Simulation of charmed particle production in Geant4/FTF

A. Galoyan and V. Uzhinsky, 10.03.2020

Charmed particles production was observed and measured in fixed target experiments performed in **CERN, Fermilab and DESY** with hadron beams at energies from 200 GeV up to 900 GeV. Charmed particles production is studied by all **RHIC** and **LHC** collaborations. It is expected that the charmed particles will be copiously produced at FCC. Thus, simulation of charmed particles production and propagation in matter will be needed. Maybe, there is a possibility to study asymmetry of charmed particles at SPD.

Production of the charmed particles at high Pt can be described in QCD using mainly 4 parameters: heavy quark mass, coupling constant and 2 scales.

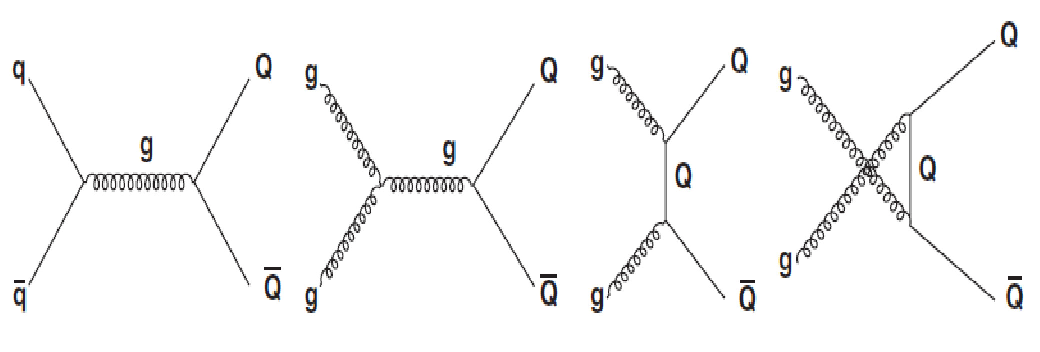


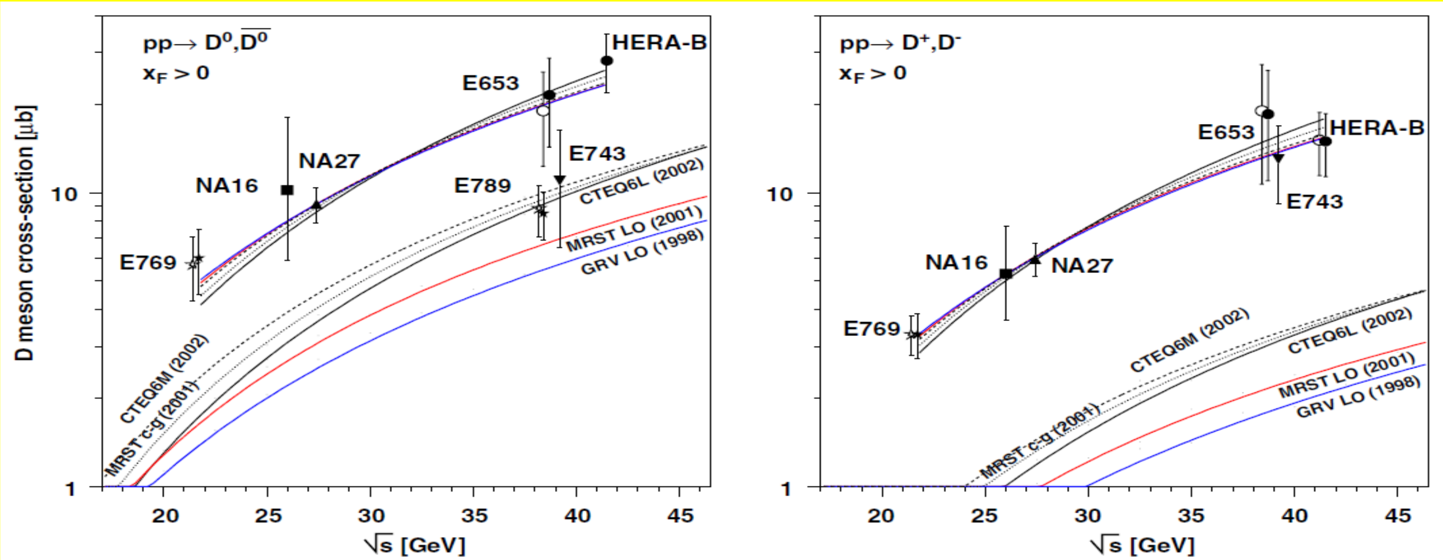
Fig. 1. Heavy flavour production mechanisms at leading order.

$$\frac{E_C d^3\sigma_{AB\to CX}}{d^3\mathbf{P_C}} = \sum_{abcd} \int dx_1 dx_2 f_A^a(x_1, Q^2) f_B^b(x_2, Q^2) \times \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}} D_c^C(z, Q^2) \frac{1}{\pi z}$$

PDF, LO, NLO, Frag. Funct.

Simulation of charmed particle production in Geant4/FTF

Charmed particles production is implemented in MC generators. First of all, it is presented in Pythia code.



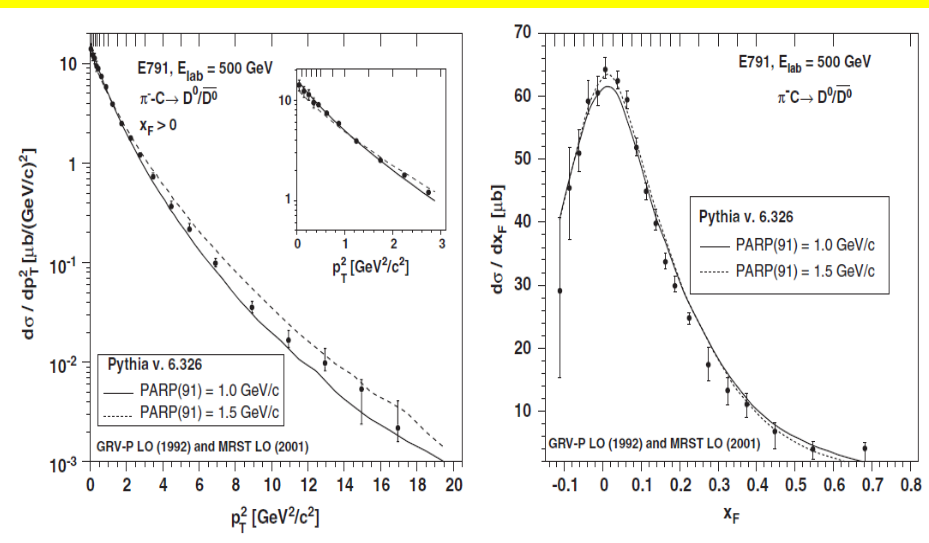


Fig. 19. p_T^2 (left) and x_F (right) distributions, as measured by the E791 Collaboration in 500 GeV π^-–C collisions and as calculated by Pythia, version 6.326.

Though, there is a problem with observed asymmetry of D^0 – antiD^0, D^+ - D^- and Λ_c - baryons. QCD does not assume the asymmetries!

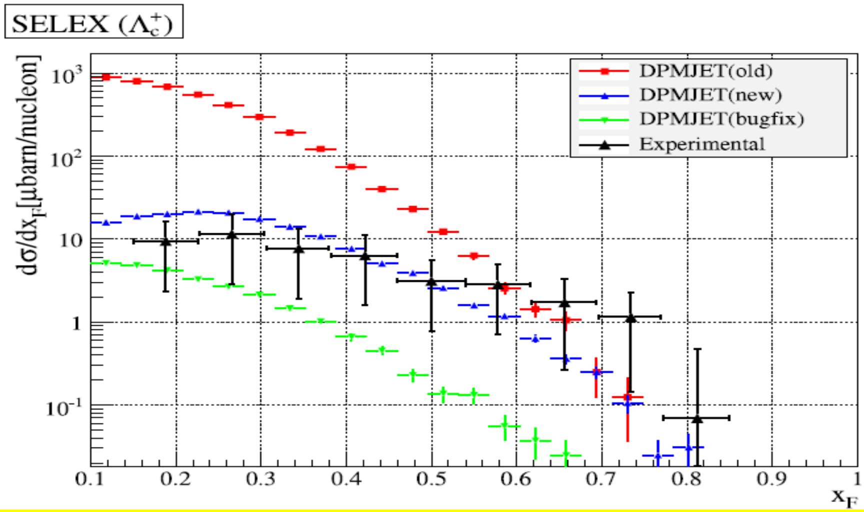
Simulation of charmed particle production in Geant4/FTF

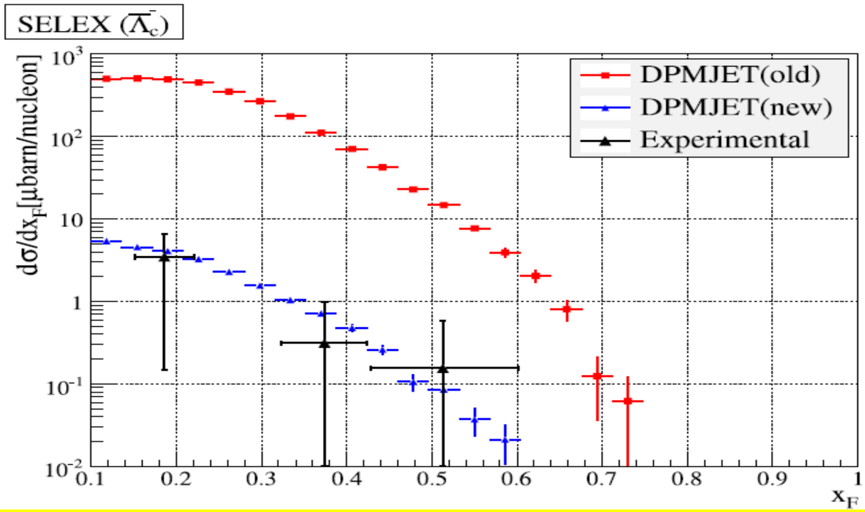
Charmed particles production is implemented in MC generators Sibyll, DPMJET, Fritiof 7.0.

XVI International Symposium on Very High Energy Cosmic Ray Interactions
ISVHECRI 2010, Batavia, IL, USA (28 June 2 July 2010) 1 Sibyll with charm
Eun-Joo Ahn[a], Ralph Engel[b], Thomas K. Gaisser[c], Paolo Lipari,[d] Todor Stanev

CORSIKA implementation of heavy quark production and propagation in extensive air showers A.Bueno, A. Gascyn Computer Physics Communications 185 (2014) 638–650

Charm production in DPMJET P Berghaus, T Montaruli1, and J Ranft
Journal of Cosmology and Astroparticle Physics 06 (2008) 003





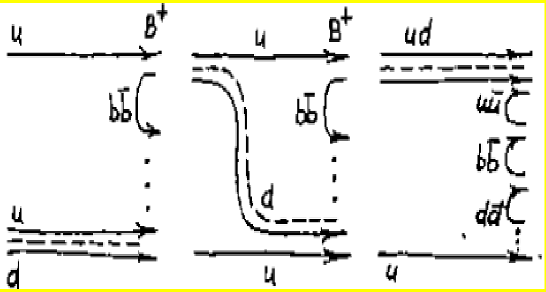
Simulation of charmed particle production in Geant4/FTF

At the same time, there is another branch of theoretical research – Quark-Gluon String Model (QGSM) by A. Kaidalov and O. Piskunova pretended to describe charmed particles production with low Pt.

"Production of Charmed Particles in the Quark - Gluon String Model" Sov. J. Nucl. Phys. 43, 994 (1986)

G.I. Lykasov, G.H. Arakelian, M.N. Sergeenko **Phys.Part.Nucl. 30 (1999) 343**

S. I. Sinegovsky, M. N. Sorokovikov **Eur. Phys. J. C80 (2020) 34**



$$1/\sigma_{inel} d\sigma/dx = \sum_{n=1}^{\infty} w_n \phi_n^h(x)$$

$$\Delta = 0.139\ ,\ \alpha' = 0.21\ \mathrm{GeV}^{-2}\ ,\ \gamma_{pp} = 1.77\ ,\ \gamma_{\pi p} = 1.07\ ,$$
$$R_{pp}^2 = 3.18\ \mathrm{GeV}^{-2}\ ,\ R_{\pi p}^2 = 2.48\ \mathrm{GeV}^{-2}\ ,\ C_{pp} = 1.5\ ,\ C_{\pi p} = 1.65$$

$$\phi_n^h(x) = f_{qq}^h(x_+, n) f_q^h(x_-, n) + f_q^h(x_+, n) f_{qq}^h(x_-, n) + 2(n-1) f_s^h(x_+, n) f_s^h(x_-, n)$$

$$f_q^h(x_+, n) = \int_{x_+}^{1} u_q(x_1, n) G_q^h(x_+/x_1) dx_1$$

$$f_p^{u_v(n)}(x) = C_n^{u_v} x^{-\alpha_R(0)} (1-x)^{\alpha_R(0) - 2\alpha_N(0) + n - 1}, \quad (10)$$

$$G_d^{D^-}(x/x_1) = G_{\bar{u}}^{D^0}(x/x_1) = (1 - x/x_1)^{\lambda - \alpha_\psi(0)} [1 + a_1 (x/x_1)^2], \quad (11)$$

where $\alpha_R(0) = 0.5$, $\alpha_N(0) = -0.5$, $\lambda = 2 < p_\perp^2 > \alpha'_R = 0.5$, and the coefficient $C_n^{u_v}$ is determined by normalization

The observed asymmetries of D^0 – antiD^0, D^+ - D^- and Λ_c- baryons are explained in the approach

Simulation of charmed particle production in Geant4/FTF

$$
\begin{aligned}
u_{uu}(x,n) &= C_{uu} x^{2.5}(1-x)^{n-1.5} \\
u_{ud}(x,n) &= C_{ud} x^{1.5}(1-x)^{n-1.5} \\
u_{u}(x,n) &= C_{u} x^{-0.5}(1-x)^{n+0.5} \\
u_{d}(x,n) &= C_{d} x^{-0.5}(1-x)^{n+1.5}
\end{aligned}
$$

$$G_u^{\overline{D^0}} = G_d^{D^-} = a_0(1-z)^{\lambda-\alpha_\psi(0)}(1+a_1 z^2) \quad ,$$

$$G_u^{D^-} = G_u^{D^+} = G_u^{D^0} = G_d^{D^+} = G_d^{D^0} = G_d^{\overline{D^0}} = a_0(1-z)^{1+\lambda-\alpha_\psi(0)} \quad ,$$

$$G_{uu}^{D^+} = G_{uu}^{D^-} = G_{uu}^{D^0} = G_{ud}^{D^+} = G_{ud}^{D^0} = a_0(1-z)^{3+\lambda-\alpha_\psi(0)} \quad ,$$

$$G_{uu}^{\overline{D^0}} = a_0(1-z)^{2+\lambda-\alpha_\psi(0)}(1+a_2 z^2) \quad ,$$

$$G_{ud}^{\overline{D^0}} = a_0(1-z)^{2+\lambda-\alpha_\psi(0)}(1-z+$$

$$G_{uu}^{\Lambda_c} = G_{ud}^{\Lambda_c} = a_{01}(1-z)^{6+\lambda-\alpha}$$

$$G_{u}^{\Lambda_c} = G_{d}^{\Lambda_c} = a_{01}(1-z)^{2+\lambda-\alpha}$$

$$G_{\bar u}^{\Lambda_c} = G_{\bar d}^{\Lambda_c} = G_{u}^{\Lambda_c}(1-z)$$

Parameter	QGSMa	QGSMb	QGSMc
$\alpha_\psi(0)$	-2	-2	-2
a_0	0.024	0.024	0.02
a_1	10	10	0
a_2	50	50	16
a_{01}	0.011	0.011	0.007
a_{02}	0.005	.005	0.0025
$\alpha_\Upsilon(0)$	-8	-8	-8
b_0	0.011	0.011	0.0055
b_1	5	5	6
b_2	25	25	40
b_{01}	0.005	0.005	0.0015
b_{02}	0.0004	.0004	0.0018

Simulation of charmed particle production in Geant4/FTF

Implementation in Geant 4: **QGS and FTF models**

G4VLongitudinalStringDecay
G4LundStringFragmentation **G4FTFParameters**
G4QGSMFragmentation **G4Reggeons**

G4VLongitudinalStringDecay:

```
G4double ProbCCbar;  // Probability of C-Cbar pair creation // Uzhi 2019
G4double ProbEta_c;  // Mixing of Eta_c and J/Psi
G4double ProbBBbar;  // Probability of B-Bbar pair creation // Uzhi 2019
G4double ProbEta_b;  // Mixing of Eta_b and Ipsilon_b
G4double ProbCB;     // = ProbCCbar + ProbBBbar

G4double minMassQQbarStr[5][5];
G4double minMassQDiQStr[5][5][5];

G4int    Meson[5][5][7];               // Uzhi 2019 [3][3][6] -> [5][5][6]
G4double MesonWeight[5][5][7];         // Uzhi 2019 [3][3][6] -> [5][5][6]
G4int    Baryon[5][5][5][4];           // Uzhi 2019 [3][3][3][4] -> [5][5][5][4]
G4double BaryonWeight[5][5][5][4];     // Uzhi 2019 [3][3][3][4] -> [5][5][5][4]
```

Simulation of charmed particle production in Geant4/FTF

Implementation in Geant 4: **QGS and FTF models**

G4VLongitudinalStringDecay

G4LundStringFragmentation **G4FTFParameters**

G4QGSMFragmentation **G4Reggeons**

```
void G4QGSMFragmentation::SetFFq2q()
{  // // q-> q' + Meson (q anti q'){
  for(G4int i=0; i < 5; i++){
     FFq2q[i][0][0] = 2.0      ;  FFq2q[i][0][1] = -arho + alft;  // q->d + (q dbar) Pi0, Eta, Eta',
     FFq2q[i][1][0] = 2.0      ;  FFq2q[i][1][1] = -arho + alft;  // q->u + (q ubar) Pi-, Rho-
     FFq2q[i][2][0] = 1.0      ;  FFq2q[i][2][1] = -aphi + alft;  // q->s + (q sbar) K0, K*0
     FFq2q[i][3][0] = 1.0      ;  FFq2q[i][3][1] = -aJPs + alft;  // q->c + (q+cbar) D-, D*-
     FFq2q[i][4][0] = 1.0      ;  FFq2q[i][4][1] = -aUps + alft; // q->b + (q bbar) EtaB, Upsilon
//------------------------------------------------------------------------------------------
   }
}
void G4QGSMFragmentation::SetFFq2qq()           // q-> anti (q1'q2') + Baryon (q + q1 + q2)
{ for(G4int i=0; i < 5; i++){//                     ???
    FFq2qq[i][ 0][0] = 0.0 ; FFq2qq[i][ 0][1] = arho - 2.0*an    + alft   ;// q->dd bar + (q dd)
    FFq2qq[i][ 1][0] = 0.0 ; FFq2qq[i][ 1][1] = arho - 2.0*an    + alft   ;// q->ud bar + (q ud)
    FFq2qq[i][ 2][0] = 0.0 ; FFq2qq[i][ 2][1] = arho - 2.0*ala   + alft   ;// q->sd bar + (q sd)
    FFq2qq[i][ 3][0] = 0.0 ; FFq2qq[i][ 3][1] = arho - 2.0*alaC  + alft   ;// q->cd bar + (q cd)
  }
```

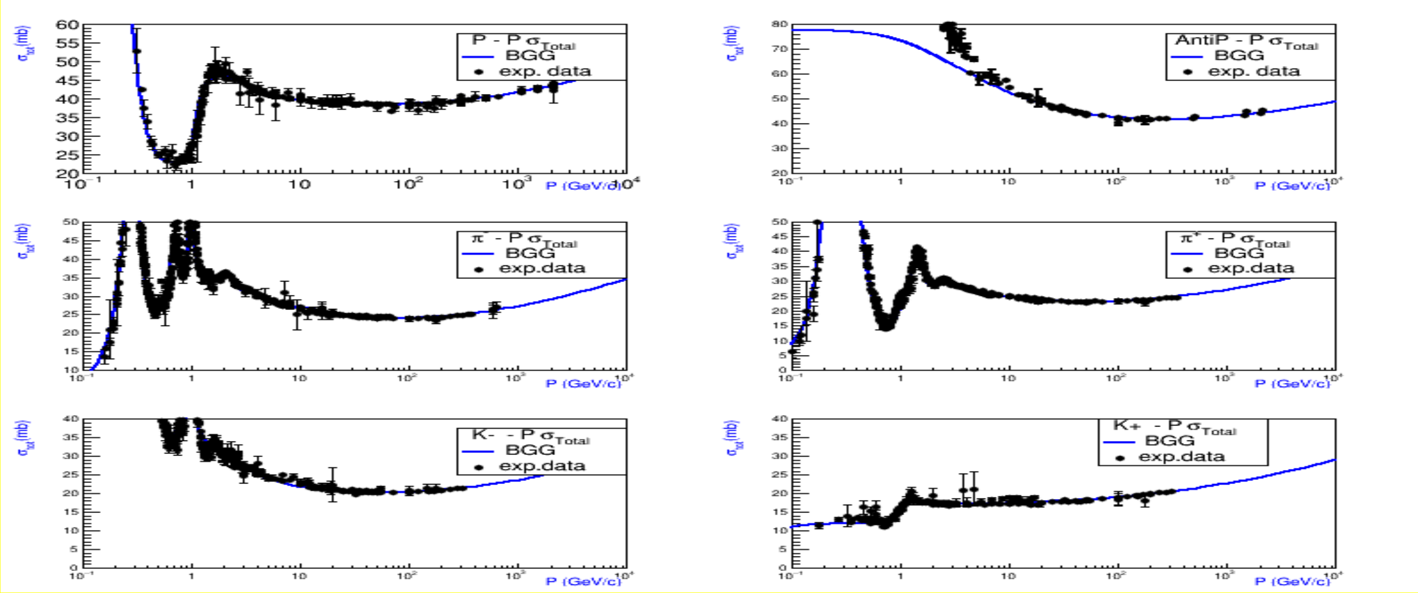
Simulation of charmed particle production in Geant4/FTF

Cross sections of PP, PbarP, $\pi^{\pm}$P, $K^{\pm}$ P , PN, PbarN and so on are

Barashenkov-Glauber-Gribov cross sections

Recent developments in Geant4

J. Allison (Geant4 Assoc. & Manchester U.) *et al.*. Nucl.Instrum.Meth. A835 (2016) 186



For heavy (charmed and bottom) hadrons we use cross sections by Grishin's extension for strange, charmed and beauty hadron projectiles!

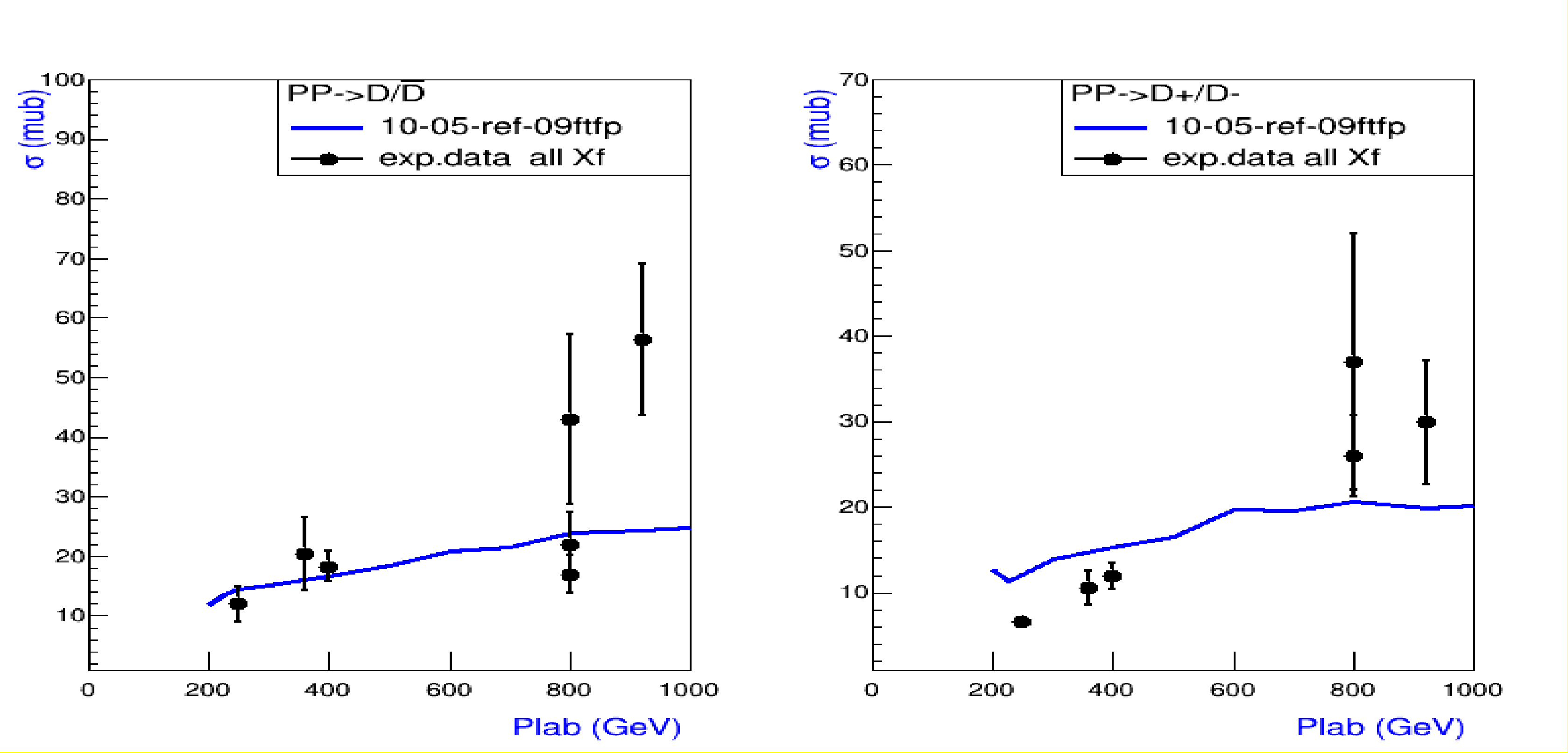
A corresponding paper is prepared **by Geant4 developers.**

```
if ( PDGcode == 511 || PDGcode ==-511 ||
    PDGcode == 521 || PDGcode ==-521   ) {      coeff = llMesCof1B;    }
if (PDGcode == 421 || PDGcode ==-421 ||
    PDGcode == 411 || PDGcode ==-411   ) {      coeff = llMesCof1C;    }
Gamma_pomeron_Pr *= coeff;
```

Tuning of charm quark production probability

Heavy flavour hadro-production from fixed-target to collider energies
C. Lourenco (CERN), H.K. Wohri (Lisbon, IST & CERN). **Phys.Rept. 433 (2006) P.127**

There is a review of the hadro-production data presently available on open charm and beauty absolute production cross-sections, collected by experiments at CERN, DESY and Fermilab. The published charm production cross-section values are updated, in particular for the "time evolution" of the branching ratios. There are summarised the data used in the present study, obtained with proton and pion beams, at energies ranging from Elab = 200 to 920 GeV.

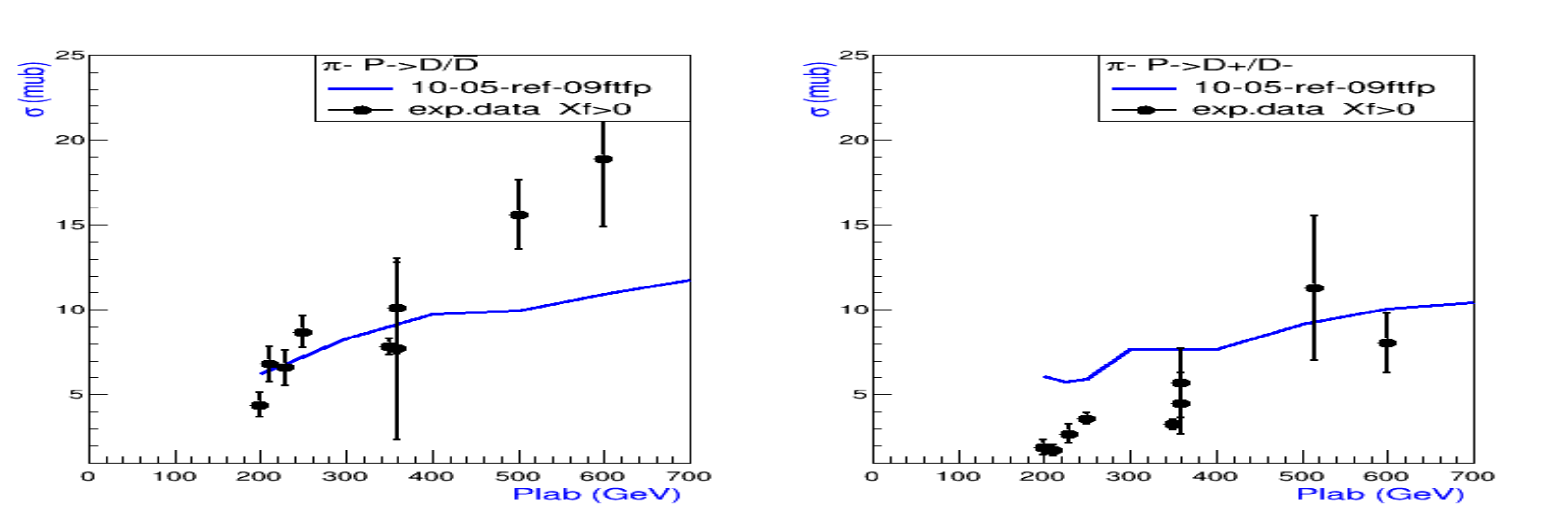


FTF

Tuning of charm quark production probability

Heavy flavour hadro-production from fixed-target to collider energies

C. Lourenco (CERN), H.K. Wohri (Lisbon, IST & CERN). 2006. **Phys.Rept. 433 (2006) 127-180**



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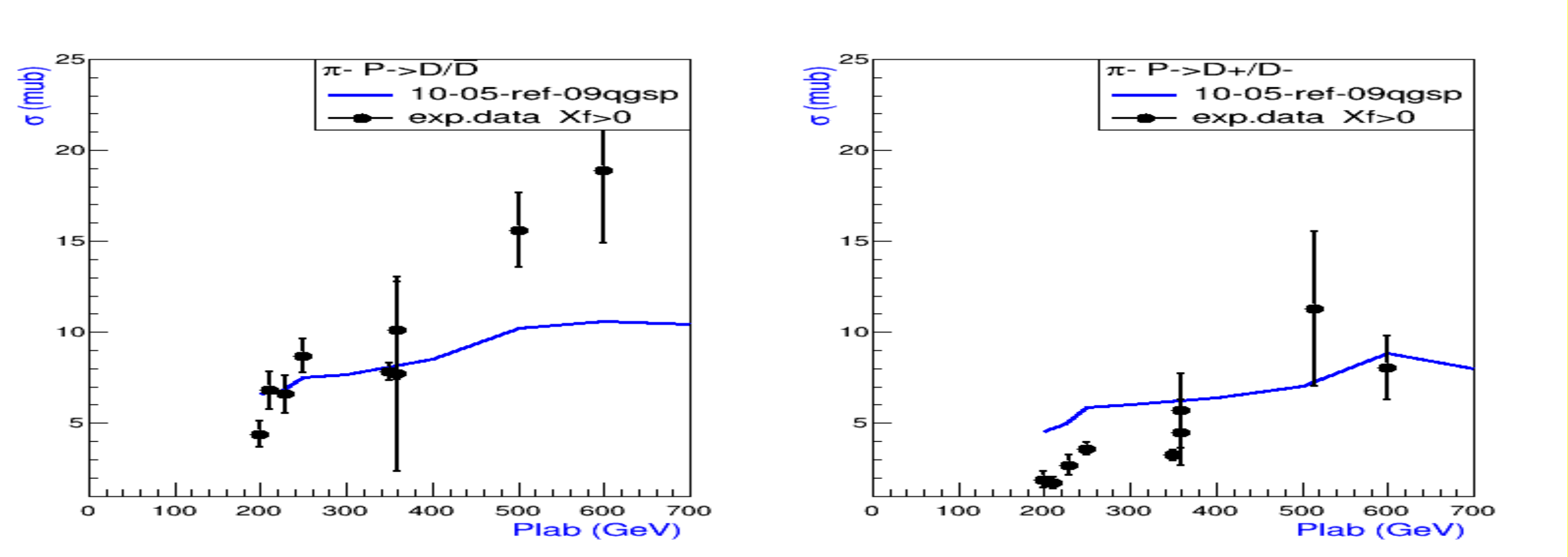


QGS

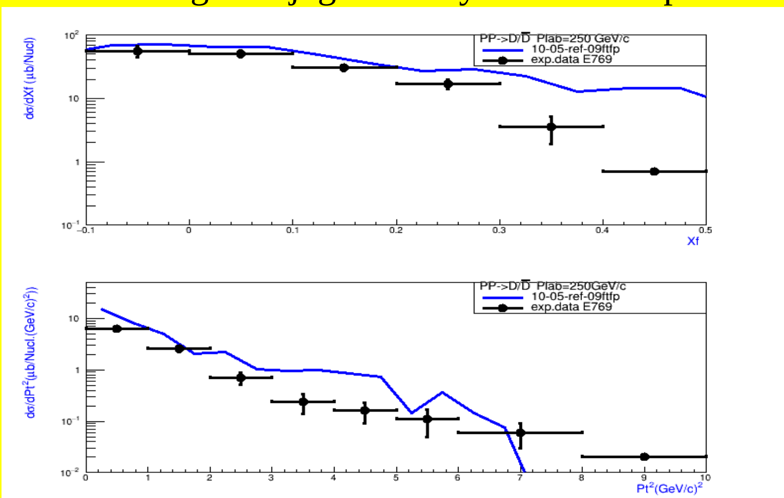
Differential distributions of charmed mesons

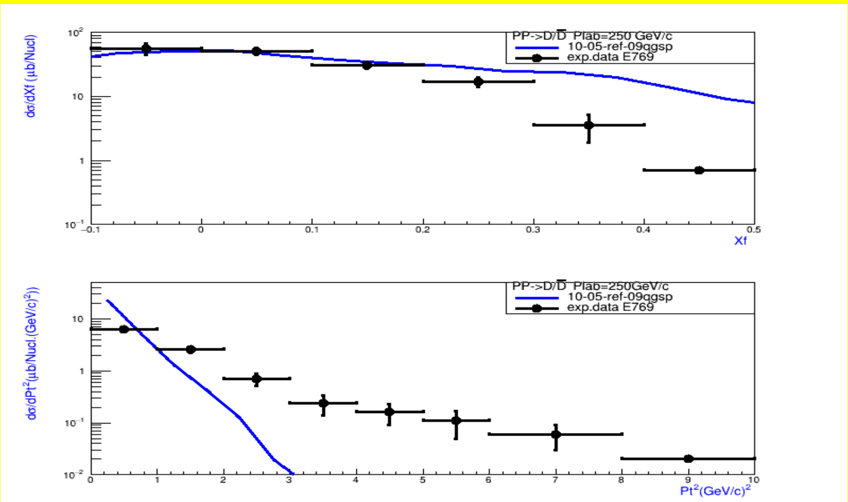
Feynman-x and Transverse Momentum Dependence of D Meson Production in 250 GeV p, K, and π Interactions with Nuclei . (Fermilab E769 Collaboration) G. A. Alves, et.al,
Phys.Rev. Lett, V77, N 12, 1996, 239

The E769 data set was collected using collisions of negatively and positively charged 250 GeV mixed secondary beams on a multifoil target of Be, Cu, Al, and W. D meson signals are obtained by combining the decays: D+→K-pi+pi+, D0→K-PI+ . Charge conjugate decays are also implied.

$$\sigma_A = \sigma_n A^{\alpha}$$

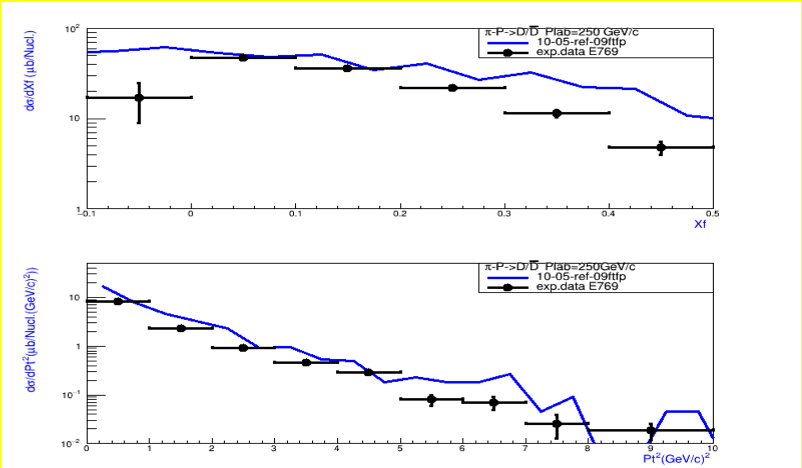
FTF

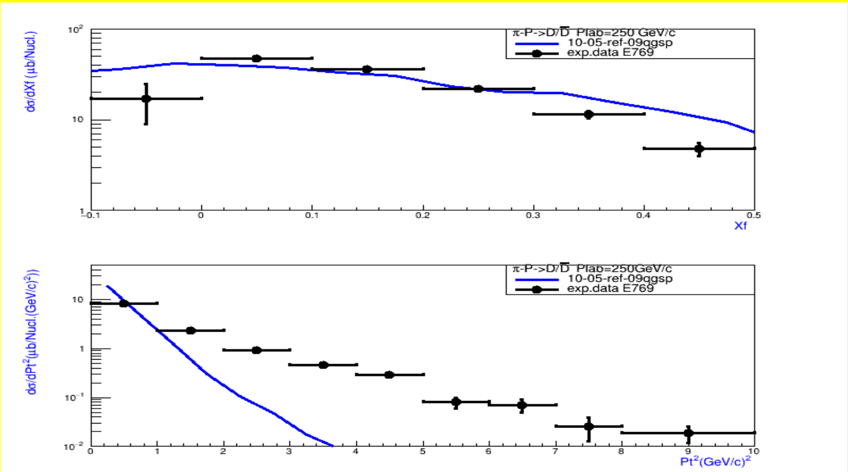




QGS

FTF





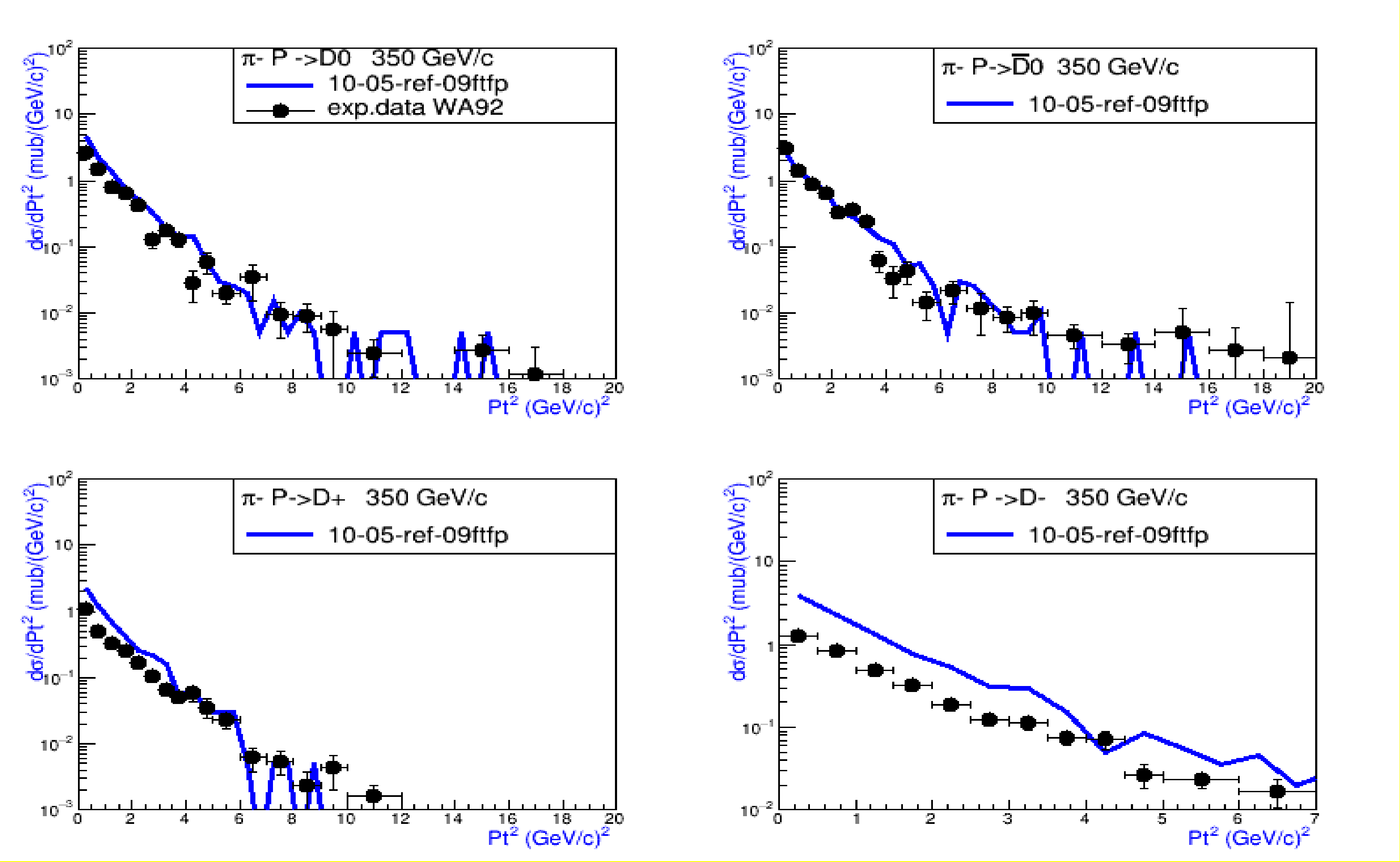
QGS

Differential distributions of charmed mesons

Measurements of charmed-meson production in interactions between 350 GeV/c π-particles and nuclei.

Beatrice Collaboration (Adamovich.et al.,) **Nucl. Phys. B495 (1997) 3-37**

FTF



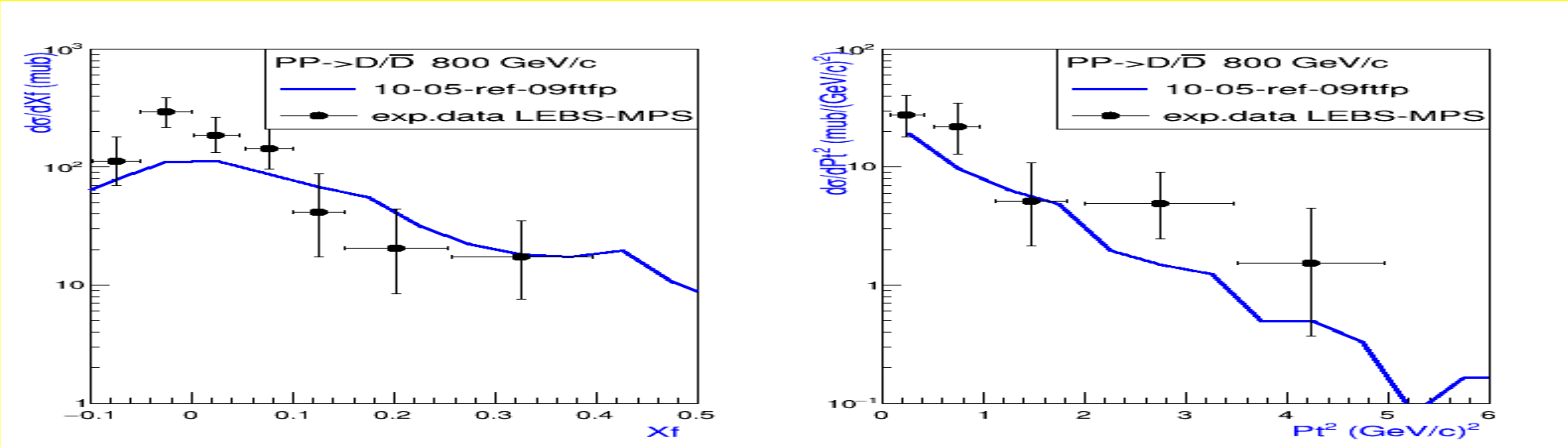
The Pt^2 spectra obtained for different types of charmed meson all have a similar shape.

Differential distributions of charmed mesons

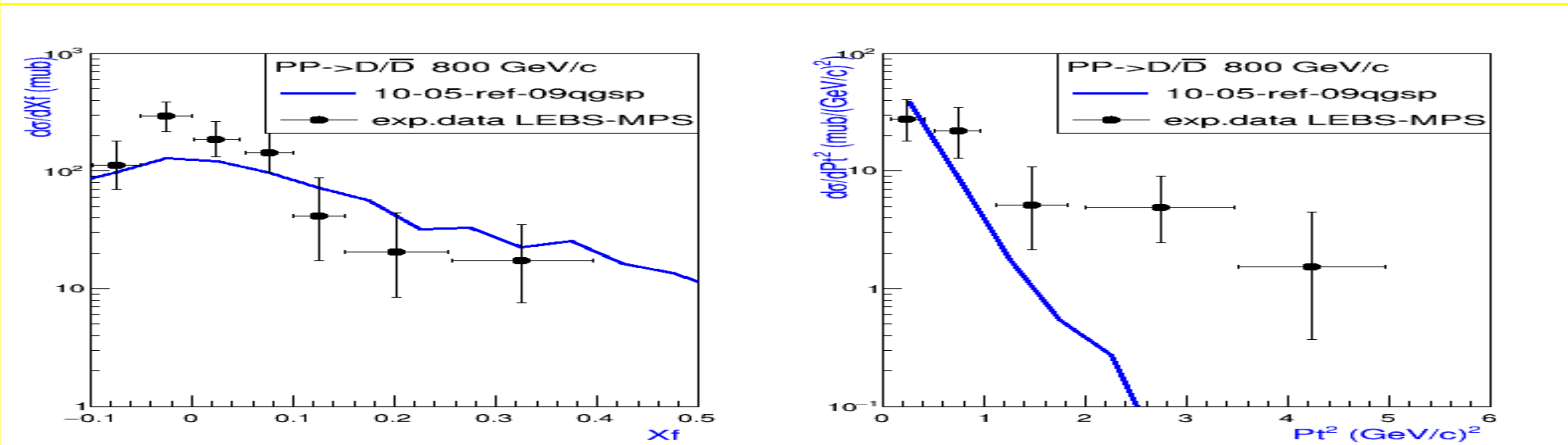
D-Meson Production in 800-GeV/c pp Interactions .

LEBC-MPS Collaboration (R. Ammar et. al.,) **Phys. Rev. Lett. 61, N19, 1988, P.2185**

Here, measurements of the D meson Xf and Pt behaviour are determined from both liquid hydrogen bubble chamber (LEBS) and mutiparticle spectrometer Fermilab MPS. The apparatus was exposed to 800-GeV/c protons.



FTF



QGS

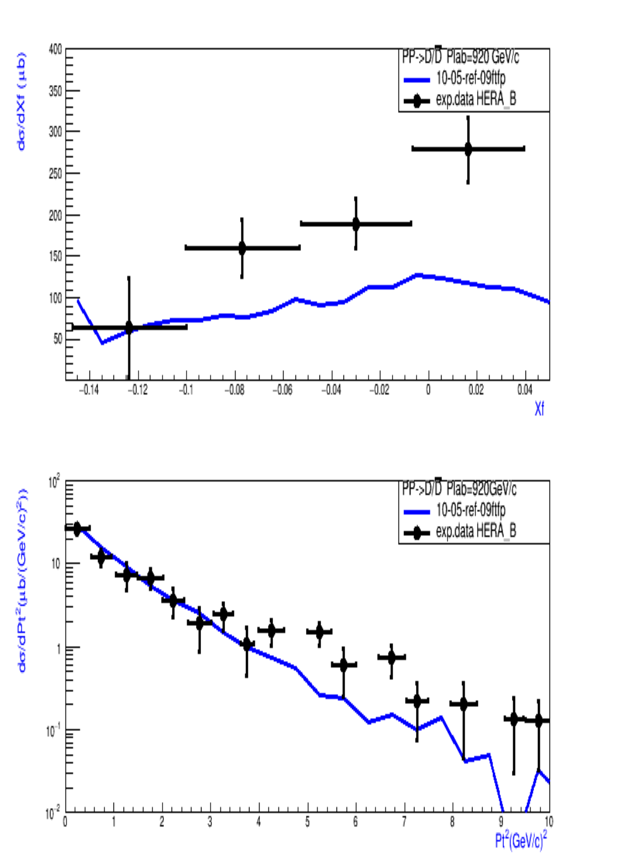
The authors used QCD parton-fusion model for describing these data. In the paper inclusive D meson production cross sections were given at 800 GeV/c for all Xf.

Differential distributions of charmed mesons

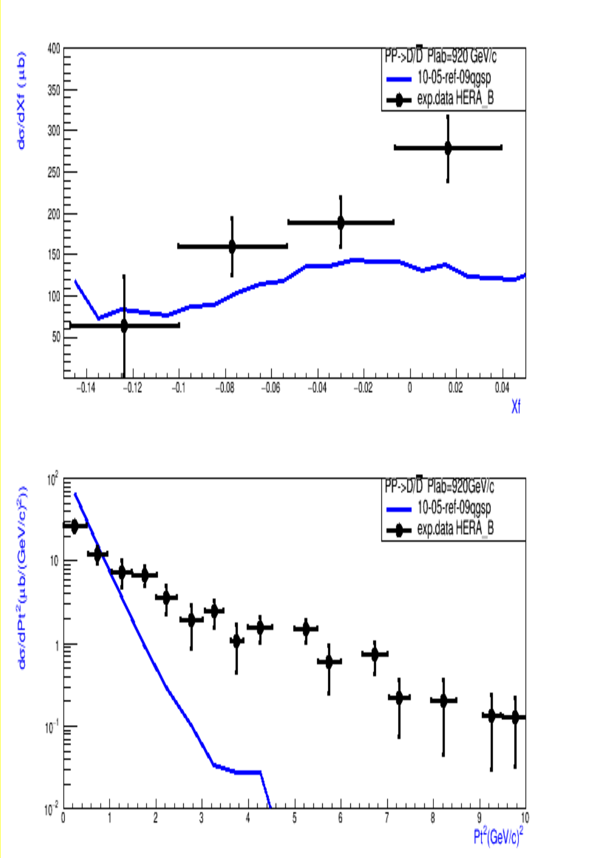
Measurement of D^0, D^+, D_s^+ and D^{*+} production in fixed target 920 GeV proton–nucleus collisions. The HERA-B Collaboration (I. Abt et al.,) **Eur. Phys. J. C 52, 531(2007)**

Collisions of the 920 GeV HERA accelerator proton beam in C, Ti and W fixed targets have been measured with the HERA-B fixed targed spectrometer. Here D represents a D^0, D^+, D_s^+ or D^{*+} detected through the decay channels: $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to \varphi\pi^+ \to K^-K^+\pi^+$, and $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$ and charge conj. channels.

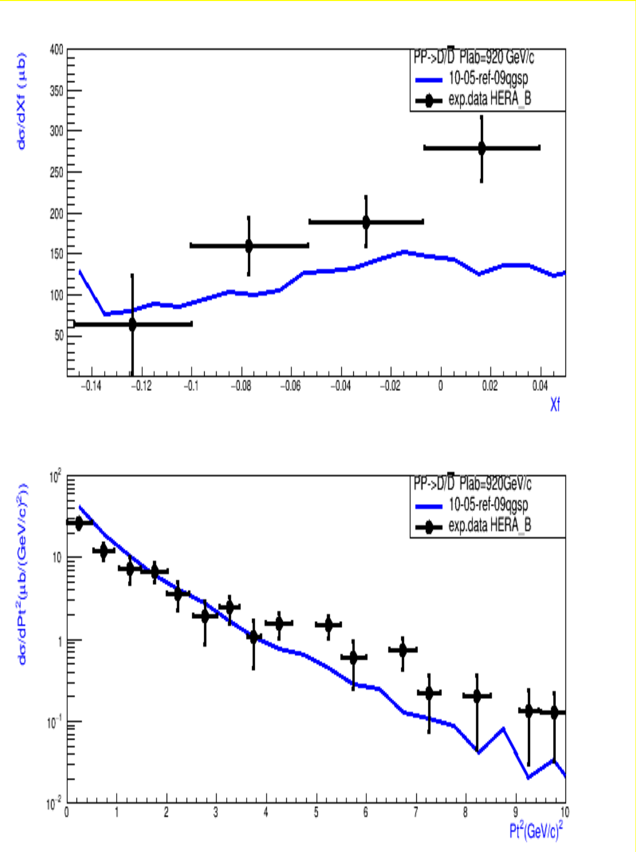
FTF



QGS



QGS +Mt distr.

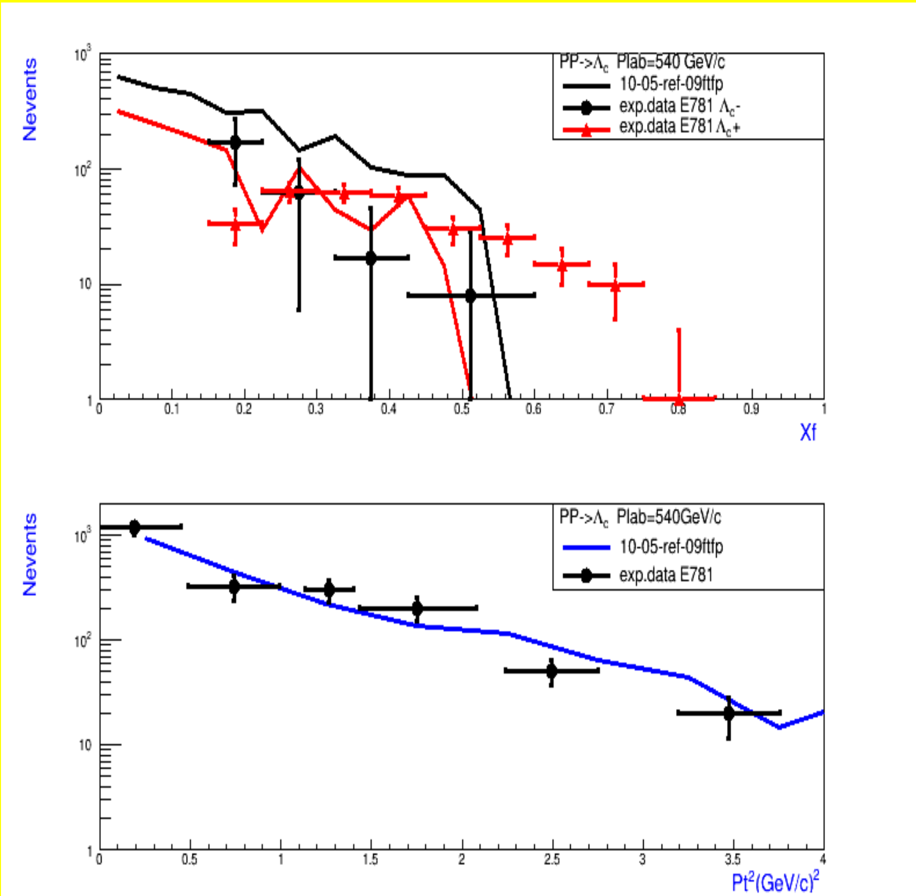


Differential distributions of charmed baryons

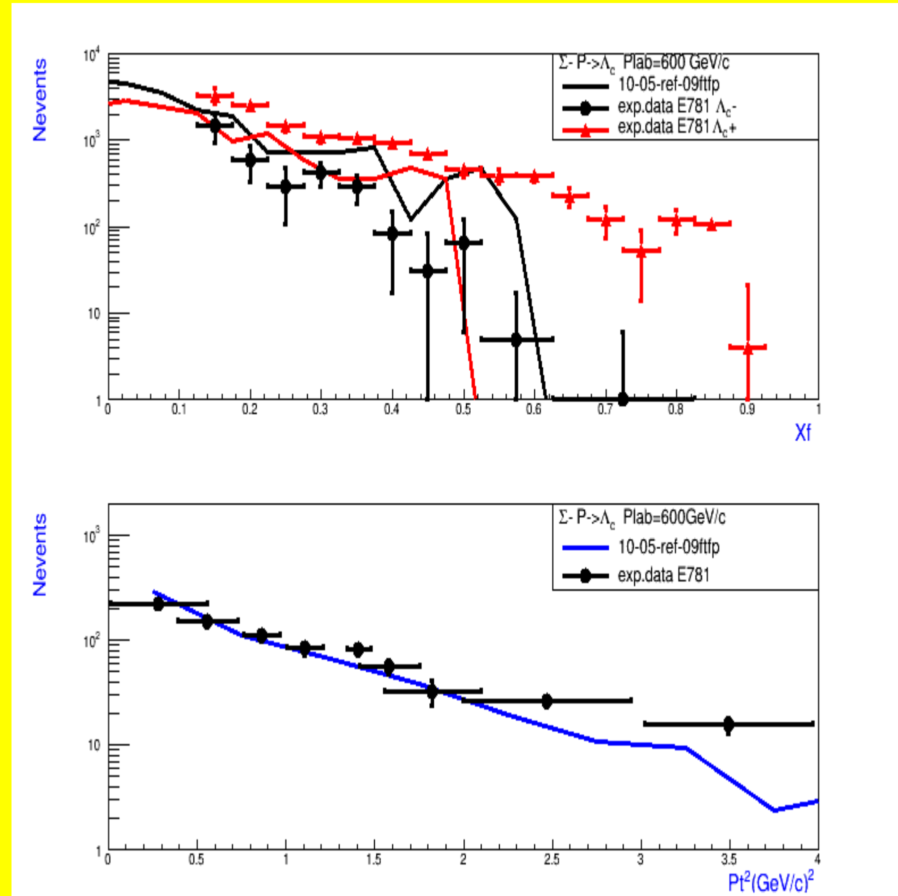
Hadronic production of Λc from 600 GeV/c π − , Σ− and p beams.

SELEX Collaboration (F.G. Garcia et/al.,) **Physics Letters B 528 (2002) 49**

FTF PP 540 GeV/c

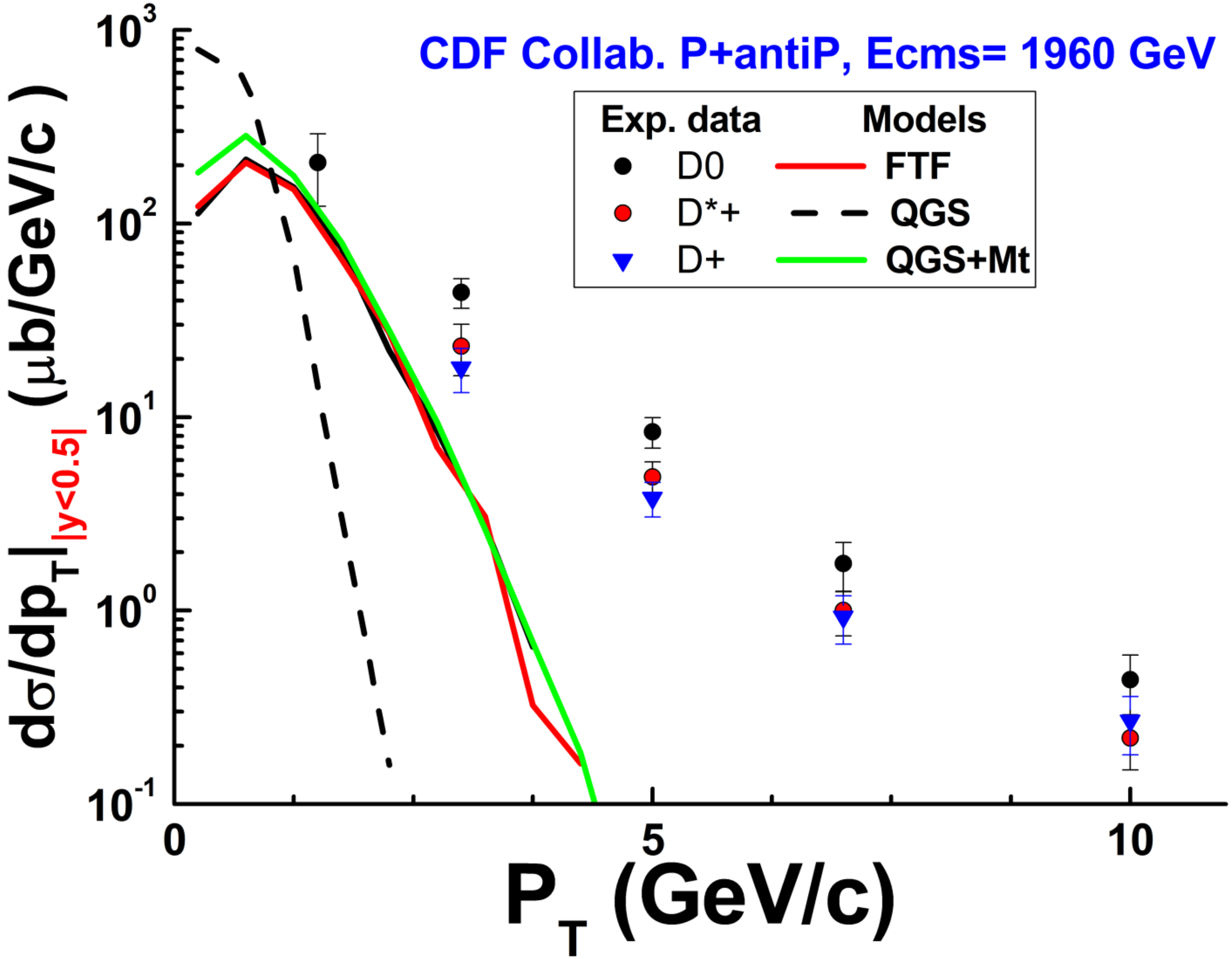


FTF Σ− P 600 GeV/c



Exp. data show that **Xf** dependence of **Λc+** production is similar for all three beams. Both baryon beams show a strong enhancement of the production of **Λc+** over **Λc-**, while the two are produced comparably from a pion beam.

Simulation of charmed particle production in Geant4/FTF



Conclusion

For the first time, charm production is implemented in G4 hadronic generators – FTF and QGS models.

1. **BGG cross sections with Grishin's extension are used for estimations of X's of charmed and beauty particles interactions with nuclei**

2. **Charmed quark pair production Probability is estimated approximately.**

3. **Differential cross sections of D-meson production in PP and πP interactions at energies from 200 GeV/c to 920 GeV/c are calculated in FTF and QGS models.**

4.Comparison with exp. data shows quite good description of D-meson Pt^2 distributions in FTF model. QGS model with Gaussian distribution for Pt^2 does not give reasonable results for Pt^2 distributions. First attempt of implementation of "mT" distribution in QGSM leads to promising results.
Results of comparison for Xf distributions of D-mesons are satisfactorily at low energies. At high energies, it is needed to take into account QCD processes for description of Xf spectra.

5. Xf and Pt2 distributions are calculated for Λc^+ and Λc^- produced in PP, π^-P, and Σ^-P interactions at initial momenta 600 GeV/c and compared with exp. data. Calculated Pt2 distributions are comparable with exp. data. To reproduce Xf spectra of $\Lambda c\pm$,
it is needed a fine tuning of FTF parameters.

SetProbCCbar(0.0); //(0.005); // According to O.I. Piskunova Yad. Fiz. 56 (1993) 1094
SetProbBBbar(0.0); //(5.0e-5); // According to O.I. Piskunova Yad. Fiz. 56 (1993) 1094