High-pT particle production at RHIC and LHC energies

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HCBM Workshop

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1. Jet and hadron production in proton-proton and proton-antiproton collisions

--- from RHIC to LHC energies ---
[Exp. data & theory (pQCD)]

Hard physics: pion production in pp collision at high- p_T

Asilomar HP'2005

Perturbative QCD calculations in NLO for p+p → π + X process with finite -k_T

NLO : M. Aversa et al. NPB327,105; P. Chiappetta et al. NPB412,3; P. Aurenche et al. NPB399,34; ...)

+ intrinsic kT: G. Papp, P. Levai, G.G. Barnaföldi, G. Fai, hep-ph/0212249, EPJC33(2004)609

$$E_\pi \frac{d\sigma^{pp}}{d^3 p_\pi} = \frac{1}{S} \sum_{abc} \int_{VW/z_c}^{1-(1-V)/z_c} \frac{dv}{v(1-v)} \int_{VW/vz_c}^{1} \frac{dw}{w} \int^1 dz_c$$

$$\int d^2\boldsymbol{k}_{Ta} \int d^2\boldsymbol{k}_{Tb} \; f_{a/p}(x_a, \boldsymbol{k}_{Ta}, Q^2) \; f_{b/p}(x_b, \boldsymbol{k}_{Tb}, Q^2)$$

$$\left[\frac{d\sigma^{BORN}}{dv}\delta(1-w) + \frac{\alpha_s(Q_R)}{\pi} K_{ab,c}(s, v, w, Q, Q_R, Q_F)\right] \frac{D_c^\pi(z_c)}{\pi z_c^2}$$

An approximation for the unintegrated parton distribution functions (PDFs) :

$$f_{a/p}(x_a, \boldsymbol{k}_{Ta}, Q^2) = f_{a/p}(x_a, Q^2) \quad g(\boldsymbol{k}_{Ta})$$

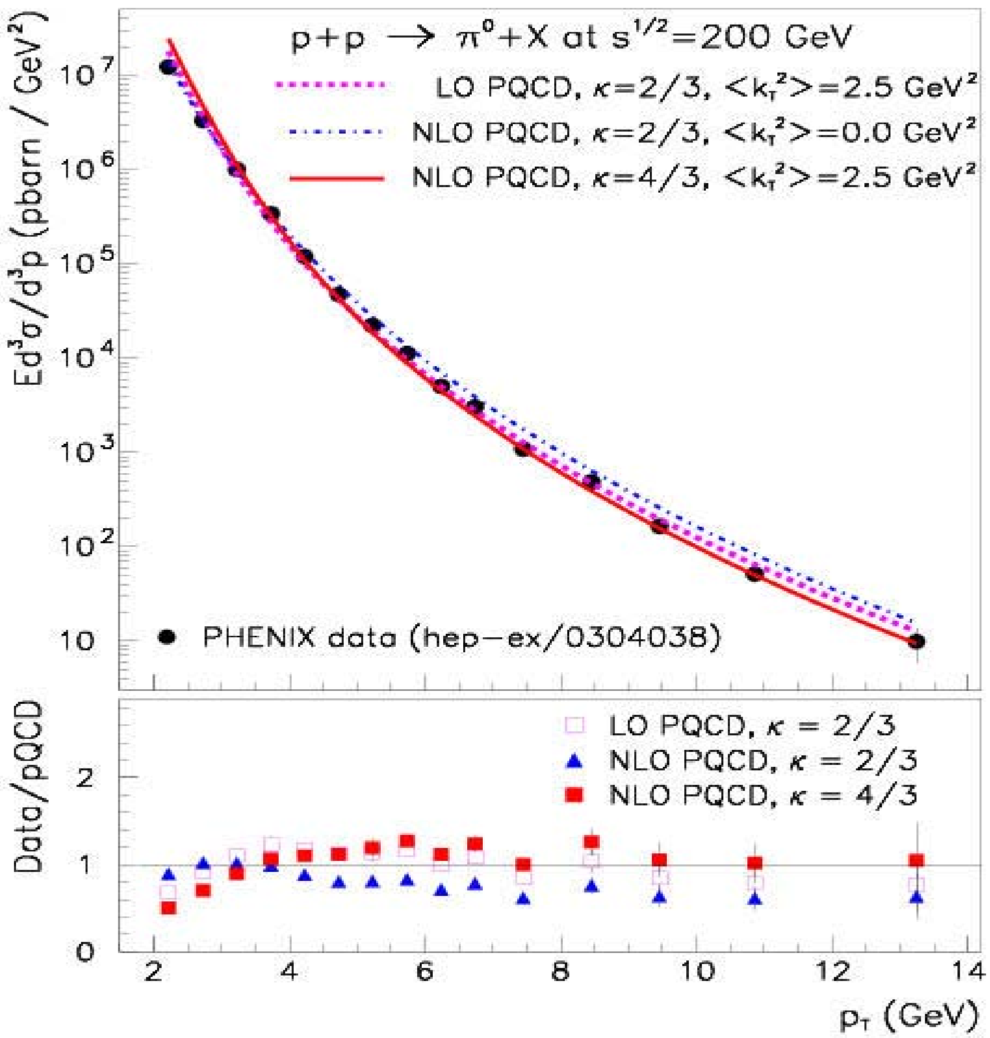
Where we use gaussian

$$g(\boldsymbol{k}_{Ta}) = \frac{1}{\pi \langle k_T^2 \rangle} e^{-k_T^2/\langle k_T^2 \rangle}$$

The width of the gaussian distribution for intrinsic-kT

Hard physics: pion production in pp collision at high- p_T

Perturbative QCD calculations in LO and NLO for pp --- including intrinsic- kT



LO:

$$Q = \kappa\, p_T / z_c\,,\quad Q_F = \kappa\, p_T$$

NLO:

$$Q = Q_R = \kappa\, p_T / z_c\,,\quad Q_F = \kappa\, p_T$$

All descriptions are approx.
good enough at 2 GeV < pT < 5 GeV.

Which κ should be used ?

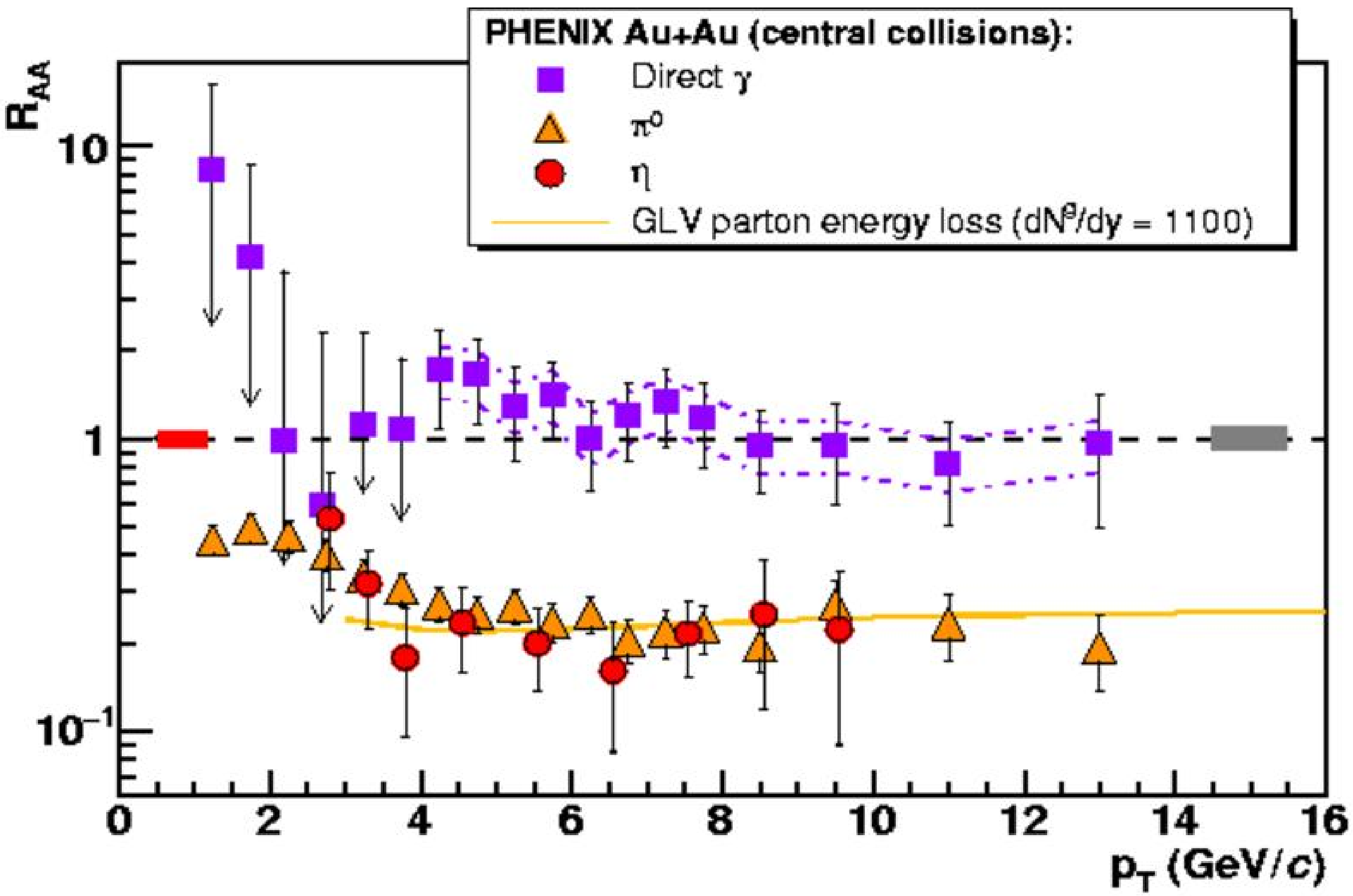
P.L, G. Papp, G.G. Barnaföldi, G. Fai
May 2003

Hard physics: pion production in AuAu collision at high- pT

Jet energy loss -> Jet-tomography, corona-graphy, ...

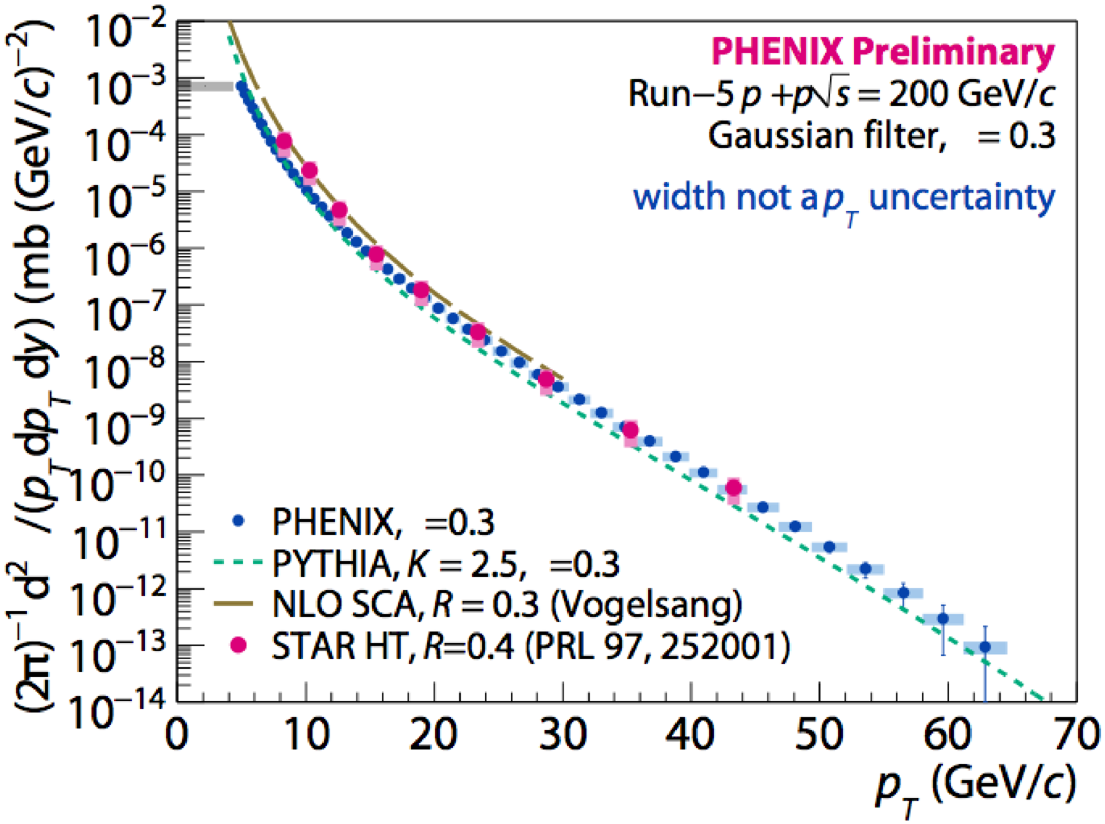
See Miklós Gyulassy's Talk

wQGP vs. sQGP, heavy quark energy loss, AdS/CFT, ...



nucl-ex/0601037

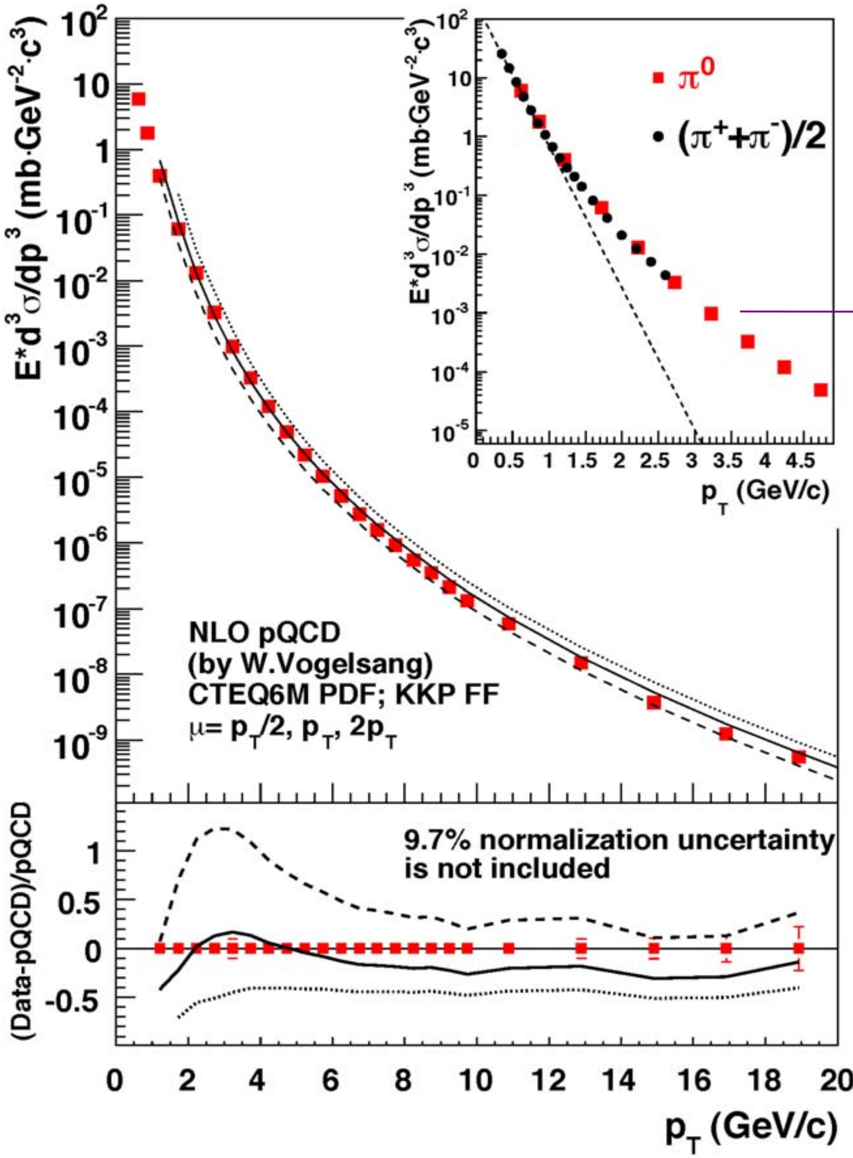
Jet production in pp collisions in the high-pT region at RHIC:



PHENIX and STAR results (2010, Prag) at 200 GeV

NLO pQCD and PYTHIA seems to reproduce the exp. data very well (on this log scale)

Hadron production in pp collisions in the high-pT region at RHIC:

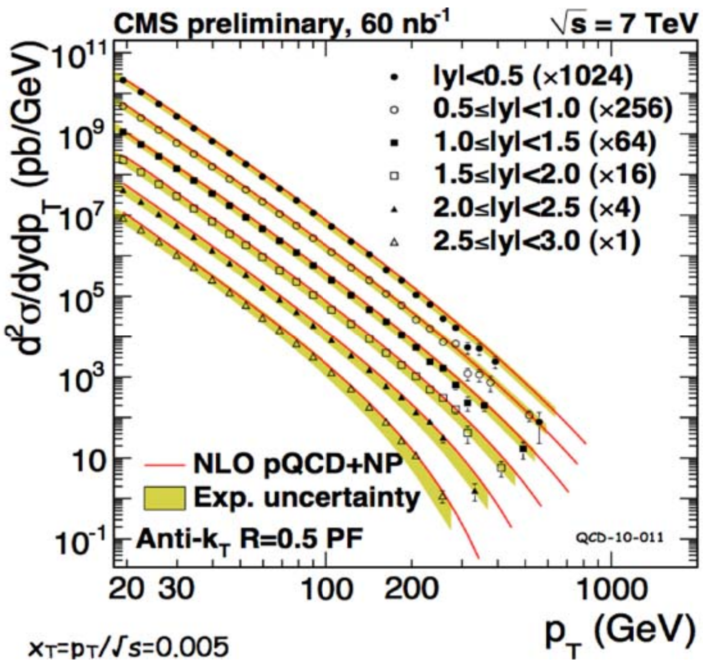


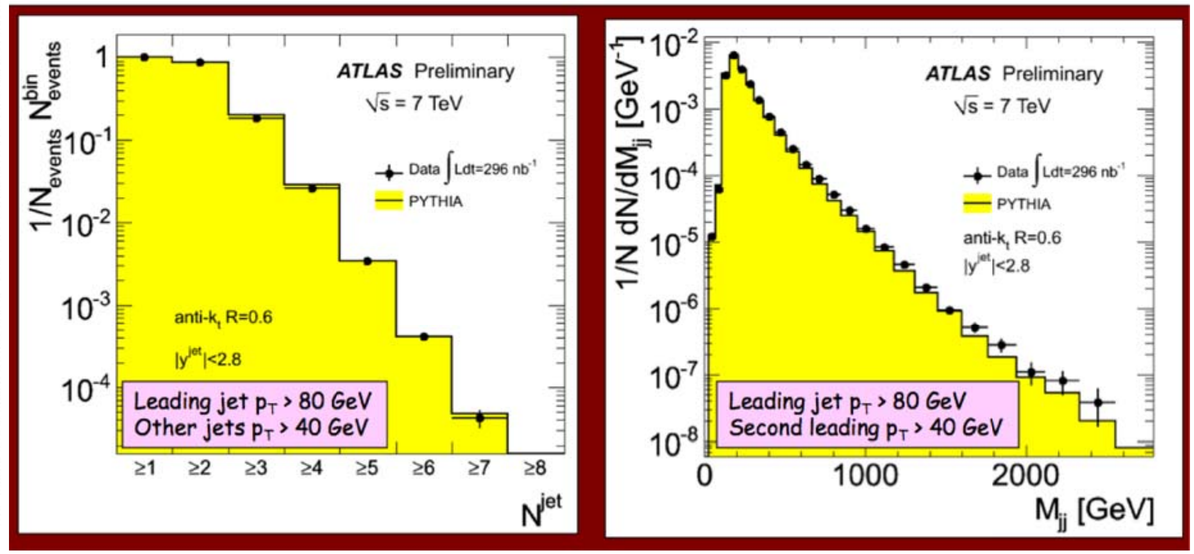
PHENIX results (2006)
p+p -> pi0 at 200 GeV

NLO pQCD seems to reproduce the exp. data very well

(Main 'propaganda' slide.)

Jet production in pp collisions in the high-pT region at LHC:



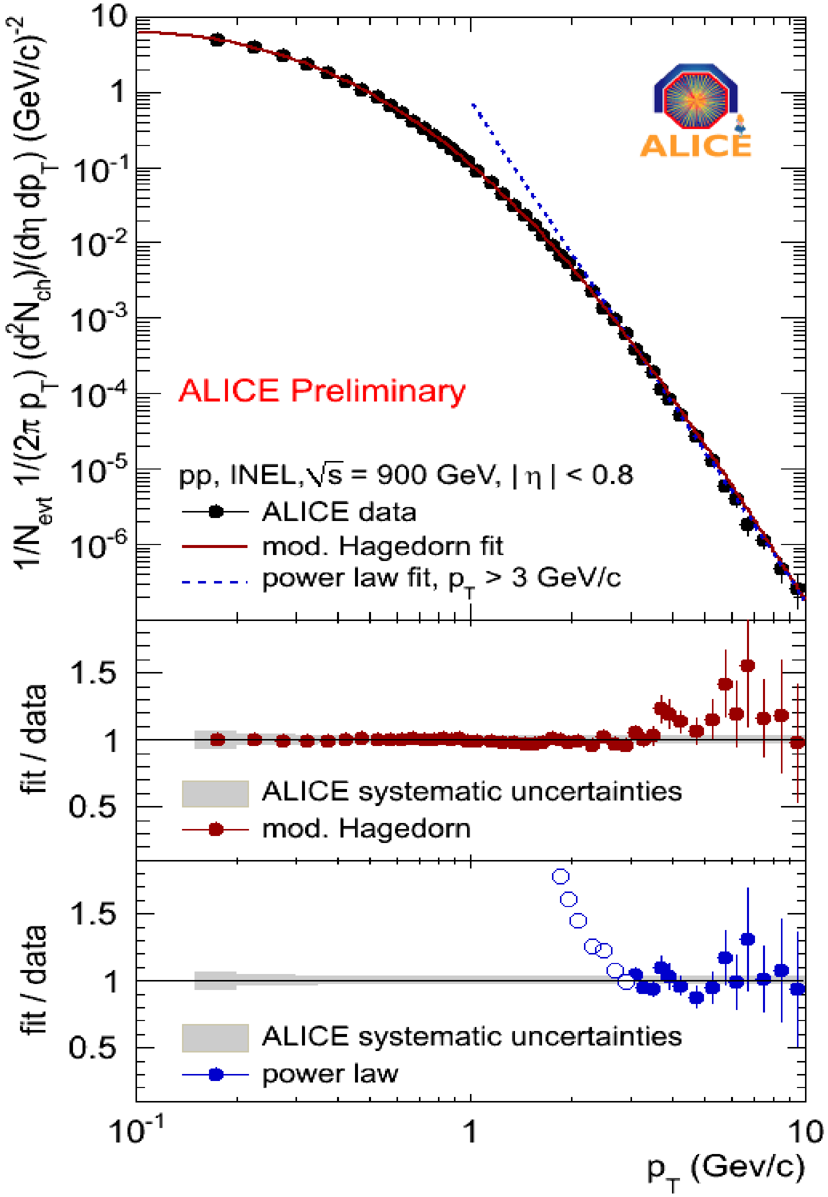


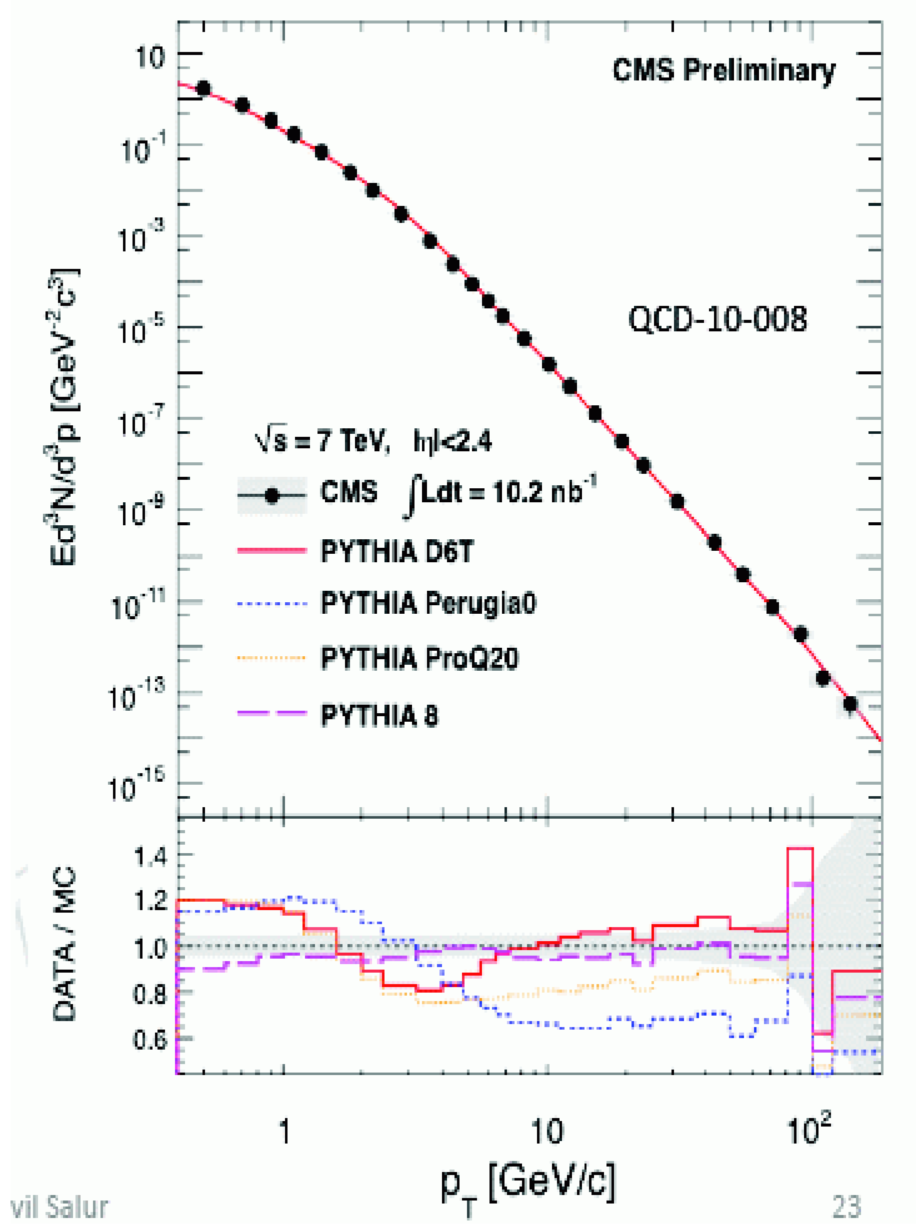
CMS result at 7 TeV **ATLAS results at 7 TeV**

NLO pQCD (+NP) seems to reproduce the exp. data (First 100 nb^{-1})

Prag WS 2010

Charged hadron production in pp collisions in the high-pT region :



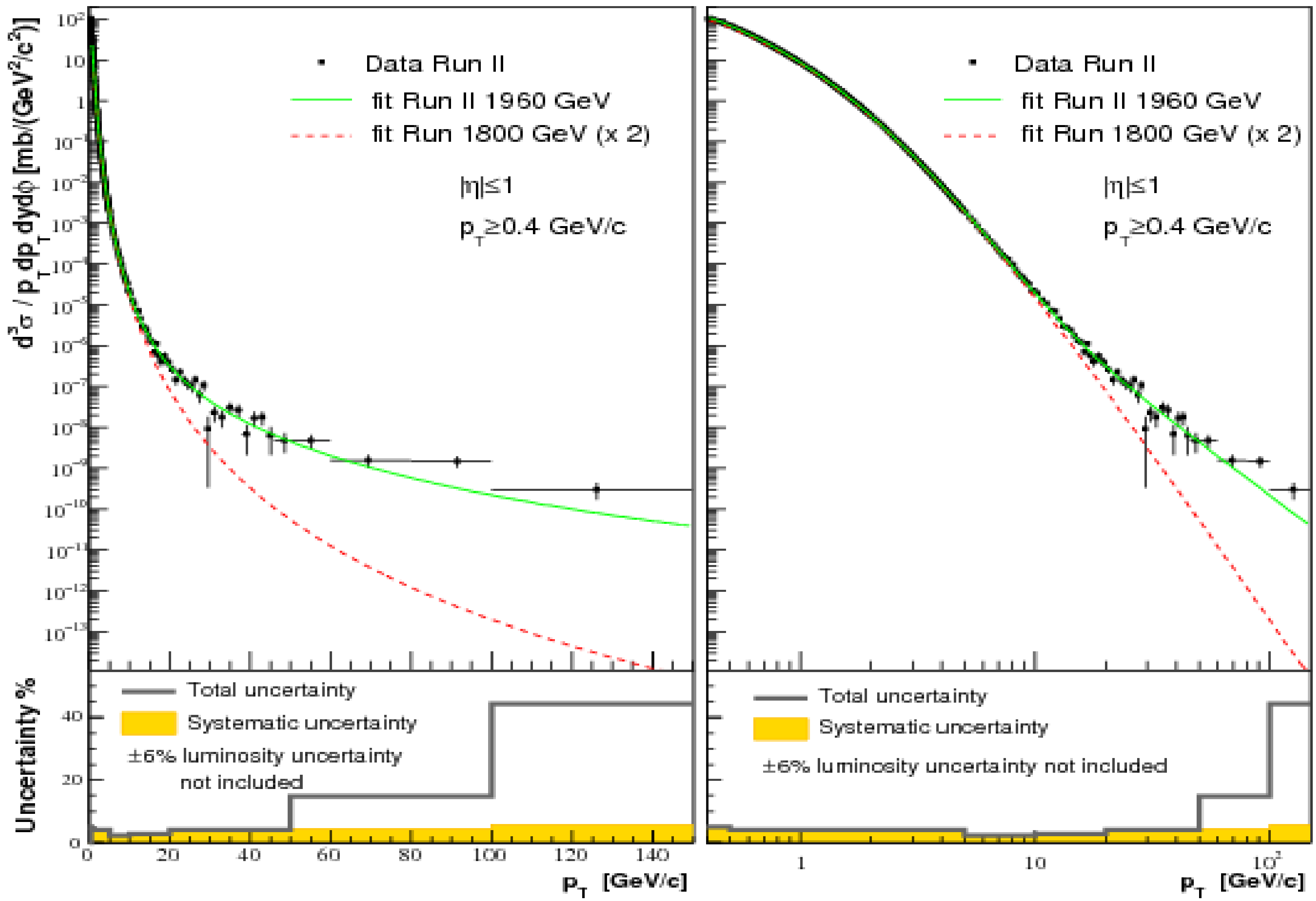


LHC ALICE (Prag'10)

LHC CMS (Prag'10)

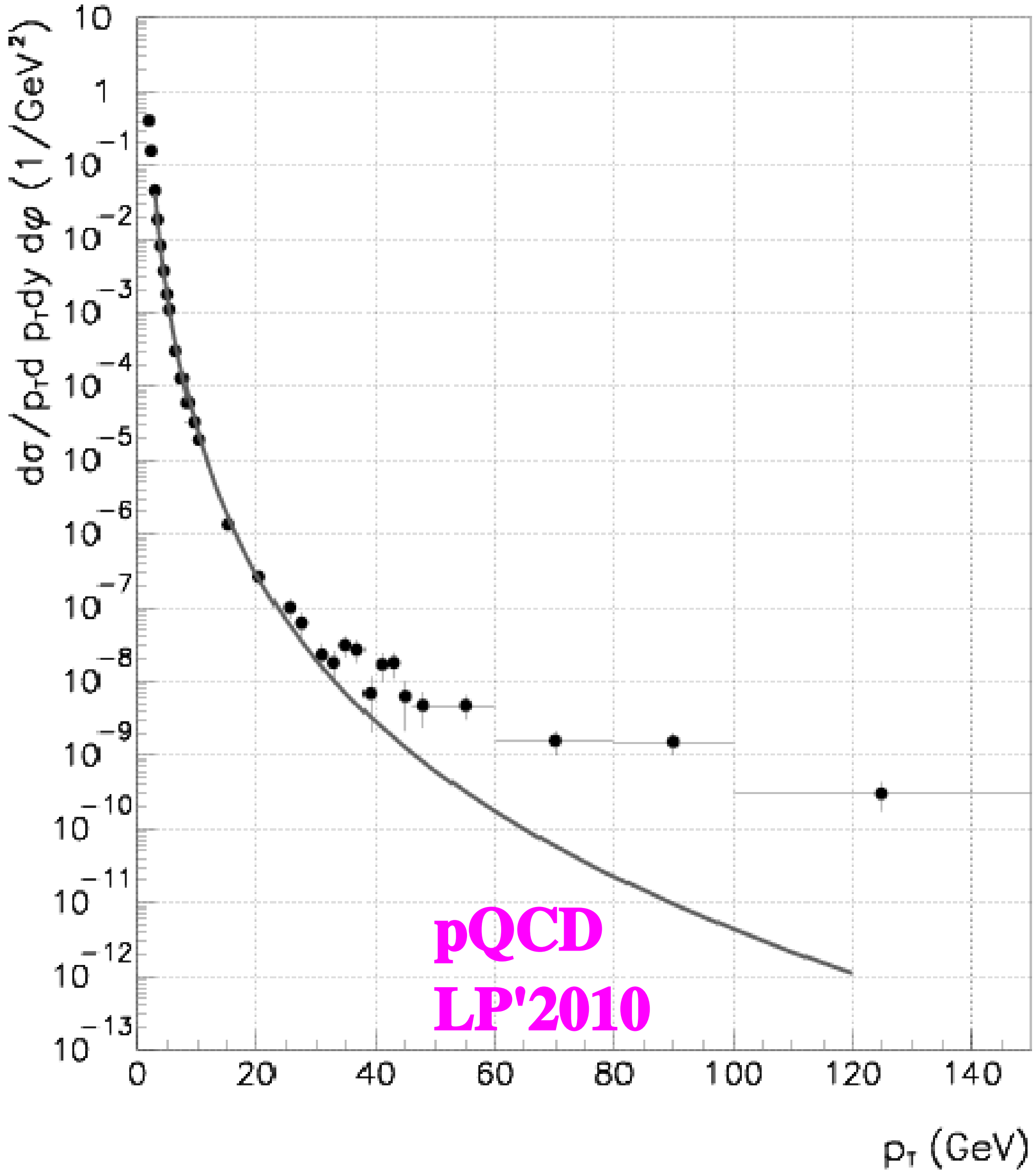
BOMB SHELL (!) :

Charged hadron production in pp collisions at TEVATRON :



New data from TEVATRON CDF experiment: PRD 79 (2009) 112005.

Charged hadron production in pp collisions at TEVATRON :



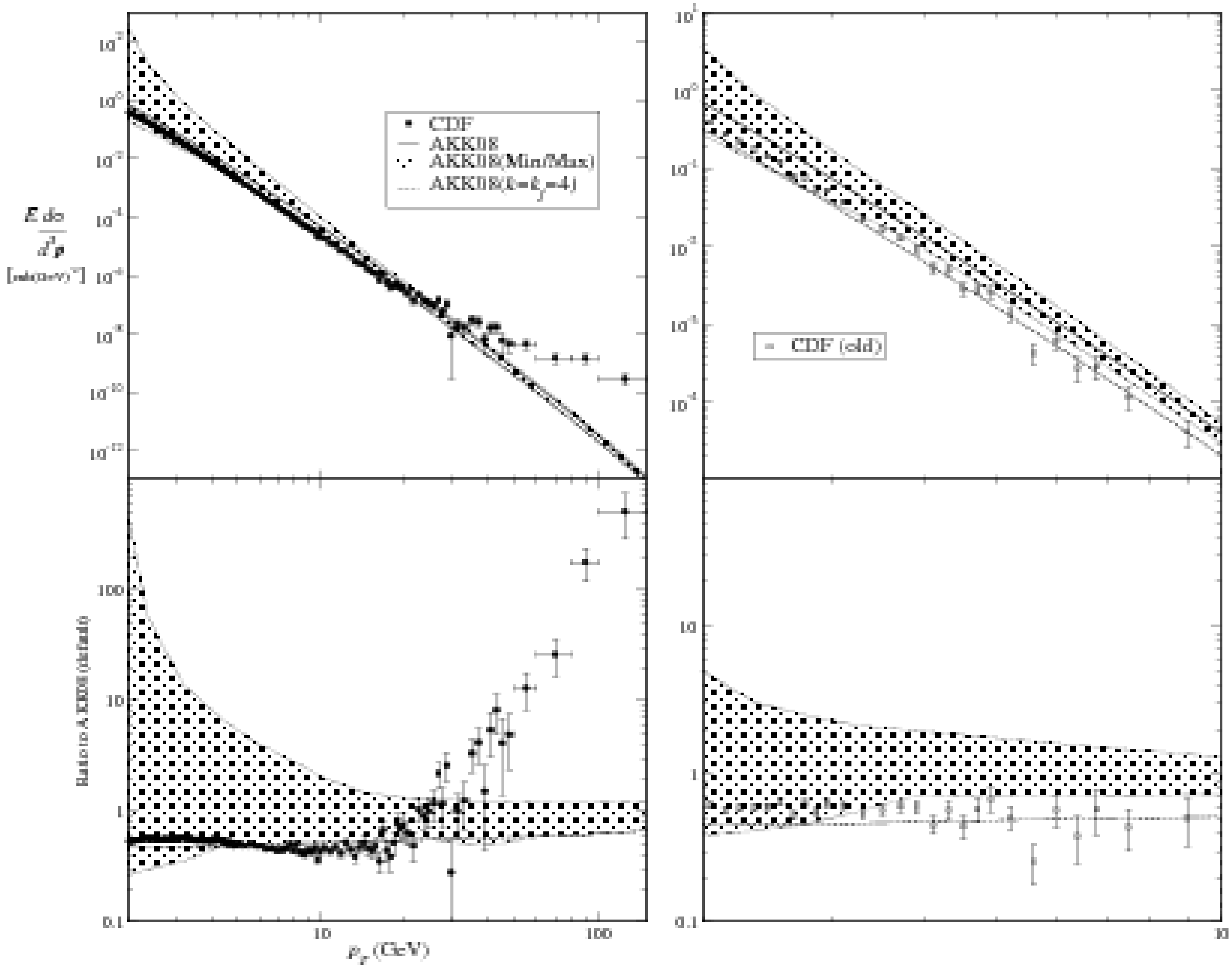
Charged hadrons at 2 TeV p+antip

Data vs. LO pQCD calc.

2 TeV <-> 30 GeV
xT = 0.015
|||
7 TeV <-> 100 GeV

New data from TEVATRON CDF : PRD 79 (2009) 112005.

Charged hadron production in pp collisions at TEVATRON :



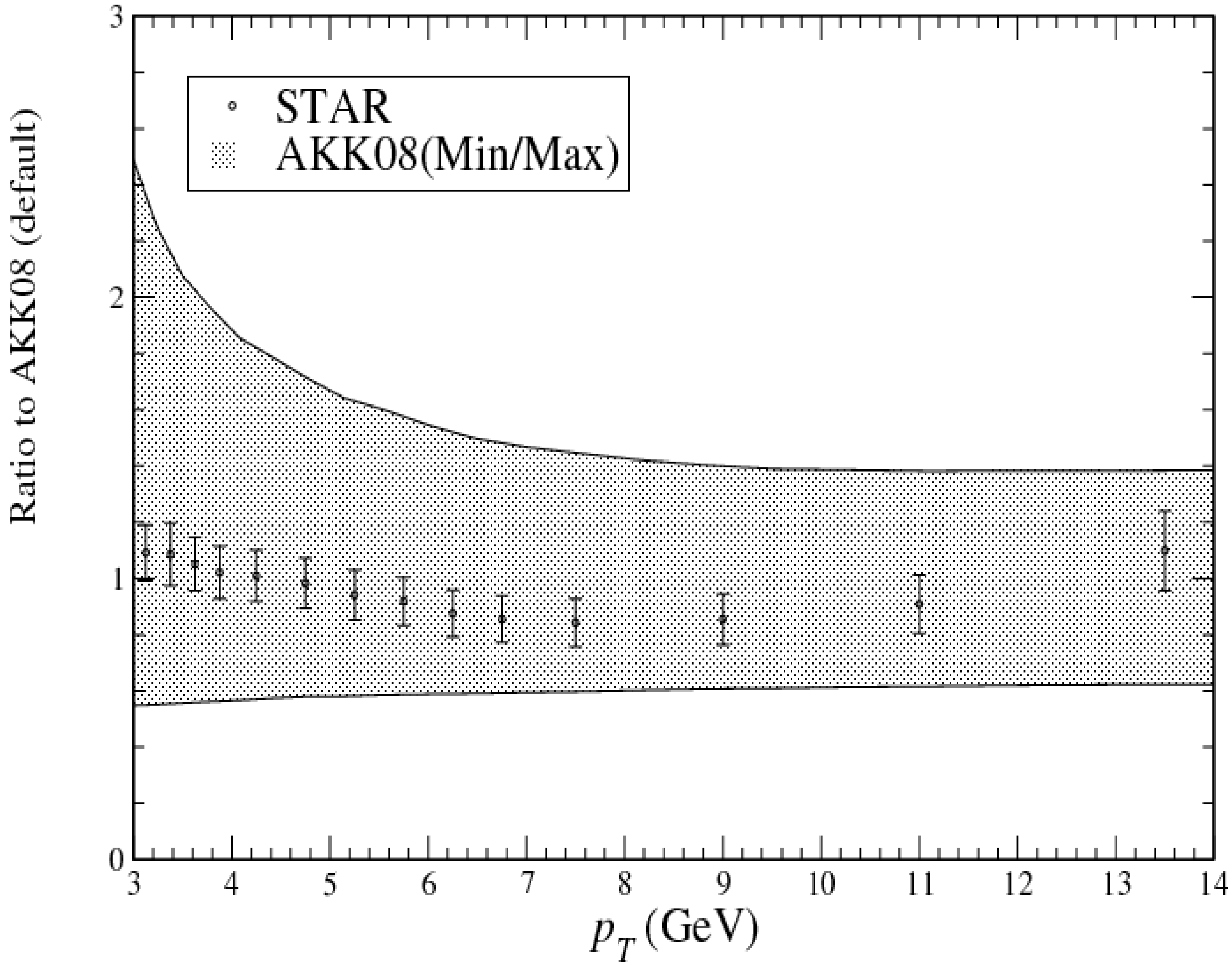
NLO PQCD calculation (investigation) from AKK:

MWST'08 PDF
AKK'08 FF

Latest parametr.

New data	Old data	Theory - AKK
PRD 79 (2009) 112005.	PRL 60 (1988) 1819	PRL 104 (2010) 242001

Charged hadron production in pp collisions at RHIC (200 GeV) :



NLO PQCD calculation (investigation) from AKK:

MWST'08 PDF
AKK'08 FF

Latest parametr.

New STAR data
Y. Xu, EPJ C62 (2009) 187

Theory - AKK
PRL 104 (2010) 242001

Long time valid conclusion:

(NLO) pQCD can reproduce

jet and hadron production at high-pT

in proton+ proton (antiproton) collisions

at RHIC, TEVATRON and LHC energies

New CDF data at TEVATRON!

If they valid (let us assume this), then possible answers:

- **--- a production mechanism is missing;**
- **--- a channel is missing;**
- **--- NLO is not enough, but NNLO, NNNLO, ...**
- **--- multiparton collisions are needed;**
- **--- multi-jet production ---> S. Pochybova talk**
- **--- something is wrong with the PDF fits;**
- **--- something is wrong with the FF fits (at high-pt);**
- **--- ... (???)**

Jet and hadron production mechanisms in heavy ion collisions

--- from RHIC to LHC energies ---

[Theory]

And what about proton-proton collisions ?

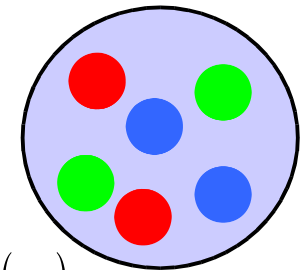
Particle production mechanisms in high energy HI collisions:

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

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

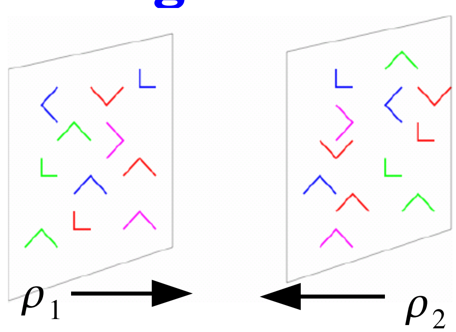
$$E_\pi \frac{d\sigma^{pp}}{d^3 p_\pi} = \int dx_1 \int dx_2 \int dz_c \, f_{a/p}(x_a, Q^2) \, f_{b/p}(x_b, Q^2) \frac{d\sigma}{d\hat{t}} \frac{D_c^\pi(z_c)}{\pi z_c^2}$$

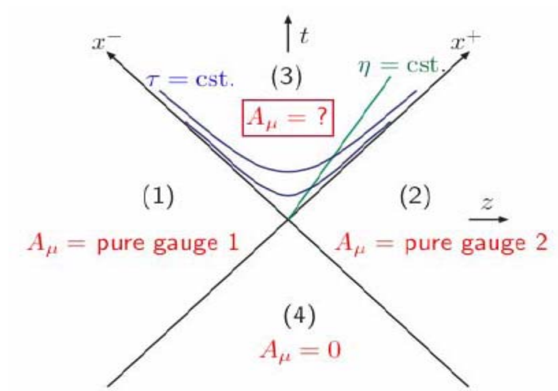
$$E_\pi \frac{d\sigma^{AB}}{d^3 p_\pi} = \int d^2 b \, d^2 r \;\; t_A(\vec{r}) t_B(|\vec{b} - \vec{r}|) \;\; E_\pi \frac{d\sigma^{pp}}{d^3 p_\pi} \otimes S(\ldots) \otimes M(\ldots) \otimes Q(\ldots) \otimes F(\ldots)$$

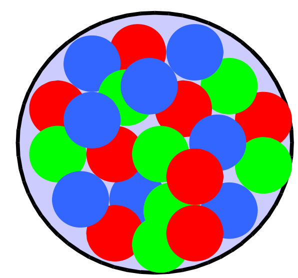


Dilute gas

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







CGC: high density gluons

CGC initial condition:

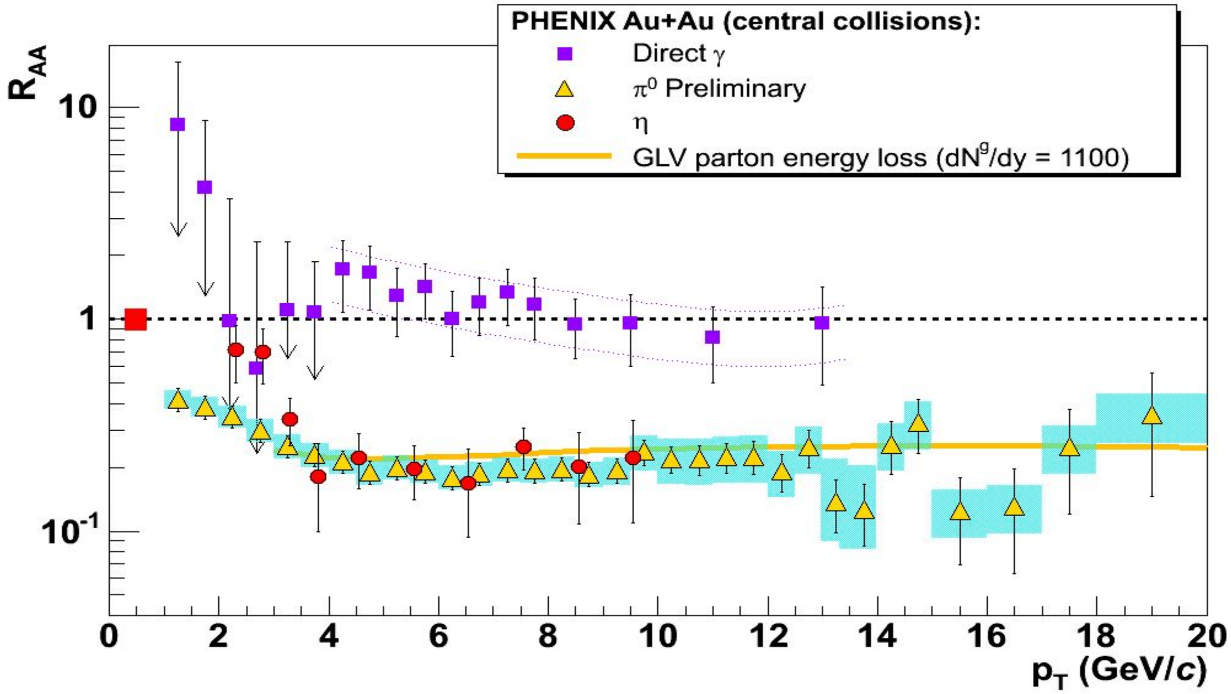
$$J^\mu = \delta^{\mu +} \delta(x^-) \rho_1(\mathbf{x}_T) + \delta^{\mu -} \delta(x^+) \rho_2(\mathbf{x}_T)$$

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:

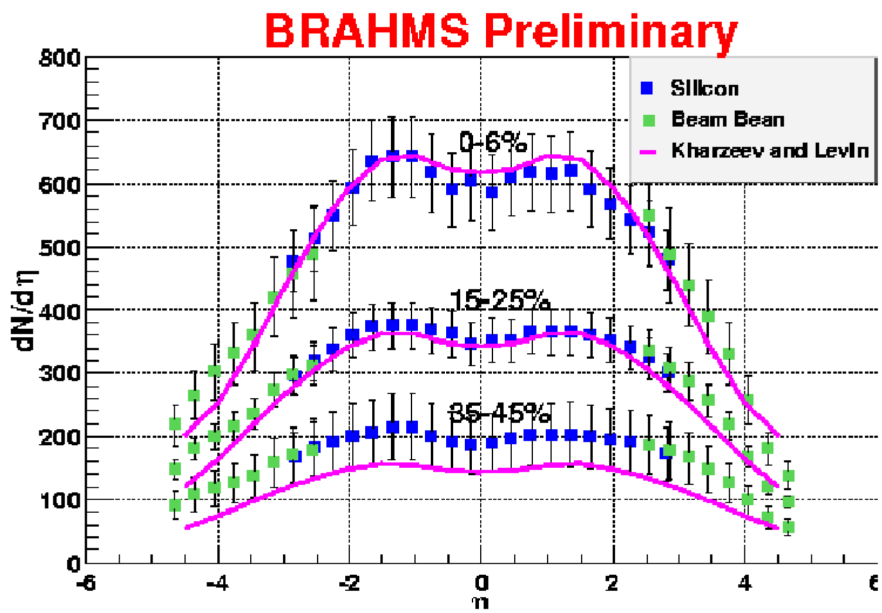
I. pQCD model:

- --- hard probes
- --- high-p_T physics
- --- jets
- --- h-h correlations
- --- ...



II. CGC model:

- --- soft physics
- --- multiplicities
- --- centrality dependence
- --- E_T production
- --- rapidity distributions
- --- ...

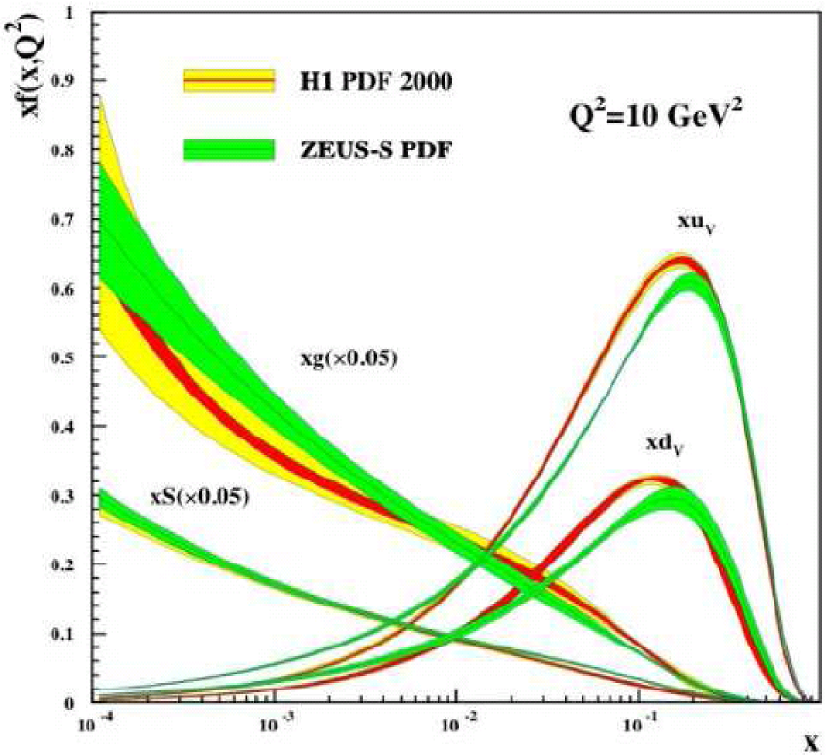


Problems:

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:

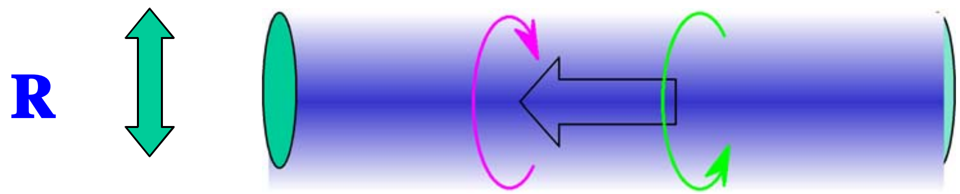


Large-x: valence partons
random color charge, $\rho^a(x)$
Small-x: radiation field,
created by $\rho^a(x)$

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:

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

integrated probability at mass m:

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

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

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

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

--- 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:

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

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):

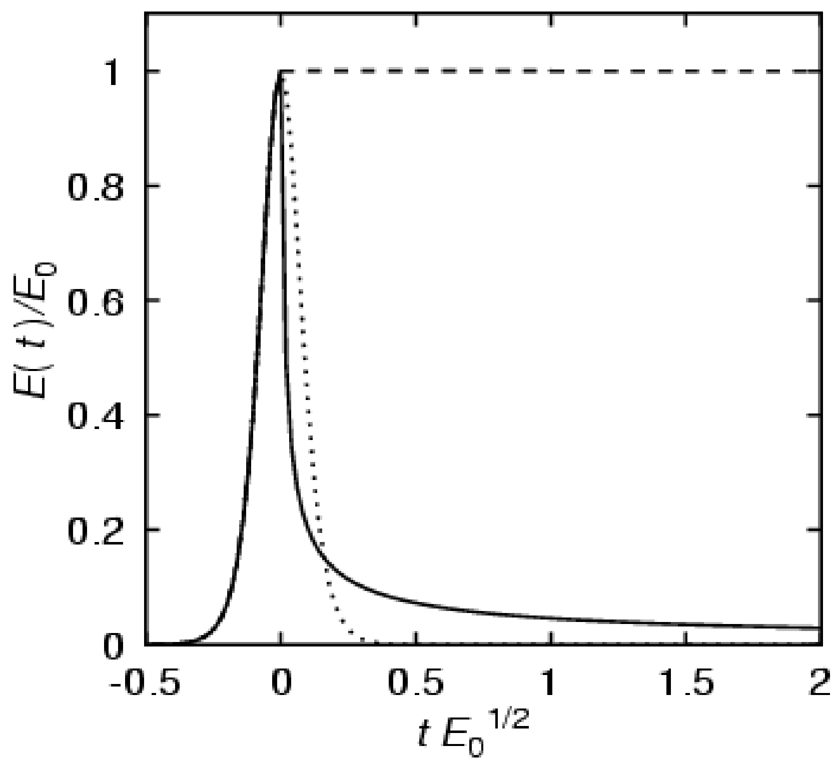
$$E_{pulse}(t) = E_0\left[1 - \tanh^2(t/\delta)\right]$$

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):

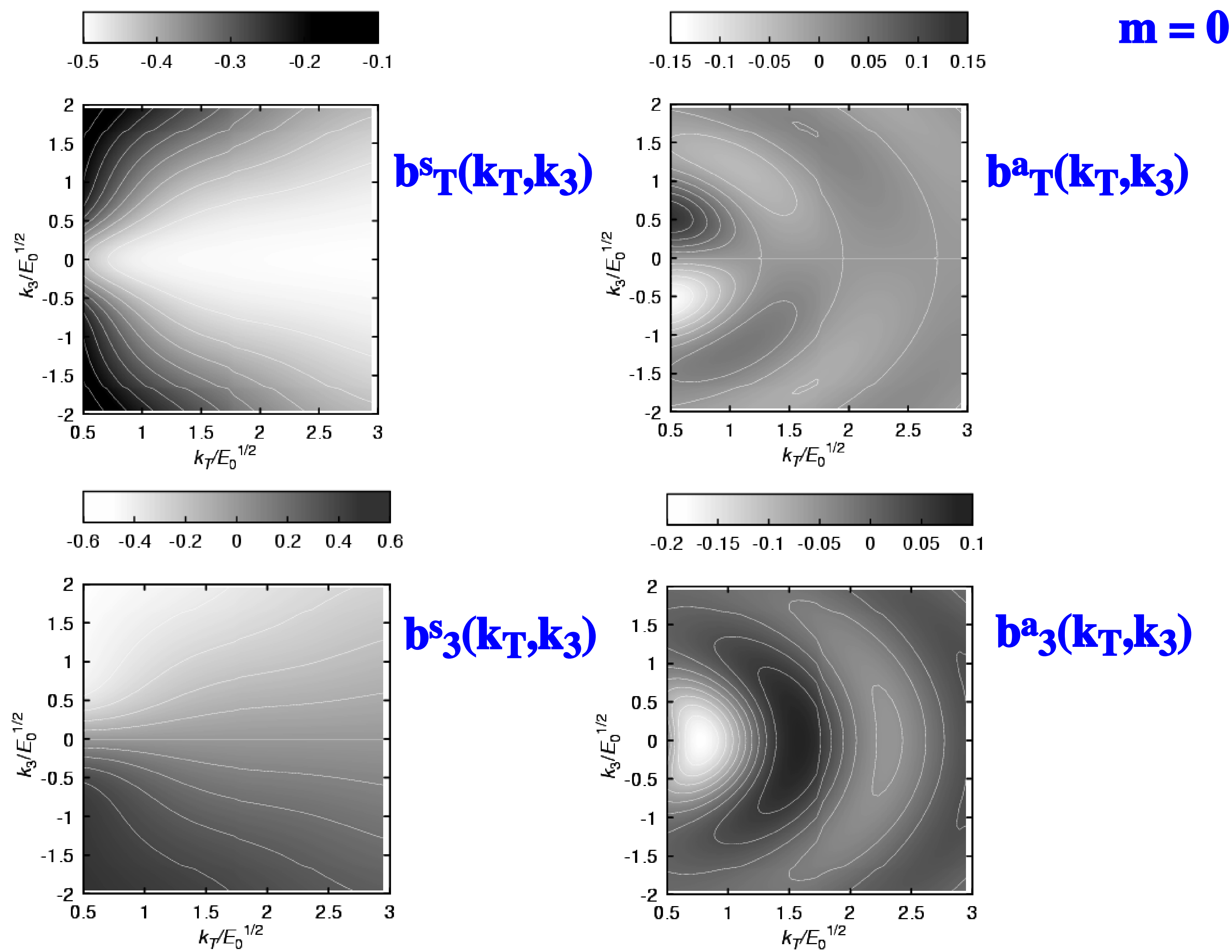
$$E_{scaled}(t) = E_{pulse}(t) \quad at \quad t<0$$
$$E_{scaled}(t) = \frac{E_0}{(1+t/t_0)^{\kappa}} \quad at \quad t<0$$



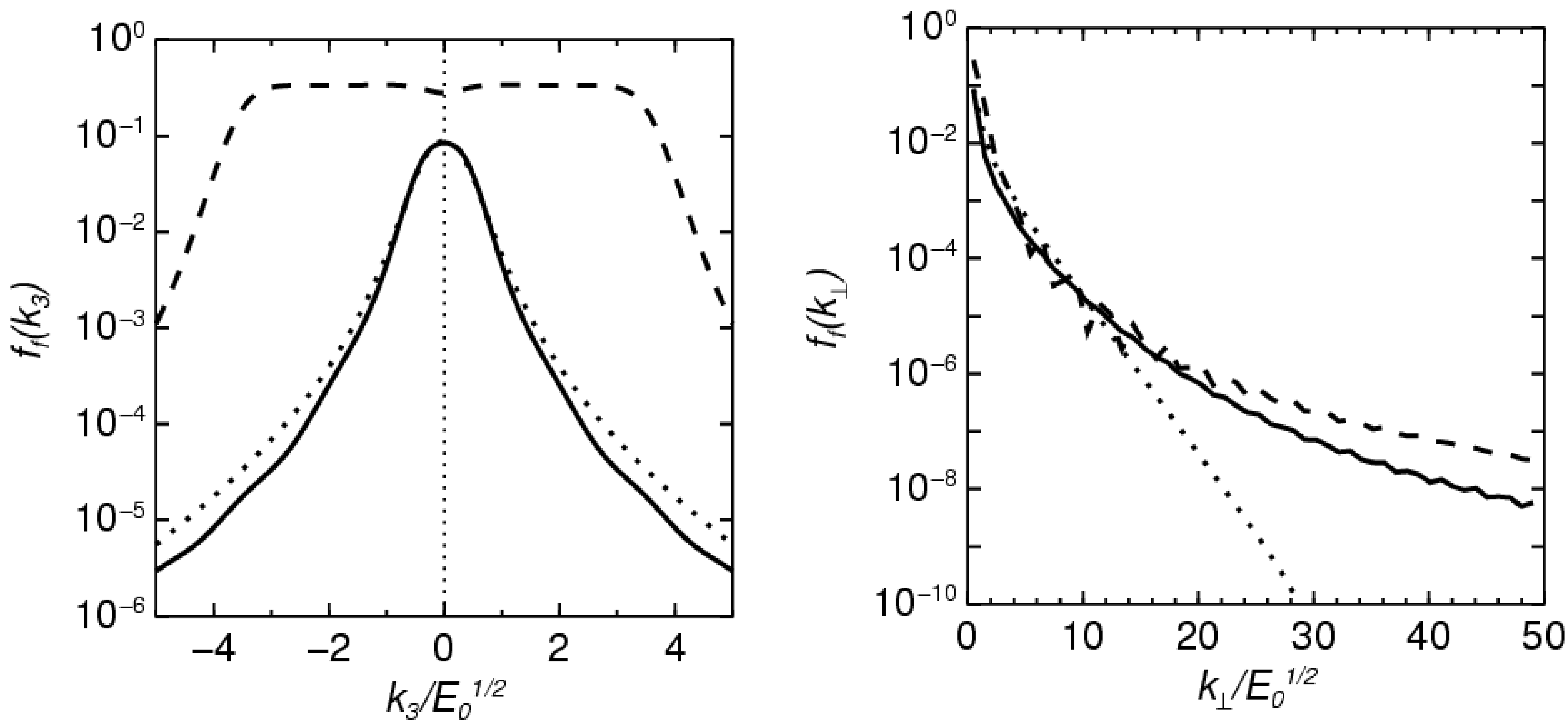
$$\delta = 0.1/E_0^{1/2} \quad at\ RHIC\ energy$$

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

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



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



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

$k_T/\sqrt{E_0} = 0.5$

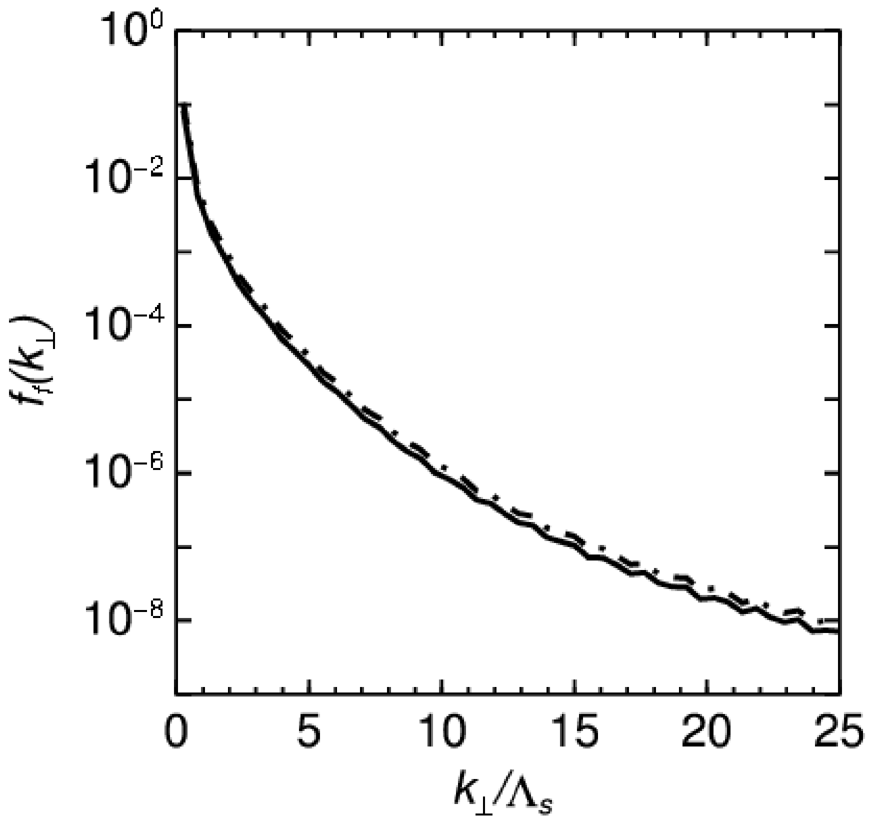
$f_f(k_T)$: transv. mom. distr.

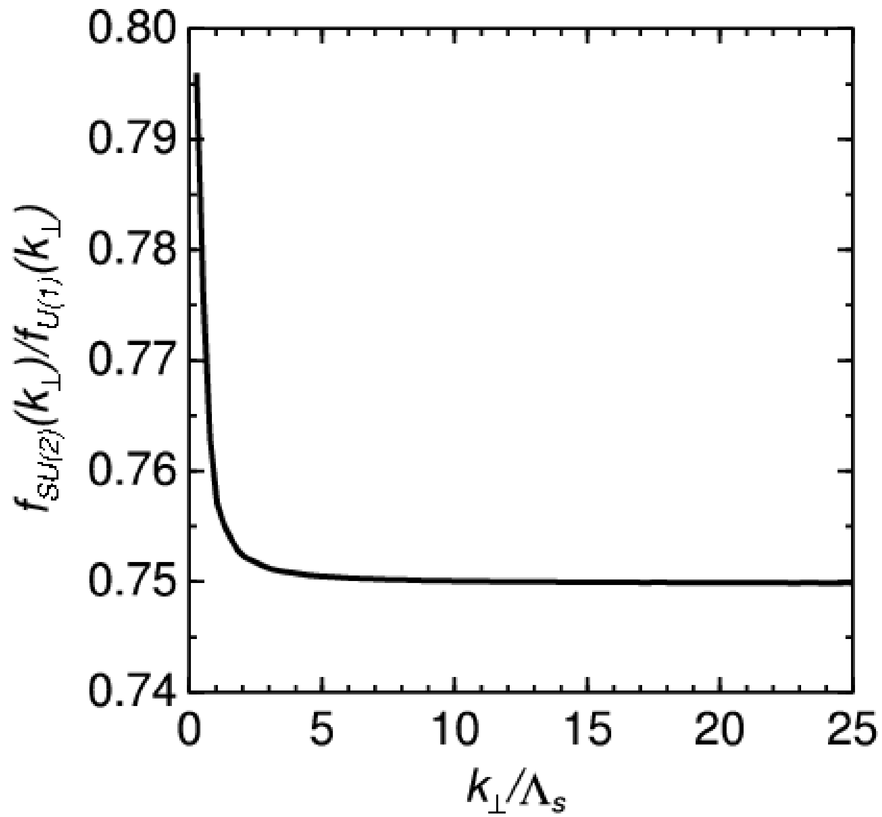
$k_3 = 0$

⇒ exponential (pulse)

⇒ polinomial (scaled)

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





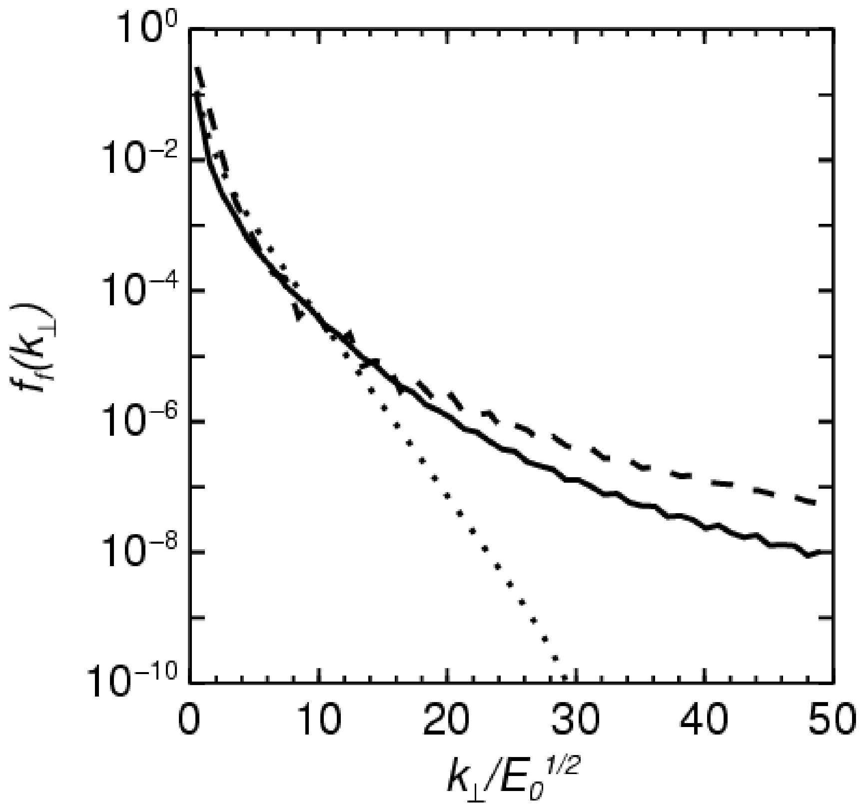
$f_f(k_T)$: transv. mom. distr.

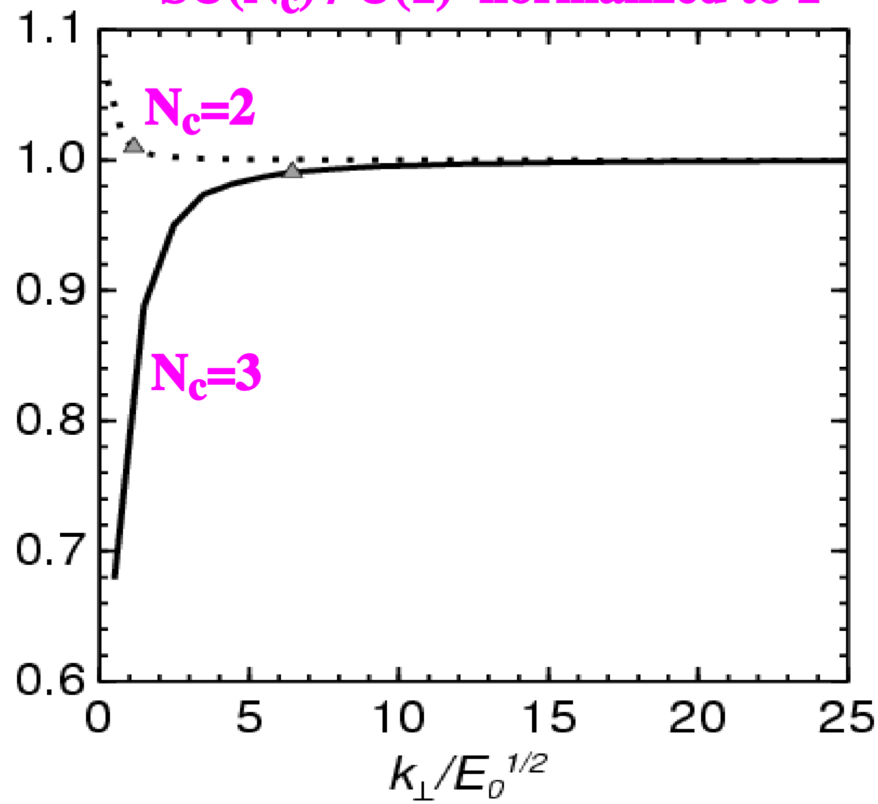
at $k_T/\sqrt{E_0} = 0.5$
in U(1) and SU(2)
[Bjorken scaled]

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.)

Conclusions - I:

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

2. The overlap of colliding heavy ions (protons ?!) determine the space-time structure of the early phase, which can be substituted by a pulse-like strong field.

3. Short pulses: the time evolution of the pulse determines the shape of the transverse momentum spectra.

4. Thus: non-perturbative production could be suppressed
   at intermediate pT and
   could become dominant at high-pT (beyond pQCD).

5. Could we validate the formation of a strong field in pp ?

Q: Do we have another way to check the overlap of pQCD and NPQCD yields ?

A: Quark-pair production in strong SU(N) fields

--- quark mass dependence ---

Mass dependent fermion production in SU(2):

Quark-pair production depends on the mass:

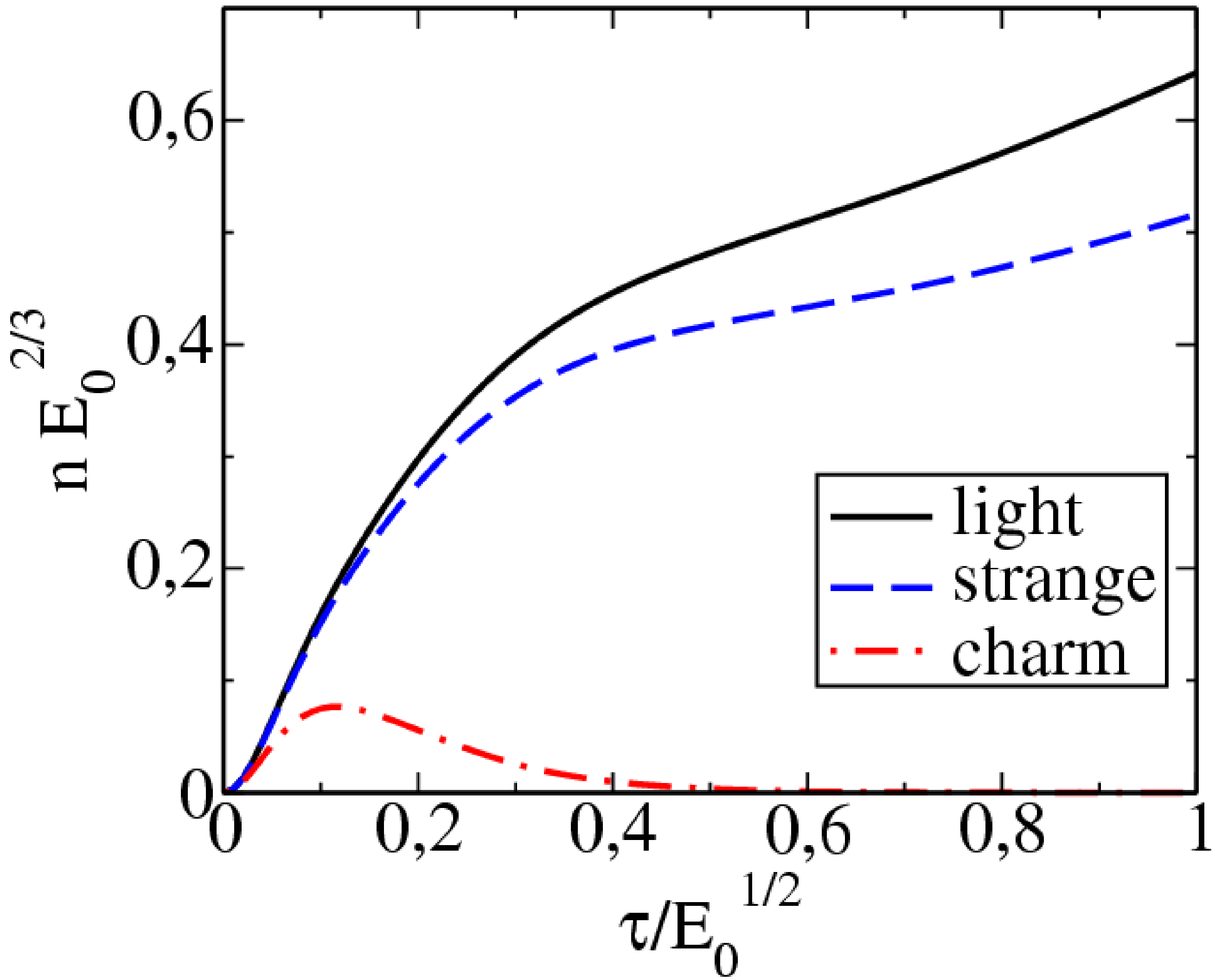
m(light)	**=**	**8 MeV**
m(strange)	**=**	**150 MeV**
m(charm)	**=**	**1200 MeV**
m(bottom)	**=**	**4200 MeV**

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) ??

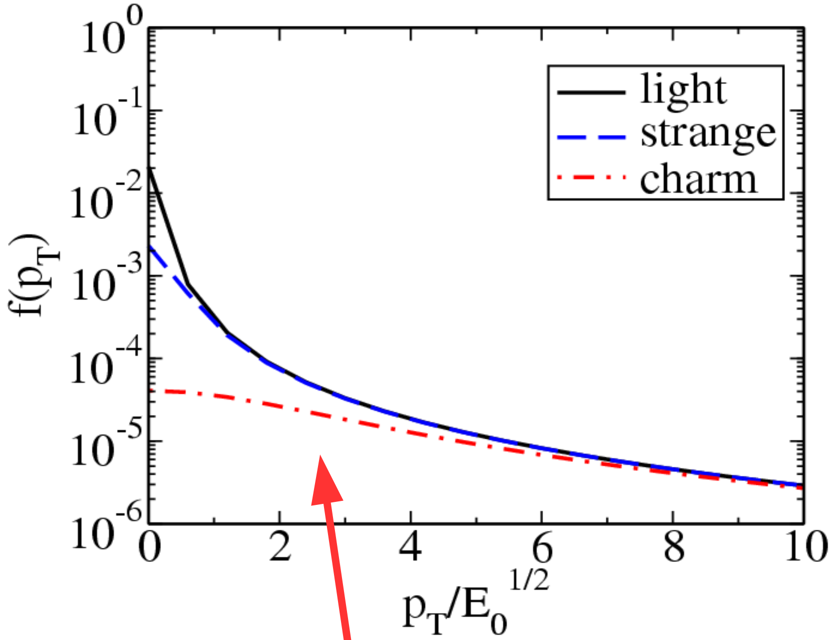
$\tau \quad \Rightarrow\Rightarrow \quad \delta$

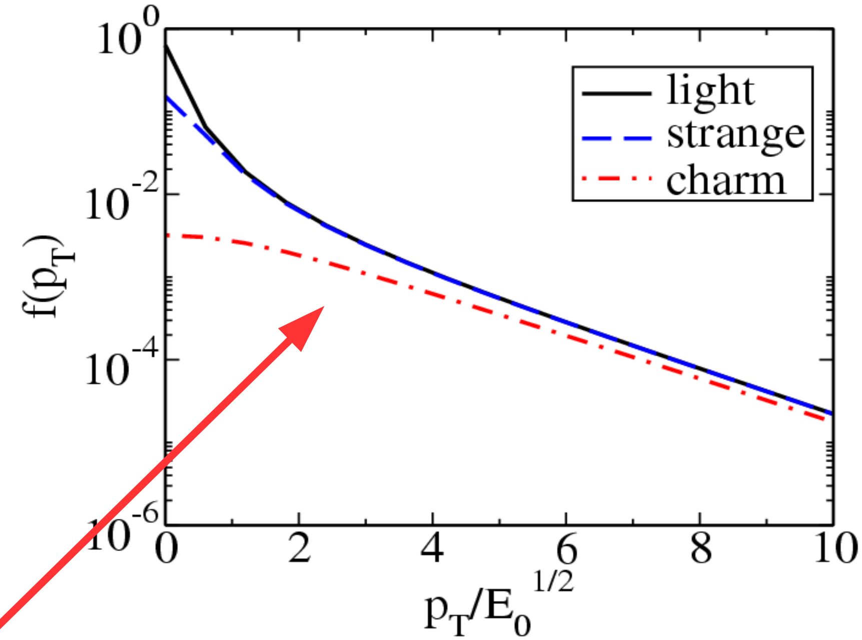
Mass dependent fermion production in SU(2) [pulse-like time dep.]



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

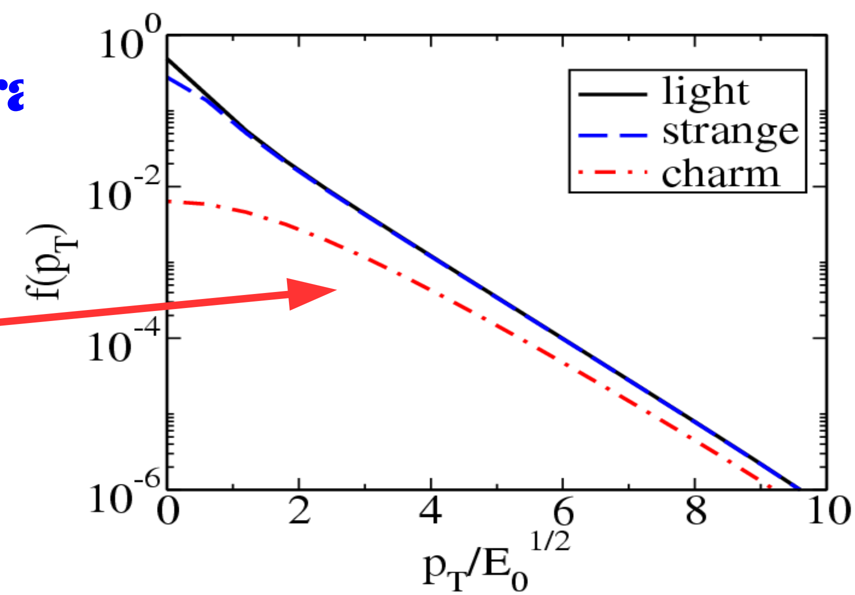
Mass dependent fermion production in SU(2) [pulse-like time dep.]



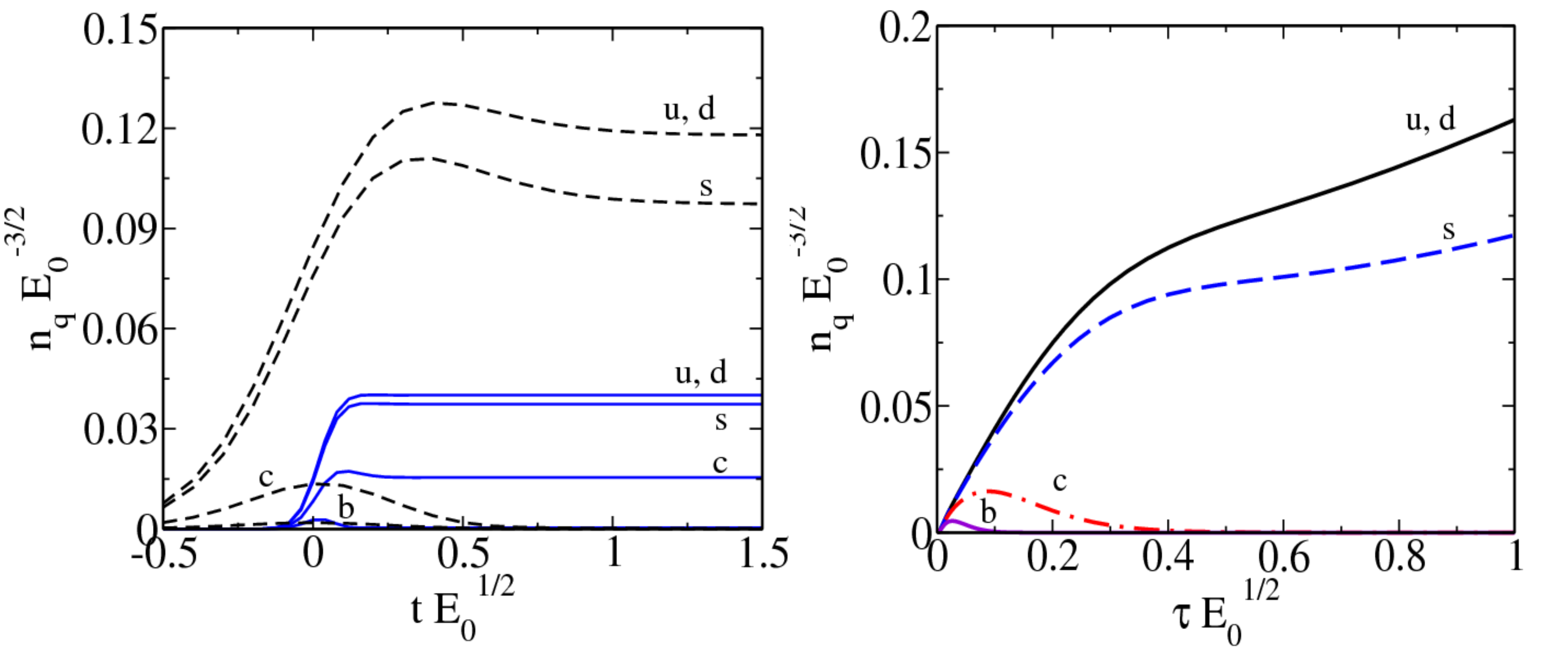


Transverse momentum spectra at different pulse width:

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



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



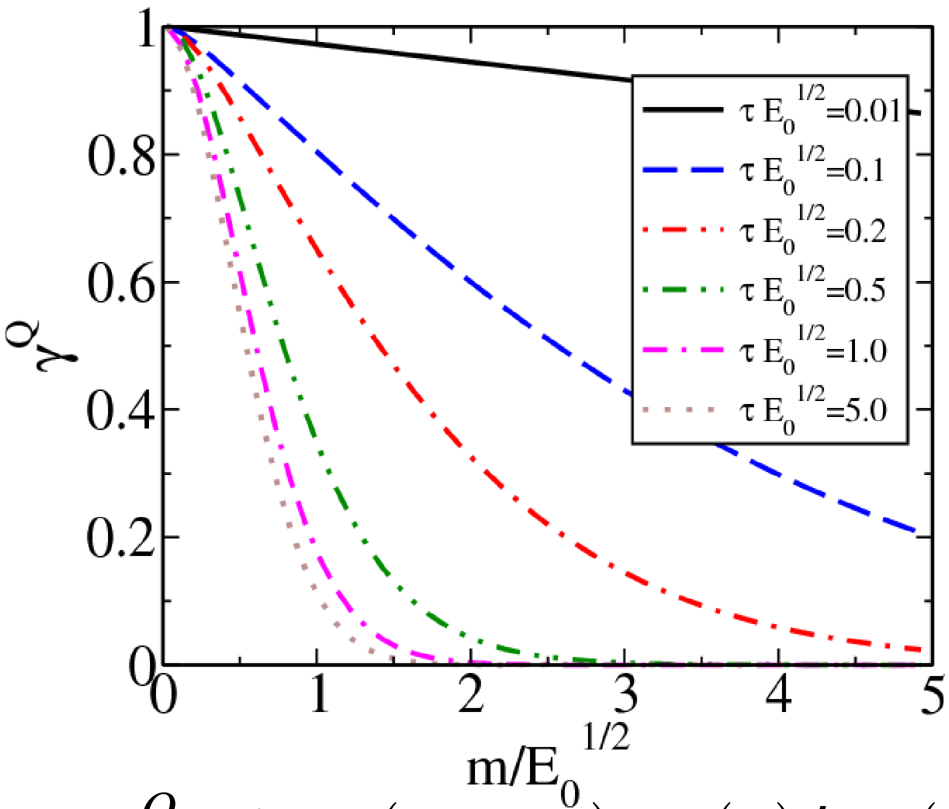
t: time in the CM frame **τ: pulse width ($t \to \infty$)**

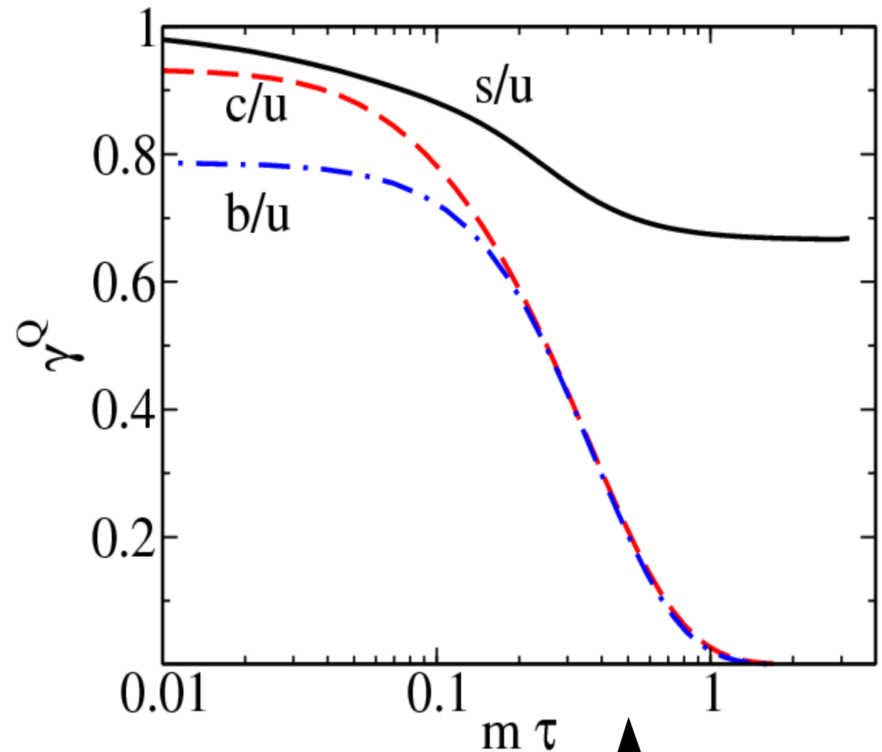
Full line: $\tau\sqrt{E_0} = 0.1$ ($\tau =$ 0.05 fm)

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

$m\tau$ scaling !!!!

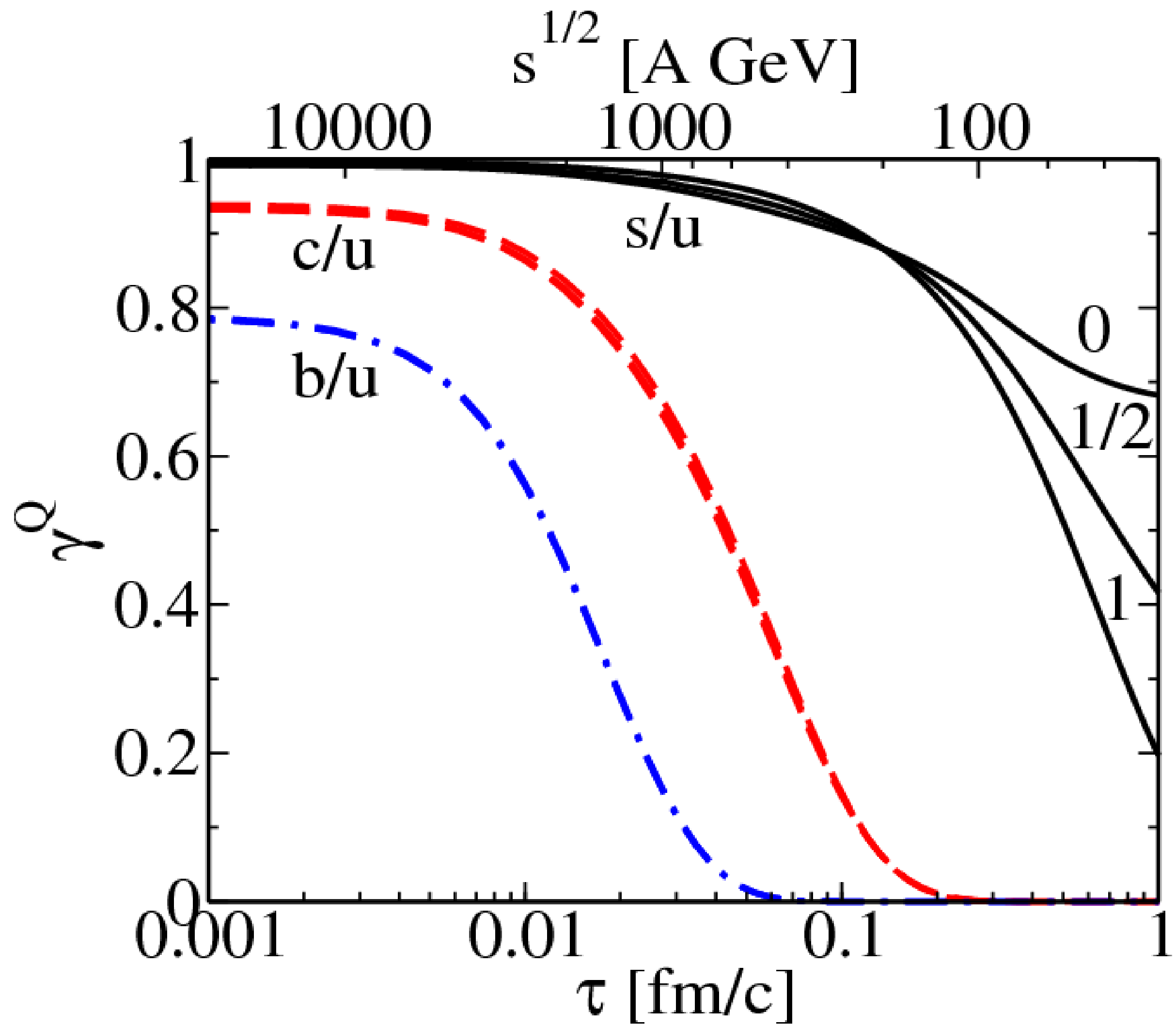
Blue line: $\tau\sqrt{E_0} = 0.1$ ($\tau =$ 0.05 fm)

At large τ heavy quarks are suppressed.

Enhanced heavy fermion production at small τ

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

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:

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

Suppression factor:

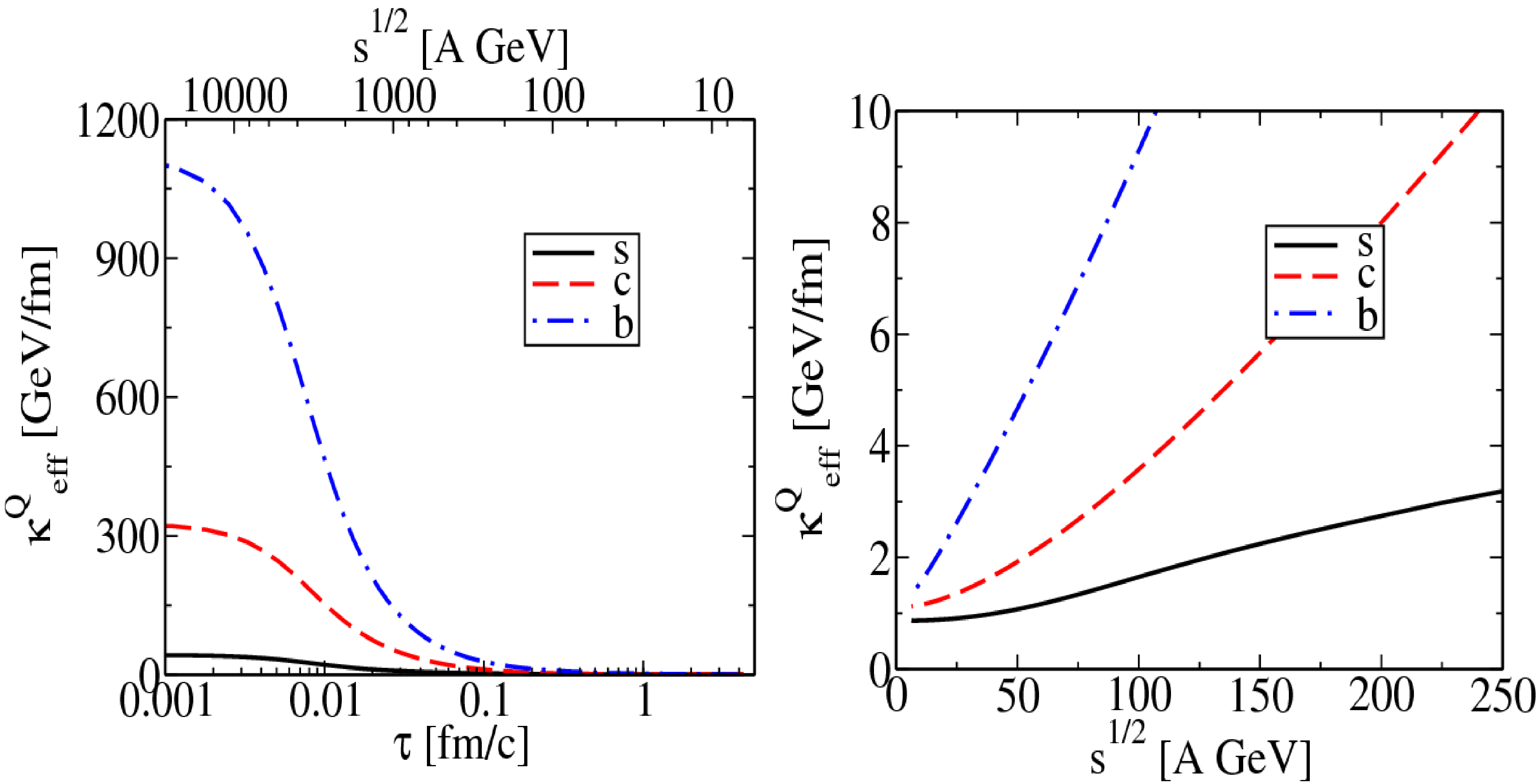
$$\gamma^Q = \exp\left(-\pi\left(m_Q^2 - m_q^2\right)/\kappa\right)$$

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:

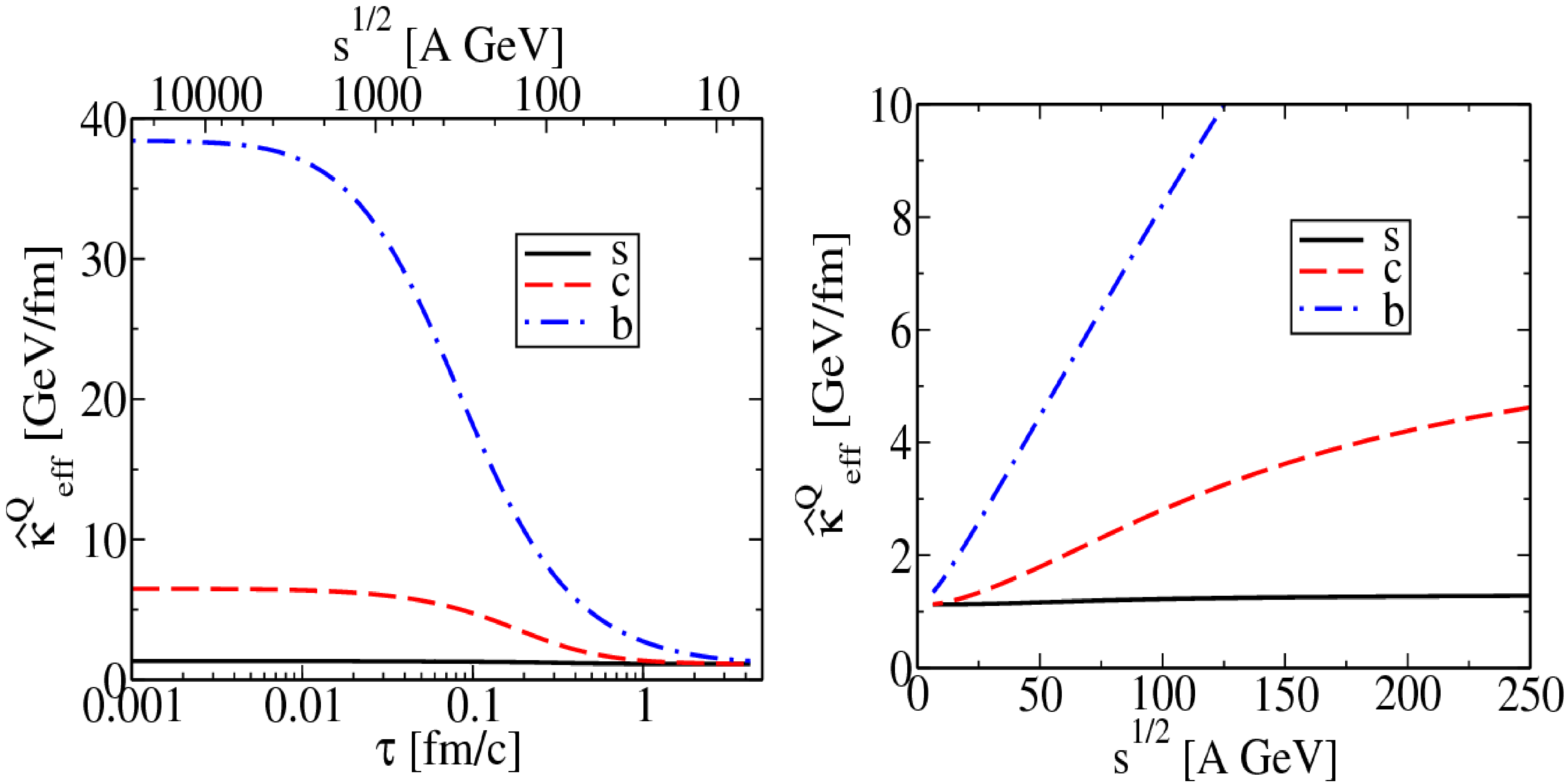
Let us keep a fixed string constant for the light quarks

$$\hat{\kappa}^{u}_{eff} = 1.17\, GeV / fm$$

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

$$\hat{\gamma}^{Q}_{\infty} = \left(\frac{\hat{\kappa}^{Q}_{eff}}{\hat{\kappa}^{u}_{eff}}\right)^{2} \exp\left(-\pi \frac{m_Q^2}{\hat{\kappa}^{Q}_{eff}} + \pi \frac{m_u^2}{\hat{\kappa}^{u}_{eff}}\right) = \gamma^{Q}(\tau)$$

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:

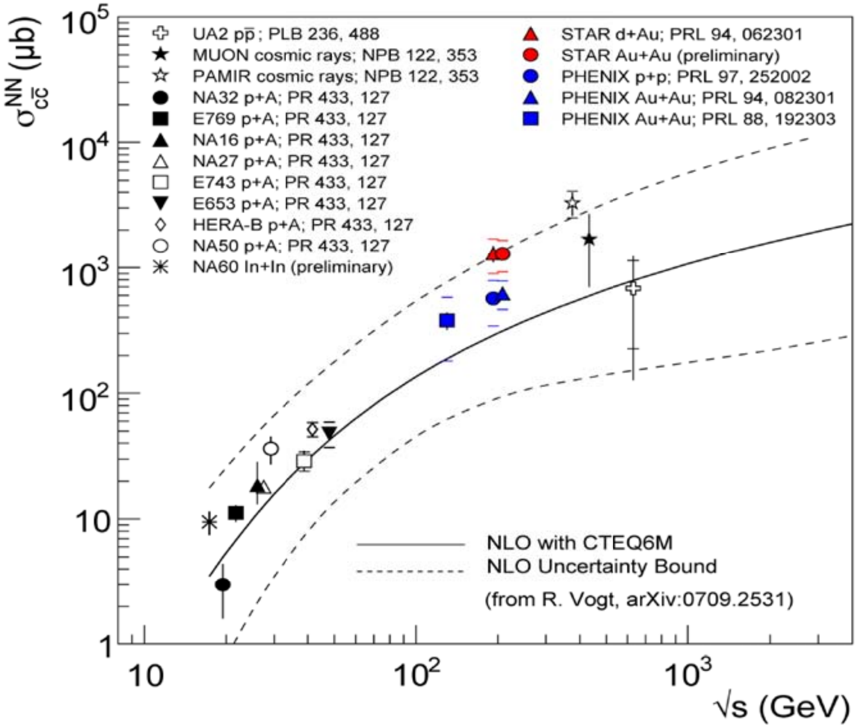
	130 AGeV	200 AGeV	1 ATeV	2 ATeV	5.5 ATeV
u,d	1.17	1.17	1.17	1.17	1.17
s	1.24	1.26	1.32	1.33	1.34
c	3.32	4.2	6.1	6.3	6.5
b	10.3	14.7	32	36	38

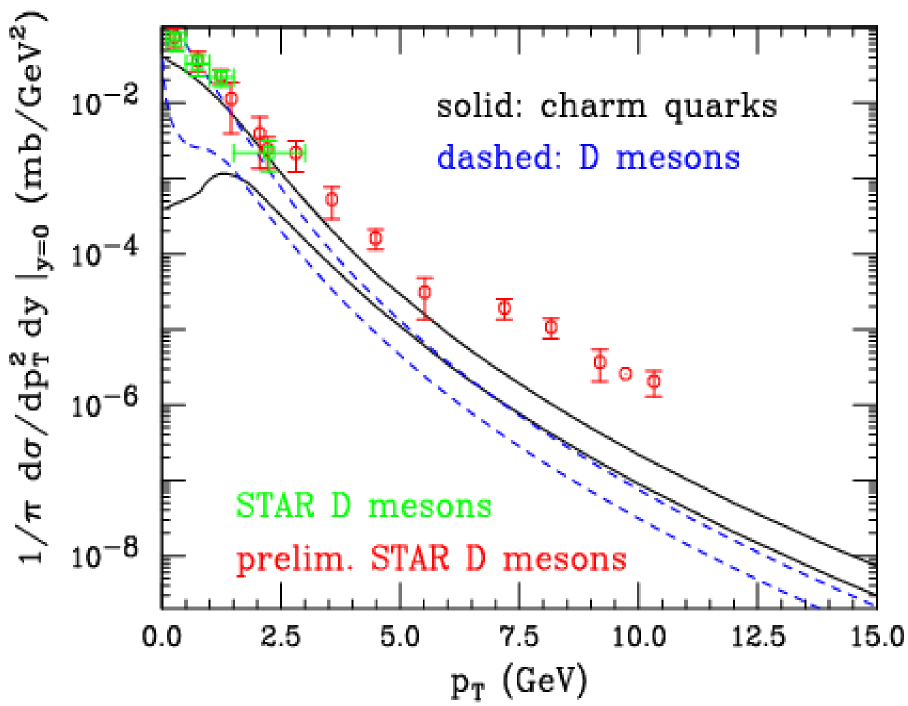
Saturation at higher LHC energies !!!!

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**

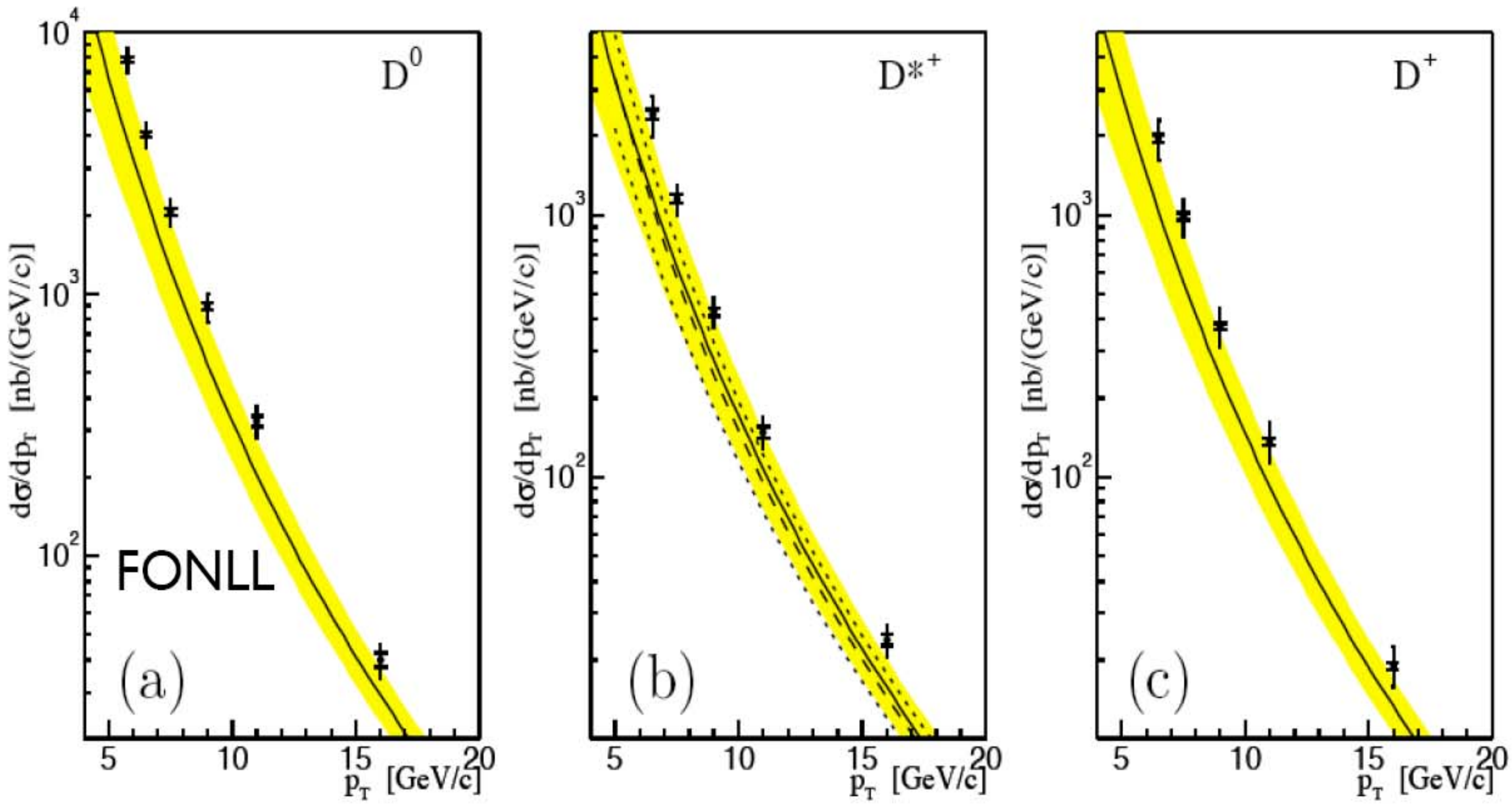
Data are at the upper limit of theory (or beyond) !?? (m_c = 1.2 GeV)

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)

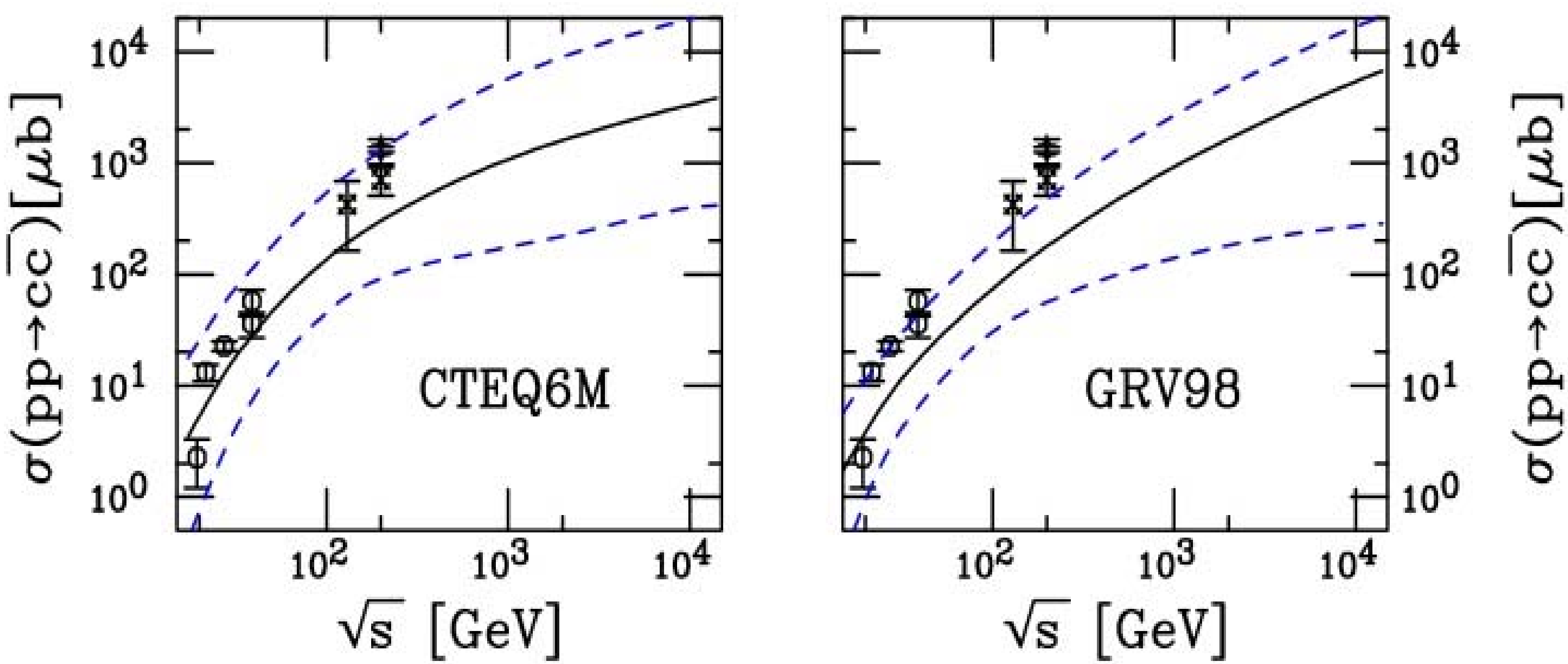
CDF Run II c → D data [PRL 91:241804,2003]



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, √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).

Theoretical conclusions (today):

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

2. If the overlap of colliding objects is very short (the time scale of the initial phase is also short), then
   - --- transverse momentum spectra depend on overlap
   - --- heavy quark production is not suppressed large mass.

3. High-pT spectra can carry message about the formation of a coherent strong field (even in pp collision)

4. 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 ~ $\sqrt{s}$ = 1-2 TeV (and wait for LHC data)

Experimental side: Particle identification at high-pT at LHC

1. LHC ALICE: TPC + TOF + ITS

   Statistically up to 40-50 GeV/c

2. LHC ALICE upgrade: VHMPID (track-by-track)

   Very High Momentum Particle Identification Detector

   RICH modul + Trigger modul

   Module-0: Installation in 2013 (hopefully)

   Modul-Xs: Installation in 2015

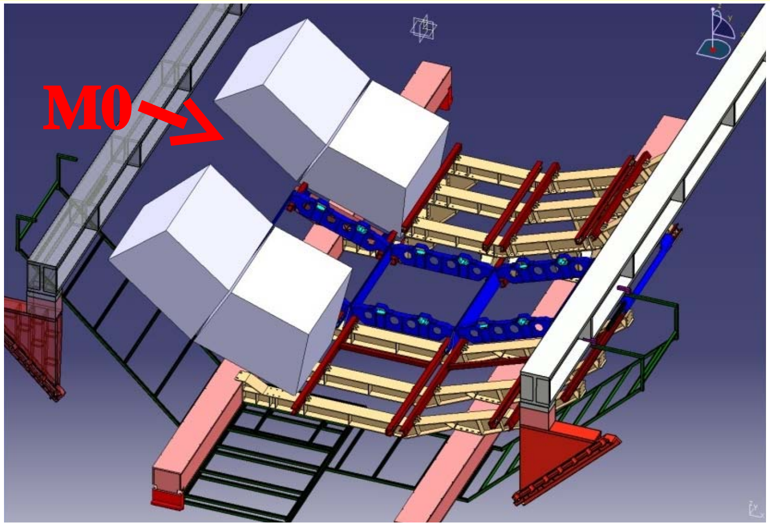
VHMPID mission: to identify charged hadrons

up-to 25 GeV (C_4F_{10})

or at even higher momenta (CH_4)

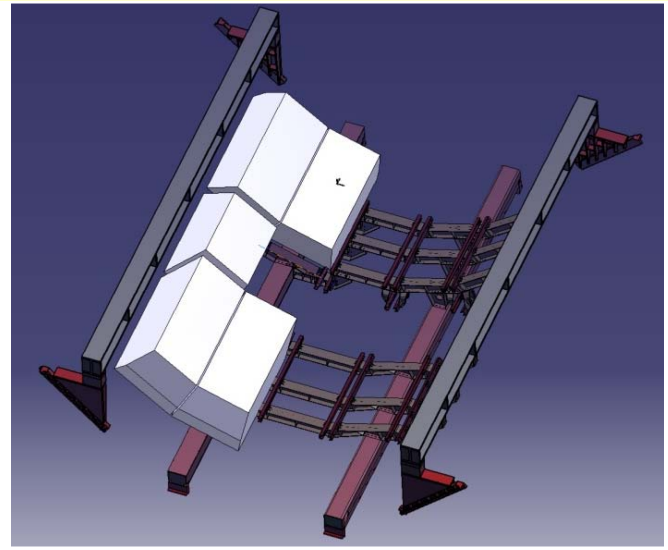
VHMPID layout evolution (2009-2010)

16 April 2010



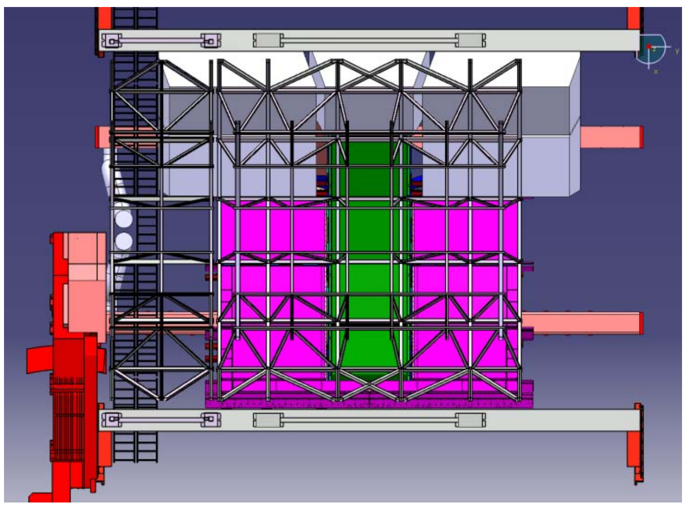
single boxes on the sides

12 May 2010



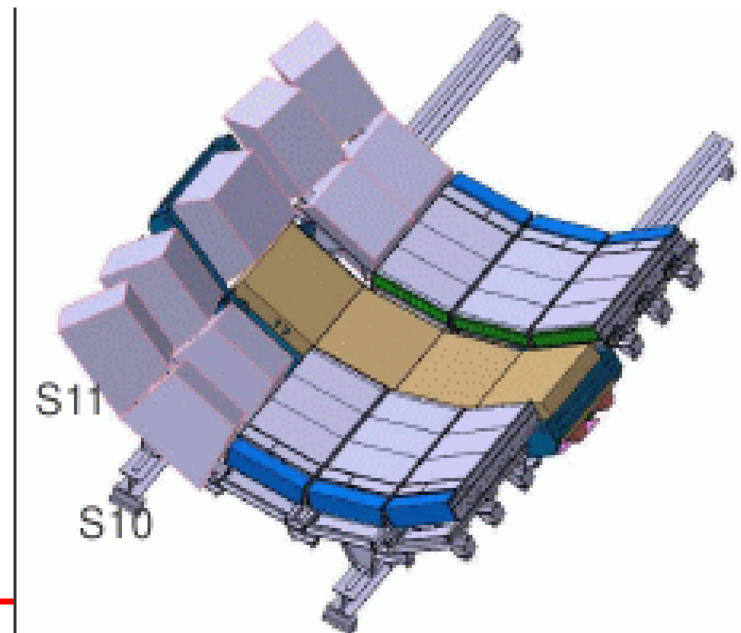
Zero module added, larger side-boxes

20 May 2010



Critical remark from the Technical coordination:
we should stay within the space-frame length

Original plan (2009):



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