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Non-perturbative particle production in strong non-Abelian fields

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Non-perturbative particle production in time-dependent strong non-Abelian fields

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Phys. Rev. D71 (2005) 094010.
Phys. Rev. D78 (2008) 054004.
J. Phys. G36 (2009) 064068.
arXiv: 0909.2323 [hep-th]

Gribov – 80 Workshop, ICTP
27 May 2010, Trieste, Italy

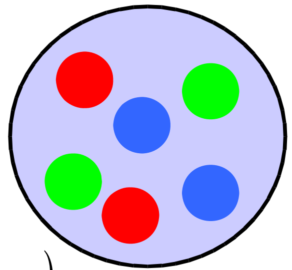
Particle production mechanisms in high energy HI collisions:

I. Dilute parton gas limit as initial condition + parton cascade:

PDF(p,n) +pQCD + Glauber + [Shad; Multisc; Quench; Fluct; ...]

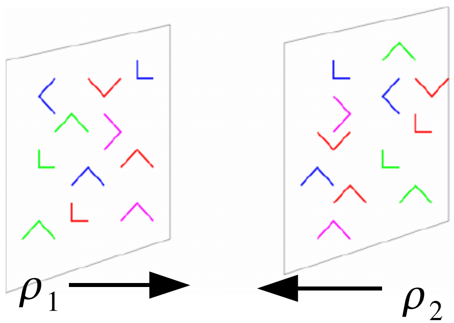
$$E_\pi \frac{d\sigma^{pp}}{d^3 p_\pi} = \int dx_1 \int dx_2 \int dz_c\, f_{a/p}(x_a, Q^2)\, f_{b/p}(x_b, Q^2) \frac{d\sigma}{dt} \frac{D_c^\pi(z_c)}{\pi z_c^2}$$

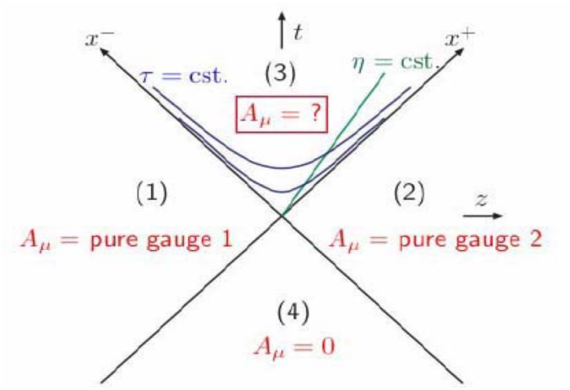
$$E_\pi \frac{d\sigma^{AB}}{d^3 p_\pi} = \int d^2 b\, d^2 r\;\; t_A(\vec{r})\, t_B(|\vec{b}-\vec{r}|)\;\; E_\pi \frac{d\sigma^{pp}}{d^3 p_\pi} \otimes S(\ldots) \otimes M(\ldots) \otimes Q(\ldots) \otimes F(\ldots)$$

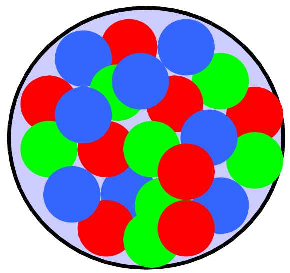


Dilute gas

II. Dense gluon matter limit as initial condition + hydro:







CGC initial condition:

CGC: high density gluons

$$J^\mu = \delta^{\mu+}\delta(x^-)\rho_1(\mathbf{x}_T) + \delta^{\mu-}\delta(x^+)\rho_2(\mathbf{x}_T)$$

where $-D_i \alpha^i_{(m)} = \rho_{(m)}(\mathbf{x}_\perp)$. ***and*** α_1, α_2 ***gluon fields of nuclei***

Successful applications of I and II:

I. pQCD model:

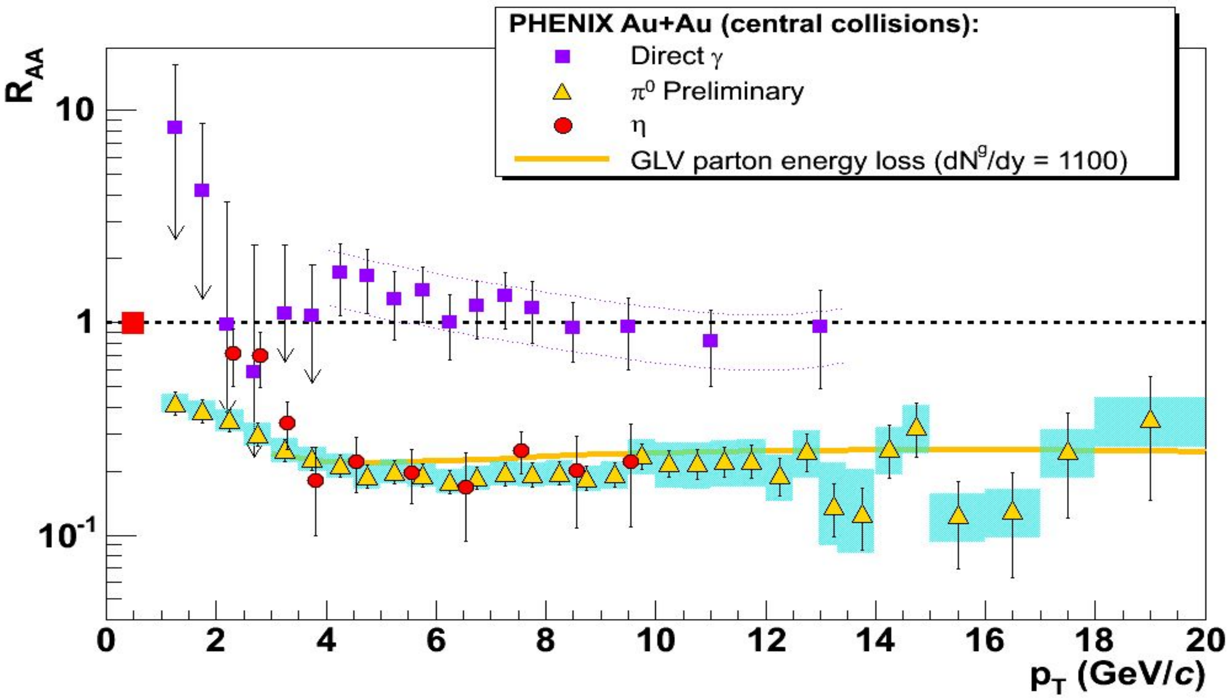
--- hard probes

--- high-p_T physics

--- jets

--- h-h correlations

--- ...



II. CGC model:

--- soft physics

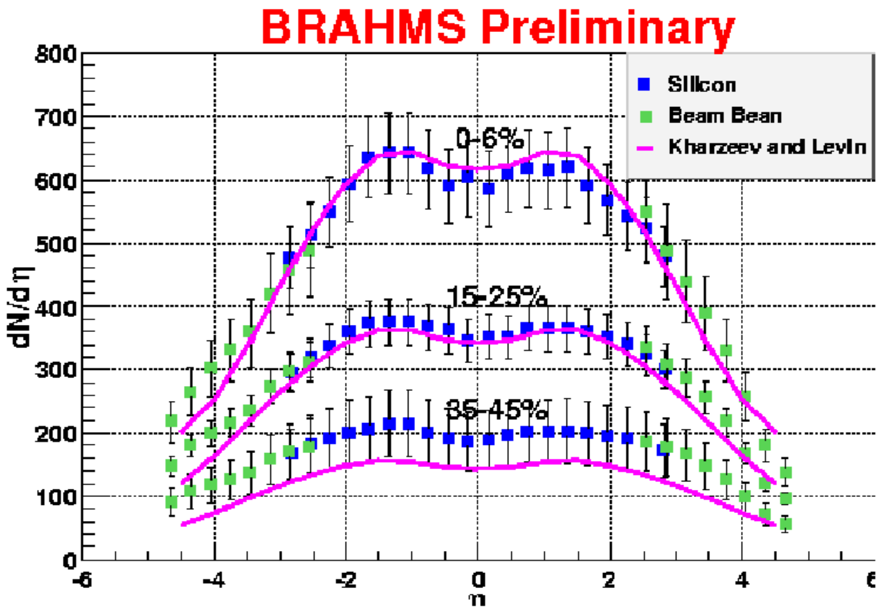
--- multiplicities

--- centrality dependence

--- E_T production

--- rapidity distributions

--- ...



Problems:

I. pQCD model (Feynman graphs):

--- LO, NLO, ... ?

--- factorization (k_T)

--- resummations

--- soft physics

--- heavy quark quenching

--- ...

II. CGC model (asymptotic):

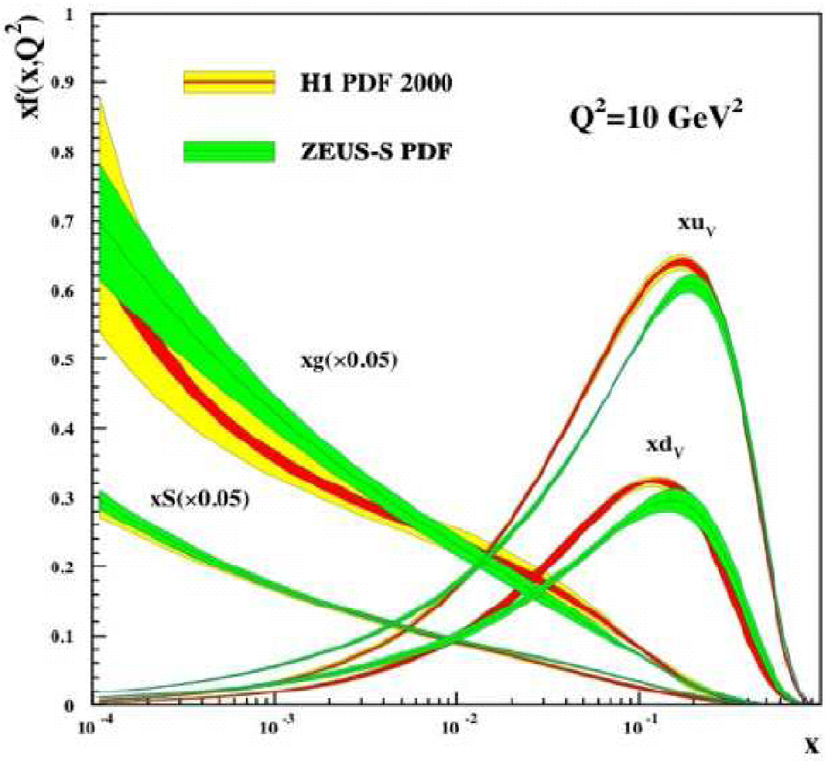
--- hard probes

--- jet physics

--- correlations

--- ...

Connection between I and II:



Large-x: valence partons

random color charge, $\rho^a(x)$

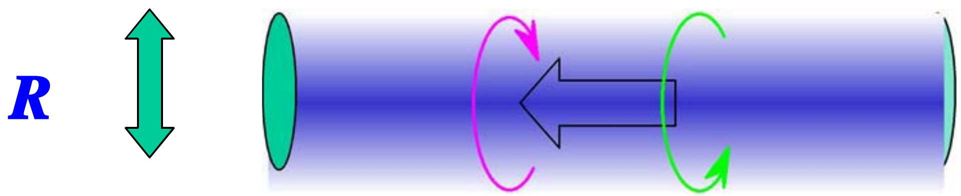
Small-x: radiation field,

created by $\rho^a(x)$

A further model for particle production:

III. Non-perturbative, non-asymptotic color transport:
"confined flux tube formation and breaking"

- --- *phenomenological approximations are known (string, rope)*
- --- *phenomenology is applied successfully in string-based codes*
- --- *FRITIOF, PYTHIA, HIJING are using strings*
- --- *URQMD, HIJING-BB is using ropes (melted strings)*
- --- *good agreement with data at different energies*
- --- ...



- --- *formal QCD-based equations are known (Heinz, Mrowczynski)*
- --- *YM-field evolution in 3+1 dim, collision (Poschl, Müller)*
- --- *lattice-QCD calculations have been started (Krasnitz, Lappi)*
- --- ...

A further model for particle production:

III. Non-perturbative, non-asymptotic color transport: "pair-creation in strong fields"

--- strong (Abelian) static E field: Schwinger mechanism

probability of pair-creation:

$$P(p_T)\,d^2 p_T = -\frac{eE}{4\pi^3}\ln(1-\exp[-\pi\frac{m^2+p_T^2}{eE}])\,d^2 p_T$$

integrated probability at mass m:

$$P_m = \frac{(eE)^2}{4\pi^3}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp[-\pi\frac{n m^2}{eE}]$$

ratio of production rates (e.g. strange to light)

$$\gamma_s = \frac{P(s\bar{s})}{P(q\bar{q})} = \exp[-\pi\frac{m_s^2 - m_q^2}{eE}]$$

$$eE = 0.9\,GeV/fm$$

--- strong time dependent SU(N) color fields:

Kinetic Equation for the color Wigner function

A.V. Prozokevich, S.A. Smolyansky, S.V. Ilyin, hep-ph/0301169.

Kinetic equation for fermion pair production:

Wigner function: $W(k_{1,}k_{2,}k_3)$

Color decomposition: $W = W^s + W^a t^a, \quad where \quad a = 1, 2, \ldots, N_c^2 - 1$

Spinor decomposition: $W^{s;a} = a^{s;a} + b_\mu^{s;a}\gamma^\mu + c_{\mu\nu}^{s;a}\sigma^{\mu\nu} + d_\mu^{s;a}\gamma^\mu\gamma^5 + i e^{s;a}\gamma^5$

Color vector field (longit.): $A_\mu^a = (0, -\vec{A}) = (0, 0, 0, A_3^a)$

Kinetic equation for Wigner function:

$$\partial_t W + \frac{g}{8}\frac{\partial}{\partial k_i}\left(4\{W, F_{0,i}\} + 2\{F_{i\nu}, [W, \gamma^0\gamma^\nu]\} - [F_{i\nu}, \{W, \gamma^0\gamma^\nu\}]\right) =$$
$$= i k_i\{\gamma^0\gamma^i, W\} - i m[\gamma^0, W] + ig[A_i, [\gamma^0\gamma^i, W]].$$

for details see V.V. Skokov, PL: PRD71 (2005) 094010 for U(1)
PRD78 (2008) 054004 for SU(2)
in preparation for SU(3)

Distribution function for fermions with mass m:

$$f_f(\vec{k}, t) = \frac{m a^s(\vec{k}, t) + \vec{k}\vec{b}^s(\vec{k}, t)}{\omega(\vec{k})} + \frac{1}{2}$$

Time dependent external field, E(t) and neglected mass, m=0:

A, Pulse field (dotted):

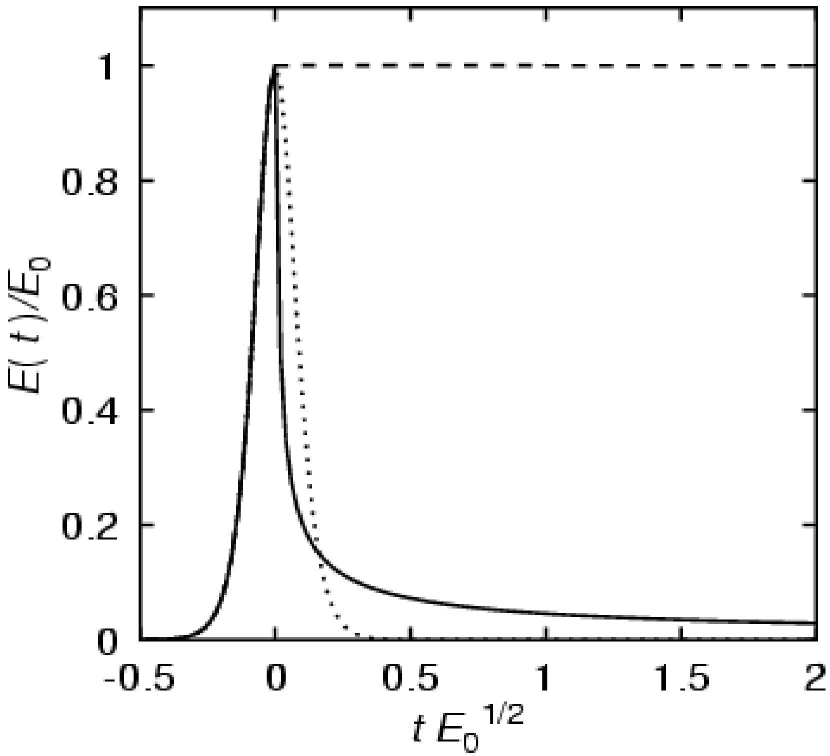
$$E_{pulse}(t) = E_0\left[1 - \tanh^2(t/\delta)\right]$$

B, Constant field (dashed):

$$E_{const}(t) = E_{pulse}(t) \quad at \quad t < 0$$
$$E_{const}(t) = E_0 \quad at \quad t > 0$$

C, Scaled field (solid):

$$E_{scaled}(t) = E_{pulse}(t) \quad at \quad t < 0$$
$$E_{scaled}(t) = \frac{E_0}{(1 + t/t_0)^{\kappa}} \quad at \quad t < 0$$

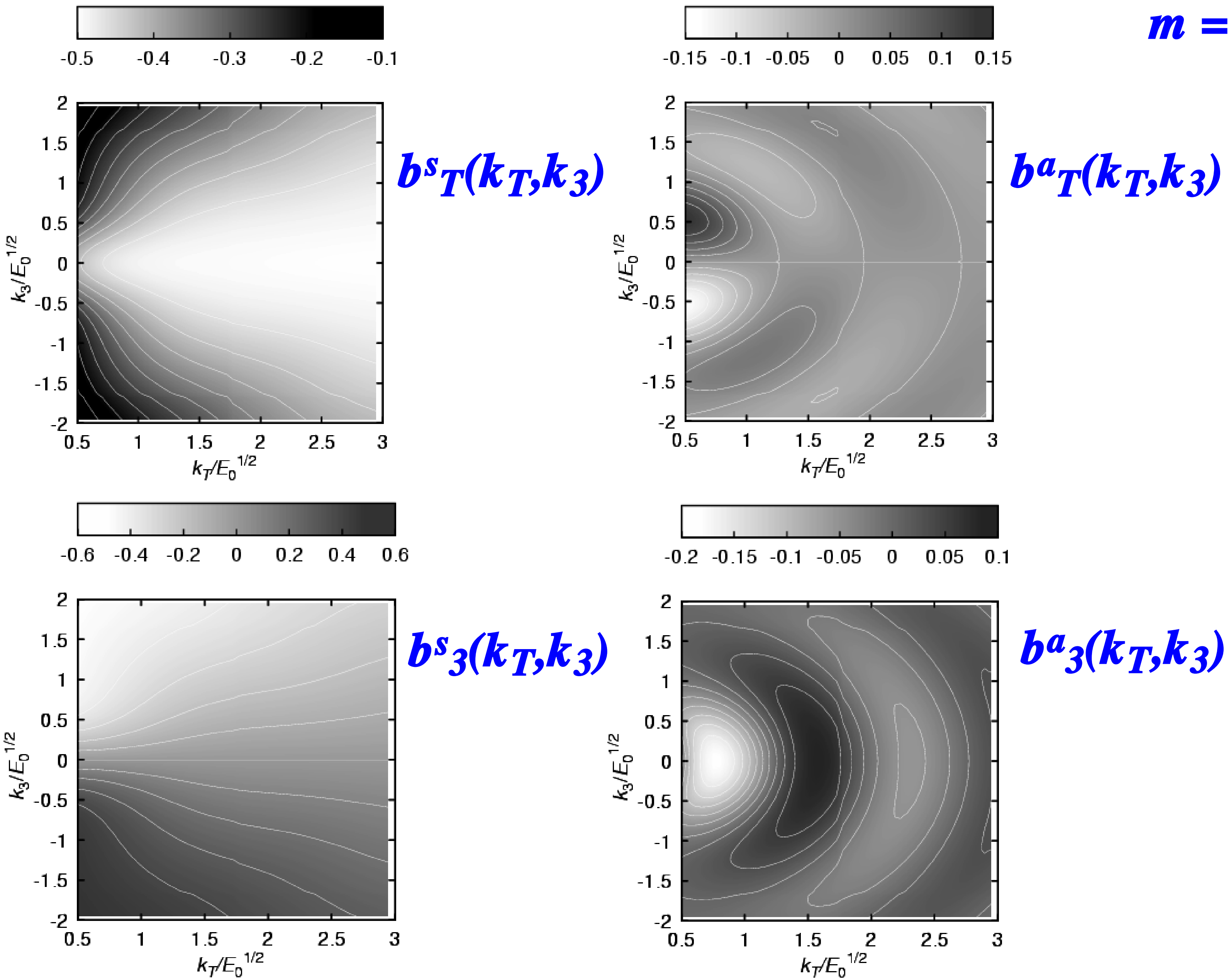


$$\delta = 0.1 / E_0^{1/2} \quad at\ RHIC\ energy$$

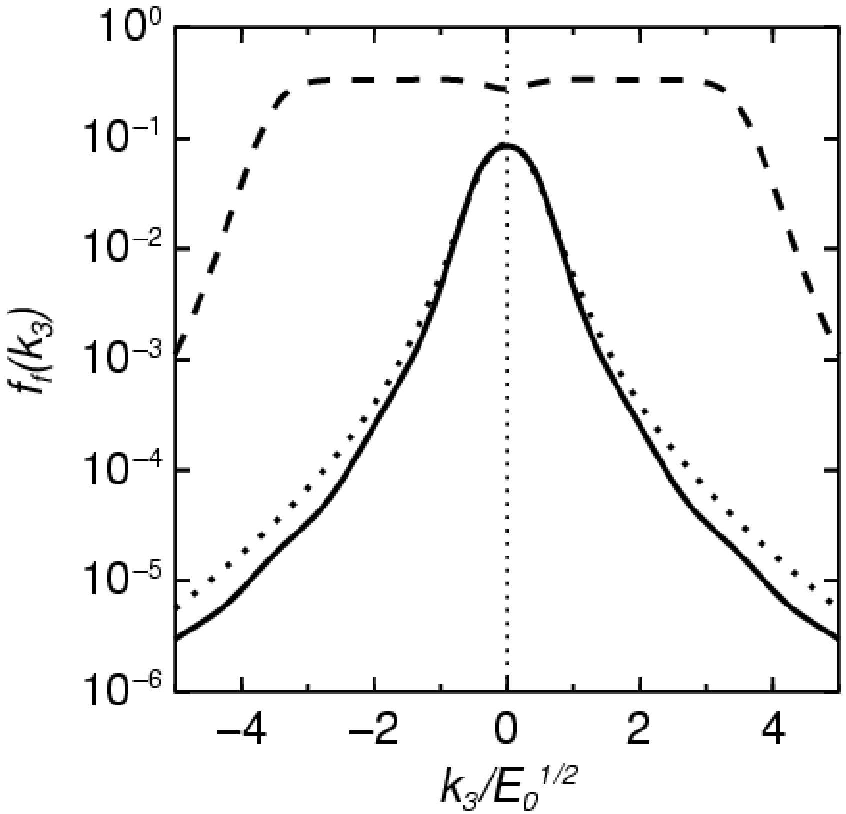
$$\kappa = 2/3 \quad for\ scaled\ Bjorken\ expans.$$
$$with \quad t_0 = 0.01 / E_0^{1/2}$$

Numerical results (b^i) for the Bjorken expansion at $t = 2/\sqrt{E_0}$ in SU(2):

$m = 0$

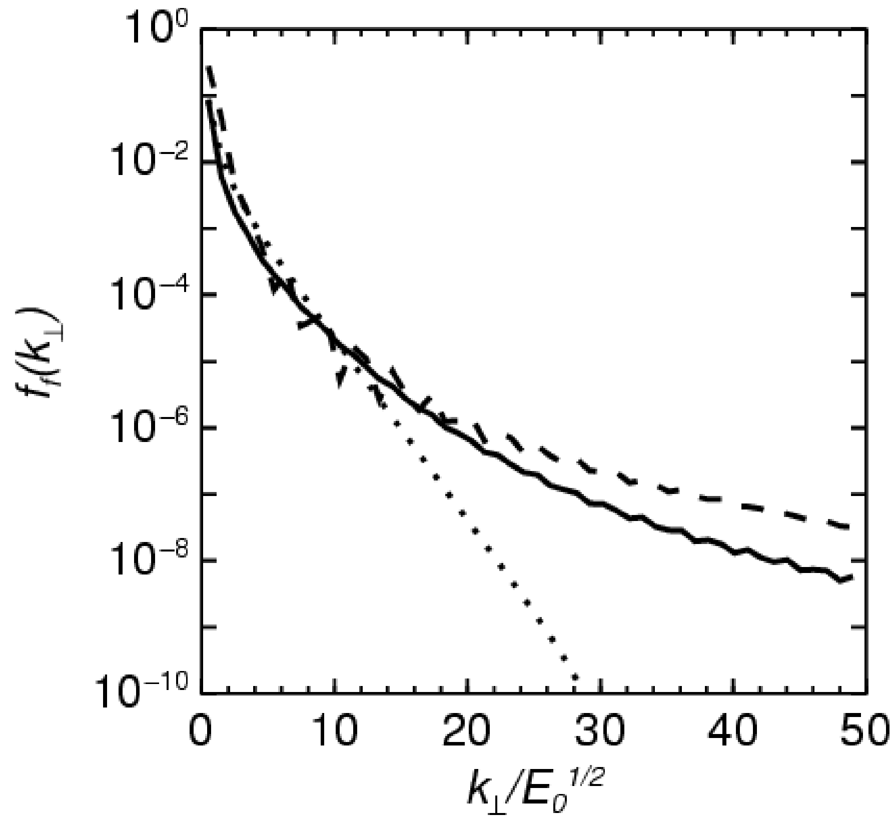


Numerical results for fermion distributions at $t = 2/\sqrt{E_0}$ in SU(2):



$f_f(k_3)$: longitudinal mom. distr.

$k_T/\sqrt{E_0} = 0.5$



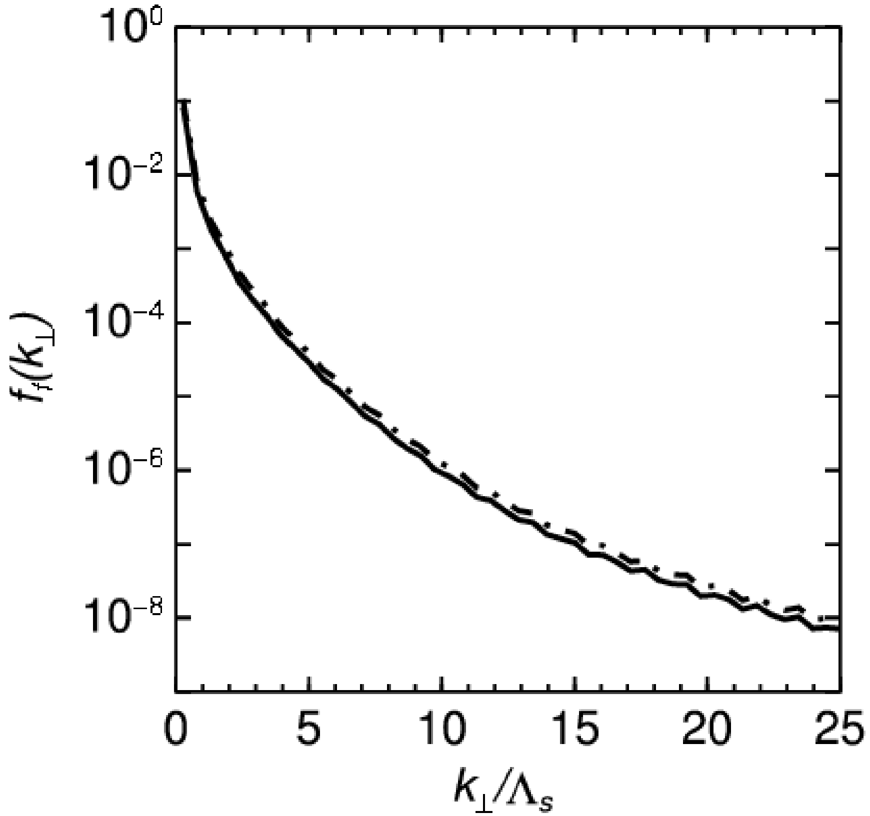
$f_f(k_T)$: transv. mom. distr.

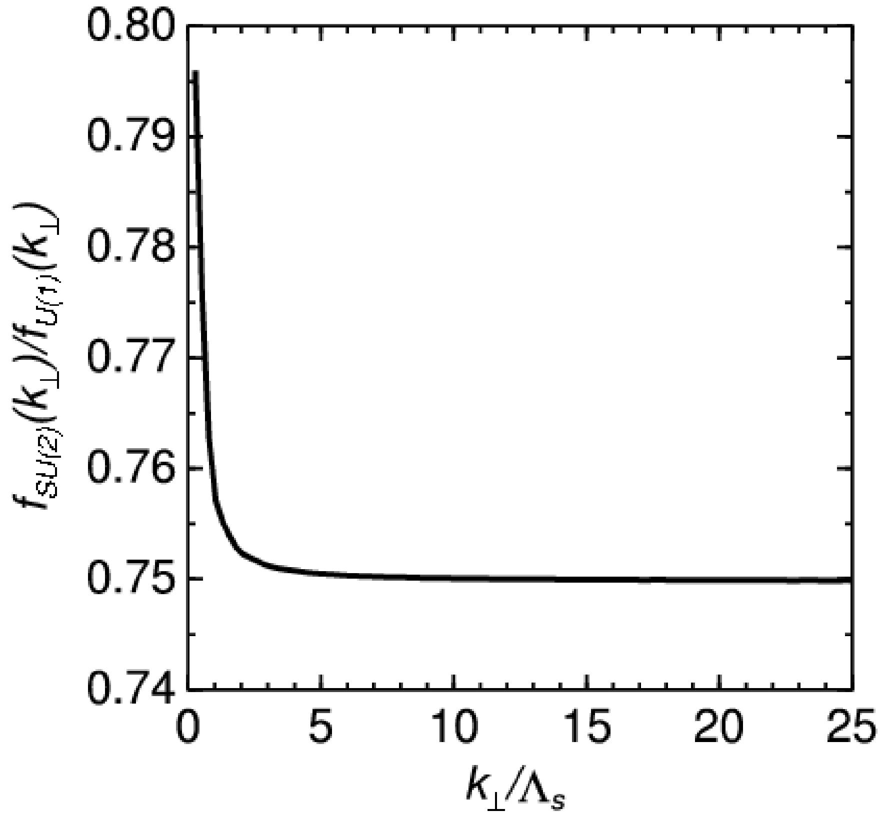
$k_3 = 0$

⇒ exponential (pulse)

⇒ polinomial (scaled)

Transverse momentum distr: scaling between U(1) and SU(2) at high-pT





$f_f(k_T)$: transv. mom. distr.

at $k_T/\sqrt{E_0} = 0.5$

in U(1) and SU(2)

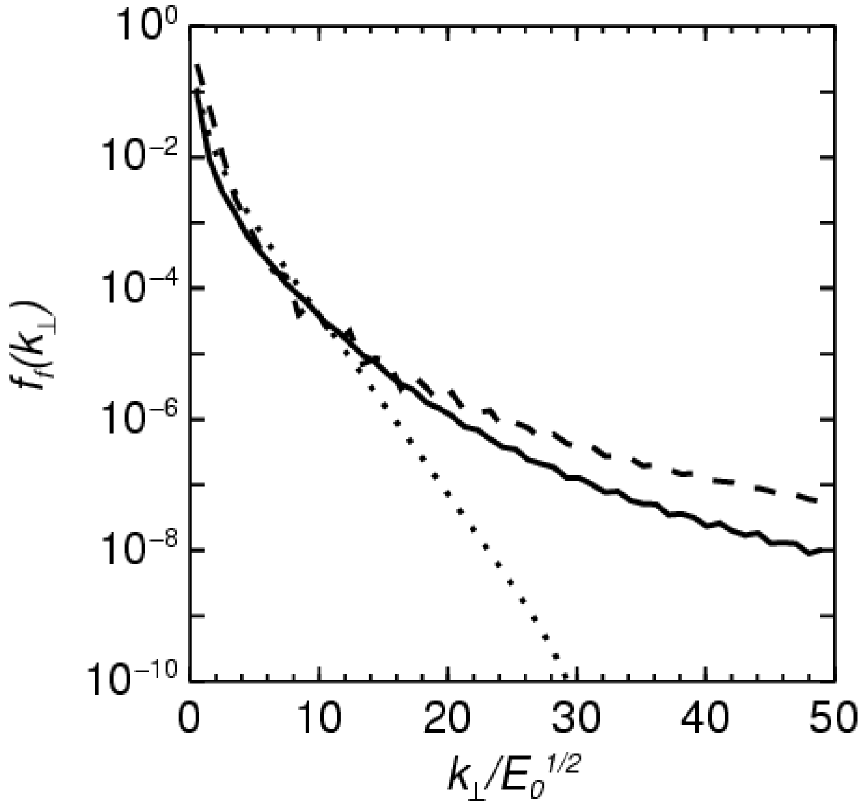
[Bjorken scaled]

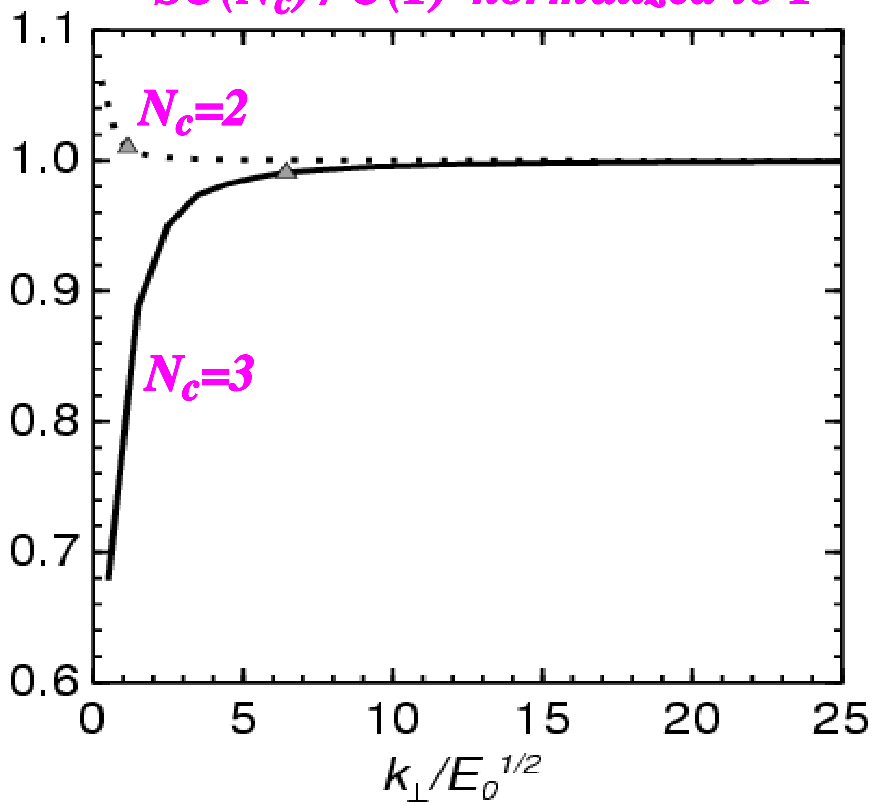
ratio: SU(2) / U(1)

$\Rightarrow$ ¾ at $k_T/\Lambda_s > 3$

(scaling in the Kinetic Eq.)

Transverse momentum distr: scaling in SU(3) at high-pT (m=0)





$f_f(k_T)$: transv. mom. distr.

in SU(3)

3 cases of E(t)

[similar to SU(2)]

Ratios (scaled time evol.):

SU(2) / U(1) ⇒ 3/4

SU(3) / U(1) ⇒ 4/3

(scaling in the Kinetic Eq.)

Quark-pair production in strong SU(2) field
--- quark mass dependence ---

Mass dependent fermion production in SU(2):

Quark-pair production depends on the mass:

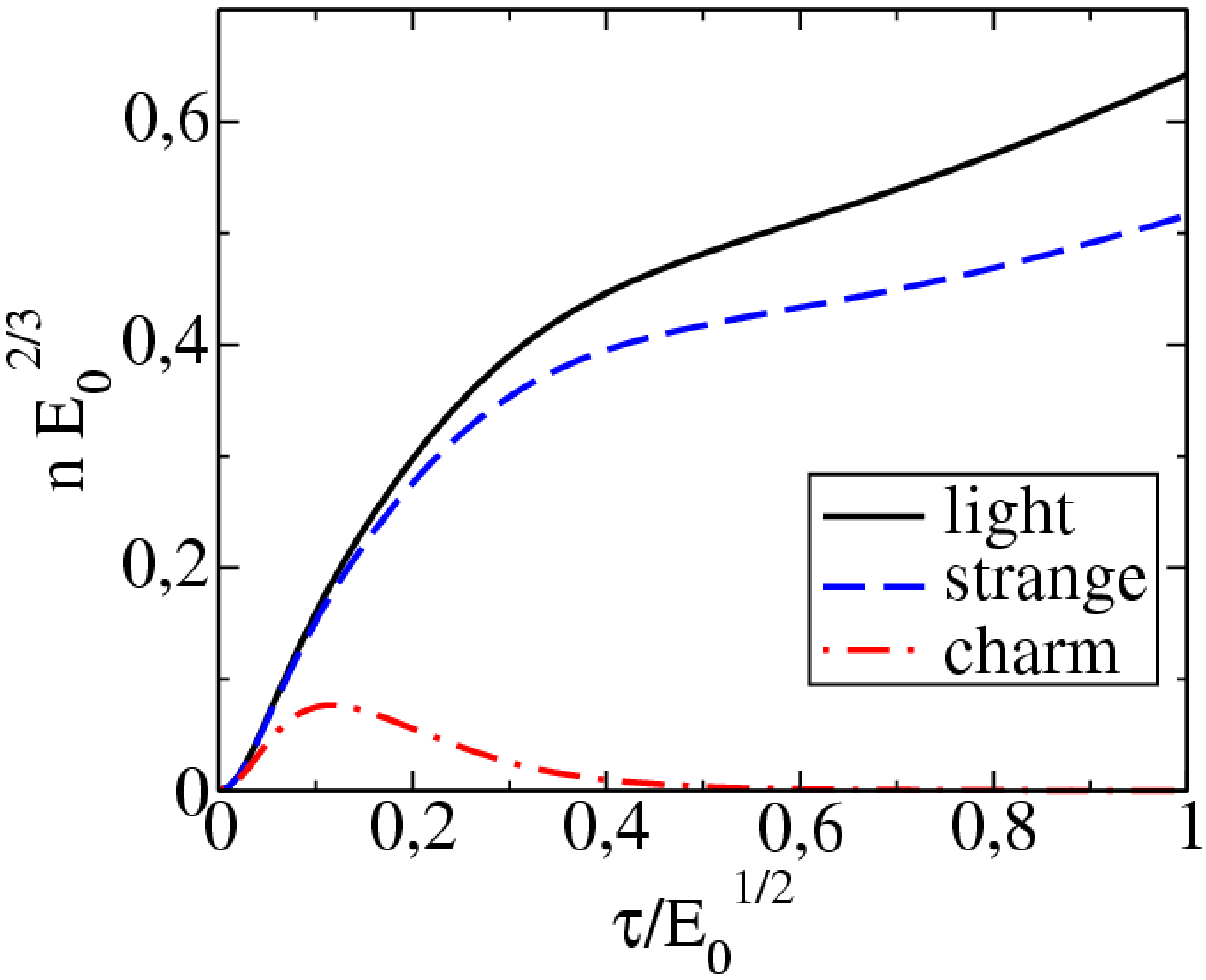
m(light) = 8 MeV
m(strange) = 150 MeV
m(charm) = 1200 MeV
m(bottom) = 4200 MeV

Usually 'm' mass behaves as a scale (see electron mass in QED).

But, what about zero mass limit?
What is the scale in that case?
Since we have non-zero fermion production,
then some scale must exist.
The characteristic time of the changes in E(t) ??

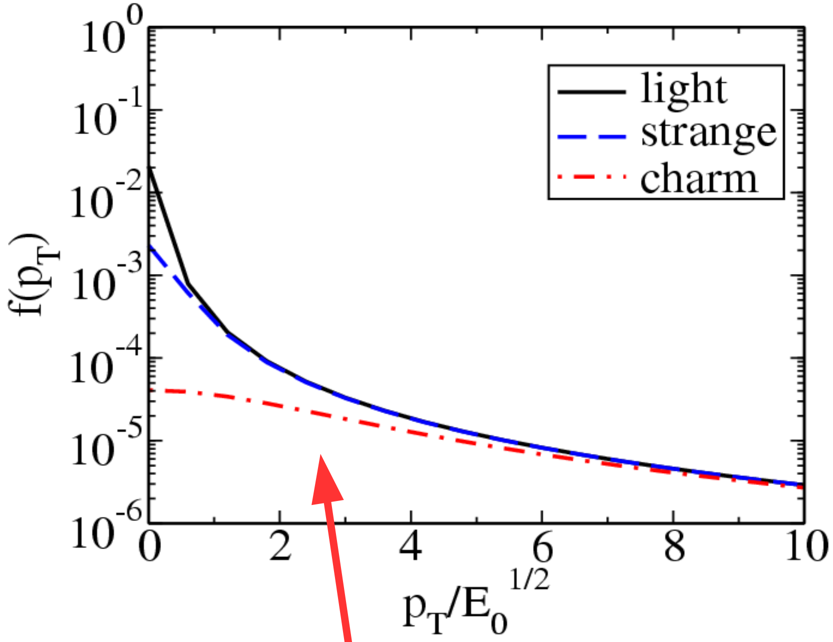
$\tau \quad \Rightarrow\Rightarrow \quad \delta$

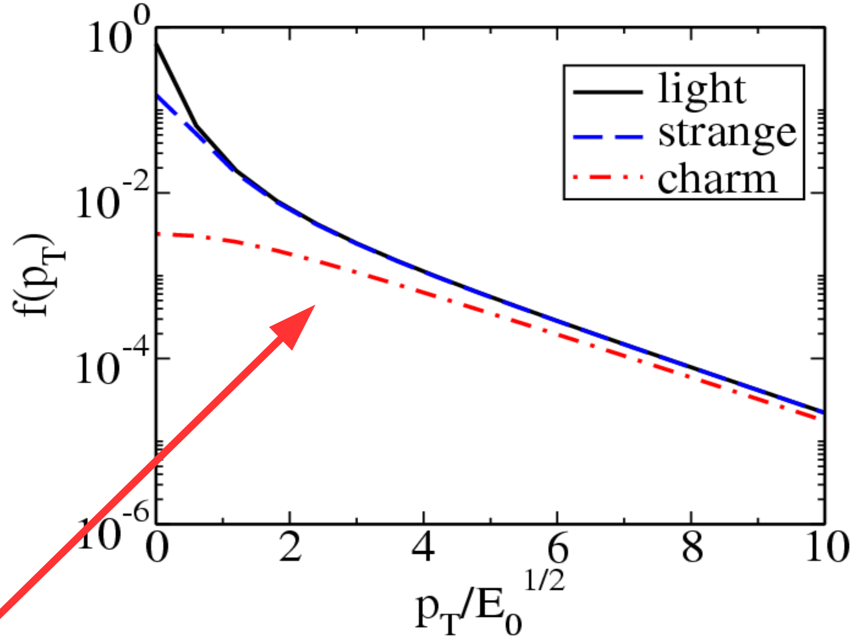
Mass dependent fermion production in SU(2) [pulse-like time dep.]



Fermion number (n) depends on the characteristic time of the pulse width: $\tau = \delta$ ***in the pulse scenario***

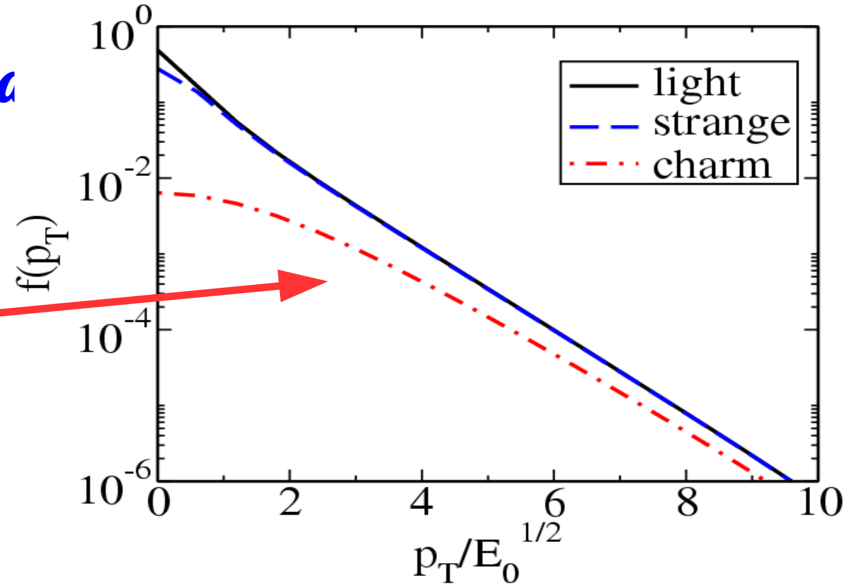
Mass dependent fermion production in SU(2) [pulse-like time dep.]



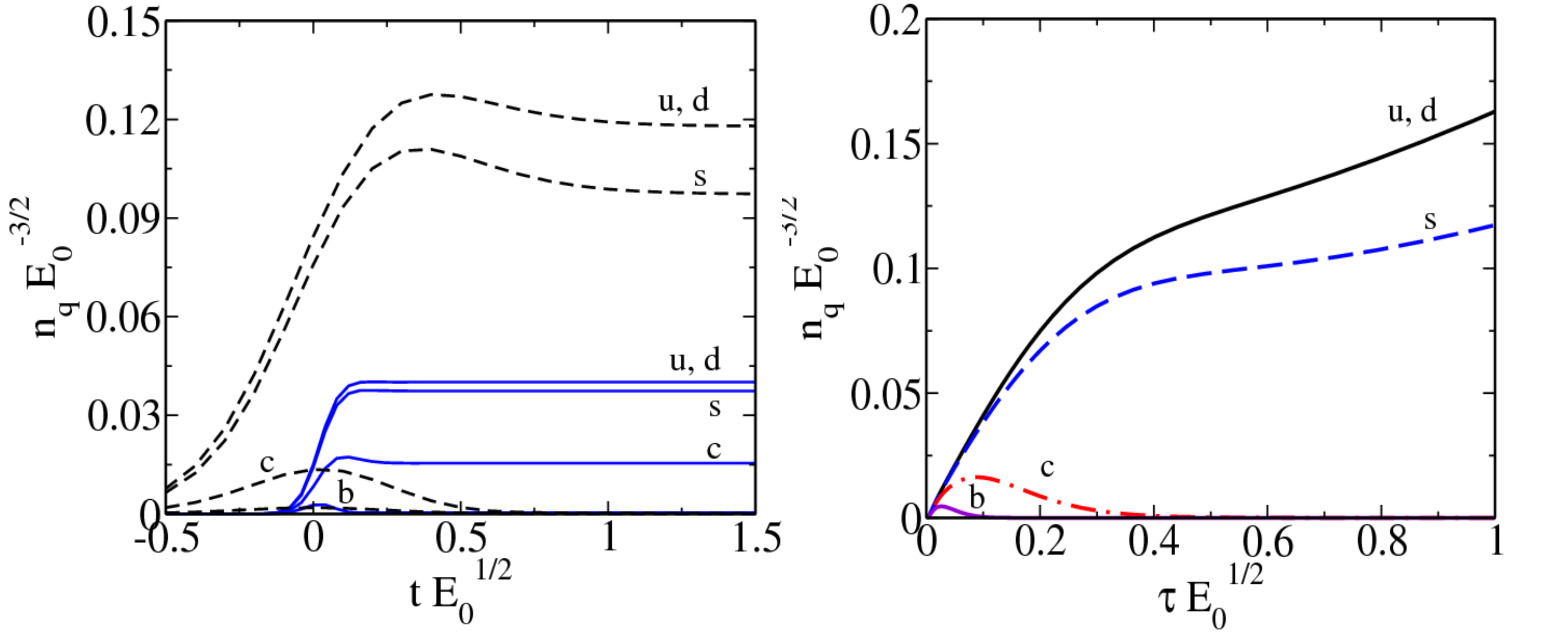


Transverse momentum spectra at different pulse width:

$\tau\sqrt{E_0} = 0.01;\ 0.1;\ 0.2$



Mass dependent fermion production in SU(2) [pulse-like time dep.]



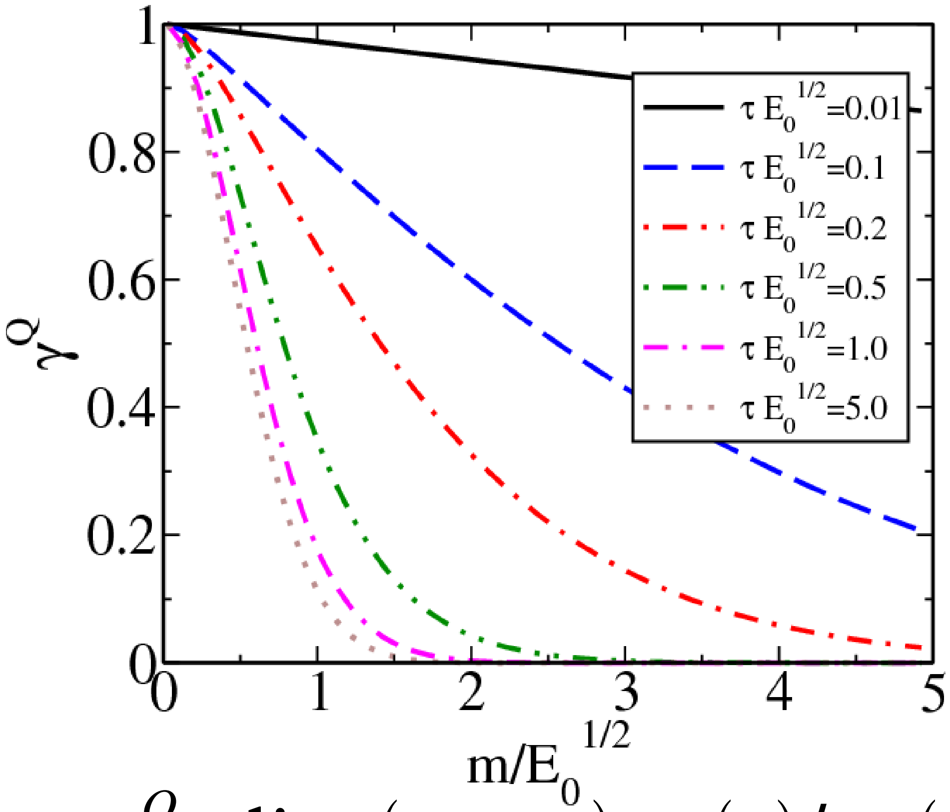
t: time in the CM frame *τ: pulse width* *($t \to \infty$)*

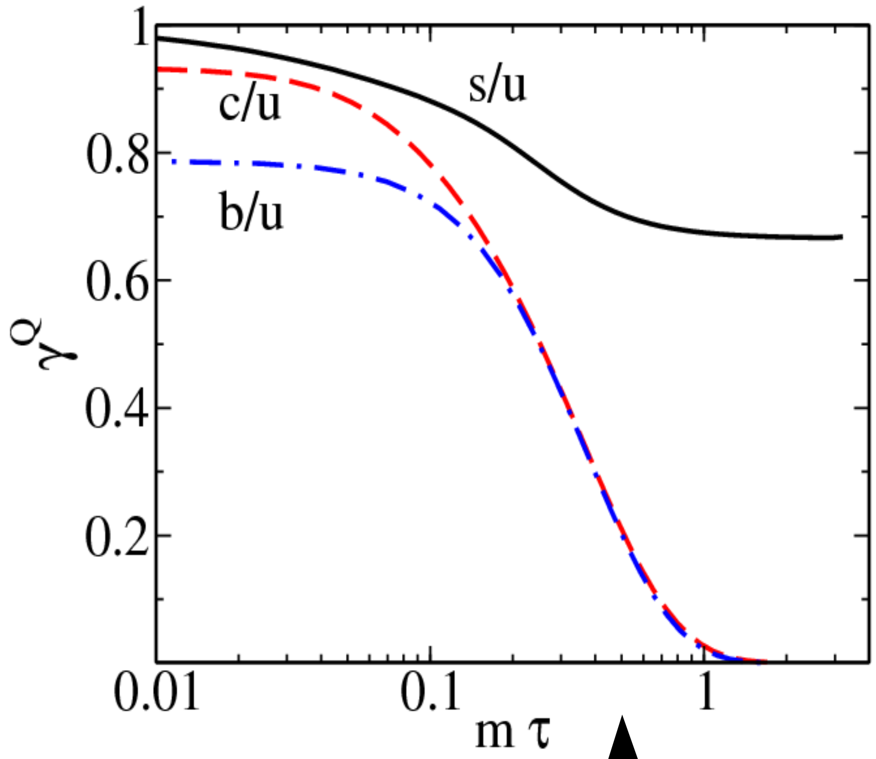
Full line: $\tau\sqrt{E_0} = 0.1$ ($\tau =$ 0.05 fm)

Dashed line: $\tau\sqrt{E_0} = 0.5$ ($\tau =$ 0.25 fm)

$E_0 = 0.68$ GeV/fm , $g=2$ $\to\to\to$ $g \cdot E_0 \propto \kappa = 1.17$ GeV/fm

Mass dependent fermion production in SU(2) [pulse-like time dep.]





$$\gamma^Q = \lim\,(t \to \infty)\, n_Q(t) / n_u(t)$$

flavour suppression factor

mτ scaling !!!!

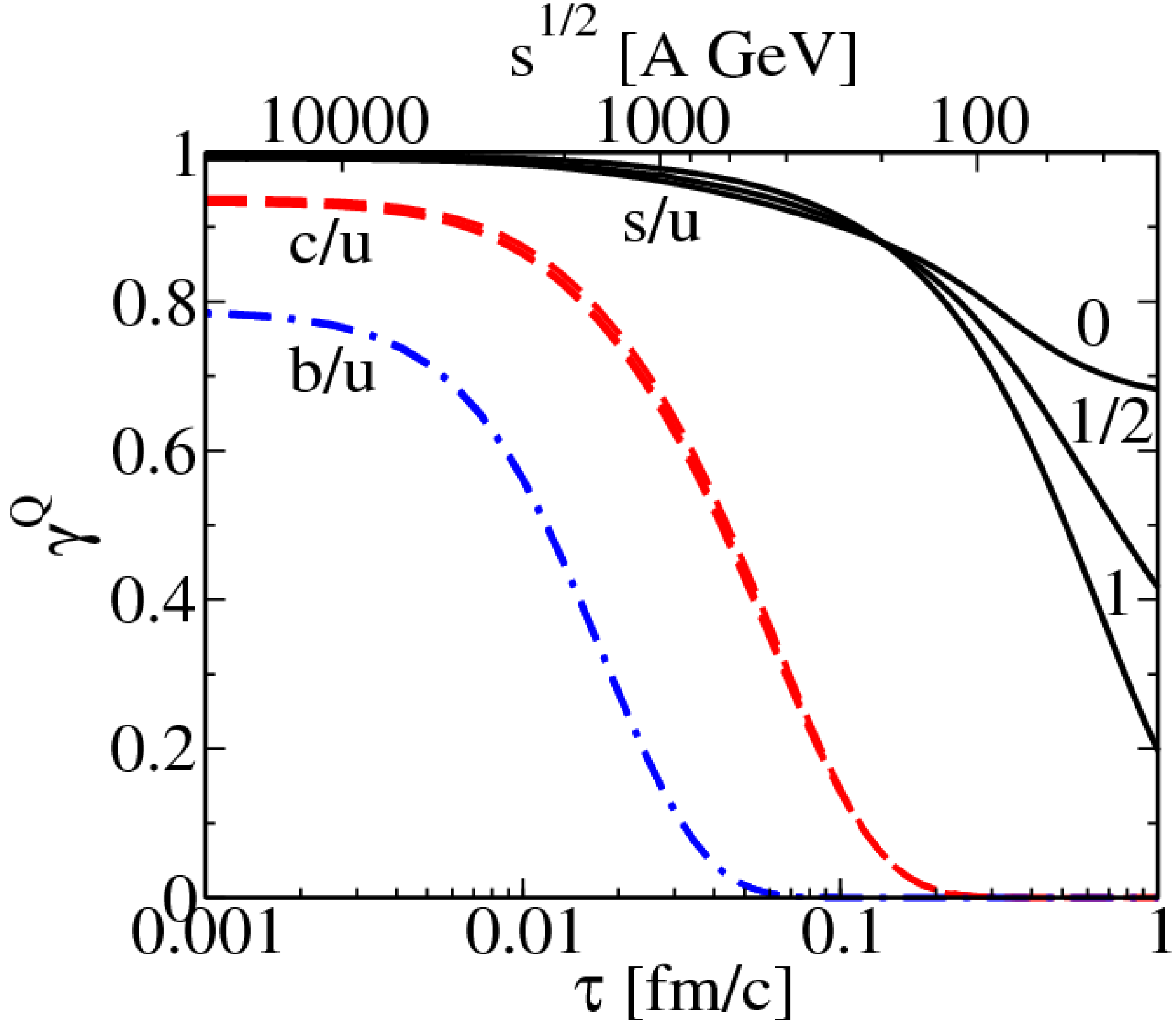
Blue line: $\tau\sqrt{E_0} = 0.1$ ($\tau = 0.05$ fm)

At large τ heavy quarks are suppressed.

Enhanced heavy fermion production at small τ

$\tau_{\text{eff}} = \delta + m^{-1}$ [$m_{eff} \Rightarrow\Rightarrow \delta^{-1}$]

Mass dependent fermion production in SU(2) [pulse-like time dep.]



Collisional energy dependence of the quark flavour suppression

+ $E_0(t) = E_0\,(\tau_0/\tau)^\beta$ where β : 0, 1/2, 1

Mass dependent fermion production in SU(2)

Numerical values for suppression factors :

	Schwinger	130 AGeV	200 AGeV	1 ATeV	2 ATeV	5.5 ATeV
s	0.74	0.84	0.88	0.96	0.98	0.99
c	3 10-9	9 10-3	0.06	0.66	0.82	0.91
b	≈ 0	≈ 0	10-6	0.15	0.45	0.72

Effective string constants and massive fermion suppression in SU(2)

Schwinger formula for static field and static string:

$$\frac{dN}{dt\, d^3 x} = \frac{\kappa^2}{4\pi^3} \exp\left(-\pi\, m^2/\kappa\right)$$

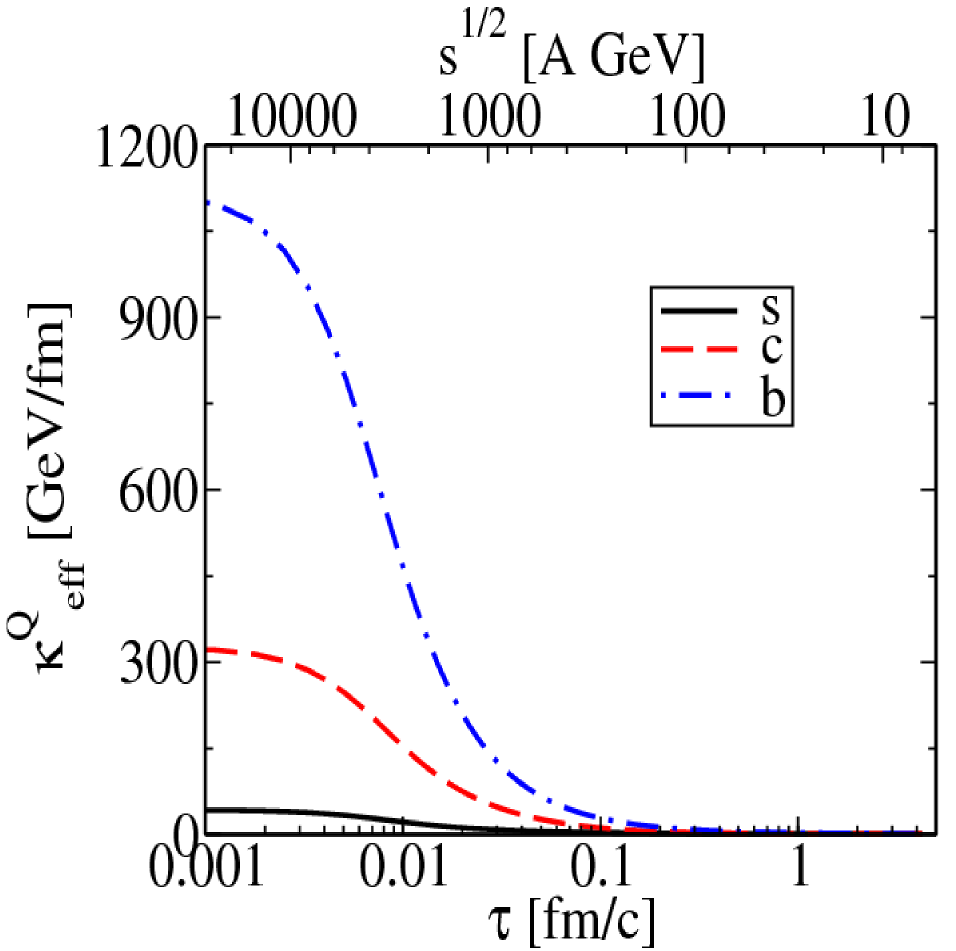
Suppression factor:

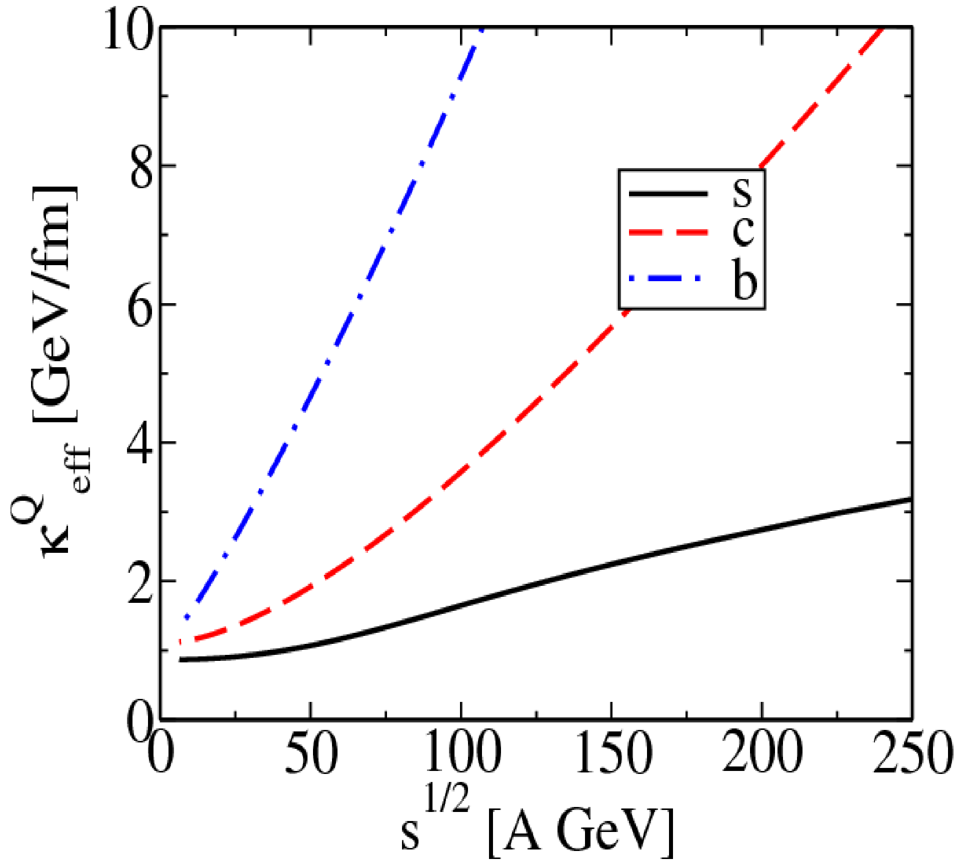
$$\gamma^Q = \exp\left(-\pi\left(m_Q^2 - m_q^2\right)/\kappa\right)$$

Results of our dynamical calculation can be fit by an effective string tension, κ_{eff}***:***

$$\gamma_\infty^Q\left(\kappa_{eff}^Q\right) = \gamma^{(Q)}(\tau)$$

Effective string constants and massive fermion suppression in SU(2)





Pulse width and collisional energy dependence
of the flavour dependent effective string constant
---- too much difference (and what about for light quarks)

Effective string constants and massive fermion suppression in SU(2)

Solution:

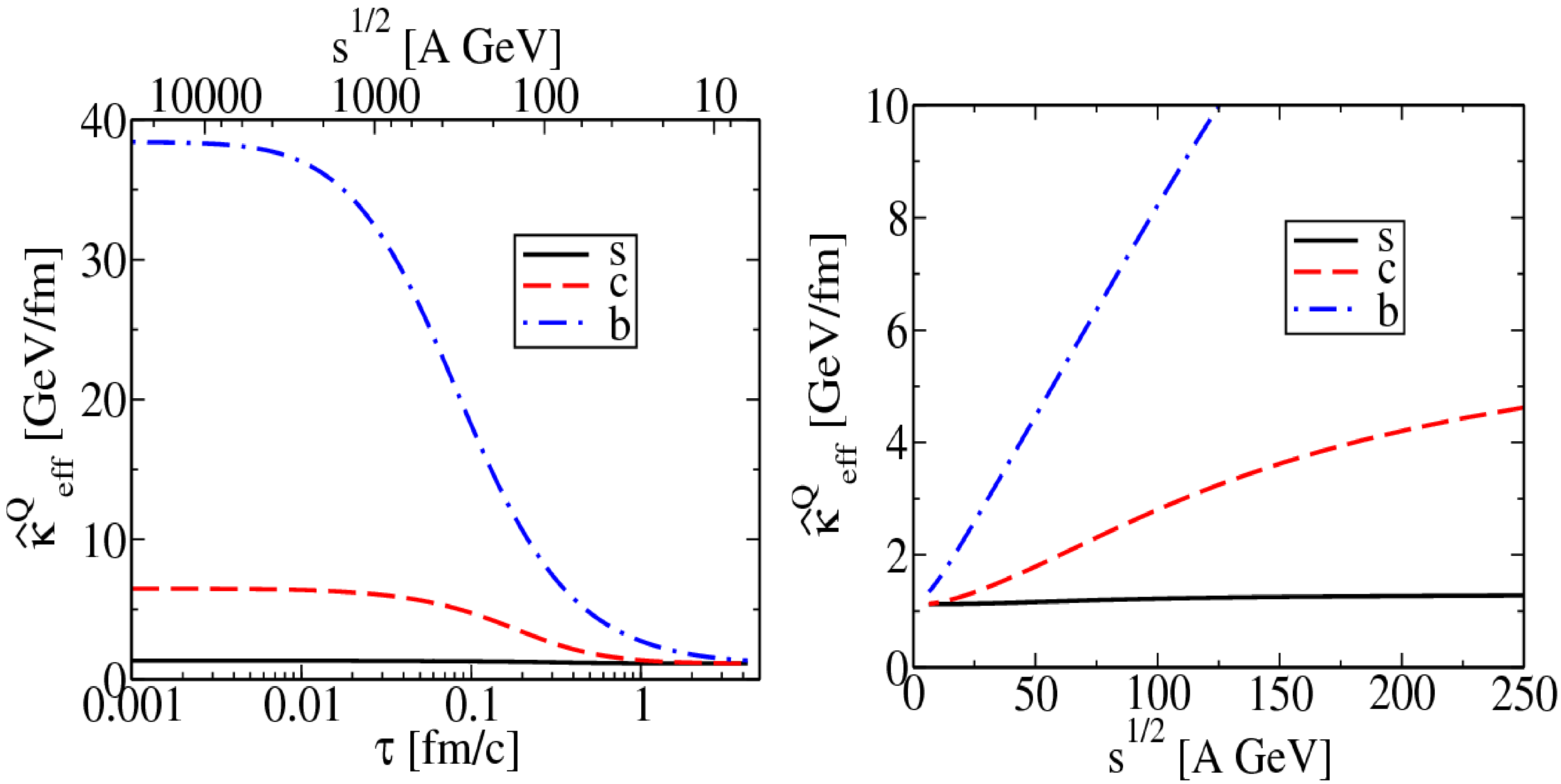
Let us keep a fixed string constant for the light quarks

$$\kappa^u_{eff} = 1.17\, GeV / fm$$

and fix flavour specific effective string constant for the heavier quarks (strange, charm, bottom):

$$\gamma^Q_\infty = \left(\frac{\kappa^Q_{eff}}{\kappa^u_{eff}}\right)^2 \exp\left(-\pi \frac{m^2_Q}{\kappa^Q_{eff}} + \pi \frac{m^2_u}{\kappa^u_{eff}}\right) = \gamma^Q(\tau)$$

Effective string constants and massive fermion suppression in SU(2)



Pulse width and collisional energy dependence
of the flavour specific effective string constants
--> strange string constant is nice, for heavy Q we get large values

Effective string constants and massive fermion suppression in SU(2)

Numerical values for flavour specific effective string constants in GeV/fm:

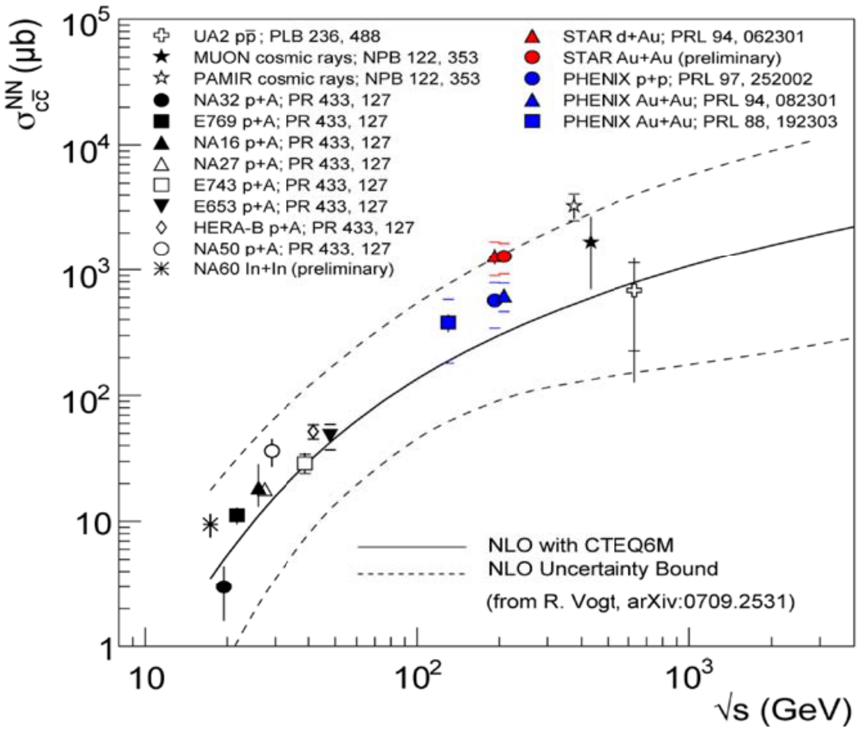
	130 AGeV	200 AGeV	1 ATeV	2 ATeV	5.5 ATeV
u,d	1.17	1.17	1.17	1.17	1.17
s	1.24	1.26	1.32	1.33	1.34
c	3.32	4.2	6.1	6.3	6.5
b	10.3	14.7	32	36	38

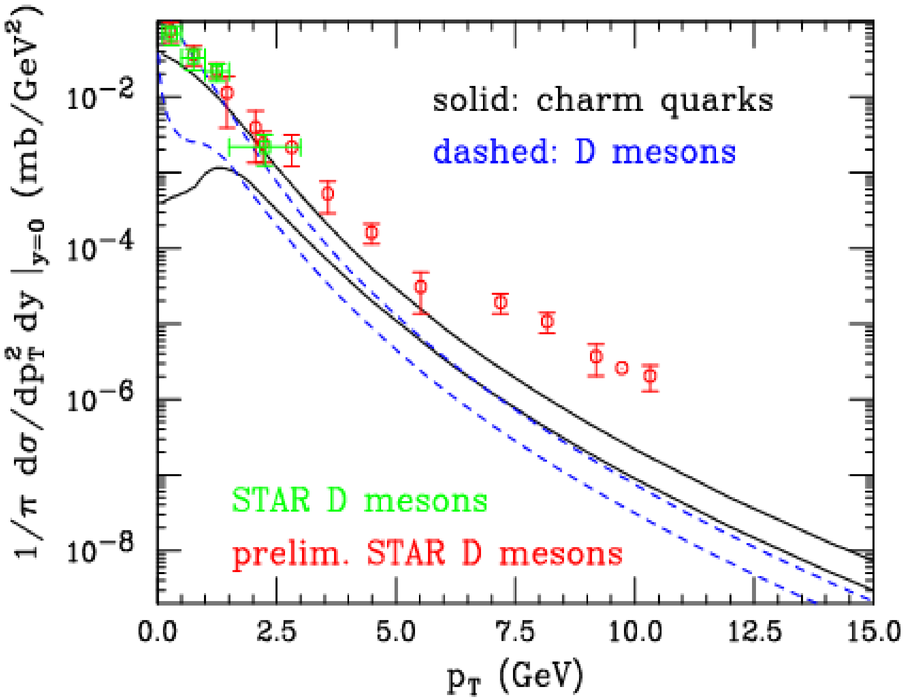
Saturation at higher LHC energies !!!!

Discussion: How large is the primary charm production ?
Do we have room for non-perturbative charm yield ?

Charm pair production can be (must be ?) calculated in pQCD:
LO, NLO, NLL, FONLL, ...

Results at RHIC energies





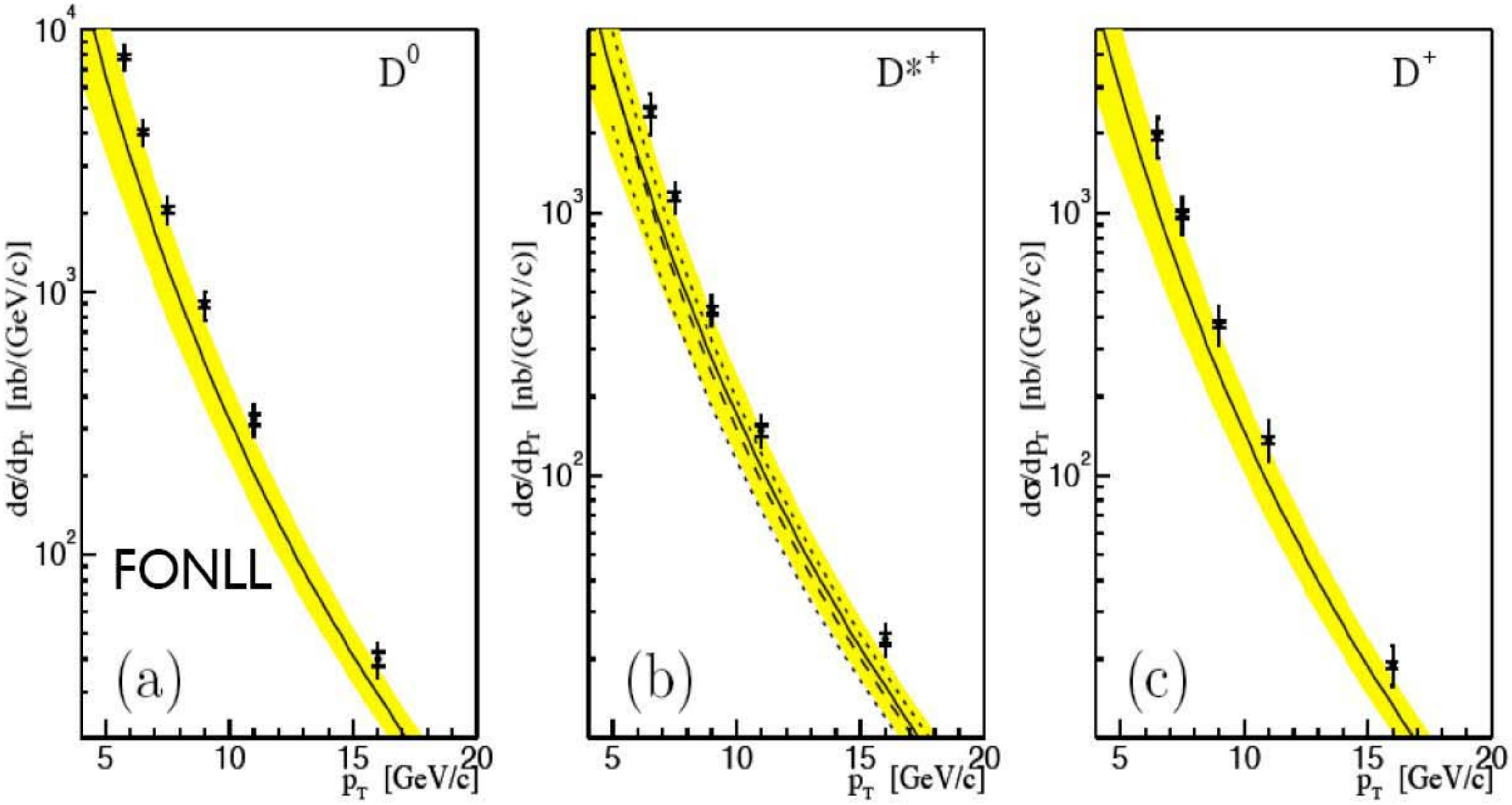
R. Vogt, EPJ ST 155 (2008) 213. *M. Cacciari, ..., PRL95,122001*

Data are at the upper limit of theory (or beyond) !?? (m_c = 1.2 GeV)

Discussion: How large is the primary charm production ?
Do we have room for non-perturbative charm yield ?

Charm production at FERMILAB energies ($p\bar{p}$, $\sqrt{s}$ = 1.96 TeV)

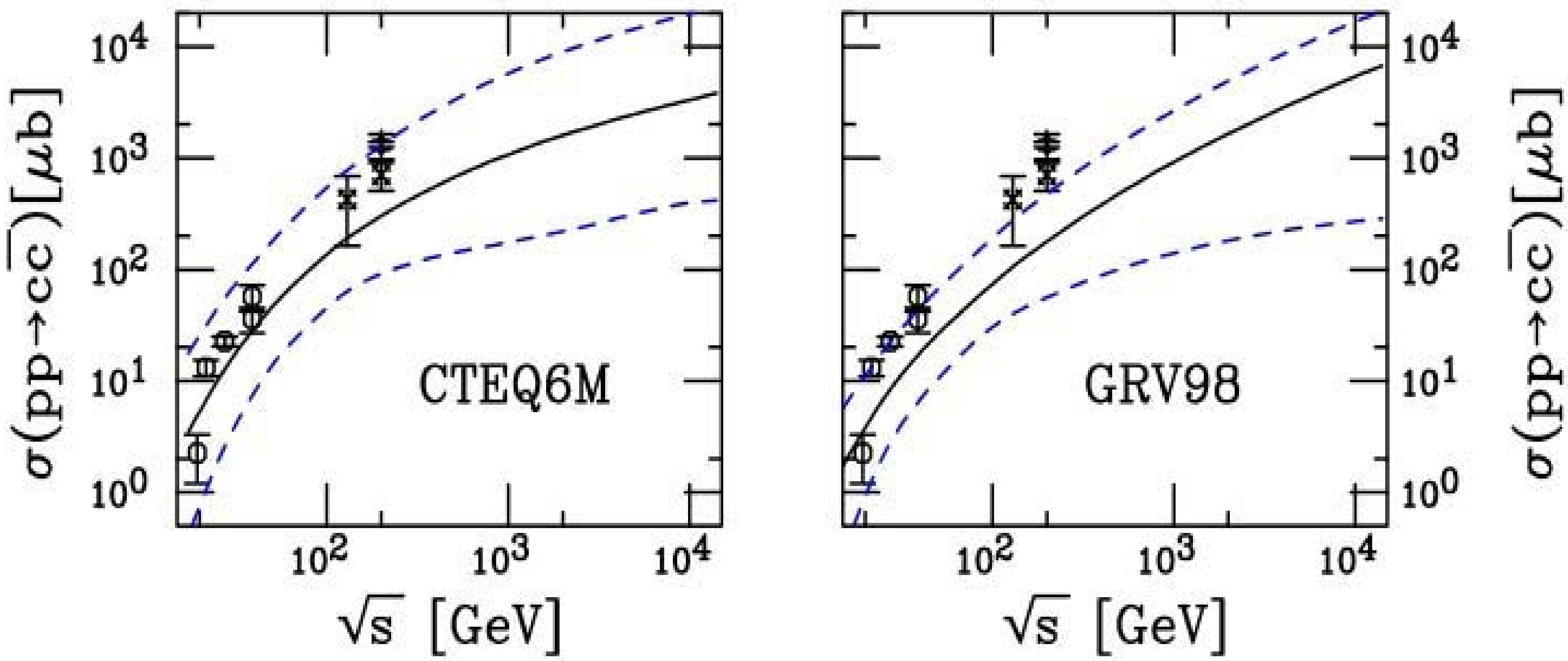
CDF Run II c → D data [PRL 91:241804,2003]



Data are at the upper limit of theory (or beyond) !?? (factor of 2 ?)

Discussion: How large is the primary charm production ?
Do we have room for non-perturbative charm yield ?

Charm production at LHC energies (pp, $\sqrt{s}$ = 2-14 TeV)



R. Vogt, Private comm., 2009

Large uncertainties --> more data are needed to fix parameters

There is room for non-perturbative contributions (today).

Conclusions:

1. *Particle production mechanisms are not fully explored in non-Abelian cases, especially in case of strong fields.*

2. *If the overlap of heavy ions is very short, and the time scale of the initial phase is also short, then heavy quark production is not suppressed by the heavy mass.*

3. *Short pulse: the time scale of the initial 'pulse' determines the heavy quark production and not the charm mass.*

4. *Thus: heavy quark production can carry message about the time scale of the initial overlap at LHC energies. (strange quark mass is too close to light quark mass)*

5. *LHC data are extremely interesting, turning point is ~ 1-2 TeV.*