Production of Charm Quarks in AA Collisions using Parton Cascade Model

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arXiv:1705.05542 & under preparation

Motivation

1. Charm (and bottom) quarks are produced very early in pp or AA collisions when their numbers get frozen and they clearly stand out in the background.

2. They traverse the plasma, colliding with other partons in the plasma and radiating gluons.

3. They may or may not thermalize.

4. They may lose energy during the hadronic state of the system as well.

Epilogue as a Prologue-I

1. We extend the Parton Cascade Model (VNI/BMS) to include production and propagation of heavy quarks in hadronic/ nuclear collisions.

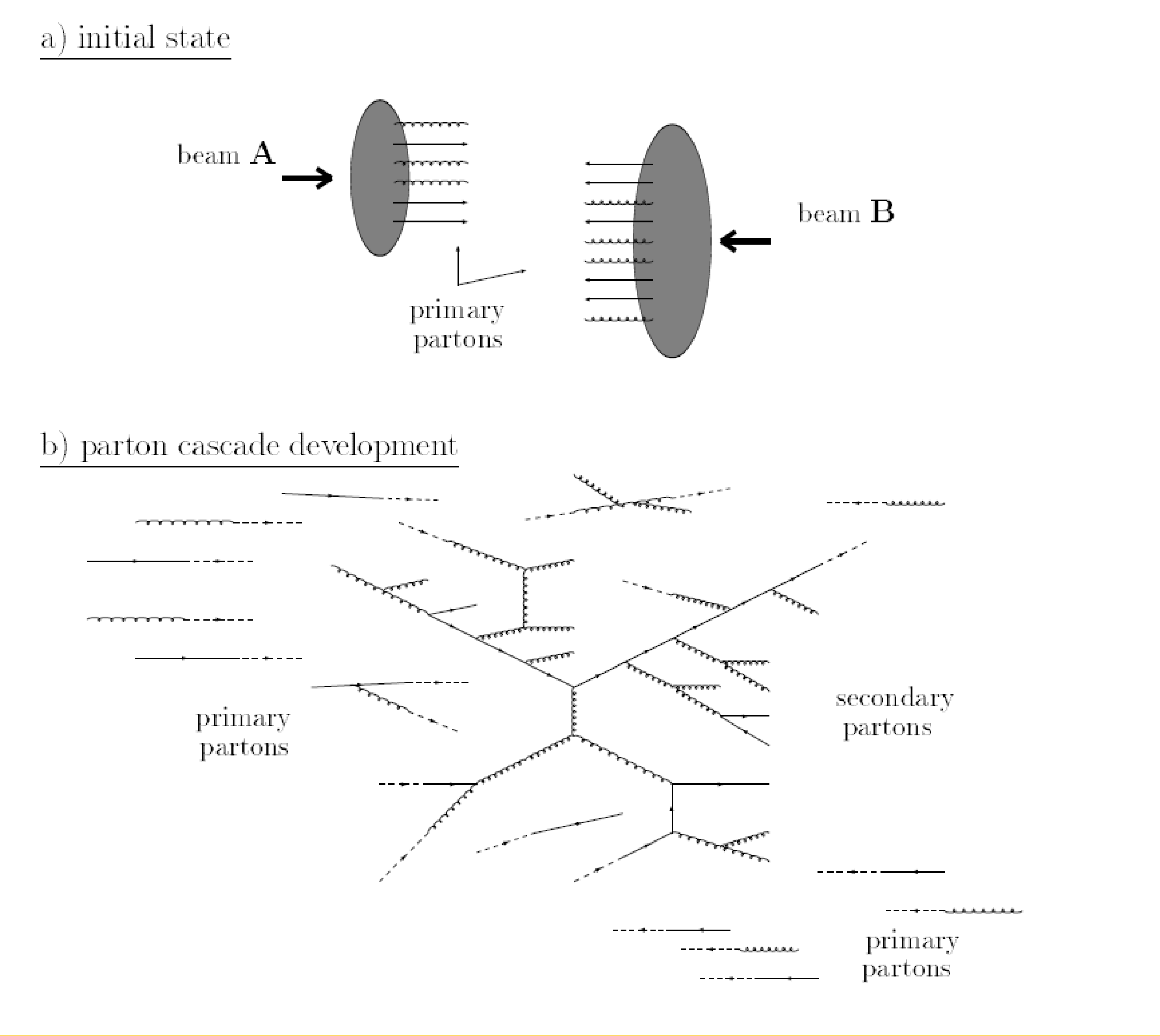
2. We study production of charm quarks etc. in Au+Au collisions at top RHIC energy and in pp collisions at 0.2, 2.76, 5.02, 7.00 and 14.00 TeV.

Epilogue as a Prologue-II

3. **The trend of R_{AA} for charm quarks at RHIC energies is closely reproduced if we permit multiple collisions of partons followed by radiation of gluons.**

4. **The production of strange and charm quarks is seen to rise with centre of mass energy and with decrease in $p_T^{cut\text{-}off}$ used to regularize the pQCD cross-sections and with decrease in impact parameter in pp collisions.**

Basic Principles of the PCM



- **Parton Cascade Model, VNI/BMS, is a relativistic quantum-kinetic description of the dynamics of evolution of high energy hadronic collisions.**

- **The description includes semi-hard pQCD interaction of partons populating the nucleons (which populate the nuclei) undergoing scatterings and fragmentations while propagating.**

- **The pQCD cross-sections are regularized by introducing a lower p_T (cut-off).**

- **The fragmentations are terminated once the virutuality of the partons falls to $M_0^2=m_i^2+\mu_0^2$, where μ_0=1 GeV and m_i is the current mass of the parton.**

- degrees of freedom: quarks and gluons
- classical trajectories in phase space (with relativistic kinematics)
- initial state constructed from experimentally measured nucleon structure functions and elastic form factors
- an interaction takes place if at the time of closest approach d_{min} of two partons

$$d_{\min} \leq \sqrt{\frac{\sigma_{tot}}{\pi}} \quad \text{with} \quad \sigma_{tot} = \sum_{p_3, p_4} \int \frac{d\sigma\left(\sqrt{\hat{s}}; p_1, p_2, p_3, p_4\right)}{d\hat{t}} d\hat{t}$$

- system evolves through a sequence of binary (2→2) elastic and inelastic scatterings of partons and (initial and) final state radiations within a leading-logarithmic approximation (2→N)
- binary cross sections are calculated in leading order pQCD with either a momentum cut-off or Debye screening to regularize IR behaviour
- guiding scales: initialization scale Q_0, p_T cut-off p_0 / Debye-mass μ_D, intrinsic k_T, virtuality > μ_0

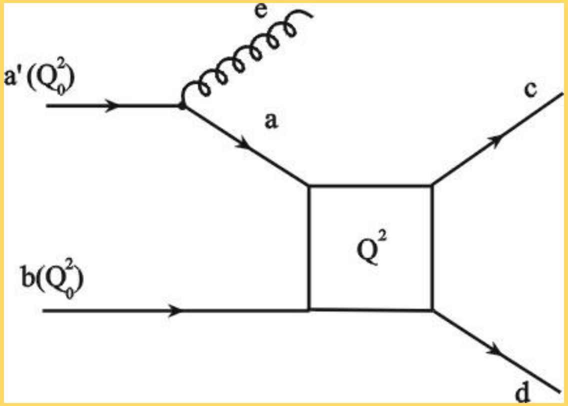
Parton-Parton Scattering Cross-Sections

g g → g g	$\frac{9}{2}\left(3-\frac{tu}{s^2}-\frac{su}{t^2}-\frac{st}{u^2}\right)$	q q′ → q q′	$\frac{4}{9}\frac{s^2+u^2}{t^2}$
q g→ q g	$-\frac{4}{9}\left(\frac{s}{u}+\frac{u}{s}\right)+\frac{s^2+u^2}{t^2}$	q qbar→ q′ qbar′	$\frac{4}{9}\frac{t^2+u^2}{s^2}$
g g → q qbar	$\frac{1}{6}\left(\frac{t}{u}+\frac{u}{t}\right)-\frac{3}{8}\frac{t^2+u^2}{s^2}$	q g →q γ	$-\frac{e_q^2}{3}\left(\frac{u}{s}+\frac{s}{u}\right)$
q q → q q	$\frac{4}{9}\left(\frac{s^2+u^2}{t^2}+\frac{s^2+t^2}{u^2}\right)-\frac{8}{27}\frac{s^2}{tu}$	q qbar → g γ	$\frac{8}{9}e_q^2\left(\frac{u}{t}+\frac{t}{u}\right)$
q qbar → q qbar	$\frac{4}{9}\left(\frac{s^2+u^2}{t^2}+\frac{u^2+t^2}{s^2}\right)-\frac{8}{27}\frac{u^2}{st}$	q qbar → γ γ	$\frac{2}{3}e_q^4\left(\frac{u}{t}+\frac{t}{u}\right)$
q qbar → g g	$\frac{32}{27}\left(\frac{t}{u}+\frac{u}{t}\right)-\frac{8}{3}\frac{t^2+u^2}{s^2}$		

- a common factor of $\pi\alpha_s^2(Q^2)/s^2$ etc.
- further decomposition according to colour flow

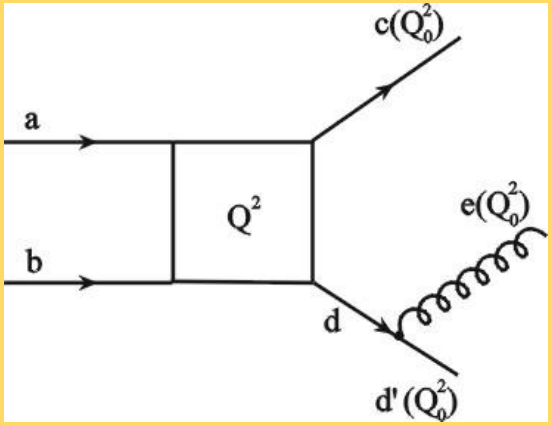
(Initial &) Final State Radiation (base on PYTHIA)

Probability for a branching is given in terms of the Sudakov form factors:



(initial state) space-like branchings:

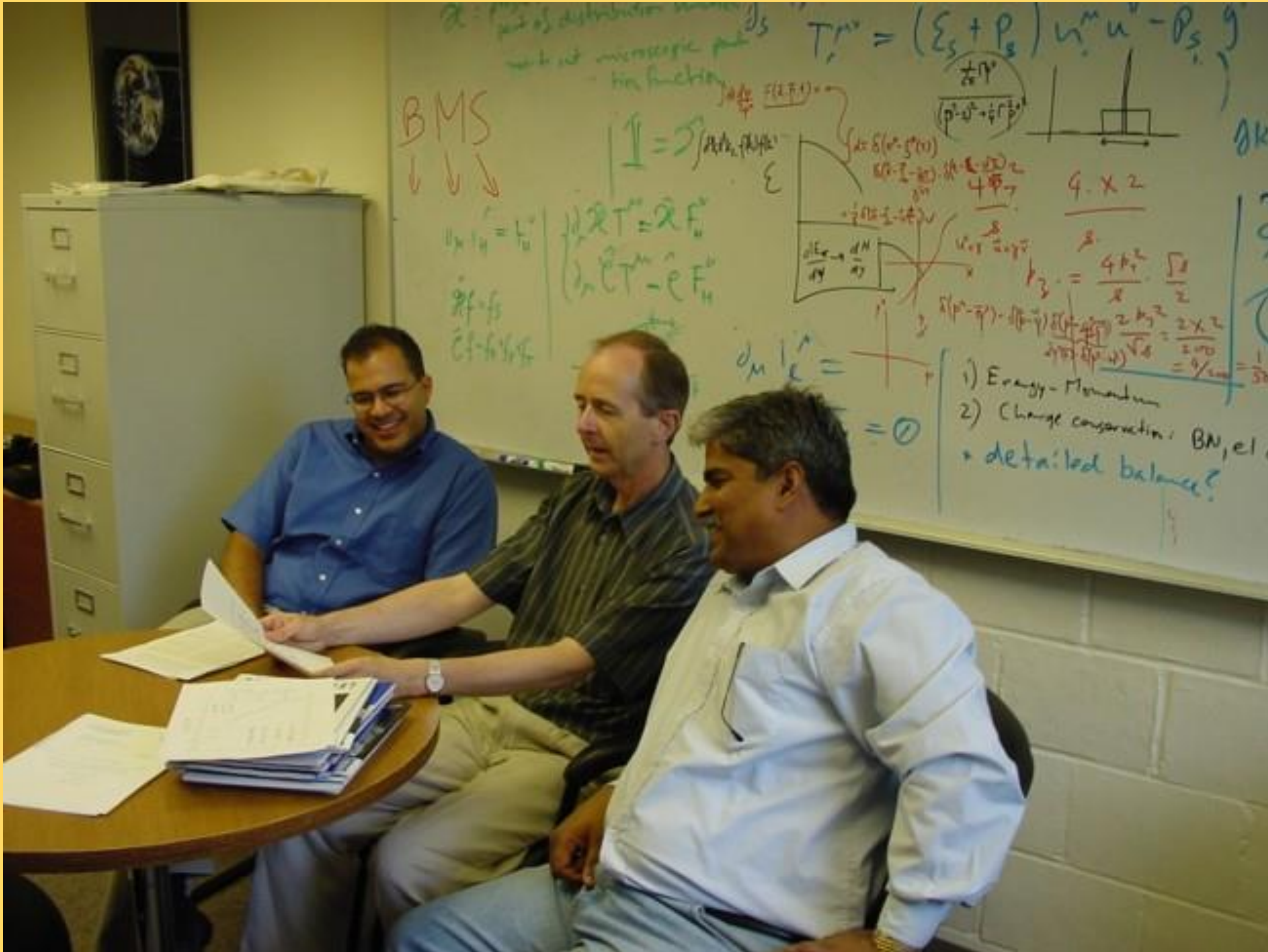
$$S_a\left(x_a, t_{\max}, t\right) = \exp\left\{-\int_t^{t_{\max}} dt' \frac{\alpha_s(t')}{2\pi} \sum_{a'} \int dz\, P_{a'\to ae}(z) \frac{x_{a'} f_{a'}(x_{a'}, t')}{x_a f_a(x_a, t')}\right\}$$



(final state) time-like branchings (with angular ordering):

$$T_d\left(x_d, t_{\max}, t\right) = \exp\left\{-\int_t^{t_{\max}} dt' \frac{\alpha_s(t')}{2\pi} \sum_{a'} \int dz\, P_{d\to d'e}(z)\right\}$$

Altarelli-Parisi splitting functions included: $P_{q\to qg}$, $P_{g\to gg}$, $P_{g\to qqbar}$ & $P_{q\to q\gamma}$


BMS
1) Energy-Momentum
2) Charge conservation
+ detailed balance?

2002

- **Parton rescattering and screening in Au+Au collisions at RHIC, Phys. Lett. B 551, 277 (2003)**
- **Light from cascading partons in relativistic heavy ion collisions, Phys. Rev. Lett. 90, 082301 (2003),**
- **Semi-hard scattering of partons at SPS and RHIC: A Study in Contrast, Phys. Rev. C 66, 061902 (2002),**
- **Photon interferometry of Au + Au collisions at the BNL RHIC, Phys. Rev. Lett. 93, 162301 (2004),**
- **Dynamics of the LPM effect in Au + Au collisions at S**(1/2) = 200-AGeV, Phys. Lett. B 632, 632 (2006),**
- **Net baryon density in Au+Au collisions at the relativistic heavy ion collider, Phys. Rev. Lett. 91, 052302 (2003),**
- **Transverse momentum distribution of net baryon number at RHIC, J. Phys. G 29, L51 (2003),**
- **Strangeness production at RHIC in the perturbative regime, J. Phys. G 30, L7 (2004),**
- **Perturbative dynamics of strangeness production at RHIC, J. Phys. G 31, S1005 (2005).**

Production of Heavy Quarks

q qbar → Q Qbar and g g → Q Qbar

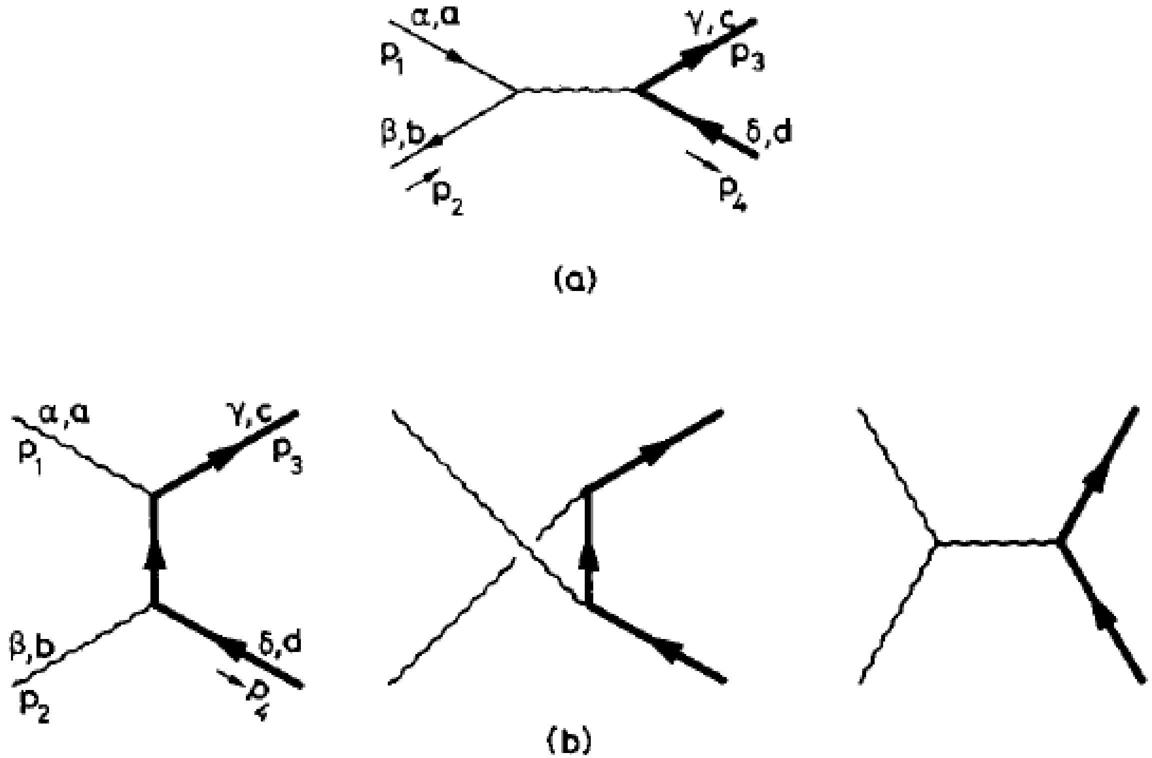


Fig. 1. Lowest-order QCD diagrams for the "flavour-creation" processes: (a) $q\bar{q} \to c\bar{c}$; (b) $gg \to c\bar{c}$

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{1}{16\pi \hat{s}^2} \sum |\mathcal{M}|^2 \, ,$$

For g g → Q Qbar

$$\sum |\mathcal{M}|^2 = \pi^2 \alpha_s^2(Q^2) \left[a_1 + a_2 + a_3 + a_4 + a_5 + a_6\right]$$

where

$$
\begin{aligned}
a_1 &= \frac{12}{\hat{s}^2}(M^2-\hat{t})(M^2-\hat{u}) \\
a_2 &= \frac{8}{3}\,\frac{(M^2-\hat{t})(M^2-\hat{u})-2M^2(M^2+\hat{t})}{(M^2-\hat{t})^2} \\
a_3 &= \frac{8}{3}\,\frac{(M^2-\hat{t})(M^2-\hat{u}-2M^2(M^2+\hat{u})}{(M^2-\hat{u})^2} \\
a_4 &= -\frac{2M^2(\hat{s}-4M^2)}{3(M^2-\hat{t})(M^2-\hat{u})} \\
a_5 &= -6\,\frac{(M^2-\hat{t})(M^2-\hat{u})+M^2(\hat{u}-\hat{t})}{\hat{s}(M^2-\hat{t})} \\
a_6 &= -6\,\frac{(M^2-\hat{t})(M^2-\hat{u})+M^2(\hat{t}-\hat{u})}{\hat{s}(M^2-\hat{u})}
\end{aligned}
$$

And for q qbar→Q Qbar

$$\sum |\mathcal{M}|^2 = \frac{64}{9}\pi^2\alpha_s^2(Q^2) \times \left[\frac{(M^2-\hat{t})^2 + (M^2-\hat{u})^2 + 2M^2\hat{s}}{\hat{s}^2}\right]$$

Note that these differential cross-sections remain finite and no momentum cut-off is needed.

We have also included the scatterings qQ→ qQ and gQ→gQ, which require a momentum cut-off for regularization. These matrix elements for qQ→qQ are:

$$\sum |\mathcal{M}|^2 = \frac{64}{9}\pi^2\alpha_s^2(Q^2) \times \left[\frac{(M^2-\hat{u})^2+(\hat{s}-M^2)^2+2M^2\hat{t}}{\hat{t}^2}\right]$$

While for gQ→ gQ, these are given by:

$$\sum |\mathcal{M}|^2 = \pi^2 \alpha_s^2(Q^2) \times [b_1 + b_2 + b_3 + b_4 + b_5 + b_6] ,$$

with

$$b_1 = 32\frac{(\hat{s}-M^2)(M^2-\hat{u})}{\hat{t}^2},$$

$$b_2 = \frac{64}{9}\frac{(\hat{s}-M^2)(M^2-\hat{u})+2M^2(\hat{s}+M^2)}{(\hat{s}-M^2)^2},$$

$$b_3 = \frac{64}{9}\frac{(\hat{s}-M^2)(M-\hat{u})+2M^2(M^2+\hat{u})}{(M^2-\hat{u})^2},$$

$$b_4 = \frac{16}{9}\frac{M^2(4M^2-\hat{t})}{(\hat{s}-M^2)(M^2-\hat{u})},$$

$$b_5 = 16\frac{(\hat{s}-M^2)(M^2-\hat{u})+M^2(\hat{s}-\hat{u})}{\hat{t}(\hat{s}-M^2)},$$

$$b_6 = -16\frac{(\hat{s}-M^2)(M^2-\hat{u})-M^2(\hat{s}-\hat{u})}{\hat{t}(M^2-\hat{u})}.$$

Initial State

Nucleon positions sampled from:

$$\rho(r) = \rho_0/\left[1 + \exp\left(\frac{r-R}{a}\right)\right]$$

Parton positions sampled from:

$$h(r) = [\nu^3/(8\pi)]\exp(-\nu r)$$

where R_{rms}=sqrt(12/ν)=0.81 fm

Parton momenta sampled from PDF (GRV-HO) initialized at:

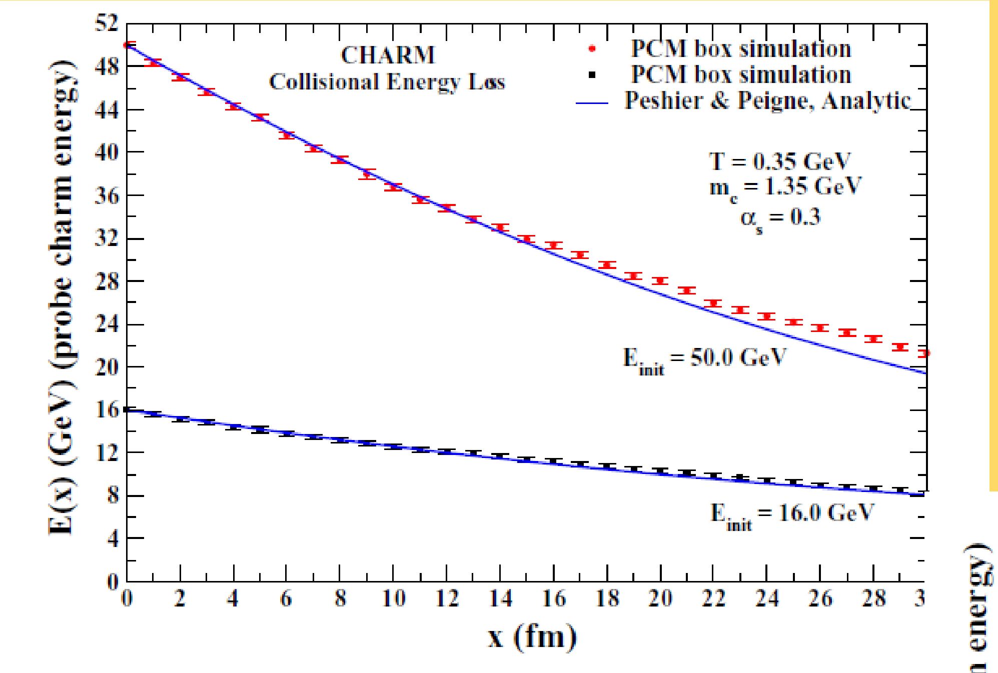
$$(Q_{ini})^2 = (p_T^{cut\text{-}off})^2$$

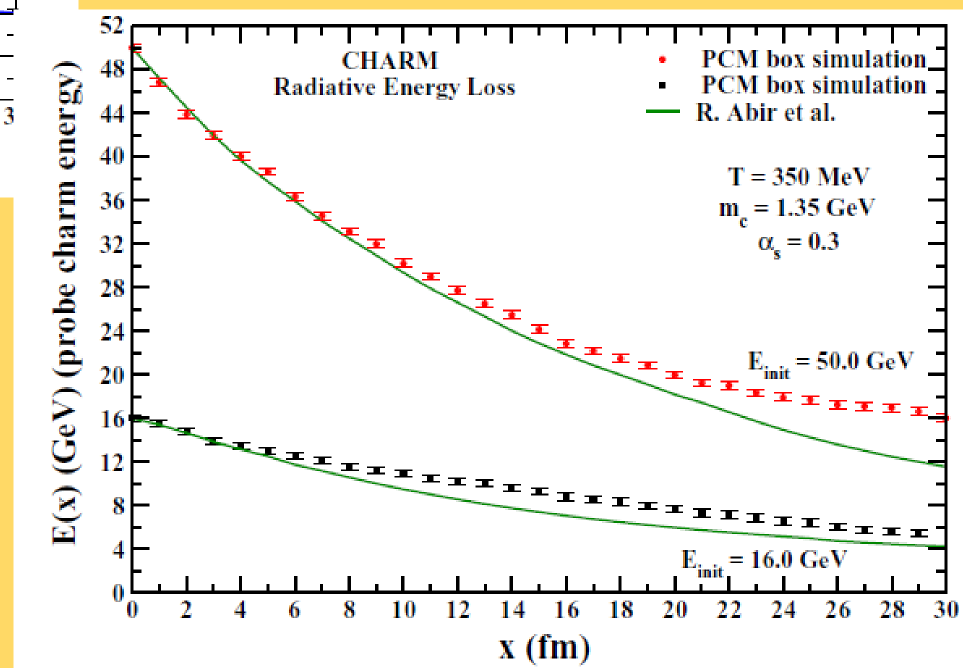
For most of our calculations at top RHIC energy, we have used:

$$(p_T^{cut\text{-}off})^2 = 0.589\ \text{GeV}^2\ .$$

$x_1\, x_2\, \mathrm{sqrt}\{s_{NN}\} > 2p_T$, $x_i^{min} \sim 2p_T^{cut\text{-}off}/\mathrm{sqrt}\{s_{NN}\}$

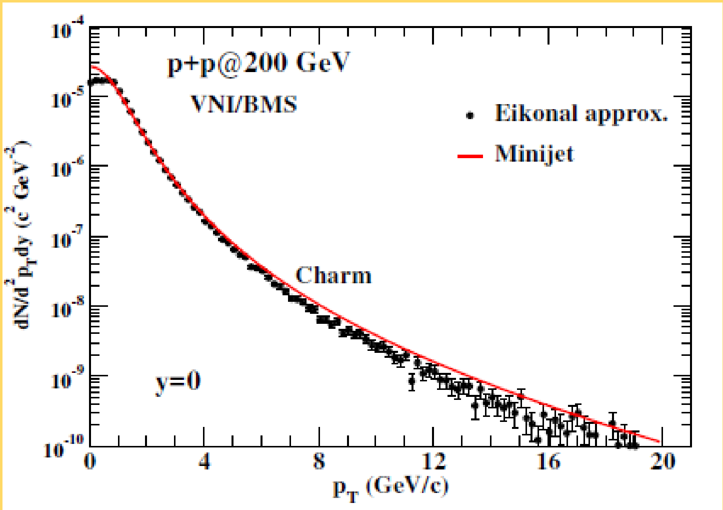
Box Mode

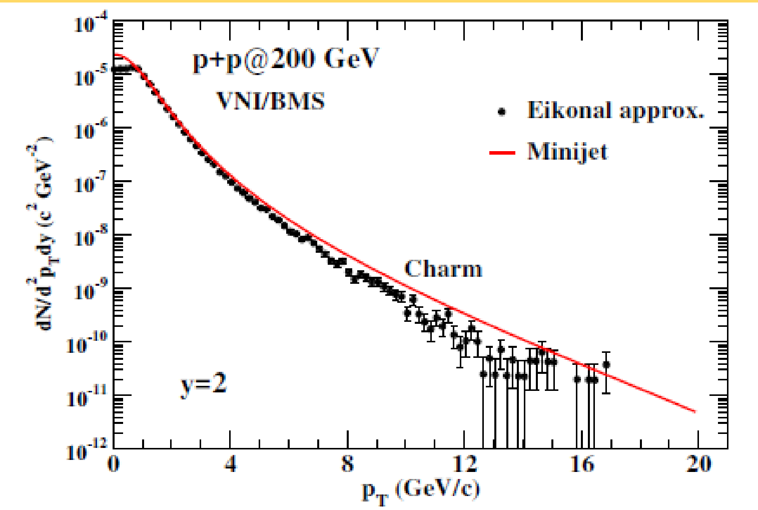


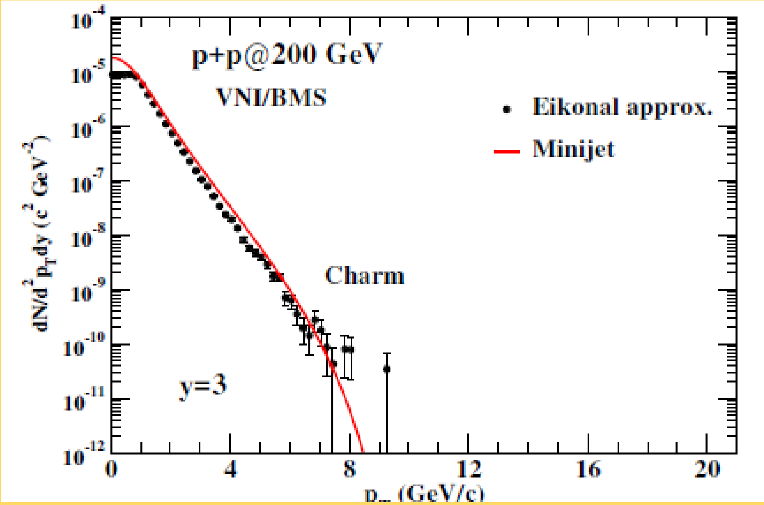


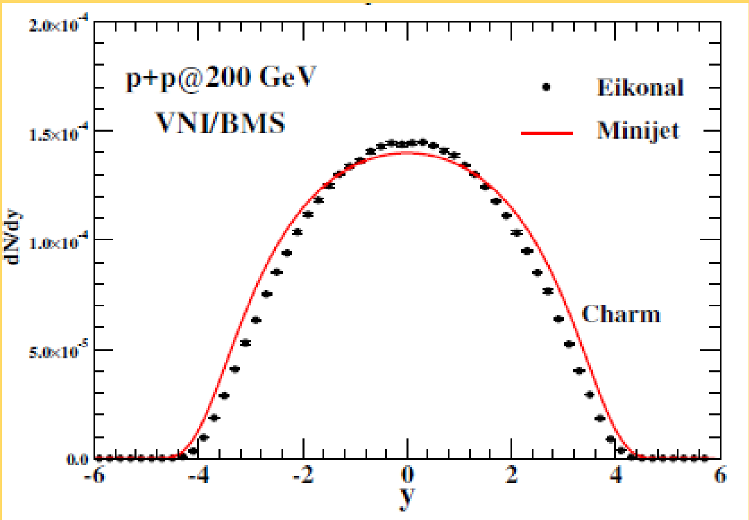
**M. Younus,
C. Coleman-Smith,
S. A. Bass and DKS,
PRC 91 (2015) 024912**

Validation: Eikonal and independent minjet calculation







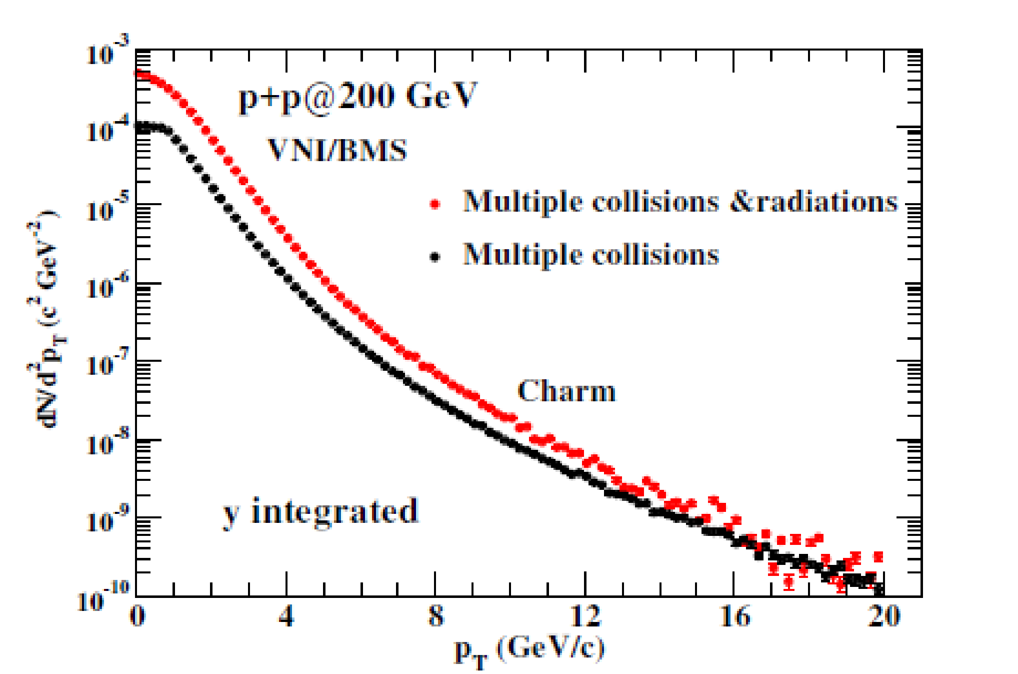


Three sets of calculations

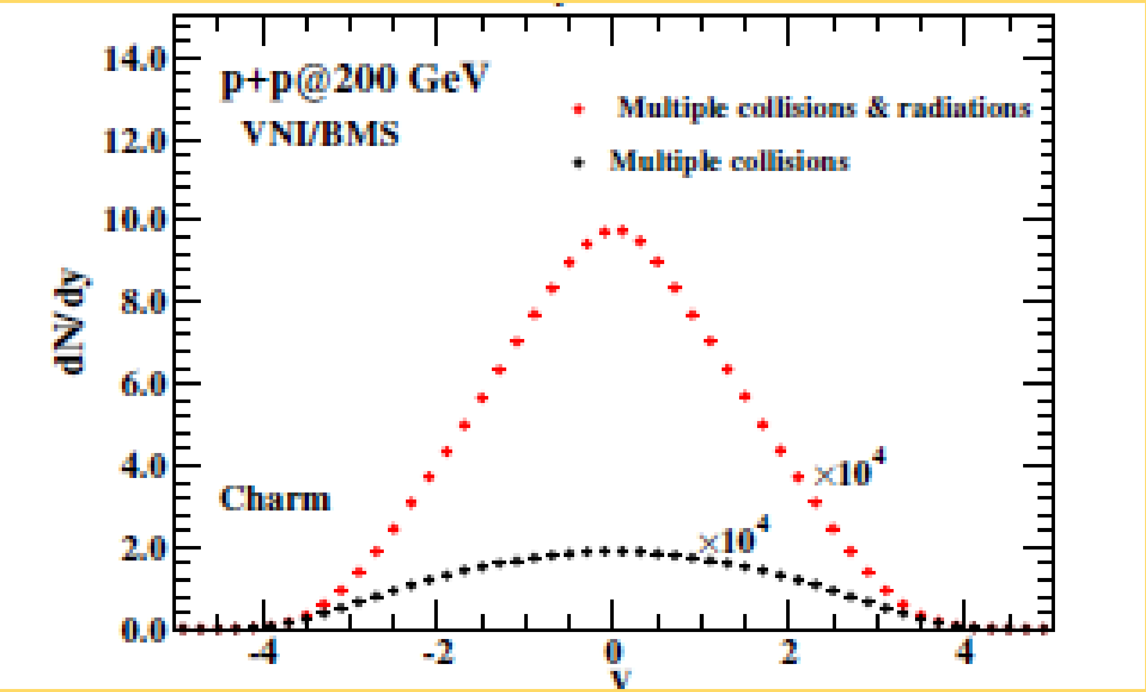
1. Collisions involving only primary partons.

2. Multiple collisions involving primary as well as secondary partons (without fragmentaions).

3. Multiple collisions *as well as* radiations (fragmentations) off final state partons.

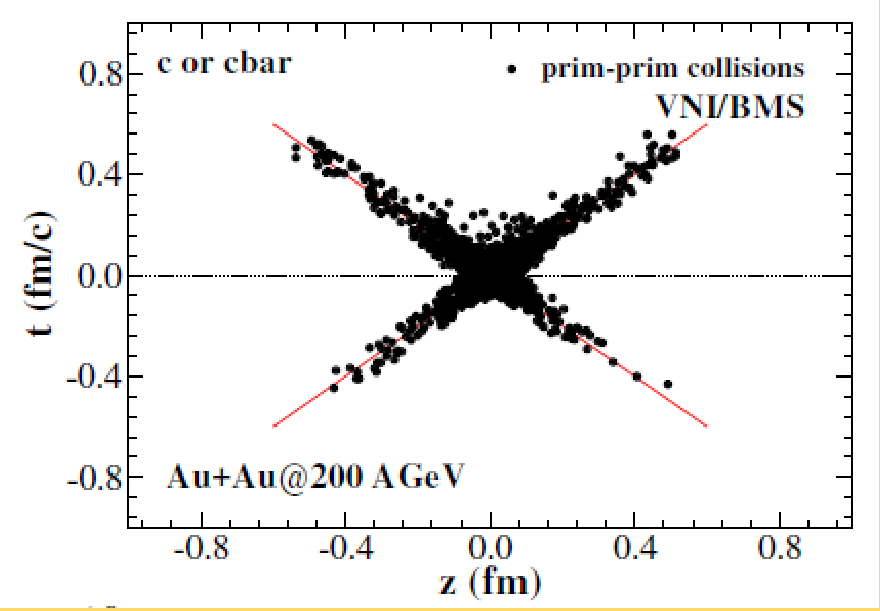


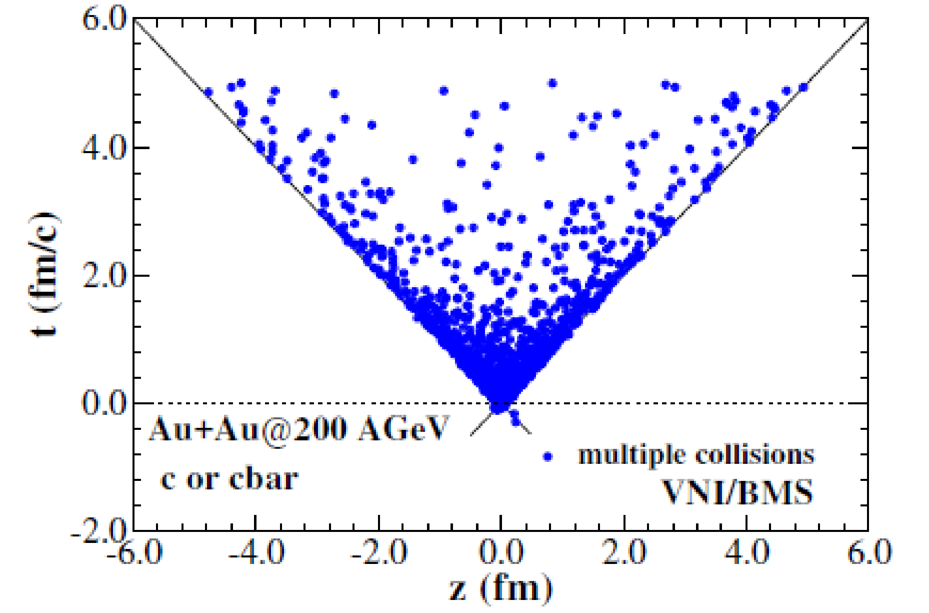
What does fragmentation of final state partons do?

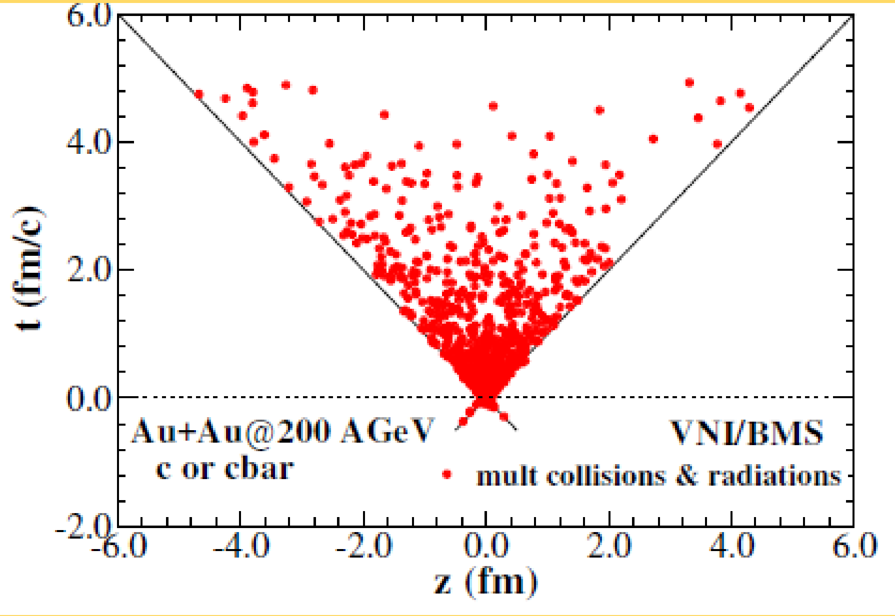


Already in pp collisions!

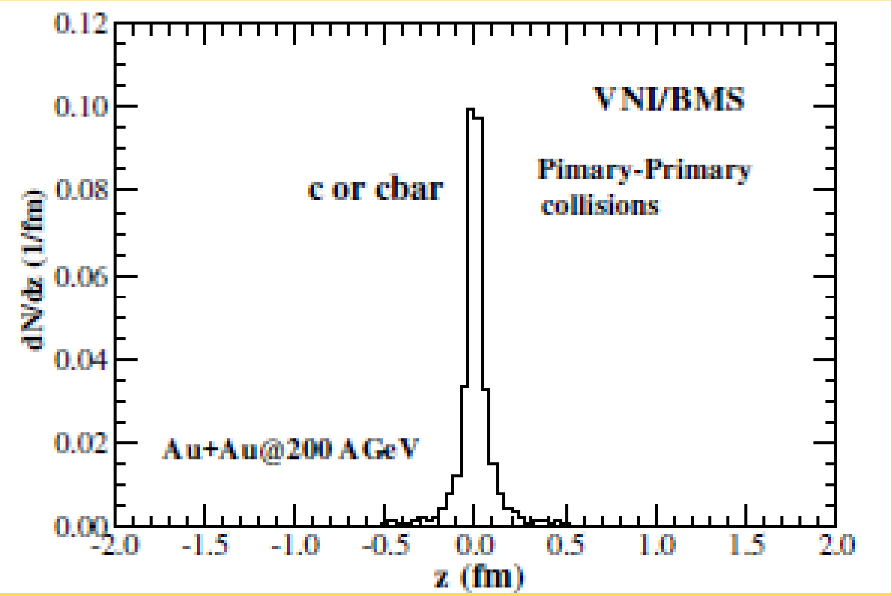
- **Where are the charm quarks produced?**
- **N_c~2700**

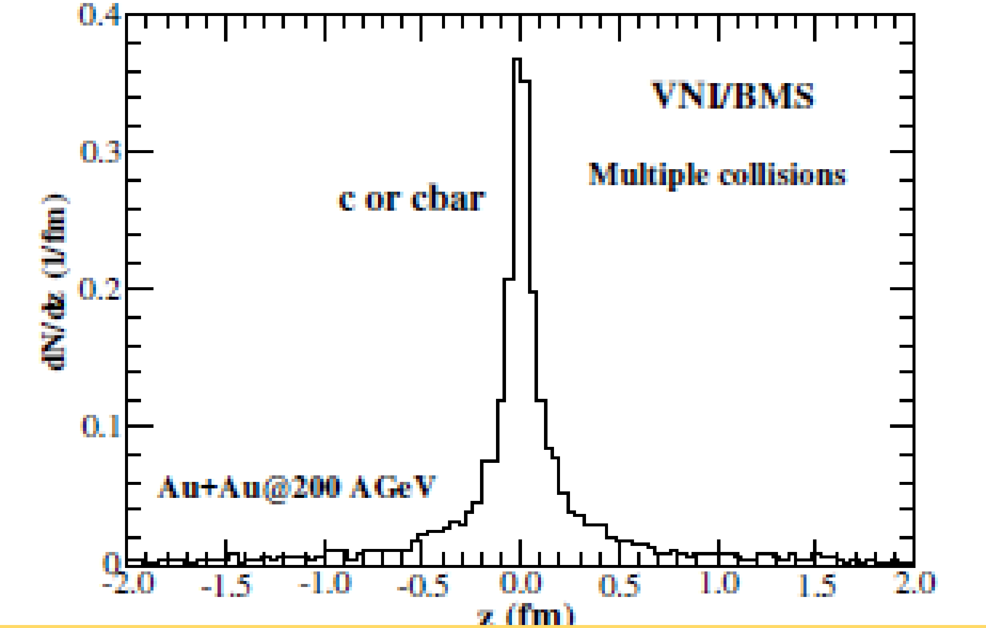


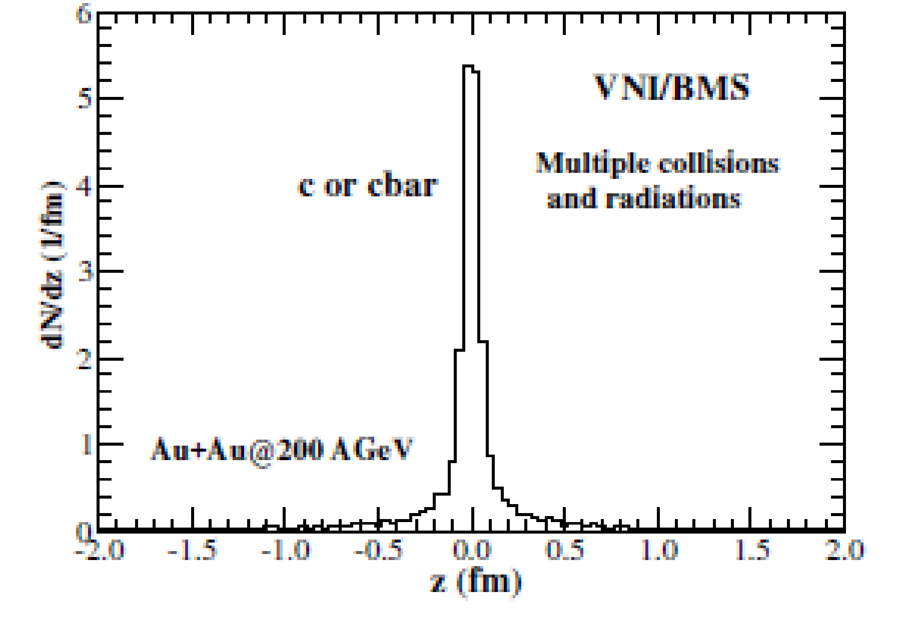




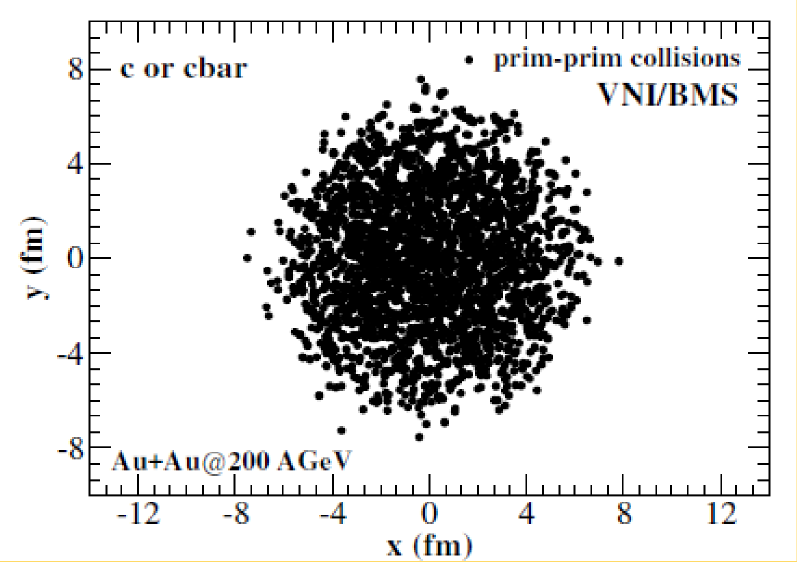
- **Where are the charm quarks produced?**

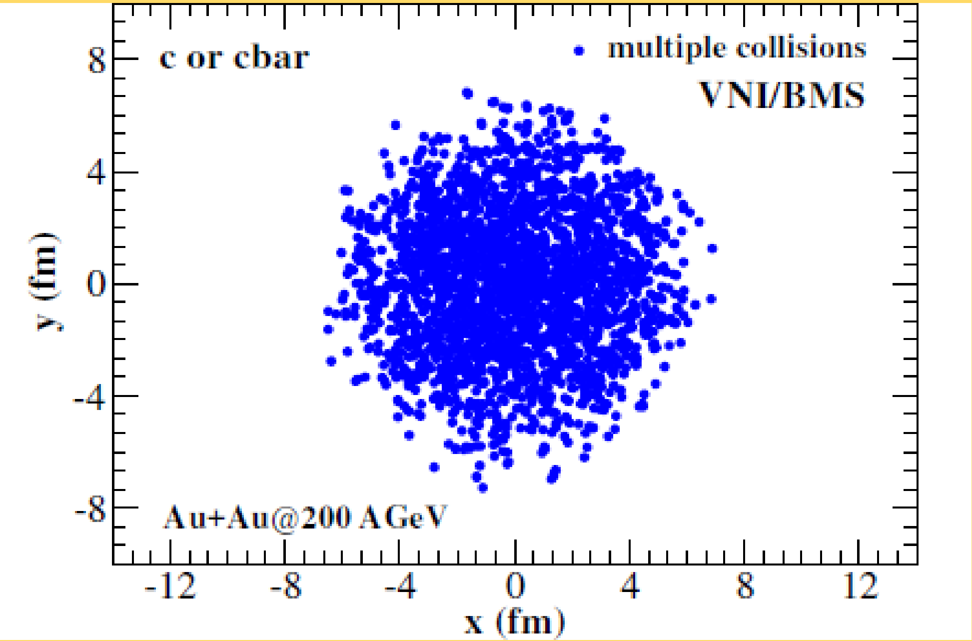


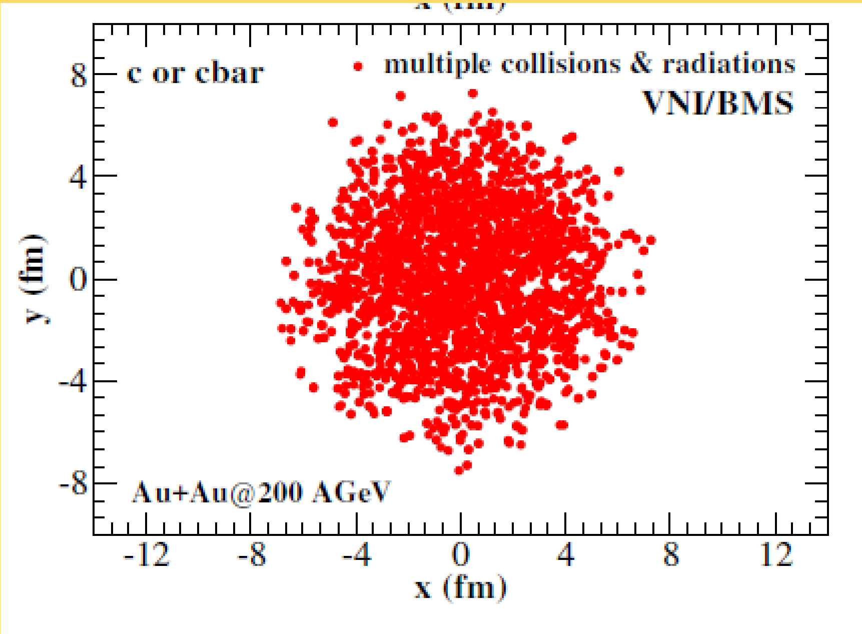




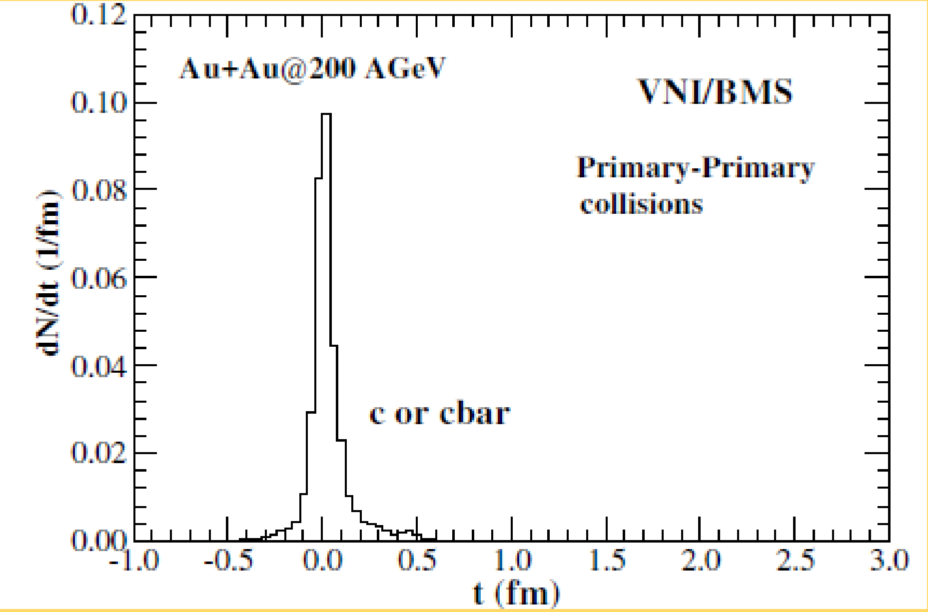
- **Where are the charm quarks produced?**
- **N_c~2700**
- **~ T_{AB}(x,y, b=0)**

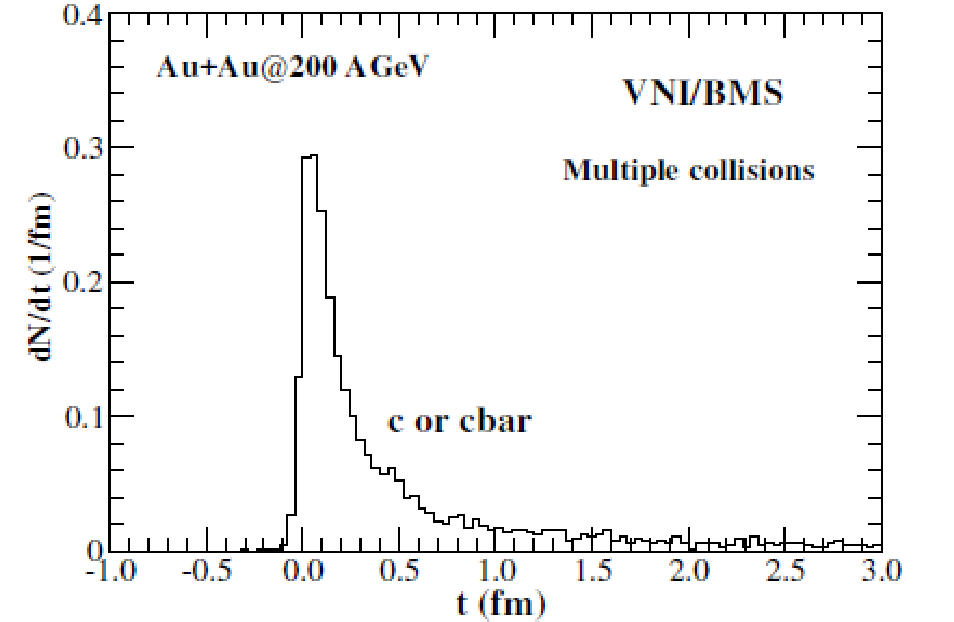


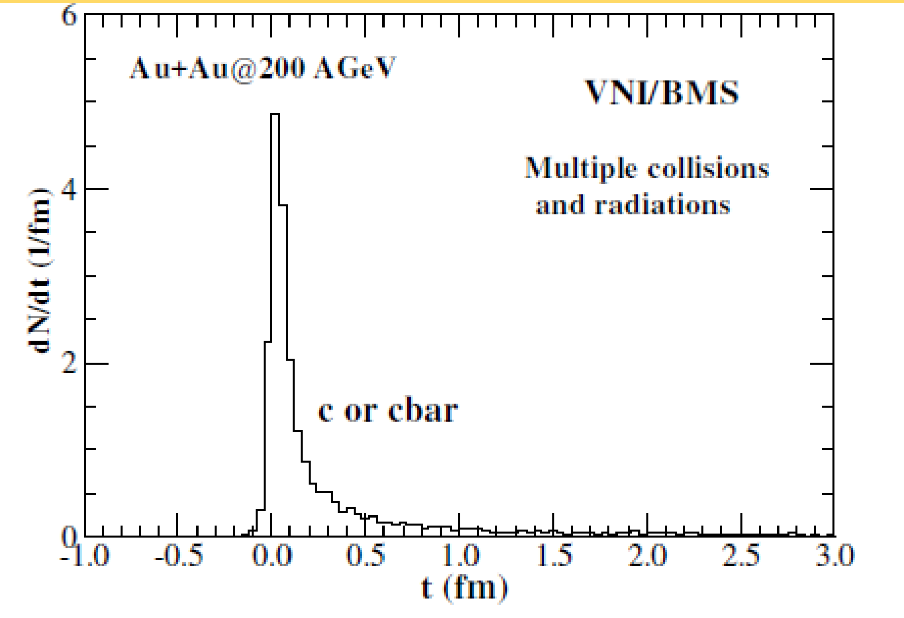




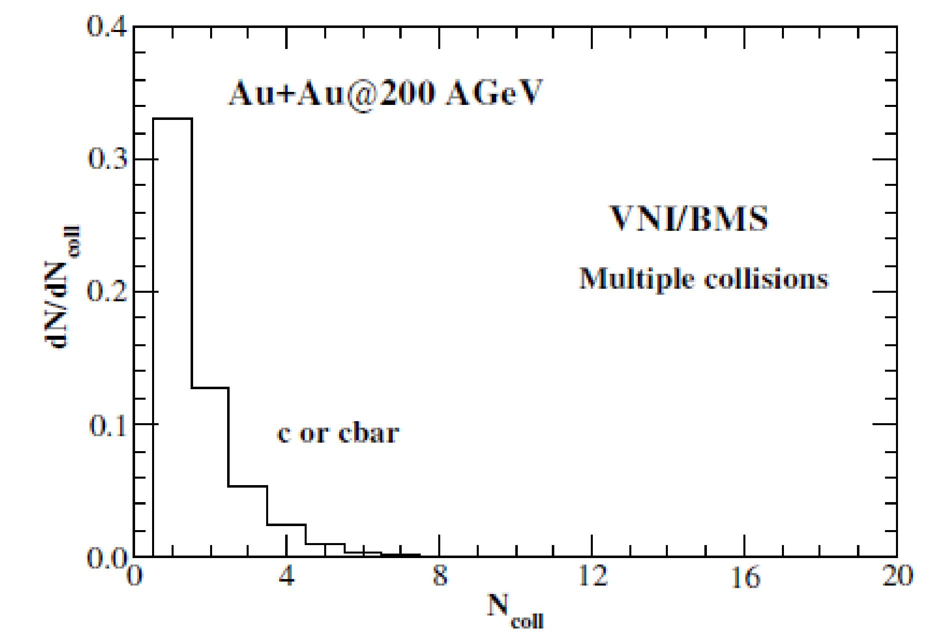
- **When are the charm quarks produced?**

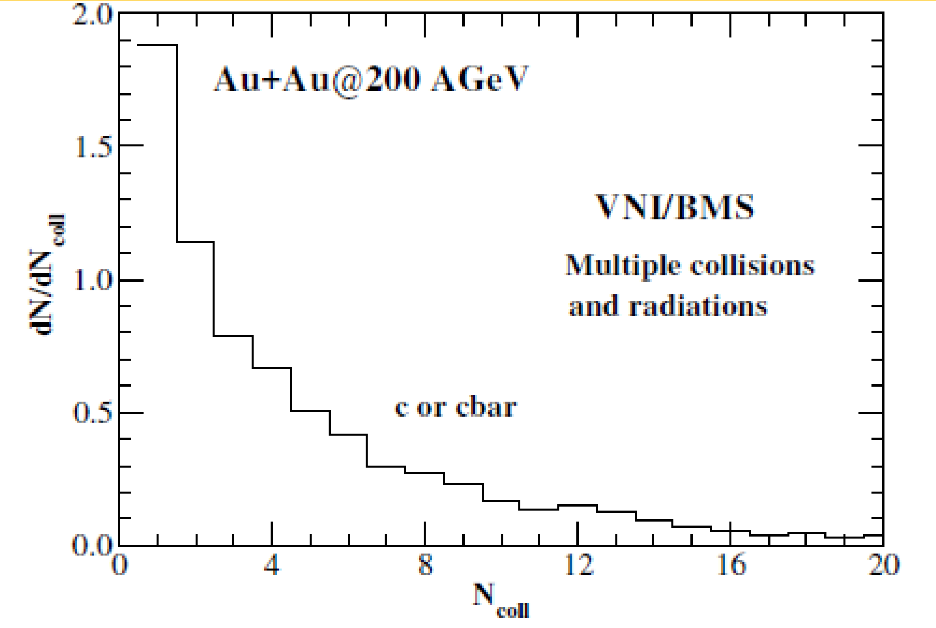


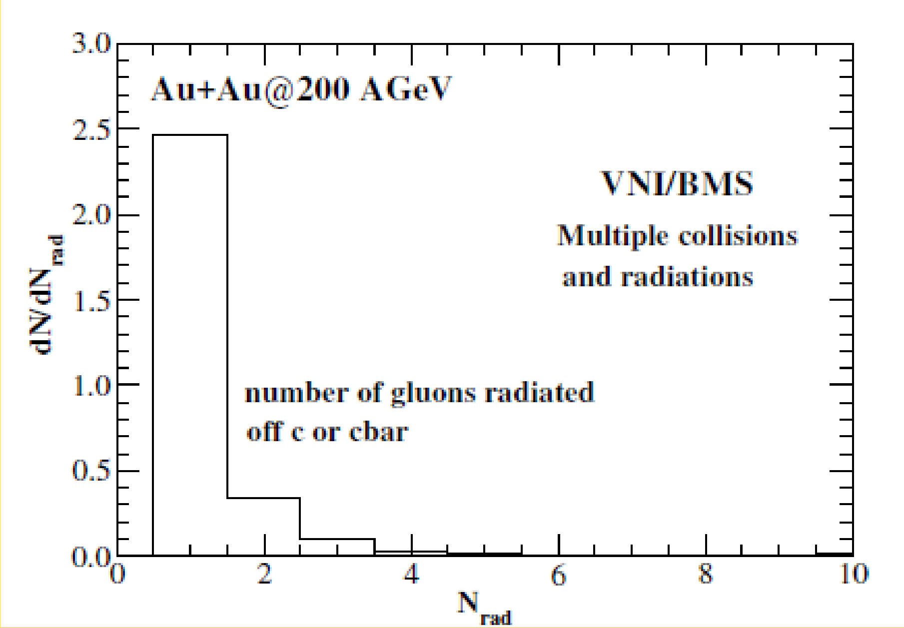




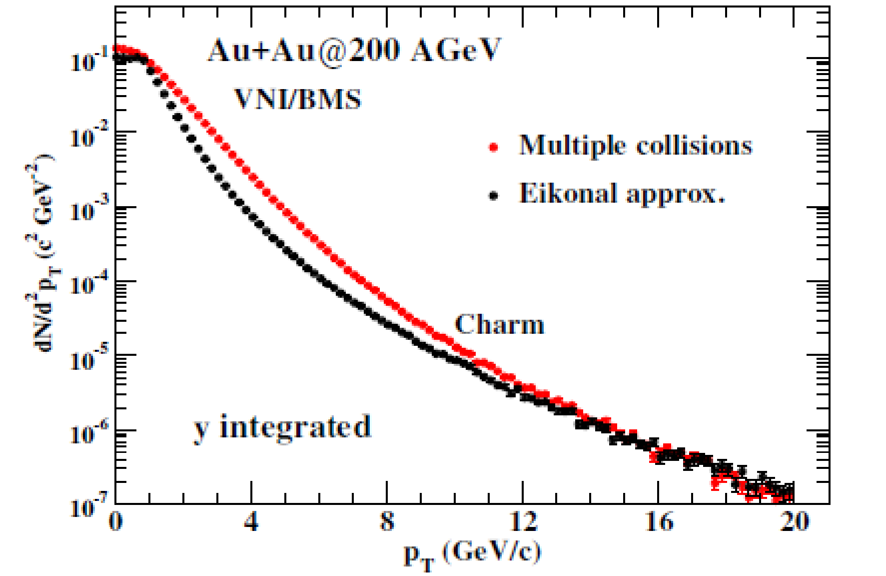
- How often do the charm quarks collide?
- How often do they radiate gluons?





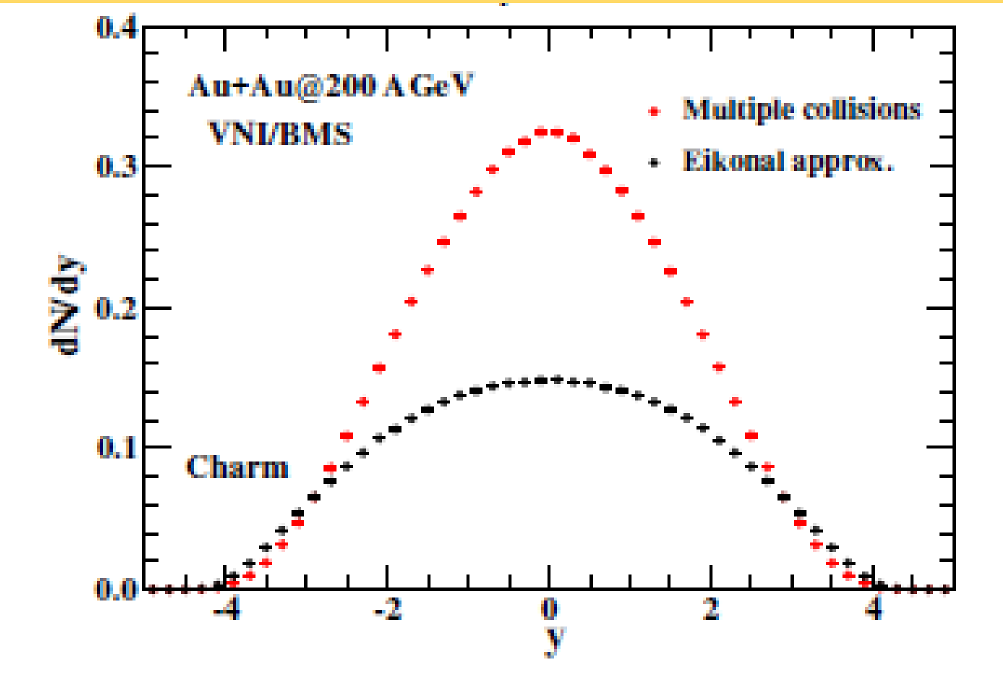


Testing Eikonal Approximation in Au+Au Collisions

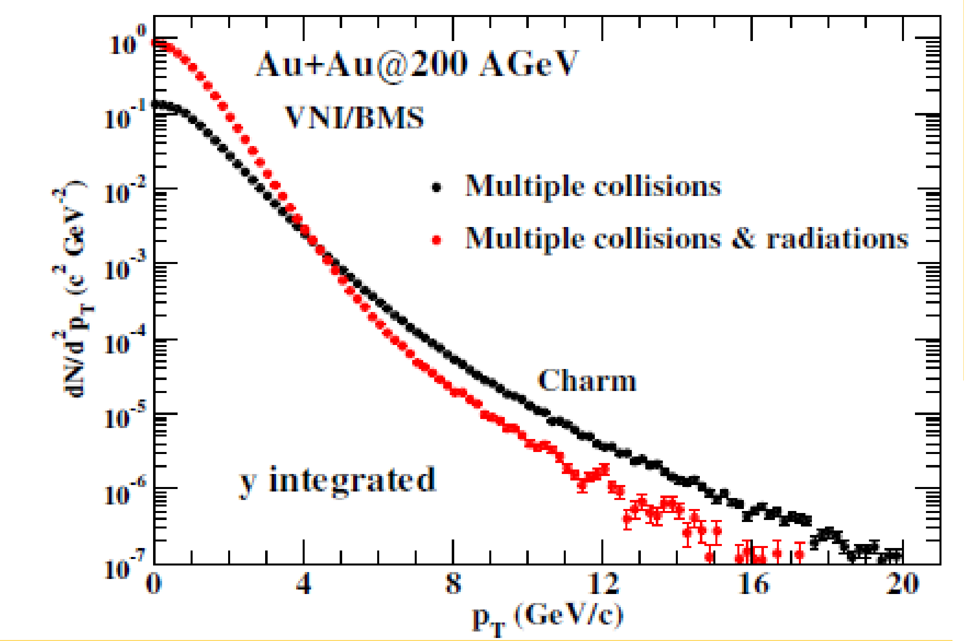


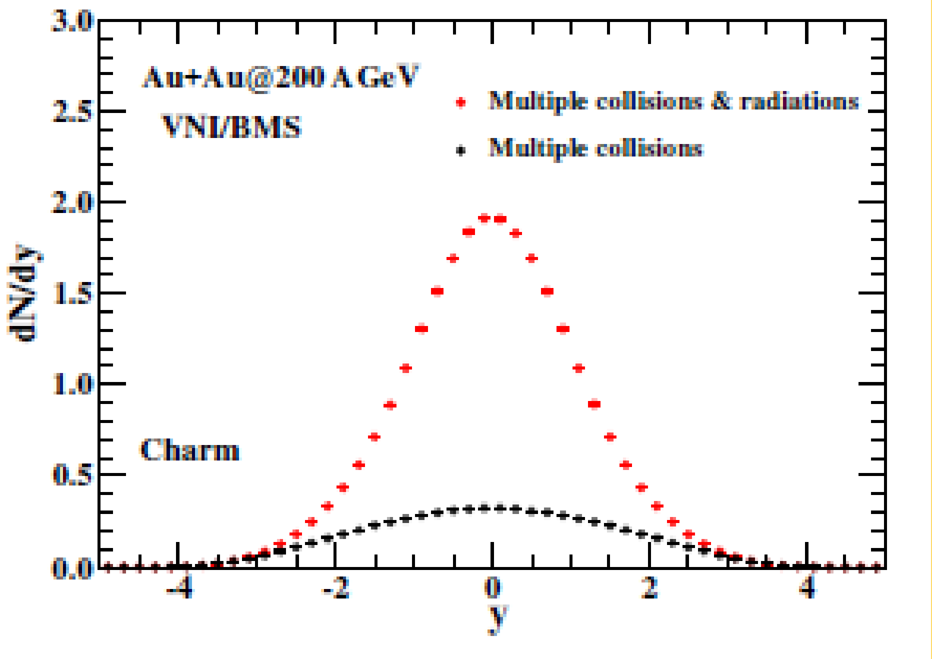
Additional production at low pT from mini-jet mini-jet interaction

Levai, Muller, wang, PRC 51
Lin and Gyulassy, PRC 51
Younus and Srivastava, JPG 37.

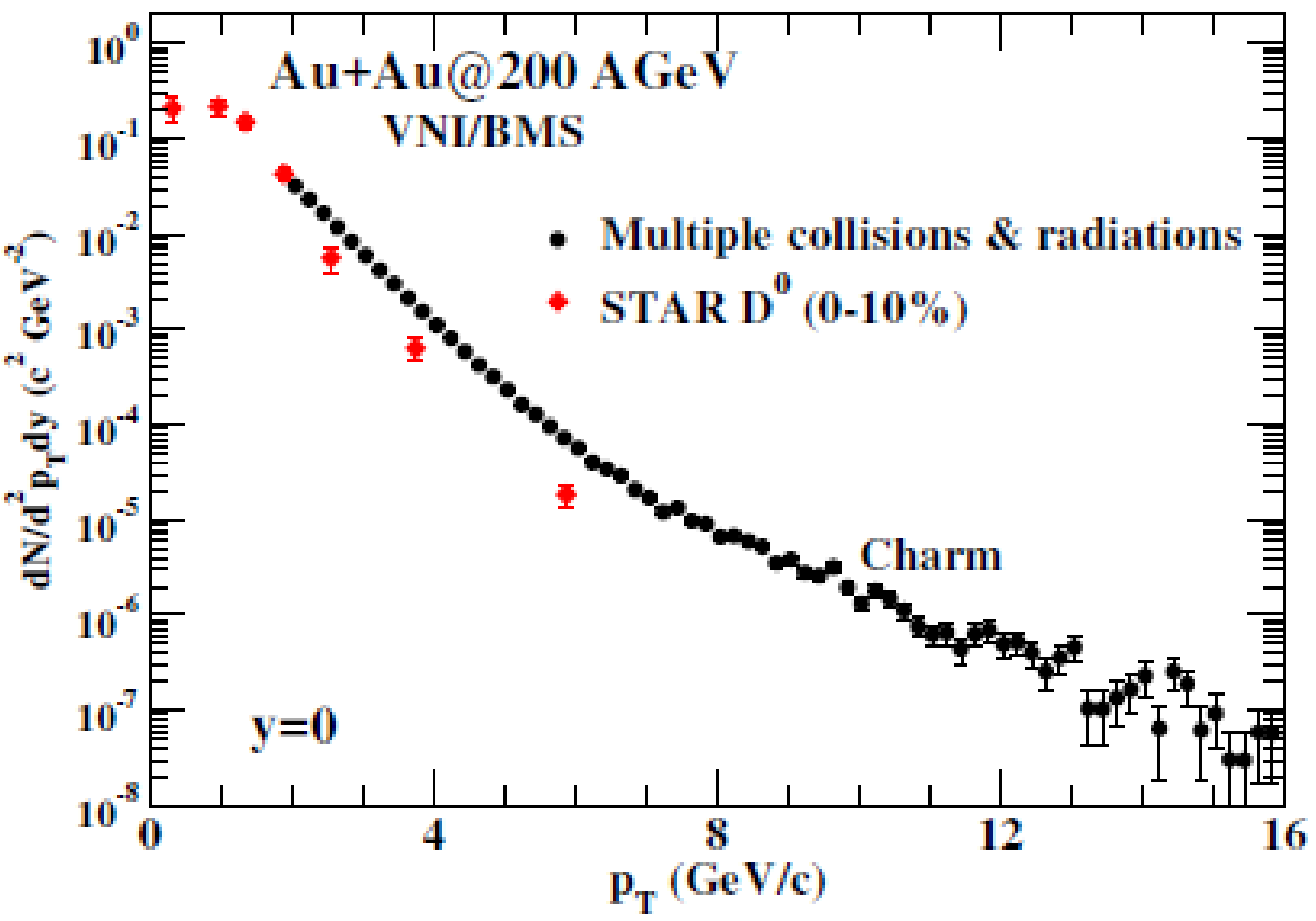


The consequences of fragmentations off final state partons

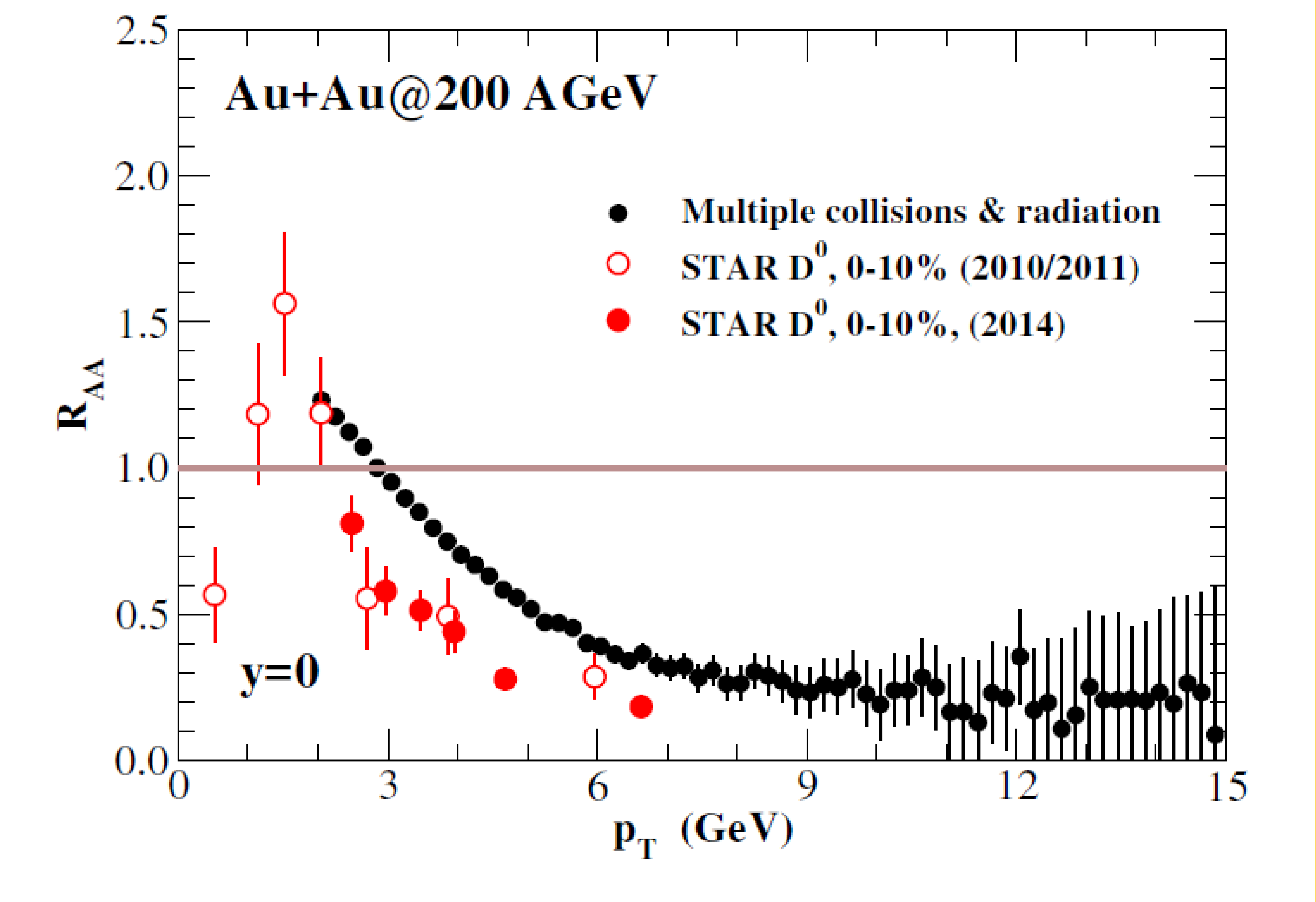




Spectra with $D_{cD}(z) \sim \delta(1-z)$
No Free Parameters



$R^D_{AA}(p_T)$ (b=0)



Au+Au@200 AGeV
Multiple collisions & radiation
STAR D⁰, 0-10% (2010/2011)
STAR D⁰, 0-10%, (2014)
y=0
R_AA
p_T (GeV)
0.0
0.5
1.0
1.5
2.0
2.5
0
3
6
9
12
15

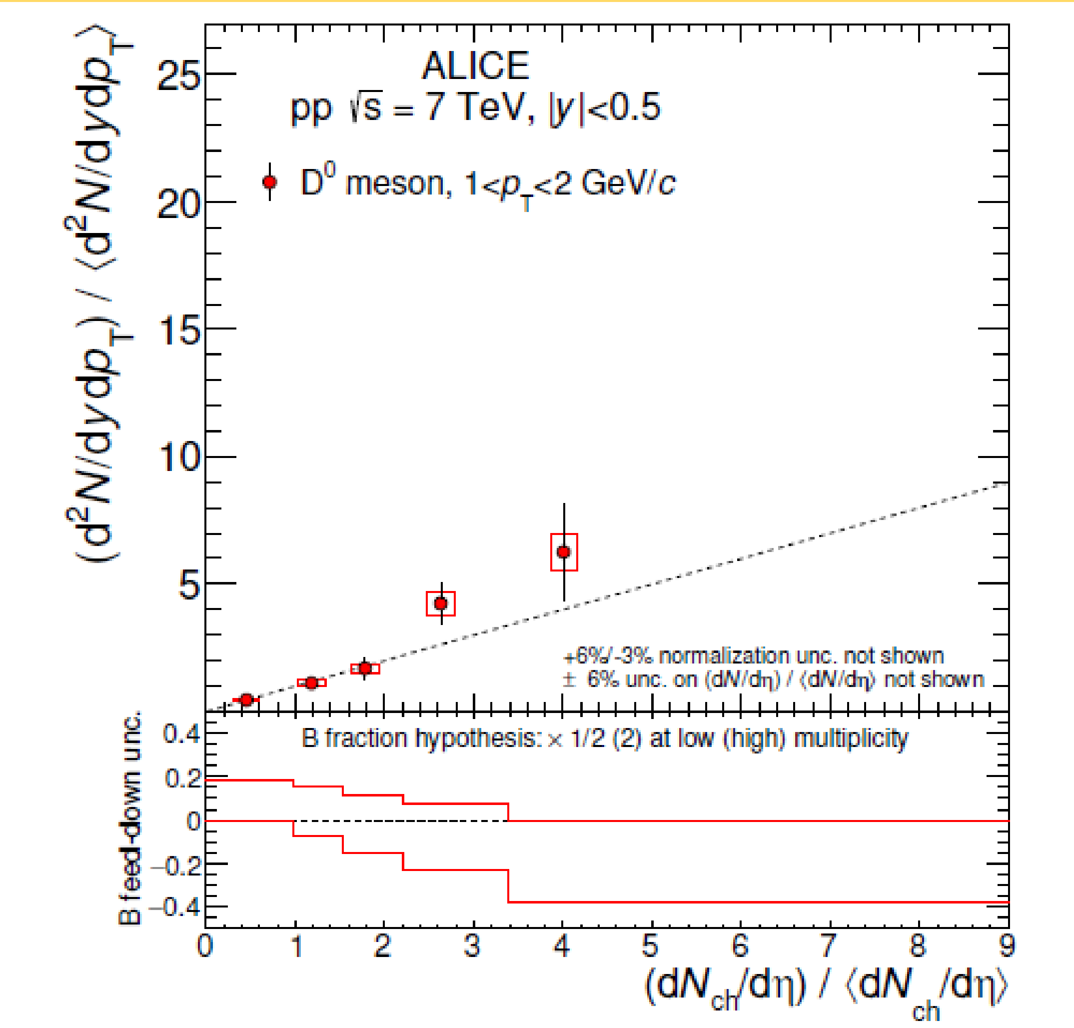
Summary: Part I

- Fragmentation of final state partons following a collision leads to:

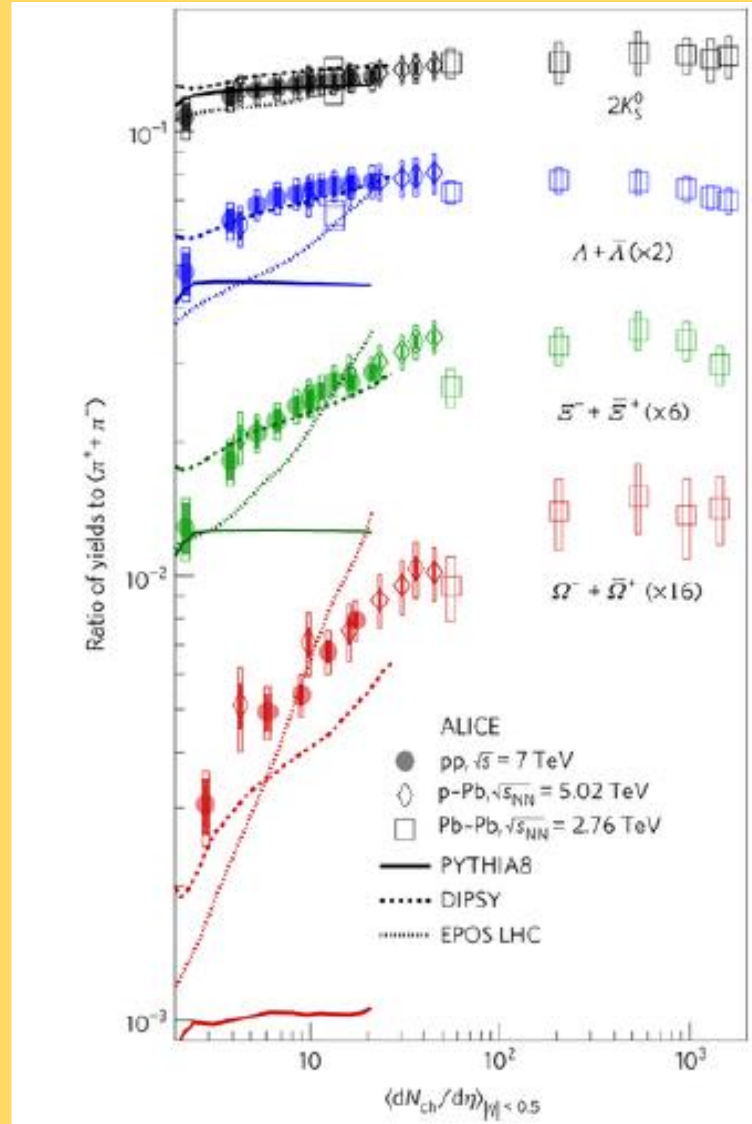
  i) parton multiplication.

  ii) increase in collisions.
- It thus feeds and is fed by multiple collisions.
- Calculations involving multiple collisions and fragmentations lead to suppression of charm mesons at large p_T .

Why pp?



ALICE
pp √s = 7 TeV, |y|<0.5
D0 meson, 1<pT<2 GeV/c
+6%/-3% normalization unc. not shown
± 6% unc. on (dN/dη) / ⟨dN/dη⟩ not shown
B fraction hypothesis: × 1/2 (2) at low (high) multiplicity
(d2N/dydpT) / ⟨d2N/dydpT⟩
B feed-down unc.
(dNch/dη) / ⟨dNch/dη⟩

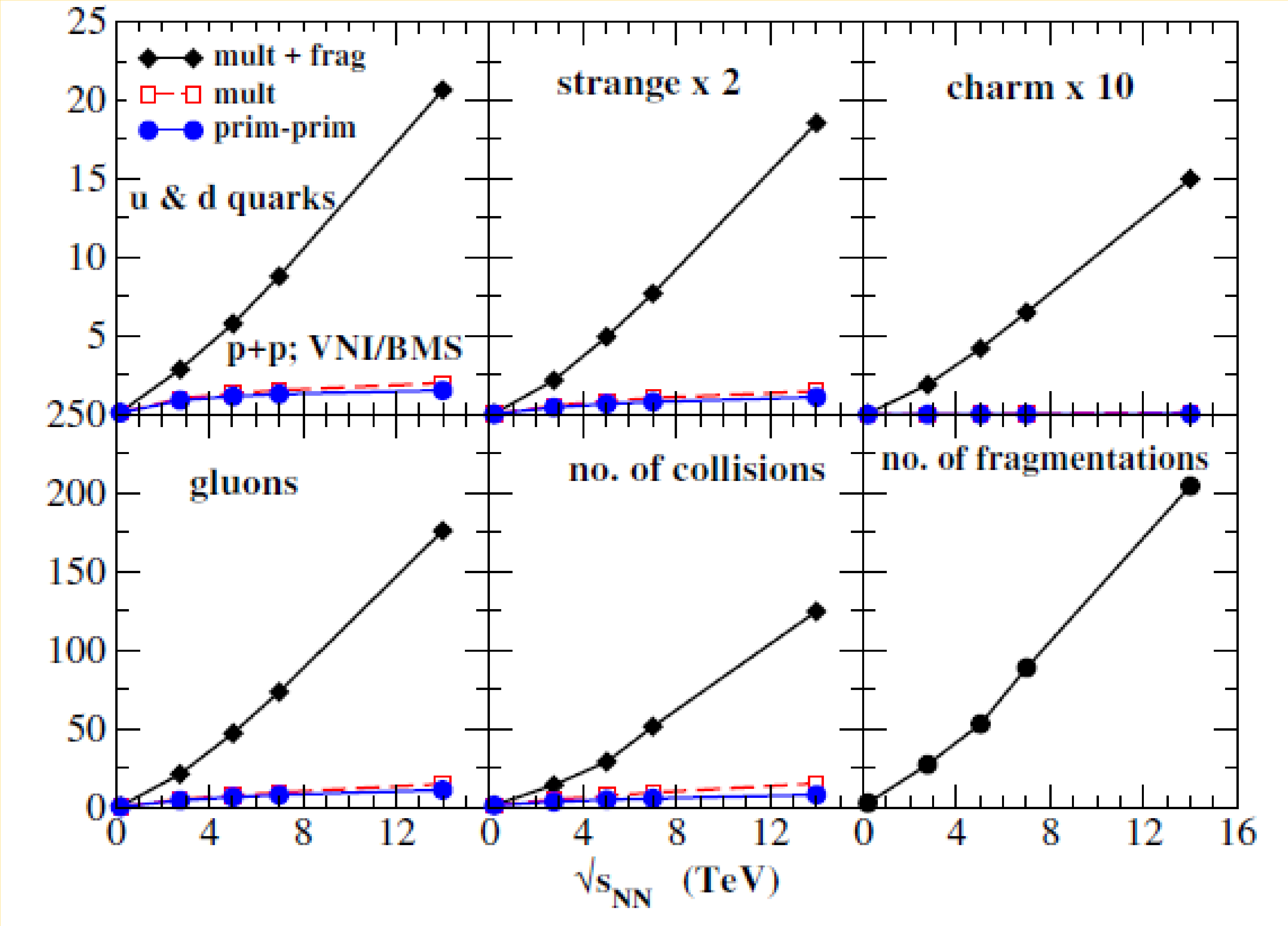


2K0S
Λ + Λ̄ (×2)
Ξ⁻ + Ξ̄⁺ (×6)
Ω⁻ + Ω̄⁺ (×16)
ALICE
pp, √s = 7 TeV
p-Pb, √sNN = 5.02 TeV
Pb-Pb, √sNN = 2.76 TeV
PYTHIA8
DIPSY
EPOS LHC
Ratio of yields to (π⁺ + π⁻)
⟨dNch/dη⟩|η|<0.5

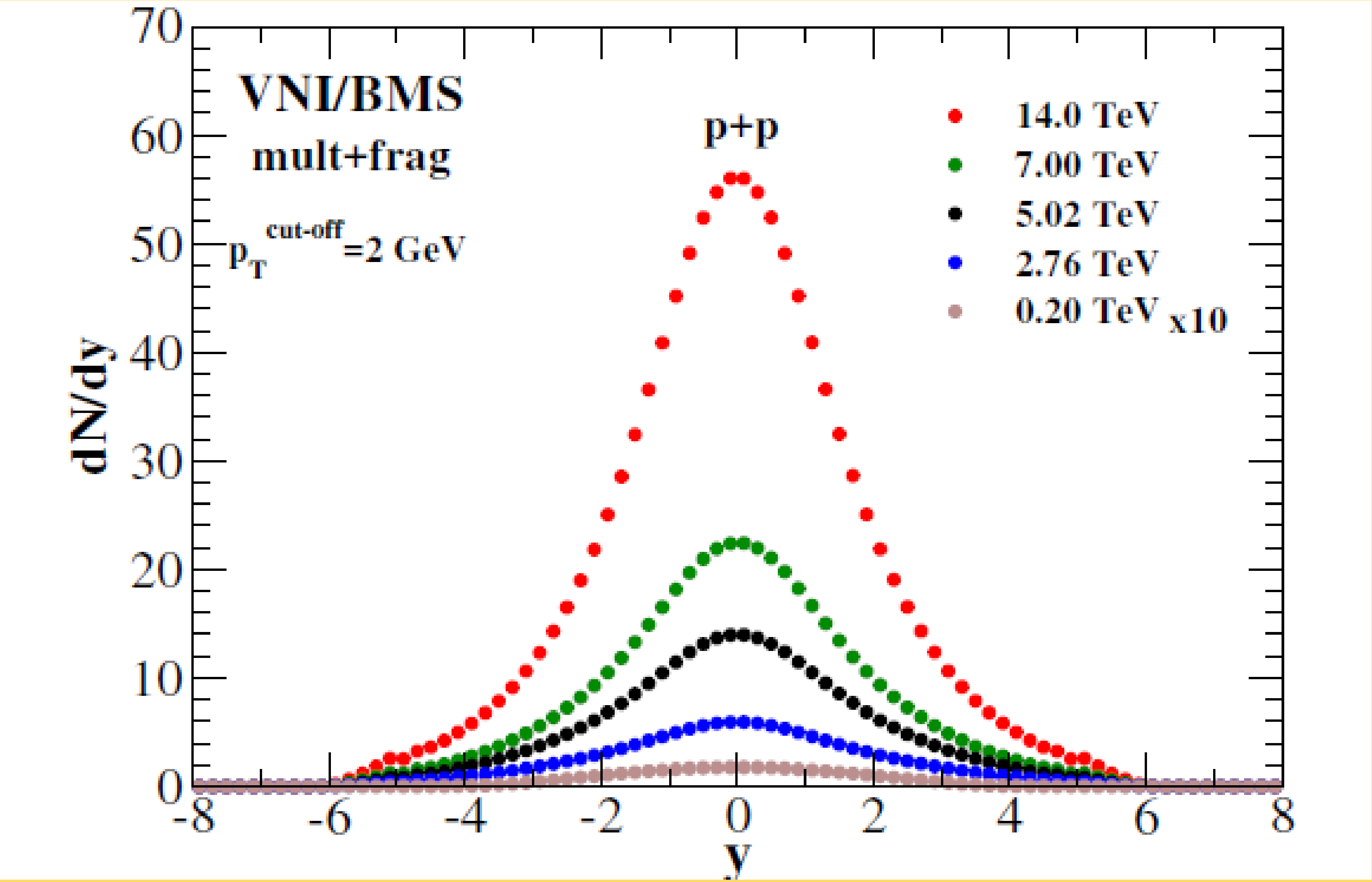
pp collisions at 0.2, 2.76, 5.02, 7.00, & 14 TeV

- $Q_{ini}^2 = (2\ \text{GeV})^2$
- $p_T^{\text{cut-off}} = 2$ GeV (etc.)
- $\mu_0 = 1$ GeV; such that lowest virtuality $Q_0^2 = (m_i^2 + \mu_0^2)$ where m_i is current mass of the parton.
- Results for minimum bias.
- Results for b=0.0, 0.2,……, 1.0 at 7.00 TeV

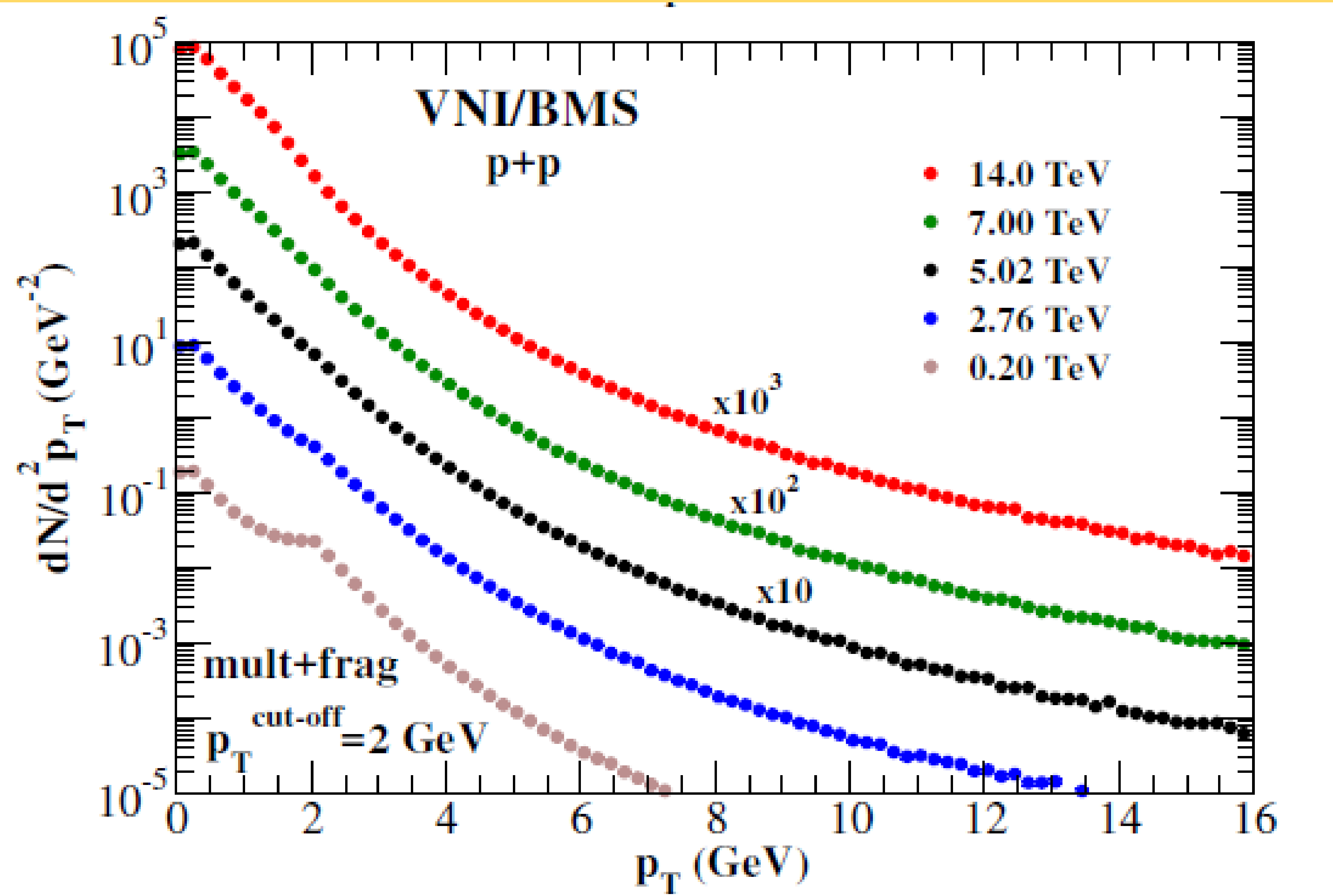
Parton production in semi-hard interactions



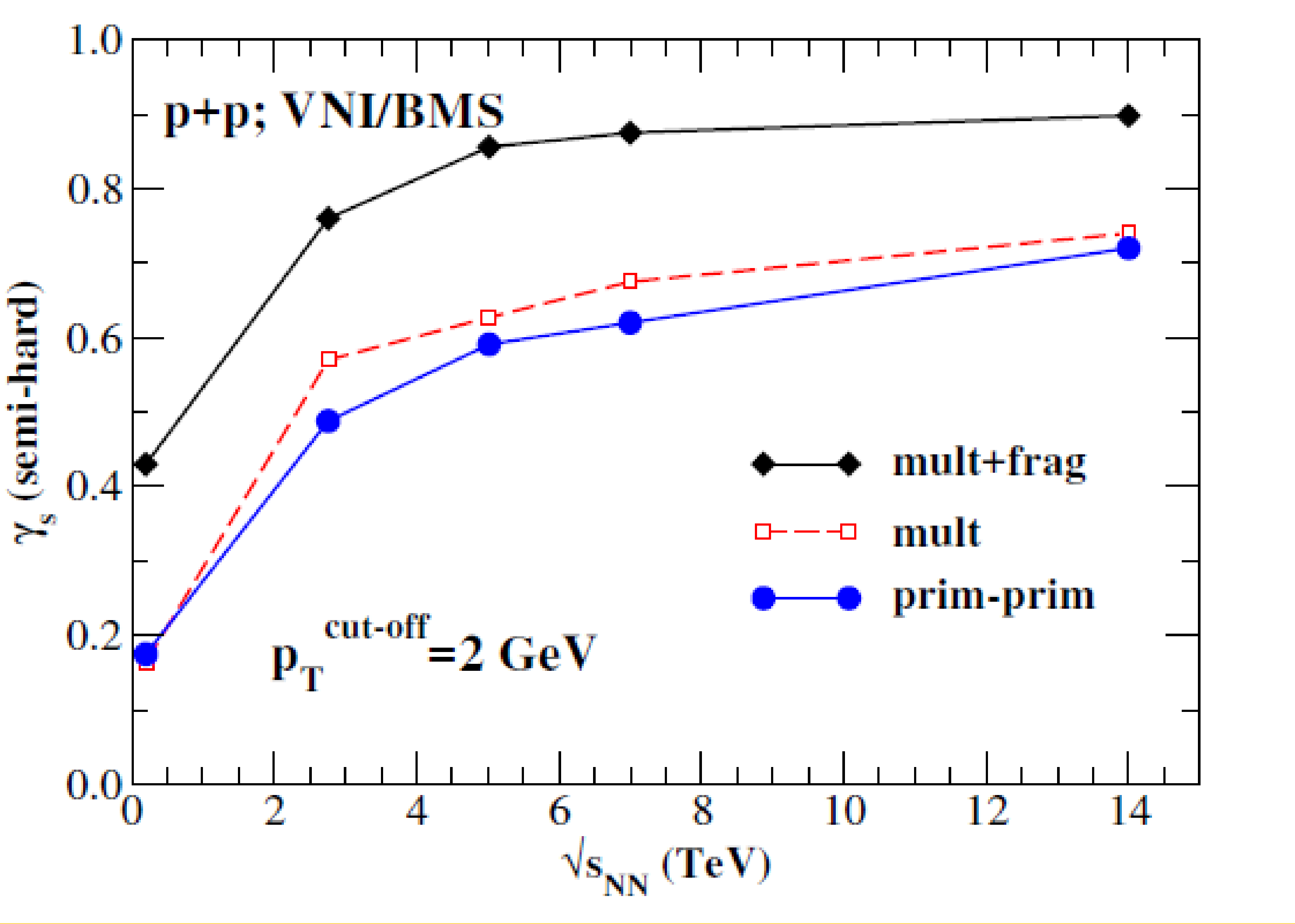
Rapidity spectra for produced partons



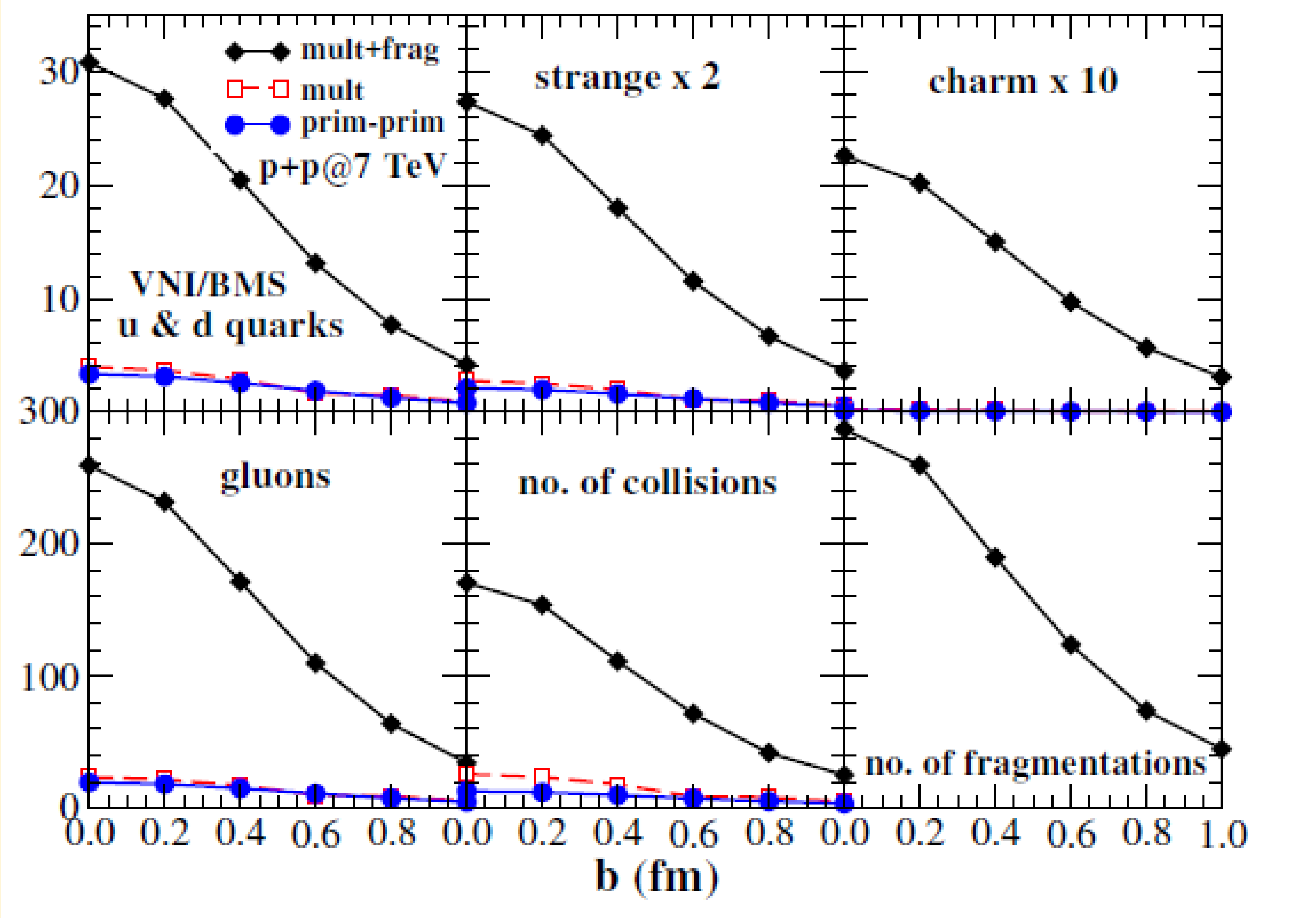
p_T spectra of produced partons



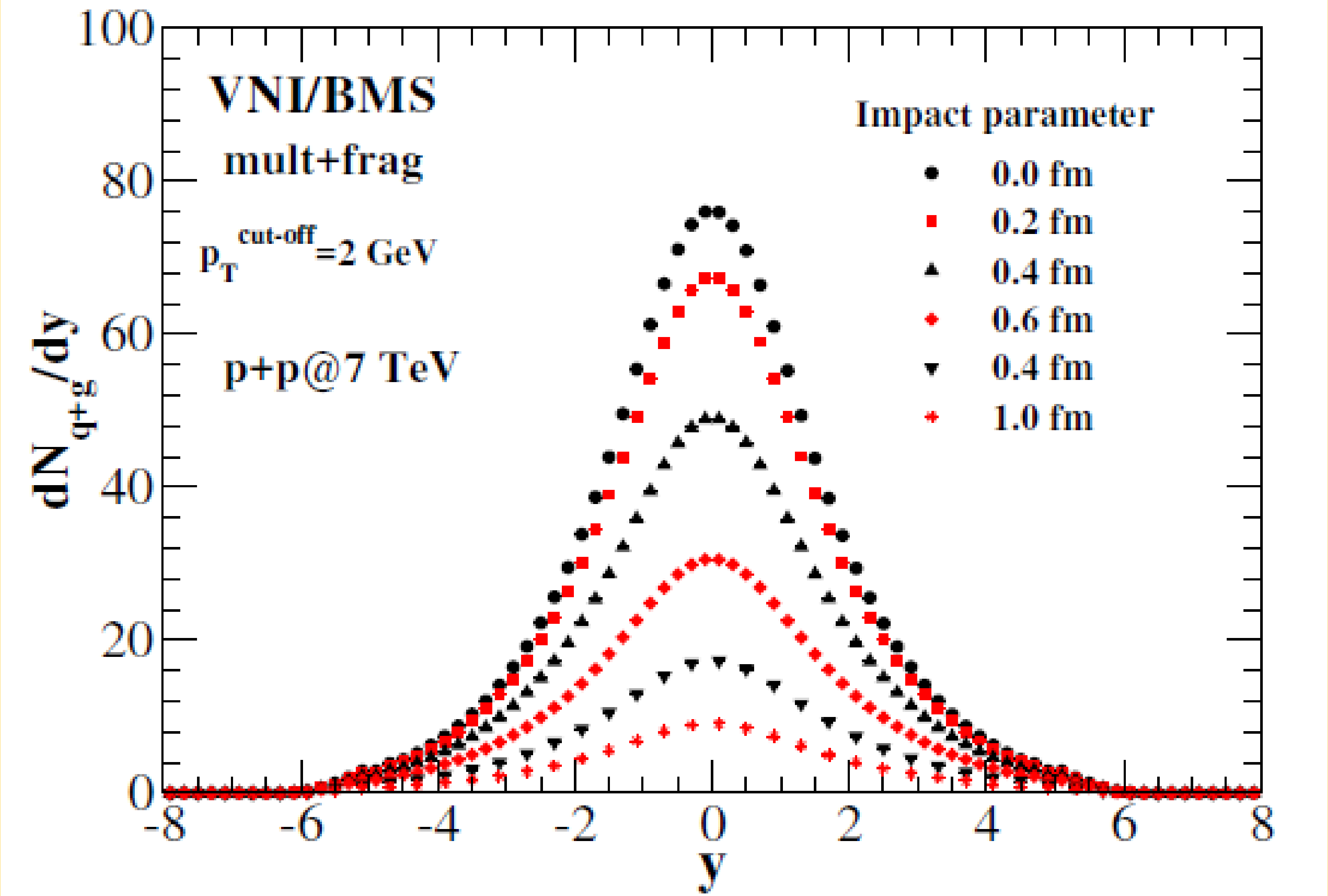
$$\gamma_s = 2(N_s + N_{sbar})/(N_u + N_{ubar} + N_d + N_{dbar})$$



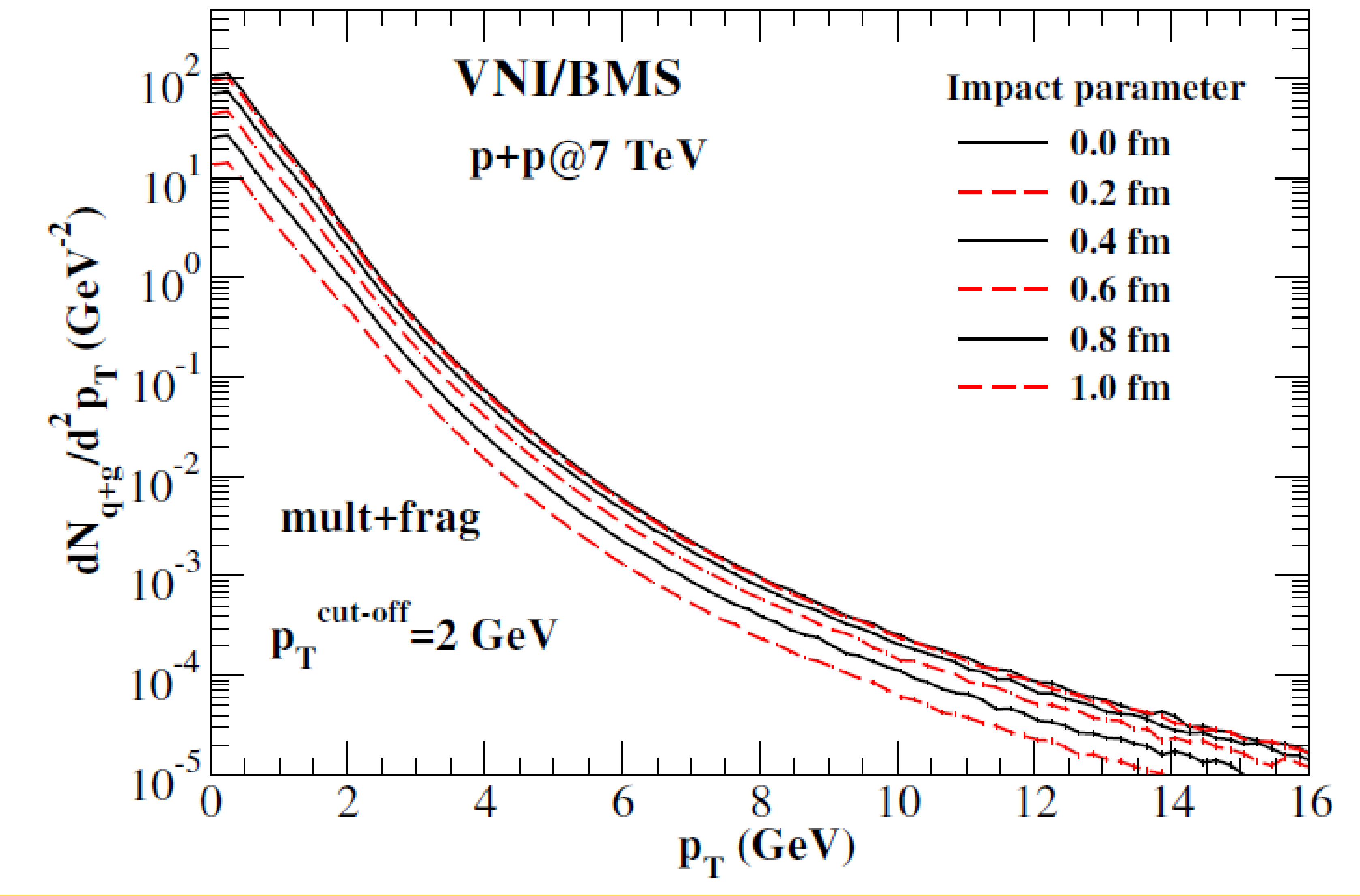
Impact parameter dependence; 7.00 TeV



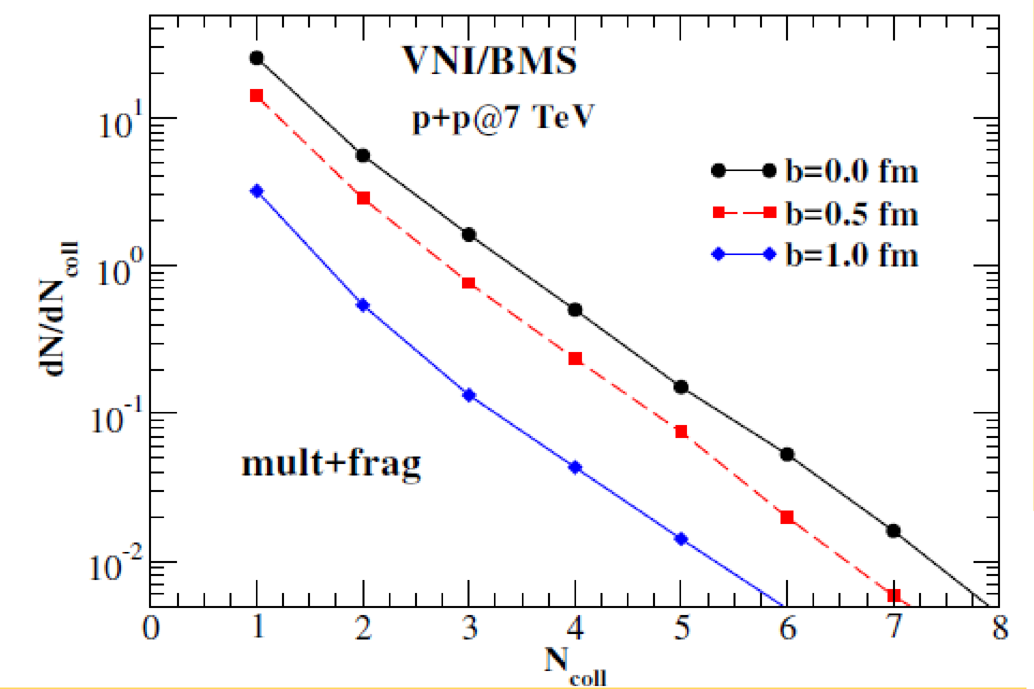
Impact parameter dependence
Rapidity spectra

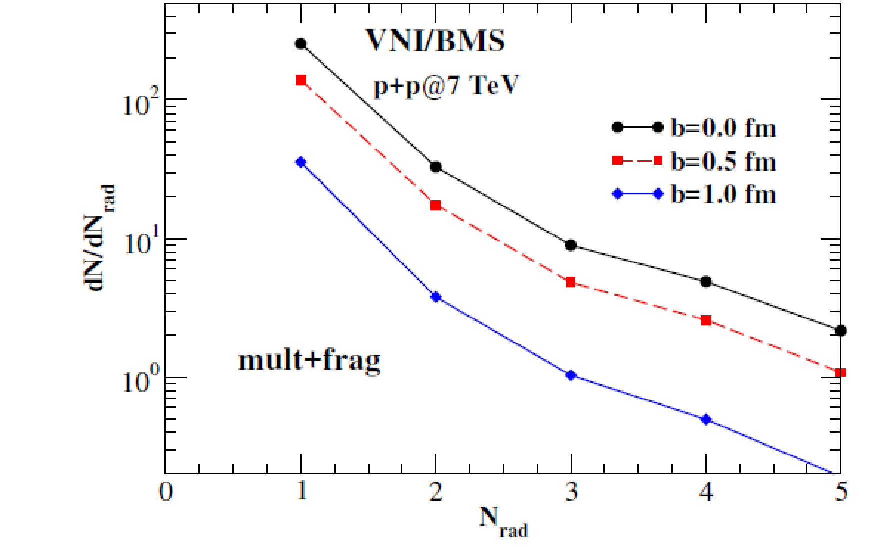


Impact parameter dependence p_T spectra

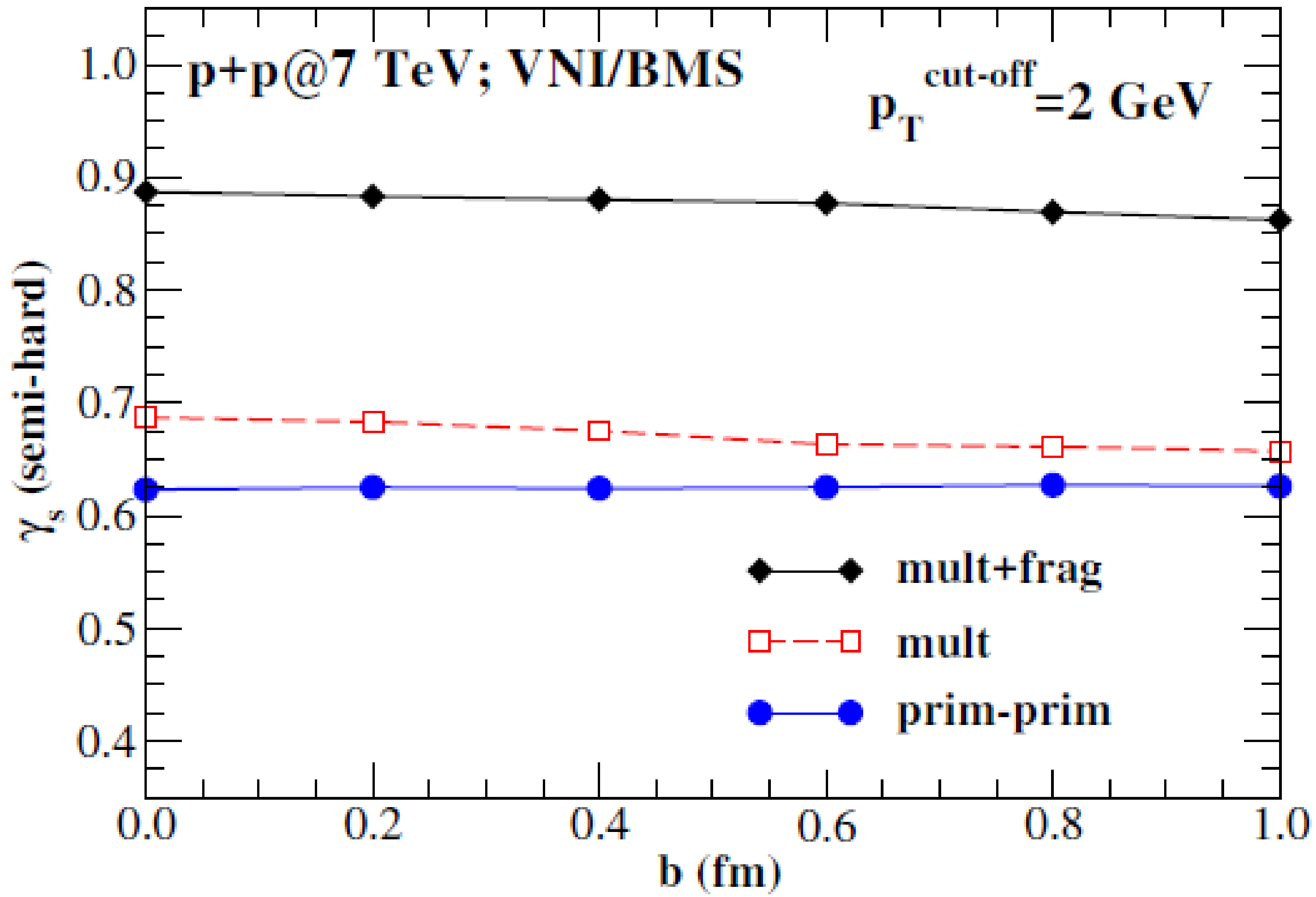


Impact parameter dependence of frequency of collisions and fragmentations for partons

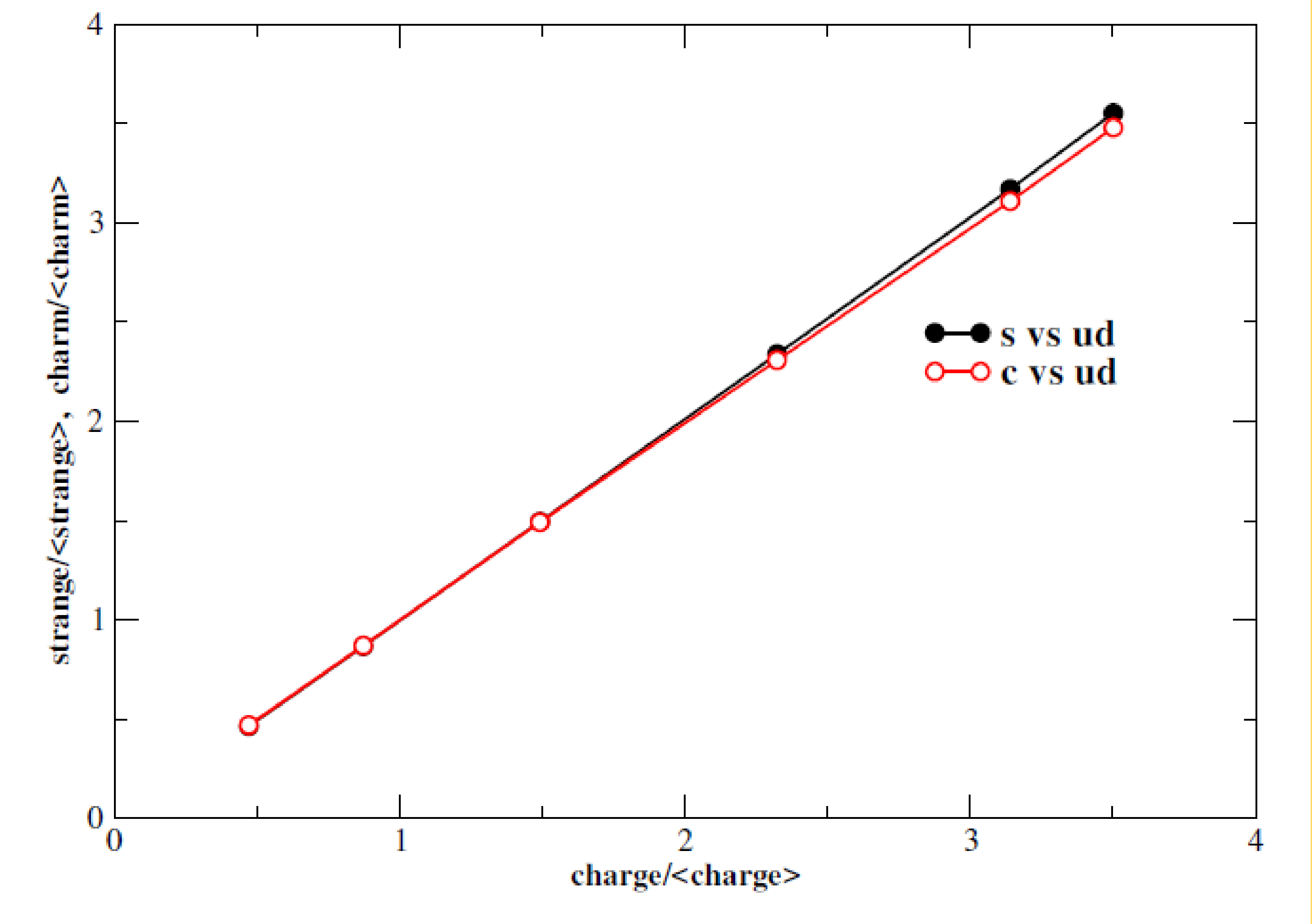




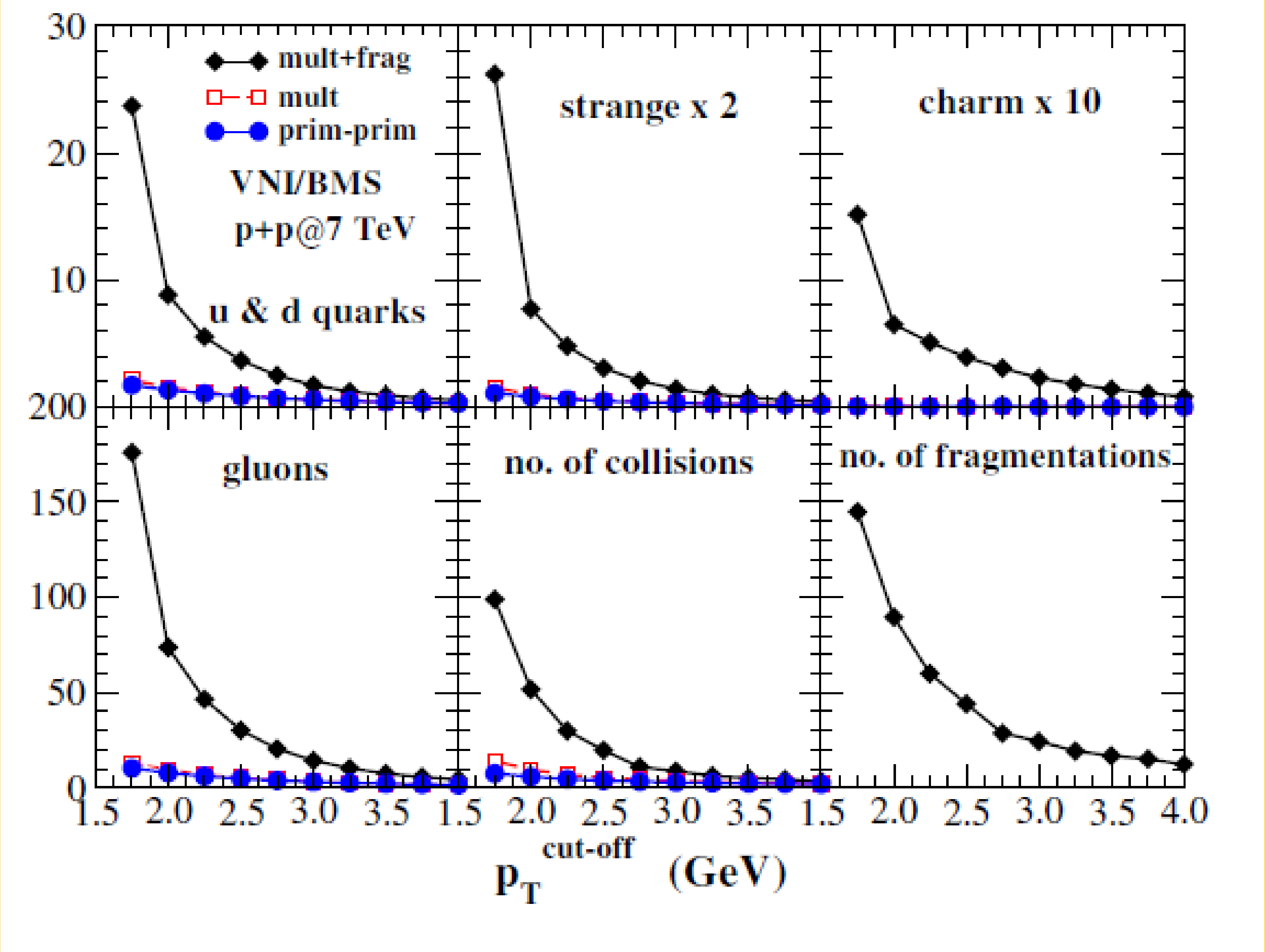
Impact parameter dependence of γ_s (semi-hard) at 7.00 TeV



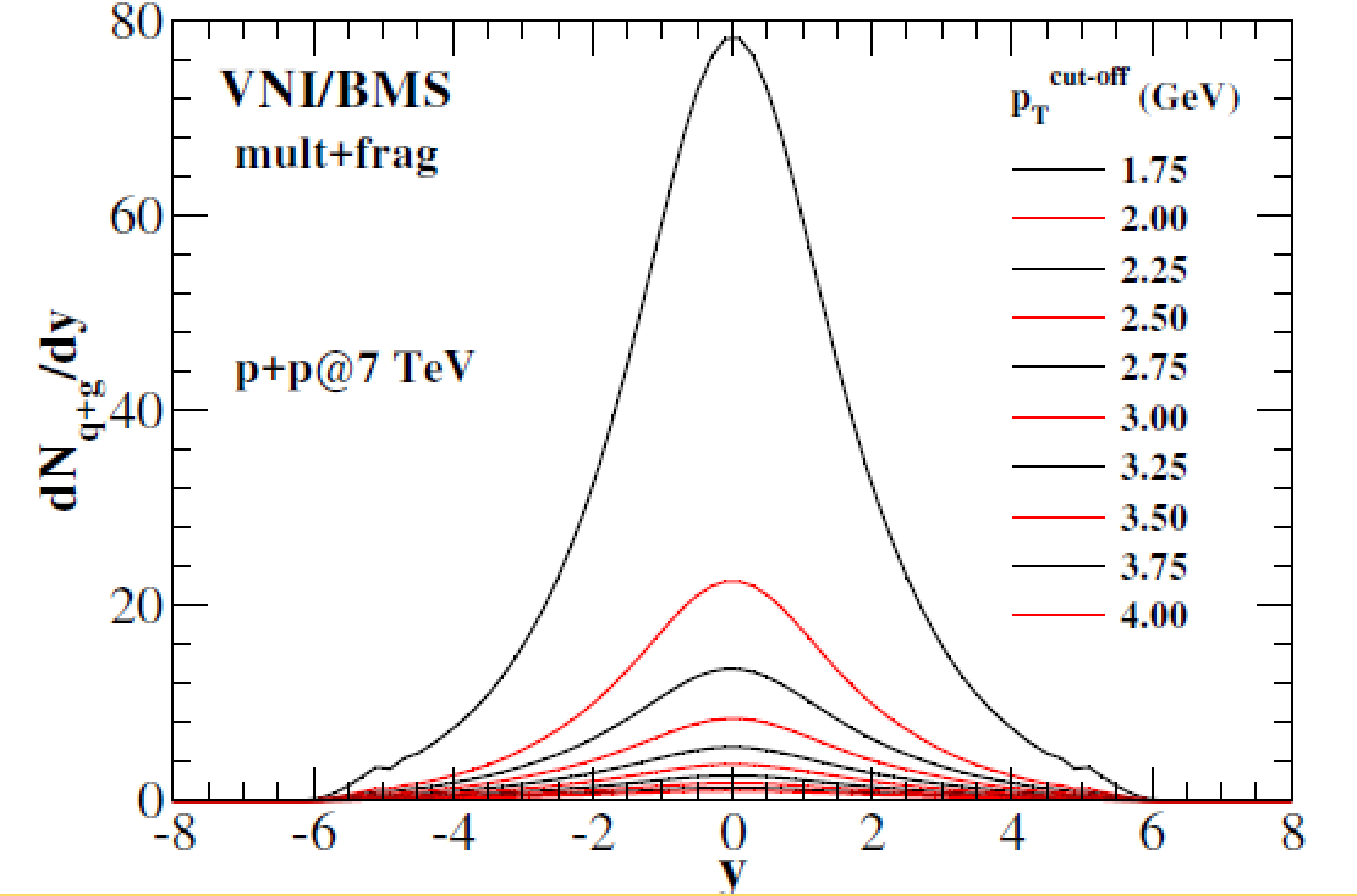
Enhanced Production of Strangeness & Charm ?



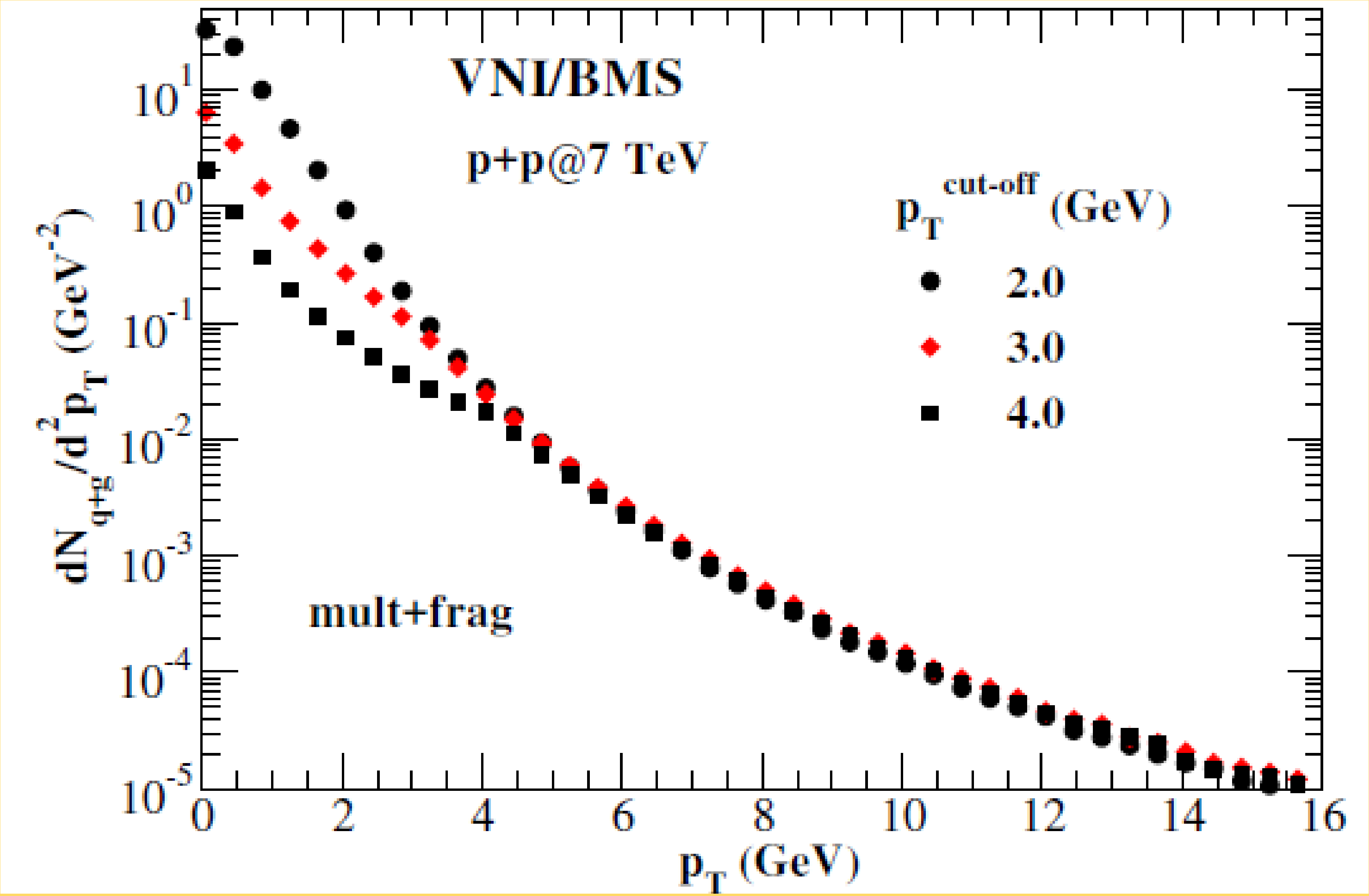
Parton production etc. & $p_T^{cut-off}$



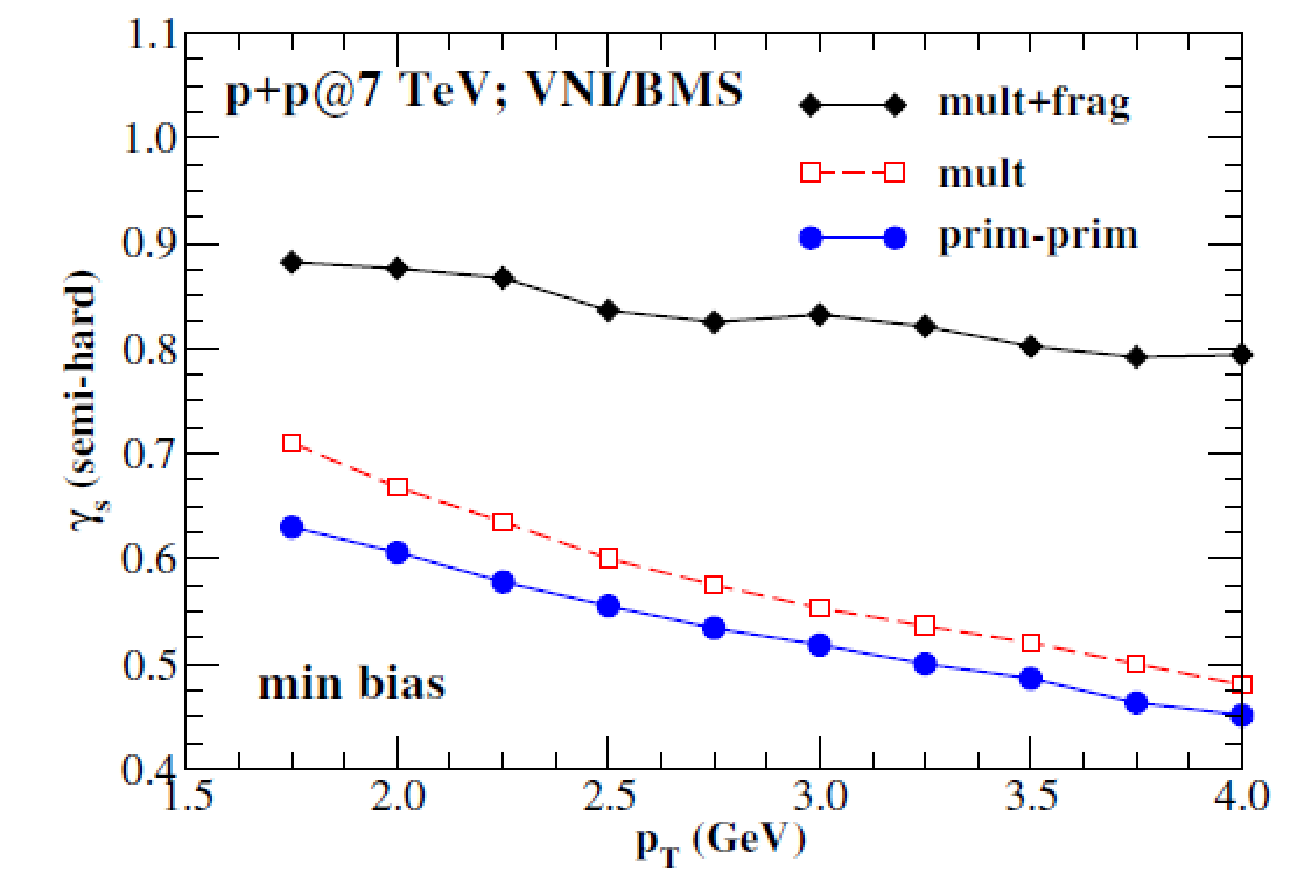
Rapidity spectra and $p_T^{cut\text{-}off}$



p_T spectra and $p_T^{cut\text{-}off}$



γ_s (semi-hard) and $p_T^{cut\text{-}off}$



Summary: Part II

- Parton Cascade Model applied to pp collisions at LHC energies gives interesting insights.
- Parton production and number of collisions in a typical pp collision are considerably enhanced by fragmentation of final state partons following a scattering.
- γ_s (semi-hard) is close to unity at larger LHC energies.
- Frequency of number of collisions and raditions suffered by partons is quite often more than unity! (Interacting medium?)
- There is substantial production of charm (and strangeness) at smaller b and higher energies.

Limitations and ..

Fundamental Limitations:

- lack of coherence of initial state (though all partons have colour and colour flow is taken care of).
- range of validity of the Boltzmann Equation
- interference effects are included only schematically (angular ordering).
- hadronization has to be modeled in an ad-hoc fashion
- how much can we stretch perturbative physics!

Medium ?

- Need to evolve the cascades in medium

  - a hydrodynamic river?

  - medium modified matrix elements?

  - add drag without double counting?

  - add 3→2 for detailed balance?

Conclusions

- Parton Cascade Model applied to Au+Au collisions at 200 AGeV provides valuable insights into the dynamics of production and propagation of charm quark and suggests its suppressed production at large p_T due to collisions and radiations.
- Parton Cascade Model applied to pp collisions at LHC energies points to opening up of semi-hard interactions leading to multiple collisions and fragmentations and a large production of strangeness and charm, especially at smaller impact parameters and higher energies..


THANK YOU