A study of charmed hadron production in e^+e^--annihilation

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Plan

- Perturbative QCD evolution
- Non-perturbative fragmentation functions
- Retrieval of non-perturbative FF from experimental data
- Production of
    - D^* and Λ_C - from 10 to 90 GeV
    - D-mesons - directly and from decays of D^*
    - $D^{(*)}$ and Λ_C in B-meson decays

Factorization

- $$e^+e^- \to V(q) \to H(p_H) + X$$
- $$\frac{d\sigma_H}{dx} = \sum_a \frac{d\hat{\sigma}_a}{dx}(x, \sqrt{s}) \otimes D_{a/H}(x, m_Q, \mu),$$
- $$x = \frac{2p_H \cdot q}{q^2} \stackrel{\text{c.m.}}{=} \frac{2E_H}{\sqrt{s}}$$

Factorization

- $$D_{a/H} \;=\; D^{\text{pert}}_{a/H} \otimes D^{np}_{Q/H}$$

- Need to separate short $p \sim q$ and long $p \sim \Lambda_{QCD}$ distance effects

- For $x \to 1$ perturbative FF itself contains long-distance contributions from terms $\sim \ln(m_Q(1-x)) \sim \ln(\Lambda_{QCD})$

- Non-perturbative regime at $x > x_{br} \approx 1 - \Lambda_{QCD}/m_Q$

DGLAP evolution

- $$\frac{dD_{a/Q}}{d\ln\mu^2}(x, m_Q, \mu) = \sum_b \int_x^1 \frac{dz}{z} P_{ba}\left(\frac{x}{z}, \alpha_s(\mu)\right) D_{b/Q}(z, m_Q, \mu)$$
- NLL evolution (NLO splitting functions)
- NLO initial condition and NLO partonic cross sections
- $$D^{\text{ini}}_{Q/Q}(x, m_Q, \mu_0) \;=\; \delta(1-x) + \bar{\alpha}_s(\mu_0)\, d_Q^{(1)}(x, m_Q, \mu_0) + \mathcal{O}(\bar{\alpha}_s^2)\,,$$
  $$d_Q^{(1)}(x, m_Q, \mu_0) \;=\; C_F\left[\frac{1+x^2}{1-x}\left(\ln\frac{\mu_0^2}{m_Q^2} - 2\ln(1-x) - 1\right)\right]_+$$

DGLAP evolution

- Mellin transformation $f(N) \equiv \int_0^1 dx\, x^{N-1} f(x)$

- $$D_{Q/Q}(N, m_Q, \mu) = E(N, \mu, \mu_0) D^{\rm ini}_{Q/Q}(N, m_Q, \mu_0),$$
$$E(N, \mu, \mu_0) = \exp\left\{ \ln \frac{\alpha_s(\mu_0)}{\alpha_s(\mu)} \frac{P^{(0)}_{QQ}(N)}{2\pi b_0} + \right.$$
$$\left. + \frac{\alpha_s(\mu_0) - \alpha_s(\mu)}{4\pi^2 b_0} \left[P^{(1)}_{QQ}(N) - \frac{2\pi b_1}{b_0} P^{(0)}_{QQ}(N) \right] \right\}$$

- $\sigma_c(N, \sqrt{s}) = \hat{\sigma}_Q(N, \sqrt{s})\, E(N, \mu, \mu_0)\, D^{\rm ini}_{Q/Q}(N, \mu_0, m_Q)$

DGLAP evolution

- $$\hat{\sigma}_Q(N, \sqrt{s}, \mu) = 1 + \frac{\alpha_s}{2\pi} \hat{a}_Q^{(1)}(N, \sqrt{s}, \mu)$$
- $$D_{Q/Q}^{ini}(N, \mu_0, m_Q) = 1 + \frac{\alpha_s}{2\pi} d_Q^{(1)}(N, \mu_0, m_Q)$$
- $$a_Q^{(1)}(N, \sqrt{s}, \mu) = C_F \left[\ln^2 N + \left(\frac{3}{2} + 2\gamma_E - 2\ln\frac{s}{\mu^2} \right) \ln N + \alpha_Q + \mathcal{O}(1/N) \right],$$
- $$d_Q^{(1)}(N, \mu_0, m_Q) = C_F \left[-2\ln^2 N + 2\left(\ln\frac{m^2}{\mu_0^2} - 2\gamma_E + 1 \right) \ln N + \delta_Q + \mathcal{O}(1/N) \right]$$
- $$N_{\mathrm{ini}}^L = \exp\left(\frac{1}{2\, b_0 \alpha_s(\mu_0)} \right) \simeq \frac{\mu_0}{\Lambda_{\mathrm{QCD}}}$$
- $$N_q^L = \exp\left(\frac{1}{b_0 \alpha_s(\mu)} \right) \simeq \frac{\mu^2}{\Lambda_{\mathrm{QCD}}^2}$$

DGLAP evolution

- $$\hat{\sigma}_Q(N, \sqrt{s}, \mu) = 1 + \frac{\alpha_s}{2\pi}\hat{a}_Q^{(1)}(N, \sqrt{s}, \mu)$$
- $$D_{Q/Q}^{ini}(N, \mu_0, m_Q) = 1 + \frac{\alpha_s}{2\pi}d_Q^{(1)}(N, \mu_0, m_Q)$$
- $$a_Q^{(1)}(N, \sqrt{s}, \mu) = C_F\left[\ln^2 N + \left(\frac{3}{2} + 2\gamma_E - 2\ln\frac{s}{\mu^2}\right)\ln N + \alpha_Q + \mathcal{O}(1/N)\right],$$
- $$d_Q^{(1)}(N, \mu_0, m_Q) = C_F\left[-2\ln^2 N + 2\left(\ln\frac{m^2}{\mu_0^2} - 2\gamma_E + 1\right)\ln N + \delta_Q + \mathcal{O}(1/N)\right]$$
- $$\sigma_Q(N, m_Q, \mu_0) = D_{Q/Q}^{ini}(N, \mu_0, m_Q) + \frac{\alpha_s}{2\pi}\hat{a}_Q^{(1)}(N, m_Q, \mu_0)$$

$$\exp\left\{\ln\frac{\alpha_s(\mu_0^2)}{\alpha_s(\mu^2)}\frac{P_{qq}^{(0)}(N)}{2\pi b_0} + \frac{\alpha_s(\mu_0^2) - \alpha_s(\mu^2)}{4\pi^2 b_0}\left[P_{qq}^{(1)}(N) - \frac{2\pi b_1}{b_0}P_{qq}^{(0)}(N) - 2\pi b_0\hat{a}_Q^{(1)}(N)\right]\right\}$$

Non-perturbative FF (KLP)

- Gribov-Lipatov "reciprocity relation":

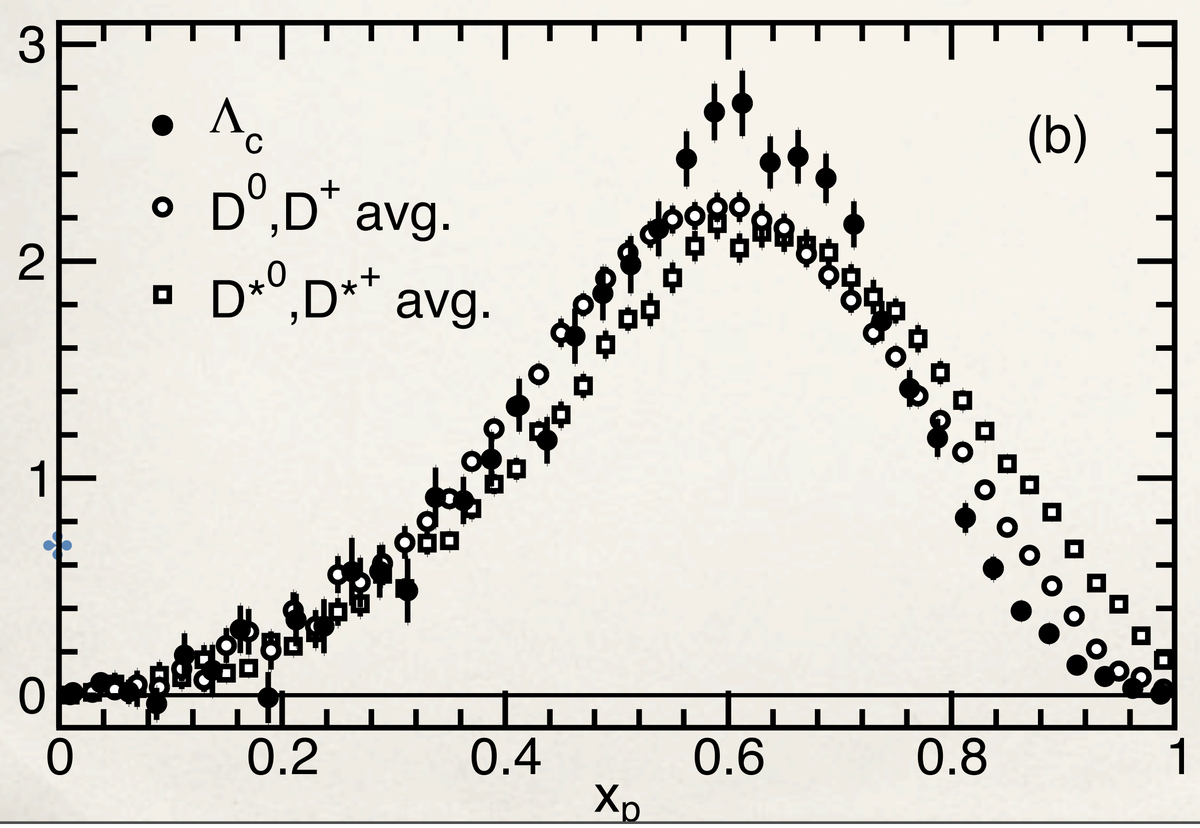
$$D^{\rm np}_{Q/H}(z) \overset{z\to 1}{=} f^{Q}_{H}(z) \qquad\qquad z = p_H/p_c$$

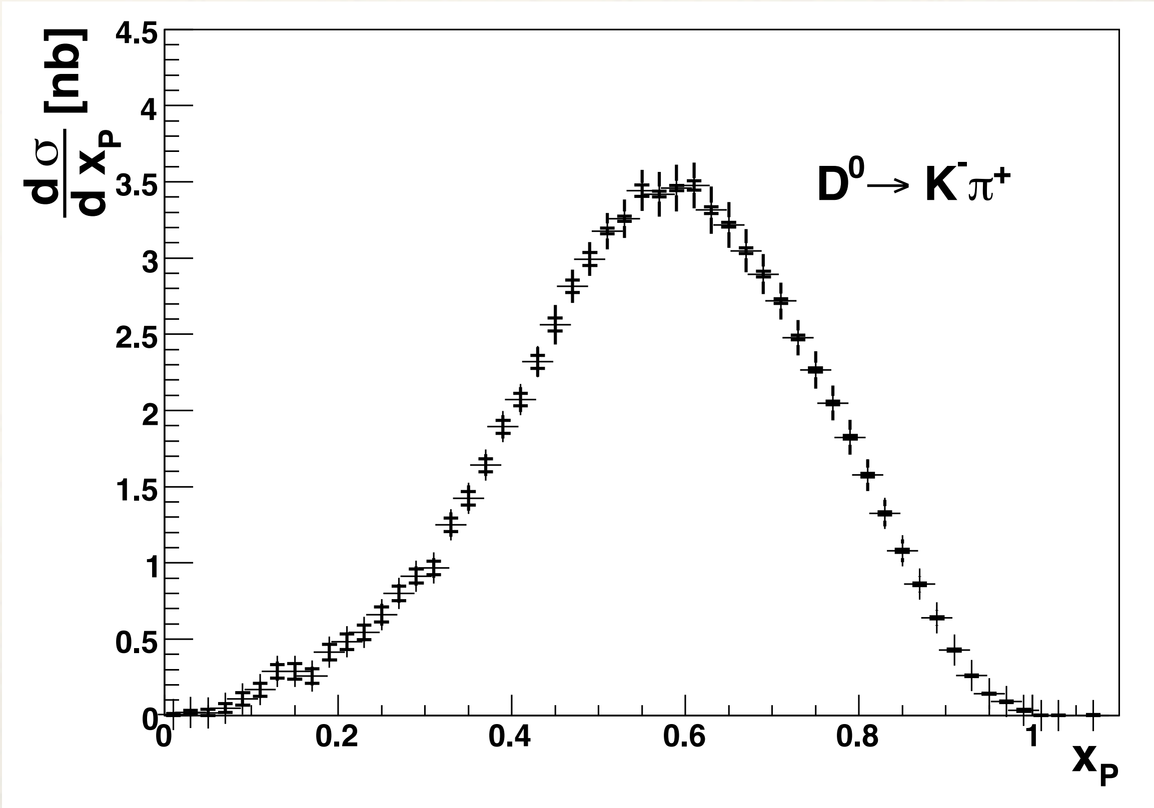
- $$f^c_{D^*}(x) = \frac{\Gamma(2+\gamma_M-\alpha_Q-\alpha_q)}{\Gamma(1-\alpha_Q)\Gamma(1+\gamma_M-\alpha_q)} x^{-\alpha_Q}(1-x)^{\gamma_M-\alpha_q}$$

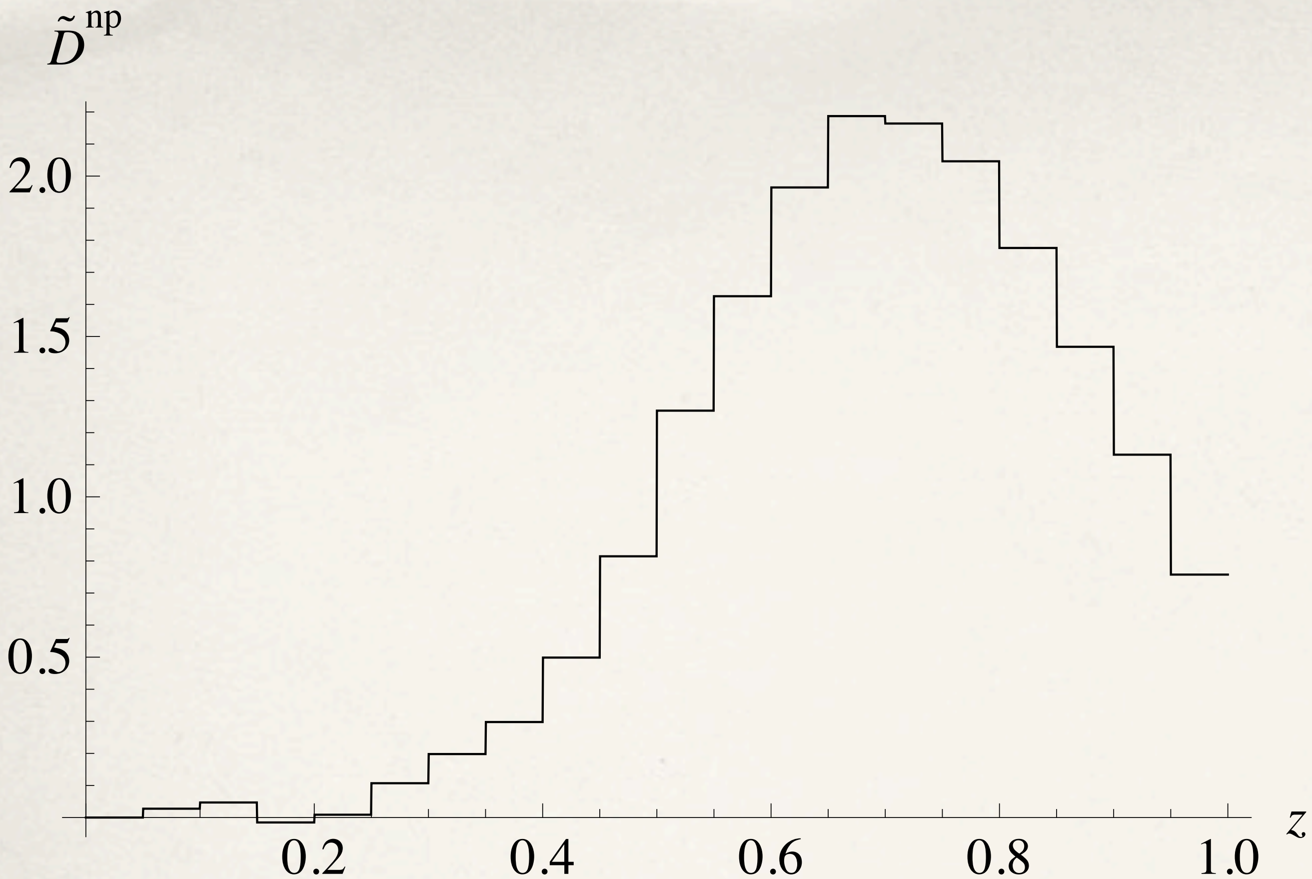
- $$f^c_{\Lambda_c}(x) = \frac{\Gamma(3+\gamma_B-\alpha_Q-2\alpha_q)}{\Gamma(1-\alpha_Q)\Gamma(1+\gamma_B-2\alpha_q)} x^{-\alpha_c}(1-x)^{1+\gamma_B-2\alpha_q}$$

Retrieval of non-perturbative FFs

- $$\widetilde{D}^{\rm np}(z) = \sum_{i=1}^{n} c_i \, \Theta\left(z - \frac{i-1}{n}\right) \Theta\left(\frac{i}{n} - z\right)$$
- $$\widetilde{D}^{\rm np}(N) = \sum_{i=1}^{n} c_i \int_{\frac{i-1}{n}}^{\frac{i}{n}} z^{N-1} dz = \sum_{i=1}^{n} c_i \, \frac{(i/n)^N - ((i-1)/n)^N}{N}$$






$\tilde{D}^{\mathrm{np}}$
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1.5
1.0
0.5
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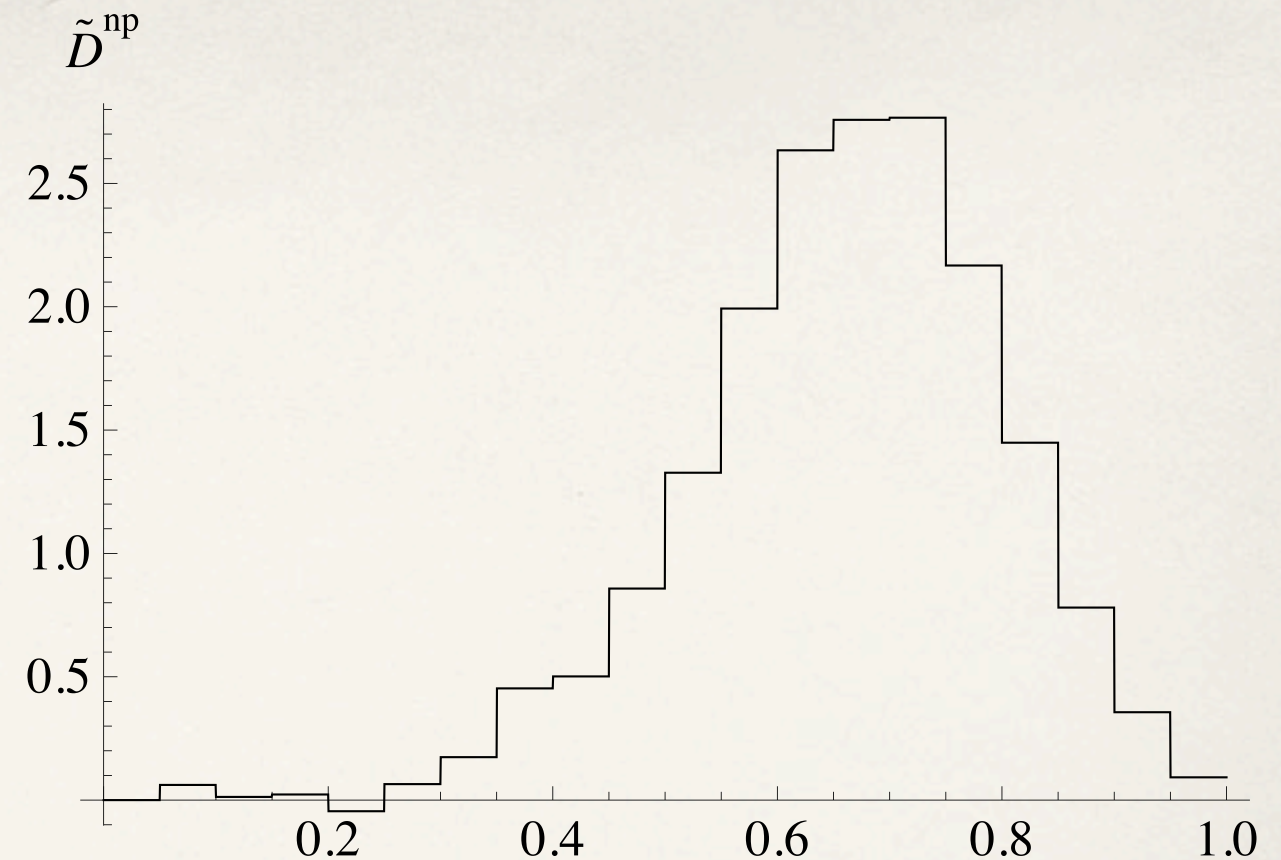
0.4
0.6
0.8
1.0
z


$\tilde{D}^{\mathrm{np}}$
2.5
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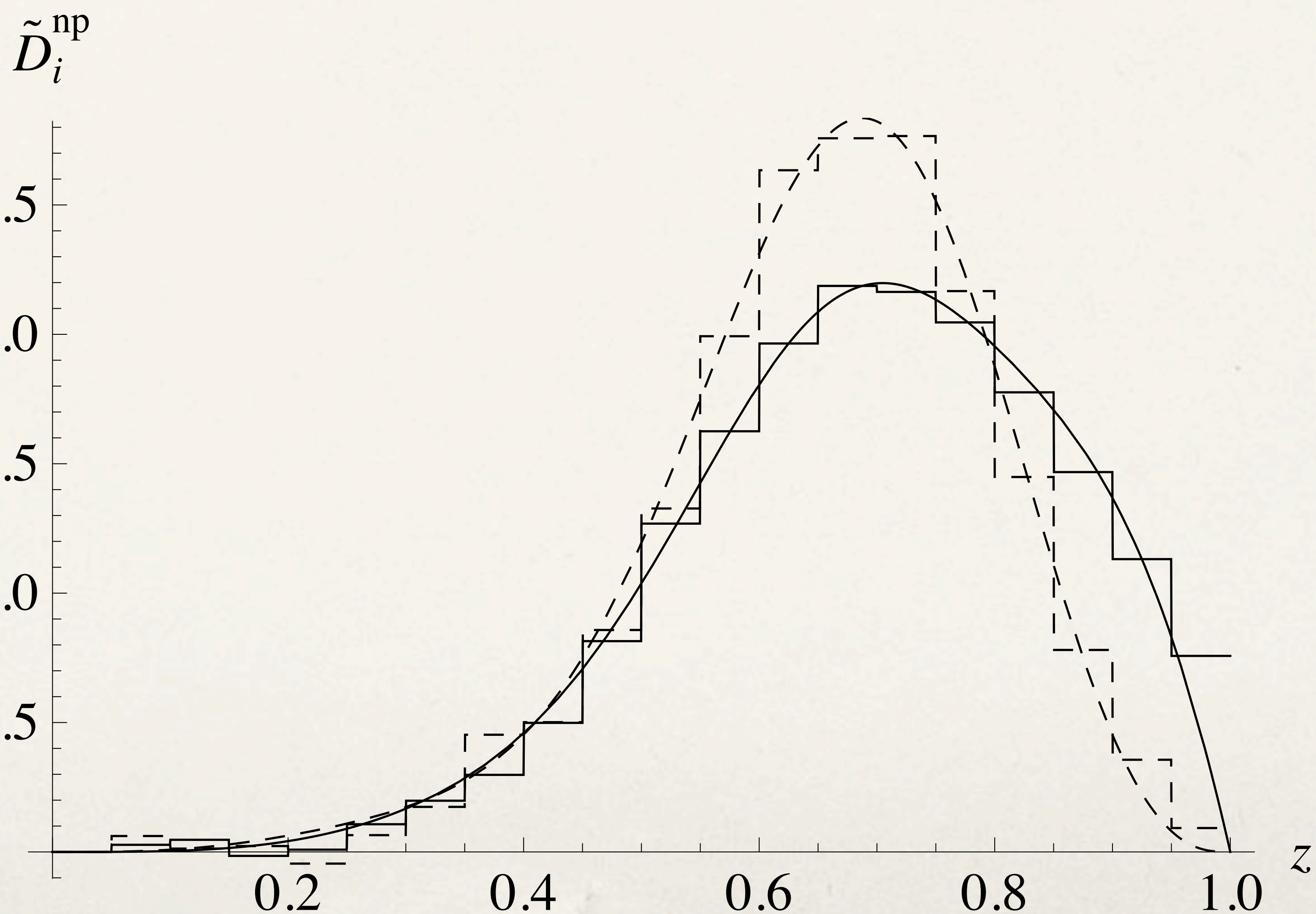
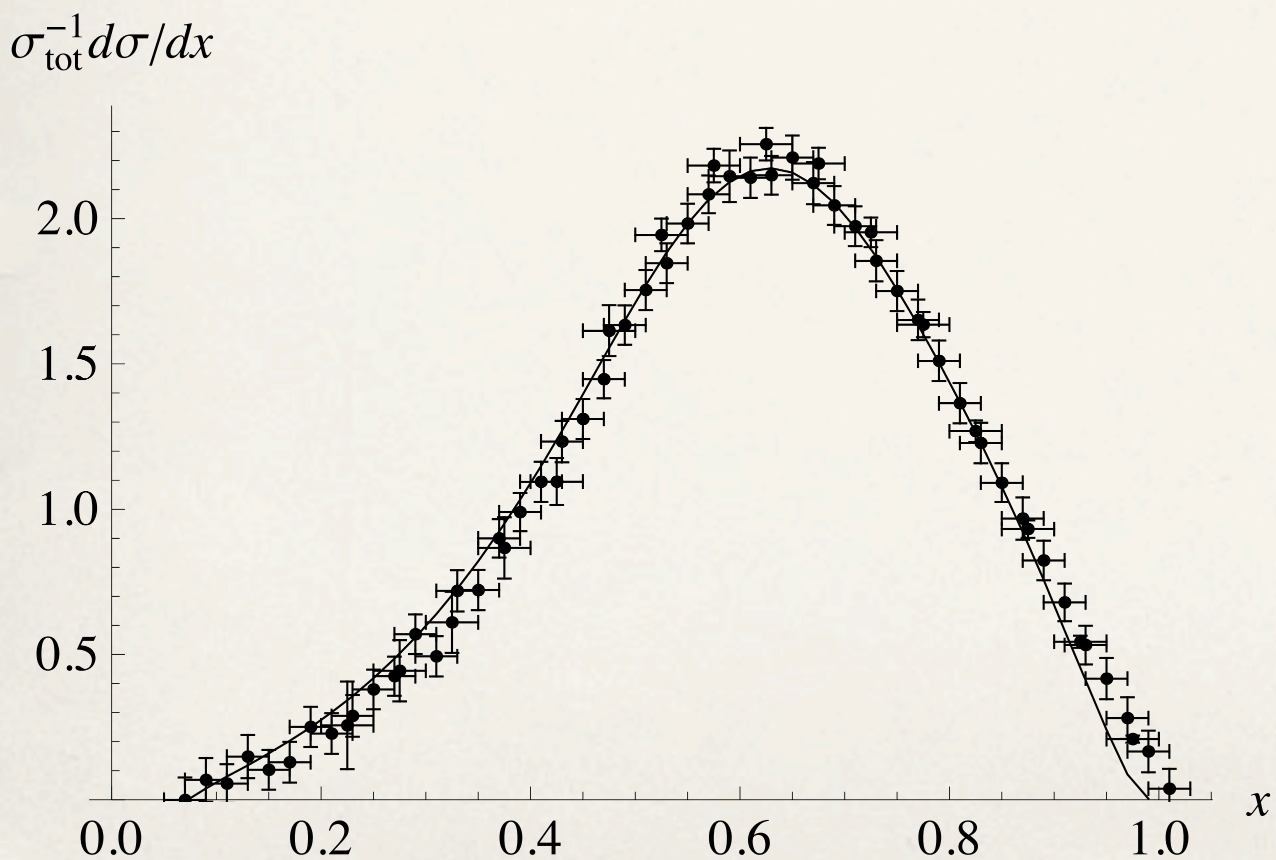
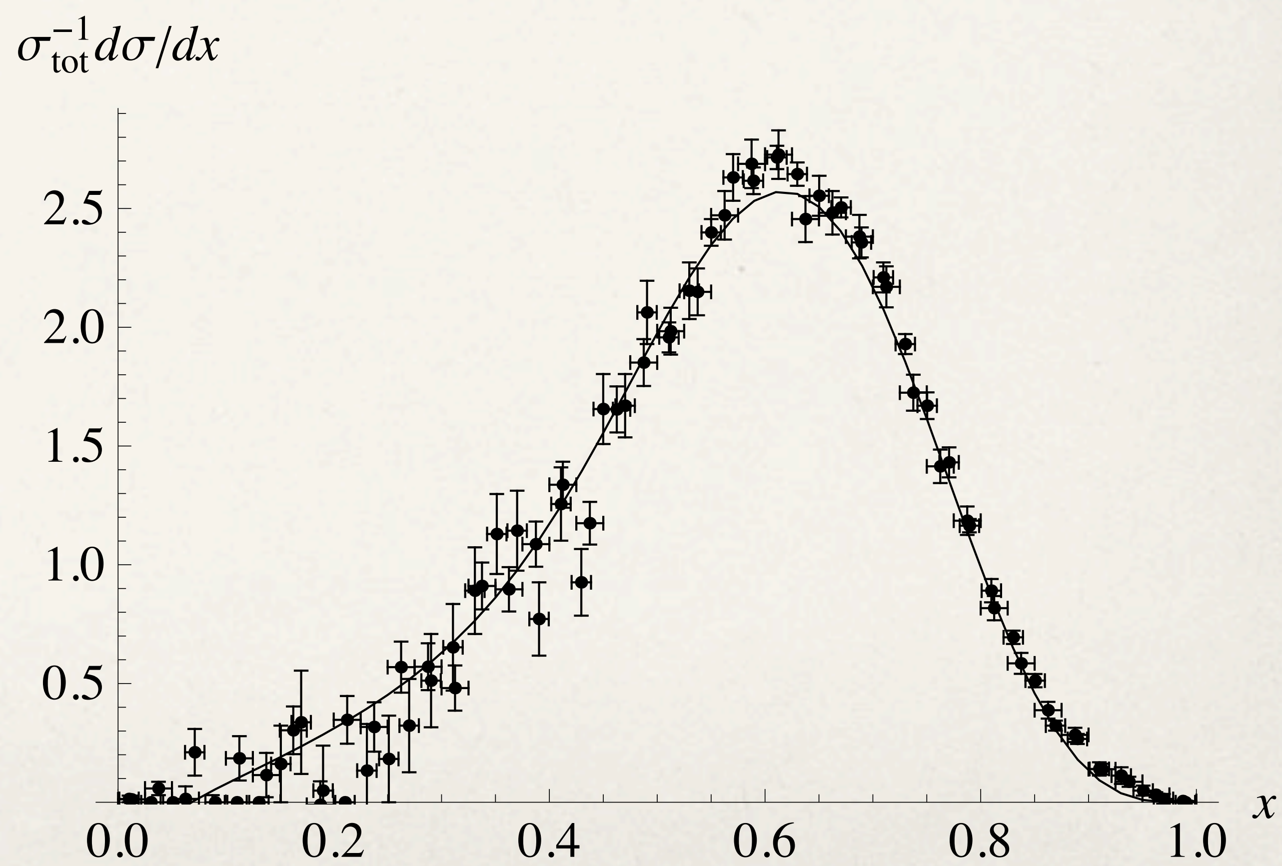

$\tilde{D}_i^{\mathrm{np}}$
2.5
2.0
1.5
1.0
0.5
0.2
0.4
0.6
0.8
1.0
z

Retrieval of non-perturbative FFs

$$\widehat{D}_c^{D^*}(z) = 20.1 z^{3.7}(1-z) + 2.77\,10^3 z^{13}(1-z)^7,$$

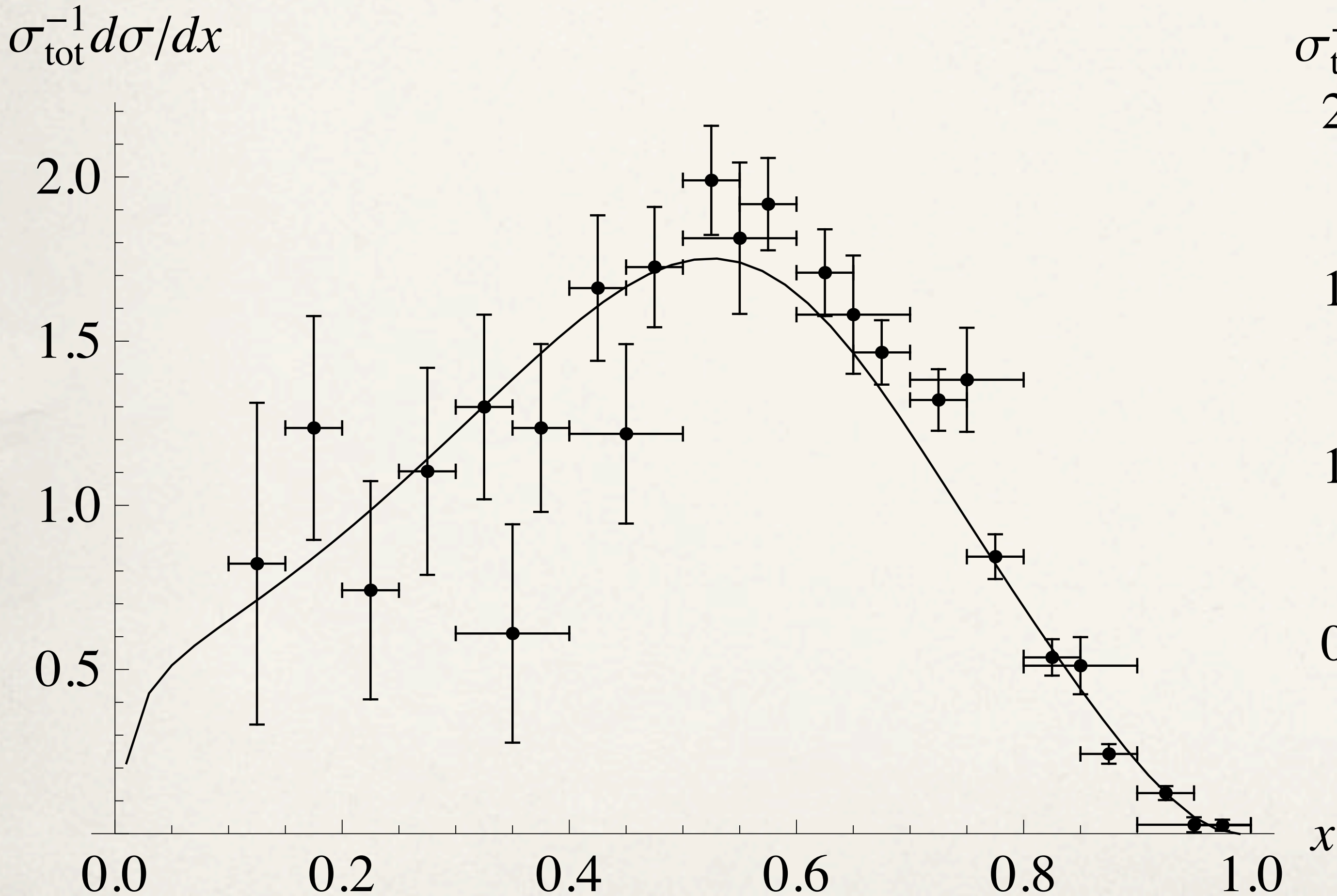
$$\widehat{D}_c^{\Lambda_c}(z) = 72.9 z^{3.7}(1-z)^5 + 2.93\,10^4 z^{10}(1-z)^5 + 10^3 z^{10}(1-z)^3.$$

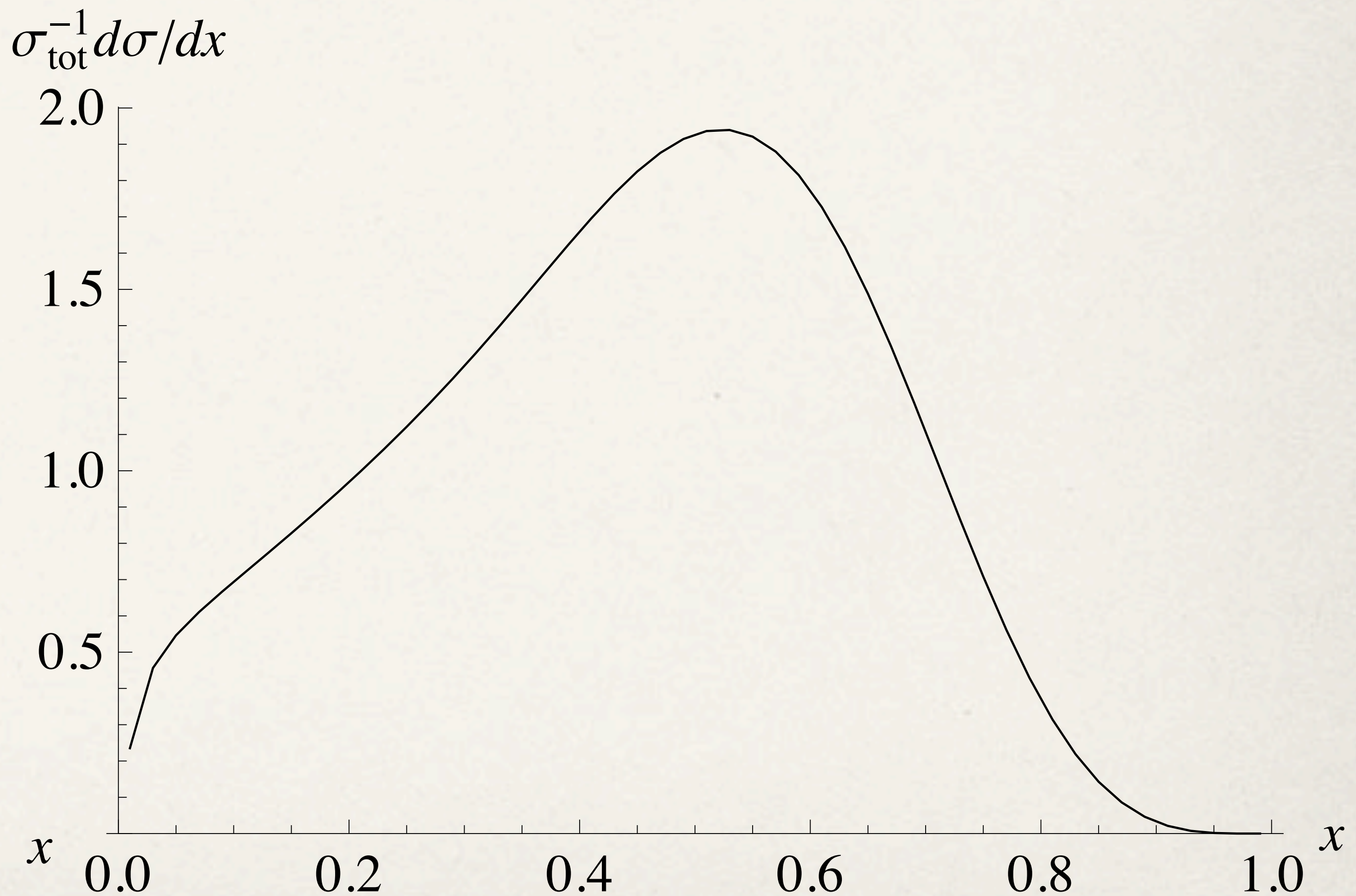




From 10 to 90 GeV (LEP data)

- D^* @ 90 GeV
- Λ_C @ 90 GeV





D-mesons production

- The decay D*→ D π takes place very close to the threshold:

$$\tilde{D}^{D\pi}(z) = D_c^{D^*}\left(z\frac{m_{D^*}}{m_D}\right)\theta\left(1 - z\frac{m_{D^*}}{m_D}\right)\frac{m_{D^*}}{m_D}$$

- For the D → Dγ decay:

$$\tilde{D}^{D\gamma}(z) = \int_0^1 dz^* \int_{-1}^1 \frac{d\cos\theta}{2} D_c^{D^*}(z^*)\,\delta\left(z - \gamma\,\frac{p'\cos\theta + \beta\epsilon'}{p_{\max}}\right)$$

-

$$Br_{D^{*+}\to D^0\pi^+} = 67.7 \pm 0.5, \%$$
$$Br_{D^{*+}\to D^+\pi^0} = 30.7 \pm 0.5, \%$$
$$Br_{D^{*+}\to D^+\gamma} = 1.6 \pm 0.4, \%$$

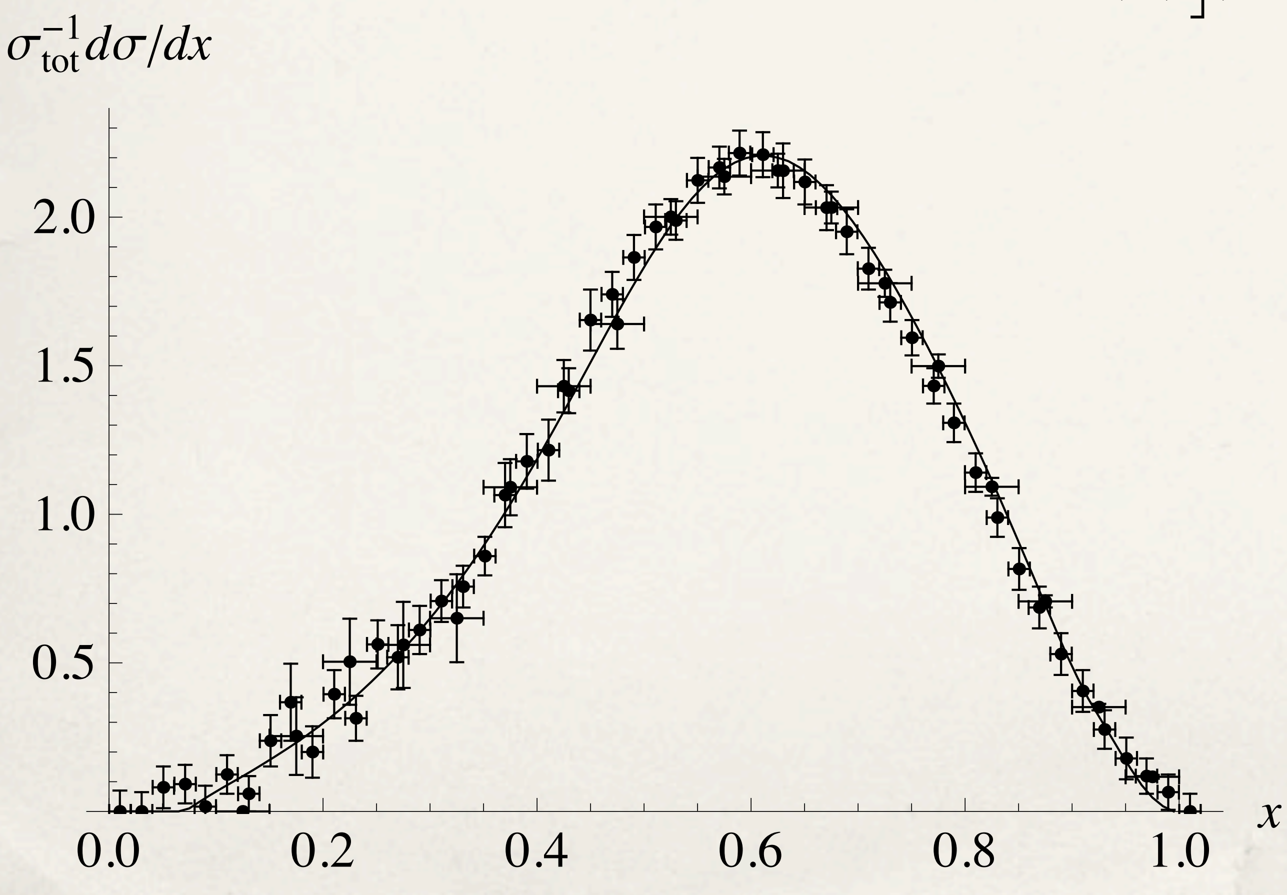
$$Br_{D^{*0}\to D^0\pi^0} = 61.9 \pm 2.9, \%$$
$$Br_{D^{*0}\to D^0\gamma} = 38.1 \pm 2.9. \%$$

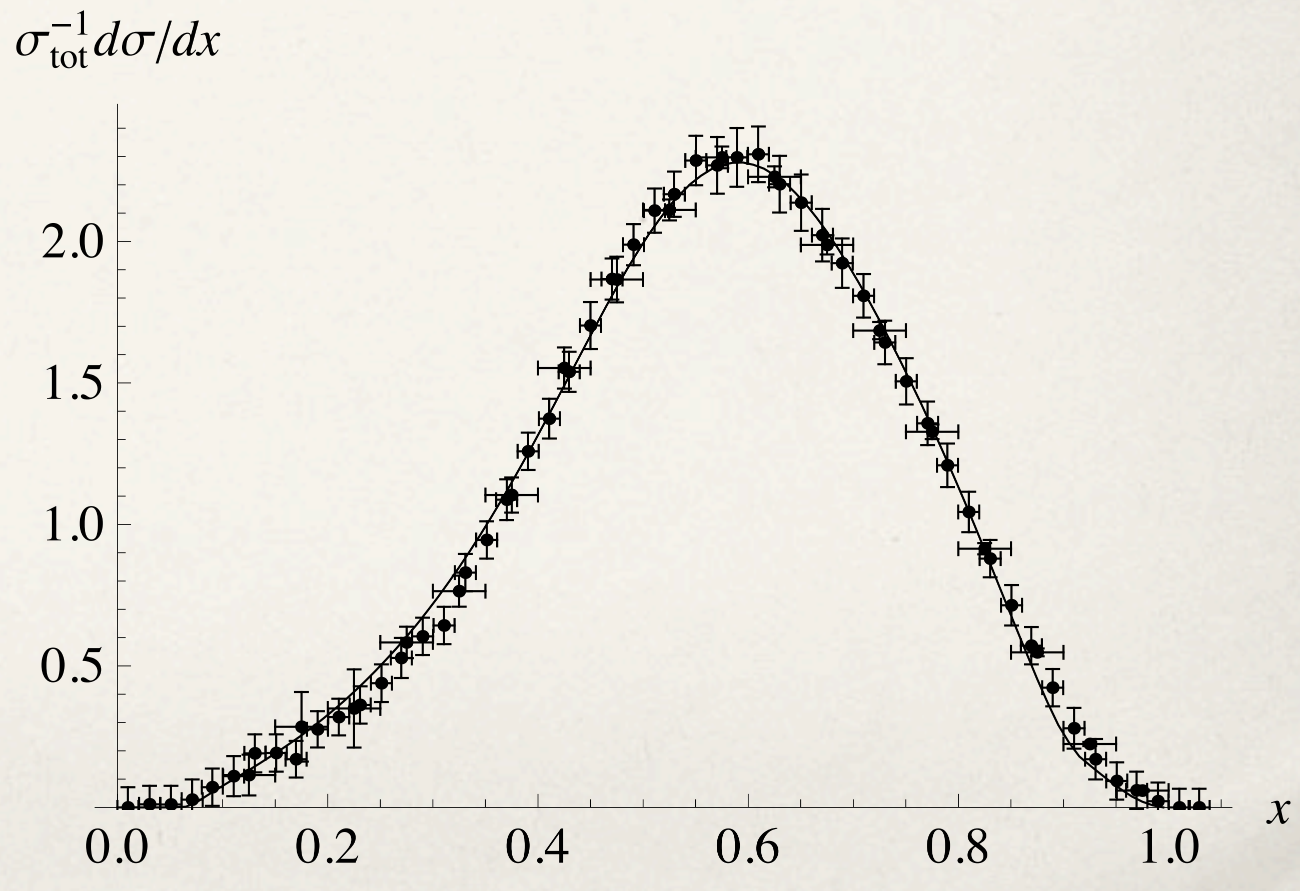
D-mesons production

$$\tilde{D}_c^{D^0}(z) = n^{D^0}\Big(D_c^D(z) + c\Big[Br_{D^{*0}\to D^0\gamma}\tilde{D}^{D\gamma}(z) + $$
$$+ \left(Br_{D^{*+}\to D^0\pi^+} + Br_{D^{*0}\to D^0\pi^0}\right)\tilde{D}^{D\pi}(z)\Big]\Big)$$

$$C = 2.$$

$$\tilde{D}_c^{D^+}(z) = n^{D^+}\Big(D_c^D(z) + c\Big[Br_{D^{*+}\to D^+\gamma}\tilde{D}^{D\gamma}(z) + $$
$$+ Br_{D^{*+}\to D^+\pi^0}\tilde{D}^{D\pi}(z)\Big]\Big)$$

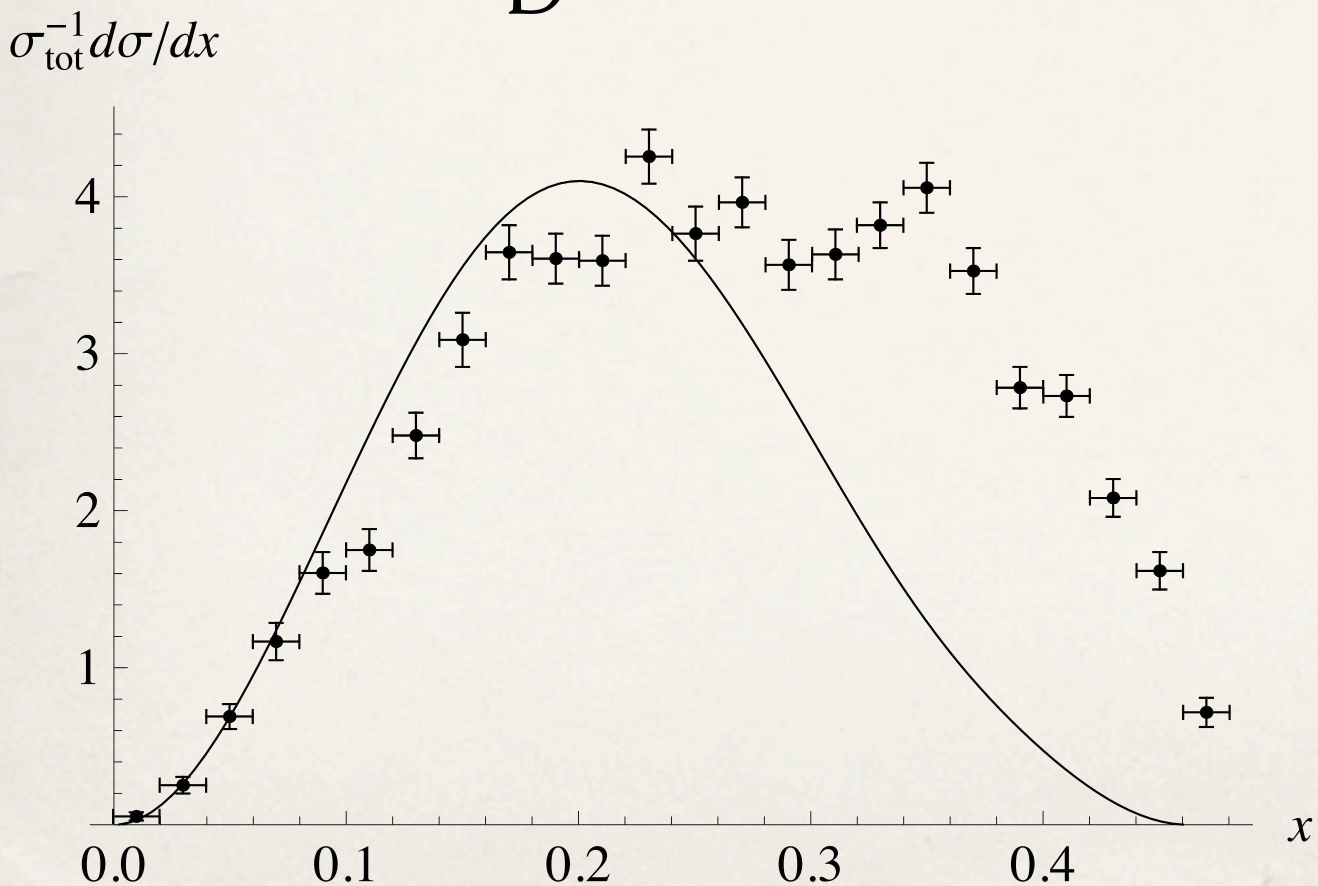




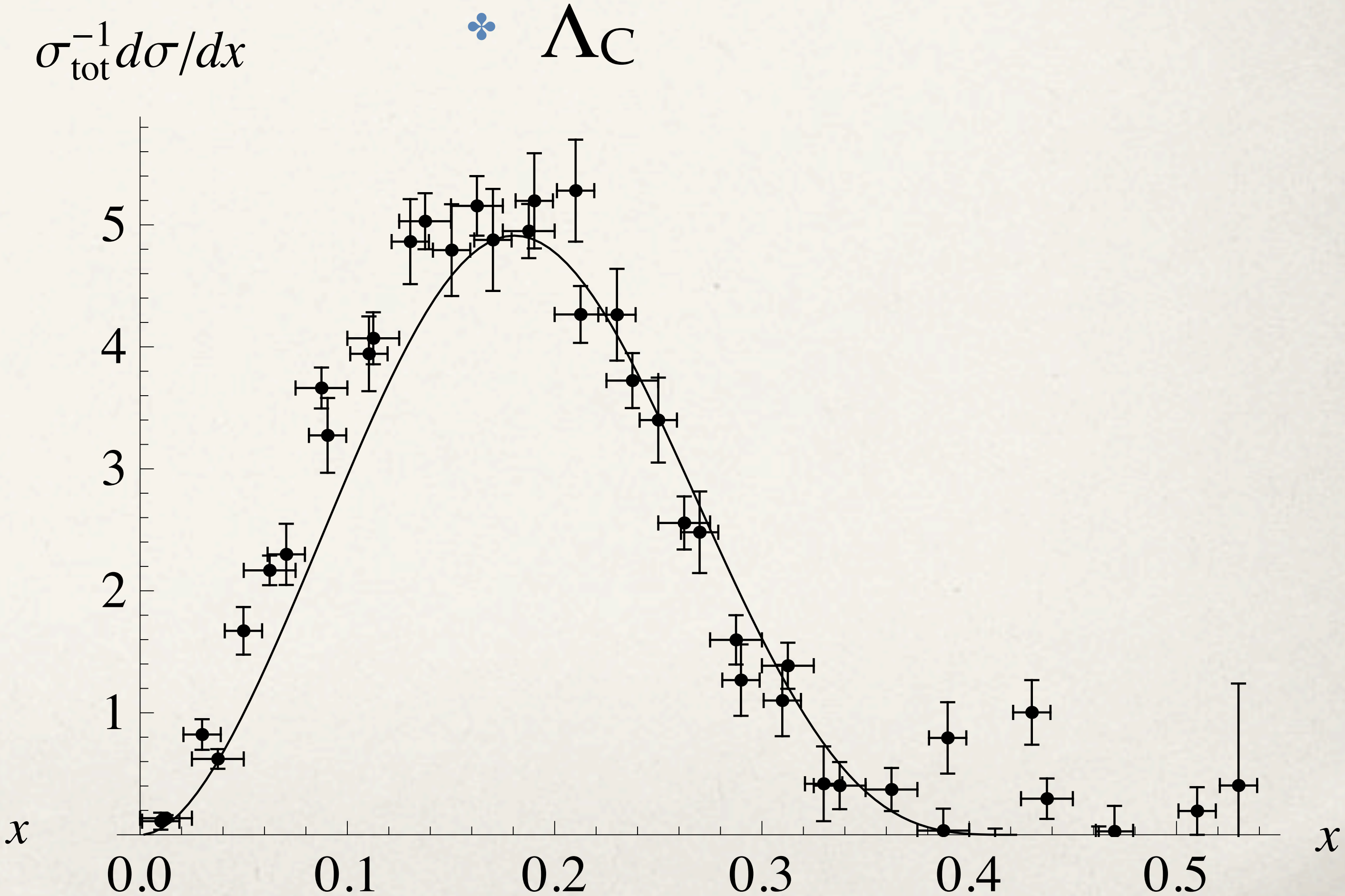
Charm production in B decays

$$\frac{d\sigma_H}{dx}(x) = \int_x^1 \frac{dz}{z}\left(\frac{d\sigma_{b\to c}}{dz}(z)\right) D_c^{\mathrm{np}}\left(\frac{x}{z}\right)$$

- D*



- Λ_C



Recombination with spectator

- B^- consists of b and u-bar quarks
- c u-bar = $D^{(*)0}$, thus its production is enhanced:

$$D^{np}_{D^0}(z) \;=\; \frac{1}{2}(1-A)\frac{\Gamma(\alpha+3)}{\Gamma(\alpha+1)}z^{\alpha}(1-z)+A\delta(1-z)$$

- For $D^{(*)+}$ recombination is not possible

$$D^{np}_{D^+}(z) \;=\; \frac{1}{2}(1-A)\frac{\Gamma(\alpha+3)}{\Gamma(\alpha+1)}z^{\alpha}(1-z)$$

- A = 1.5

Charm production in B decays

$$
\begin{aligned}
Br_{B^-\to D^0+X} &= \frac{\Gamma^{tot}_{B\to D+X}}{\Gamma_C+\Gamma_{\bar{C}}}\frac{1}{2}\left((1+A)(1+C\,Br_{D^{*0}\to D^0})+(1-A)C\,Br_{D^{*+}\to D^0}\right)\\
Br_{B^-\to D^++X} &= \frac{\Gamma^{tot}_{B\to D+X}}{\Gamma_C+\Gamma_{\bar{C}}}\frac{1}{2}\left((1-A)(1+C\,Br_{D^{*+}\to D^+})\right)\\
Br_{B^-\to \bar{D}^0+X} &= Br_{\bar{B}^0\to\bar{D}^0} = \frac{\Gamma^{tot}_{B\to D+X}}{\Gamma_C+\Gamma_{\bar{C}}}\frac{\Gamma_{\bar{C}}}{\Gamma_C}\frac{1}{2}\left((1+C(Br_{\bar{D}^{*0}\to\bar{D}^0}+Br_{D^{*-}\to\bar{D}^0}))\right)\\
Br_{B^-\to D^-+X} &= Br_{\bar{B}^0\to D^-} = \frac{\Gamma^{tot}_{B\to D+X}}{\Gamma_C+\Gamma_{\bar{C}}}\frac{\Gamma_{\bar{C}}}{\Gamma_C}\frac{1}{2}\left((1+C\,Br_{D^{*-}\to\bar{D}^-})\right)\\
Br_{\bar{B}^0\to\bar{D}^0+X} &= \frac{\Gamma^{tot}_{B\to D+X}}{\Gamma_C+\Gamma_{\bar{C}}}\frac{1}{2}\left((1+C(Br_{\bar{D}^{*0}\to\bar{D}^0}+Br_{D^{*-}\to\bar{D}^0}))\right)\\
Br_{\bar{B}^0\to D^++X} &= \frac{\Gamma^{tot}_{B\to D+X}}{\Gamma_C+\Gamma_{\bar{C}}}\frac{1}{2}\left((1+A)(1+C\,Br_{D^{*+}\to D^+})\right), \qquad C=2.
\end{aligned}
$$

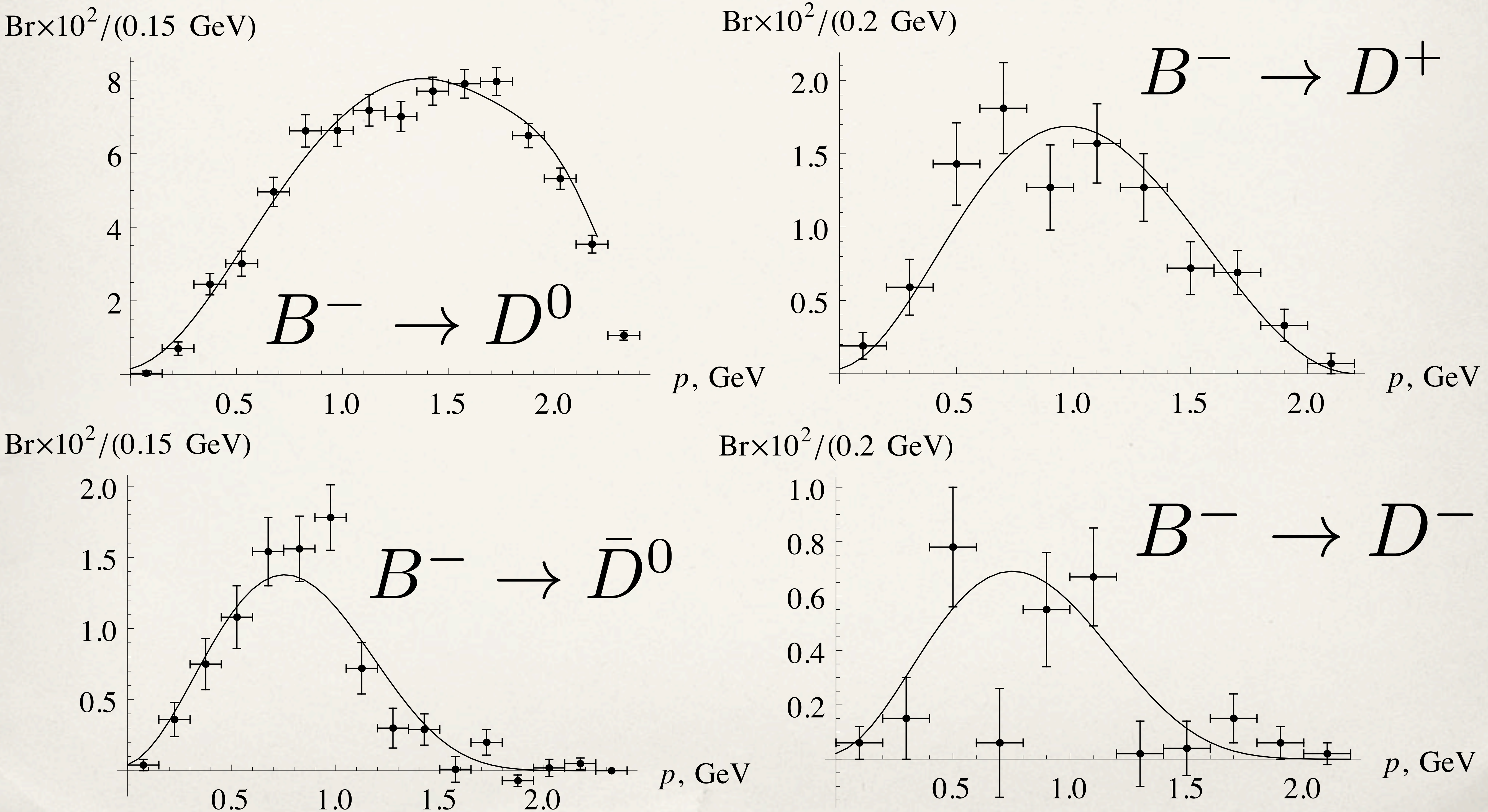
Charm production in B decays

$Br_{B^-\to D^0+X}$	77.0	$78.6 \pm 1.6 \pm 2.7^{+2.0}_{-1.9}$
$Br_{B^-\to D^++X}$	9.4	$9.9 \pm 0.8 \pm 0.5^{+0.8}_{-0.7}$
$Br_{B^-\to \bar{D}^0+X}$	7.8	$8.6 \pm 0.6 \pm 0.3^{+0.2}_{-0.2}$
$Br_{B^-\to D^-+X}$	2.9	$2.5 \pm 0.5 \pm 0.1^{+0.2}_{-0.2}$
$Br_{\bar{B}^0\to D^0+X}$	48.6	$47.4 \pm 2.0 \pm 1.5^{+1.3}_{-1.2}$
$Br_{\bar{B}^0\to D^++X}$	37.8	$36.9 \pm 1.6 \pm 1.4^{+2.6}_{-2.3}$
$Br_{\bar{B}^0\to \bar{D}^0+X}$	7.8	$8.1 \pm 1.4 \pm 0.5^{+0.2}_{-0.2}$
$Br_{\bar{B}^0\to D^-+X}$	2.9	$2.3 \pm 1.1 \pm 0.3^{+0.2}_{-0.1}$

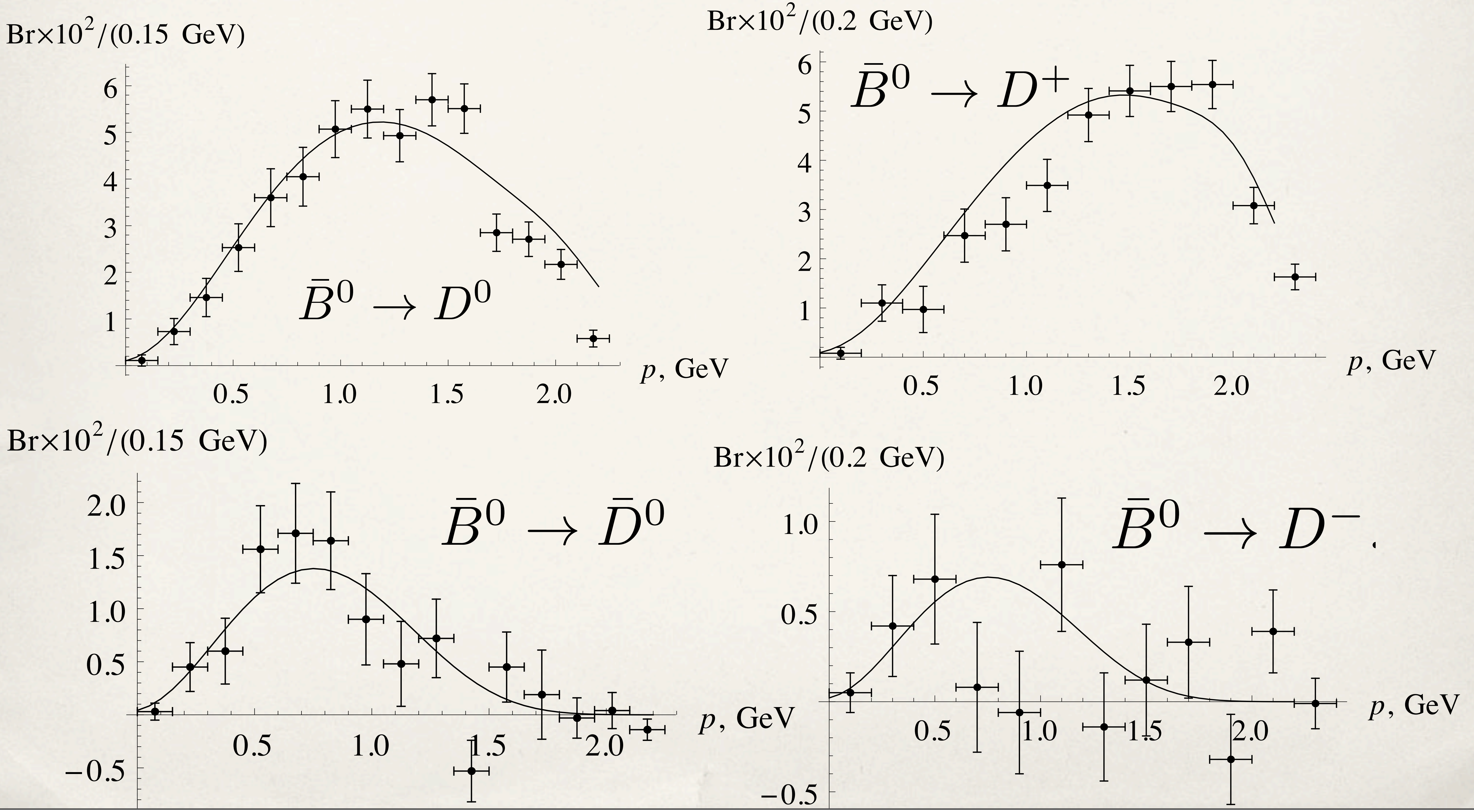
- Data by BABAR collaboration

$Br_{B^-\to \bar{D}^0+X}/Br_{B^-\to D^0+X}$	0.092	$0.098 \pm 0.007 \pm 0.001$
$Br_{B^-\to D^-+X}/Br_{B^-\to D^++X}$	0.237	$0.204 \pm 0.035 \pm 0.001$
$Br_{\bar{B}^0\to \bar{D}^0+X}/Br_{\bar{B}^0\to D^0+X}$	0.138	$0.146 \pm 0.022 \pm 0.006$
$Br_{\bar{B}^0\to D^-+X}/Br_{\bar{B}^0\to D^++X}$	0.072	$0.058 \pm 0.028 \pm 0.006$

Charm production in B⁻ decays



Charm production in B decays



Conclusions

- Factorization is satisfied in range from 10 to 90 GeV
- The difference between masonic and baryonic FFs is related to difference in quark structure
- At 5.2GeV(=m_B) fragmentation model corrupts but the reason of it is clear

Thank you for attention!