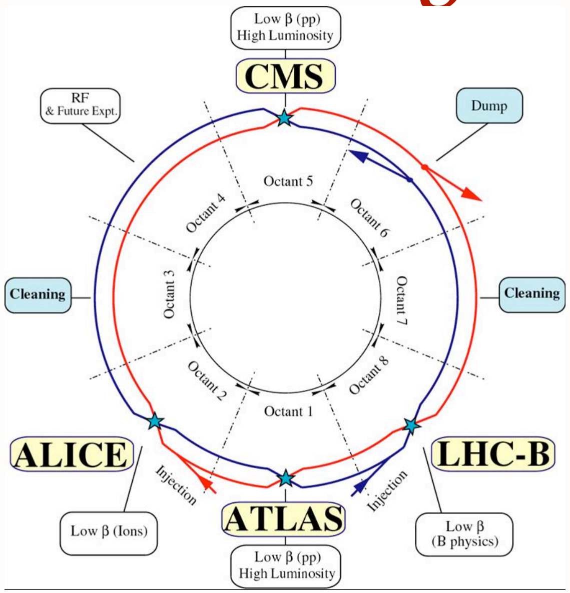
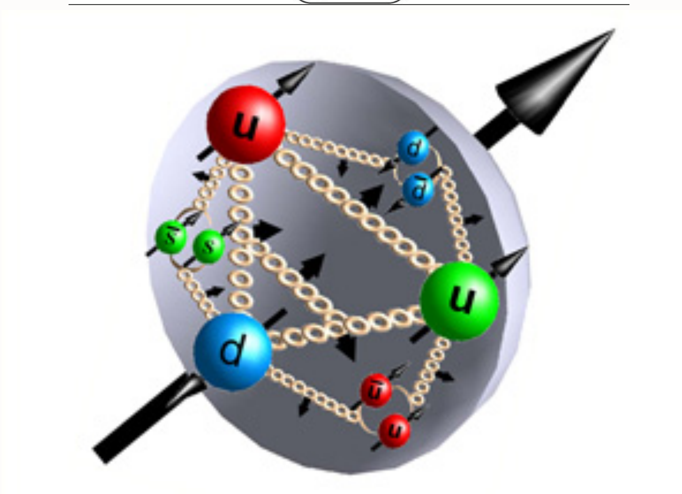
The Physics Case for AFTER: Fixed Target Experiments @ the LHC



AFTER @ LHC



Stan Brodsky

CP³ - Origins
Particle Physics & Origin of Mass

SLAC
NATIONAL ACCELERATOR LABORATORY

Fall meeting of the GDR PH-QCD: Nucleon and Nucleus Structure Studies with a LHC fixed-target experiment and Electron-Ion Collider

The France-Stanford Center for Interdisciplinary Studies

Thanks to: J.-P. Lansberg, F. Fleuret

October 20, 2011

A Compelling Idea for QCD:

Utilize the High-Energy LHC proton and nuclear beams in a fixed-target mode

AFTER @ LHC

A Fixed-Target ExpeRiment

A new hadron physics laboratory for studying and testing QCD

AFTER @ LHC

- *7 TeV proton beam collisions on a proton or nuclear target -- Extract beam with Crystals -*
- *Minimal effects on the collider*
- *Equivalent to Ecm = 115 GeV*
- *Nuclear and Polarized Targets*
- *Nuclear Beams: Produce QGP in Rest Frame of Target Nucleus*
- *Study Dynamics at extreme rapidities:* $X_F = -1$
- *Secondary Beams -- Even B and D*
- *Diffraction on Nucleons and Nucleus*
- *Cosmic Ray Simulations*

A Fixed Target ExperRiment

Generalities

- *pp* or *pA* with a 7 TeV *p* beam : $\sqrt{s} \simeq 115$ GeV (+Fermi motion for *pA*)
- Same ballpark as electron-ion colliders $\rightarrow$ **complementary**
- For *pA*, a Fermi motion of 0.2 GeV would induce a spread of 10 % of $\sqrt{s}$

S.Fredriksson, NPB 94 (1975) 337

- The beam may be extracted using "Strong cristalline field"

E. Huggerhøj, U.I Huggerhøj, NIM B 234 (2005) 31, Rev. Mod. Phys. 77 (2005) 1131 (see later)

- Expected luminosities with 5×10^8 *p*/s extracted (1cm-long target)

Target	ρ (g.cm^{-3})	A	$\mathcal{L}$ (μb^{-1}.s^{-1})	$\mathcal{L}$ (pb^{-1}.y^{-1})
Liq. H_2	0.07	1	21	210
Liq. D_2	0.16	2	24	240
Be	1.85	9	60	600
Cu	8.96	64	40	400
W	19.1	185	30	300
Pb	11.35	207	16	160

(preliminary !)

- Using **NA51**-like 1.2m-long liquid H_2 & D_2 targets, $\mathcal{L}_{H_2/D_2} \simeq 20$ fb$^{-1}y^{-1}$
- For comparison, PHENIX recorded lumi for Run9 pp at 200 GeV: 16 pb^{-1} & Run8 *d*Au at 200 GeV : 0.08 pb^{-1}

- Both p and Pb LHC beams can be extracted without disturbing the other experiments
- Extracting a few per cent of the beam $\rightarrow 5 \times 10^8$ protons per sec
- This allows for high luminosity pp, pA and PbA collisions at $\sqrt{s} = 115$ GeV and $\sqrt{s_{NN}} = 72$ GeV
- **Example**: precision quarkonium studies taking advantage of
  - high luminosity (reach in y, P_T, small BR channels)
  - target versatility (CNM effects, strongly limited at colliders)
  - modern detection techniques (e.g. γ detection with high multiplicity)
- This would likely prepare the ground for $g(x, Q^2)$ extraction
- A wealth of possible measurements:
  DY, Open b/c, jet correlation, UPC... (not mentioning secondary beams)
- Planned LHC long shutdown (< 2020 ?) could be used to install the extraction system
- Very good complementarity with electron-ion programs

Beam extraction

- **Beam extraction @ LHC**

… there are extremely promising possibilities to extract 7 TeV protons from the circulating beam by means of a bent crystal.

… The idea is to put a bent, single crystal of either Si or Ge (W would perform slightly better but needs substantial improvements in crystal quality) at a distance of $\simeq 7\sigma$ to the beam where it can intercept and deflect part of the beam halo by an angle similar to the one the foreseen dump kicking system will apply to the circulating beam.

… ions with the same momentum per charge as protons are deflected in a crystal with similar efficiencies

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NIM B Beam Interactions with Materials & Atoms
Nuclear Instruments and Methods in Physics Research B 234 (2005) 31–39
www.elsevier.com/locate/nimb

Strong crystalline fields – a possibility for extraction from the LHC

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Received 9 September 2004; received in revised form 6 January 2005
Available online 24 February 2005

If the crystal is positioned at the kicking section, the whole dump system can be used for slow extraction of parts of the beam halo, the particles that are anyway lost subsequently at collimators.

AFTER @ LHC – Luminosity

- **Intensity: expect 5.10^8 protons.s^{-1}**
  - **Beam:** 2808 bunches of 1.15×10^{11} protons = **3.2×10^{14} protons**
  - **Bunch:** Each bunch passes IP at the rate: 3.10^5km.s^{-1}/27 km ~ **11 kHz**
  - **Instantaneous extraction:** IP sees 2808 x 11000~3.10^7 bunches passing every second
    ➔ extract $5.10^8/3.10^7$ ~ **extract 16 protons in each bunch at each pass**
  - **Integrated extraction:** Over a 10h run: extract 5.10^8p x 3600s.h^{-1} x 10h=1.8 10^{13}p.run^{-1}
    ➔ extract 1.8 x 10^{13}/(3.2 x 10^{14})~**5.6% of the protons stored in the beam**
- **Instantaneous Luminosity**
  $\mathcal{L} = N_{beam} \times N_{Target} = N_{beam} \times (\rho \times e \times \mathcal{N}_A)/A$
  - N_{beam}=5 x 10^8 p^+/s
  - **e** (target thickness) = 1 cm
- **Integrated luminosity**
  - 9 months running/year
  - ➔ 1year ~ 10^7 s
  - ➔ $\int_{year}\mathcal{L} = \mathcal{L}_{inst}\times10^7$
- **Pb+A intensity : expect 7.10^5Pb.s^{-1}**
  - PHENIX @ RHIC recorded in 2010
    - Au+Au @ 200 GeV : 1.3 nb^{-1}
    - Au+Au @ 62 GeV: 0.11 nb^{-1}

p+A

Targ	ρ ($g.cm^{-3}$)	A	$\mathcal{L}_{inst}$ ($\mu b^{-1}.s^{-1}$)	$\int_{year}\mathcal{L}$ ($pb^{-1}.y^{-1}$)
Liq H	0.068	1	20	200
Liq D	0.16	2	24	240
Be	1.85	9	62	620
Cu	8.96	64	42	420
W	19.1	185	31	310
Pb	11.35	207	16	160

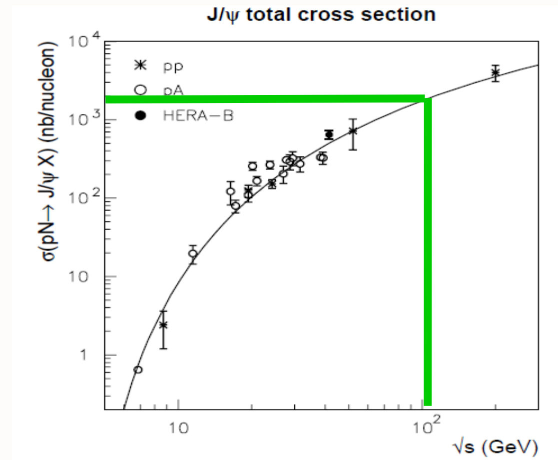
Pb+A

Target	ρ ($g.cm^{-3}$)	A	$\mathcal{L}$ ($mb^{-1}.s^{-1}$)=$\int\mathcal{L}$ ($nb^{-1}.yr^{-1}$)
Liq. H_2	0.07	1	28
Liq. D_2	0.16	2	34
Be	1.85	9	84
Cu	8.96	64	56
W	19.1	185	42
Pb	11.35	207	22

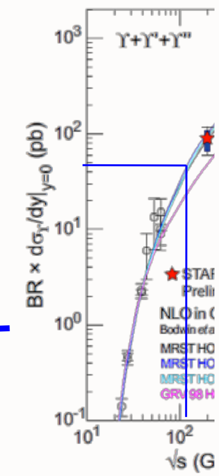
AFTER @ LHC – Luminosity

- **Typical numbers**
  - **J/Ψ @ √s=115 GeV**
    - **σ_Ψ ~ 1.5 10^3 nb**

    ➔ $Br_{\Psi \to e+e-}\, d\sigma_\Psi/dy(y=0)$ ~ 30 nb



  - **Υ @ √s=115 GeV**
    - **$Br_{\Upsilon \to e+e-}\, d\sigma_\Upsilon/dy(y=0)$@ 115 GeV ~ 50 pb**



With 1 cm thick target

Target	ρ (g.cm⁻³)	A	$\mathcal{L}$ ($\mu b^{-1}.s^{-1}$)	$\mathcal{L}$ ($pb^{-1}.y^{-1}$)	$N_{J/\Psi}\|_{y=0}$ (y^{-1}) $N_{J/\Psi} = A\mathcal{L}\sigma_\Psi$	$N_\Upsilon\|_{y=0}$ (y^{-1}) $N_\Upsilon = A\mathcal{L}\sigma_\Upsilon$
Liq H	0.068	1	20	200	6 10^6	1. 10^5
Liq D	0.16	2	24	240	1.4 10^7	2.4 10^5
Be	1.85	9	62	620	1.6 10^8	2.8 10^5
Cu	8.96	64	42	420	8.1 10^8	1.3 10^6
W	19.1	185	31	310	1.7 10^9	2.9 10^6
Pb	11.35	207	16	160	1. 10^9	1.7 10^6

Fixed Target Physics with the LHC Beams

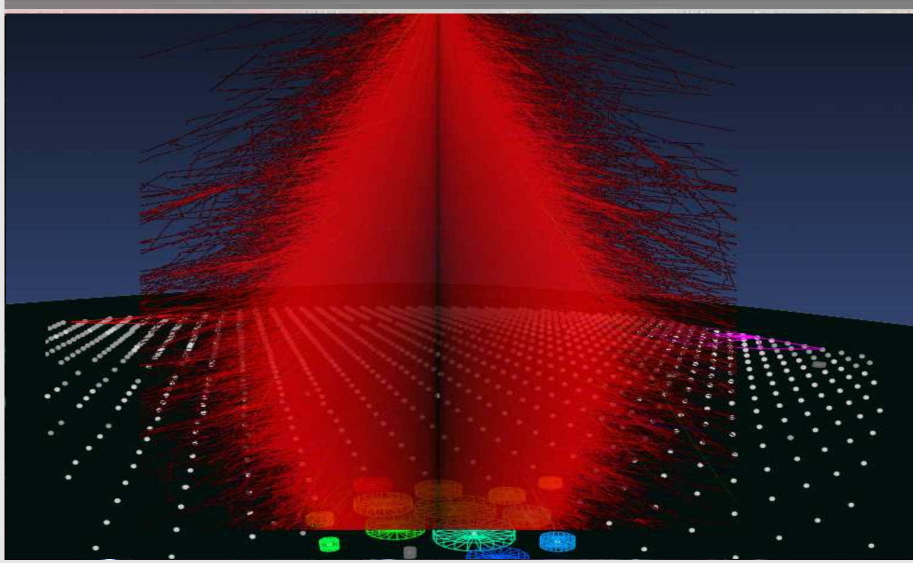
- 7 TeV proton beam, nuclear beams
- Full Range of Nuclear and Polarized Targets
- Cosmic Ray simulations!
- Single-Spin Asymmetries, Transversity Studies, A_N
- High-x_F Dynamics
- High-x_F Heavy Quark Phenomena
- Production of ccq to ccc to bbb baryons
- Quark-Gluon Plasma in Nuclear Rest System
- Anti-Shadowing: Flavor Specific?

Karlsruhe Institute of Technology

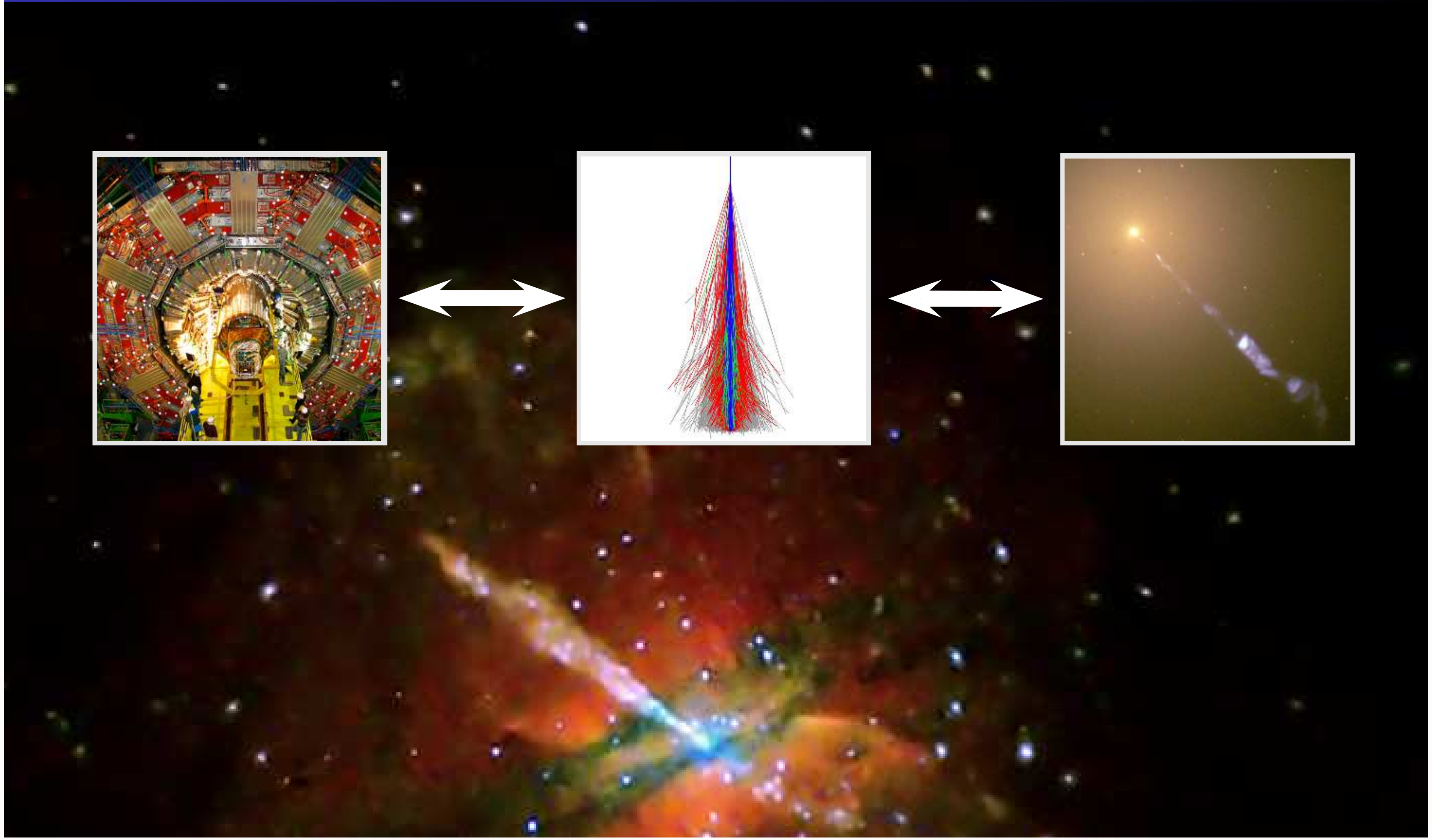
Ultra-High Energy Cosmic Ray Interactions at the Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

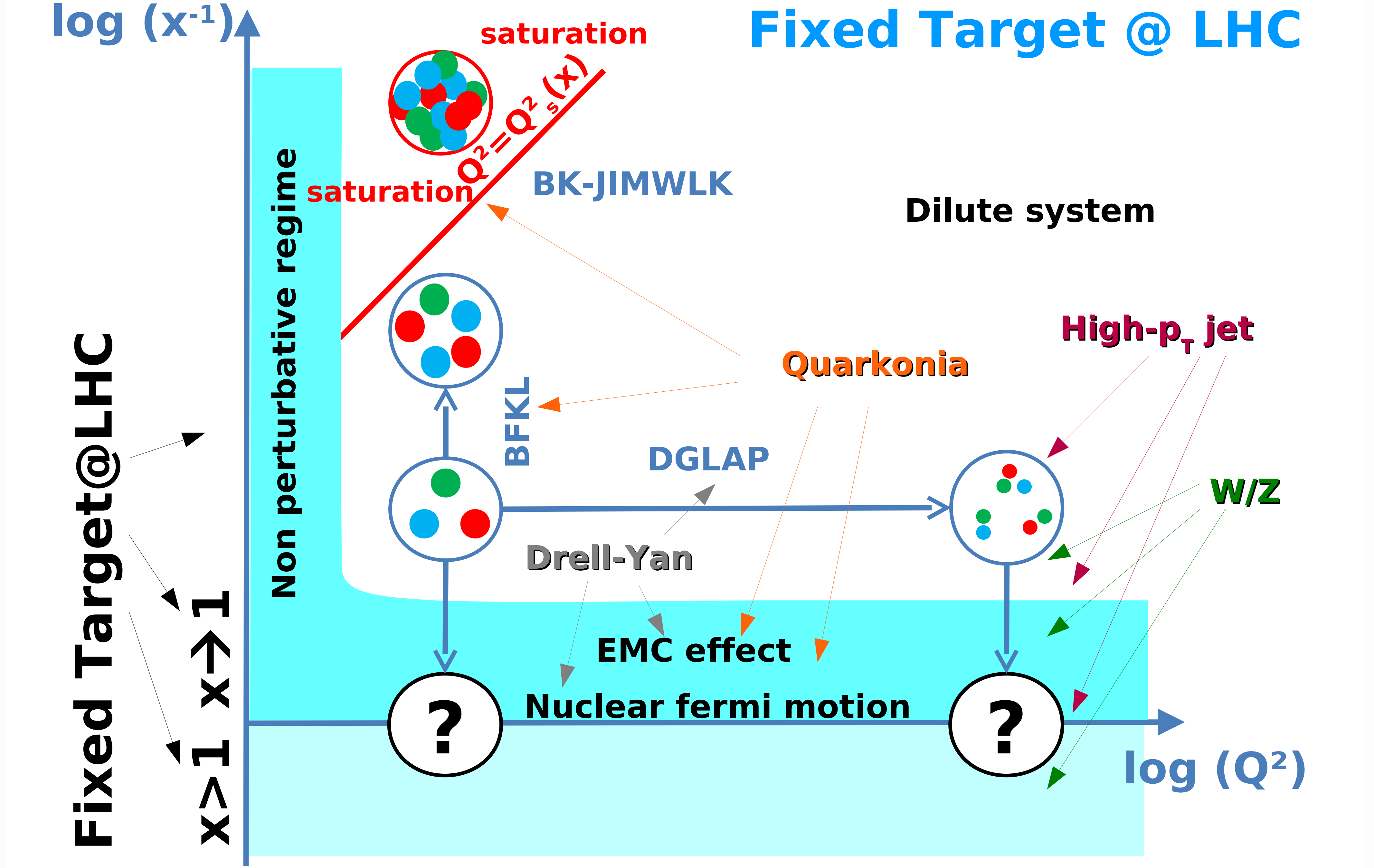
Ralf Ulrich for the Pierre Auger Collaboration, Florence, October 2011



Connecting High Energy Particle Physics with Cosmic Rays



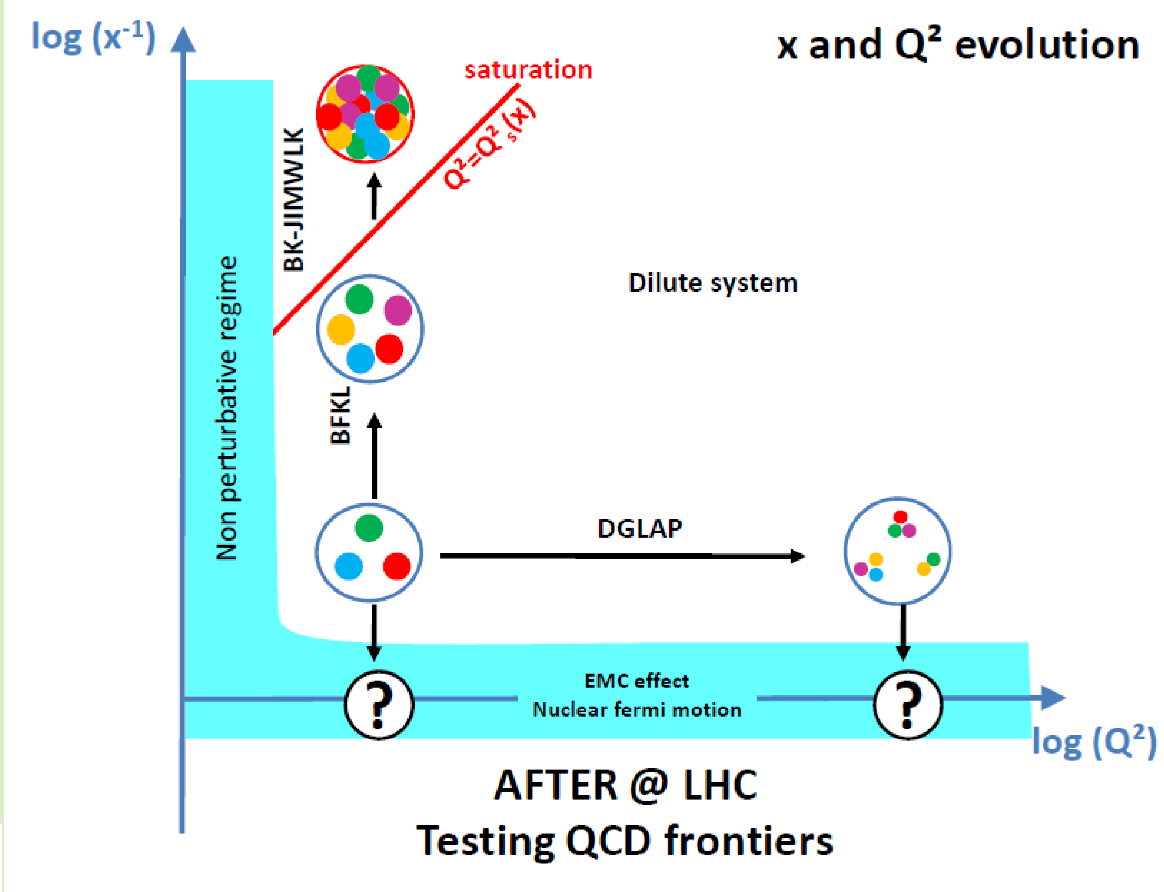
Fixed Target @ LHC



AFTER @ LHC – Physics

- **Idea : use LHC beam on fixed target**
  – *7 TeV proton beam*
  – *2.75 TeV Pb beam*

- ***High boost and luminosity giving access to***
  – *QCD at large x*
  – *nPDF and shadowing*
  – *Spin physics …*



A Fixed Target ExperRiment

Generalities

- *Pbp* or *PbA* with a 2.75 TeV Pb beam : $\sqrt{s} \simeq 72$ GeV
- Cristal channeling is also possible (to extract a few per cent of the beam)
- Requires cristals highly resistant to radiations: progress with diamonds

P. Ballin *et al.*, **NIMB 267 (2009) 2952**

- Expected luminosities with 7×10^5 Pb/s extracted (1cm-long target)

Target	ρ (g.cm^{-3})	A	$\mathcal{L}$ (mb^{-1}.s^{-1})=$\int\mathcal{L}$ (nb^{-1}.yr^{-1})
Liq. H_2	0.07	1	**28**
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Pb	11.35	207	**22**

(Preliminary !)

- For comparison, Phenix recorded lumi for Run10
  AuAu at 200 GeV: 1.3 nb^{-1} & AuAu at 62 GeV: 0.11 nb^{-1}

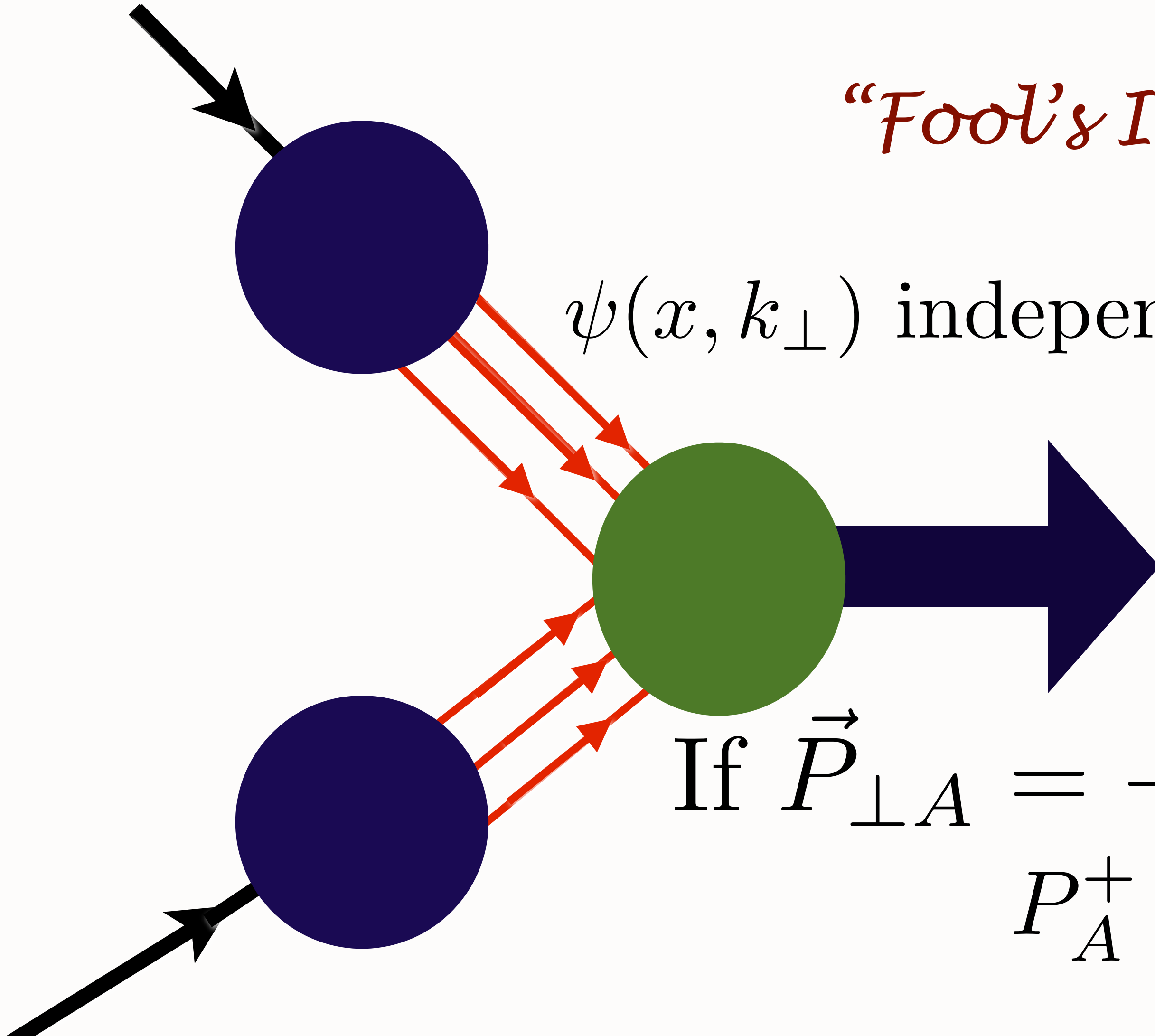
Nuclear Collisions with AFTER

- Nucleus-Nucleus and Proton-Nucleus Scattering in Lab Frame Look at Target Fragmentation Region $x_F=-1$
- What happens to Target Nucleus when QGP is formed?
- Ridge at extreme rapidity
- What are the critical parameters for the onset of QGP
- Light-Front Description: Frame-Independent
- Use Fool's ISR Frame -- No Lorentz Contraction of LFWF
- Energy Loss Studies, LPM, Non-Abelian
- Quarkonium Production, Polarization
- Open charm, bottom

$$P_A^\mu = (P_A^+, P_A^-, \vec{P}_{\perp A})$$

$$P^- = \frac{P_\perp^2 + M^2}{P^+}$$

"Fool's ISR Frame"



$\psi(x, k_\perp)$ independent of $P^+, \vec{P}_\perp$

If $\vec{P}_{\perp A} = -\vec{P}_{\perp B} = \vec{P}_\perp$

$$P_A^+ = P_B^+$$

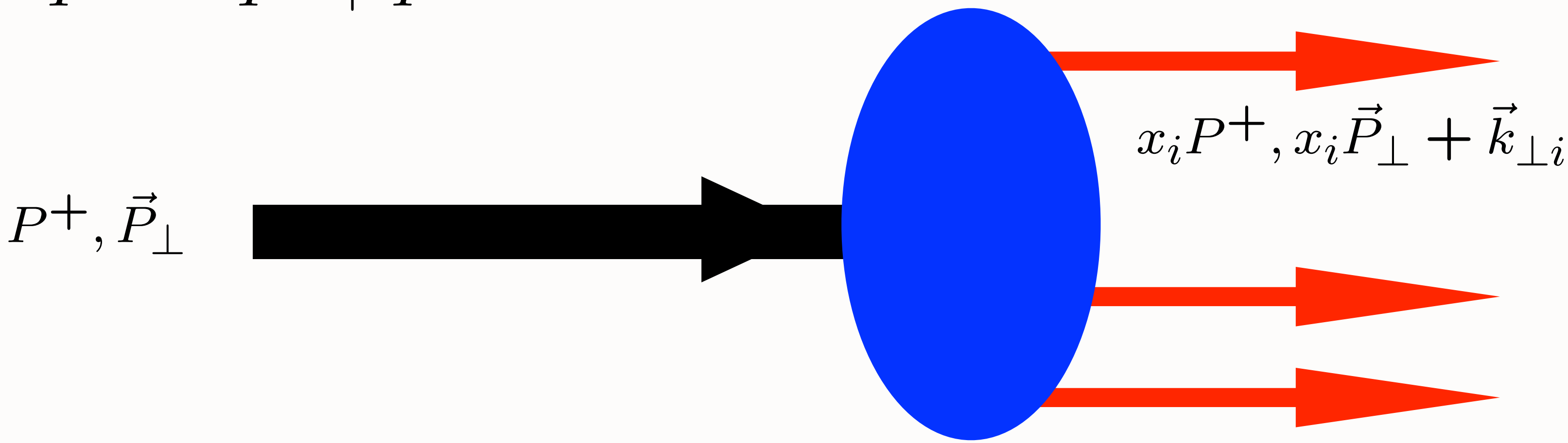
$$s \simeq 4P_\perp^2$$

$$P_B^\mu = (P_B^+, P_B^-, \vec{P}_{\perp B})$$

$$s = (P_A + P_B)^2 = M_A^2 + M_B^2 + \frac{P_{\perp A}^2 + M_A^2}{P_A^+} P_B^+ + \frac{P_{\perp B}^2 + M_B^2}{P_B^+} P_A^+ - 2\vec{P}_{\perp A} \cdot \vec{P}_{\perp B}$$

Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$



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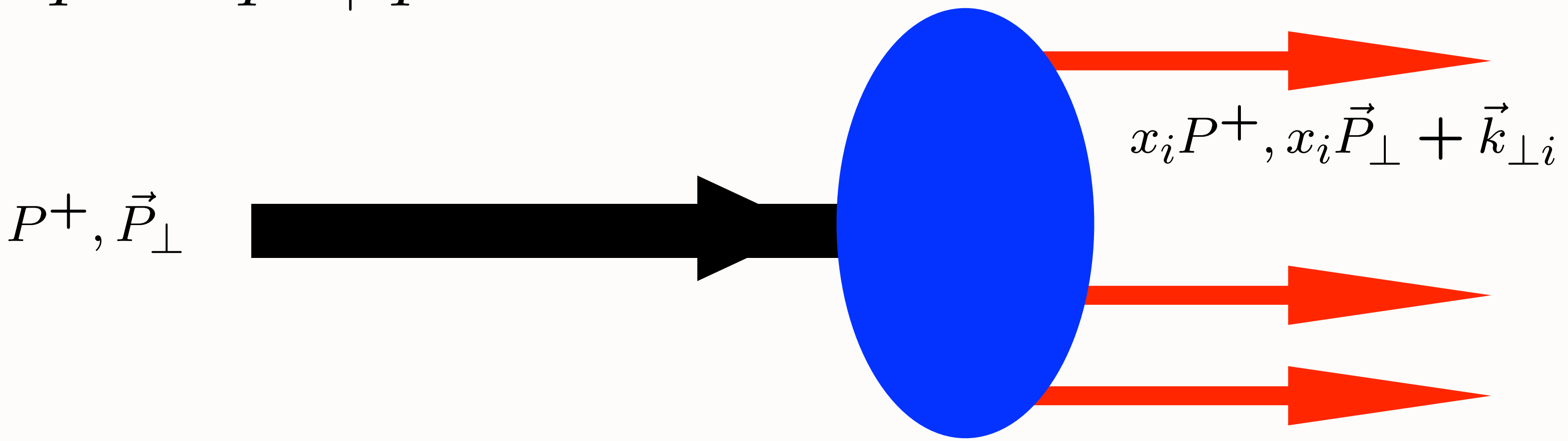

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

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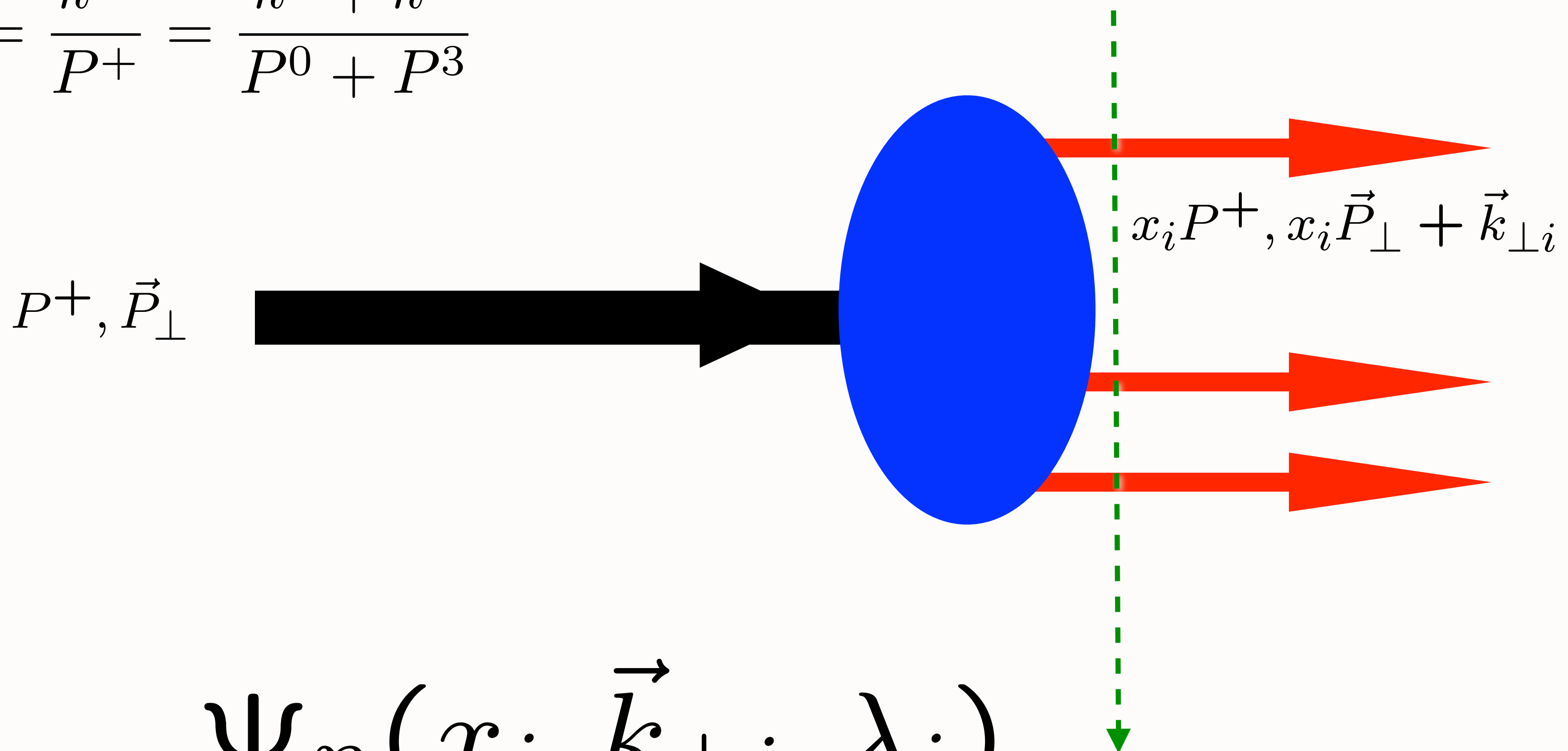

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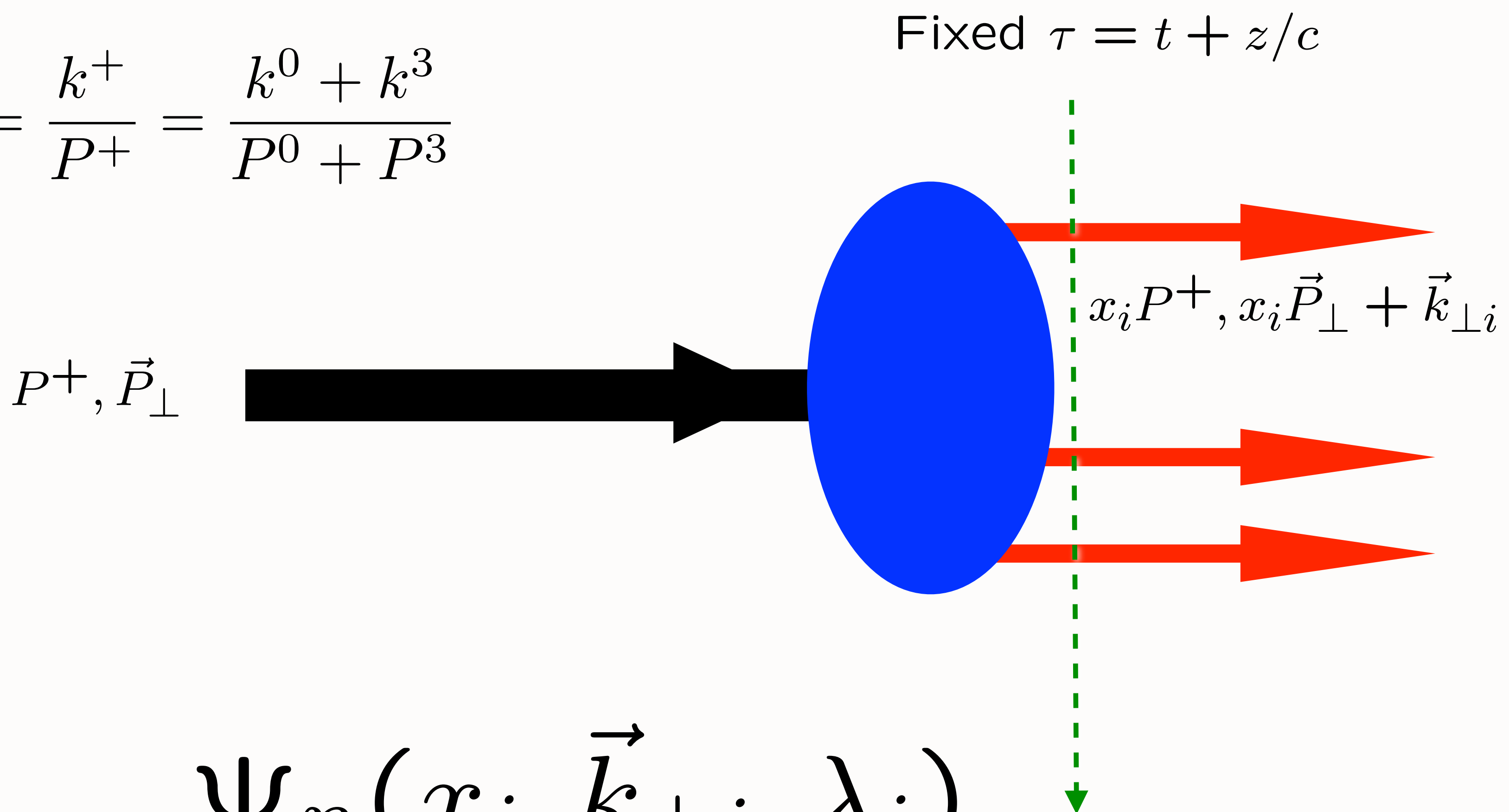

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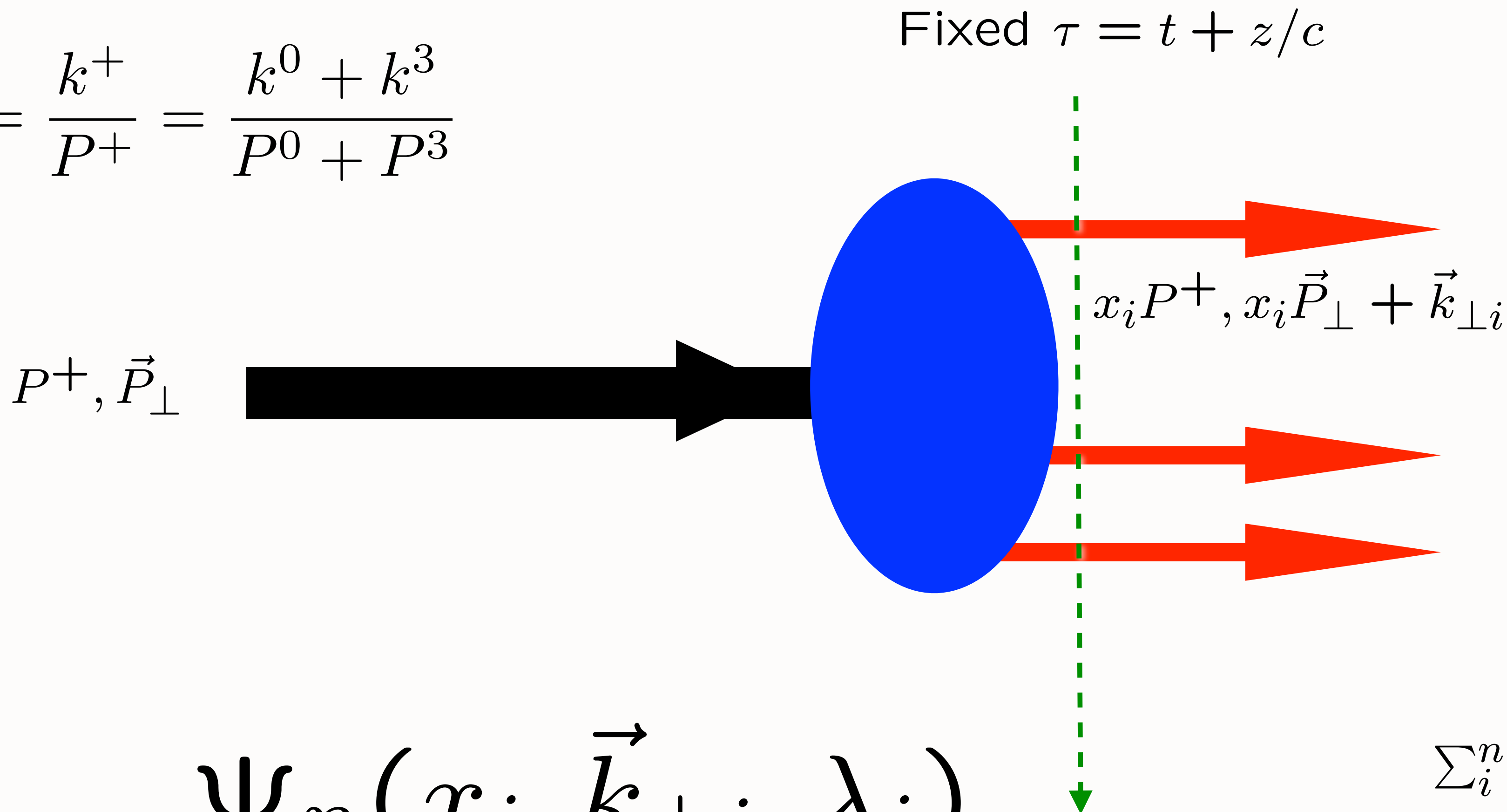

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$\sum_i^n x_i = 1$

Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

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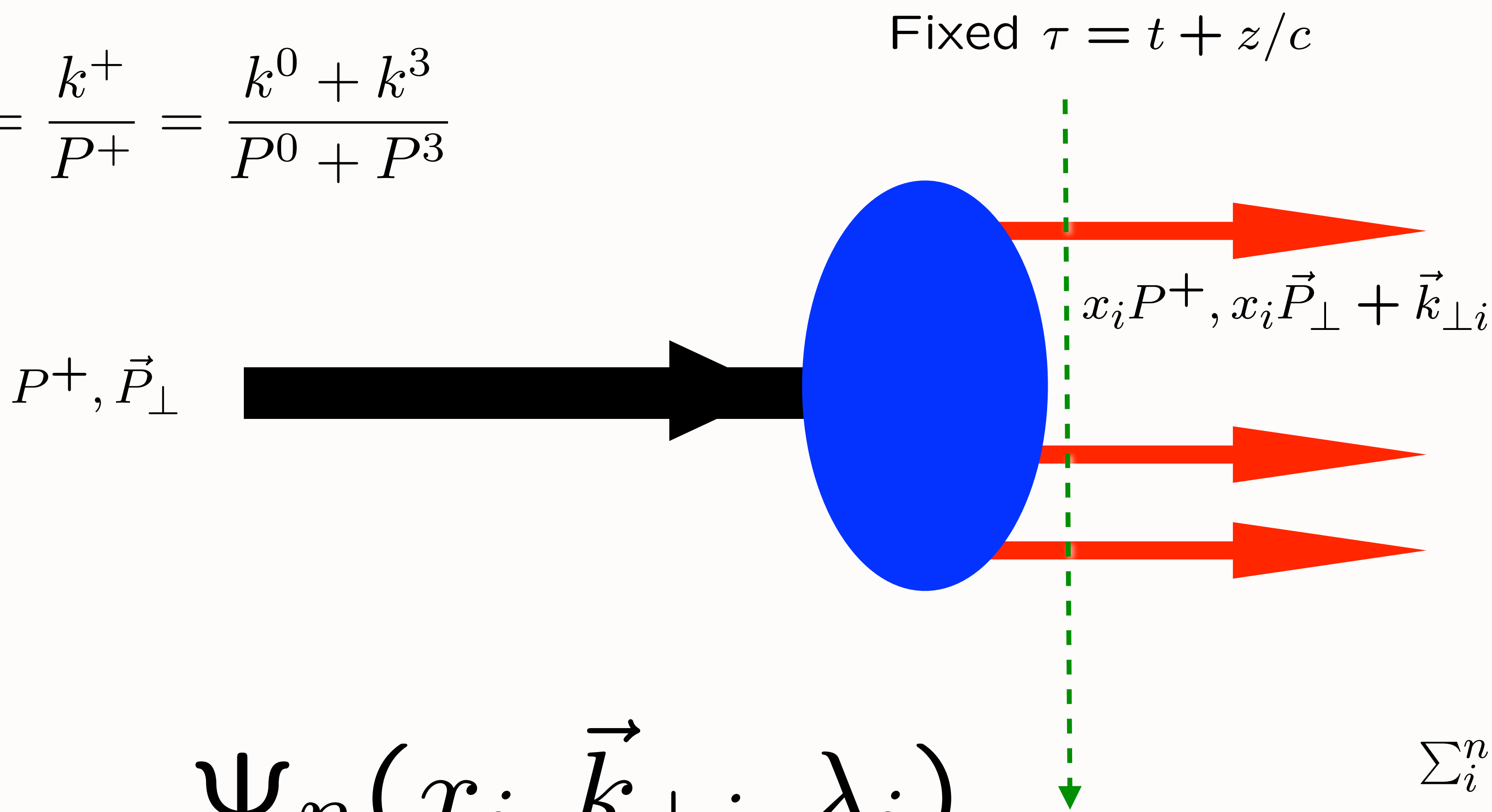


$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$$\sum_i^n x_i = 1$$

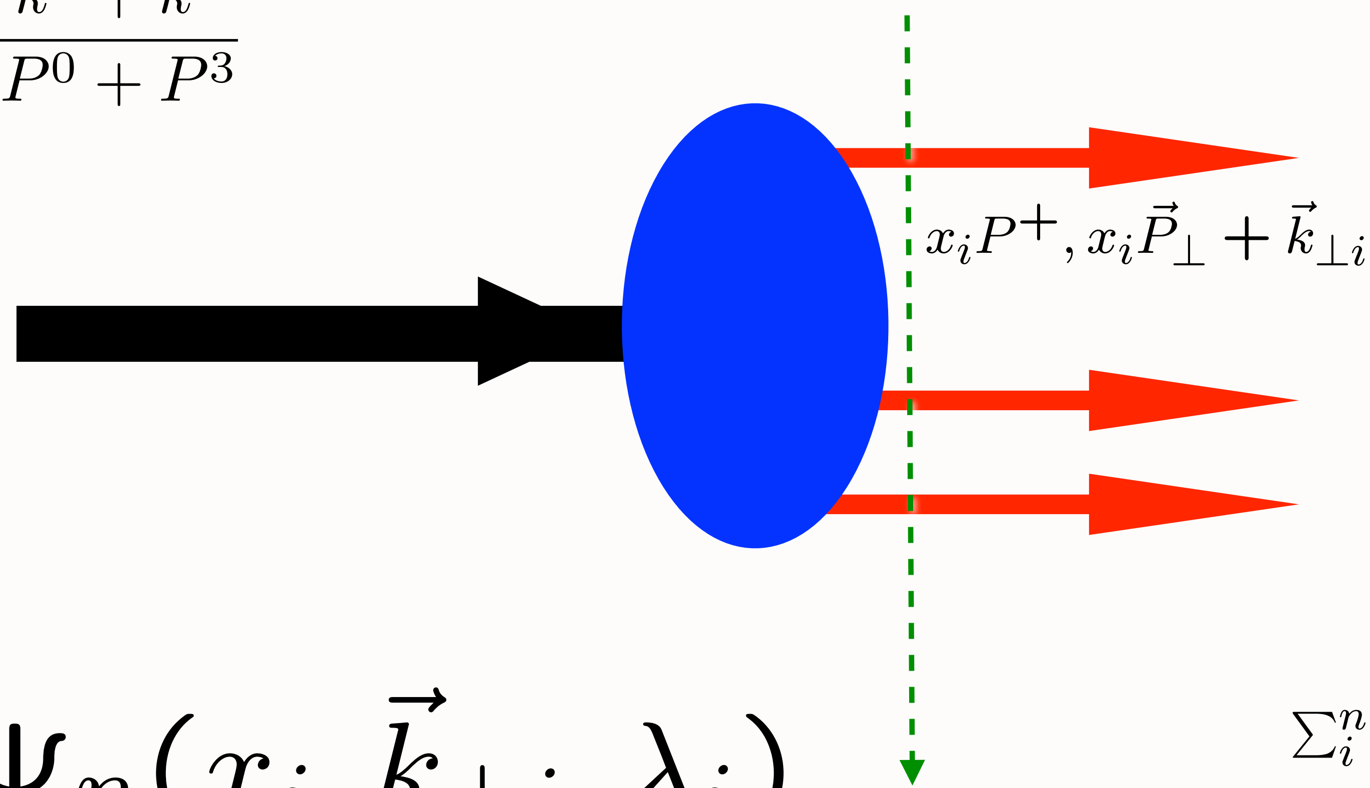
$$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$$

Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$

Fixed $\tau = t + z/c$

$P^+, \vec{P}_\perp$



$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$\sum_i^n x_i = 1$

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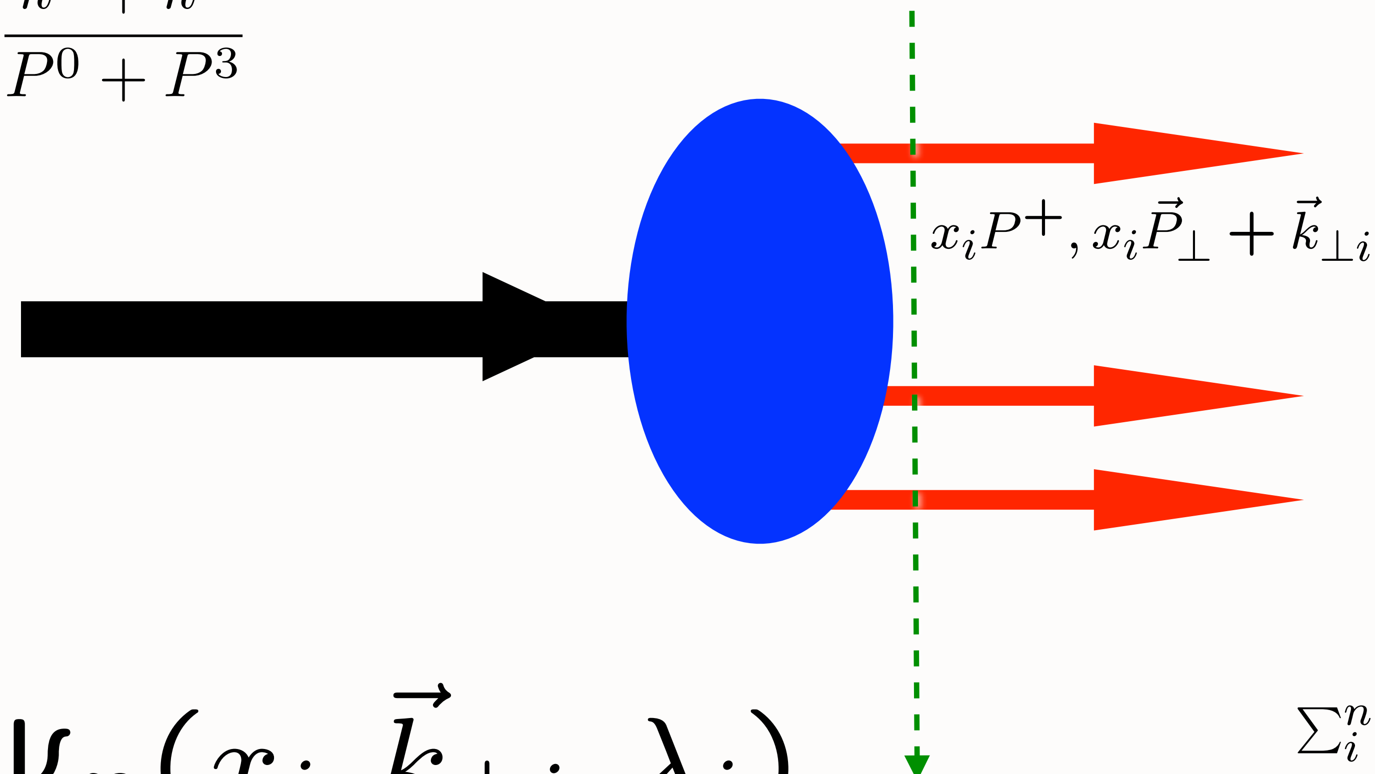
Invariant under boosts! Independent of P^μ

Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

Fixed $\tau = t + z/c$

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$

$P^+, \vec{P}_\perp$



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$\sum_i^n x_i = 1$

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Invariant under boosts! Independent of P^μ

High x_F at AFTER

- Drell Yan at high x_F
- W, Z
- Structure Functions at High x
- Direct Processes
- Polarization Correlations
- Intrinsic Heavy Quark Studies
- Diffractive Channels
- Proton Diffraction to 3 Jets
- Quarkonium Dynamics
- Open Flavor, B and D

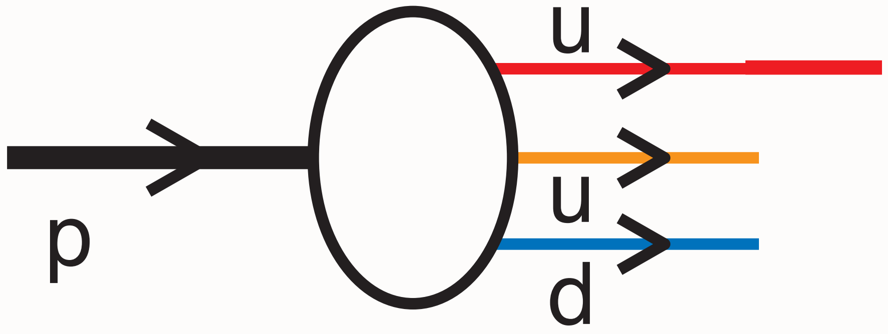
Novel Physics at AFTER,

- **Secondary Beams: Pions Kaons, Muons, even B and D**
- **Pion Exchange: Effective Pion Collisions**
- **Deuteron Target: Hidden Color**
- **Spin-Correlations with Polarized Targets**
- **Huge single spin asymmetries at high xF**
- **pA to Quarkonium -- non-factorizing nuclear dependence**
- **Breakdown of Factorization: Double Boer-Mulders**
- **Photon plus Heavy Quark Anomalies**
- **Shadowing, Antishadowing**
- **Odderon Search**

Target Polarization Studies with AFTER

AFTER @ LHC

- T-Odd Sivers, Boer-Mulders Effects
- Non-Factorization
- Strong Effects at Charm, Bottom, Thresholds
- Study Anomalously Large A_N for Hadron Production at high x_F
- Quarkonium Spin and Correlations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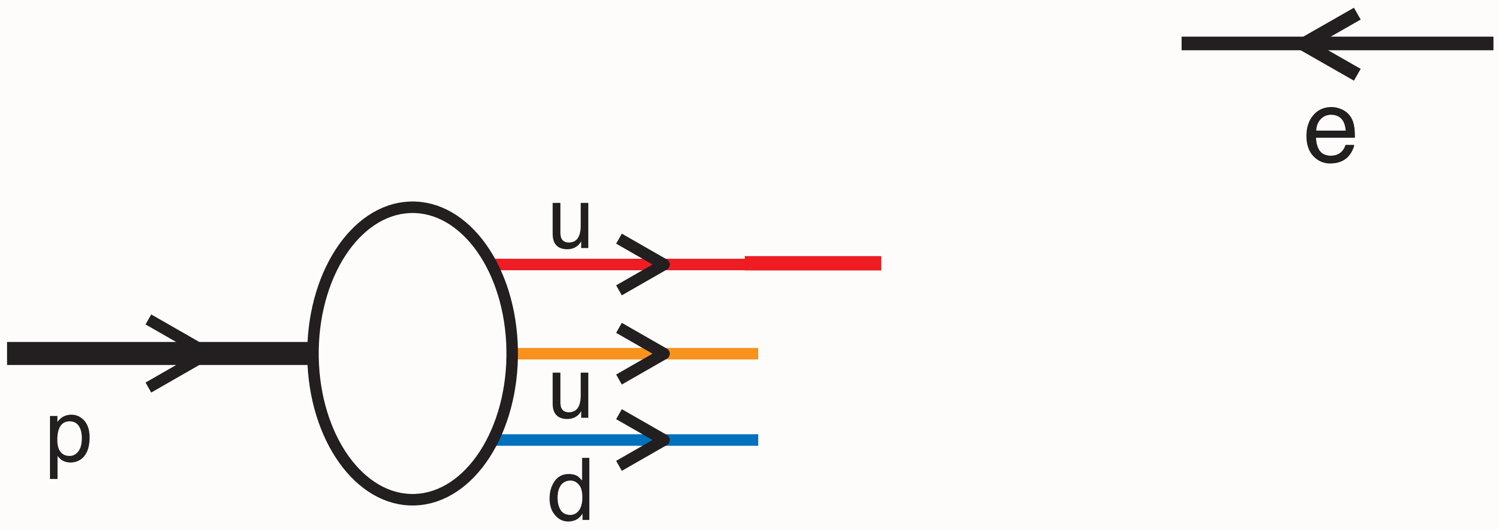
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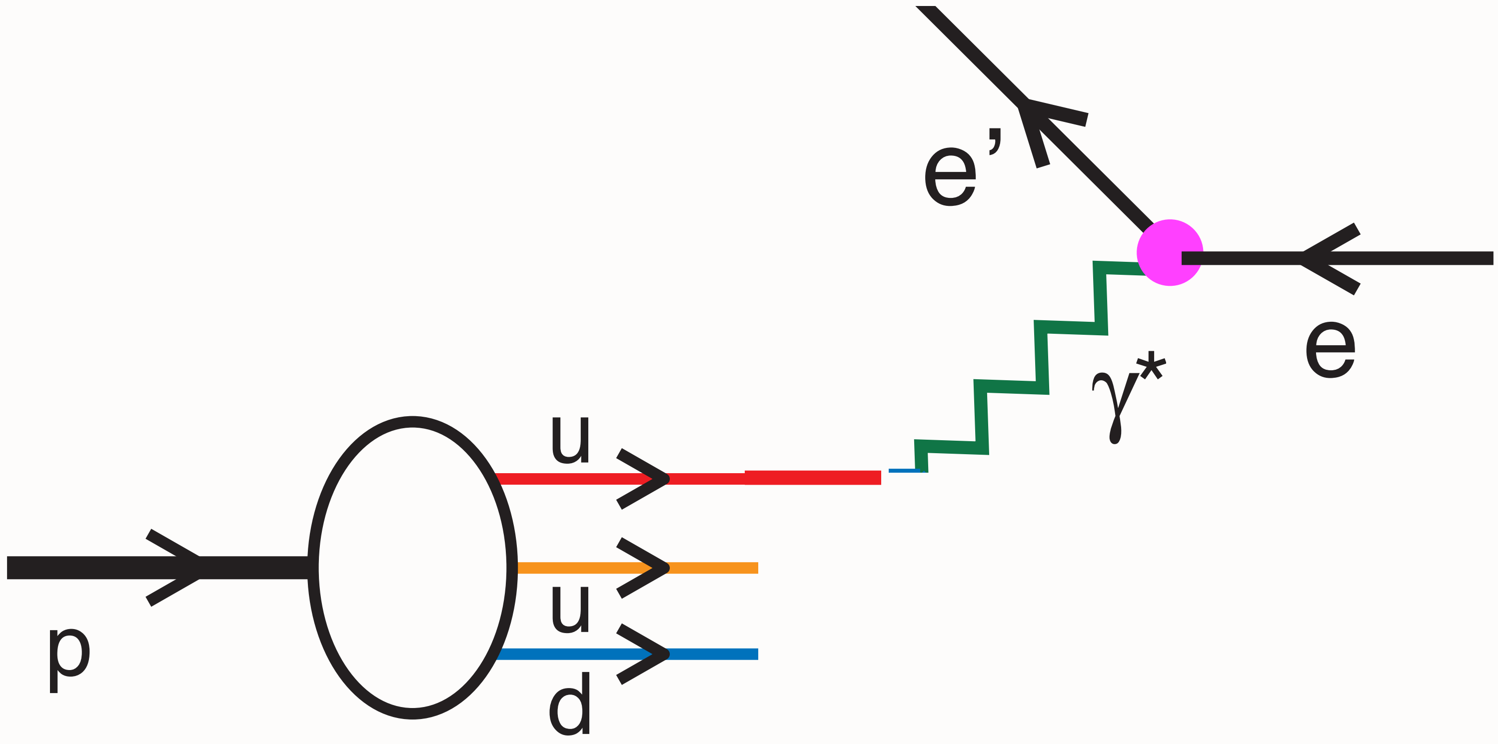
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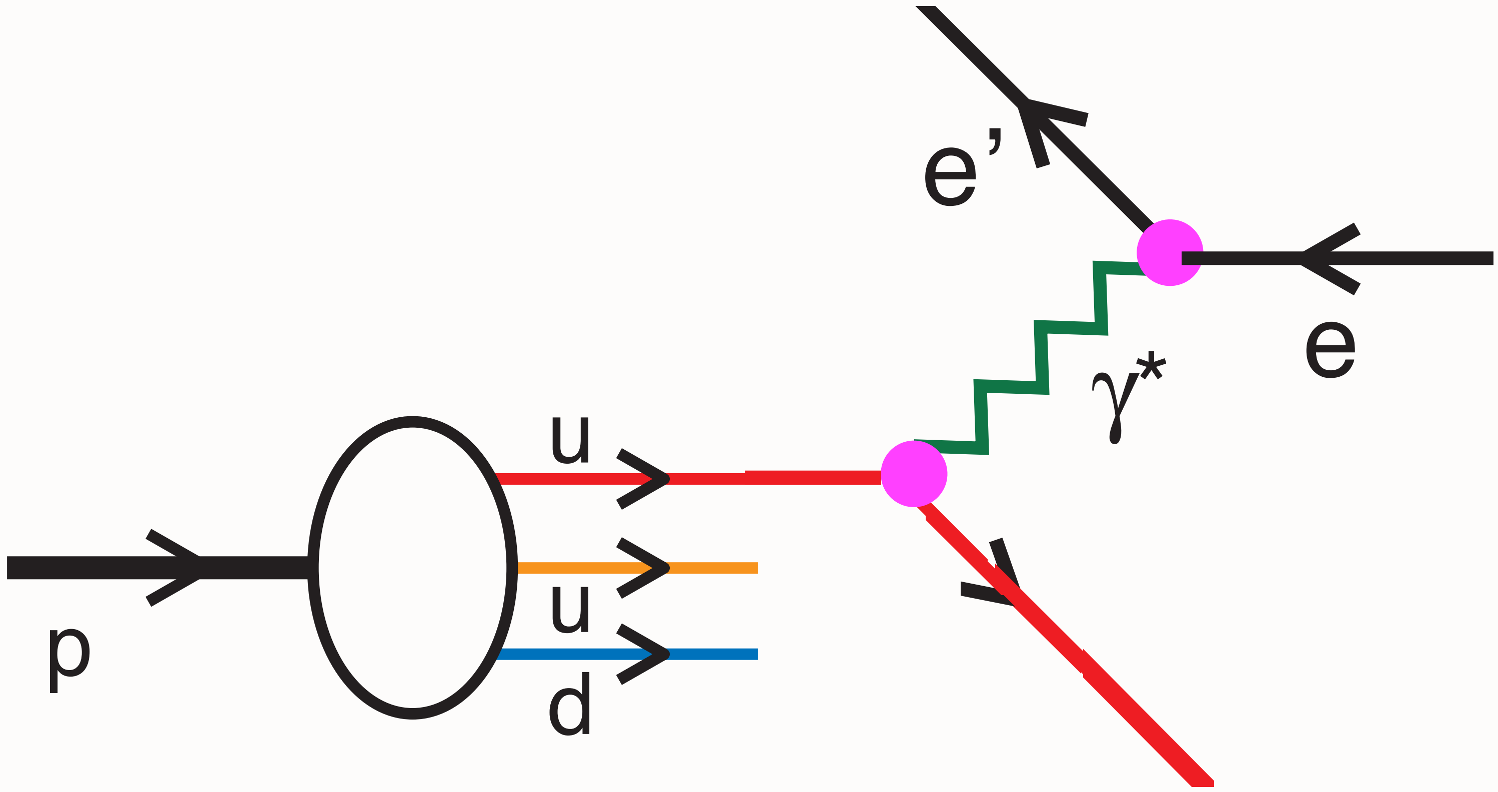
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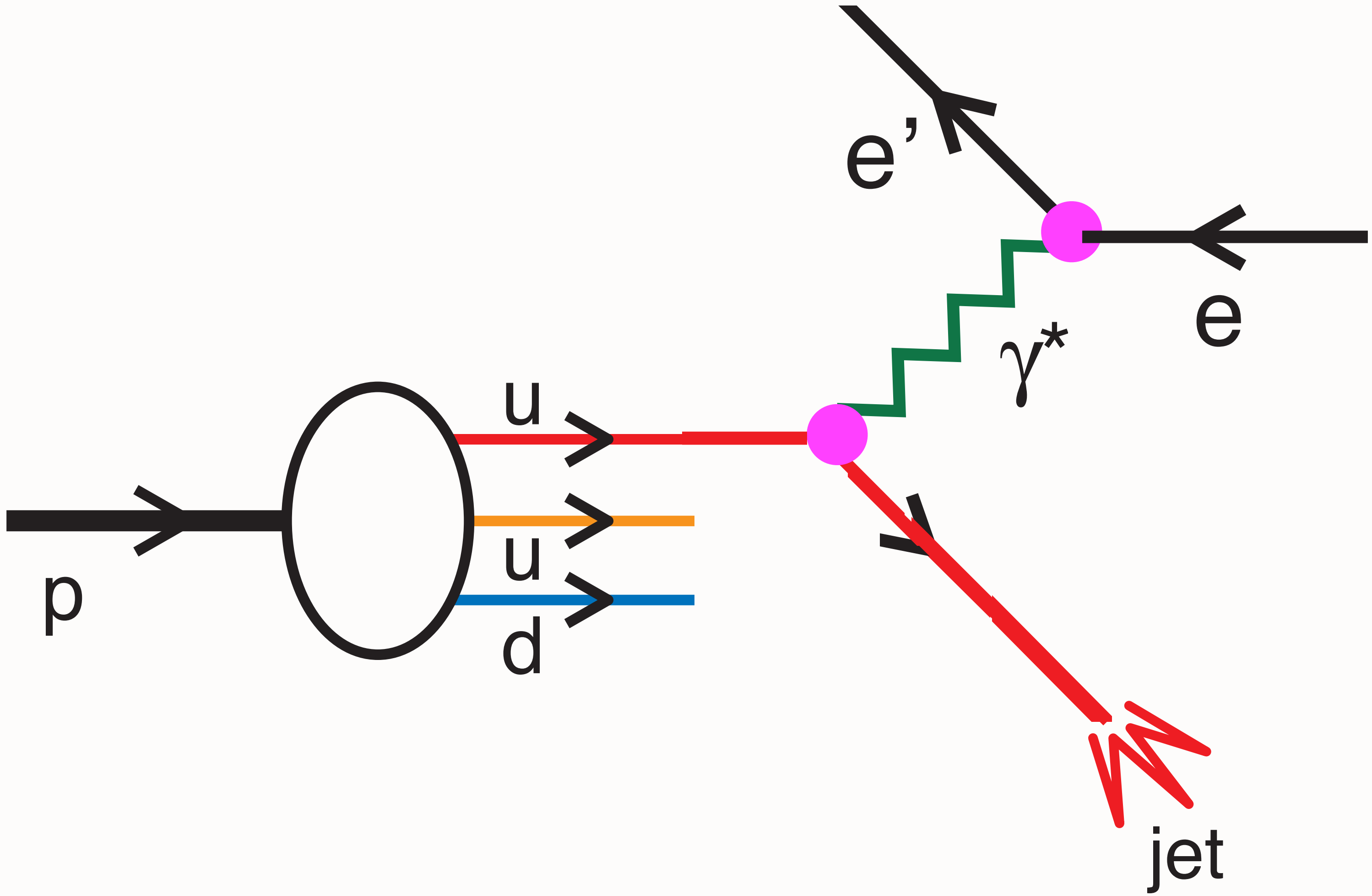
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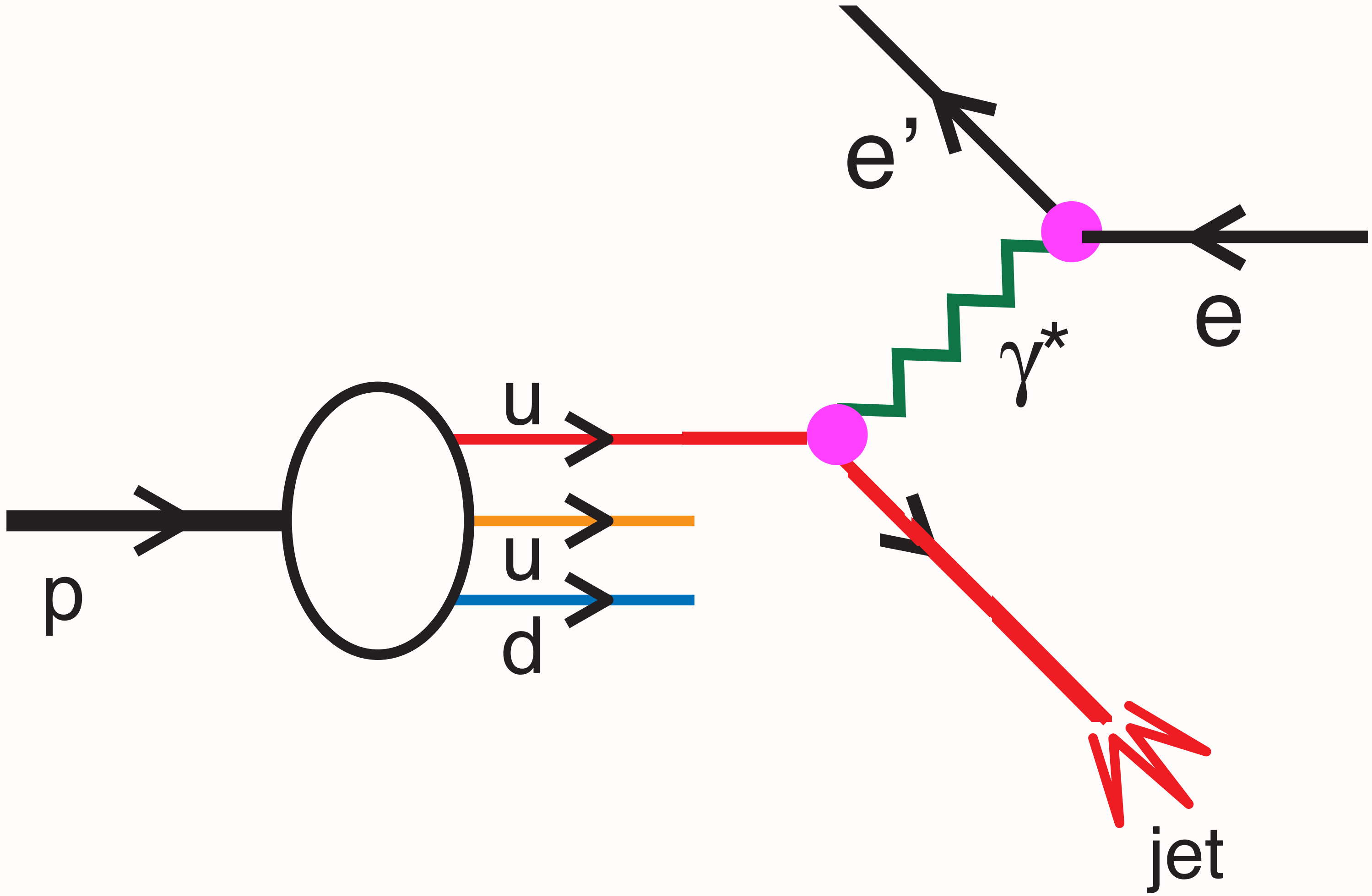
Deep Inelastic Electron-Proton Scattering



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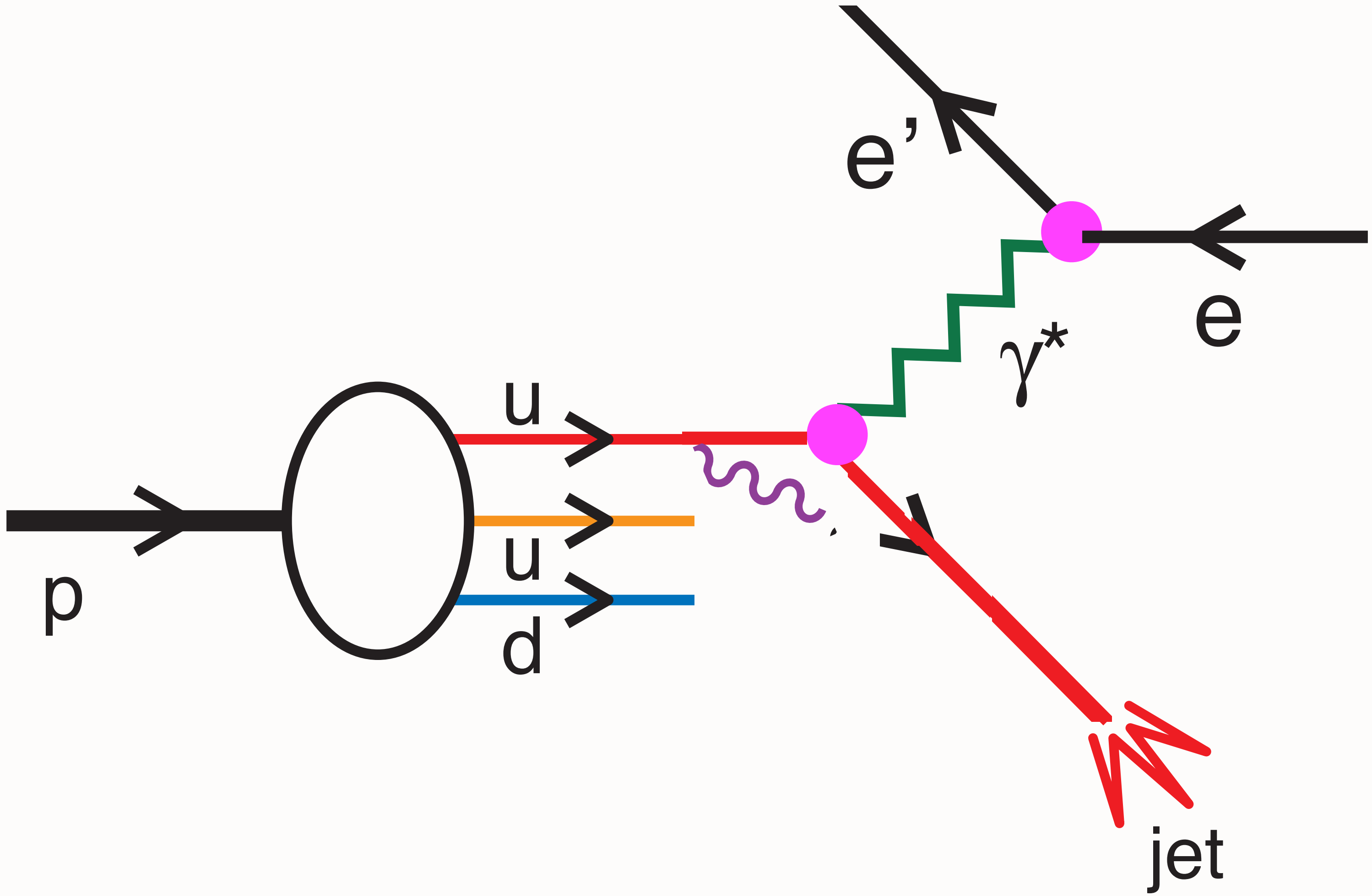

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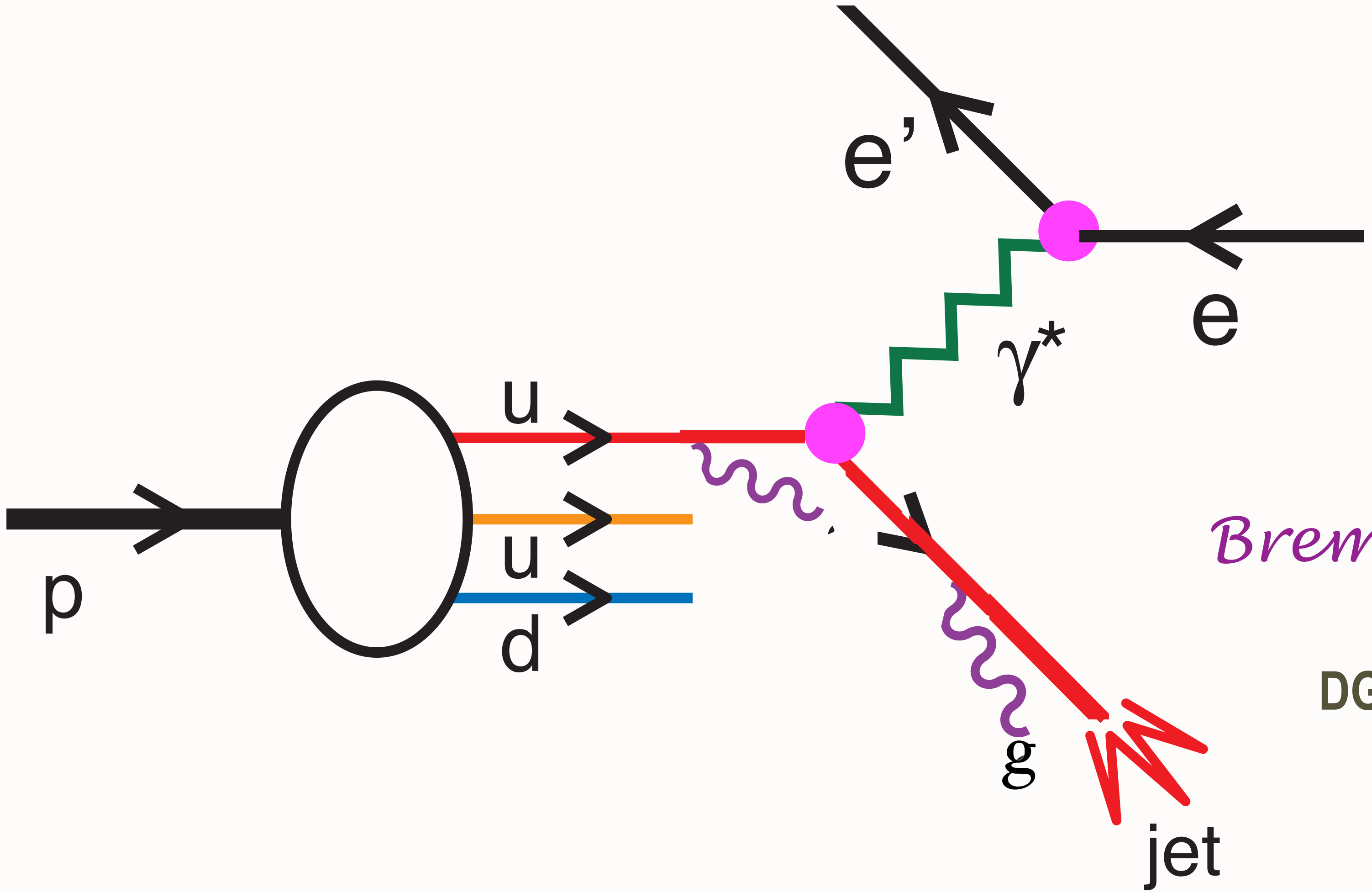
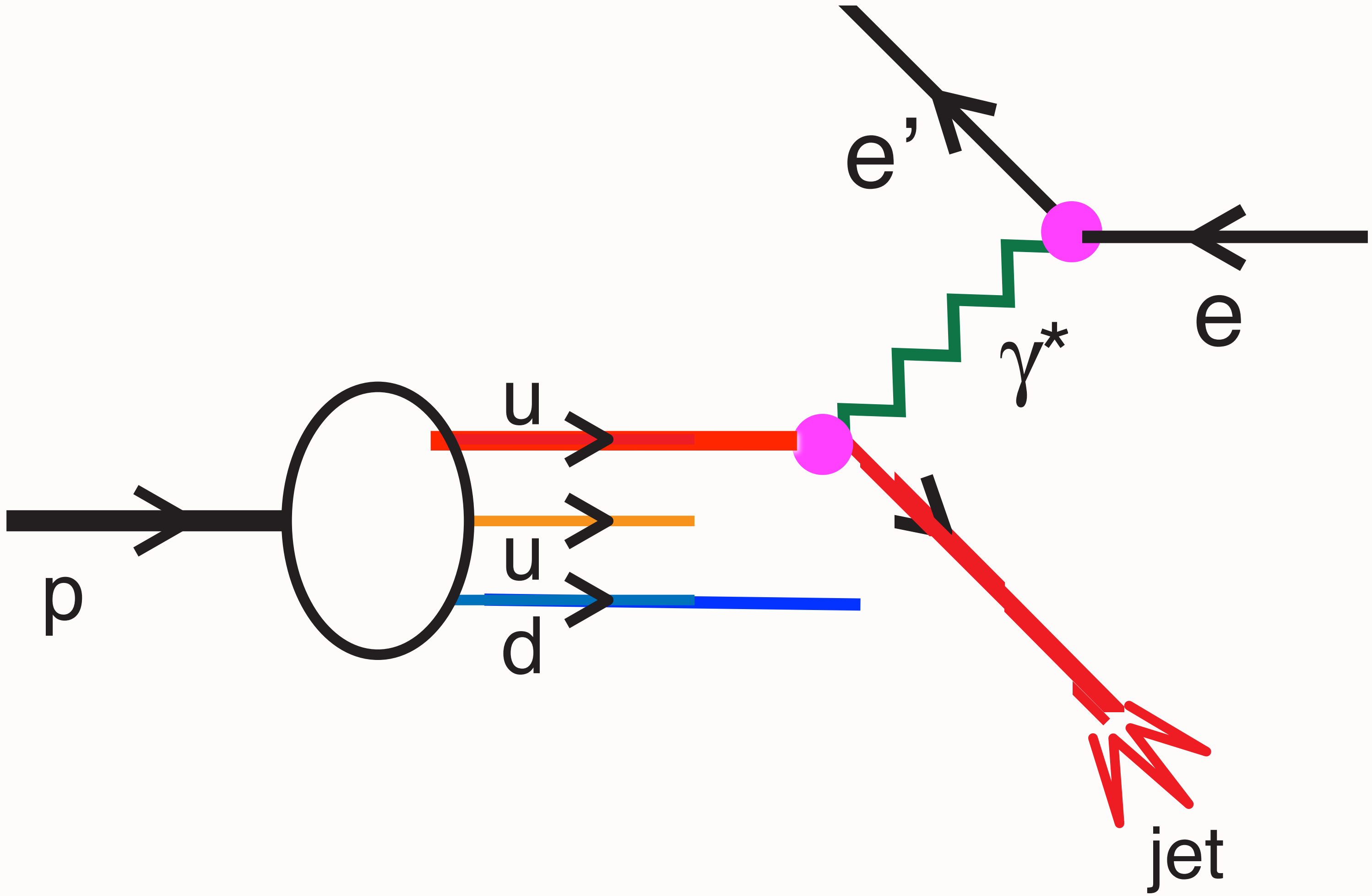


Gluonic Bremmstrahlung

DGLAP Evolution

Deep Inelastic Electron-Proton Scattering



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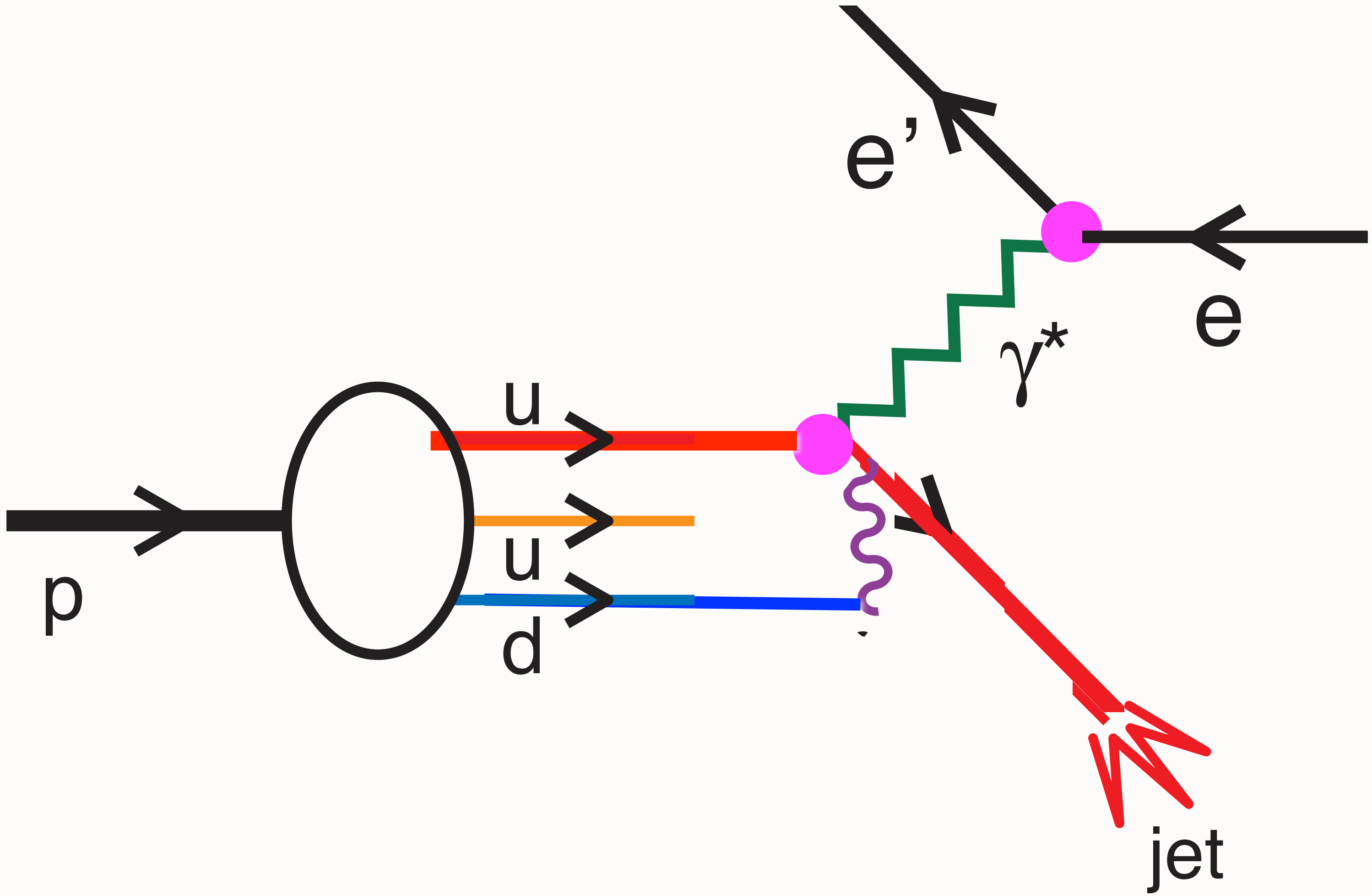

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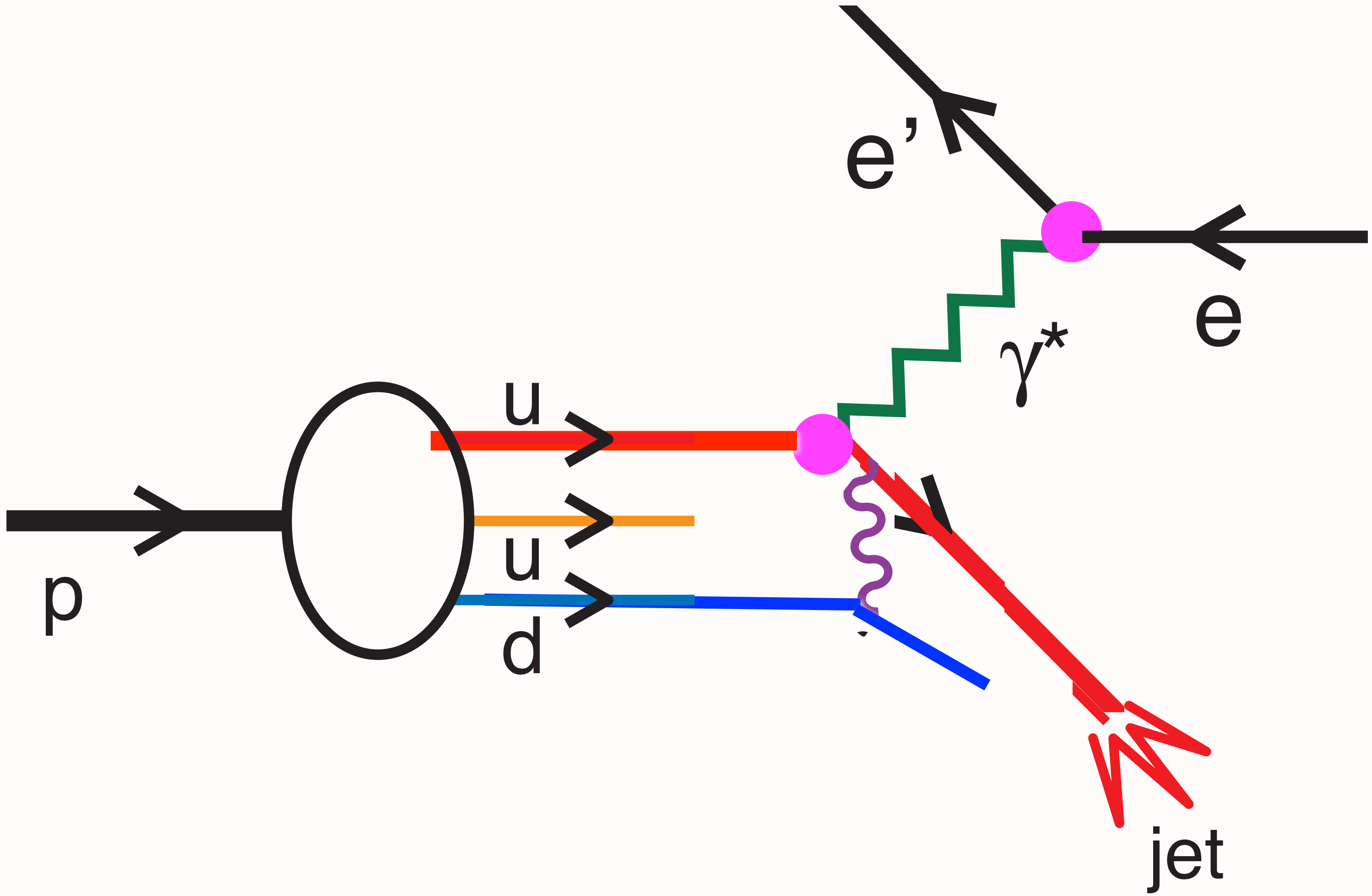

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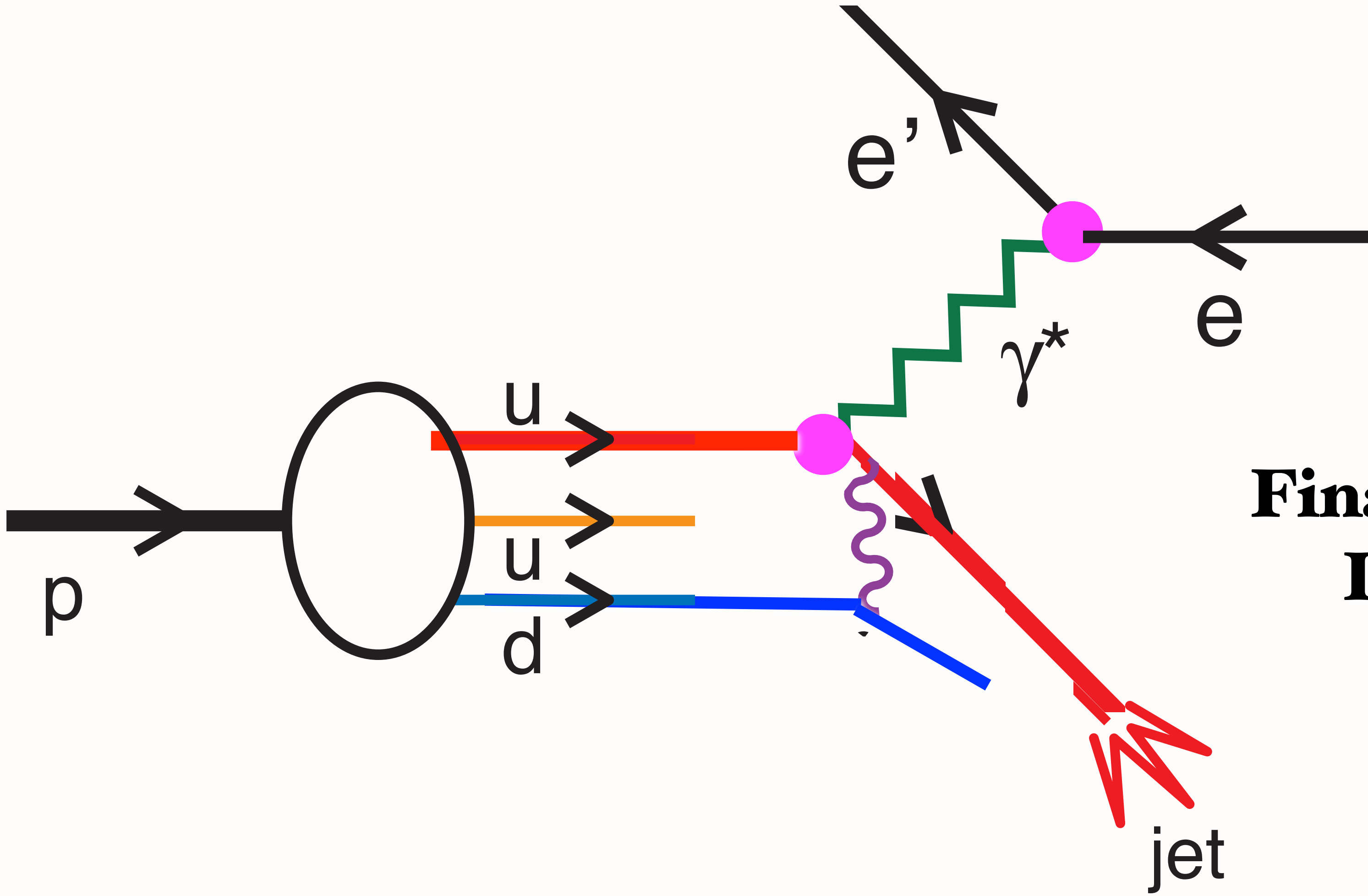
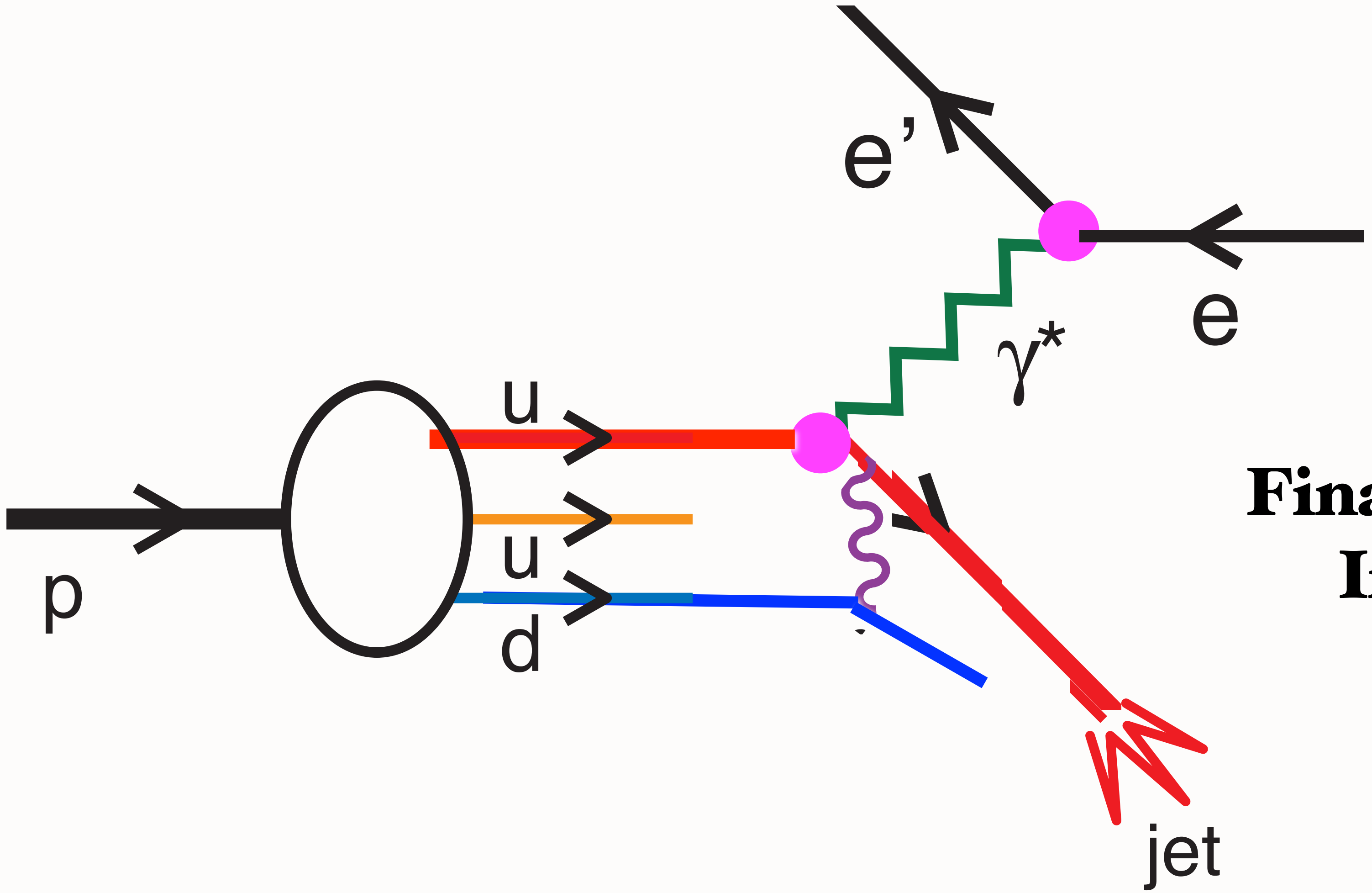


Final-State QCD Interaction

Deep Inelastic Electron-Proton Scattering

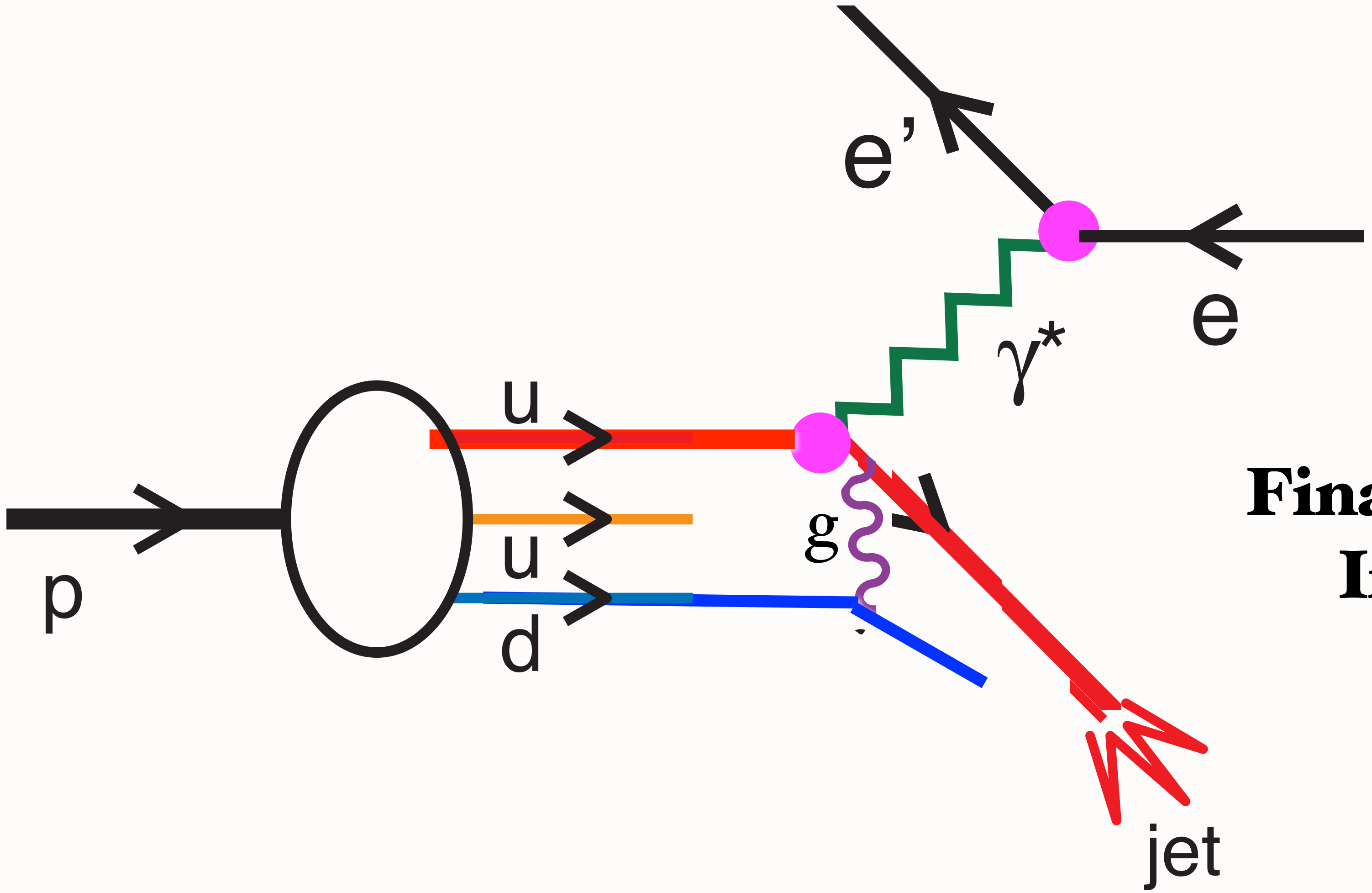


Final-State QCD Interaction

Conventional wisdom:

Final-state interactions of struck quark can be neglected

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

Conventional wisdom:
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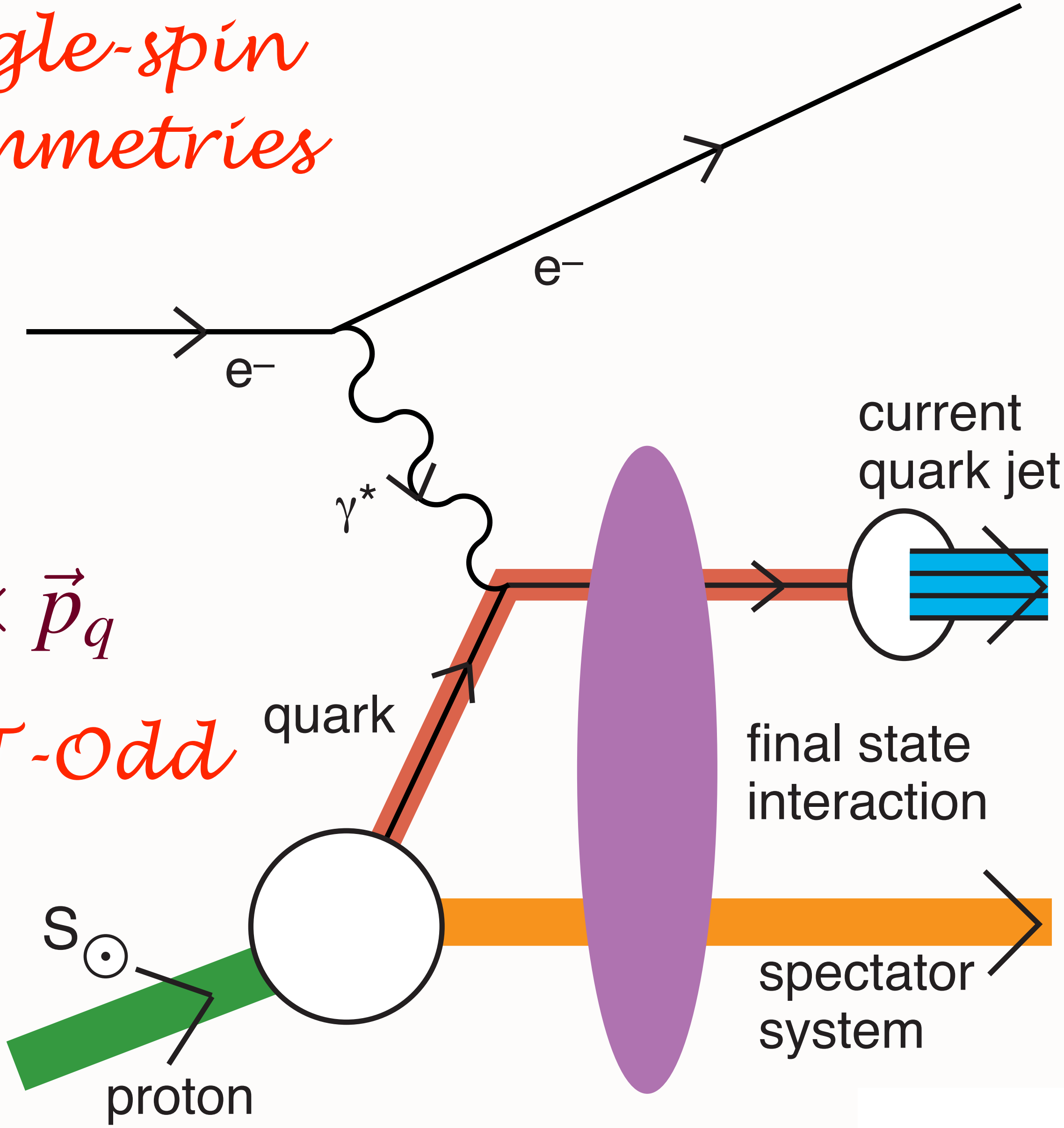
Single-spin asymmetries



$$\vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

T-Odd

Dae Sung Hwang, Ivan Schmidt, sjb

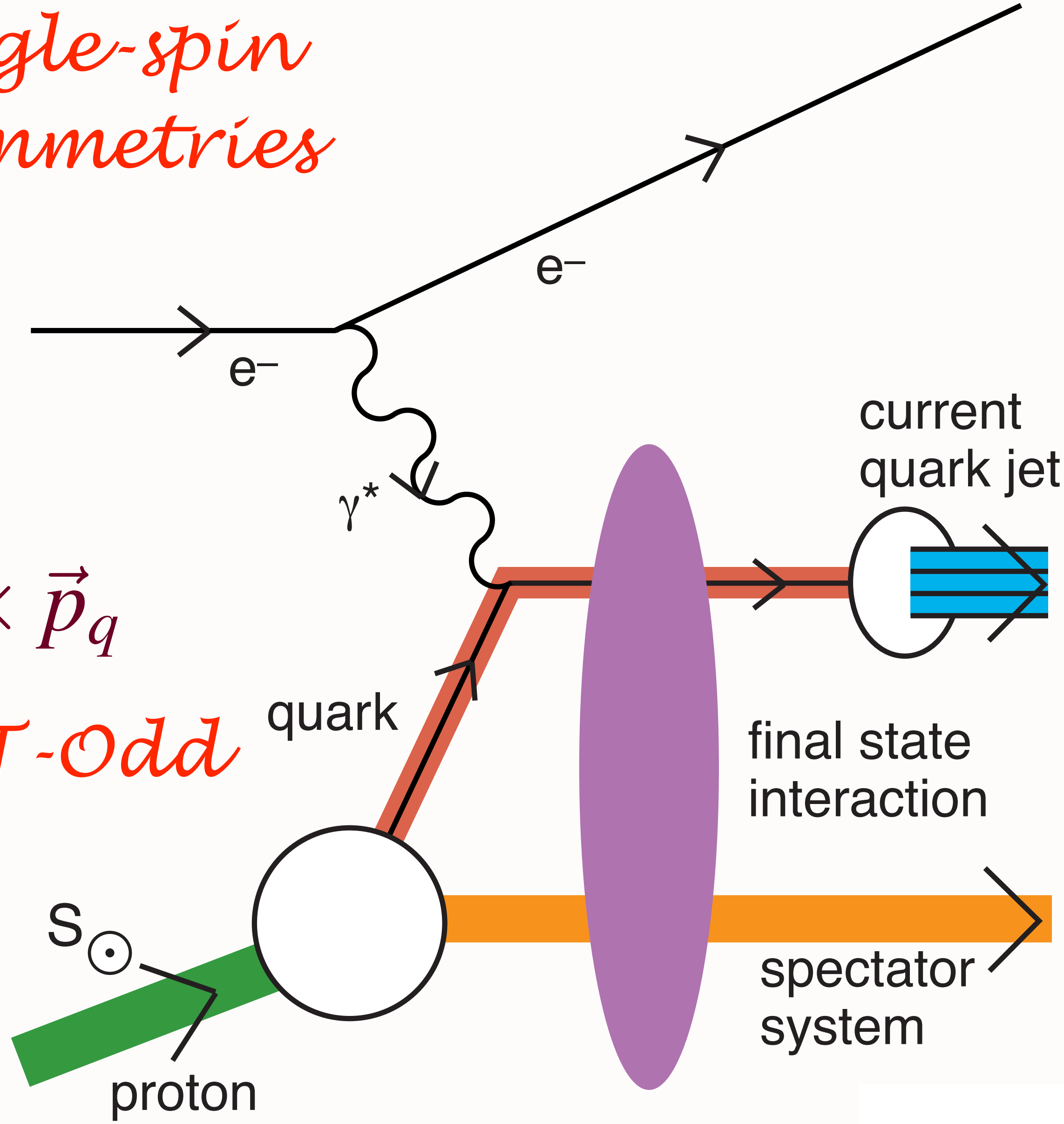
Single-spin asymmetries

Leading Twist Sivers Effect

Dae Sung Hwang, Ivan Schmidt, sjb

$$\vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

T-Odd



Leading Twist Sivers Effect

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Dae Sung Hwang, Ivan Schmidt, sjb

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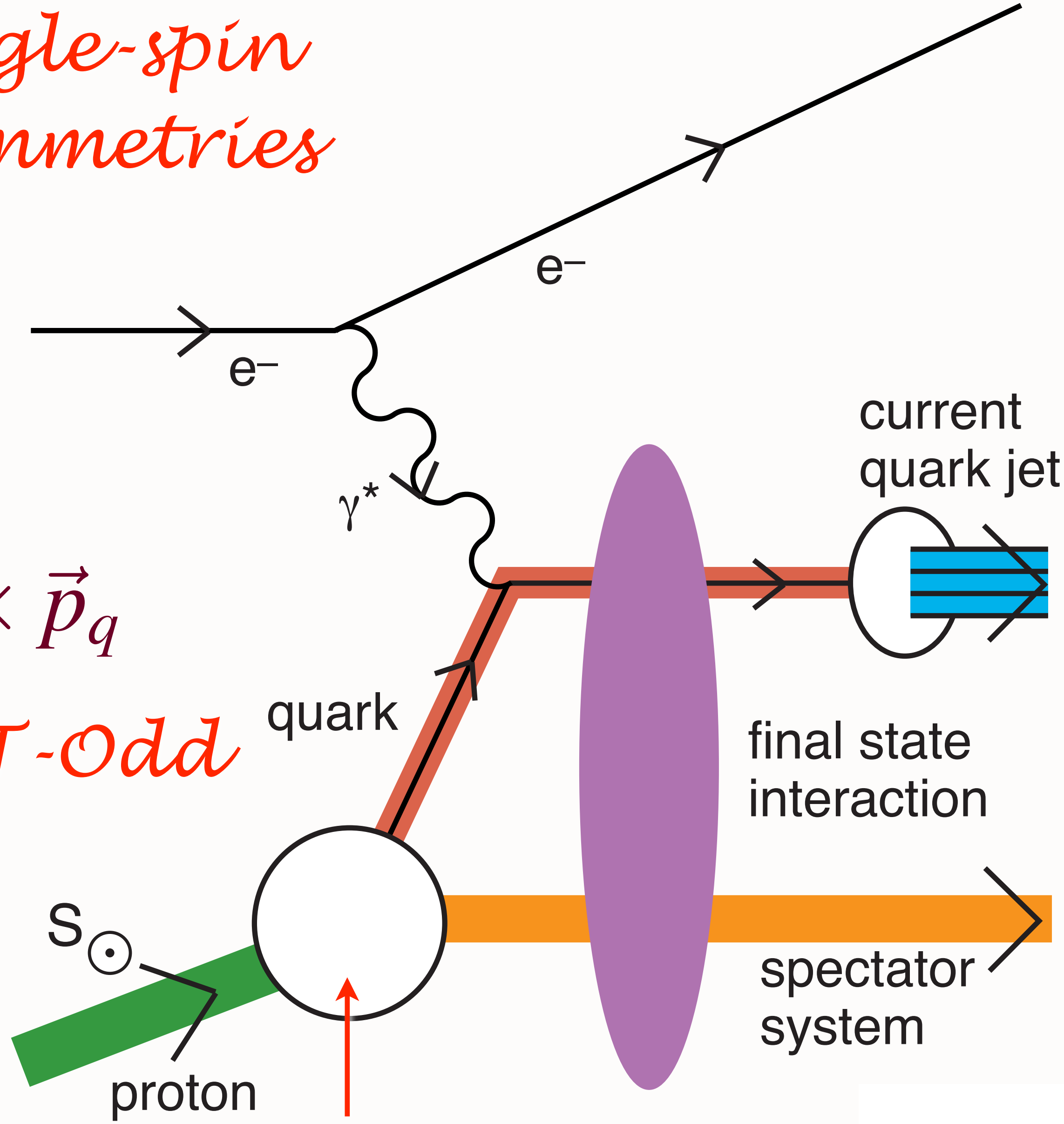

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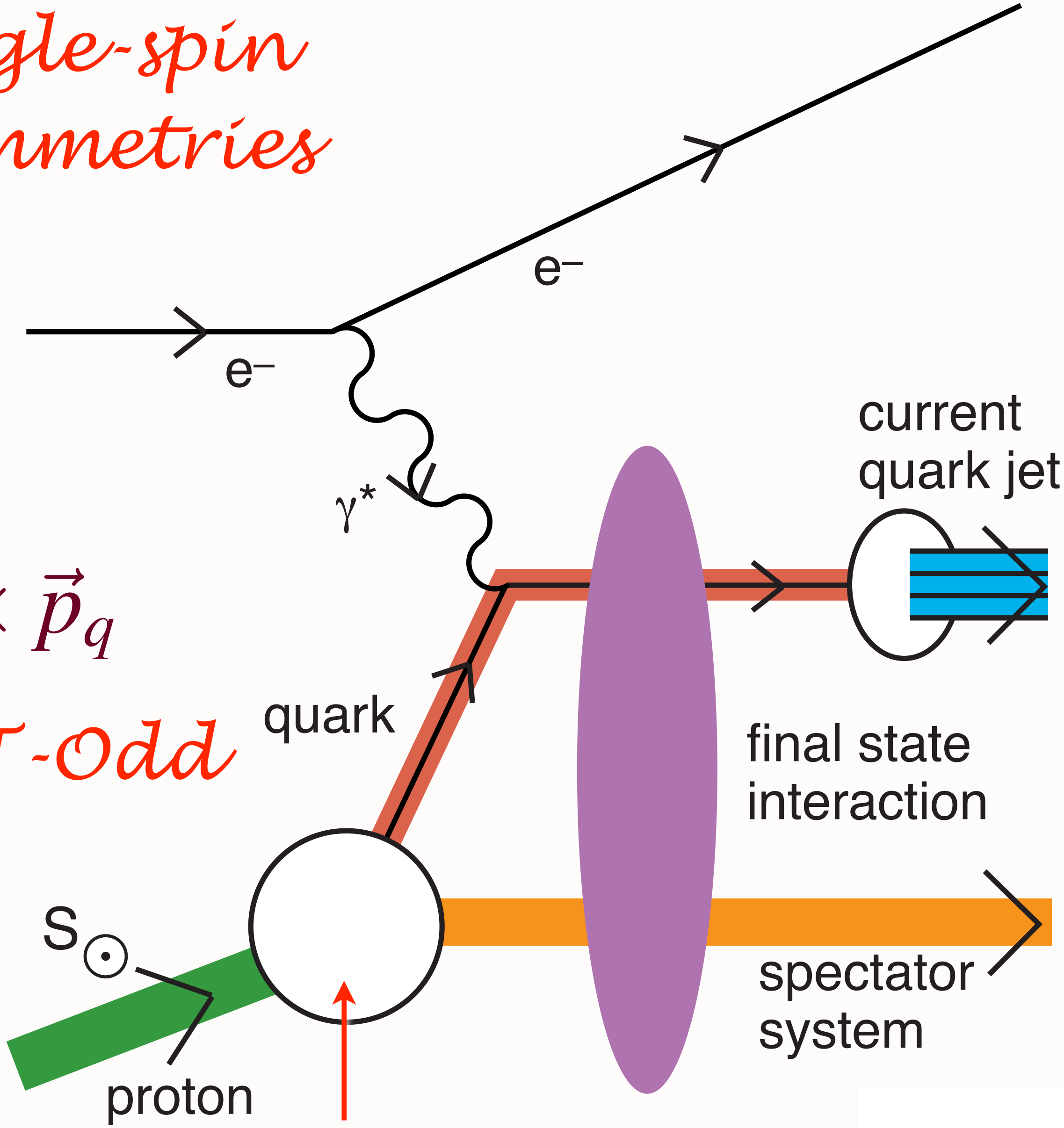

Light-Front Wavefunction S and P- Waves

Single-spin asymmetries

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Dae Sung Hwang, Ivan Schmidt, sjb

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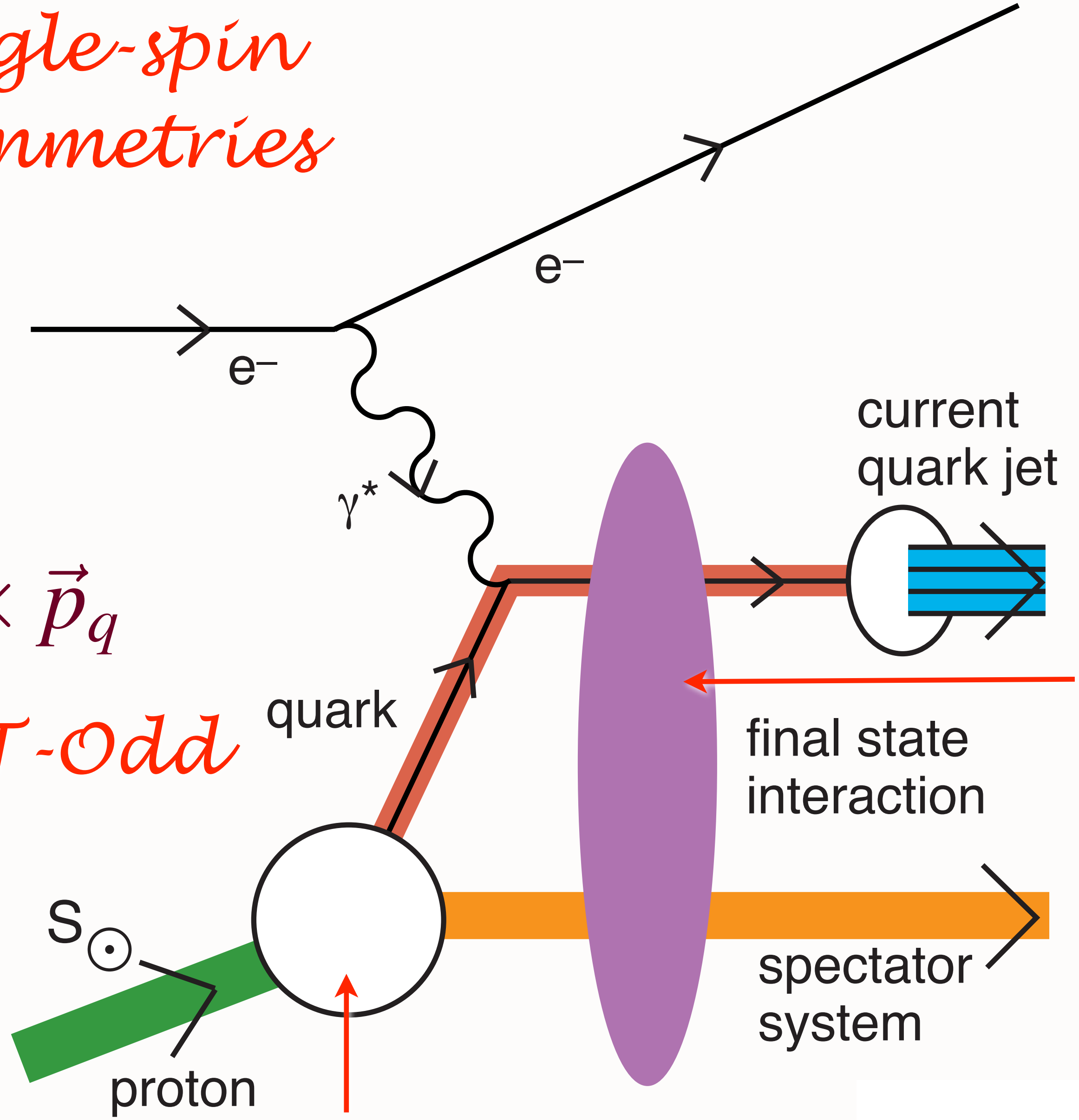

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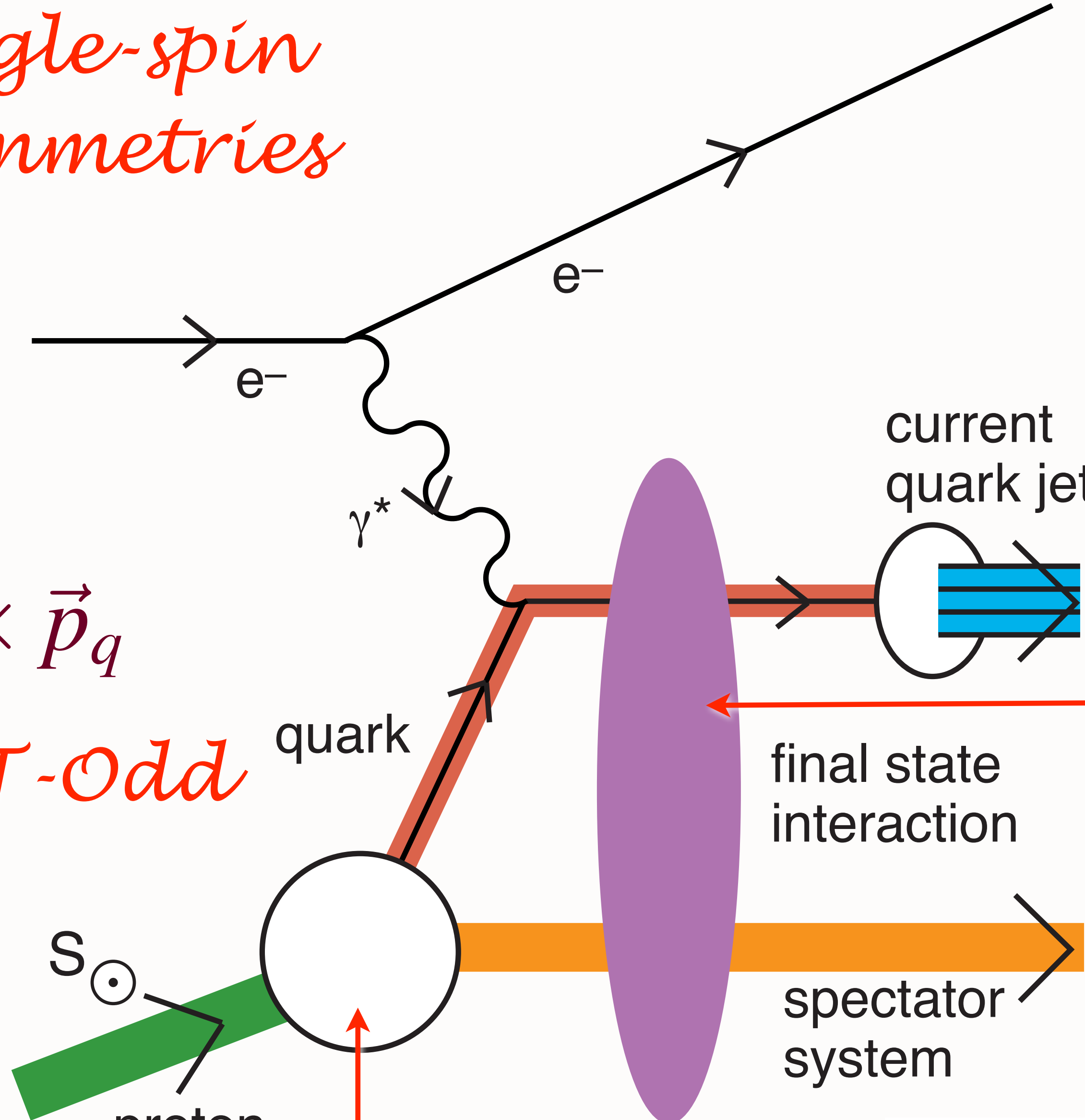


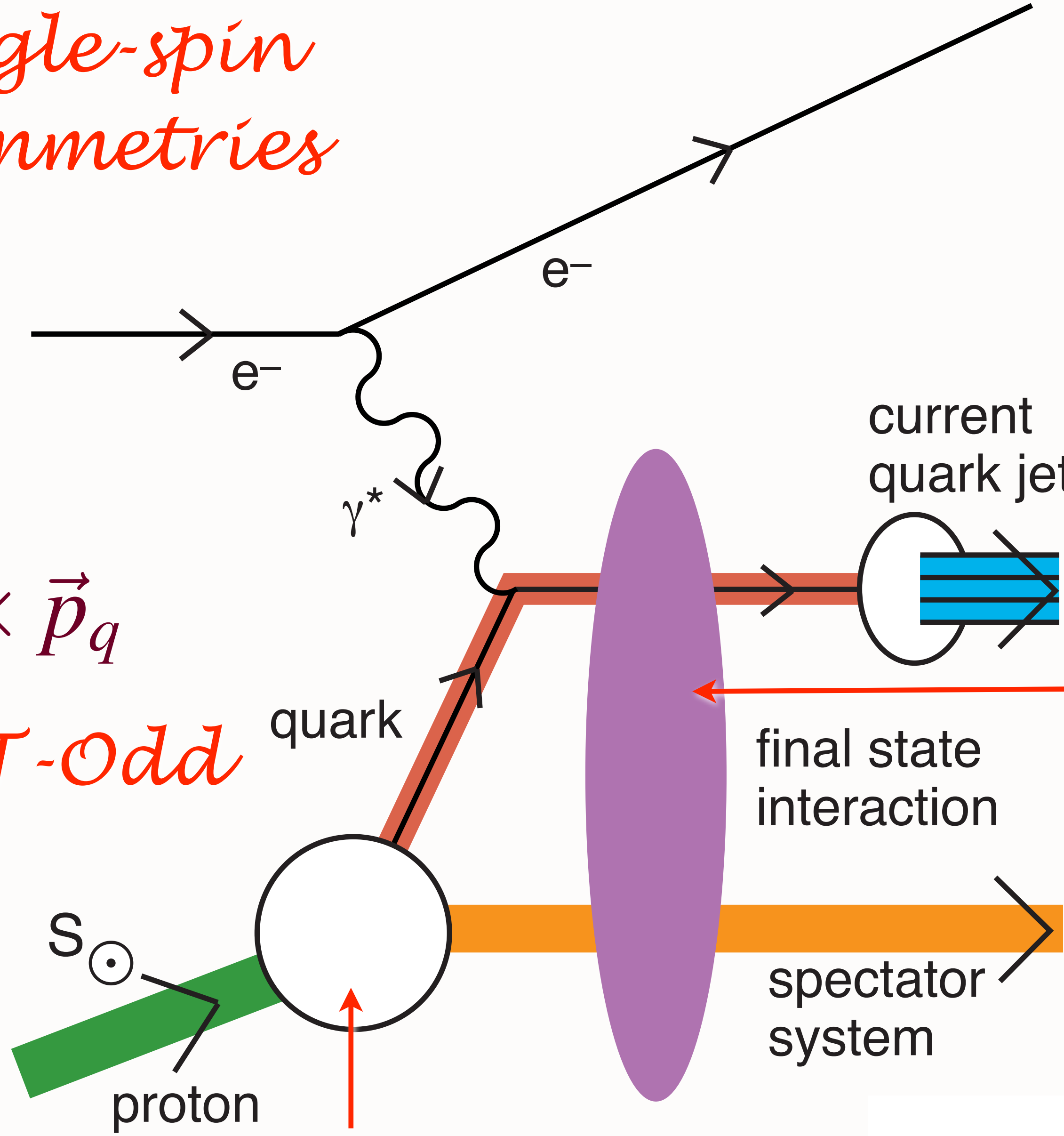
QCD S- and P-
Coulomb Phases
--Wilson Line

Light-Front Wavefunction
S and P- Waves

Single-spin asymmetries

Leading Twist Sivers Effect

Dae Sung Hwang, Ivan Schmidt, sjb



$$i \; \vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

T-Odd

QCD S- and P-
Coulomb Phases
--Wilson Line

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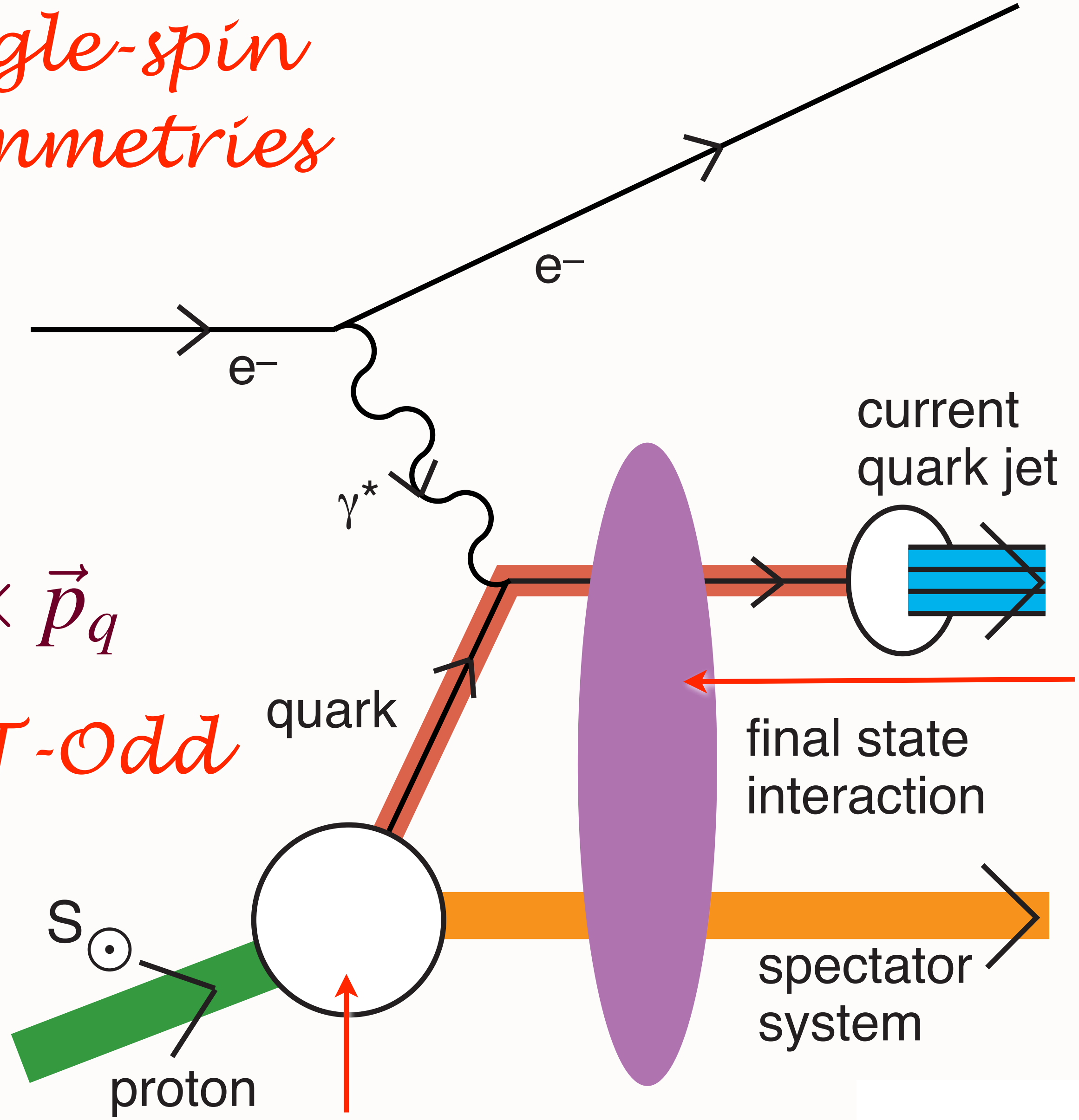


$$i\ \vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

Pseudo-T-Odd

QCD S- and P- Coulomb Phases --Wilson Line

Light-Front Wavefunction S and P- Waves

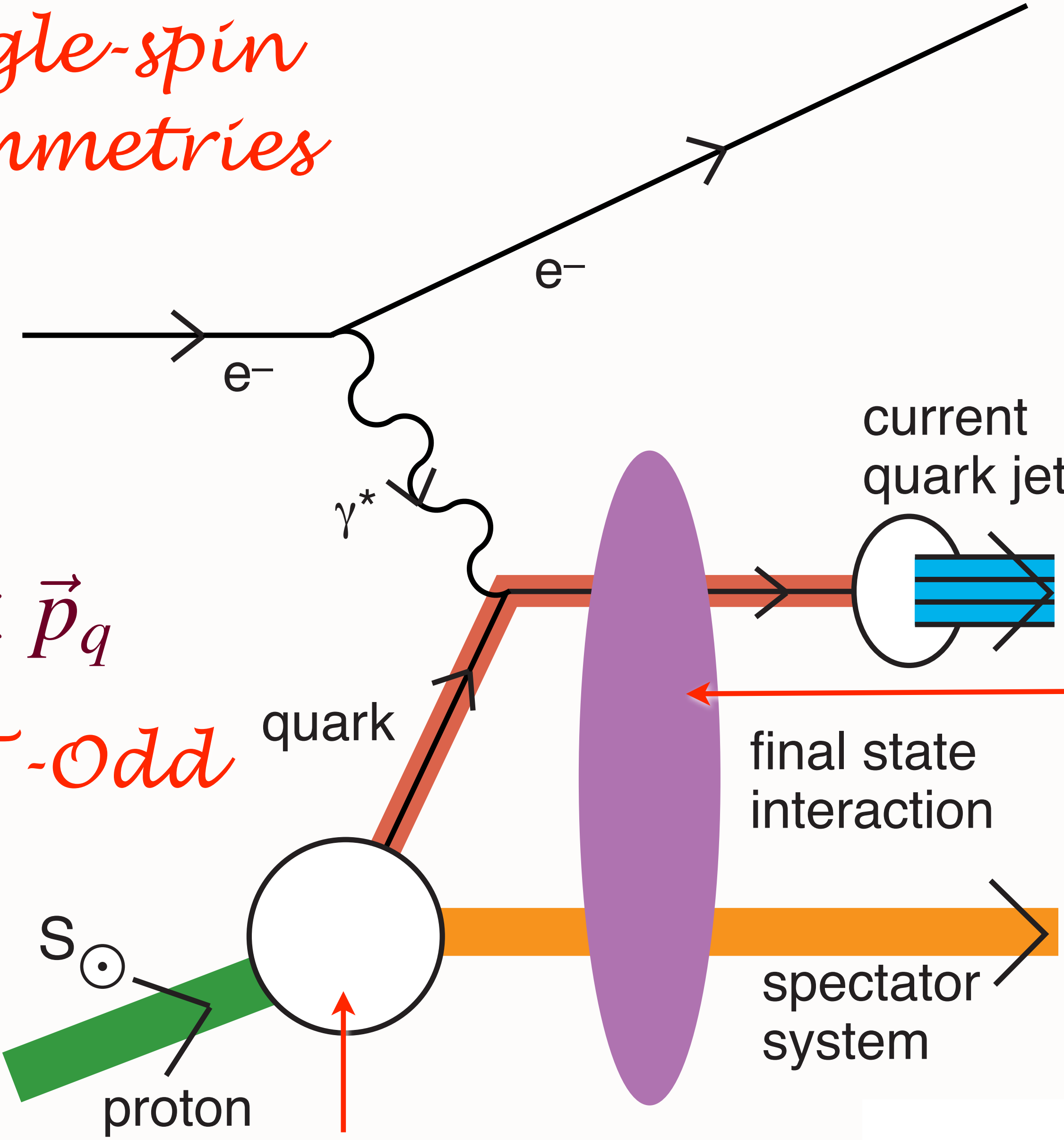
Single-spin asymmetries

Leading Twist Sivers Effect

Dae Sung Hwang, Ivan Schmidt, sjb

$$i\ \vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

Pseudo-T-Odd



QCD S- and P-Coulomb Phases --Wilson Line

Light-Front Wavefunction S and P- Waves

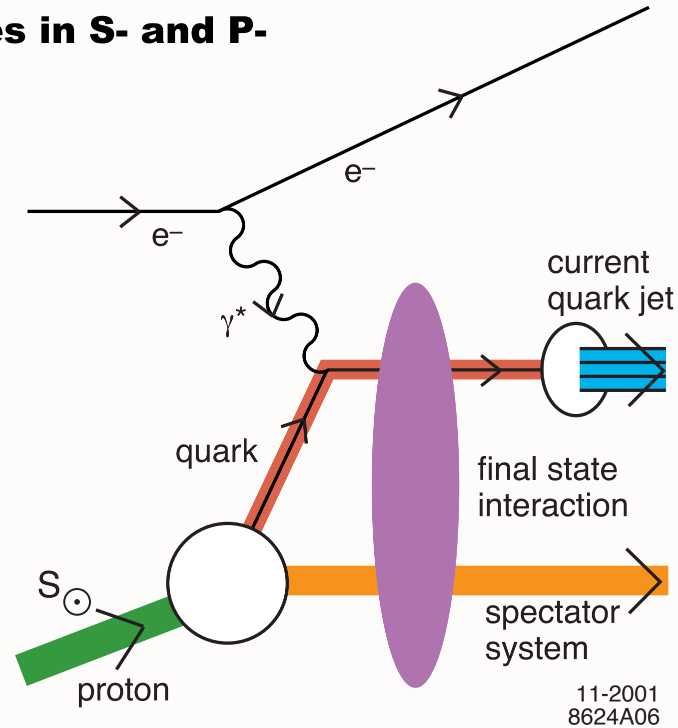
Leading-Twist Rescattering Violates pQCD Factorization!

Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

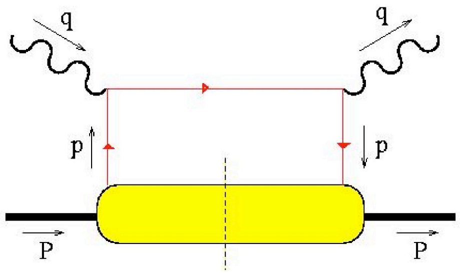
Hwang, Schmidt, sjb
Collins

$$\mathbf{i}\ \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

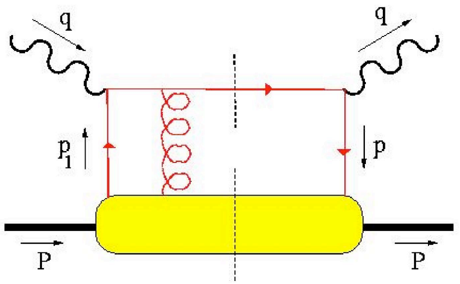
- **Leading-Twist Bjorken Scaling!**
- **Requires nonzero orbital angular momentum of quark**
- **Arises from the interference of Final-State QCD Coulomb phases in S- and P-waves;**
- **Wilson line effect -- gauge independent**
- **Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases**
- **QCD phase at soft scale!**
- **New window to QCD coupling and running gluon mass in the IR**
- **QED S and P Coulomb phases infinite -- difference of phases finite!**
- **Alternate: Retarded and Advanced Gauge: Augmented LFWFs**



Pasquini, Xiao, Yuan, sjb
Mulders, Boer **Qiu, Sterman**



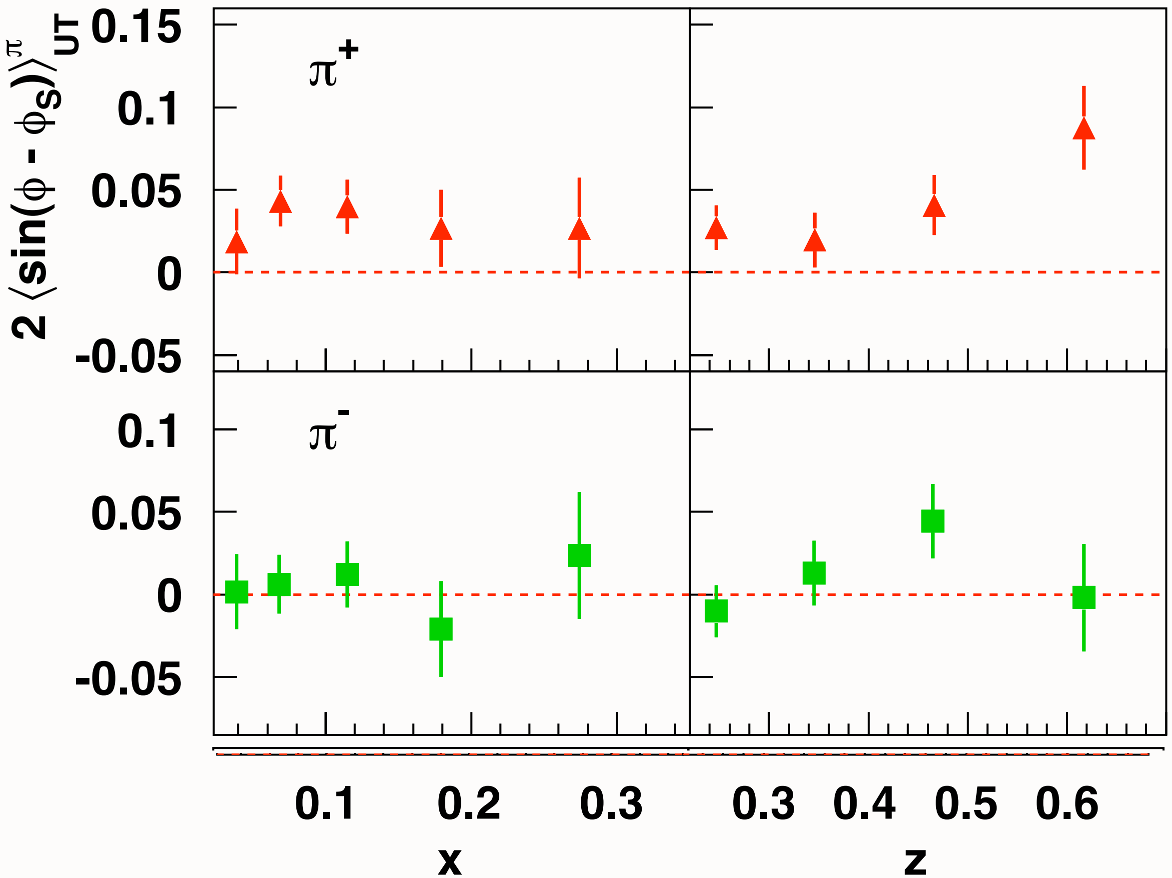
can interfere with



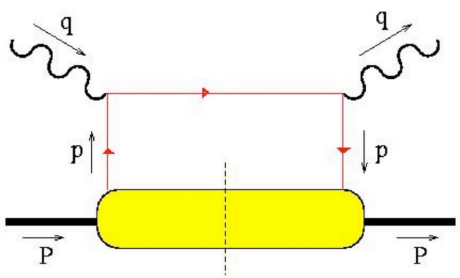
and produce a T-odd effect! (also need $L_z \neq 0$)

HERMES coll., A. Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002.

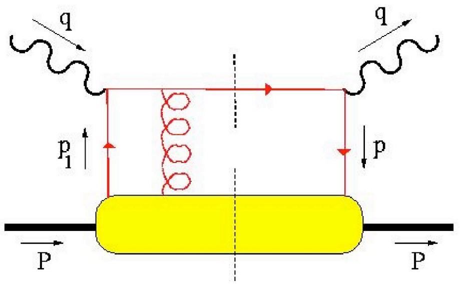
Sivers asymmetry from HERMES



- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for **π⁺**...
  Consistent with zero for **π⁻**...



can interfere with



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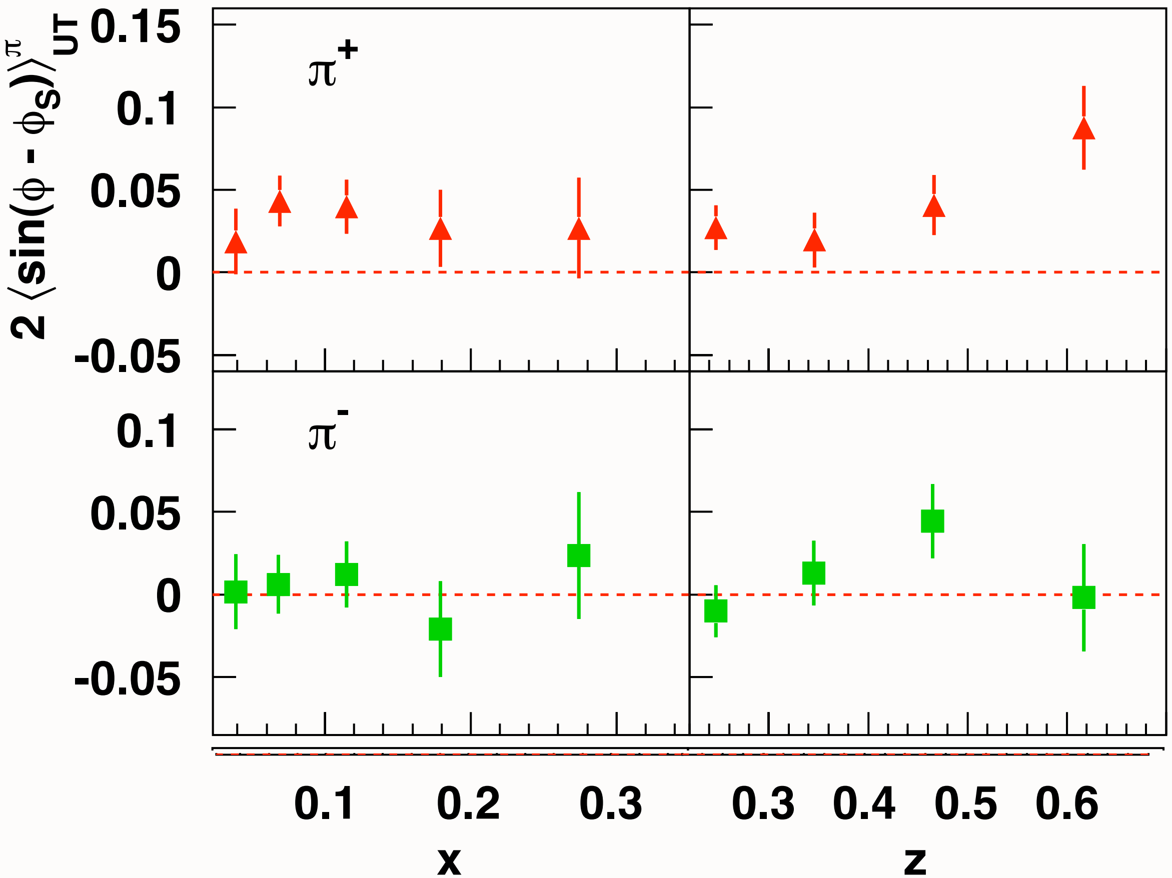

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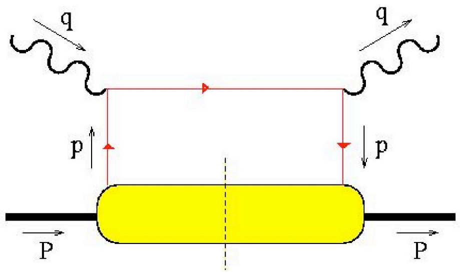
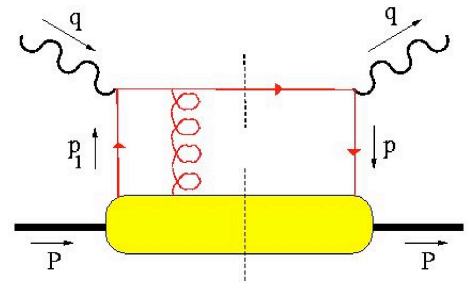
Gamberg: Hermes data compatible with BHS model



can interfere with



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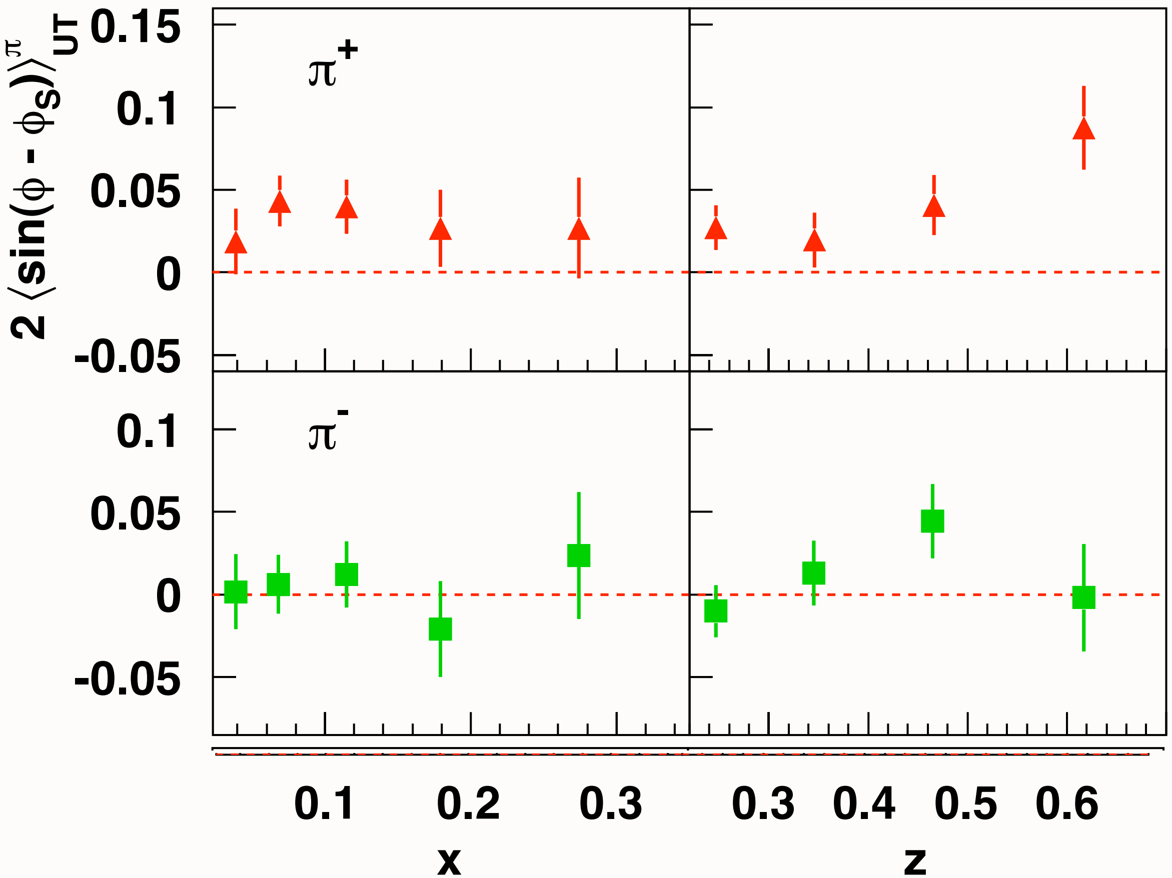

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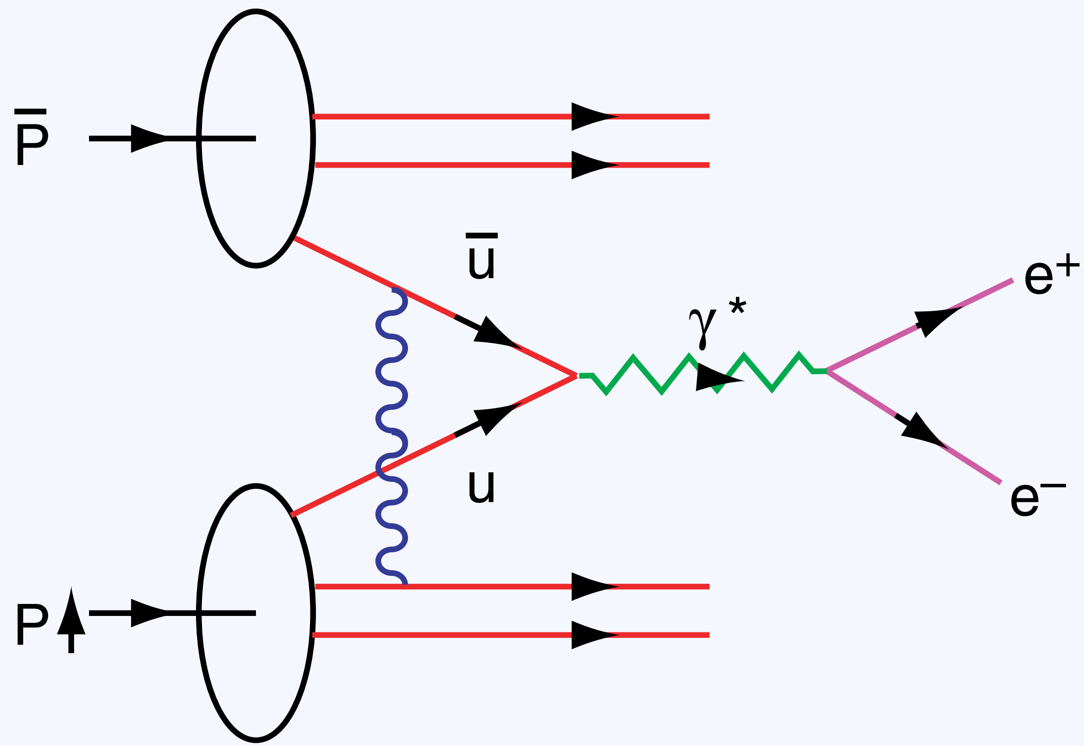
Gamberg: Hermes data compatible with BHS model

Schmidt, Lu:
Asymmetry ratios should follow quark contributions to anomalous moment

Predict Opposite Sign SSA in DY !



Collins

Hwang
Schmidt
sjb

Single Spin Asymmetry In the Drell Yan Process

$\vec{S}_p \cdot \vec{\bar{p}} \times \vec{q}_{\gamma^*}$

Quarks Interact in the Initial State

Interference of Coulomb Phases for *S* and *P* states

Produce Single Spin Asymmetry [Siver's Effect]Proportional to the Proton Anomalous Moment and α_s.

Opposite Sign to DIS! No Factorization

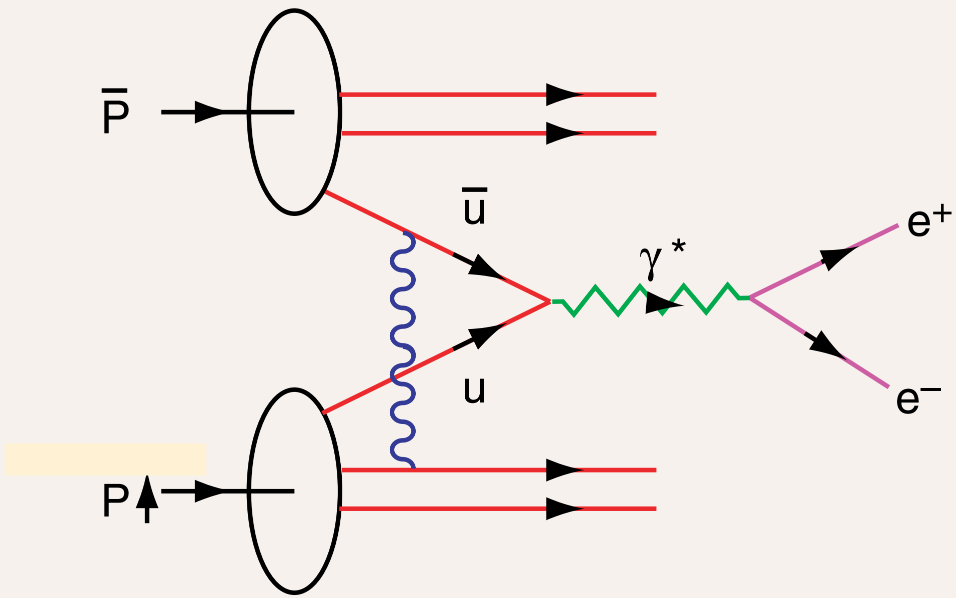
Key QCD Experiment

Collins; Hwang, Schmidt. sjb

Measure single-spin asymmetry A_N in Drell-Yan reactions

Leading-twist Bjorken-scaling A_N from S, P-wave initial-state gluonic interactions

Predict: $A_N(DY) = -A_N(DIS)$
Opposite in sign!



$$\bar{p}p_{\uparrow} \rightarrow \ell^{+}\ell^{-}X$$

$\vec{S} \cdot \vec{q} \times \vec{p}$ correlation

Spin Physics with A Fixed Target ExpeRiment at the LHC

- A further undisputable property of fixed-target experiments is the possibility of polarising the target

see COMPASS, HERMES, CLAS, ...

- The polarisation can be longitudinal and transverse
- Single Transverse Spin Asymmetries unravel the correlations between the parton k_T and the proton spin
  $\rightarrow$ **information on orbital motion of partons in the proton !**
- Double Longitudinal Spin Asymmetries allow for the extraction of polarised PDFs
- Double Transverse Spin Asymmetries probe transversity
- The beam may become transversely polarised during the crystal extraction

M. Ukhanov, Nucl. Instrum. Meth. A 582 (2007) 378.

$\rightarrow$ to be experimentally checked . . .

Spin Asymmetries and quarkonia

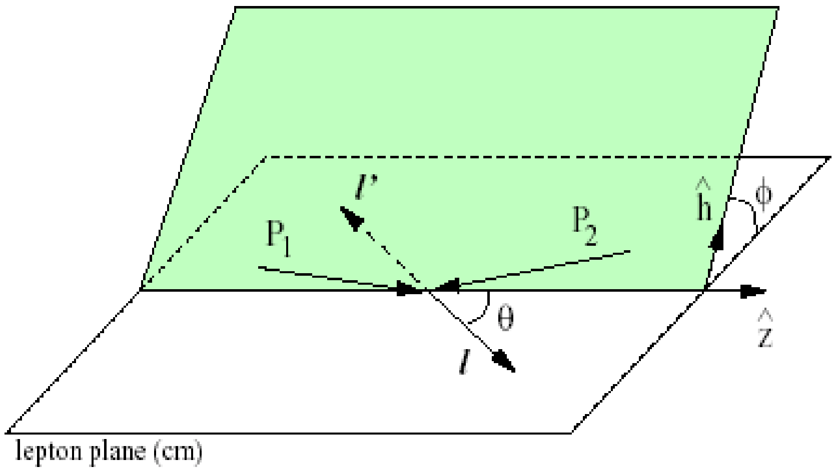
Large Range of Target Single-Spin Asymmetry Phenomena

- For now, such Transverse SSA can be used to discrimate between production mechanism
- The situation is likely to change in the future, allowing us to measure gluon Sivers function from quarkonia (J/ψ, χ_c, Υ)
- It remains to be investigated how quarkonium polarisation can be used to form DSA

Attempt in: J. L. Cortes, B. Pire, Phys. Rev. **D38**, 3586 (1988).

- Of course, transverse SSA can be studied in parallel for other mesons (*D*, *B*, ...)
- In general, the backward region is the most favourable allowing for measurements in the large *x* region of the polarised nucleon

Drell-Yan angular distribution



Unpolarized DY

- Experimentally, a violation of the Lam-Tung sum rule is observed by sizeable cos2Φ moments
- Several model explanations
  - higher twist
  - spin correlation due to non-triva QCD vacuum
  - Non-zero Boer Mulders function

$\mathrm{Lam-Tung\ SR:}\ 1-\lambda = 2\nu$

$\mathrm{NLO\ pQCD:}\ \lambda \approx 1\ \mu \approx 0\ \nu \approx 0$

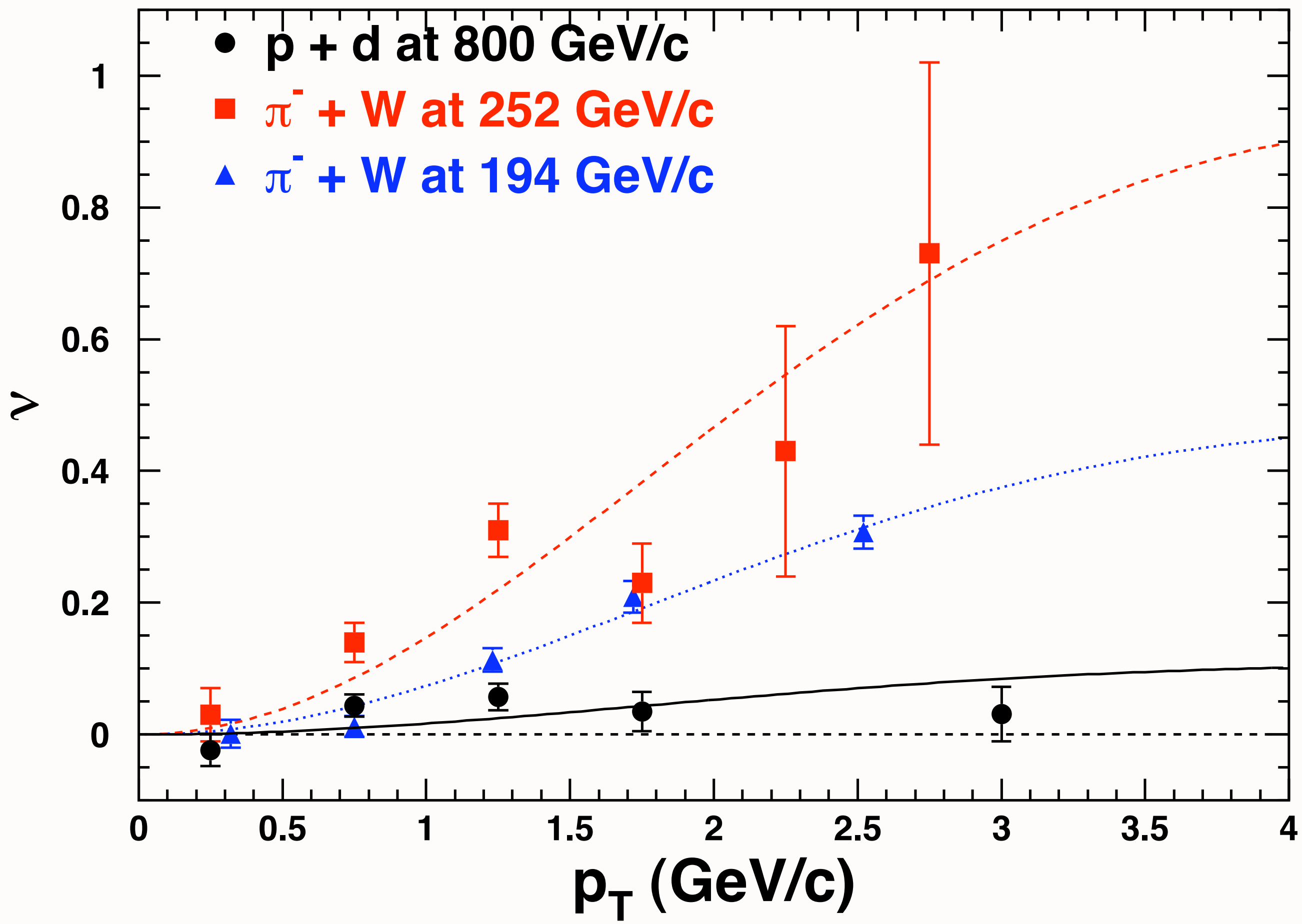
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

$\mathrm{Experiment:}\ \nu \simeq 0.6$

B. Seitz

Measurement of Angular Distributions of Drell-Yan Dimuons in $p+d$ Interaction at 800 GeV/c

(FNAL E866/NuSea Collaboration)

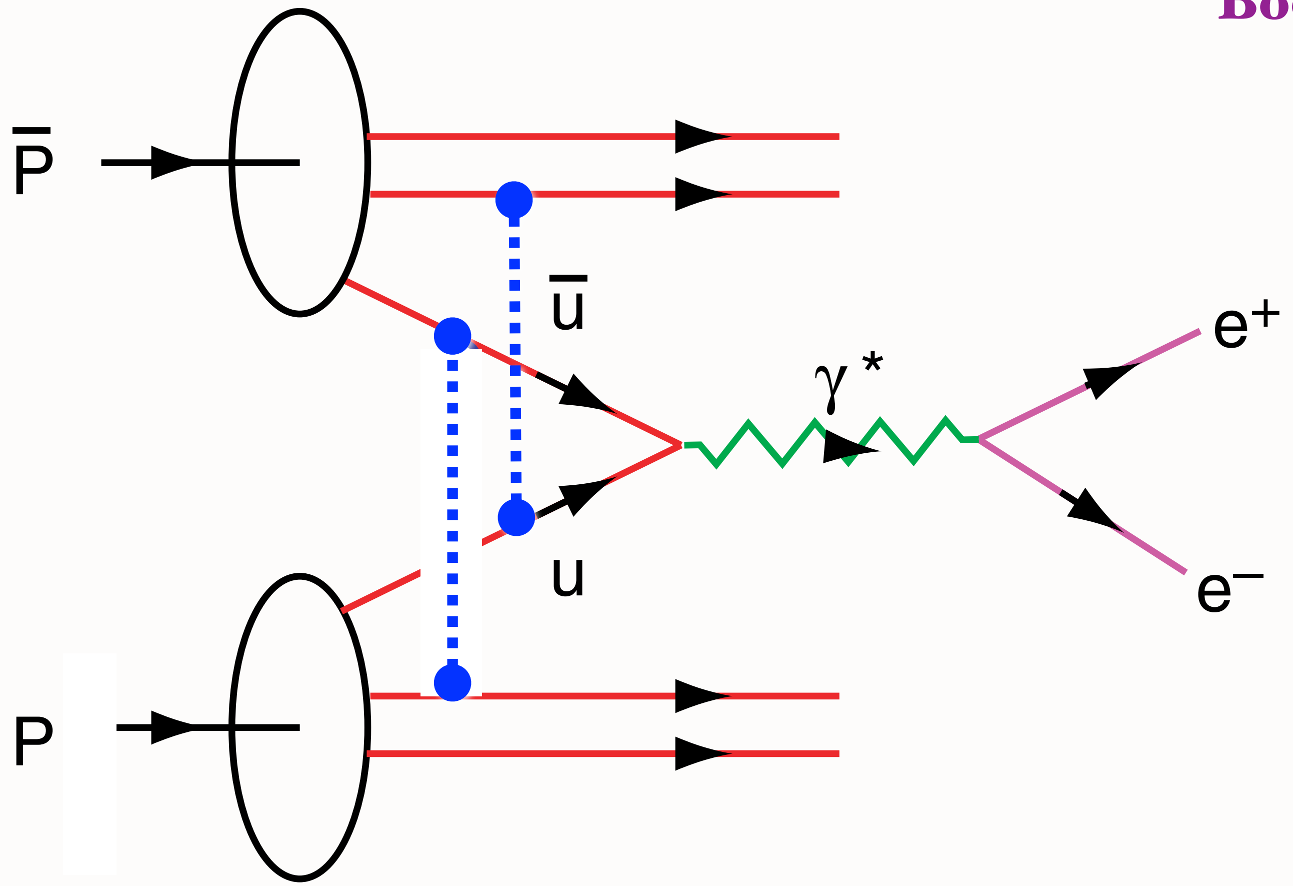


Huge Effect in $\pi W \to \mu^+\mu^- X$

Negligible Effect $pd \to \mu^+\mu^- X$

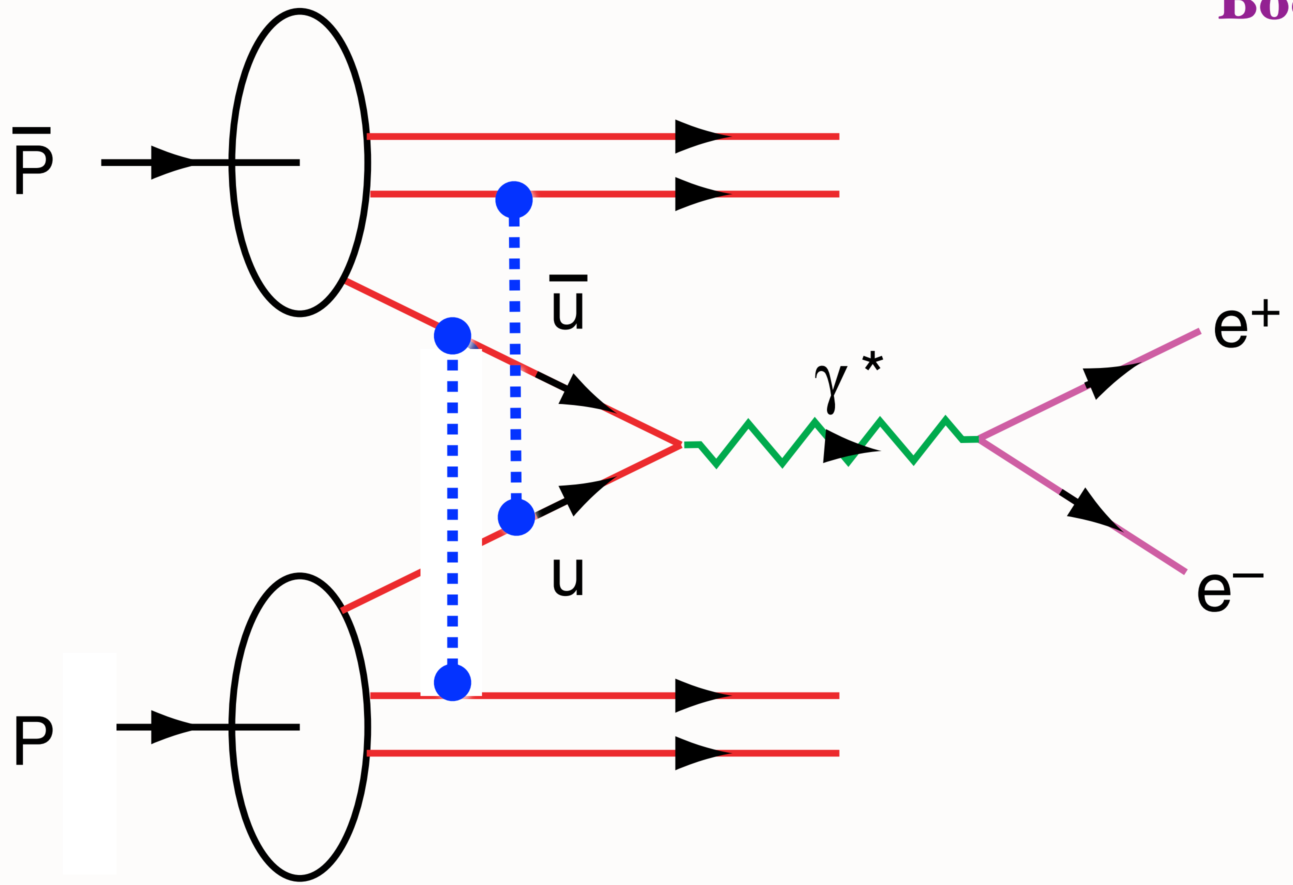
Parameter ν vs. p_T in the Collins-Soper frame for three Drell-Yan measurements. Fits to the data using Eq. 3 and $M_C = 2.4$ GeV/c^2 are also shown.

Boer, Hwang, sjb



DY $\cos 2\phi$ correlation at leading twist from double ISI

Boer, Hwang, sjb



DY $\cos 2\phi$ correlation at leading twist from double ISI

Product of Boer - Mulders Functions

$$h_1^{\perp}(x_1, \boldsymbol{p}_{\perp}^2) \times \bar{h}_1^{\perp}(x_2, \boldsymbol{k}_{\perp}^2)$$

Double Initial-State Interactions generate anomalous $\cos 2\phi$

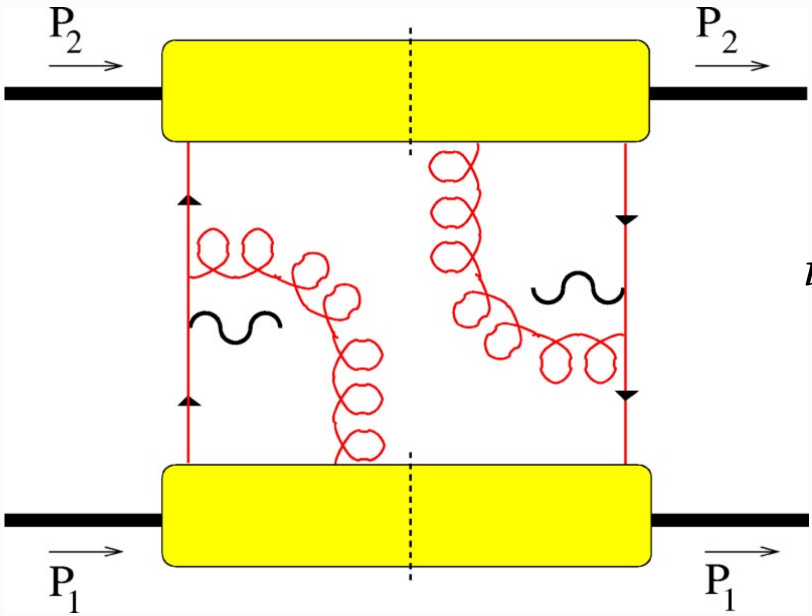
Drell-Yan planar correlations

Boer, Hwang, sjb

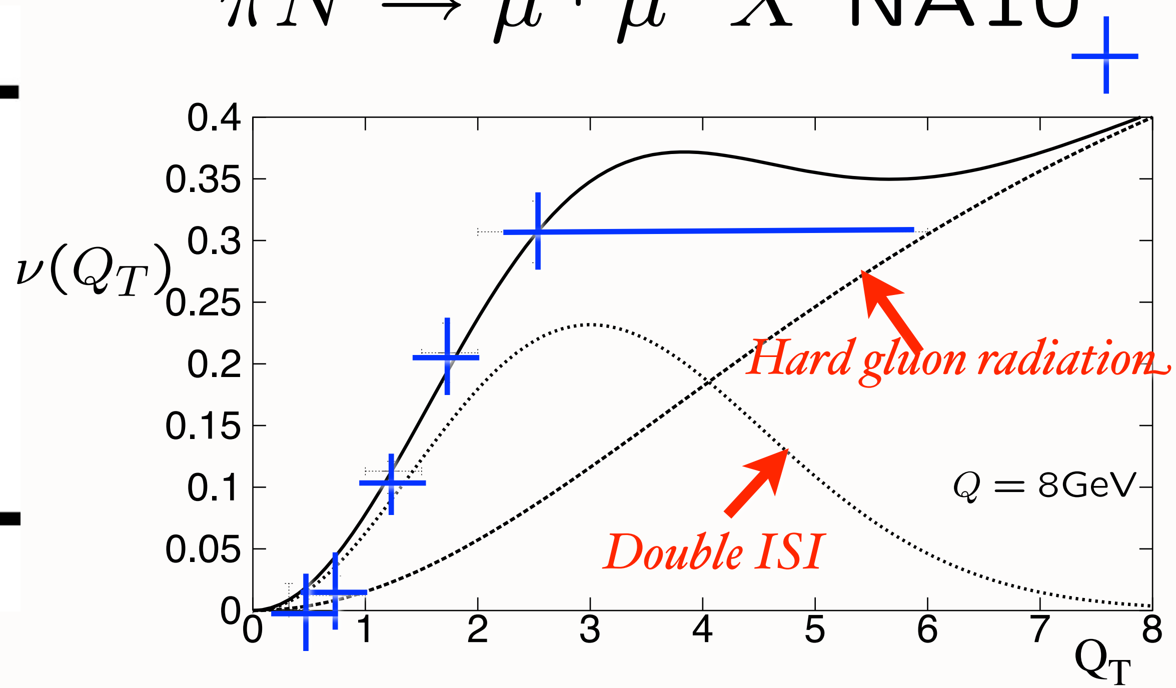
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \, \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi\right)$$

PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

$$\frac{\nu}{2} \propto h_1^\perp(\pi)\, h_1^\perp(N)$$



$\pi N \to \mu^+\mu^- X$ NA10

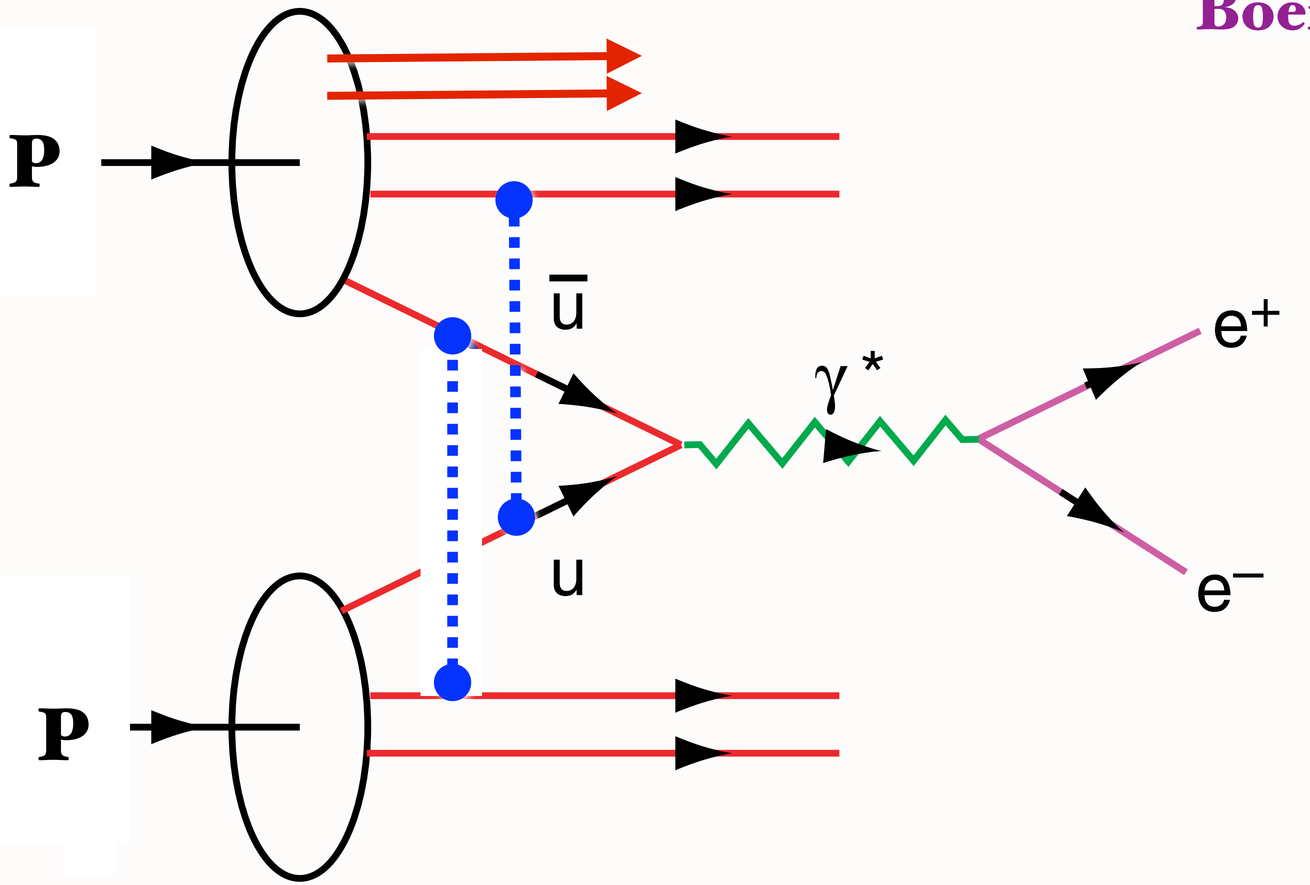


Violates Lam-Tung relation!

Model: Boer,

AFTER Experiment

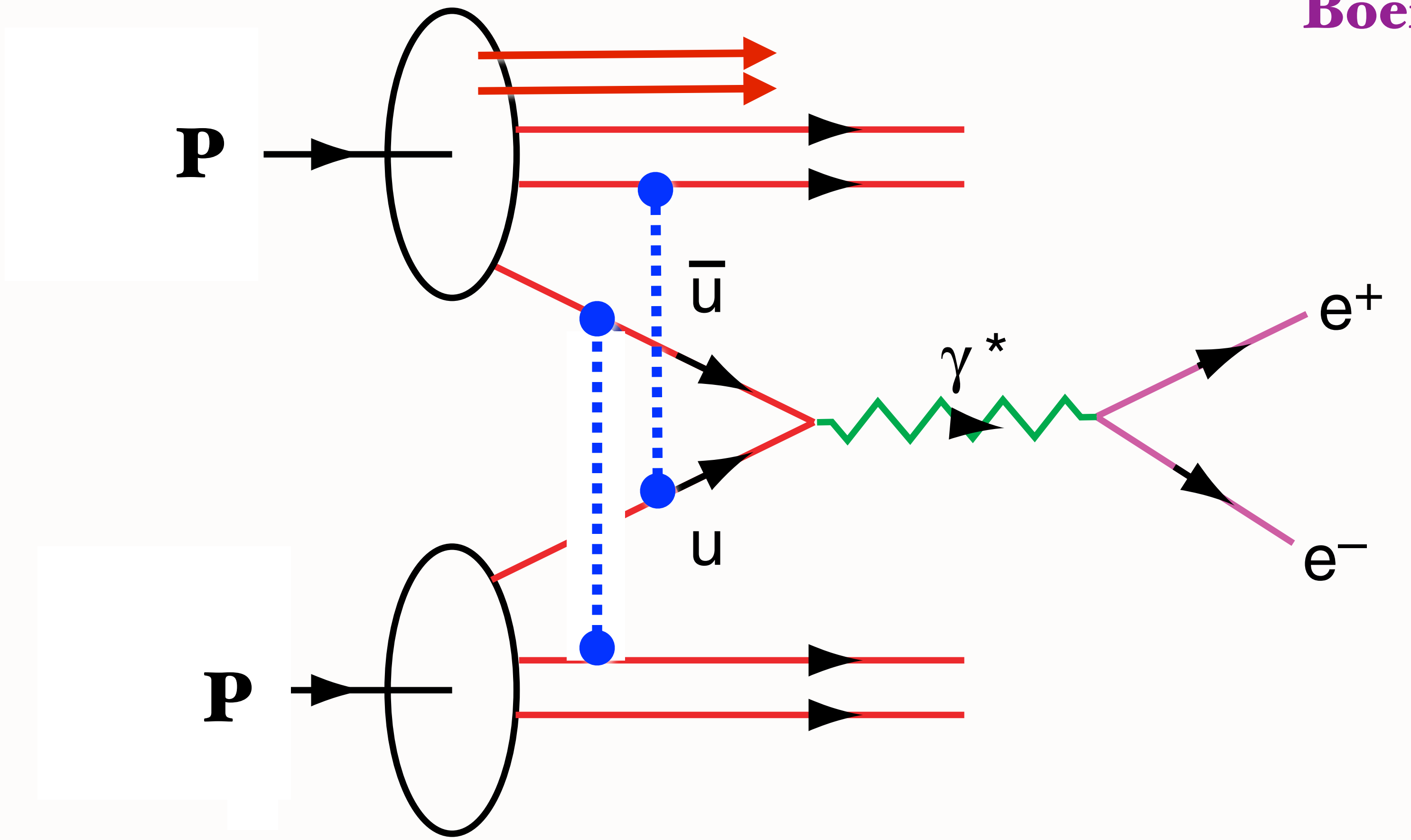
Boer, Hwang, sjb



DY $\cos 2\phi$ **correlation at leading twist from double ISI**

AFTER Experiment

Boer, Hwang, sjb



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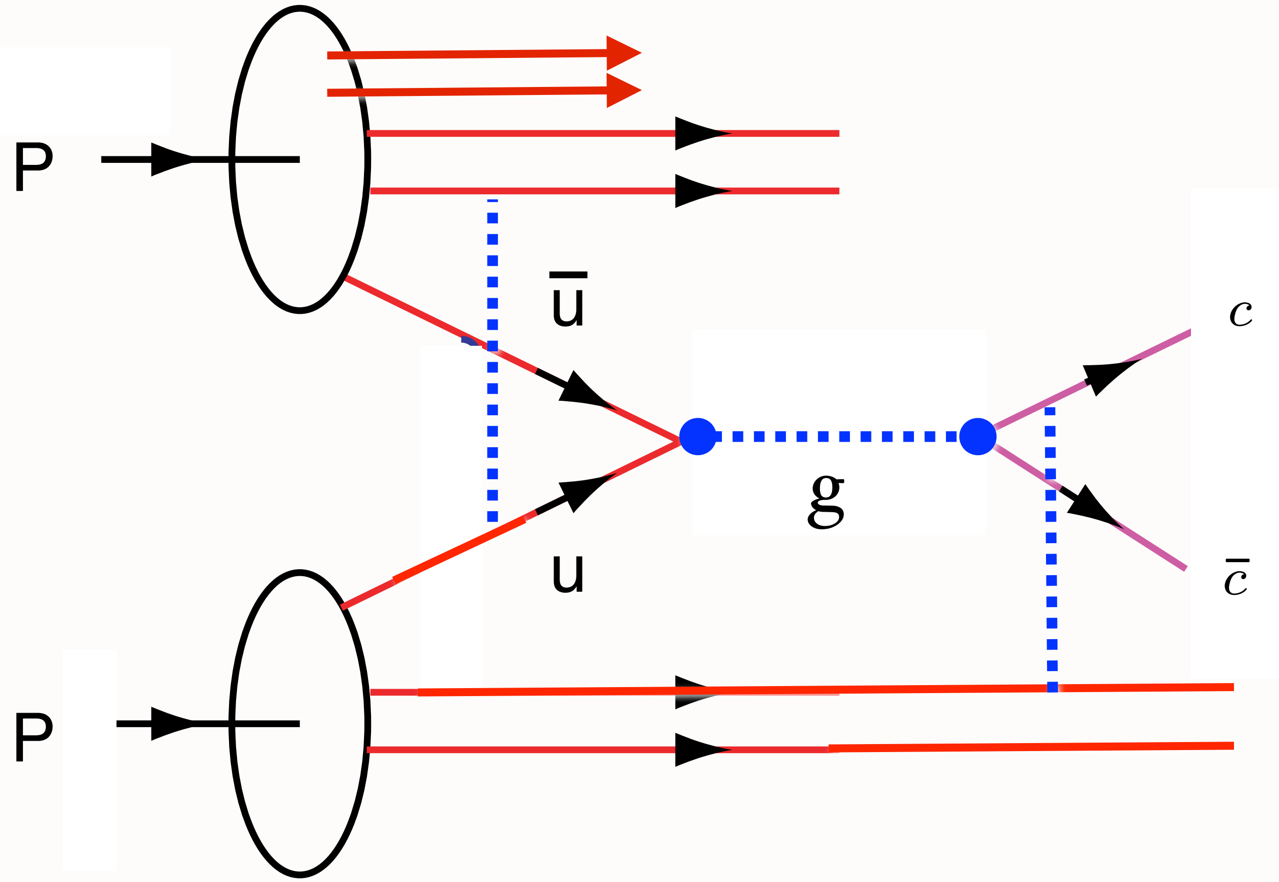
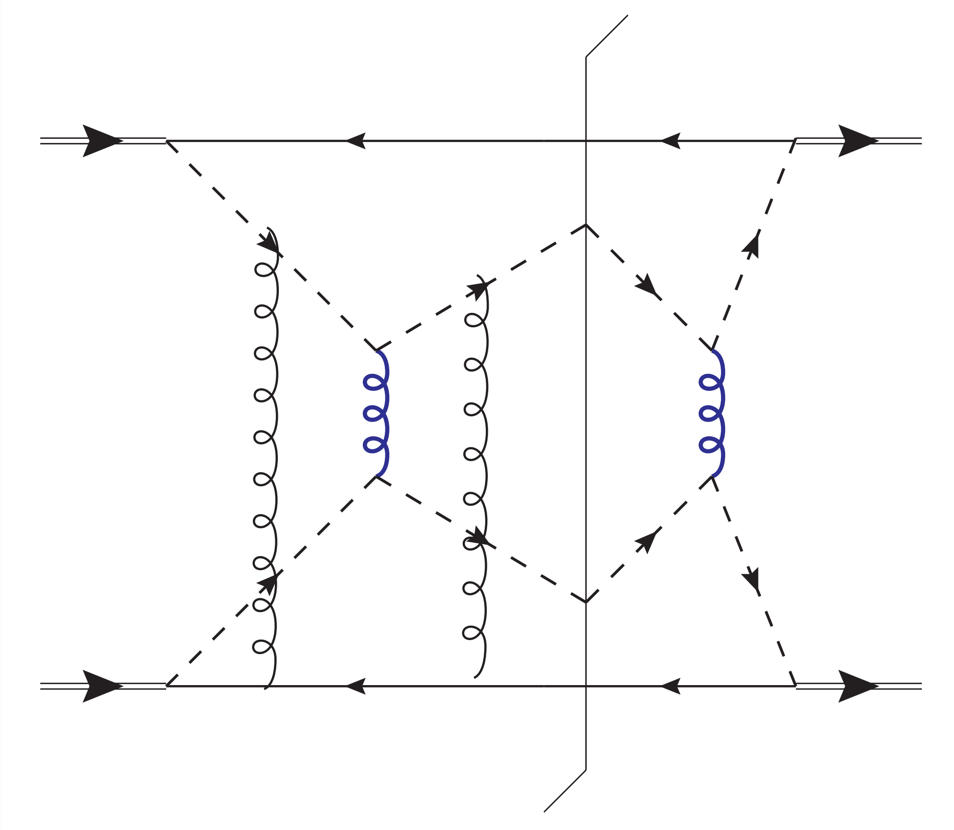


Problem for factorization when both ISI and FSI occur

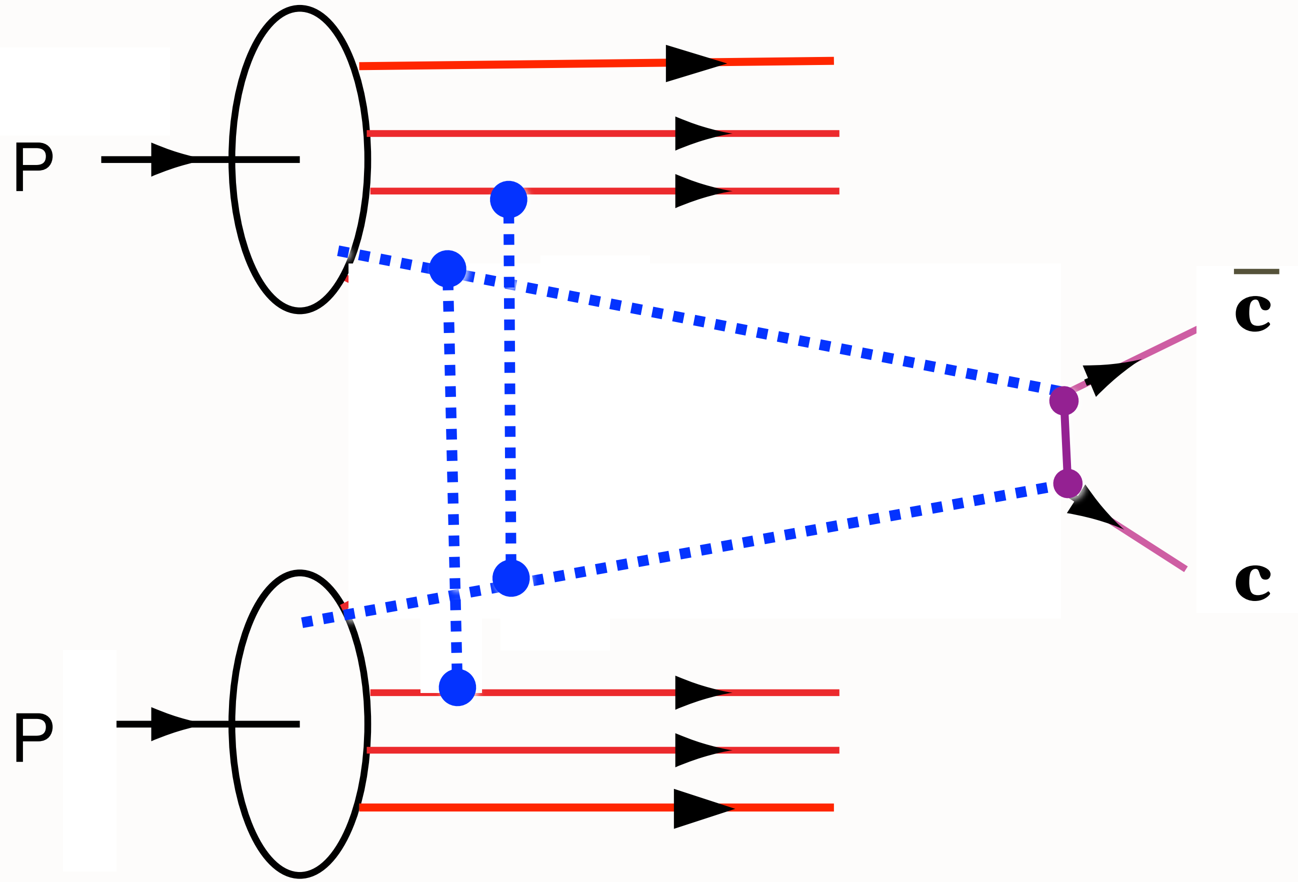
Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions

John Collins, Jian-Wei Qiu . ANL-HEP-PR-07-25, May 2007.

e-Print: **arXiv:0705.2141** [hep-ph]



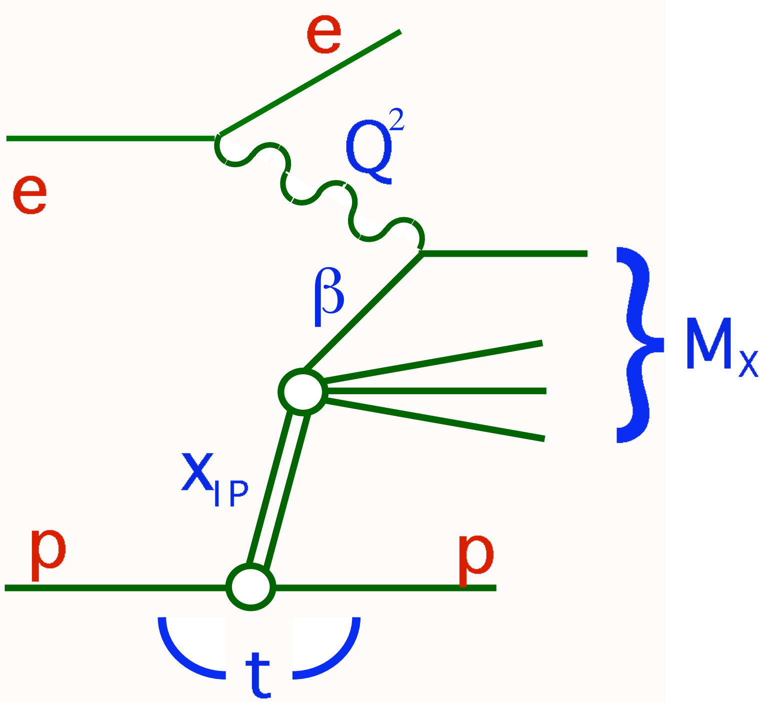
The exchange of two extra gluons, as in this graph, will tend to give non-factorization in unpolarized cross sections.

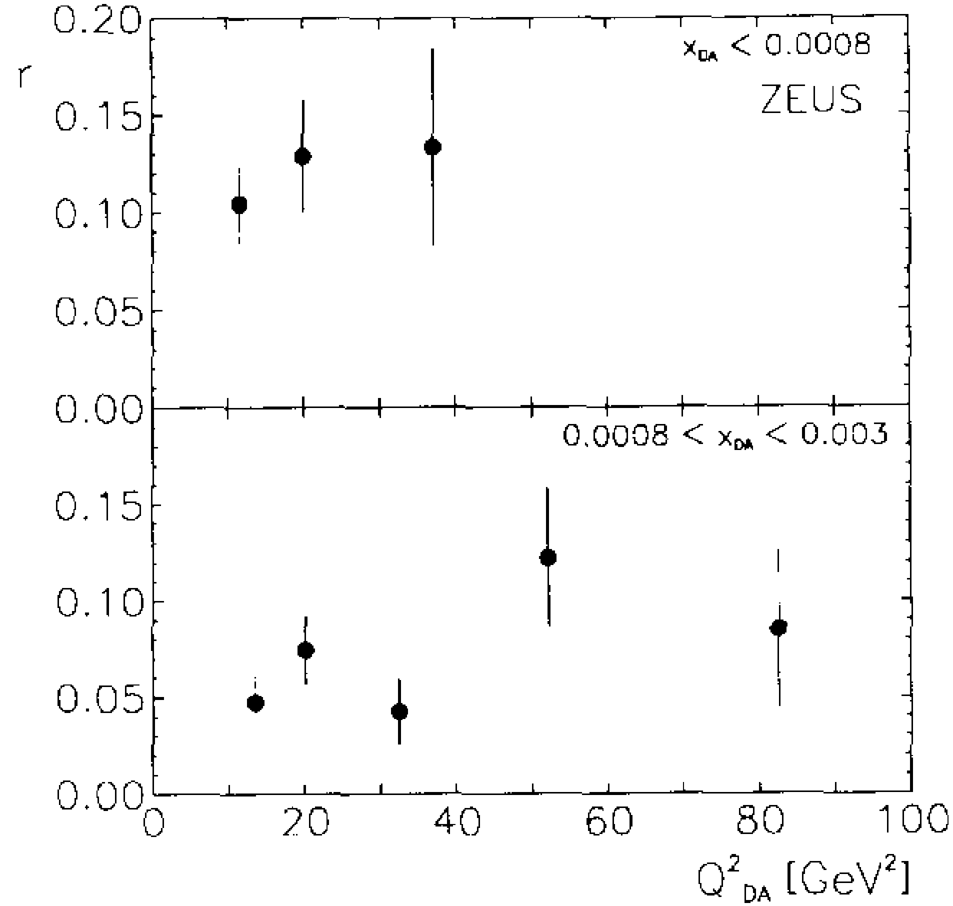


$\cos 2\phi$ correlation for quarkonium production at leading twist from double ISI

Enhanced by gluon color charge

Remarkable observation at HERA



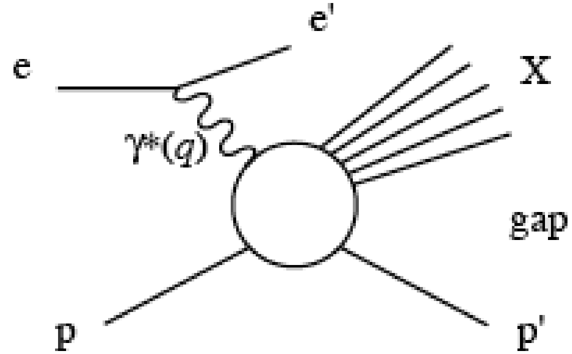


Fraction r of events with a large rapidity gap, $\eta_{\max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

10% to 15% of DIS events are diffractive !

M. Derrick et al. [ZEUS Collaboration], Phys. Lett. B 315, 481 (1993)

DDIS

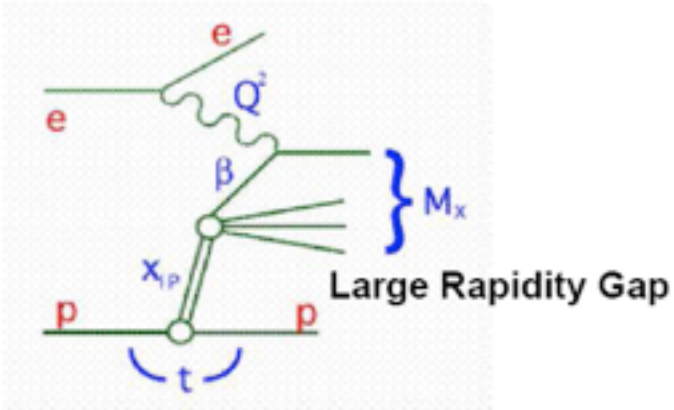


- In a large fraction ($\sim$ 10–15%) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum
- This leaves a large *rapidity gap* between the proton and the produced particles
- The t-channel exchange must be *color singlet* $\rightarrow$ a pomeron??

Diffractive Deep Inelastic Lepton-Proton Scattering

ISR, Tevatron: Single and Double Diffractive Events de Roeck

Diffractive Structure Function F_2^D



Diffractive inclusive cross section

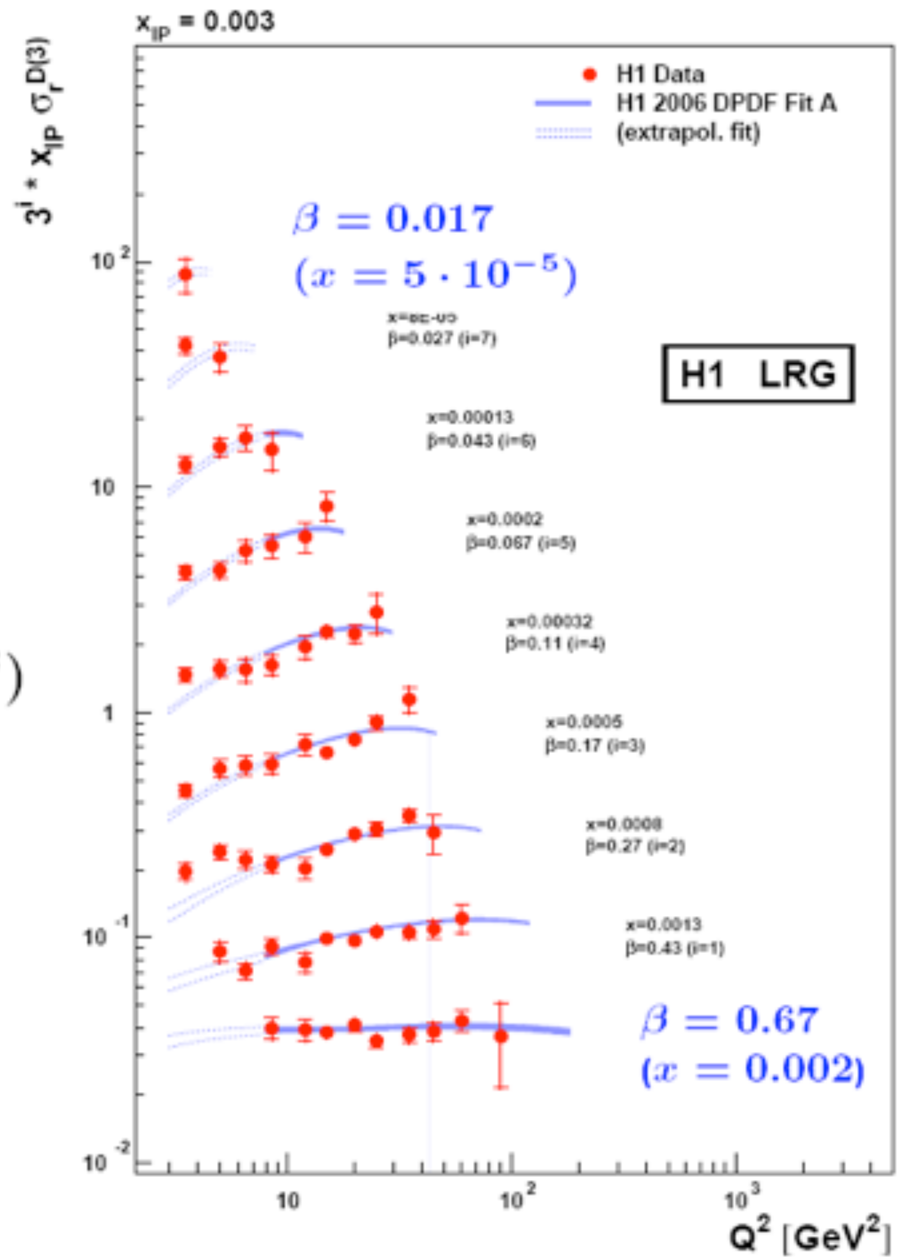
$$\frac{d^3\sigma_{NC}^{diff}}{dx_{I\!P}\, d\beta\, dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$$

$$F_2^D(x_{I\!P}, \beta, Q^2) = f(x_{I\!P}) \cdot F_2^{I\!P}(\beta, Q^2)$$

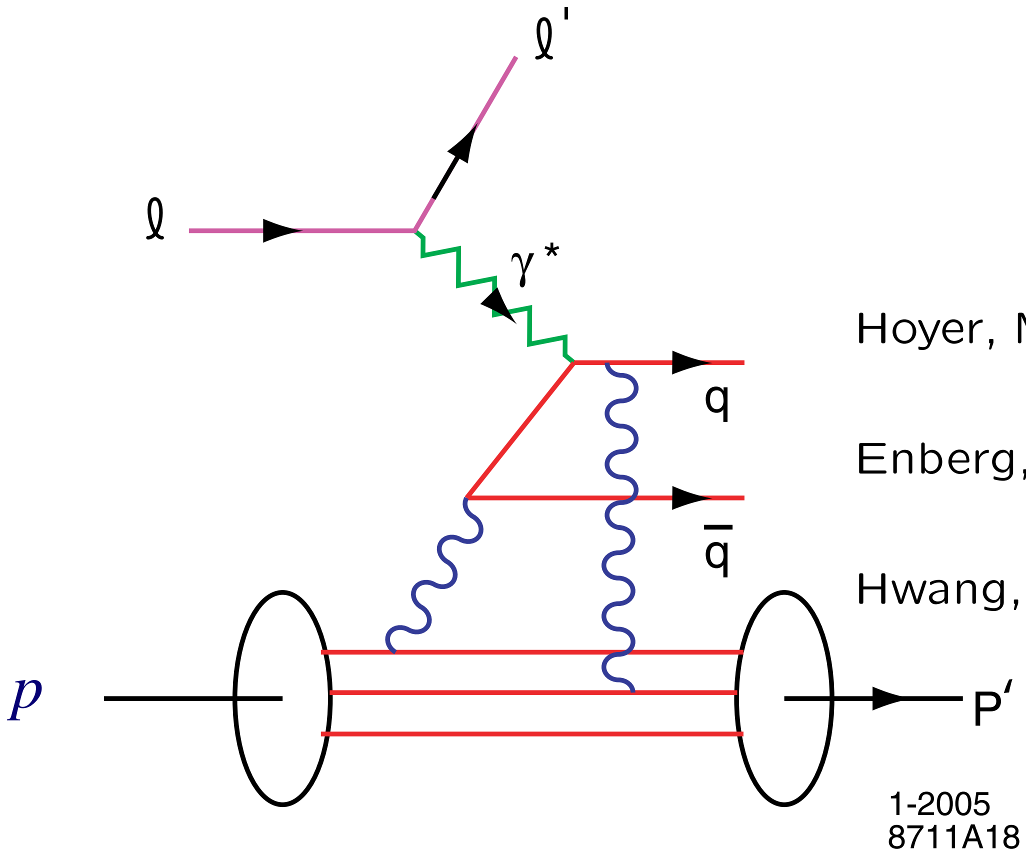
extract DPDF and $xg(x)$ from scaling violation

Large kinematic domain $3 < Q^2 < 1600\ \mathrm{GeV}^2$

Precise measurements *sys 5%, stat 5–20 %*



Final-State Interaction Produces Diffractive DIS



Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHMPS)

Enberg, Hoyer, Ingelman, SJB

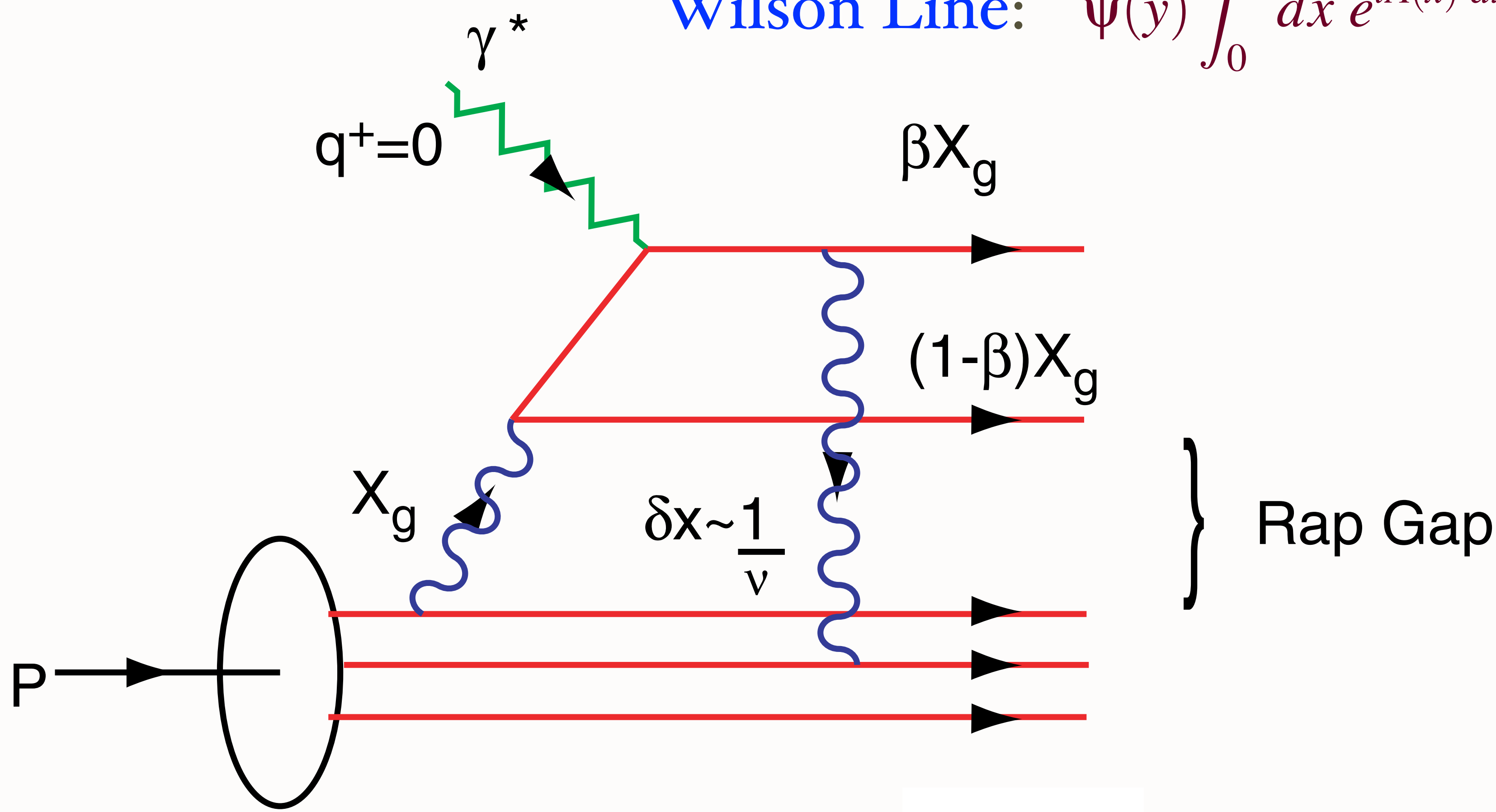
Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron

Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps

Wilson Line: $\overline{\psi}(y) \int_0^y dx \, e^{iA(x)\cdot dx} \, \psi(0)$



Reproduces lab-frame color dipole approach

Hoyer, Marchal, Peigne, Sannino, sjb

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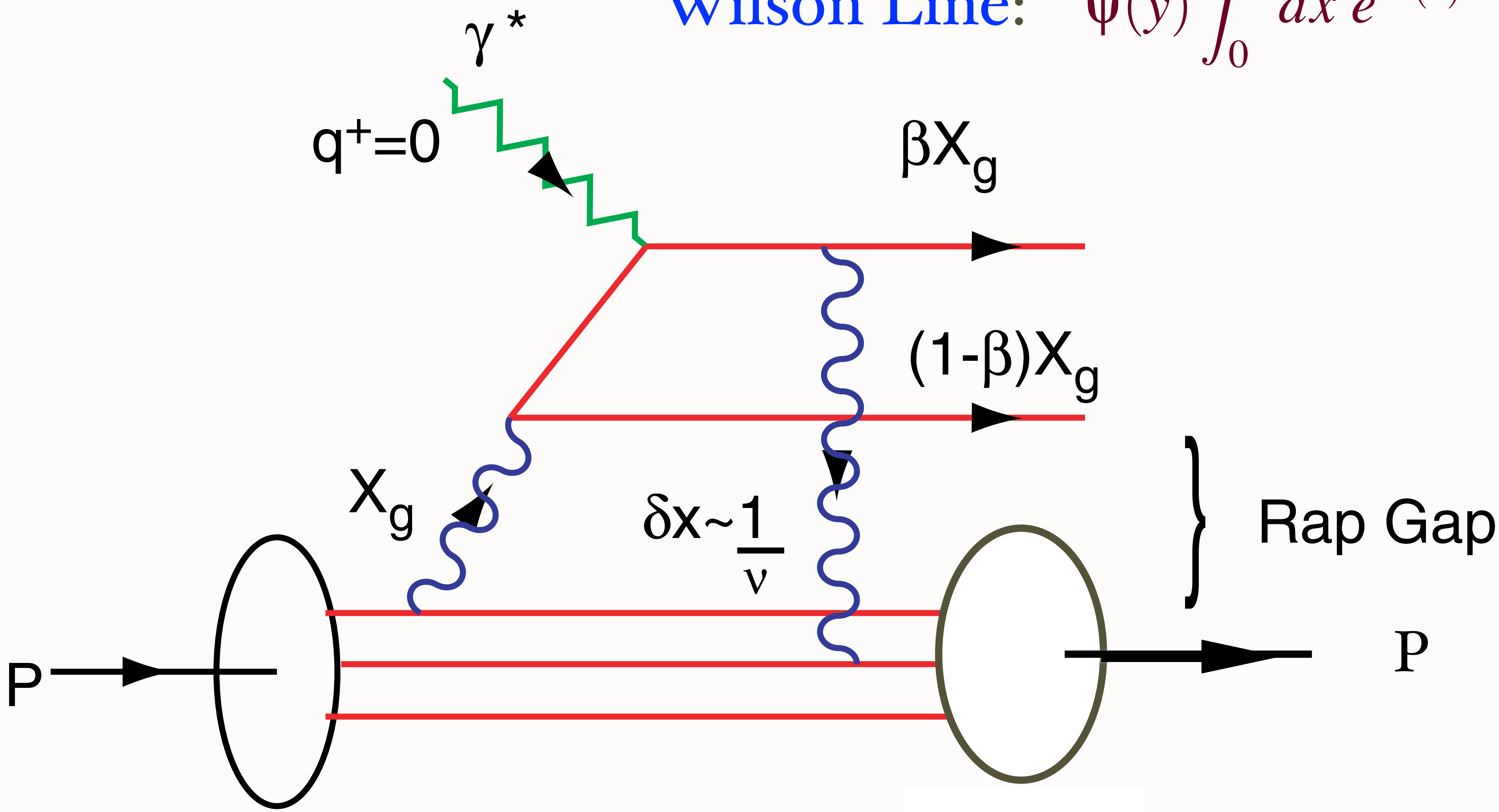
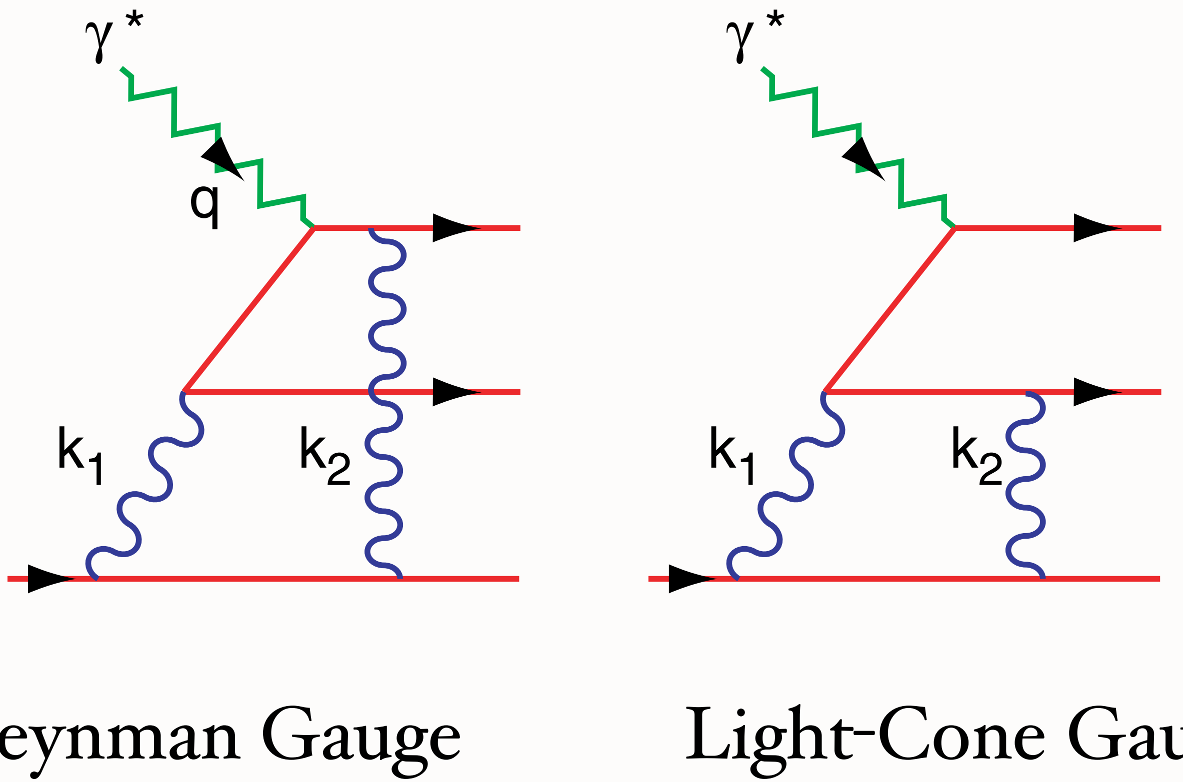
Wilson Line: $\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$

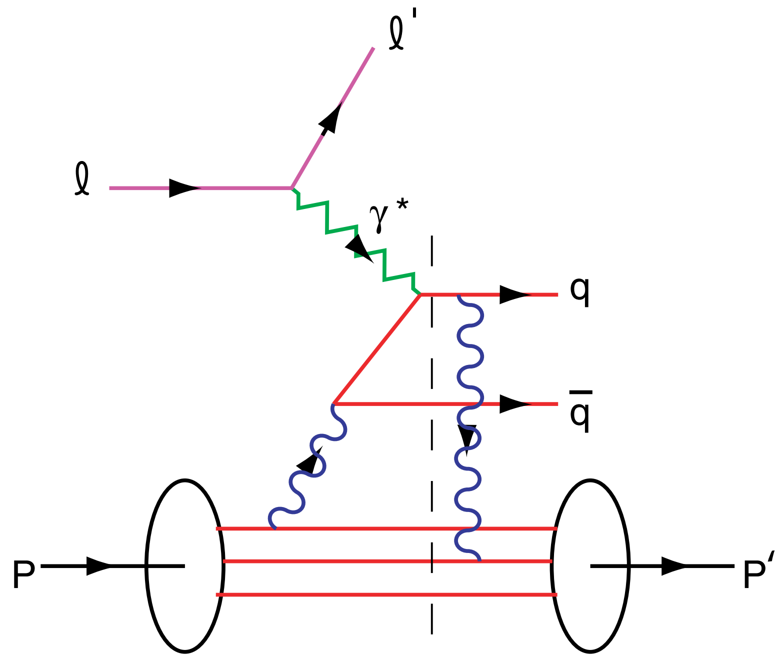


Reproduces lab-frame color dipole approach

Final State Interactions in QCD



Result is Gauge Independent



Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron and DDIS

Need Imaginary Phase to Generate
T-Odd Single-Spin Asymmetry

Physics of FSI not in Wavefunction of Target!

Physics of Rescattering

- Sivers Asymmetry and Diffractive DIS: New Insights into Final State Interactions in QCD

- Origin of Hard Pomeron

- Structure Functions not Probability Distributions! *Not square of LFWFs*

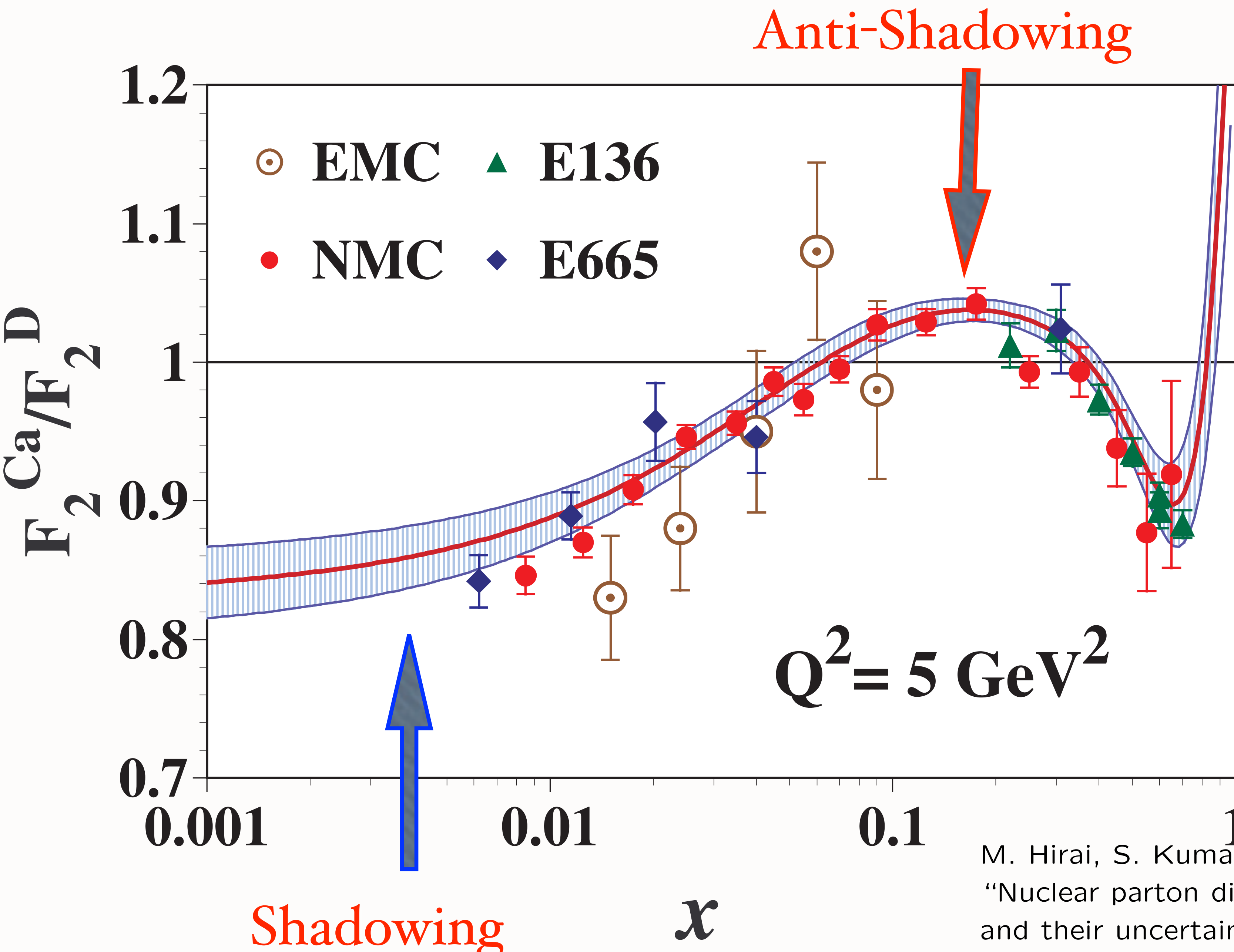
- T-odd SSAs, Shadowing, Antishadowing

- Diffractive dijets/ trijets, doubly diffractive Higgs

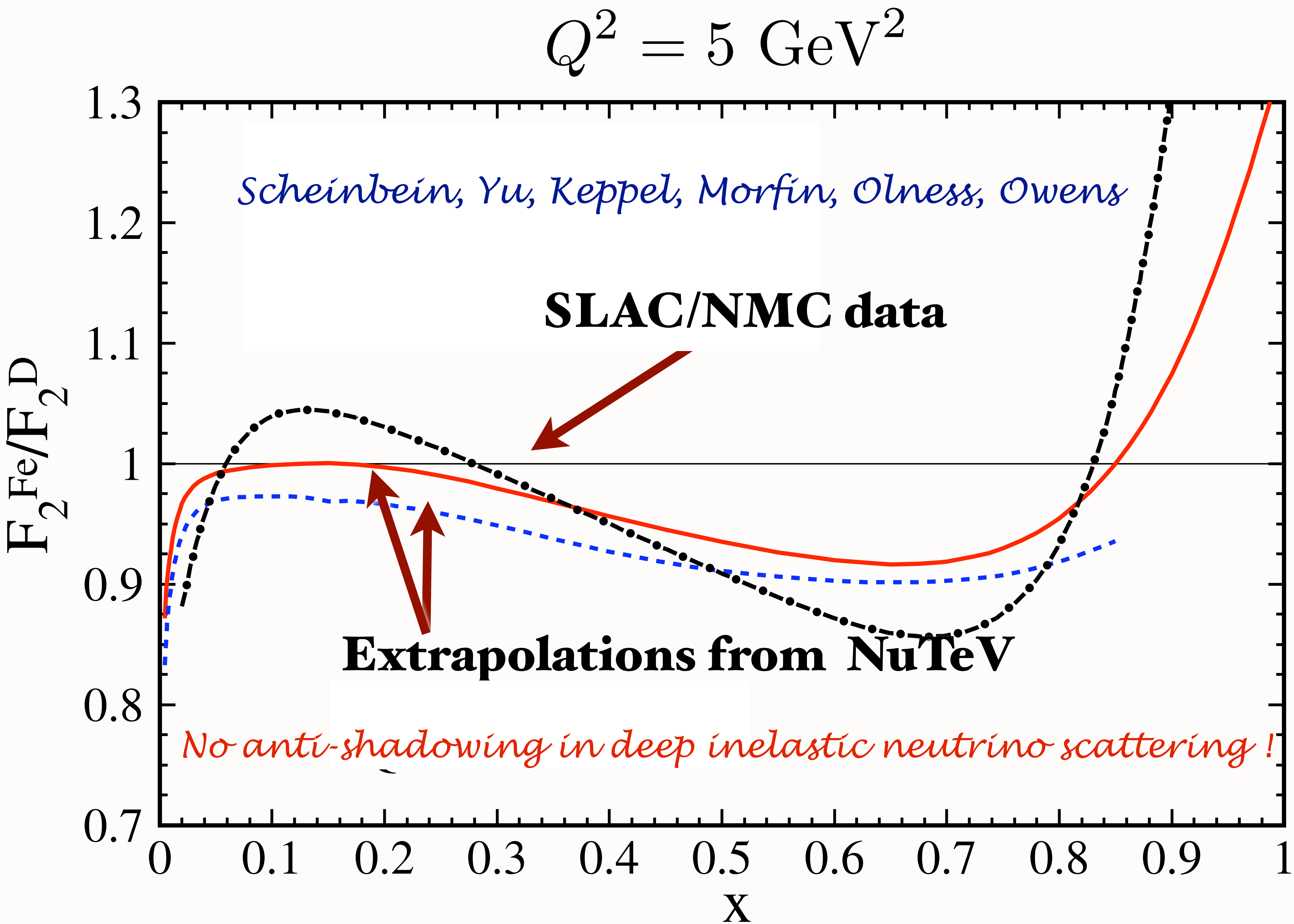
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon

Diffraction at AFTER

- Multi-gluon exchange leaves target intact
- Many Channels
- Nucleus remains intact at high energy
- Many types of Diffractive Channels
- Odderon Search in $pp \to c\bar{c}X$
- Look for heavy quark asymmetry
- Proton Diffracts to 3 Jets -- measures valence LFWF

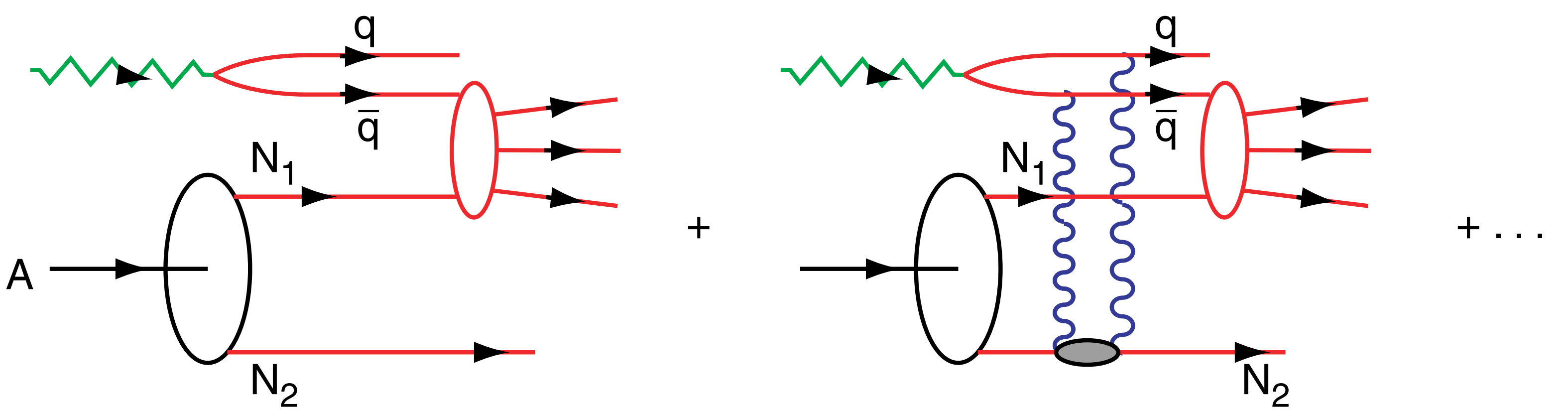


M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093].


$Q^2 = 5\ \mathrm{GeV}^2$
Scheinbein, Yu, Keppel, Morfin, Olness, Owens
SLAC/NMC data
Extrapolations from NuTeV
No anti-shadowing in deep inelastic neutrino scattering !
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

Stodolsky
Pumplin, sjb
Gribov

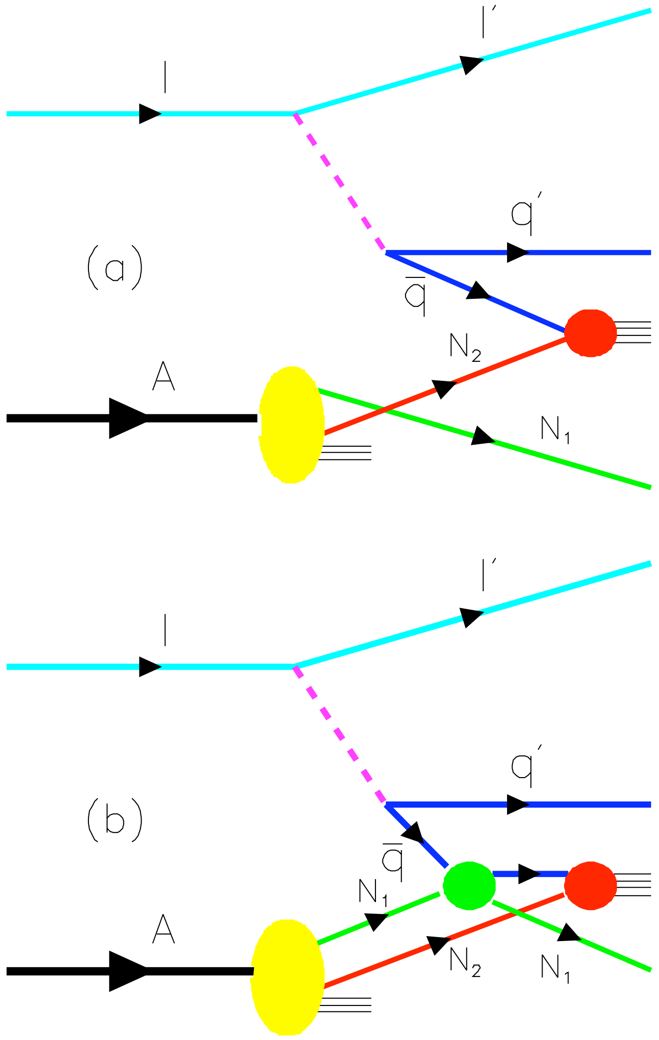
Nuclear Shadowing in QCD



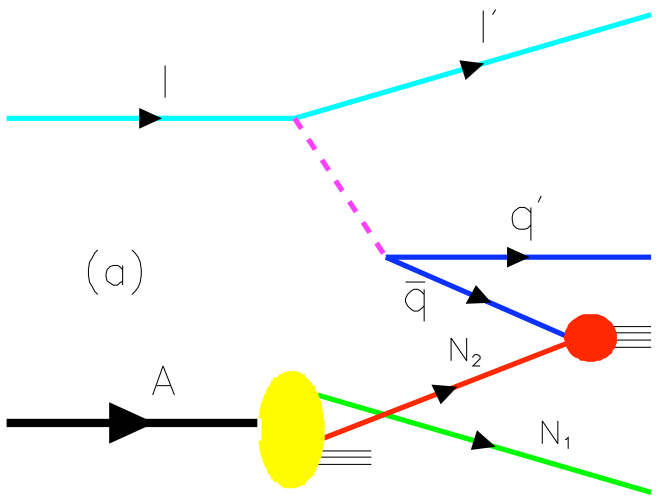
Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus

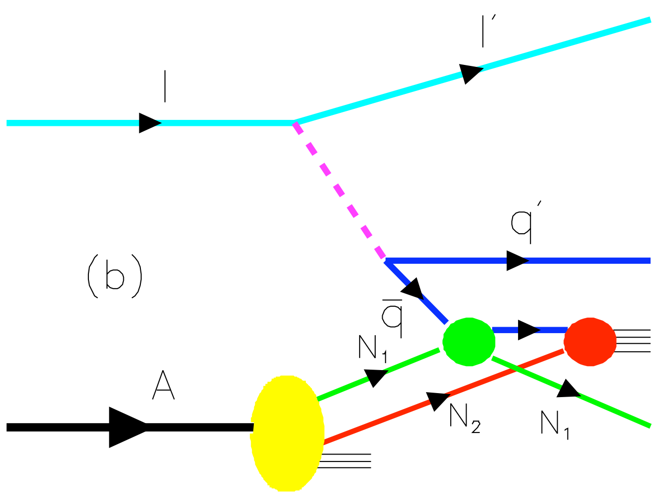


l'
l
q'
(a)
q̄
N2
A
N1
l'
l
q'
(b)
q̄
N1
A
N2
N1

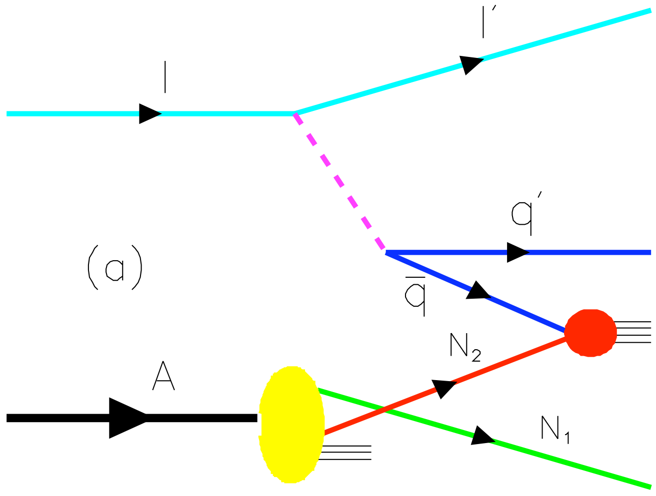


The one-step and two-step processes in DIS on a nucleus.

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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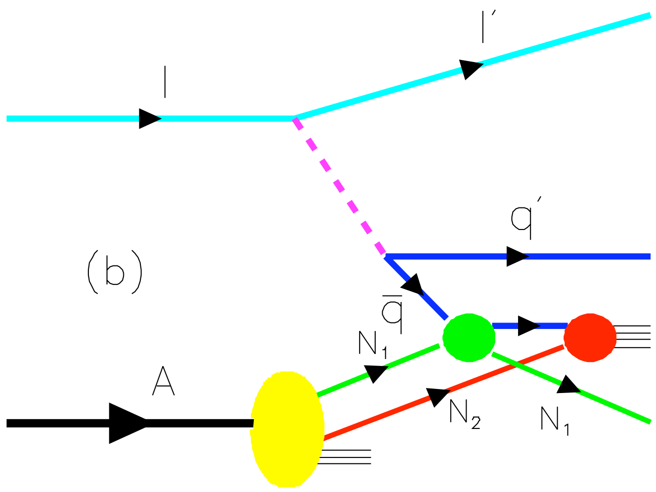
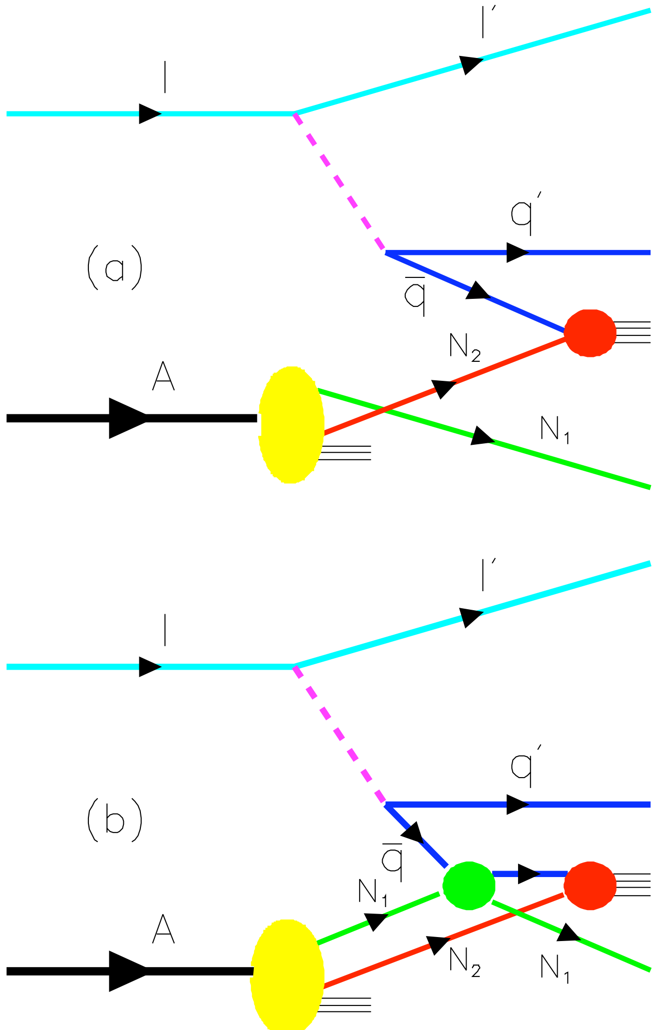


If the scattering on nucleon N_1 is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\bar{q}$ flux reaching N_2.

$\rightarrow$ Shadowing of the DIS nuclear structure functions.



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

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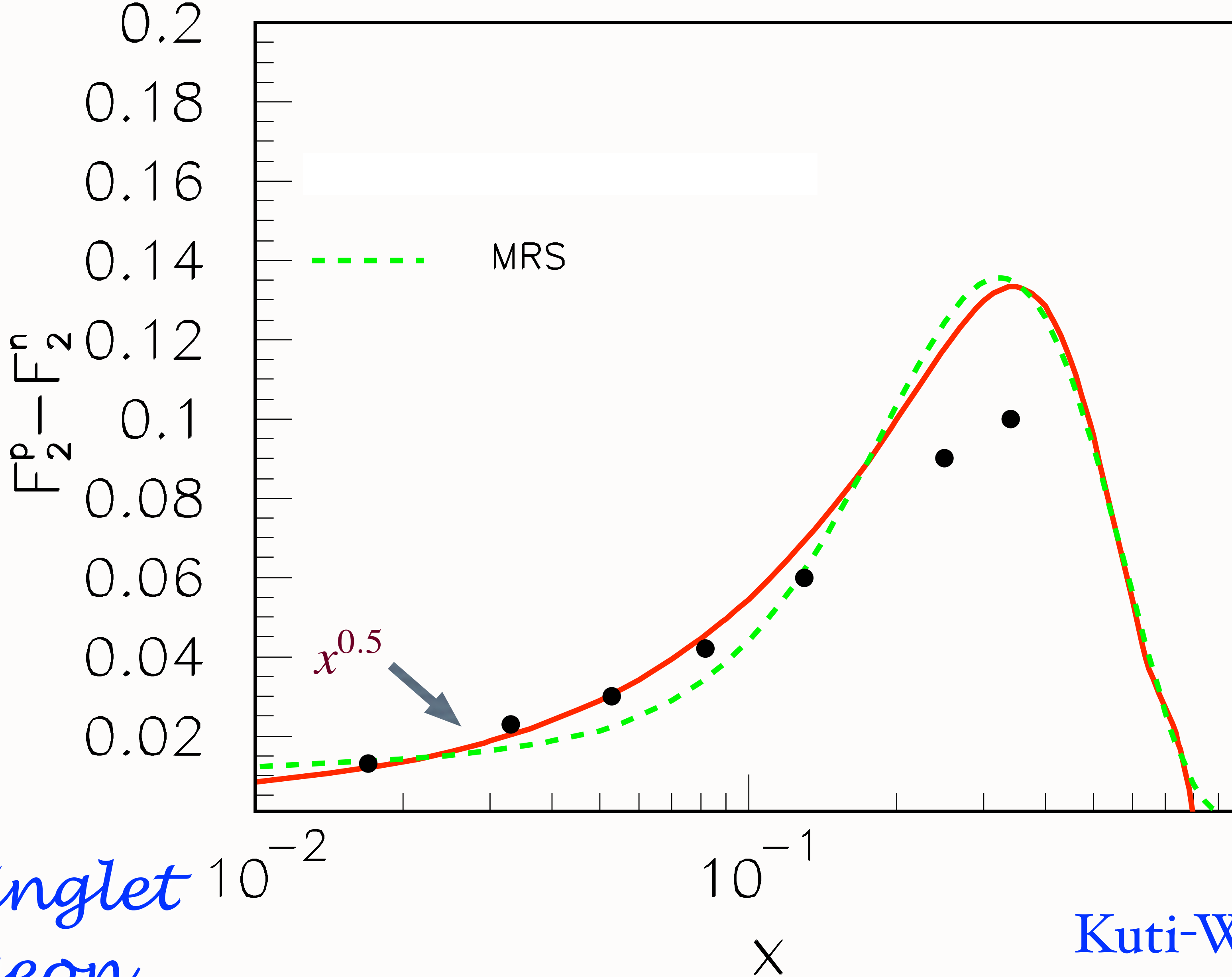
Observed HERA DDIS produces nuclear shadowing



Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior

Reggeon Exchange

Phase of two-step amplitude relative to one step:

$$\frac{1}{\sqrt{2}}(1-i)\times i = \frac{1}{\sqrt{2}}(i+1)$$

Constructive Interference

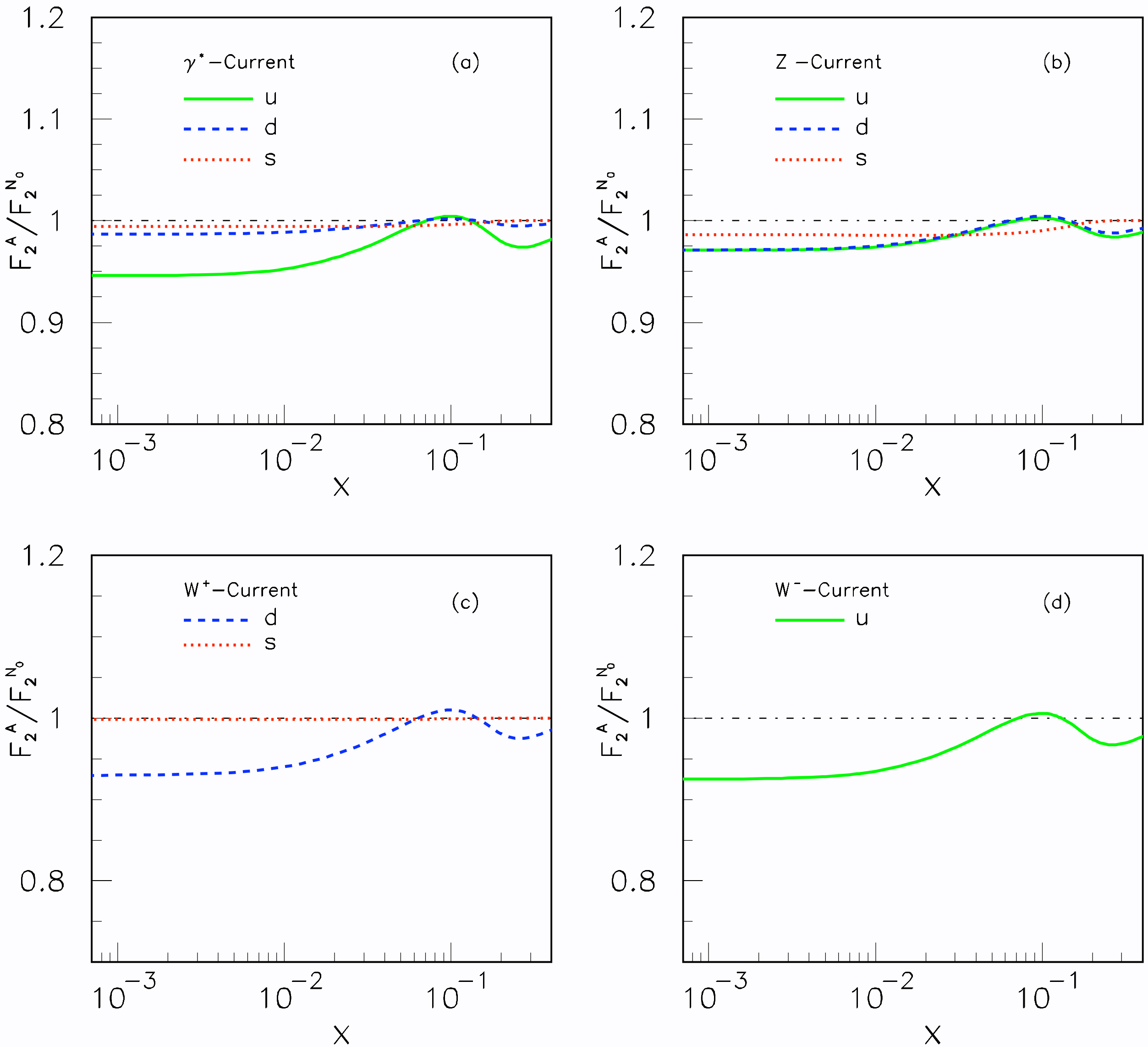
Depends on quark flavor!

Thus antishadowing is not universal

Different for couplings of $\gamma^*, Z^0, W^\pm$

Critical test: Tagged Drell-Yan

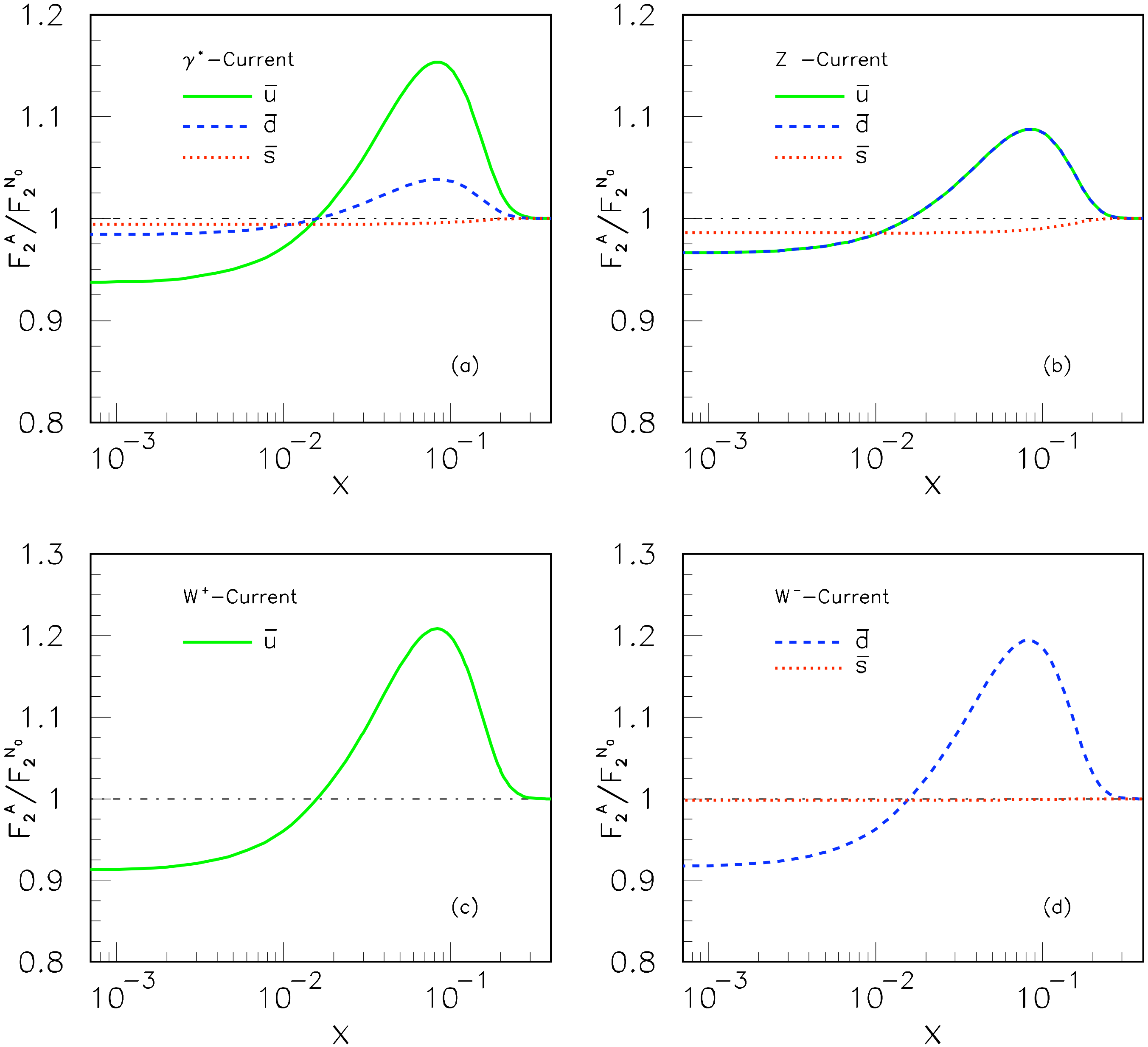
Shadowing and Antishadowing of DIS Structure Functions



S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

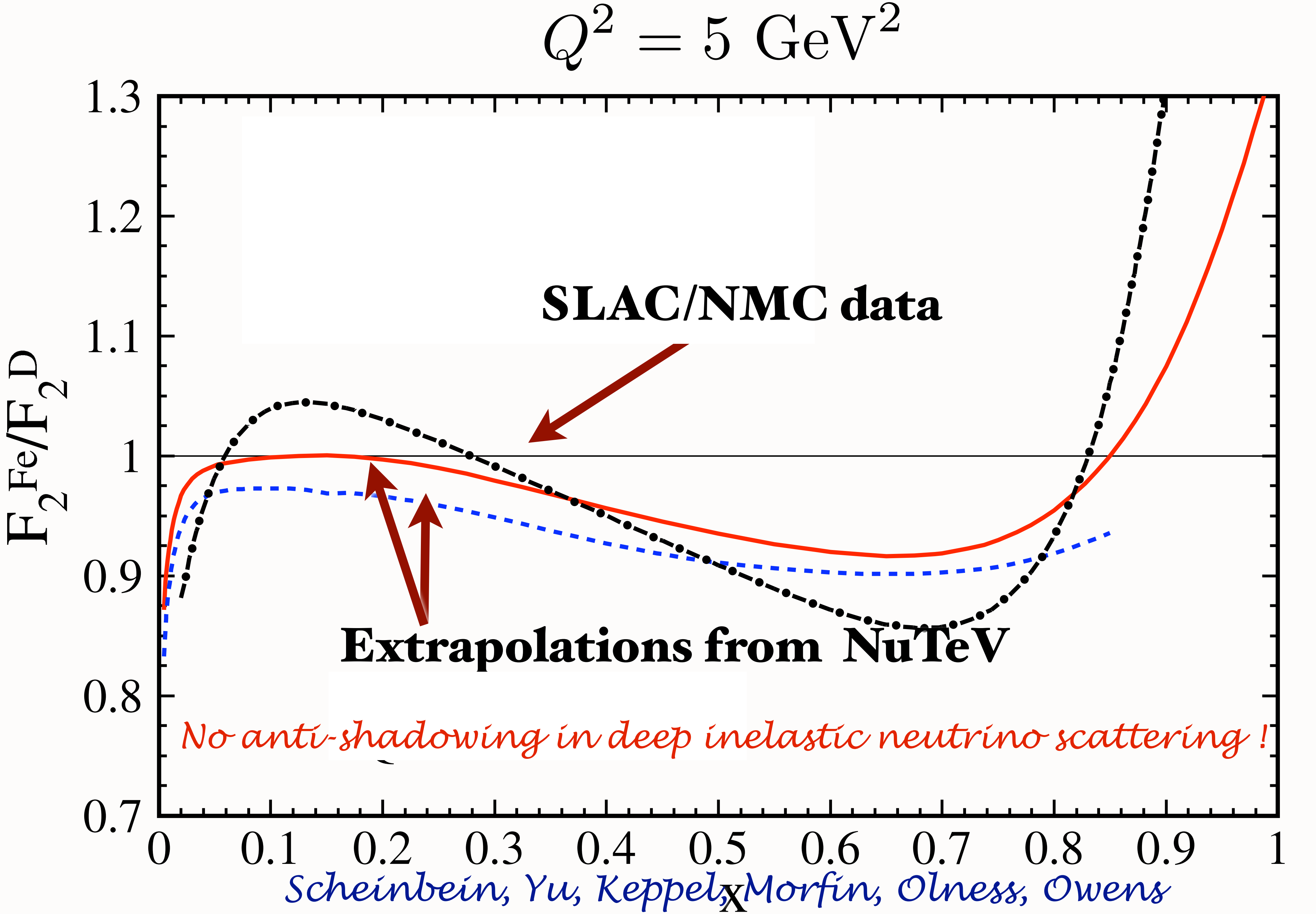
Modifies NuTeV extraction of $\sin^2\theta_W$

Test in flavor-tagged lepton-nucleus collisions



Schmidt, Yang; sjb

Nuclear Antishadowing not universal !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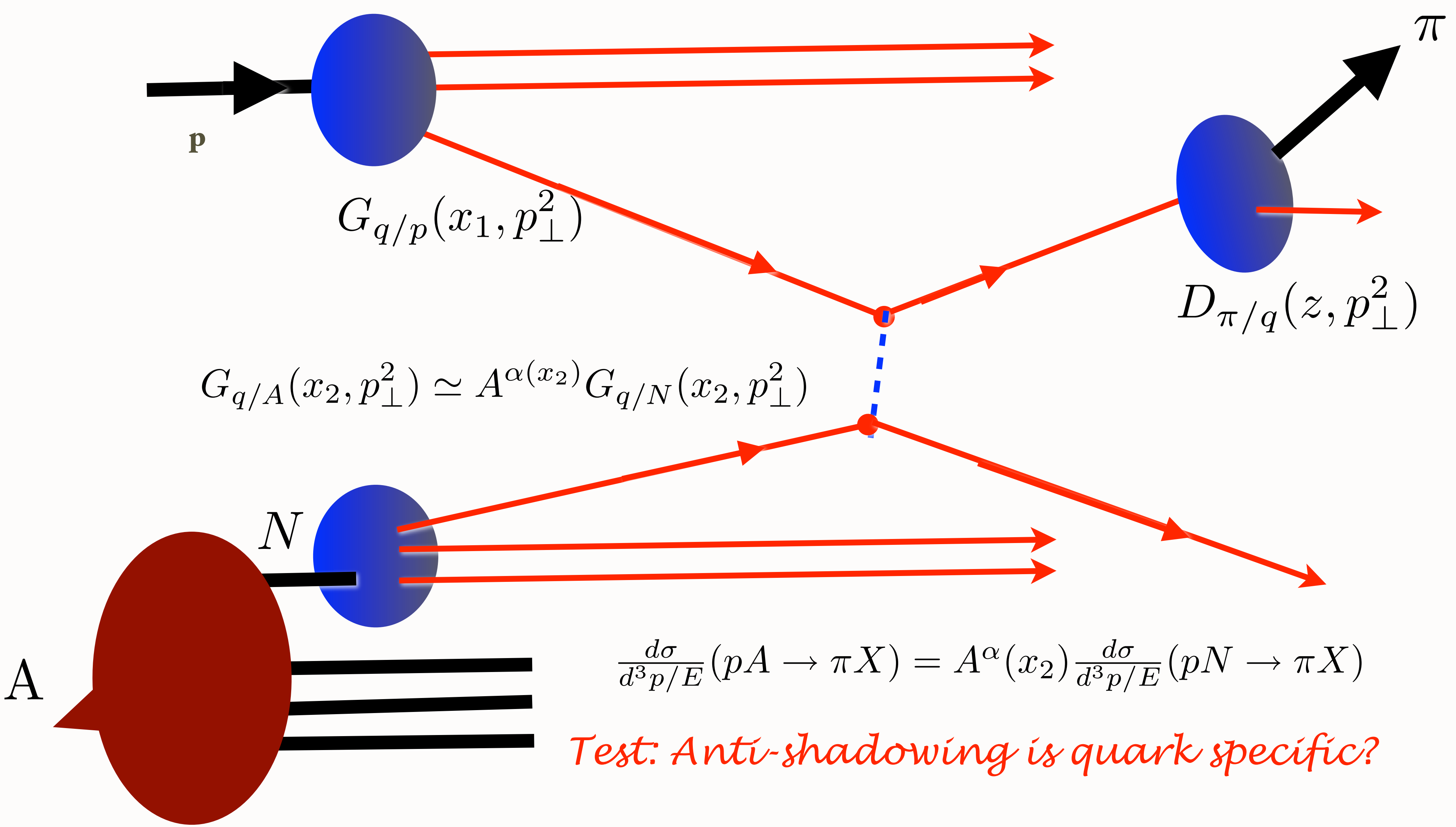
0.8
0.9
1
x
Scheinbein, Yu, Keppel, Morfin, Olness, Owens

LHC p-A Collisions

Leading-Twist Contribution to Hadron Production on Nuclei



$$\frac{d\sigma}{d^3p/E}(pA \to \pi X) = A^{\alpha}(x_2) \frac{d\sigma}{d^3p/E}(pN \to \pi X)$$

Test: Anti-shadowing is quark specific?

Static	Dynamic
Square of Target LFWFs	Modified by Rescattering: ISI & FSI
No Wilson Line	Contains Wilson Line, Phases
Probability Distributions	No Probabilistic Interpretation
Process-Independent	Process-Dependent - From Collision
T-even Observables	T-Odd (Sivers, Boer-Mulders, etc.)
No Shadowing, Anti-Shadowing	Shadowing, Anti-Shadowing, Saturation
Sum Rules: Momentum and J^z	Sum Rules Not Proven
DGLAP Evolution; mod. at large x	DGLAP Evolution
No Diffractive DIS	Hard Pomeron and Odderon Diffractive DIS

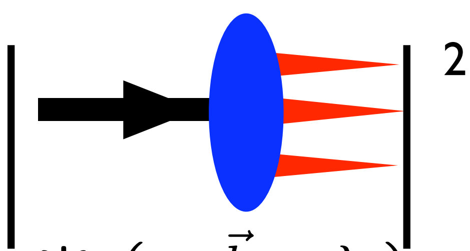
Hwang, Schmidt, sjb,

Mulders, Boer

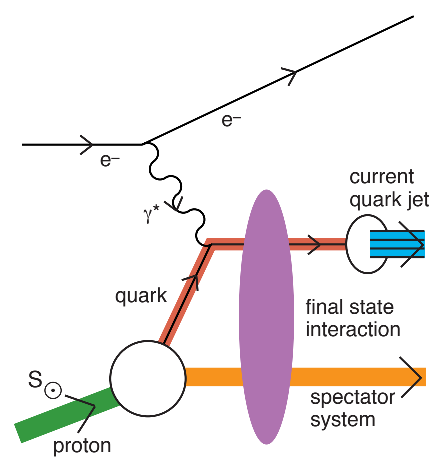
Qiu, Sterman

Collins, Qiu

Pasquini, Xiao, Yuan, sjb



$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



Physics of Rescattering

- Sivers Asymmetry and Diffractive DIS: New Insights into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions!   *Not square of LFWFs*
- T-odd SSAs, Shadowing, Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon

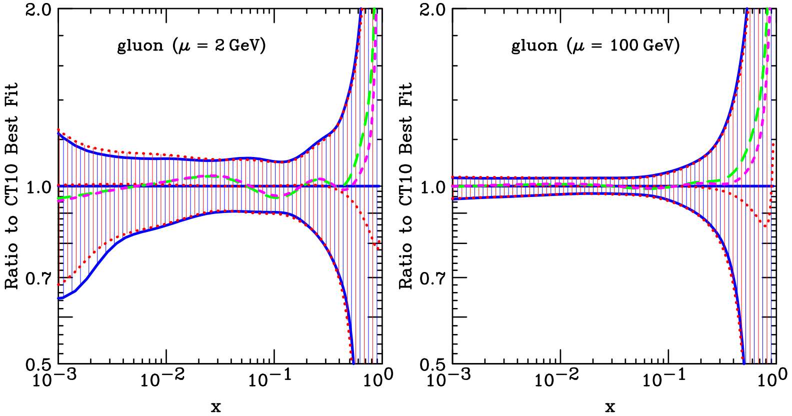
Need for a quarkonium observatory

- To put an end to production controversies (since 1995 !), we need
  - a study of direct J/ψ yield (χ_c only measured in *pp* by CDF and PHENIX)
  - a study of direct $\Upsilon(nS)$ (χ_b only measured in *pp* by CDF (1 point))
  - a study of the polarisation of direct yields
    (at least in 2 frames or 2D distrib.)
  - + probably associated production
- $\chi_{c,b}$ production is badly known, even worse for the η_c
- The latter are **potentially better probes** of glue in *pp*
- LO processes are $gg \to \begin{cases} \chi_{c,b,2} \\ \eta_{c,b} \end{cases}$
- For that, we need
  - high stats
    $\to$ wide acceptance (also help not to bias 1D polarisation analyses)
  - a vertex detector
  - state-of-the-art calorimetry for γ ($\chi_Q \to {}^3S_1 + \gamma$, $\eta_c \to \gamma\gamma$)
  - adapted triggers (Big issue for CMS and ATLAS)

A Fixed Target ExpeRiment: A quarkonium observatory

- Interpolating the world data set:
- Rates expected at RHIC in 2011: J/ψ: 10^6 in *pp*, Υ: 10^4 in *pp*
- 2-3 orders of magnitude higher here
  (RHIC yields are much lower in dAu compared to p*A* here)
- Numbers are for only one unit of *y* about 0
- Unique access in the backward region
- Probe of the (very) large *x* in the target
- AIM/HOPE: Extract $g(x, Q^2)$ with Q^2 as low as 10 GeV^2 from $x = 10^{-3}$ up to $\simeq$ one

Target	$N_{J/\Psi}$ (y^{-1}) $N_{J/\Psi} = A\mathcal{L}\sigma_{\Psi}$	N_{Υ} (y^{-1}) $N_{\Upsilon} = A\mathcal{L}\sigma_{\Upsilon}$
(with branching and per unit of rapidity)		
Liq. H² (1m)	0.6 10^9	10^6
Liq. D²	1.5 10^9	23 10^5
Be	0.2 10^9	2.7 10^5
Cu	0.8 10^9	13 10^5
W	1.7 10^9	27 10^5
Pb	1. 10^9	16 10^5



A quarkonium observatory in *pA* collisions

- Reminder:
- Total yield measured by PHENIX during *d*Au Run08: 9×10^5 J/ψ (inclusive yield in nearly 3 units of *y*!)
- Future plan for *d*Au runs at RHIC ?
- In principle, one can get 1000 times more J/ψ (in 1 unit of *y*), allowing for
  - χ_c measurement in *pA* via $J/\psi + \gamma$
  - Polarisation measurement as function of *A*, the centrality, *y* and P_T :

    For $\alpha^{octet} \neq \alpha^{singlet}$, probe of different obsorption of octets & singlets ?
  - Ratio ψ' over direct J/ψ measurement in *pA*
  - not to mention ratio with open charm, Drell-Yan, etc ...

Target	$N_{J/\Psi}$ (y^{-1}) $N_{J/\Psi} = A\mathcal{L}\sigma_\Psi$	N_Υ (y^{-1}) $N_\Upsilon = A\mathcal{L}\sigma_\Upsilon$
(with branching and per unit of rapidity)		
Liq. H^2 (1m)	$0.6\ 10^9$	10^6
Liq. D^2	$1.5\ 10^9$	$23\ 10^5$
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W	$1.7\ 10^9$	$27\ 10^5$
Pb	$1.\ 10^9$	$16\ 10^5$

A Fixed Target ExpeRiment: a quarkonium observatory in *PbA*

Observation of J/ψ sequential suppression seems to be hindered by

- the Cold Nuclear Matter effects: non trivial and ... not well-known, after all
- the difficulty to observe directly the excited states which would melt before the ground states
  - χ_c never studied in *AA* collisions
  - $\psi(2S)$ not yet studied in *AA* collisions at RHIC and the LHC
- the possibilities for $c\bar{c}$ recombination
  - Open charm studies are difficult where recombination matters most i.e. at low P_T
  - Only indirect indications –from the y and P_T dependence of R_{AA}– that recombination may be at work
  - CNM effects may show a non-trivial y and P_T dependence too !
  - not clear what v_2 tells us

A Fixed Target ExpeRiment: a quarkonium observatory in *PbA*

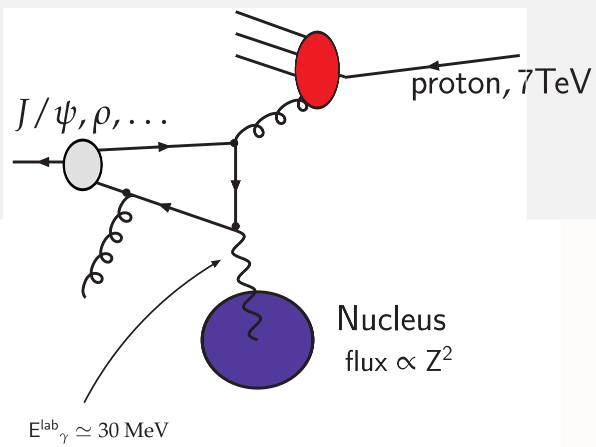
- The excellent capabilities in *pA* should help
  - to reduce the CNM uncertainties
  - to measure their dependence in y and P_T
- Even though recombination may not be large at 72 GeV:
  - Open charm may be well measured, via displaced e/μ or $D \to K\pi$ a priori even at low P_T thanks to the boost
- last but not least, excited states would be studied
  - $\psi(2S)$ thanks to the statistics and the resolution
  - χ_c thanks the excellent colorimetry in high-multiplicity environment cf. the CALICE detector using particle flow techniques
  - and maybe ... for the very first time the η_c
- As STAR people suggested, why not to look for gluon quenching in J/ψ+hadron correlations vs. centrality (I suspect that we need a good *pA* baseline)

Rough estimation of the yield: $2 \times 10^7 J/\psi$, $10^4 \Upsilon$ per year (10^6 sec)

A Fixed Target ExpeRiment

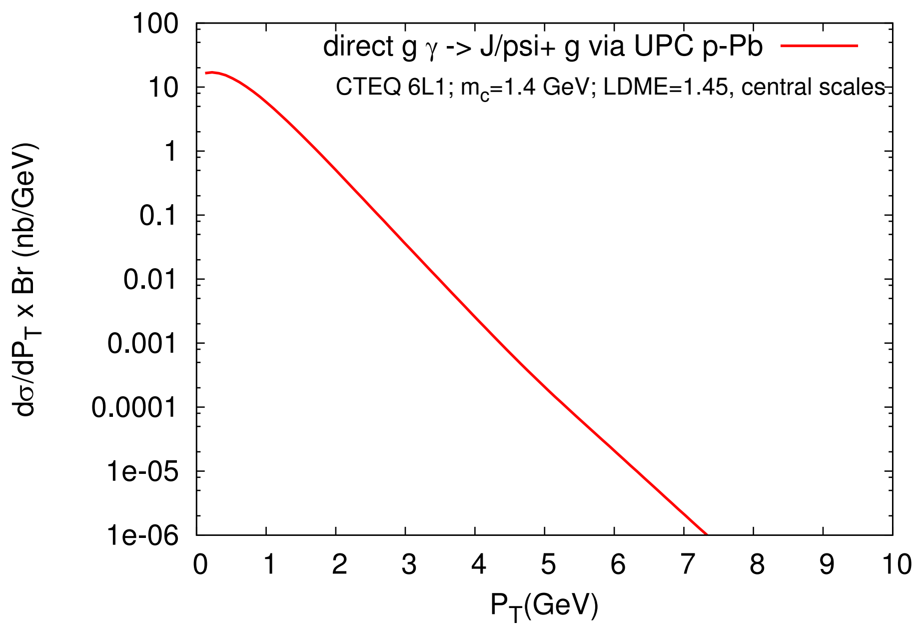
One exotic illustration of the potentialities:

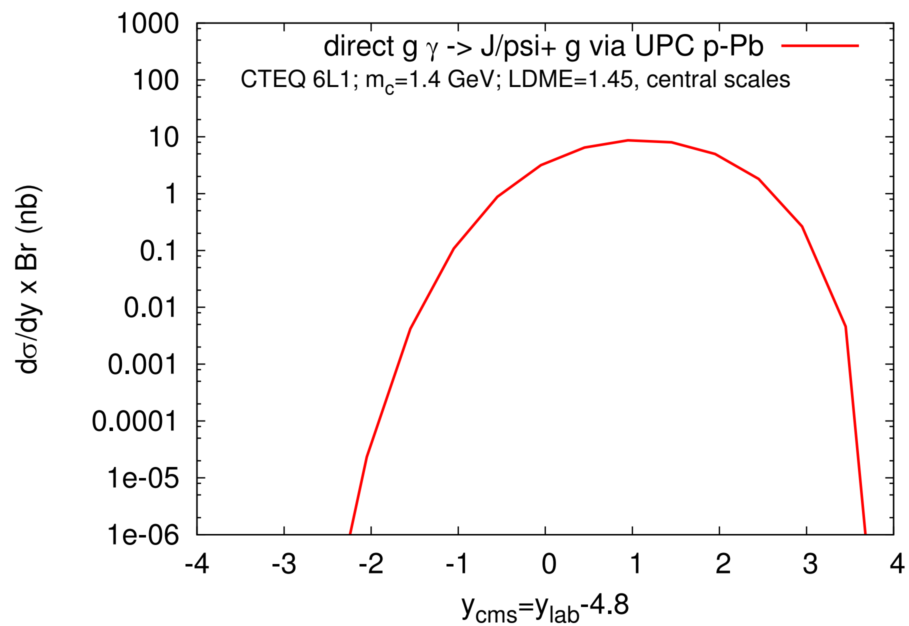
Ultra-peripheral collisions



Inelastic photoproduction of J/ψ via UPC*

Thanks to the boost: $W^{max}_{\gamma+p}$ for a coherent photon emission (Z^2 fact.) can be as high as 25 GeV !





Disclaimer: these numbers suppose a dedicated trigger and are preliminary

*(In the extraction mode, pile-up is drastically reduced)

A Fixed Target ExpeRiment

A dilepton observatory

➟ Region in x probed by dilepton production as function of $M_{\ell\ell}$

→ Above $c\bar{c}$: $x \in [10^{-3}, 1]$

→ Above $b\bar{b}$: $x \in [9 \times 10^{-3}, 1]$

Note: $x_{target} (\equiv x_2) > x_{projectile} (\equiv x_1)$

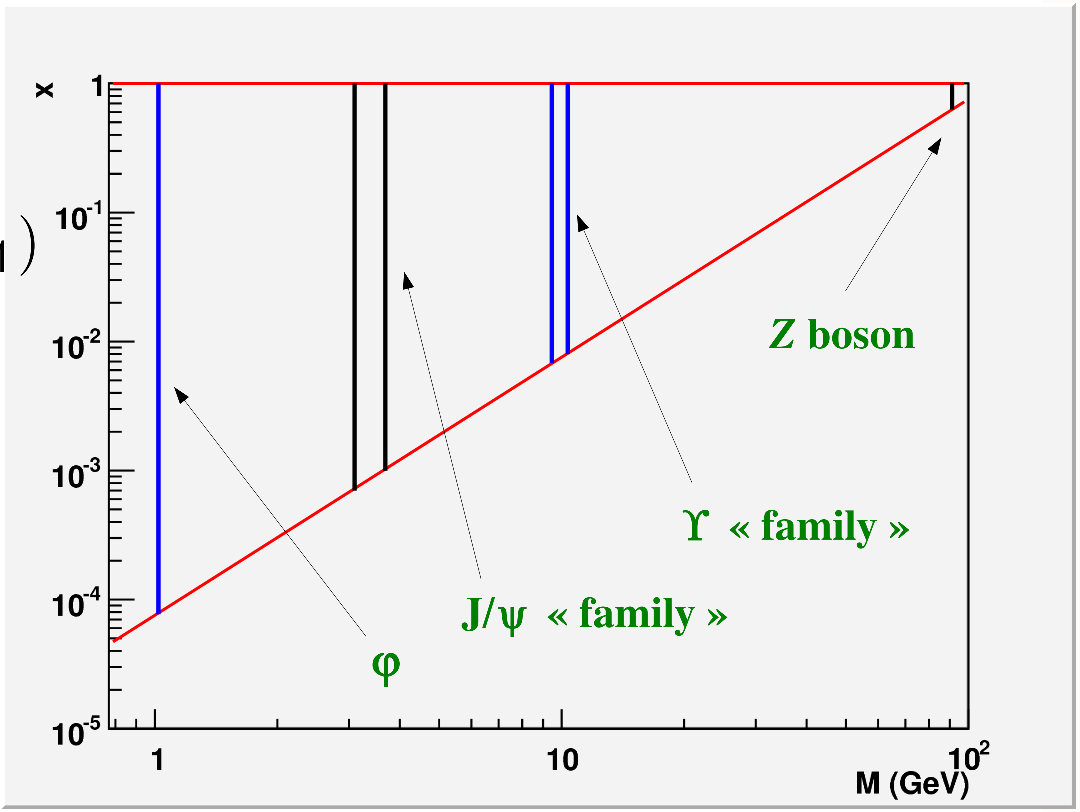
"backward" region

→ sea-quark asymetries

via p and d studies

- at large(est) x: backward ("easy")

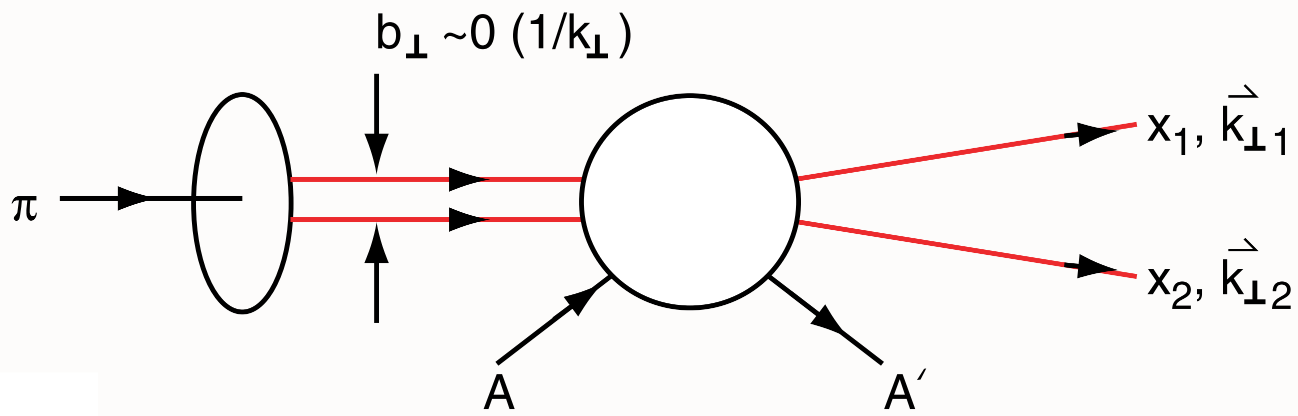
- at small(est) x: forward (need to stop the (extracted) beam)



➟ To do: to look at the rates to see how competitive this will be

Diffractive Dissociation of Pion into Quark Jets

E791 Ashery et al.



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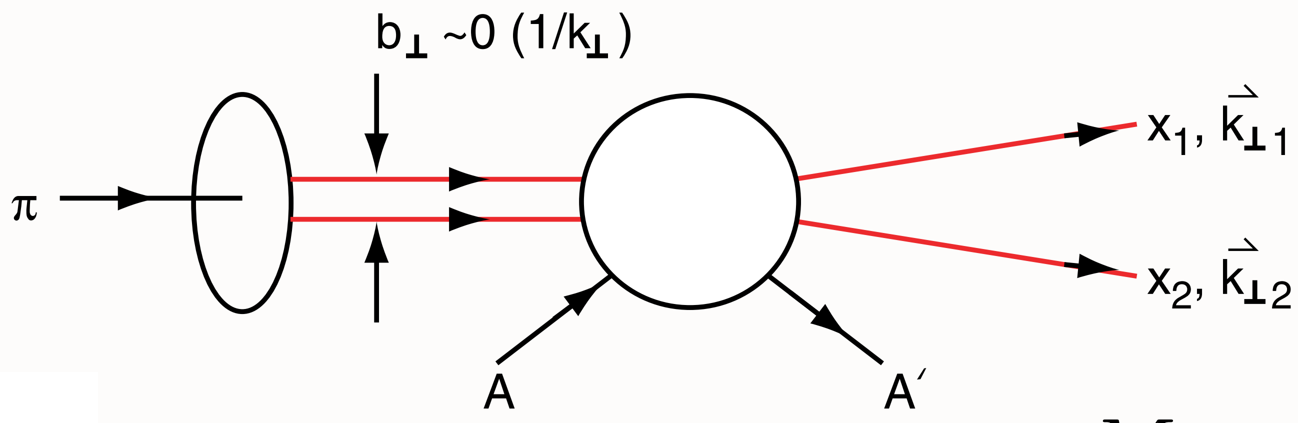

$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

Diffractive Dissociation of Pion into Quark Jets

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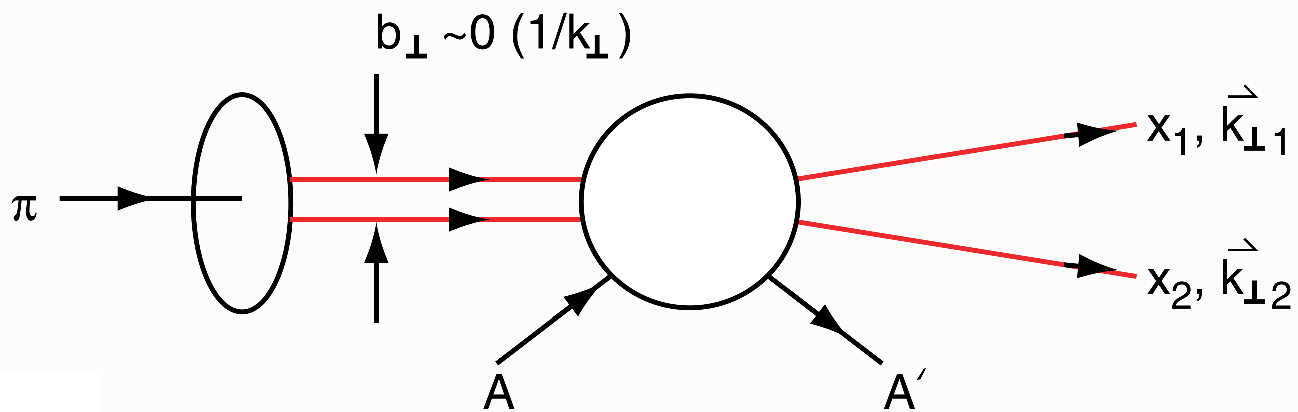


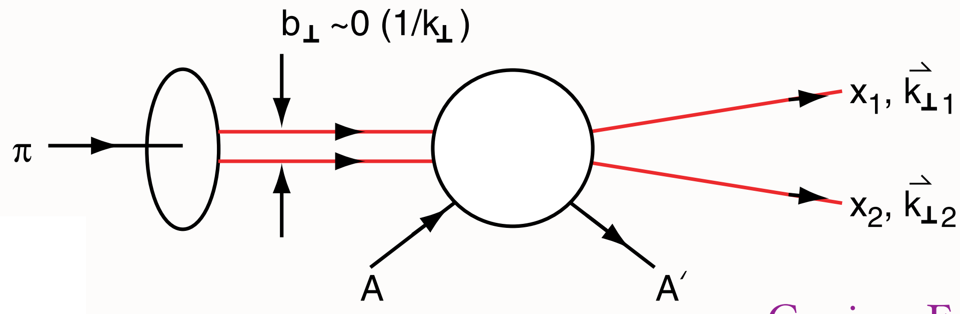
$$M \propto \frac{\partial^2}{\partial^2 k_\perp}\psi_\pi(x, k_\perp)$$

Measure Light-Front Wavefunction of Pion

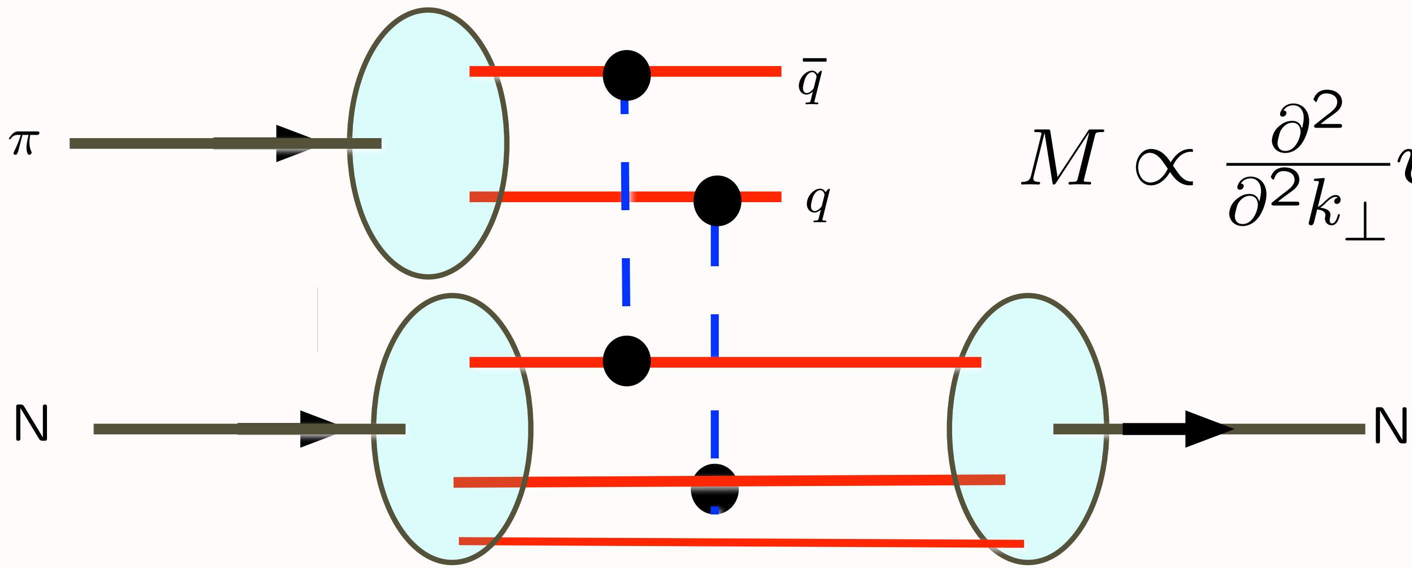
Minimal momentum transfer to nucleus

Nucleus left Intact!

E791 FNAL Diffractive DiJet



Gunion, Frankfurt, Mueller, Strikman, sjb
Frankfurt, Miller, Strikman



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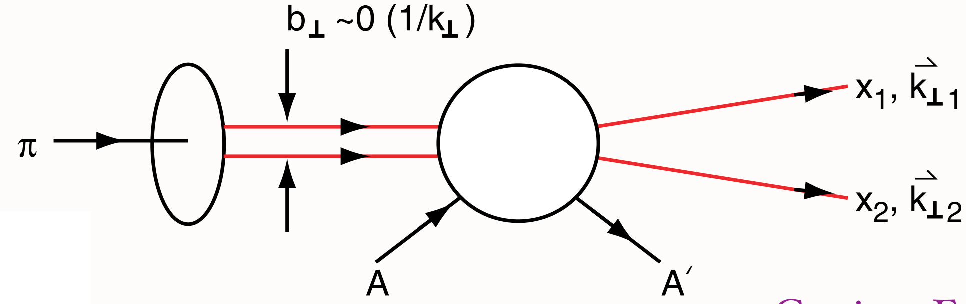
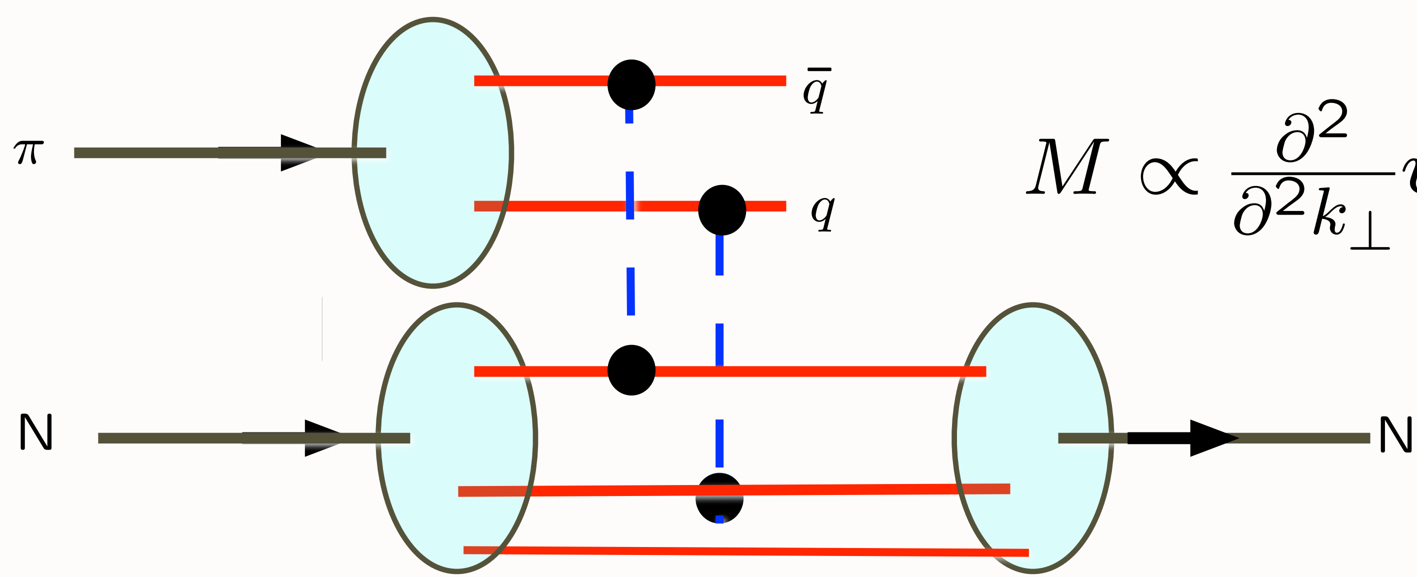


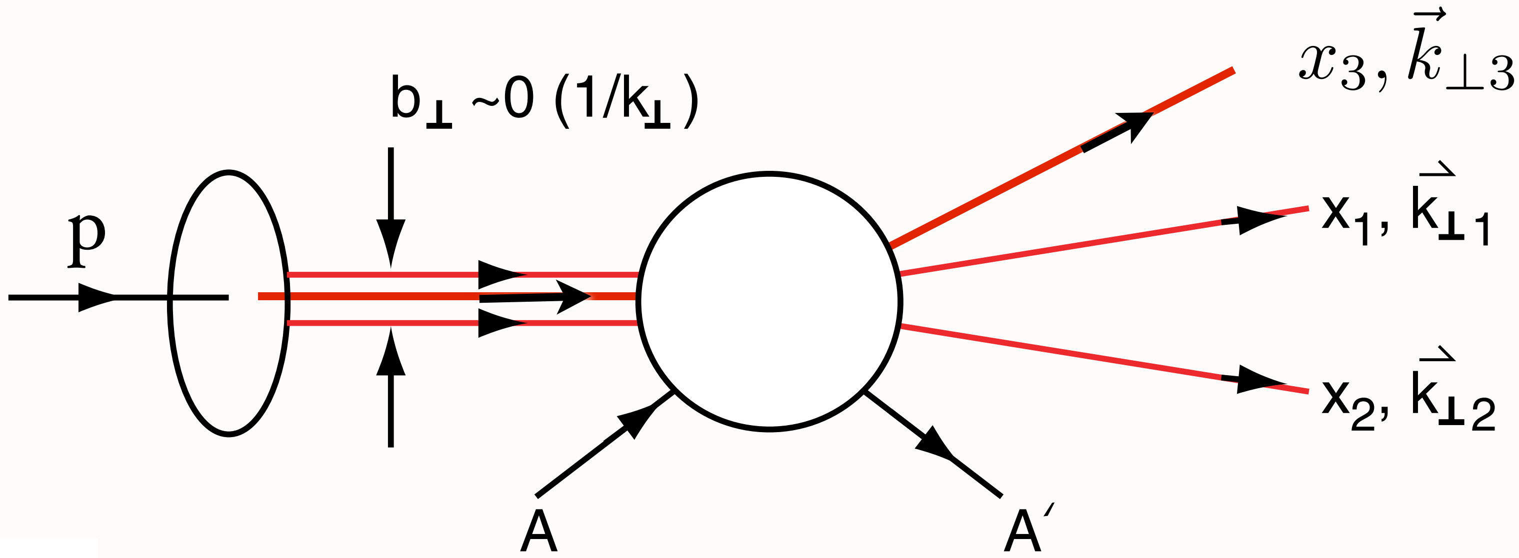
Gunion, Frankfurt, Mueller, Strikman, sjb
Frankfurt, Miller, Strikman

Two-gluon exchange measures the second derivative of the pion light-front wavefunction

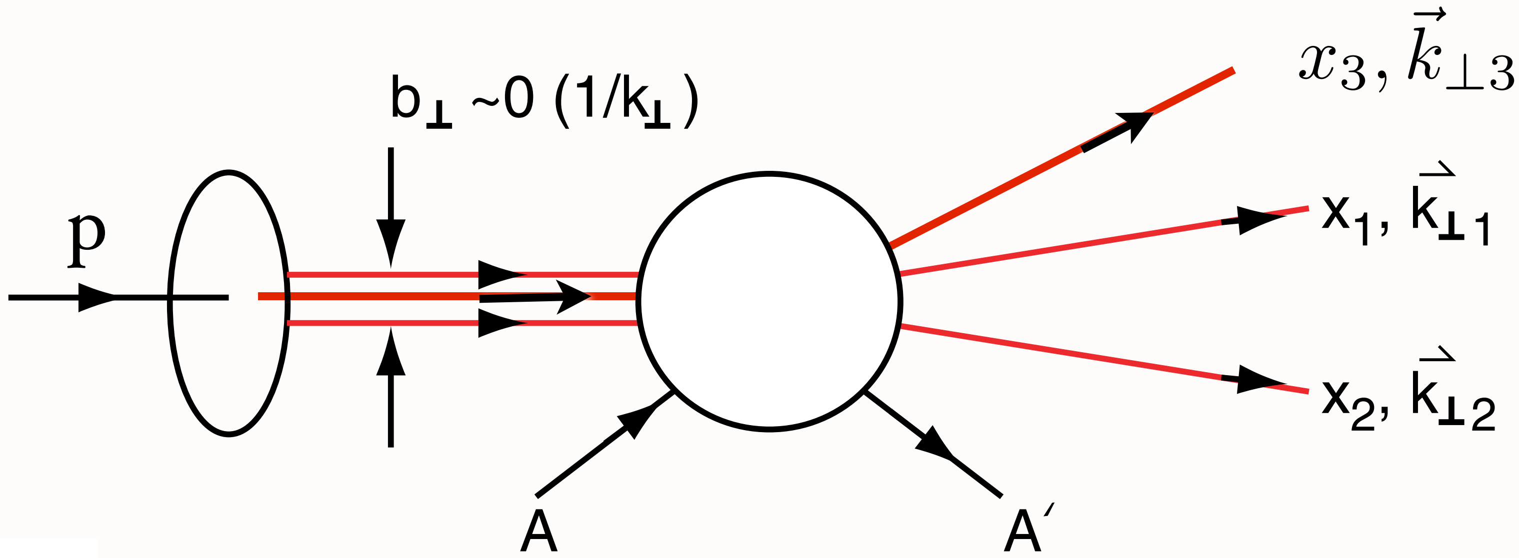


$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

Diffractive Dissociation of Proton into Three Quark Jets



Diffractive Dissociation of Proton into Three Quark Jets

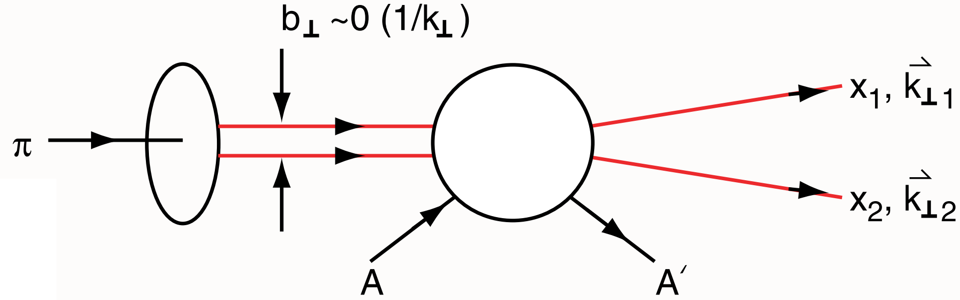


Measure Light-Front Wavefunction of Proton

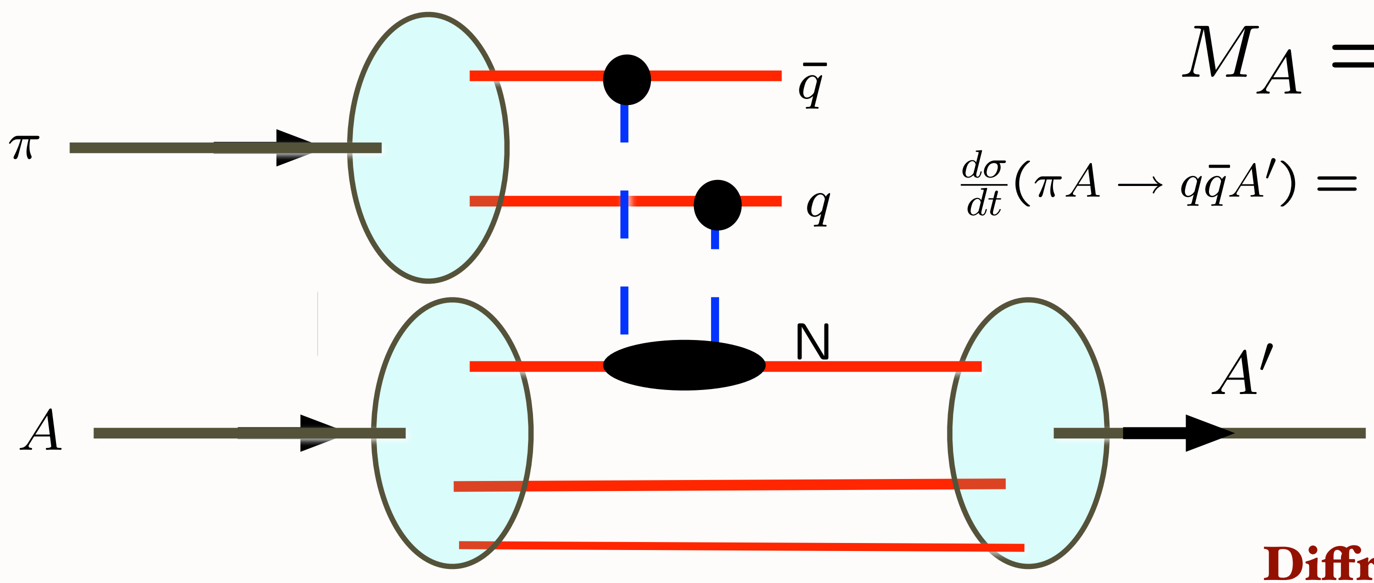
Minimal momentum transfer to nucleus

Nucleus left Intact!

Key Ingredients in E791 Experiment



Brodsky Mueller
Frankfurt Miller
Strikman



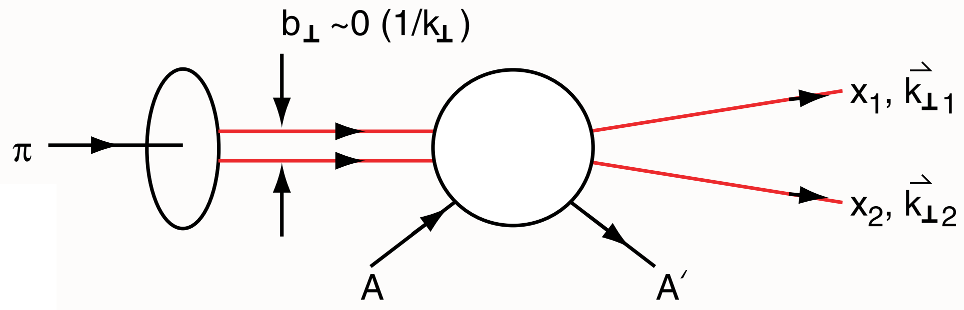
$$M_A = A \; M_N$$

$$\frac{d\sigma}{dt}(\pi A \to q\bar{q}A') = A^2 \; \frac{d\sigma}{dt}(\pi N \to q\bar{q}N') \;\; F^2_A(t)$$

Target left intact

Diffraction, Rapidity gap

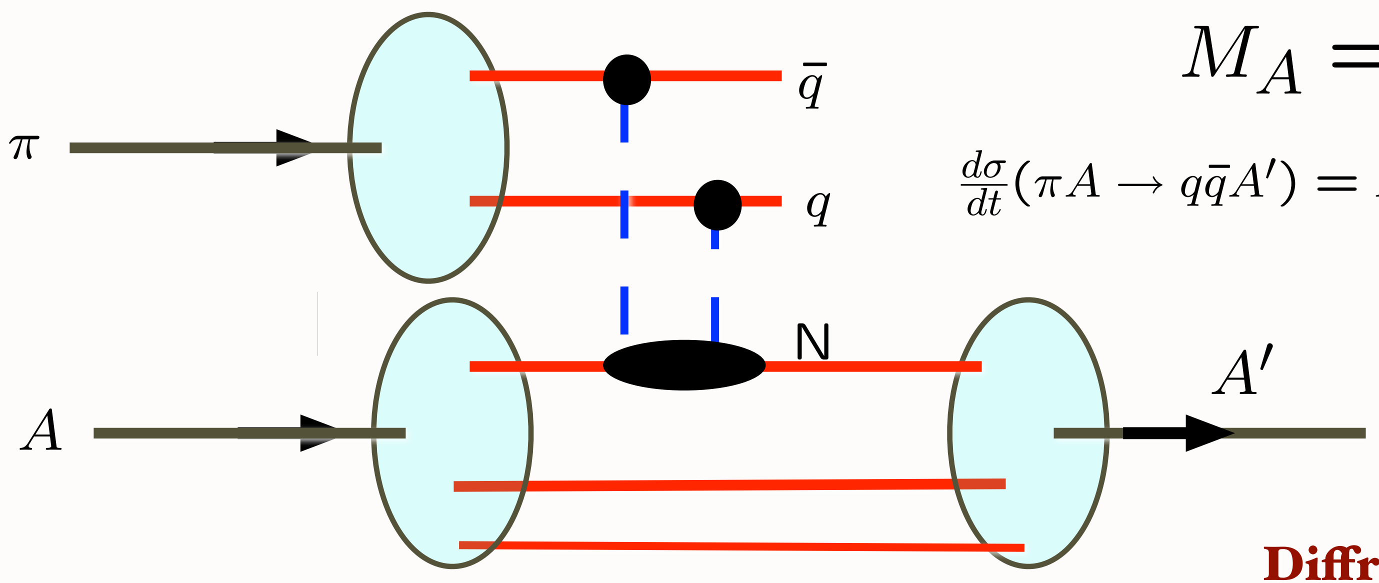
Key Ingredients in E791 Experiment



Brodsky Mueller
Frankfurt Miller
Strikman

Small color-dipole moment pion not absorbed;
interacts with <u>each</u> nucleon coherently

<u>QCD COLOR Transparency</u>



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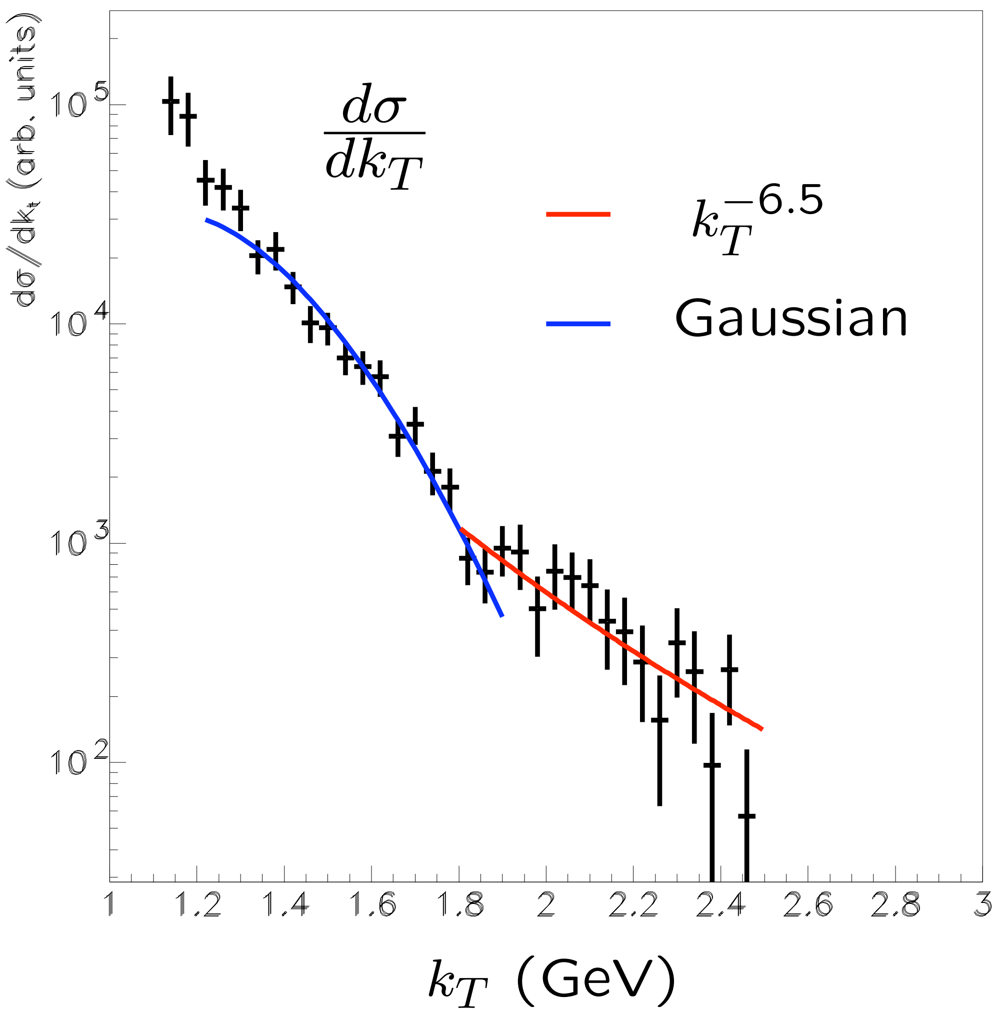
Diffraction, Rapidity gap

E791 Diffractive Di-Jet transverse momentum distribution

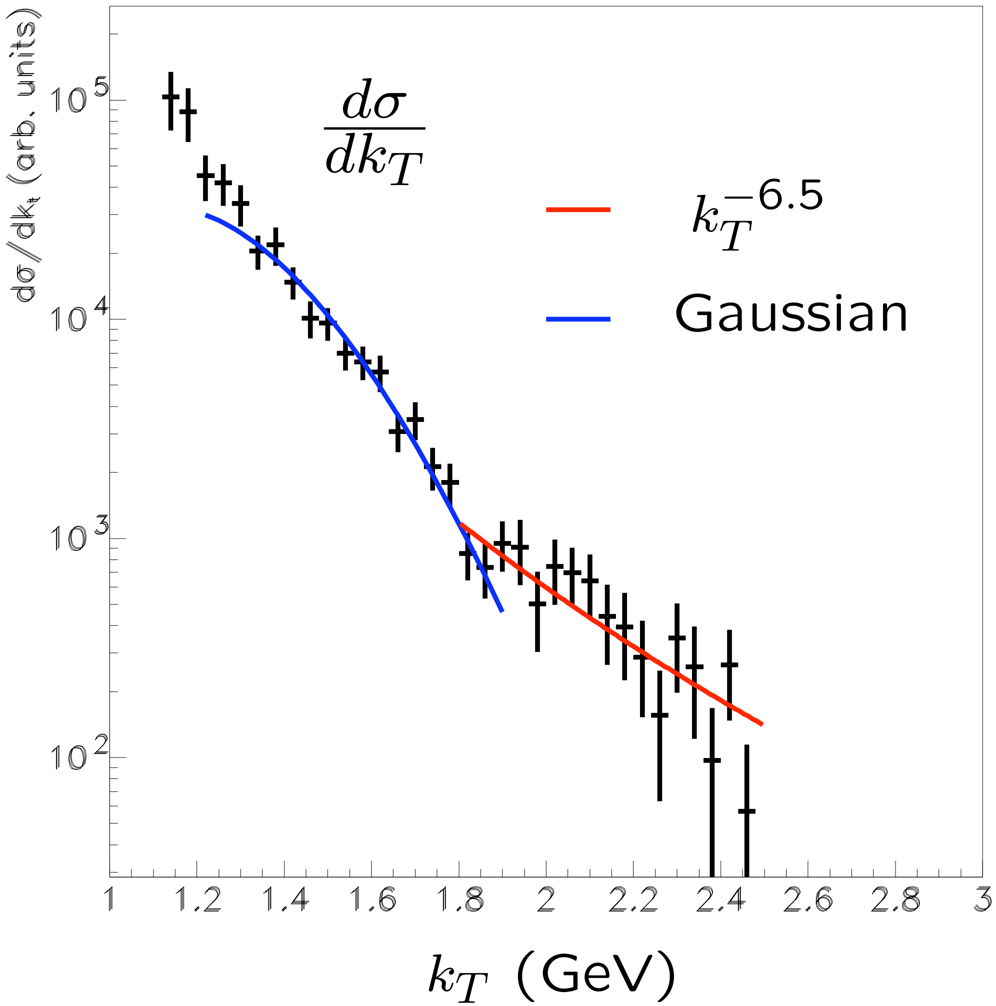


Two Components

High Transverse momentum dependence consistent with PQCD, ERBL Evolution $k_T^{-6.5}$

Gaussian component similar to AdS/CFT HO LFWF

E791 Diffractive Di-Jet transverse momentum distribution



Two Components

High Transverse momentum dependence consistent with PQCD, ERBL Evolution $k_T^{-6.5}$

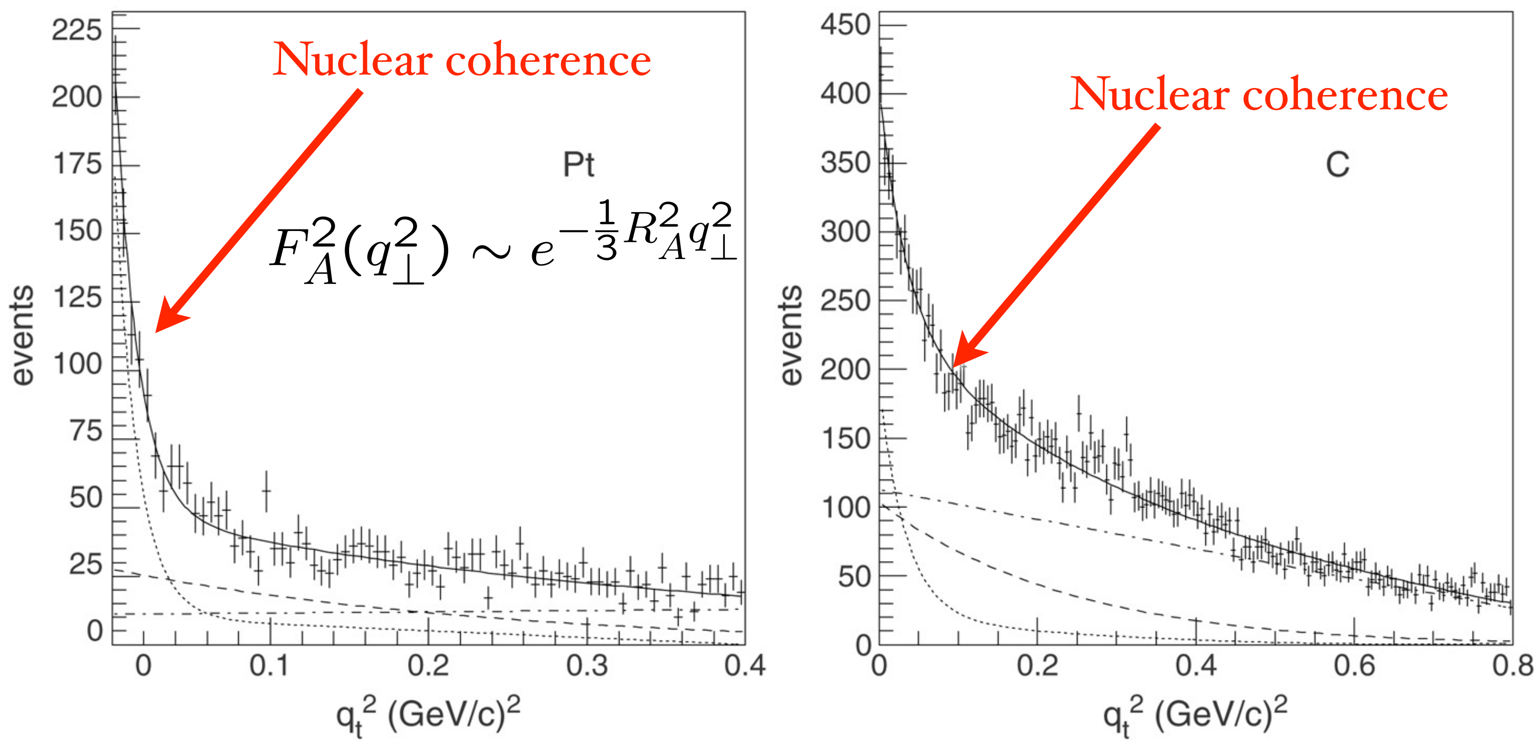
Gaussian component similar to AdS/CFT HO LFWF

- Fully coherent interactions between pion and nucleons.
- Emerging Di-Jets do not interact with nucleus.

$$\mathcal{M}(\mathcal{A}) = \mathcal{A} \cdot \mathcal{M}(\mathcal{N})$$

$$\frac{d\sigma}{dq_t^2} \propto A^2 \quad q_t^2 \sim 0$$

$$\sigma \propto A^{4/3}$$



Mueller, sjb; Bertsch et al;
Frankfurt, Miller, Strikman

Measure pion LFWF in diffractive dijet production
Confirmation of color transparency

A-Dependence results: $\sigma \propto A^{\alpha}$

k_t range (GeV/c)	α	α (CT)
$1.25 < k_t < 1.5$	1.64 +0.06 -0.12	1.25
$1.5 < k_t < 2.0$	1.52 ± 0.12	1.45
$2.0 < k_t < 2.5$	1.55 ± 0.16	1.60

Ashery E791

α (Incoh.) $= 0.70 \pm 0.1$

Mueller, sjb; Bertsch et al;
Frankfurt, Miller, Strikman

Measure pion LFWF in diffractive dijet production
Confirmation of color transparency

A-Dependence results: $\sigma \propto A^{\alpha}$

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Conventional Glauber Theory Ruled Out !

Factor of 7

Color Transparency

Bertsch, Gunion, Goldhaber, sjb
A. H. Mueller, sjb

- Fundamental test of gauge theory in hadron physics
- Small color dipole moments interact weakly in nuclei
- Complete coherence at high energies
- Clear Demonstration of CT from Diffractive Di-Jets

$$\pi^- N \to \mu^+ \mu^- X \text{ at } 80 \text{ GeV}/c$$

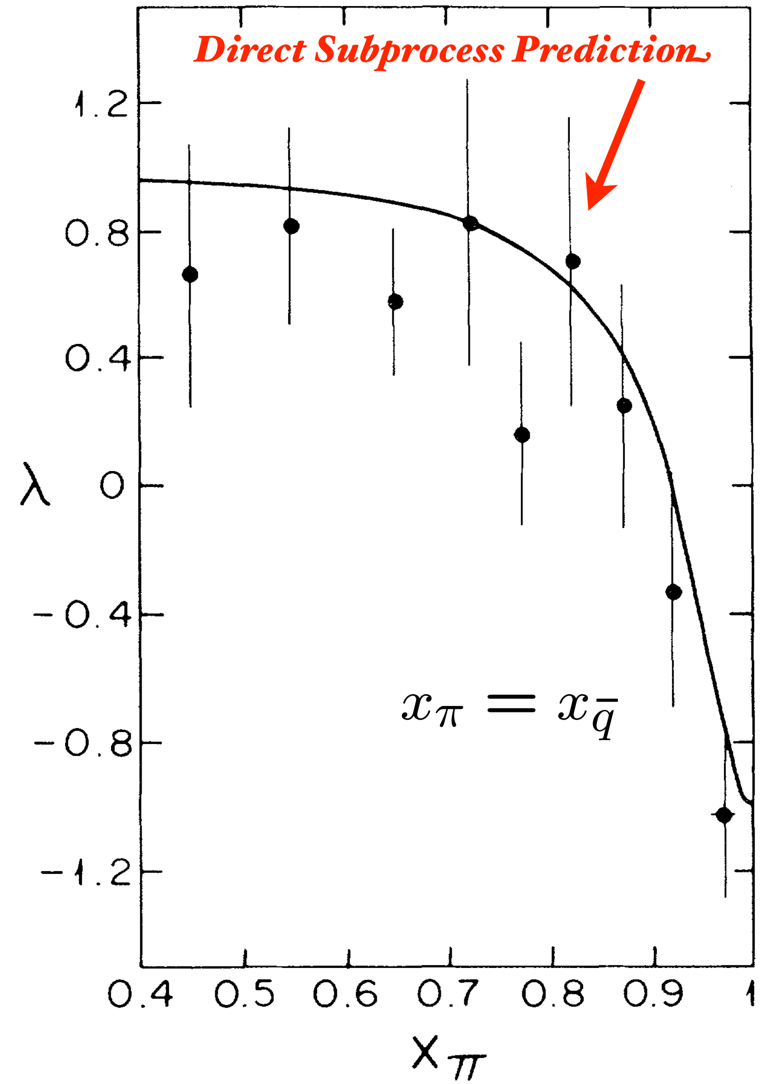
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \rho \sin 2\theta \cos\phi + \omega \sin^2\theta \cos 2\phi.$$

$$\frac{d^2\sigma}{dx_\pi d\cos\theta} \propto x_\pi \left[(1-x_\pi)^2 (1+\cos^2\theta) + \frac{4}{9} \frac{\langle k_T^2 \rangle}{M^2} \sin^2\theta \right]$$

$$\langle k_T^2 \rangle = 0.62 \pm 0.16 \ \text{GeV}^2/c^2$$

$$Q^2 = M^2$$

Dramatic change in angular distribution at large x_F



Chicago-Princeton Collaboration

Phys.Rev.Lett.55:2649,1985

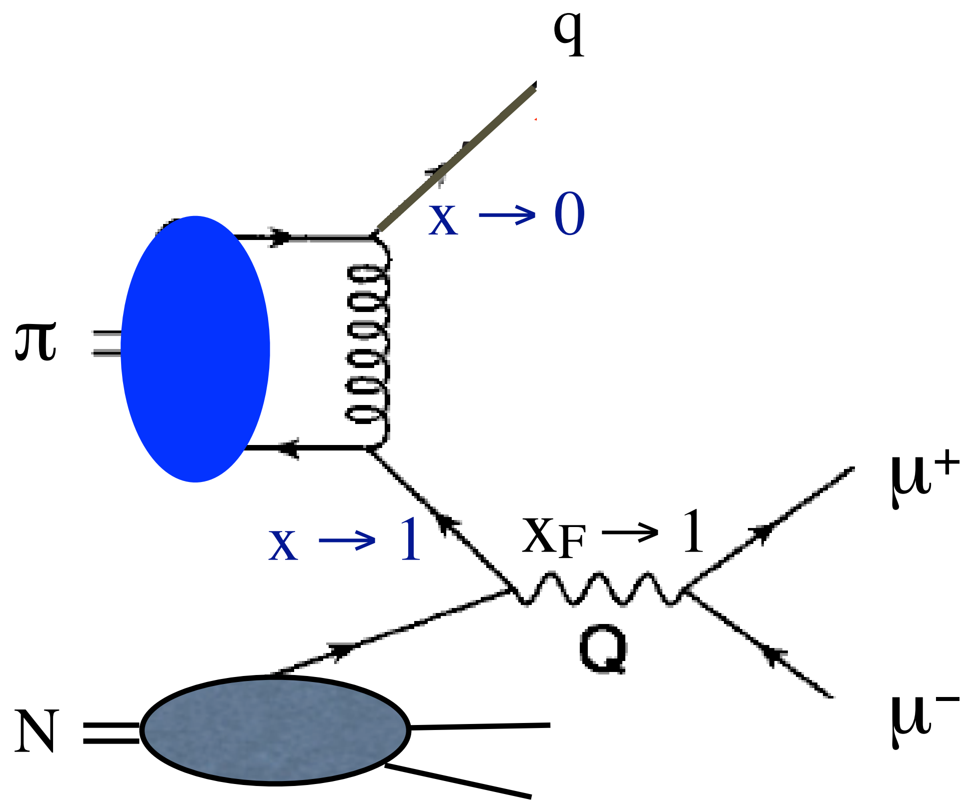
Example of a higher-twist direct subprocess

Many Tests at AFTER

$\pi N \to \mu^+ \mu^- X$ at high x_F

In the limit where $(1-x_F)Q^2$ is fixed as $Q^2 \to \infty$

Entire pion wf contributes to hard process



Virtual photon is longitudinally polarized

Berger, sjb
Khoze, Brandenburg, Muller, sjb

Hoyer Vanttinen

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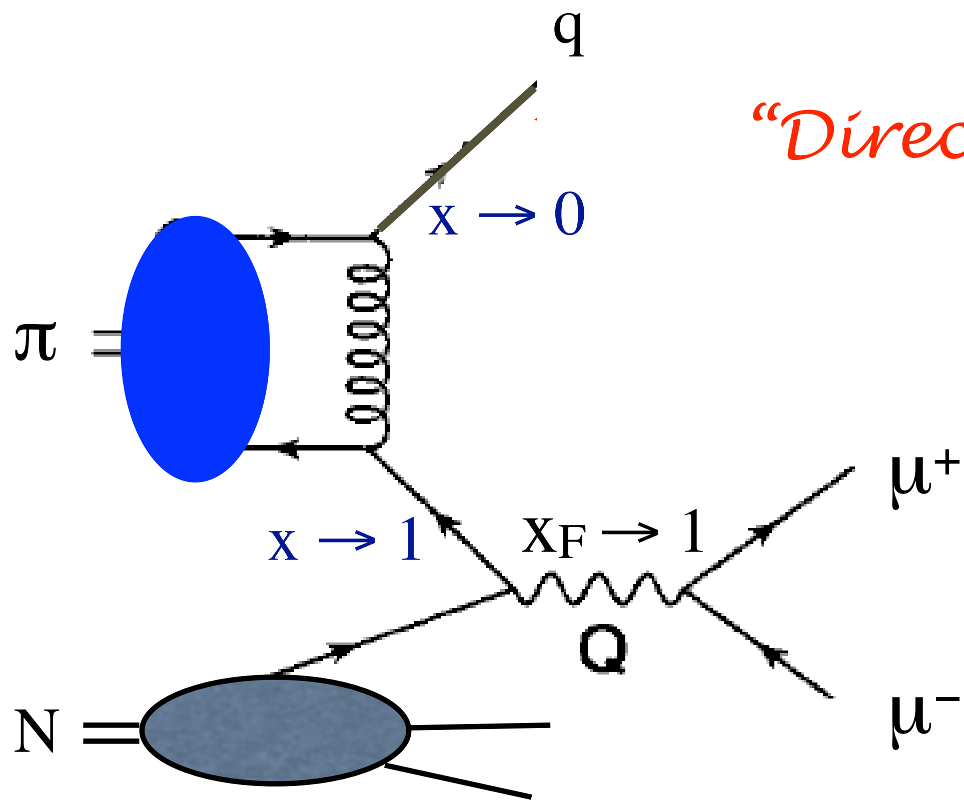

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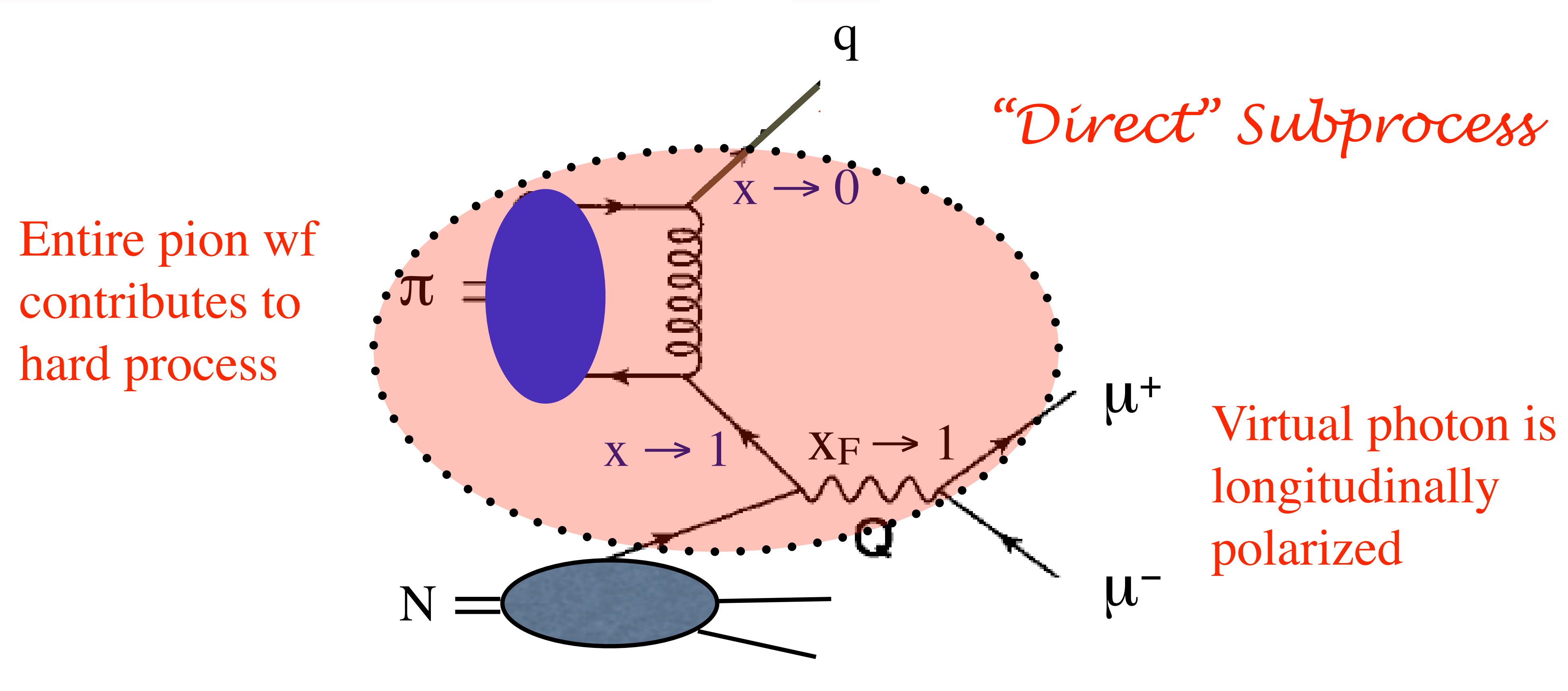

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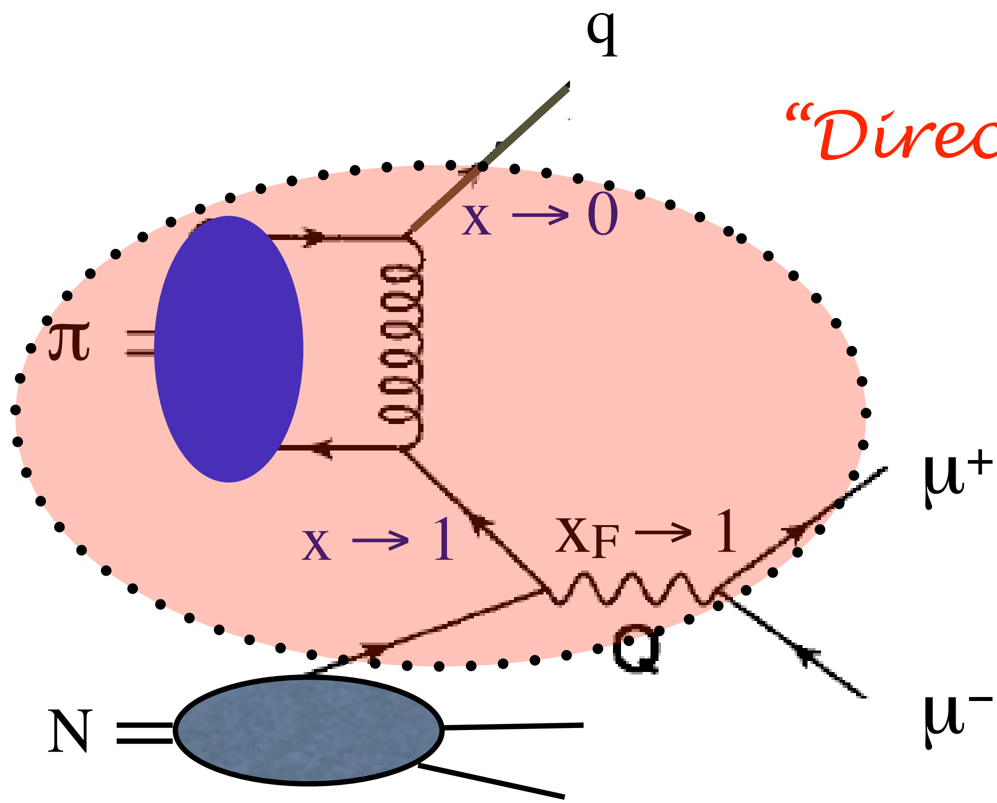
Distribution amplitude from AdS/CFT



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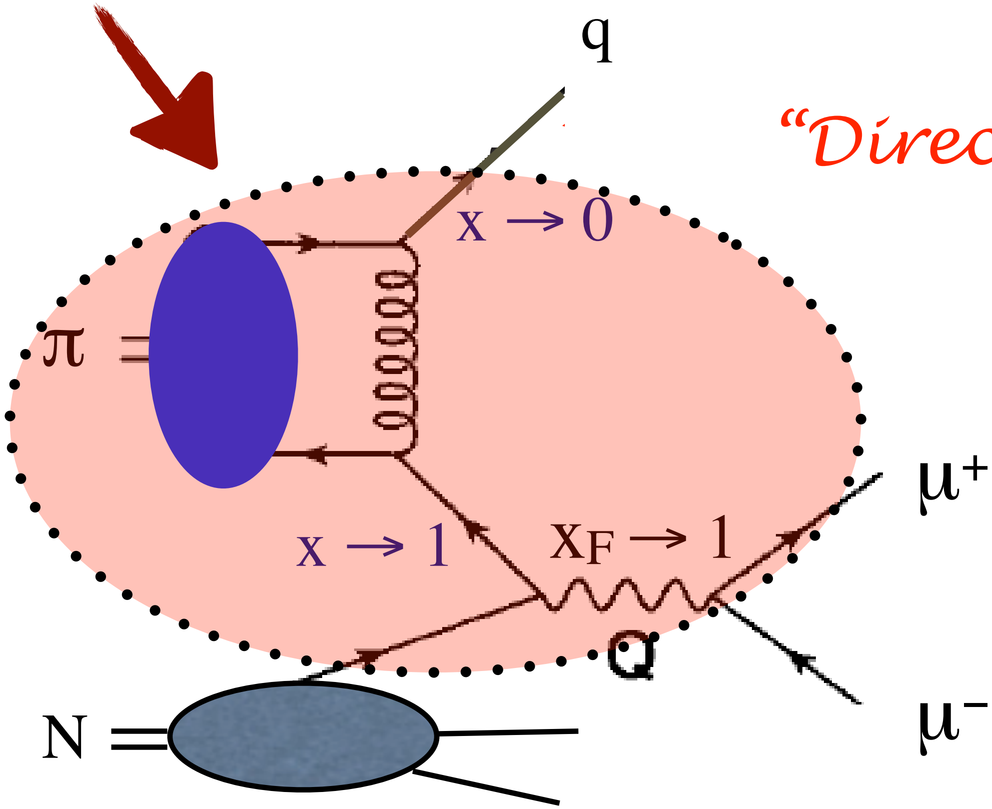

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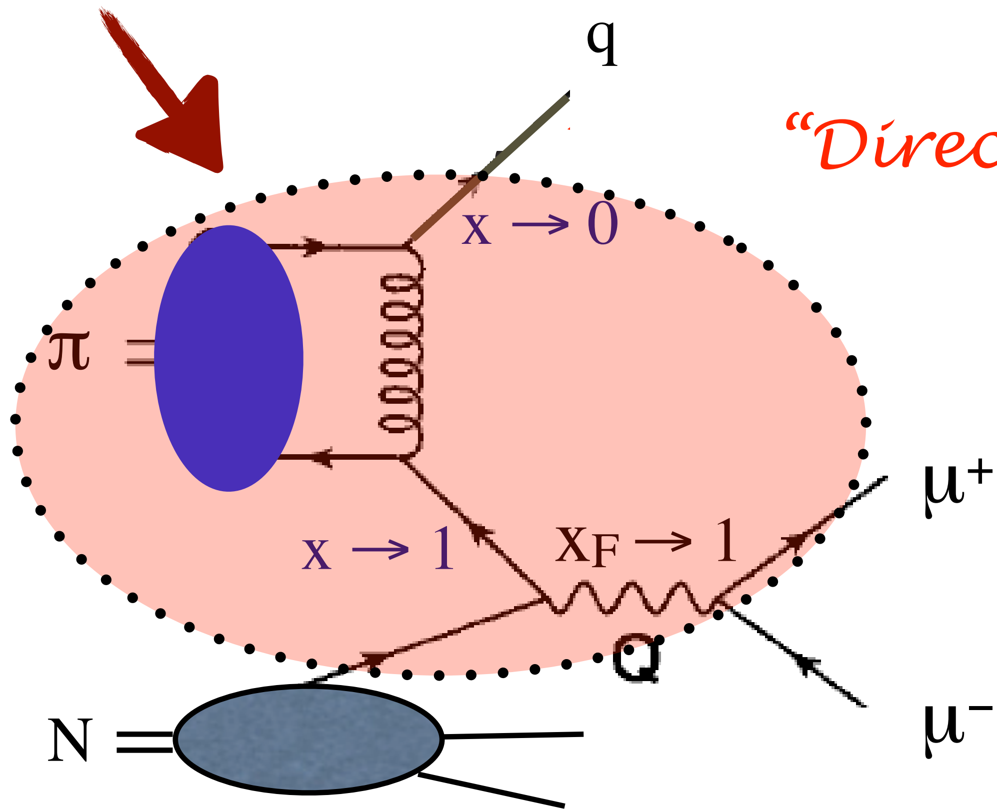
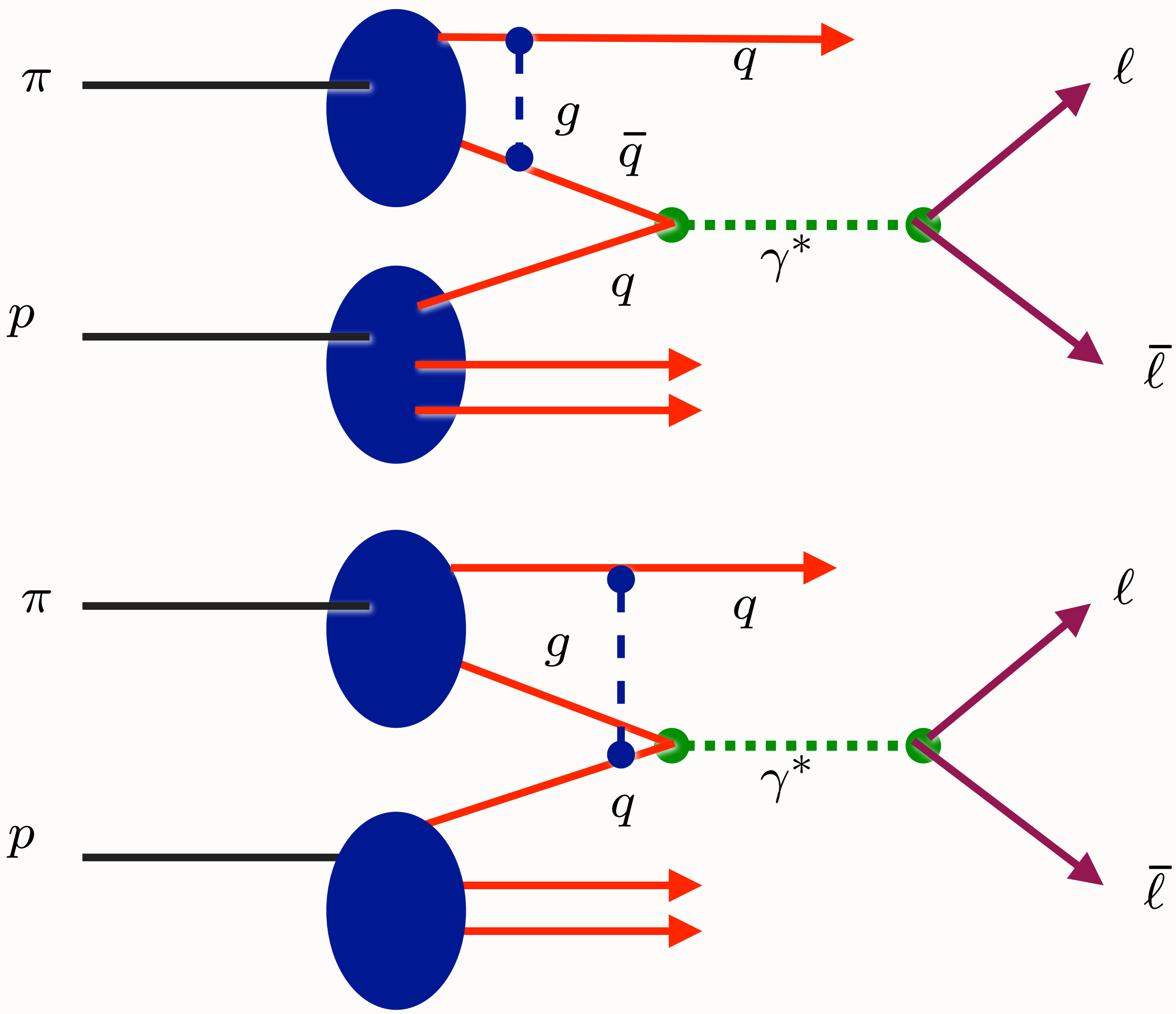


Virtual photon is longitudinally polarized

Similar higher twist terms in jet hadronization at large z

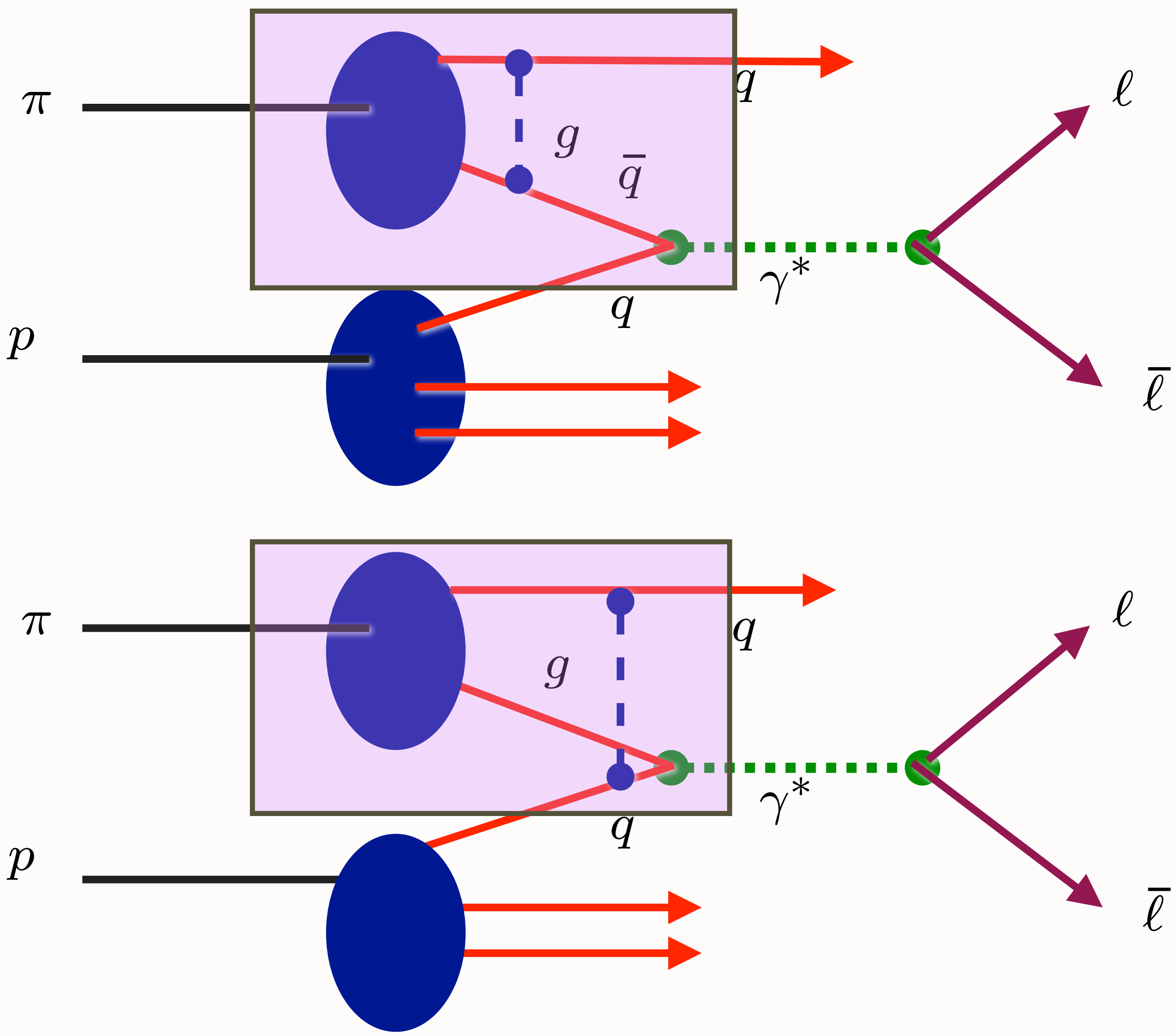
Berger, sjb
Khoze, Brandenburg, Muller, sjb
Hoyer Vanttinen

Berger, Lepage, sjb



Initial State Interaction

Berger, Lepage, sjb

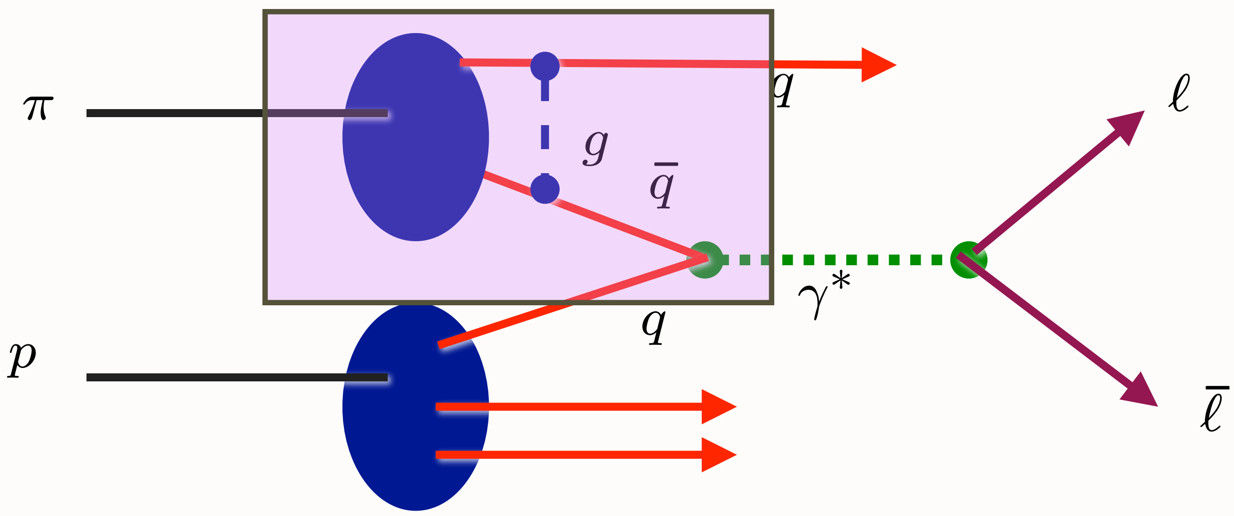


$$\pi q \to \gamma^* q$$

Initial State Interaction

Pion appears directly in subprocess at large x_F

Berger, Lepage, sjb



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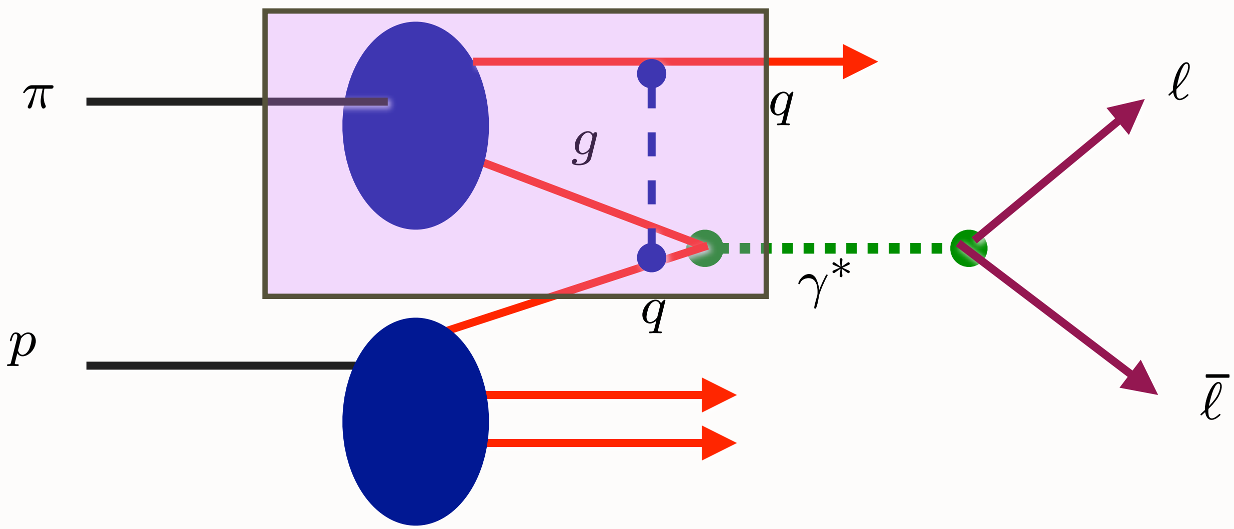

Initial State Interaction

Pion appears directly in subprocess at large x_F

All of the pion's momentum is transferred to the lepton pair

Lepton Pair is produced longitudinally polarized

$$|p,S_z> = \sum_{n=3} \Psi_n(x_i,\vec{k}_{\perp i},\lambda_i)|n;\vec{k}_{\perp_i},\lambda_i>$$

sum over states with n=3, 4, ...constituents

The Light Front Fock State Wavefunctions

$$\Psi_n(x_i,\vec{k}_{\perp i},\lambda_i)$$

are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

$$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0+k_i^z}{P^0+P^z}$$

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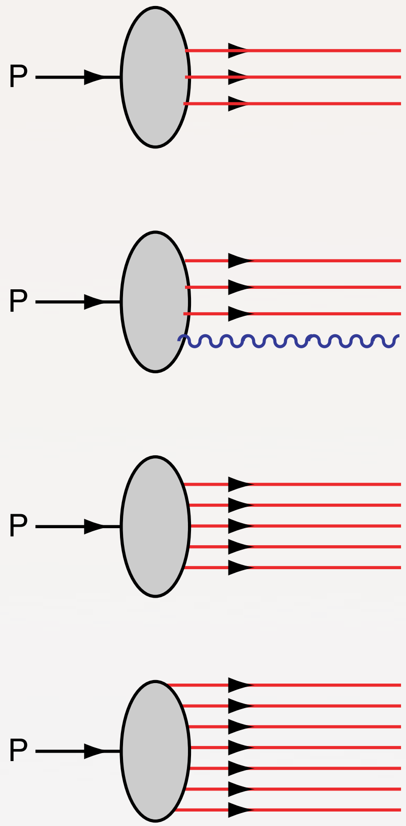

Intrinsic heavy quarks $\bar{s}(x) \neq s(x)$

c(x), b(x) at high x ! $\bar{u}(x) \neq \bar{d}(x)$

Mueller: gluon Fock states BFKL

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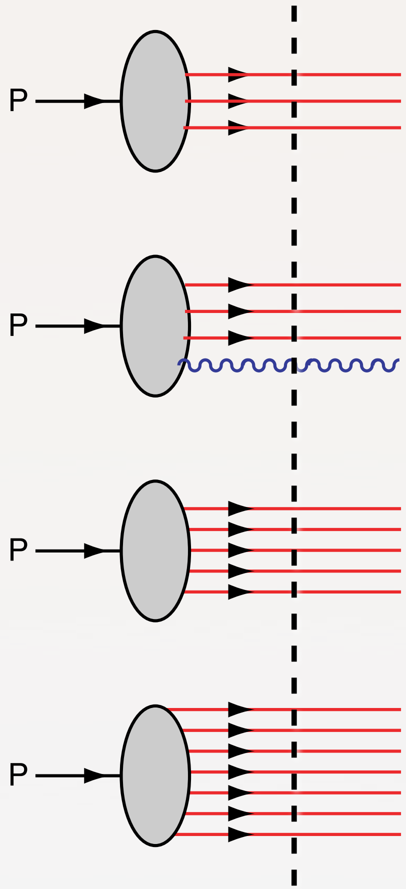

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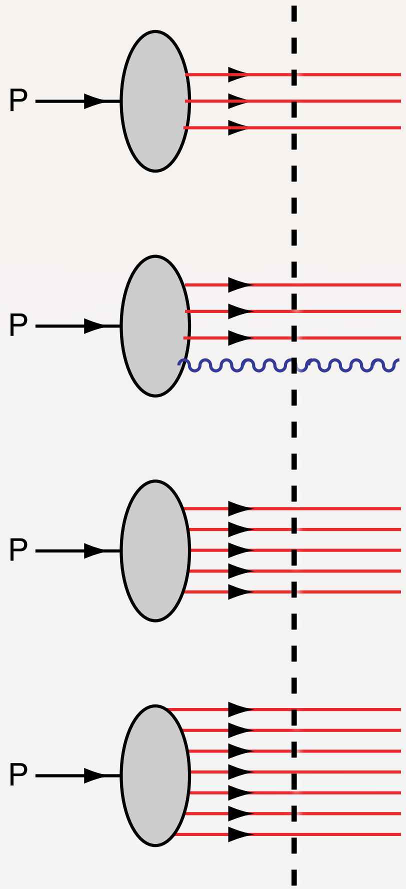

Fixed LF time

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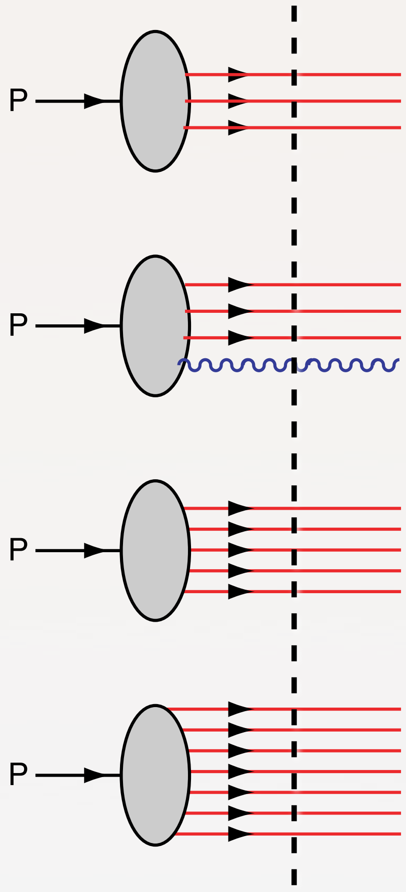

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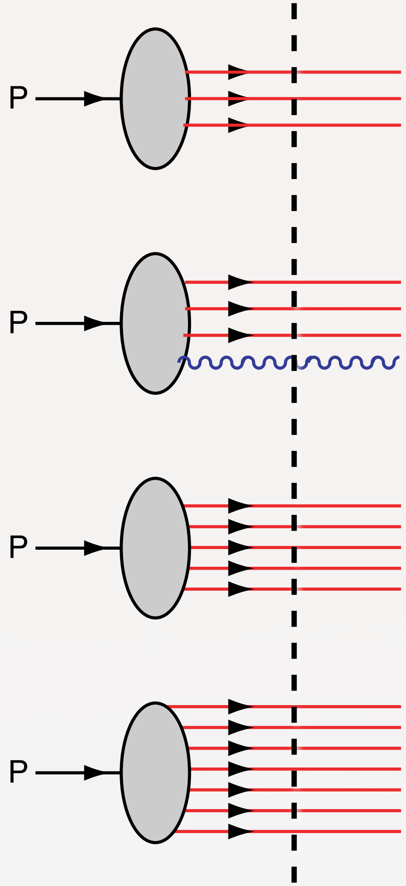

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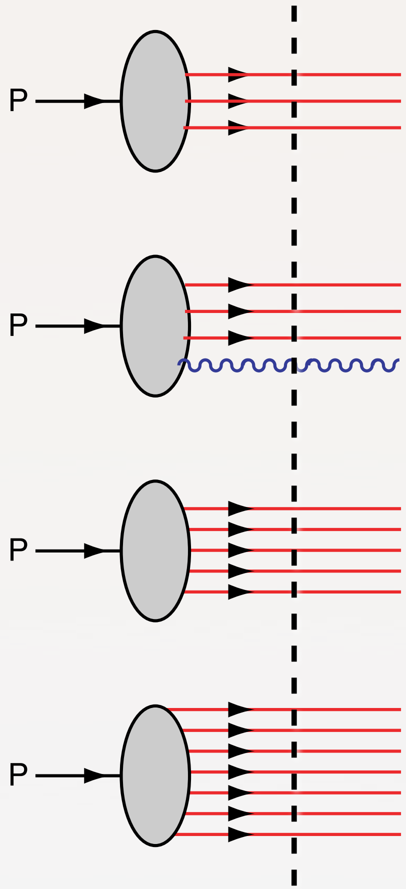

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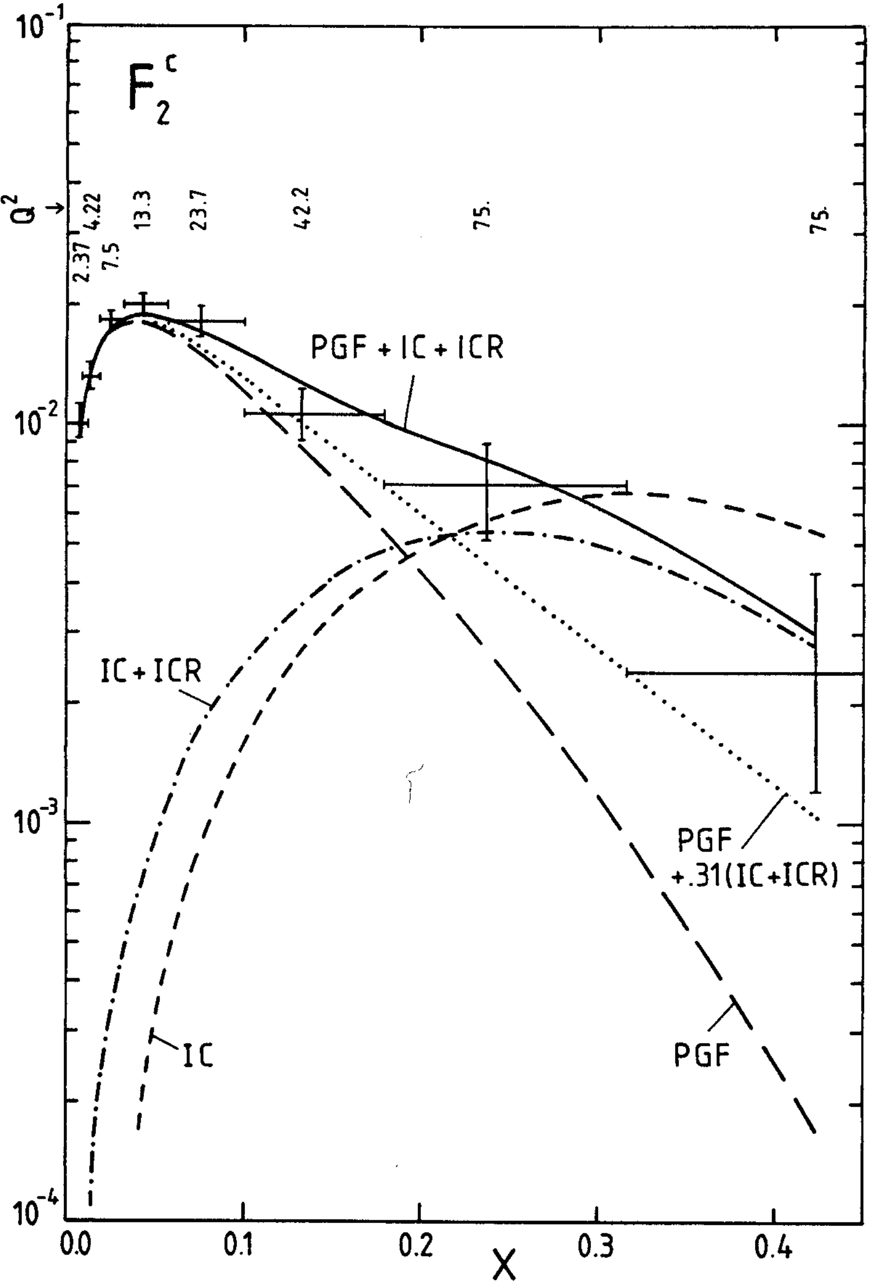
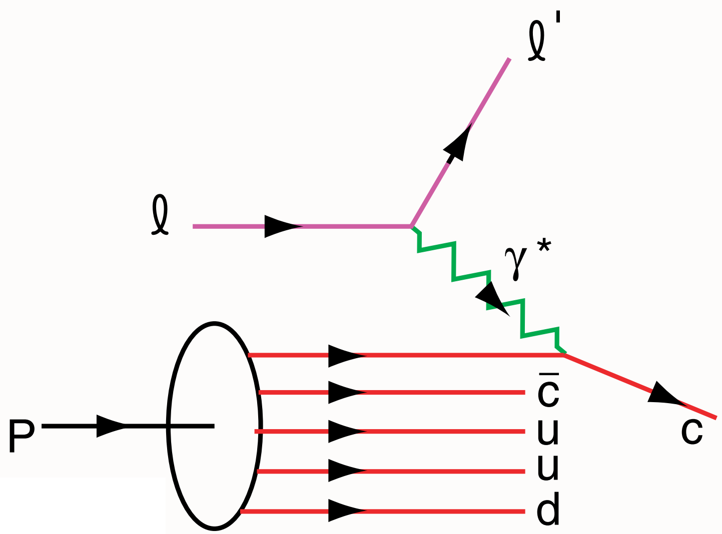
Hidden Color



Measurement of Charm Structure Function

J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

First Evidence for Intrinsic Charm



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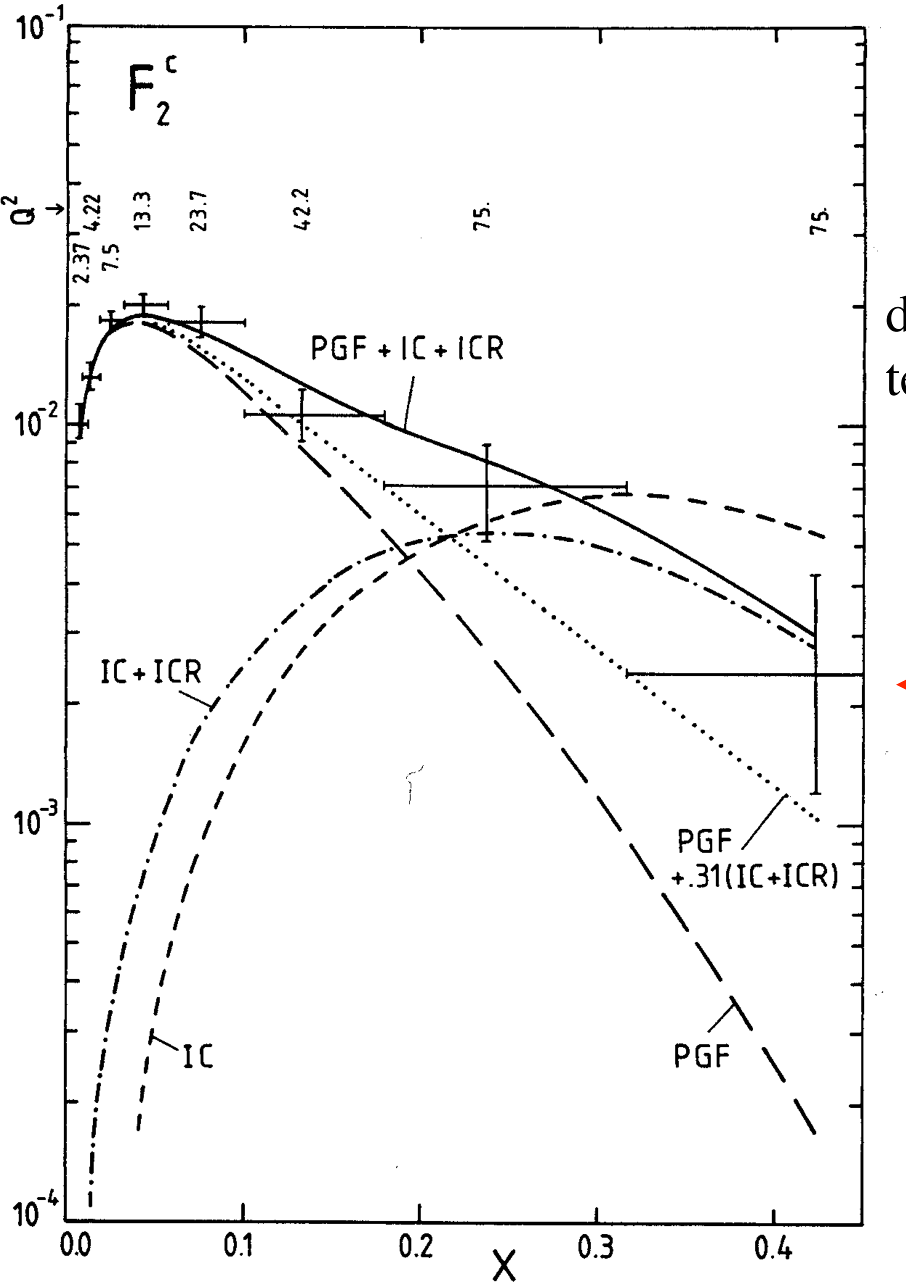

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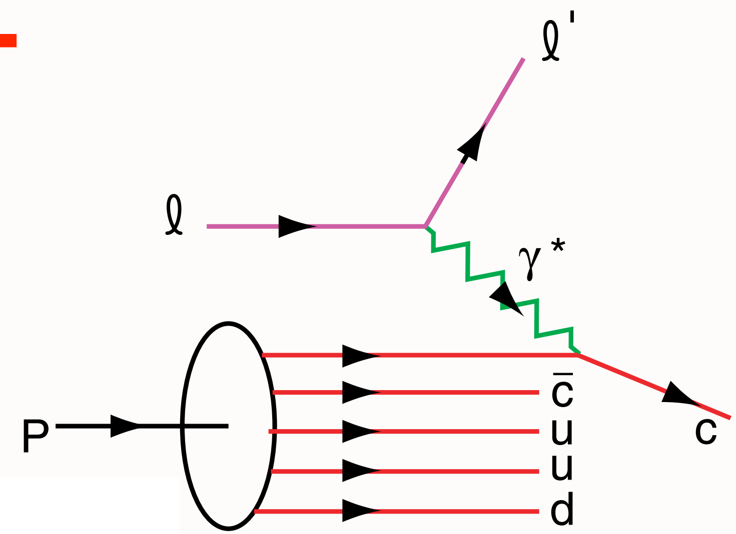

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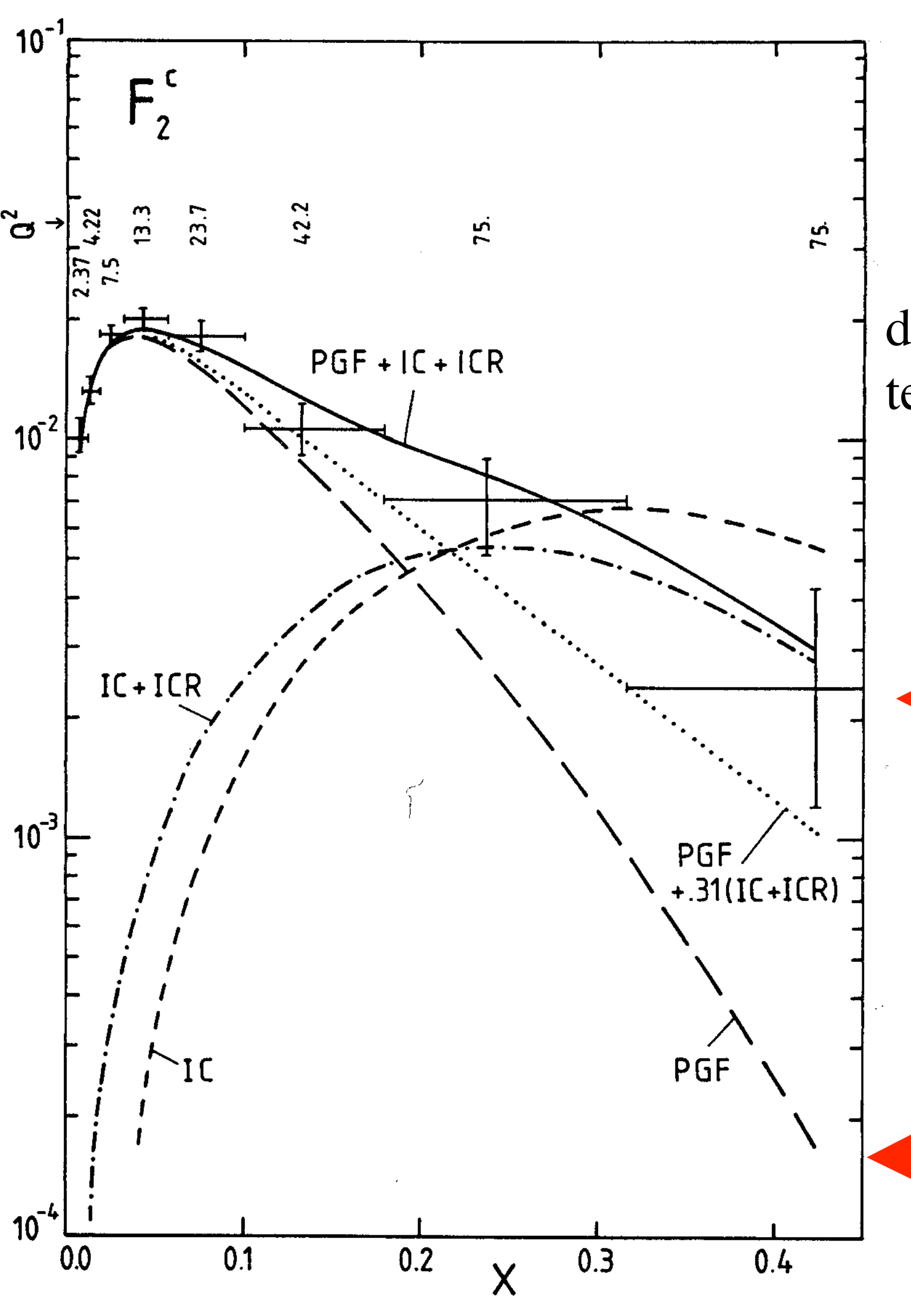

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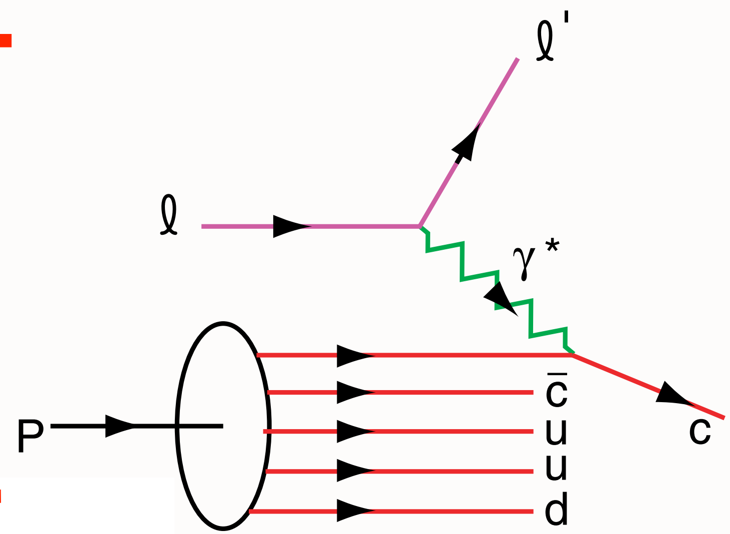

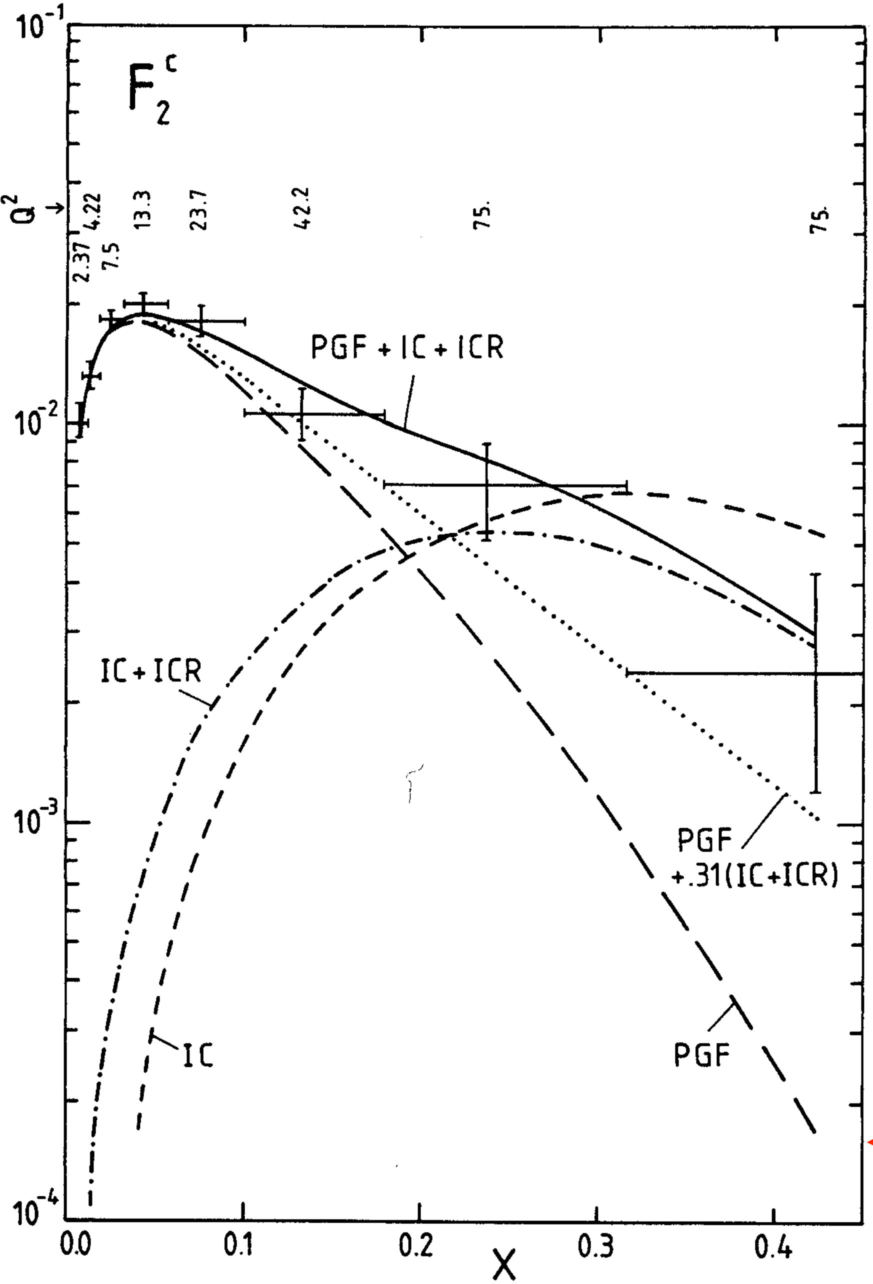

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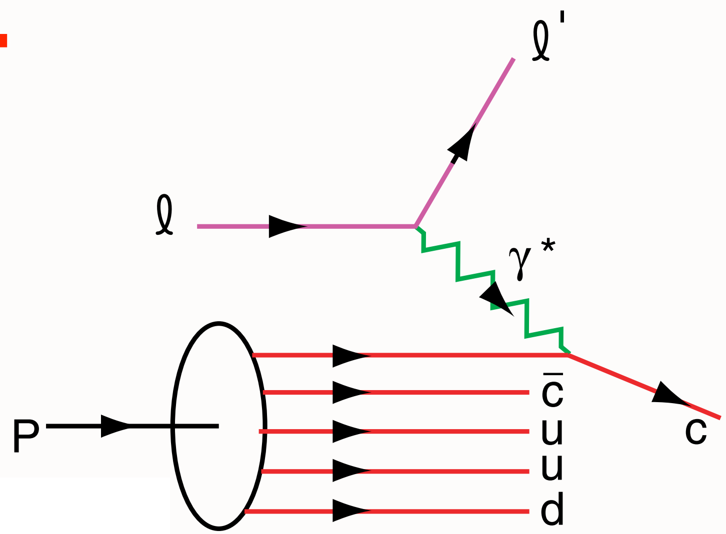

DGLAP / Photon-Gluon Fusion: factor of 30 too small

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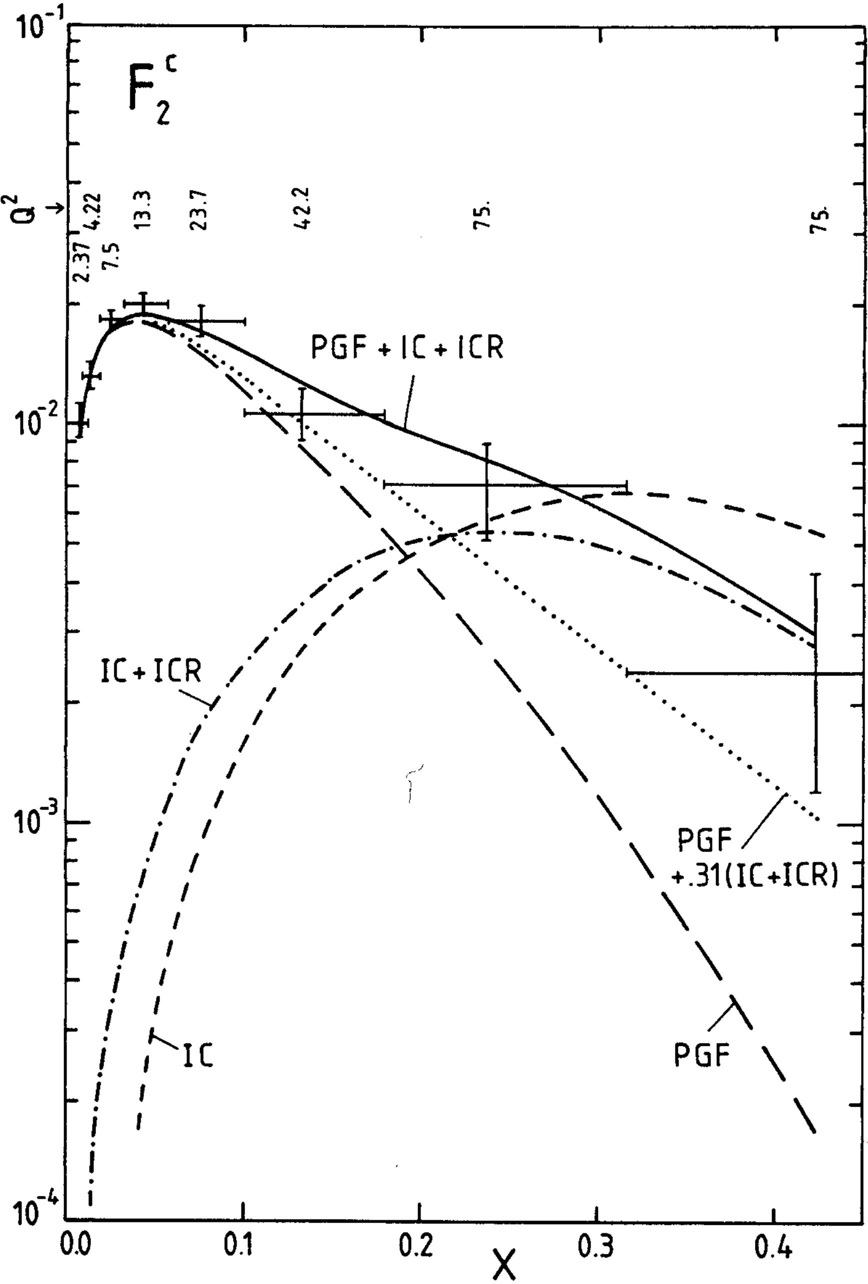

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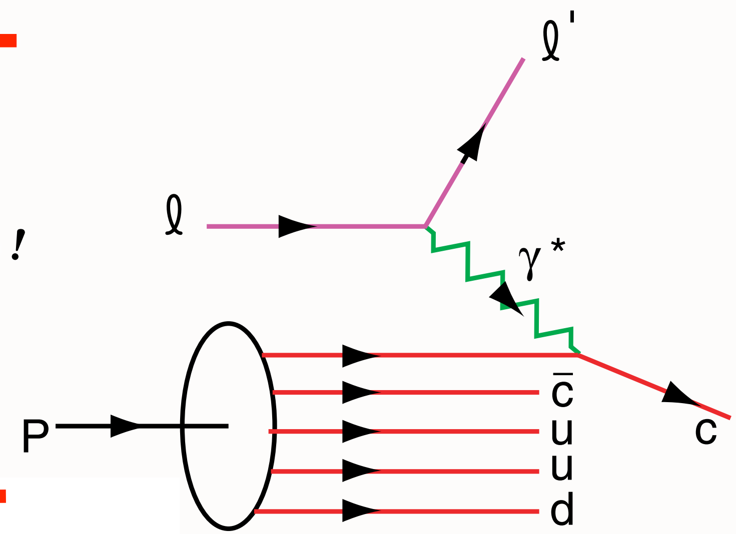

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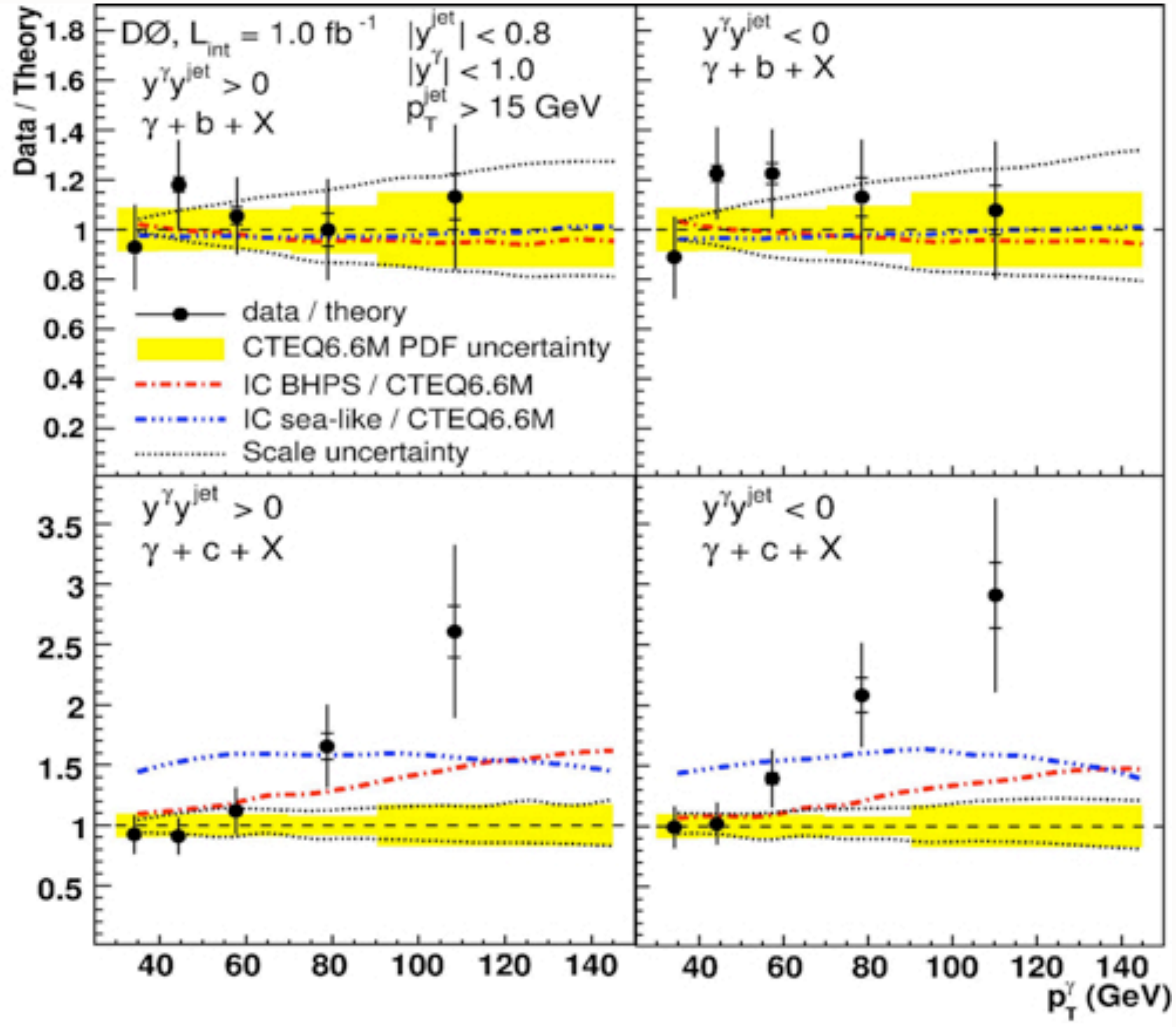
PRL 102, 192002 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

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 ?

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

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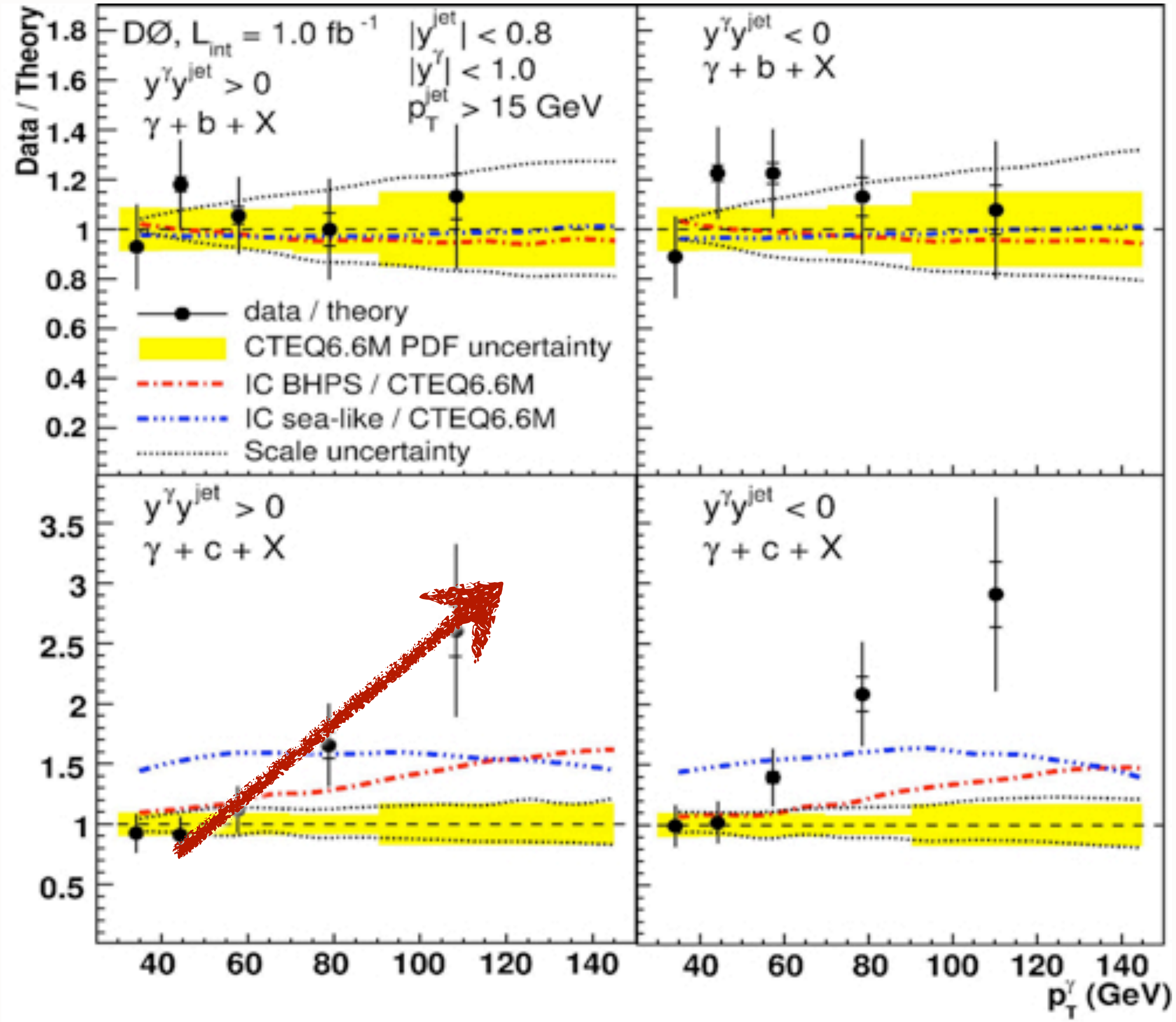

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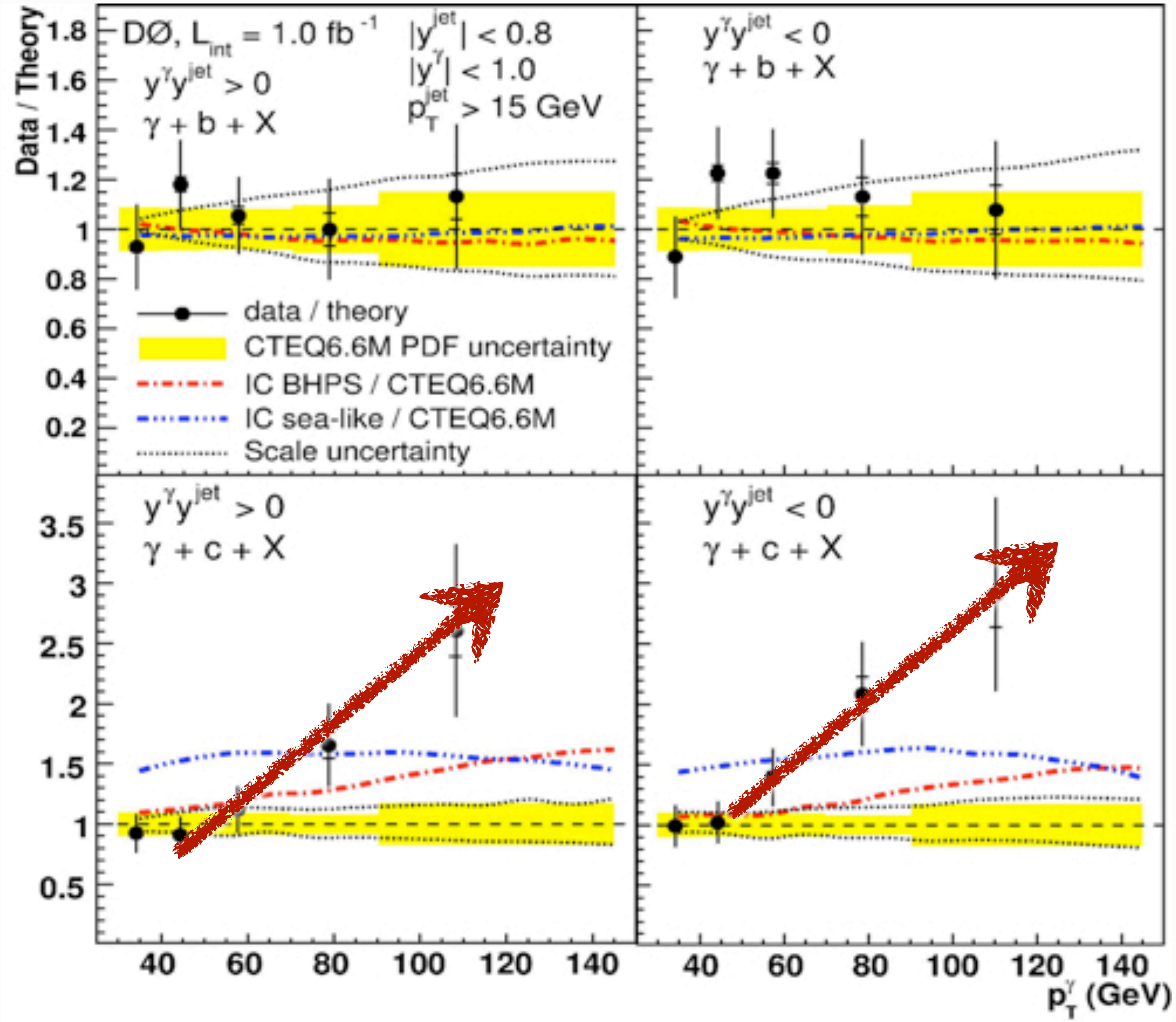

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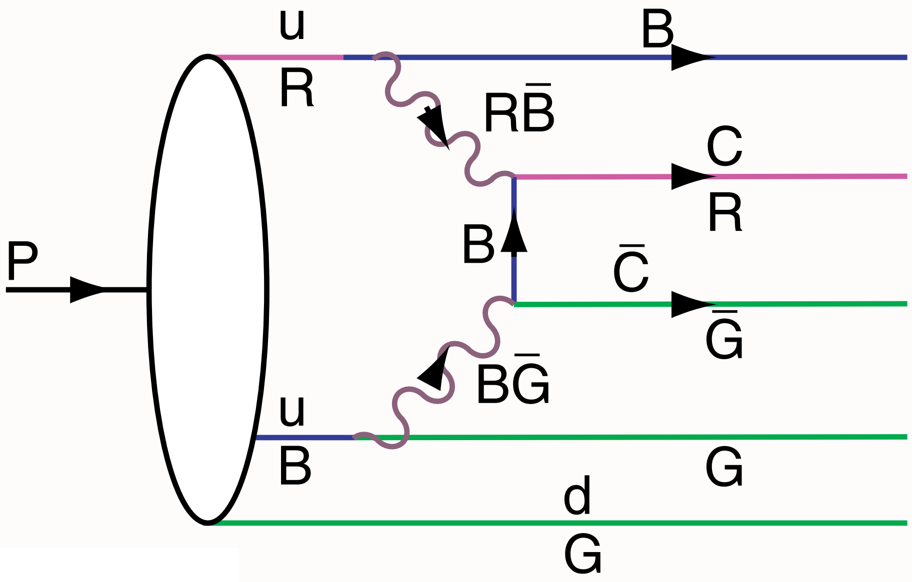
Hoyer, Peterson, Sakai, sjb



$|uudc\bar{c} >$ Fluctuation in Proton

QCD: Probability $\frac{\sim\Lambda^2_{QCD}}{M^2_Q}$

$|e^+e^-\ell^+\ell^- >$ Fluctuation in Positronium

QED: Probability $\frac{\sim(m_e\alpha)^4}{M^4_\ell}$

OPE derivation - M.Polyakov et al.

$< p|\frac{G^3_{\mu\nu}}{m^2_Q}|p >$ vs. $< p|\frac{F^4_{\mu\nu}}{m^4_\ell}|p >$

$c\bar{c}$ in Color Octet

Distribution peaks at equal rapidity (velocity)
Therefore heavy particles carry the largest momentum fractions

$$\hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

High x charm! *Charm at Threshold*

Action Principle: Minimum KE, maximal potential

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

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

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

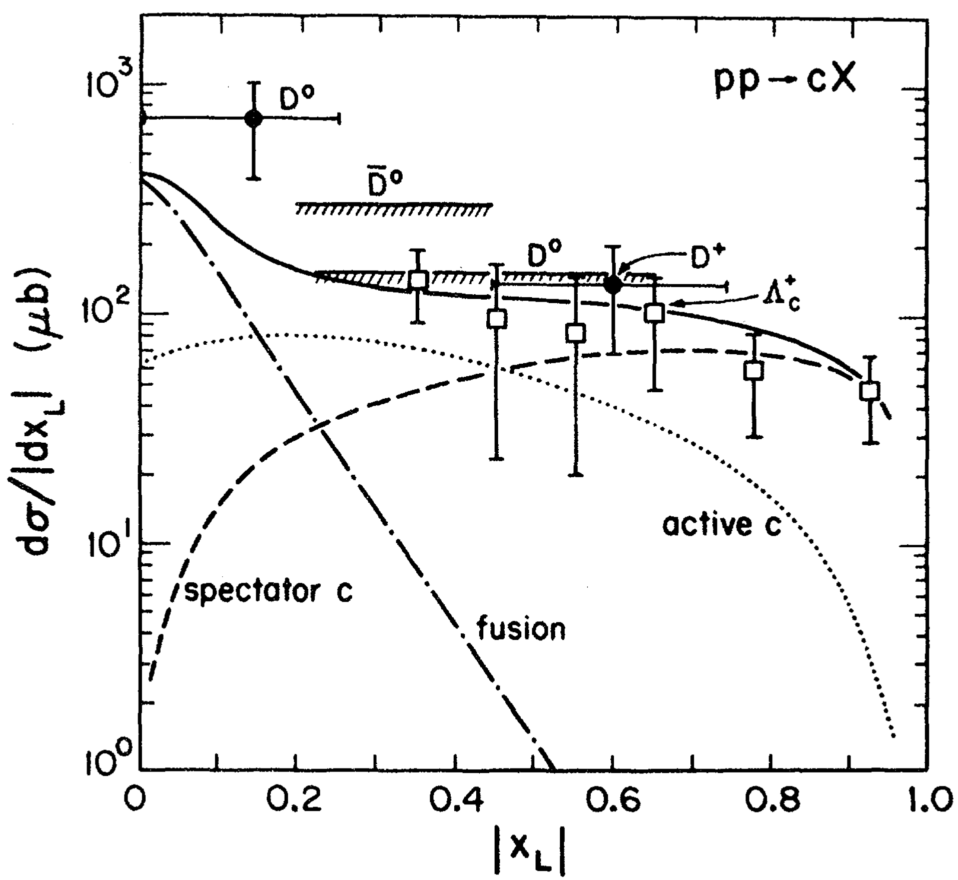
- High x_F $pp \to \Lambda_c X$

- High x_F $pp \to \Lambda_b X$

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

IC Structure Function: Critical Measurement for EIC

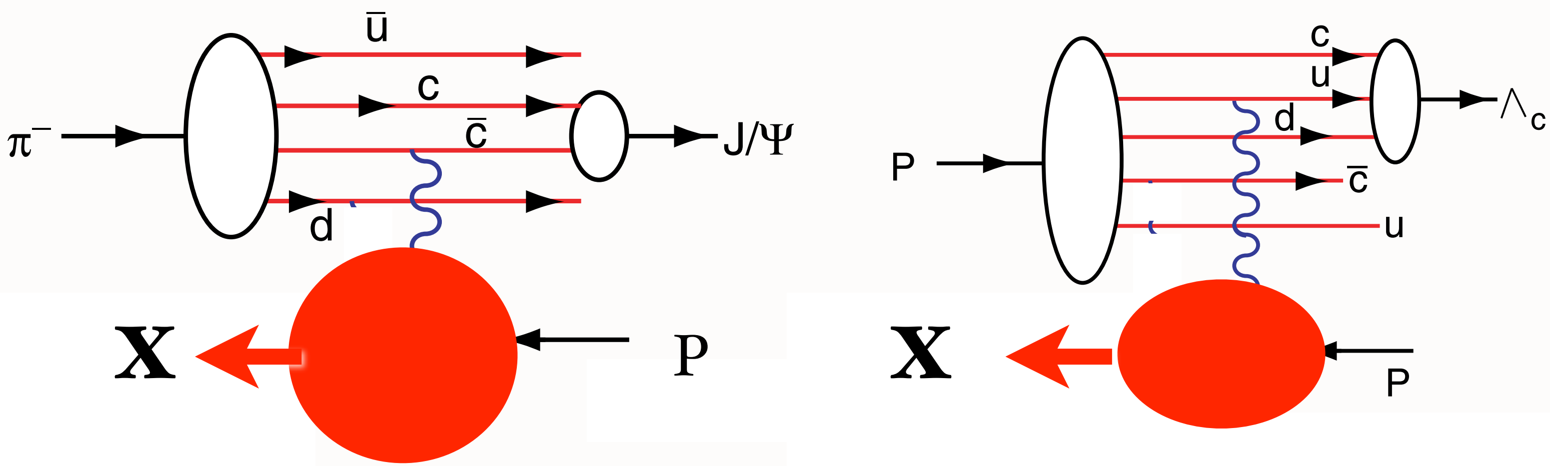
Many interesting spin, charge asymmetry, spectator effects



Model similar to Intrinsic Charm

V. D. Barger, F. Halzen and W. Y. Keung,
"The Central And Diffractive Components Of Charm Production,"
Phys. Rev. D 25, 112 (1982).

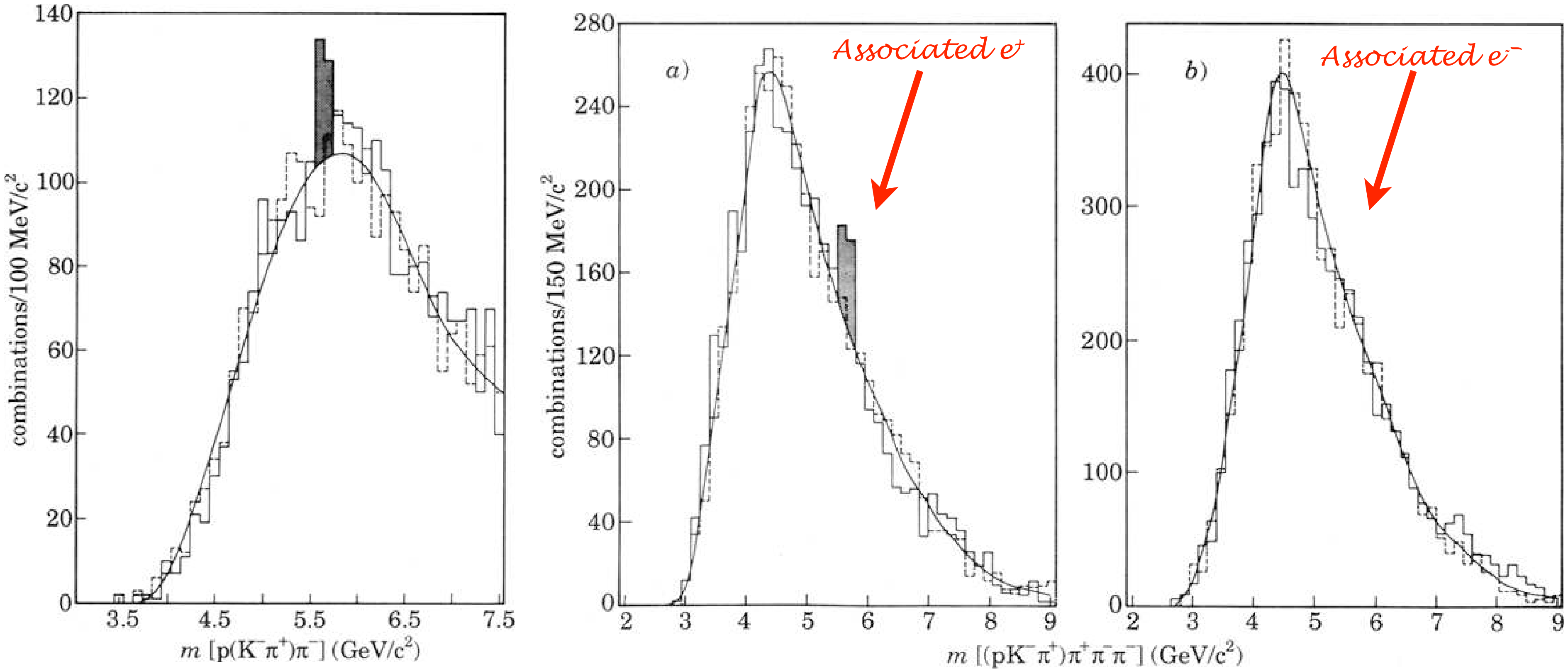
Leading Hadron Production from Intrinsic Charm



Coalescence of Comoving Charm and Valence Quarks
Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

$pp \to \Lambda_b(bud)B(\bar{b}q)X$ at large x_F

CERN-ISR R422 (Split Field Magnet), 1988/1991

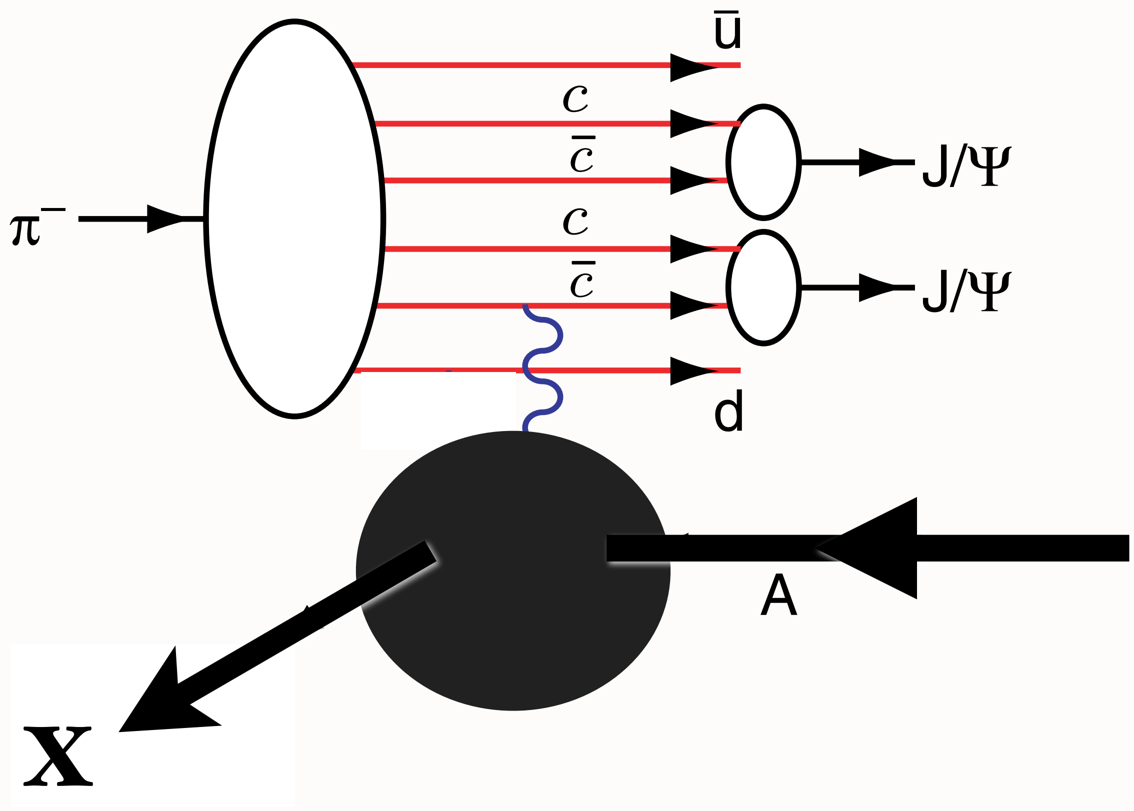


$\Lambda_b^0 \to pD^0\pi^-$

$\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$

Il Nuovo Cimento 104, 1787

Production of Two Charmonia at High x_F



$\pi A \to J/\psi J/\psi X$

R, Vogt, sjb

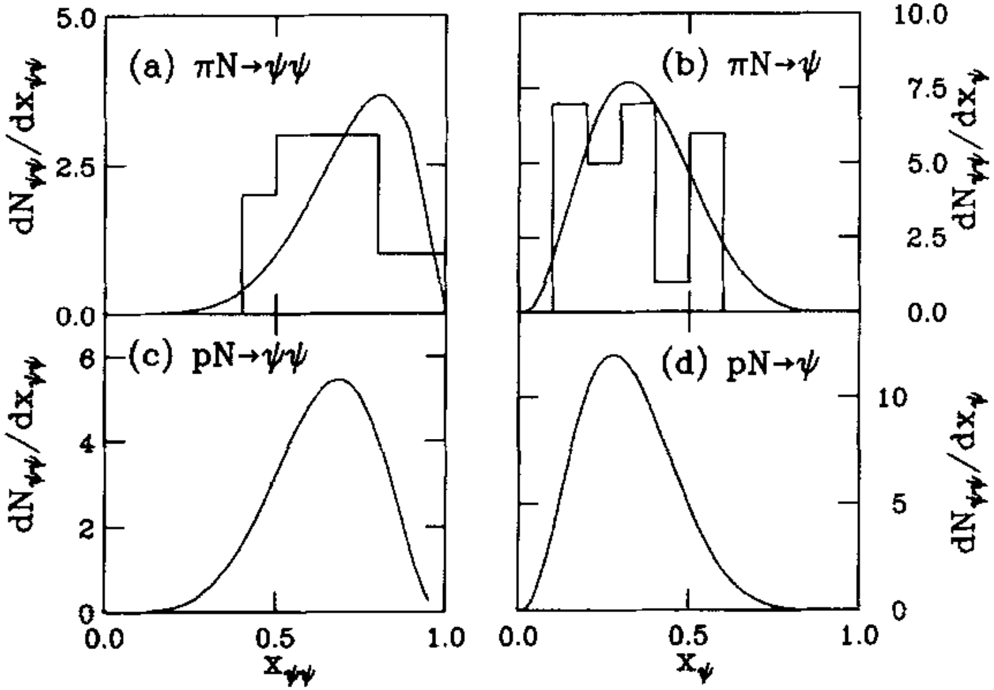


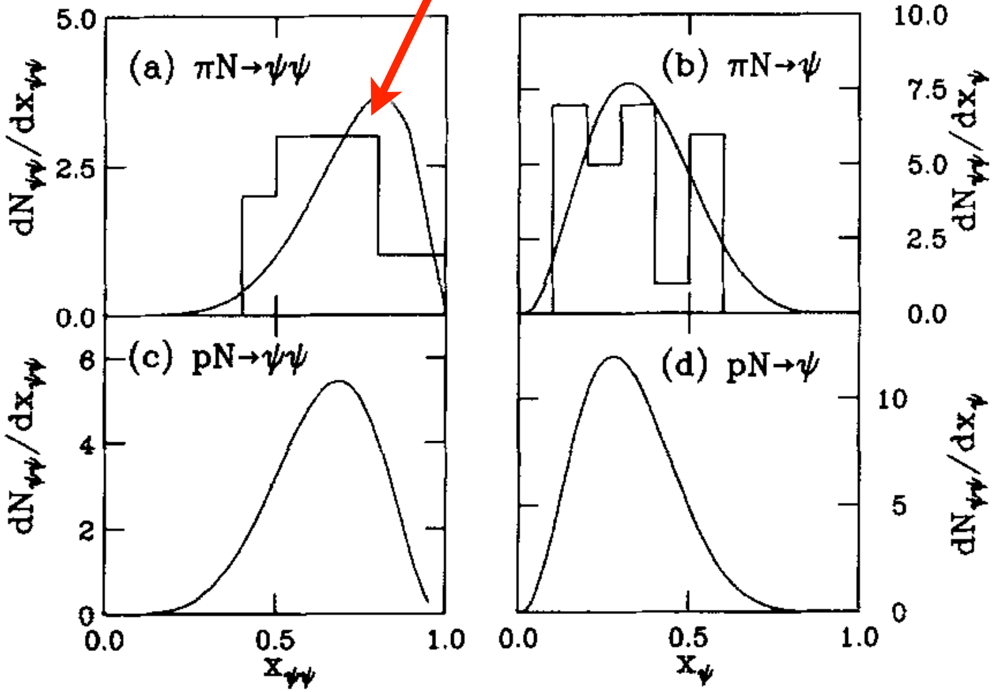
Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized to the number of pairs from both pion beams (a) and the number of pairs from the 400 GeV proton measurement (c). The number of single J/ψ's is twice the number of pairs.

NA3 Data

The probability distribution for a general n-particle intrinsic $c\bar{c}$ Fock state as a function of x and $\boldsymbol{k}_T$ is written as

$$\frac{dP_{\rm ic}}{\prod_{i=1}^n dx_i d^2 k_{T,i}} = N_n \alpha_s^4(M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^n \boldsymbol{k}_{T,i})\delta(1-\sum_{i=1}^n x_i)}{(m_h^2 - \sum_{i=1}^n (m_{T,i}^2/x_i))^2},$$

All events have $x^F_{\psi\psi} > 0.4$!



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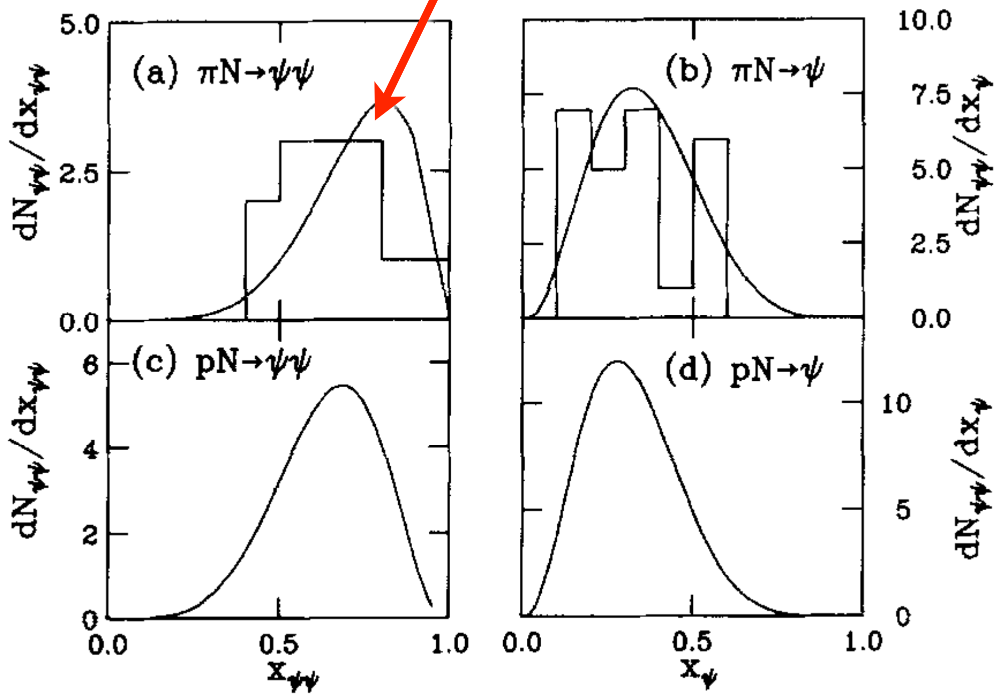
Excludes `color drag' model



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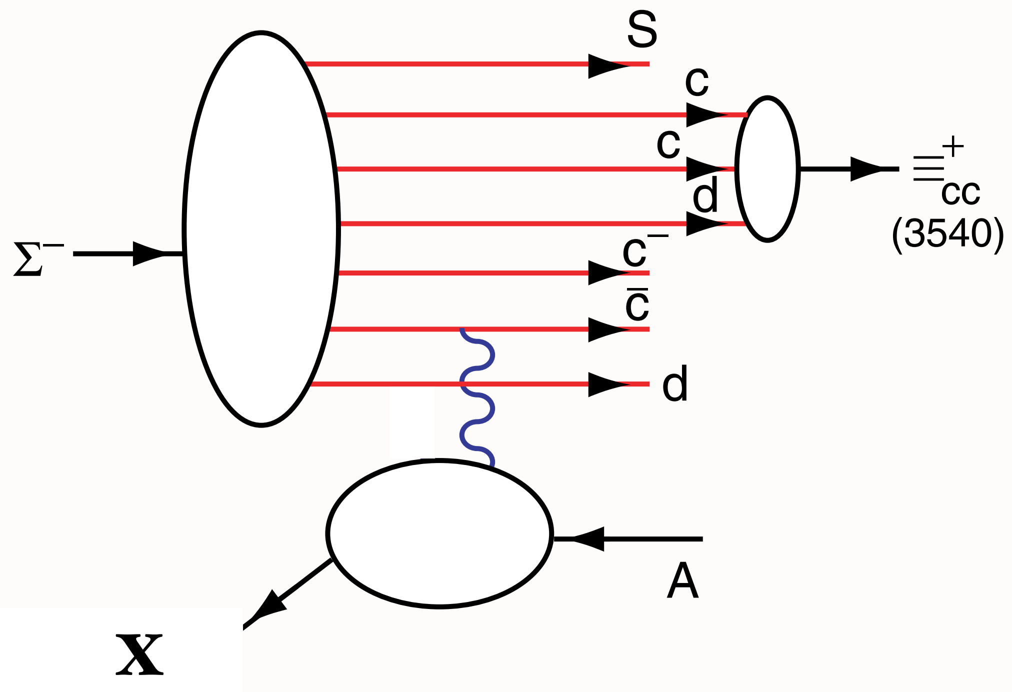
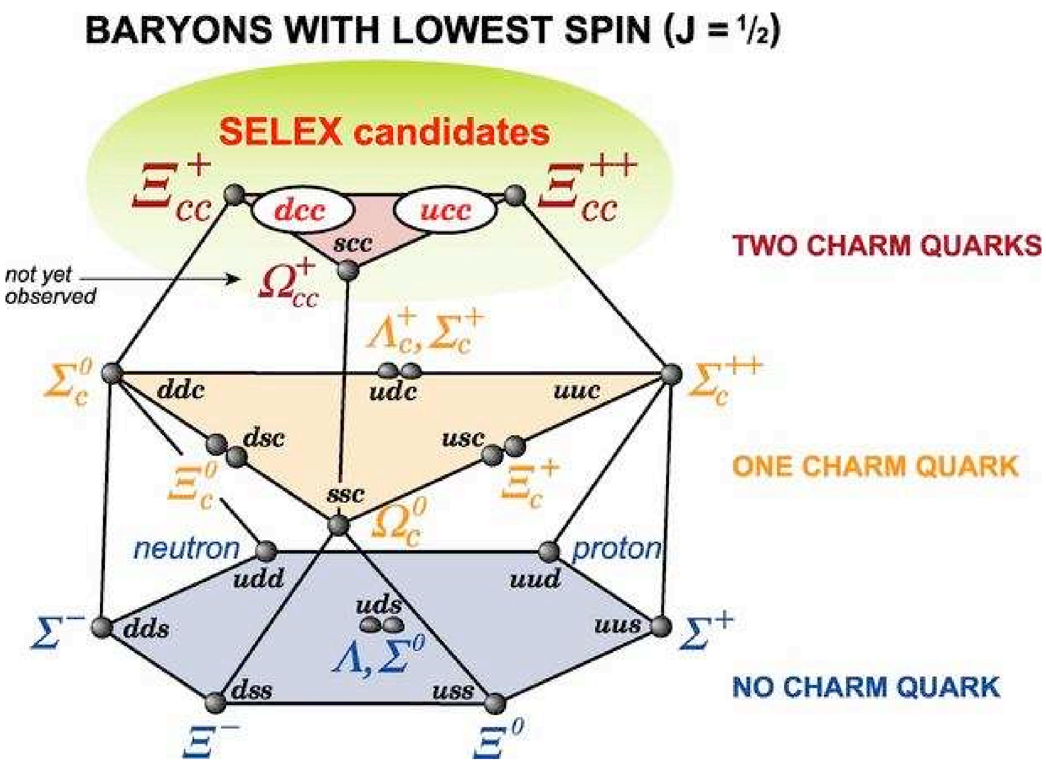
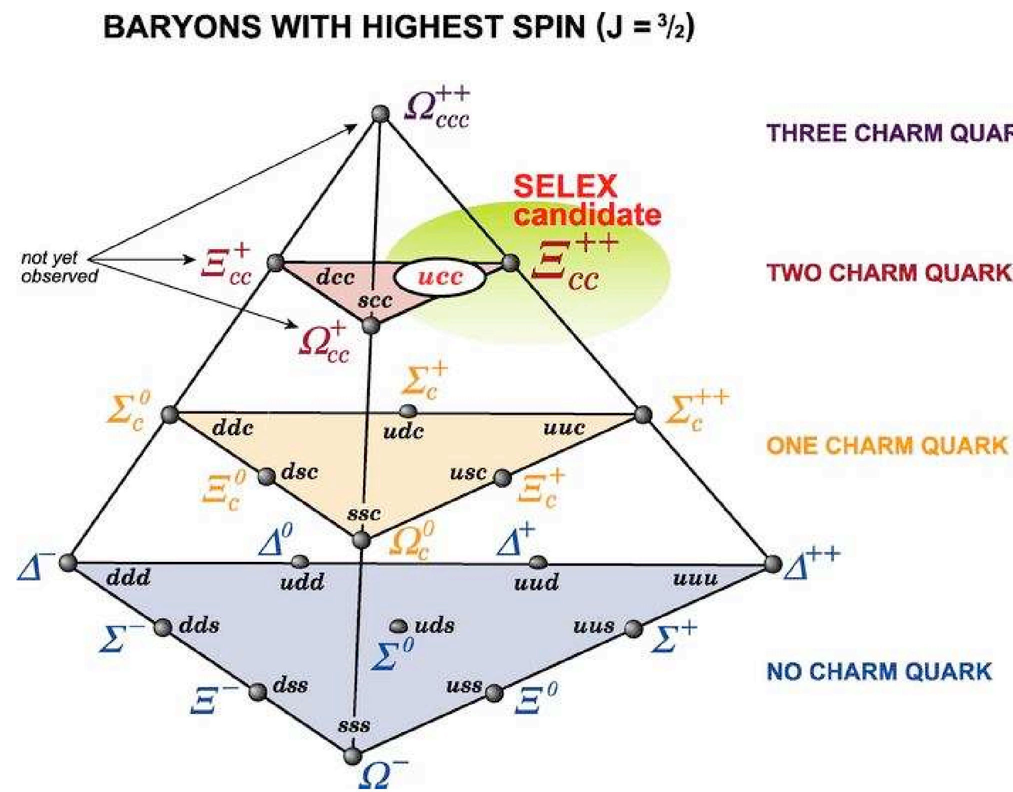


Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

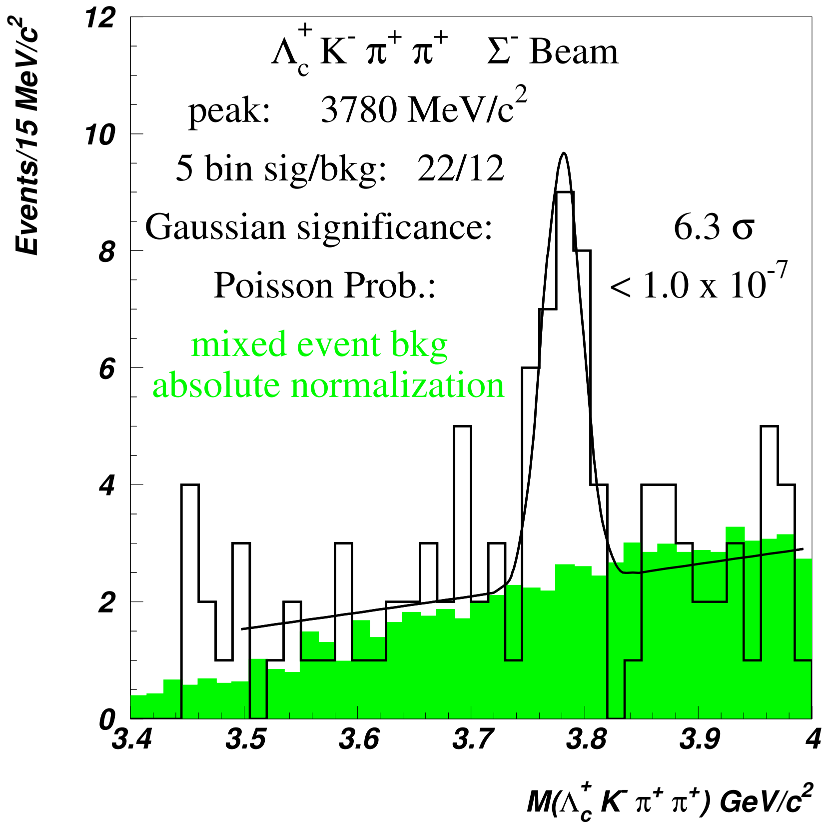
Doubly Charmed Baryons





$\Xi_{cc}(3780)^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

- Re-Analyzed Data
- Restrict to Σ^-–Beam
- Peak wider than Resolution
- Half decay to $\Xi_{cc}^+(3520)$
- Still working on Details



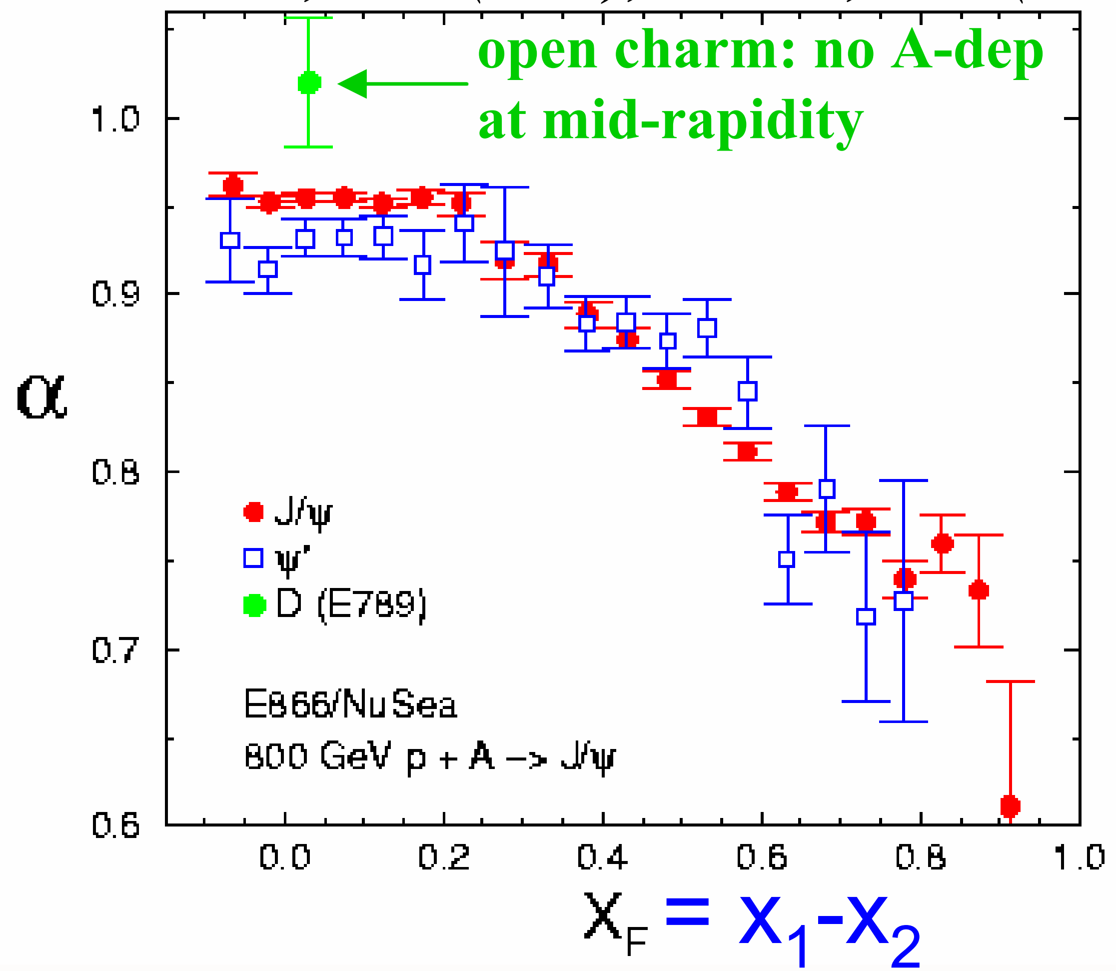
Produce entire set of Heavy Baryons up to bbb

AFTER @ LHC

M. Leitch

800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^{\alpha}$

PRL 84, 3256 (2000); PRL 72, 2542 (1994)



$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

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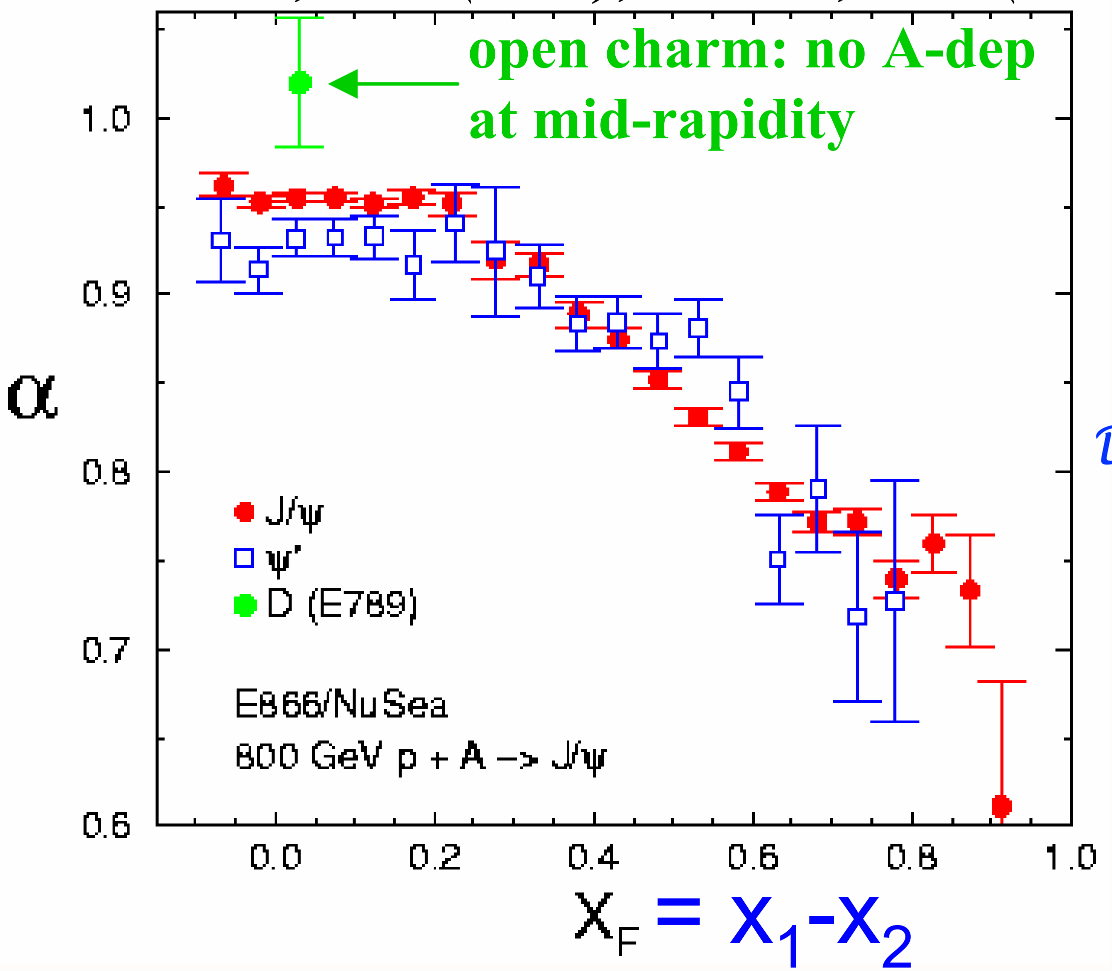
M. Leitch



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Remarkably Strong Nuclear Dependence for Fast Charmonium

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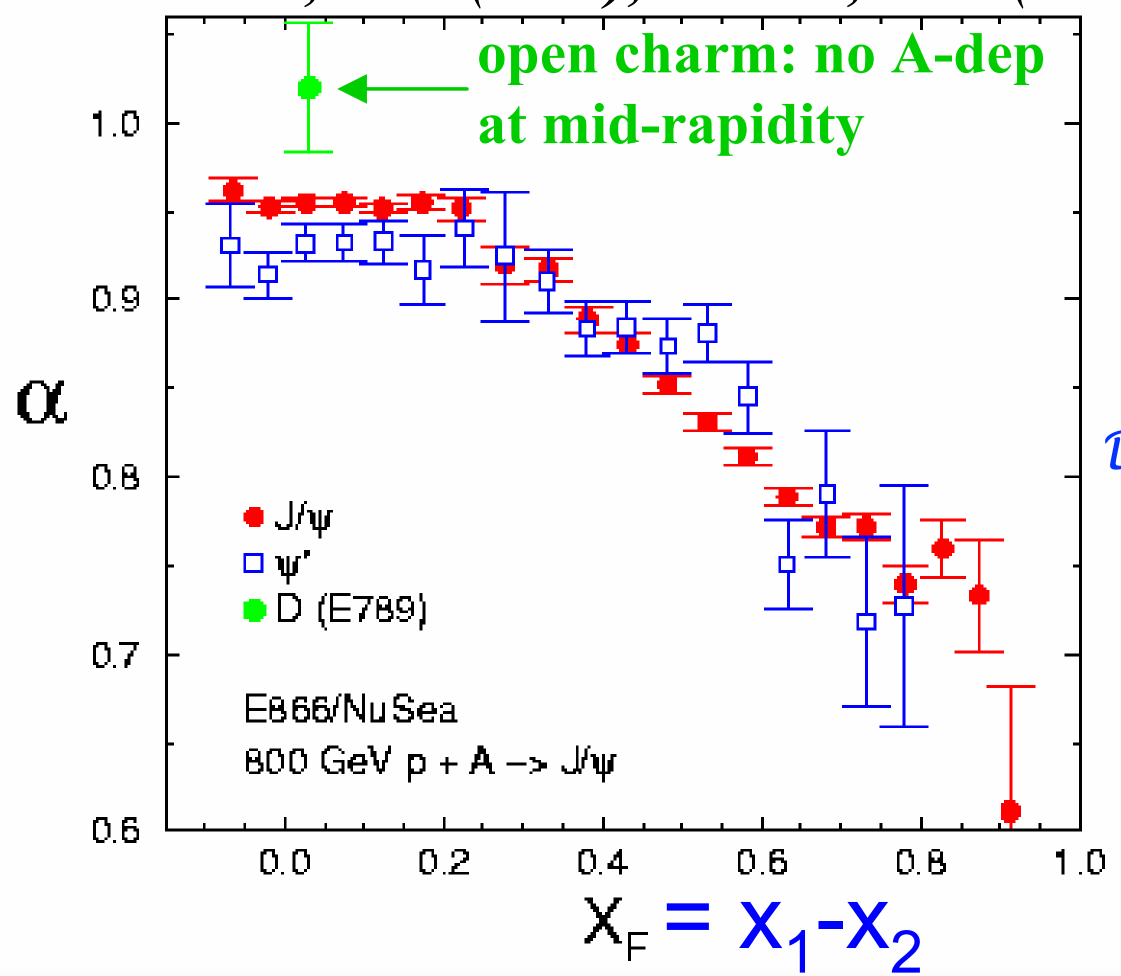

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Remarkably Strong Nuclear Dependence for Fast Charmonium

Violation of PQCD Factorization

Violation of factorization in charm hadroproduction.

P. Hoyer, M. Vanttinen (Helsinki U.) , U. Sukhatme (Illinois U., Chicago) . HU-TFT-90-14, May 1990. 7pp.

Published in Phys.Lett.B246:217-220,1990

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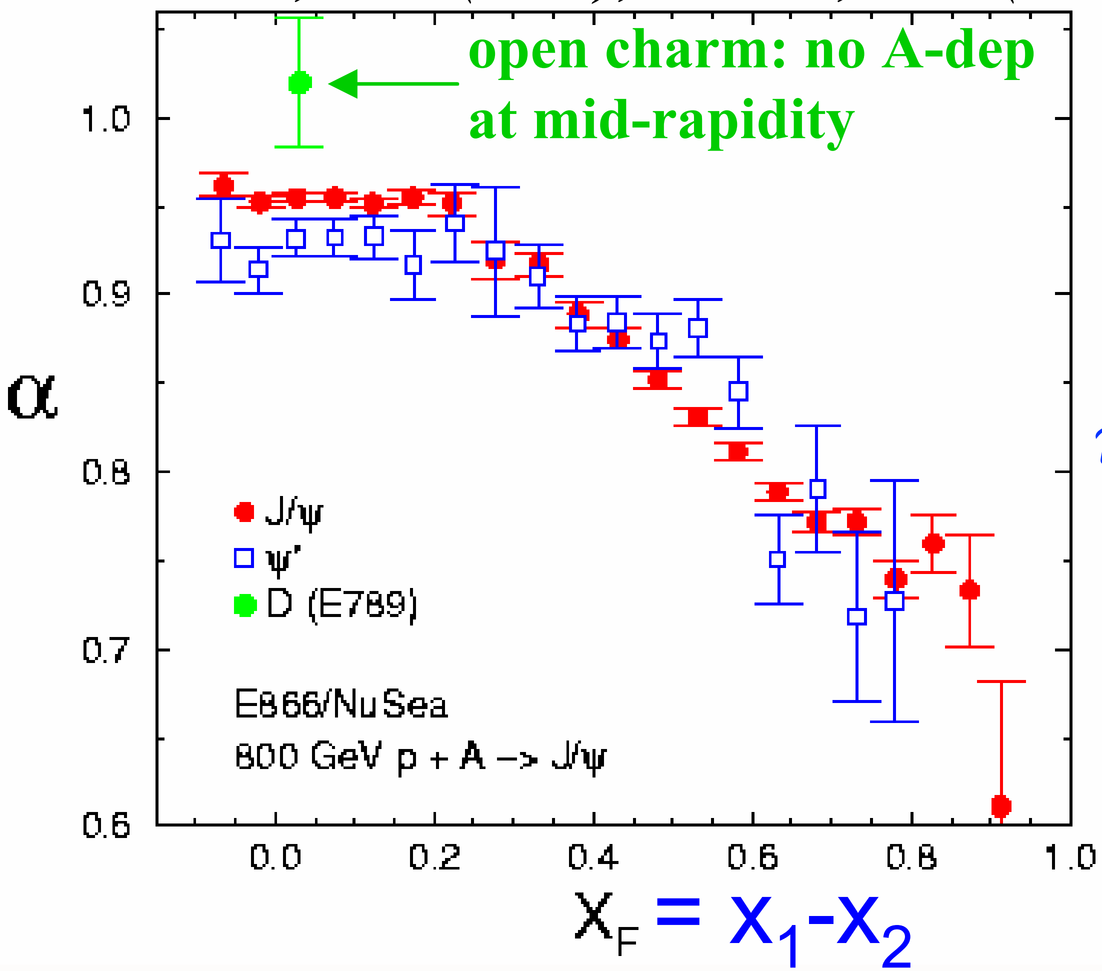

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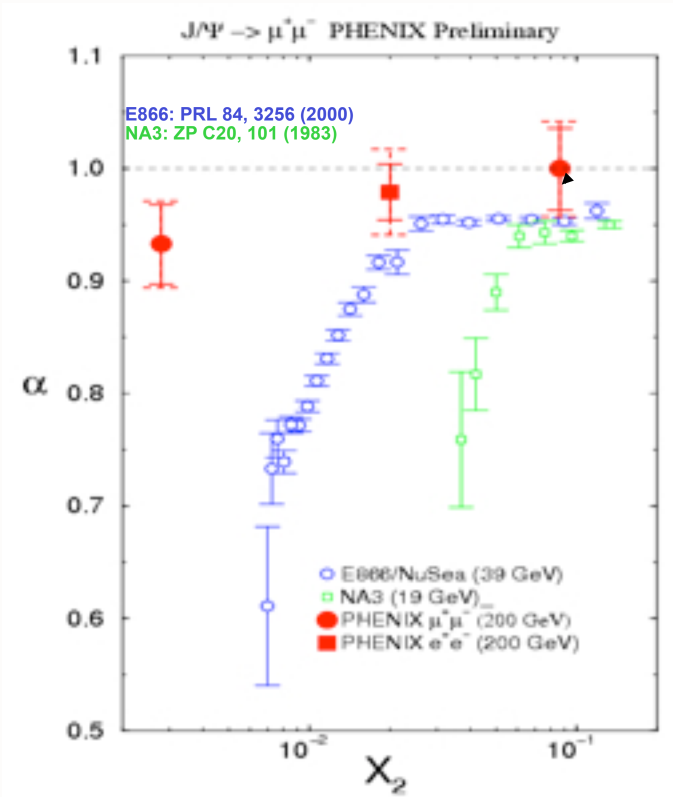
IC Explains large excess of quarkonia at large x_F, A-dependence

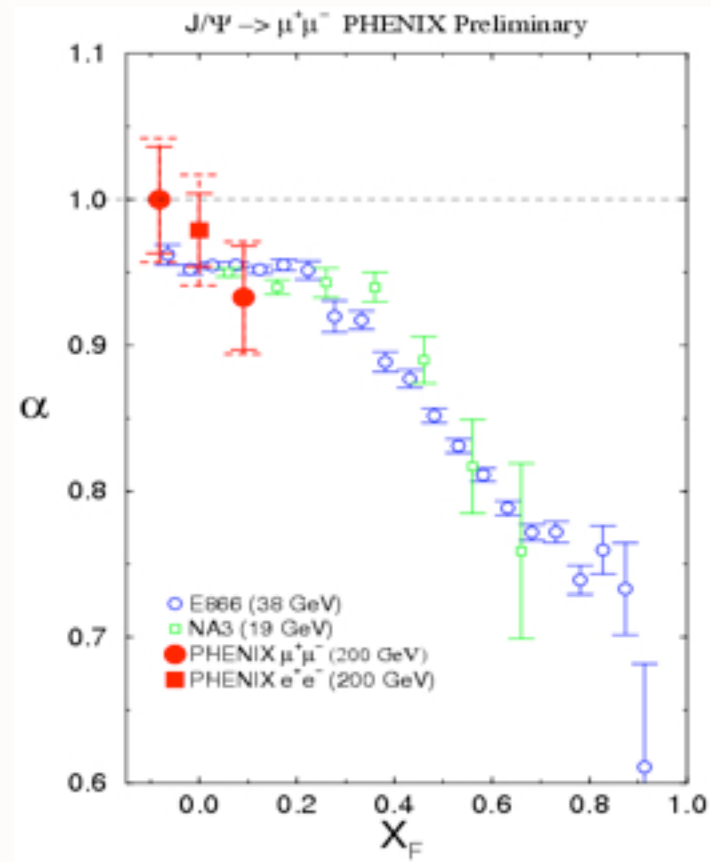
J/ψ nuclear dependence vrs rapidity, x_{Au}, x_F

M.Leitch

PHENIX compared to lower energy measurements



Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001



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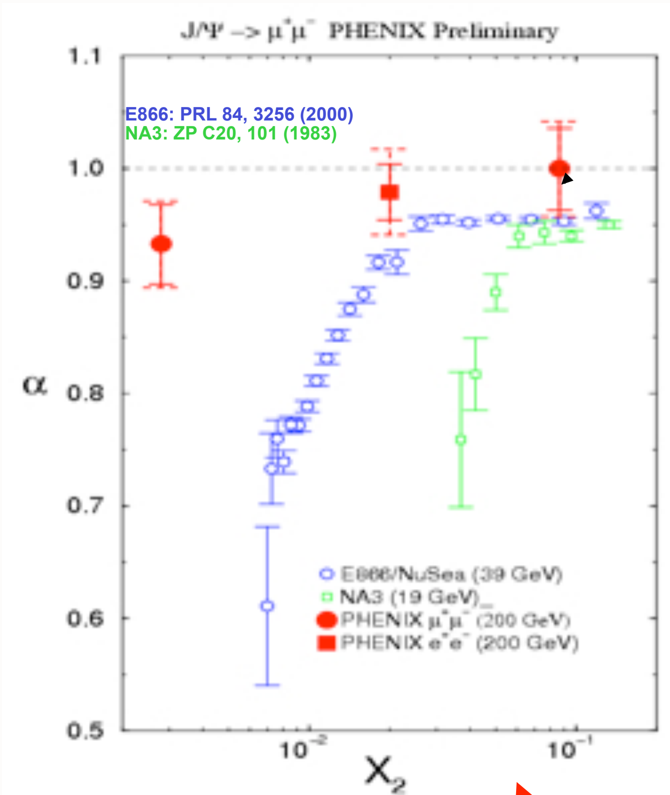

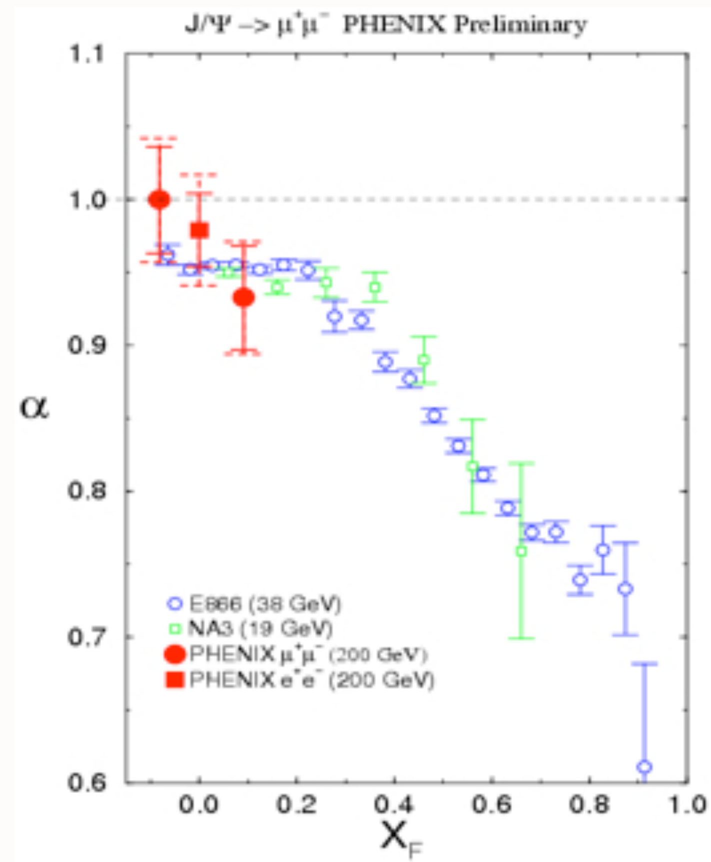

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Violates PQCD factorization!

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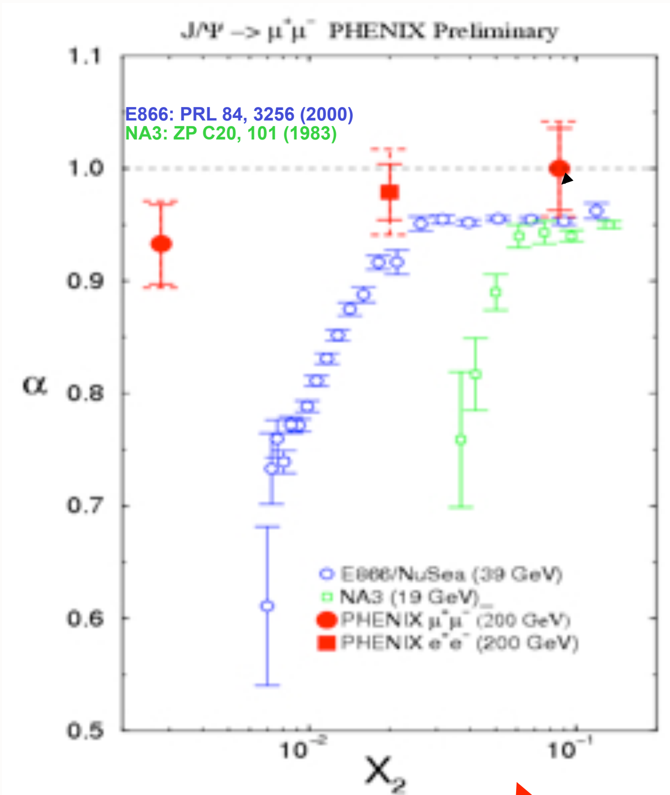

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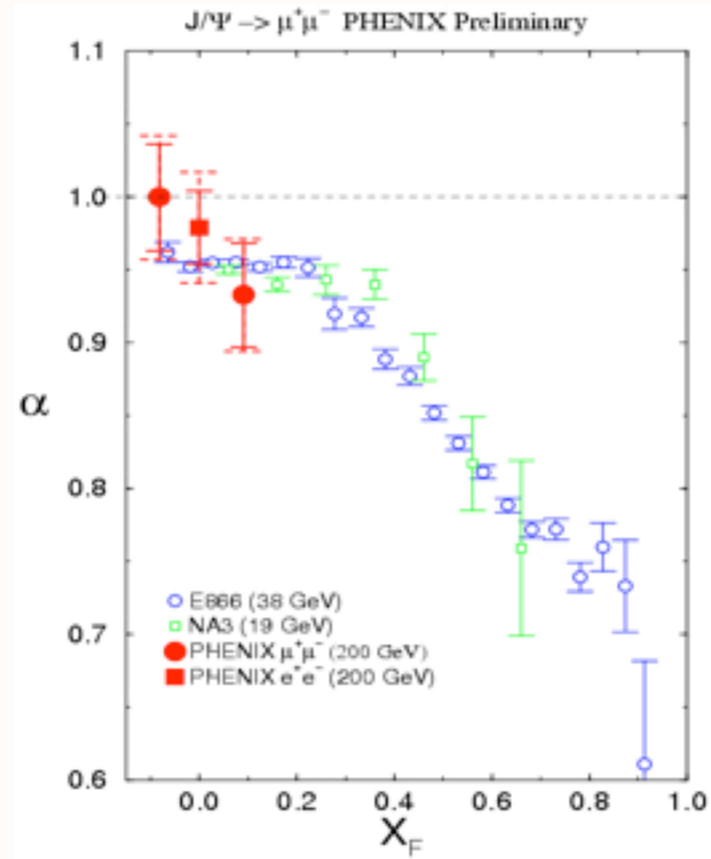


Huge "absorption" effect

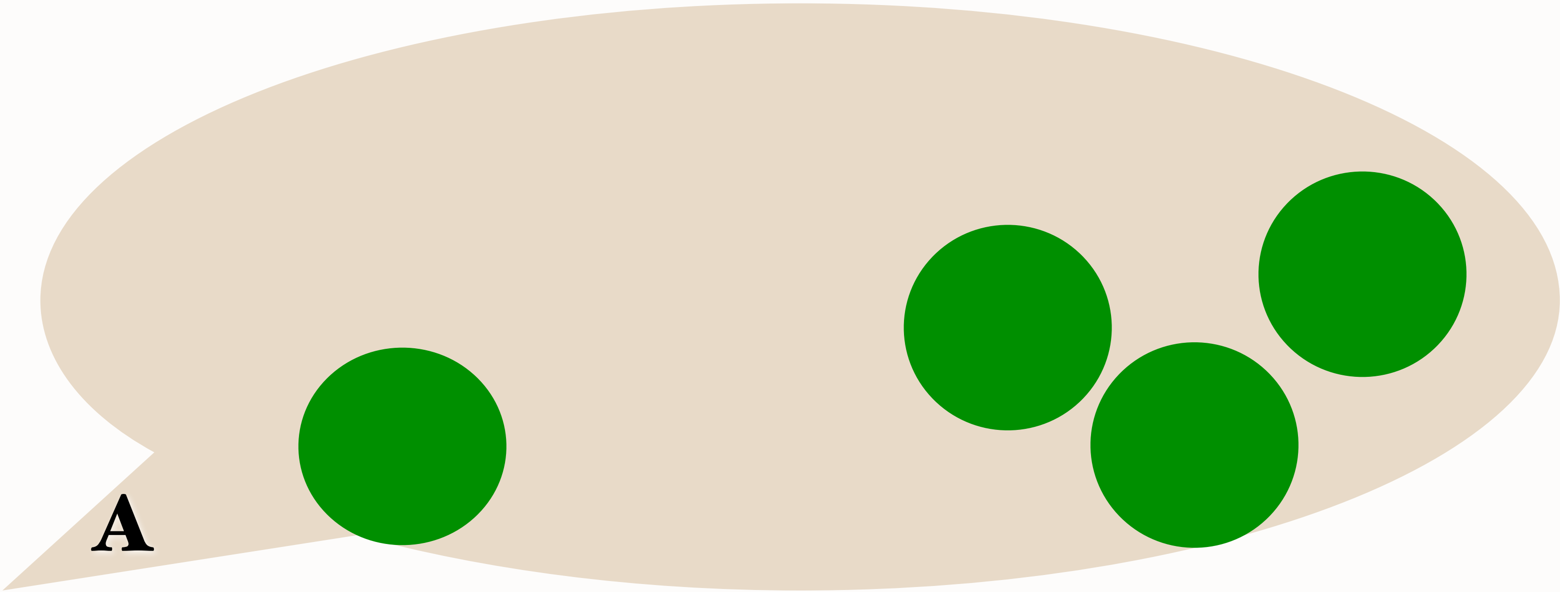
Violates PQCD factorization!

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

Hoyer, Sukhatme, Vanttinen

Color-Opaque IC Fock state interacts on nuclear front surface

Kopeliovich, Schmidt, Soffer, sjb



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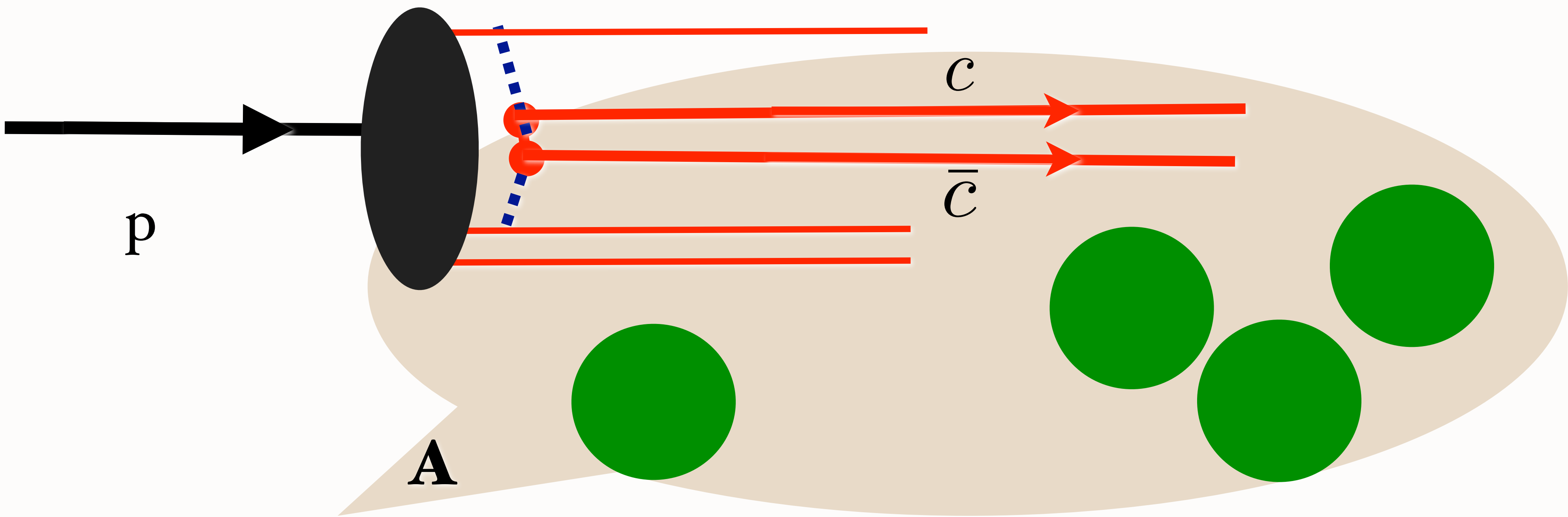

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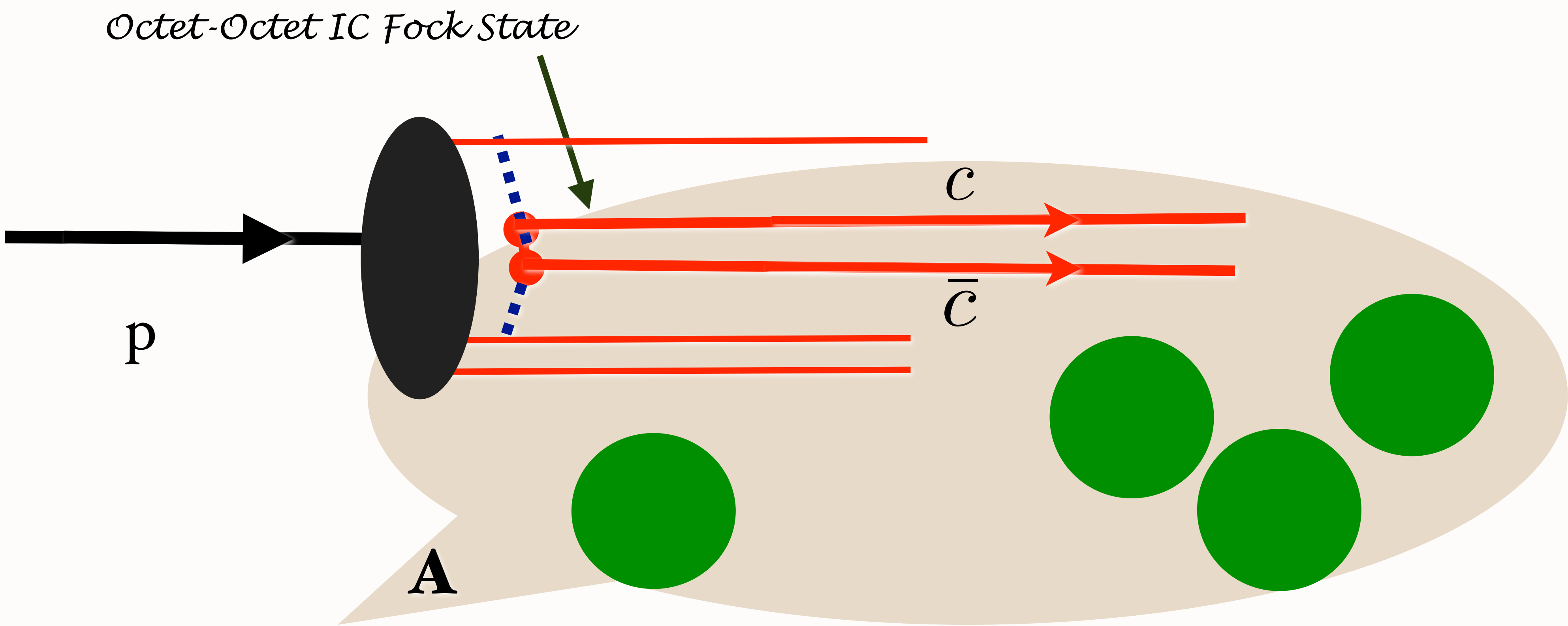

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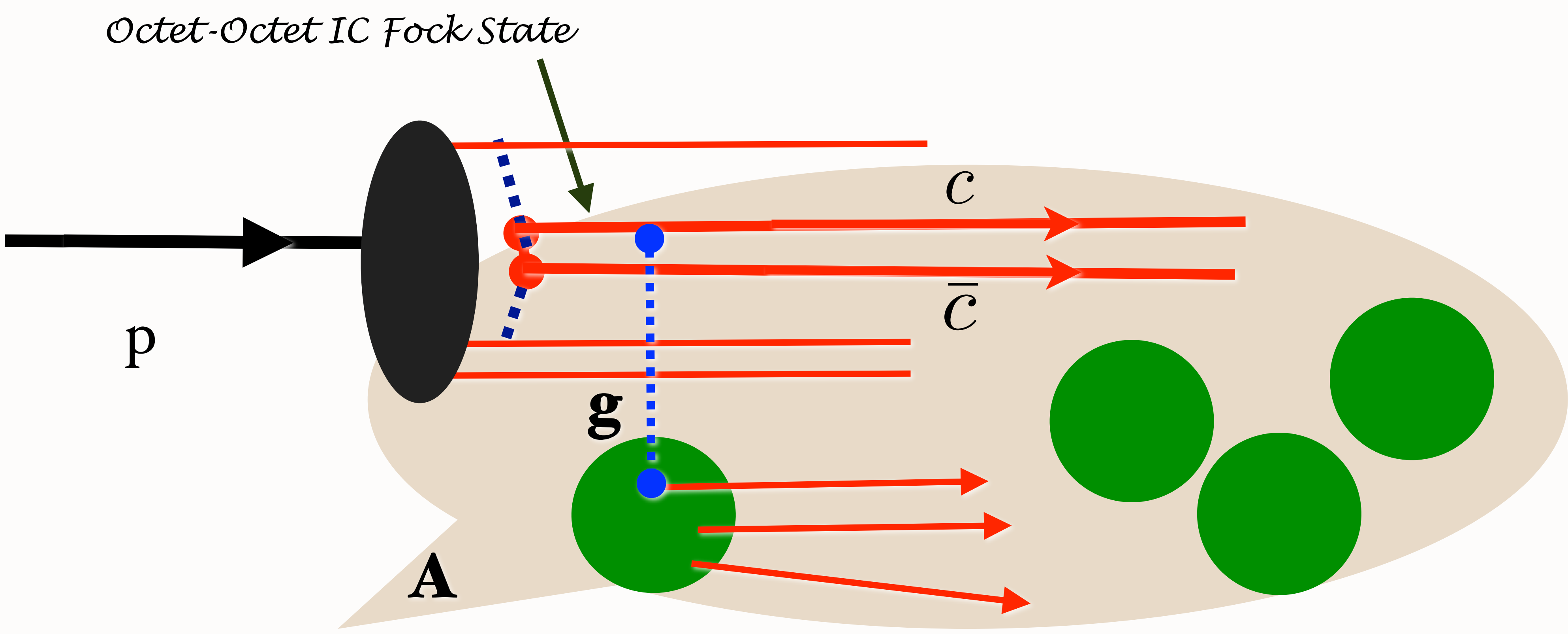

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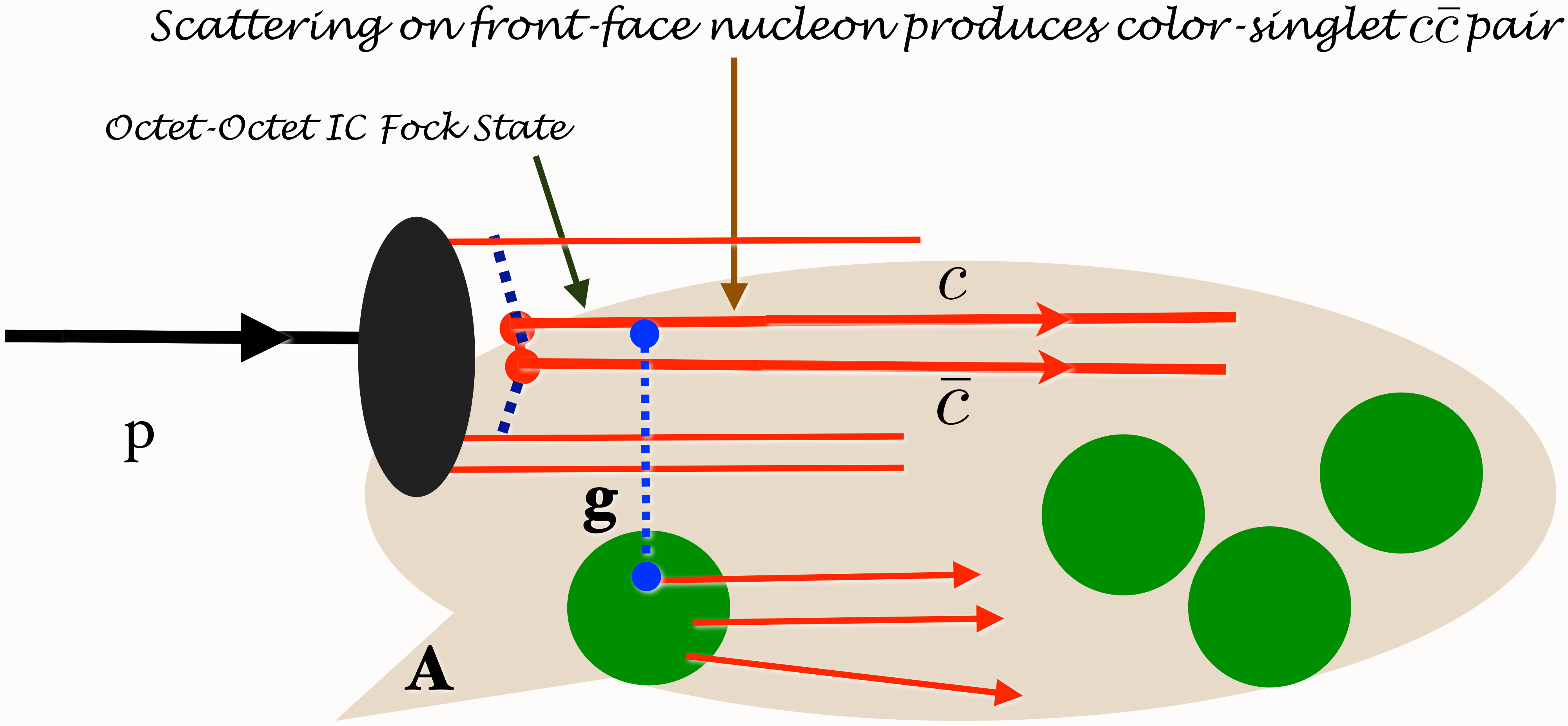

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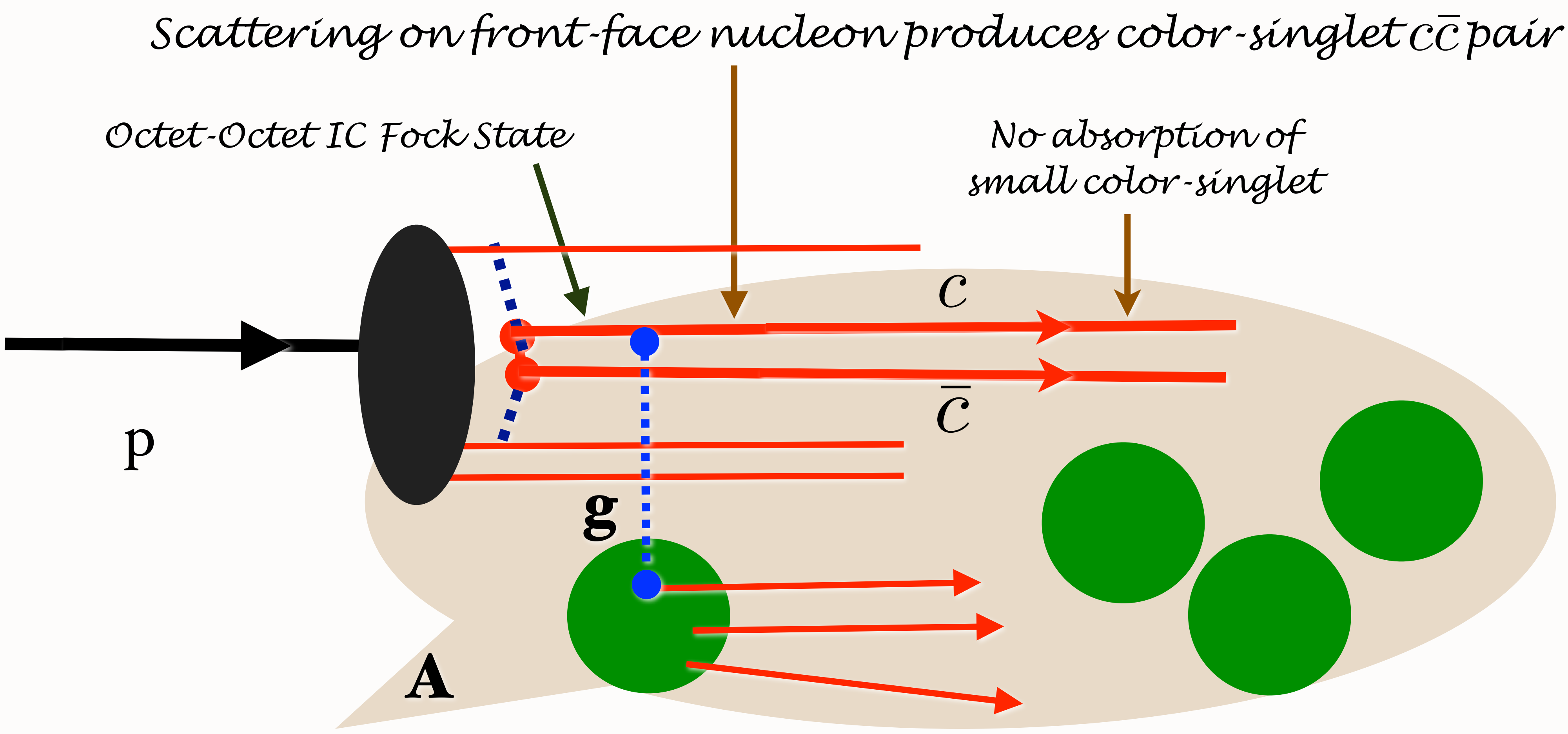

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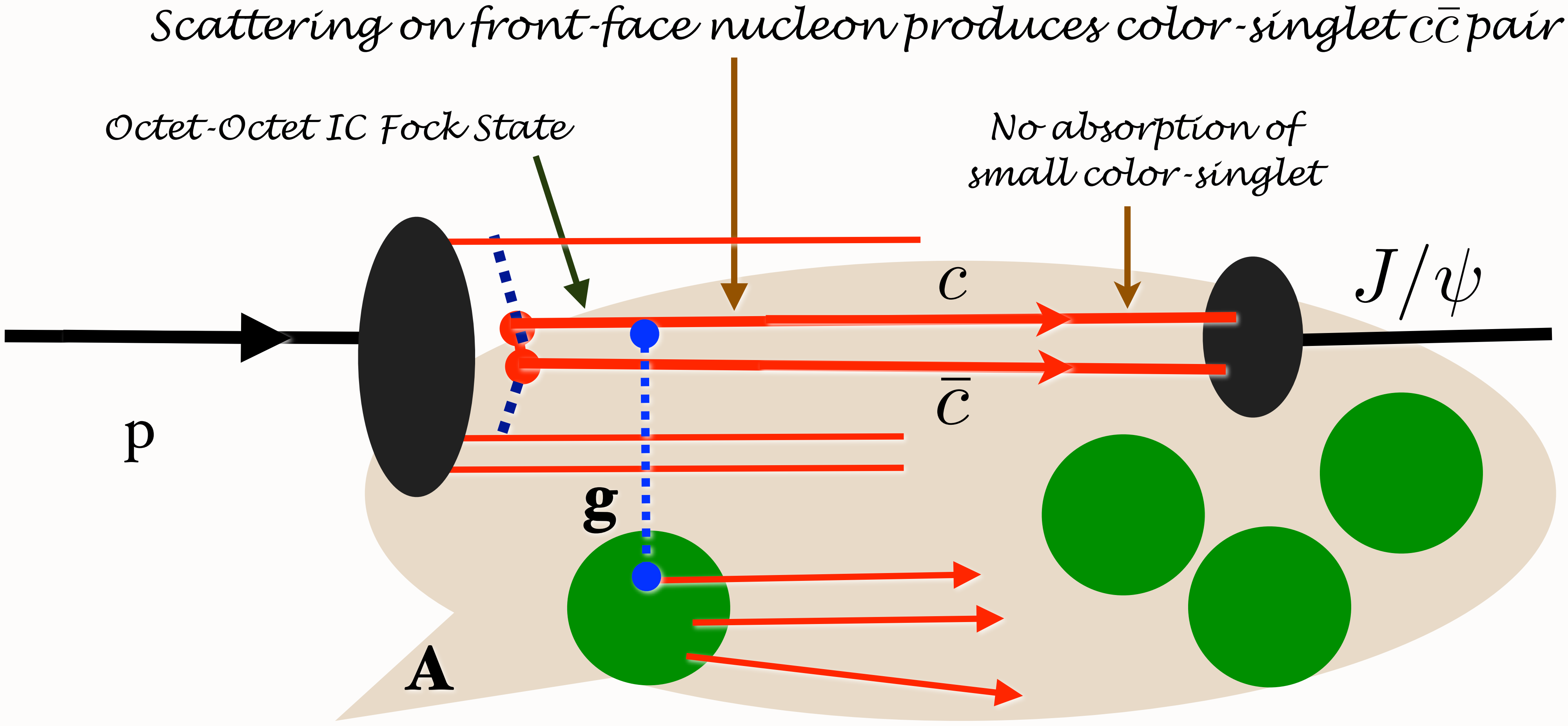

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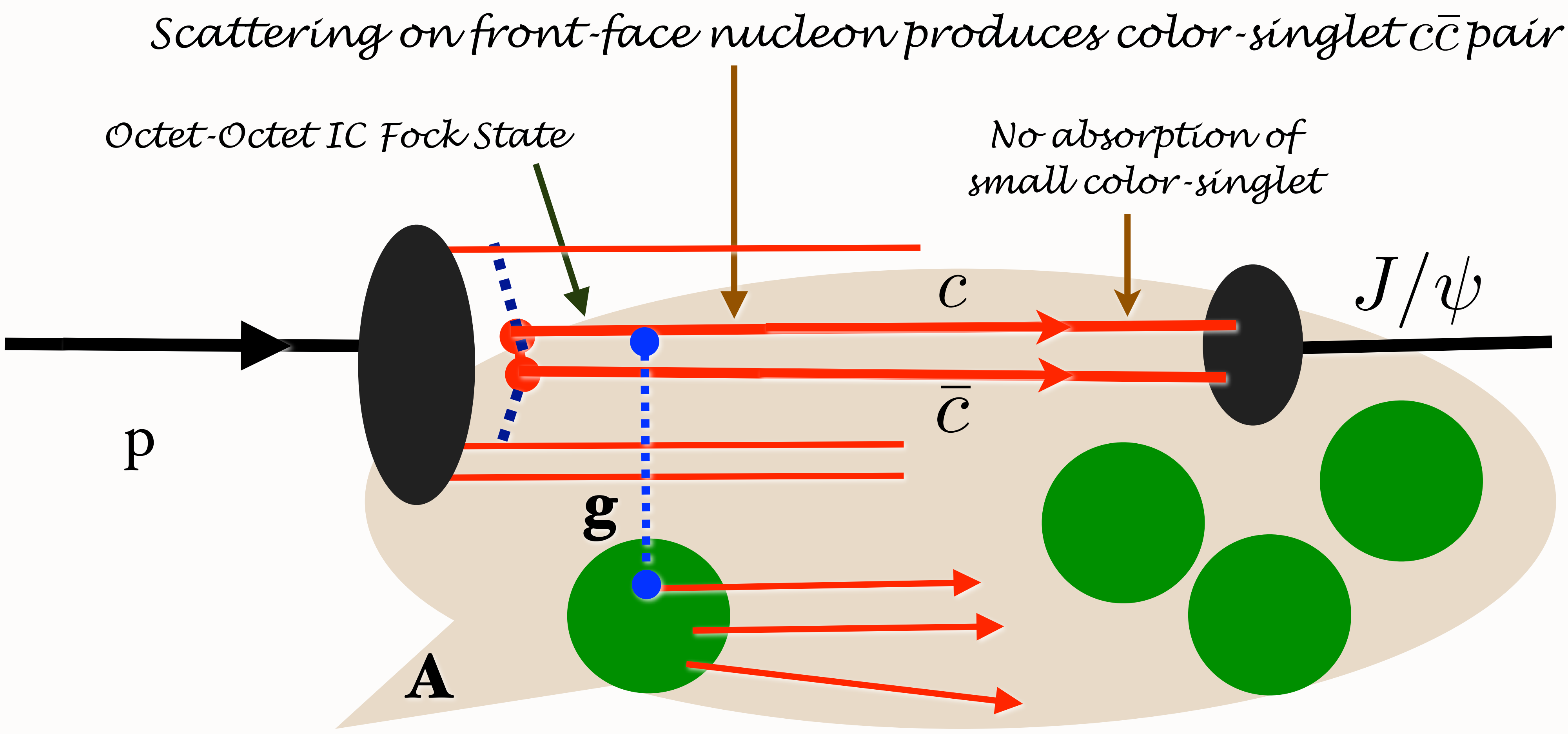
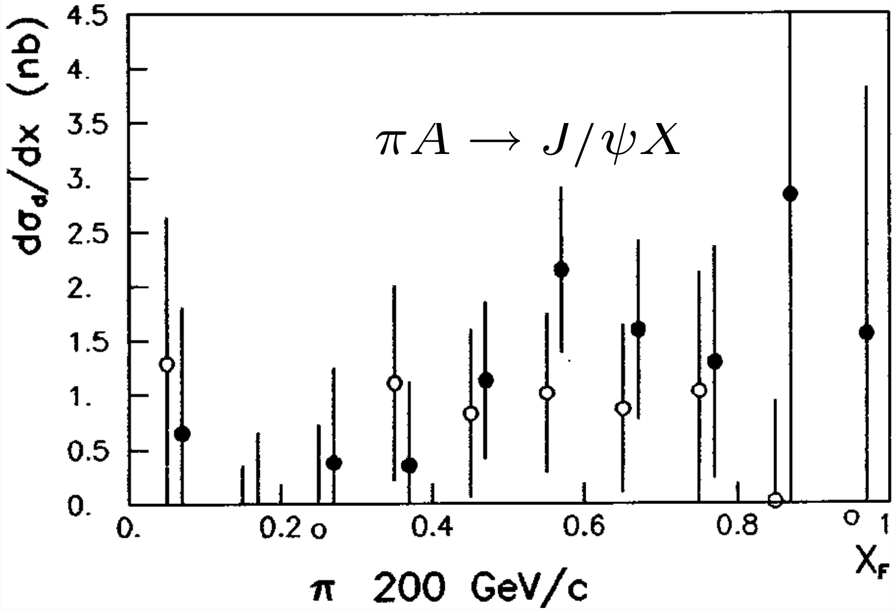
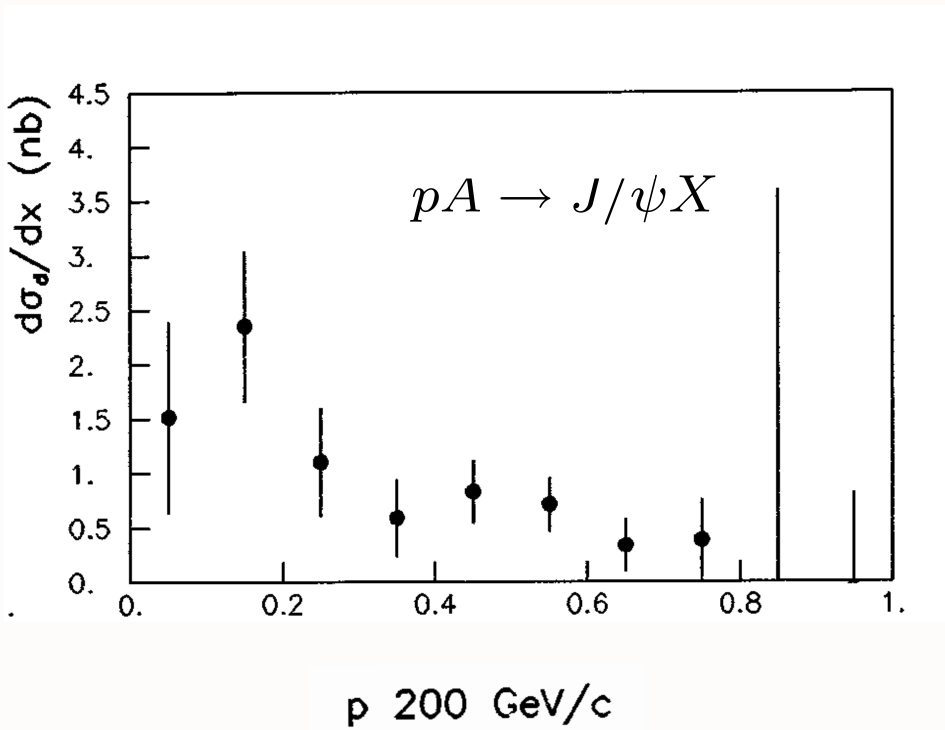


$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$



$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3} \frac{d\sigma_{2/3}}{dx_F}$$



$A^{2/3}$ component

J. Badier et al, NA3

Excess beyond conventional PQCD subprocesses

- IC Explains Anomalous $\alpha(x_F)$ not $\alpha(x_2)$ dependence of $pA \to J/\psi X$
(Mueller, Gunion, Tang, SJB)

- Color Octet IC Explains $A^{2/3}$ behavior at high x_F (NA3, Fermilab)
(Kopeliovitch, Schmidt, Soffer, SJB)

Color Opaqueness

- IC Explains $J/\psi \to \rho\pi$ puzzle
(Karliner, SJB)

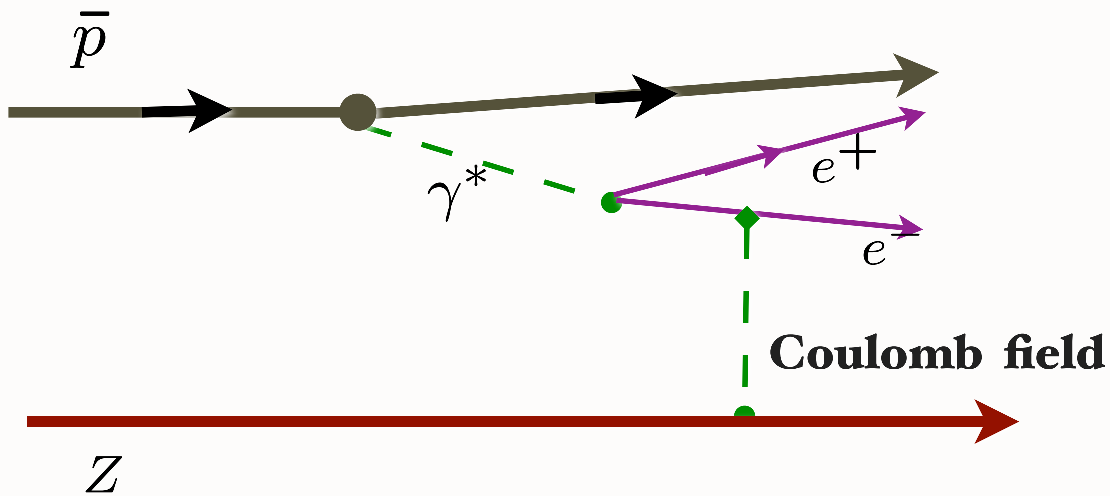
- IC leads to new effects in B decay
(Gardner, SJB)

Higgs production at x_F = 0.8

Formation of Relativistic Anti-Hydrogen

Measured at CERN-LEAR and FermiLab

Munger, Schmidt, sjb



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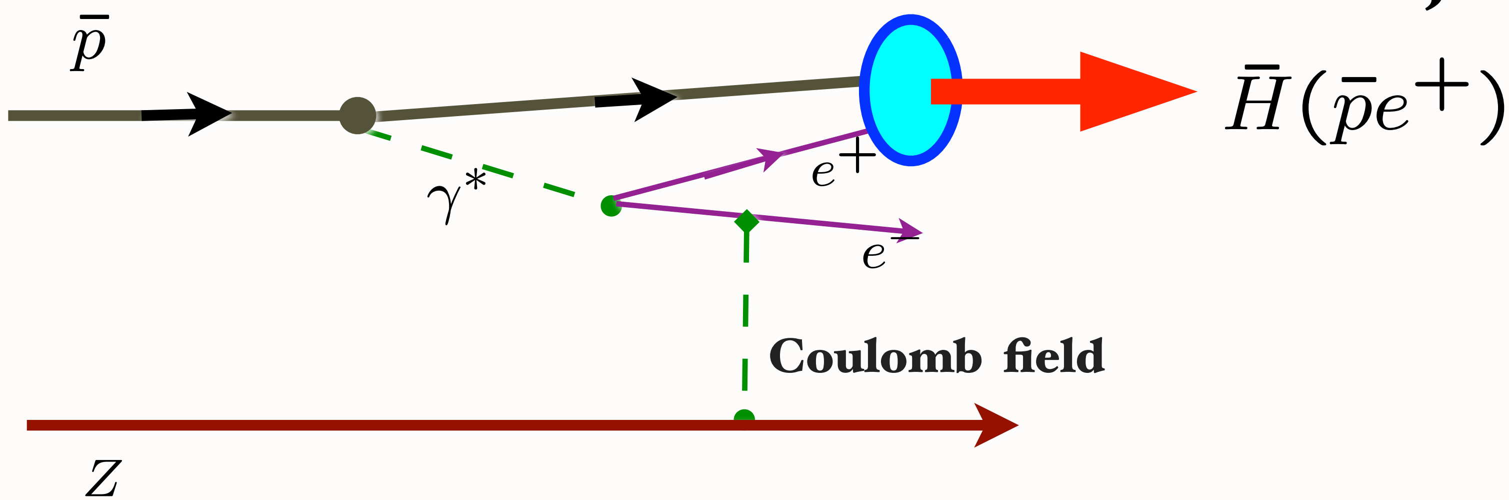

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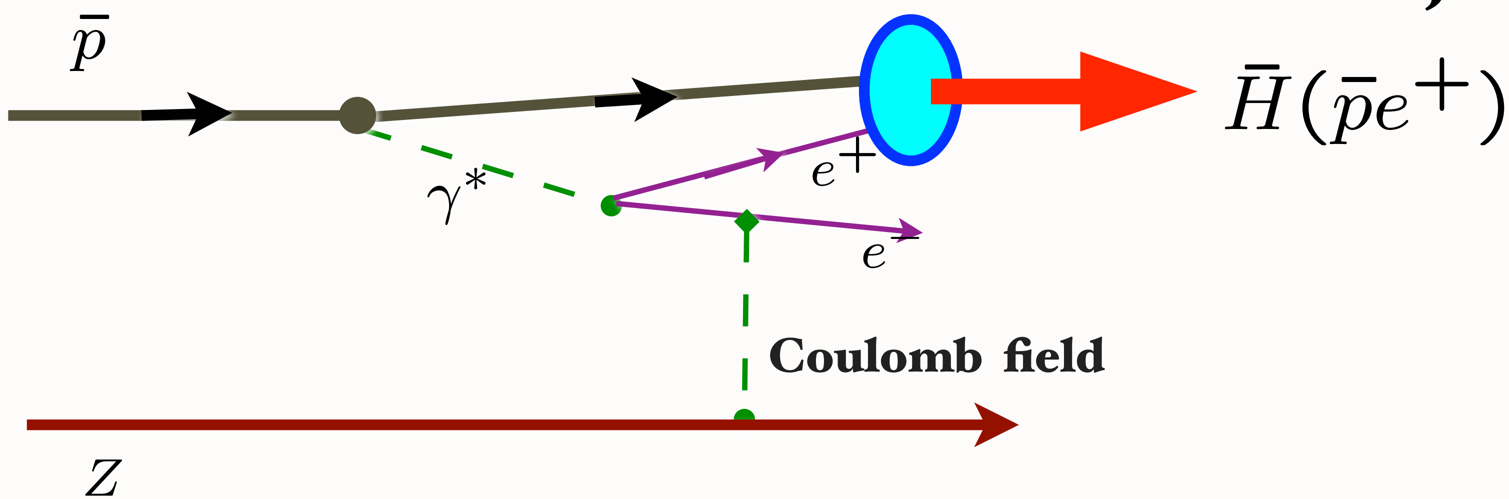

Coalescence of off-shell co-moving positron and antiproton

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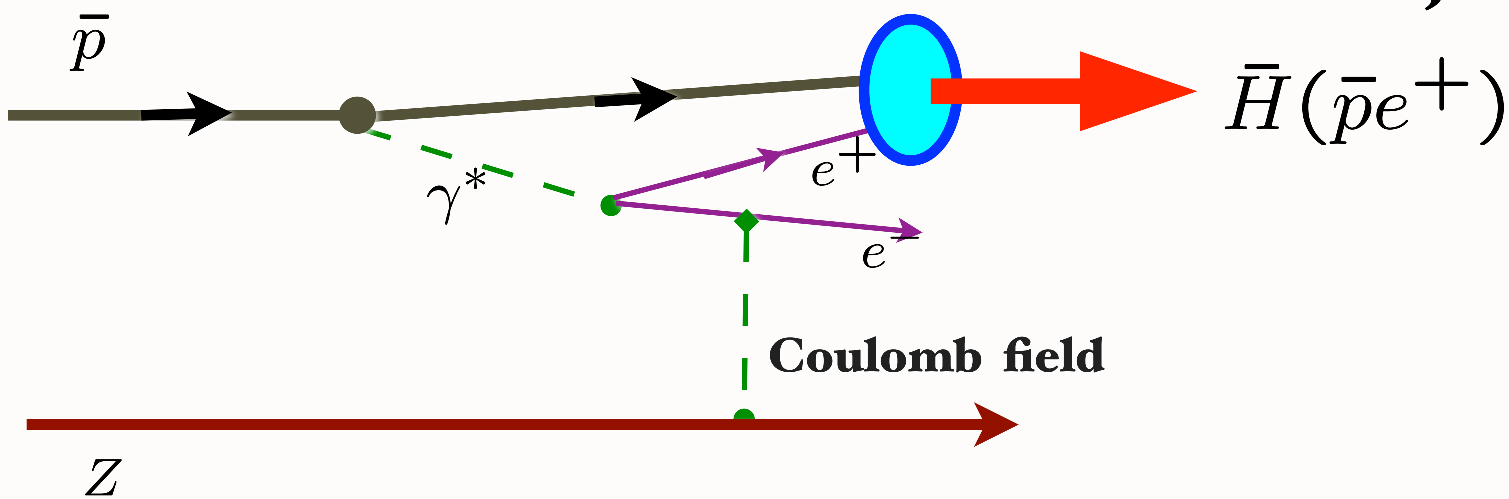

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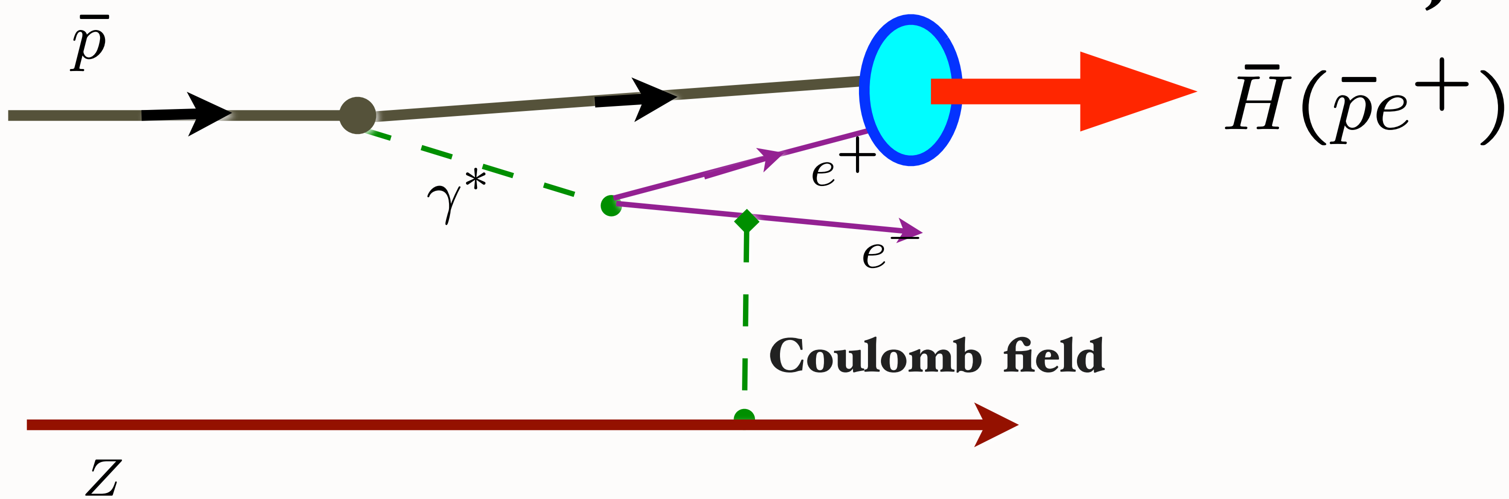

Coalescence of off-shell co-moving positron and antiproton

Wavefunction maximal at small impact separation and equal rapidity

Formation of Relativistic Anti-Hydrogen

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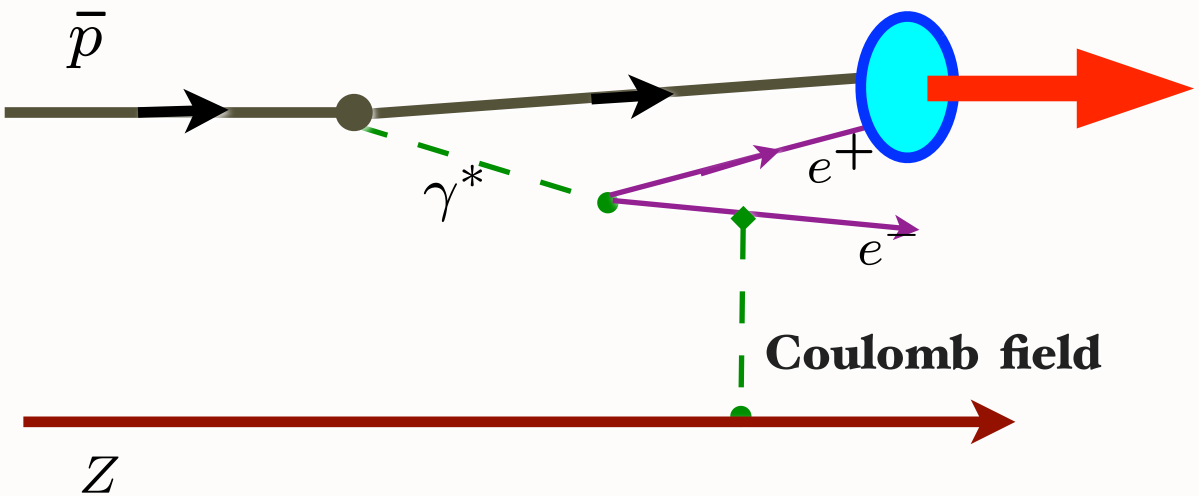

$\bar{H}(\bar{p}e^+)$

$b_\perp \leq \frac{1}{m_{red}\alpha}$

$y_{\bar{p}} \simeq y_{e^+}$

Coalescence of off-shell co-moving positron and antiproton

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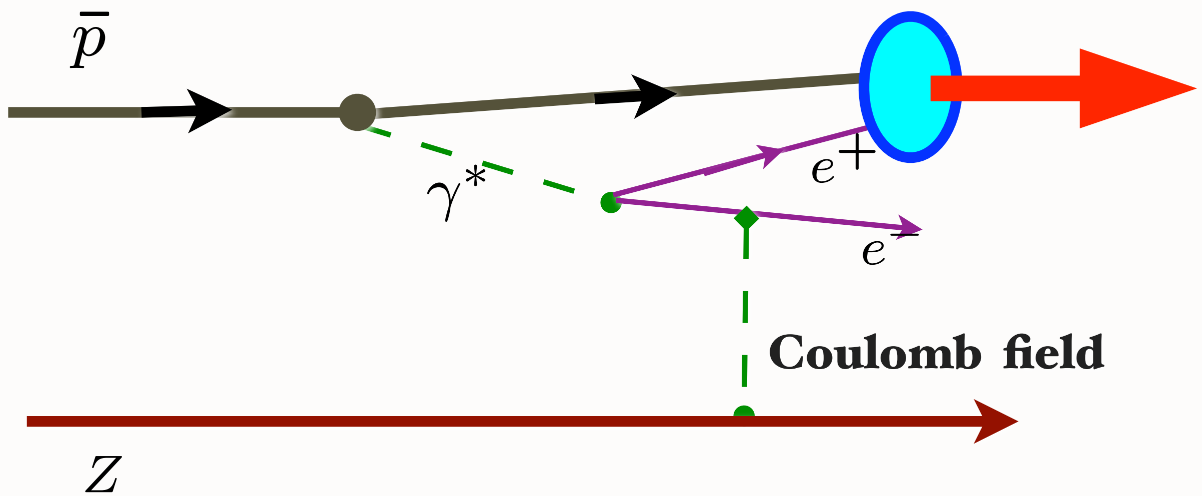

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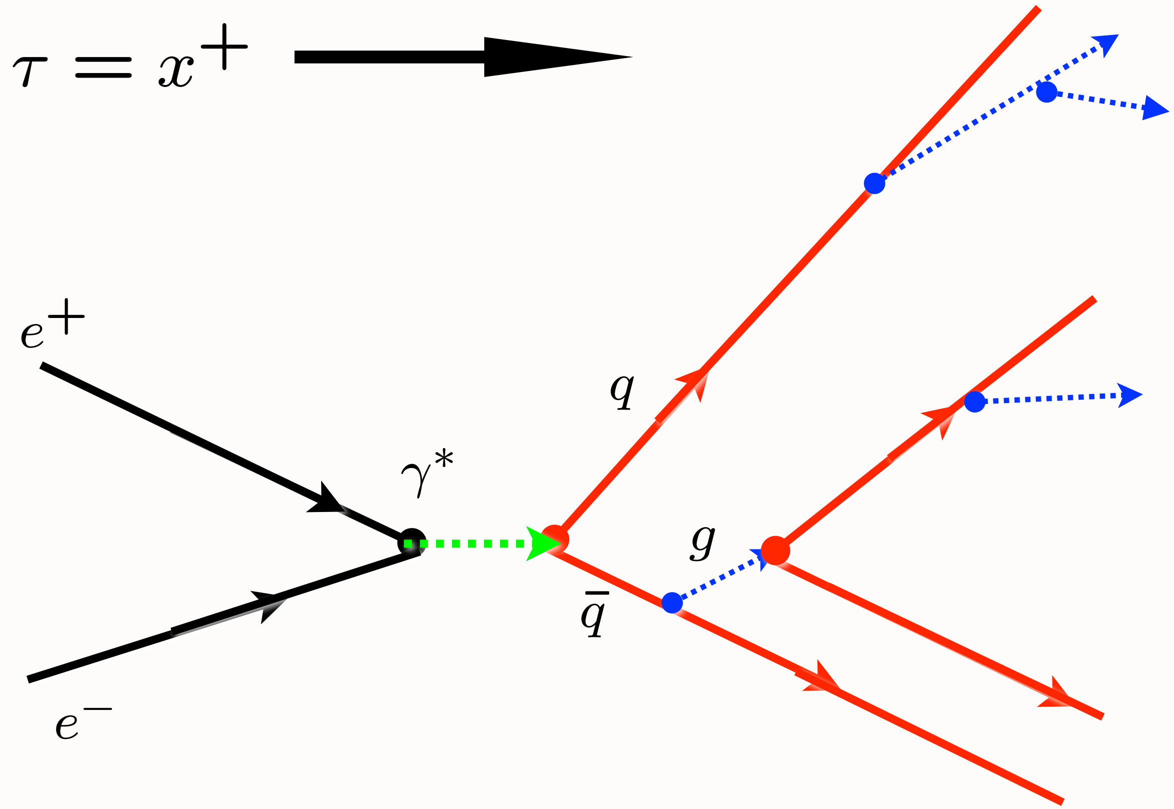
Coalescence of off-shell *co-moving positron and antiproton*

Wavefunction maximal at small impact separation and equal rapidity

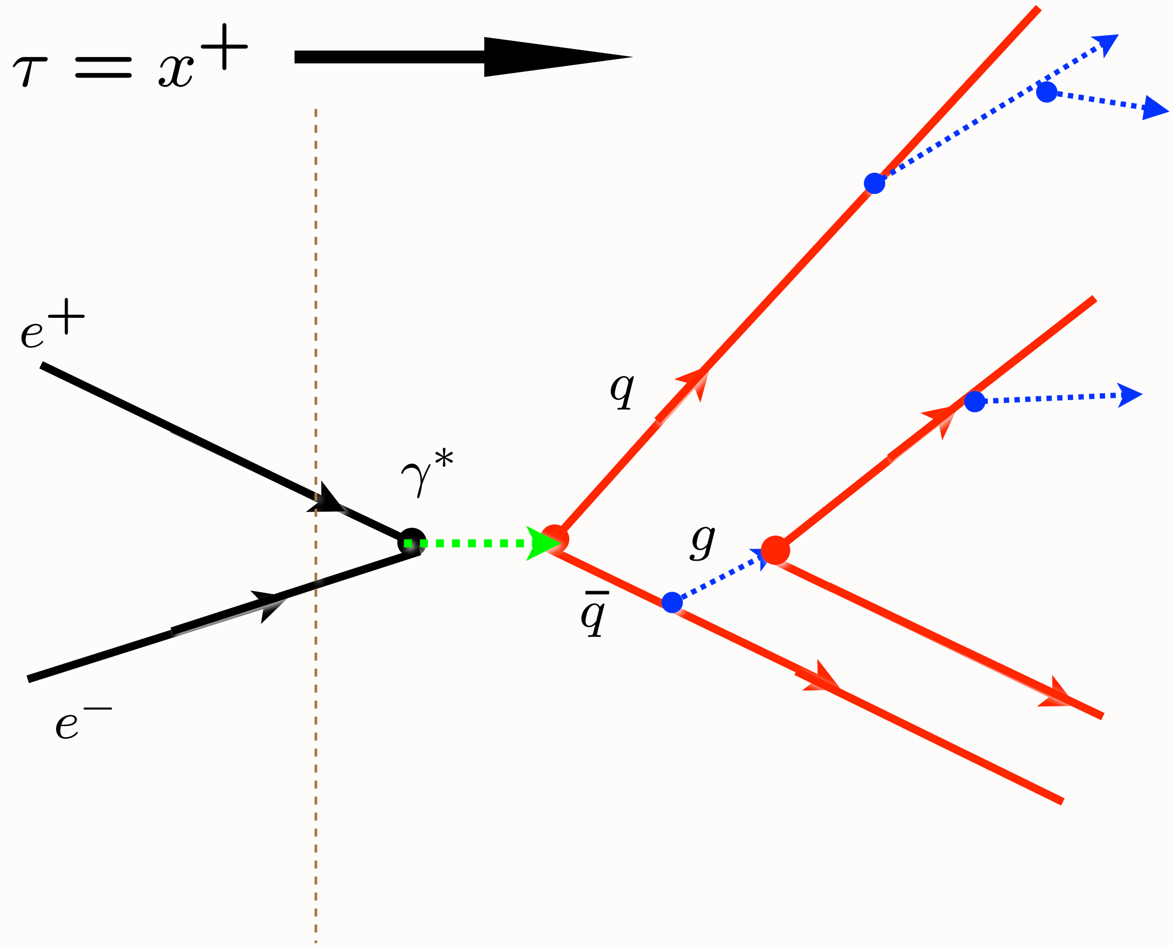
"Hadronization" at the Amplitude Level

Hadronization at the Amplitude Level



Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

Hadronization at the Amplitude Level



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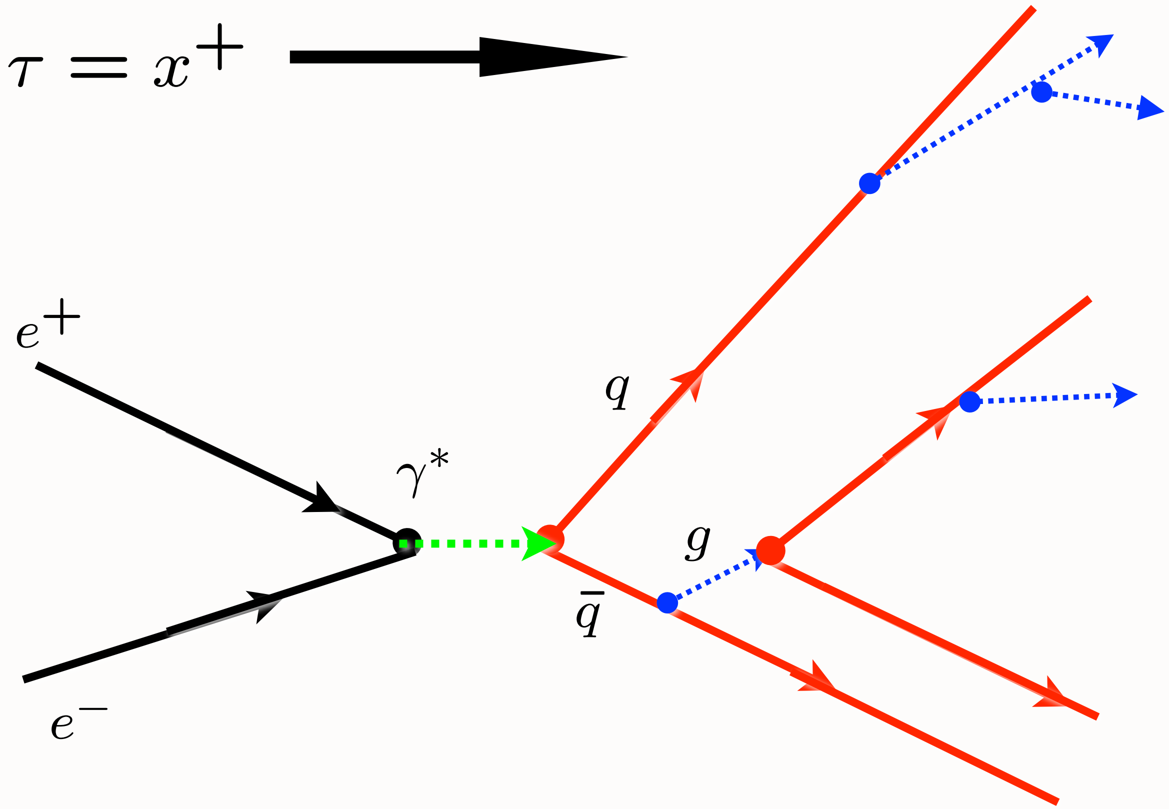

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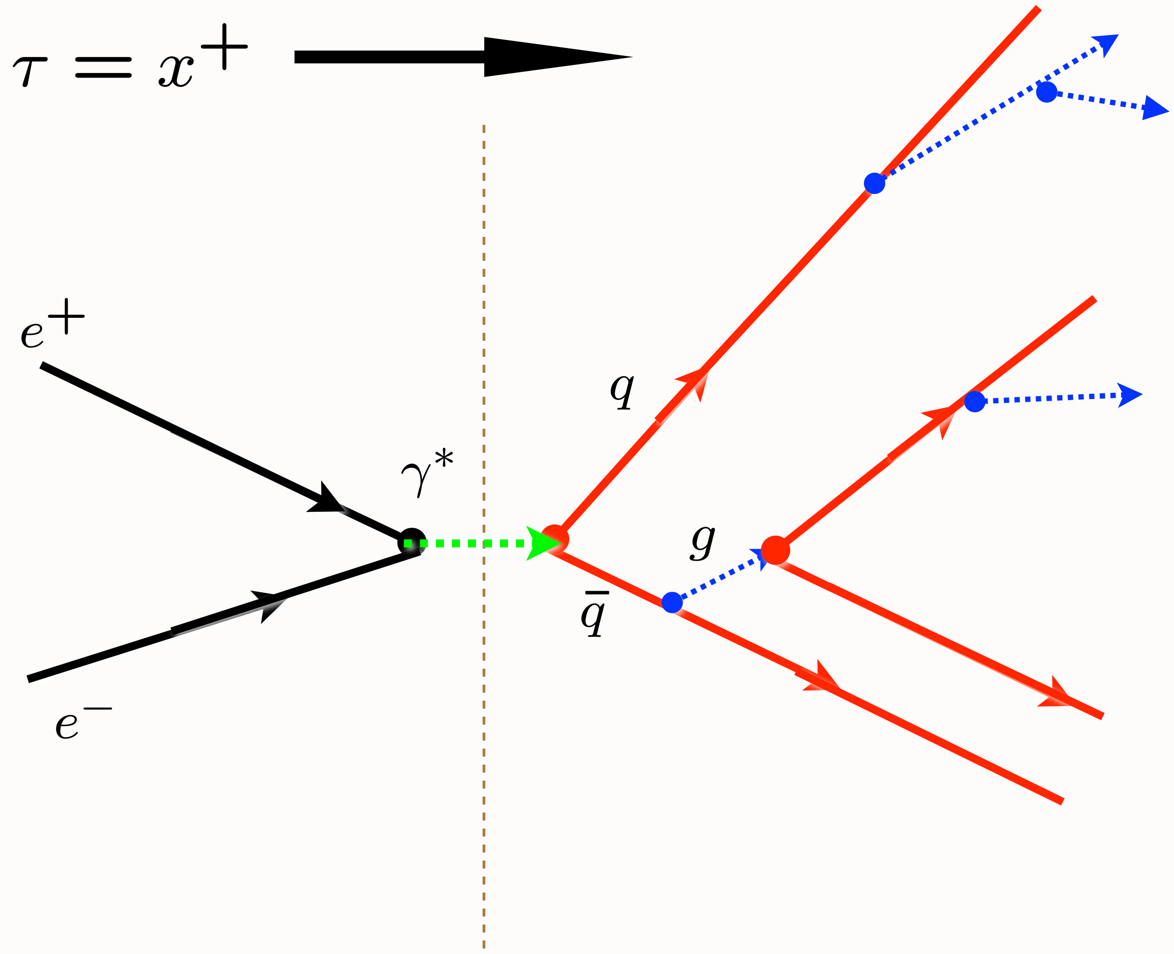

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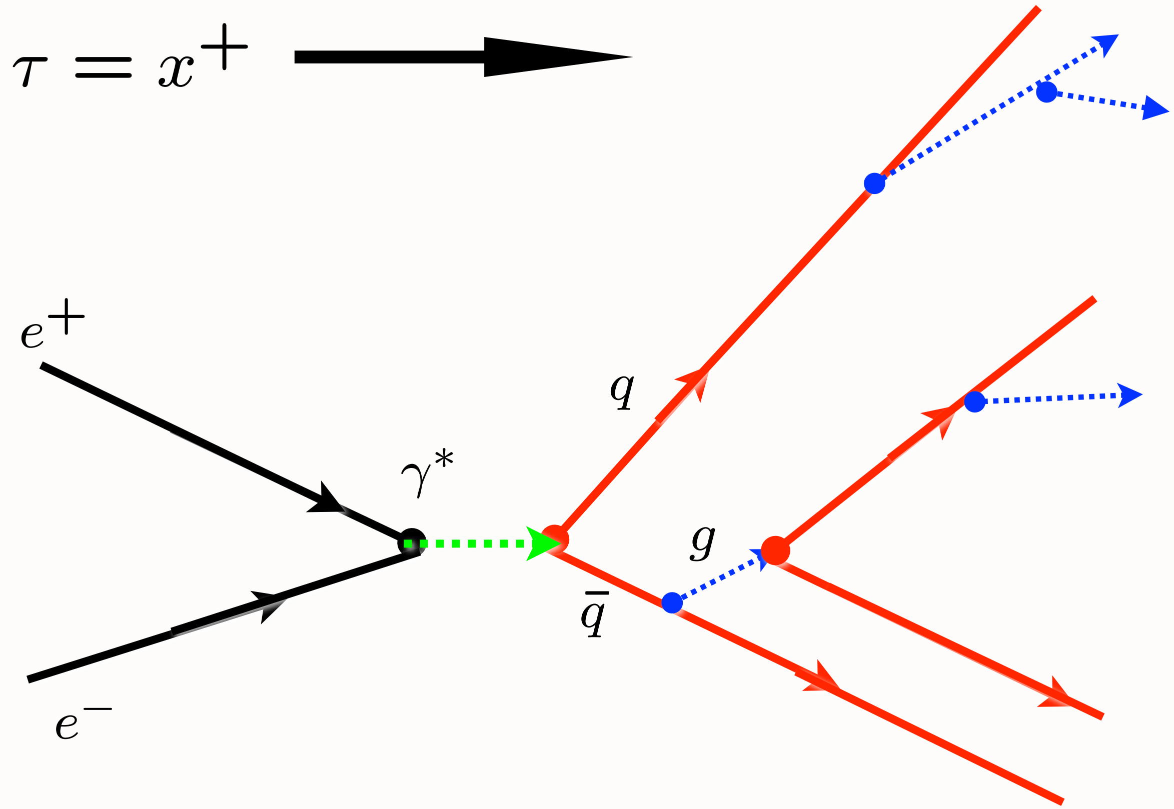

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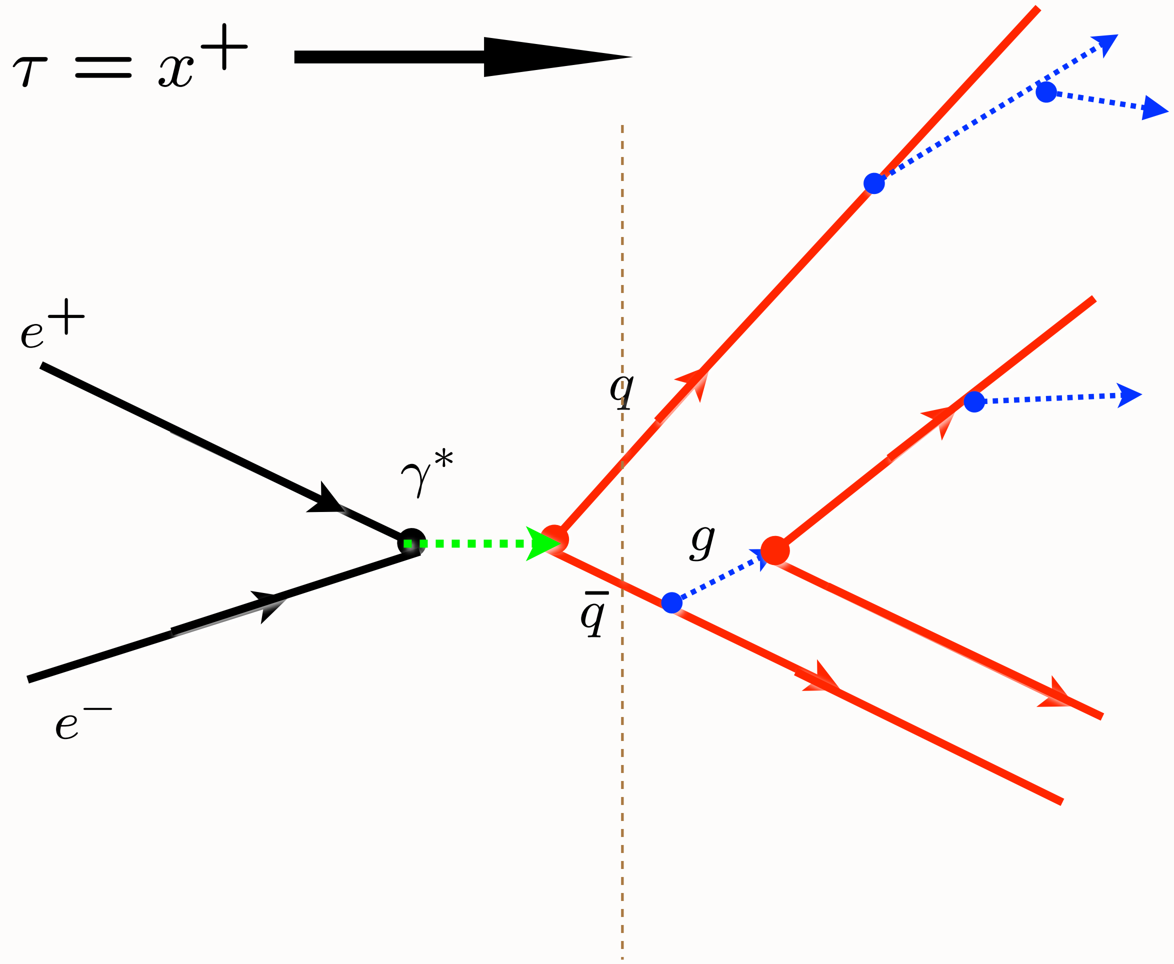

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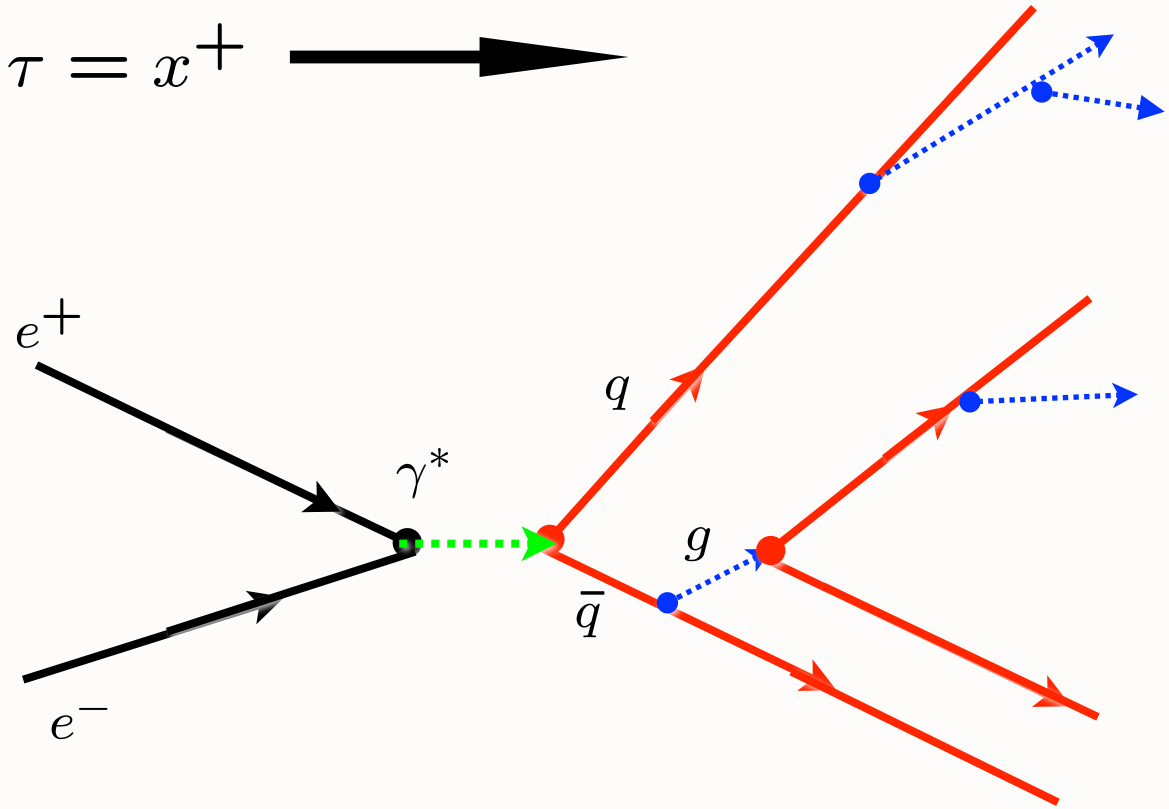

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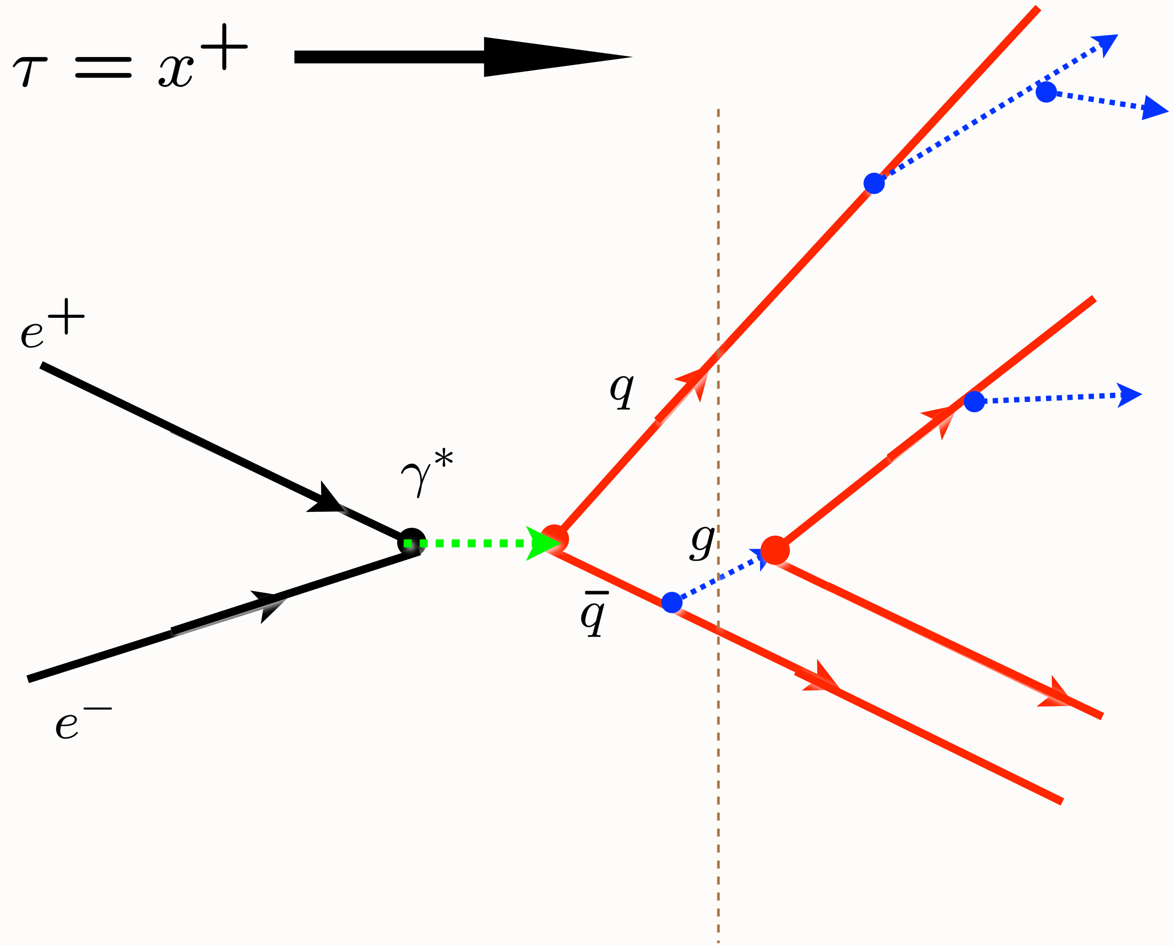

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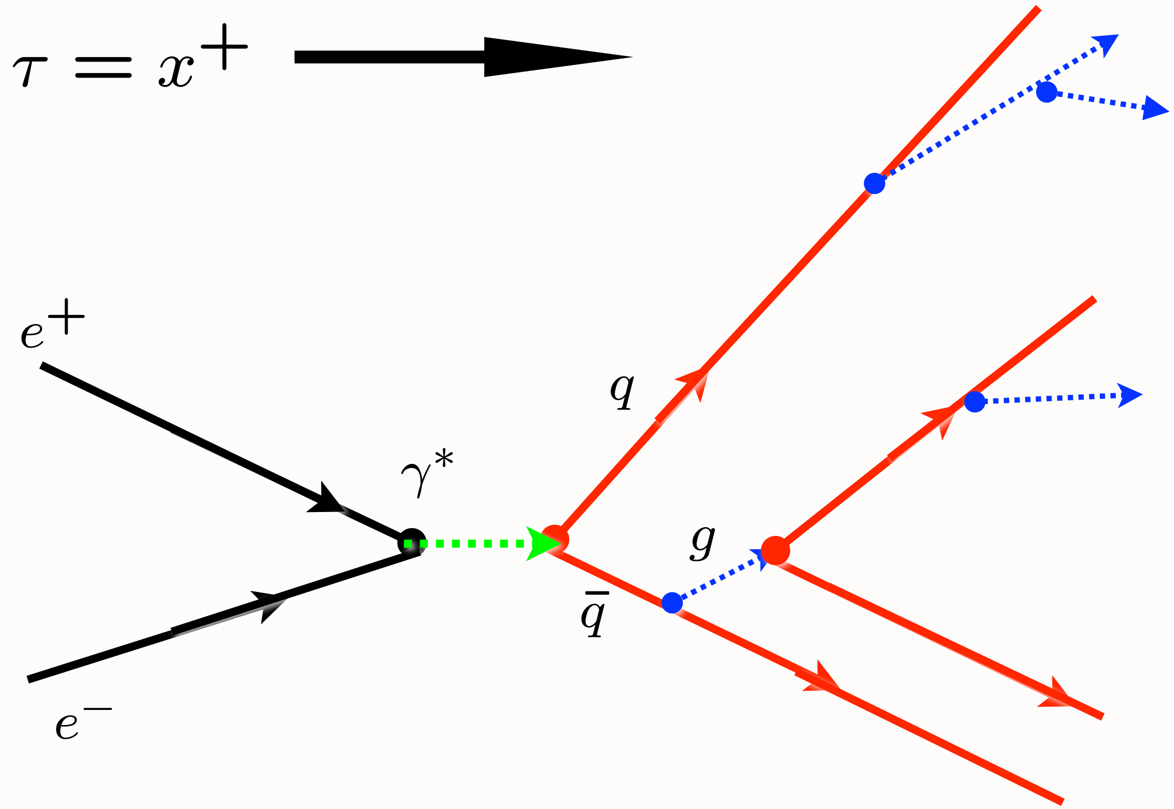

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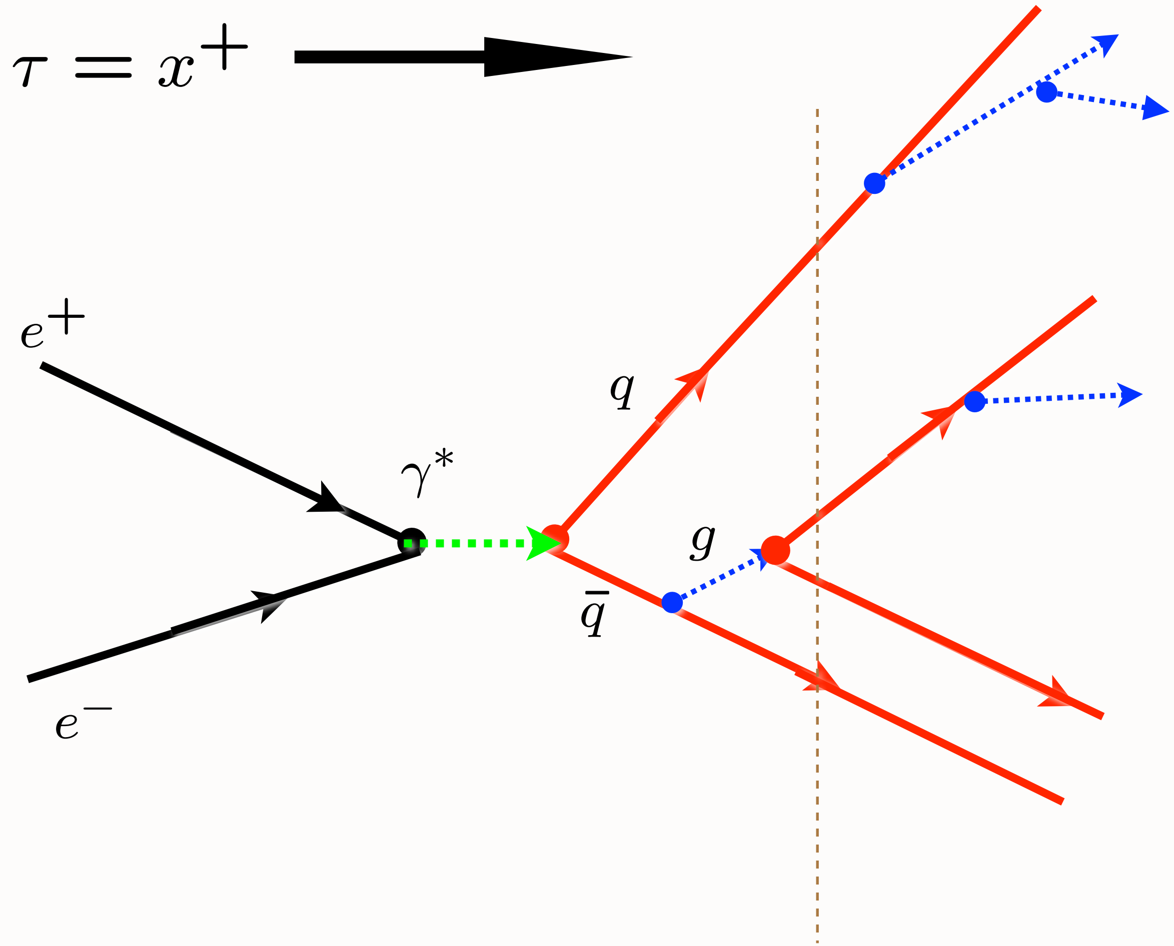

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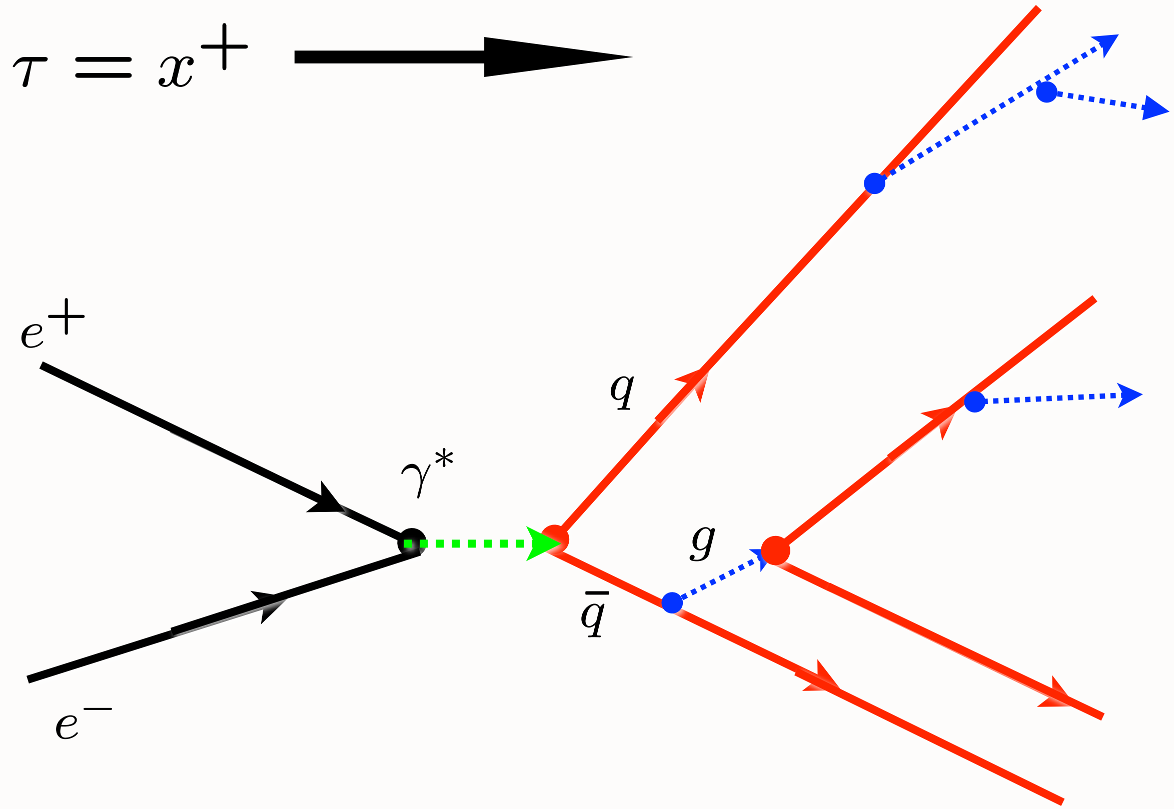

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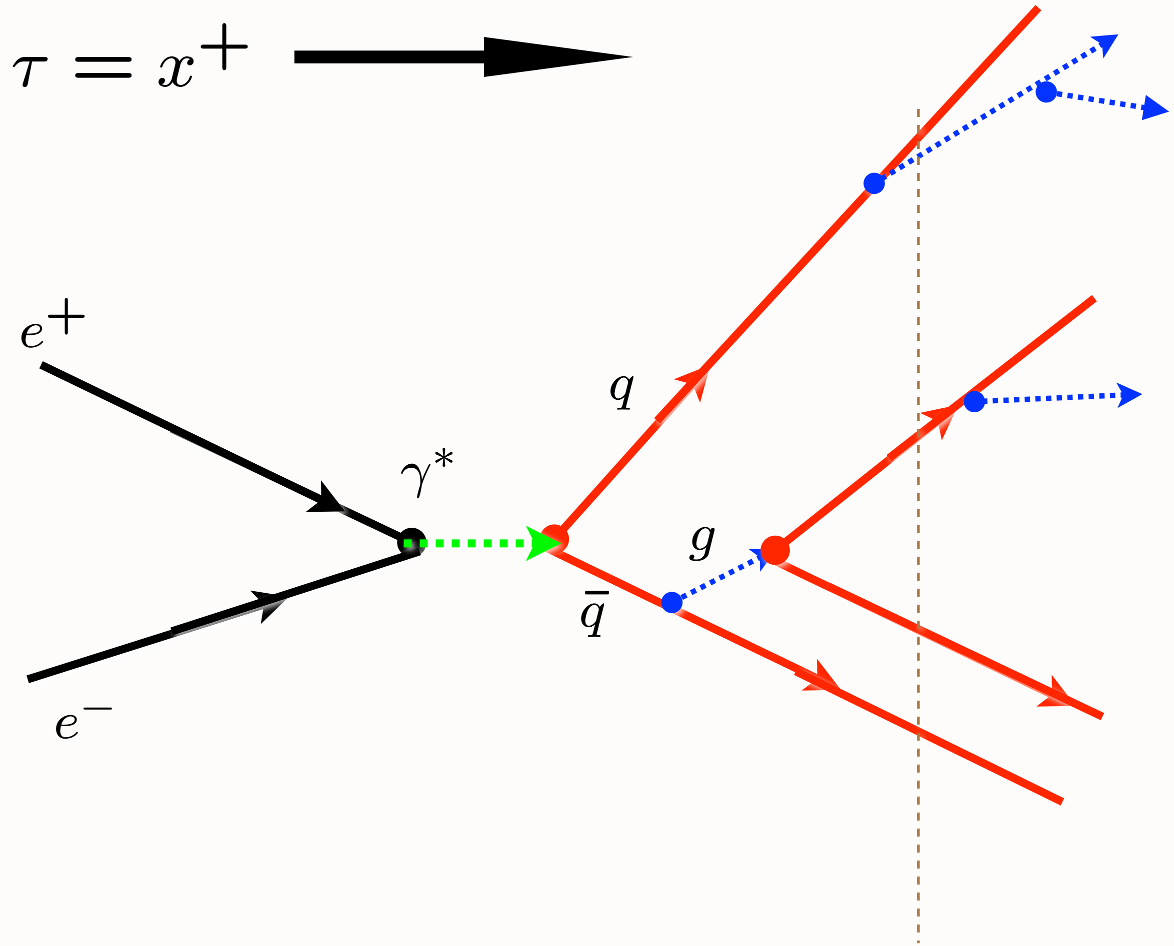
Hadronization at the Amplitude Level



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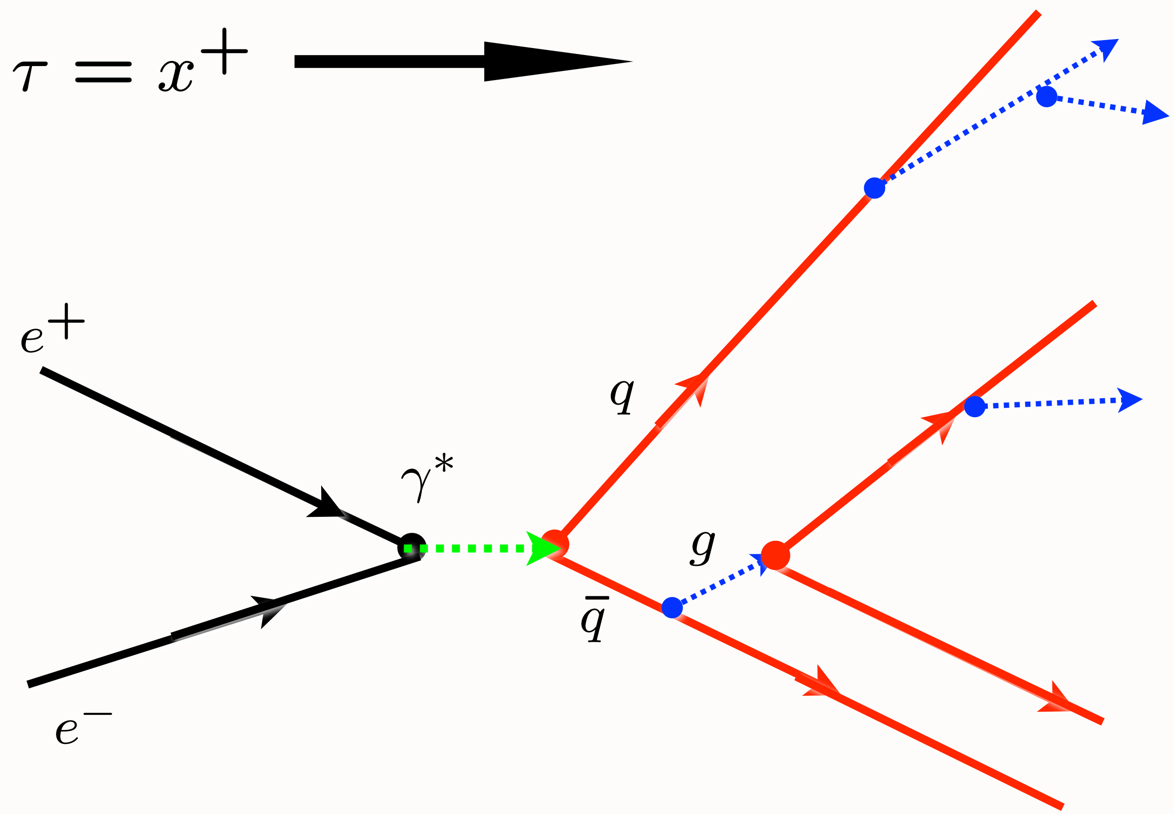

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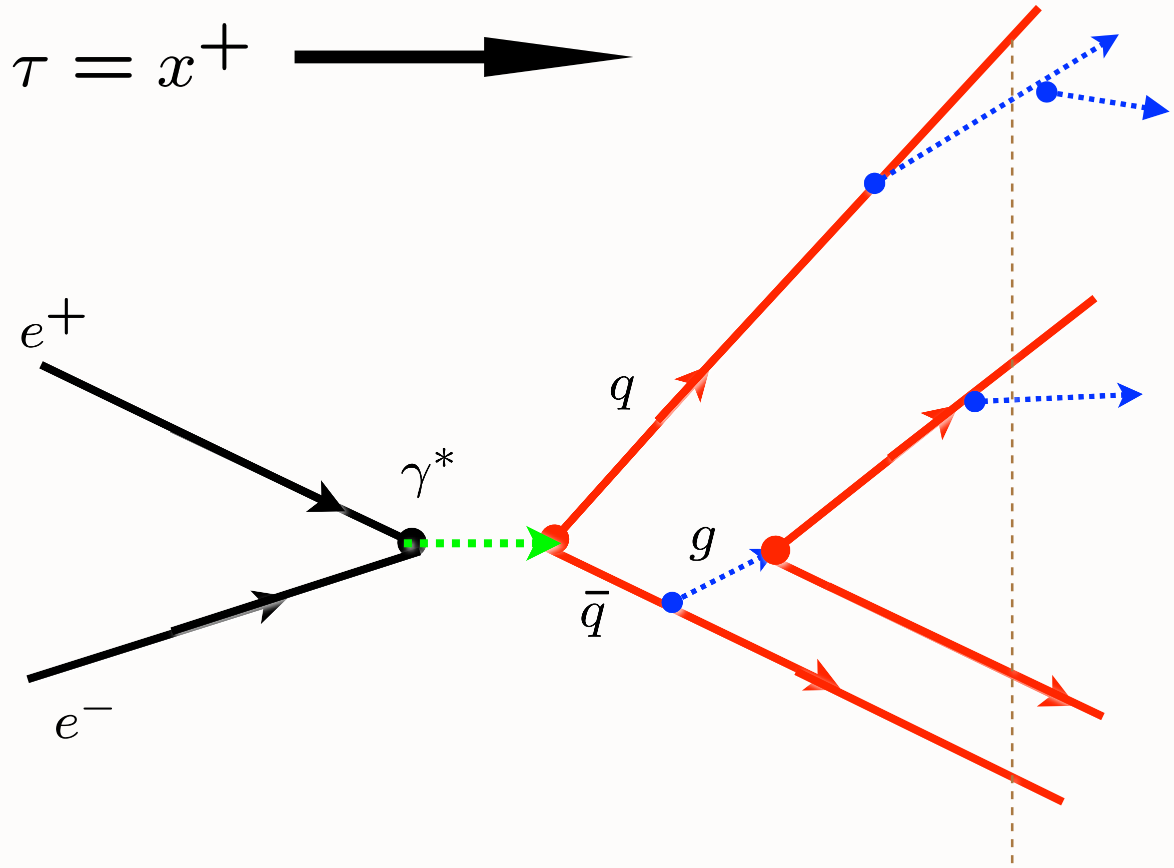

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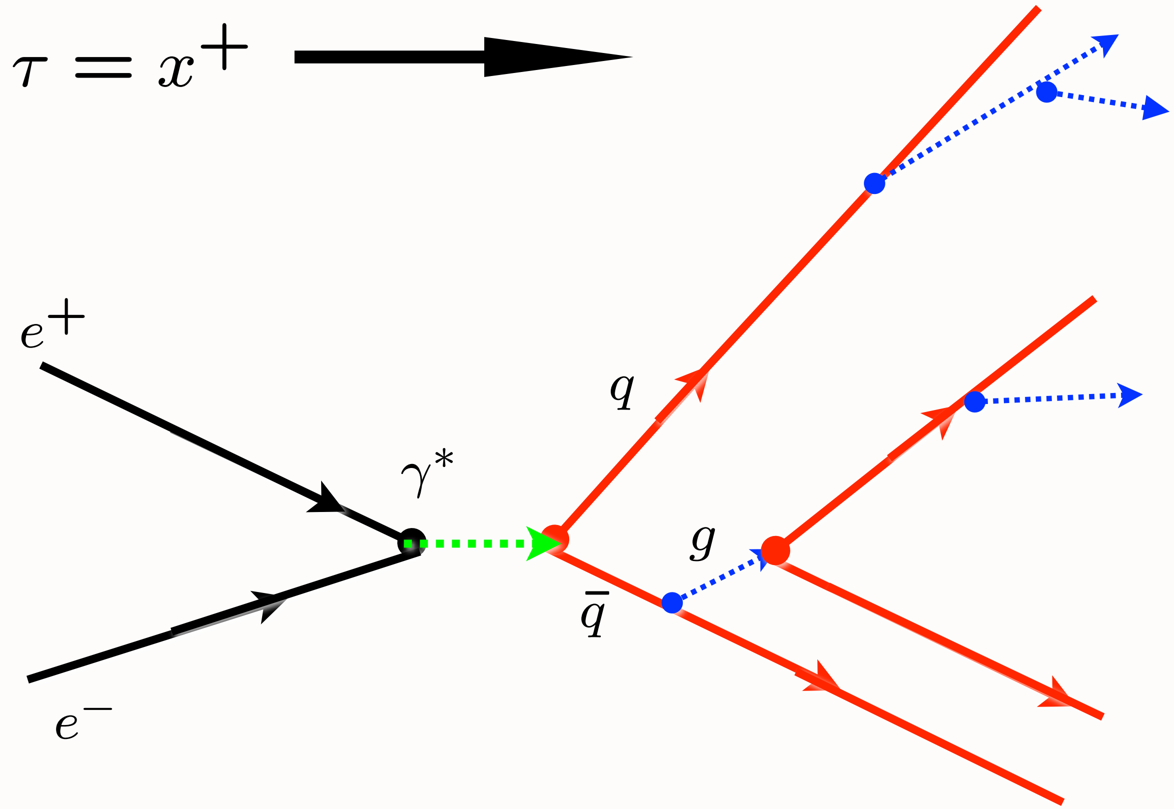

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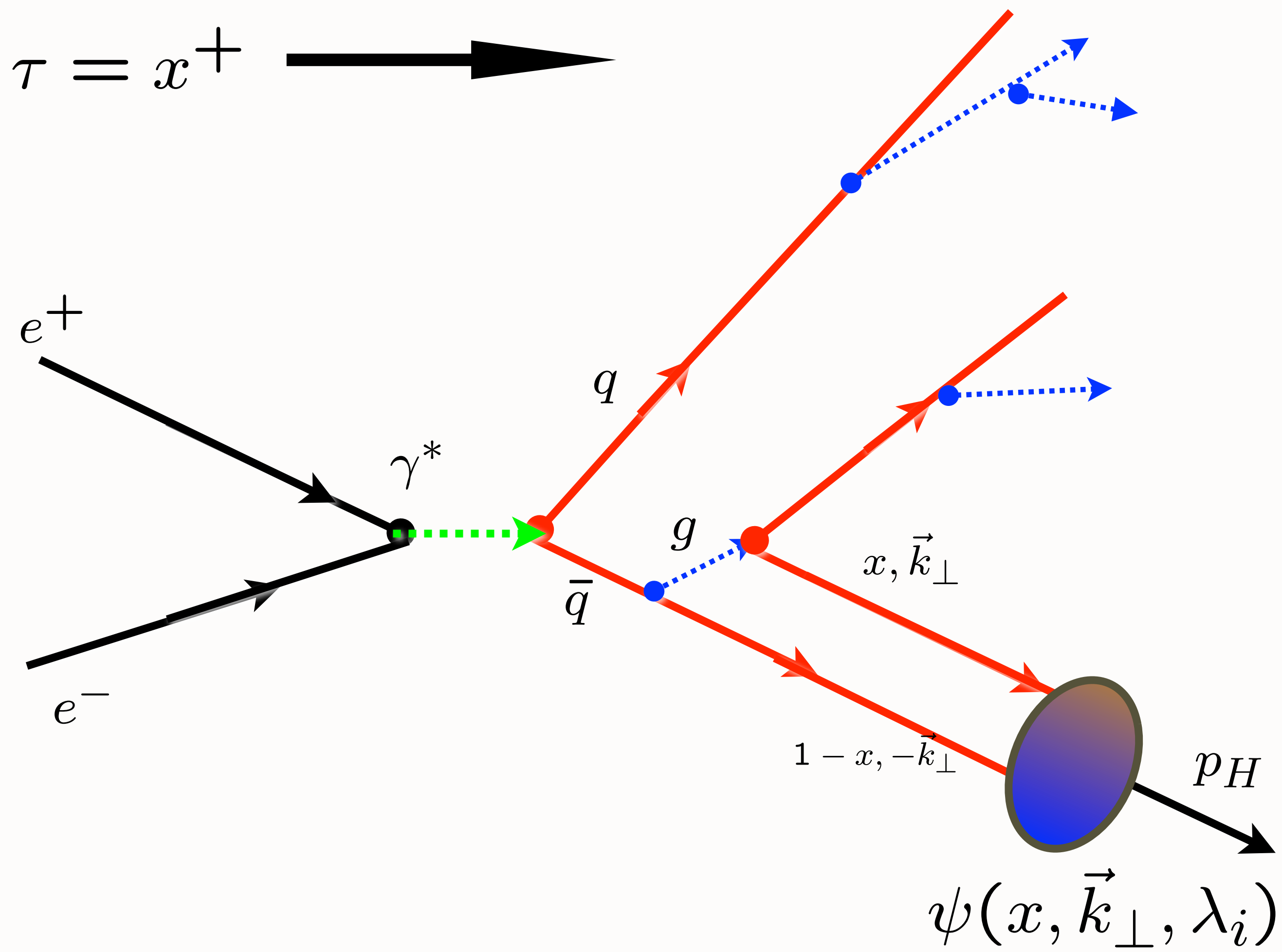

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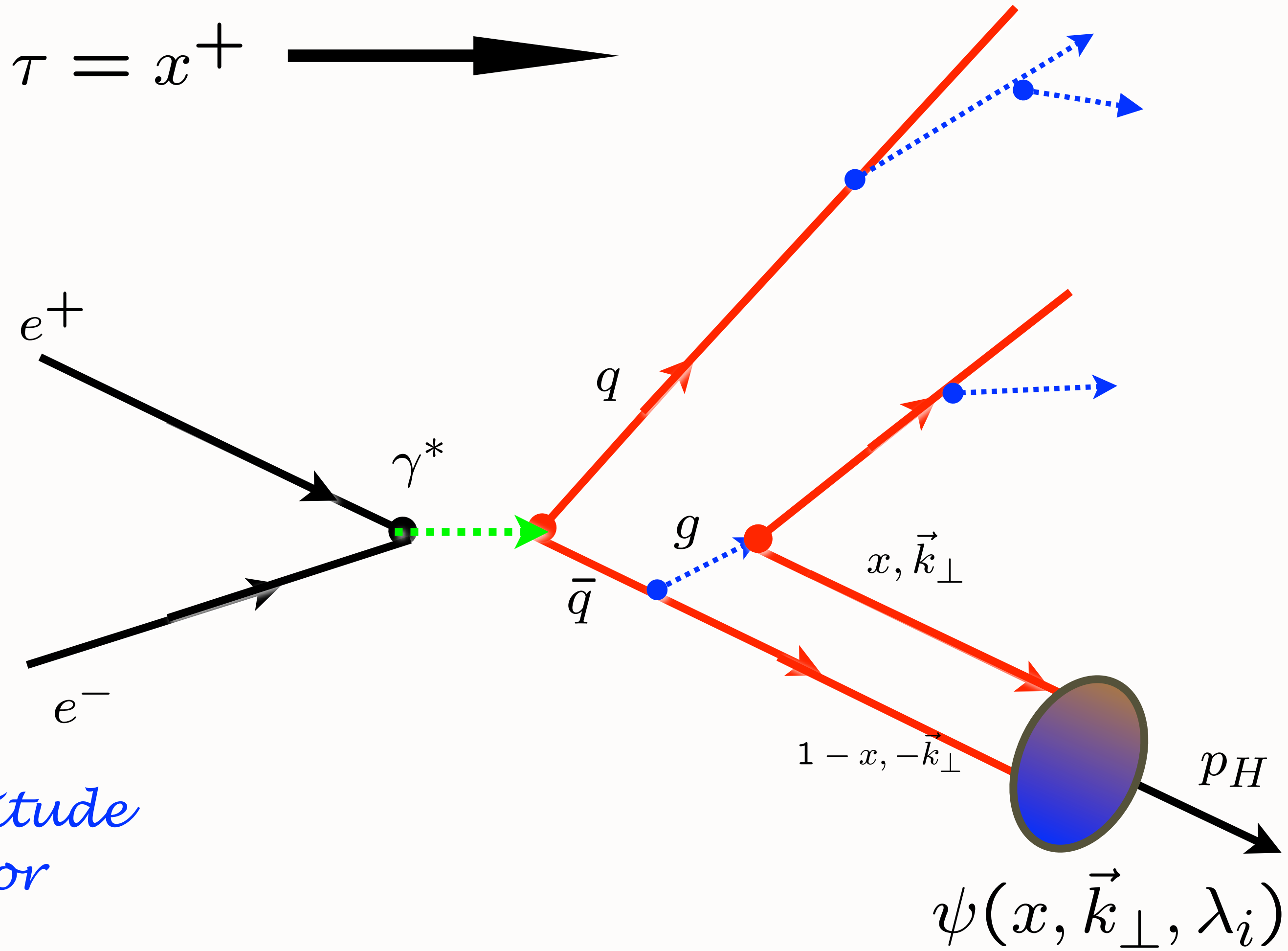
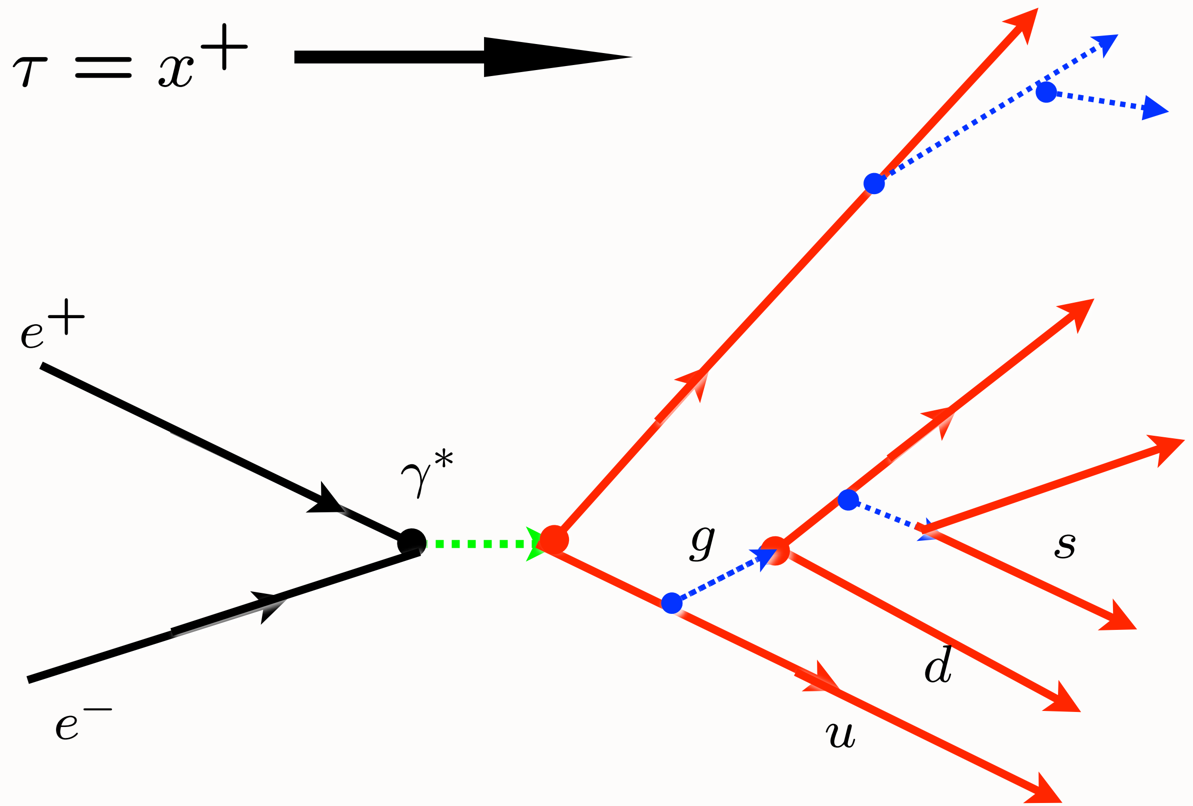


Event amplitude generator

Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

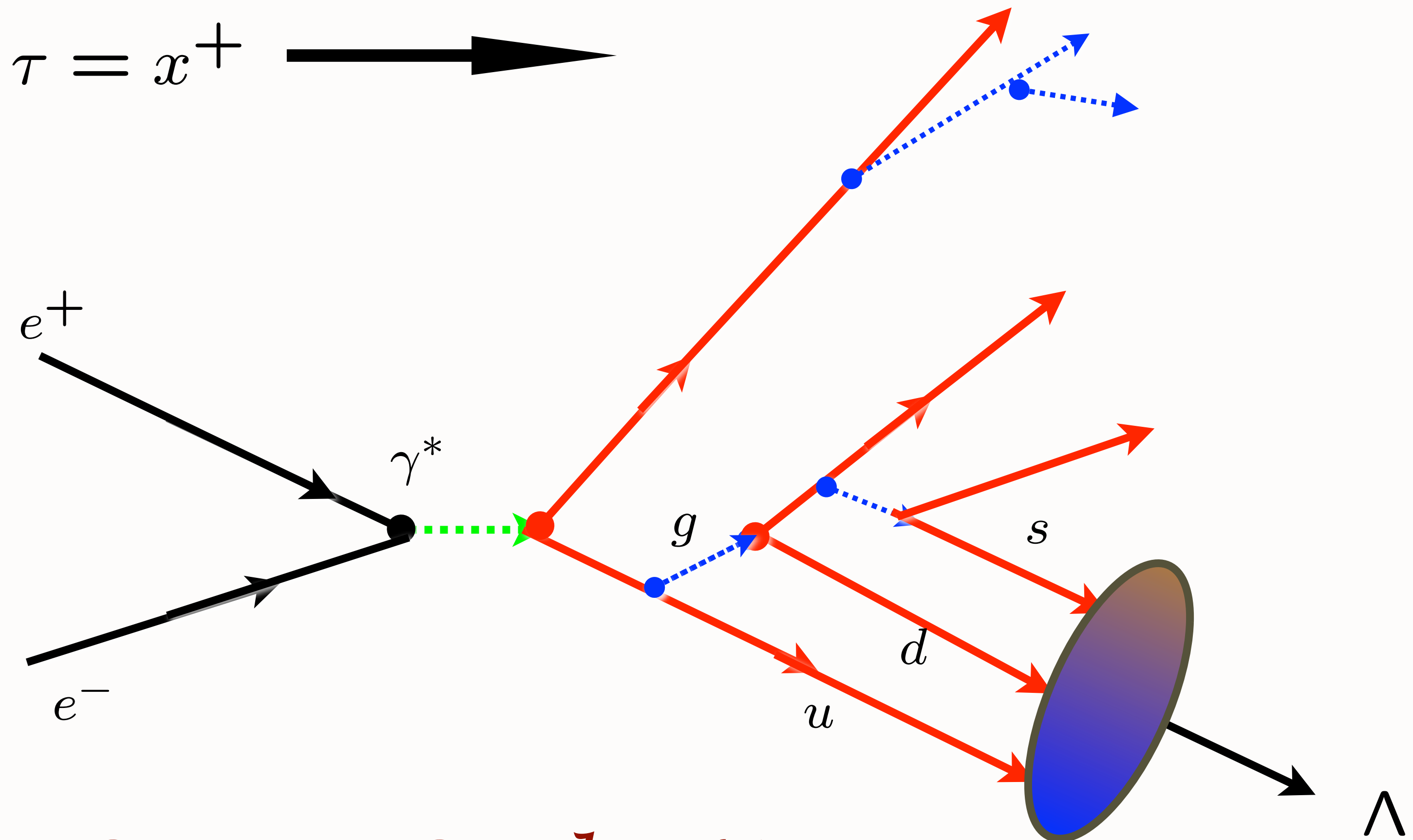
Hadronization at the Amplitude Level



Baryon Production

Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

Hadronization at the Amplitude Level



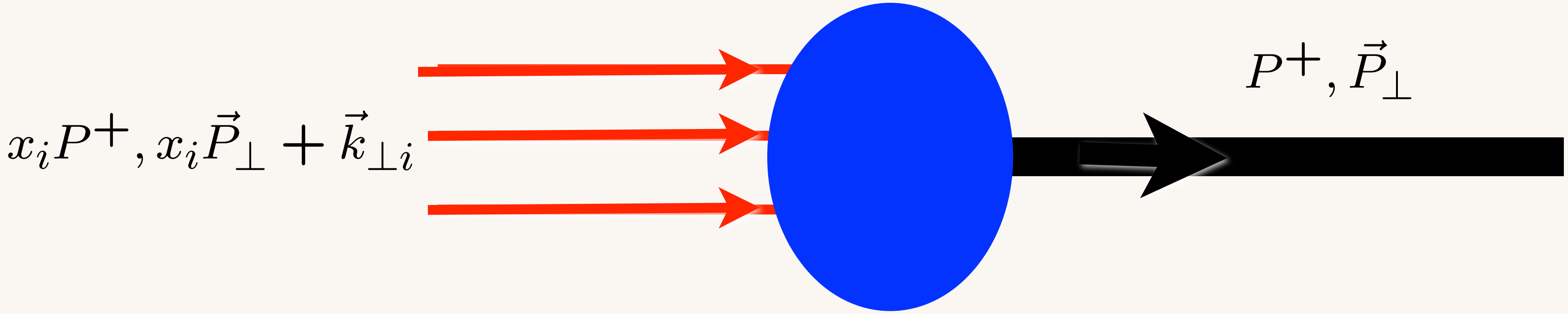
Baryon Production

$\psi(x, \vec{k}_\perp, \lambda_i)$

Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

Features of LF T-Matrix Formalism
"Event Amplitude Generator"

- Same principle as antihydrogen production: off-shell coalescence
- coalescence to hadron favored at equal rapidity, small transverse momenta
- leading heavy hadron production: D and B mesons produced at large z
- hadron helicity conservation if hadron LFWF has $L^z = 0$
- Baryon AdS/QCD LFWF has aligned and anti-aligned quark spin



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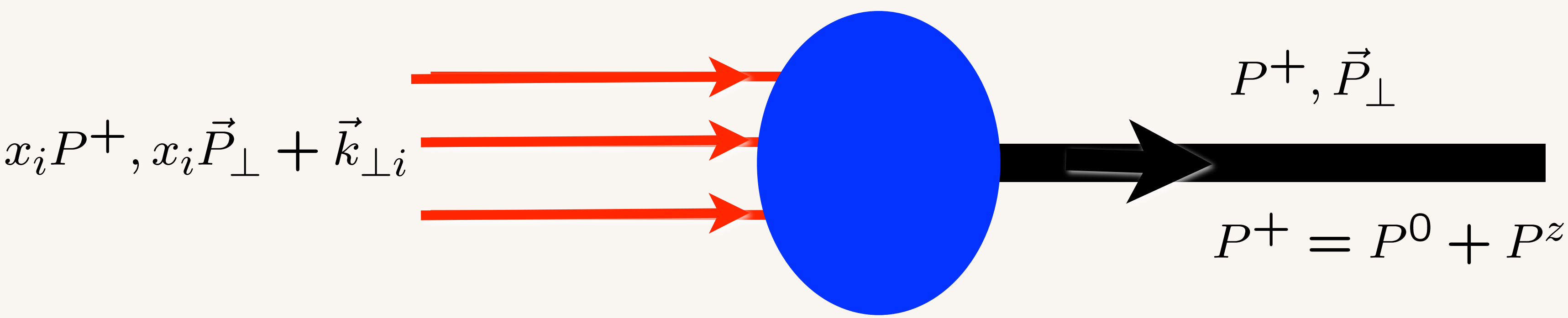
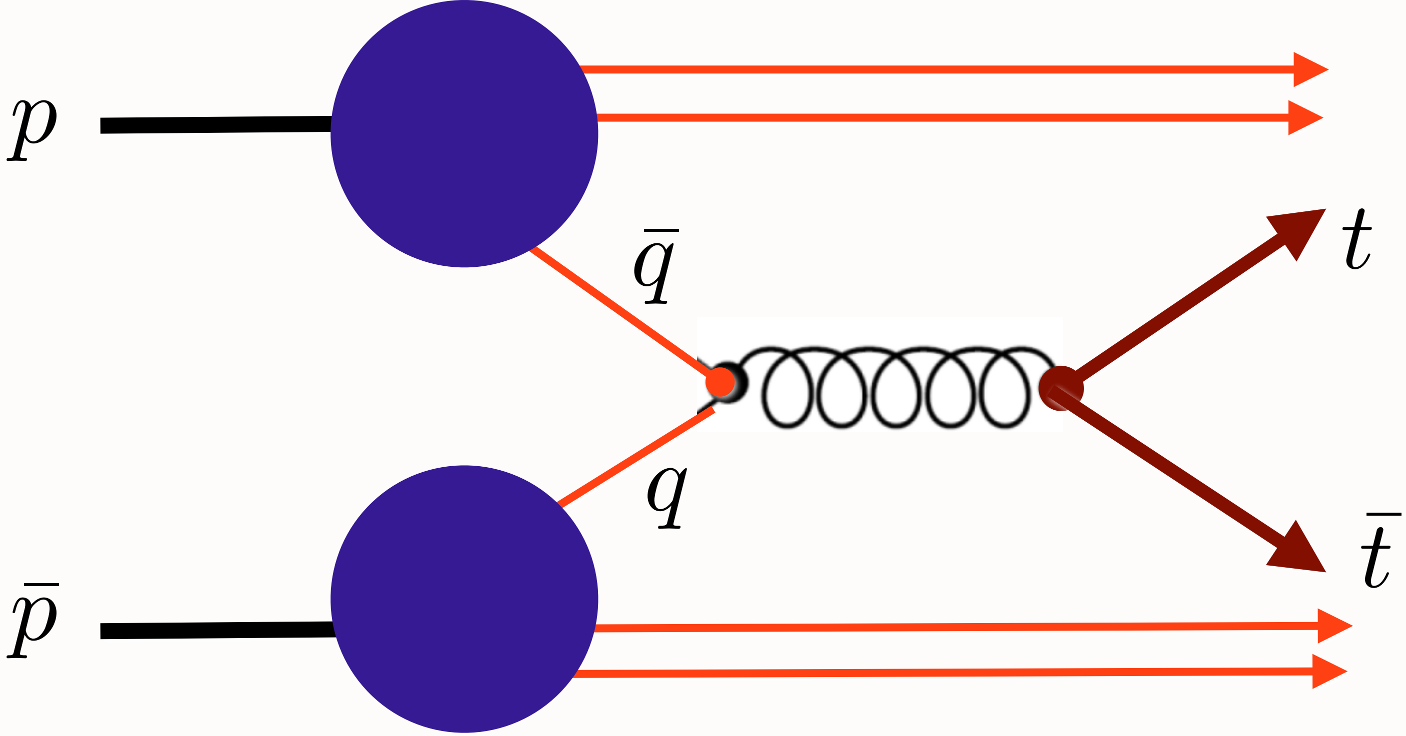
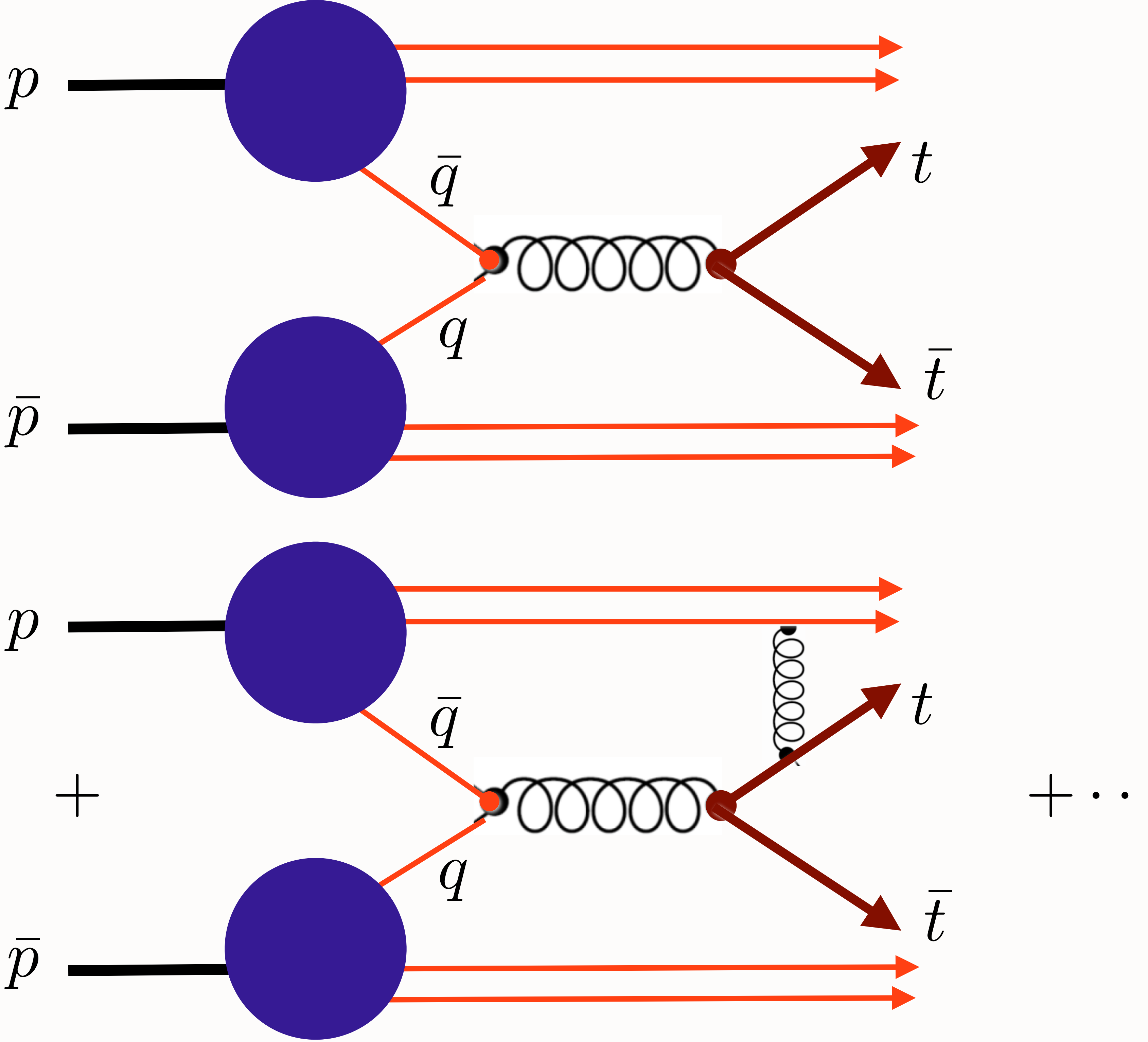
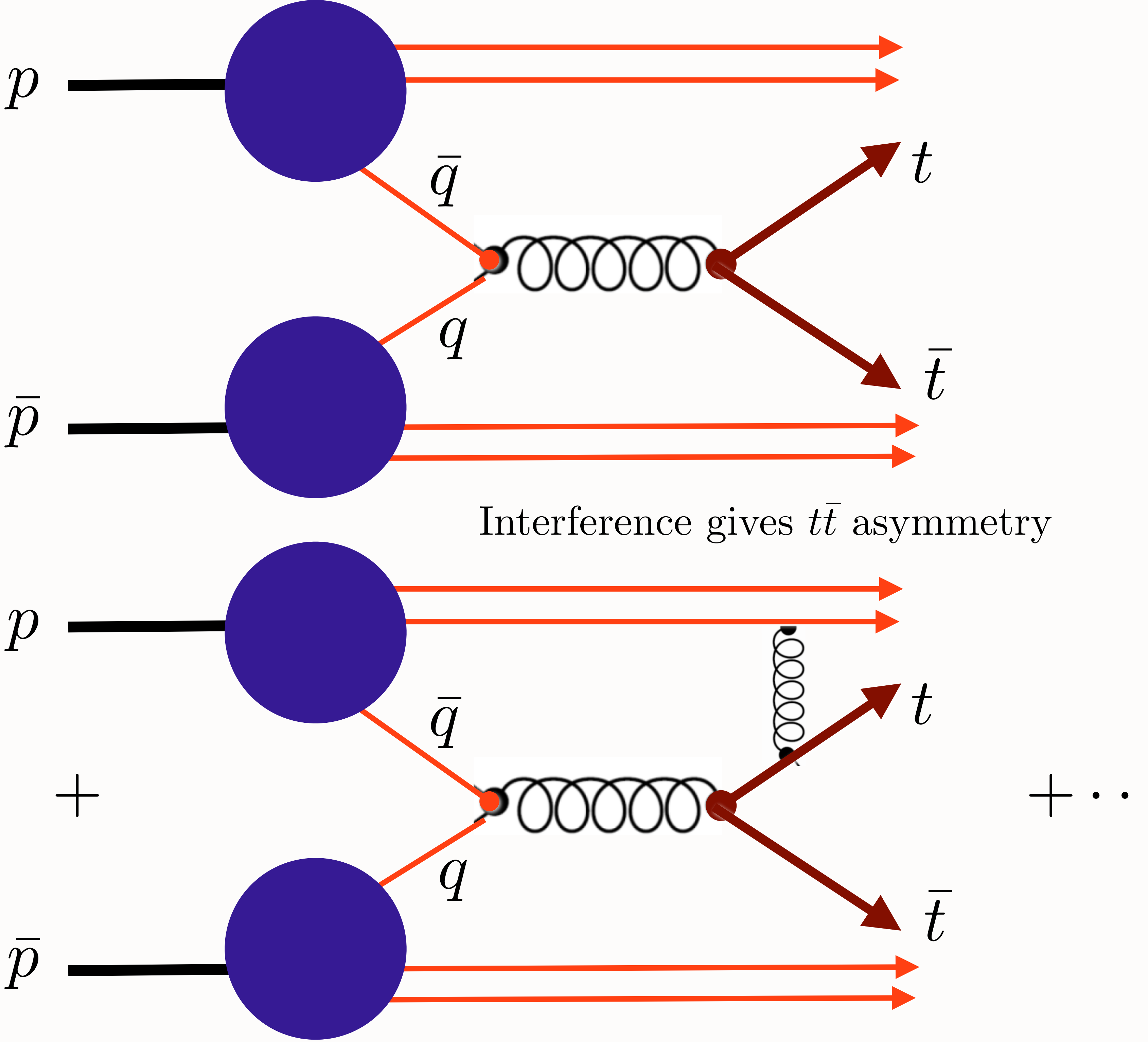




$+$ $+\cdots$


p
$\bar{q}$
t
q
$\bar{t}$
$\bar{p}$
p
$\bar{q}$
t
$+$
$+\cdots$
q
$\bar{t}$
$\bar{p}$



p
$\bar{q}$
t
q
$\bar{t}$
$\bar{p}$
Interference gives $t\bar{t}$ asymmetry
p
$\bar{q}$
t
$+$
$+\cdots$
q
$\bar{t}$
$\bar{p}$

QCD Analysis of heavy quark asymmetries

B. von Harling, Y. Zhao, sjb

- **Include Radiation Diagrams**
- **FSI similar to Sivers Effect**

$$\pi Z\alpha \rightarrow \pi C_F \alpha_s$$

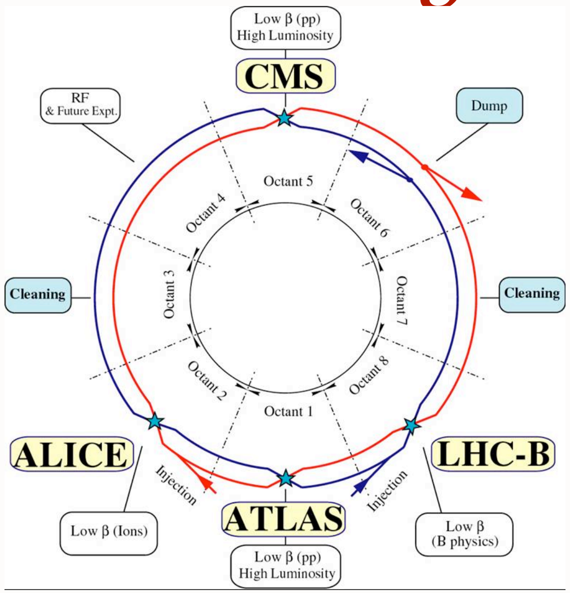
- **Renormalization scale relatively soft**

Fixed Target Physics with the LHC Beams

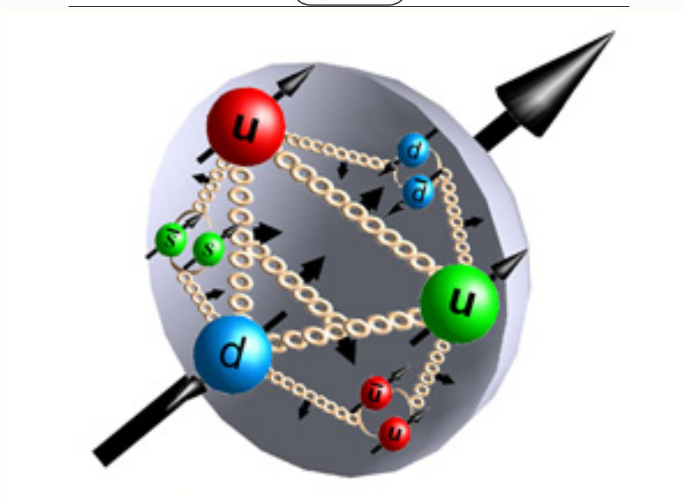
AFTER @ LHC

- 7 TeV proton beam, nuclear beams
- Full Range of Nuclear and Polarized Targets
- Cosmic Ray simulations!
- Single-Spin Asymmetries, Transversity Studies, A_N
- High-x_F Dynamics
- High-x_F Heavy Quark Phenomena
- Production of ccc to bbb baryons
- Quark-Gluon Plasma in Nuclear Rest System

The Physics Case for AFTER: Fixed Target Experiments @ the LHC



AFTER @ LHC



Stan Brodsky

CP³ - Origins
Particle Physics & Origin of Mass

SLAC
NATIONAL ACCELERATOR LABORATORY

Fall meeting of the GDR PH-QCD: Nucleon and Nucleus Structure Studies with a LHC fixed-target experiment and Electron-Ion Collider

The France-Stanford Center for Interdisciplinary Studies

Thanks to: J.-P. Lansberg, F. Fluret

October 20, 2011