Discovery of high-energy color transparency and quest for color opacity

M.Strikman, PSU

KEK, November 16, 05

Outlook

- History - rise, fall and Renaissance of quantum field theory
- Quantum chromodynamics - why still bother to study?
- High resolution needs high energies - is there a price to pay?
- Discovery of color transparency(CT) and observation of small size components in pions in the coherent diffraction: $\pi + A \to jet_1 + jet_2 + A$
- Hard exclusive diffraction at ep collider (HERA)
- Future directions:
  - *Looking for disappearance of CT at high energies - ultraperipheral collisions at LHC, eRHIC*
  - *Discovering intermediate energy CT and using it to reveal rich structure of 3q, 4q$\bar{q}$, ... configurations in the nucleon/baryons - J-PARC, GSI*

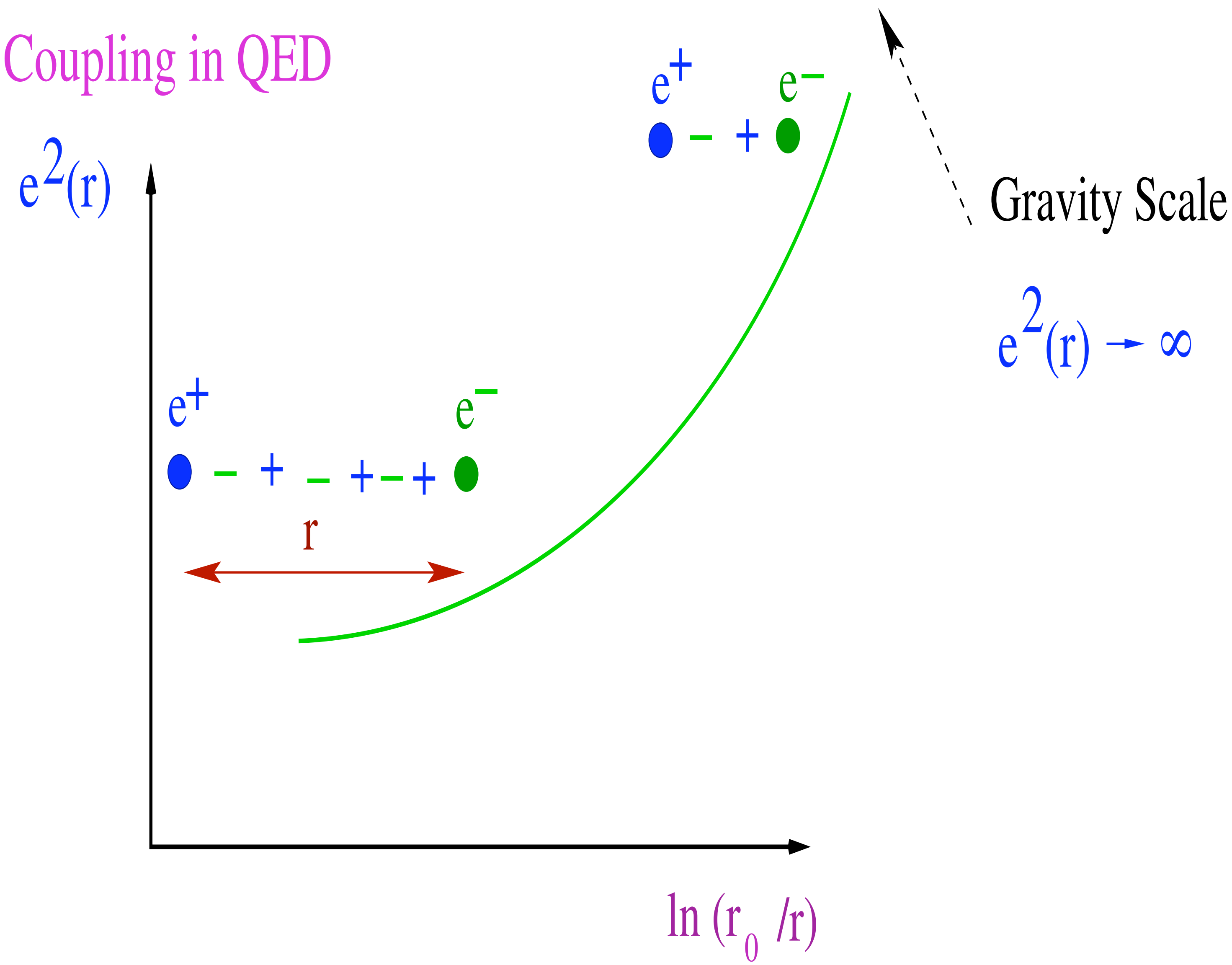
History: Soon after QED was introduced as a regular method for calculations of electrodynamical procees it was discovered that it has a fundamental problem - zero charge - Landau and Pomeranchuk (1955)

Consider interaction of two charges at distance $r < r_0$:

$$V(r) = \frac{e^2(r)}{r}, e^2(r) = \frac{e^2(r_0)}{(1 - R\frac{e^2(r_0)}{12\pi^2}\ln(r_0^2/r^2))}$$

where R=8 for $r < 10^{-17}$ cm.

Coupling in QED



$\rightarrow$ If $e^2(r=0)$ is finite, $e^2(r \rightarrow \infty)=0$

The ZERO charge problem is a generic problem for a wide class of QFT - all QFT known before 1972. For meson-nucleon QFT - a huge problem because the strength of interaction is large ~ 1 at large distances.

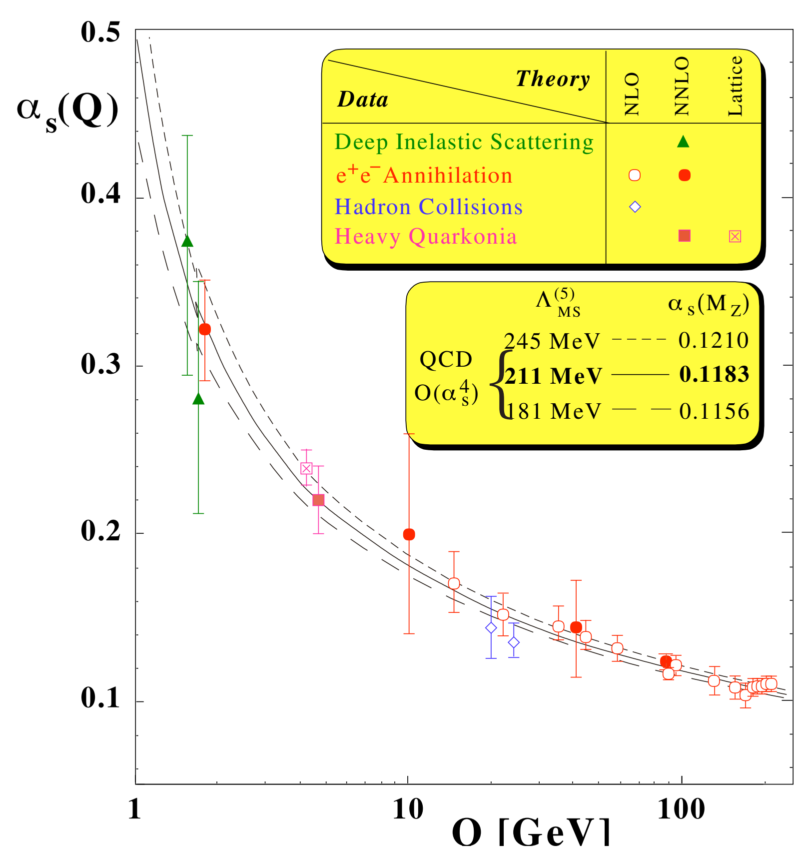
I.Pomeranchuk (∼ 1956) - "Our theory predicts infinities for the pion-nucleon interaction for small energies, but Nature seems not to know about this."

$\Longrightarrow$ No interest in using QFT to describe elementary particle dynamics (except QED) for nearly twenty years.

Why QCD is interesting

QCD is the only QFT realized in Nature which is potentially self consistent at all distances:

Interaction is strong at large distances - may provide confinement	$\Leftrightarrow$	Interaction is weak at small distances. No problems except perhaps small x.



Summary of measurements of $\alpha_s \propto$ the square of the color charge. Fits correspond to the theory predictions.

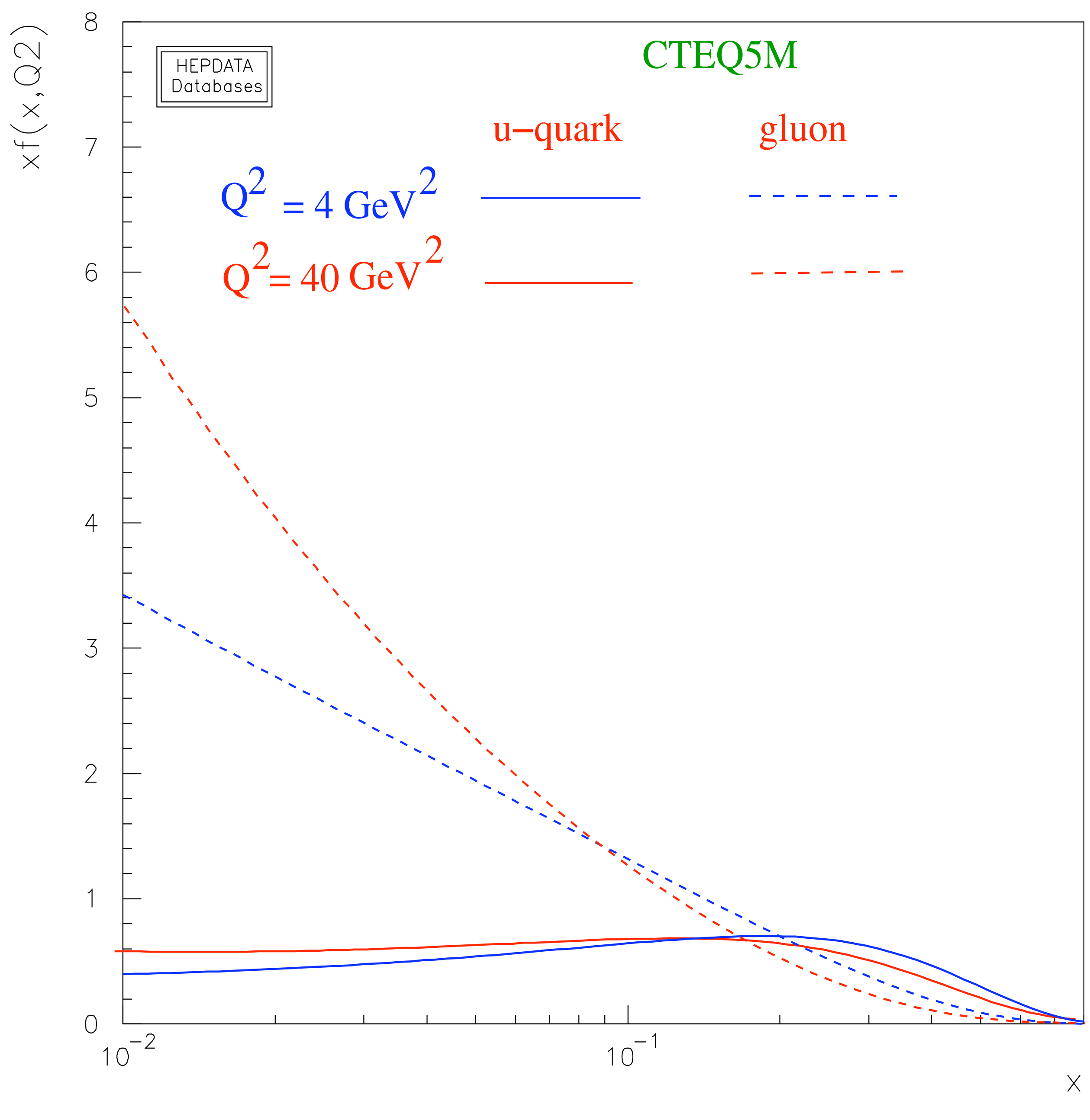
Hence in QCD situation is opposite to the one in quantum electrodynamics (and electroweak theory) where *interaction is weak at large distances and increases at small distances.*

Experiments decisively confirm QCD for hard inclusive processes when a large momentum is exchanged between quarks/gluons and extracted distributions of partons over x- the fraction of the proton energy carried by a constituent for different *resolution scales*.

Two observations important for our discussion:

• the large Q^2 "deep inelastic" electron - nucleon scattering shows (see next slide) that in line with QCD expectations at high resolution nucleon consists of not simply three quarks and few gluons but of tens of constituents and the number of constituents rapidly grows with energy.

♡ Gluons carry $\sim$ 50% of the nucleon momentum at the resolution scales as low as $Q^2 \sim m_N^2$.



xf(x,Q2)
HEPDATA Databases
CTEQ5M
u−quark
gluon
Q2 = 4 GeV2
Q2= 40 GeV2
8
7
6
5
4
3
2
1
0
10−2
10−1
X

⇒ The main trusts now are to understand nonperturbative aspects of the theory, structure of the bound state, and interplay with perturbative physics in various limits. Achieving this goal would certainly have many implications for building grand unified theories and improve interface with nuclear physics.

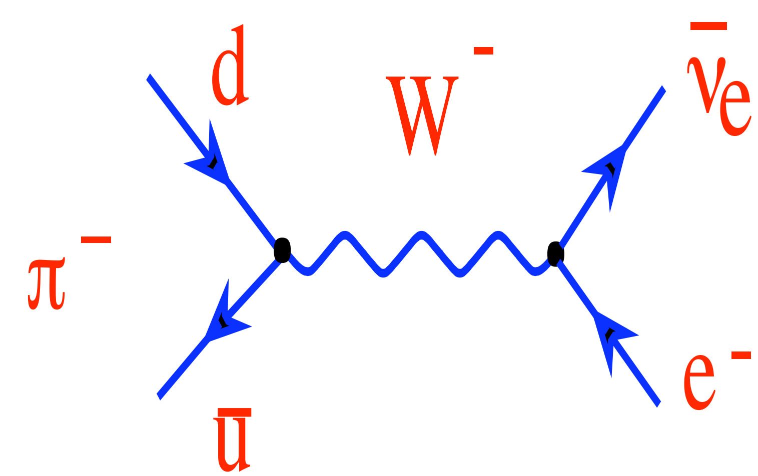
⇒ Understanding of the high-energy QCD dynamics would allow to ask more advanced questions for intermediate energies, like color transparency for large angle exclusive reactions at the energy range which was started at BNL and which can be studied in detail at JPARC and GSI

Two questions important for the understanding of strong interactions which can be addressed via studies of color transparency/opacity phenomena:

- What is the origin of the total cross sections of hadron-hadron interactions? Are they always a weak function of energy? Can hadron collapse to a small configuration and interact with much smaller cross section than the average one - color transparency. If so, would this effect disappear at very high energies - color opacity.

- Can one measure the wave functions of hadrons? Can a high energy hadron exist is a configuration with no gluon field if looked at by a high resolution probe?

How can the process of decay happen like $\pi^- \to W^- \to \mu\bar{\nu}_\mu$, $\rho \to e^+e^-$, where q and $\bar{q}$ have to come very close together **and leave no gluon field behind.**

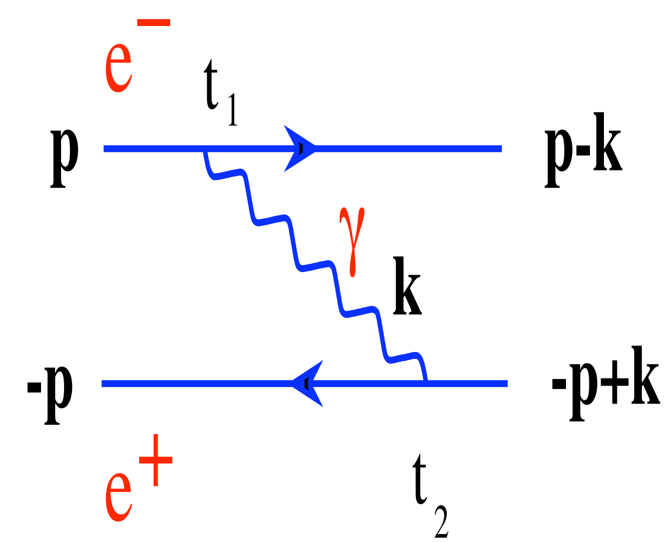


remember - in average gluons carry 50% of momentum !!

Measurement of the wave function in QFT is tricky - *in difference from quantum mechanics the wave function of a bound state depends on the resolution - Landau and Peierls (1930) argued that wave funcion cannot be measured at all for distances smaller than the pion Compton length*

How can we understand this in the rest frame: Consider a bound state of electron and positron - positronium. Binding is via photon exchange.

At the moment $t = t_1$ a photon with momentum k is emitted by e^- and **later** absorbed at $t = t_2$ by e^+. What is $\Delta t = t_2 - t_1$



Consider an example:

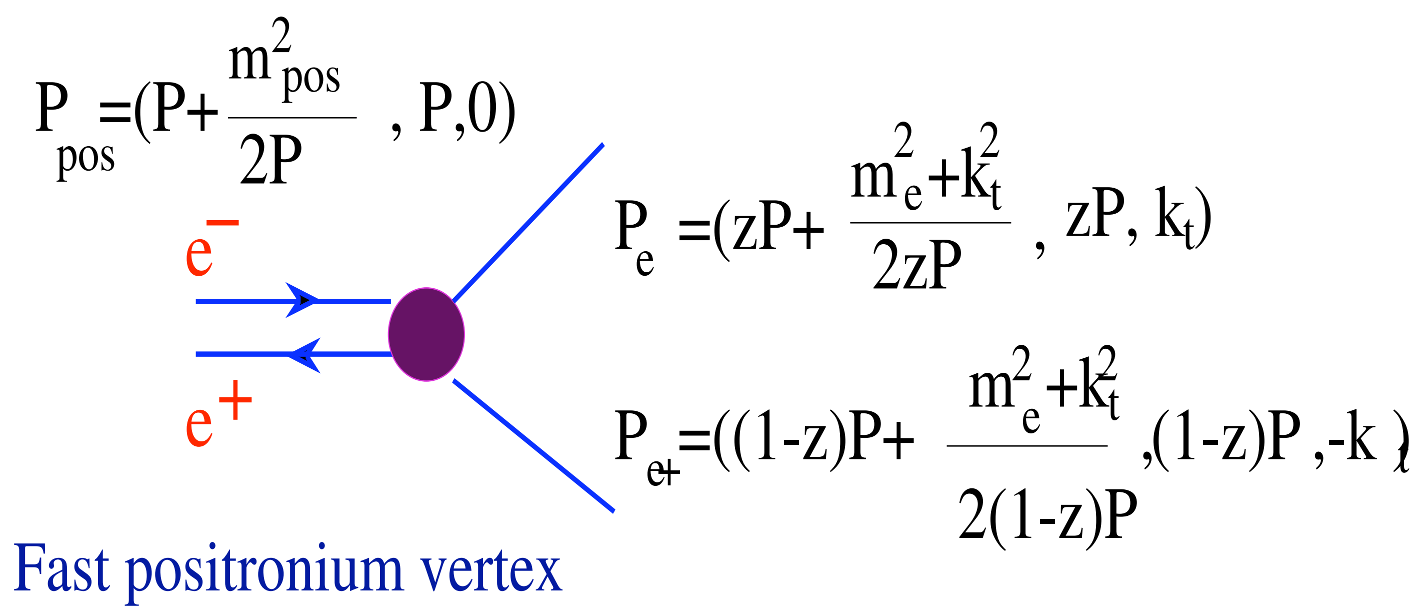
$|\vec{p}| \ll \left|\vec{k}\right|$ $(c = \hbar = 1)$: $\Delta t \sim \frac{1}{\Delta E} \approx \frac{1}{E_{int.state} - E_{Positr}} \approx \frac{1}{\sqrt{m_e^2 + k^2} + |k| - m_e} \Rightarrow$ $\Delta t \leq \frac{1}{|k|}$

If positronium is probed via transferring small energy & momentum $q \ll \Delta E \sim k$ $\rightarrow$ averaging over the high frequencies $\rightarrow$ cannot resolve the photons with momenta $\sim k$.

At low energies the time of interaction is comparable to the time of transition from one configuration to another $\rightarrow$ *no effective way to probe microscopic structure of the bound states.*

At high energies the key new element is the Lorentz slowdown of transitions between different configurations. Δt for a fast positronium $P_{pos} \gg 2m_e$

increases dramatically.



$$\Delta t = \frac{1}{\Delta E} = \frac{2P}{M^2_{int.state}}\Big|_{P\to\infty} \to \infty, \quad M^2_{int.state} = \frac{k_t^2+m_e^2}{z(1-z)}$$

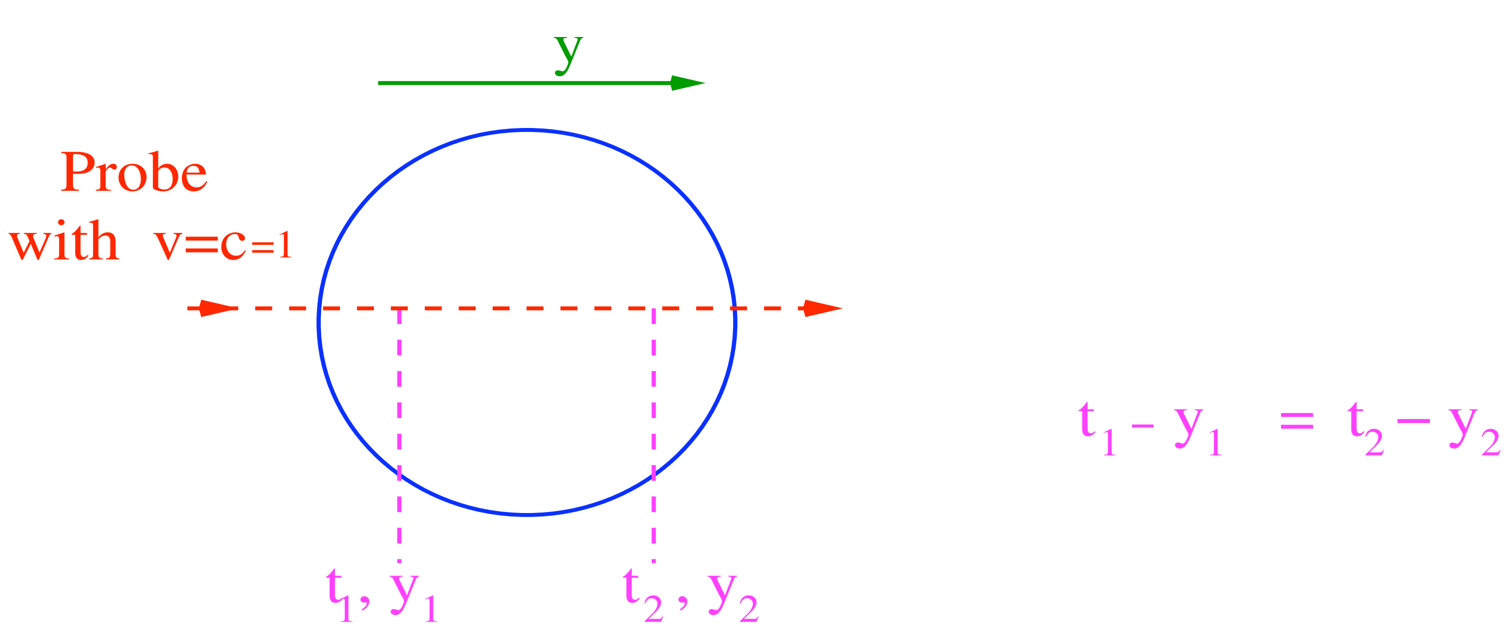
- At high energies transition from one $e^+e^-, e^+e^-\gamma, \ldots$ (quark-gluon) configuration $|n\rangle$ in the projectile h to another configuration takes distances larger than the size of the target: $l_{coh} = c\Delta t \gg 2R_{target}$.

$\Longrightarrow$ *The longitudinal fractions - z's and the transverse separations between the constituents in the projectile do not change during the interaction if E is large enough.*

For a fast positronium it is feasible to reach distances comparable to a thickness of a lead foil. For protons at LHC energies - $l_{coh} \sim$ inter-atomic distances.

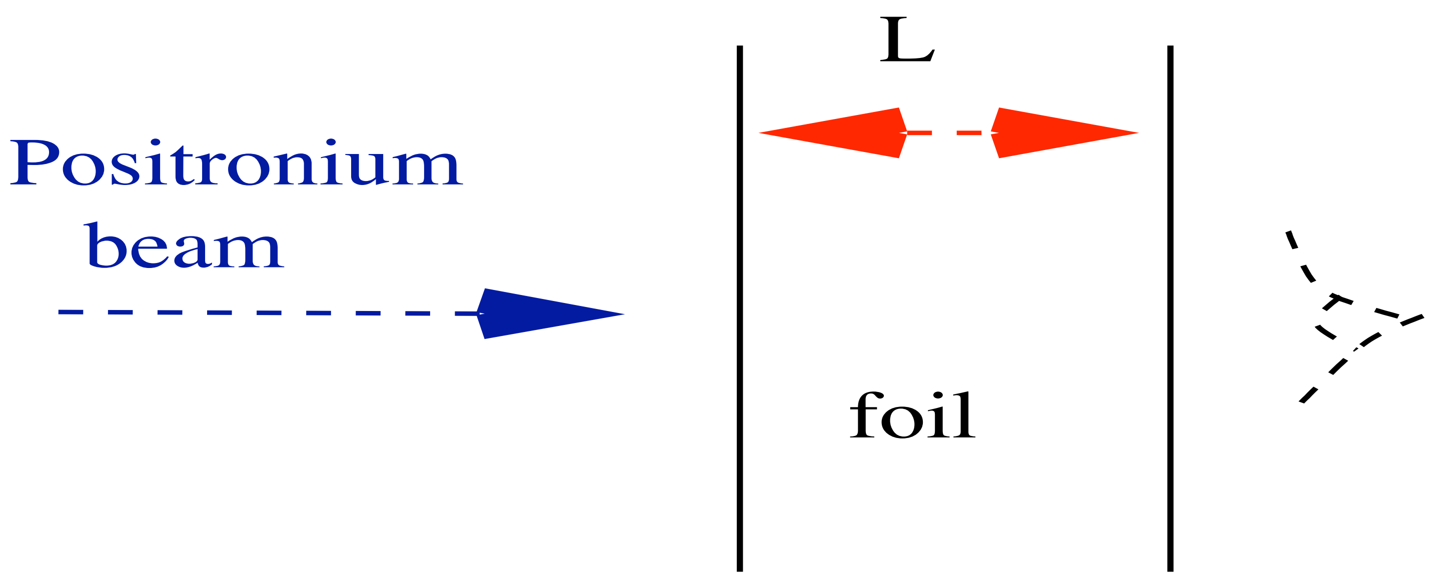
$\Longrightarrow$ A wave function which can be probed at high energies can be parameterized in terms of the fraction of the energy(momentum) carried by constituents and transverse momenta or transverse distances - so called light-cone wave functions.

In the rest frame of the object we want to probe light cone dominance means that the probe correlates points with $t_1 - t_2 = z_1 - z_2$ not with equal times.



Instructive example: *propagation of a very fast positronium through a foil:*

$$\frac{P_{pos}}{2m_e} \cdot \frac{1}{\Delta E(\sim few\ m_e \alpha^2)} \gg L(foil)$$



For a classical particle the probability not to interact while traveling a small distance dr is $1 - \lambda dr$ *independent of the point along the path*.

$\Longrightarrow$ For a distance r the survival probability is $\exp(-\lambda r)$ and

$$\lambda = (density\ of\ matter[L^{-3}]) \bullet\ (a\ quantity\ of\ dimention\ [L^2])$$
$$(a\ quantity\ of\ dimension\ [L^2]) \equiv\ cross\ section$$

For the positronium at high energies transverse size is frozen during traversing through the foil - so interaction is of dipole-dipole type $\sigma(d) \propto d^2$, where $d = r_t^e - r_t^{e^+}$.

Probability of producing *a final state* $\langle f|$ *by the initial state* $|i\rangle$:

$$|M_{if}|^2 = \left[\int d^3r \Psi_{pos}(r)\Psi_f^*(r)\exp(-\frac{\sigma(d)\rho L}{2})\right]^2$$

If $\frac{4}{<\sigma>\rho L} \ll 1$ only small transverse size configurations survive and contribute. $\Rightarrow$ *Absorption is not exponential!!! Result of coherence of the projectile wave function during the interaction.*

Qualitative argument - Nemenov 80, quantitative treatment Frankfurt & MS 91

$|M_{pos\to pos}|^2 = \frac{16}{(<\sigma>\rho L)^2}$, for $<\sigma>\rho L/4 \gg 1$.

$\Sigma_{f=e^+e^-}|M_{pos\to f}|^2 = \int d^3r|\Psi_{pos}(r)|^2\exp(-\sigma(d)\rho L) \to \frac{2}{<\sigma>\rho L} \gg |M_{pos\to pos}|^2$

$\Longrightarrow$ *The nonexponentiality is a manifestation of high-energy quantum coherence.*

$\Longrightarrow$ Filtering enhances contribution of *small size configurations.*

$\Longrightarrow$ Filtering enhances production of electron positron pairs with the same longitudinal momentum as the initial positronium but with large transverse momenta:

$\gg \sqrt{\langle p_e^2(positronium)_{c.m.}\rangle}$ - an analog of inelastic "hard" diffraction.

$\Longrightarrow$ High transverse momentum pairs in diffraction predominantly originate from *small size electron-positron configurations in the initial positronium* and *reflect the short-distance structure of positronium.*

From QED to QCD - similarities and differences

- Can a light meson, nucleon wave function collapse to a small volume?

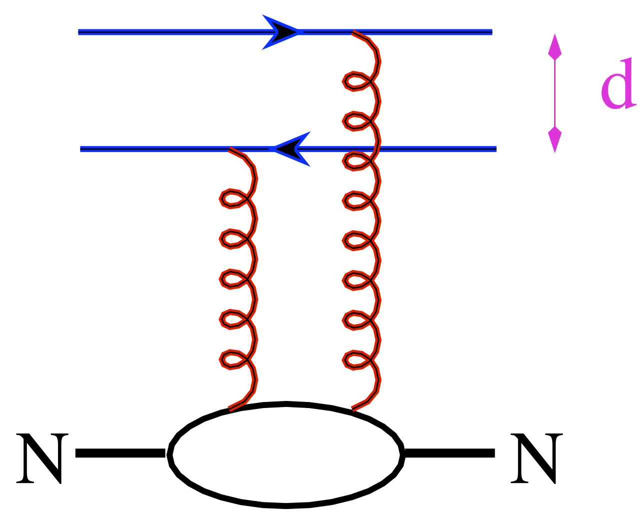
- Would a small high-energy color dipole interact weakly with the nuclear media?

- Would the color transparency phenomenon survives at very high energies $\equiv$ Would the interaction of a small dipole with media remain small at very high energies?

- Is the pattern of the interaction of a high-energy dipole with media similar in QED and QCD?

Interaction of small dipoles with nuclear medium is governed by perturbative QCD $\rightarrow$ can be used as a starting point for the analysis.

Naive expectation: small objects interact weakly, like small dipoles in QED.

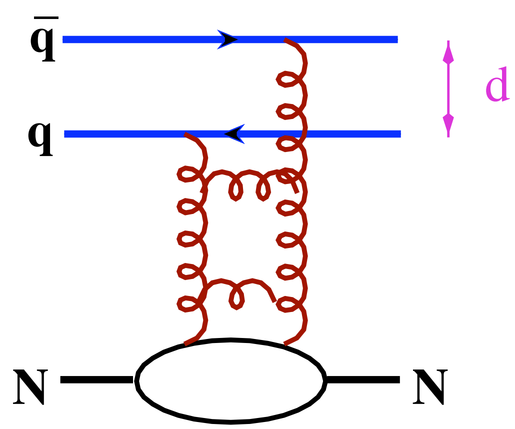


Two gluon exchange model

F.Low & S.Nussinov 75

$\sigma = C\, b^{2}$ **(F.Low 75)**

C does not depent on E_{inc}

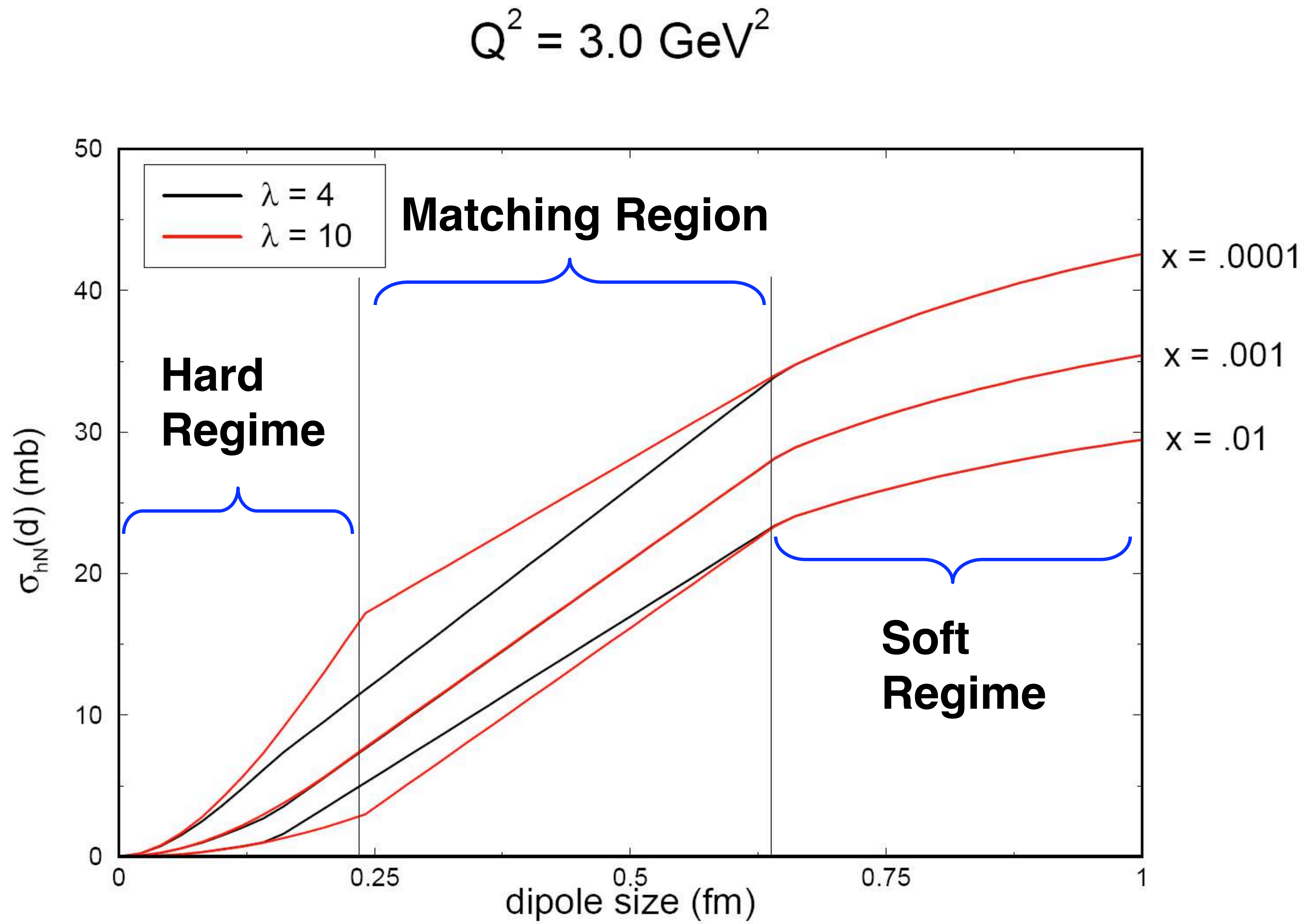


pQCD in the leading log d approximation **(Baym, Blattel,FS, 93)**

$$\sigma^{inel}_{q\bar{q}N}(d,E_{inc}) = \frac{\pi^2}{3}\, d^2 \alpha_s\left(\frac{\lambda}{d^2}\right) \text{ x } G_N\left(x, \frac{\lambda}{d^2}\right)$$

Qualitative difference from QED: cross section rapidly increases with energy - a fingerprint of small size dipole interaction in a wide energy range ($\lambda(x = 10^{-3}, Q^2 = 10\ GeV^2 \approx 9$). Leads to emergence of an exciting new physics of high densities in the perturbative regime at very high energies. Also, qualitatively different from soft physics: $\sigma_{tot}(soft) \propto s^{0.1}, \sigma_{tot}^{dipole-N}(d = .3fm) \propto s^{0.2}, \sigma_{tot}^{dipole-N}(d = .1fm) \propto s^{0.4}$.

Analysis of Frankfurt et al.: Data on the DIS at HERA, exclusive vector meson production: data are consistent with pQCD expression for cross section for small $d \leq 0.3$ fm $q\bar{q}$ dipoles and smooth matching with soft physics at $d \geq 0.6$ fm:



$\Longrightarrow$ **Need to trigger on small size configurations at high energies.**

Two ideas:

$\diamond$ Select special final states: diffraction of pion into two high transverse momentum jets - an analog of the positronium inelastic diffraction. Qualitatively - from the uncertainty relation $d \sim 1/p_t(jet)$

$\diamond\ \diamond$ Select a small initial state - diffraction of longitudinally polarized virtual photon into mesons. Employs the decrease of the transverse separation between q and $\bar{q}$ in the wave function of γ_L^*, $d \propto 1/Q$.

Recently a number of two-body processes off nucleon, nucleus, γ... was discovered which can be **legitimately** *calculated in pQCD due to color screening/transparency for interaction of small color singlets:*

- ◇ π + T $\to$ 2 jets +T   Frankfurt, Miller, S. 93
- ◇ $\gamma_L^* N \to V(\rho, J/\Psi, \rho'..) + N$ Brodsky, Frankfurt, Gunion, Mueller, S., 94
- ◇ $\gamma_L^* N \to Meson(\pi, K, \eta,)\,[Few\ meson\ system] + Baryon$ Collins, FS 96
- ◇ $\gamma_L^* p \to forward\ \ N + \pi, \gamma_L^* p \to forward\ \ \Lambda + K^+$
  $\gamma_L^* p \to forward\ \ \bar{p} + NN$,   FS & Polyakov 98
- ◇ $\gamma^* + N \to \gamma + N$ Bartels &Loewe 82; Dittes, Muller, Robaschik, Geyer,Horejse 88; Ji 96-97, Radyushkin 96-98, Freund & FS 97, Freund & Collins 98
- ◇ $\gamma^* + \gamma \to \pi\pi$ M. Diehl, T. Gousset, B. Pire 98

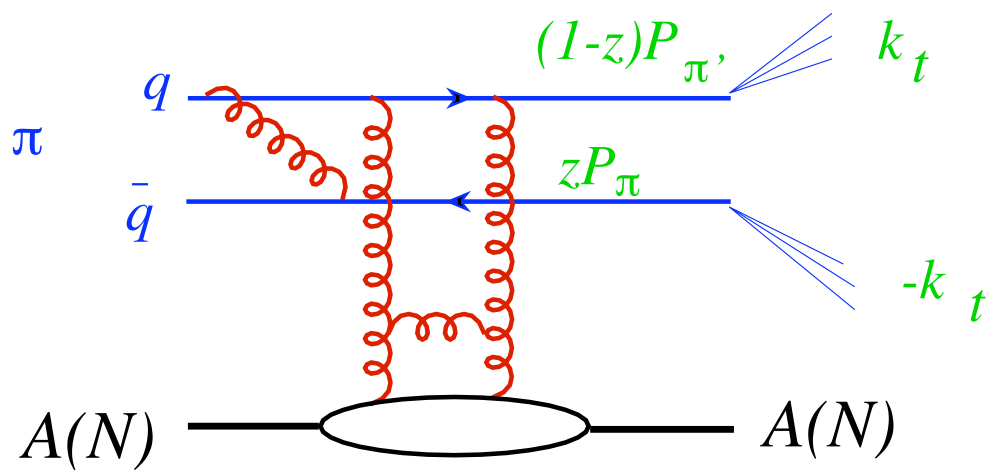
$$\pi + N(A) \rightarrow \text{“}2\ high\ p_t\ jets'' + N(A)$$

Mechanism:

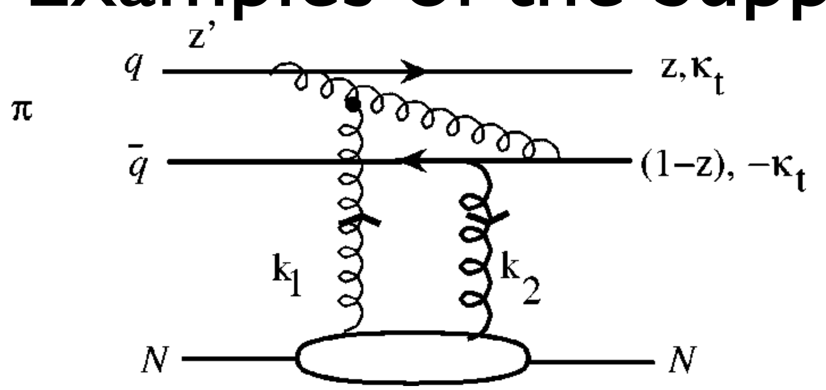
Pion approaches the target in a frozen small size $q\bar{q}$ configuration and scatters elastically via interaction with $G_{target}(x, Q^2)$.

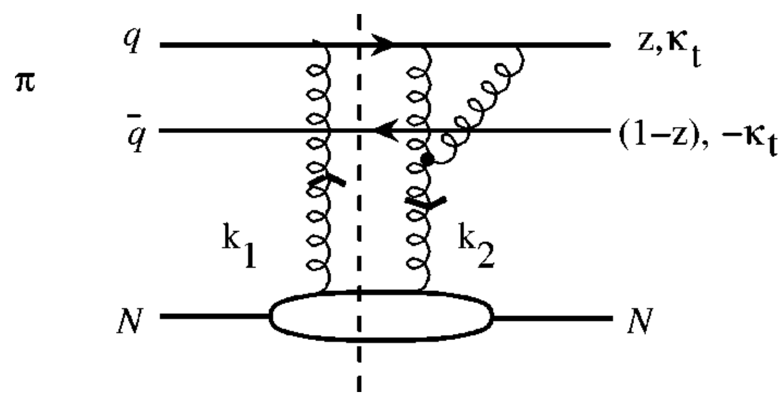
- First attempt of the theoretical analysis of πN process - Randa 80 - power law dependence of p_t of the jet (wrong power)
- First attempt of the theoretical analysis of πA process - Brodsky et al 81 - exponential suppression of p_t spectra, weak A dependence ($A^{1/3}$)
- pQCD analysis - Frankfurt, Miller, MS 93; elaborated arguments related to factorization 2003

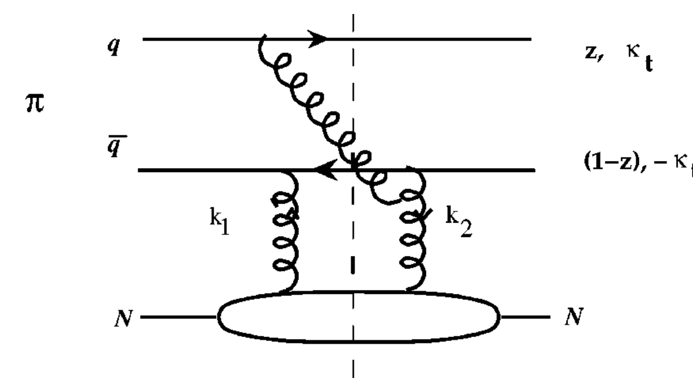
Dominant diagram

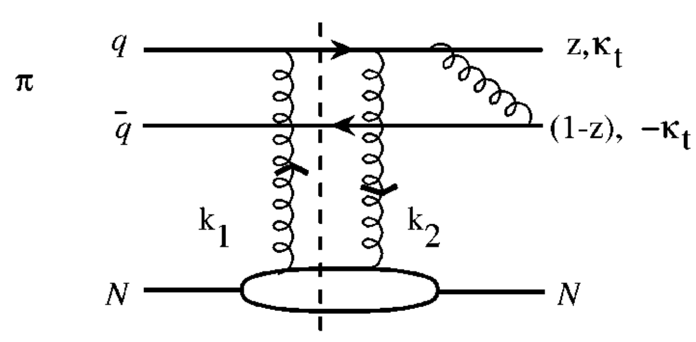


Examples of the Suppressed diagrams









A slightly simplified final answer is

$$A(\pi + N \rightarrow 2\, jets + N)(z, p_t, t = 0) \propto$$

$$\int d^2 d \psi_\pi^{q\bar{q}} \sigma_{q\bar{q}-N(A)}(d, s) \exp(i p_t d)$$

$$d = r_t^q - r_t^{\bar{q}},$$

$\psi_\pi^{q\bar{q}}(z, d) \propto z(1 - z)_{d \rightarrow 0}$ is the quark-antiquark Fock component of the meson light cone wave function

$\Longrightarrow$ A-dependence: $A^{4/3}\left[\frac{G_A(x,k_t^2)}{AG_N(x,k_t^2)}\right]^2$, where $x = M^2_{dijet}/s$. $(A^{4/3} = A^2/R_A^2)$

$\Longrightarrow$ $\frac{d\sigma(z)}{dz} \propto \phi_\pi^2(z) \approx z^2(1-z)^2$ where $z = E_{jet_1}/E_\pi$.

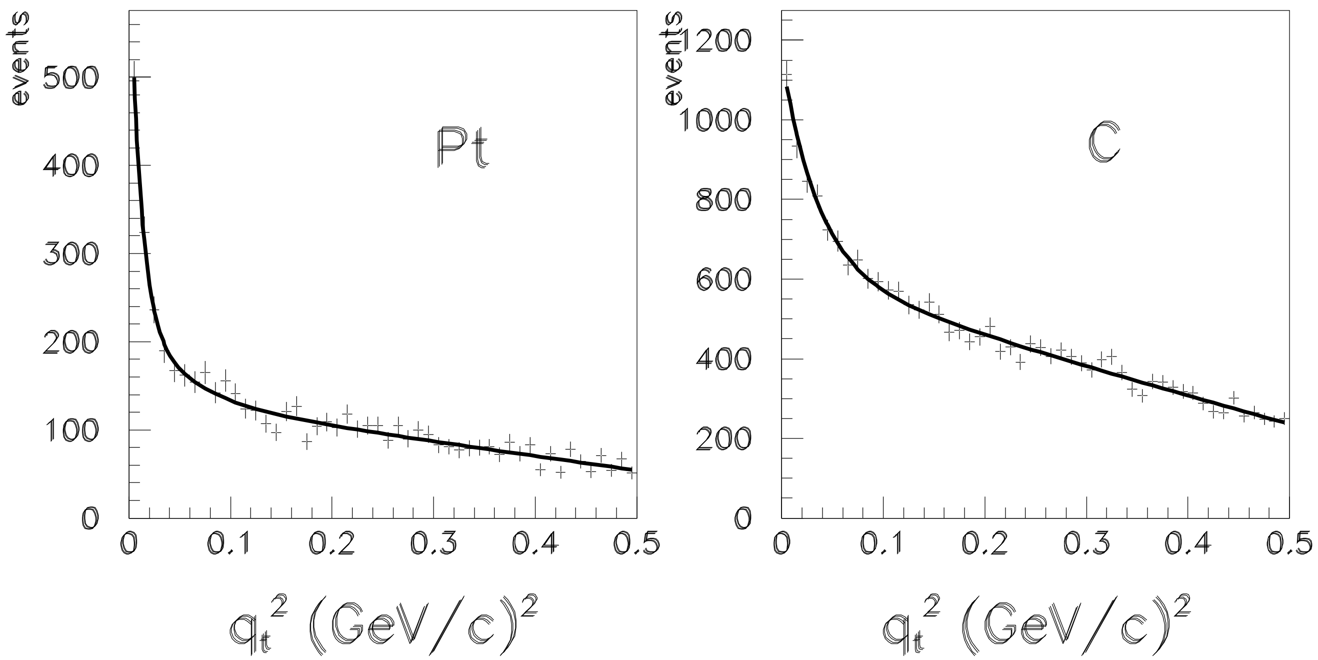
$\Longrightarrow$ k_t dependence: $\frac{d\sigma}{d^2k_t} \propto \frac{1}{k_t^n}, n \approx 8$ for $x \sim 0.02$

$\Longrightarrow$ Absolute cross section is also predicted

What is the naive expectation for the A-dependence of pion dissociation for heavy nuclei? Pion scatters off a black absorptive target. So at impact parameters $b < R_A$ interaction is purely inelastic, while at $b > R_A$ no interaction. Hence $\sigma_{inel} = \pi R_A^2$. How large is σ_{el}? Remember the Babinet's principle from electrodynamics: scattering off a screen and the complementary hole are equivalent. Hence $\sigma_{el} = \pi R_A^2$, while inelastic diffraction occurs only due to the scattering off the edge and hence $\propto A^{1/3}$

The E-791 (FNAL) data $E^{\pi}_{inc} = 500 GeV$ (D.Ashery et al, PRL 2000)

♡ Coherent peak is well resolved:



Number of events as a function of q_t^2, where $q_t = \Sigma_i p_t^i$ for the cut $\Sigma p_z \geq 0.9 p_\pi$.

$\heartsuit\heartsuit$ Observed A-dependence $A^{1.61\pm0.08}$ $[C \to Pt]$

FMS prediction $A^{1.54}$ $[C \to Pt]$ for large k_t & extra small enhancement for intermediate k_t.

For soft diffraction the Pt/C ratio is ~ 7 times smaller!!

(An early prediction Bertsch, Brodsky, Goldhaber, Gunion 81

$\sigma(A) \propto A^{1/3}$)

In soft diffraction color fluctuations are also important leading to

$$\sigma_{soft\ diffr}(\pi + A \to X + A) \propto A^{.7}$$

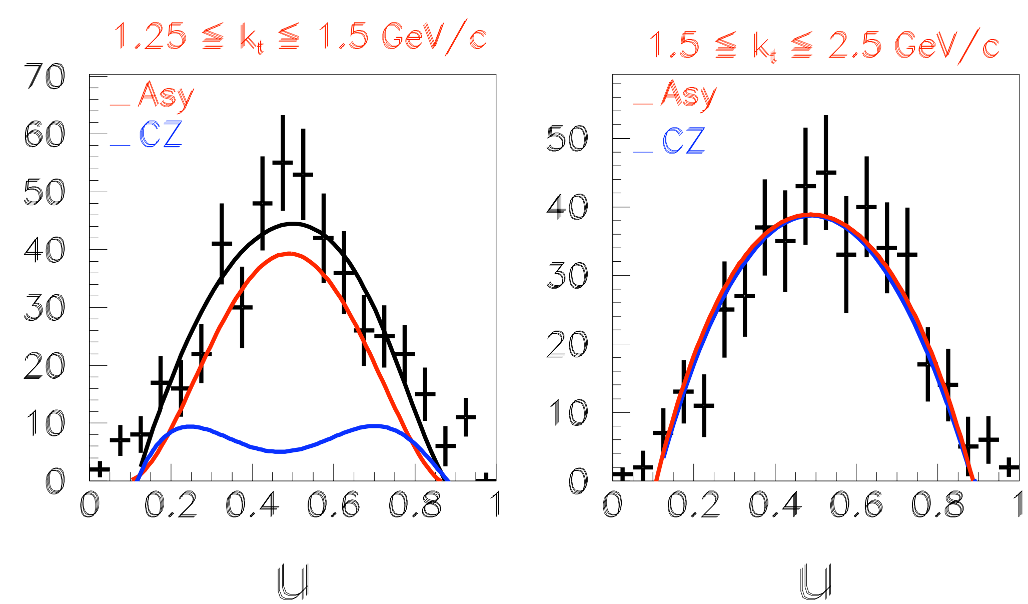
Miller Frankfurt &S, 93

♡♡♡ *The z dependence is consistent with dominance of the asymptotic pion wave function* $\propto z(1-z)$.

THE $q\bar{q}$ MOMENTUM WAVE FUNCTION

MEASURED BY DI-JETS

Fermilab E791 Collaboration, PRL 86, 4768 (2001)



$1.5\mathrm{GeV/c} \ \leq\ \mathrm{k_t}\ \leq\ 2.5\mathrm{GeV/c}; \quad \mathrm{Q}^2 \sim 16\ (\mathrm{GeV/c})^2:$ $\quad \phi^2 \ > \ 0.9\phi^2_{Asy}$

$1.25\mathrm{GeV/c} \ \leq\ \mathrm{k_t}\ \leq\ 1.5\mathrm{GeV/c}; \quad \mathrm{Q}^2 \sim 8\ (\mathrm{GeV/c})^2:$

Black and red curves - predicted asymptotic behavior -

CZ Chernyak Zhitnitski model of pion wave function

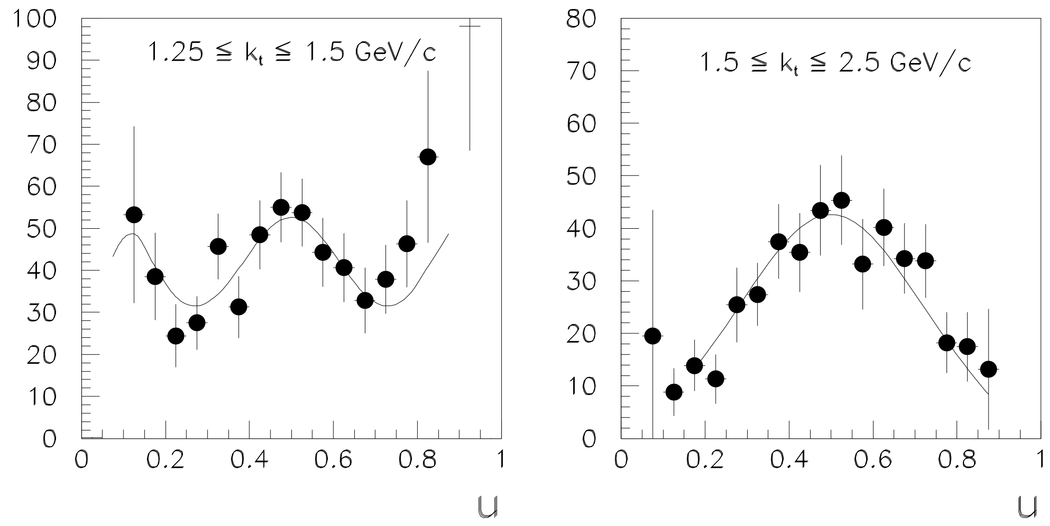
Fit to Gegenbauer Polynomials

Generate Acceptance-Corrected Momentum distributions

Assume $\frac{d\sigma}{du} \propto \phi_\pi^2(u, Q^2)$ **in both** $k_\perp$ **regions**

Fit distributions to:

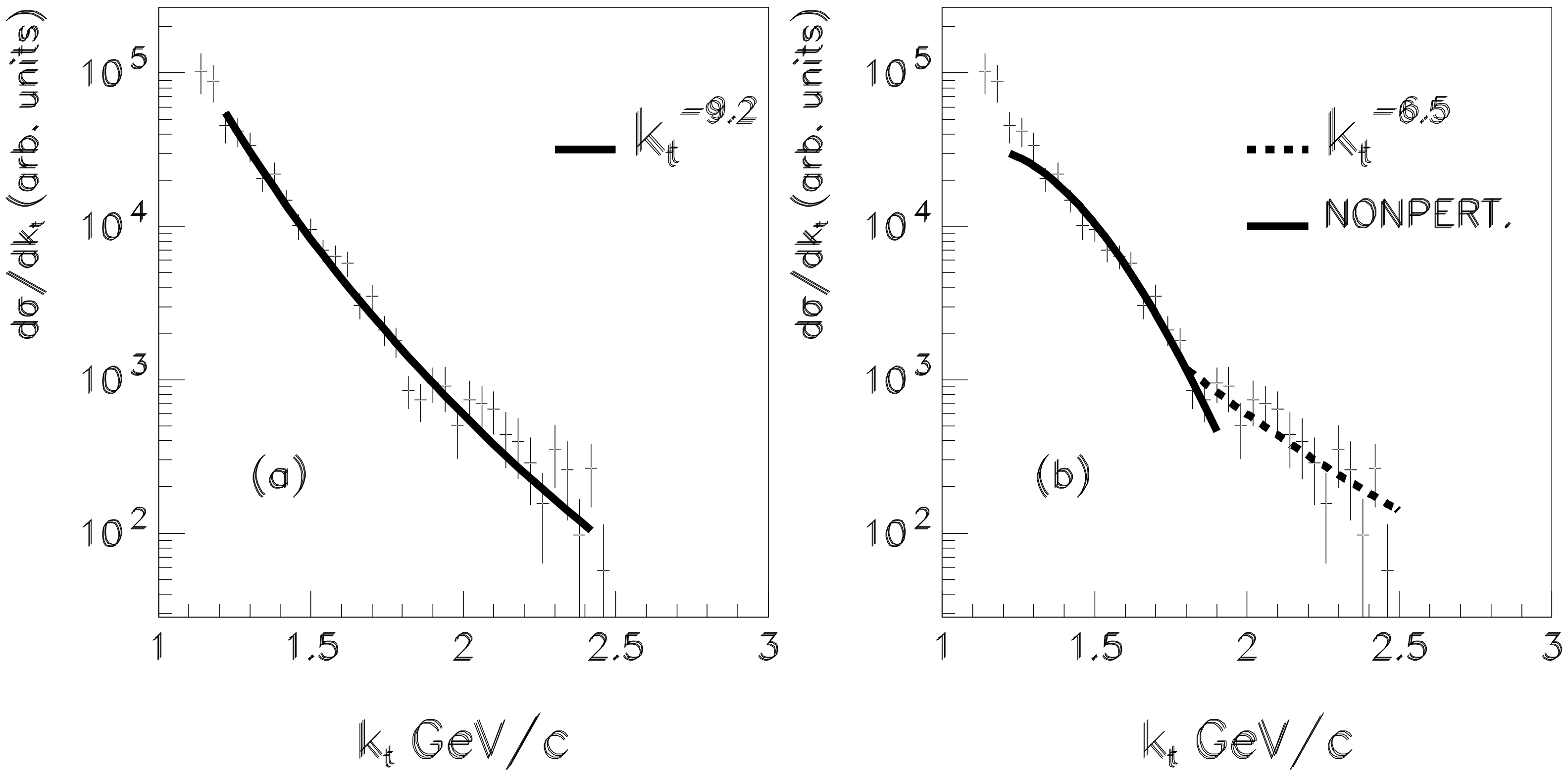
$$\frac{d\sigma}{du} \propto \phi_\pi^2(u, Q^2) = 36u^2(1-u)^2 \left(1.0 + a_2 C_2^{3/2}(2u-1) + a_4 C_4^{3/2}(2u-1)\right)^2$$



For high k_t : $a_2 = a_4 = 0 \rightarrow$ **Asymptotic**

For low k_t : $a_2 = 0.30 \pm 0.05, \quad a_4 = (0.5 \pm 0.1) \cdot 10^{-2} \rightarrow$ **Transition**

♡♡♡♡ k_t^{-n} *dependence of* $d\sigma/dk_t^2 \propto 1/k_t^{7.5}$ *for* $k_t \geq 1.7GeV/c$ *close to the QCD prediction -* $n \sim 8.0$ *for the kinematics of E971*

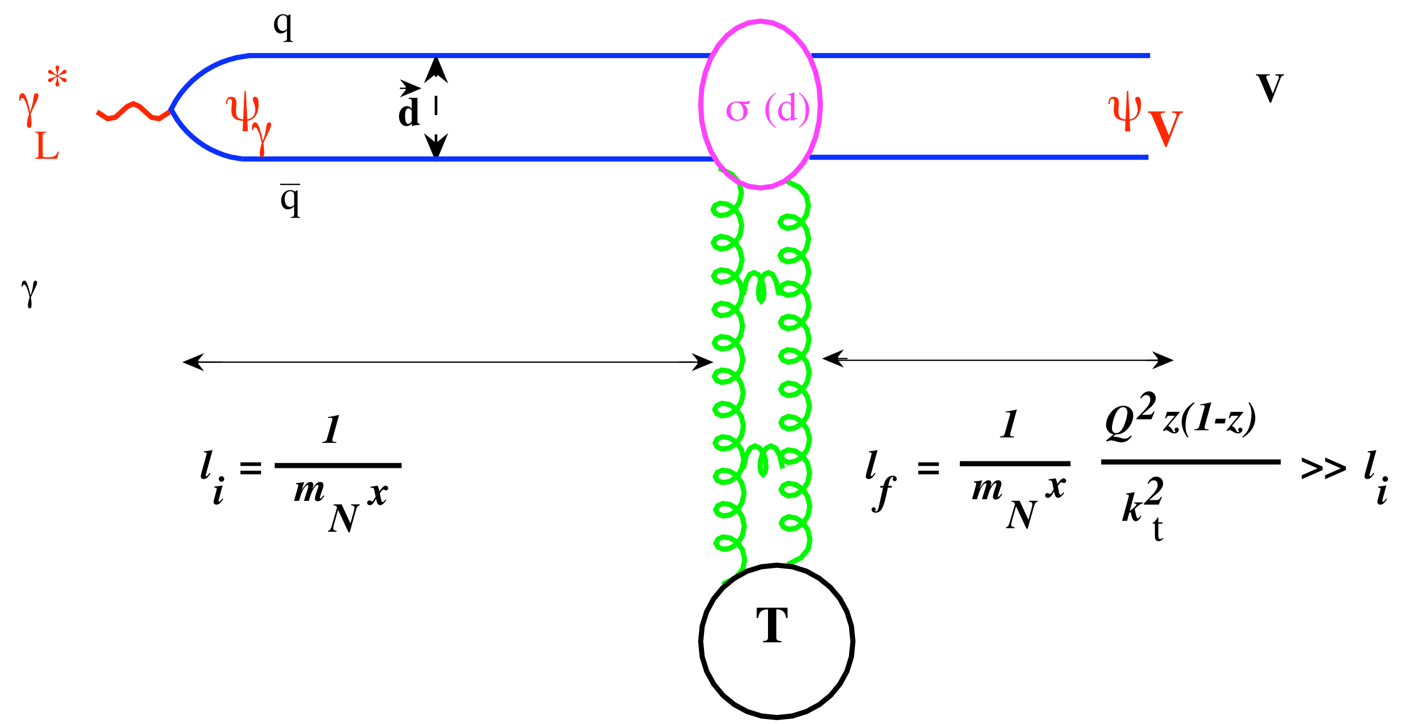


$\Longrightarrow$ • *High-energy color transparency is* **directly** *observed.*

• *The pion* $q\bar{q}$ *wave function is* **directly** *measured.*

Vector meson diffractive production: Theory and HERA data

Space-time picture of Vector meson production at small x in the target rest frame



$\Rightarrow$ *Similar to the* $\pi + T \to 2jets + T$ *process,* $A(\gamma^*_L + p \to V + p)$ *at* $p_t = 0$ *is a convolution of the light-cone wave function of the photon* $\Psi_{\gamma^* \to |q\bar{q}\rangle}$, *the amplitude of elastic* $q\bar{q}$ *- target scattering,* $A(q\bar{q}T)$, *and the wave function of vector meson,* ψ_V: $A = \int d^2 d \psi^L_{\gamma*}(z,d)\sigma(d,s)\psi^{q\bar{q}}_V(z,d)$.

The leading twist parameter free answer is BFGMS94

$$\left.\frac{d\sigma^L_{\gamma^* N\to VN}}{dt}\right|_{t=0} =$$

$$\frac{12\pi^3\Gamma_{V\to e^+e^-} M_V \alpha_s^2(Q)\eta_V^2 \left|\left(1+i\frac{\pi}{2}\frac{d}{d\ln x}\right) xG_T(x,Q^2)\right|^2}{\alpha_{EM} Q^6 N_c^2}$$

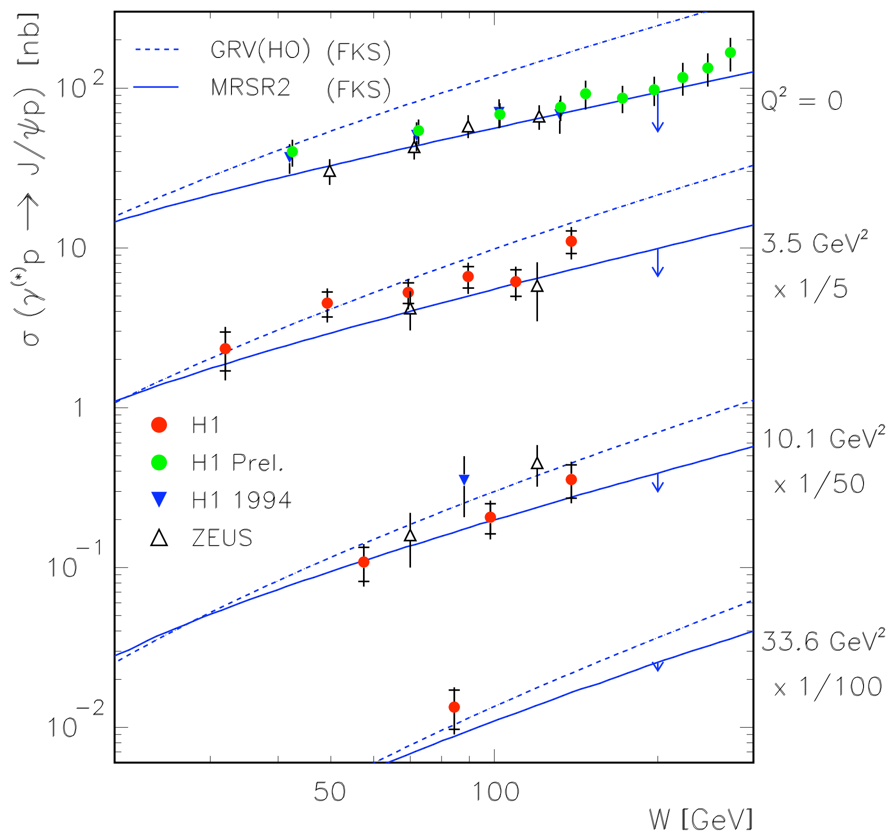
. *Here,* $\Gamma_{V\to e^+e^-}$ *is the decay width of* $V \to e^+e^-$;

$$\eta_V \equiv \frac{1}{2}\frac{\int \frac{dz\, d^2k_t}{z(1-z)}\,\Phi_V(z,k_t)}{\int dz\, d^2k_t\, \Phi_V(z,k_t)} \to 3 \;|_{Q^2\to\infty}$$

Note: In the leading twist d=0 in $\psi_V(z,d)$. *Finite b effects in the meson wave function is one of the major sources of the higher twist effects.*

Extensive data on VM production from HERA support dominance of the pQCD dynamics. Numerical calculations including finite b effects in $\psi_V(b)$ explain key elements of high Q^2 data. The most important ones are:

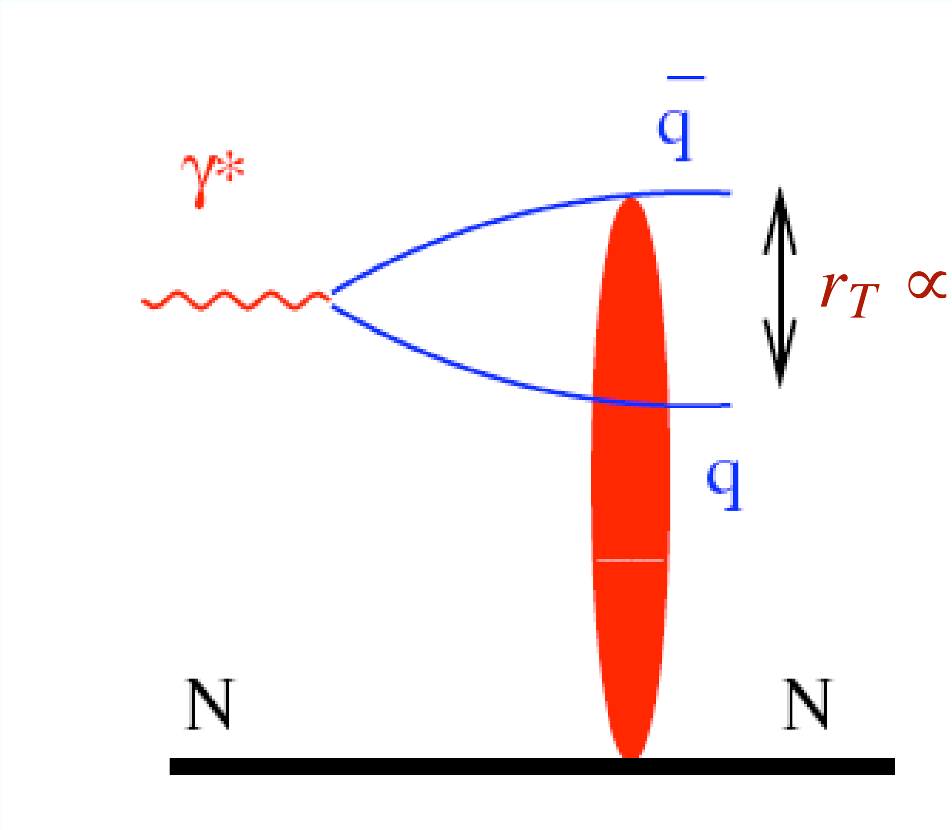
(i) Energy dependence of J/ψ production; absolute cross section of $J/\psi, \Upsilon$ production.



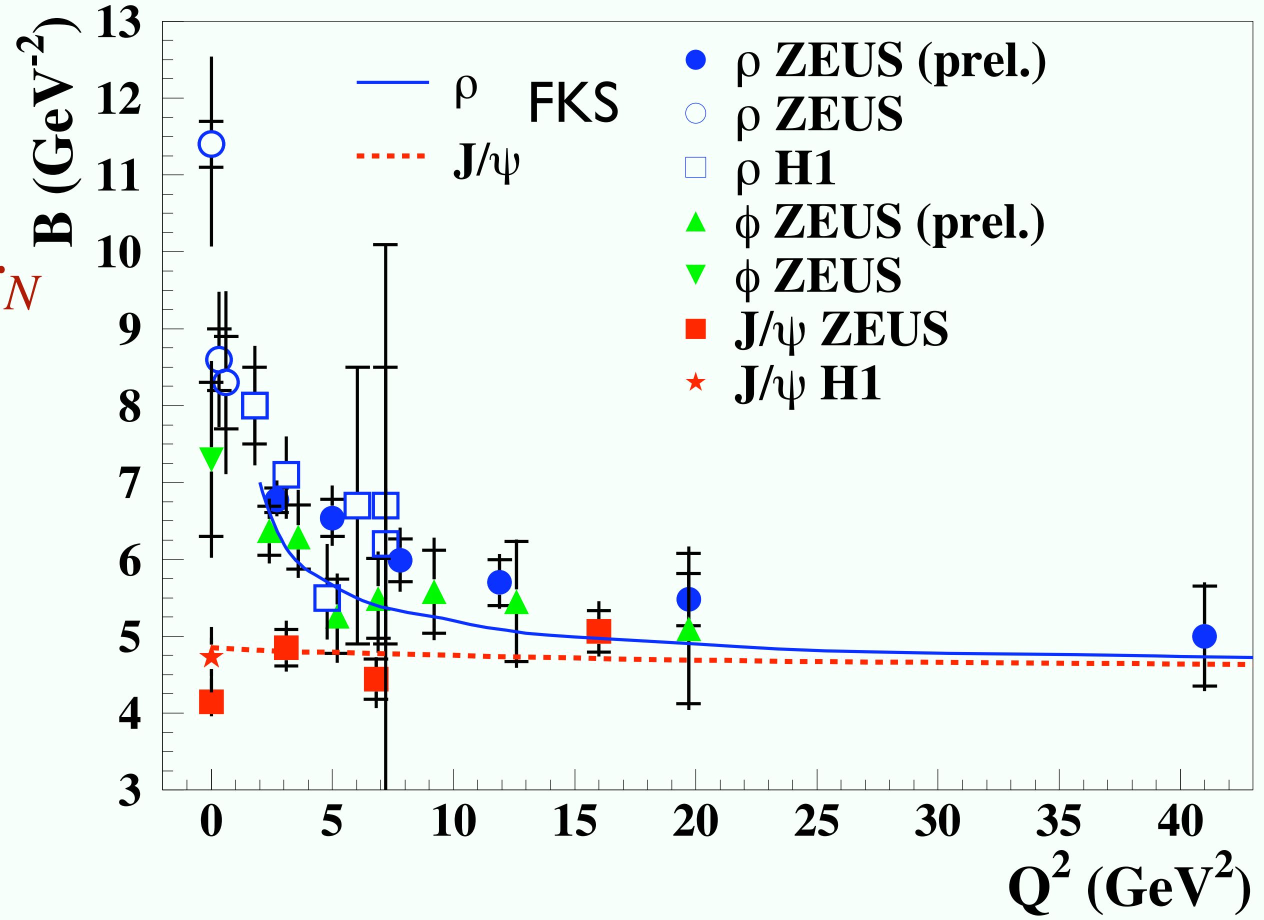
(ii) Absolute cross section of ρ production at $Q^2 \sim 20 - 30\ GeV^2$ and its energy dependence at $Q^2 \sim 20\ GeV^2$. Explanation of the data at lower Q^2 is more sensitive to the higher twist effects, and uncertainties of the low Q^2 gluon densities.

(iii) Universal t-slope: process is dominated by the scattering of quark-antiquark pair in a small size configuration - t-dependence is predominantly due to the transverse spread of the gluons in the nucleon - two gluon nucleon form factor, $F_g(x,t)$. $d\sigma/dt \propto F_g^2(x,t)$.

Onset of universal regime FKS[Frankfurt,Koepf, MS] 97.



$$r_T \propto \frac{1}{Q}\left(\frac{1}{m_c}\right) \ll r_N$$



Convergence of the t-slopes, B ($\frac{d\sigma}{dt} = A\exp(Bt)$,
of ρ-meson electroproduction to the slope of
J/ψ photo(electro)production.

⇒ Transverse distribution of gluons can be extracted from $\gamma + p \to J/\psi + N$

(iv) the ratio $\sigma_L/\sigma_T >> 1$ at large Q^2 for ρ and φ-meson production

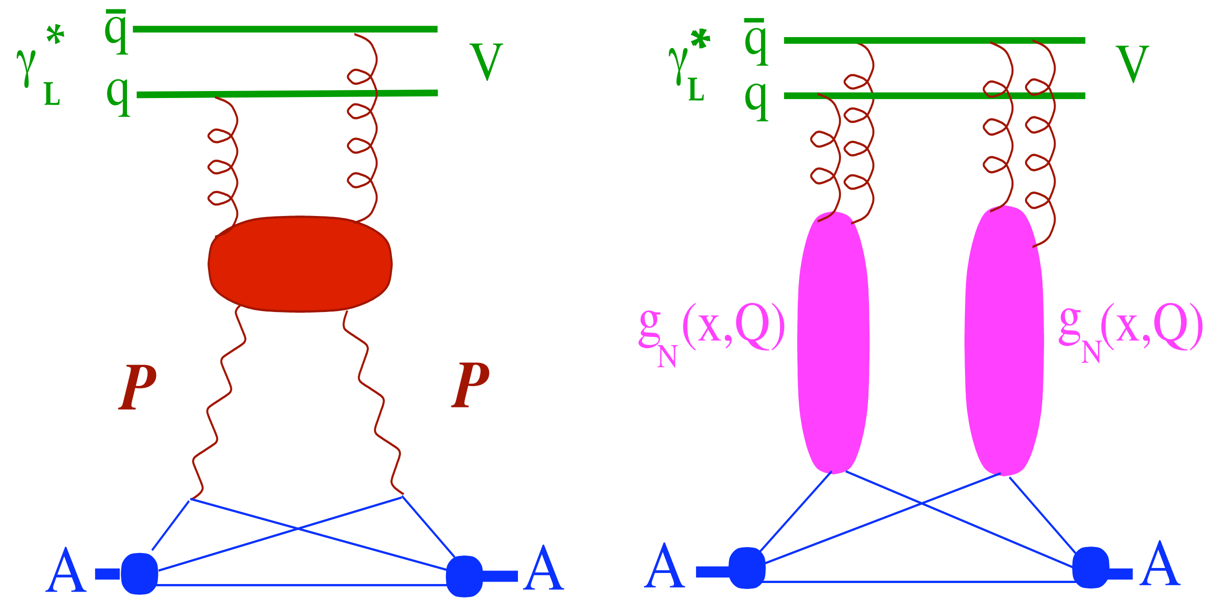
(v) at $Q^2 > 5\ GeV^2$ for SU(3) symmetry is restored for φ/ρ - ratio ~ 2/9

- Presence of small size $q\bar{q}$ Fock componentss in light mesons is unambigously established
- At transverse separations $d \leq 0.3$ fm pQCD reasonably describes "small $q\bar{q}$ - dipole"- nucleon interaction for $10^{-4} < x < 10^{-2}$
- Color transparency is established for the interaction of small dipoles with nucleons and with nuclei (for $x \sim 10^{-2}$)

Open questions & directions for the future studies

- At what energies color transparency will disappear in the interaction with nuclei? - Color opacity
- Can one trigger on small size qqq configurations in nucleons/ baryons?
- How to comparison of small size qqq configurations in different baryons?
- How small qqq configuration should be, to experience color transparency?
- How a small $q\bar{q}$ (qqq) configuration evolves with in space-time?

Color opacity - possibility of a small dipole to interact with several nucleons - two mechanisms - leading twist due to gluon shadowing and eikonal mechanism (higher twist) due to increase of the dipole - nucleon cross section with energy



Absorption in high-energy coherent vector meson production:

Leading twist ***Higher twist eikonal***

appears to be a small correction for $x \geq 10^{-4}$

Factorization theorem for production of vector mesons in DIS limit (or photoproduction of heavy oniums):

$$\frac{\frac{d\sigma}{dt}(\gamma^* A \to MA)\Big|_{t=0}}{\frac{d\sigma}{dt}(\gamma^* N \to MN)\Big|_{t=0}} = \frac{G_A^2(x,Q)}{G_N^2(x,Q)}$$

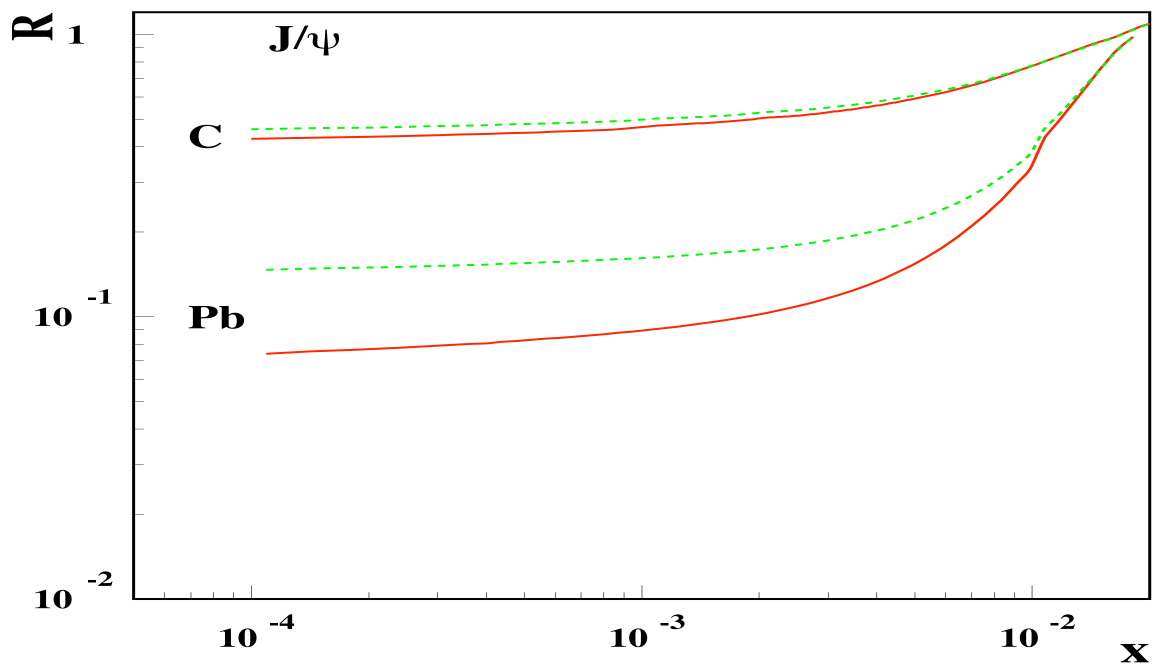
$\Longrightarrow$ ♣ **Color transparency** *for* $x \geq 0.02$

For J/ψ *at all* Q^2; *For* $\rho, \phi, \pi\pi, ...$ *at* $Q^2 \geq 5\ GeV^2$ *?.*

$\Longrightarrow$ ♣ **Perturbative color opacity for** $x < 0.01$ **due to leading twist gluon shadowing (to be studied at EIC and ultraperipheral collisions at LHC)**

Physics seminar - Dec.6

Large perturbative color opacity effect is predicted based on the theorem (FS98) connecting the leading twist gluon shadowing to the hard diffractive phenomena studied at HERA.



Color opacity effect for coherent J/ψ photoproduction: suppression of the cross section as compared to the color transparency prediction due to leading twist gluon shadowing.

Intermediate energies – prime focus looking CT for baryons

Main challenge: |qqq> is not an eigenstate of the QCD Hamiltonian. So even if we find an elementary process in which interaction is dominated by small size configurations - they are not frozen. They evolve with time - expand after interaction to average configurations and contract before interaction from average configurations.

➡ Need energies above 10 GeV to ensure that expansion effects are small at least on the scale of the internucleon distance of 2 fm and sufficiently large momentum transfers in the elementary reactions.

$\Downarrow$

J-PARC will have proper energies and intensities to discover and explore these phenomena

A sample of large momentum transfer (-t> few GeV^2) processes which J-PARC can explore

$$\boxed{h\,A \to h(h') + N + (A-1)}$$

- ☛ A-dependence - study of CT
- ☛ h vs h' (N vs Δ-isobar) - comparison of the baryon wave functions
- ☛ Use of hard process as a filter of baryons with large wave function in the origin

$$\boxed{h + {}^2H \to h(h') + p + n}$$

- ☛ Study of CT with minimal expansion effects

Summary

- *Prediction of high-energy CT in* $\pi A \rightarrow 2jets + A$ *is confirmed.*

- *Exclusive (few) meson production in DIS and dijet diffraction of a mesons are calculable in QCD in the same sense as the leading twist DIS processes.*

- *Hard exclusive processes provide unique ways to:*
  ◇ *Study minimal Fock state components of mesons, structure functions of mesons;*
  ◇◇ *Compare skewed parton distributions in a multitude of baryons. (did not have no time to discuss)*

Further studies:

LHC:

- Search for proton dissociation into three jets (TOTEM-CMS)
- Investigation of color opacity in ultraperipheral collisions

Fixed targets:

Jlab - 12 GeV
J-PARC, GSI

- Search for CT for the interaction of baryons
- Study of the short distance baryon wave functions, looking for new baryon states

COMPASS - CT for vector mesons in DIS