# Study of one-particle spectra at high-pT at LHC energies

## Perturbative and non-perturbative particle production mechanisms at LHC energies

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***5th Workshop on High-pT Physics at LHC***
***28 September 2010, Mexico City***

# *1. Motivation*

## *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 $p+p \rightarrow \pi + X$ 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**

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

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

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

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

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

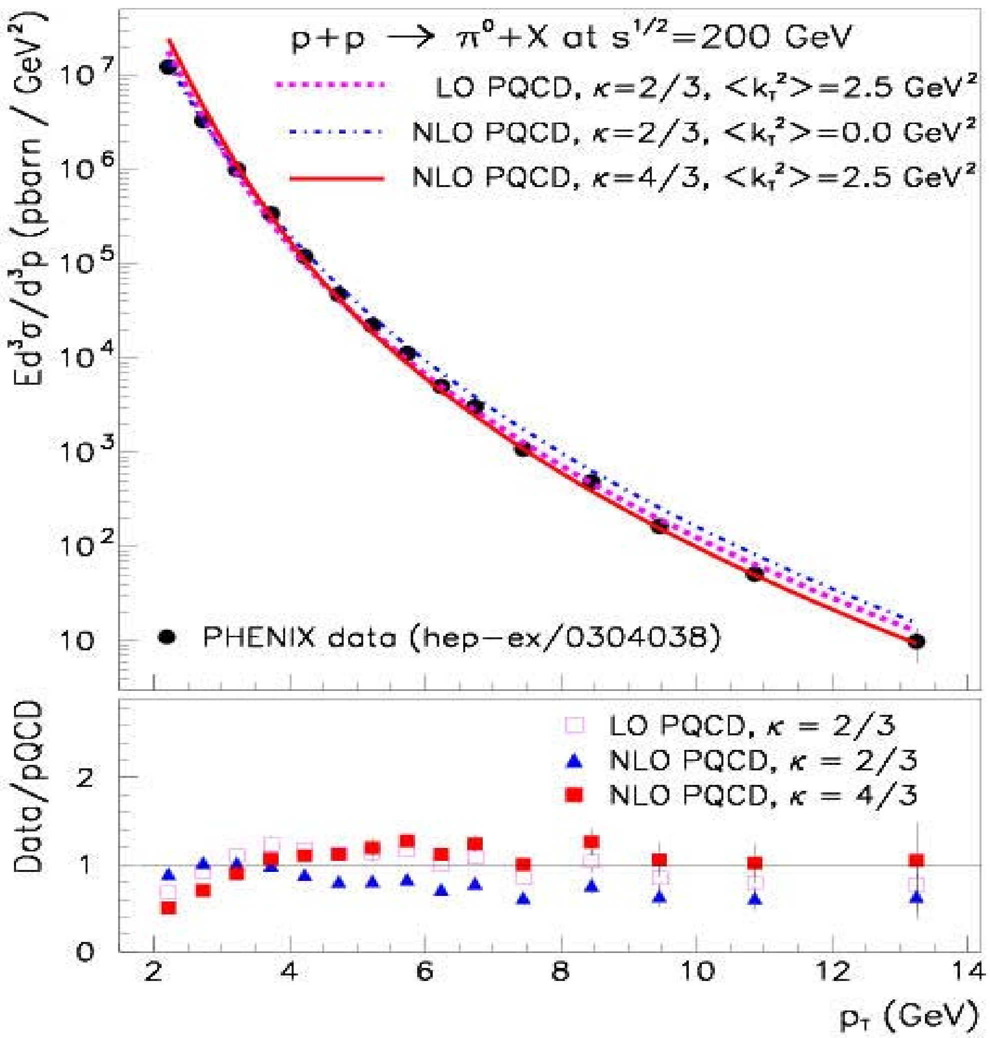
**Where we use gaussian**

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

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.***

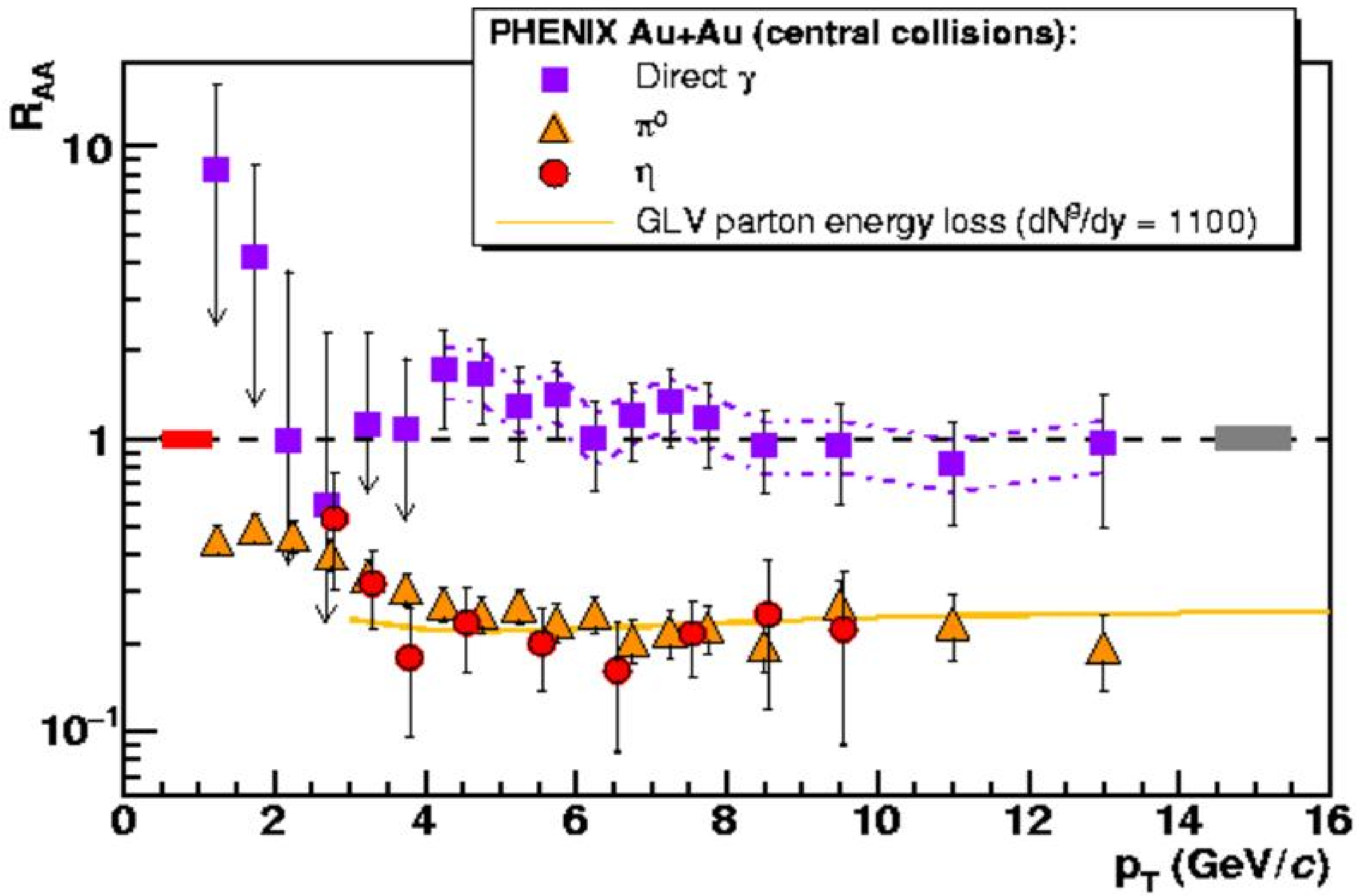
***Which $\kappa$ should be used ?***

***Y. Zhang, G. Fai, G. Papp, G.G. Barnaföldi, P.L.: PRC 65 (2002) 034903.***

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

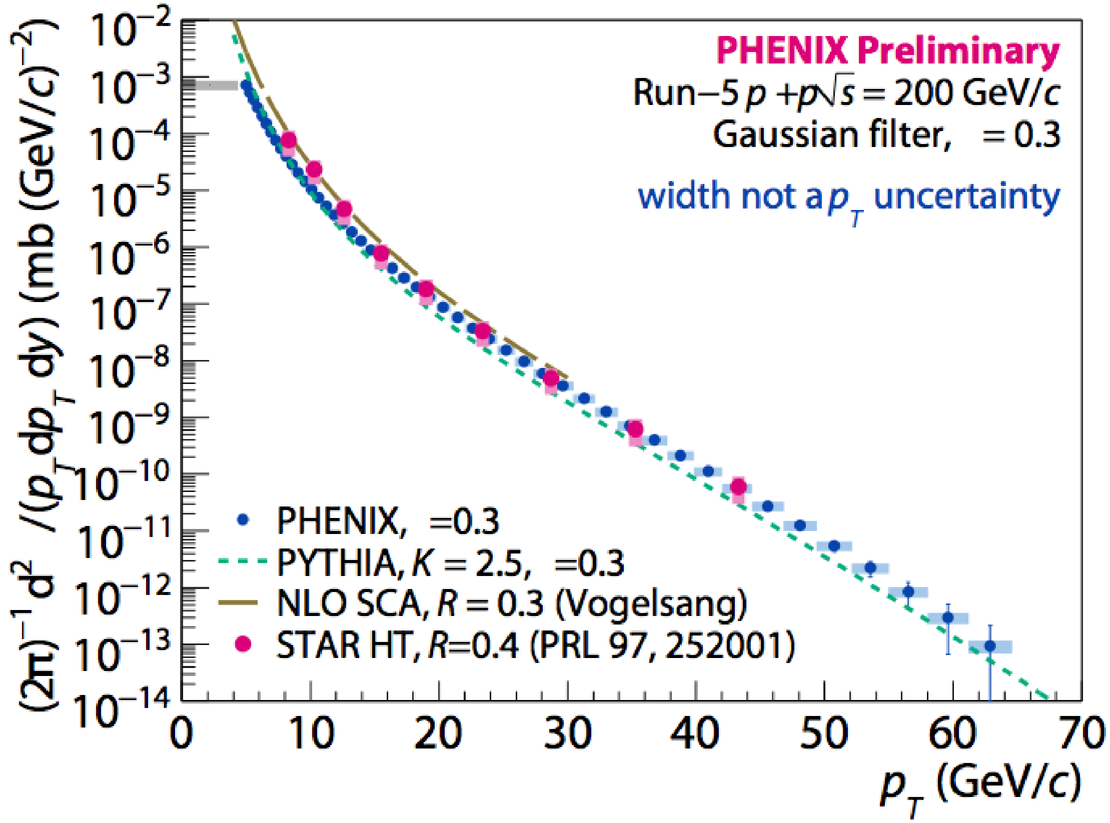
**Jet energy loss -> Jet-tomography, corona-graphy, ...**

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




nucl-ex/0601037

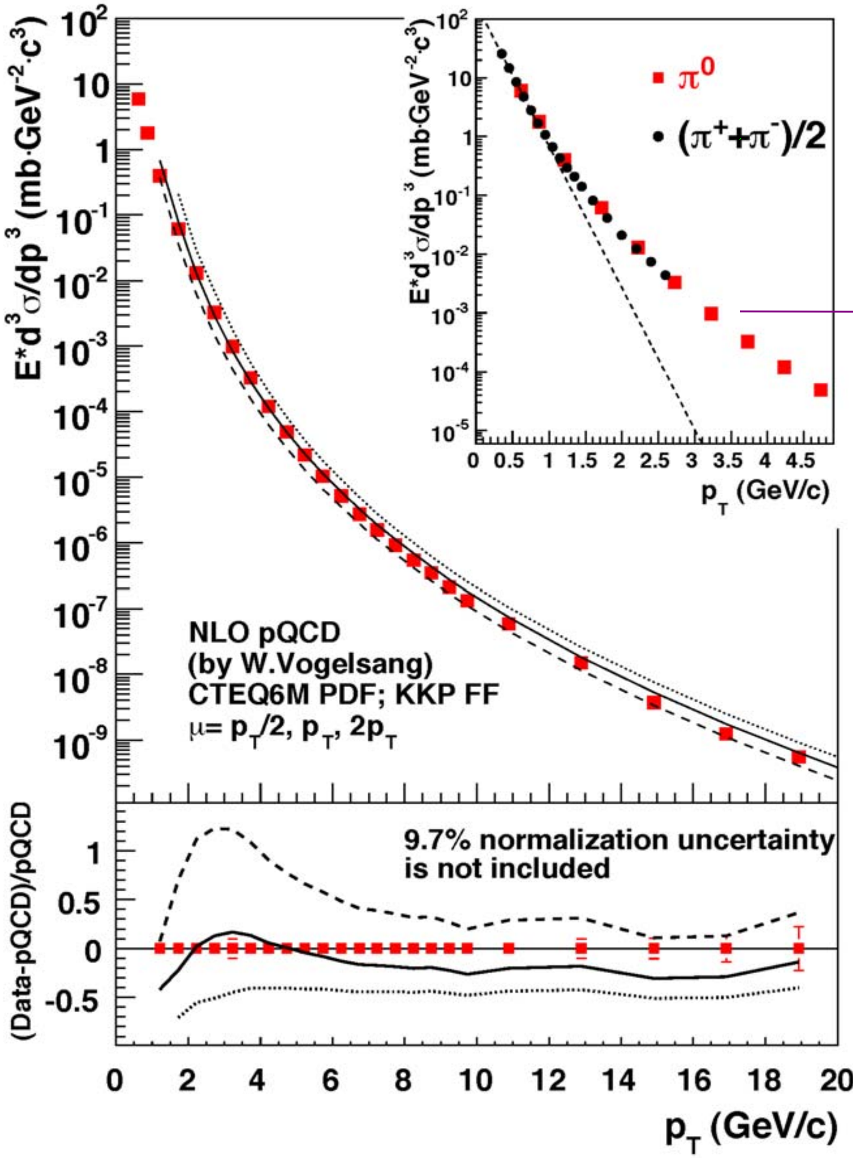
# Jet production in pp collisions in the high-pT region at RHIC:




*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:

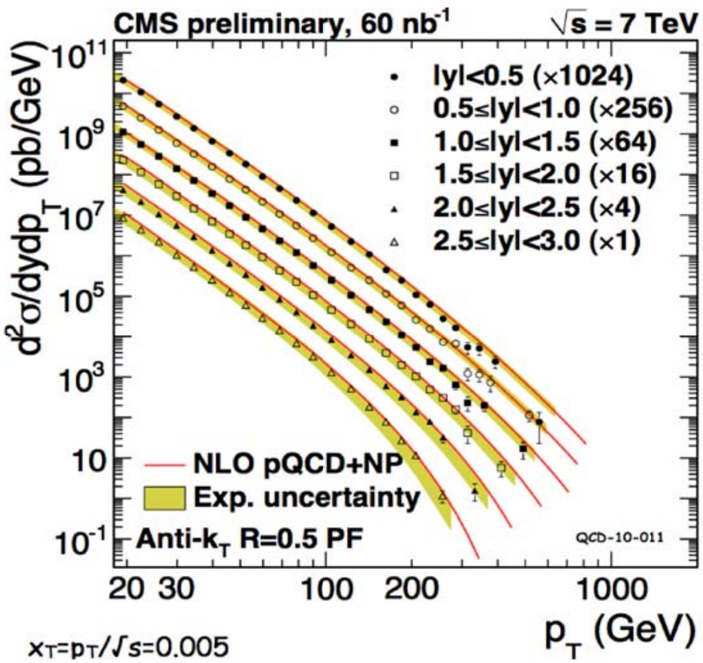


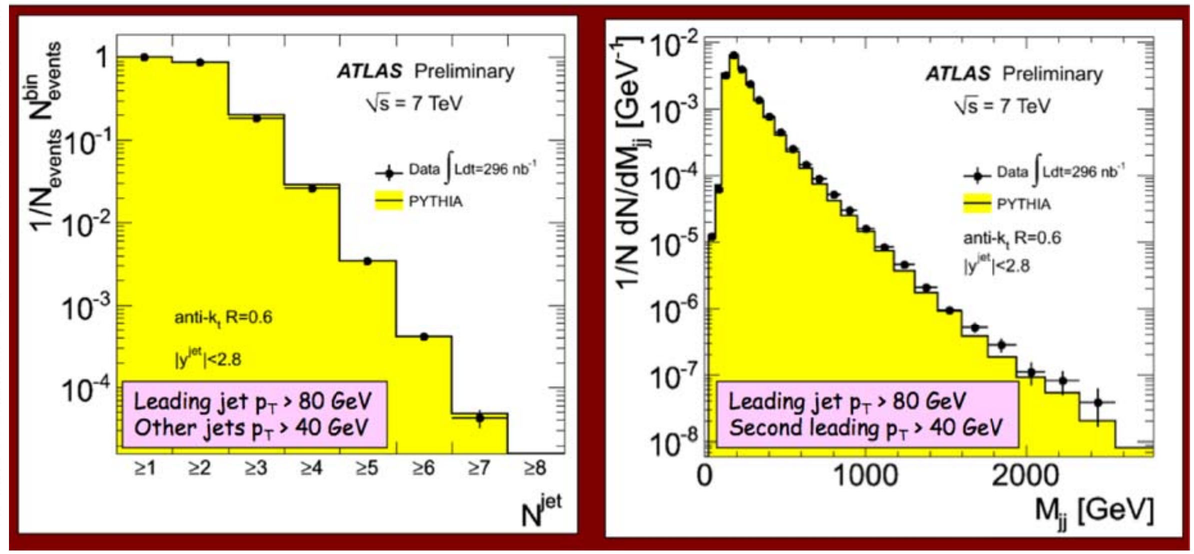

*PHENIX results (2006)*
*p+p -> pi0 at 200 GeV*

*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:



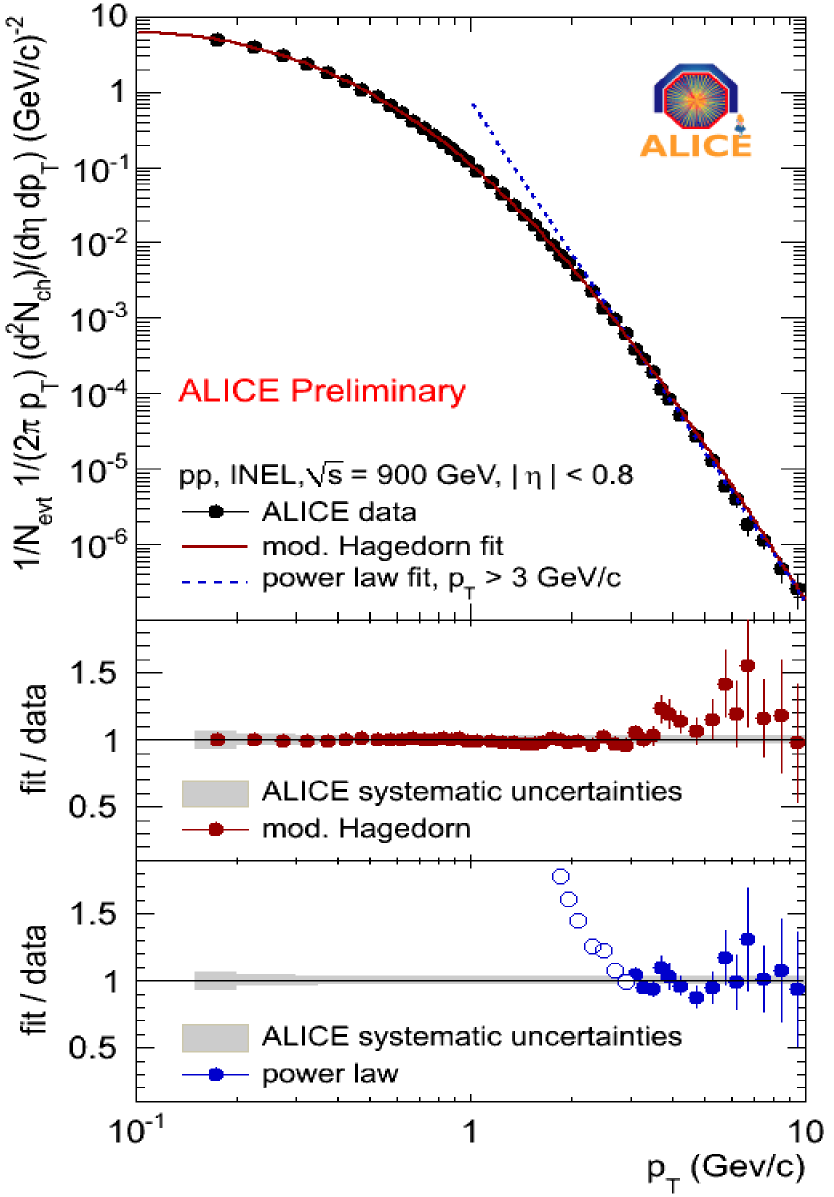

*CMS result at 7 TeV*

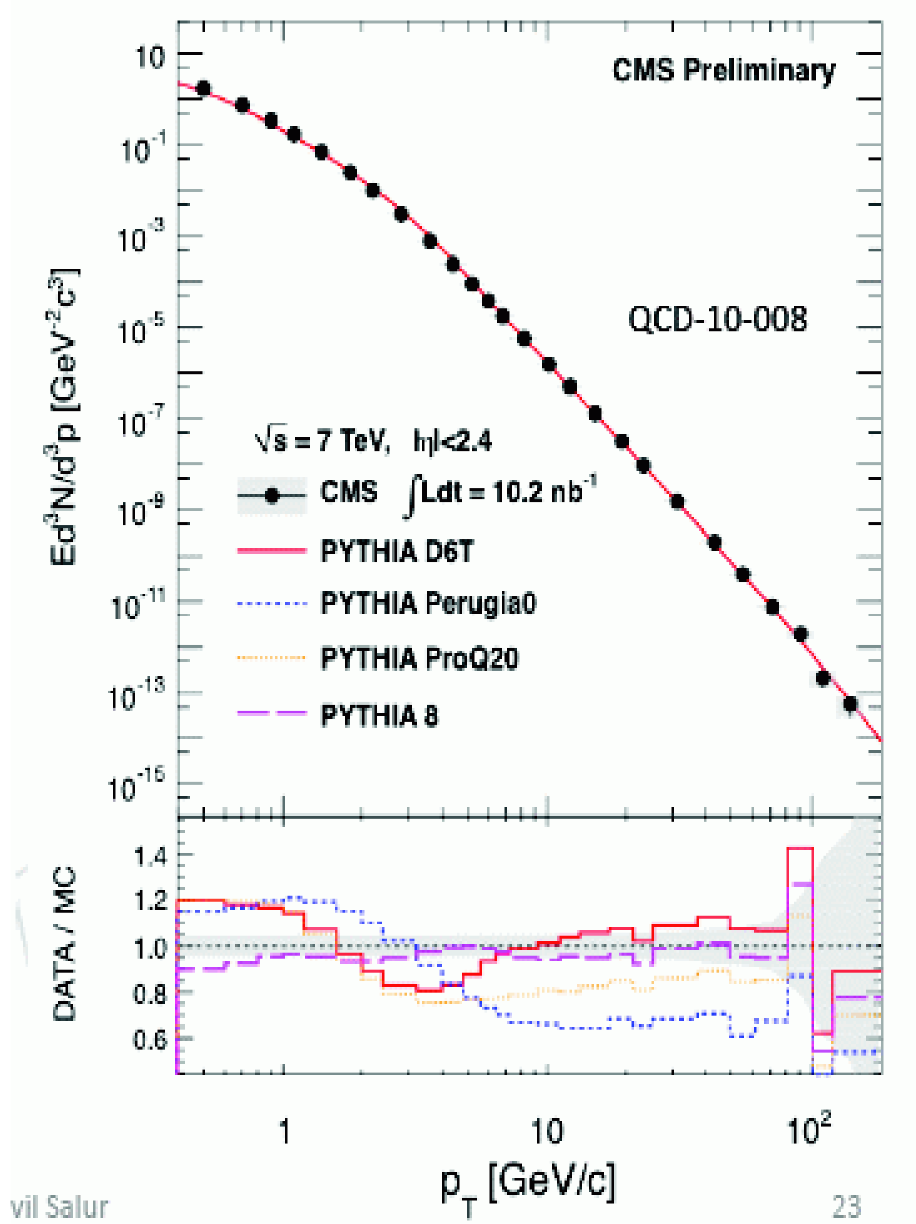
*ATLAS results at 7 TeV*

*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 :

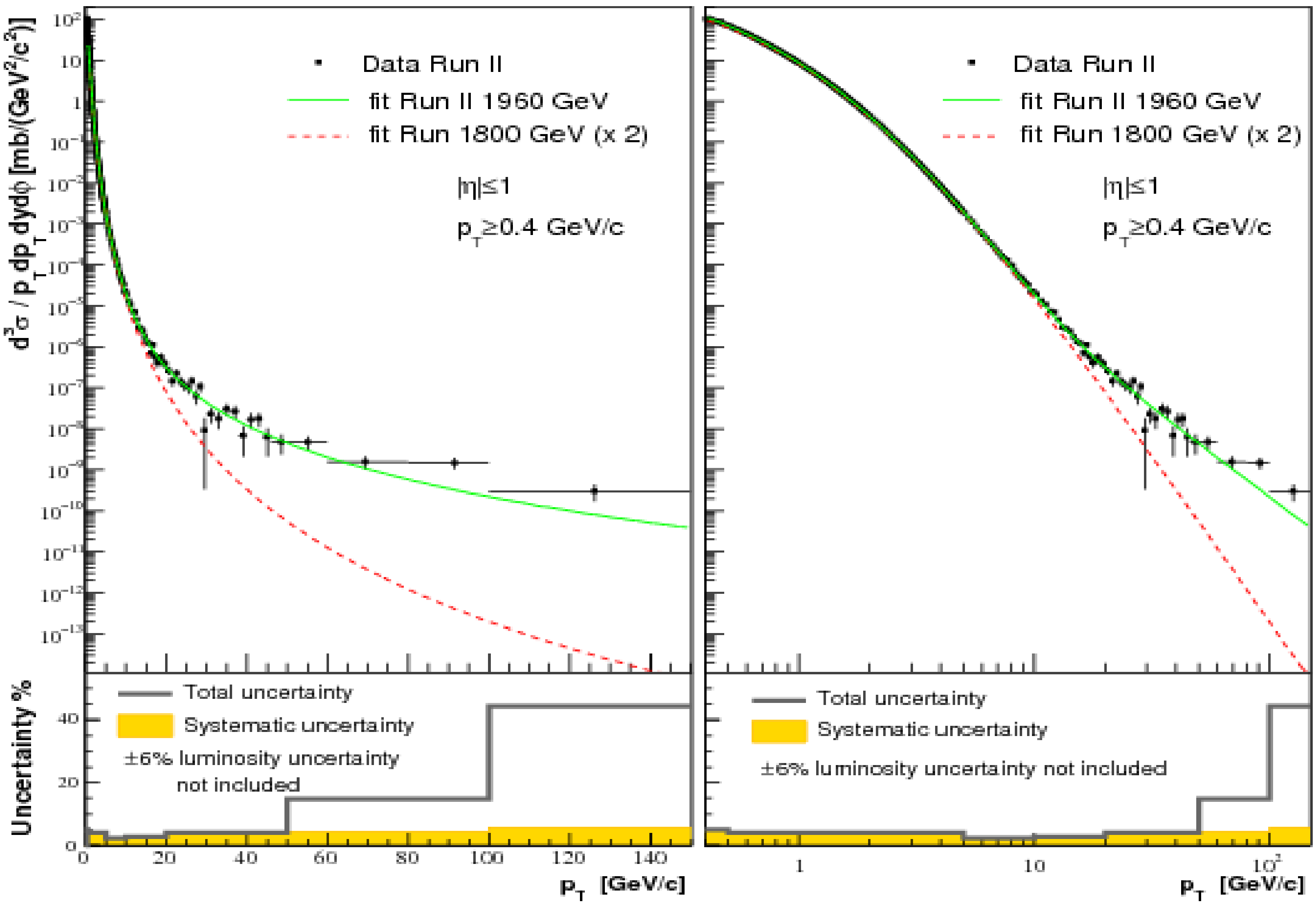



LHC ALICE (Prag'10) LHC CMS (Prag'10)

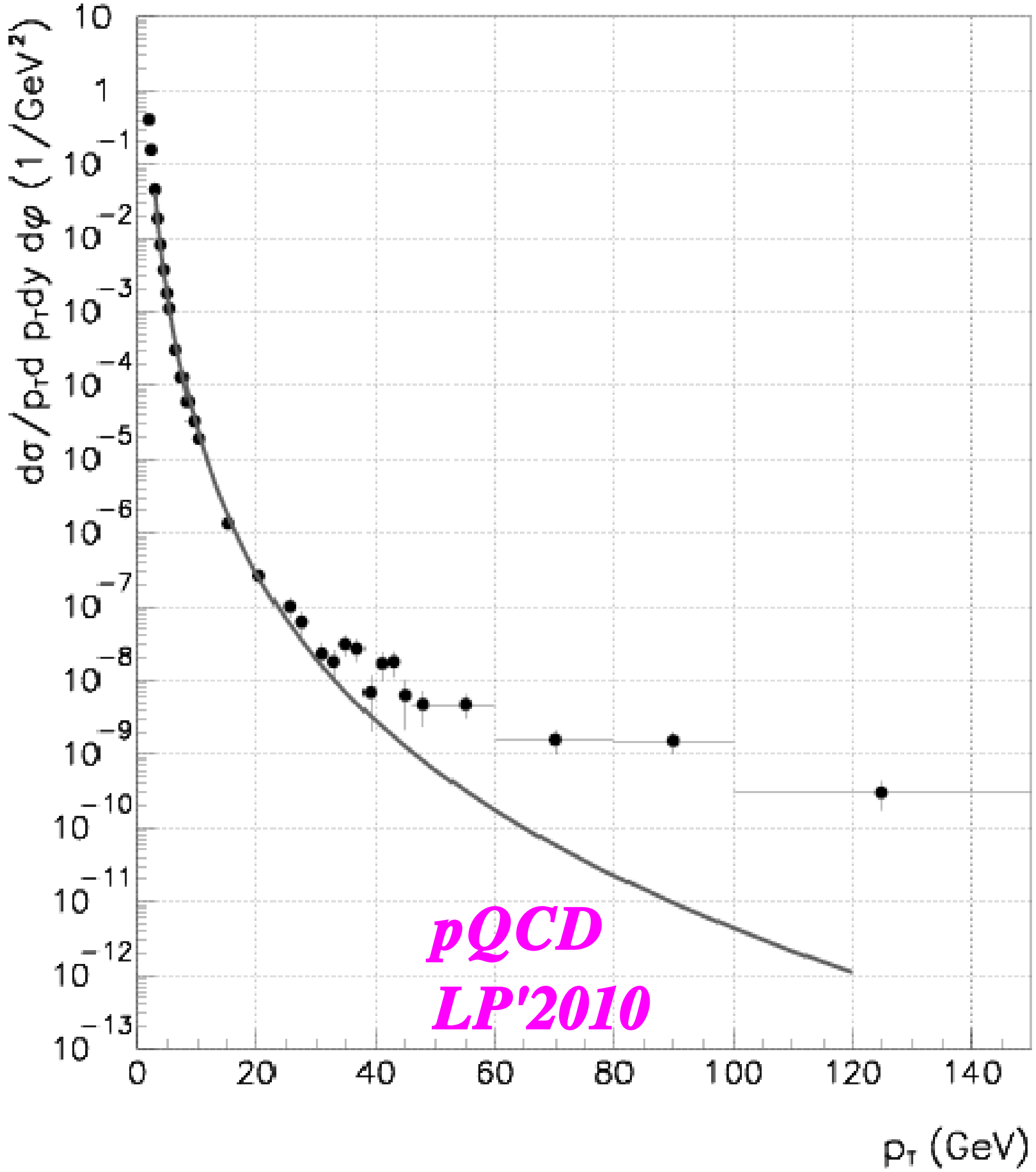
## BOMB SHELL (!) :

## 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 :



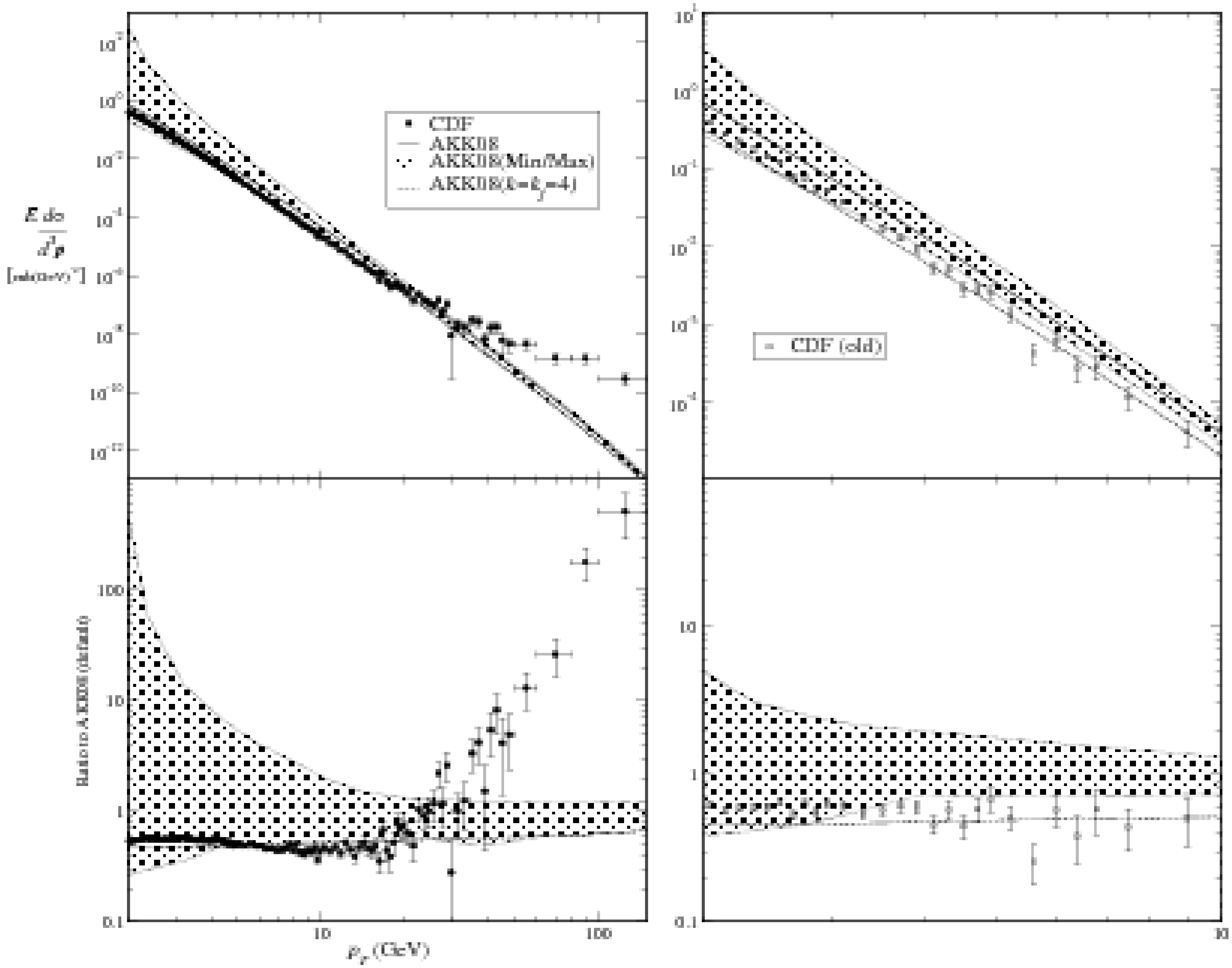

Charged hadrons
at 2 TeV
p+antip

Data vs.
LO pQCD calc.

2 TeV <-> 30 GeV
xT = 0.015
$\approx$
7 TeV <-> 100 GeV

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

# Charged hadron production in pp collisions at TEVATRON :



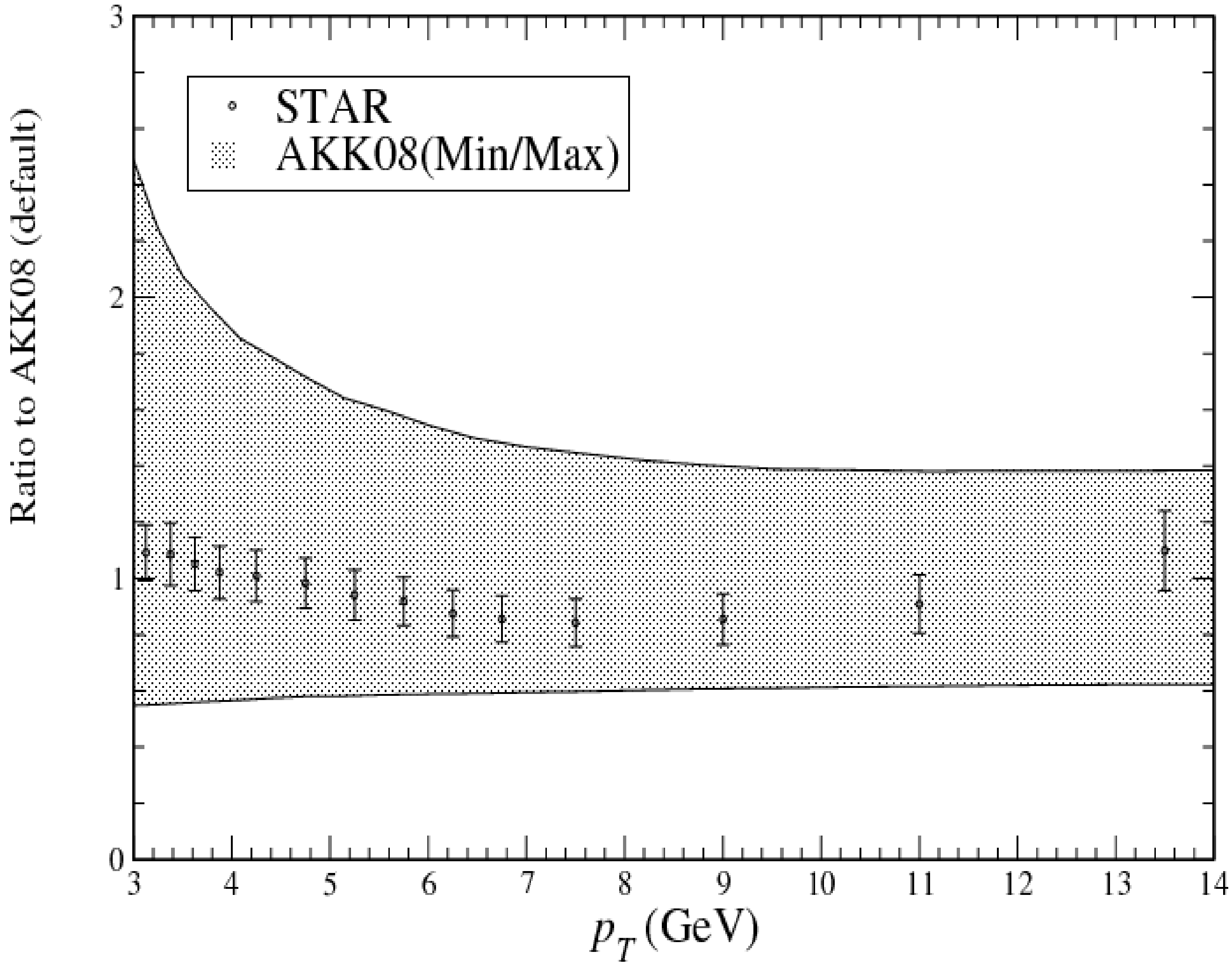

*NLO PQCD calculation (investigation) from AKK:*

*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 (UE) --> G.G. Barnaföldi*
- *--- multi-jet production (3/4/...) --> S. Pochybova talk*
- *--- something is wrong with the PDF fits;*
- *--- something is wrong with the FF fits (at high-pt);*
- *--- ... (???)*

## *2. Jet and hadron production mechanisms in heavy ion collisions*

## *--- from RHIC to LHC energies ---*
## *[Theory]*

***And what about proton-proton collisions ?***

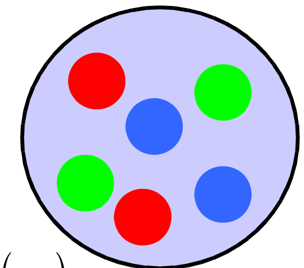
# Particle production mechanisms in high energy HI collisions:

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

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

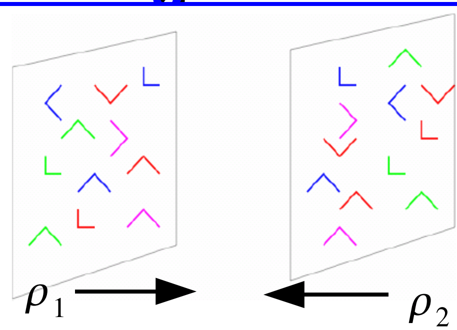
$$E_\pi \frac{d\sigma^{pp}}{d^3 p_\pi} = \int dx_1 \int dx_2 \int dz_c \, f_{a/p}(x_a, Q^2) \, f_{b/p}(x_b, Q^2) \frac{d\sigma}{d\hat{t}} \frac{D_c^\pi(z_c)}{\pi z_c^2}$$

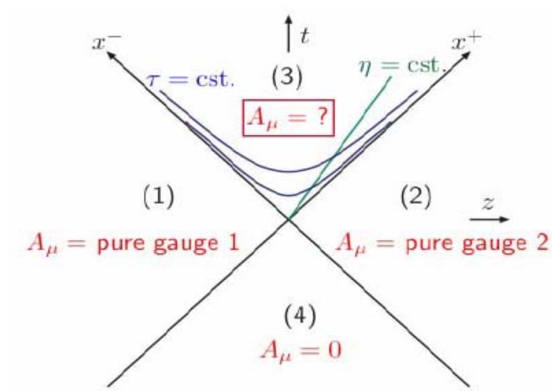
$$E_\pi \frac{d\sigma^{AB}}{d^3 p_\pi} = \int d^2b \, d^2r \;\; t_A(\vec{r}) t_B(|\vec{b}-\vec{r}|) \;\; E_\pi \frac{d\sigma^{pp}}{d^3 p_\pi} \otimes S(\ldots) \otimes M(\ldots) \otimes Q(\ldots) \otimes F(\ldots)$$

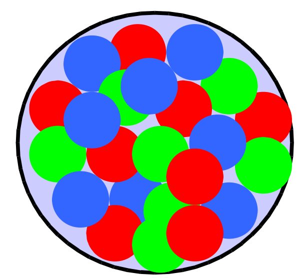


Dilute gas

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



CGC: high density gluons

**CGC initial condition:**

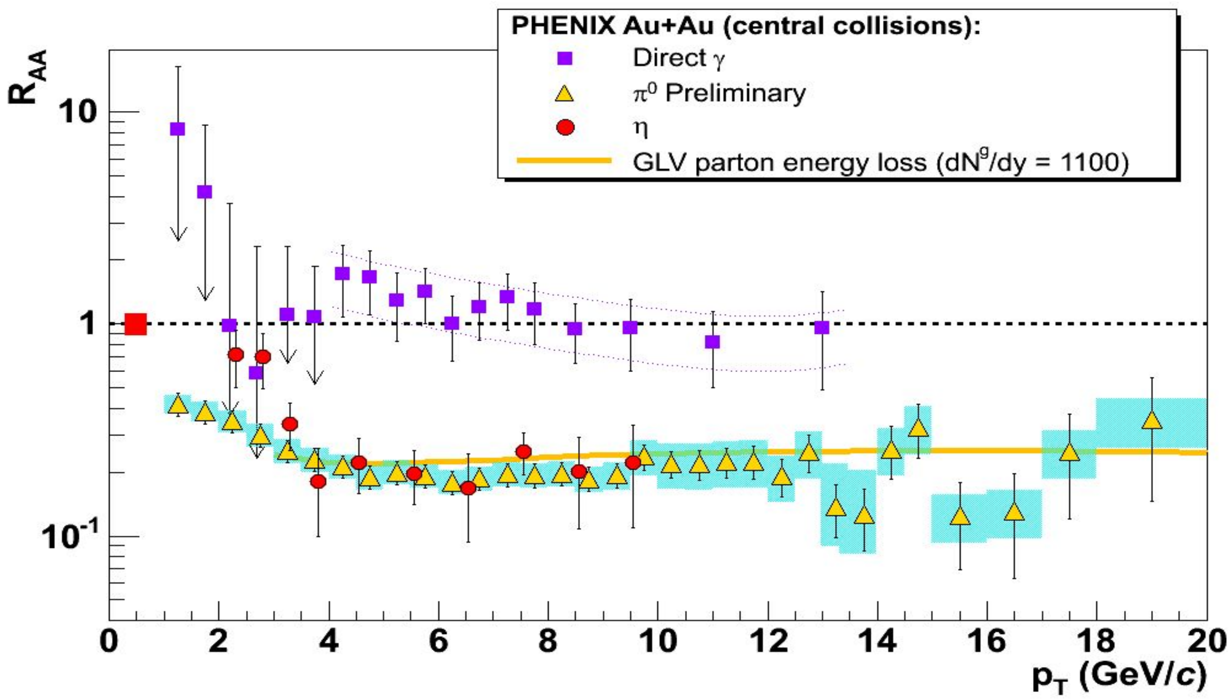
$$J^\mu = \delta^{\mu+}\delta(x^-)\rho_1(\mathbf{x}_T) + \delta^{\mu-}\delta(x^+)\rho_2(\mathbf{x}_T)$$

**where** $-D_i \alpha^i_{(m)} = \rho_{(m)}(\mathbf{x}_\perp).$ **and** $\alpha_1, \alpha_2$ **gluon fields of nuclei**

# Successful applications of I and II:

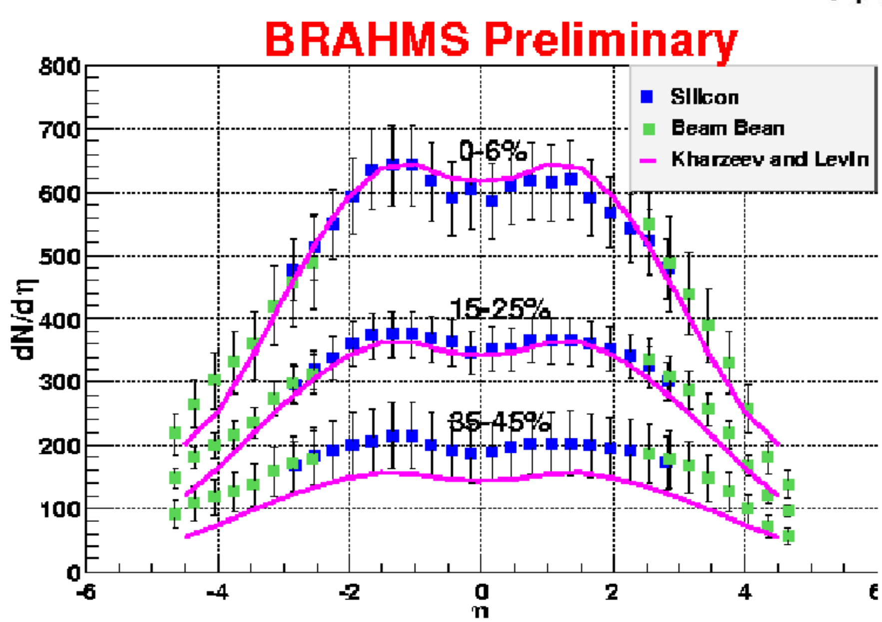
## I. pQCD model:

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




## II. CGC model:

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



## Problems:

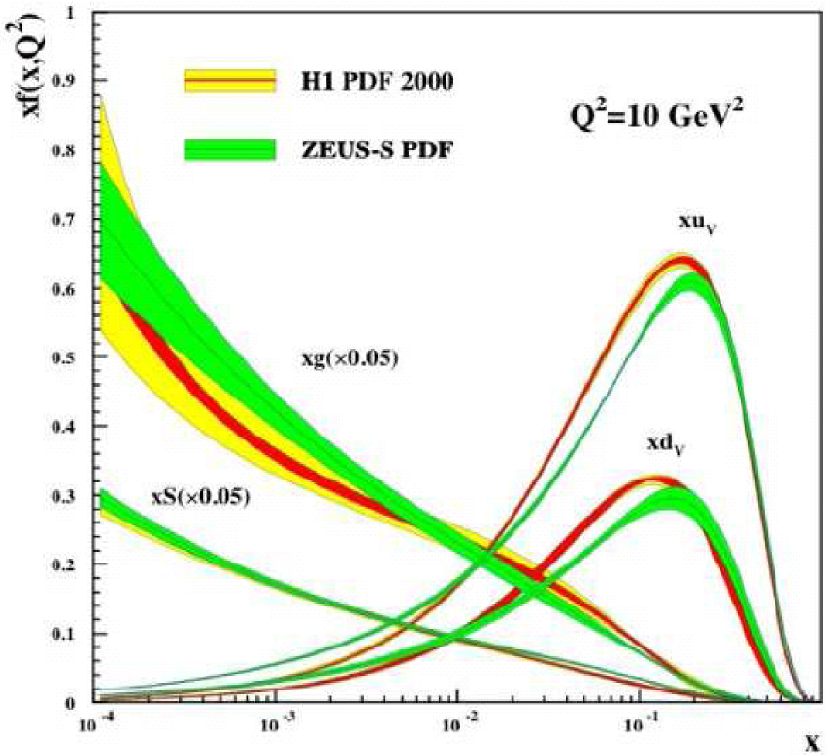
*I. pQCD model (Feynman graphs):*

- *--- 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:

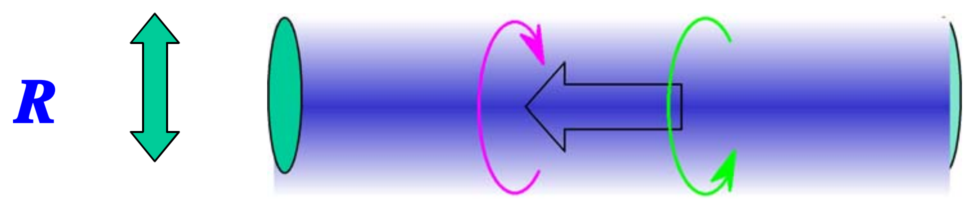



*Large-x: valence partons*
*random color charge, $\rho^a(x)$*
*Small-x: radiation field,*
*created by $\rho^a(x)$*

## 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:**

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

**integrated probability at mass m:**

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

**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):**

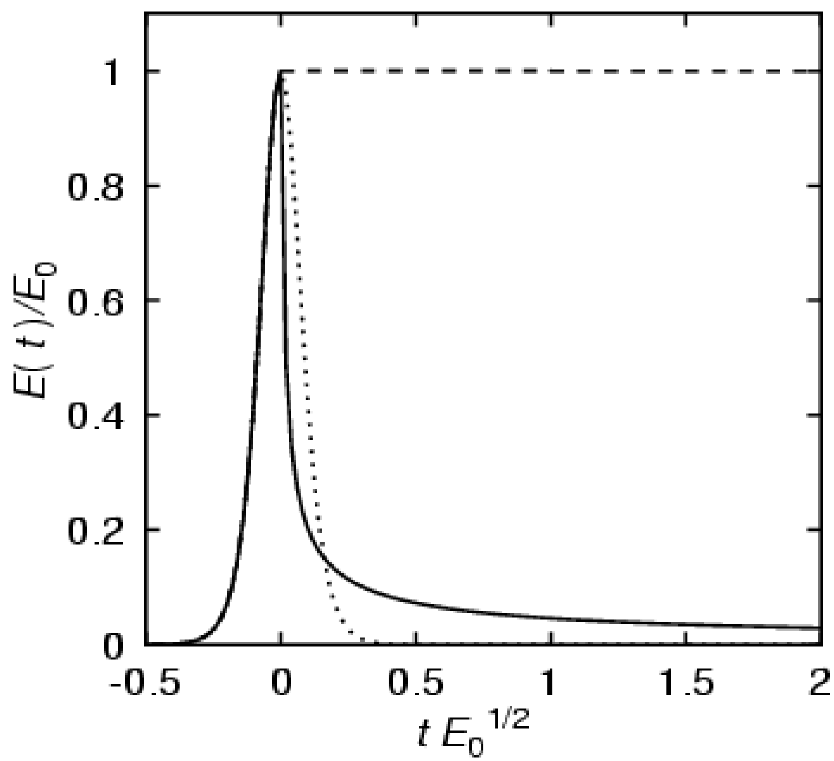
$$E_{pulse}(t) = E_0\left[1 - \tanh^2(t/\delta)\right]$$

**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):**

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

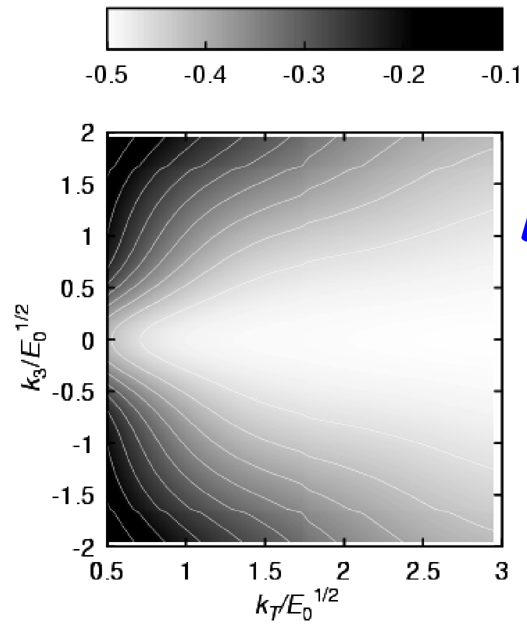



$$\delta = 0.1/E_0^{1/2} \quad at\ RHIC\ energy$$

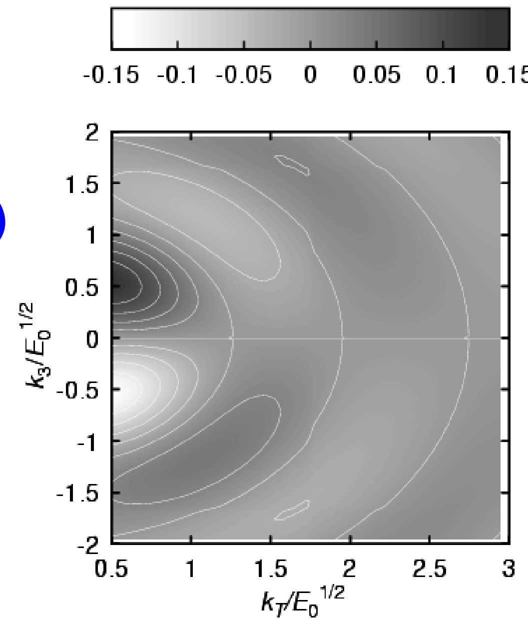
$$\kappa = 2/3 \quad for\ scaled\ Bjorken\ expans.$$
$$with \quad t_0 = 0.01/E_0^{1/2}$$

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

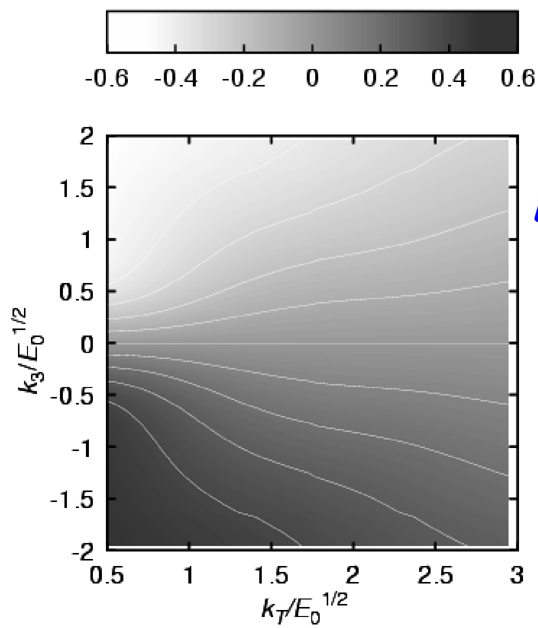
*m = 0*



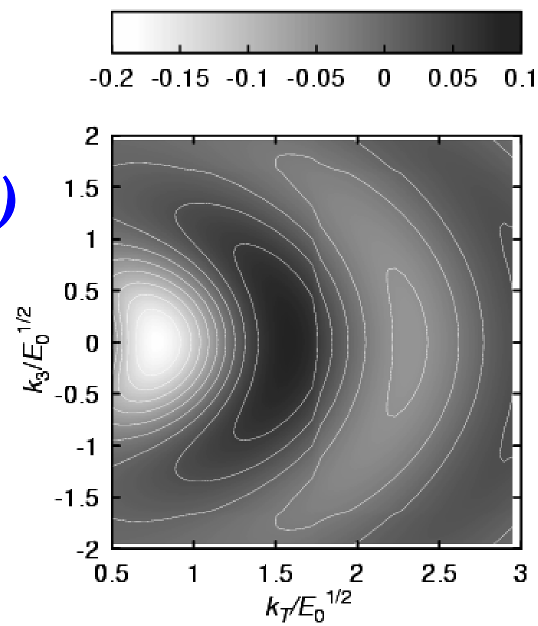

$b^s{}_T(k_T,k_3)$




$b^a{}_T(k_T,k_3)$

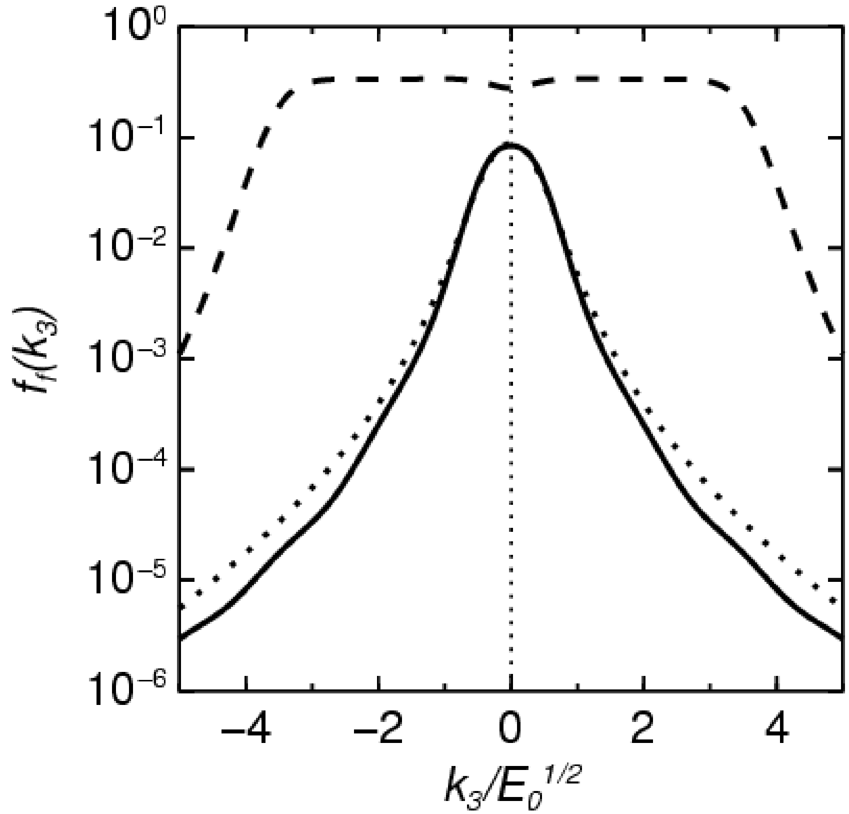



$b^s{}_3(k_T,k_3)$



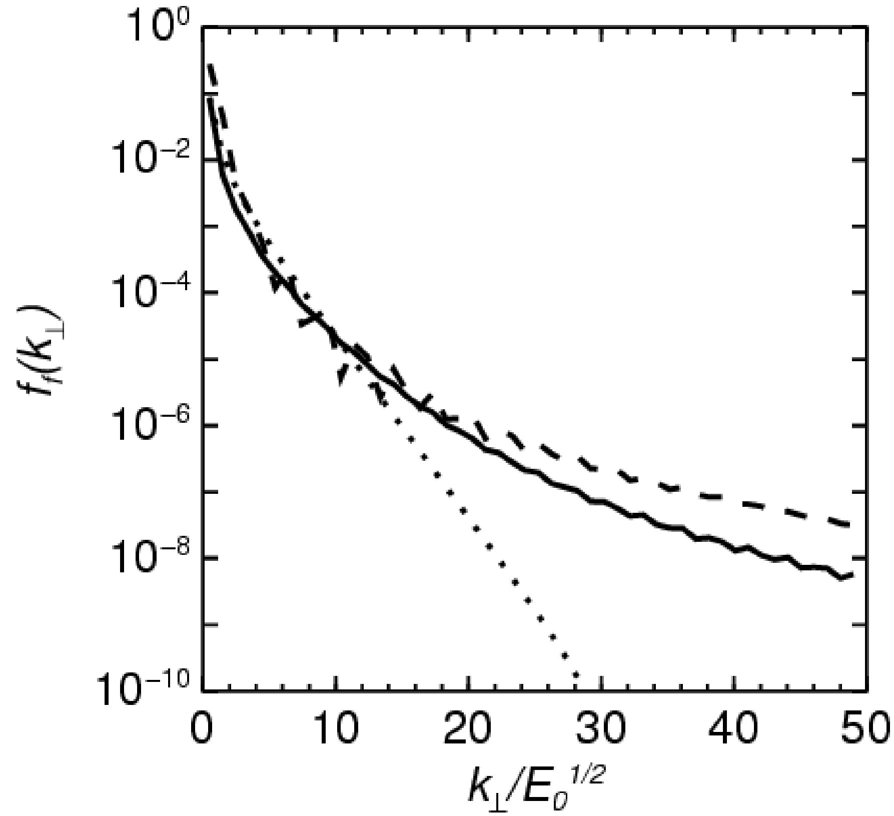

$b^a{}_3(k_T,k_3)$

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




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

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



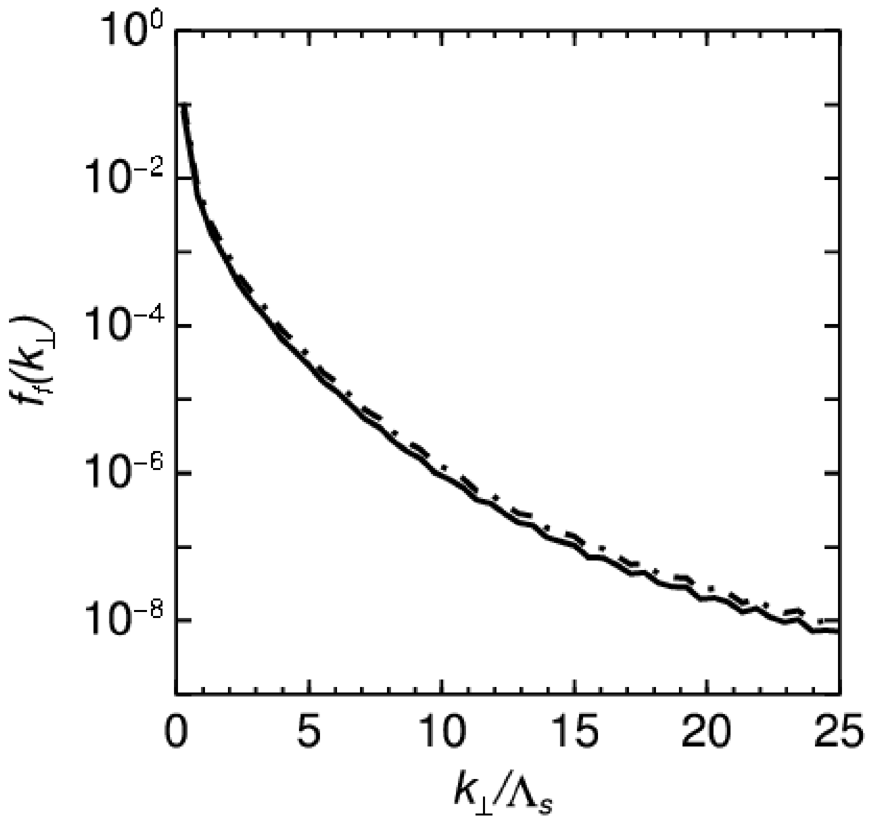

***$f_f(k_T)$: transv. mom. distr.***

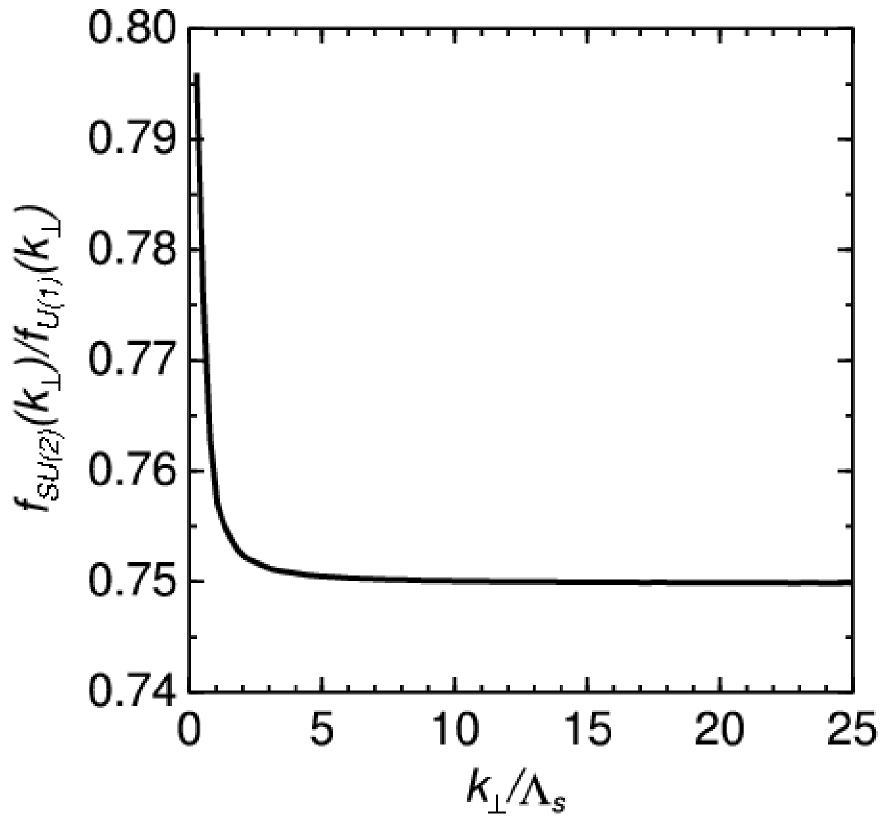
***$k_3 = 0$***

*⇒ 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)***

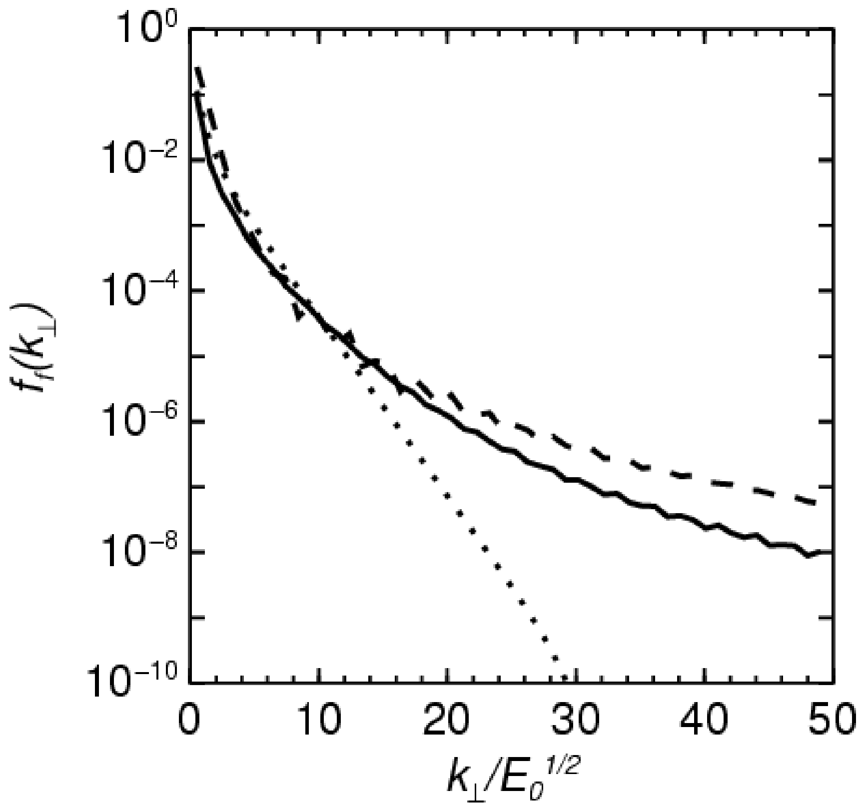
***[Bjorken scaled]***

***ratio: SU(2) / U(1)***

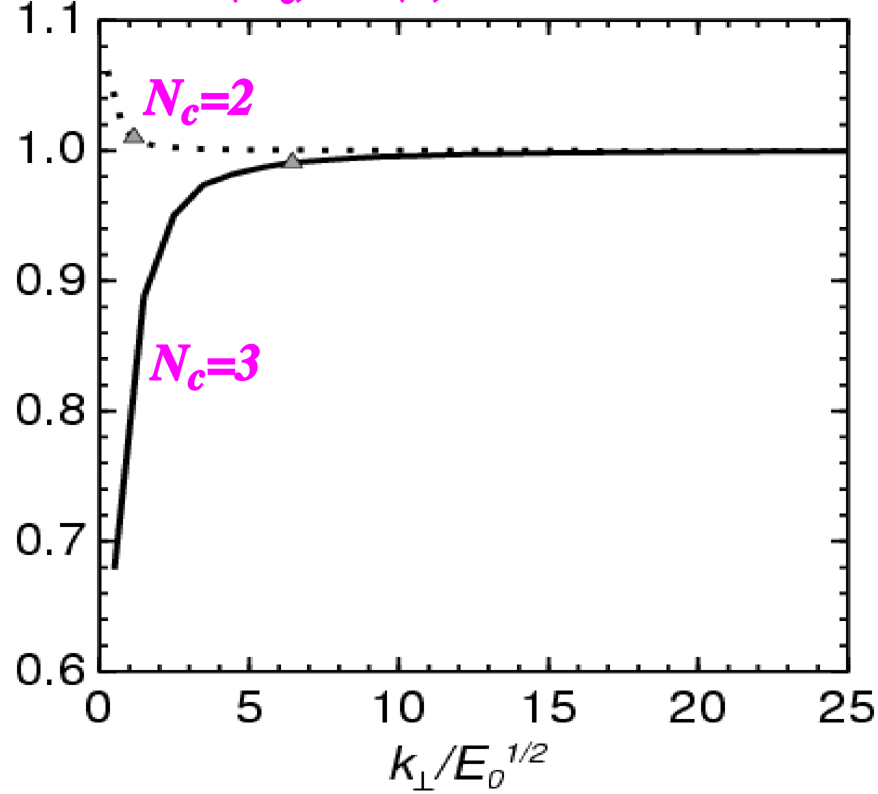
***$\Rightarrow$ ¾ at $k_T/\Lambda_s > 3$***

***(scaling in the Kinetic Eq.)***

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




SU($N_c$) / U(1) normalized to 1




$f_f(k_T)$: 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 ---***

## 3. Mass-dependence of non-perturbative particle production

***P. L. , V.V. Skokov:***
***--- J. Phys. G36 (2009) 064068.***
***--- arXiv: 0909.2323 [hep-th]***
***accepted in PRD (2010)***

## Mass dependent fermion production in SU(2):

*Quark-pair production depends on the mass:*

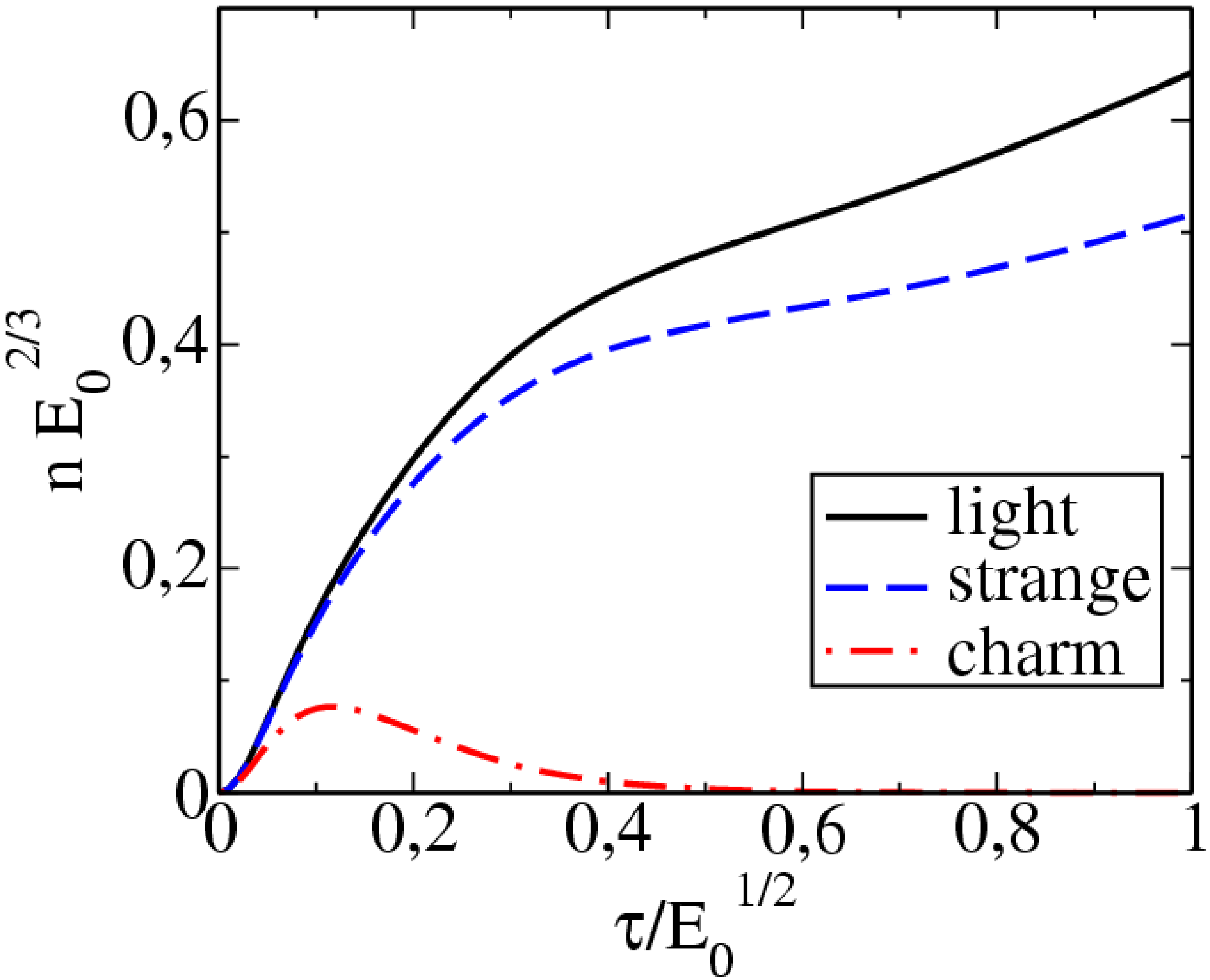
$m(\text{light}) = 8\ \text{MeV}$
$m(\text{strange}) = 150\ \text{MeV}$
$m(\text{charm}) = 1200\ \text{MeV}$
$m(\text{bottom}) = 4200\ \text{MeV}$

*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) ??*

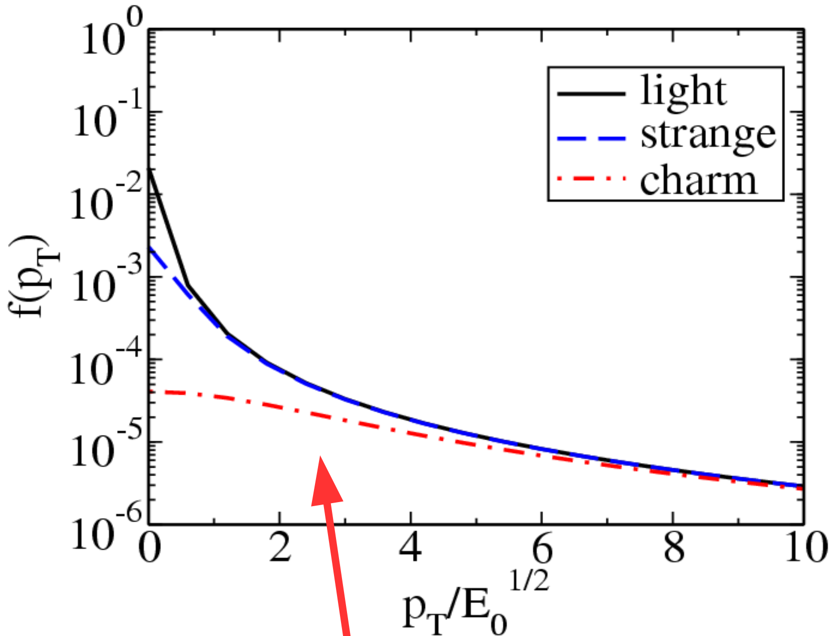
$\tau \quad \Rightarrow\Rightarrow \quad \delta$

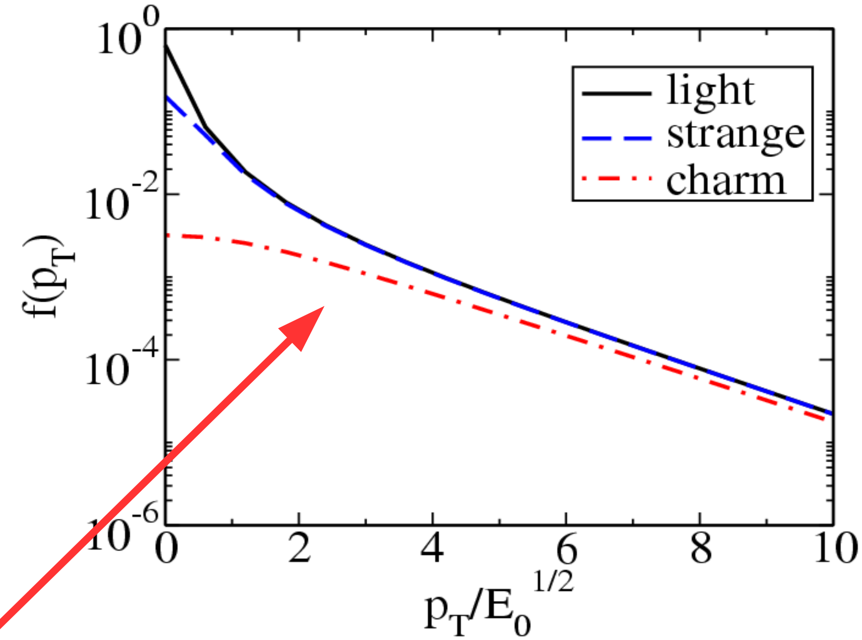
# Mass dependent fermion production in SU(2) [pulse-like time dep.]




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

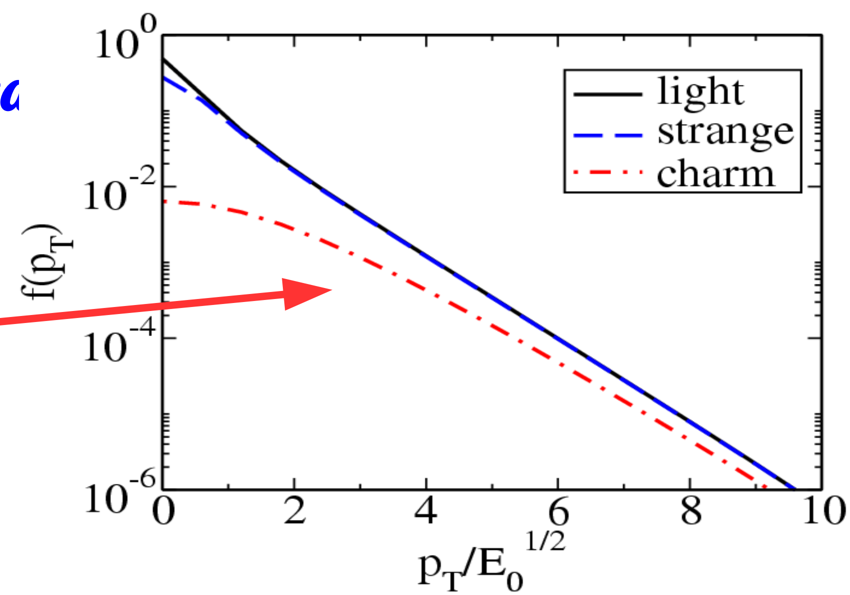
# ***Mass dependent fermion production in SU(2) [pulse-like time dep.]***



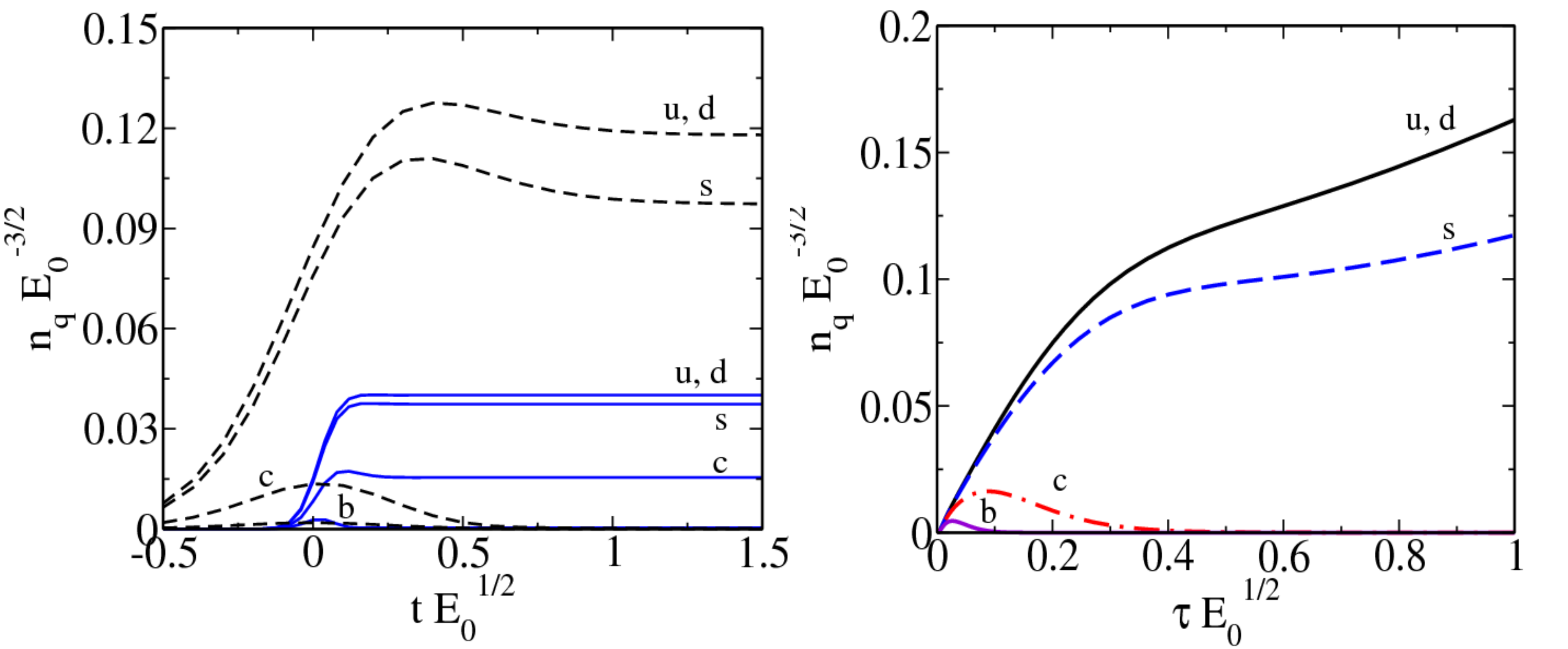




***Transverse momentum spectra at different pulse width:***

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



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



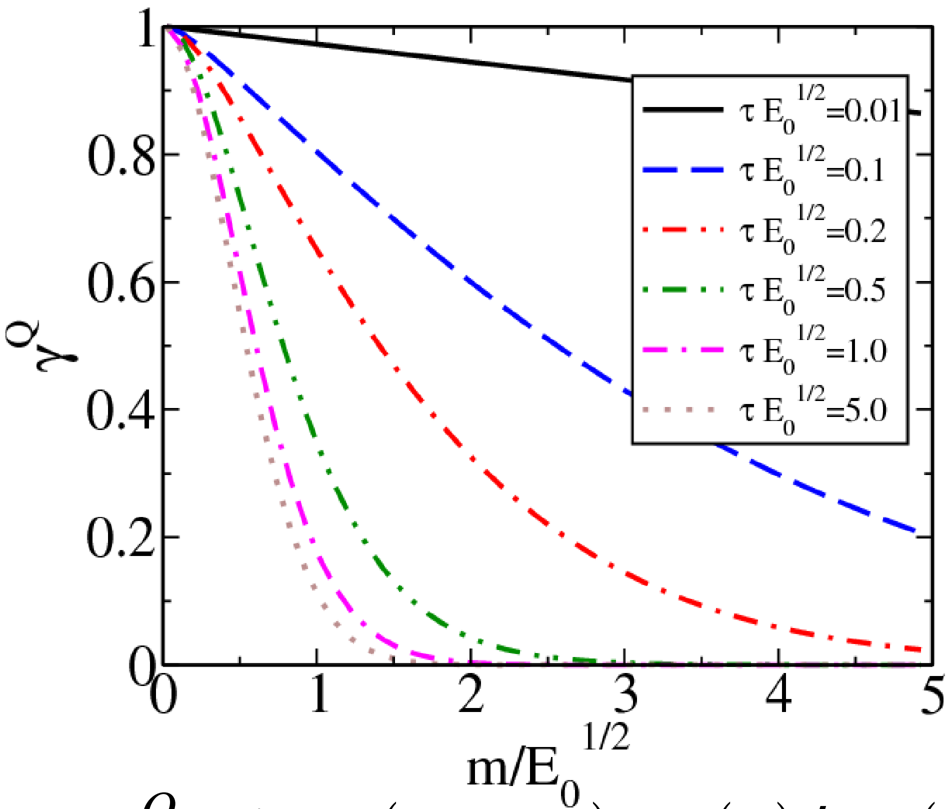

***t: time in the CM frame*** ***τ: pulse width (t→∞)***

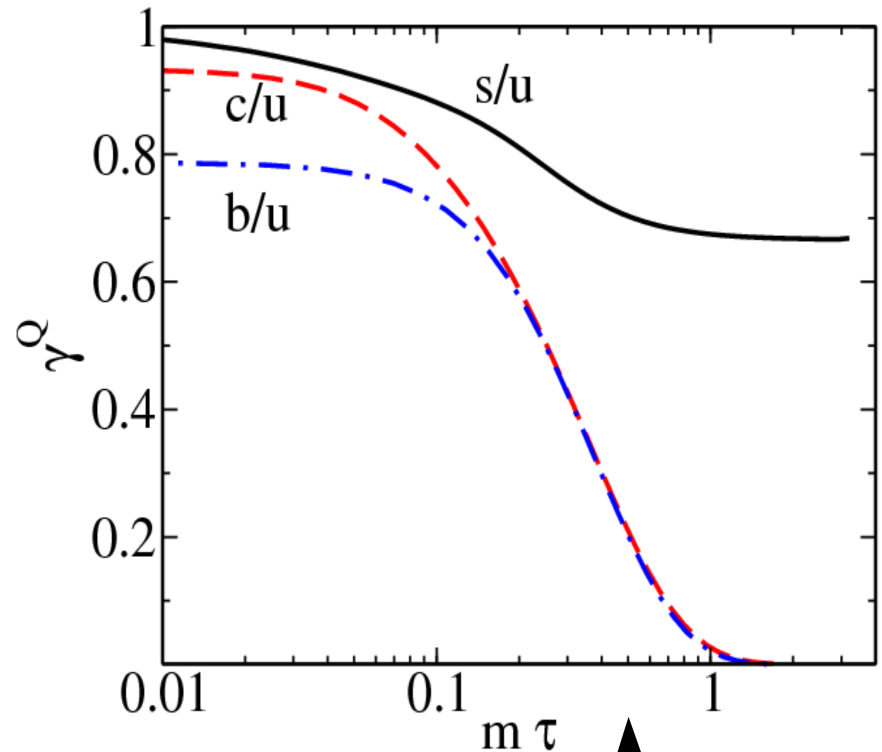
***Full line:*** $\tau\sqrt{E_0} = 0.1$ ($\tau = 0.05$ fm)

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

$E_0 = 0.68$ GeV/fm, $g=2$ →→→ $g \cdot E_0 \propto \kappa = 1.17$ 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 !!!!***

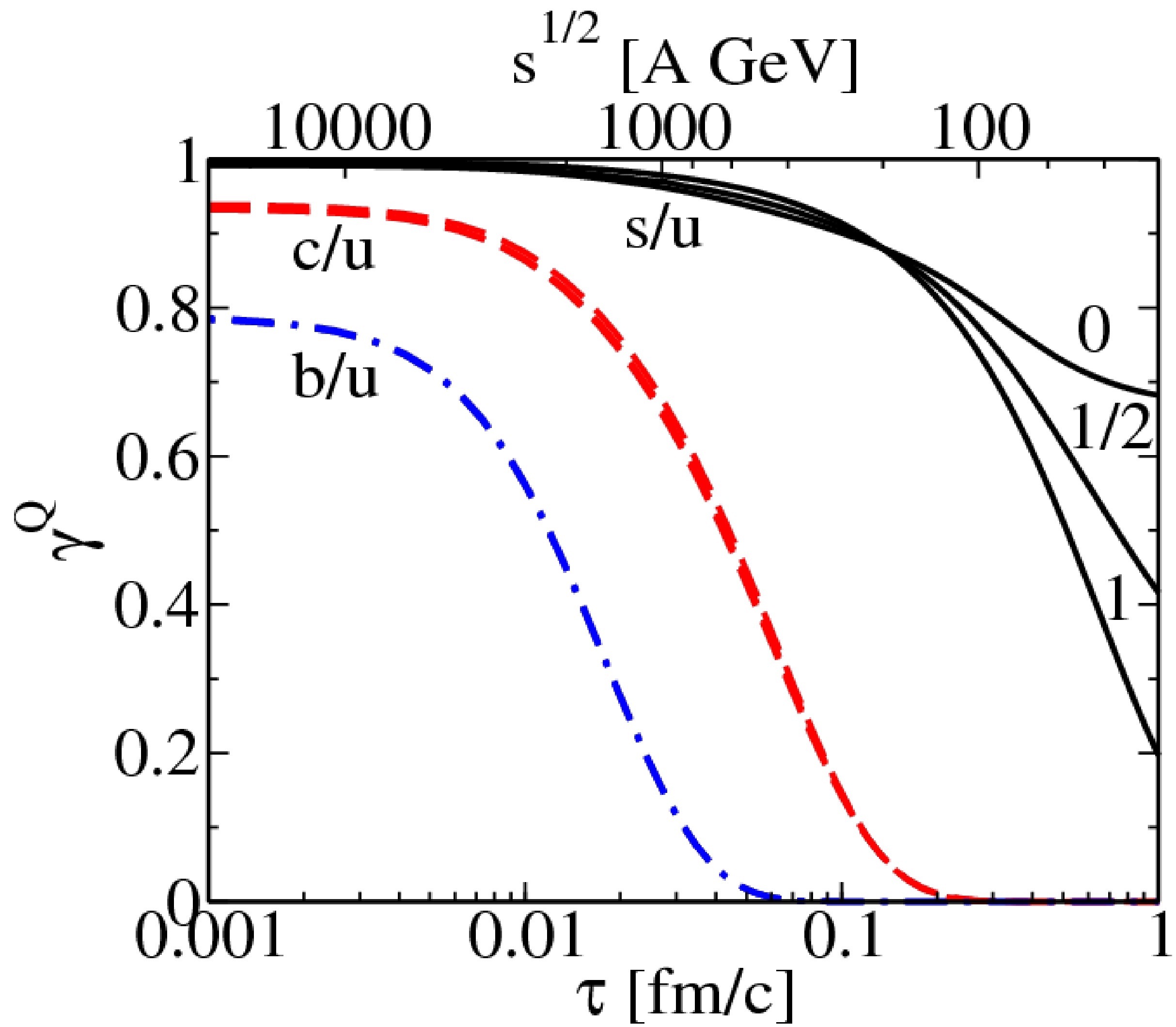
***Blue line:*** $\tau\sqrt{E_0} = 0.1$ ***(τ = 0.05 fm )***

***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 $\beta$ : 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:**

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

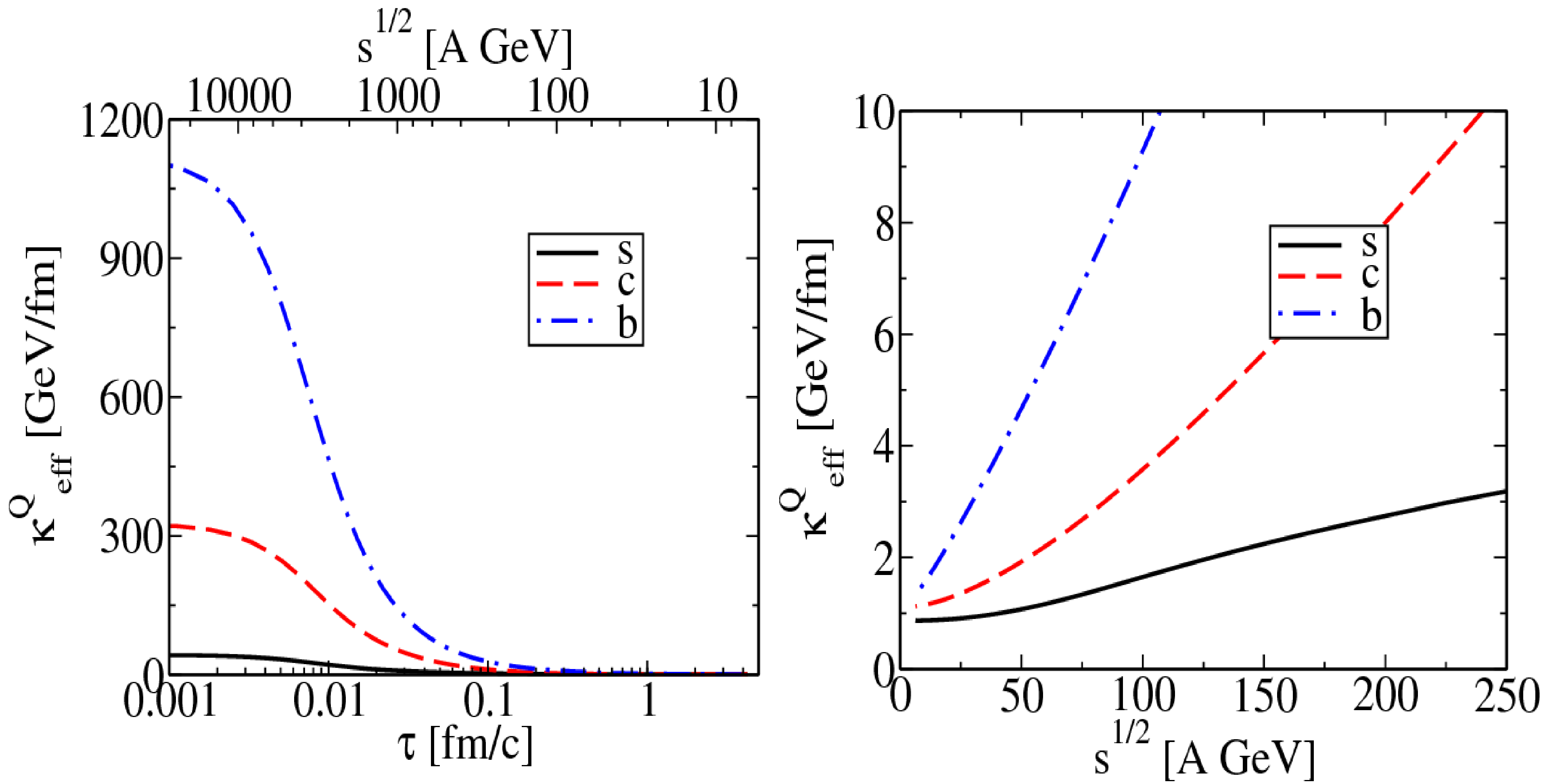
**Suppression factor:**

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

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

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

# 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:***

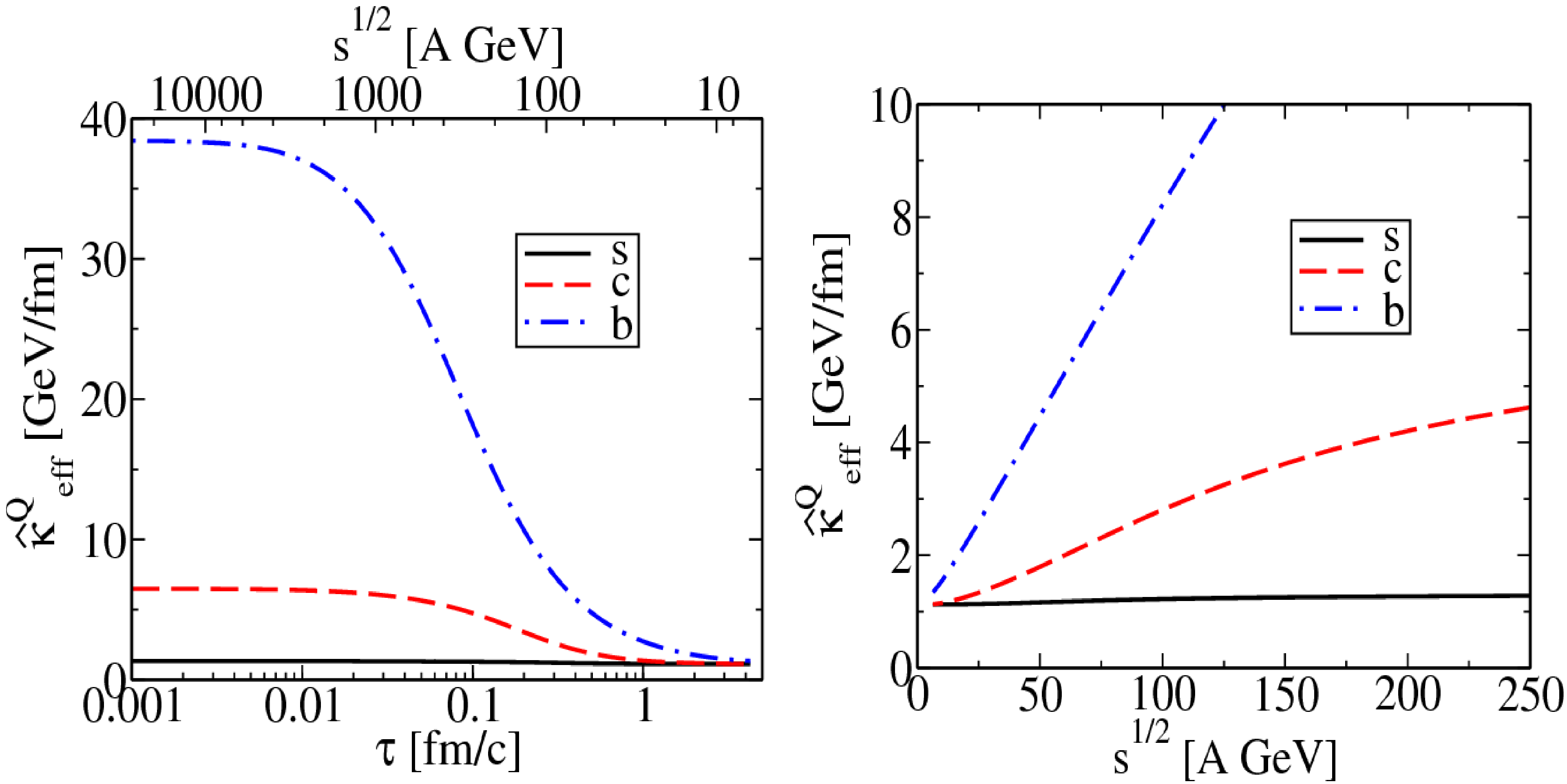
***Let us keep a fixed string constant for the light quarks***

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

***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:*

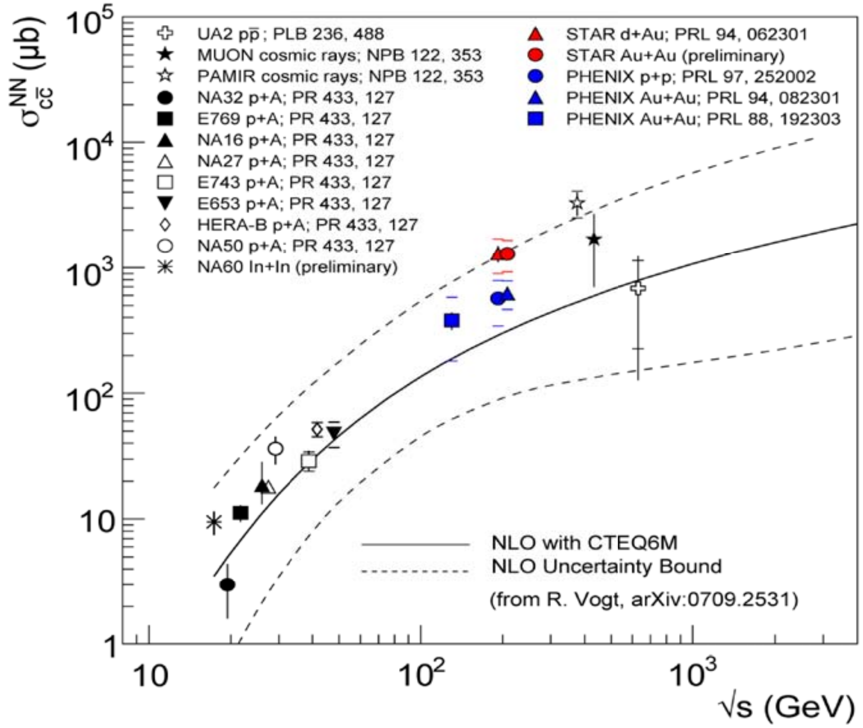
| | 130 AGeV | 200 AGeV | 1 ATeV | 2 ATeV | 5.5 ATeV |
|---|---|---|---|---|---|
| u,d | 1.17 | 1.17 | 1.17 | 1.17 | 1.17 |
| s | 1.24 | 1.26 | 1.32 | 1.33 | 1.34 |
| c | 3.32 | 4.2 | 6.1 | 6.3 | 6.5 |
| b | 10.3 | 14.7 | 32 | 36 | 38 |

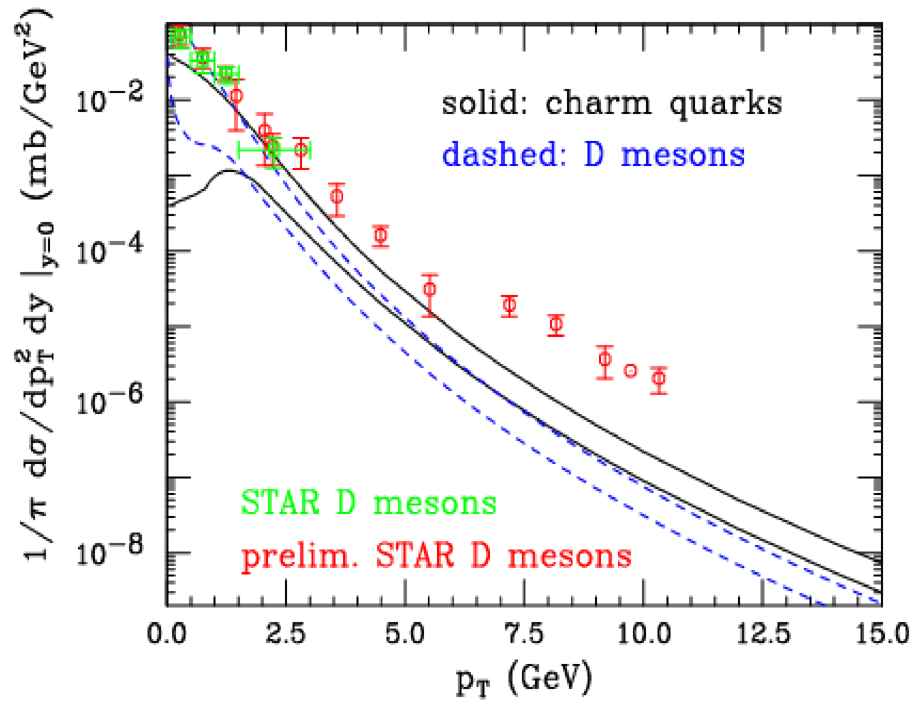
*Saturation at higher LHC energies !!!!*

## 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***



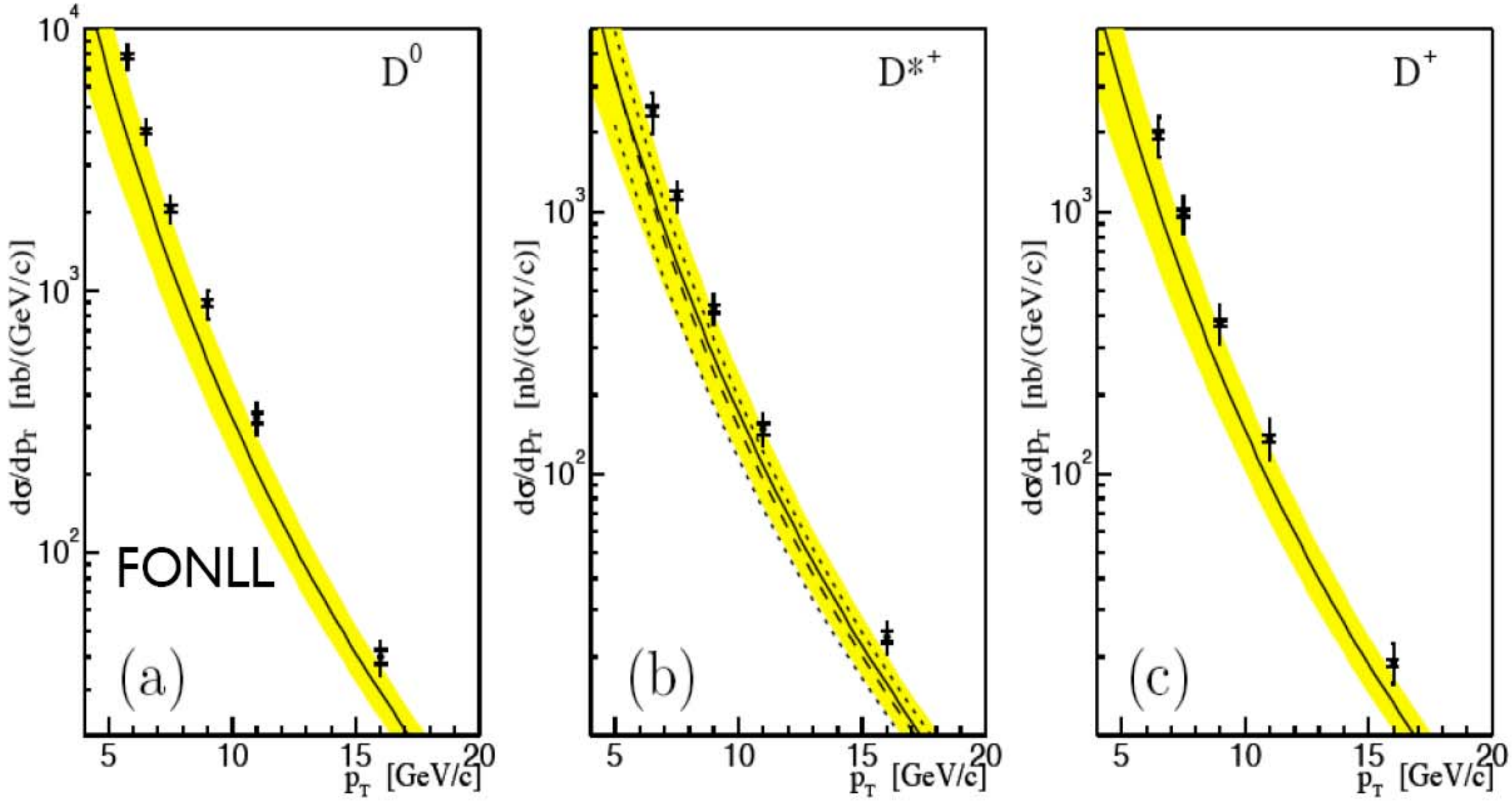

***R. Vogt, EPJ ST 155 (2008) 213.*** ***M. Cacciari, ..., PRL95,122001***

***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)***

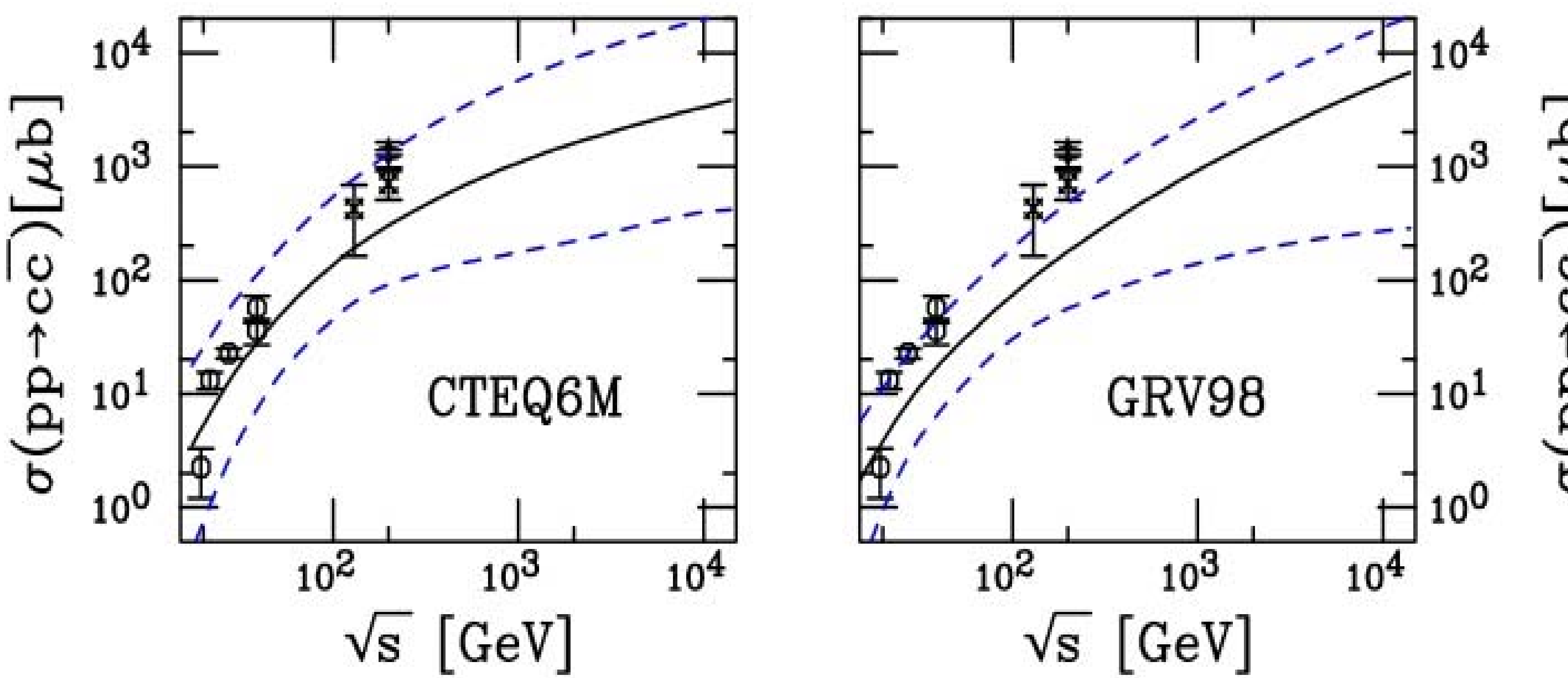
CDF Run II  c → D data  [PRL 91:241804,2003]




***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, $\sqrt{s}$ = 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).*

## ***<u>Theoretical conclusions (today) on this section:</u>***

*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 $\sim \sqrt{s} = 1\text{-}2$ 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)***

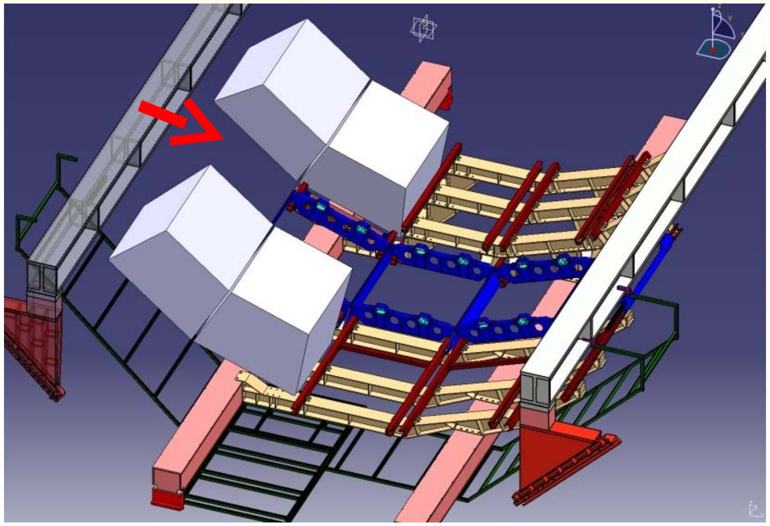
***Modul-Xs: Installation in 2015***

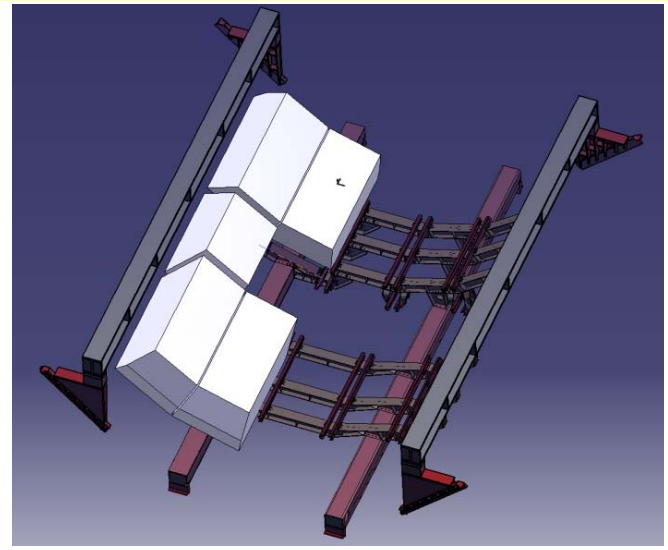
***VHMPID mission: to identify charged hadrons***

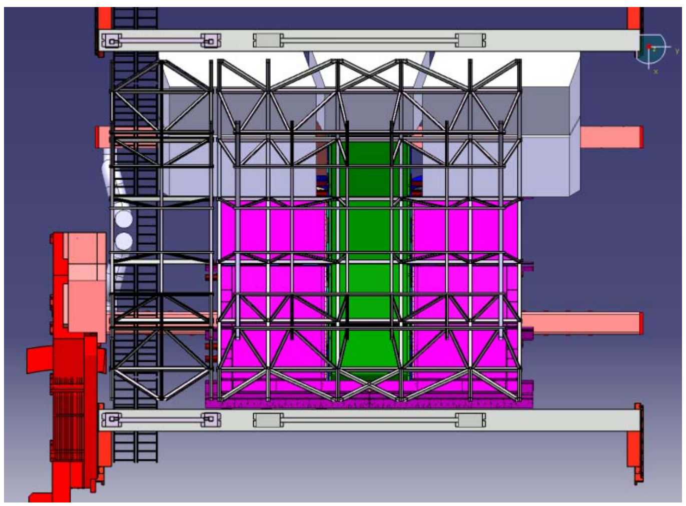
***up-to 25 GeV ($C_4F_{10}$)***

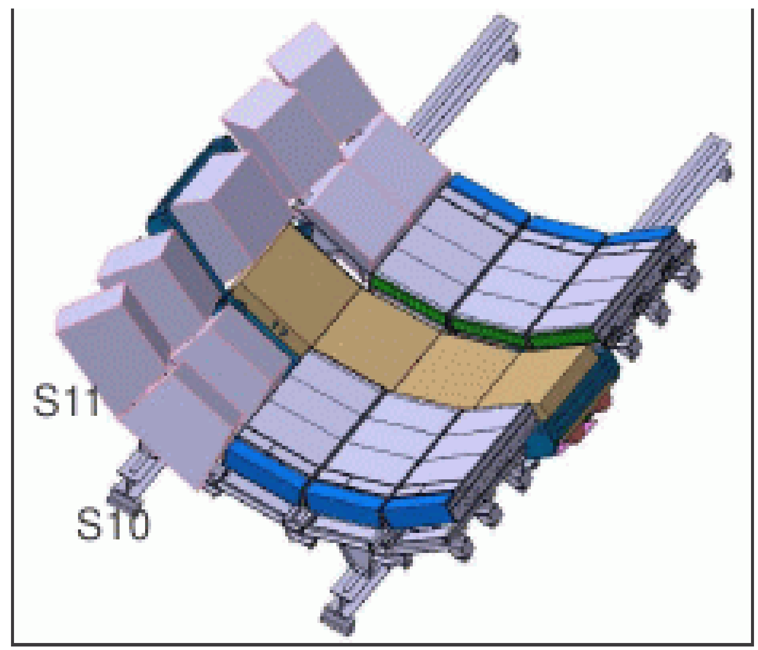
***or at even higher momenta ($CH_4$)***

# VHMPID layout evolution (2009-2010)









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