Heavy hadron production asymmetry at the LHC from heavy quark recombination mechanism

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$D^{\pm}$ PRODUCTION ASYMMETRY

Asymmetry in $D^{\pm}$ partial width:

$$a_{CP}^{f} = \frac{\Gamma(D^+ \to f) - \Gamma(D^- \to \bar{f})}{\Gamma(D^+ \to f) + \Gamma(D^- \to \bar{f})} \tag{1}$$

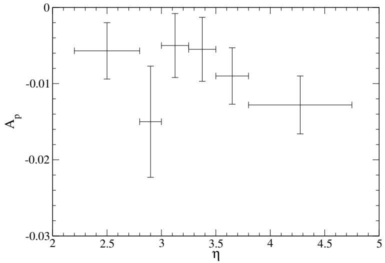
- Signal for CP violation
- Expected to be $\lesssim \mathcal{O}(0.1\%)$
- Measurement affected by $D^{\pm}$ production asymmetry
  $\Longrightarrow$ Need good theoretical prediction for production asymmetry

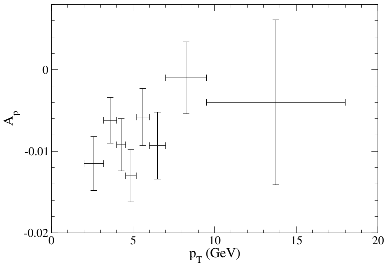
$D^{\pm}$ production asymmetry:

$$A_p = \frac{\sigma(D^+) - \sigma(D^-)}{\sigma(D^+) + \sigma(D^-)} \tag{2}$$

LHCb[1]:

$A_p = -0.96 \pm 0.26 \pm 0.18\%$ at 7 TeV ($2.0\text{ GeV} < p_T < 18\text{ GeV}, 2.2 < \eta < 4.75$)





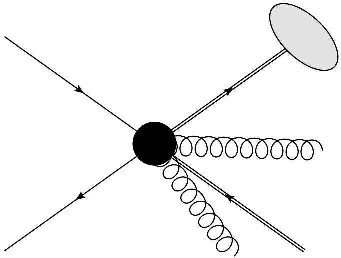
Surplus of D^- ($d\bar{c}$) over D^+ ($\bar{d}c$)

[1]R. Aaij et al. (LHCb Collaboration) (2013) [1210.4112]

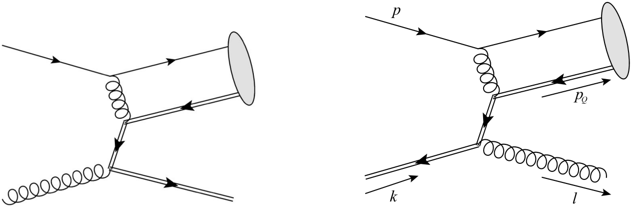
Standard perturbative QCD:

$$d\sigma[pp \to D + X] = \sum_{i,j} f_{i/p} \otimes f_{j/p} \otimes d\hat{\sigma}[ij \to c + X] \otimes D_{c\to D} \qquad (3)$$

- Gives $A_p = 0$
- Neglect $1/p_T$ corrections



Heavy quark recombination mechanism[2]:



[2] E. Braaten, Y. Jia and T. Mehen (2002) [hep-ph/0108201]

$$
\begin{aligned}
(a) \qquad & d\hat{\sigma}[\overline{D}] = d\hat{\sigma}[qg \to (\bar{c}q)^n + c]\rho[(\bar{c}q)^n \to \overline{D}] && \text{(4a)}\\
(b) \qquad & d\hat{\sigma}[\overline{D}] = d\hat{\sigma}[q\bar{c} \to (\bar{c}q)^n + g]\rho[(\bar{c}q)^n \to \overline{D}] && \text{(4b)}\\
(c) \qquad & d\hat{\sigma}[\overline{D}] = d\hat{\sigma}[\bar{q}g \to (c\bar{q})^n + \bar{c}]\rho[(c\bar{q})^n \to H] \otimes D_{\bar{c}\to\overline{D}} && \text{(4c)}
\end{aligned}
$$

$(\bar{c}q)^n$: $\bar{c}q$ pair with relative momentum $\sim \Lambda_{QCD}$ at state $n = {}^{2S+1}L_J^{(1,8)}$

$\rho[(\bar{c}q)^n \to \overline{D}]$: probability for $(\bar{c}q)^n$ to hadronize into $\overline{D}$

- $d\hat{\sigma}$ suppressed by $\alpha_s \left(\frac{m_Q}{p_T}\right)^2$ relative to Eq. (3) at large p_T
- $\rho \sim \Lambda_{QCD}/m_Q$ at leading power
- Successfully applied to explain asymmetres in fixed target experiments

ρ at leading power:

$$
\begin{aligned}
\rho_1^{sm} &= \rho[c\bar{d}({}^1S_0^{(1)}) \to D^+] & \rho_1^{sf} &= \rho[c\bar{d}({}^3S_1^{(1)}) \to D^+]\\
\rho_8^{sm} &= \rho[c\bar{d}({}^1S_0^{(8)}) \to D^+] & \rho_8^{sf} &= \rho[c\bar{d}({}^3S_1^{(8)}) \to D^+] && (5)
\end{aligned}
$$

Heavy quark spin symmetry:

$$
\begin{aligned}
\rho[c\bar{d}({}^1S_0^{(c)}) \to D^+] &= \rho[c\bar{d}({}^3S_1^{(c)}) \to D^{*+}]\\
\rho[c\bar{d}({}^3S_1^{(c)}) \to D^+] &= \rho[c\bar{d}({}^1S_0^{(c)}) \to D^{*+}] && (6)
\end{aligned}
$$

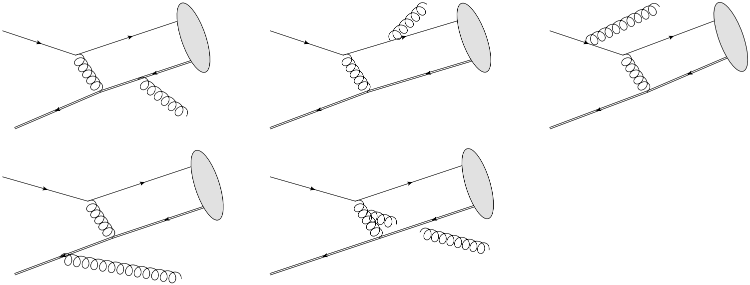
$d\hat{\sigma}[qg \to (\bar{c}q)^n + c]$ calculated by Braaten et al.
We calculate $d\hat{\sigma}[q\bar{c} \to (\bar{c}q)^n + g]$:

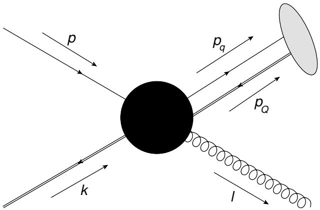
$$
\begin{aligned}
\frac{d\hat{\sigma}}{d\hat{t}}[\overline{Q}q(^1S_0^{(1)})] &= \frac{2\pi^2\alpha_s^3}{243}\frac{m_Q^2}{S^3}\left[\frac{64S^2}{T^2} - \frac{m_Q^2 S}{UT}\left(79 - \frac{112S}{U} - \frac{64S^2}{U^2}\right) + \frac{16m_Q^4}{U^2}\left(1 - \frac{8S}{U}\right)\right] \\
\frac{d\hat{\sigma}}{d\hat{t}}[\overline{Q}q(^3S_1^{(1)})] &= \frac{2\pi^2\alpha_s^3}{243}\frac{m_Q^2}{S^3}\left[\frac{64S^2}{T^2}\left(1 + \frac{2S^2}{U^2}\right) - \frac{m_Q^2}{T}\left(28 - \frac{4U}{S} - \frac{19S}{U} - \frac{368S^2}{U^2} + \frac{64S^3}{U^3}\right)\right. \\
&\qquad \left. + \frac{48m_Q^4}{U^2}\left(1 - \frac{8S}{U}\right)\right] \\
\frac{d\hat{\sigma}}{d\hat{t}}[\overline{Q}q(^1S_0^{(8)})] &= \frac{4\pi^2\alpha_s^3}{243}\frac{m_Q^2}{S^3}\left[\left(9 + \frac{9S}{T} + \frac{4S^2}{T^2}\right) - \frac{m_Q^2}{T}\left(\frac{9U}{S} - \frac{79S}{2U} - \frac{7S^2}{U^2} - \frac{4S^3}{U^3}\right)\right. \\
&\qquad \left. - \frac{m_Q^4}{U^2}\left(8 + \frac{8S}{U} + \frac{9U}{S}\right)\right] \\
\frac{d\hat{\sigma}}{d\hat{t}}[\overline{Q}q(^3S_1^{(8)})] &= \frac{4\pi^2\alpha_s^3}{243}\frac{m_Q^2}{S^3}\left[\left(16 + \frac{13U}{T} + \frac{14T}{U} + \frac{12U^2}{T^2} + \frac{8T^2}{U^2}\right)\right. \\
&\qquad + \frac{m_Q^2}{T}\left(158 + \frac{133U}{S} + \frac{233S}{2U} + \frac{5S^2}{U^2} - \frac{4S^3}{U^3}\right) \\
&\qquad \left. - \frac{3m_Q^4}{U^2}\left(8 + \frac{8S}{U} + \frac{9U}{S}\right)\right] \qquad (7)
\end{aligned}
$$

$S = \hat{s} - m_Q^2 = (k+p)^2 - m_Q^2,\ T = \hat{t} = (k - p_Q)^2,\ U = \hat{u} - m_Q^2 = (k - l)^2 - m_Q^2$

Illustrating the method:

Do a tree level matching for $d\hat{\sigma}[\overline{D}] = d\hat{\sigma}[q\bar{c} \to (\bar{c}q)^n + g]\rho[(\bar{c}q)^n \to \overline{D}]$





In rest frame of p_Q, $p_q \sim \mathcal{O}(\Lambda_{QCD})$. So take the leading singular piece for $p_q \to 0$.

$$\mathcal{M} = g^3 \mathrm{Tr}\left[v(p_Q)\bar{u}(p_q)\left(\frac{A_1}{2p\cdot p_q} + \frac{A_2}{2l\cdot p_q} \right)\right] \tag{8}$$

where

$$\begin{aligned} A_1 &= \epsilon_\nu T^b \gamma_\mu u(p)\bar{v}(k) \left\{ T^b\gamma^\mu \frac{1}{-(\not{p}_Q + \not{l}) - m_Q} T^a \gamma^\nu + T^a\gamma^\nu \frac{1}{\not{l} - \not{k} - m_Q} T^b\gamma^\mu \right. \\ &\left. + i f^{abc} T^c \frac{[(-\not{l} - \not{p})g^{\mu\nu} + 2p^\nu\gamma^\mu + 2l^\mu\gamma^\nu]}{(k-p_Q)^2} \right\} \\ A_2 &= -\epsilon_\nu \frac{T^a\gamma^\nu \not{l} T^b \gamma^\mu u(p)\bar{v}(k) T^b \gamma_\mu}{(k-p_Q)^2} \end{aligned} \tag{9}$$

For $\overline{Q}q(^1S_0^{(1)})$, $v_i(p_Q)\bar{u}_j(p_q) \longrightarrow \frac{\delta_{ij}}{\sqrt{N_c}} m_Q(\not{p}_Q - m_Q)\gamma_5$

Define ρ in HQET:

$$\rho[\overline{Q}q(^1S_0^{(1)}) \to \overline{H}] = \frac{1}{2m_Q}\int \frac{d\eta_1}{\eta_1}\int \frac{d\eta_2}{\eta_2} W(\eta_1,\eta_2) \tag{10}$$

$$W(\eta_1,\eta_2) = -\frac{1}{4}\int \frac{d\omega_1}{2\pi}\int \frac{d\omega_2}{2\pi} e^{-i\eta_1\omega_1 + i\eta_2\omega_2} \langle 0|\bar{h}_v(0)\gamma_5 q(\omega_2 v) a^\dagger_{\overline{H}} a_{\overline{H}} \bar{q}(\omega_1 v)\gamma_5 h_v(0)|0\rangle \tag{11}$$

- Easily see $\rho \sim \Lambda_{QCD}/m_Q$ by power counting
- $1/\eta$ absorbs IR divergence $1/\Lambda_{QCD}$ of partonic diagrams

$$\rho[\overline{Q}q(^1S_0^{(1)}) \to \overline{Q}q(^1S_0^{(1)})] = \frac{N_c m_Q^2}{(v\cdot p_q)^2} + \mathcal{O}(\alpha_s) \tag{12}$$

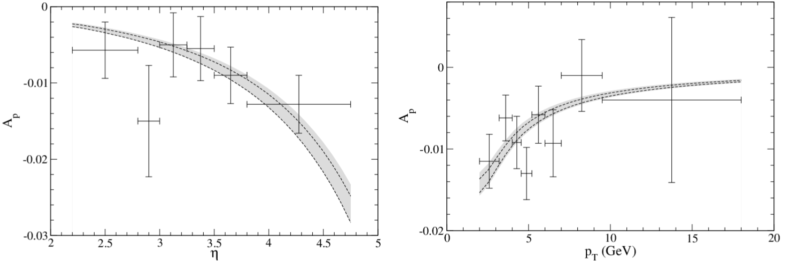
So tree-level matching is equivalent to

$$\begin{aligned} v_i(p_Q)\bar{u}_j(p_q) &\longrightarrow \frac{\delta_{ij}}{N_c} m_Q(\not{p}_Q - m_Q)\gamma_5 \rho[\overline{Q}q(^1S_0^{(1)}) \to \overline{H}] \\ \frac{1}{p\cdot p_q} &\longrightarrow \frac{1}{p\cdot p_Q} \\ \frac{1}{l\cdot p_q} &\longrightarrow \frac{1}{l\cdot p_Q} \end{aligned} \tag{13}$$

Similarly for $^1S_0^{(8)}, {}^3S_1^{(1)}, {}^3S_1^{(8)}$

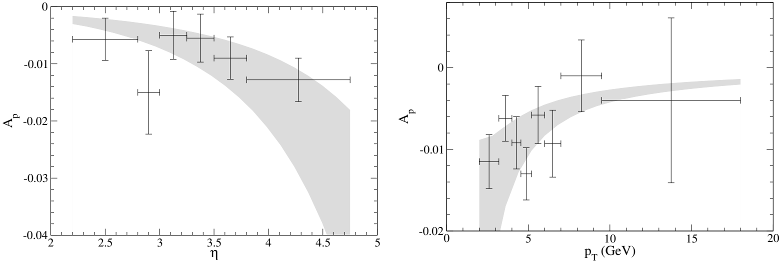
Result

- Use ρ_1^{sm} and ρ_8^{sm} determined from fixed target experiments with single-parameter fit. Set $\rho_1^{sf} = \rho_8^{sf}$ and fit to data.
- Include feeddown from $D^{*\pm}$
- Restrict H in (c) to be D or D^* only; sum over $\bar{q} = \bar{u}, \bar{d}$ and $\bar{s}$ with $SU(3)$ flavor symmetry assumed
- Use Peterson fragmentation function $D_{c\rightarrow H}(z) = \dfrac{N_H}{z\left(1-\frac{1}{z}-\frac{\epsilon_c}{1-z}\right)^2}$ (N_H and ϵ_c from ZEUS Collaboration)
- Take $\mu_f = \sqrt{p_T^2 + m_Q^2}$. Use MSTW 2008 LO PDFs. Use LO cross section for the standard pQCD part.



Grey band from varying the ρs in the intervals $0.055 < \rho_1^{sm} < 0.065$, $0.65 < \rho_8^{sm} < 0.8$, $0.24 < \rho_1^{sf} < 0.30$ and $0.24 < \rho_8^{sf} < 0.30$ respectively. Dashed lines from varying $0.055 < \epsilon_c < 0.69$.

Integrated A_p: $-0.88\% < A_p < -1.07\%$ (data: $A_p = -0.96 \pm 0.26 \pm 0.18\%$)



A_p distributions with $\frac{1}{2}\sqrt{p_T^2 + m_Q^2} < \mu_f < 2\sqrt{p_T^2 + m_Q^2}$

Baryon production asymmetry

No data from LHCb yet. Here we simply make an order-of-magnitude prediction.

Production asymmetry of Λ_Q (udQ):

$$A_p = \frac{\sigma(\Lambda_Q) - \sigma(\overline{\Lambda}_Q)}{\sigma(\Lambda_Q) + \sigma(\overline{\Lambda}_Q)} \tag{14}$$

$$(a) \qquad d\hat{\sigma}[\Lambda_Q] = d\hat{\sigma}[qg \to (Qq)^n + \overline{Q}]\eta_{inc}[(Qq)^n \to \Lambda_Q] \tag{15}$$

$$(b) \qquad d\hat{\sigma}[\Lambda_Q] = d\hat{\sigma}[Qq \to (Qq)^n + g]\eta_{inc}[(Qq)^n \to \Lambda_Q] \tag{16}$$

$$(c) \qquad d\hat{\sigma}[\Lambda_Q] = \sum_n d\hat{\sigma}[qg \to (\overline{Q}q)^n + Q] \sum_{\overline{H}_{meson}} \rho[(\overline{Q}q)^n \to \overline{H}_{meson}] \otimes D_{Q\to\Lambda_Q} \tag{17}$$

$$(d) \qquad d\hat{\sigma}[\Lambda_Q] = \sum_n d\hat{\sigma}[\bar{q}g \to (\overline{Q}\bar{q})^n + Q] \sum_{\overline{H}_{baryon}} \eta[(\overline{Q}\bar{q})^n \to \overline{H}_{baryon}] \otimes D_{Q\to\Lambda_Q} \tag{18}$$

H taken to be a low-lying heavy hadron

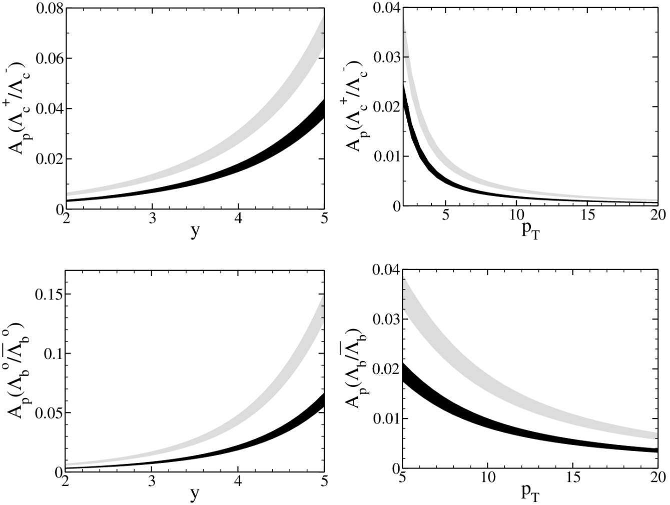
$$\eta_{inc}[(Qq)^n \to \Lambda_Q] = \eta[(Qq)^n \to \Lambda_Q] + \sum_{H_{baryon}\neq\Lambda_Q} \eta[(Qq)^n \to H_{baryon}]B[H_{baryon} \to \Lambda_Q + X] \tag{19}$$

$$\sum_{\overline{H}_{baryon}} \eta[(\overline{Q}\bar{q}')^n \to \overline{H}_{baryon}] \approx \frac{3}{2}\eta_{inc}[(Qq)^n \to \Lambda_Q] \tag{20}$$

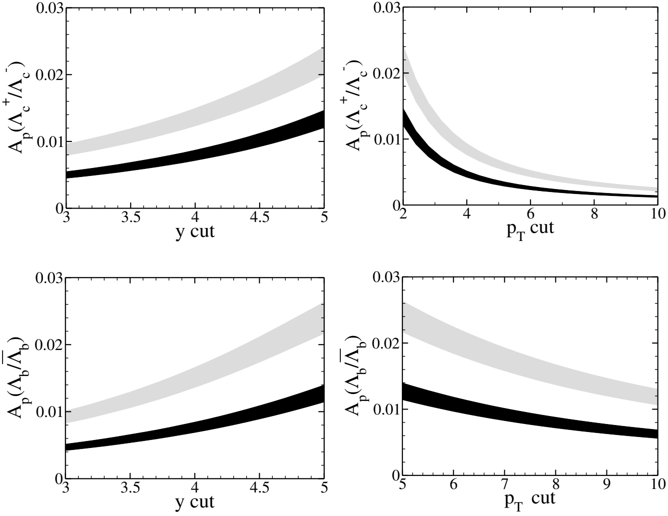
η at leading power:

$$\eta_3 = \eta[Qq(^1S_0^{(\bar{3})}) \to \Lambda_Q] \qquad \tilde{\eta}_3 = \eta[Qq(^3S_1^{(\bar{3})}) \to \Lambda_Q]$$
$$\eta_6 = \eta[Qq(^1S_0^{(6)}) \to \Lambda_Q] \qquad \tilde{\eta}_6 = \eta[Qq(^3S_1^{(6)}) \to \Lambda_Q] \tag{21}$$

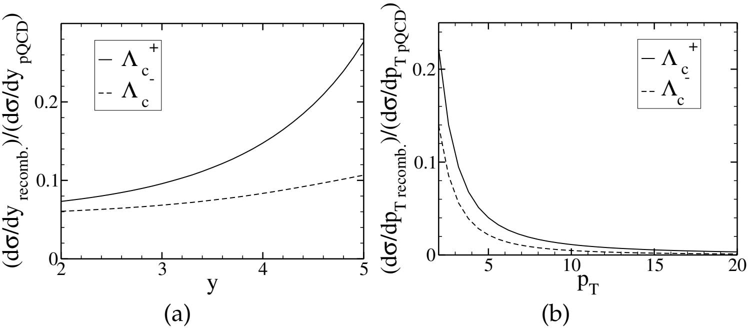
- Use same values of ρs as for $D^{\pm}$ case
- For $\Lambda_c^{\pm}$ production, use $\tilde{\eta}_{3,inc}$ determined from fixed-target experiment with single-parameter fit. Set $\eta_{3,inc} = \eta_{6,inc} = \tilde{\eta}_{6,inc} = 0$.
- For ηs for Λ_b and ρs for B, simply mutliply Λ_c and D counterparts by the theoretical scaling factor m_c/m_b
- Take $D_{Q\to\Lambda_Q}(z) = f_{\Lambda_Q}\delta(1-z)$



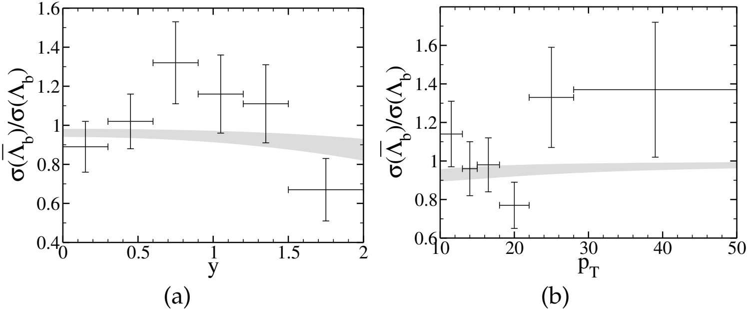
A_p distributions, $2 < y < 5$ and 2 GeV $< p_T < 20$ GeV in 7 TeV (grey band) and 14 TeV (black band) pp collisions



Integrated A_p versus cuts, $2 < y < 5$ and 2 GeV $< p_T <$ 20 GeV in 7 TeV (grey band) and 14 TeV (black band) pp collisions



$d\sigma_{recomb.}/d\sigma_{pQCD}$ distributions in 7 TeV pp collisions.



Data at 7 TeV from CMS (S. Chatrchyan et al. (CMS Collaboration) (2012) [1205.0594]). Grey band from heavy quark recombination mechanism with all η_{inc}s set equal to each other, with $0.2 < \eta_{inc} < 1$.

Outlook

- Global fit for ρs in $D^\pm$ production asymmetry (mostly done)
- NLO calculation of heavy quark recombination mechanism. Add soft Wilson lines to definition of ρ:

$$\rho[\overline{Q}q(^1S_0^{(1)}) \to \overline{H}] = \frac{1}{2m_Q}\int \frac{d\eta_1}{\eta_1}\int \frac{d\eta_2}{\eta_2} W(\eta_1, \eta_2) \tag{22}$$

$$W(\eta_1, \eta_2) = -\frac{1}{4}\int \frac{d\omega_1}{2\pi}\int \frac{d\omega_2}{2\pi} e^{-i\eta_1\omega_1 + i\eta_2\omega_2} \langle 0|\bar{h}_v(0)\gamma_5 S(0, \omega_2 v) q(\omega_2 v) a^\dagger_{\overline{H}} a_{\overline{H}} \bar{q}(\omega_1 v)\gamma_5 S(\omega_1 v, 0) h_v(0)|0\rangle \tag{23}$$

(in progress)

- Compare with predictions from other models of soft QCD processes

Thank you.