Implementation of charmed particle production in Geant4 hadronic models

V. Uzhinsky, 20 Nov. 2019

Charmed particles production is observed and measured by all RHIC and LHC collaborations. It is expected that the particles will be copiously produced at FCC. Thus a simulation of their propagation in matter will be needed.

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.

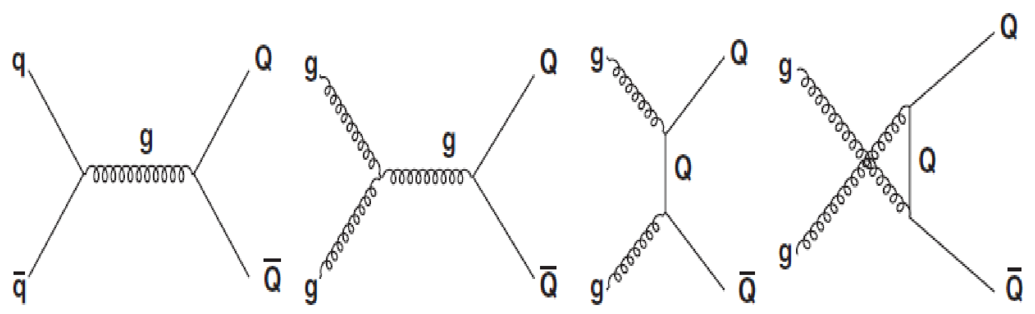
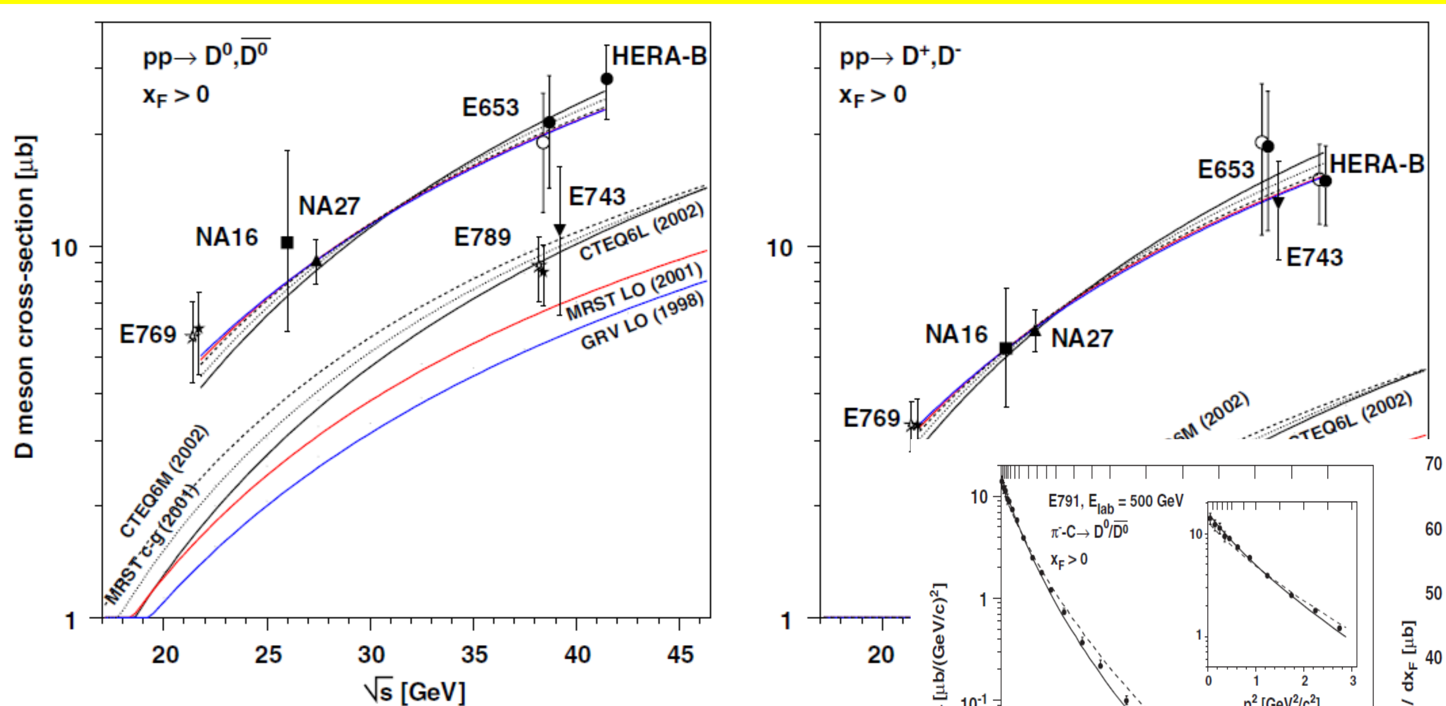


Fig. 1. Heavy flavour production mechanisms at leading order.

$$\sigma^{pp}_{Q\overline{Q}} = \sum_{i,j} \int \mathrm{d}x_1 \cdot \mathrm{d}x_2 \cdot f_i^p(x_1, Q^2) \cdot f_j^p(x_2, Q^2) \cdot \hat{\sigma}_{ij}(\hat{s}).$$

PDF, LO, NLO, Frag. Funct.

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



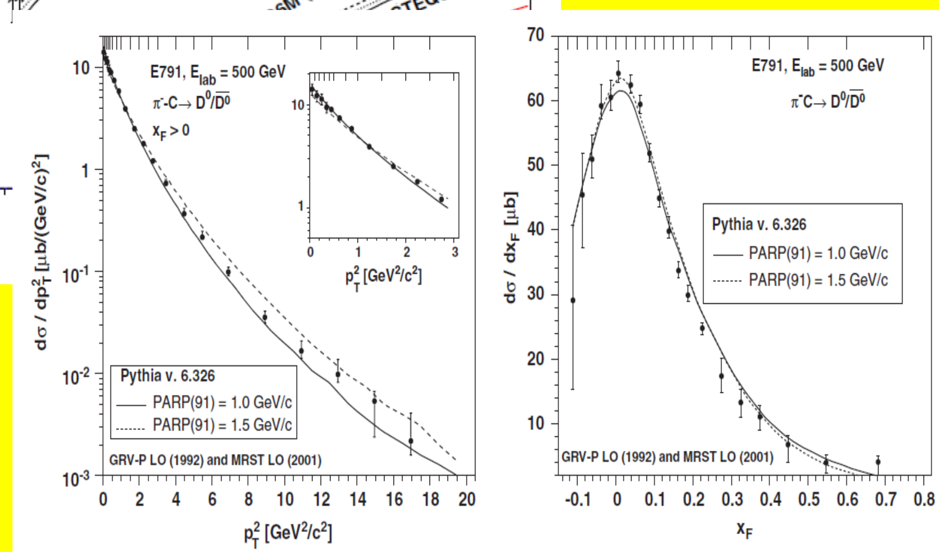


Fig. 19. p_T^2 (left) and x_F (right) distributions, as measured by the E791 Collaboration in 500 GeV π^-–C collisions and as calculated by Pythia, version 6.326.

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

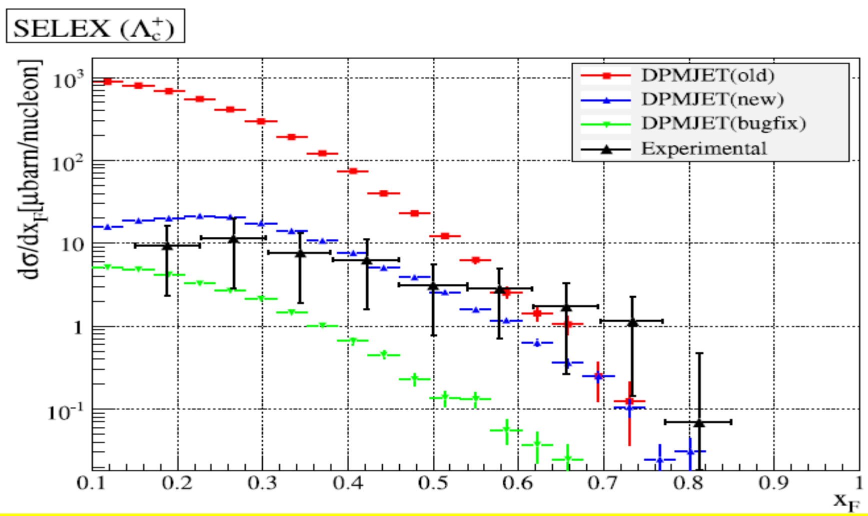
XVI International Symposium on Very High Energy Cosmic Ray Interactions

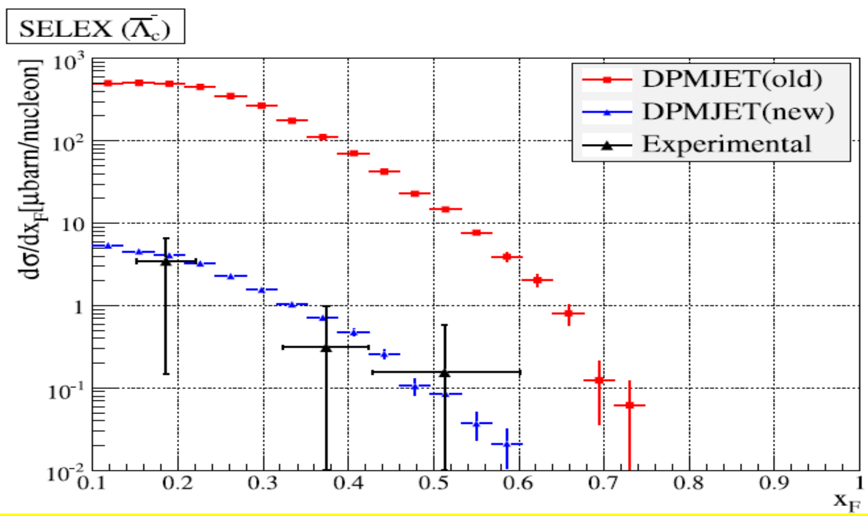
ISVHECRI 2010, Batavia, IL, USA (28 June 2 July 2010) 1 Sibyll with charm

Eun-Joo Ahn[a], Ralph Engel[b], Thomas K. Gaisser[c], Paolo Lipari,[d] Todor Stanev

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

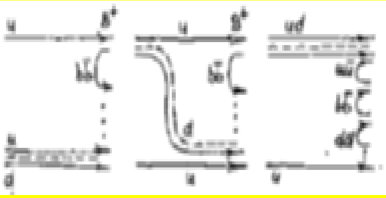
Charm production in DPMJET P Berghaus1 , T Montaruli1,3 and J Ranft2 Journal of Cosmology and Astroparticle Physics 06 (2008) 003





Implementation of charmed particle production in Geant4 hadronic models

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.



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

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

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

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

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

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

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

Implementation of charmed particle production in Geant4 hadronic models

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

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

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

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

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

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

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

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

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

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

Implementation of charmed particle production in Geant4 hadronic models

Charmed particle production in hadron-hadron collisions
G.H. Arakelyan 1, P.E. Volkovitsky, Z. Phys. A 353, 87-101 (1995)

$$f_i^n(x,n) = C_i x^{\alpha_i}(1-x)^{\beta_i^n}$$

$$G_{1i}^h(x) = d^h x^{\varepsilon_i} F_1(x)(1-x)^{\gamma_k}$$

$$G_{2i}^h(x) = \alpha_0^h F_1(x)(1-x)^{\delta_m}$$

n	π^-		p		Σ^-		Ξ^-	
i	α	β	α	β	α	β	α	β
u			$-\alpha_\rho^0$	$\alpha_\rho^0-2\alpha_N^0$	$-\alpha_\rho^0$	$\alpha_\rho^0-2\alpha_N^0$ $+\alpha_\rho^0-\alpha_\varphi^0$	$-\alpha_\rho^0$	$\alpha_\rho^0-2\alpha_N^0$ $+2(\alpha_\rho^0-\alpha_\varphi^0)$
d	$-\alpha_\rho^0$	$-\alpha_\rho^0$	α_ρ^0 $-\alpha_\rho^0$	$\alpha_\rho^0-2\alpha_N^0$ $+1$	$-\alpha_\rho^0$	$\alpha_\rho^0-2\alpha_N^0$ $+\alpha_\rho^0-\alpha_\varphi^0$	$-\alpha_\rho^0$	$\alpha_\rho^0-2\alpha_N^0$ $+2(\alpha_\rho^0-\alpha_\varphi^0)$
$\bar{u}$	$-\alpha_\rho^0$	$-\alpha_\rho^0$	$-\alpha_\rho^0$	$\alpha_\rho^0-2\alpha_N^0$	$-\alpha_\rho^0$	$\alpha_\rho^0-2\alpha_N^0$ $+\alpha_\rho^0-\alpha_\varphi^0$	$-\alpha_\rho^0$	$\alpha_\rho^0-2\alpha_N^0$ $+2(\alpha_\rho^0-\alpha_\varphi)$
$\bar{d}$	$-\alpha_\rho^0$	$-\alpha_\rho^0$	$-\alpha_\rho^0$	α_ρ^0- $+1$				
s	$-\alpha_\varphi^0$	$-\alpha_\varphi^0$	$-\alpha_\varphi^0$	α_ρ^0- $+\alpha_\rho^0$				
$\bar{s}$	$-\alpha_\varphi^0$	$-\alpha_\varphi^0$	$-\alpha_\varphi^0$	α_ρ^0- $+\alpha_\rho^0$				
uu			$\alpha_\rho^0-2\alpha_N^0$	$-\alpha_\rho^0$				
dd			$+1$					
ud			$\alpha_\rho^0-2\alpha_N^0$	$-\alpha_\rho^0$				
us								
ds								
ss								

N	l	ε_l
1	q	$1-\alpha_\rho^0$
2	s	$1-\alpha_\varphi^0$
3	$q+j$	$2(\alpha_\rho-\alpha_N)$
4	$s+j$	$2(\alpha_\rho-\alpha_N)+\alpha_\rho-\alpha_\varphi$
5		
6		
7		
8		

N	k	γ_k
1	q	0
2	s	0
3	qcj	$2(\alpha_\rho-\alpha_N)$
4	scj	$2(\alpha_\rho-\alpha_N)+\alpha_\rho-\alpha_\varphi^0$

Implementation of charmed particle production in Geant4 hadronic models

Implementation in Geant 4:

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]
```

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G4VLongitudinalStringDecay
G4LundStringFragmentation **G4FTFParameters**
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G4QGSMFragmentation

```
 // model parameters
G4double arho;
G4double aphi;
G4double aJPs;      // alpha_J/Psi Uzhi Oct. 2019
G4double aUps;      // alpha_Y     Uzhi Oct. 2019
G4double an;
G4double ala;        G4double FFq2q[5][5][2];
G4double alaC;       G4double FFq2qq[5][15][2];
G4double alaB;       G4double FFqq2q[15][5][2];
G4double aXi;        G4double FFqq2qq[15][5][2];
G4double aXiC;
G4double aXiB;
G4double aXiCC;
G4double aXiCB;
G4double aXiBB;
```

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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)
  }
```

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Implementation in Geant 4:

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

void G4VLongitudinalStringDecay::SetMinMasses()

```
/* Uzhi 2019                         //DDbar, DUbar, DSbar, DCbar, DBbar in MeV
G4double minMQQbarStr[5][5] ={ { 350.0,  350.0,  710.0, 2080.0,  5490.0},
                                //UDbar, UUbar, USbar, UCbar, UBbar in Mev
                                       { 350.0,  350.0,  710.0, 2080.0,  5490.0 },
                                //SDbar, SUbar, SSbar, SCbar, SBbar in MeV
                                       { 710.0,  710.0, 1070.0, 2440.0,  5850.0},
                                //CDbar, CUbar, CSbar, CCbar, CBbar in MeV
                                       {2080.0, 2080.0, 2440.0, 3810.0,  7220.0},
                                //BDbar, BUbar, BSbar, BCbar, BBbar in MeV
                                       {5490.0, 5490.0, 5850.0, 7220.0, 10630.0}};
*/ // Uzhi 2019// ---------------- Determination of minimal mass of q-qbar strings
G4ParticleDefinition * hadron1;    G4int Code1;
G4ParticleDefinition * hadron2;    G4int Code2;
  for (G4int i=1; i < 6; i++) { Code1 = 100*i + 10*1 + 1;    hadron1 = FindParticle(Code1);
                                if (hadron1 != NULL) {
                                  for (G4int j=1; j < 6; j++) { Code2 = 100*j + 10*1 + 1;
                                                                hadron2 = FindParticle(Code2);
                                 if (hadron2 != NULL) {minMassQQbarStr[i-1][j-1] =
                                   hadron1->GetPDGMass() + hadron2->GetPDGMass() + 70.0 * MeV;
                                 }  } } }
```

Implementation of charmed particle production in Geant4 hadronic models

Implementation in Geant 4:

G4VLongitudinalStringDecay
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void G4VLongitudinalStringDecay::SetMinMasses()

```
Meson[0][0][0] = 111; MesonWeight[0][0][0] = (   pspin_meson) * (  scalarMesonMix[0]                 );                // Pi0
Meson[0][0][2] = 221; MesonWeight[0][0][3] = (   pspin_meson) * (1-scalarMesonMix[0]-scalarMesonMix[1]);  // Eta
Meson[0][0][3] = 331; MesonWeight[0][0][4] = (   pspin_meson) * (   scalarMesonMix[1]);                   // Eta'
//dd3 -> vectorMesonMix[0] * 113 + (1-vectorMesonMix[0]-vectorMesonMix[1]) * 223 + vectorMesonMix[1] * 333
//dd3 ->                 rho_0                                   omega                 fi
Meson[0][0][1] = 113; MesonWeight[0][0][1] = (1.-pspin_meson) * (  vectorMesonMix[0]                 );              // Rho
Meson[0][0][4] = 223; MesonWeight[0][0][4] = (1.-pspin_meson) * (1-vectorMesonMix[0]-vectorMesonMix[1]);// omega
Meson[0][0][5] = 333; MesonWeight[0][0][5] = (1.-pspin_meson) * (                 vectorMesonMix[1]);  // fi
//uu1 -> scalarMesonMix[0] * 111 + (1-scalarMesonMix[0]-scalarMesonMix[1]) * 221 + scalarMesonMix[1] * 331
//uu1 ->                 Pi0                                     Eta                   Eta'
Meson[1][1][0] = 111; MesonWeight[1][1][0] = (   pspin_meson) * (  scalarMesonMix[0]                 );  // Pi0
Meson[1][1][2] = 221; MesonWeight[1][1][2] = (   pspin_meson) * (1-scalarMesonMix[0]-scalarMesonMix[1]);  // Eta
Meson[1][1][3] = 331; MesonWeight[1][1][3] = (   pspin_meson) * (                 scalarMesonMix[1]);  // Eta'

if ( pspin_meson != 0. ) {                                             // Charmed and beautн mesons
   MesonWeight[3][3][0] *= (    ProbEta_c)/(   pspin_meson);       // Eta_c
   MesonWeight[3][3][1] *= (1.0-ProbEta_c)/(1.-pspin_meson);   // J/Psi
   MesonWeight[4][4][0] *= (    ProbEta_b)/(   pspin_meson);       // Eta_b
   MesonWeight[4][4][1] *= (1.0-ProbEta_b)/(1.-pspin_meson);   // ipsilon
}
```

Implementation of charmed particle production in Geant4 hadronic models

Implementation in Geant 4:

G4VLongitudinalStringDecay

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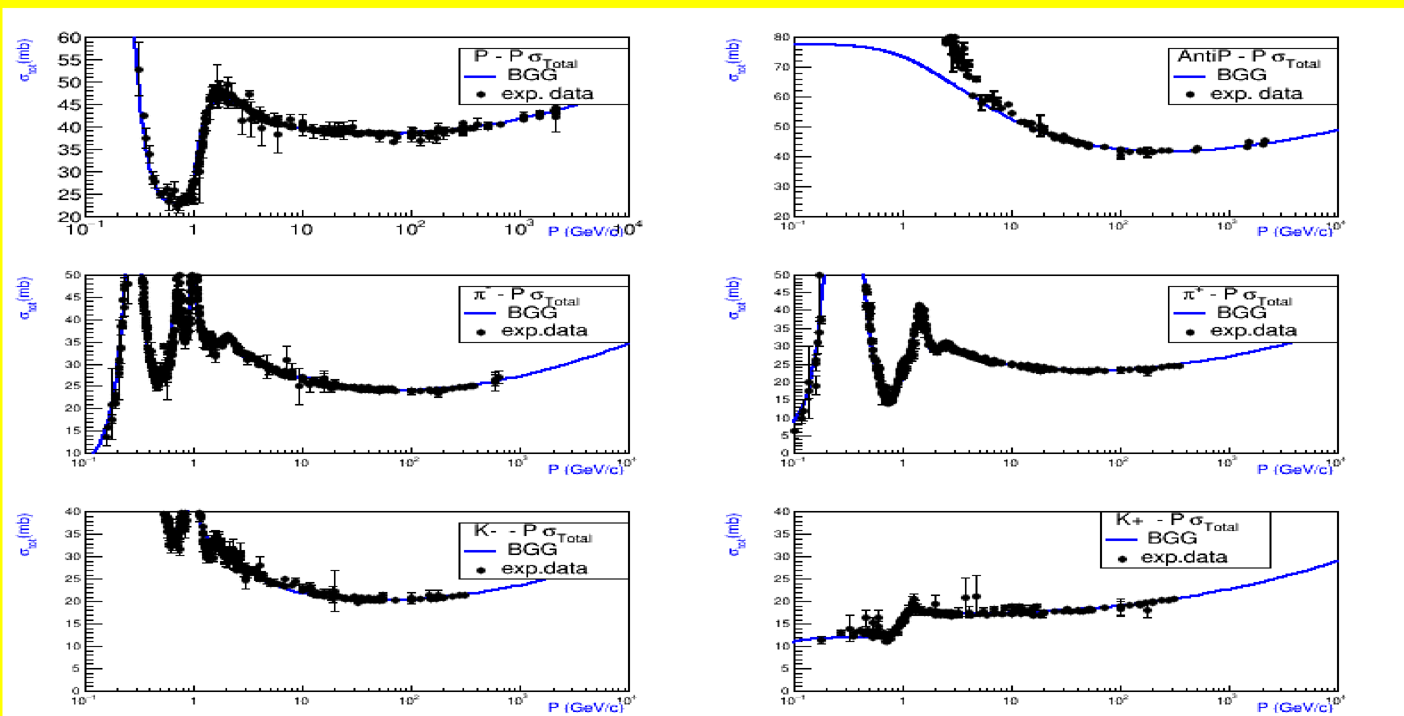
G4FTFParameters

CHIPS X -> Barashenkov-Glauber-Gribov X

+ Grishin's extension for strange, charmed and beauty hadron projectiles!

V. Ivanchenko improved the application.



Implementation of charmed particle production in Geant4 hadronic models

Implementation in Geant 4:

G4VLongitudinalStringDecay

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G4QGSMFragmentation **G4Reggeons**

G4Reggeons.cc (a'la Grishin extension for X calculations)

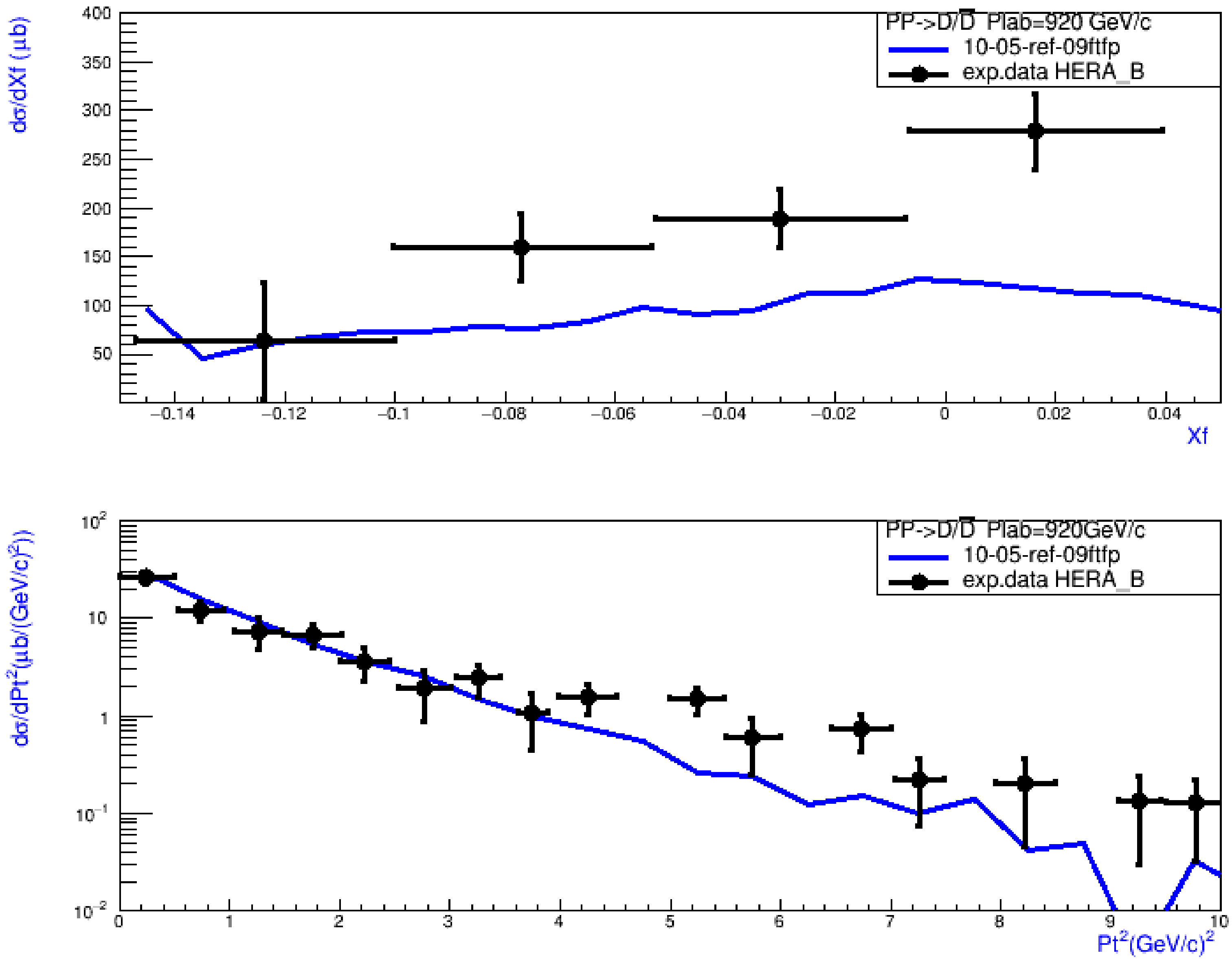
```
// Copied from G4HadronNucleonXsc::HyperonNucleonXscNS(...)
 if ( PDGcode == 3122 || PDGcode == 3222 ||
      PDGcode == 3112 || PDGcode == 3212 ||
      PDGcode ==-3122 || PDGcode ==-3222 ||
      PDGcode ==-3112 || PDGcode ==-3212   ) {      coeff = lBarCof1S;    }
 if ( PDGcode == 3312 || PDGcode == 3322 ||
      PDGcode ==-3312 || PDGcode ==-3322   ) {      coeff = lBarCof2S;    }
  if ( PDGcode == 3334 || PDGcode ==-3334 ) {      coeff = lBarCof3S;    }

Gamma_pomeron_Pr *= coeff;

// Copied from G4HadronNucleonXsc::SCBMesonNucleonXscNS(...)
 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;
```

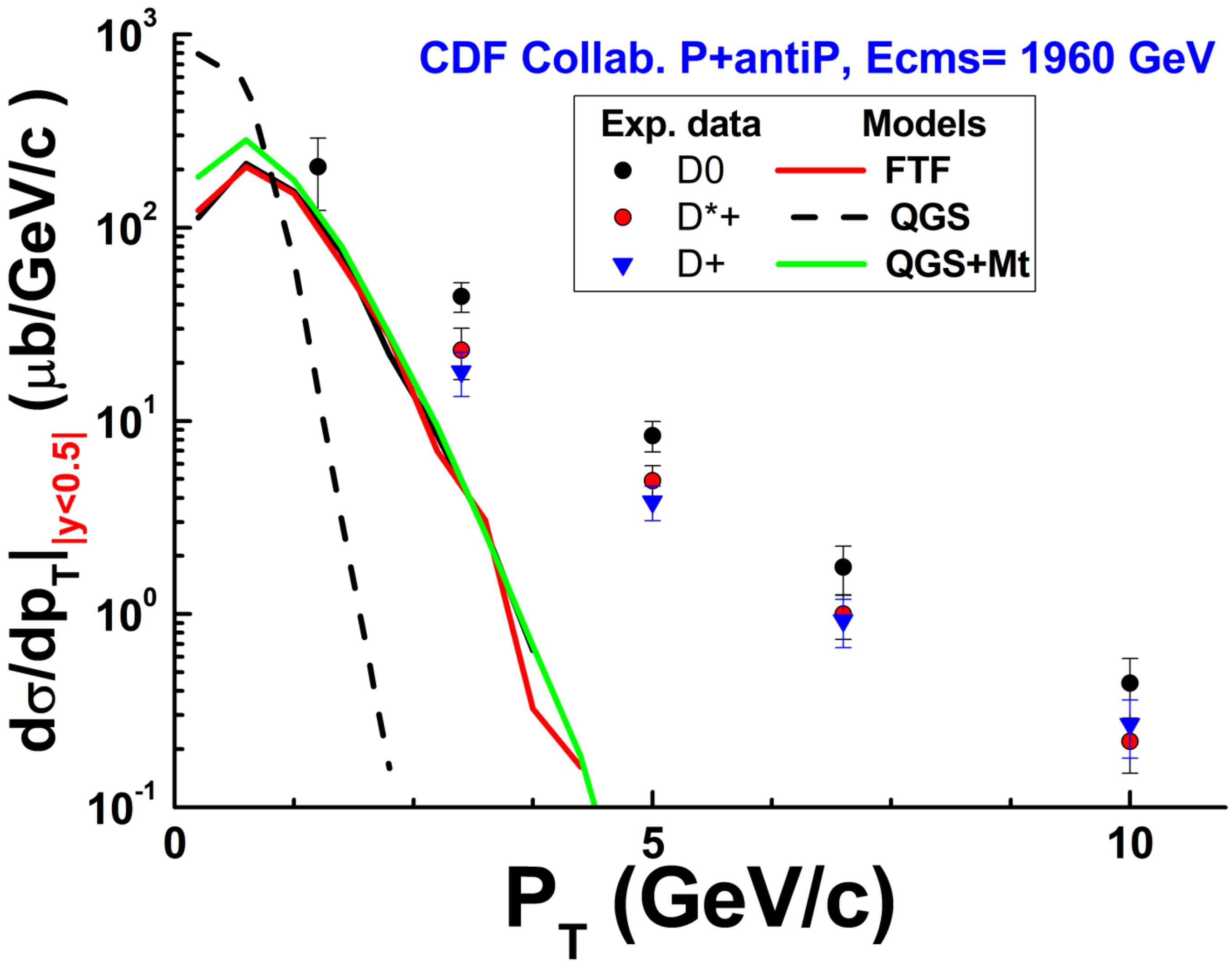
Implementation of charmed particle production in Geant4 hadronic models

Some results.



Implementation of charmed particle production in Geant4 hadronic models

Some results.



Conclusion

Charm and beauty particle production is implemented in QGS and FTF models

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

Tuning of the parameters, testing and validation of the codes are needed!

Advertising of our effort would be desirable.

Physics results have to be published!