STATUS AND PROSPECTS OF HEAVY QUARK PRODUCTION IN QCD

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Heavy quark production is the most inclusive way to study processes with one (hadron interaction) or two (DIS) scales of hardness.

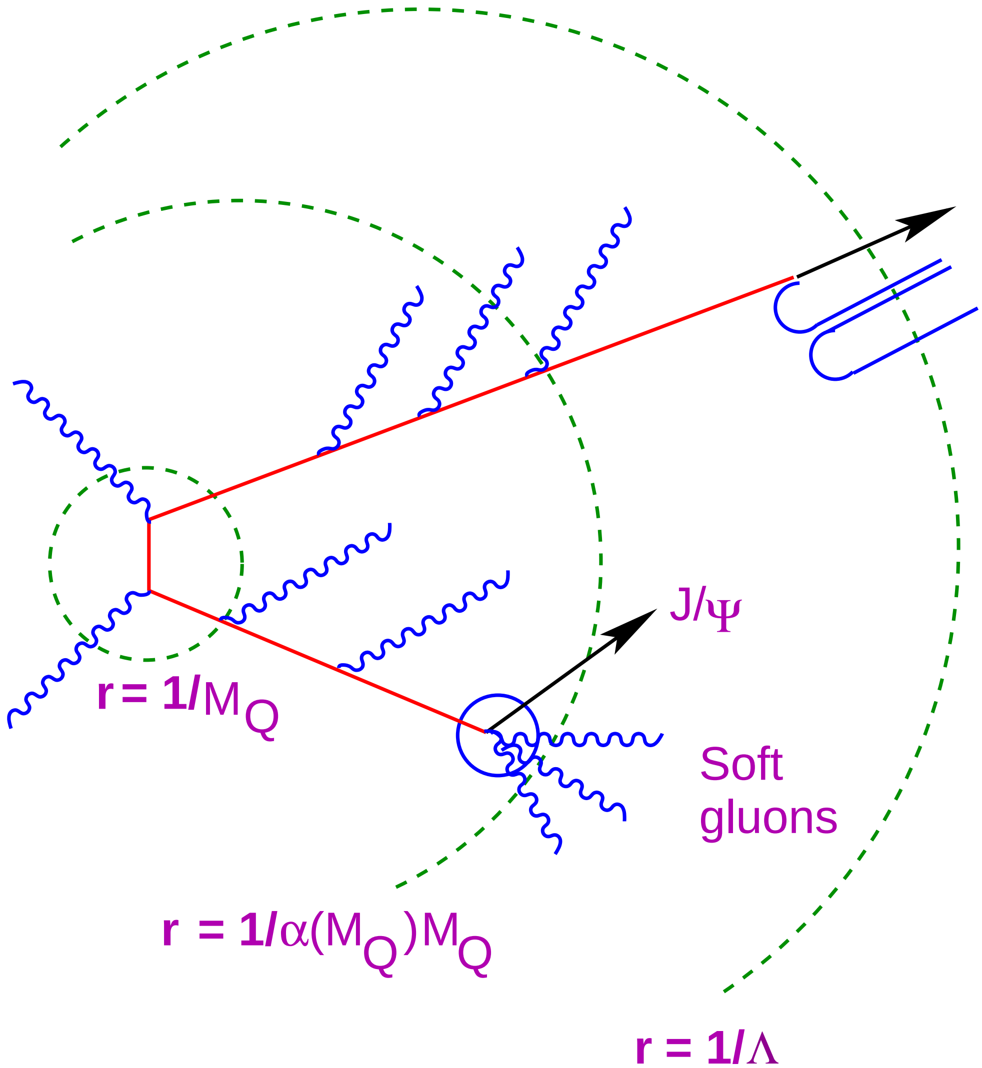
Three stages of understanding:

- **Everything is clear;**
- **Nothing is clear;**
- **Something becomes understandable for them who survived the first two stages**

The good news:

We are in the third stage

Everything is clear



Everything is clear

- $\Delta r \Delta p \sim 1$

$$\frac{p^2}{M_Q} = \frac{1}{M_Q\, r^2}$$

- $\frac{p^2}{M_Q} - \frac{\alpha_S(r)}{r} = \epsilon \approx 0$

$$\frac{1}{M_Q\, r^2} = \frac{\alpha_S(r)}{r}$$

- **Solution:**

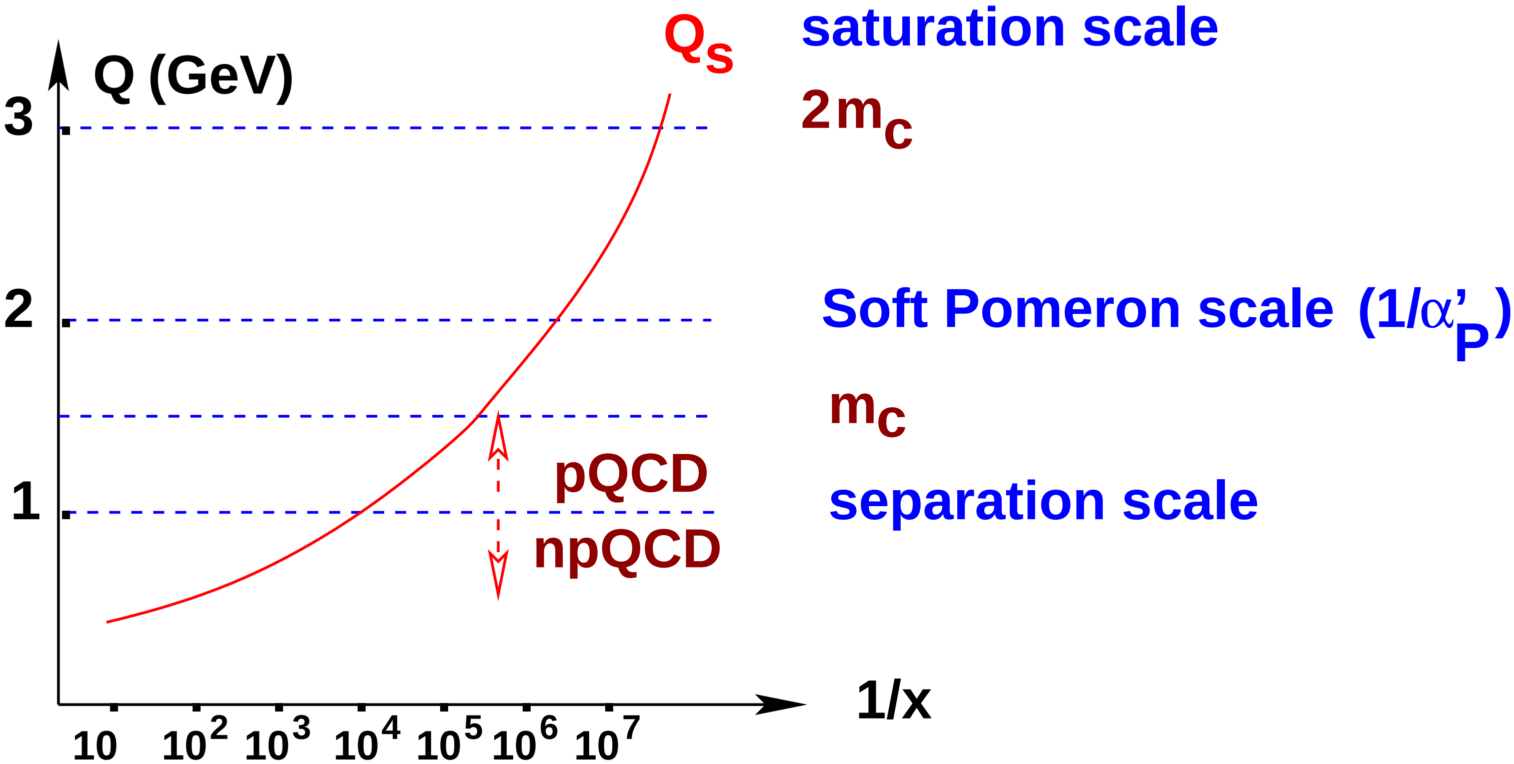
$$r \propto \frac{1}{\alpha_S(1/M_Q)\ M_Q} \ll \frac{1}{\Lambda}$$

- **Velocity:**

$$p = M_Q v = M_Q\, \alpha_S(1/M_Q)$$

$$v \approx \alpha_S(1/M_Q) \ll 1$$

Everything is clear



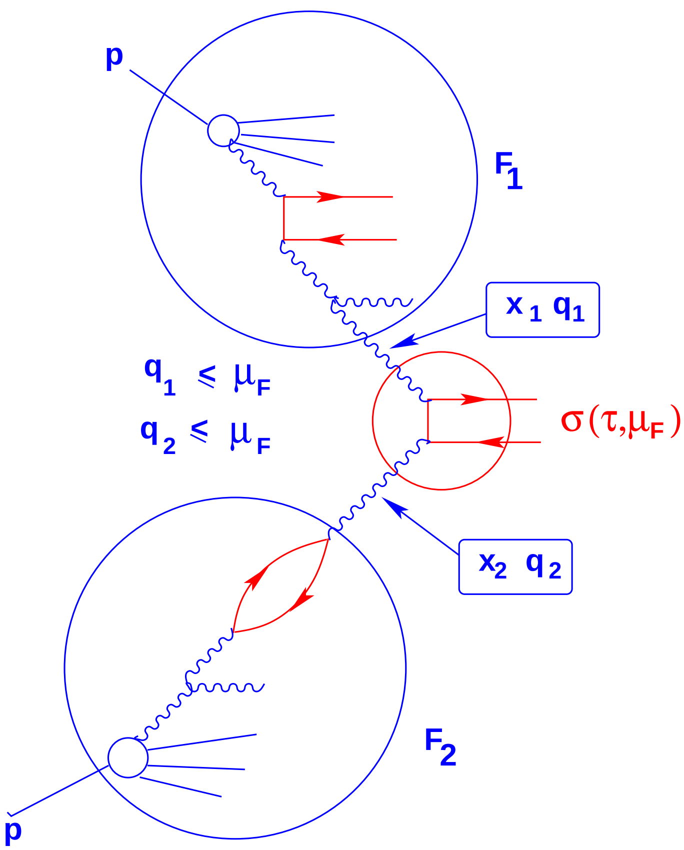
My personal hope:

- HQ production will tell about the structure of 'soft' Pomeron;
- HQ production will show the collective effects due to saturation;

Nothing is clear

$$\sigma_{pp}(s, M_Q^2) \;=\; \sum_{j,i=q,\bar{q},G}$$

$$\int_{\frac{4M_Q^2}{s}}^{1} \frac{d\tau}{\tau}\, \delta(x_1 x_2 - \tau)\, F_i^p(x_1, \mu_F)\;\; F_i^p(x_2, \mu_F)\; \sigma_{i,j}(\tau, M_Q^2, \mu_F)$$



- **What is the value of factorization scale μ_F?**
- **What is the value of renormalization scale μ_R?**
- **From experiment:**
  if $\mu_F = m_c$ m_c= 1.4 GeV
  if $\mu_F = 2\,m_c$ m_c= 1.2 GeV
- **Should $\mu_R = \mu_F$?**

Nothing is clear

- **How to include the $Q\bar{Q}$ threshold in the running QCD coupling ?**

- **How to include the $Q\bar{Q}$ threshold in the structure functions ?**

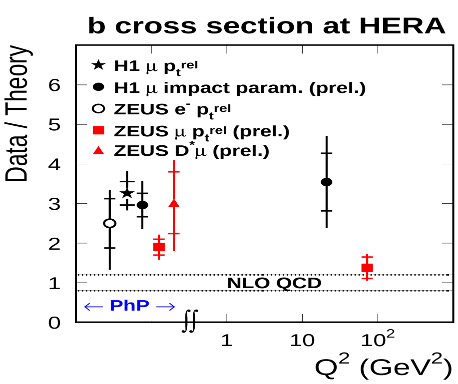
- **How to explain three major disagreements with experiment:**

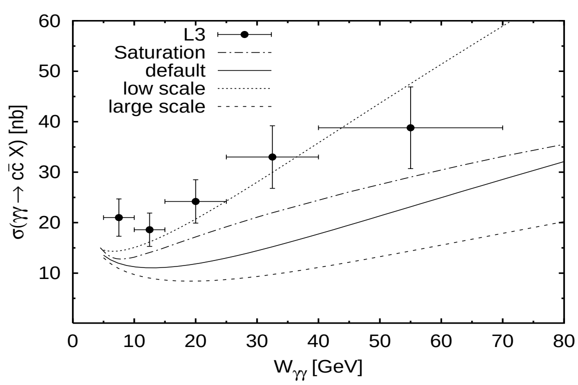
  – $\sigma^{EXP}(pp \to J/\Psi) \approx 10\ \sigma^{QCD}(pp \to J/\Psi)$
  – $\sigma^{EXP}(R \to b\bar{b}) \approx 3\ \sigma^{QCD}(R \to b\bar{b})$

  for reactions:

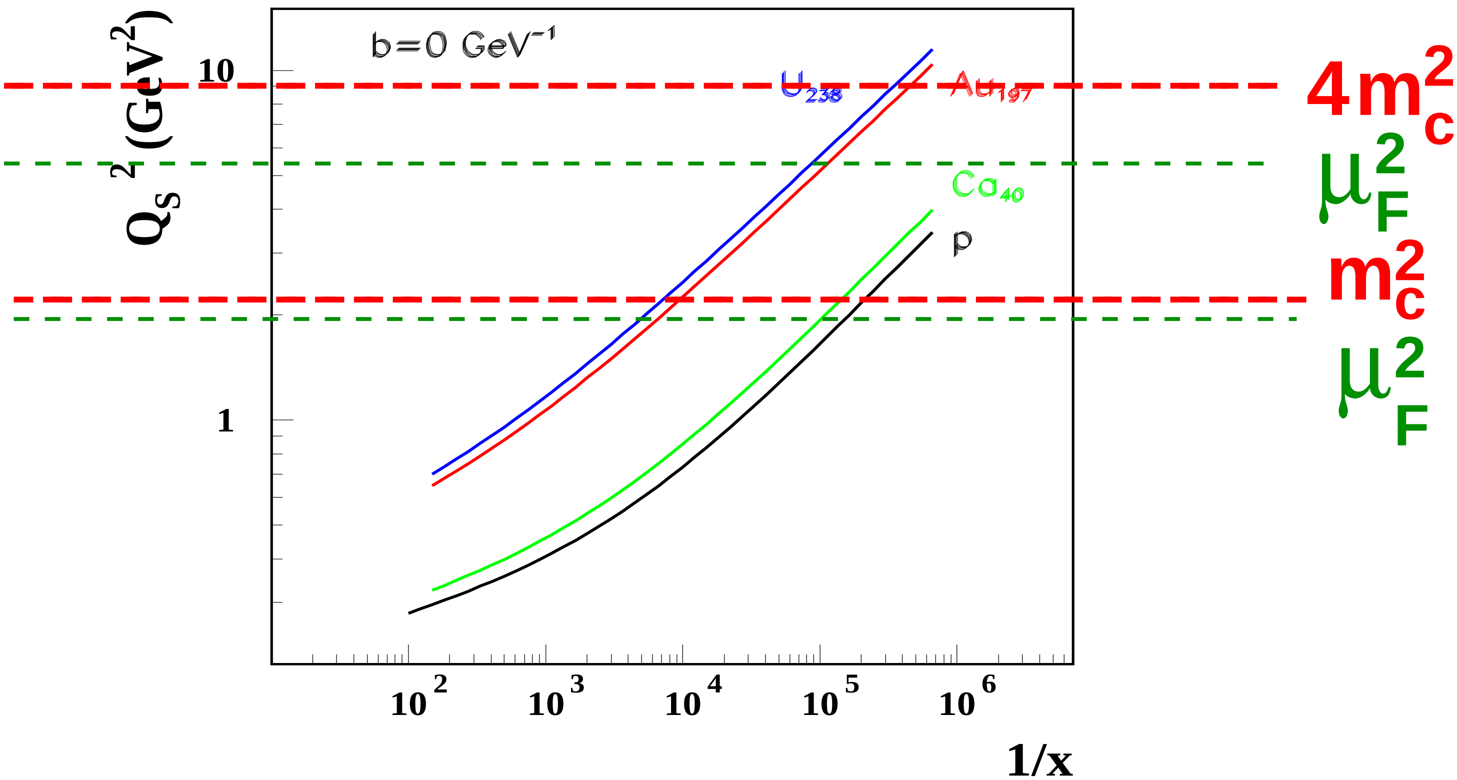
  * $\gamma^* + p$ **(HERA)**
  * $p + p$ **(TEVATRON)**

  – $\sigma^{EXP}(\gamma^*\gamma^* \to c\bar{c}) \approx 2\sigma^{QCD}(\gamma^*\gamma^* \to c\bar{c})$





- **Loss of hope**



b=0 GeV⁻¹
10
1
U_{238}
Au_{197}
Ca_{40}
p
Q_s^2 (GeV²)
10^2
10^3
10^4
10^5
10^6
1/x
$4m_c^2$
μ_F^2
m_c^2
μ_F^2

Something becomes understandable

- **LO + NLO pQCD;**

  Kniehl, Wing, Gerhards,Behnke, Hochman , Loizides, Filthaut, Bussey , Gladilin and . . . ;

- **(LO + NLO) versus k_t factorization;**

  Zotov, Jung, Baranov , Likhoded and round table discussion;

- **NR QCD and heavy quarkonium production;**

  Zwirner, Baranov, Meyer, Katkov and round table discussion;

- **HQP and saturation;**

  Zotov, Baranov

- **HQP in ion-ion collisions;**

- **Diffractive HQP;**

  Bartels, Vlasov, Vinokurova , Soares and round table discussion;

pQCD: general strategy

- $$F_2^{Q\bar{Q}}\left(x; \frac{Q^2}{\Lambda^2}, \frac{Q^2}{M_Q^2}\right) =$$

$$\sum_{n=0}^{\infty} C_N\left(x; \ln(Q^2/\Lambda^2), \ln(Q^2/M_Q^2)\right) \alpha_S^n$$

$$+ \frac{M^2}{Q^2} F_2^{HT}\left(x; \ln(Q^2/\Lambda^2), \ln(Q^2/M_Q^2)\right);$$

- $$R\left(x; \frac{Q^2}{\Lambda^2}, \frac{Q^2}{M_Q^2}\right) = \frac{F_2^{Q\bar{Q}}\left(x; \frac{Q^2}{\Lambda^2}, \frac{Q^2}{M_Q^2}\right)}{F_2^{Q\bar{Q},LO}\left(x; \frac{Q^2}{\Lambda^2}, \frac{Q^2}{M_Q^2}\right)}$$

$$= \sum_{n=0}^{N} r_n \pm r_{N+1} + O\left(\frac{M^2}{Q^2}\right);$$

- $$F_2^{Q\bar{Q},LO}\left(x; \frac{Q^2}{\Lambda^2}, \frac{Q^2}{M_Q^2}\right) = ?$$

  - $LLog(1/x)$ **(BFKL) :**

$$F_2^{Q\bar{Q},LO} = \sum_{n=0}^{\infty} C_n\left(\ln(Q^2/\Lambda^2), \ln(Q^2/M_Q^2)\right) (\alpha_S \ln(1/x))^n;$$

– $LLog(Q/\Lambda)$ (DGLAP) :

$$F_2^{Q\bar{Q},LO} = \sum_{n=0}^{\infty} C_n \left(x; \ln(Q^2/M_Q^2) \right) \left(\alpha_S \ln(Q^2/\Lambda^2) \right)^n ;$$

– Two scales ???:

$$F_2^{Q\bar{Q},LO} = \sum_{n=0}^{\infty} C_n (x) \ \alpha_S^n \ \ln^m(Q^2/\Lambda^2) \ ln^{n-m}(Q^2/M_Q^2)$$

- N =?

- $$F_2^{HT} \left(x; \ln(Q^2/\Lambda^2), \ln(Q^2/M_Q^2) \right) = ?$$

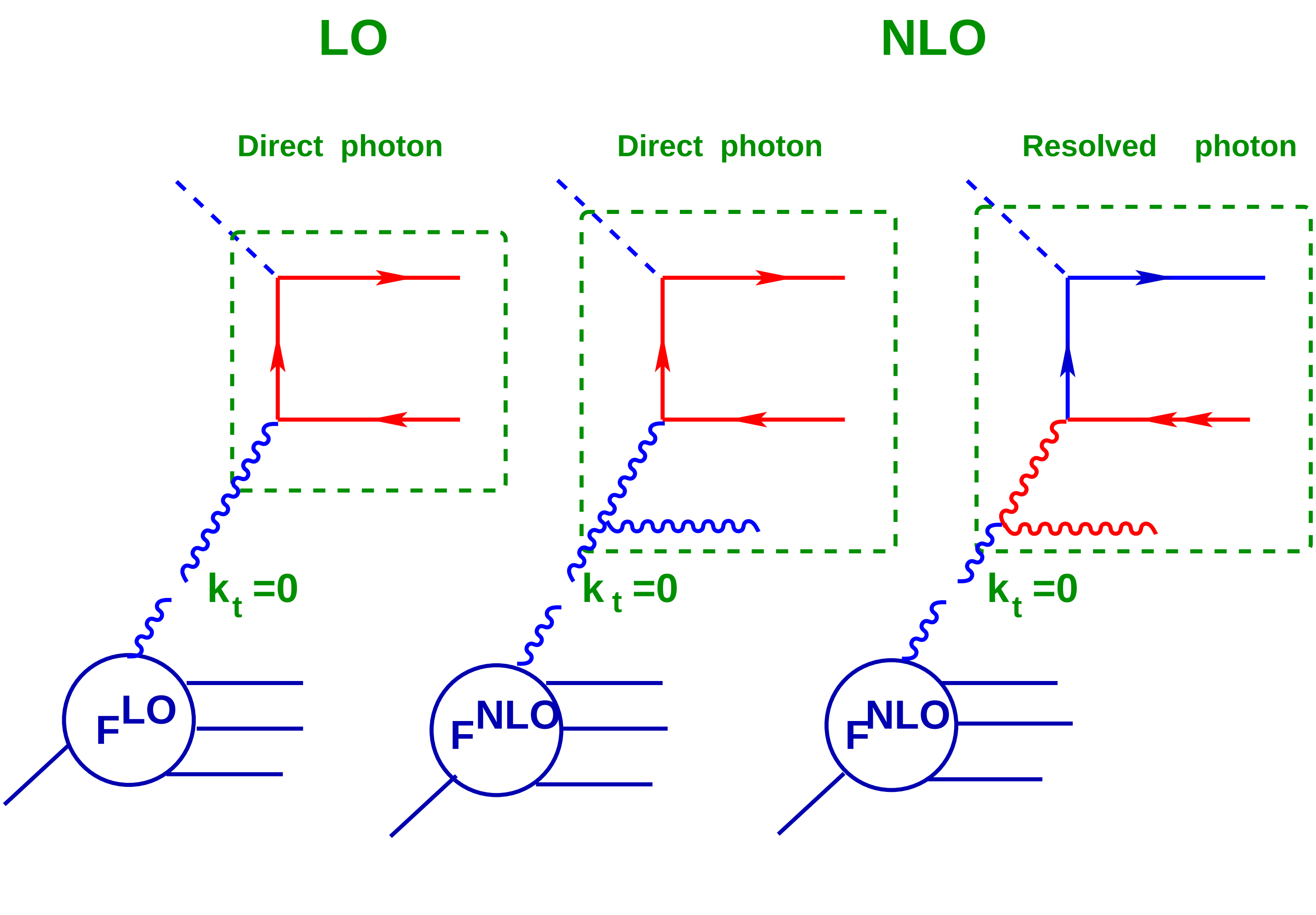
– We know the DGLAP equations for it;
– We do not know a solution to these equation;
– We do not know initial conditions for them;
– Only saturation models lead to the estimates;

LO + NLO pQCD

$$\sigma_{i,j}(\tau, M_Q^2, \mu_F) \;=\; \frac{\alpha_S^2(\mu_R)}{M_Q^2} \times$$

$$\left(f_{i,j}^{LO}(\tau) \;+\; 4\pi\alpha_S(\mu_R)\,[f_{i,j}^{NLO}(\tau) \;+\; \bar{f}_{i.j}^{NLO}\;\ln(\mu_F^2/M_Q^2)] \right)$$

$$\tau \;=\; \frac{4M_Q^{@}}{\hat{s}}\;, \quad \hat{s} \;=\; x_1\,x_2\,s$$



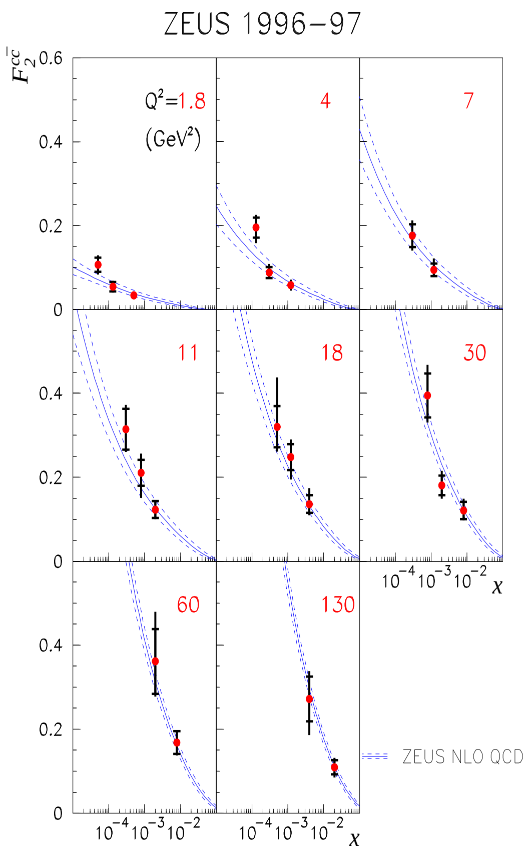
Advantages:

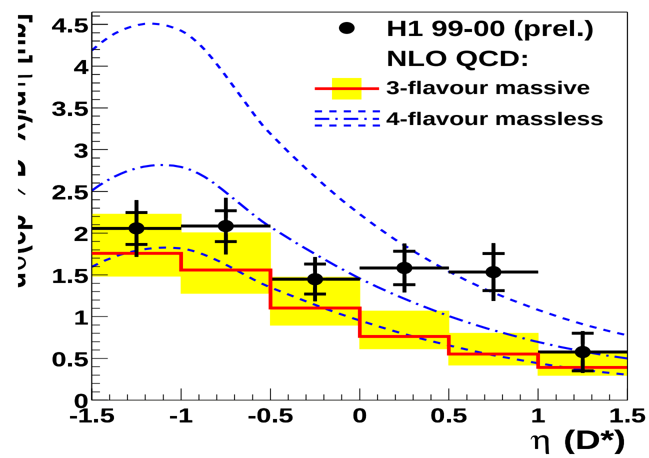
It is well defined (?) procedure:

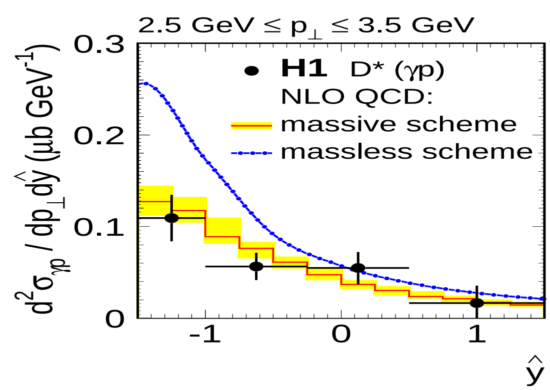
- F^{LO} and F^{NLO} as well as σ^{hard} is gauge invariant and finite;
- $\alpha_S^k \ln^n(\mu_F/m_q)$ are included in p.d.f.
- BUT $\alpha_S^k \ln^n(\mu_F/M_Q)$ are included either in p.d.f. or in hard cross section depending on factorization scheme;
- ACOT (Aivas,Collins,Olness & W.-K.Tung) :
  - all $\ln(\mu_F/M_Q)$ in hard cross section for $\mu_F < M_Q$;
  - all $\ln(\mu_F/M_Q)$ in p.d.f. for $\mu_F > M_Q$;
- ACOT scheme has been implemented for description of HQP in CTEQ6HQ and in the paper of Nadolsky,Kidomakis, Olness & C.-P.Yan (2003);

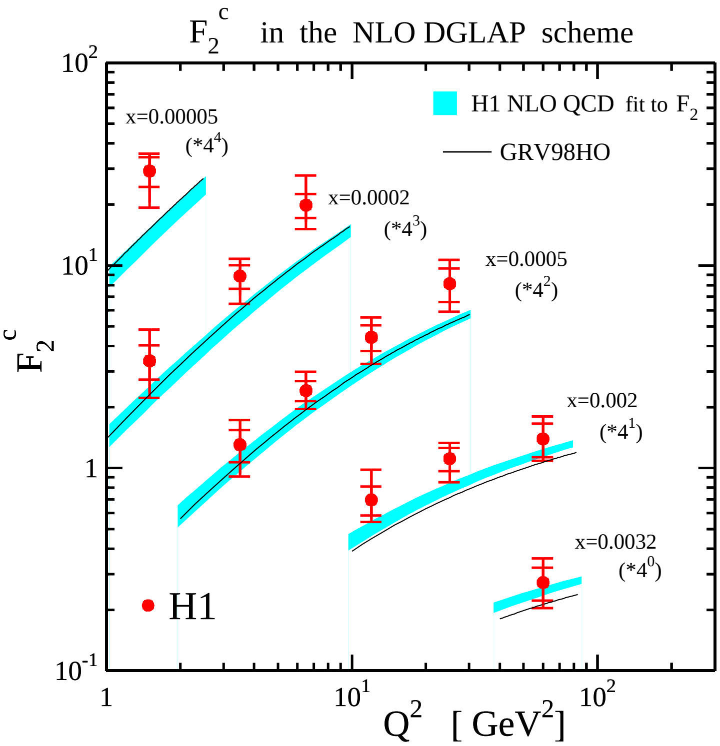
Disadvantages:

- Both scales: μ_F an μ_R are arbitrary and there are no ideas how to fix them;
- F^{LO} and F^{NLO} are well defined but they lost the meaning on the number of parton with $k_t < \mu_F$;

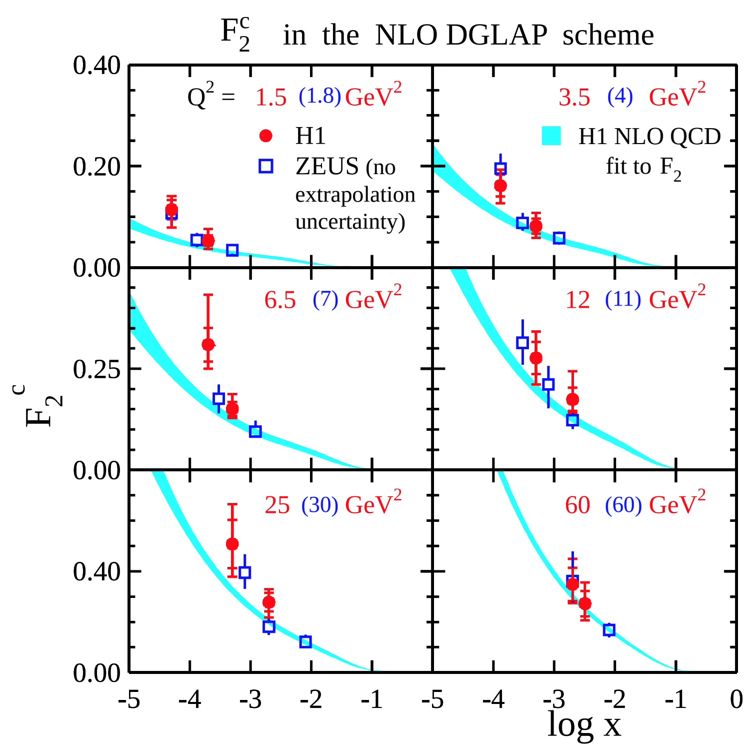








F_2^c in the NLO DGLAP scheme
H1 NLO QCD fit to F_2
GRV98HO
x=0.00005 (*4^4)
x=0.0002 (*4^3)
x=0.0005 (*4^2)
x=0.002 (*4^1)
x=0.0032 (*4^0)
H1
F_2^c
Q^2 [GeV^2]

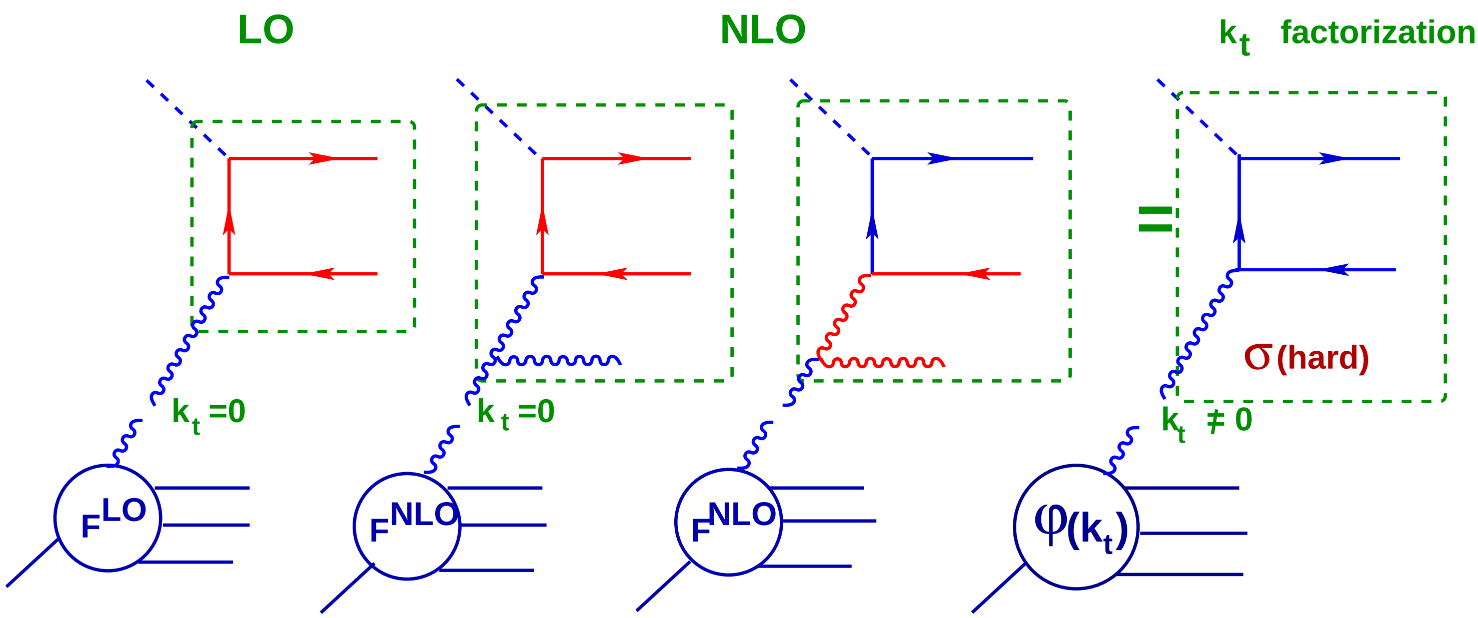


F_2^c in the NLO DGLAP scheme
Q^2 = 1.5 (1.8) GeV^2
H1
ZEUS (no extrapolation uncertainty)
3.5 (4) GeV^2
H1 NLO QCD fit to F_2
6.5 (7) GeV^2
12 (11) GeV^2
25 (30) GeV^2
60 (60) GeV^2
F_2^c
log x

(LO + NLO) versus k_t -factorization

$$\sigma_{pp}(s, M_Q^2) \;=\; \sum_{j,i=q,\bar{q},G} \int_{\frac{4M_Q^2}{s}}^{1} \frac{d\tau}{\tau}\, \delta(x_1 x_2 - \tau)\, \delta(\vec{k}_1 + \vec{k}_2 - \vec{p}_1 - \vec{p}_2)$$

$$\varphi_i^p(x_1, k_1)\;\; \varphi_i^p(x_2, k_2)\;\; \sigma_{i,j}(\tau, M_Q^2, k_{1,t}, k_{2,t})$$



Difficulties: φ and $\sigma(hard)$ are not gauge invariant separately.

Advantages: φ has a meaning of the density of parton with given transverse momentum.

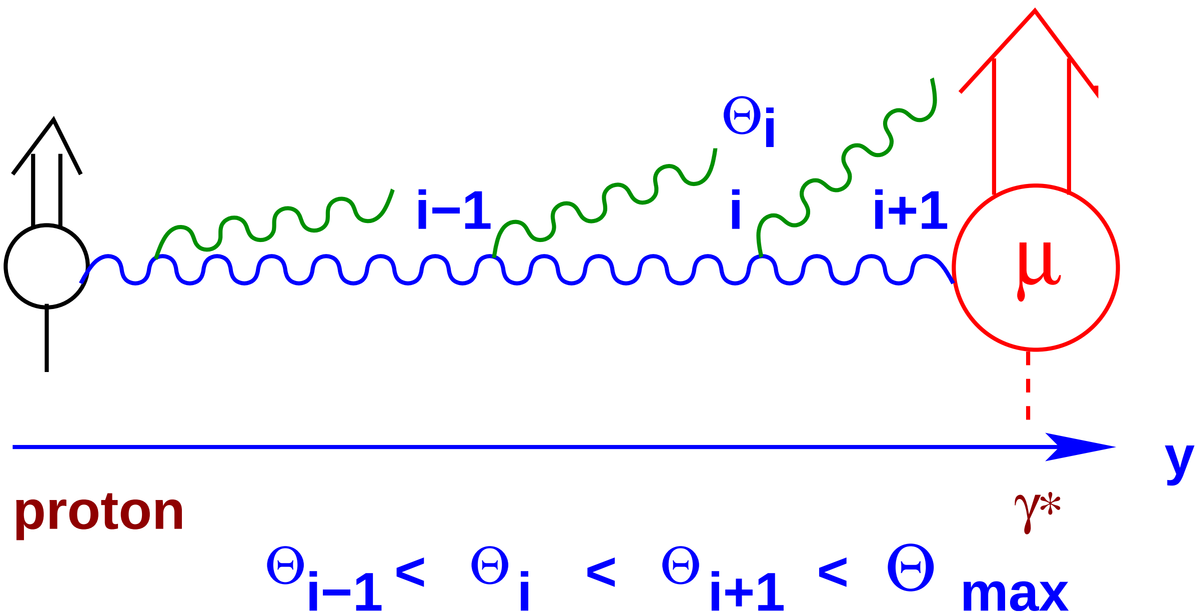
$$xG(x, \mu_F) \;\propto\; \int^{\mu_F} dk_t^2\; \varphi(k_t)$$

But only at $x \longrightarrow 0$!!!

Advantages: the factorization scale μ_F can be determined as $< k_t >$

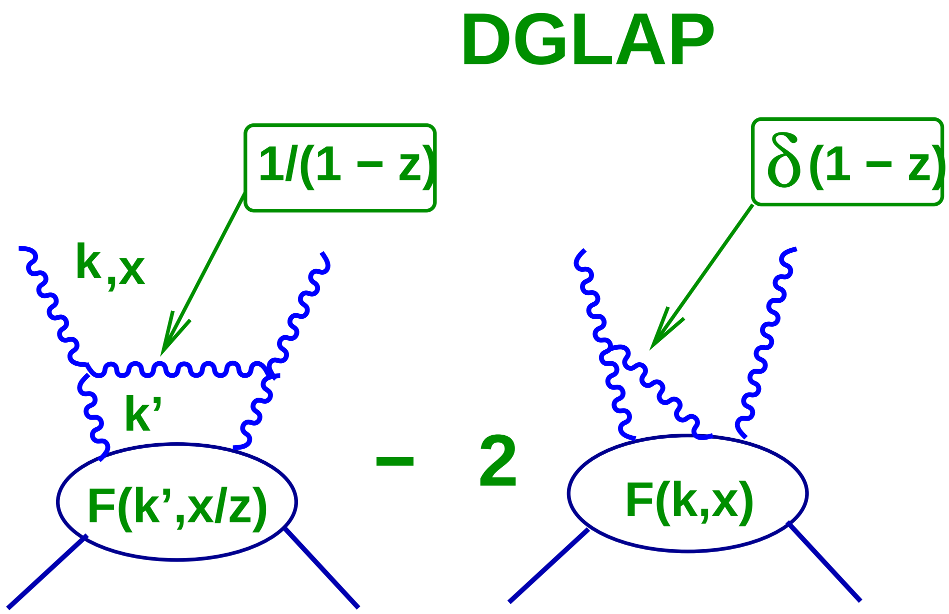
CCFM parton cascade

CCFM = Ciafaloni, Catani, Fiorani & Marchesini



$\varphi(k_t, \mu; x)$ depends on two dimensional variables and CCFM equation is the correct way to introduce such function in the case of two scales of hardness

Difficulties: φ **at** $z \to 1$ **is divergent** **(J.Gollins 2003)**



Solution: **In CCFM equation φ is defined as (see also MRS 2002)**

$$\varphi(k_t, \mu; x) \;=\; \frac{\partial}{\partial \ln(k_t^2)} \left(x G(x, k_t^2)\, T(k_t^2, \mu^2) \right)$$

where T is Sudakov form factor which says that there is no emission with transverse momenta between k_t and μ

$$T(k_t^2, \mu^2) \;=\; exp \left(- \int_{k_t^2}^{\mu^2} \frac{d k_t^2}{k_t^2} \int_0^{1-\delta} d\zeta\, \zeta\, P^{DGLAP}(\zeta) \right)$$

Market of unintegrated parton distributions

Small x Collaboration: Eur.Phys. J C 25 (2002) 77

One scale approximation:

- (GLR) :

$$\varphi(k_t, x) = \frac{d\, xG(x, \mu^2)}{d\mu^2}|_{\mu = k_t}$$

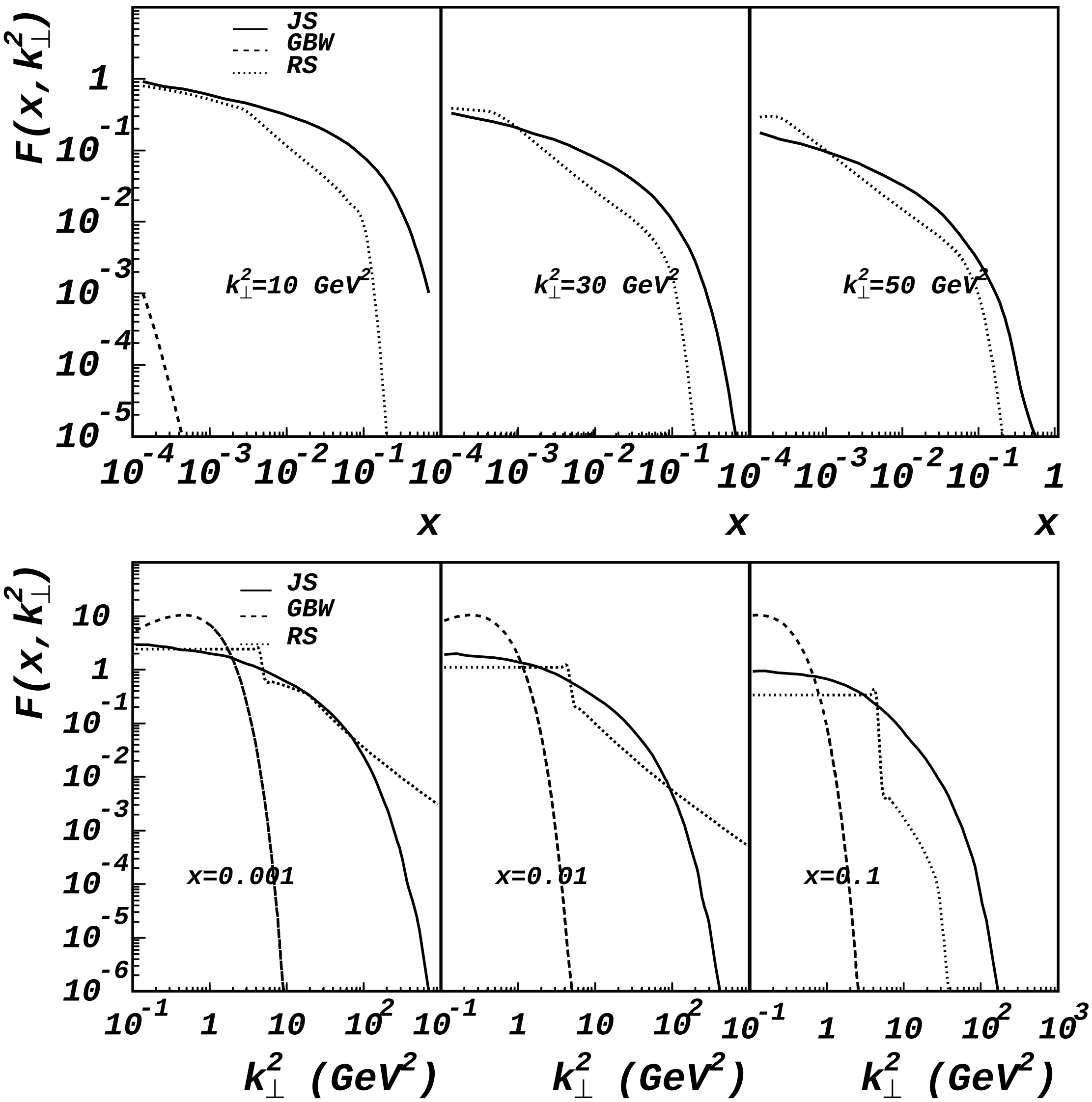
- (RS) : $\varphi(k_t, x)$ is solution to the BFKL equation, initial condition: $\varphi(k_t, x) = xG(x, Q_0)/Q_0^2$ for $k_t < Q_0$

- (KMS) : $\varphi(k_t, x)$ is solution of the BFKL equation for $k_t > k_0 = 1GeV$, the non-perturbative region is provided by $xG(x, k_0^2)$

- (GBW) :

$$\varphi(k_t, x) = \frac{3\sigma_0}{4\pi^2 \alpha_S} k_t^2\, R^2(x)\, e^{-k_t^2\, R^2(x)}$$

,
with $\sigma_0 = 29.12 mb$ and $\alpha_S = 0.2$


JS
GBW
RS
F(x, k⊥²)
k⊥²=10 GeV²
k⊥²=30 GeV²
k⊥²=50 GeV²
x
x=0.001
x=0.01
x=0.1
k⊥² (GeV²)

Two scale unintegrated parton densities:

- **(JB) :** $\varphi(k_t, \mu; x) =$

  $\int_0^1 B(z, k_t^2, \mu^2)\,(x/z)G(x/z, \mu^2)\,dz$

  with a universal function B;

- **(KMR) :** $\varphi(k_t, \mu; x) =$

  $$= T(k_t^2, \mu^2)\,\frac{\alpha_S(k_t)}{2\pi k_t^2}\int_x^{1-\delta} P(z)\,(x/z)G(x/z, k_t)\,dz$$

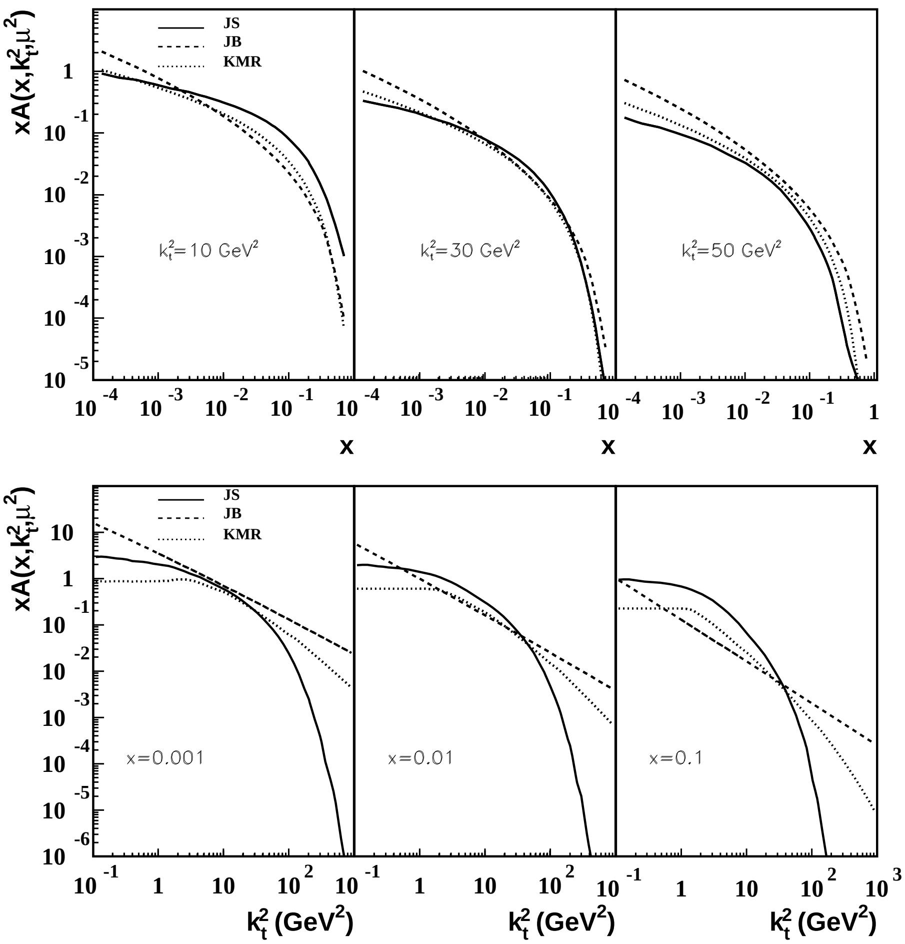
  $$= \frac{\partial}{\partial \ln(k_t^2)}\left(xG(x, k_t^2)\,T(k_t^2, \mu^2)\right)$$

  with initial condition as in RS.

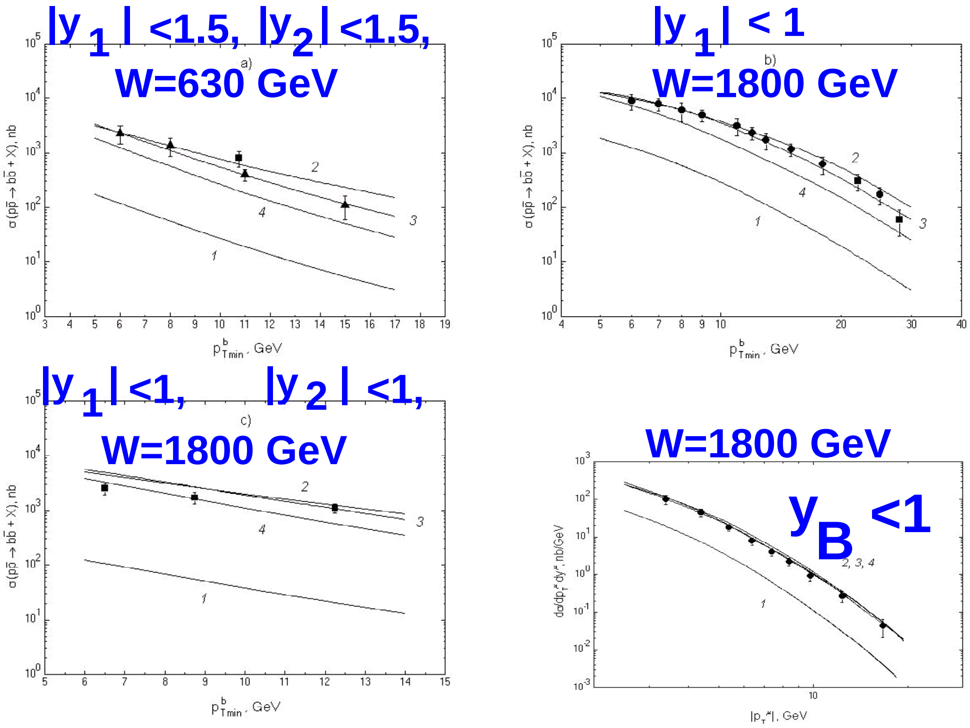
- **(JS) :** $\varphi(k_t, \mu; x)$ **is a numeric (Monte Carlo) solution to the CCFM equation . The free parameters are determined from F_2 for $x < 10^{-2}$ and $Q^2 > 5\,GeV^2$.**

  The best that we have at the moment

- **(LDC) : This model provides a smooth transition between DGLAP and BFKL dynamics which quite close to the CCFM equation but not exactly it**


JS
JB
KMR
k_t^2=10 GeV^2
k_t^2=30 GeV^2
k_t^2=50 GeV^2
xA(x,k_t^2,μ^2)
x
x=0.001
x=0.01
x=0.1
k_t^2 (GeV^2)

Inclusive production



▲ – UA1

● – D0

■ – CDF

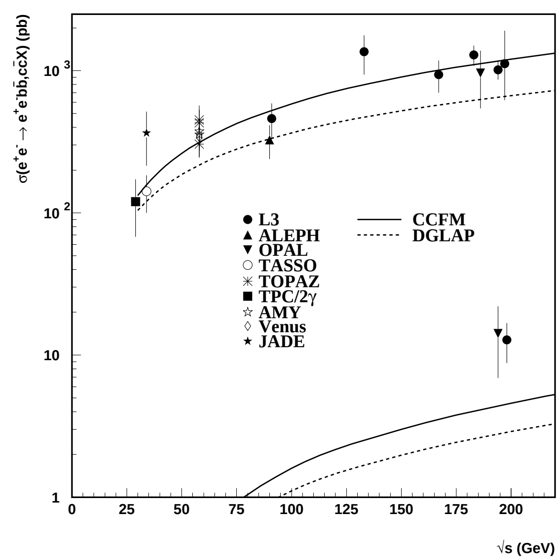
1 – GRV(LO)

2 – JS

3 – KMS

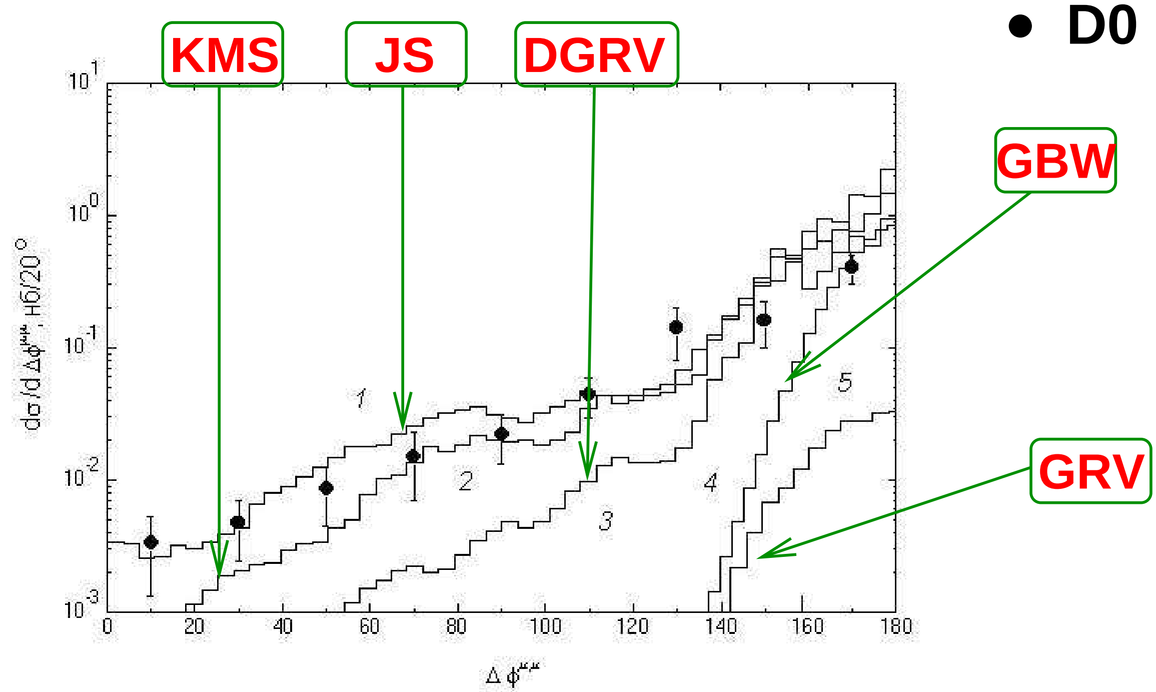
4 – DGRV

- Baranov, Lipatov & Zotov (2003)



- Hansson &Jung (2003)

Correlations



- D0

- Baranov, Lipatov & Zotov (2003)

Resume and Questions

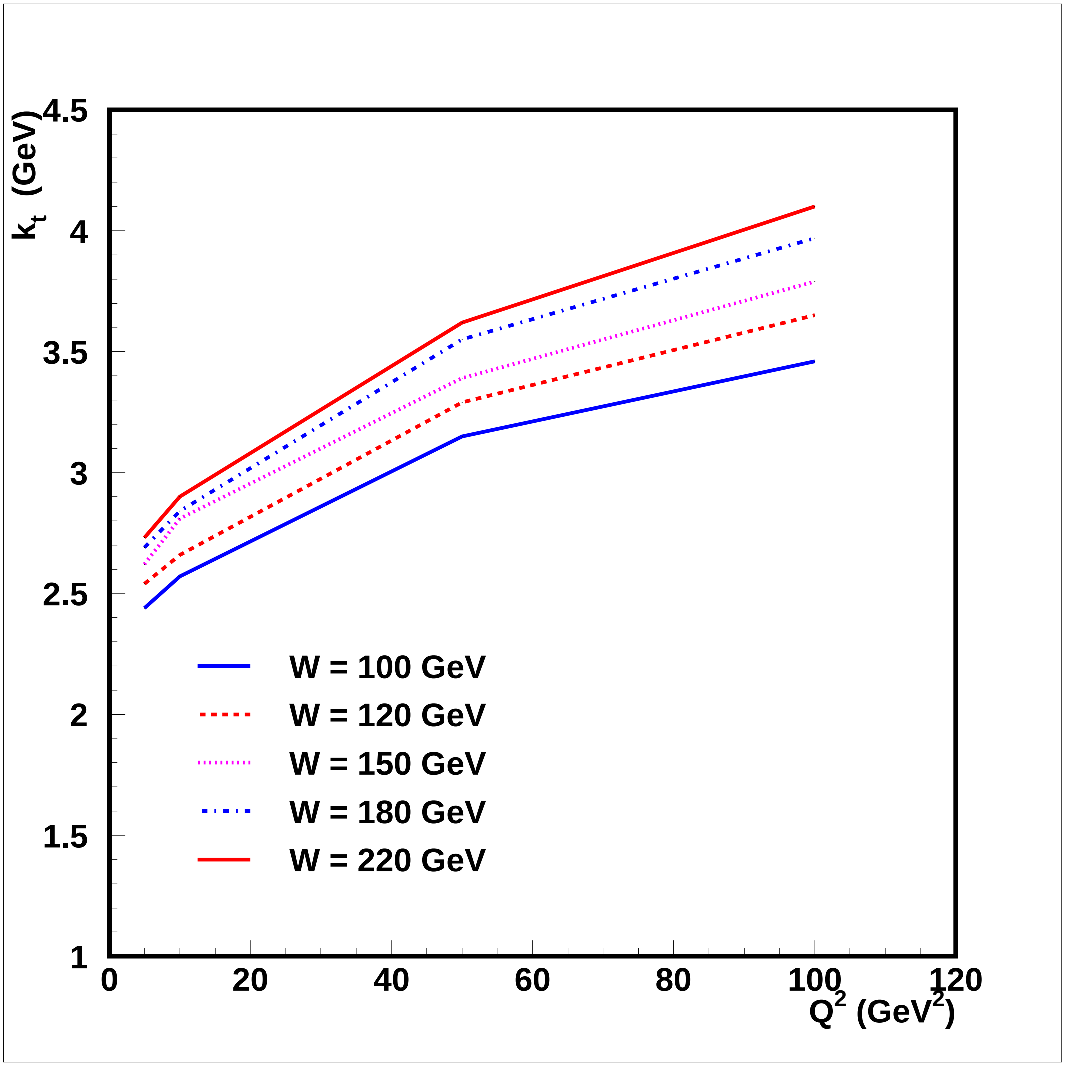
LO $\varphi(k_t, \mu; x)$

- **has a transparent meaning of probability to find a parton with given k_t in a reaction with the scale of hardness μ;**

- **describes a substantial part of NLO pQCD calculations;**

- **leads to possibility to estimate the value of the factorization scale in pQCD approach;**

Average $k_t = \mu$



- H. Jung (JS) (2003)

NLO $\varphi(k_t, \mu; x, s_0)$ = ???

- the BFKL equation in NLO has been developed

  (Fadin,Lipatov +...(2000));

- the way how to resum the NLO BFKL to obtain a smooth matching with the DGLAP evolution has been found

  (Ciafaloni & Salam (2001));

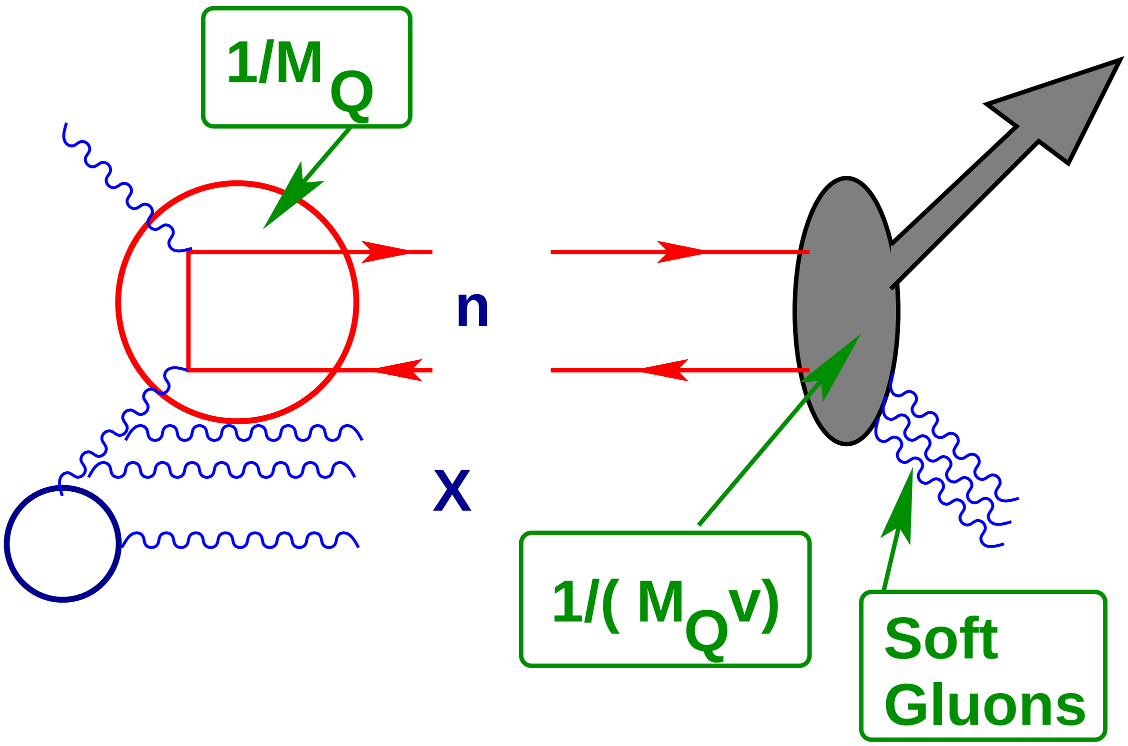
- CCFM equation in NLO = ?

- Coefficient functions (impact factors) = ?

- A new dimension scale is needed which says what energy is high and the problem becomes three scale problem (?) which has not been studied;

NR QCD

NR QCD Factorization



$$d\sigma\,(H + X) = \sum_{n} d\sigma\,(Q\bar{Q}\,[n] + X\,)\,\langle O^{H}[n]\rangle$$

• • •

$$L^{NRQCD} = \psi^{+}\left(iD_0 + \frac{\vec{D}^2}{2M_Q}\right)\psi + \chi^{+}\left(iD_0 - \frac{\vec{D}^2}{2M_Q}\right)\chi$$

$$+L^{light} + \delta L$$

• • •

$$\delta L_{bilinear} = \frac{c_1}{8M_Q^3}\psi^{+}\vec{D}^4\psi + \frac{c_2}{8M_Q^2}\psi^{+}\left(\vec{D}\cdot g\vec{E} - g\vec{E}\cdot\vec{D}\right)\psi$$

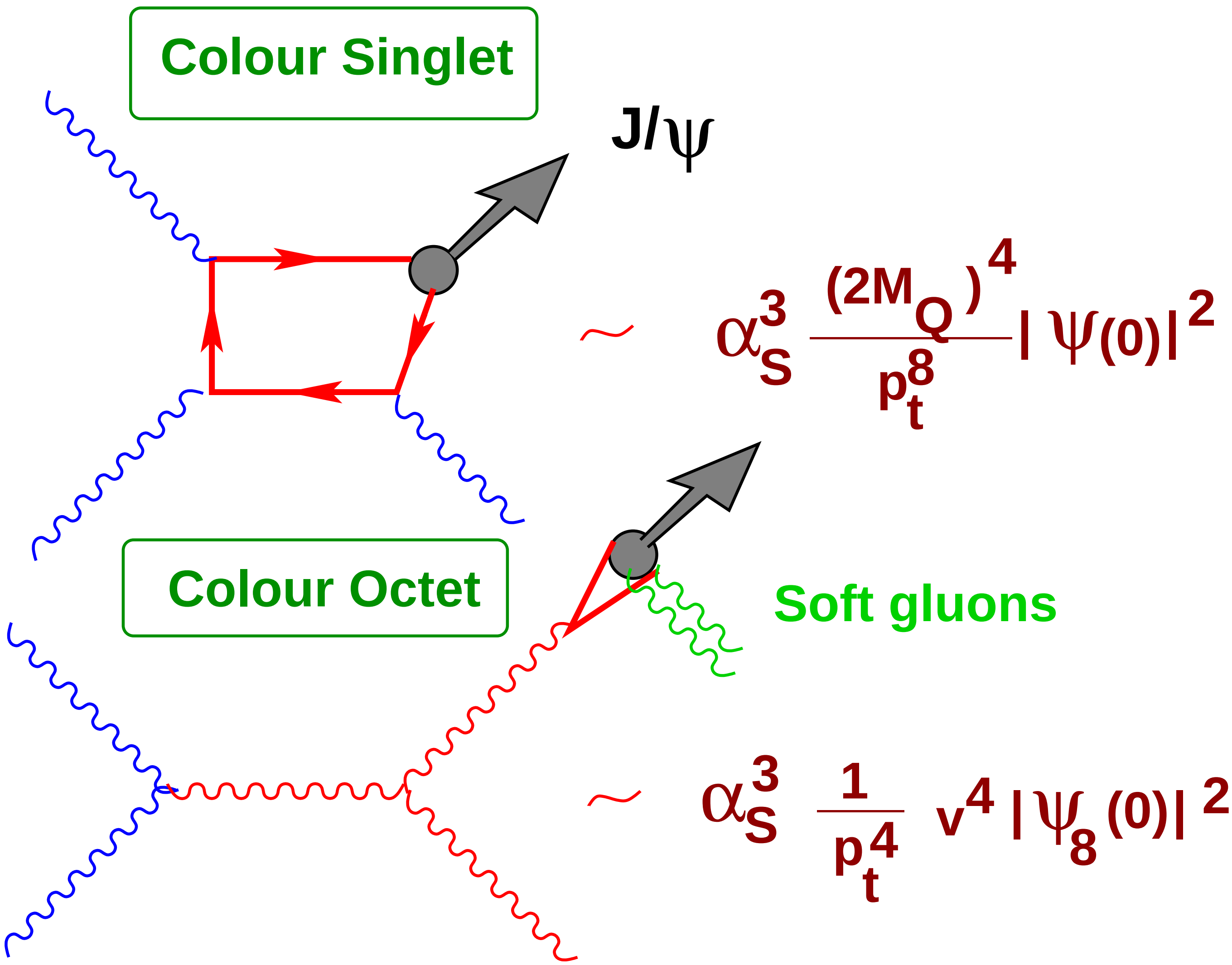
$$+\frac{c_3}{8M_Q^2}\sigma^{+}\left(i\vec{D}\times g\vec{E} - ig\vec{E}\times\vec{D}\right)\cdot\vec{\sigma}\psi + \frac{c_4}{8M_Q}\psi^{+}g\vec{B}\cdot\vec{\sigma}\psi$$

$$+c.c.terms$$

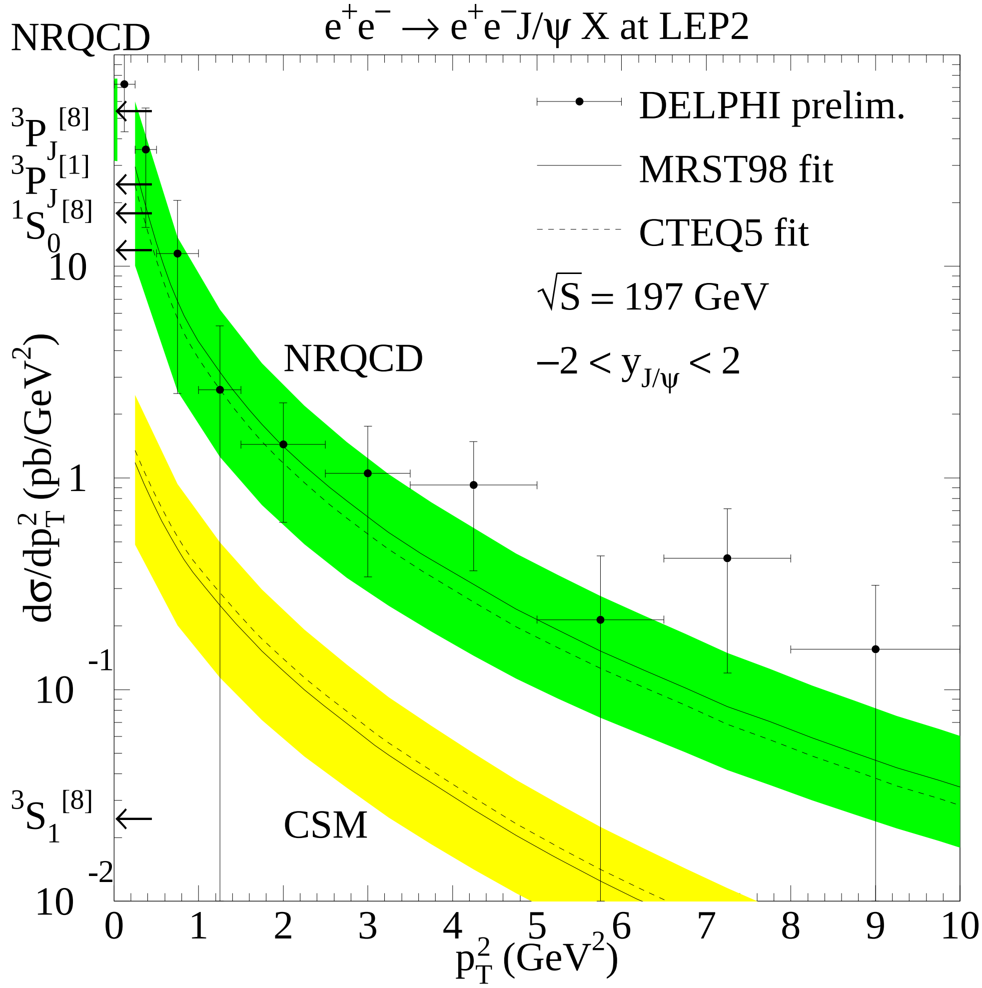
• • •

$$\delta L_{4-fermion} = \sum_i \frac{d_i}{M_Q^2}\left(\psi^{+}K_i\chi\right)\left(\chi^{+}K_i'\psi\right)$$

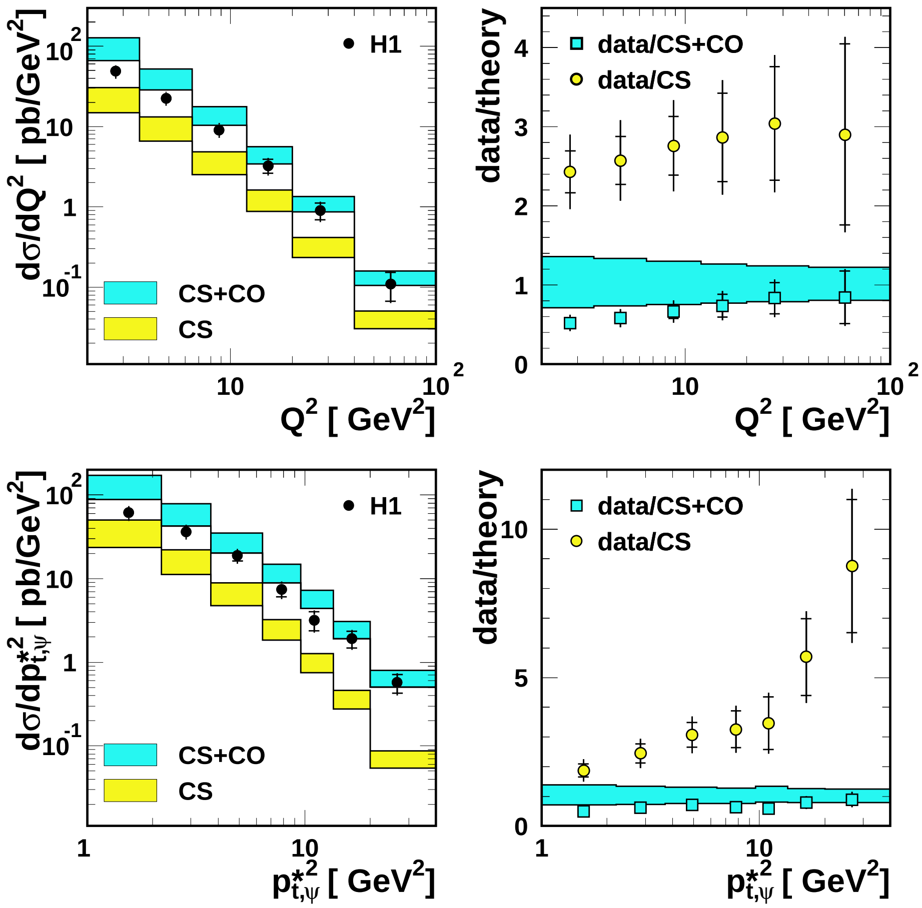
ψ	$\propto$	$(M_Q v)^{\frac{3}{2}}$	χ	$\propto$	$(M_Q v)^{\frac{3}{2}}$
D_t	$\propto$	$M_Q v^2$	$\vec{D}$	$\propto$	$M_Q v$
$g\,\vec{E}$	$\propto$	$M_Q^2 v^3$	$g\,\vec{B}$	$\propto$	$M_Q^2 v^4$
$g\,\phi$	$\propto$	$M_Q v^2$	$g\,\vec{A}$	$\propto$	$M_Q v^3$



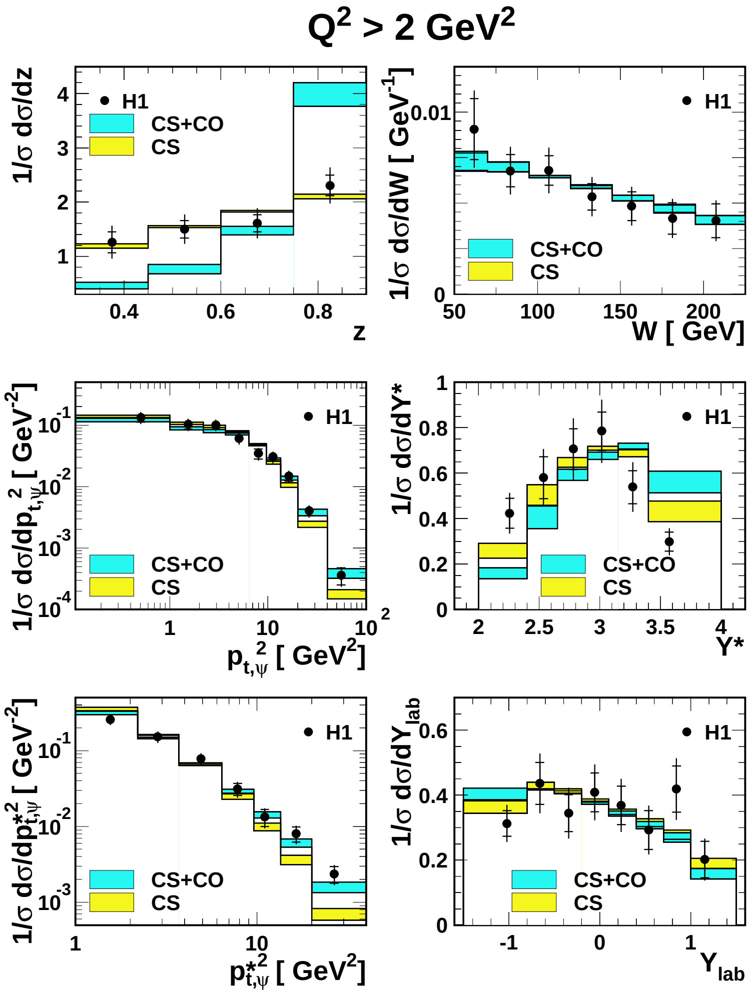
NR QCD for J/Ψ



- **Klasen, Kniehl, Mihaila & Steinhauser (2002)**



- Kniehl & Zwirner (2002)



- Kniehl & Zwirner (2002)

Two problems:

- Unrealistic values for $|\Psi(0)|^2$ (see red in the table);
- On qualitative level polarization should be transverse one in clear disagreement with the experiment;

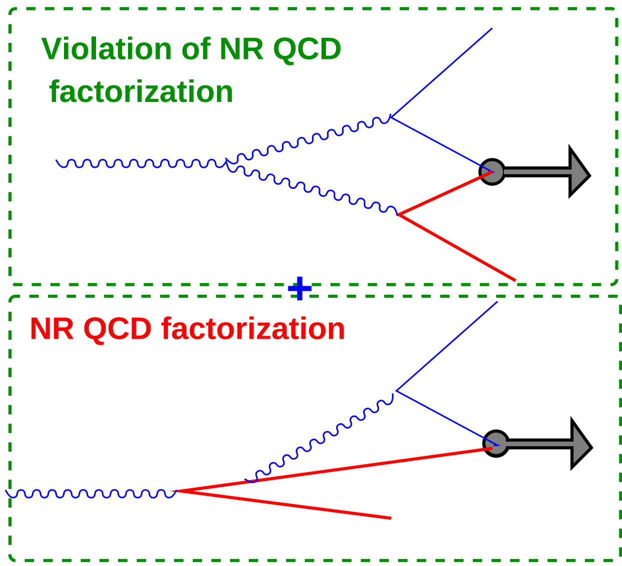
The uninegrated str. function approach gives a natural explanation for both difficulties

- See Baranov's talk here

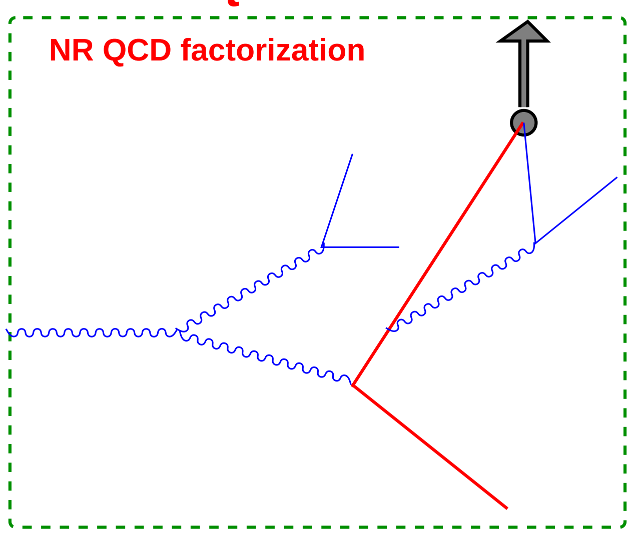
NR QCD factorization ? !

- **Likhoded's talk**

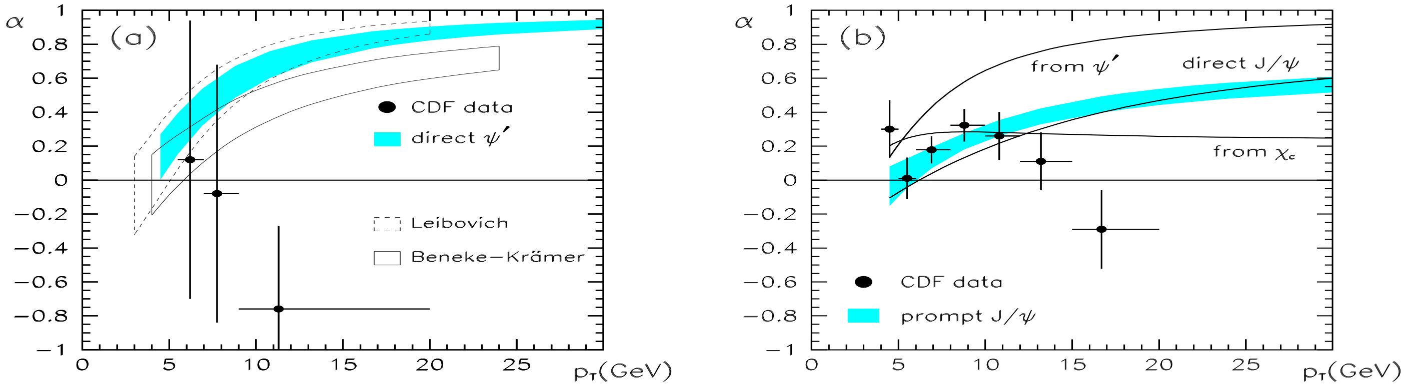
p_t < 10 GeV



p_t > 10 GeV

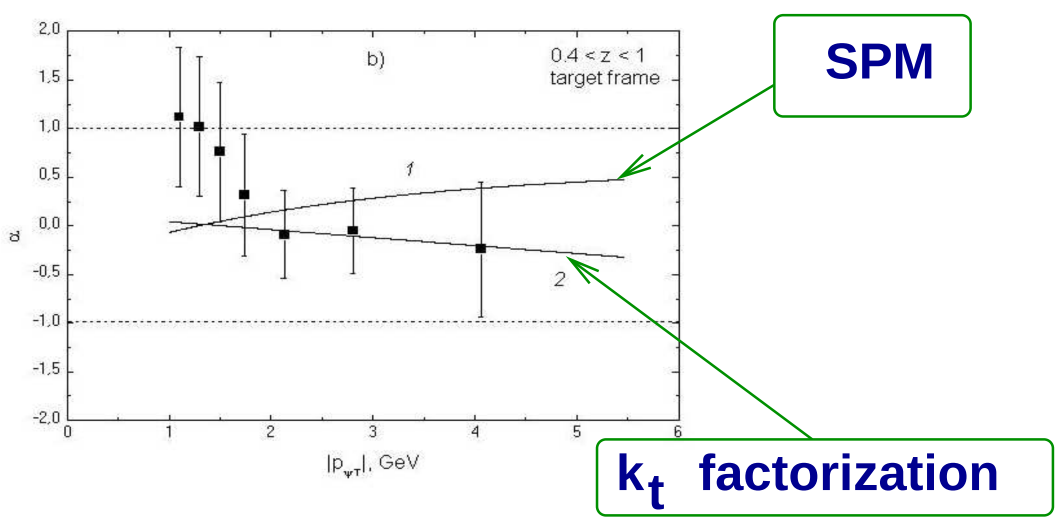


Polarization ? !



- **Braaten, Kniehl & Lee (2000)**

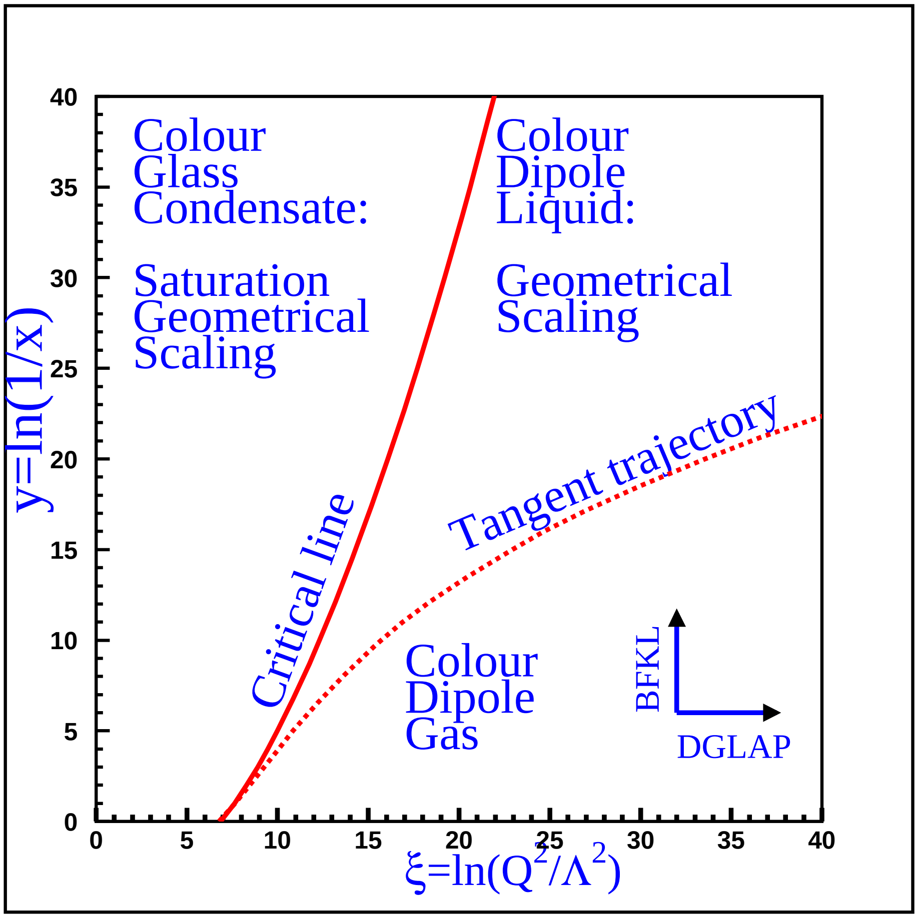
$\alpha = +1$	**transverse polarized Ψ/J**
$\alpha = 0$	**unpolarized d Ψ/J**
$\alpha = -1$	**longitudinal polarized Ψ/J**



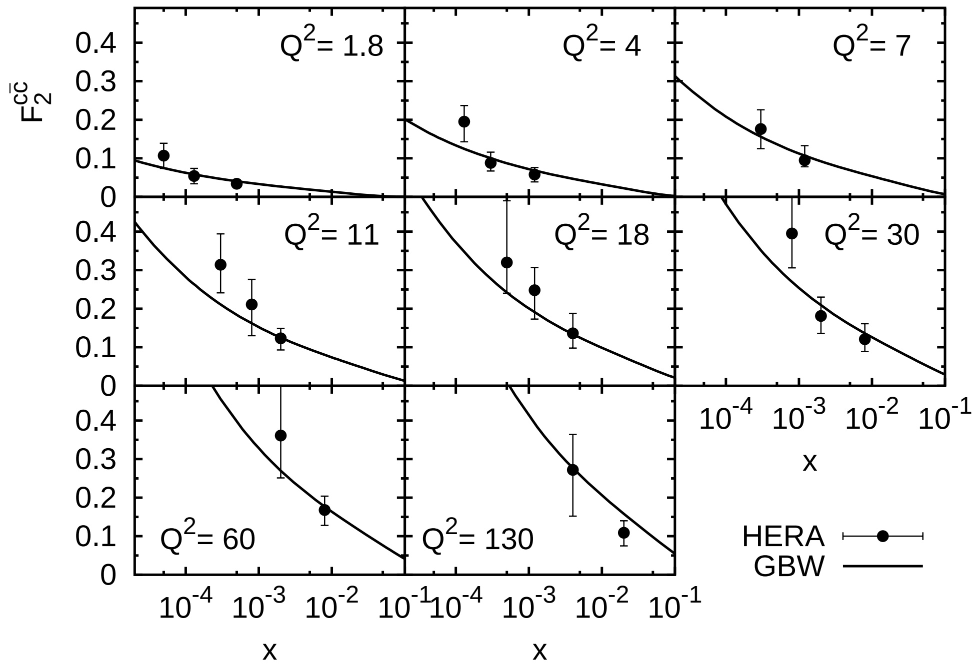
- **Lipatov & Zotov (2003)**

HQP and QCD saturation.

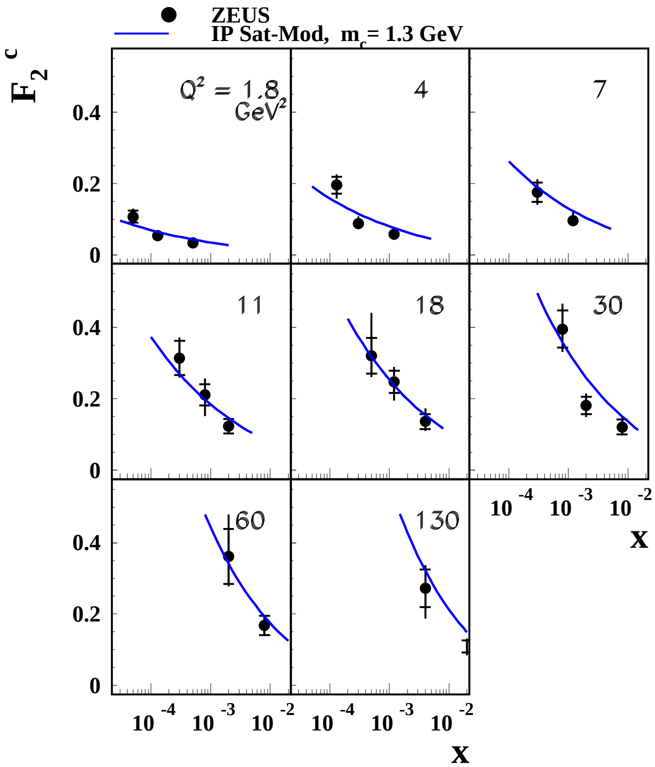
Phase map of QCD



Saturation models work



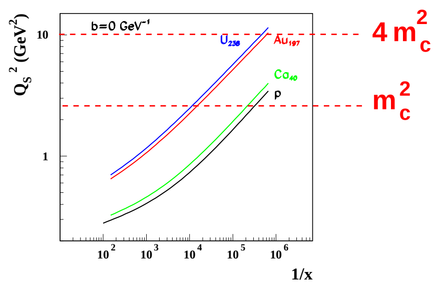
- **Motyka & Timneanu (2003)**



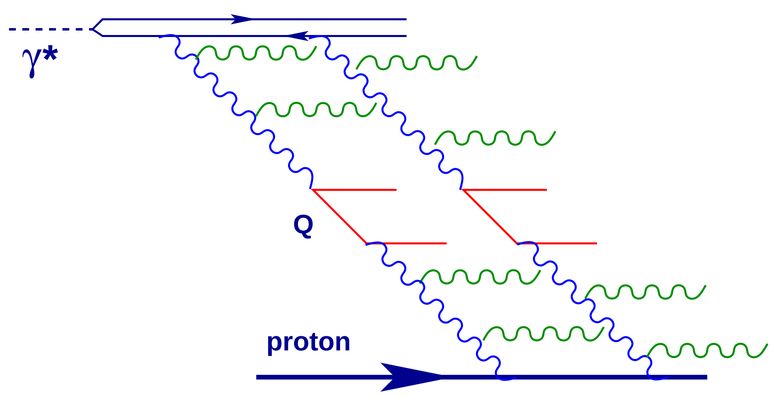
- **Kowalski & Teaney (2003)**

However the real test of QCD saturation is still ahead

- p_t -distribution of $Q\bar{Q}$ pair (correlations);



- Production of two $Q\bar{Q}$ pairs with the same rapidities;



- Inclusive production of $Q\bar{Q}$ pair with measuring the acompaning particles;

- HQP in ion-ion collisions ;

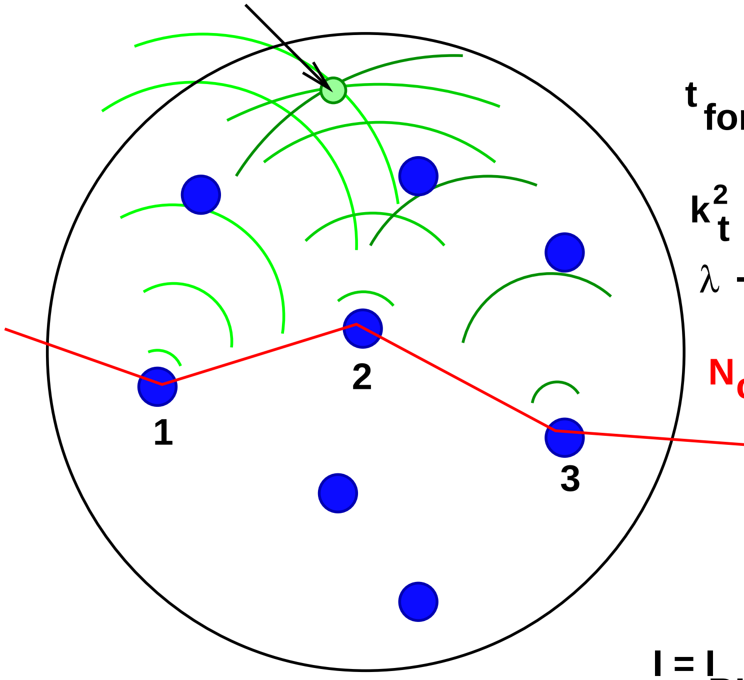
- Diffractive HQP;

HQP in ion-ion collisions.

Landau - Pomeranchuk - Migdal effect

- Baier, Dokshitzer, Mueller, Peigne, Schiff & Zakharov (1995 -)

$$I = | A_1 + A_2 + A_3 |^2 = | A_1 |^2 + | A_2 |^2 + | A_3 |^2 = I_{BH}$$



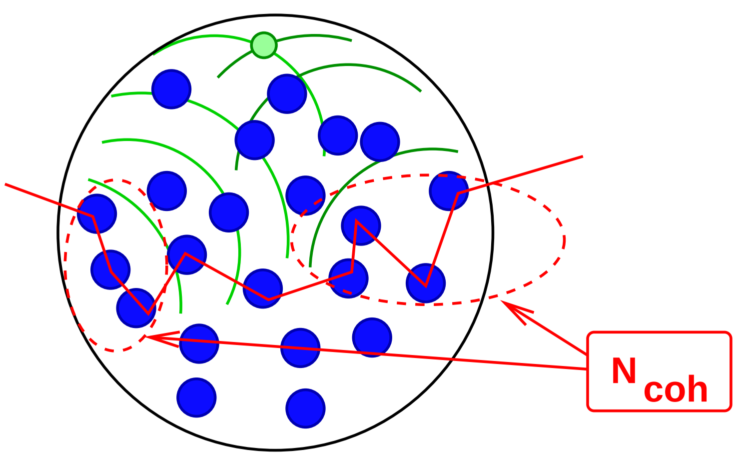
$$t_{form} = \frac{\omega}{k_t^2}$$

$$k_t^2 = \mu^2 \frac{t_{form}}{\lambda}$$

λ − mean free path

$$N_{coh} = \frac{t_{form}}{\lambda} = \sqrt{\frac{\omega}{\mu^2 \lambda}}$$

$$I = I_{BH} \cdot \frac{1}{N_{coh}} = \frac{\alpha_s C}{\pi \omega \lambda} \sqrt{\frac{\mu^2 \lambda}{\omega}}$$



- $$\frac{dW}{d\omega\, dz} = \left(\frac{dW}{d\omega\, dz}\right)^{BH} \cdot \frac{1}{N_{coh}} = \frac{\alpha_S C_R}{\pi\ \omega} \sqrt{\frac{\hat{q}}{\omega}}$$

  - $\hat{q}$ is transport coefficient: $\hat{q} \equiv \rho \int \frac{d\sigma}{dq^2} q^2\, d\, q^2$

- $\hat{q} \simeq \frac{4\pi^2 N_C}{N_C^{@} - 1} \rho\, x G(x, Q^2) \approx Q_s^2 / L$

- Taking $Q_s^2 = 2GeV^2$, $L = (4/3) R_A$ we get $\hat{q}_{cold} \approx 0.08\, GeV^3$

- For 'hot' nuclear matter we expect $\hat{q}_{hot} \approx (10 \div 20) \hat{q}_{cold}$

Inclusive energy distribution:

$\frac{dW}{d\omega} \simeq \frac{\alpha_S C_R}{\pi\ \omega} \cdot \sqrt{\frac{\omega_1}{\omega}}$ with $\omega_1 = Q_s^2\, L$.

Typical parameters of medium induced radiation:

- **Energy:** ω_1 ;

- t_{form} : $t_{form} = L \cdot \sqrt{\frac{\omega_1}{\omega}} > L$ for $\omega > \omega_1$;

- k_t^2: $k_t^2 \simeq \sqrt{\hat{q}\omega}$;

- **Angle θ:** $\theta = \frac{k_t}{\omega} \sim \left(\frac{\hat{q}}{\omega^3}\right)^{\frac{1}{4}}$;

Radiation off HQ:dead cone and enhancement factor

- Dokshitzer & Kharzeev (2001)

- $$dP = \frac{\alpha_S C_F}{\pi} \frac{d\omega}{\omega} \frac{(k_t^2 dk_t^2}{(k_t^2 + \omega^2 \theta_0^2)^2} \qquad \theta_0 \equiv \frac{M_Q}{E}$$

- $$dP_{HQ} = dP_0 \left(1 + \frac{\theta_0^2}{\theta^2}\right)^2$$

- $$I(\omega) = \frac{\alpha_S C_F}{\pi} \sqrt{\frac{\omega_1}{\omega}} \frac{1}{\left(1 + (\frac{E_{HQ}}{E})^2 (\frac{\omega}{\omega_1})^{\frac{3}{2}}\right)^2}$$

with

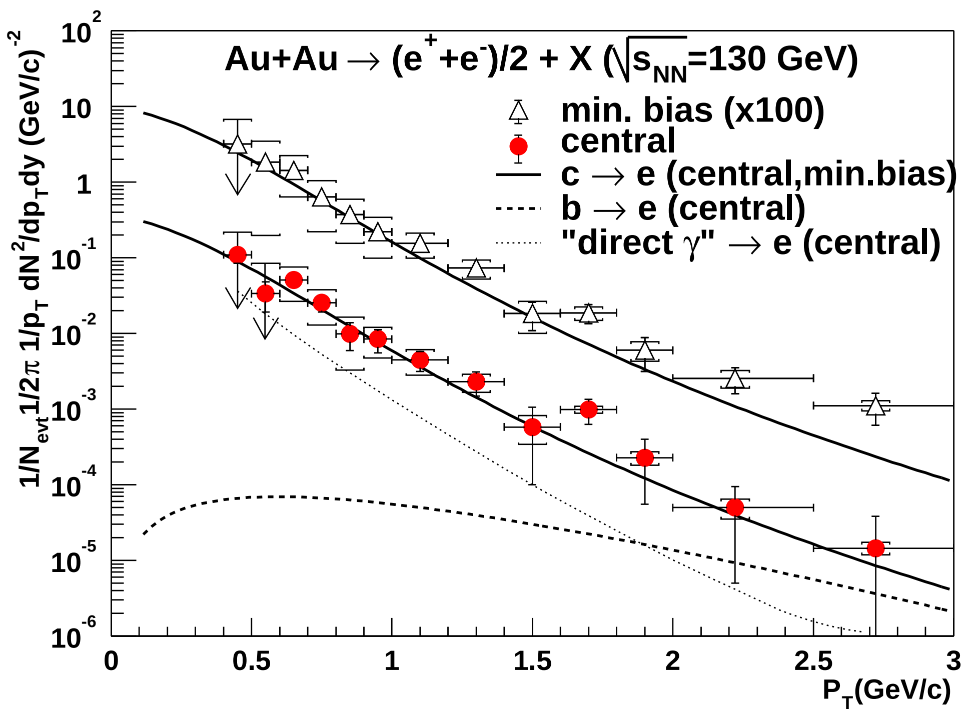
$$E_{HQ} \equiv M_Q \cdot Q_s \cdot L$$

Therefore, only if $E > E_{HQ}$ the quark mass become irrelevant.

The dead cone leads to an enhancement of the radiation off HQ :

- $$\frac{Q_{HQ}(p_t)}{Q_{LQ}(p_t)} \simeq exp\left(\frac{16\alpha_S C_F}{9\sqrt{3}} L \left(\frac{Q_s^2 M_Q^2 L}{M_Q^2 + p_t^2}\right)^{\frac{1}{3}}\right)$$

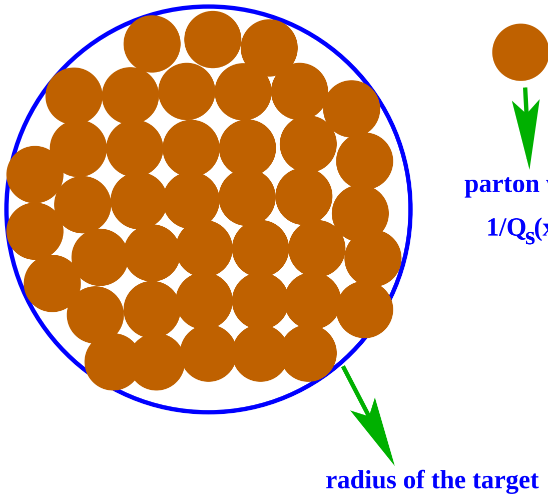
So far NO medium effect on HQP experimentally

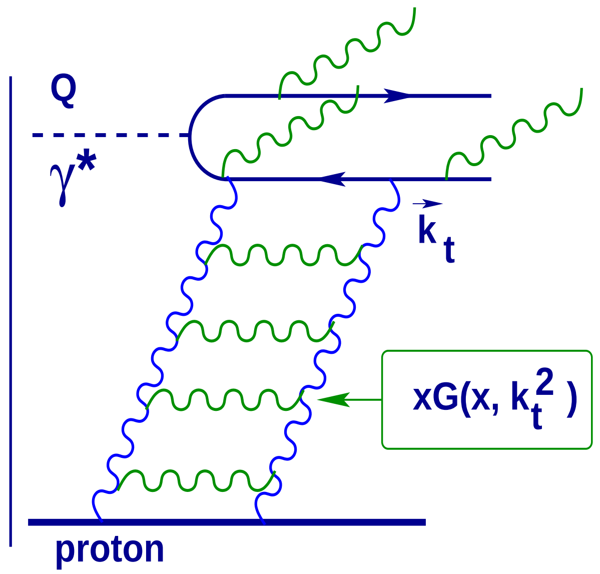


- PHENIX (2002)

Diffractive HQP

Inclusive Diffraction





- Q^2- **photon virtuality ;** $x_P = \frac{Q^2+M^2}{s}$;

$\beta = \frac{Q^2}{Q^2+M^2}$;

$$x_P \frac{d\sigma^T_{DD}(\gamma^* \rightarrow q+\bar{q})}{dx_P dt} \propto \int_{Q_0^2}^{\frac{M^2}{4}} \frac{dk_\perp^2}{k_\perp^2} \times \frac{\left(\alpha_S \, x_P \, G(x_P, \frac{k_\perp^2}{1-\beta})\right)^2}{k_\perp^2}$$

$$x_P \frac{d\sigma^L_{DD}(\gamma^* \rightarrow q+\bar{q})}{dx_P dt} \propto \int_{Q_0^2}^{\frac{M^2}{4}} \frac{dk_\perp^2}{Q^2} \times \frac{\left(\alpha_S \, x_P \, G(x_P, \frac{k_\perp^2}{1-\beta})\right)^2}{k_\perp^2}$$

In saturation region

$$xG \propto R^2 Q^2$$

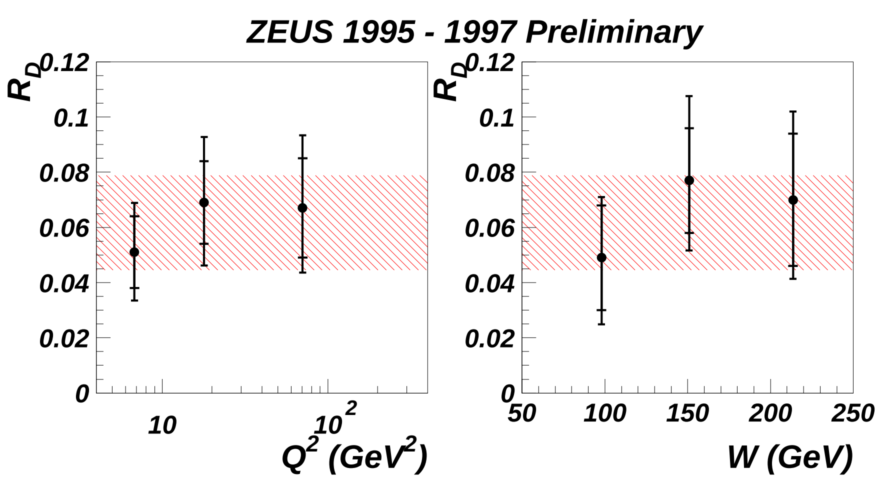
Therefore :

- $$x_P\,\sigma^L_{DD} \quad \propto \quad R^4\; Q^2_s(x_P)$$

- $$F_2 \propto \quad R^2\; Q^2_s(x)$$

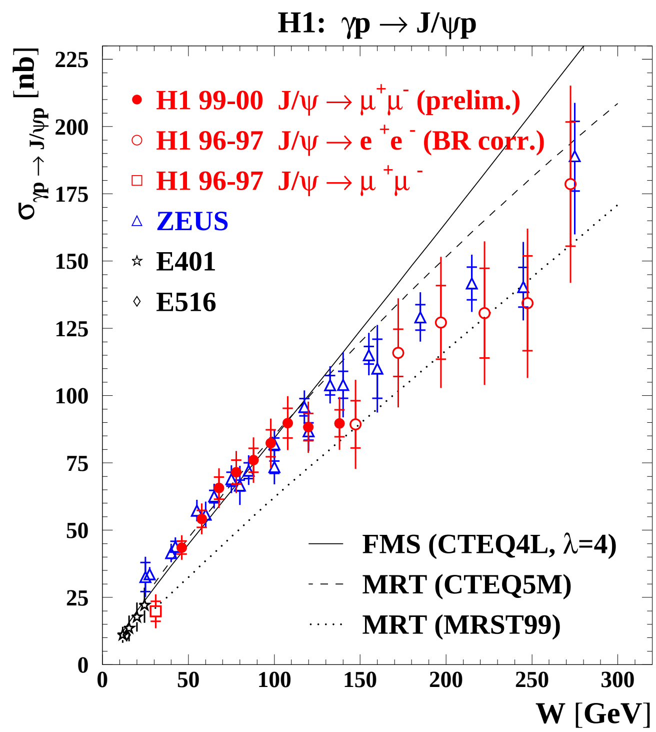
and

- $$\frac{F_2}{\sigma^T_{DD}} \quad = \quad Const W, Q^2)$$

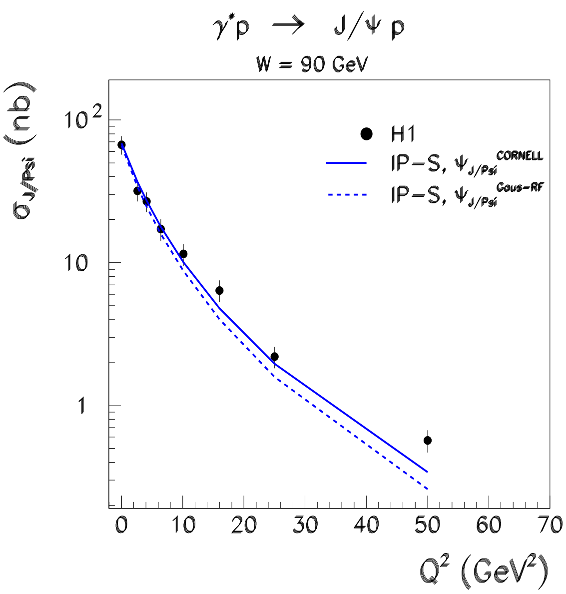


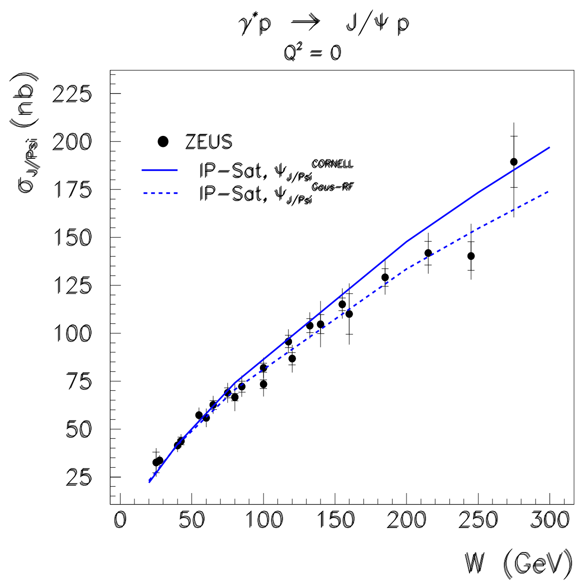
Diffractive J/Ψ production: typical 'hard' process ! ?

- $\sigma \propto W^{4\Lambda}$ with $\lambda > \Delta_{softP}$;



- **Saturation models work**

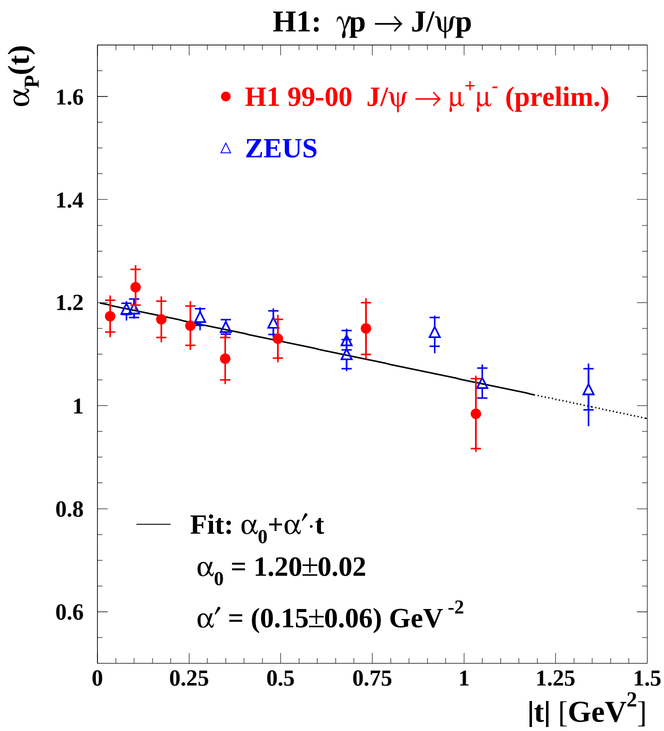




- **Kowalski & Teaney (2003)**

However

• Effractive shrinkage of the forward peak



Two explanations:

– Sum of 'soft' and 'hard' Pomeron:

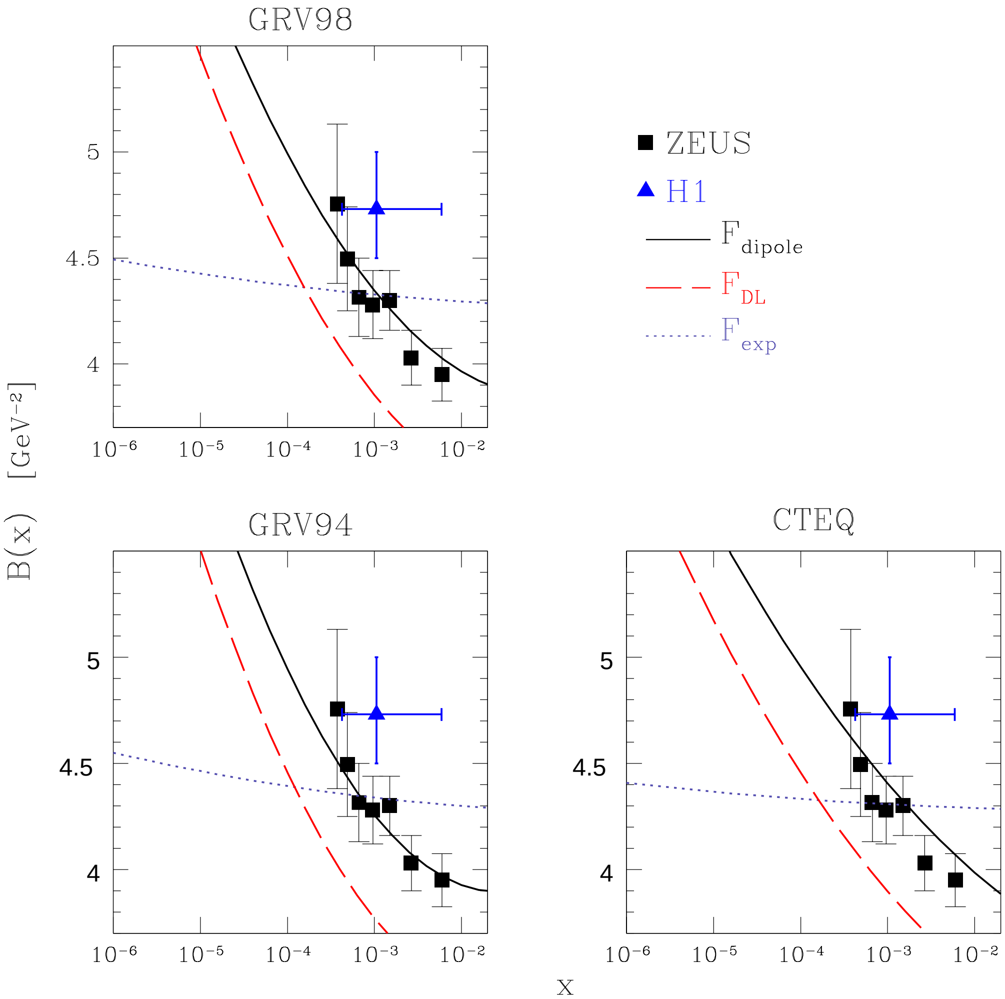
α'_{eff} decreases with W

– Saturation:

α'_{eff} increases with W

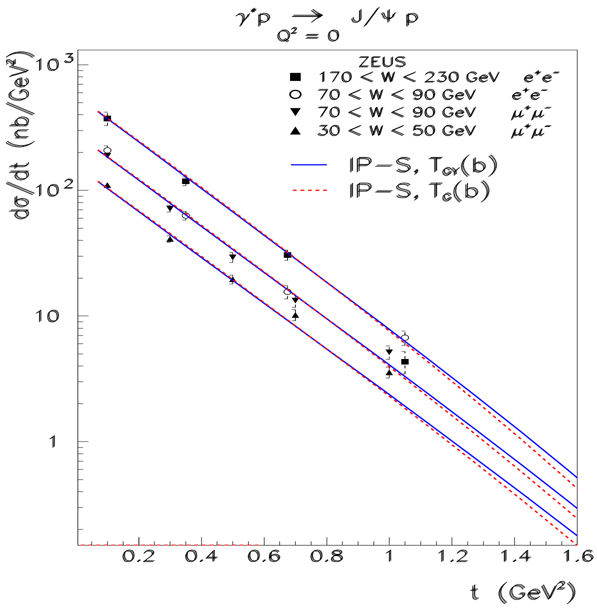
• Gotsman, Levin & Maor (1997)

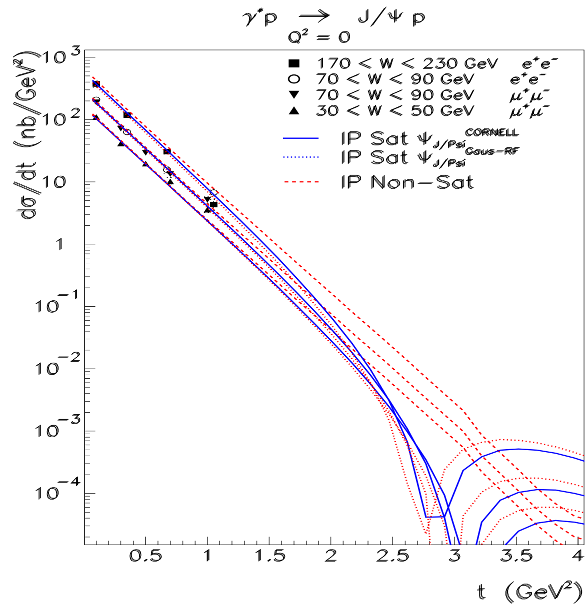
Only prediction is physics   Table $\Longrightarrow$



- **Gotsman, Levin, Maor & Naftali (2001)**

Diffraction picture in J/Ψ production





- Kowalski & Teaney (2003)

RESUME

- **Experimentalists are working hard and new data, better and more, are coming;**
- **Theorists have fresh ideas and methods of calculations;**
- **A lot of difficult and challenging pronblems are still ahead**

Therefore

We have

a bright future

which depends

on US

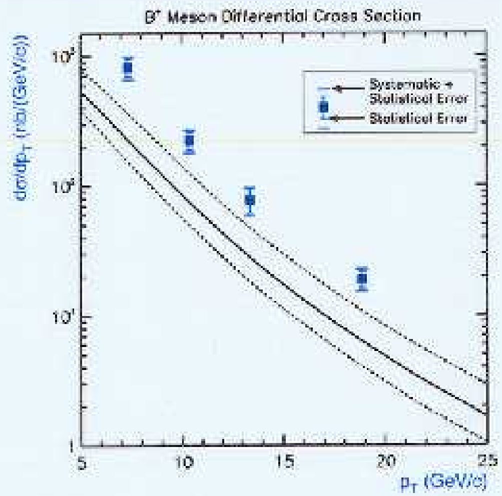
Heavy Hadron Production

Differential distributions

long-standing excess of b-quark transverse momentum

distributions in $p\bar{p}$, γp, $\gamma\gamma$

measured final state: B hadrons, e.g. CDF: $B^{\pm}$



Theoretical prediction:

$$\frac{\mathrm{d}\sigma^{B^{\pm}}}{\mathrm{d}p_T} = f_{a/p} \otimes f_{b/\bar{p}} \otimes \frac{\mathrm{d}\sigma^{ab\to b\bar{b}}}{\mathrm{d}p_T} \otimes D_{b\to B^{\pm}}$$

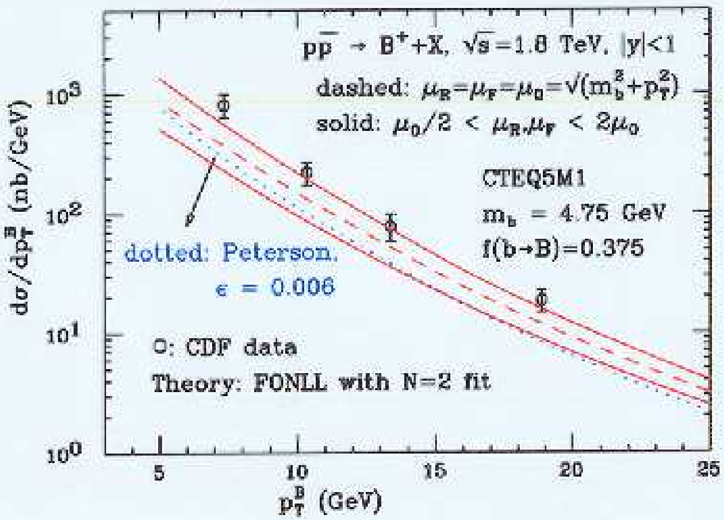
$f_{a/p}$: parton distribution function

$D_{b\to B^{\pm}}$: fragmentation function

Heavy Hadron Production

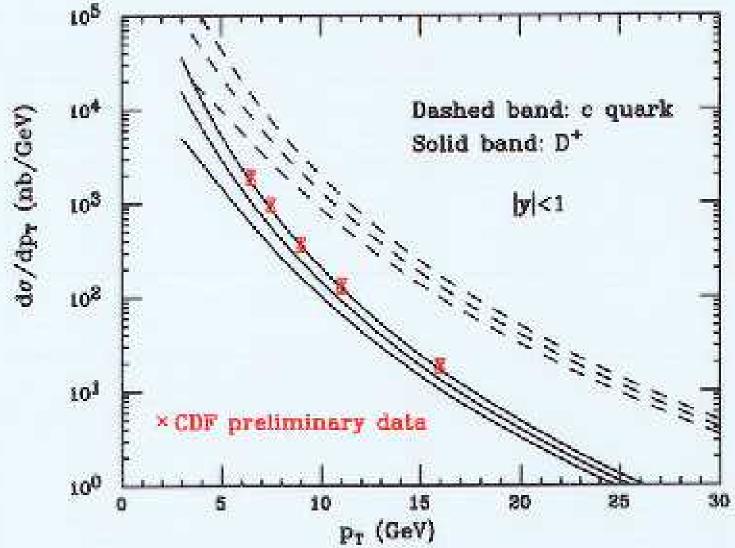
Resummation of $\ln(m_b^2/p_T^2)$ and $\ln(m_b^2/s)$

M. Cacciari, P. Nason



- must re-fit $D_{b\to B^\pm}$ from e^+e^- data
- done in moment space to expose information content relevant to $p\bar{p}$
- use of the resummed (FONLL) scheme enhances transverse momentum spectrum

recently extended to D hadrons:
considerable improvement between data and theory



$|\Psi(0)|^2$ for different states

- **NR QCD** (Braaten, Kniehl & Lee (2000))

DF	$\langle O_1^{J/\psi}(^3S_1)\rangle$	$\langle O_8^{J/\psi}(^3S_1)\rangle$	$M_{3.4}^{J/\psi}$	$\langle O_1^{\psi'}(^3S_1)\rangle$	$\langle O_8^{\psi'}(^3S_1)\rangle$	$M_{3.5}^{\psi'}$	$\langle O_1^{\chi c0}(^3P_0)\rangle$	$\langle O_8^{\chi c0}$
T98LO	1.3 ± 0.1	4.4 ± 0.7	8.7 ± 0.9	6.5 ± 0.6	4.2 ± 1.0	1.3 ± 0.5	8.9 ± 1.3	$2.3 \pm$
:Q5L	1.4 ± 0.1	3.9 ± 0.7	6.6 ± 0.7	6.7 ± 0.7	3.7 ± 0.9	0.78 ± 0.36	9.1 ± 1.3	$1.9 \pm$
nit	GeV^3	10^{-3}GeV^3	10^{-2}GeV^3	10^{-1}GeV^3	10^{-3}GeV^3	10^{-2}GeV^3	10^{-2}GeV^5	10^{-3}
nates	v^3	v^7	v^5	v^3	v^7	v^5	v^5	v^5

- **k_t factorization + NR QCD** (Baranov (2002))

	$\langle O_1^{J/\psi}(^3S_1)\rangle$	$\langle O_8^{\chi c0}(^1S_0)\rangle$	$\langle O_8^{\psi'}(^3S_1)\rangle$	$\langle O_8^{\chi c0}(^3S_1)\rangle$
value	0.8	1.6	0	1.4
unit	GeV^3	10^{-3}GeV^3	10^{-3}GeV^3	10^{-3}GeV^3
estimates	v^3	v^5	v^7	v^7

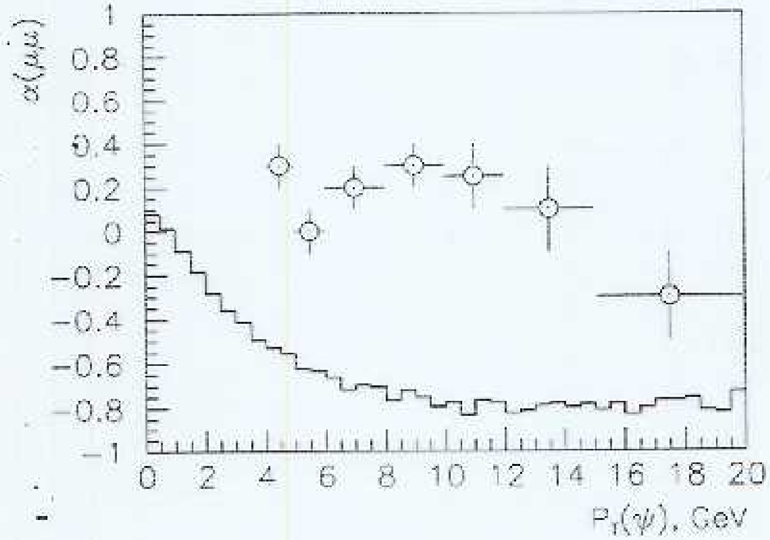
J/ψ AND ψ′ SPIN ALIGNEMENT AT TEVATRON CONDITIONS

(Baranov)

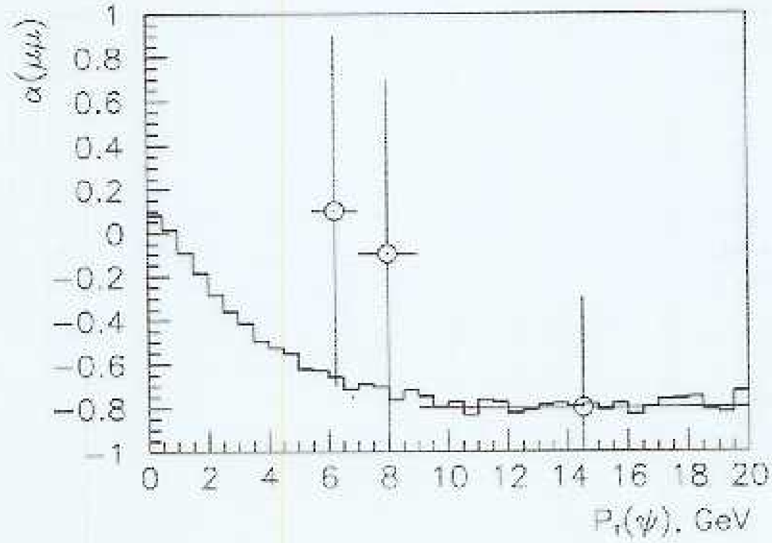
——— theoretical predictions (k_T-factorization)

⌖ experimental data (CDF)

J/ψ

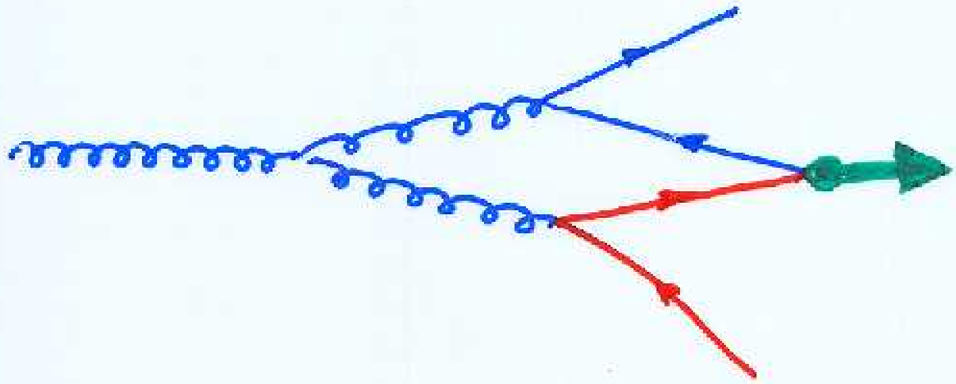


ψ′

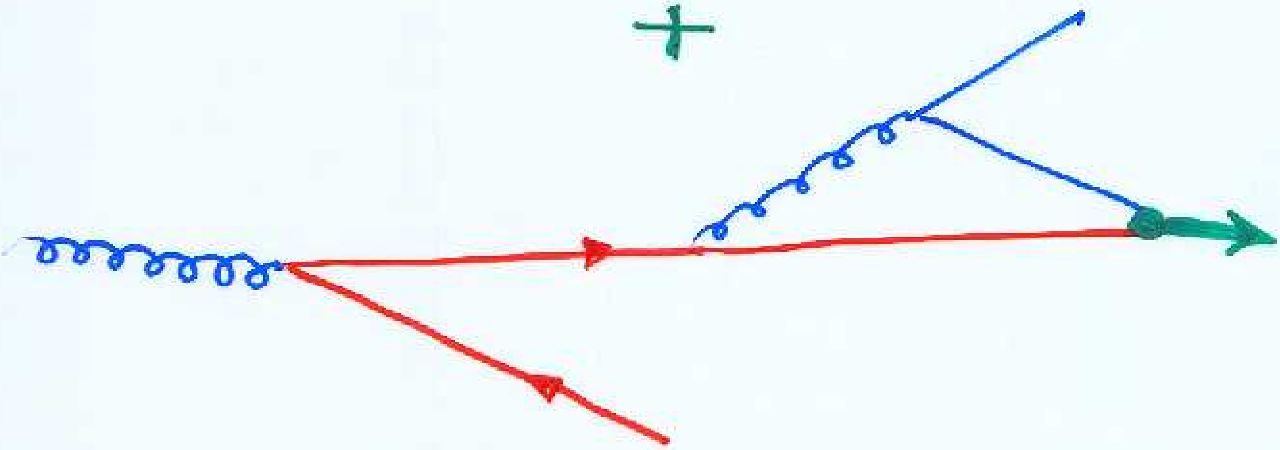


Likhoded

$p_t \lesssim 10$ GeV



+



$p_t > 10$ GeV

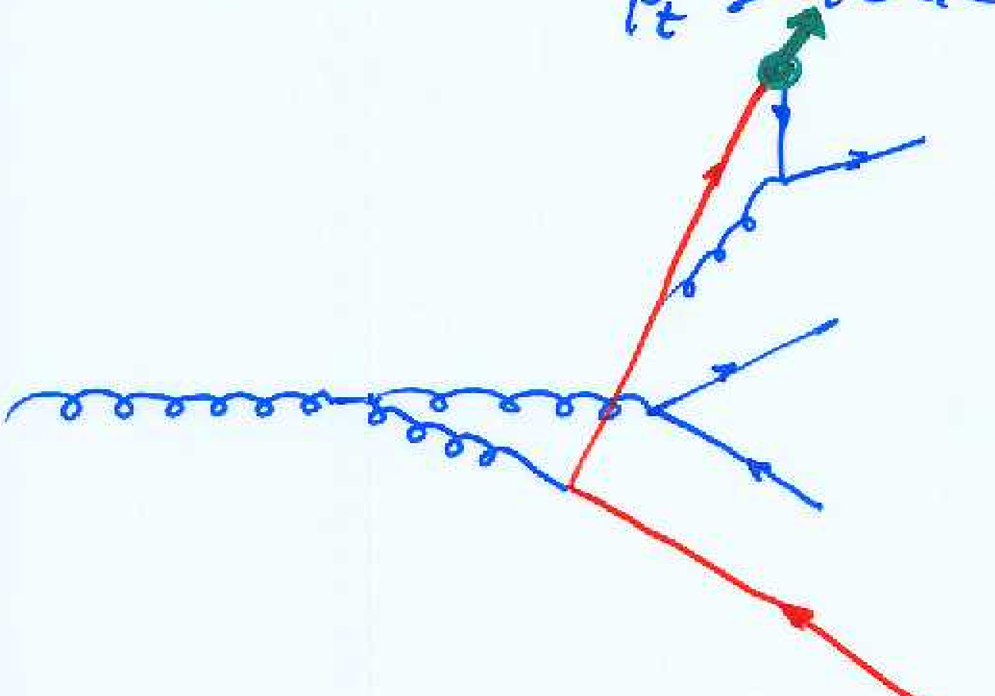
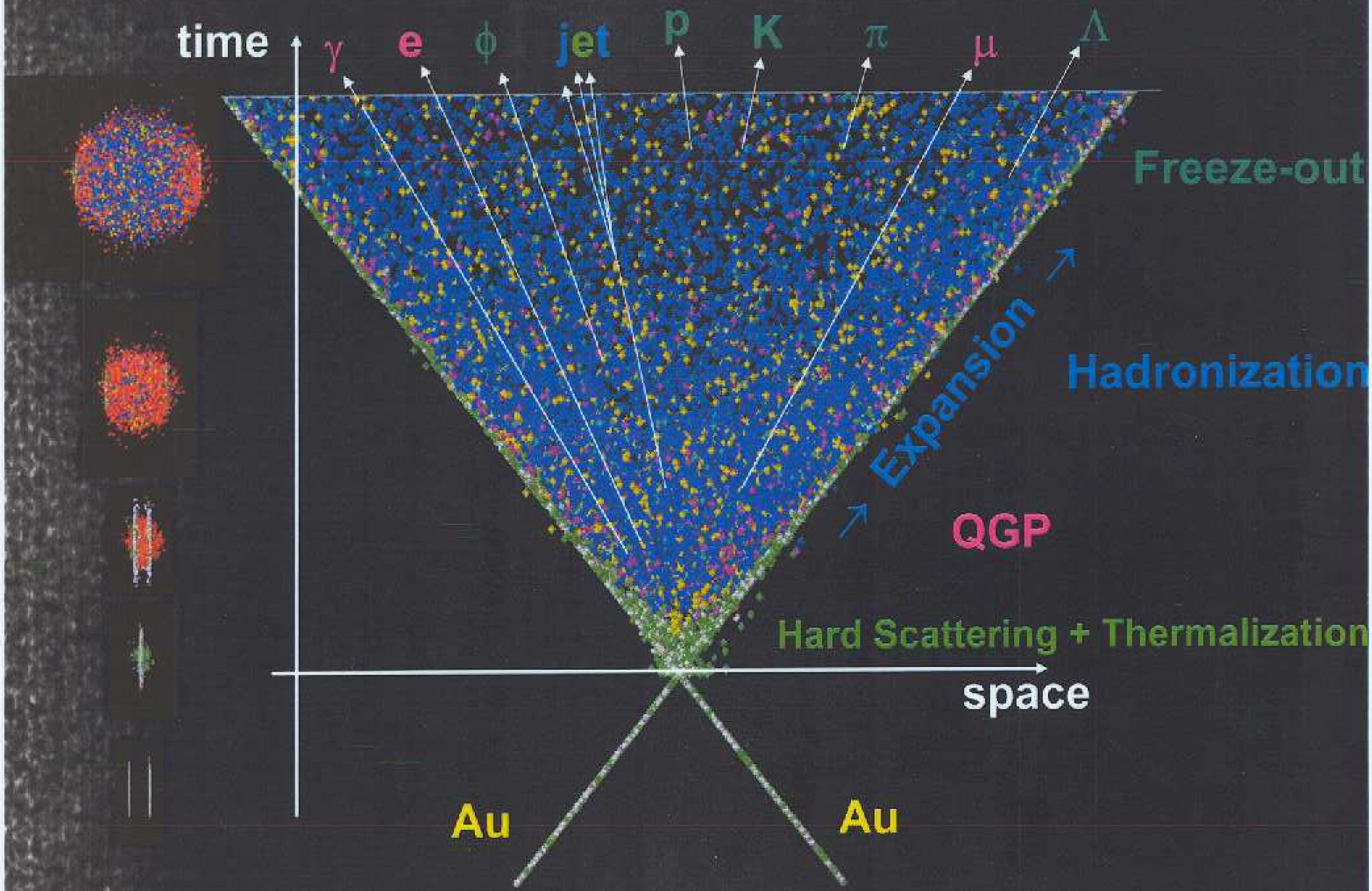


Table 1:

Parameters of the effective "hard" Pomeron trajectory $\alpha_P^{eff}(t) = 1 + \epsilon + \alpha'_{eff}\,t$ in the GRV parametrization for the gluon structure function(Q^2 in GeV^2, α'_{eff},R_i^2 in GeV^{-2}).

	J/Ψ						ρ					
Q^2	without SC		$R_1^2 = 6$, $R_2^2 = 2$		$R_1^2 = 10$, $R_2^2 = 3$		without SC		$R_1^2 = 6$, $R_2^2 = 2$		$R_1^2 = 10$,$R_2^2 = 3$	
	ϵ	α'_{eff}	ϵ	α'_{eff}	ϵ	α'_{eff}	ϵ	α'_{eff}	ϵ	α'_{eff}	ϵ	α'_{eff}
0	0.32	0	0.21	0.076	0.23	0.135	N/A	N/A	N/A	N/A	N/A	N/A
5	0.38	0	0.27	0.06	0.29	0.114	0.2	0	0.15	0.08	0.17	0.11
10	0.40	0	0.31	0.06	0.33	0.103	0.32	0	0.20	0.07	0.22	0.11
20	0.45	0	0.37	0.06	0.38	0.08	0.38	0	0.27	0.06	0.28	0.07
50	0.52	0	0.46	0.045	0.48	0.054	0.45	0	0.36	0.05	0.38	0.04

Space-time Evolution of Collisions



David Hardtke - LBNL