Charm in QGSJET(-II)

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Heavy Quark Hadroproduction
Mainz, September 30 - October 11, 2019

Few comments on the contribution of charm to ν-spectra

- Inclusive flux of particles X from primary CRs A: expressed via 'Z-moments' [e.g. Gaisser, 1990]

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Z^X_{A-\mathrm{air}}(E) &\propto \int dE_0\, I_A(E_0)\, \frac{d\sigma_{A-\mathrm{air}\to X}(E_0,E)}{dE} \\
&= \int dz\, I_A(EA/z)\, \frac{d\sigma_{A-\mathrm{air}\to X}(E/z,z)}{dz}
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Power-law spectra ($I_A(E_0) \propto E_0^{-\alpha_A}$) can be decoupled

$$
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Z^{X}_{A-\mathrm{air}}(E) &\propto I_A(E)\, \tilde{Z}^{X}_{A-\mathrm{air}}(E,\alpha) \\
\tilde{Z}^{X}_{A-\mathrm{air}}(E,\alpha) &= A^{-\alpha} \int dz\, z^{\alpha-1}\, \frac{d\sigma_{A-\mathrm{air}\to X}(E/z,z)}{dz}
\end{aligned}
$$

- $\tilde{Z}^{X}_{A-\mathrm{air}}$: via production spectrum of X, weighted by $z^{\alpha-1}$

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Thus, we are left with $p-\text{air} \to h_c \to \nu_\mu$, $h_c = D, \bar{D}, D^*, \Lambda_c \ldots$

- $\tilde{Z}^{\nu}_{p-\text{air}}$: factorizable as product of production & decay moments

$$\tilde{Z}^{\nu}_{p-\text{air}}(E,\alpha) = \sum_{h_c} \tilde{Z}^{h_c}_{p-\text{air}}(E,\alpha)\, Z^{\text{decay}}_{h_c\to\nu}(\alpha)$$

$$\tilde{Z}^{h_c}_{p-\text{air}}(E,\alpha) = \int dz\, z^{\alpha-1}\, \frac{d\sigma_{p-\text{air}\to h_c}(E/z,z)}{dz}$$

$$Z^{\text{decay}}_{h_c\to\nu}(\alpha) = \int dz\, z^{\alpha-1}\, \frac{dn_{\nu/h_c}(z)}{dz}$$

Few comments on the contribution of charm to ν-spectra

Generally, we have both perturbative & intrinsic charm contributions [Brodsky et al., 1980]

$$\sigma_{p-\mathrm{air}\to h_c} = \sigma^{\mathrm{pert}}_{p-\mathrm{air}\to h_c} + \sigma^{\mathrm{IC}}_{p-\mathrm{air}\to h_c}$$

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$$\sigma^{\mathrm{pert}}_{p-\mathrm{air}\to h_c} \propto \int dx^+ dx^- \int \frac{d\hat{t}}{\hat{s}^2}\, g_p(x^+, M_{\mathrm{F}}^2)\, g_{\mathrm{air}}(x^-, M_{\mathrm{F}}^2)$$

$$\times \quad |M_{gg\to c\bar{c}}|^2 \int \frac{dz}{z^2}\, D_{c(\bar{c})\to h_c}(z, M_{\mathrm{F}}^2)$$

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- neglecting scaling violations for $D_{c(\bar{c})\to h_c}$, one can factorize out moments of fragmentation functions

$$\tilde{Z}^{\nu(\mathrm{pert})}_{p-\mathrm{air}}(E,\alpha) \simeq \tilde{Z}^{c(\bar{c})(\mathrm{pert})}_{p-\mathrm{air}}(E,\alpha) \left[\sum_{h_c} Z^{\mathrm{fragm}}_{c(\bar{c})\to h_c}(\alpha)\, Z^{\mathrm{decay}}_{h_c\to\nu}(\alpha)\right]$$

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- $\Rightarrow$ one can compare approaches at c-quark production level

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$z^{\alpha-1}$ weighting in $\tilde{Z}_{p-\mathrm{air}}^{c(\bar{c})(\mathrm{pert})}$ $(\alpha \simeq 3) \Rightarrow$ asymmetric configuration

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Intrinsic charm: concentrates at large x, weakly energy-dependent

- $\Rightarrow$ one can factor out σ_{inel} & n_{h_c}

$$\tilde{Z}^{h_c(\text{IC})}_{p-\text{air}}(E,\alpha) = \int dz\, z^{\alpha-1}\, \frac{d\sigma^{(\text{IC})}_{p-\text{air}\to h_c}(E/z,z)}{dz} \simeq \sigma^{\text{inel}}_{p-\text{air}}\, \langle n_{h_c} \rangle\, \langle x^{\alpha-1}_{h_c} \rangle$$

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- e.g. for $\alpha = 3$: $\langle x_{h_c}^2\rangle = \langle x_{h_c}\rangle^2 + \sigma_{h_c}^2$

Charm production in QGSJET: aimed on studying the effect on EAS [Kalmykov et al., Proc. ICRC-1995]

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We investigated also the role of charm particles production in EAS development and found it to be negligible within the statistical accuracy of the calculation (1% for N_μ, 3% for N_e and 3 g/cm^2 for X_{max}). That result can be understood if we take into consideration two contributions to charm particle production. First one is the incident nucleon conversion into leading $\Lambda_c D$-pair. The cross-section of this process remains small even at high energies (see Table 1). Another one is the charm particles generation in the central region; corresponding cross-sections increase rapidly with energy but as energy spectrum of such particles is quite soft they cannot influence EAS development.

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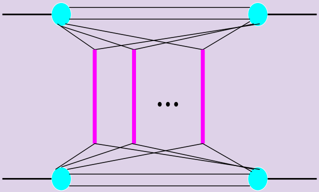
- charm hadrons: mostly at low x
  $\Rightarrow$ irrelevant for EAS development

QGSJET(-II): Reggeon Field Theory (RFT) approach

Original approach: Quark-Gluon String model
[Kaidalov & Ter-Martirosyan, 1982]

- multiple scattering = multi-Pomeron exchanges (multiple parton cascades)
- allows to calculate: cross sections & partial probabilities of final states



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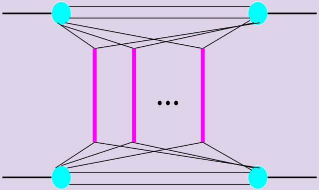

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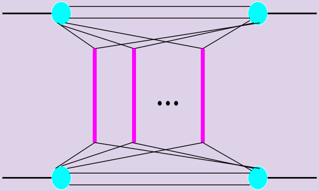


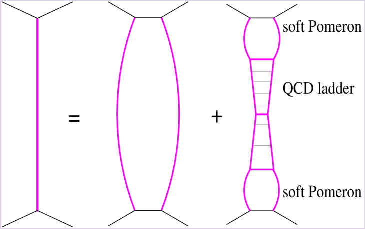
- particle production: hadronization of quark-gluon strings

QGSJET(-II): Reggeon Field Theory (RFT) approach

Hard processes: via 'semihard Pomeron' approach *[Drescher, Hladik, SO, Pierog & Werner, Phys. Rep. 350 (2001) 93]*

- soft Pomerons to describe soft (parts of) cascades $(p_t^2 < Q_0^2)$
  - $\Rightarrow$ transverse expansion governed by the Pomeron slope
- DGLAP for hard cascades
- taken together: 'general Pomeron'

$$\chi_{pp}^{\rm tot}(s,b,Q_0^2) = \chi_{pp}^{\mathbb{P}_{\rm soft}}(s,b) + \chi_{pp}^{\mathbb{P}_{\rm semihard}}(s,b,Q_0^2)$$



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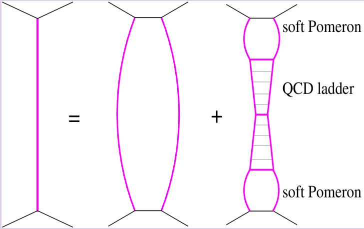

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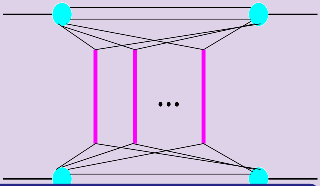
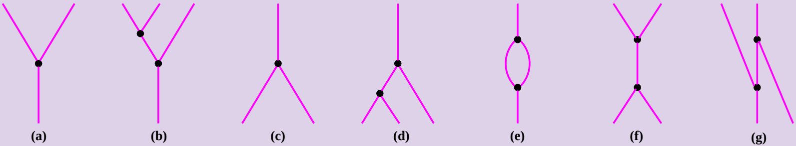


In QGSJET-II: Pomeron-Pomeron interactions (scattering of intermediate partons off the proj./target hadrons & off each other)



thick lines = Pomerons = 'elementary' parton cascades

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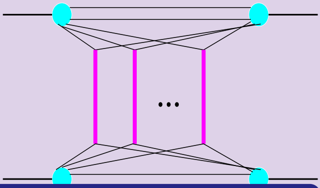

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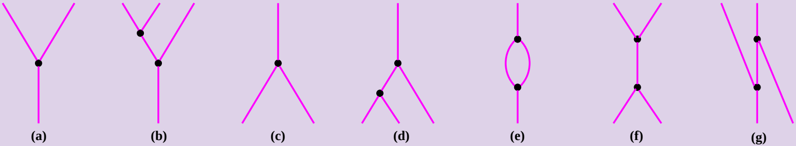

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- contributions resummed to all orders (sign-altering series)

Charm production in QGSJET: purely phenomenological

Charm included at the hadronization step: fragmentation of strings

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  - fragmentation of the hadron 'remnant' (spectator partons): kind of 'intrinsic charm'

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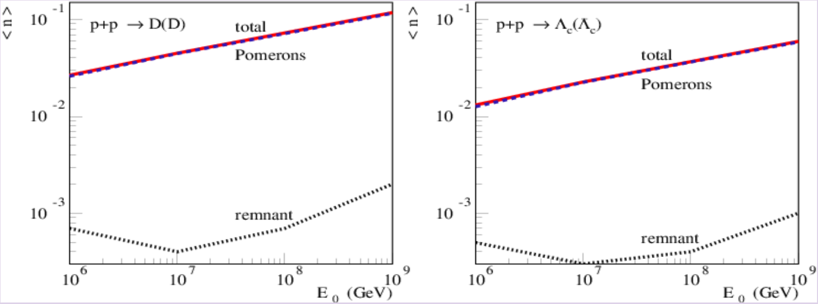
- acceptable agreement with data (see e.g. comparisons by Goswami, 2007)

Energy-dependence of moments for charm production

Multiplicity of $D, \bar{D}$ & Λ_c: quickly rising with energy



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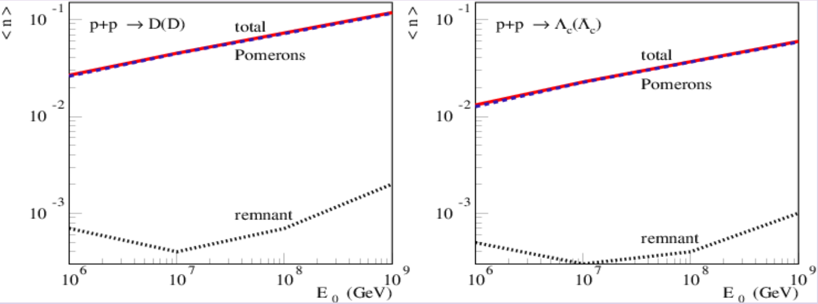

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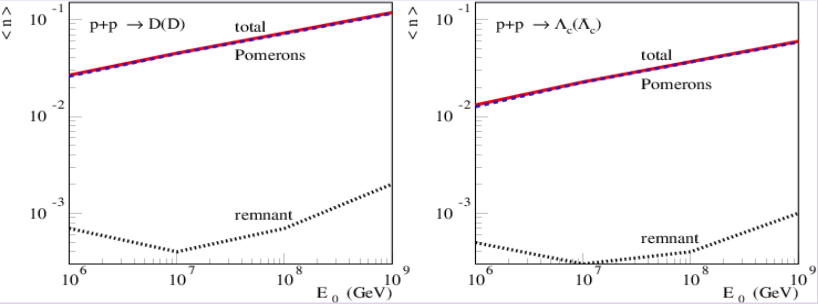

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- NB: 'remnant' contribution at sub-percent level
  - consistent with present limits on IC
  - sufficient to describe exp. data (e.g. Λ_c-asymmetry)

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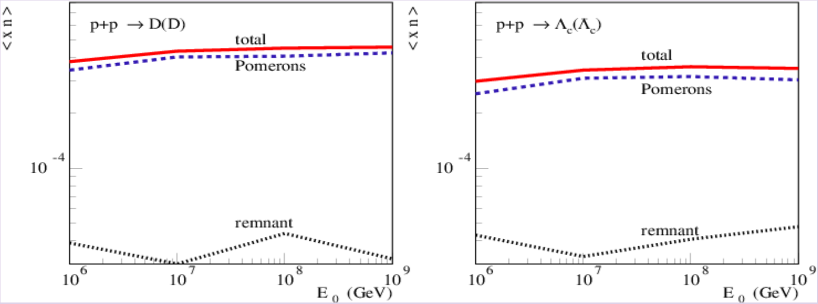
Energy fraction in $D, \bar{D}$ & Λ_c: nearly energy-independent



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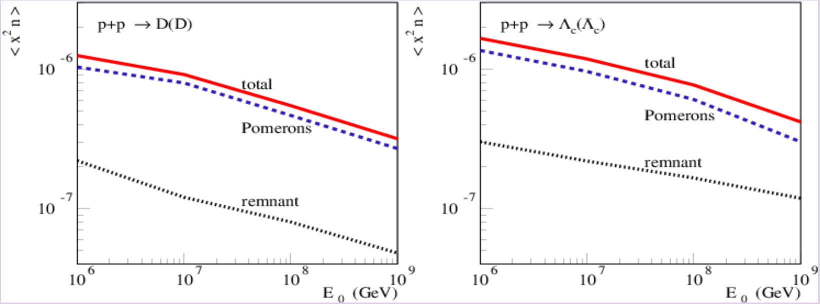
Energy-dependence of moments for charm production

Squared energy fraction in $D, \bar{D}$ & Λ_c: nearly energy-independent



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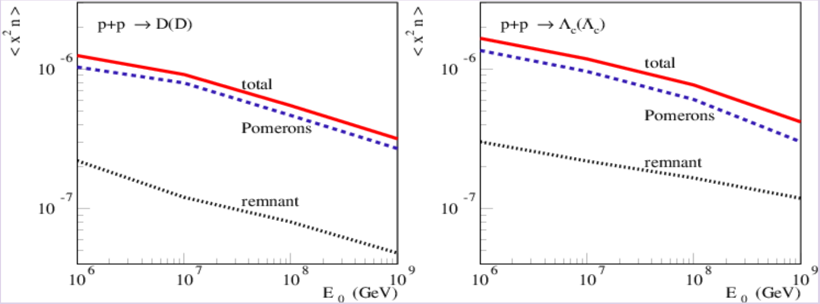

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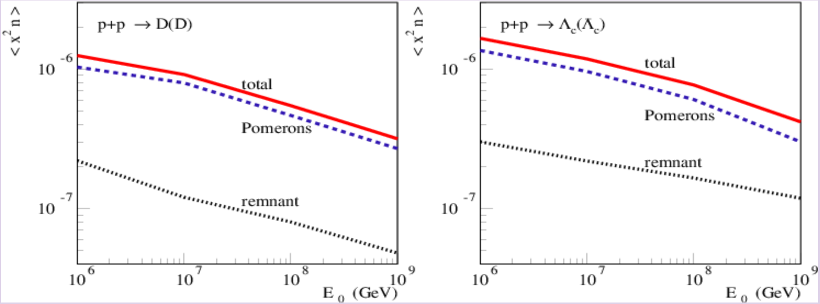
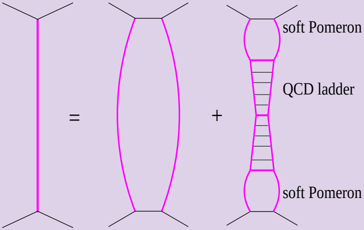


- directly projects itself into ν-fluxes
- energy-decrease: feature/drawback of a particular phenomenological treament
- main lesson: describing overall yield of charm & fixed target data doesn't warranty valid predictions

Charm production in QGSJET-II (in progress)

Perturbative contribution: relatively transparent

- $gg \to c\bar{c}$ matrix element for hard process
- plus fragmentation contribution: $g \to c\bar{c}$ in the (perturbative) final state cascades



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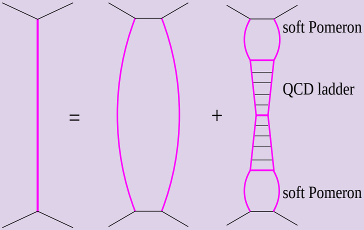
- caveat: energy-momentum sharing for multiple scattering distorts forward spectra



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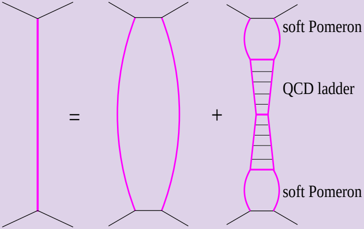


- caveat: energy-momentum sharing for multiple scattering distorts forward spectra

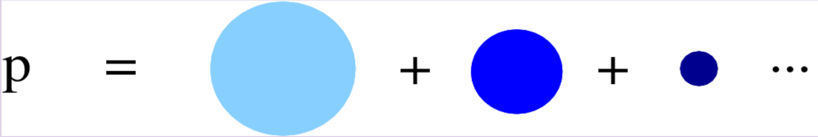
How to constrain intrinsic charm?

- possibly: correlations with forward production of other hadrons

Charm production in QGSJET-II (in progress)

Color fluctuations approach [Frankfurt et al., 2008]

- proton = superposition of many multi-parton Fock states: $|p\rangle = \sum_i \sqrt{C_i}\,|i\rangle$



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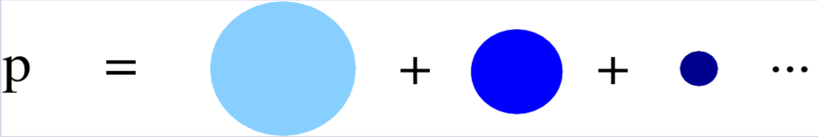

- characteristic parton virtuality $\langle q^2\rangle$: $\propto 1/R^2$

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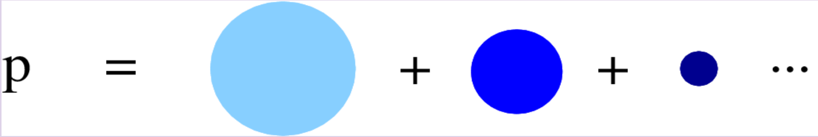

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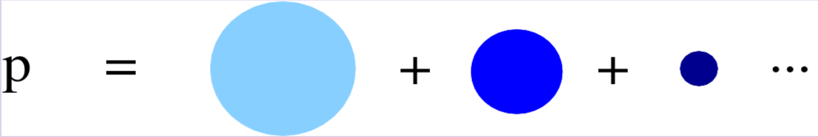

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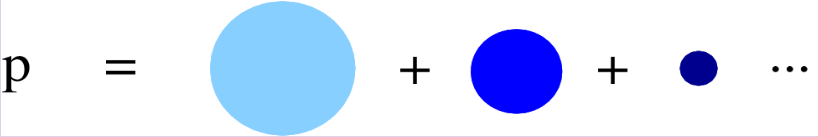

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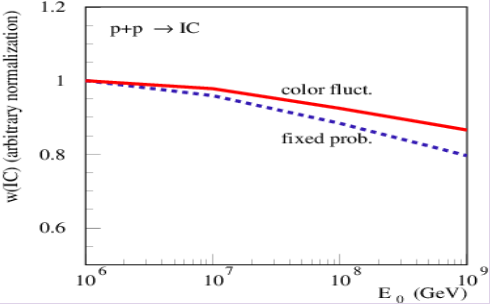
- $\Rightarrow$ Pomeron coupling: $\propto R^2$
- IC probability: $\propto m_c^2/\langle q^2 \rangle \propto 1/R^2$

Charm production in QGSJET-II (in progress)

Energy-dependence of IC in pp (arbitrary normalization)



- flatter dependence
- stronger effect expected due to energy-distribution (still in progress)