Applications of high-energy QCD

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Valparaiso, Chile

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Outline

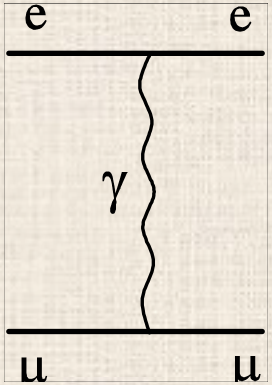
- Introduction: QCD vs QED
- Exclusive reactions, Color Transparency
- Confinement, string model, hadronization
- High-energy hadronic collisions: QCD vs Regge
- DIS: small x physics
- Drell-Yan process
- Diffraction: soft and hard; breakdown of QCD factorization
- Nuclear shadowing
- Diffractive dileptons, W,Z, Higgs production
- Color glass condensate/saturation
- Color dipoles in a hot medium.

B.K. & A.Rezaeian, arXiv:0811.2024

QCD versus QED

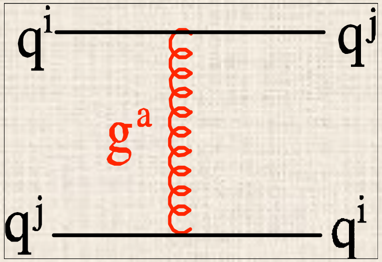
similarities and differences

Similarities:



✓ The color charged quarks emit and absorb gluons in the same way as the electrically charged leptons emit and absorb photons;

✓ the gluon and the photon are massless;

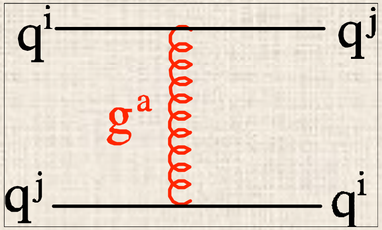


✓ the gluon and the photon have spin 1. Quarks are spin 1/2 point-like particles.

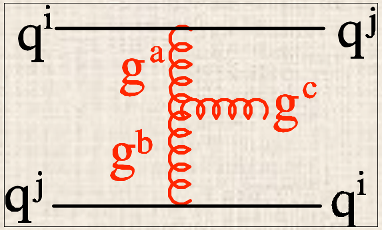
QCD versus QED

Differences:

✓ Radiation of a photon does not change the charge of the electron (abelian theory), while a gluon can change the quark's color (non-abelian). Gluons carry unbalanced color charges;

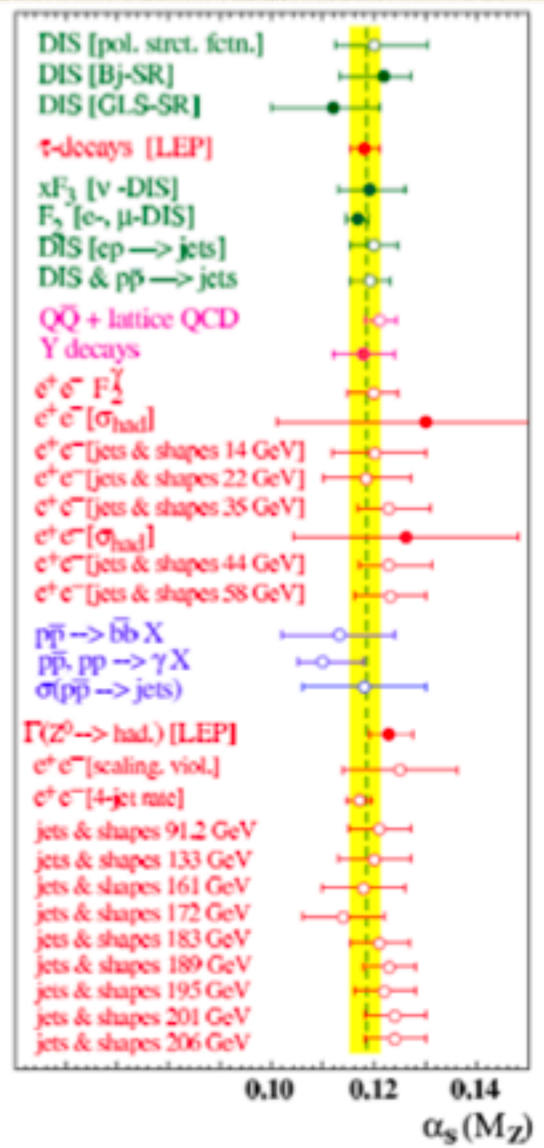


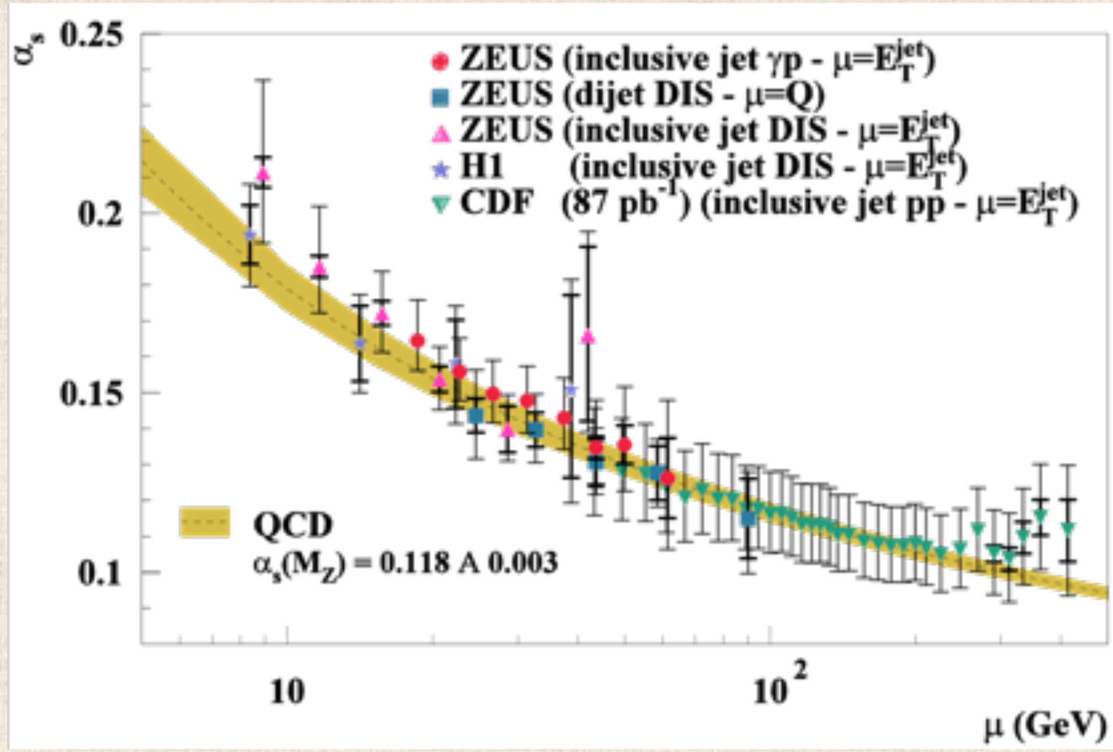
✓ the response of gluons to color charge, as measured by the QCD coupling constant, is much more vigorous than the response of photons to electric charge;



✓gluons, unlike photons, interact directly with one another.

Measurements of the running coupling





$$\alpha_s(Q) = \frac{4\pi}{\beta_0 \ln \frac{Q^2}{\Lambda^2}}$$

$$\Lambda = 211\,MeV$$

Evidences for color dynamics

So far the color was just a new quantum number for quarks that distinguishes them. Are there any direct evidences that the color color is responsible for strong interactions?

* **Color Transparency**

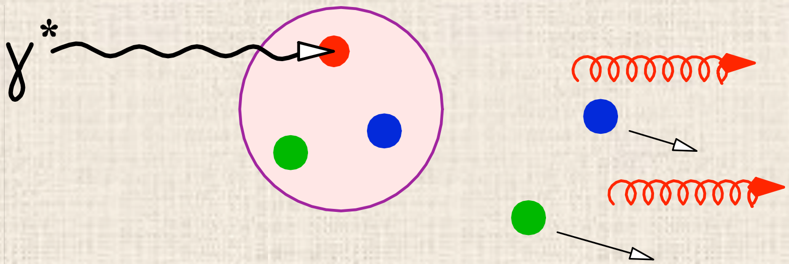
How can a colorless hadron interact?
- Only via its color-dipole moment

A point-like colorless object cannot interact with external color fields. Therefore the cross section of a small color dipole of transverse size r_T vanishes as

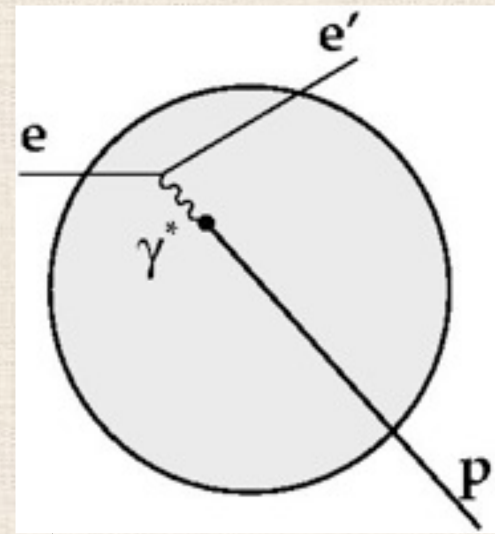
$$\sigma\left(r_T\right) \propto r_T^2$$

* Quasielastic electron scattering off nuclei $A(e,e'p)A'$

The nucleus acts as a color filter



a "big proton" is destroyed;
a "little proton" survives

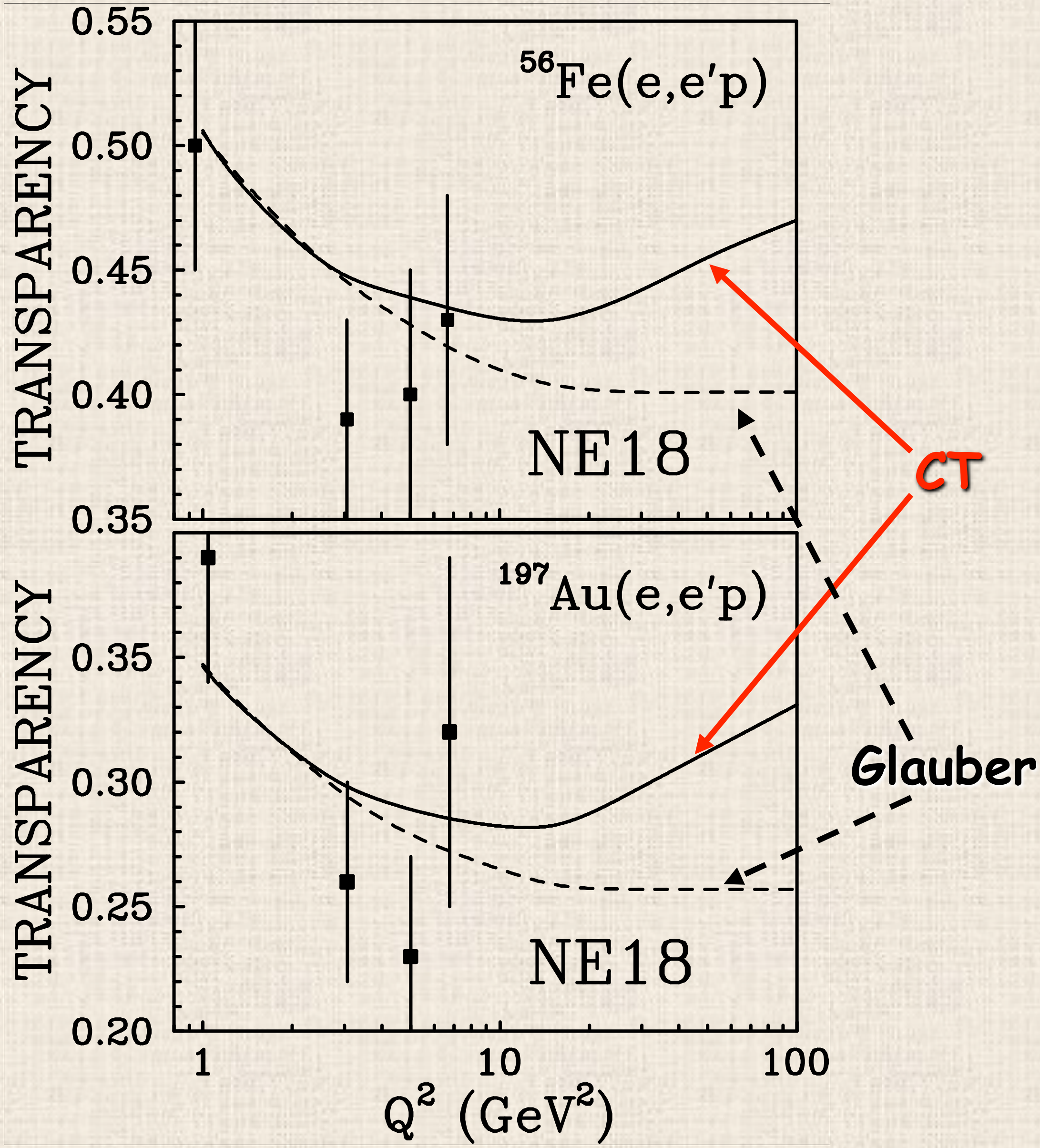


The recoil "proton" has a reduced size and experiences weaker final state interactions in the nucleus. Therefore, due to **CT** it should escape the nucleus with a higher probability, than is suggested by the **Glauber model**.

Unfortunately, the experiment NE18 at SLAC was not successful in hunting for CT

$$\mathbf{Tr} = \frac{\sigma(\mathbf{eA} \to \mathbf{e'pA^*})}{\mathbf{Z}\sigma(\mathbf{ep} \to \mathbf{e'p})}$$

Even data with a higher statistics would be unable to discriminate between the two models at $\mathbf{Q^2 < 10\,GeV^2}$



Why these experiments failed to detect a signal of CT

Even if a small-size partonic state is produced, eventually it becomes a proton. How long does it take to form the proton wave function?

$$l_f < \frac{2E_p}{m_{p^*}^2 - m_p^2} \approx 0.4\,fm \times E_p(GeV)$$

$$E_p = \frac{Q^2 + 2m_p^2}{2m_p}$$

is the recoil proton energy.

At the maximal virtuality Q^2=8GeV^2 the formation length l_f=2fm is of the order of the mean inter-nucleon spacing in a nucleus.
Thus, the proton is too slow to keep the initial small size, and attenuates with the mean proton cross section.

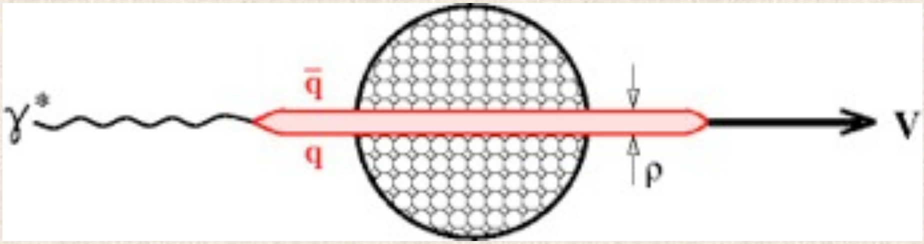
$$Tr = \frac{1}{A}\int d^2b \int\limits_{-\infty}^{\infty} dz\,\rho_A(b,z)\exp\left[-\sigma_{in}^{pN}\int\limits_{z}^{\infty} dz'\,\rho_A(b,z')\right]$$

(Glauber model)

Trying just to increase E_p one has to go to higher Q^2, and the cross section drops down dramatically.

* Diffractive virtual photoproduction of vector mesons off nuclei

The value of Q^2 can be large, but it does not correlate with the hadron energy.



Not a vector meson, but a quark-antiquark fluctuation of the photon propagates through the nucleus.

The transverse size of the dipole is controled by the photon virtuality

$$\sigma(r_T) \propto r_T^2 \sim \frac{1}{Q^2}$$

The dipole lifetime, called coherence time (length) is

$$l_c = \frac{2E_{\gamma^*}}{Q^2}$$

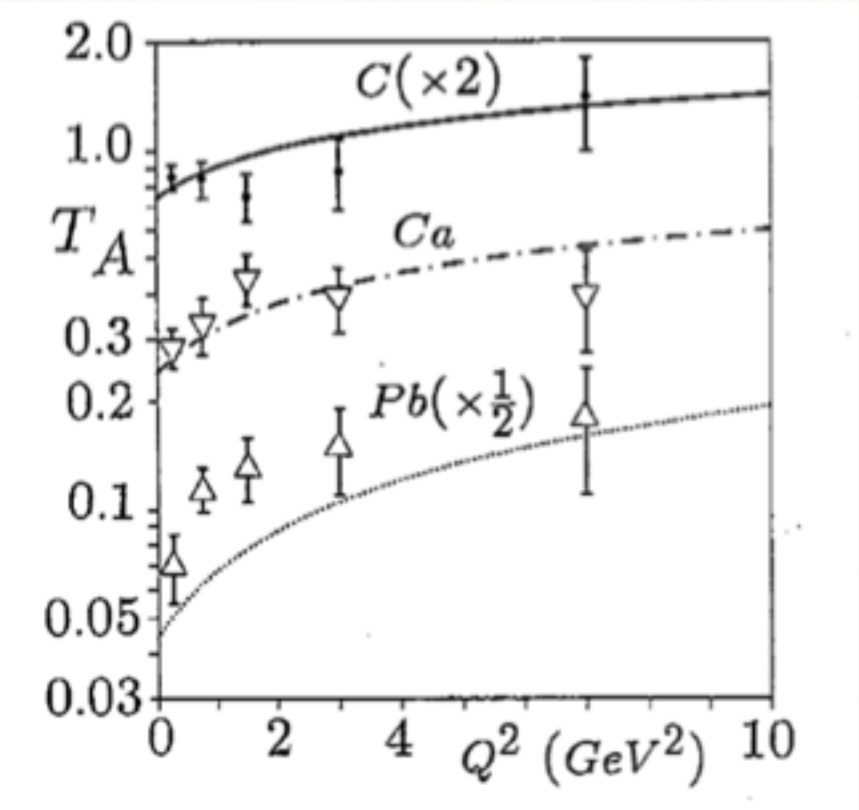
In this process the photon energy and virtuality vary independently.

CT should be at work: the A-dependence is expected to vary from $A^{1/3}$ at low Q^2 up to A at high Q^2

Successful experiments searching for CT in $\gamma^* \mathbf{A} \to \rho \mathbf{A}^*$

Nuclear transparency $T_A = \dfrac{\sigma_A}{A\sigma_N}$:

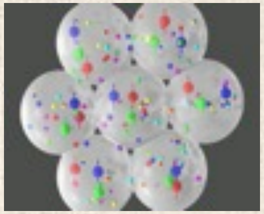
data versus theoretical predictions



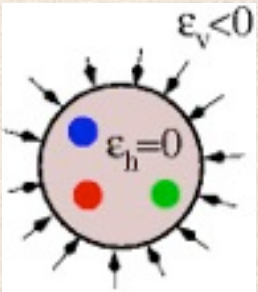
E665 experiment at Fermilab measured quasi-elastic electro-production $\gamma^* \mathbf{A} \to \rho \mathbf{A}^*$

HERMES data at HERA for diffractive electro-production of ρ mesons also well confirmed CT

Why don't we see quarks? Bags, strings…



Gluonic condensate in vacuum pushes the energy density below the perturbative level, $\varepsilon_v<0$.



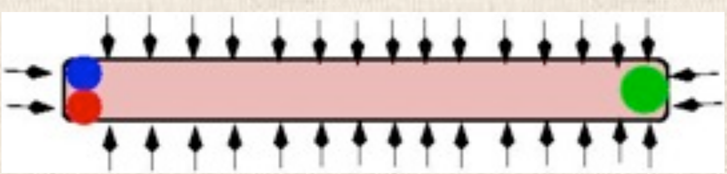
If the energy density inside the hadron is higher (e.g. perturbative), vacuum tries to squeeze the hadron.

However, the chromo-electromagnetic energy, $\frac{1}{2}(E^2+H^2)$, rises leading to an equilibrium.

What happens if a quark is knocked out with a high momentum?

"Quarks, Neutrinos… All those damn particles you can't see. That's what drove me to drink. But now I can see them!"

Due to the same properties of the QCD vacuum the chromo electric flux is squeezed into a tube of a constant cross section.



Usually the transverse size is not important, so the tube may be treated as a one-dimensional **string**.

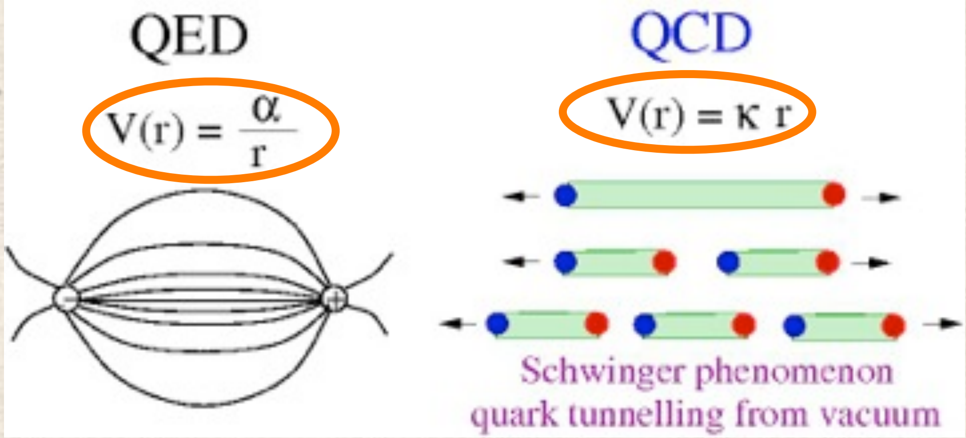
$$\pi r^2 = \frac{g^2}{8\kappa}$$

$$\kappa = \frac{1}{2\pi\alpha'_R} \approx 1\frac{GeV}{fm}$$

The string tension κ is the energy density per unit of length. It can be calculated on the lattice, but is easily related to the universal slope of Regge trajectories $\alpha'_R = 0.9\ GeV^{-2}$ (see below).

This energy is sufficient for creation of a couple of constituent quarks via tunneling from vacuum

One can hardly stretch a string longer than 1fm, it breaks up to pieces.



The Schwinger phenomenon and existence of light quarks are the main reasons why we don't see free quarks and gluons (color screening).

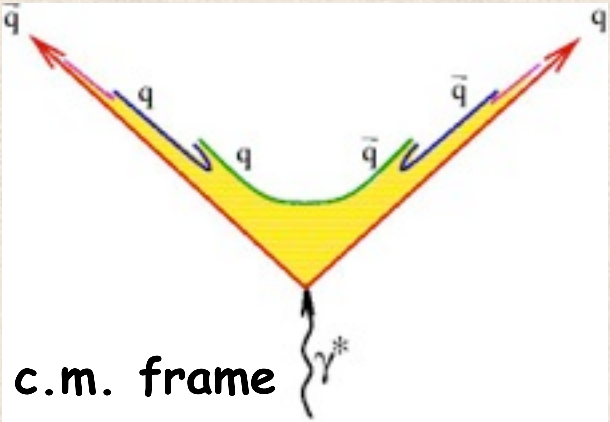
Nonperturbative hadronization

The probability of string break up over time T

$$P(t) = 1 - \exp\left[w \int_0^T dt L(t) \right]$$

where the probability density to create a quark pair over unit of time and unit of length

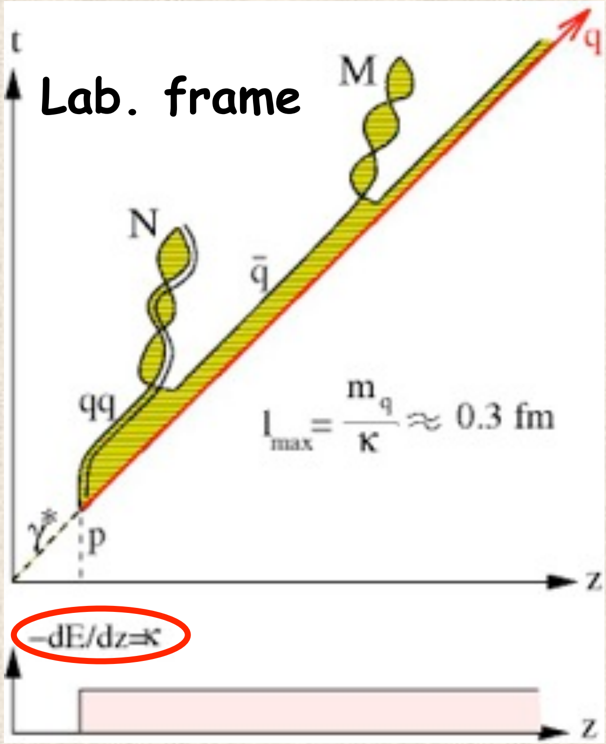
$$w = \left(\frac{\kappa\, r}{\pi}\right)^2 \exp\left(-\frac{2\pi\, m_q^2}{\kappa}\right) \approx 2\, fm^{-2}$$



The string length L(t) is getting shorter after each break, which delays the next pair production. Therefore, hadron momenta rise in geometric progression, i.e. build a plateau in rapidity.

Nevertheless, the rate of energy loss is constant, like in pQCD

$$-\left.\frac{dE}{dz}\right|_{pQCD} = \frac{2\alpha_s}{3\pi} Q^2$$



Perturbative hadronization

If a color charge gets transverse kick pT, it shakes off its color field in the forward direction and starts regenerating the field radiating gluons along the new direction.
Thus, in high-pT parton-parton scattering, 4 jets of are produced.

$$\frac{dn_g}{dx\,dk_T^2} = \frac{2\alpha_s(k_T^2)}{3\pi x}\,\frac{k_T^2[1+(1-x)^2]}{[k_T^2+x^2m_q^2]^2}$$

Radiation of gluons with $k_T^2 \lesssim x^2 m_q^2$, i.e. radiation with $\theta \lesssim m_q/E$ is suppressed: dead cone effect.
Heavy flavors radiate less energy than light quarks.

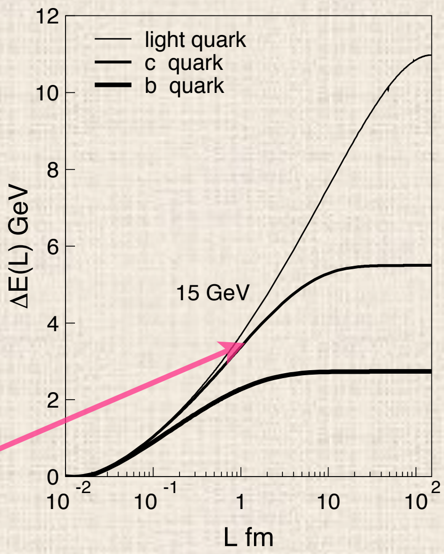
The color field of a parton originated from a hard reaction is not restored instantaneously. Radiation of a gluon takes coherence time/length

$$l_c^g = \frac{2Ex(1-x)}{k_T^2 + x^2\,m_q^2}$$

Time dependent vacuum energy loss

The energy dissipated over the pass length L is

$$\Delta E(L) = E \int_{\Lambda^2}^{Q^2} dk_T^2 \int_0^1 dx \, \frac{x\, dn_g}{dx\, dk_T^2} \, \Theta(L - l_c)$$

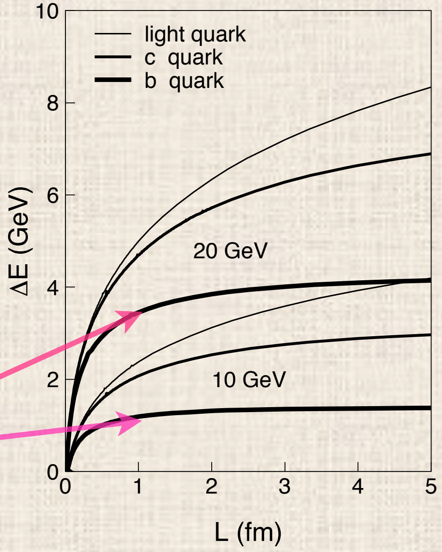


Important observations:

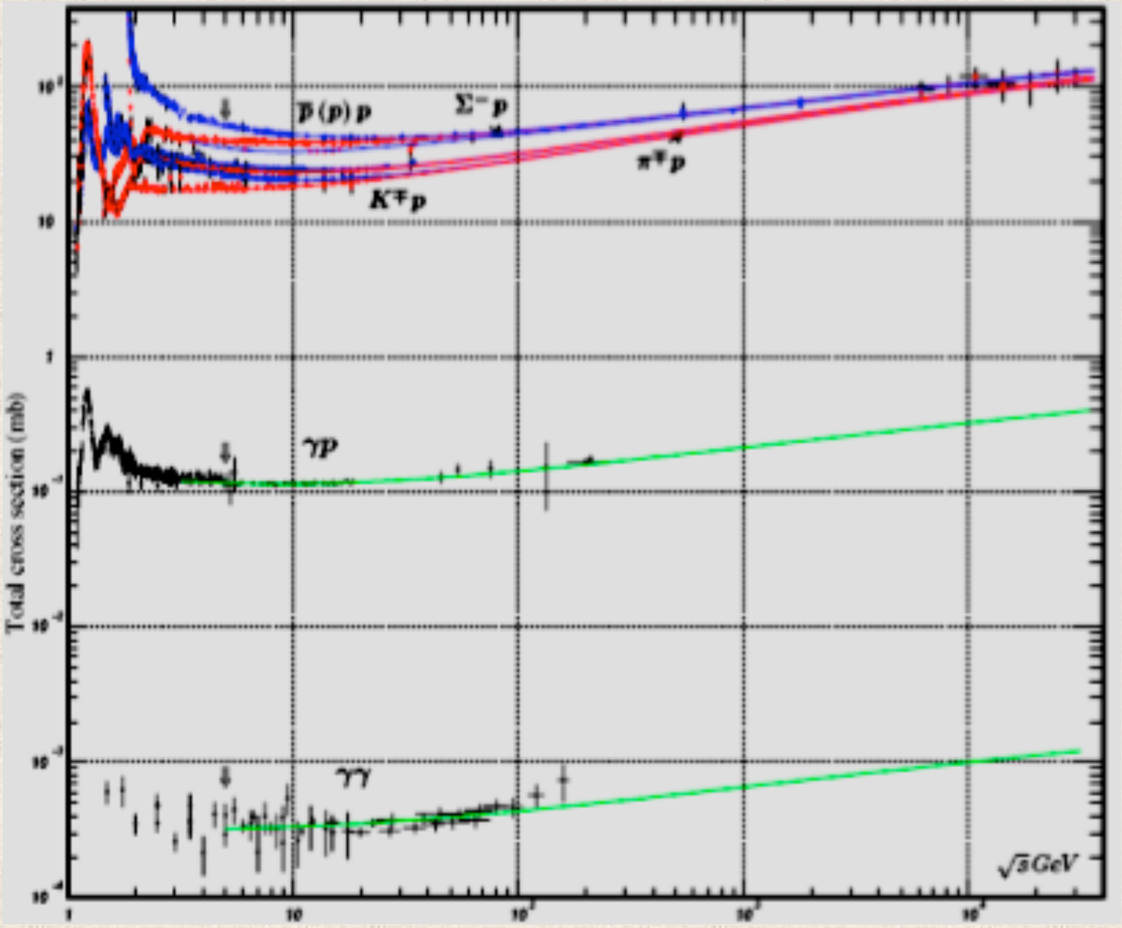
- Vacuum radiation following a hard process develops a dead cone, which may be stronger than one caused by the heavy quark mass.

- For this reason, charm and light quarks radiate and lose energy similarly during first few fm, which only matter in heavy ion collisions.

- While light and charm quarks take long time (100 or 10 fm) to regenerate their color fields, a bottom quark does it promptly, within a fermi after the hard interaction. Then it stops radiating.



Hints for the QCD dynamics from the basic features of hadronic collisions



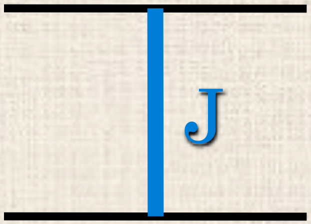
Total cross sections hardly depend on energy

$$\sigma_{tot} \approx Const$$

¿Why?

What does it tell us about the underlying dynamics?

Energy dependence of the scattering amplitude correlates with the spin of the particle exchanged in the cross channel.



$$A = \Pi_{\mu_1 \dots \mu_J \nu_1 \dots \nu_J} p_{\mu_1} \cdots p_{\mu_J} p'_{\nu_1} \cdots p'_{\nu_J} \propto s^J$$

$$\sigma_{tot}(s) = \frac{1}{s} \mathrm{Im}\, A(s) \propto s^{J-1}$$

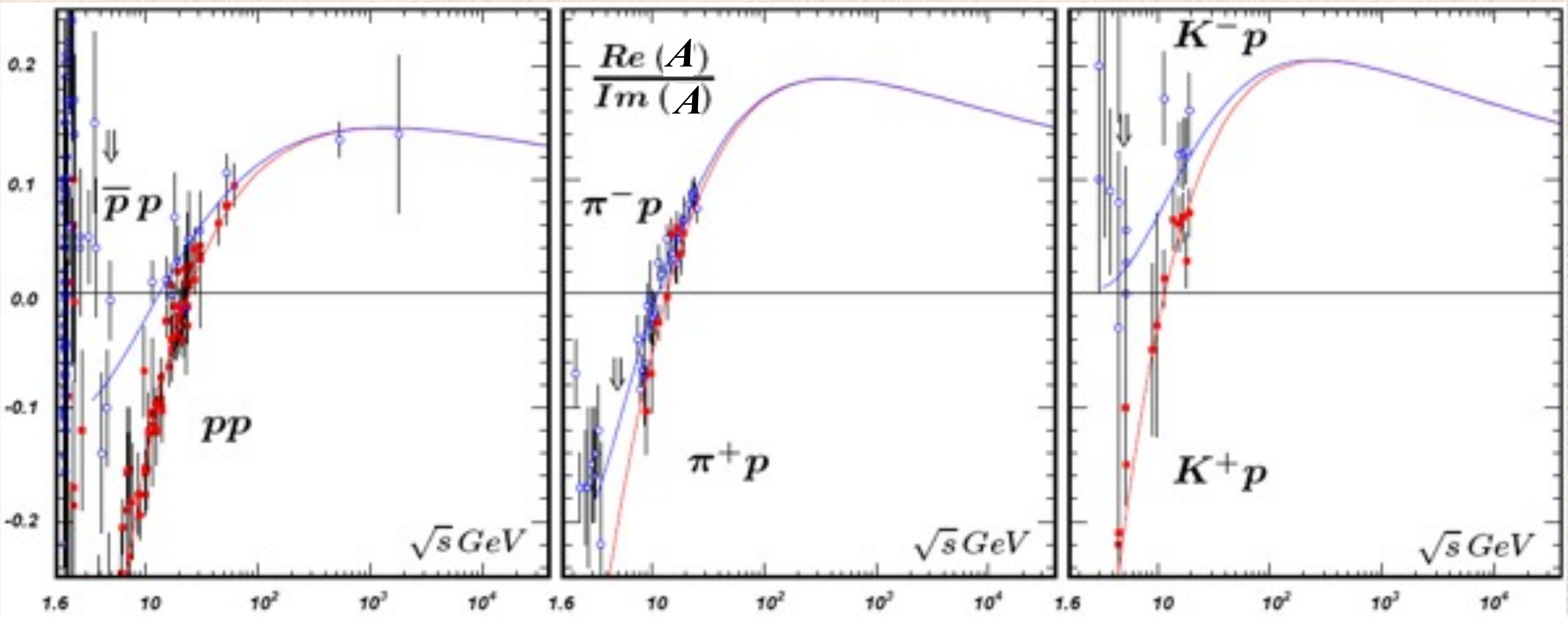
This observation is the key input for the Regge theory

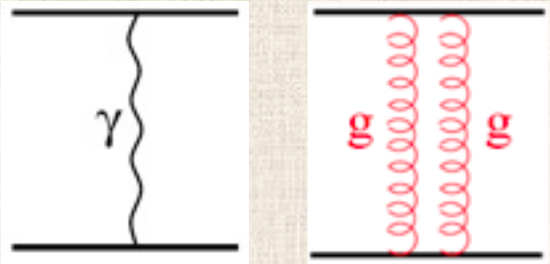
If gluons were spinless or had spin 2, the cross section would drop like 1/s, or rise as s. Neither of these complies with data. Therefore, the spin of the gluon is J=1.

Still, the cross sections slowly rise with energy, and QCD helps to understand why. Experience with DIS and HERA data is also very informative.

Evidence for a non-Abelian dynamics

The forward elastic amplitude is nearly imaginary, ReA/ImA~1





ImA=0 ReA=0

The dominant Born graphs should be two-gluon exchange in order to comply with ReA/ImA<<1.

This is possible only if gluons are colored

High-energy hadronic collisions: QCD vs Regge

The theory of Regge poles is a quite dormant topic. It does not seem to be taught very much anymore. In addition there is often found an attitude that the subject is obsolete, because it is identified so strongly with the pre-quark, pre-parton era of the S-matrix, dispersion-relations approach to strong interactions. This point of view is just plain wrong.

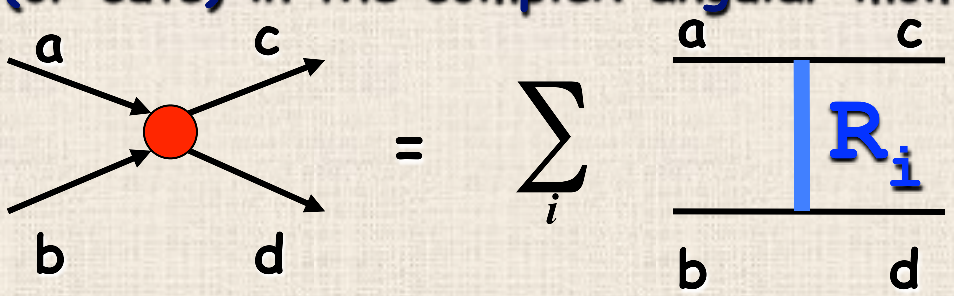
The Chew, Frautschi, Regge, et al. description of high energy behavior in terms of singularities in the complex angular momentum plane is completely general.
And the basic technique of Watson-Sommerfeld transform should be a standard part of the training in theoretical particle physics.

James Bjorken

Regge theory

A brief survey of main results

The energy dependence of the amplitude is governed by poles (or cuts) in the complex angular momentum plane.



$$A_i(t) = g_i^{ac}(t)\, g_i^{bd}(t)\, \xi_i(t) \left(\frac{s}{s_0}\right)^{\alpha_i(t)}$$

Energy dependence is given by the last factor, while the **vertex functions** $g_i(t)$, and the **signature factor** $\xi_i(t)$ depend only on t.

$$\xi_i(t) = \begin{cases} i + \mathrm{ctg}\left[\frac{\pi}{2}\alpha_i(t)\right] & s=-1 \\ -i + \mathrm{tg}\left[\frac{\pi}{2}\alpha_i(t)\right] & s=+1 \end{cases}$$

Each trajectory at t>0 passes through the states with either **odd**, or **even** spins. Signature, $s=(-1)^J$.

The energy dependence $(s/s_0)^{\alpha_i(t)}$ is controlled by the Regge trajectory $\alpha(t)$ which is nearly straight

$$\alpha(t) = \alpha(0) + \alpha' t$$

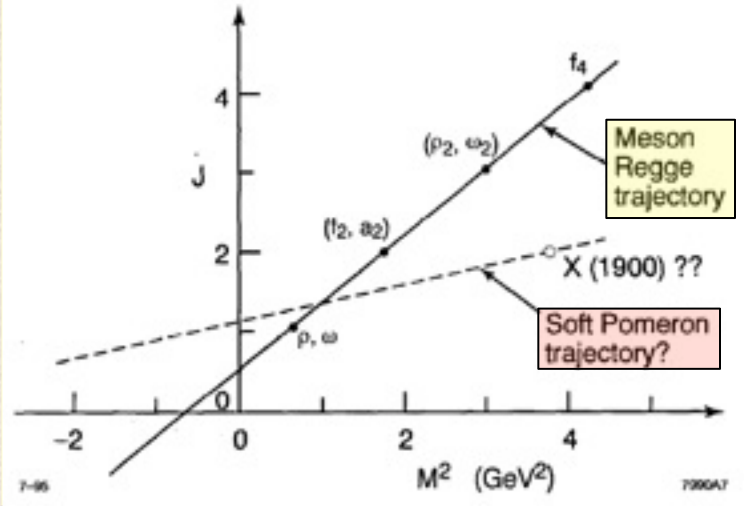
At high energies dominate Reggeons with highest intercept $\alpha(0)$.

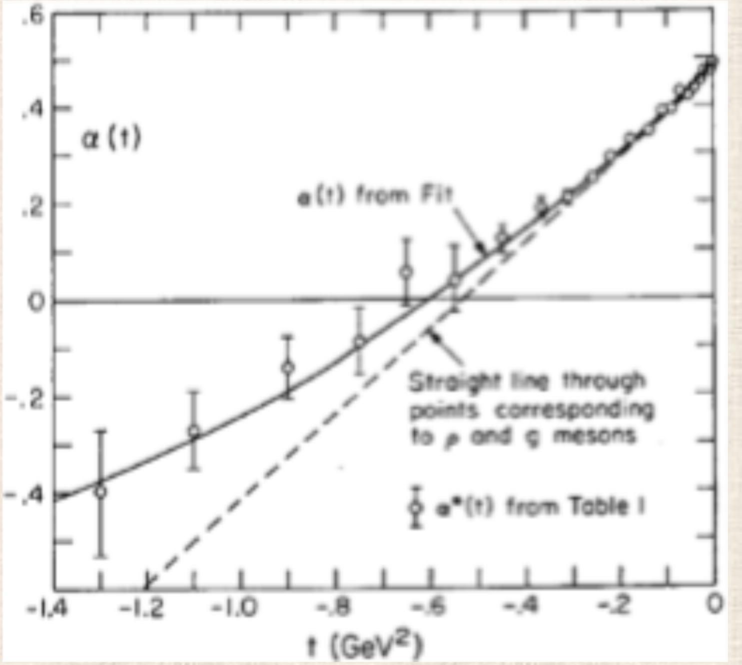
The leading Reggeons contributing to pp elastic amplitude:

Pomeron: $\alpha_P(0) \approx 1.1;$ $\alpha'_P \approx 0.25 GeV^{-2}$

$$\alpha_\omega(0) \approx \alpha_f(0) \approx \alpha_\rho(0) \approx \alpha_{a_2}(0) \approx 0.5$$

$$\alpha'_R \approx 0.9 GeV^{-2}$$





The miracle of Regge theory:
a linear Regge trajectory bridges the low-energy physics of resonances ($t=M^2>0$) with high-energy scattering ($t<0$)

Since the Pomeron intercept is above one, the total hadronic cross sections should rise with energy as $s^{a(0)-1}$.

Elastic slope.

Parametrizing the residue function as

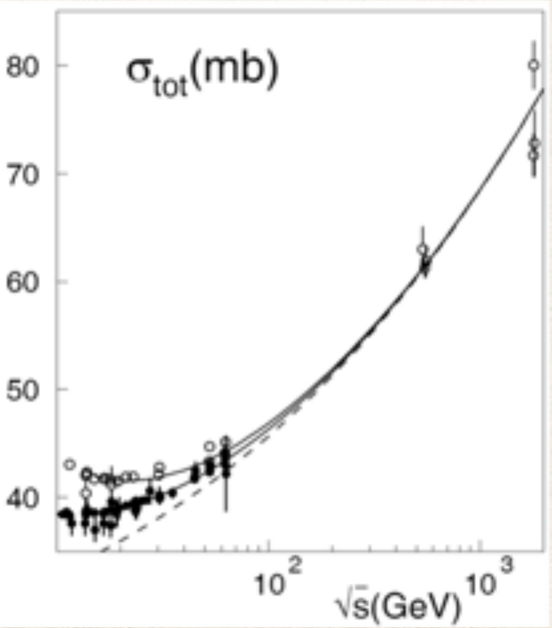
$$g_P^{pp}(t)g_P^{pp}(t) = g_P^{pp}(0)g_P^{pp}(0)e^{B_0 t/2},$$

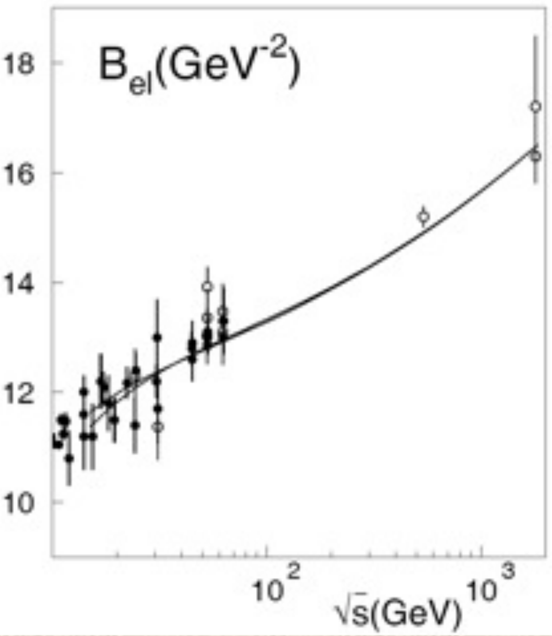
we arrive at an energy dependent t-slope of the elastic cross section,

$$A_i(t) = g_i^{ac}(t)g_i^{bd}(t)\xi_i(t)\left(\frac{s}{s_0}\right)^{\alpha_i(t)} \propto e^{B(s)t/2}$$

$$B_{el}(s) = B_0 + 2\alpha'_P \ln(s/s_0)$$

Shrinkage of the diffraction cone.





In QCD the Pomeron is not a Regge pole.

2-pole model with one nonperturbative parameter

I.Potashnikova, B.Povh, E.Predazzi, B.K.(2000)

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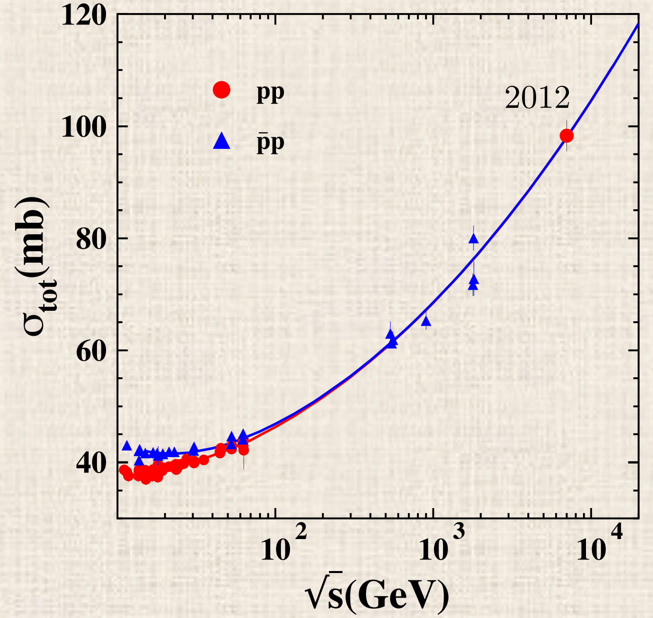

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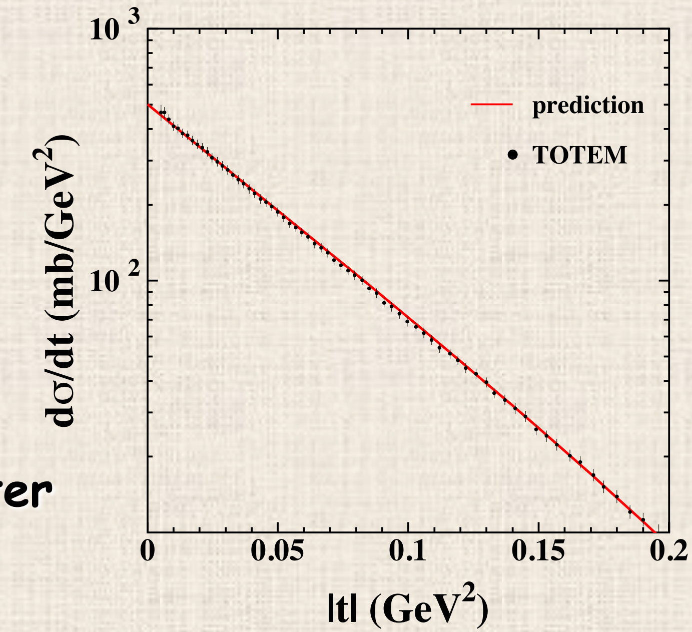
Shrinkage of the diffraction cone.



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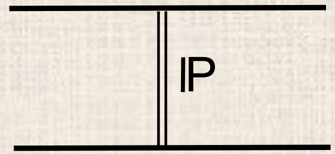
The Pomeron:



Dominates high-energy elastic/inelastic scattering.

¿Regge pole? - Probably not.
The intercept is higher for J/Ψ photoproduction and varies with Q^2 in DIS.

¿DGLAP Pomeron?
- Why ordering of transverse momenta of radiated gluons? There are indications on gluon saturation which breaks up the DGLAP.
Besides, perturbative QCD is not legitimate for the soft Pomeron.

¿BFKL Pomeron?
-Has no QCD evolution. Next-to-leading (log) order calculations revealed ~100% large corrections. The intercept is far too high for the soft Pomeron.

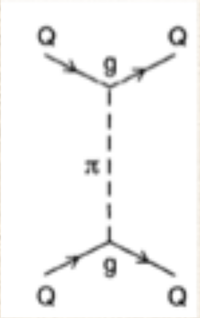
¿More ideas?..

Building the Pomeron

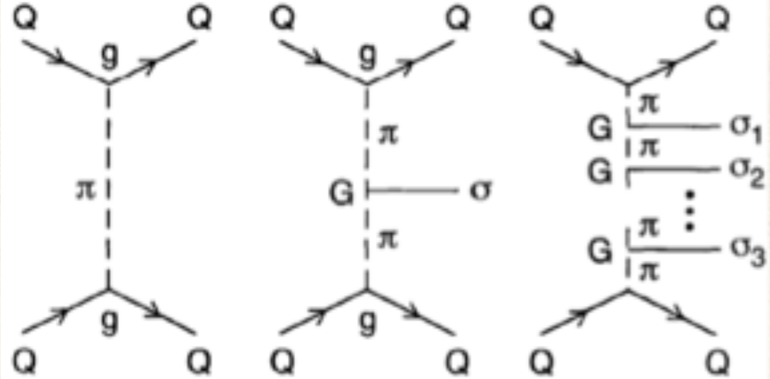
Any material is good: gluons, pions, sigmas, instantons...

Pion is the lightest hadron, it can reach furthest distances. The π-N coupling is large. **A good candidate!** The first step, however, is quite **discouraging**: the cross section related to spinless **pion exchange steeply falls with energy**.

$$\frac{d\sigma}{dt} \propto \frac{1}{s^2}\left(\frac{g^2}{4\pi}\right)^2 \frac{t^2}{(t-m_\pi^2)^2}$$



Nevertheless, "**Reggeization**" helps, integration over the phase space of the radiated sigmas provides powes of ln(s)



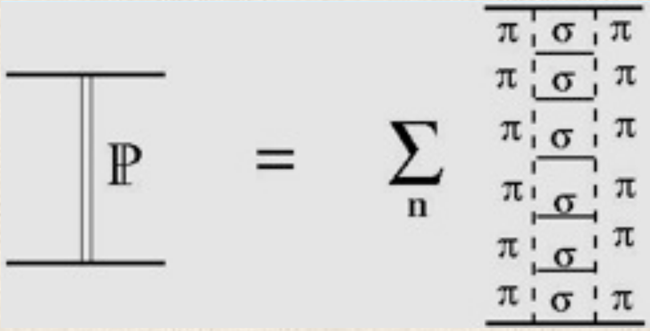
$$\int_0^{\ln s} dy_1 \int_{y_1}^{\ln s} dy_2 \cdots \int_{y_{n-1}}^{\ln s} dy_n = \frac{(\ln s)^n}{n!}$$

Summing up power of logs we get the cross section

$$\sigma = \frac{g^4}{s^2} \sum_{n=0}^{\infty} \frac{1}{n!} \left[\int \frac{d^2 p_T}{(2\pi)^3} G^2(p_T) \ln s \right]^n \propto s^{2\alpha_P(0)-2}$$

Corresponding Pomeron intercept reads,

$$\alpha_P(0) = \frac{1}{2} \int \frac{d^2 p_T}{(2\pi)^3} G^2(p_T)$$

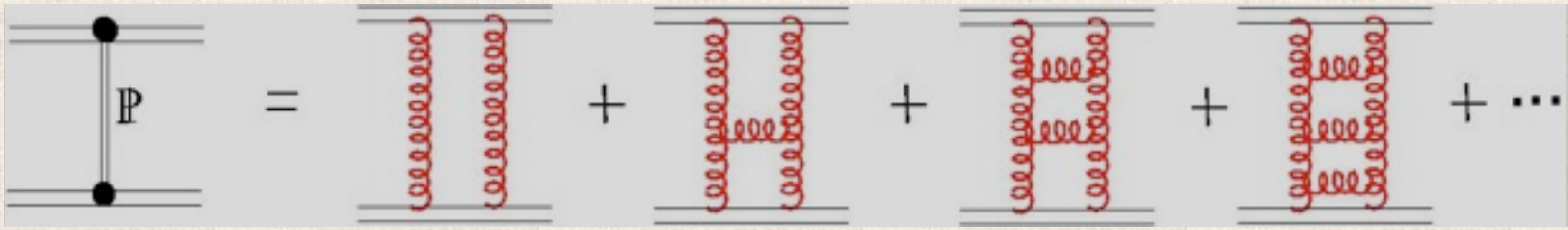


Although pion is spinless, the "pionic" Pomeron may have spin 1.

So far it is not clear how realistic is this model. It has enough freedom to reproduce the observed Pomeron intercept.
It also explains well data on different inclusive reactions.
However closeness of the Pomeron intercept to unity looks accidental.

Leading-log BFKL Pomeron:

Gluons seem to be the most suitable building material: already the Born graph provides $\alpha_P(0)=1$. The higher order corrections are expected to pull the intercept above one.



The ladder is a shadow of gluon bremsstrahlung according to the unitarity relation

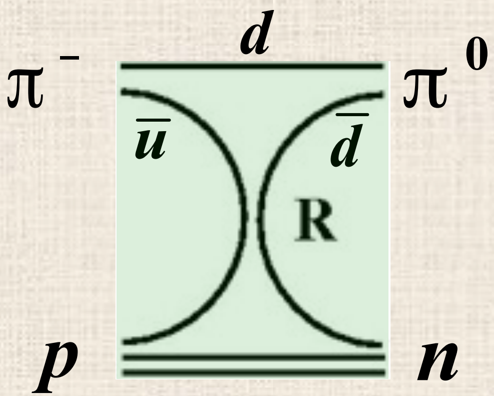
The leading-log approximation (LLA) corresponds to keeping only those terms where each coupling α_s has a big factor ln(s) (similar to the pionic Pomeron). For fixed coupling the **BFKL** result is not a Regge pole, but a Regge cut with the intercept

$$\alpha_P(0) - 1 = \frac{12\alpha_s}{\pi}\ln 2$$

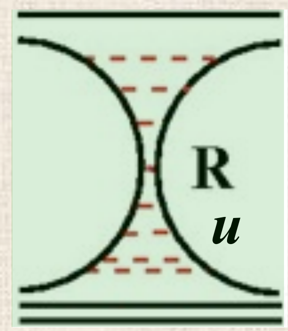
Unfortunately, the next-to-leading-log corrections (extra powers of α_s) to the intercept are of the same order as $\alpha_P - 1$.

Reggeons

Reggeons correspond to exchange of valence quarks.



Born



Reggeized

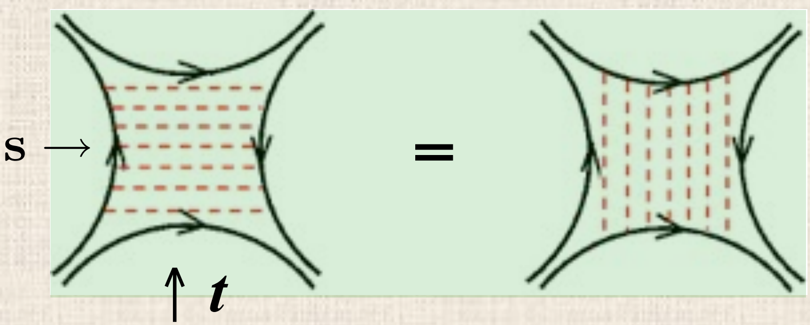
$$\alpha_R(0) = 0.5$$

$$\alpha'_R = \frac{1}{2\pi\kappa} = 0.9 GeV^{-2}$$

$$\kappa = 1 GeV / fm$$

string tension

Duality and exchange degeneracy

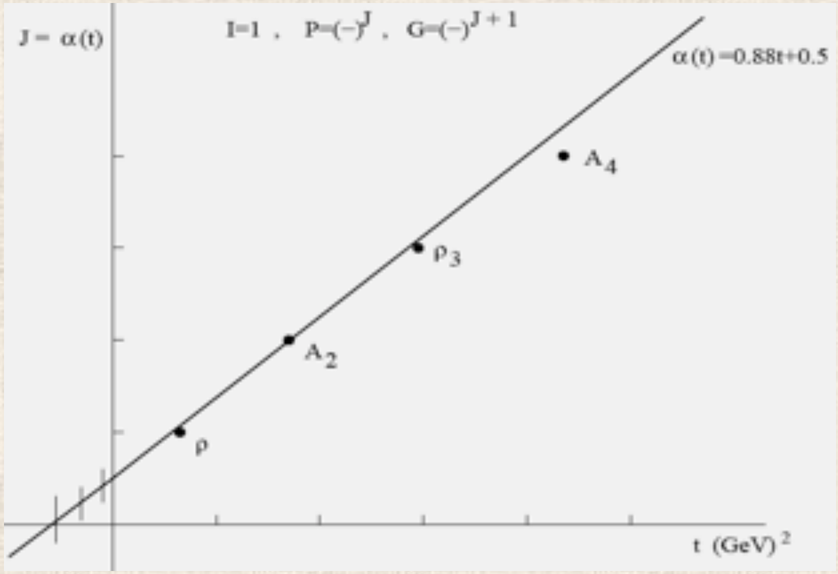


t-channel resonances

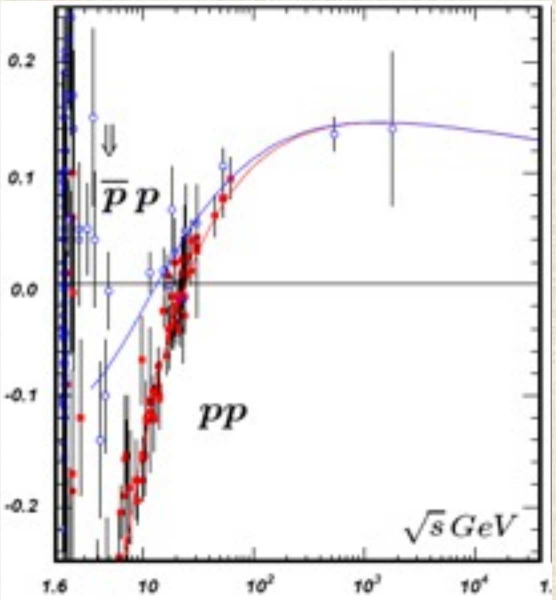
s-channel resonances

No s-channel resonances is possible in pp and K^+p elastic amplitudes. However t-channel Reggeons are present. To comply with duality they must cancel each other in the imaginary part of the amplitude.

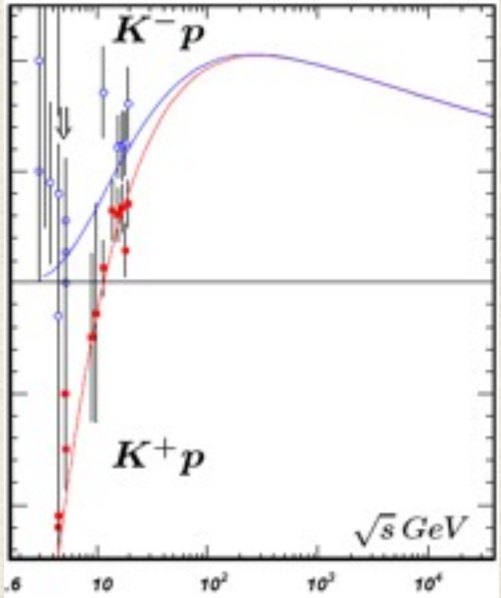
Pairs of leading Reggeons are exchange degenerate, f with ω, and a_2 with ρ, i.e. their Regge trajectories and residue functions must be identical, only the signature factors (phases) are different.



The sums, f+ω and a_2+ρ must be real for pp and K^+p, but imaginary for $\bar{p}p$ and K^-p.



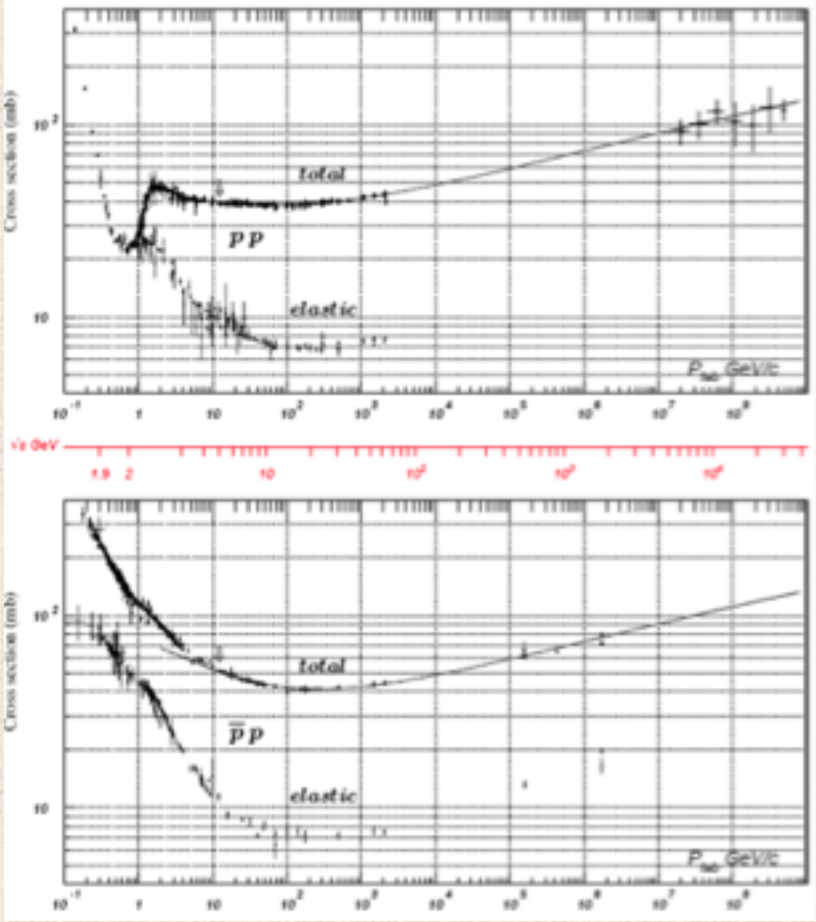
$$\frac{\mathrm{Re}\,A(0)}{\mathrm{Im}\,A(0)}$$

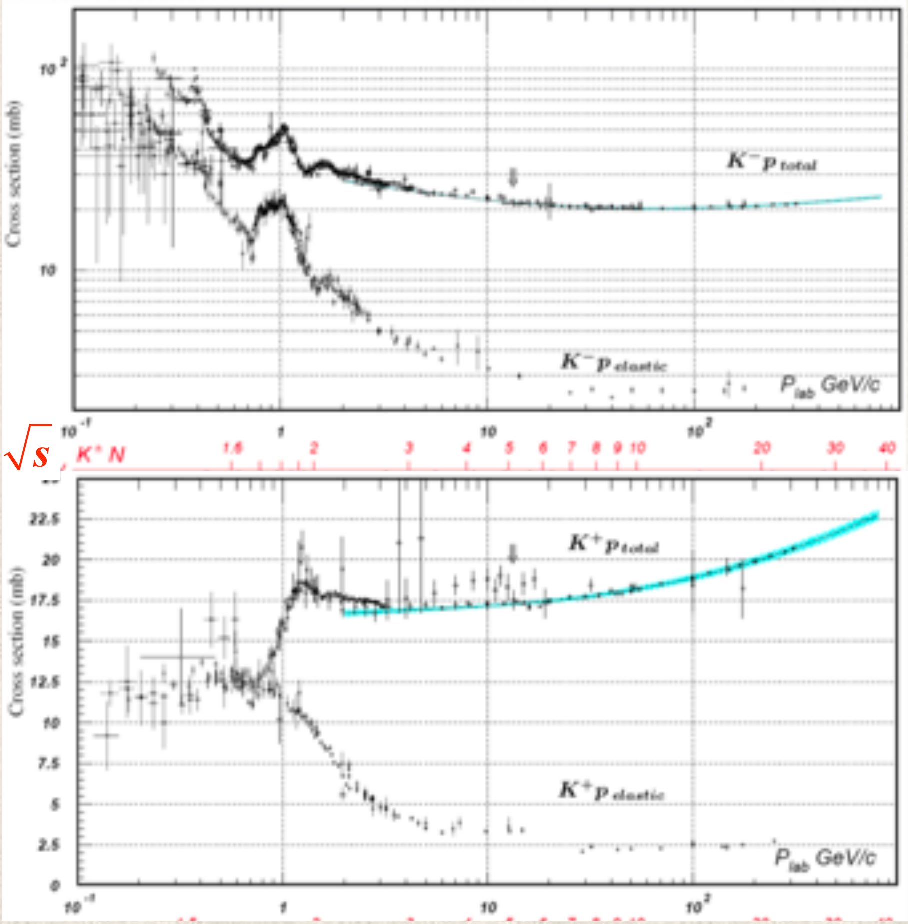


For the same reason spin effects are much stronger in $\bar{p}p$ and K^+p, than in pp and K^-p

As far as the sums, f+ω and a_2+ρ are imaginary for $p\bar{p}$ and K^-p, the total cross section decreases with energy, until the Reggeon part becomes very small.

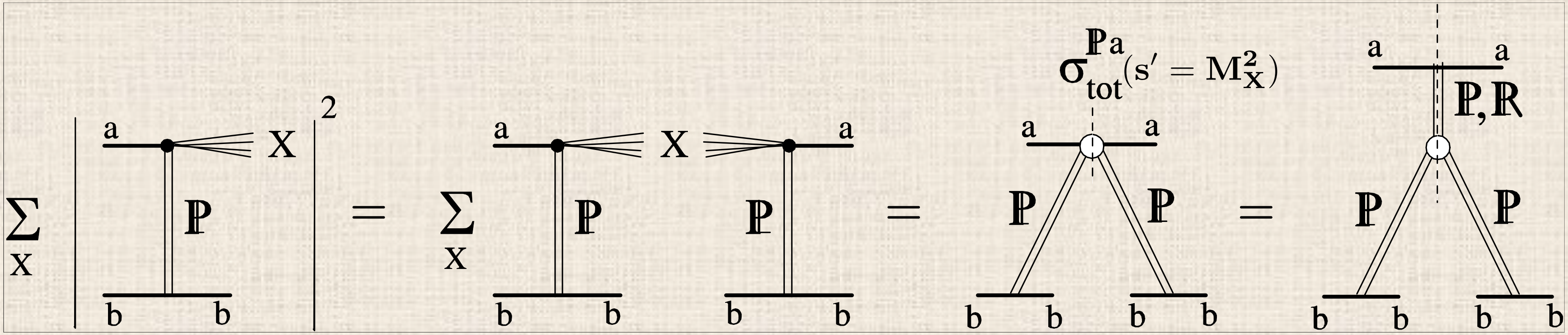
For pp and K^+p the Reggeon part is real and doesn't contribute to the total Xsection. The latter is expected to rise already at low energies





Triple Regge phenomenology

Diffractive excitation of a hadron: a+b->X+b

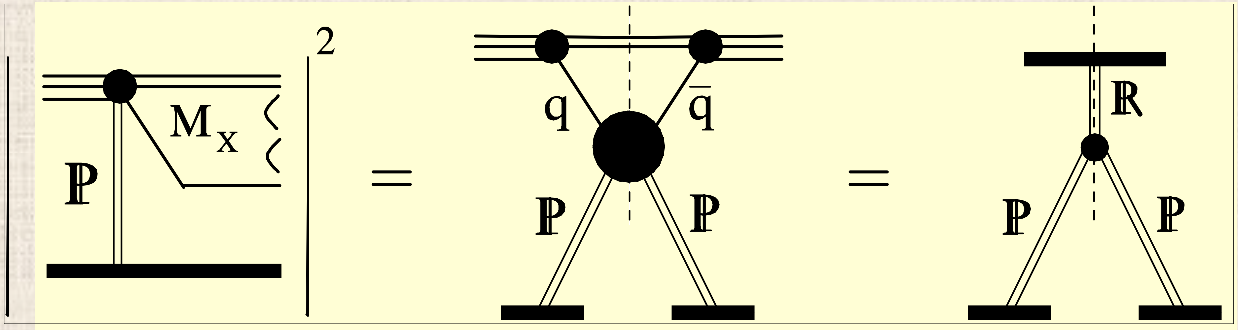


Kinematics: $s_o \ll M_X^2 \ll s;$ $\quad x_F \equiv \frac{2p_b^*}{\sqrt{s}} = 1 - \frac{M_X^2}{s}$

$$\frac{d\sigma_{sd}^{ab\to Xb}}{dx_F\,dt} = \sum_{i=\mathbb{P},\mathbb{R}} G_{\mathbb{P}\mathbb{P}i}(t)(1-x_F)^{\alpha_i(0)-2\alpha_{\mathbb{P}}(t)}\left(\frac{s}{s_0}\right)^{\alpha_i(0)-1}$$

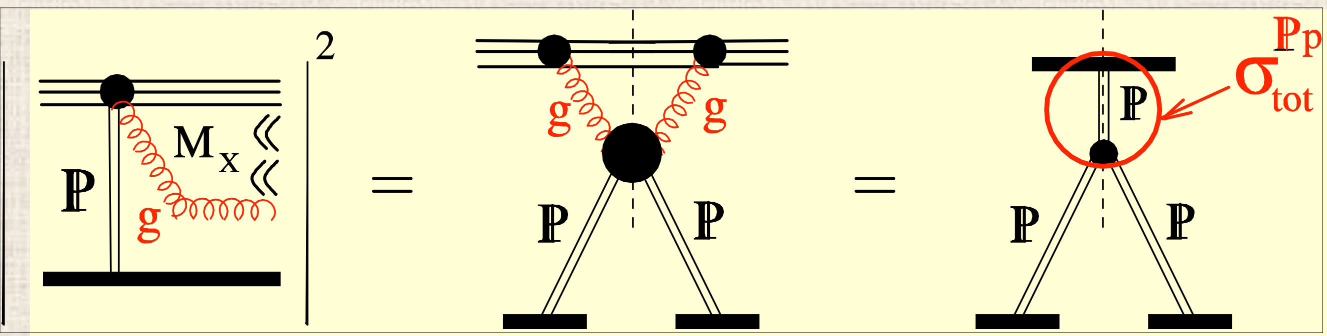
The triple-Regge couplings G_{PPP}, G_{PPR} are fitted to data.

The graph PPR corresponds to excitation of the valence quark skeleton



$$\left.\frac{d\sigma_{sd}}{dM_X^2}\right|_{PPR} \propto \frac{1}{M_X^3}$$

The triple-Pomeron graph corresponds to diffractive gluon radiation

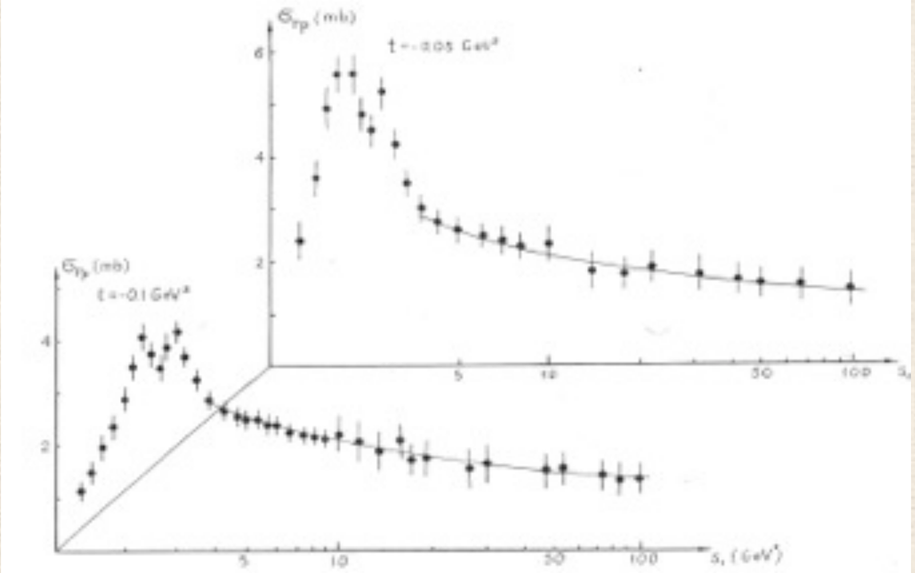


$$\left.\frac{d\sigma_{sd}}{dM_X^2}\right|_{PPP} \propto \frac{1}{M_X^2}$$

One can discriminate the two mechanisms via their M_X-dependences and find the Pomeron-proton cross section from data.

Since the Pomeron is a gluonic object it should interact stronger than a quark-antiquark meson, so one could expect

$$\sigma_{Pp}^{tot} \approx \frac{9}{4}\sigma_{\pi p}^{tot} \approx 50mb$$

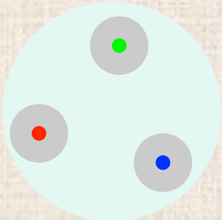


However, diffractive data suggest a **much smaller** value

$$\sigma_{Pp}^{tot} = \frac{M_x^2/s}{\left(g_{pp}^{P}(t)\right)^2} M_x^2 \frac{d^2\sigma}{dM_x^2 dt} \approx 2mb$$

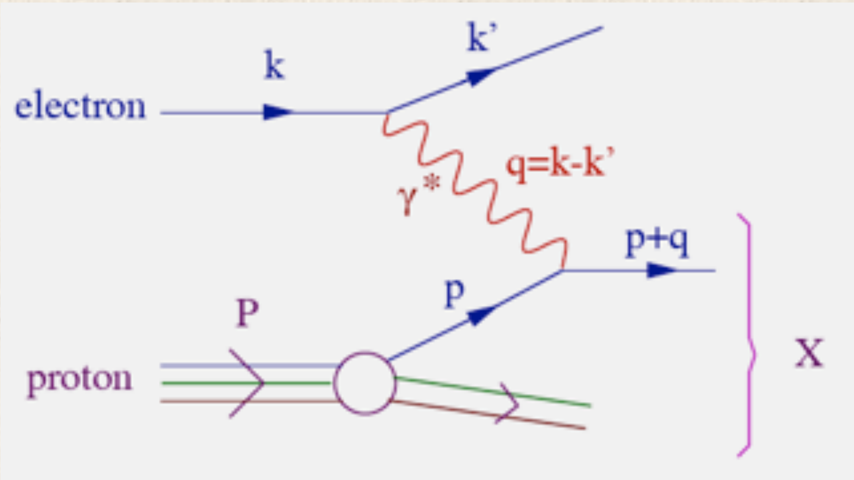
The only solution is to assume that the Pomeron is a small size object, and its cross section is small due to **C**olor **T**ransparency.

This means that gluons in the proton are located within **small spots** of radius r ~ 0.3 fm.



Important consequences for CGC and saturation scale.

DIS at small x



Inclusive Deep-Inelastic Scattering of electrons (muons) on protons.

Two independent Lorentz invariants :

$$Q^2 \equiv -q^\mu q_\mu = -(k-k')^2 \qquad (Q^2 \geq 0)$$

$$x \equiv \frac{Q^2}{2P\cdot q} = \frac{Q^2}{Q^2+W^2-M^2} \qquad (\text{Bjorken's } x)$$

DIS is characterized by two structure functions F_1 and F_2.

$$\frac{d^2\sigma^{em}}{dx\,dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[y^2 F_1^{em} + \left(\frac{1-y}{x} - \frac{xy^2M^2}{Q^2}\right) F_2^{em}\right]$$

energy loss:	$\nu = (P\cdot q)/M = E - E'$
rel. energy loss:	$y = (P\cdot q)/(P\cdot k) = 1 - E'/E$
recoil mass M_X^2:	$W^2 = (P+q)^2 = M^2 + \frac{1-x}{x}Q^2$

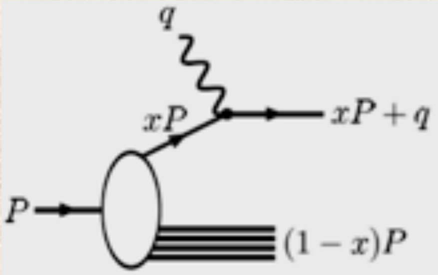
One can split the DIS cross section into the flux of virtual photons,

$$\Gamma = \frac{\alpha}{2\pi^2}\frac{E_e'}{E_e}\frac{1}{Q^2}\frac{1}{1-\epsilon}\frac{W^2-M^2}{2M}$$

and the virtual photo-absorption cross section summed over photon polarization ε,

$$\sigma_{\gamma^* p}(x,Q^2) = \sigma_T + \sigma_L = \frac{4\pi^2\alpha_{\rm em}}{Q^2} F_2(x,Q^2)$$

Thus, F_2 maybe viewed simply as the total X-section. On the other hand, it also can be interpreted as a quark distribution function in the proton. Indeed, assuming partons massless (or m~Λ) and point-like (i.e. unable to get excited) in the Breit frame (Eγ=0),



$$\begin{aligned}(p')^2 &= P^2 + 2\xi\, P\cdot q + q^2 \\ &\simeq 2\xi\, P\cdot q - Q^2 \\ &= \frac{\xi - x}{x} Q^2 \simeq 0\end{aligned}$$

The scaling variable x turns out to be the fractional momentum ξ of the parton in the infinite momentum frame (p»M).

Thus, F_2 is also the parton distribution function (PDF)

$$F_2(x) = \sum_{q,\bar{q}} e_q^2\, x q(x)$$

The structure functions depend on the photon polarization,

$$F_2 = F_T + F_L$$

$$F_1 = \frac{1}{2x} F_T$$

A spinless parton cannot absorb a transversally polarized photon (helicity ±1), while a fermion can.

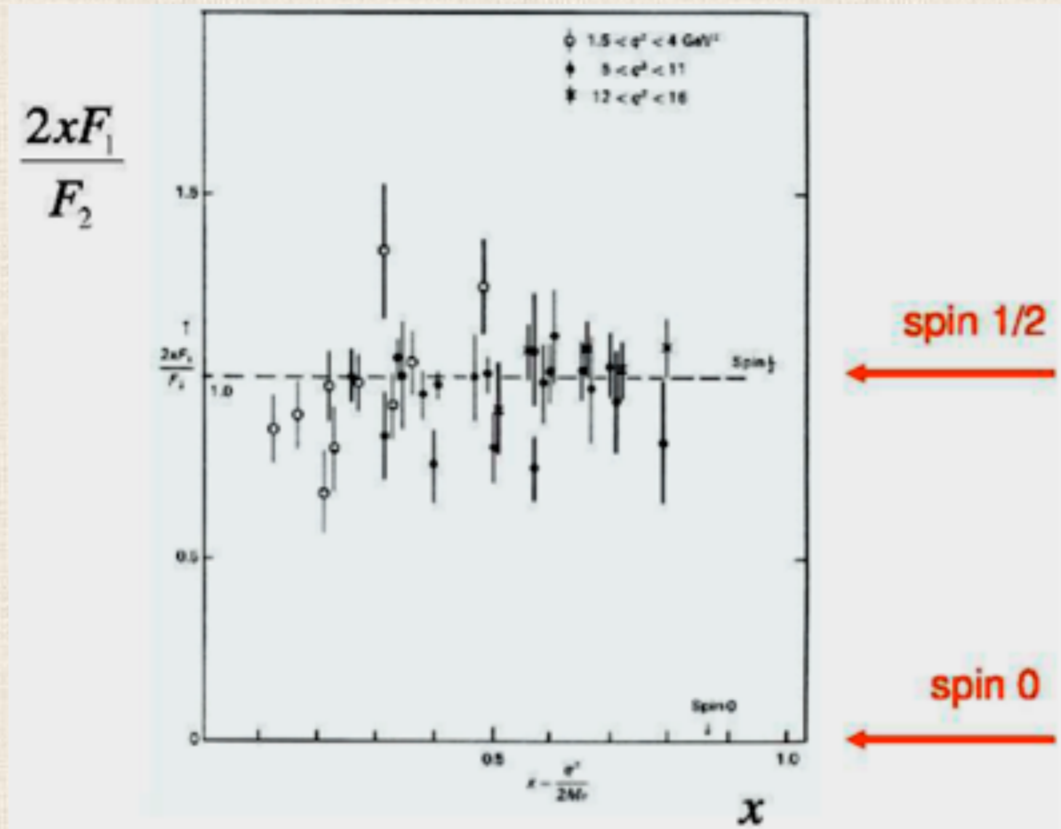
For partons with spin 0

$$F_T = 2xF_1 = 0$$

For partons with spin 1/2

$$F_2 = 2xF_1$$

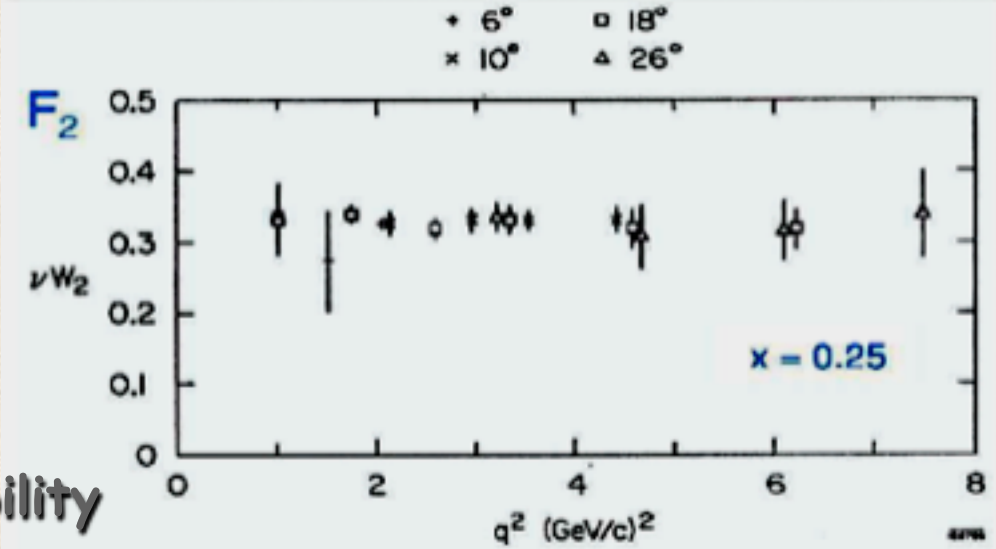
Callan-Gross relation



• "Deep inelastic" or Bjorken limit

Both Q^2 and $P \cdot q \gg M^2$ with $x =$ fixed

Bjorken scaling:
$F_2(x,Q)$ depends only on x



J.T.Friedman + H.W.Kendall, Ann. Rev. Nucl. Sci. **22** (1972) 203

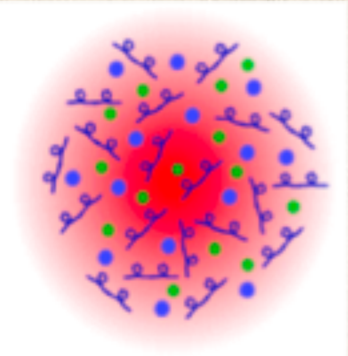
Why the proton formfactor F(Q) steeply falls with Q, while the structure function does not?

Answer: formfactor is the probability for a hadron to survive a kick of strength Q. However, in the case of inclusive DIS all final states are allowed, so the total probability saturates and is independent of Q.

Similar situation is in hadronic collisions: the t-slope of single diffraction is half of that for elastic pp, because of disappearance of one proton vertex.

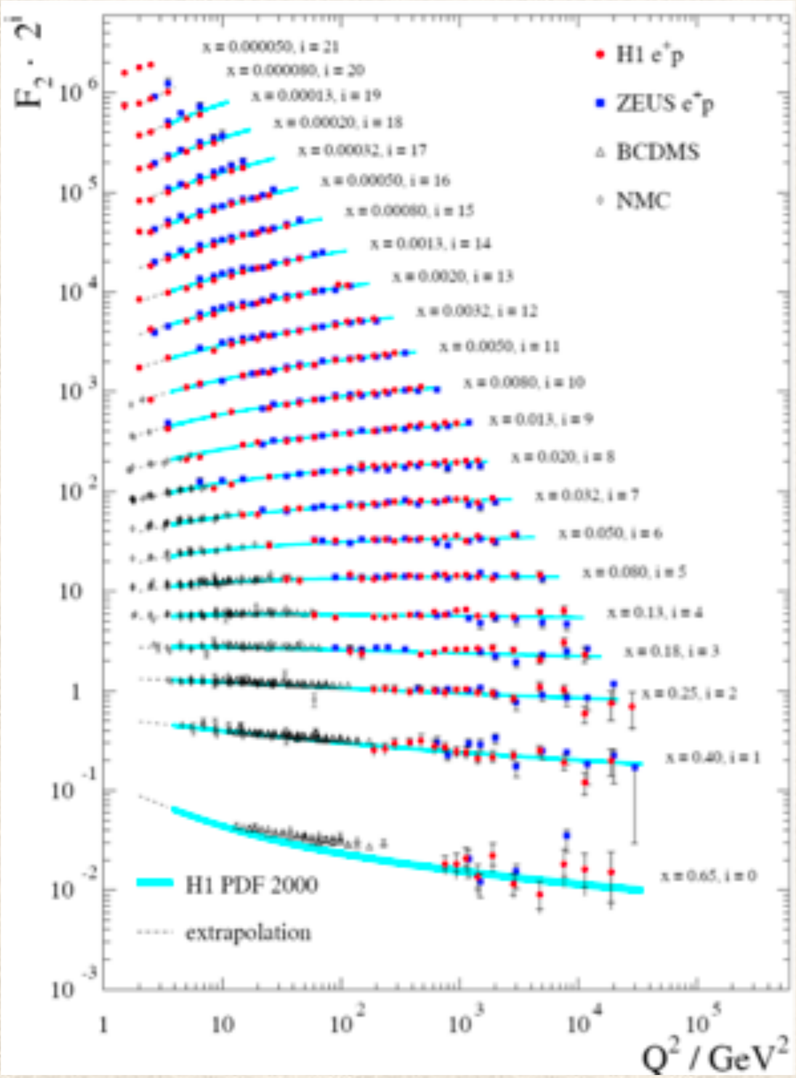
All that could be correct, if the number of parton were constant.
However, they are not classical particles, but quantum fluctuations which number depends on reference frame and resolution.

- A photon of virtuality Q can resolve partons with transverse momenta $k_T < Q$,



but is blind to harder fluctuations.
Increasing Q, one can see more partons in the proton.

Correspondingly, the parton distribution slowly changes with Q: it is getting shifted to small x, due to momentum conservation, i.e. it is expected to rise with Q at small x, but fall at large x.

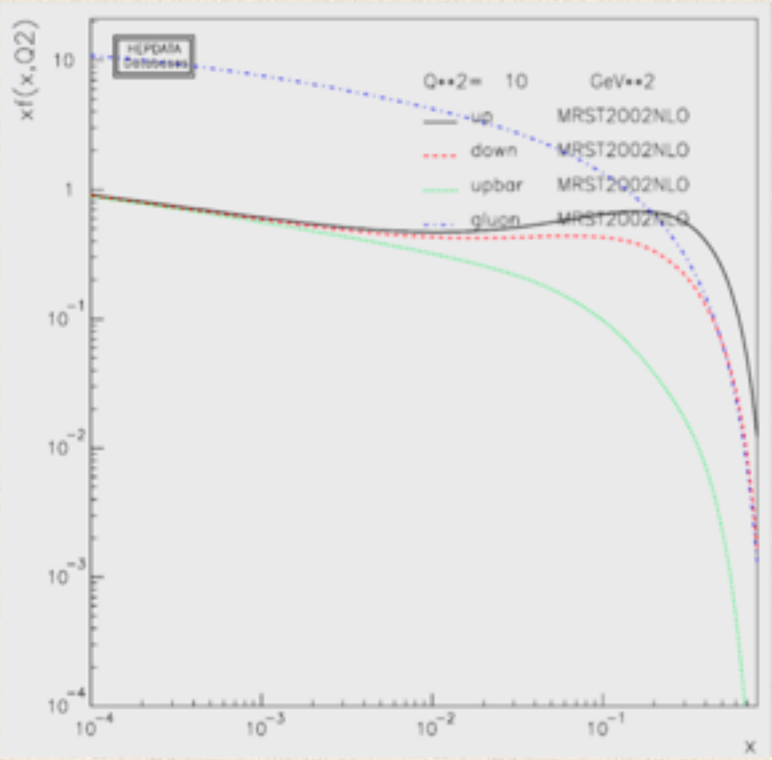


This evolution with the scale is controlled by DGLAP evolution equations (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi)

$$Q^2 \frac{d}{dQ^2} \begin{pmatrix} q_f(x_{Bj}, Q^2) \\ G(x_{Bj}, Q^2) \end{pmatrix} = \frac{\alpha_s}{2\pi} \int_{x_{Bj}}^{1} \frac{dx_1}{x_1} \begin{pmatrix} P_{ff}\left(\frac{x_{Bj}}{x_1}\right) & P_{fG}\left(\frac{x_{Bj}}{x_1}\right) \\ P_{Gf}\left(\frac{x_{Bj}}{x_1}\right) & P_{GG}\left(\frac{x_{Bj}}{x_1}\right) \end{pmatrix} \begin{pmatrix} q_f(x_1, Q^2) \\ G(x_1, Q^2) \end{pmatrix}$$

The splitting functions P are calculated perturbatively

pQCD is unable to calculate the PDFs, since that involves essential nonperturbative effects. However, one can calculate how PDFs vary when the hard scale changes.



The typical strategy for extracting PDFs from DIS data:

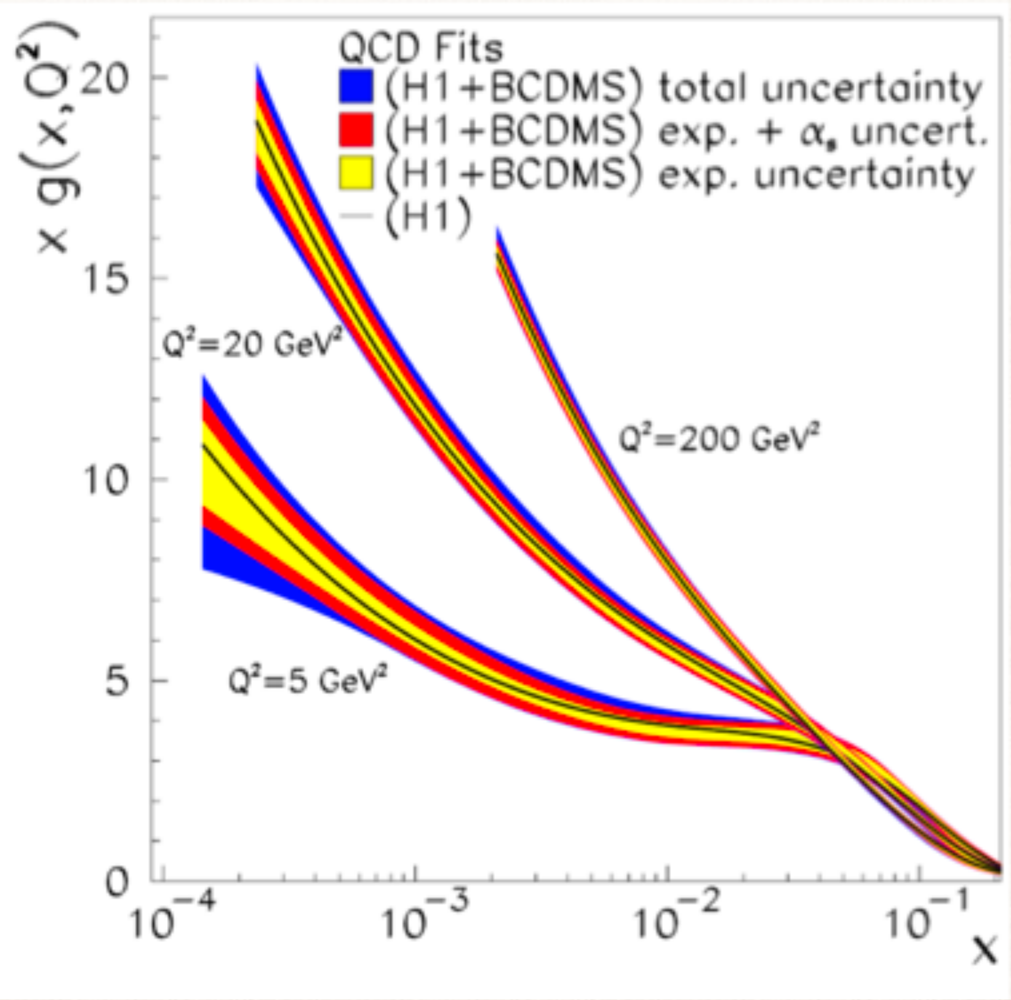
1. Introduce an ad hoc PDF at some scale
2. Evolve it with DGLAP to another scale
3. Compare with data and adjust the starting PDFs

Having good data with high statistics one can single out PDFs for different parton species.

Gluons dominate PDFs at small $x<0.1$ and steeply rise.

Actually, importance of gluons has been known since the early days of the parton model.

The momentum conservation sum rule:



$$\int_0^1 F_2(x) = \int_0^1 \sum_{q,\bar{q}} e_q^2 x q(x)$$

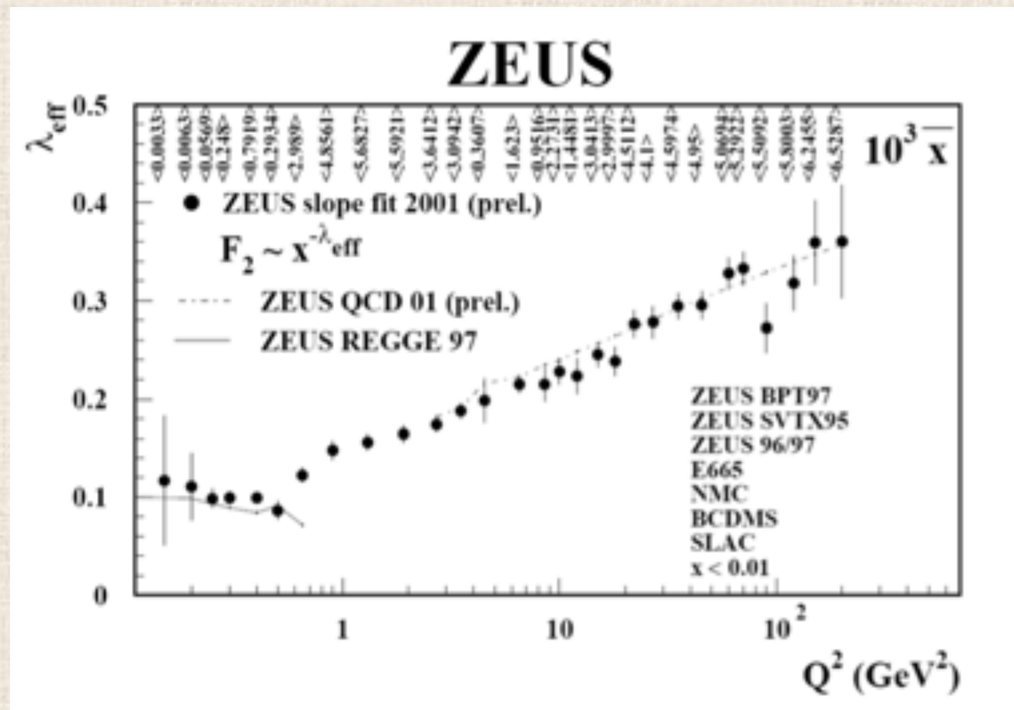
is the fraction of the total momentum carried by all quarks and antiquarks in the proton. It turns out to be only about half. Another half of the proton momentum is carried by the partons which don't interact with the photon, apparently by gluons.

The BFKL intercept does not depend on scale, while in data it does

$$\sigma_{tot}^{\gamma^* p}(x,Q^2) \propto F_2(x,Q^2) \propto \left(\frac{1}{x}\right)^{\lambda_{eff}(Q^2)}$$

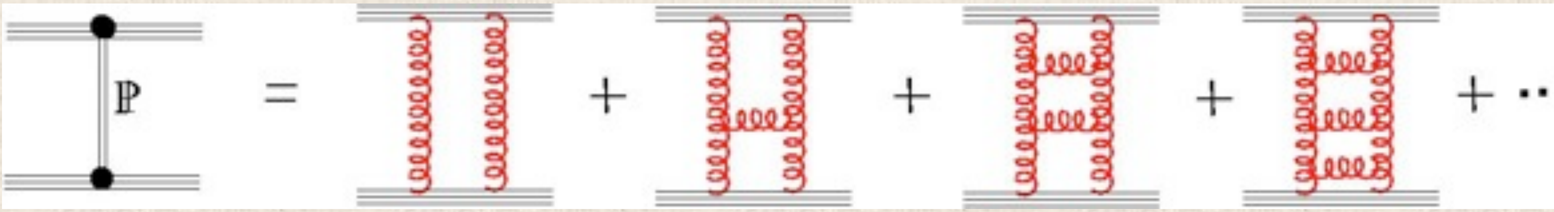
The effective Pomeron intercept is related to the effective exponent:

$$\alpha_P(0) - 1 = \lambda_{eff}(Q^2)$$



Data show that the Pomeron intercept is moving with Q to higher values. This clearly demonstrates that the Pomeron is not a Regge pole.

DGLAP Pomeron



Double-Leading-Log approximation.

Each radiated gluon is integrated over its phase space:

$$\alpha_s(k_i^2)\frac{dk_i^2}{k_i^2}\frac{dx_i}{x_i}$$

The cross section is some of powers of double logs:

$$F_2(x,Q^2) \propto \sum_{n=0}^{\infty}\frac{[\ln\ln(Q^2/\Lambda^2)]^n[\ln(1/x)]^n}{(n!)^2} \propto \exp\left[2\sqrt{\ln\ln(Q^2/\Lambda^2)\ln(1/x)}\right]$$

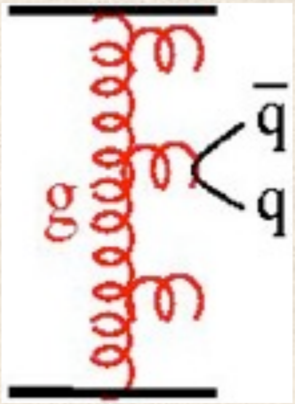
The higher the scale Q is, the steeper rises $F_2(x,Q^2)$ with 1/x.

The effective Pomeron intercept is a rising function of Q.

However at very high energies the DGLAP intercept $\alpha_{\mathbf{P}}(0) \to 1$ and BFKL wins.

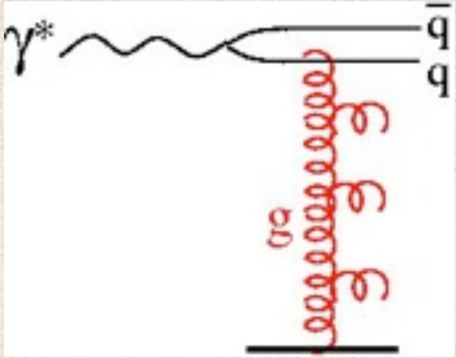
• "Small-x" or high-energy limit

$$W^2 \gg Q^2 > M^2 \quad \Longrightarrow \quad x \simeq \frac{Q^2}{W^2} \ll 1$$



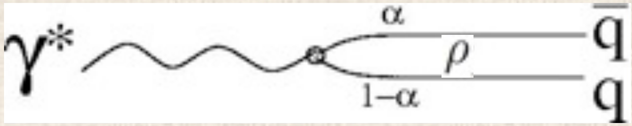
The parton model description is not Lorentz invariant, only observables are.
One cannot even say where a sea parton originated from, who is the owner, the beam or the target.

In the rest frame of the proton, the proton has no partons, all of which belong to the incoming photon. The photon fluctuates into a quark-antiquark pair which then develops a parton cloud.



Interpretation of $\mathbf{F_2(x, Q^2)}$ as a structure function of the proton is in this case rather conventional.

The wave function of a virtual photon



$$\varepsilon^2 = \alpha(1-\alpha)Q^2 + m_f^2$$

$$\left|\Psi^T_{q\bar{q}}(\alpha,\rho)\right|^2 = \frac{2N_c\alpha_{em}}{(2\pi)^2}\sum_{f=1}^{N_f} Z_f^2\left\{\left[1-2\alpha(1-\alpha)\right]\varepsilon^2\mathrm{K}_1^2(\varepsilon\rho)+m_f^2\mathrm{K}_0^2(\varepsilon\rho)\right\}$$

$$\left|\Psi^L_{q\bar{q}}(\alpha,\rho)\right|^2 = \frac{8N_c\alpha_{em}}{(2\pi)^2}\sum_{f=1}^{N_f} Z_f^2 Q^2\alpha^2(1-\alpha)^2\mathrm{K}_0^2(\varepsilon\rho),$$

$$\sigma^{\gamma^*p}_{T,L} = \int_0^1 d\alpha\int d^2\rho\left|\Psi^{T,L}_{q\bar{q}}(\alpha,\rho)\right|^2\sigma_{q\bar{q}}(\rho)$$

The dipole X-section has the property of Color Transparency.
If the mean dipole size is ρ~1/Q, the cross section is $1/Q^2$ which corresponds to the Bjorken scaling.

Q. Is inclusive DIS hard or soft reaction?

A. - Both

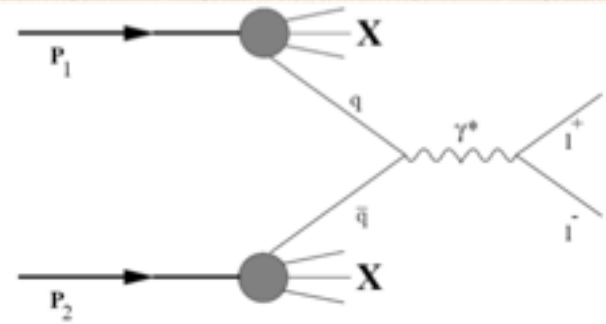
$$\langle \rho^2 \rangle \sim \frac{1}{\varepsilon^2} \sim \frac{1}{Q^2 \alpha (1-\alpha) + m_q^2}$$

In very asymmetric fluctuations $\alpha \sim 1/Q^2$, or $1-\alpha \sim 1/Q^2$ the fluctuations are soft

Fluctuation	$W_{\bar{q}q}^{\gamma*}$	$\sigma_{tot}^{\bar{q}qN}$	$W_{\bar{q}q}^{\gamma*}\sigma_{tot}^{\bar{q}qN}$
Hard ($\alpha \sim 1/2$)	~ 1	$\sim 1/Q^2$	$\sim 1/Q^2$
Soft ($\alpha \ll 1$)	$\sim \mu^2/Q^2$	$\sim 1/\mu^2$	$\sim 1/Q^2$

Inclusive DIS is semi-hard, semi-soft

Drell-Yan reaction



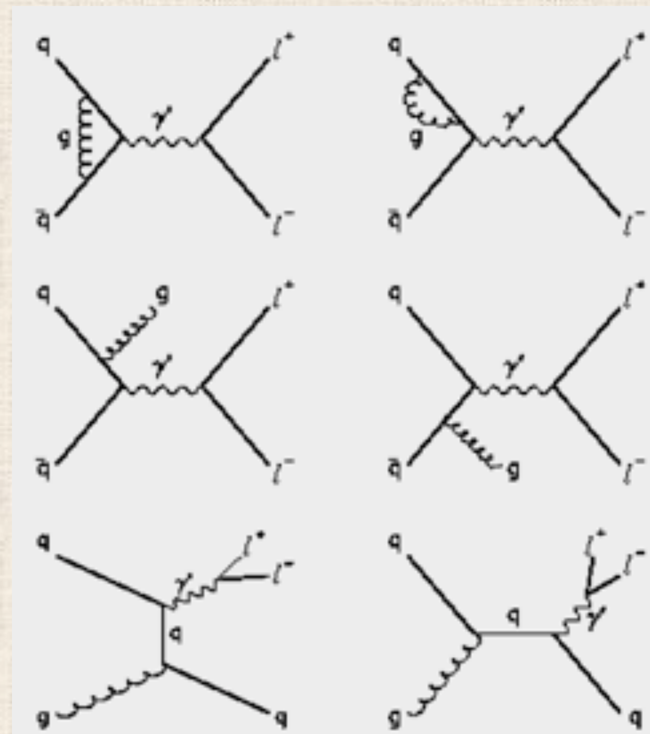
$$x_F = \frac{2p_L^{cm}}{\sqrt{S}} \approx x_1 - x_2$$

$$x_1 x_2 = \frac{M^2}{S}$$

$$M^2 \frac{d\sigma}{d\tau} = \frac{4\pi\alpha_{em}^2}{3N_c} \int_0^1 dx_1 \sum_f Z_f^2 \{q_f(x_1)\bar{q}_f(\tau/x_1) + (1 \leftrightarrow 2)\}$$

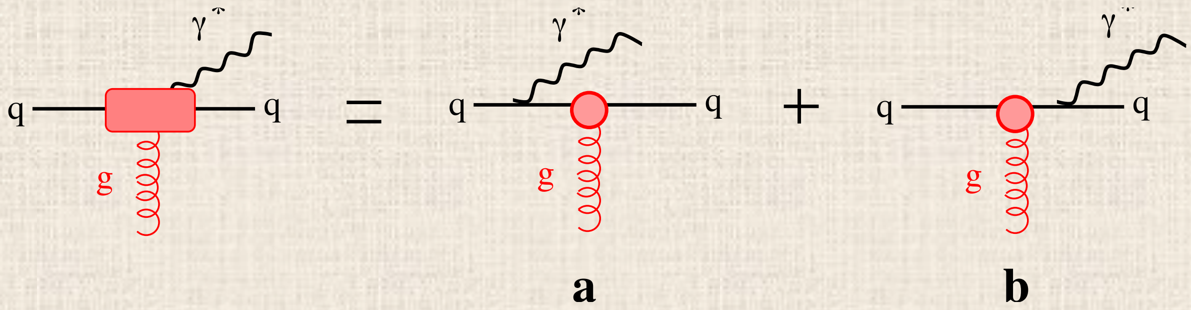
The cross section was found to be less than twice as small as data suggest.

Next-to-leading (NLO) corrections:



The correction K-factor is big, K≈2.3

In the rest frame of the target Drell-Yan Reaction looks like radiation of a heavy photon decaying into a dilepton.

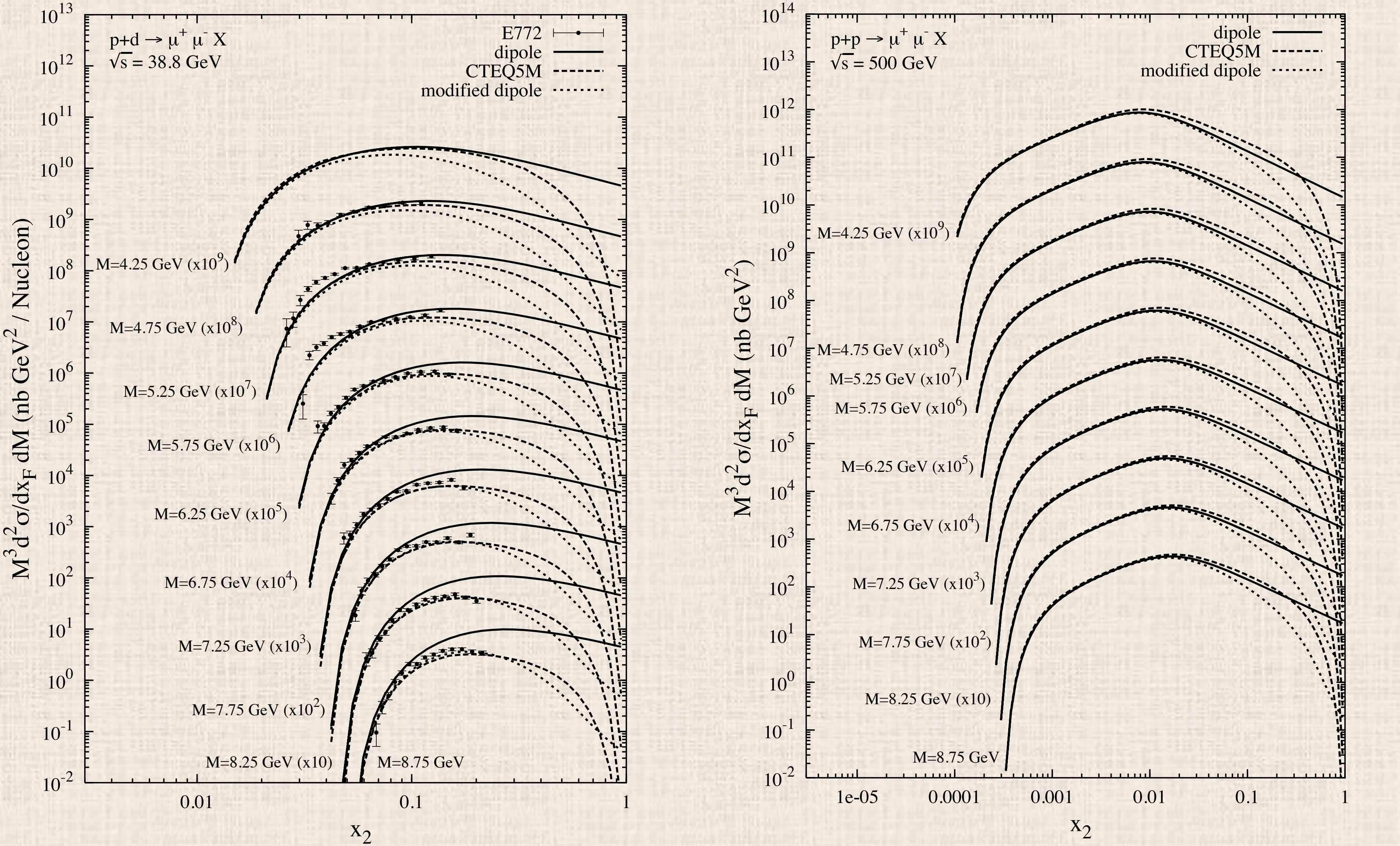


The cross section is expressed via the dipoles similar to DIS,

$$\frac{d\sigma^{DY}_{inc}(qp \to \gamma^* X)}{d\alpha} = \int d^2r \, |\Psi_{q\gamma^*}(\tilde{r},\alpha)|^2 \, \sigma(\alpha r, x_2) \qquad \alpha = \frac{p^+_{\gamma^*}}{p^+_q}$$

The measured DY cross section

$$\frac{d\sigma^{DY}_{inc}}{dx_1 dM^2} = \frac{1}{M^2 x_1} \frac{\alpha^2_{em}}{3\pi} \int\limits_{x_1}^{1} \frac{d\alpha}{\alpha} F_2(x_1/\alpha) \int d^2r \left|\Psi^{L,T}_{q\gamma^*}(\tilde{r},\alpha)\right|^2 \sigma(\alpha r, x_2)$$



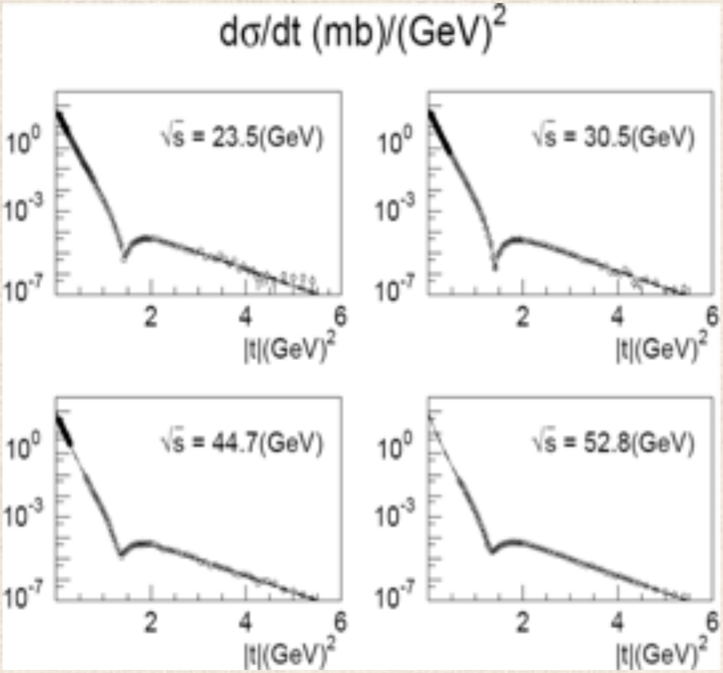
J.Raufeisen, J.C.Peng, G.Nayak

Diffraction

Diffractive elastic scattering of hadrons is a shadow of inelastic collisions.

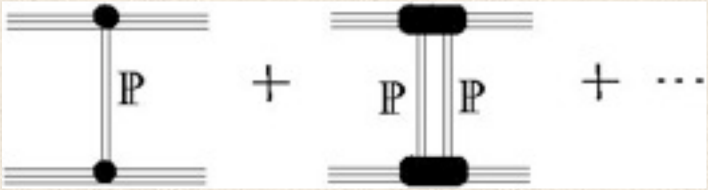
$$2\,\mathrm{Im}\, f_{el}(0) = \sigma_{tot}$$

This quantum mechanical effect has been known in classical optics.
The angular distribution of elastic diffraction has characteristic minima and maxima, for hadrons as well.



This diffraction is soft, since the main bulk of inelastic collisions is soft.

In the Regge approach this dip results from the interference of single and double Pomeron exchanges



Good-Walker mechanism of inelastic diffraction (1964)

Glauber, 1955; Fainberg-Pomeranchuk, 1956

Optical theorem: elastic diffraction is a shadow of inelastic interactions

$$2\,\mathrm{Im}\,f_{el} = \sigma_{tot}$$

How to interpret inelastic (or quasi-elastic) diffraction, a+b -> X+b ?

Hadrons are eigenstates of the mass matrix, but not of the interactions.
So they can be expanded of the eigenstate of interaction $|h\rangle = \sum_{l=1} C_l^h\,|l\rangle$

$$\sum_{h'\neq h} \frac{d\sigma_{sd}^{h\to h'}}{dt}\bigg|_{t=0} = \frac{1}{4\pi}\left[\sum_l |C_l^h|^2\,|f_l|^2 - \left(\sum_l |C_l^h|f_l\right)^2\right] \equiv \frac{\langle f_l^2\rangle - \langle f_l\rangle^2}{4\pi}$$

Diffractive excitation occurs only due to dissimilarity of the elastic eigen amplitudes

In the Froissart regime all the partial eigen amplitudes reach the unitarity limit, $\mathrm{Im}\,f_l = 1$, and single diffraction is vanishes.

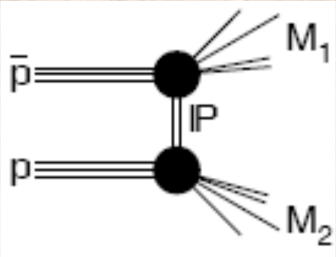
Since in the Froissart regime $R \propto \ln(s)$, so $\sigma_{tot} \propto \sigma_{el} \propto \ln^2(s)$; $\sigma_{sd} \propto \ln(s)$,

i.e. asymptotically $\sigma_{sd}/\sigma_{tot} \propto 1/\ln(s)$

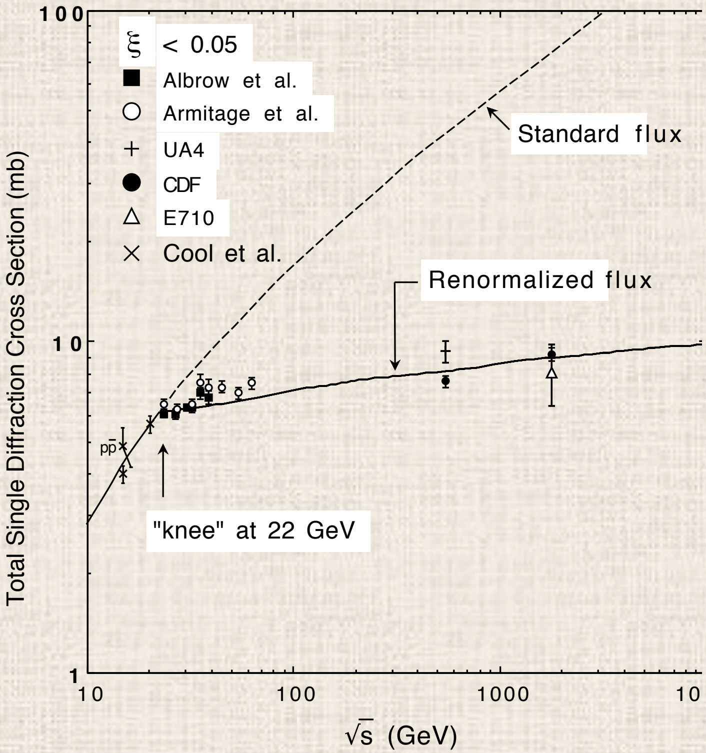
Soft inelastic diffraction

The multi-component structure of hadrons leads to diffractive excitations. Since different components interact differently (i.e. make different shadows), the final state wave packet is modified and can be projected to a new hadronic state.

Experimentally diffraction looks like a large rapidity gap event. Particles are produces only at small angles relative the beam or/and target directions. Nothing is produced in between.



Survival probability of a large rapidity gap suppresses diffraction




Rapidity Gaps
in Fireworks

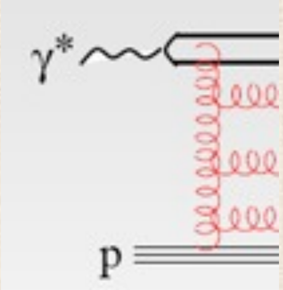
Diffraction in DIS

At high energies dipoles with a certain separation are the eigenstates of interaction.

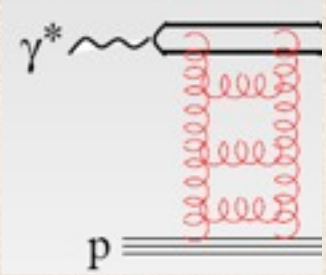
$$\langle \rho^2 \rangle \sim \frac{1}{\varepsilon^2} \sim \frac{1}{Q^2\alpha(1-\alpha)+m_q^2}$$

Q. Is diffractive DIS hard or soft?

A. - Soft !



inclusive DIS



diffractive DIS

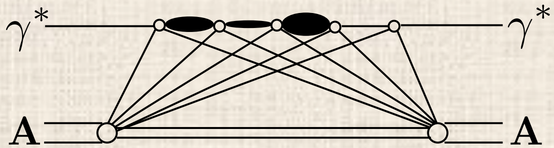
Fluctuation	$W_{\bar{q}q}^{\gamma^*}$	$\sigma_{tot}^{\bar{q}qN}$	$W_{\bar{q}q}^{\gamma^*}\sigma_{tot}^{\bar{q}qN}$	$W_{\bar{q}q}^{\gamma^*}(\sigma_{tot}^{\bar{q}qN})^2$
Hard $(\alpha \sim 1/2)$	~ 1	$\sim 1/Q^2$	$\sim 1/Q^2$	$\sim 1/Q^4$
Soft $(\alpha \ll 1)$	$\sim \mu^2/Q^2$	$\sim 1/\mu^2$	$\sim 1/Q^2$	$\sim 1/\mu^2 Q^2$

The aligned-jet dipole configurations dominate diffractive DIS.
This is why the fractional cross section is nearly Q^2 independent

$$\frac{\sigma_{\mathbf{diff}}^{\mathbf{DIS}}}{\sigma_{\mathbf{incl}}^{\mathbf{DIS}}} \approx \mathbf{Const}$$

Diffraction and nuclear shadowing

Gribov inelastic shadowing



$$\Delta\sigma_{tot}^{\gamma^* A} = -4\pi\int d^2b\, e^{-\frac{1}{2}\sigma_{tot}^{hN} T_A(b)} \int_{M^2_{min}} dM^2 \left.\frac{d\sigma_{sd}^{\gamma^* N}}{dM^2\, dp_T^2}\right|_{p_T=0} \int_{-\infty}^{\infty} dz_1\, \rho_A(b,z_1) \int_{z_1}^{\infty} dz_2\, \rho_A(b,z_1)\, e^{iq_L(z_2-z_1)}$$

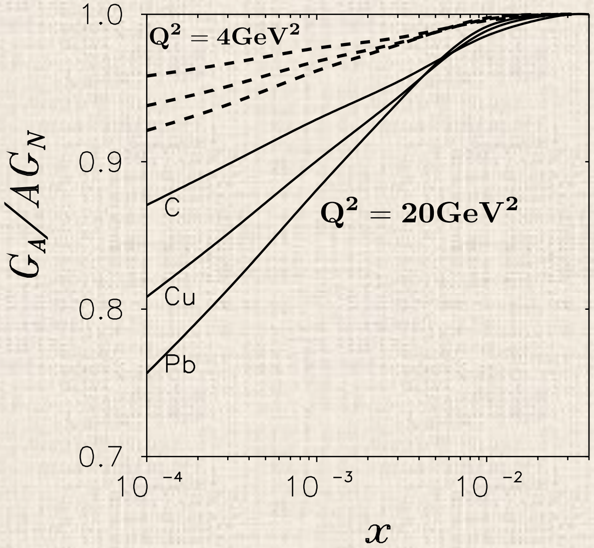
$$q_L = \frac{M^2+Q^2}{2E_{\gamma^*}}$$

Q^2 independence of $\sigma^{DIS}_{diff}/\sigma^{DIS}_{incl}$ leads to a Q^2 independent nuclear shadowing

Different triple-Reggeon terms in diffraction lead to different parts of the shadowing effect.

1. The PPR term gives quark shadowing

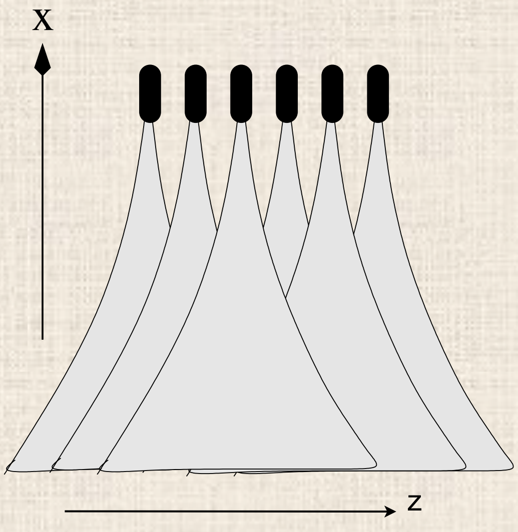
2. The PPP term gives gluon shadowing



Nuclear shadowing

Shadowing looks quite differently in the infinite momentum frame of the nucleus. Only observables must be Lorentz invariant.
If the bound nucleons are well separated in the nuclear rest frame, both the nucleon size and the inter-nucleon spacings are Lorentz contracted and the nucleons still don't "talk" to each other".

The Lorentz contraction factor is m/E for inter-nucleon spacing, but is m/xE for partons. Then, the longitudinal propagation of small-x partons is large. They overlap and do "talk" to each other, i.e. they can fuse and reduce the parton density at small x. The cross section decreases and this is shadowing.



Back of the envelope estimate

- Quark shadowing

At high energies dipoles are "frozen" by Lorentz time dilation during propagation through the nucleus. Then,

$$\left.\frac{q_A(x)}{A q_N(x)}\right|_{x\ll 1} = \frac{2}{\langle\sigma_{\bar{q}q}(r)\rangle}\int d^2b \left[1 - \left\langle e^{-\frac{1}{2}\sigma_{\bar{q}q}(r)T_A(b)}\right\rangle\right]$$

For lead $q_A/Aq_N = 0.35$

- Gluon shadowing is much weaker, since $\sigma_{\mathbb{P}p} \ll \sigma_{\pi p}$

$$\left.\frac{G_A(x)}{A G_N(x)}\right|_{x\ll 1} = \frac{2}{\langle\sigma_{GG}(r)\rangle}\int d^2b \left[1 - \left\langle e^{-\frac{1}{2}\sigma_{GG}(r)T_A(b)}\right\rangle\right]$$

$$= 1 - \frac{3C}{8} r_0^2 \rho_A R_A + \frac{C^2}{10} r_0^4 \rho_A^2 R_A^2 - \ldots \approx 0.74$$

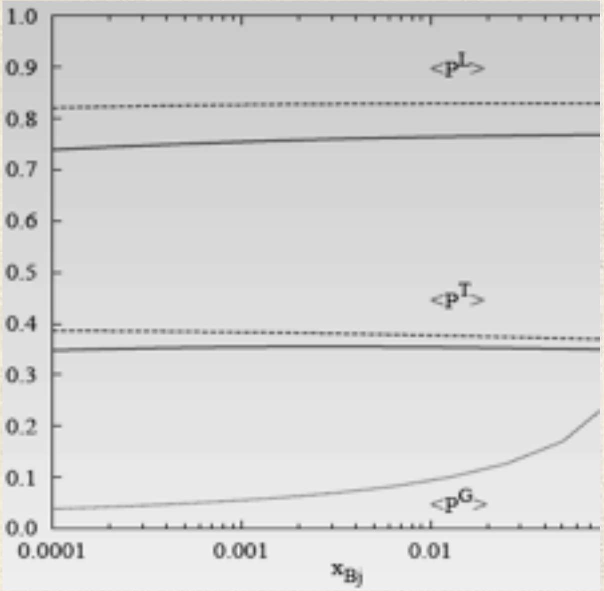
Since gluons in the proton are located within small spots, they have a little chance to overlap in transverse plane, even in heavy nuclei. The mean number of gluonic spots overlapping with this one is

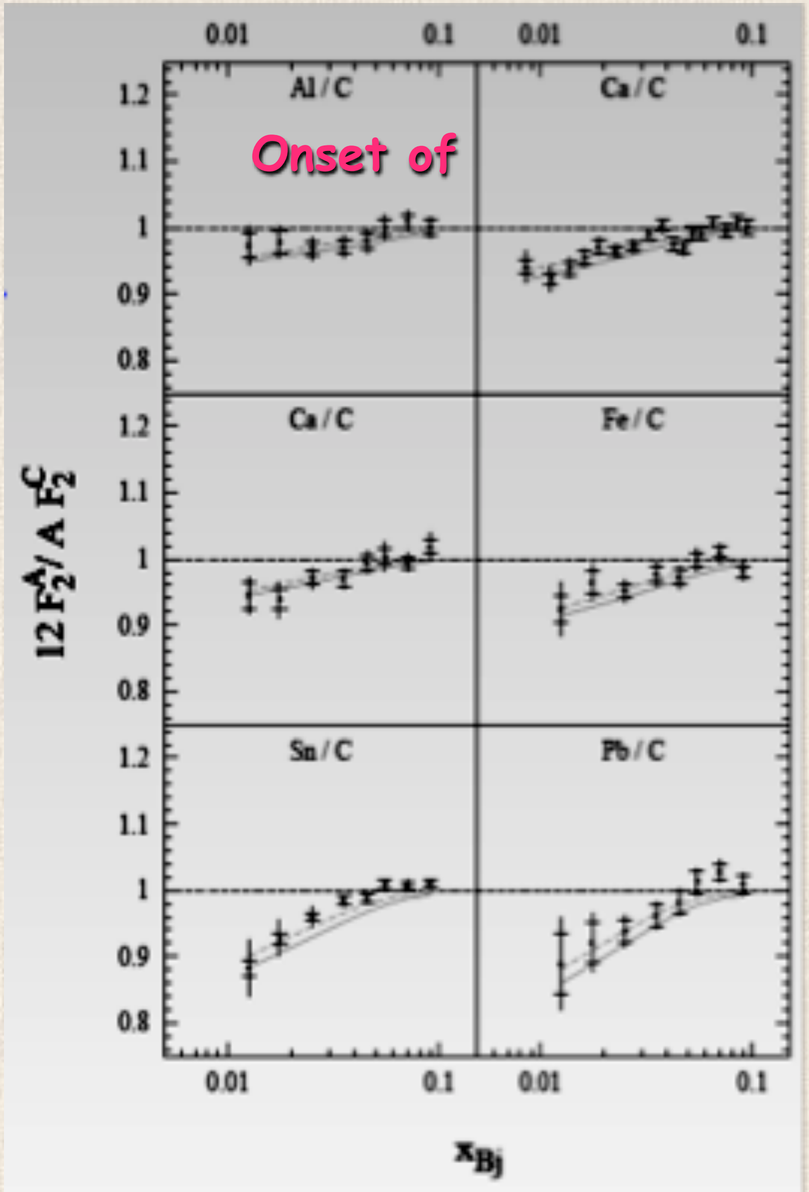
$$\langle n\rangle = \frac{3\pi}{4} r_0^2 \langle T_A\rangle = \pi r_0^2 \rho_A R_A = 0.3$$

Coherence time

In real data the photon fluctuations in DIS are not "frozen", but keep breathing during propagation through the nucleus

$$t_c = P\, t_{max} = \frac{P}{x\, m_N}$$

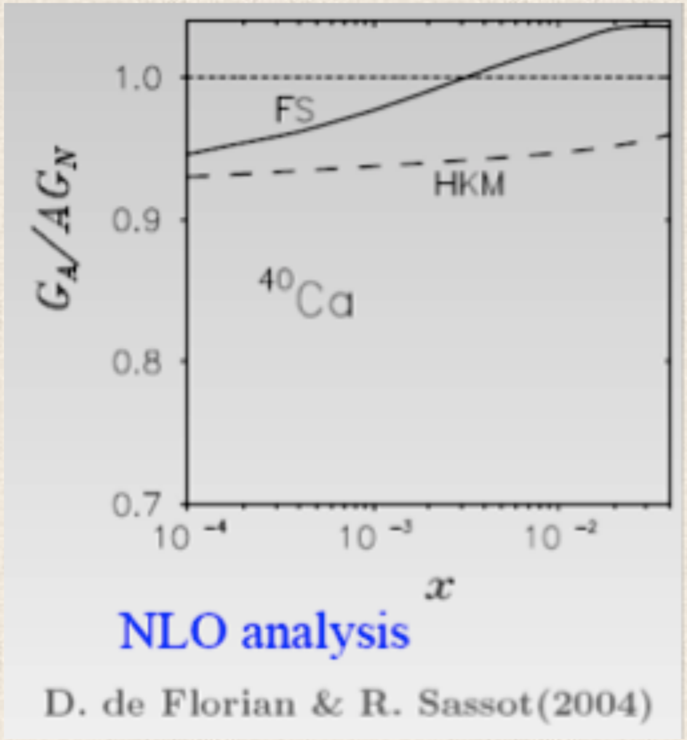




Global DGLAP analysis

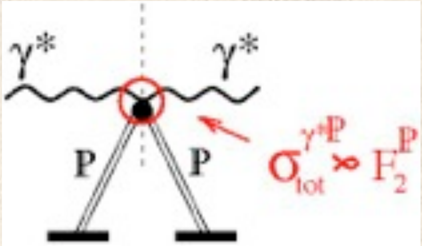
A DGLAP analyses is able to single out from data the nuclear PDFs for different species of partons. A leading order analysis failed to extract the gluon distribution from the NMC data, but the NLO fit turned out to be quite sensitive to gluons.

The results confirm a very weak gluon shadowing



QCD factorization

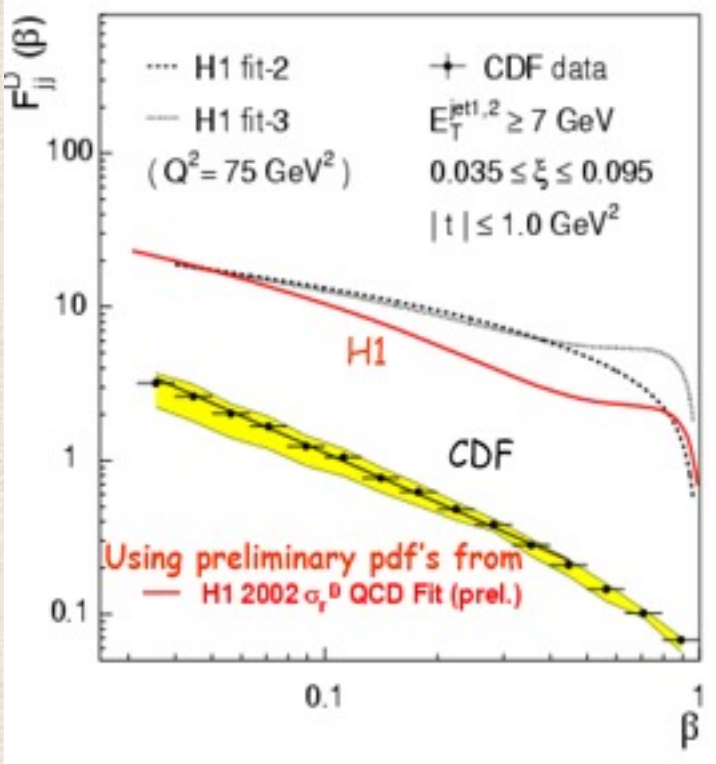
The triple-Regge graph for diffractive DIS, can be interpreted as a way to measure the structure function (PDFs) of the Pomeron. (Ingelman-Schlein)



Once the parton densities in the Pomeron are known and factorization is at work, one can predict the cross section of any hard hadronic diffraction.

However, the attempts to use this diffractive PDFs of the Pomeron for diffractive jet production failed badly: data from the Tevatron contradict the predictions by an order of magnitude. And for a well understood reason.

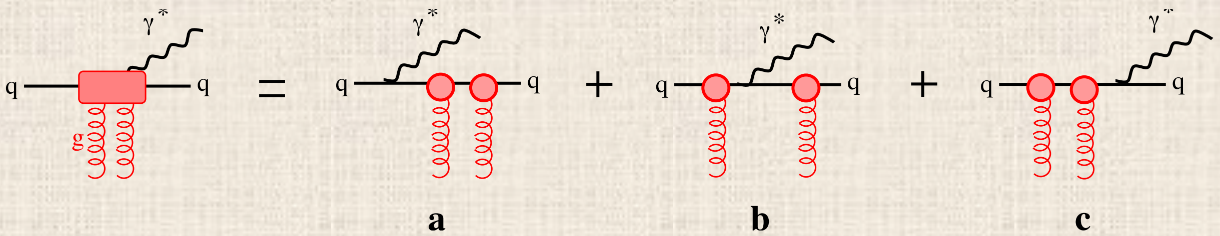
QCD factorization is broken for hadronic diffraction (more later)



Drell-Yan diffraction

QCD factorization relates inclusive DIS, $\gamma^* \to \bar{q}q$ with $q \to \gamma^* q$

In diffraction such a relation (Ingelman-Schlein factorization) is broken



Diffractive radiation of a heavy photon (any abelian field) by a quark vanishes in the forward direction

$$\left.\frac{d\sigma^{DY}_{inc}(qp \to \gamma^* qp)}{d\alpha\, dM^2}\right|_{p_T=0} = 0 \qquad !!!$$

In both Fock components of the quark, $|q\rangle$ and $|q\gamma^*\rangle$ only quark interacts, so they interact equally (b-integrated), and diffraction is impossible.

This conclusion also holds for diffractive radiation of γ,W,Z bosons, Higgs.

Drell-Yan diffraction

In a hadron of large size R a quark radiates a heavy photon and gets a small shift $\mathbf{r} \sim 1/\mathrm{M}$ in its transverse location.
The diffractive amplitude has the Good-Walker structure,

$$\sigma(\mathbf{R}) - \sigma(\mathbf{R} - \alpha\mathbf{r}) \;\propto\; \mathbf{r} \cdot \mathbf{R}$$

hadronic scale — recoil shift — hard-soft

- The diffractive amplitude is not quadratic in r like in DIS, but linear. Therefore, the soft part of the interaction is not enhanced in Drell-Yan diffraction, which is as semi-hard, semi-soft, like inclusive DIS.

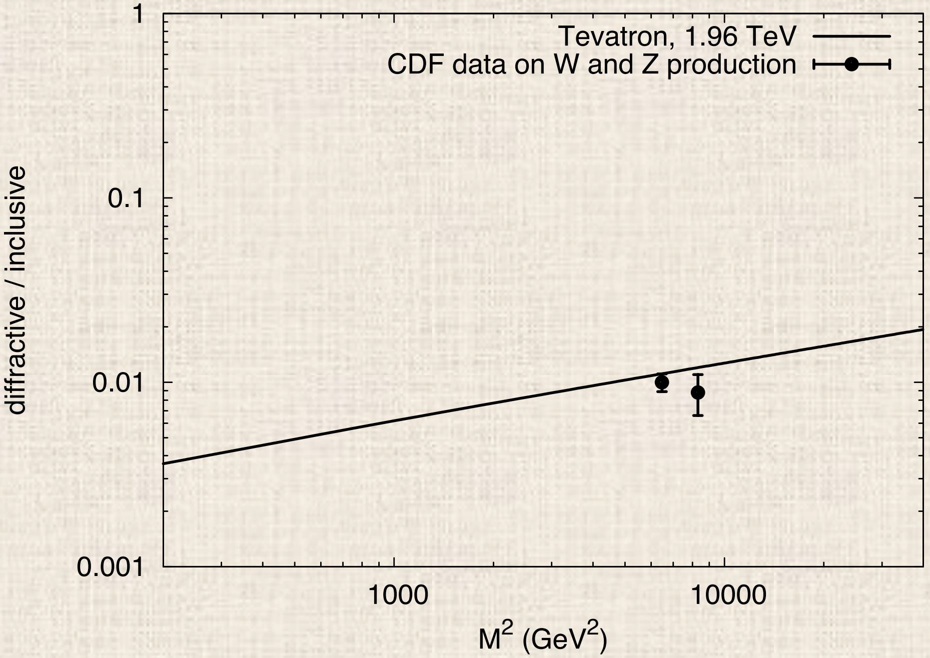
- Diffractive factorization predicts a higher twist M-dependence, $1/\mathrm{M}^4$, missing the leading twist.

Diffractive DIS is dominated by soft interactions. On the contrary, Drell-Yan diffraction gets the main contribution from the interplay of soft and hard scales, and is a leading twist $1/\mathrm{M}^2$

Diffractive production of gauge bosons

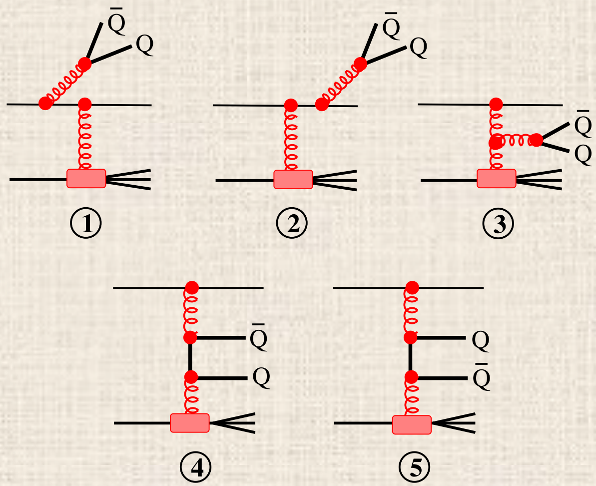
Radiation of other abelian particles has similar mechanisms.

Results for diffractive production of W and Z bosons can be compared with available data

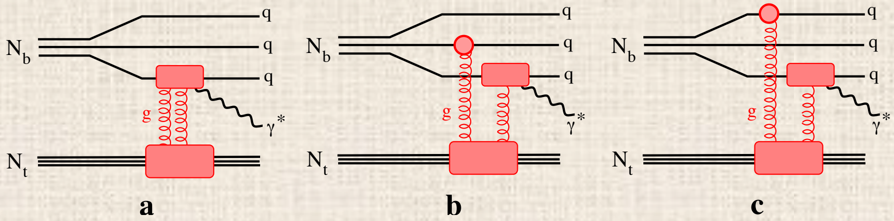


Diffractive production of heavy flavors

Inclusive production



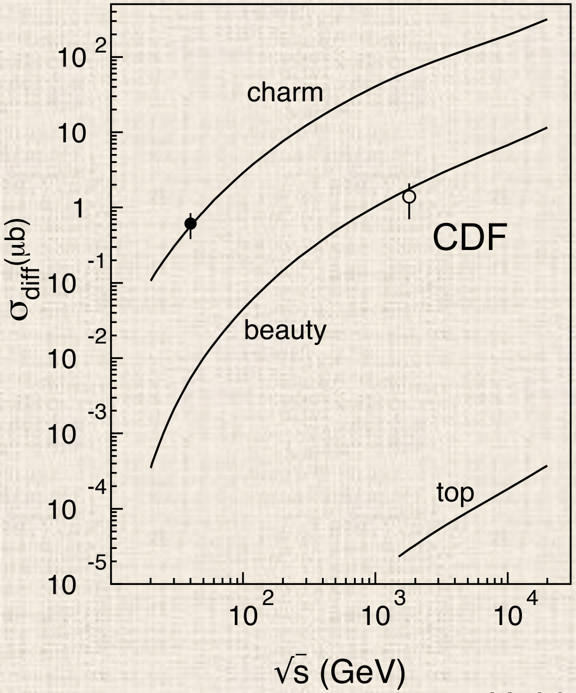
Diffractive production



$1/m_Q^4$ — **Higher twist (factorization)**

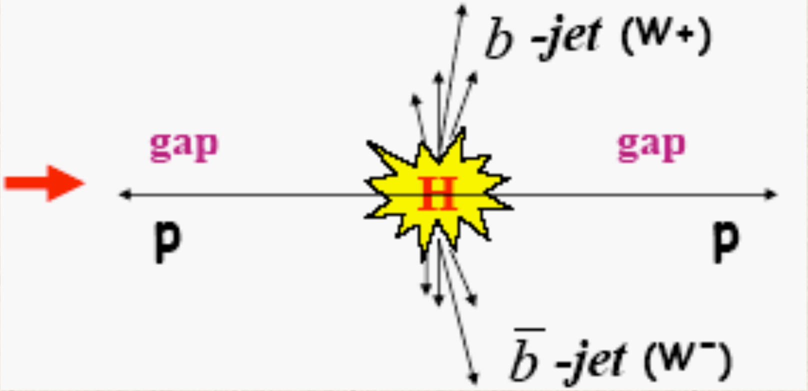
$1/m_Q^2$ — **Leading twist**

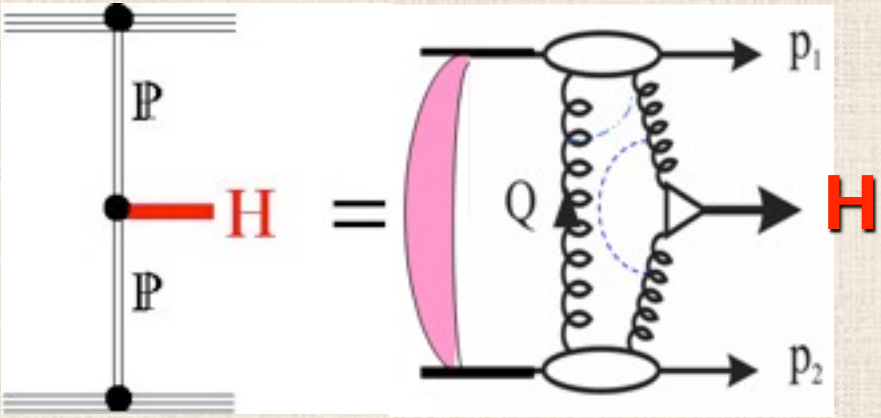
Available data agree with the parameter-free calculations and confirm the leading twist mass dependence $1/m_Q^2$, which contradicts factorization by an order of magnitude



Diffractive double-Pomeron Higgs production

$$\mathbf{p} + \mathbf{p} \rightarrow \mathbf{p} + \mathbf{H} + \mathbf{p}$$





Advantages:

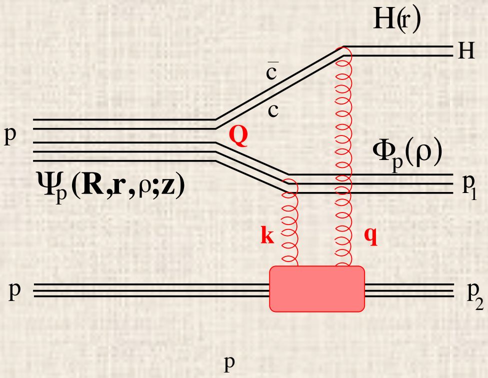
- ✓ Missing mass measurement
- ✓ Relatively low background

The expected cross section is quite low, about 1fb, but still looks doable.

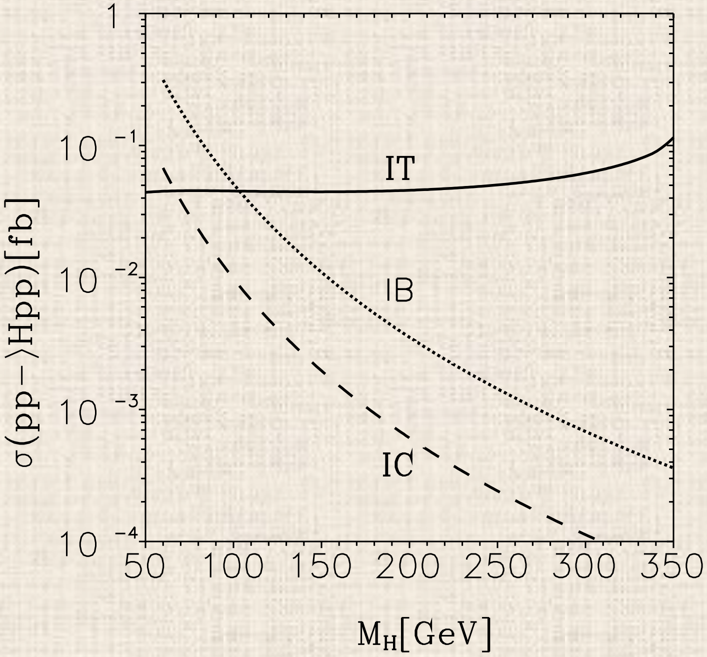
V.A. Khoze, A.D. Martin and M.G. Ryskin

Forward diffractive Higgs production

Diffractive Higgsstrahlung is similar to diffractive DY, Z, W, since in all cases the radiated particle does not participate in the interaction.
However, the Higgs decouples from light quarks, so the cross section of higgsstrahlung by light quarks is small.



A larger cross section can emerge due to admixture of heavy flavors in light hadrons. Exclusive Higgs in pp→ Hpp, via coalescence of heavy quarks, $Q\bar{Q} \to H$

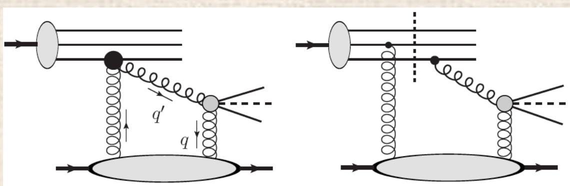


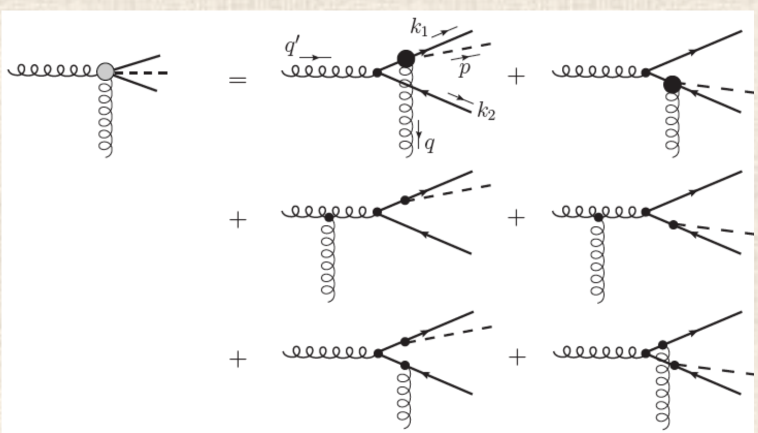
[S.Brodsky, B.K., I.Schmidt, J.Soffer 2006;
S.Brodsky, A.Goldhaber, B.K., I.Schmidt 2009].

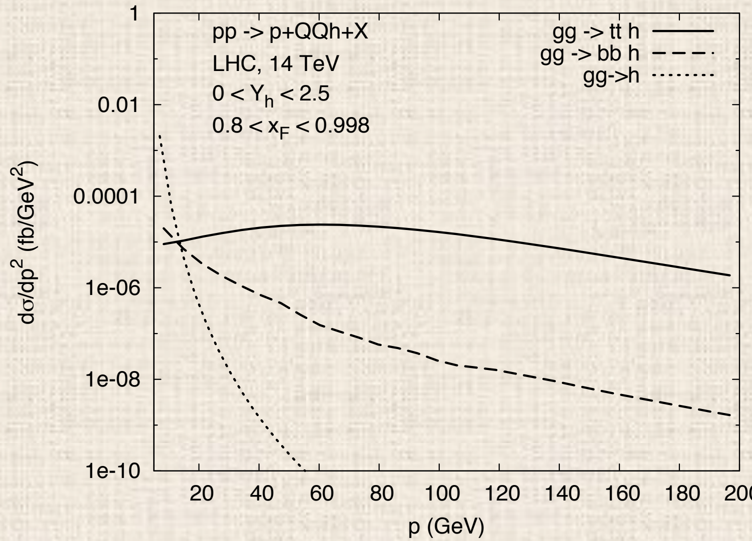
Diffractive higgsstrahlung

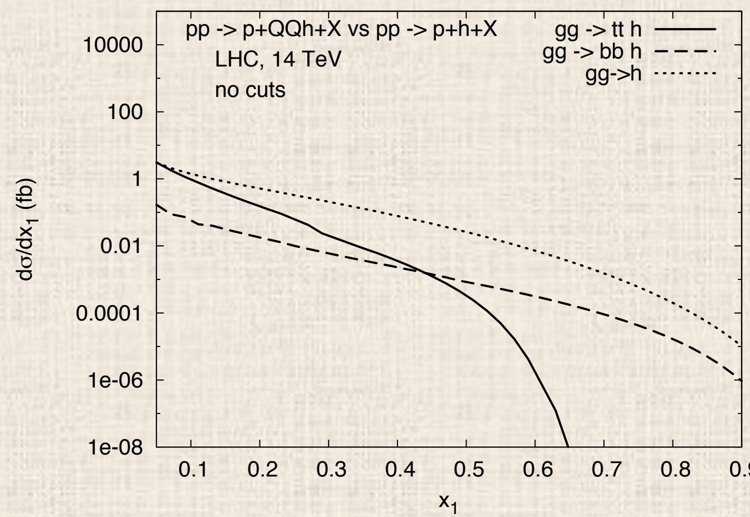
Light quark do not radiate higgs directly, only via production of heavy flavors. Therefore the mechanism is similar to the non-abelian diffractive quark production.

R.Pasechnik, B.K., I.Potashnikova 2014.

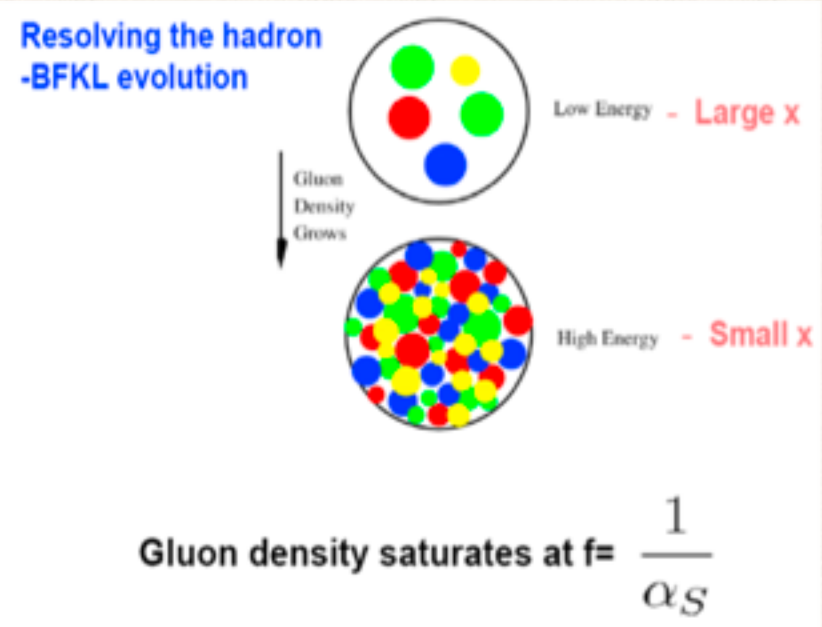








Saturation



GLR-MQ equation

$$\frac{d^2\rho}{d\ln(1/x)d\ln(Q^2)} = \frac{\alpha_s N_c}{\pi}\rho - \frac{\alpha_s^2\gamma}{Q^2}\rho^2$$

$$\rho \equiv xg(x, Q^2)$$

$$\rho_{sat} \propto 1/\alpha_s(Q^2)$$

Q is the gluon transverse momentum

HERA data demonstrate that the gluon density steeply rises towards small x.

Mechanism for parton saturation:
at small x gluons undergo branching with the rate proportional to the gluon density.
As the density becomes high, an inverse process - fusion becomes important. Its rate is quadratic in the gluon density, so rises faster than branching and eventually reach equilibrium.

Saturation scale

The mean gluon transverse momentum rises with 1/x because the momenta of fusing gluons add up. Thus, non only the nuclear gluon density is reduced at small x (shadowing), but the mean gluon momentum rises. Such a modification of the gluon transverse momentum distribution is called color glass condensate (CGC), and the mean gluon momentum squared $\langle k_T^2 \rangle \equiv Q_s^2(x)$ is called saturation scale.

How does this look like in the nuclear rest frame?

A parton propagating through a medium experiences pT-broadening:

$$\Delta p_T^2 = \langle p_T^2 \rangle_{\rm final} - \langle p_T^2 \rangle_{\rm initial} \propto T_A(b) = \int_{-\infty}^{\infty} dz \rho_A(b,z)$$

$$Q_s^2 = \Delta p_T^2$$

Broadening is related to the universal dipole cross section:

$$\Delta p_T^2(b,x) = \nabla_r^2 \sigma(r,x)\Big|_{r=0} T_A(b)$$

Measuring the saturation scale

Broadening has been measured in:

- pA (Drell-Yan; E772&E866)

$\Delta(p_T^{\bar{l}l})^2 = z_{\bar{l}l}^2 \Delta p_T^2$

(quark broadening)

$\langle z_{\bar{l}l} \rangle \approx 0.9$

- J/Ψ and Υ in pA (E772)

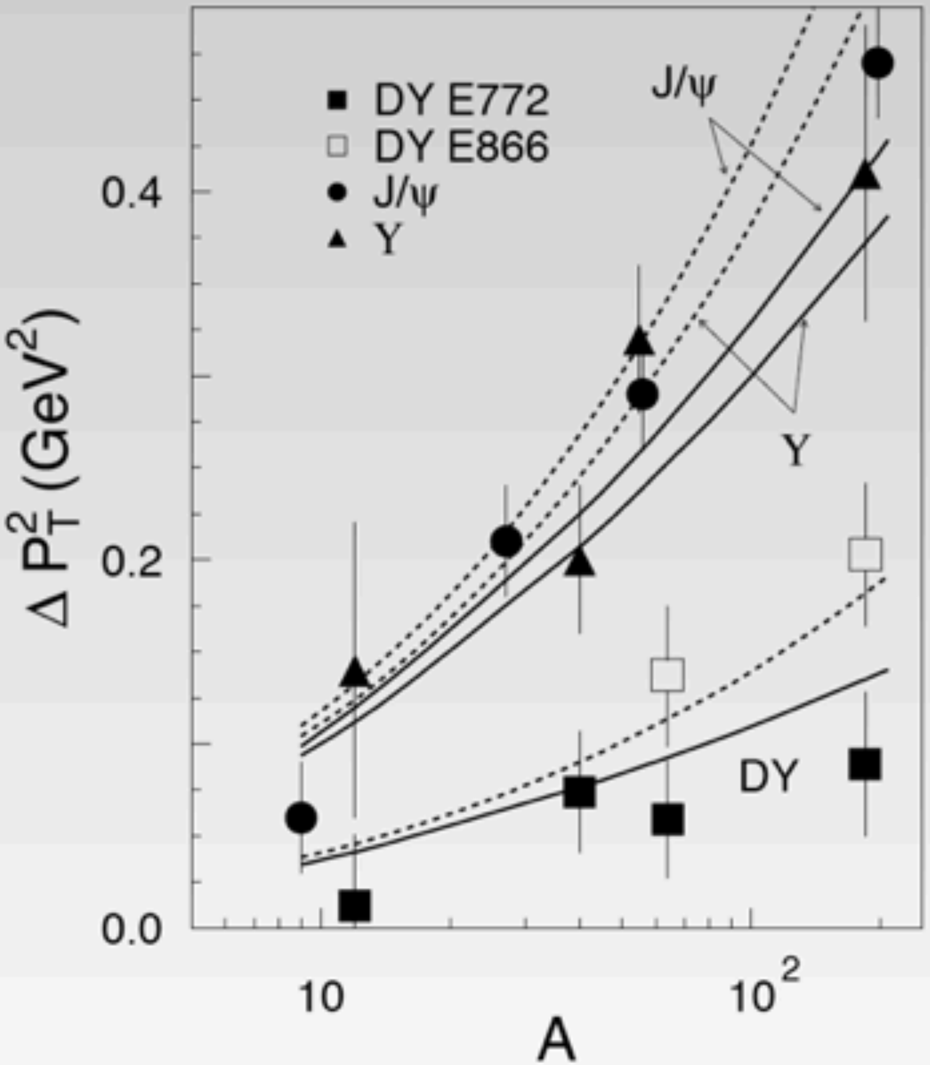
$\Delta(p^{\bar{l}l})^2 \approx \Delta p_T^2 \times 9/4$

(gluon broadening)

- eA (SIDIS; HERMES&CLAS)

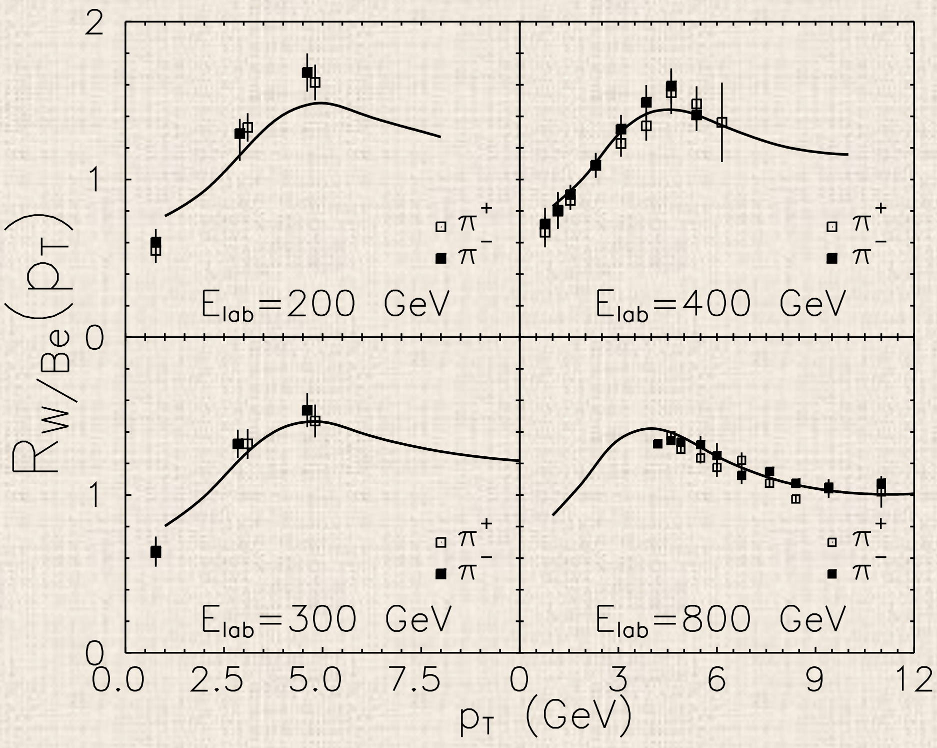
$\Delta(p_T^h)^2 = z_h^2 \Delta p_T^2$

(quark broadening)

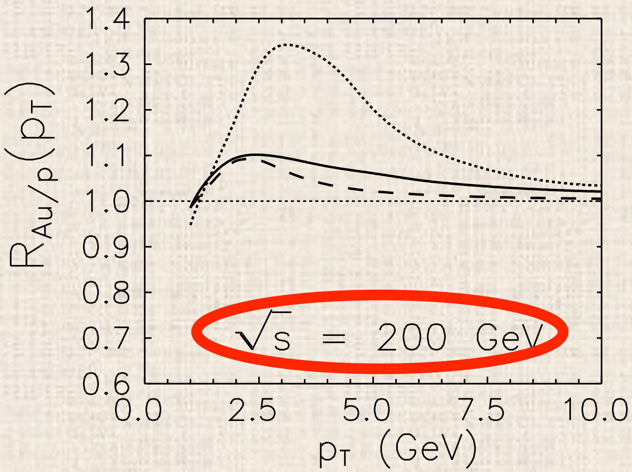


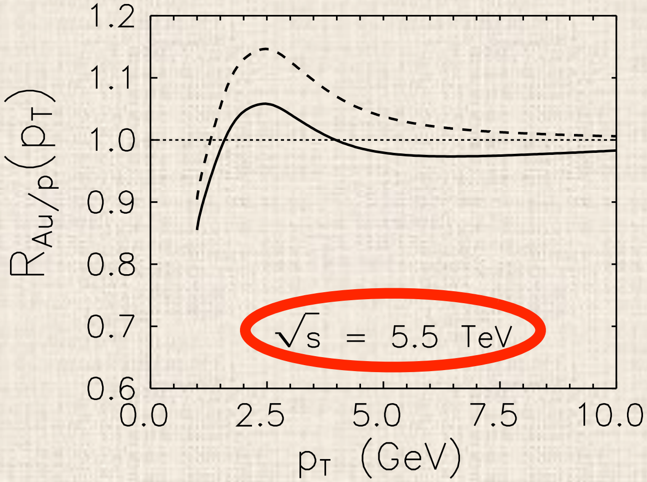
Cronin effect

High-pT hadrons can be produced coherently from multiple interactions in nuclei at very high energies (LHC), but not at low energies of fixed target experiments. Correspondingly, the mechanisms for the Cronin enhancement are different.

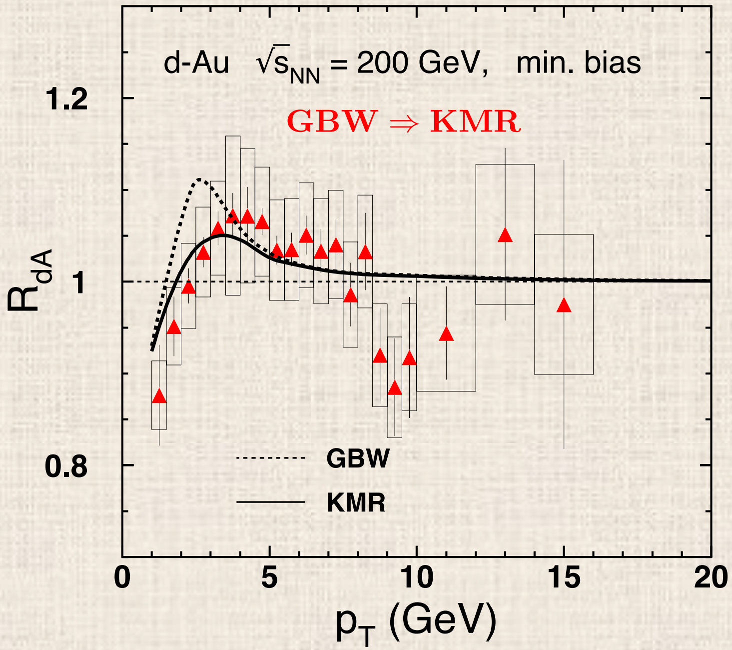


B.K., J.Nemchik, A.Schafer, A.Tarasov, PRL 88(2002)232303`

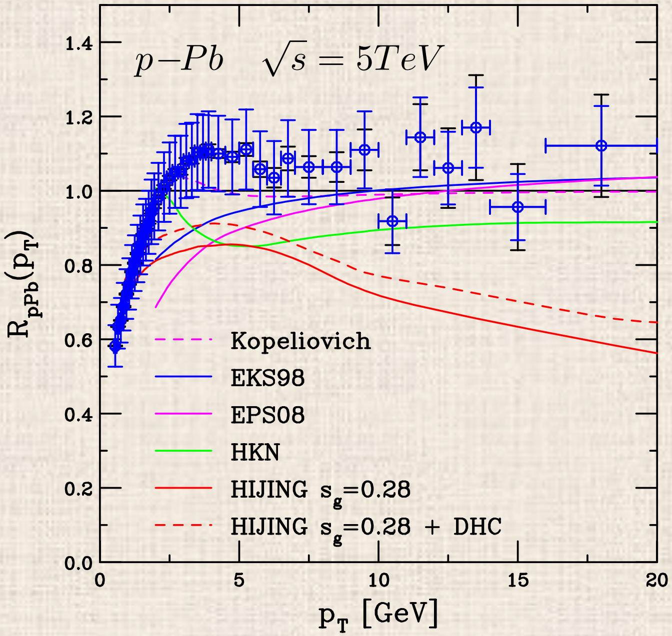


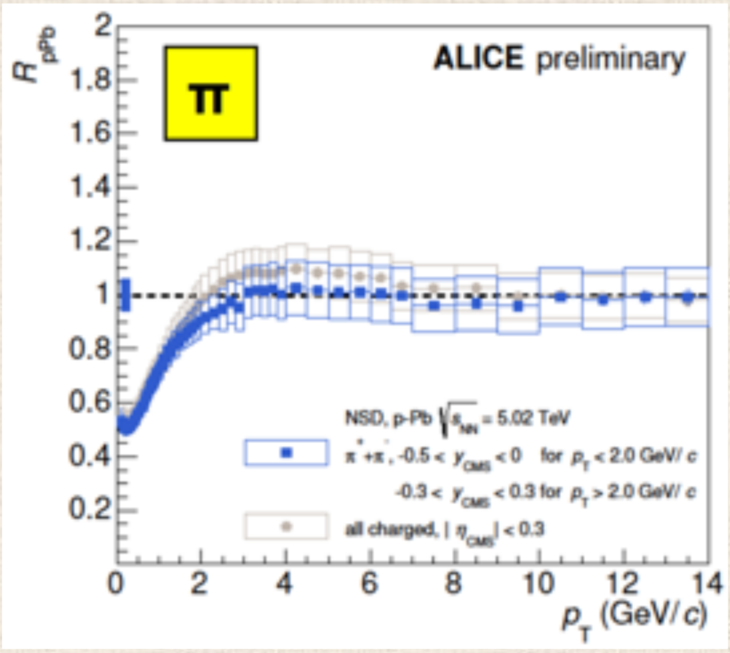


Cronin effect: predicted and observed



R.Vogt et al, arXiv: 1301.3395

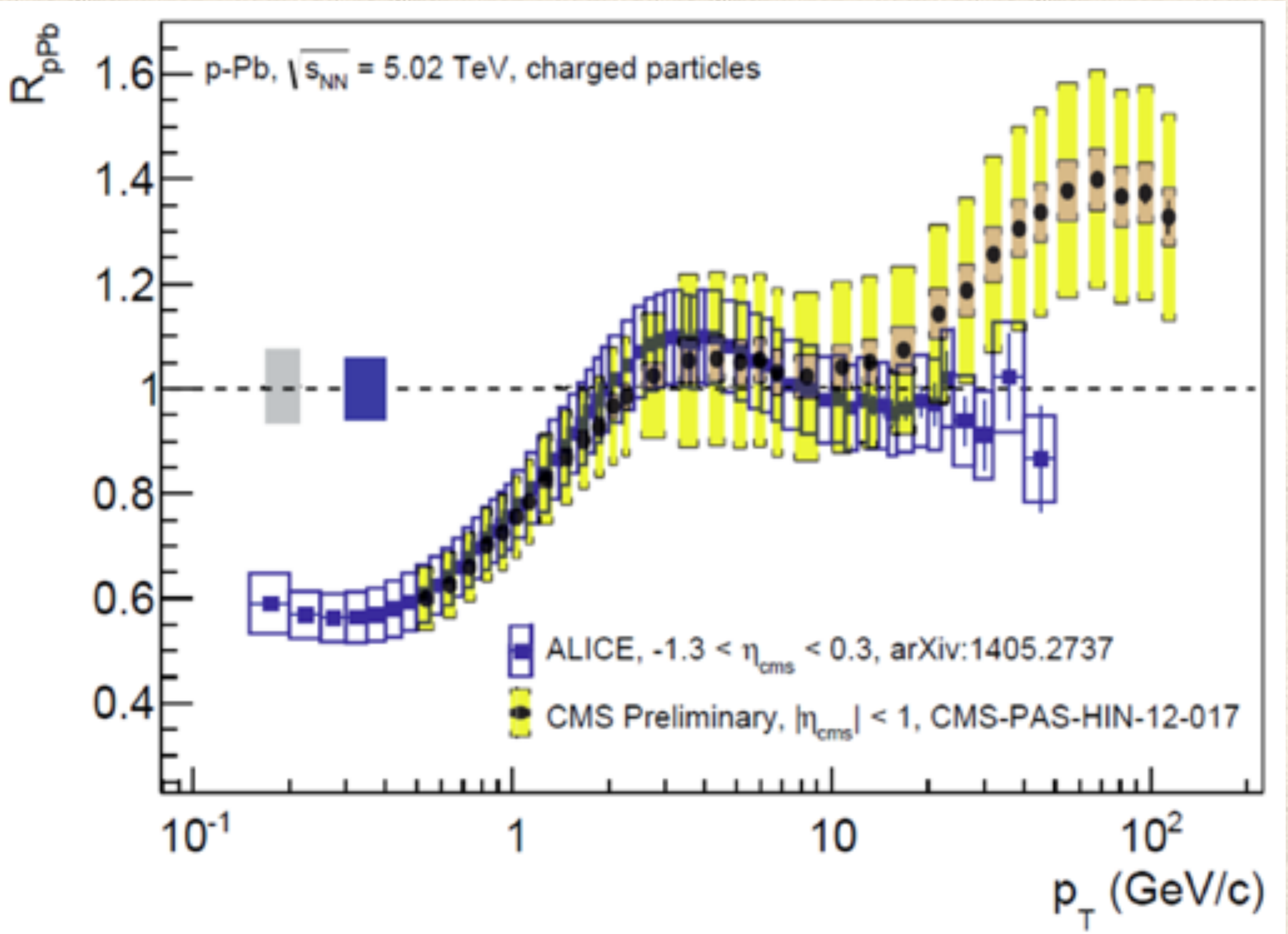




More realistic parametrization for the unintegrated gluon distribution proposed later, improves the shape

A.Martin, M.Ryskin & G.Watt, 2010

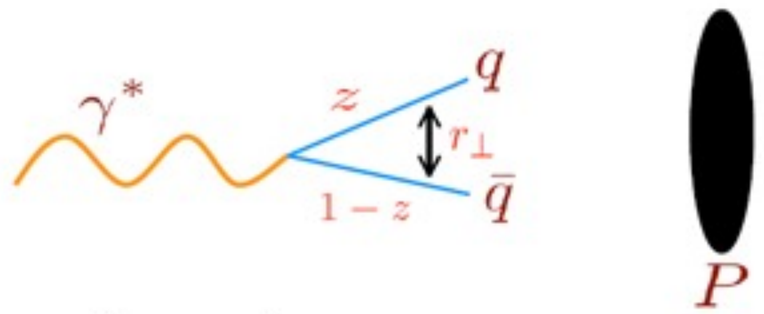
A new puzzle?



R_{pPb}
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV, charged particles
1.6
1.4
1.2
1
0.8
0.6
0.4
ALICE, -1.3 < η_{cms} < 0.3, arXiv:1405.2737
CMS Preliminary, $|\eta_{cms}|$ < 1, CMS-PAS-HIN-12-017
10^{-1}
1
10
10^2
p_T (GeV/c)

Being optimistic, one can see traces of saturation even in the proton.

Golec-Biernat & Wusthoff's model

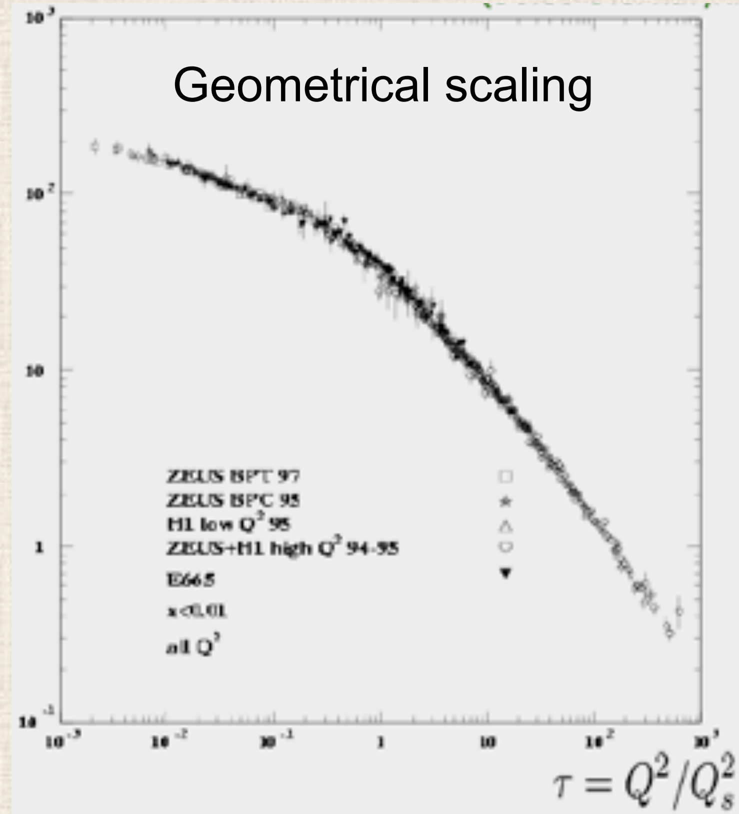


$$\sigma_{T,L}^{\gamma^*,P} = \int d^2 r_\perp \int dz\, |\psi_{T,L}(r_\perp, z, Q^2)|^2\, \sigma_{q,\bar{q},P}(r_\perp, x)$$

where $\sigma_{q\bar{q}P}(r_\perp, x) = \sigma_0 \left[1 - \exp\left(-r_\perp^2\, Q_s^2(x)\right)\right]$

& $$Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$$

Parameters: $Q_0 = 1\,\mathrm{GeV}\,;\, \lambda = 0.3\,;\, x_0 = 3 \cdot 10^{-4}$



However, DGLAP evolution describes the same data as well. So far it is not clear how much saturation is relevant to available DIS data.

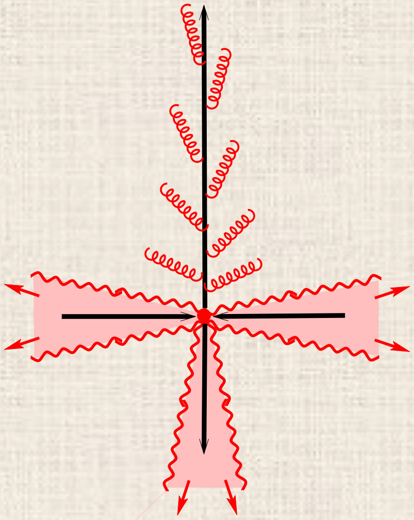
Probing a hot medium with dipoles: high-pT hadrons

High-pt parton scattering leads to formation of 4 cones of gluon radiation:

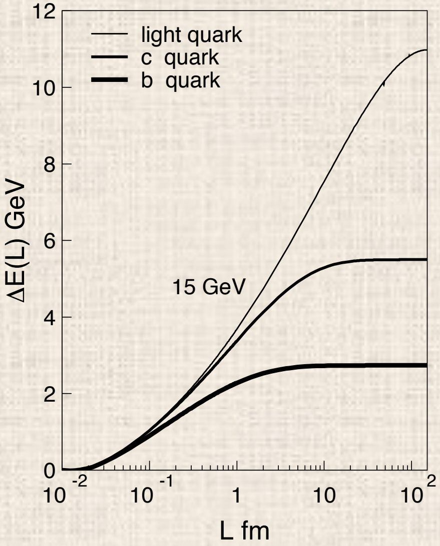
(i) the color field of the colliding partons is shaken off in forward-backward directions.

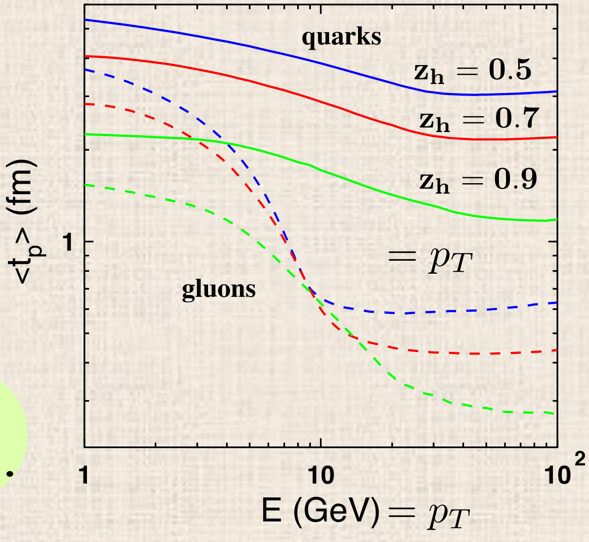
(ii) the scattered partons carry no field up to transverse momenta kt<pt.

The final state partons are regenerating the lost color field by radiating gluons and forming the up-down jets.



Time dependent energy loss of a high-pT quark in vacuum



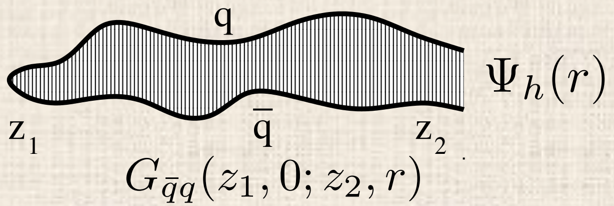


The induced energy-loss scenario is based on an ad hoc assumption that the hadron is produced outside the medium.

Quenching of high-pT hadrons

Evolution of a dipole in a medium: path integrals

One has to sum up all quark trajectories.



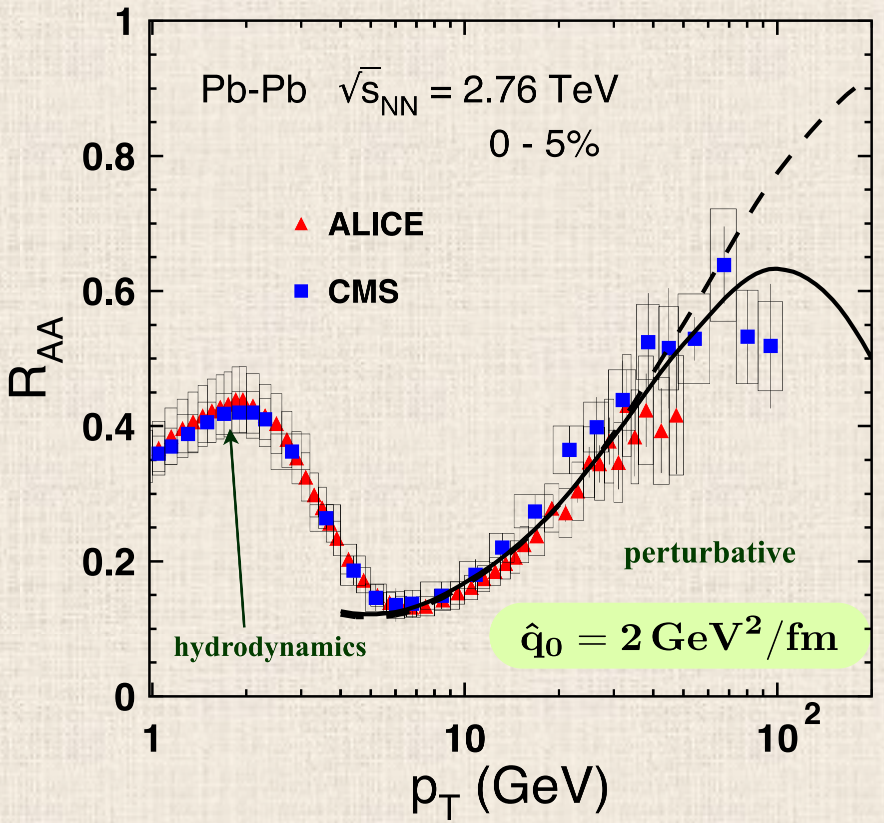
$$\left[i\frac{d}{dl_2} - \frac{m_q^2 - \Delta_{r_2}}{p_T/2} - V_{\bar{q}q}(l_2, r_2)\right] G_{\bar{q}q}(l_1, r_1; l_2, r_2) = 0$$

$$\mathrm{Im}V_{\bar{q}q}(l, r) = -\frac{1}{4}\,\hat{q}(l)\,r^2$$

R_{AA} rises with p_T due to color transparency

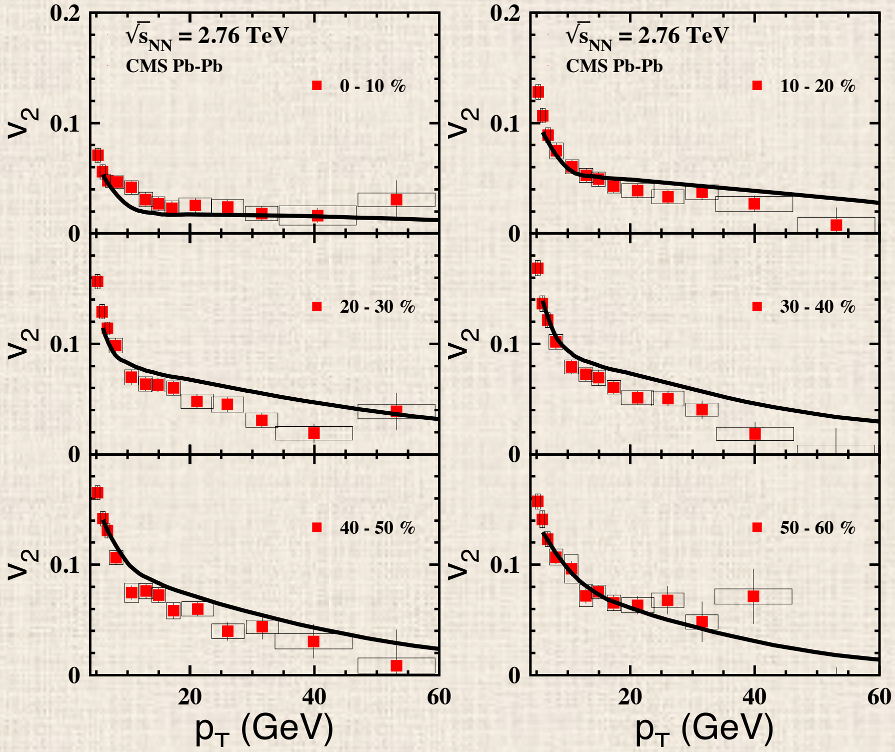
The model for $\hat{q}$

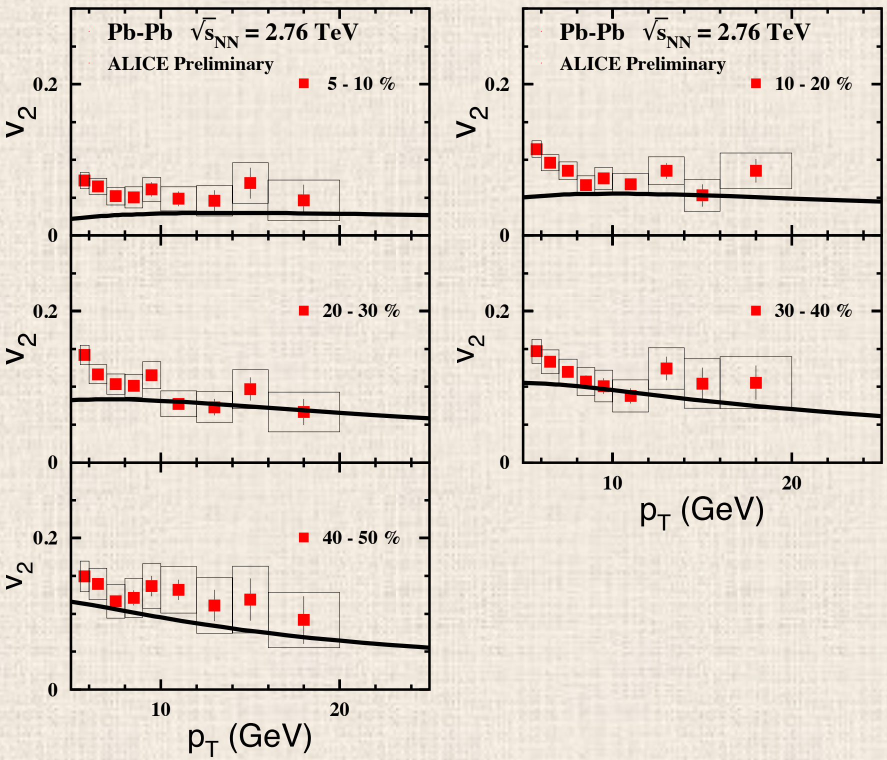
$$\hat{q}(l, \vec{b}, \vec{\tau}) = \frac{\hat{q}_0\, l_0}{l}\,\frac{n_{part}(\vec{b}, \vec{\tau})}{n_{part}(0,0)}$$



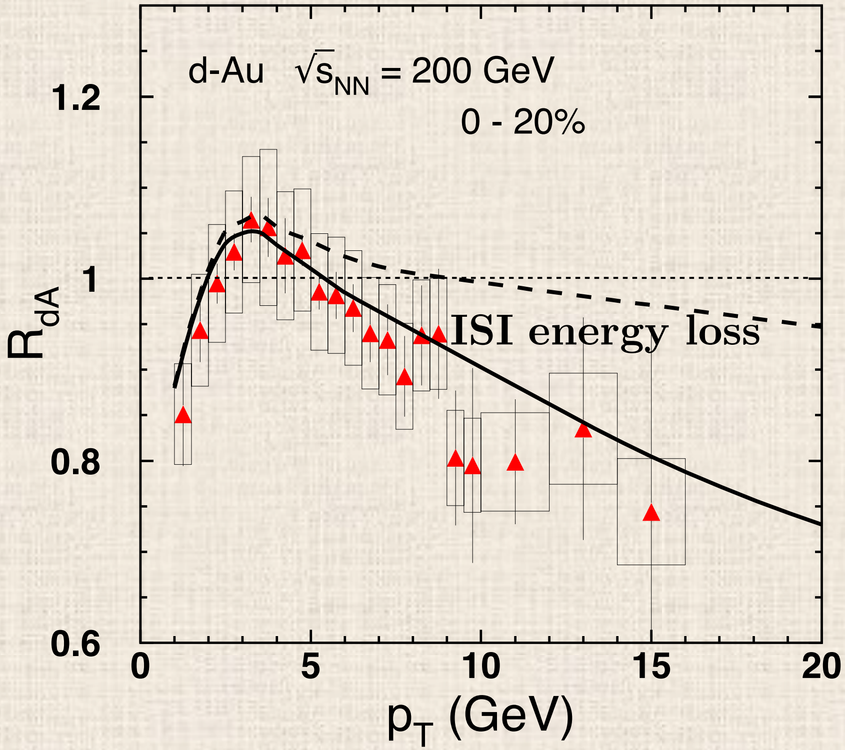
Phys.Rev. C86(2012)054904

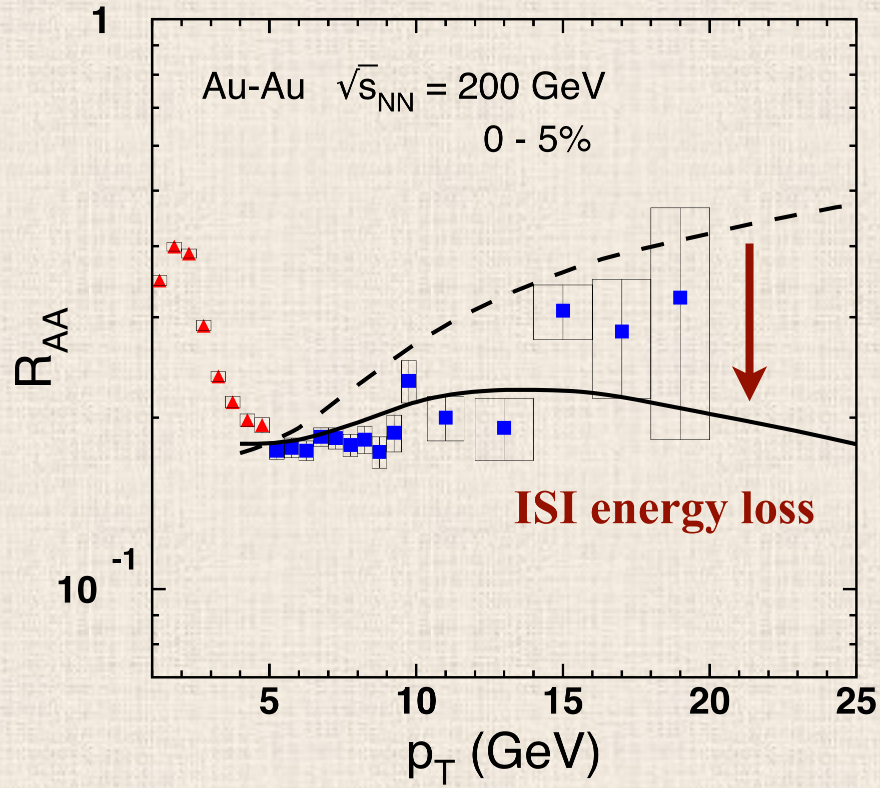
Azimuthal asymmetry





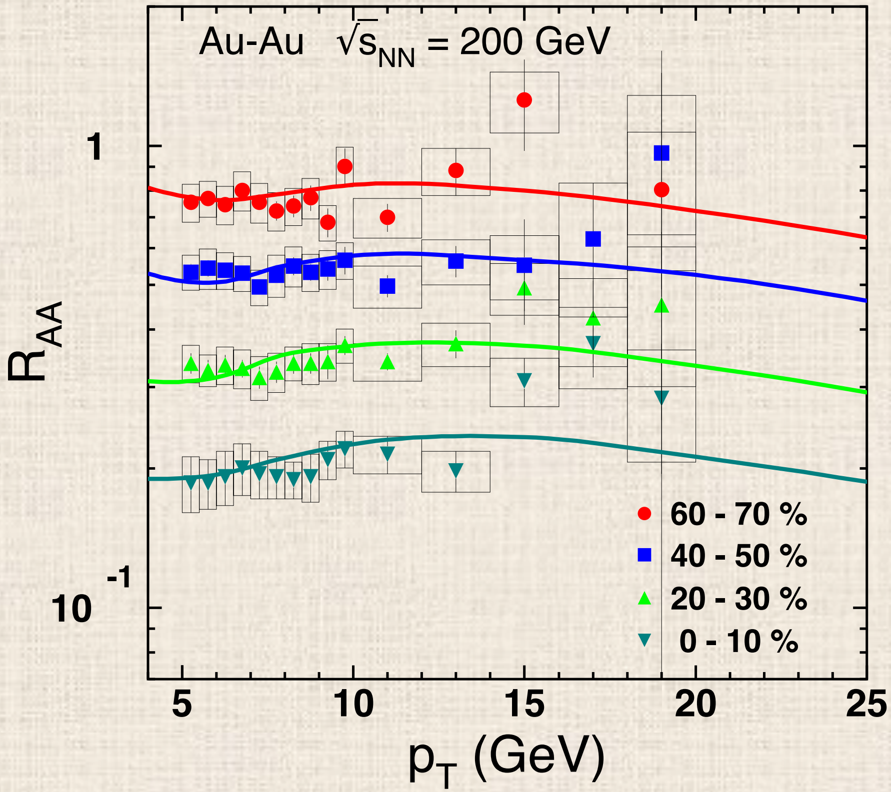
ISI and energy conservation

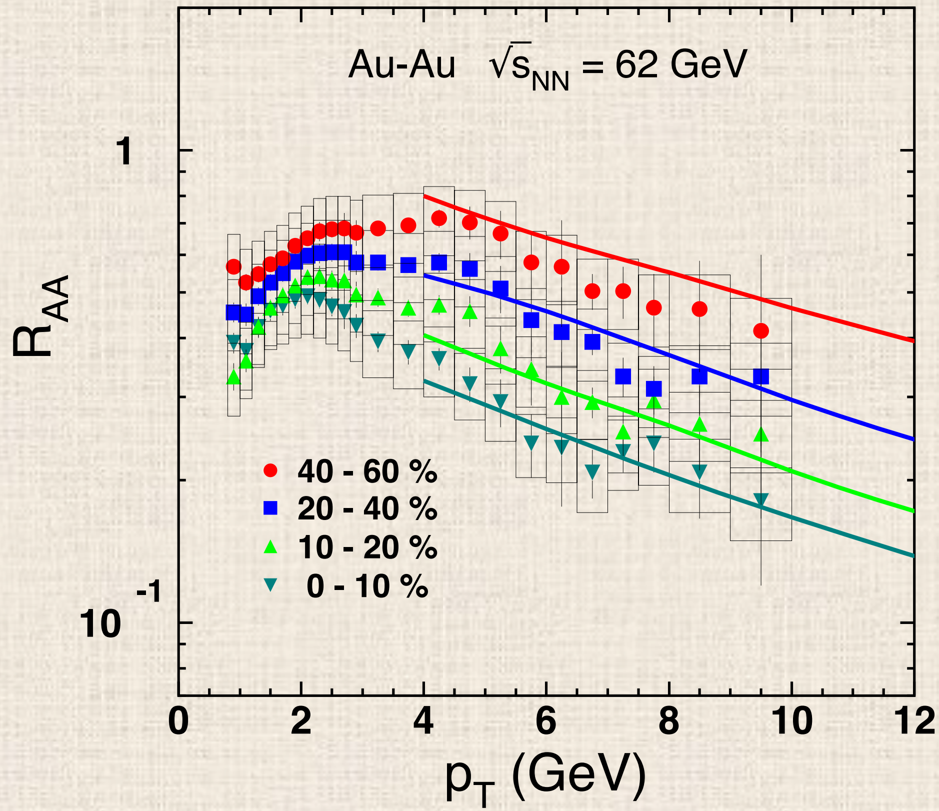




$$\hat{q}_0 = 1.6\,\mathrm{GeV}^2/\mathrm{fm}$$

ISI and energy conservation





$$\hat{q}_0 = 1.2\,\mathrm{GeV}^2/\mathrm{fm}$$

J/Ψ melting vs absorption

Two sources of J/Ψ suppression in a hot medium:

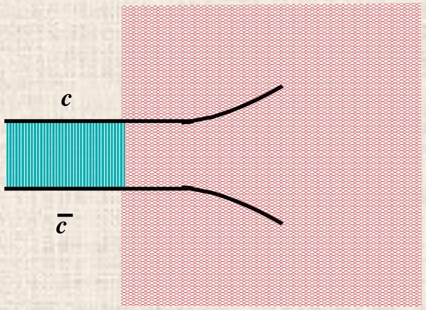
(i) Debye screening, i.e. weakening of the binding potential, which can lead to disappearance of the bound level (melting)

(ii) Color-exchange interactions of the c-cbar dipole with the medium, leading to a break-up of the colorless dipole (absorption).

Melting

A bound c-cbar state can be dissolved by Debye screening in a hot medium.

T.Matsui & H.Satz, PLB 178 (1986) 416



No clear signal of J/Psi melting has been observed so far

Where is J/Ψ melting?

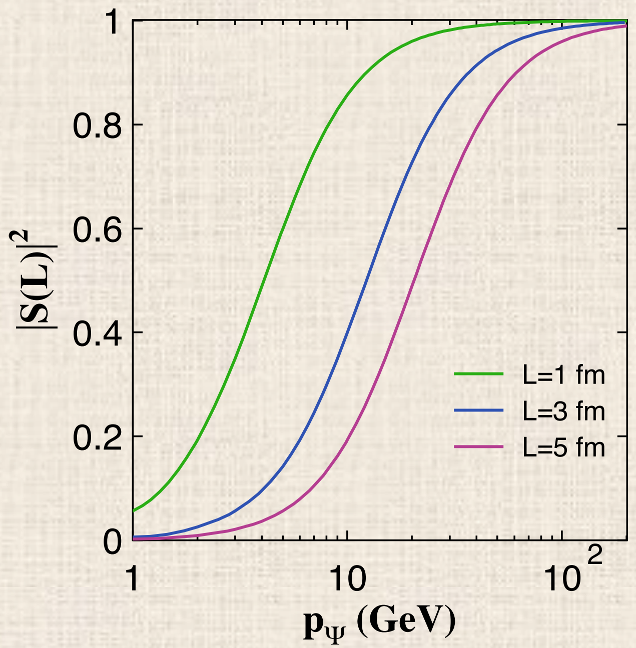
The melting scenario assumes that lacking a bound level the quarks fly away, resulting in disappearance of J/Ψ. However, the quark distribution amplitude still can be projected to the charmonium wave function.

Debye screening of the potential for J/Ψ produced at **rest** can be modeled,

However, at the LHC most of J/Ψs are fast moving $\langle \mathbf{p}_{\psi}^{2} \rangle = 8\,\mathbf{GeV}^{2}$

V(r) is not Lorentz invariant r is 3-dimensional how to make a Lorentz boost is a challenge

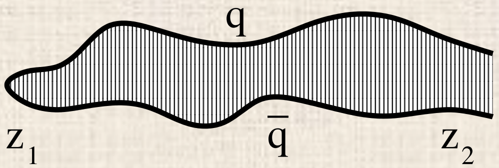
Even in the extreme case of lacking any potential between c and c-bar ($\mathrm{T} \to \infty$), still the J/Ψ can survive.



At large pT the medium becomes fully transparent, because the initial dipole size is "frozen", and the projection to the J/Ψ wave function remains the same as in pp.

Charmonium propagation through a hot medium

Path integral technique



$\Psi_h(r)$

$G_{\bar{q}q}(z_1, 0; z_2, r)$

$$\left[i\frac{d}{dz} - \frac{m_c^2 - \Delta_{r_\perp}}{E_\Psi/2} - V_{\bar{q}q}(z, r_\perp)\right] G_{\bar{q}q}(z_1, r_{\perp 1}; z, r_\perp) = 0$$

The Green function $G_{\bar{q}q}(z_1, r_1; l_2, r_2)$ describes propagation of the dipole between longitudinal coordinates $z_{1,2}$ with initial and final transverse (2D) separations $r_{1,2}$.

The imaginary part of the light-cone potential describes absorption,

$$\mathrm{Im}V_{\bar{q}q}(z, r_\perp) = -\frac{v}{4}\,\hat{q}(z)\, r_\perp^2$$

Transport coefficient $\hat{q}$, the rate of broadening, is related to the medium temperature, $\hat{q} \approx 3.6\, T^3$

$\mathrm{Re}V_{\bar{q}q}(z, r)$ corresponding to the binding potential, is known only in the rest frame of the dipole, and it also depends on longitudinal dipole separation r_L

It cannot be properly described with this 2-dimensional Schrödinger equation. Debye screening corrections make it even more challenging.

Lorentz boosted Schrödinger equation

The light cone fractional momentum distribution of quarks in a charmonium sharply peaks around x=1/2. With a realistic potential

$$\langle \lambda^2 \rangle \equiv \left\langle \left(x - \frac{1}{2} \right)^2 \right\rangle = \frac{\langle p_L^2 \rangle}{4m_c^2} = \frac{1}{4} \langle {v_L}^2 \rangle \approx 0.017$$

Introducing a variable ζ Fourier conjugate to λ,

$$\tilde{\Psi}_{\bar{c}c}(\zeta, r_\perp) = \int\limits_0^1 \frac{dx}{2\pi} \Psi_{\bar{c}c}(x, r_\perp)\, e^{2im_c\zeta(x-1/2)}$$

and making use of smallness of λ and of the binding energy, we arrive at the boost-invariant Schrödinger equation for the Green function

$$\left[\frac{\partial}{\partial z^+} + \frac{\Delta_\perp + (\partial/\partial\zeta)^2 - m_c^2}{p_\psi^+/2} - U(r_\perp, \zeta) \right] G(z^+, \zeta, r_\perp; z_1^+, \zeta_1, r_{1\perp}) = 0$$

Solving the equation

$$\mathbf{ReU_{\bar{q}q}(r_\perp,\zeta) = \frac{M_\psi}{p^+_\psi} V\left(\sqrt{r^2_\perp + \zeta^2}\right)}$$ - rest frame potential

This is the main result, a simple replacement: $\mathbf{r_L} \Rightarrow \zeta$

In the rest frame the usual Schrödinger equation is recovered.

$$\mathbf{ImU_{\bar{q}q}(r_\perp,\zeta) = -\frac{1}{4}\, v\, \hat{q}\, r^2_\perp}$$ controls absorption and is independent of ζ

Screened potential.

$$\mathbf{V_{\bar{c}c}\left(r = \sqrt{r^2_\perp + \zeta^2}\right) = \frac{\sigma}{\mu(T)}\left(1 - e^{-\mu(T)r}\right) - \frac{\alpha}{r} e^{-\mu(T)r}}$$

$$\mathbf{\mu(T) = g(T)T\sqrt{1+\frac{N_f}{6}}, \qquad g^2(T) = \frac{24\pi^2}{33\ln\left(19T/\Lambda_{\overline{MS}}\right)}}$$

F. Karsch, M. T. Mehr and H. Satz, Z. Phys. C 37, 617 (1988)

The equation is solved numerically with $\mathbf{\hat{q} = q_0 \frac{n_{part}(\tilde{\tau},\tilde{b})}{n_{part}(0,0)} \frac{t_0}{t}}$; $\quad \mathbf{q_0 = 1\,fm}$

Results

Survival probability amplitude

$$\mathbf{S(z_2, z_1) = \int d\zeta_2 d\zeta_1 d^2r_2 d^2r_1 \Psi_{J/\psi}(r_2, \zeta_2)}$$

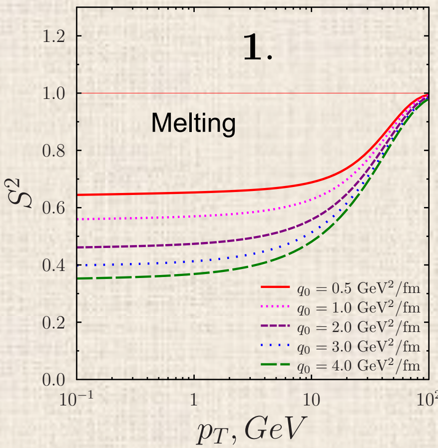
$$\mathbf{\times G(r_2, \zeta_2, z_2; r_1, \zeta_1 . z_1) \Psi_{in}(r_1, \zeta_1)}$$

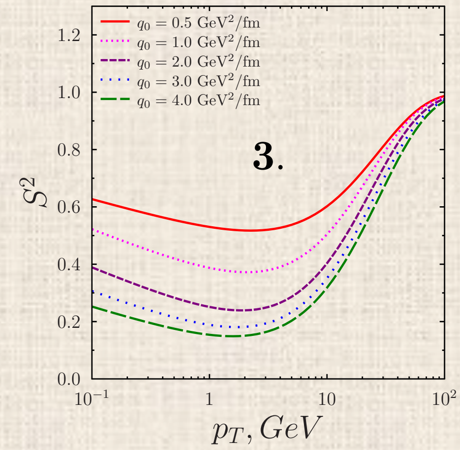
Calculations are done for central Pb-Pb collisions with realistic nuclear density.

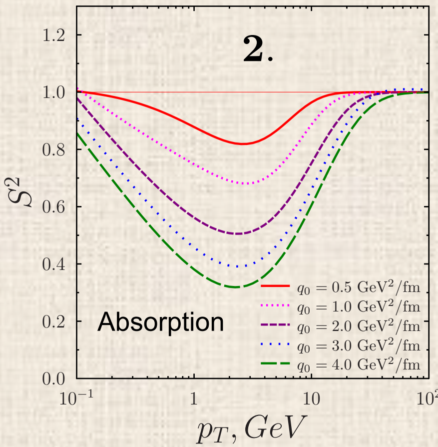
No ISI effects has been added.

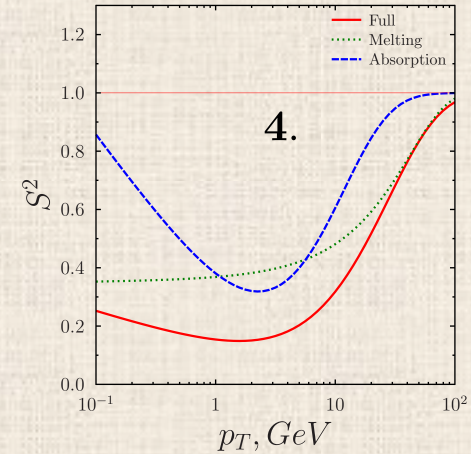
1. Net melting: $\mathbf{ReU \neq 0; ImU = 0.}$
2. Net absorption: $\mathbf{ReU = 0; ImU \neq 0.}$
3. Total suppression: $\mathbf{ReU \neq 0; ImU \neq 0.}$
4. $\mathbf{q_0 = 2\, GeV^2/fm}$

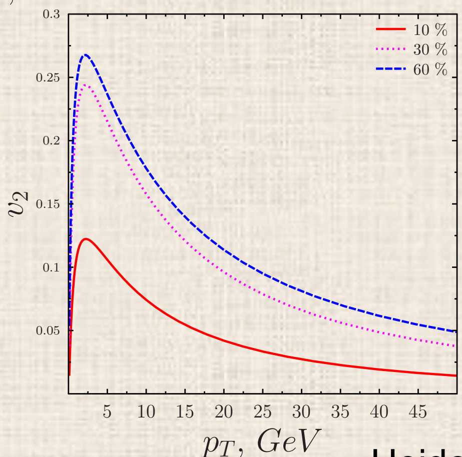
The azimuthal asymmetry v2=<cos(2φ)> is not affected by ISI, so can be directly compared with data











Conclusions

The QCD based phenomenology is pretty well developed.
Nowadays we are able to calculate almost every high-energy process without fitting to the data to be explained.

However, this might be true only for perturbative methods which are relevant to the regime of asymptotic freedom.

Unfortunately, we still have a rather poor understanding of soft nonperturbative physics which we are never free of.

The QCD applications look far more complicated and messy than the first principles, the QCD Langrangian.

Amount of models and theoretical tools keep growing.

Thank you for your attention and patience!

B.K. & A.Rezaeian, arXiv:0811.2024

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