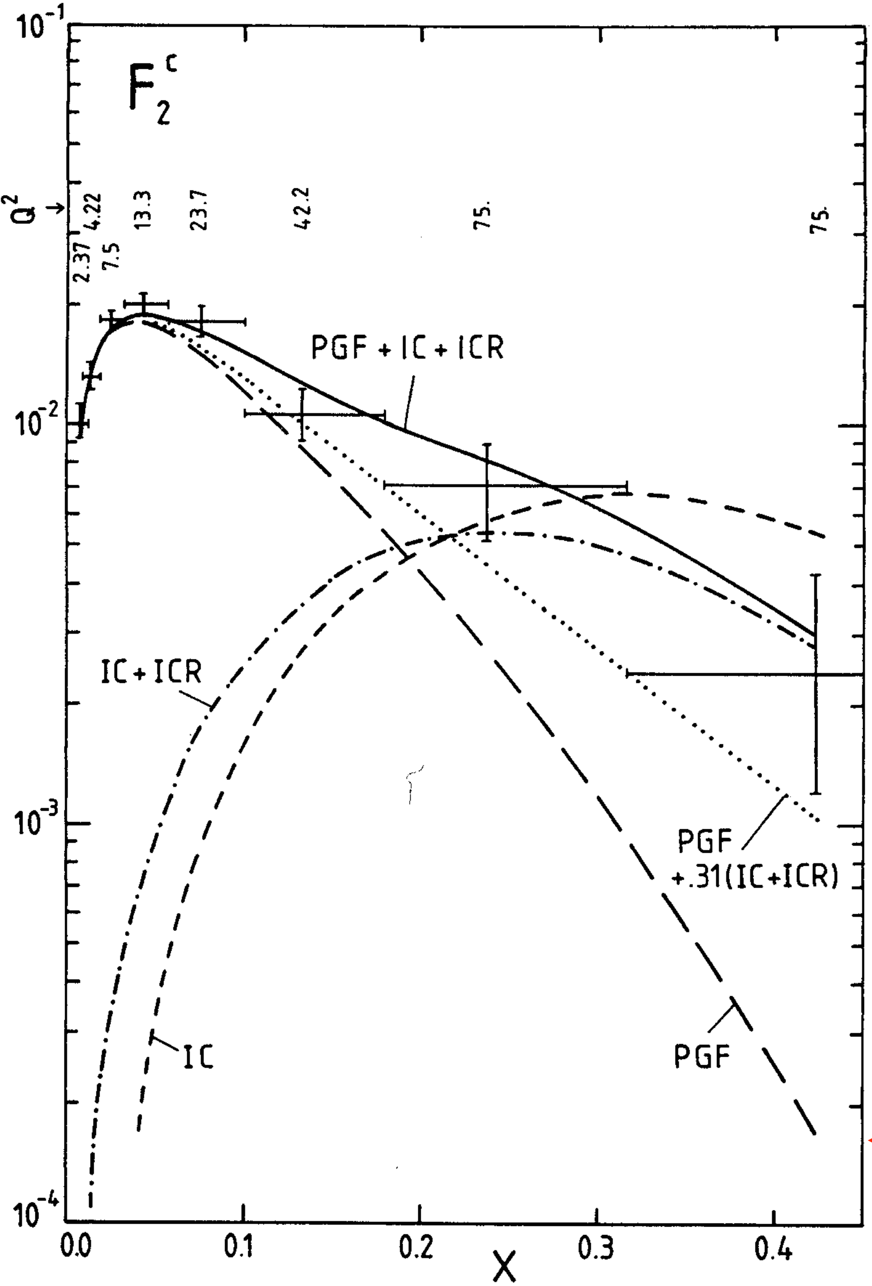

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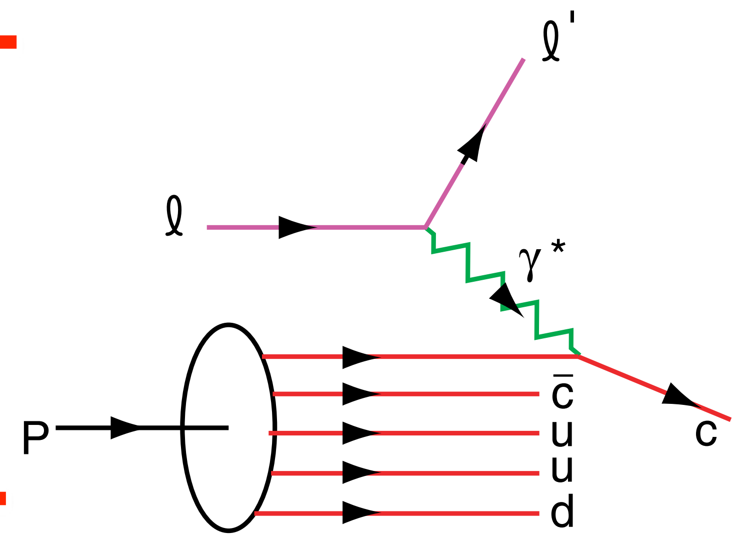
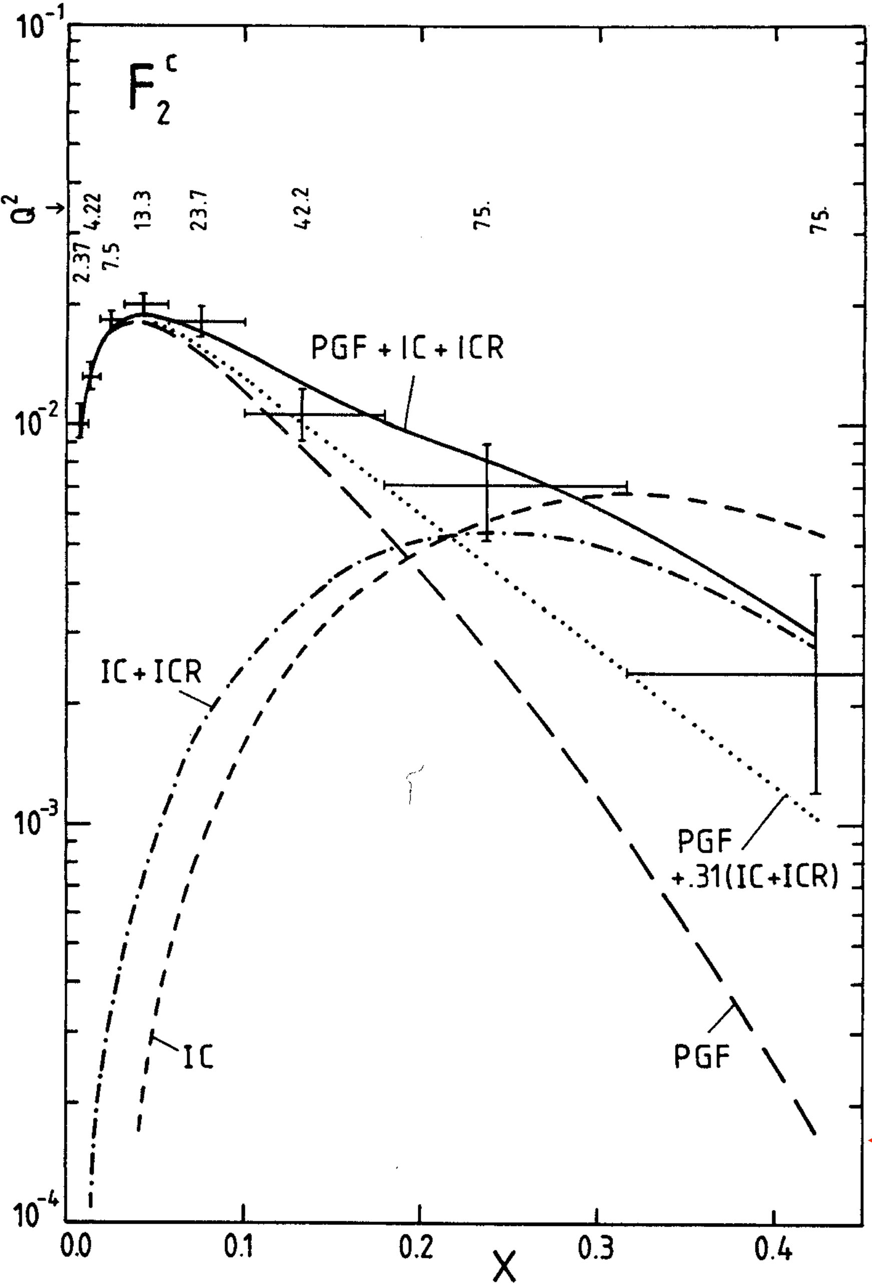


DGLAP / Photon-Gluon Fusion: factor of 30 too small



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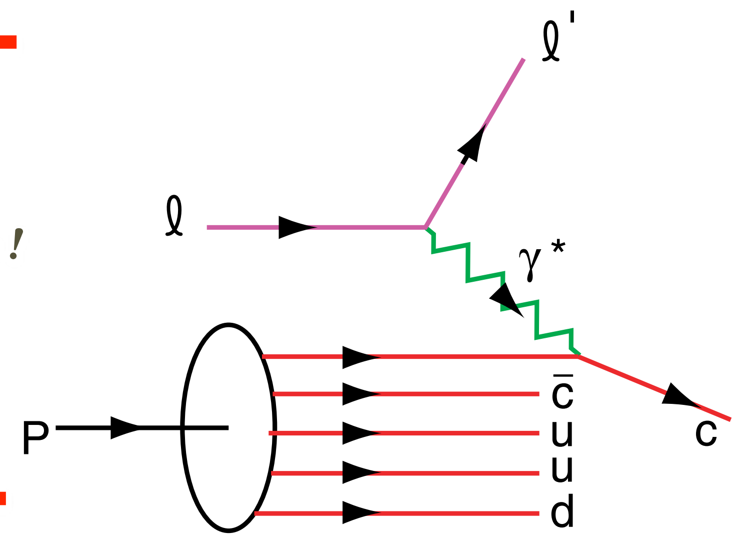
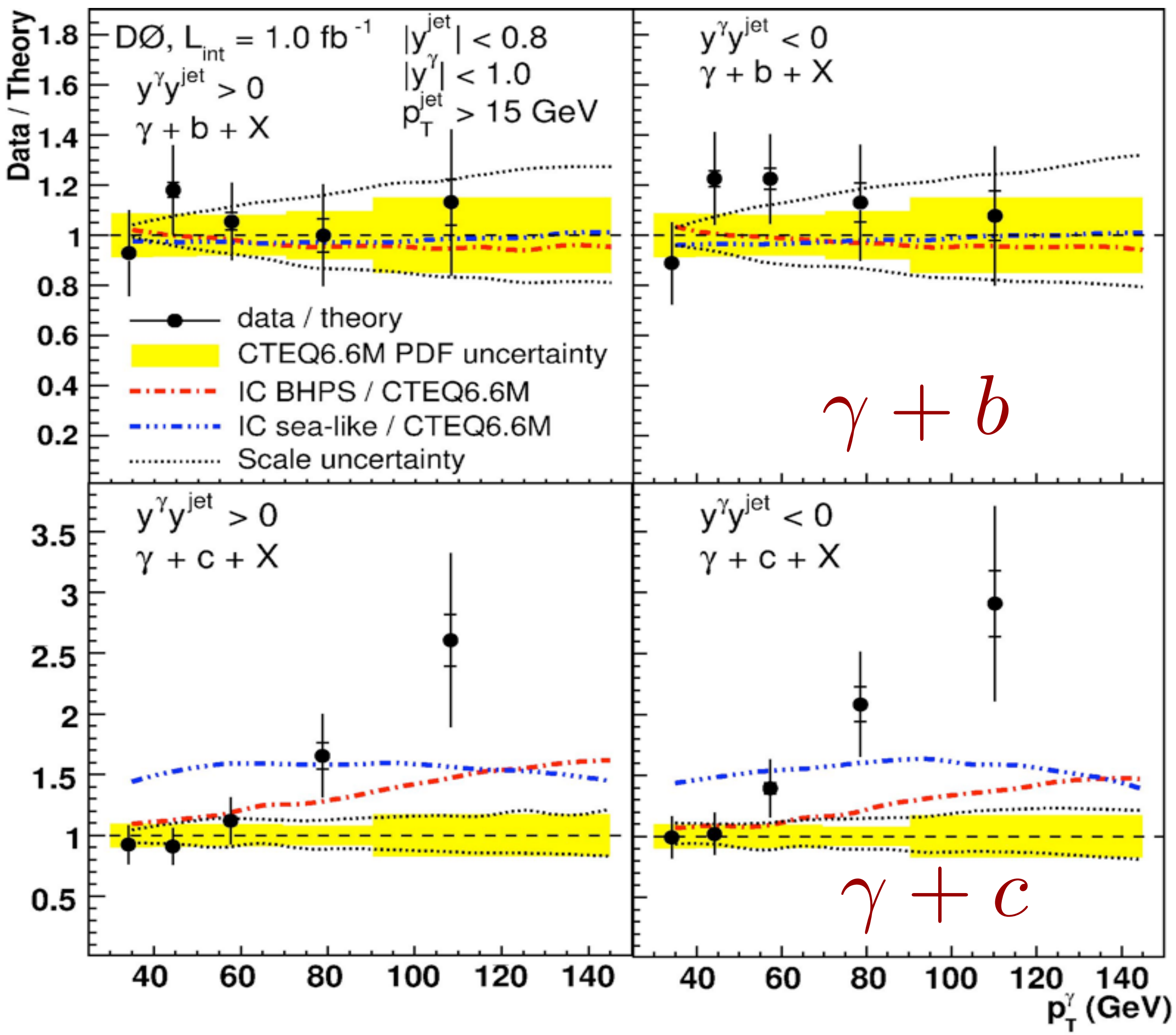
factor of 30 !



DGLAP / Photon-Gluon Fusion: factor of 30 too small

PRL **102,** 192002 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV



$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio insensitive to gluon PDF, scales

Signal for significant IC at x > 0.1

Dominant subprocess: $gQ \to \gamma Q$

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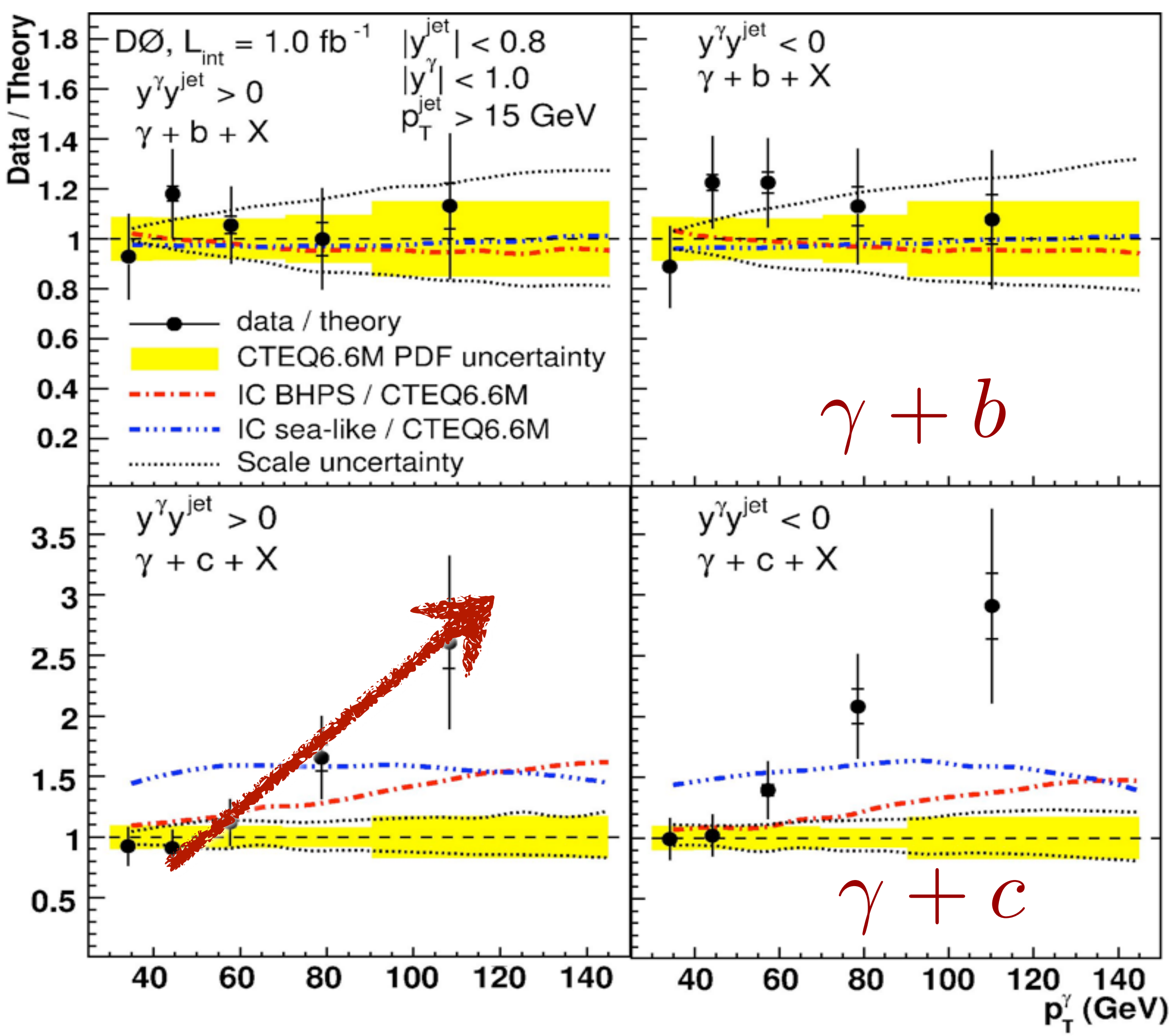

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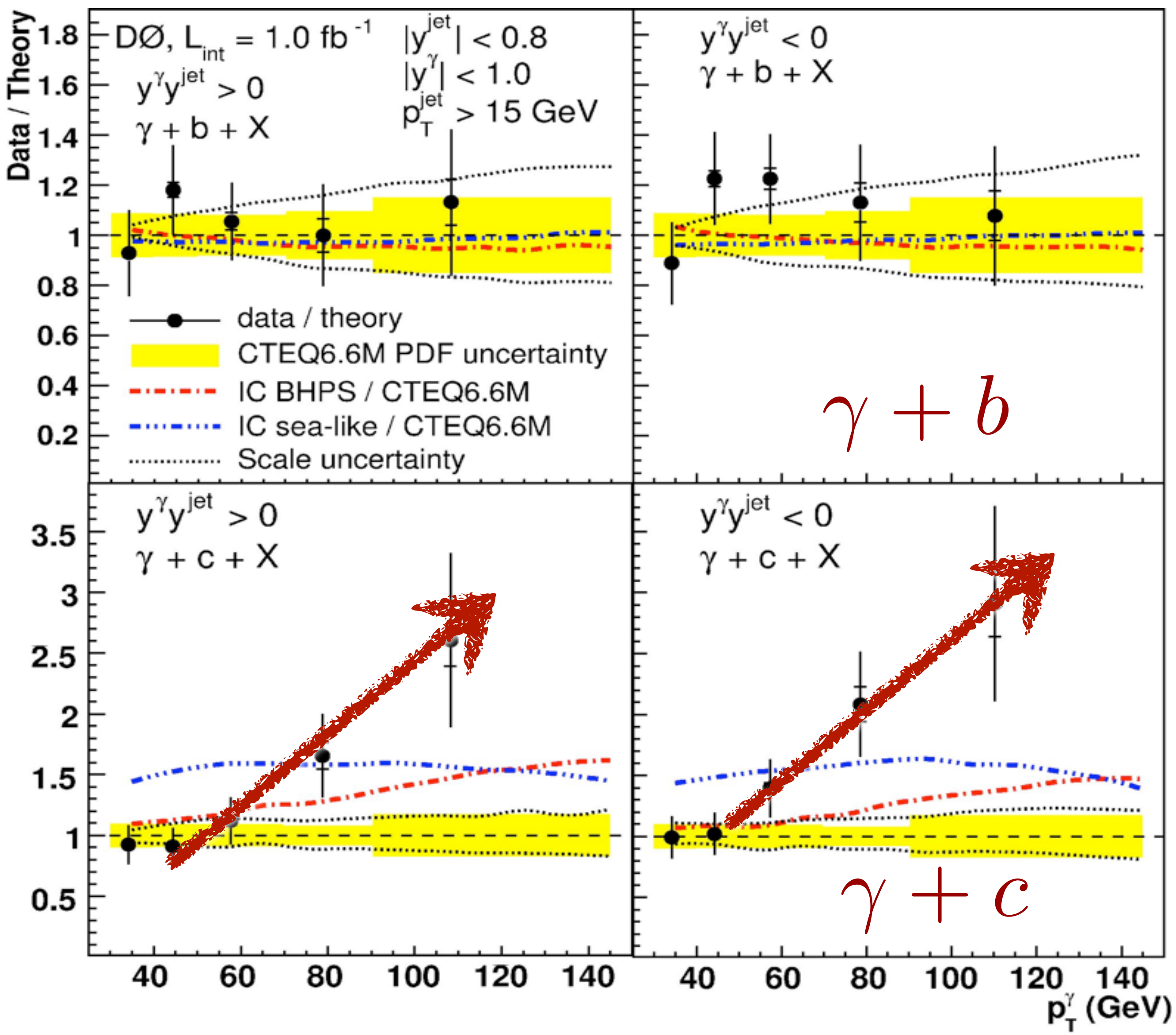

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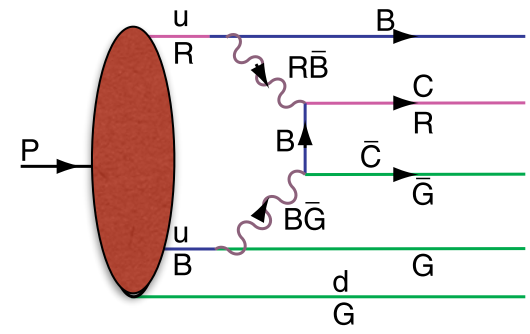
Intrinsic Heavy-Quark Fock States



- **Rigorous prediction of QCD, OPE**
- **Color-Octet Color-Octet Fock State**
- **Probability** $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- **Large Effect at high x**
- **Greatly increases kinematics of colliders such as Higgs production (Kopeliovich, Schmidt, Soffer, sjb)**
- **Underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)**
- **Many EIC tests**

- EMC data: $c(x, Q^2) > 30 \times$ DGLAP
  $Q^2 = 75$ GeV^2, $x = 0.42$

- High x_F $pp \rightarrow J/\psi X$

- High x_F $pp \rightarrow J/\psi J/\psi X$

- High x_F $pp \rightarrow \Lambda_c X$

- High x_F $pp \rightarrow \Lambda_b X$

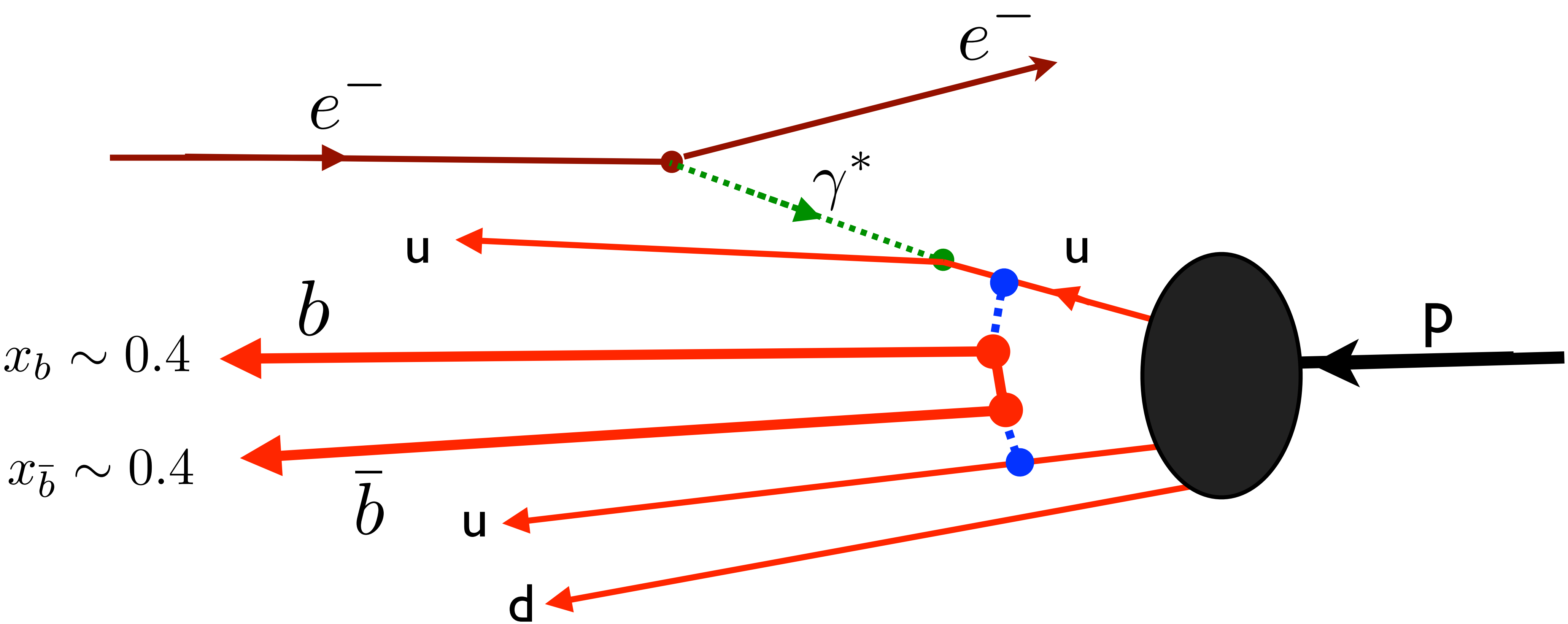
- High x_F $pp \rightarrow \Xi(ccd) X$ (SELEX)

Interesting spin, charge asymmetry, threshold, spectator effects

Excitation of Intrinsic Heavy Quarks in Proton

Amplitude maximal at small invariant mass, equal rapidity

$$x_i \sim \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$



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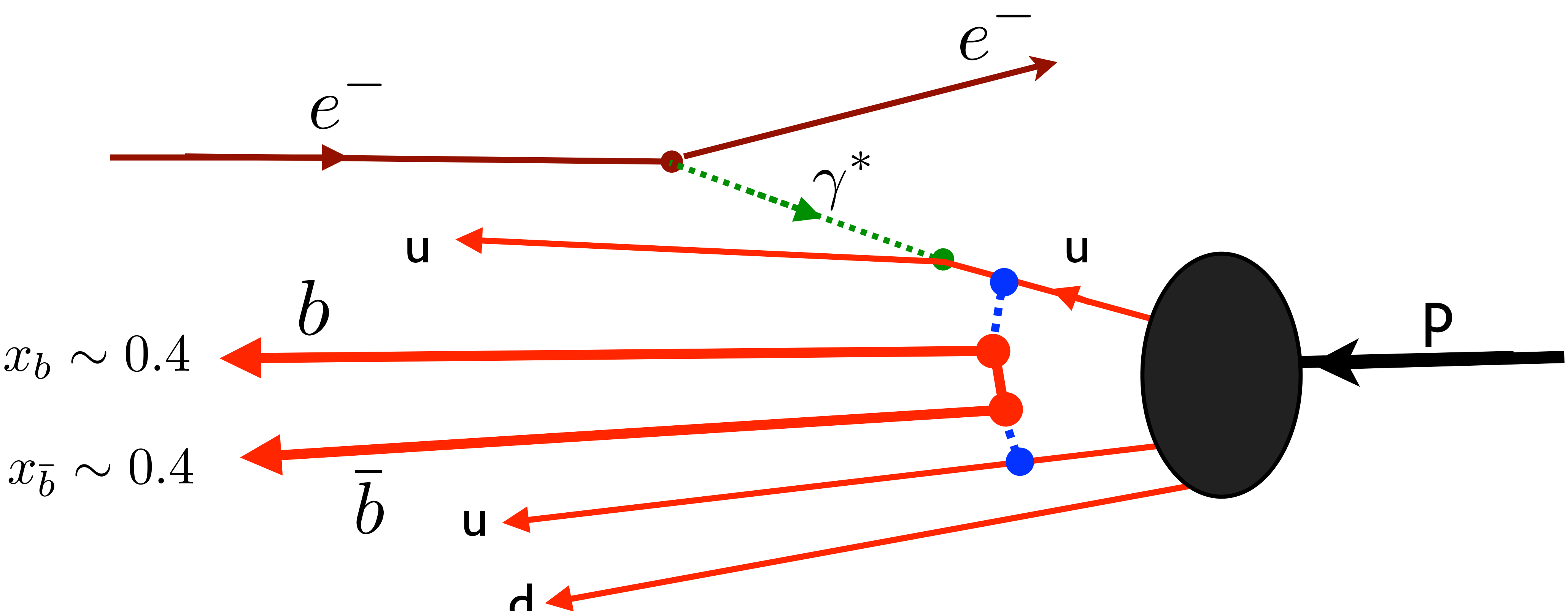
Produce forward, high x_F

$\Upsilon(b\bar{b}), \Lambda_b(bud), B^+(\bar{b}u), B^0(\bar{b}d)$



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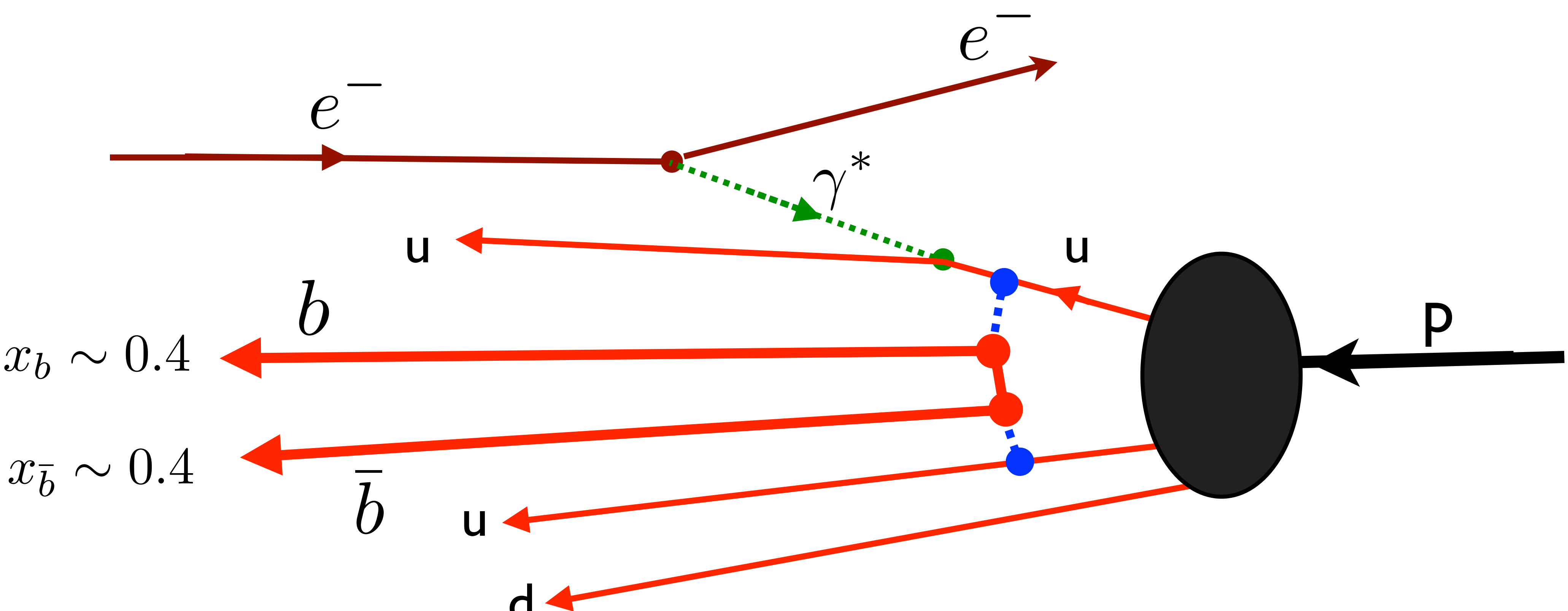
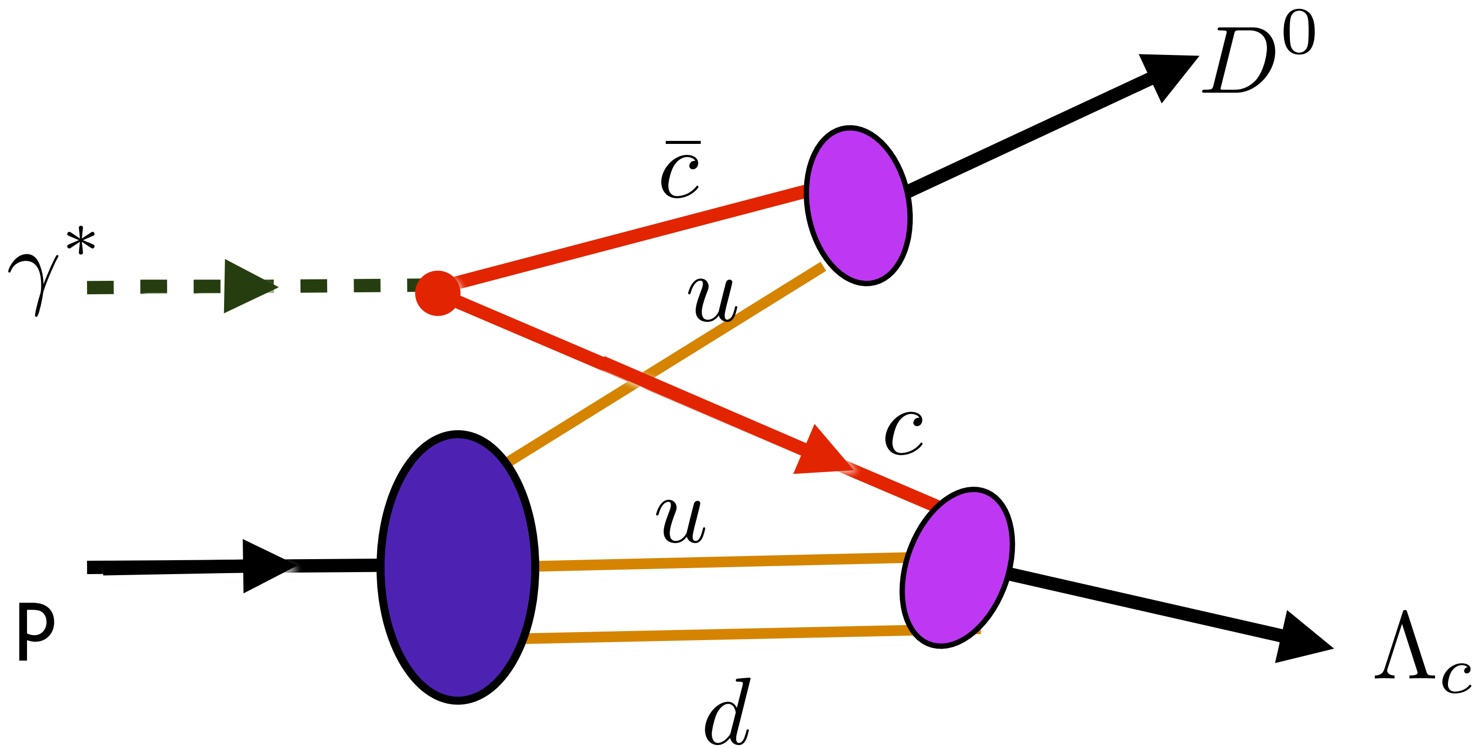
Need Forward Small Angle Detection



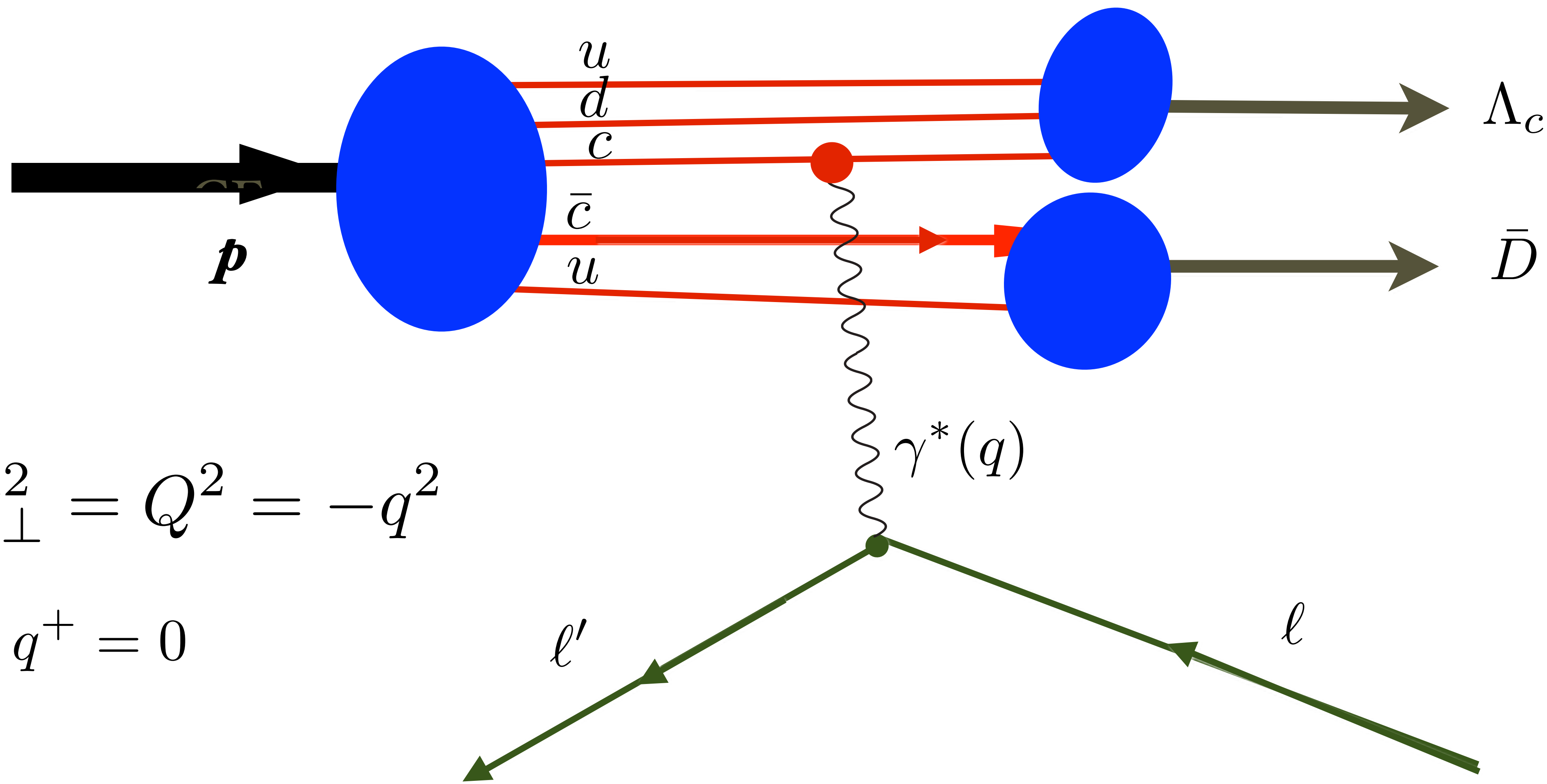
Exclusive Open Charm and Bottom Production



$$\gamma^* p \to \overline{D}^0(\bar{c}u)\Lambda_c(cud)$$

c and u quark interchange

Light-Front Wavefunctions and Heavy-Quark Electroproduction

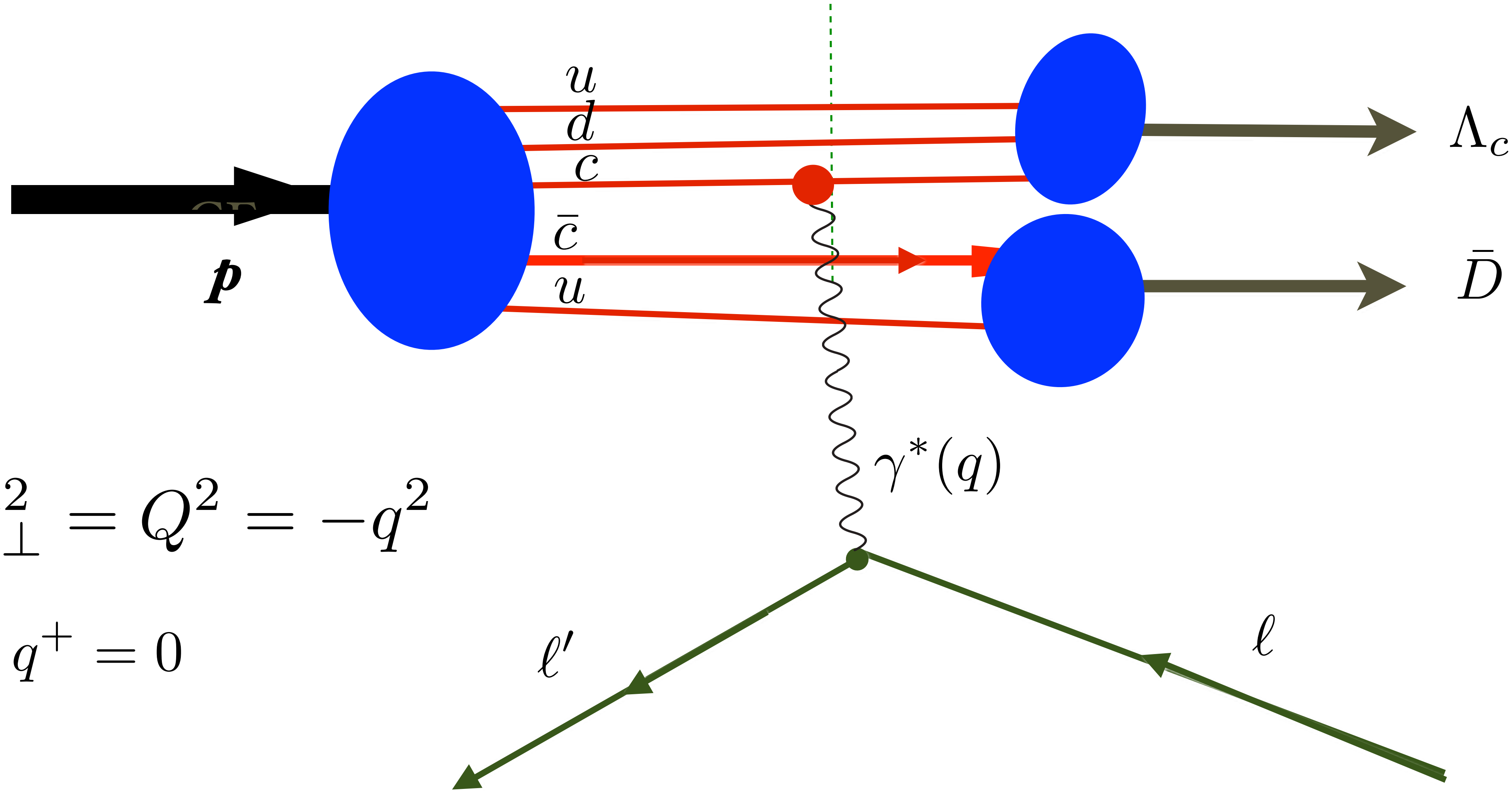


$$q_\perp^2 = Q^2 = -q^2$$

$$q^+ = 0$$

Coalescence of comovers produces $|F> = |\Lambda_c \bar{D}>$ Final State

Light-Front Wavefunctions and Heavy-Quark Electroproduction



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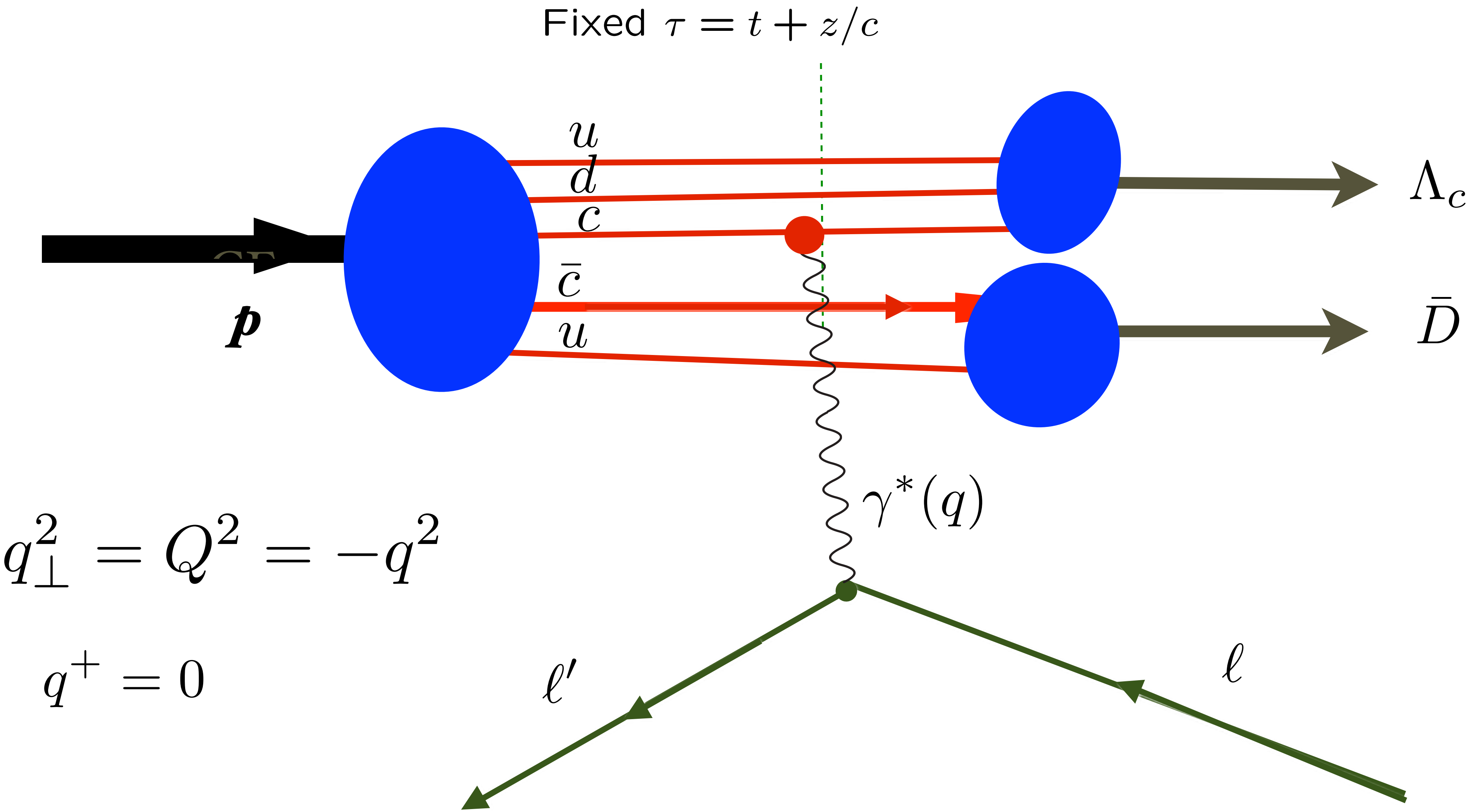
Light-Front Wavefunctions and Heavy-Quark Electroproduction



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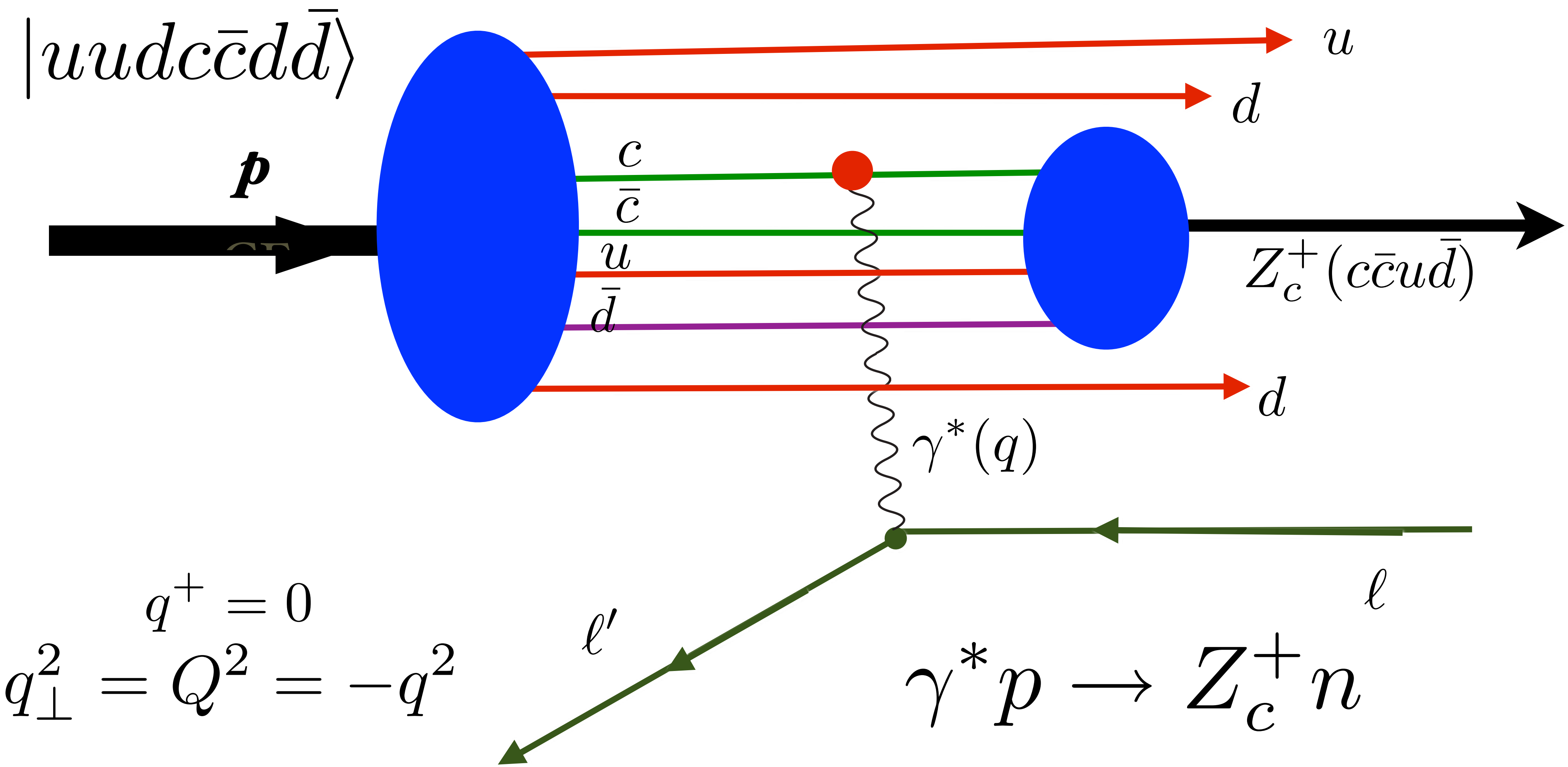

Coalescence of comovers at threshold produces
Z_c^+ tetraquark resonance

Bottom Tetraquarks

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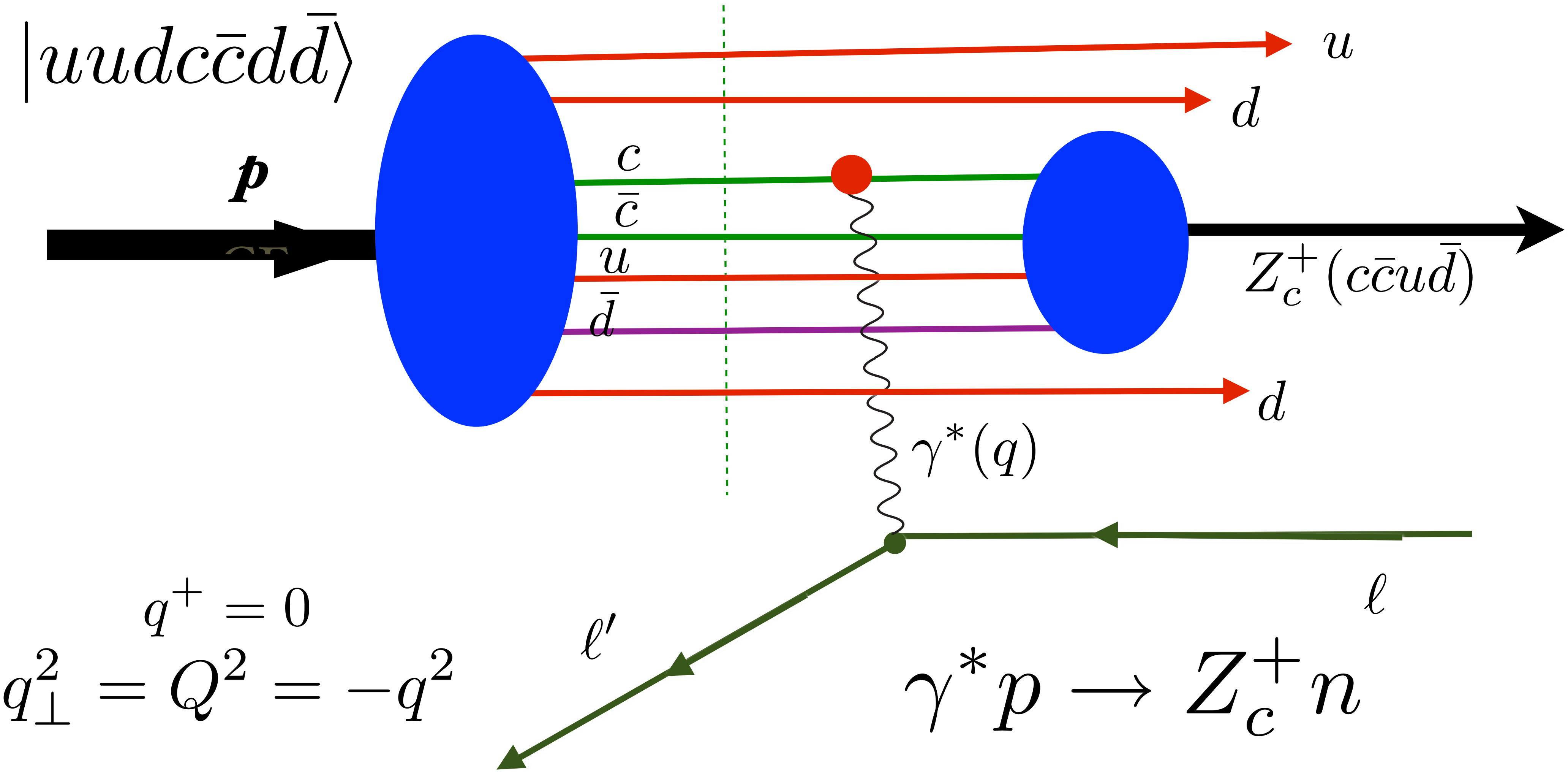

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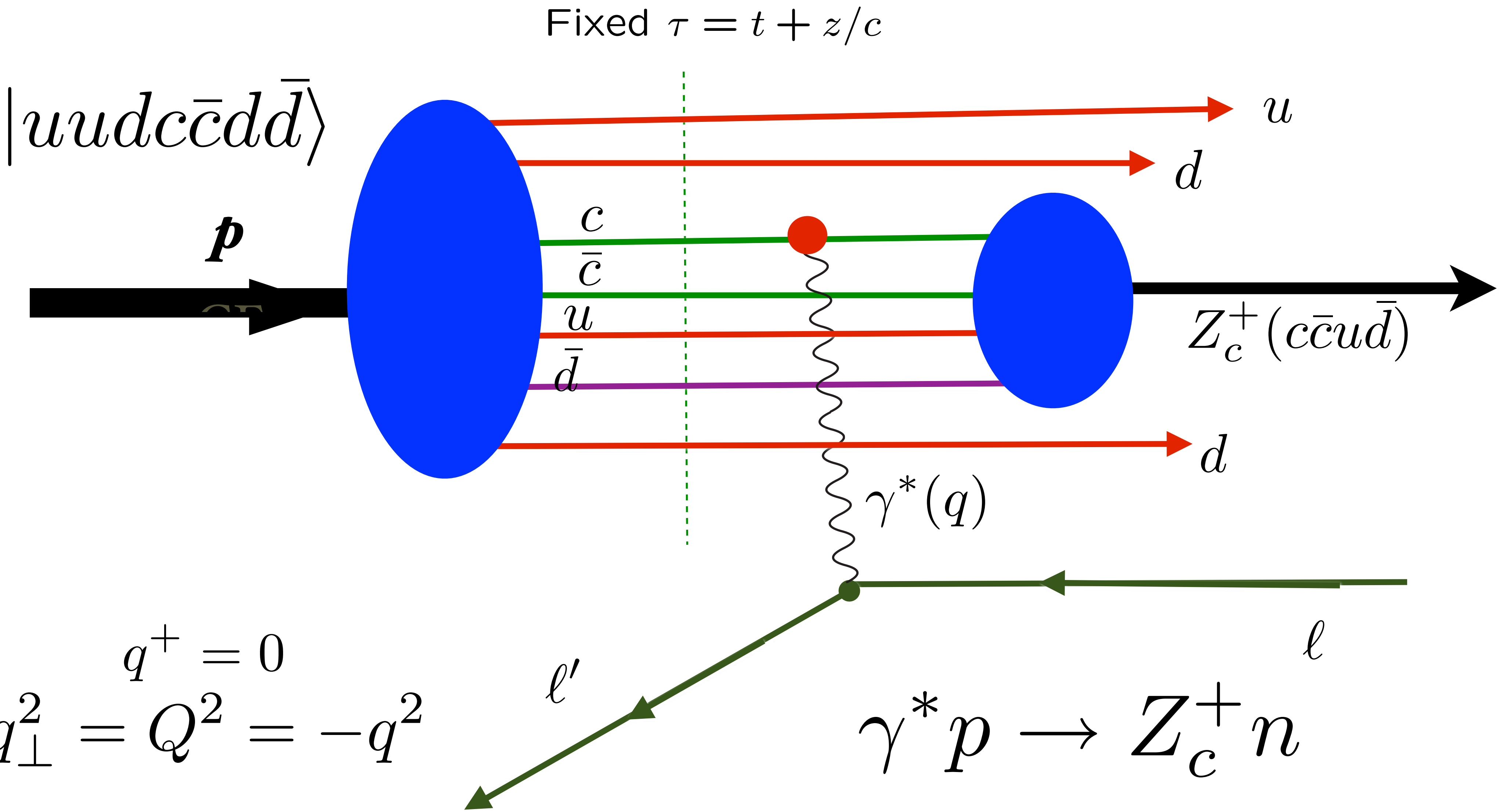

$$q^+ = 0$$
$$q_\perp^2 = Q^2 = -q^2$$

$$\gamma^* p \to Z_c^+ n$$

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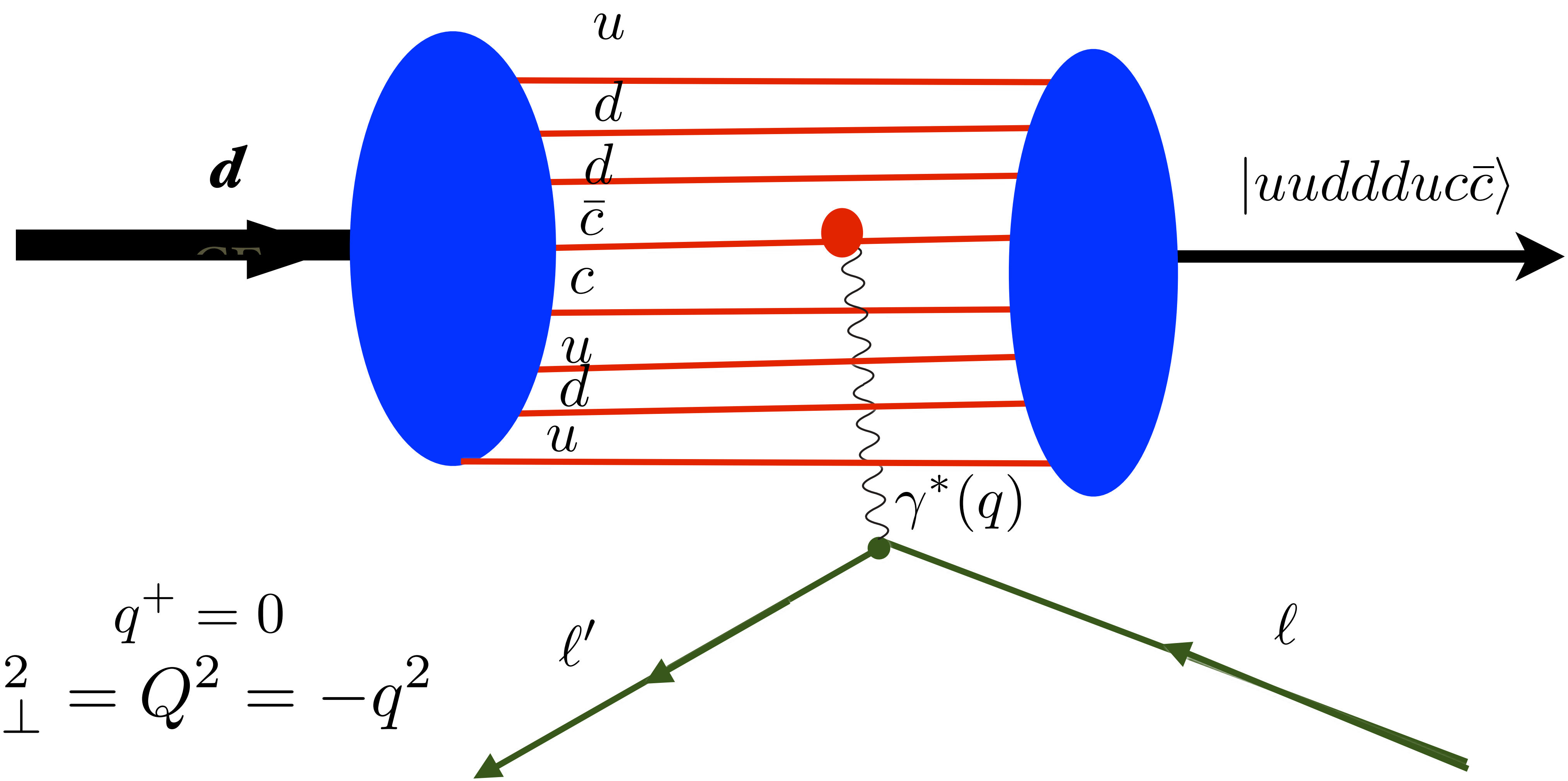
Octoquarks and Heavy-Quark Electroproduction



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Coalescence of comovers can produce the $B = +2$ $Q = +1$ isospin partner of the $B = +2$ $Q = +2$ resonance $|uduudc\bar{c}\rangle$ which produces the large R_{NN} in p p elastic scattering

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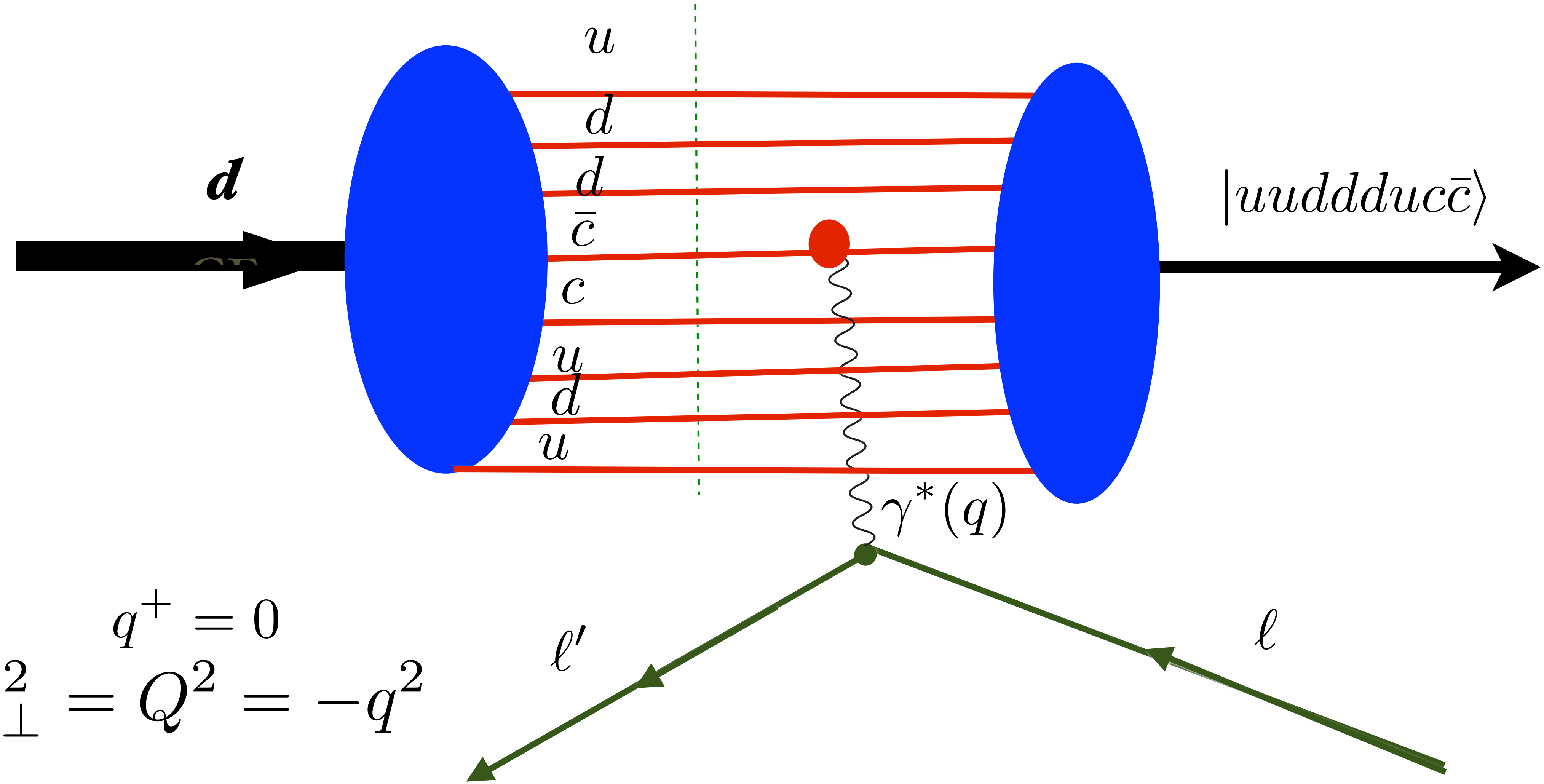

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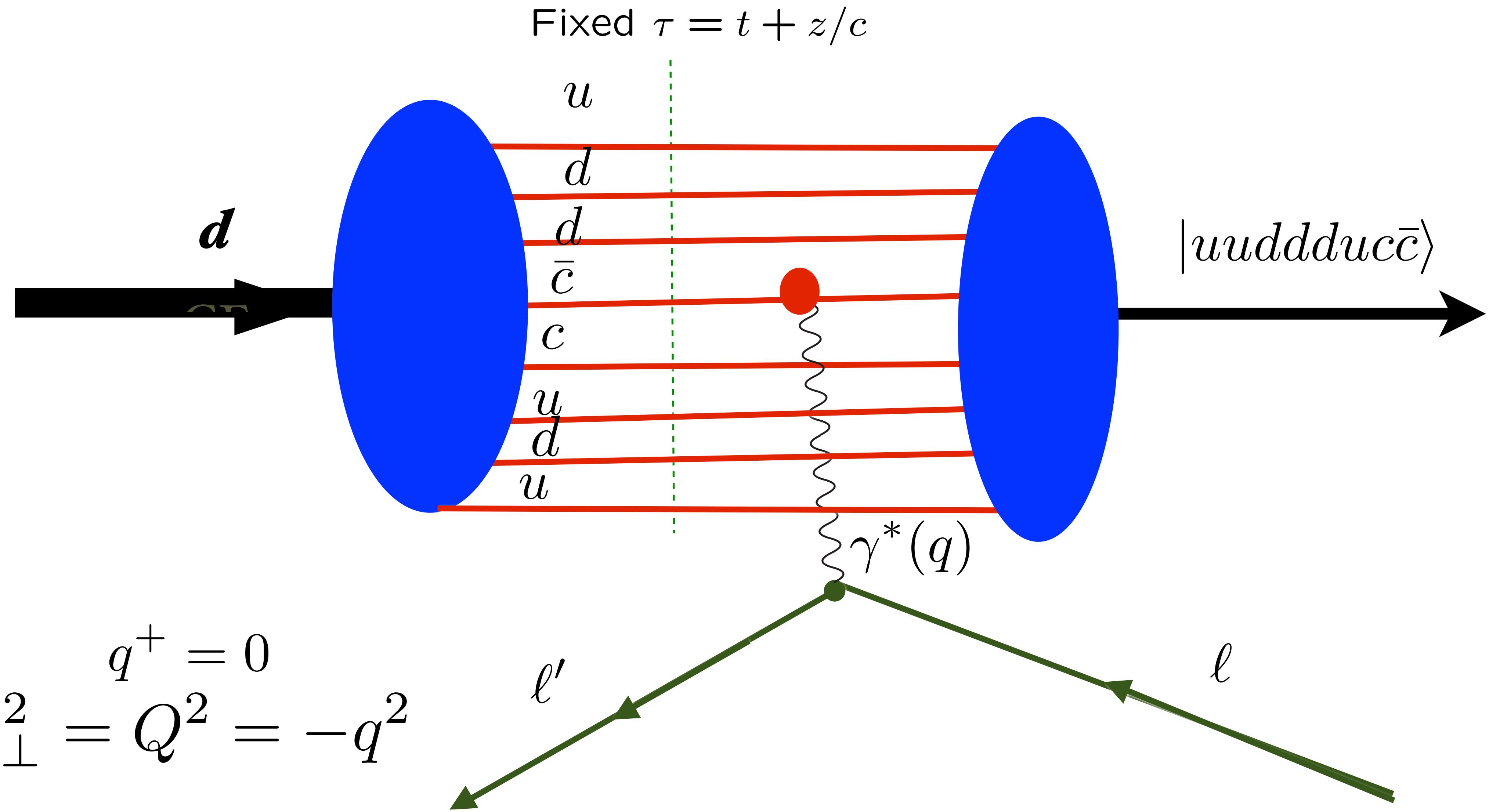

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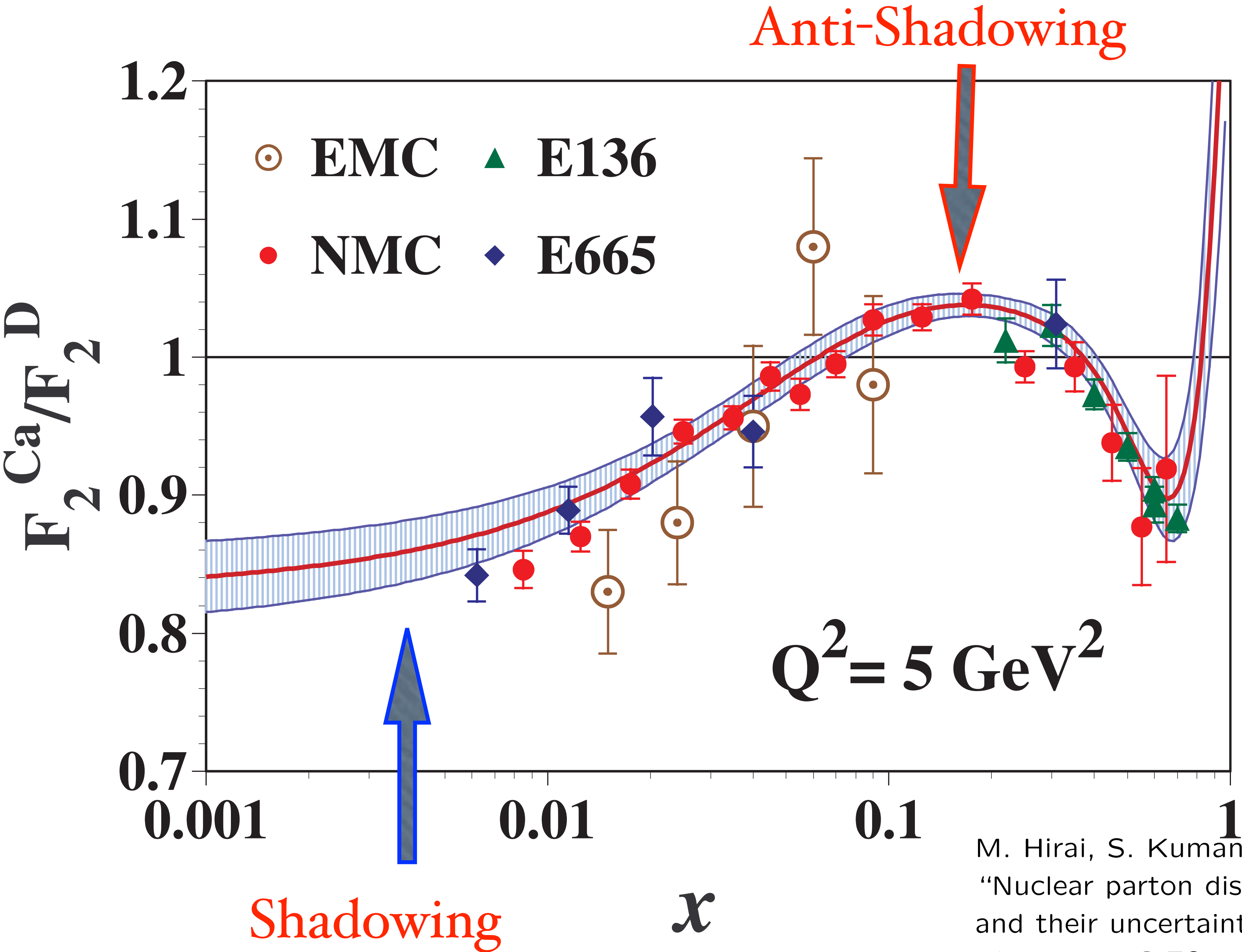
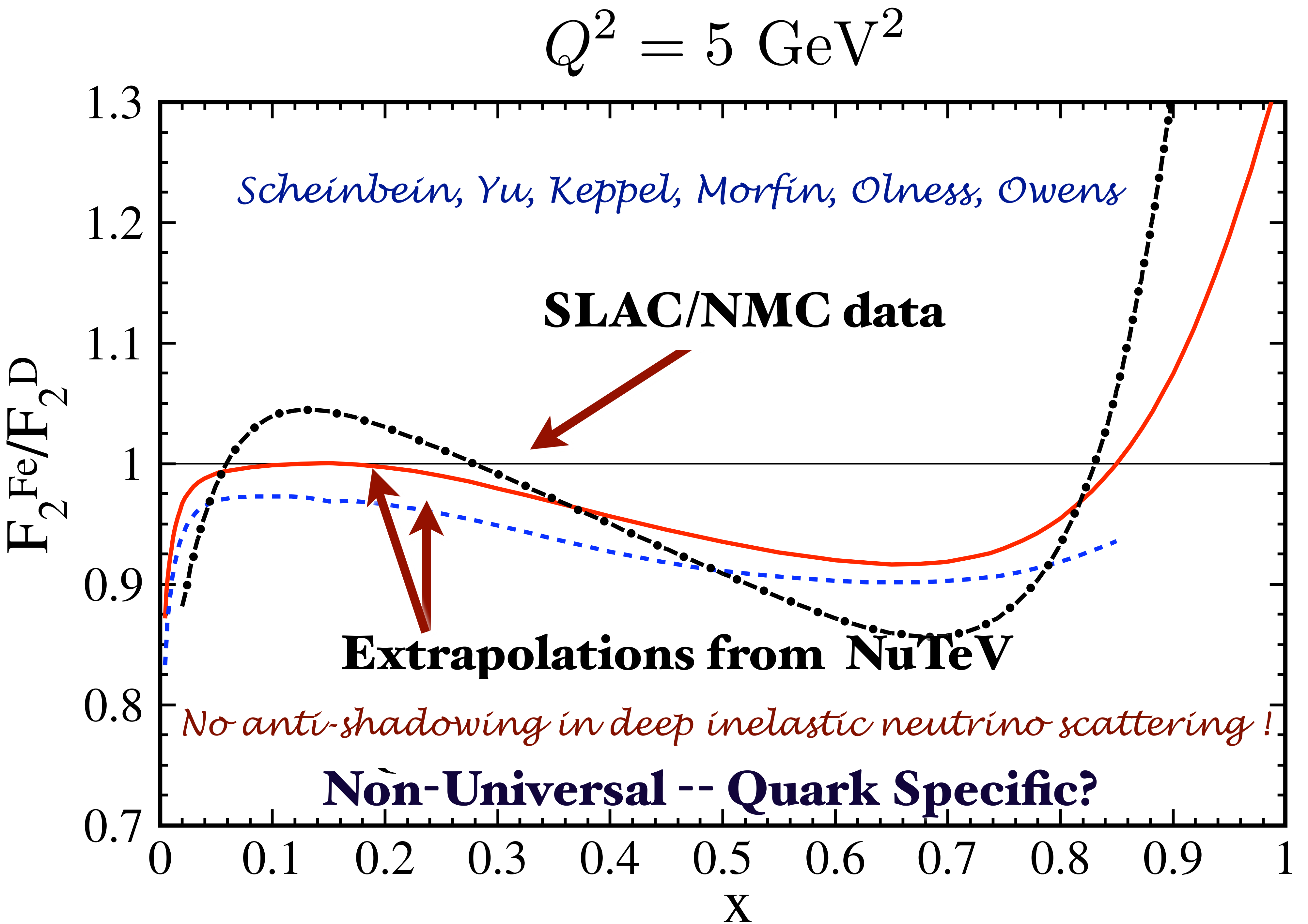
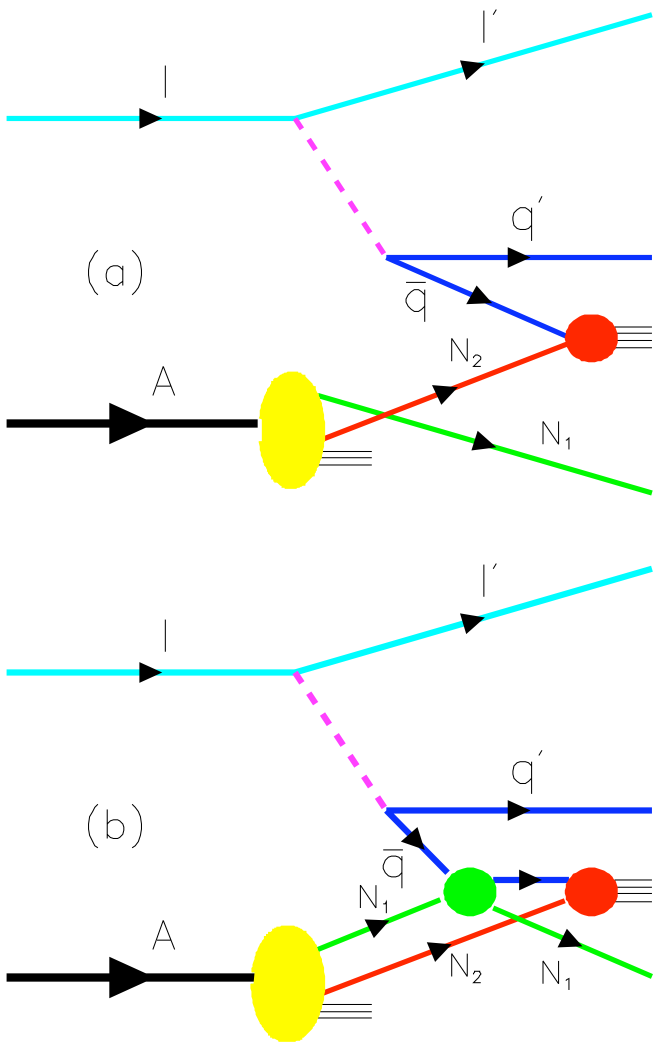
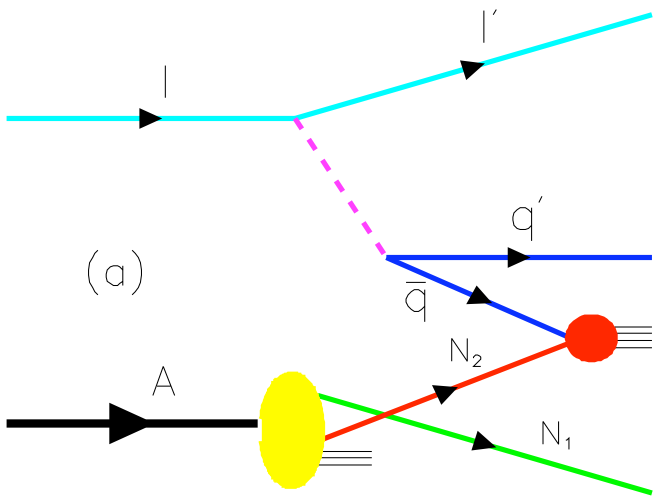


M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093].



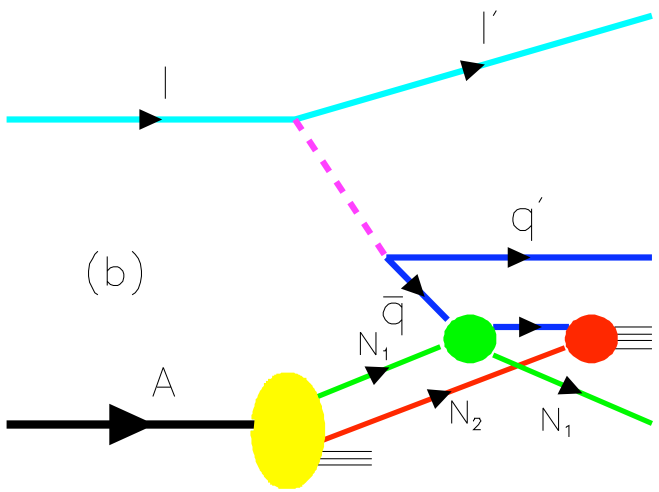
$Q^2 = 5\ \text{GeV}^2$
Scheinbein, Yu, Keppel, Morfin, Olness, Owens
SLAC/NMC data
Extrapolations from NuTeV
No anti-shadowing in deep inelastic neutrino scattering !
Non-Universal -- Quark Specific?
F_2^{Fe}/F_2^{D}
x
1.3
1.2
1.1
1
0.9
0.8
0.7
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1


l
l´
q´
(a)
q̄
N2
A
N1
l
l´
q´
(b)
q̄
N1
A
N2
N1

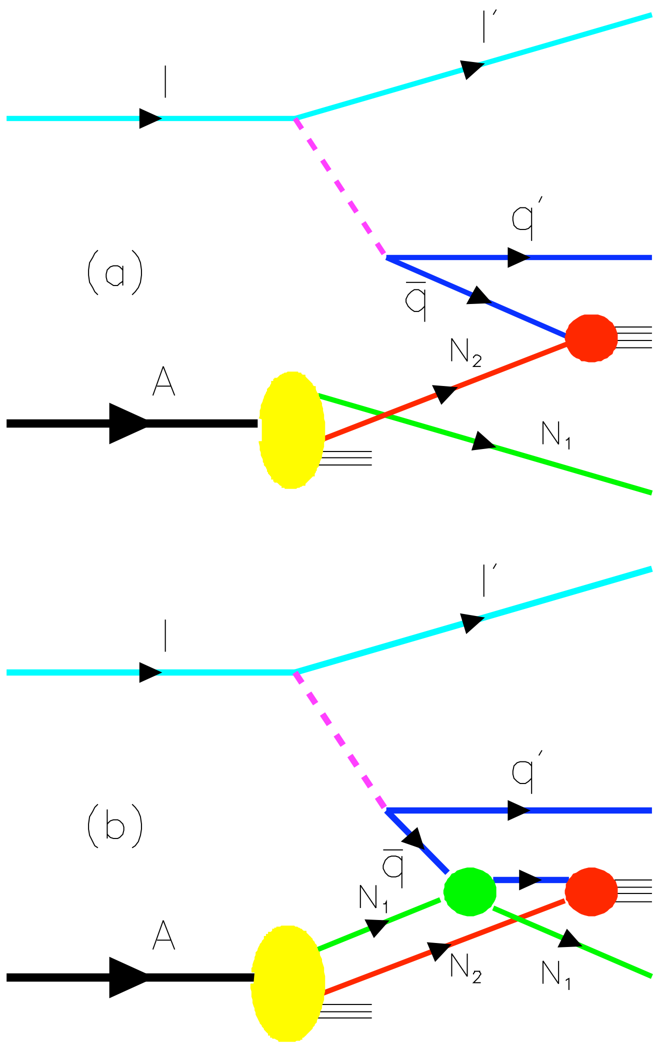


The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken x_B :
$1/Mx_B = 2\nu/Q^2 \geq L_A$.



If the scattering on nucleon N_1 is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\overline{q}$ flux reaching N_2.



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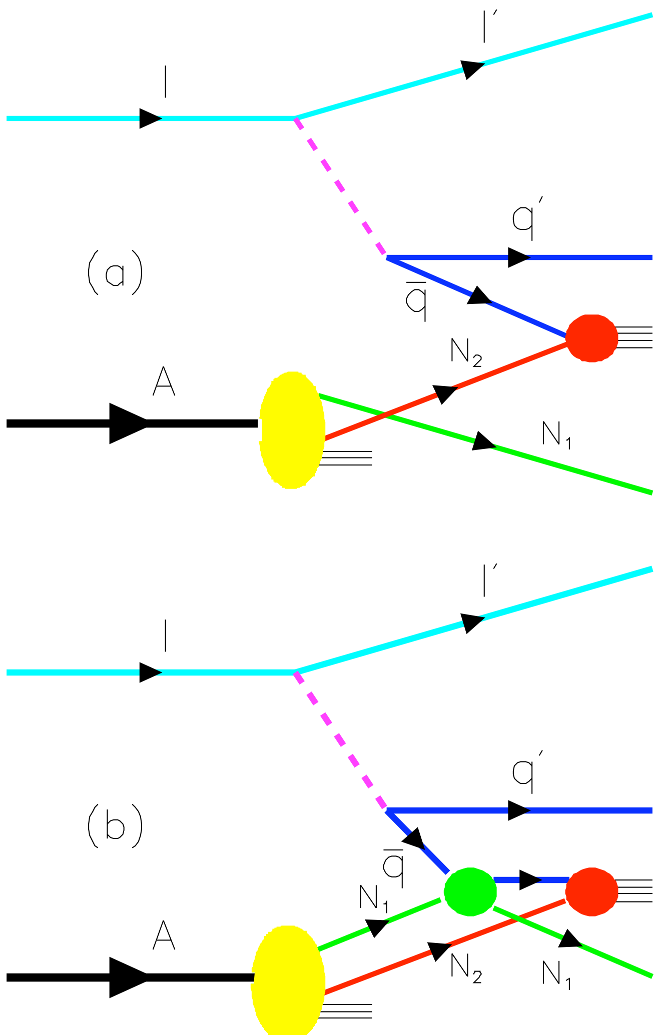

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Regge

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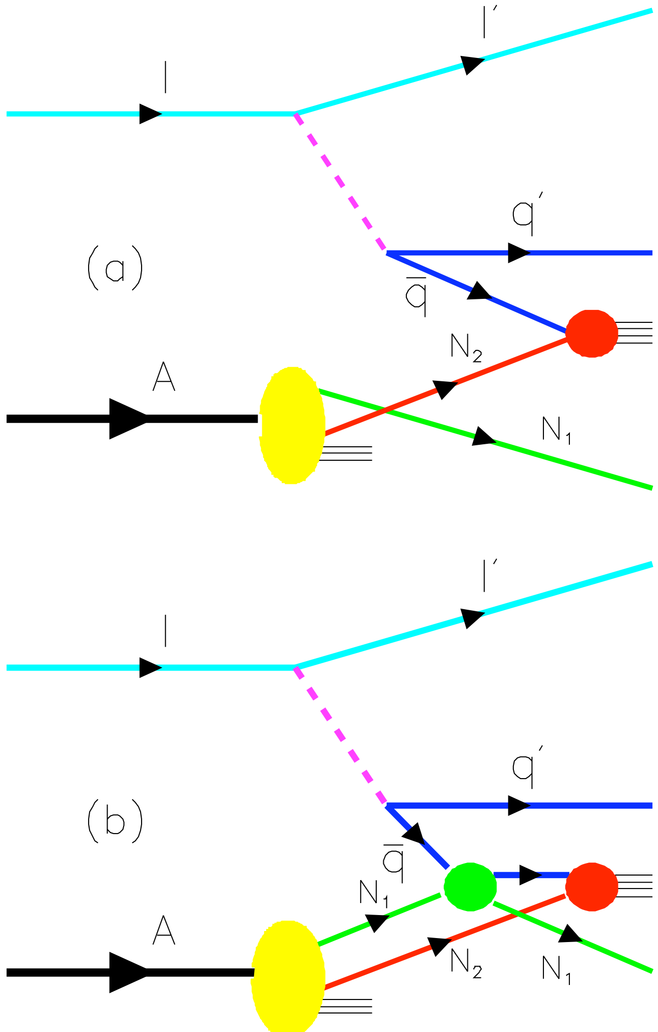
constructive in phase

thus increasing the flux reaching N_2



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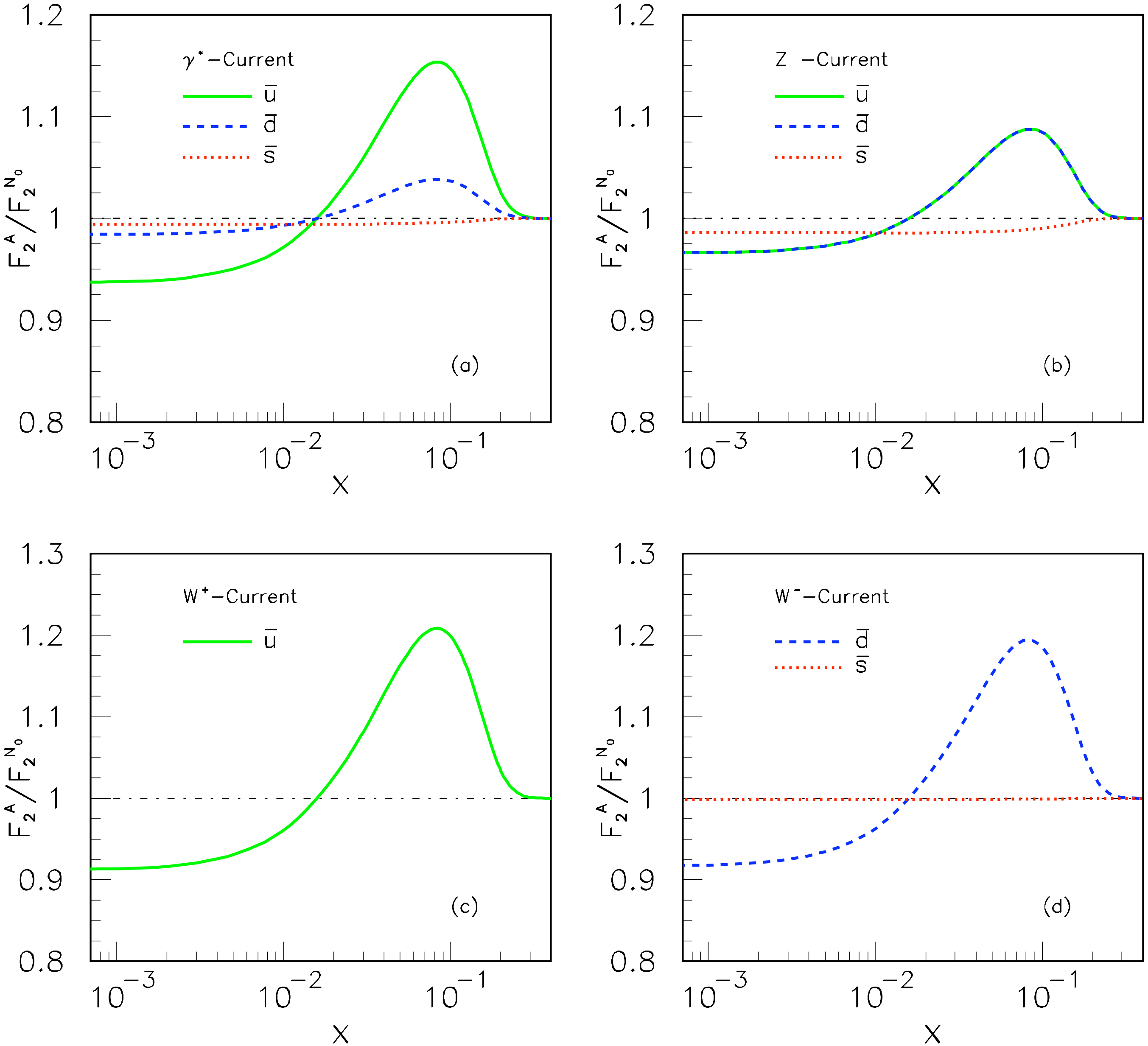
Reggeon DDIS produces nuclear flavor-dependent anti-shadowing



Schmidt, Yang; sjb

Modifies NuTeV extraction of $\sin^2\theta_W$

Test in flavor-tagged DIS at the EIC

Nuclear Antishadowing not universal !

Novel QCD Physics at the EIC

- Control Collisions of Flux Tubes and Ridge Phenomena
- Study Flavor-Dependence of Anti-Shadowing
- Heavy Quarks at Large x; Exotic States
- Direct, color-transparent hard subprocesses and the baryon anomaly
- Tri-Jet Production and the proton's LFWF
- Odderon-Pomeron Interference
- Digluon-initiated subprocesses and anomalous nuclear dependence of quarkonium production
- Factorization-Breaking Lensing Corrections