Hard processes at NICA: cross sections, spectra and spin effects

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8-10 June 2021
JINR, Dubna

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Outline

Hard processes at SPD NICA

Charmonium production: η_c, J/ψ, $\psi(2S)$, χ_{cJ}

at $0 \leq p_T \leq 4$ GeV and $|y| < 3$

$D-$meson production at $0 \leq p_T \leq 4$ GeV and $|y| < 3$

Prompt photon production at $3 \leq p_T \leq 6$ GeV and $|y| < 3$

All these processes are originated dominantly from gluon-gluon fusion or gluon-quark scattering

$$g + g \to c + \bar{c}, \quad c \to D$$

$$g + g \to c + \bar{c} + g, \quad c\bar{c} \to J/\psi$$

$$q + g \to q + \gamma$$

SPD gluon program: study collinear and TMD gluon PDFs, gluon spin structure functions, ...

Factorization for hard processes: Collinear Parton Model, TMD-factorization, HEF

Collinear Parton Model

$$\sigma(pp \to hX) = \sum_{i,j=g,q,\bar{q}} \int dx_1 \int dx_2 f_i(x_1, \mu^2) f_j(x_2, \mu^2) \hat{\sigma}^{CPM}(ij \to hk, x_1 x_2 s)$$

$$q_1^\mu = x_1 P_1^\mu, \quad q_{1T} = 0, q_1^2 = 0$$

TMD-factorization (CSS model)

$$\sigma(pp \to hX) = \sum_{i,j=g,q,\bar{q}} \int dx_1 \int dx_2 F_i(x_1, \vec{q}_{1T}, \mu^2, \zeta_1) \times$$

$$\times F_j(x_2, \vec{q}_{2T}, \mu^2, \zeta_2) \hat{\sigma}^{TMD}(ij \to hk, x_1 x_2 s)$$

$$q_1^\mu = x_1 P_1^\mu + y_1 P_2^\mu + q_{1T}^\mu, \quad q_{1T}^\mu \neq 0, \quad q_1^2 = 0$$

Factorization for hard processes: Collinear Parton Model, TMD-factorization, HEF

SPD NICA kinematical conditions for $c-$quark production processes

$$p_T \leq 3-4\ \text{GeV}, \quad \mu \simeq m_h(m_D, m_\psi, ..)$$

Collinear Parton Model works well at $p_T \geq \mu$, it has divergence at $p_T \to 0$

The CSS model (TMD) is applicable when $p_T \ll \mu$.

For most future data $p_T \sim \mu$, where predictive power of CPM and CSS is under the question

- To use Generalized Parton Model, $F(x, \vec{q}_T, \mu) = f(x, \mu) \times G(\vec{q}_T)$
- To use CPM (in LO+NLO+..) with cut $p_T > p_{T,min} \approx 2-3$ GeV
- To use an approach which smoothly interpolates between regions $p_T << \mu$ and $p_T > \mu$

Factorization for hard processes: Collinear Parton Model, TMD-factorization, HEF

Parton Reggeization Approach is based on HEF and smoothly interpolate between regions $p_T << \mu$ and $p_T \geq \mu$

$$\sigma(pp \to hX) = \sum_{i,j=g,q,\bar{q}} \int dx_1 \int dx_2 \Phi_i(x_1, \vec{q}_{1T}, \mu^2) \times$$

$$\times \Phi_j(x_2, \vec{q}_{2T}, \mu^2) \hat{\sigma}^{PRA}(ij \to hk, x_1 x_2 s)$$

$$q_1^\mu = x_1 P1^\mu + q_{1T}^\mu, \quad q_{1T} \neq 0, \quad q_1^2 = q_{1T}^2 = -\vec{q}_T^{\,2}$$

For details see following publications:

- M. Nefedov, “Sudakov resummation from BFKL,” [arXiv:2105.13915 [hep-ph]].
- M. A. Nefedov and V. A. Saleev, “High-Energy Factorization for Drell-Yan process in pp and $p\bar{p}$ collisions with new Unintegrated PDFs,” Phys. Rev. D **102** (2020), 114018
- A. V. Karpishkov, M. A. Nefedov and V. A. Saleev, “$B\bar{B}$ angular correlations at the LHC in parton Reggeization approach merged with higher-order matrix elements,” Phys. Rev. D **96** (2017) no.9, 096019

Charmonium production

Non Relativistic Quantum Chromodynamics (NRQCD)

- **NRQCD-factorization:** *Different L, S and* **color** *states of $Q\bar{Q}$-pair hadronize to X with different "probability"* – **long-distance matrix element (LDME):** $\left\langle \mathcal{O}^X \left[{}^{2S+1}L_J^{(\mathrm{color})} \right] \right\rangle$.
- LDME-s of states different from CSM-state are suppressed by powers of v^2 (~ 0.3 for J/ψ, ~ 0.1 for Υ) – *velocity-scaling rules for LDMEs*. E.g. for J/ψ and $\psi(2S)$: CSM$={}^3S_1^{(1)} = O(1)$ and ${}^3P_J^{(8)} = O(v^2)$ and ${}^3S_1^{(8)}$, ${}^1S_0^{(8)}$, contribute at $O(v^4)$.

Charmonium production

Color Evaporation Model (CEM)

- In **Improved-Color-Evaporation Model:** *all $Q\bar{Q}$ states with $M_X < M_{Q\bar{Q}} < 2M_{(\text{open flav. Q-meson})}$ hadronize to quarkonium X with the same probability –* F_X
- Optionally [Ma, Vogt, 2016] ICEM takes into account kinematic (soft-gluon recoil) corrections from the difference of masses $M_{Q\bar{Q}}$ and M_X using simple relation $p_T(X) = p_T(Q\bar{Q}) \times M_X/M_{Q\bar{Q}}$.
- ICEM can be viewed as NRQCD-factorization without velocity-scaling rules for probabilities F_X.

Both models are well-defined to all orders in α_s, but NRQCD-factorization is viewed as more “rigorous” approach by the community.

Charmonium production

Predictions for prompt J/ψ transverse momentum spectra

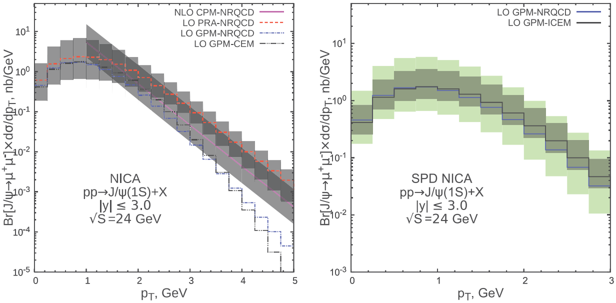


Figure 8 : Prompt J/ψ transverse momentum distribution at $\sqrt{s} = 24$ GeV, $|y| \leq 3$. Left panel: GPM results with $\langle q_T^2 \rangle = 1$ GeV^2 are shown by dash-dotted (NRQCD) and dash-double-dotted (ICEM) histograms. Solid and dashed histograms with uncertainty bands are PRA [A.V. Karpishkov, M.A. Nefedov and V.A. Saleev, J. Phys. Conf. Ser. **1435**, 012015 (2020)] and NLO CPM [M. Butenschön and B.A. Kniehl, private communication] predictions respectively. Right panel: GPM predictions in NRQCD (solid histogram with light green uncertainty band) and ICEM (dashed histogram with dark-green uncertainty band) approaches with their uncertainty bands shown.

Charmonium production

Predictions for prompt J/ψ transverse momentum spectra

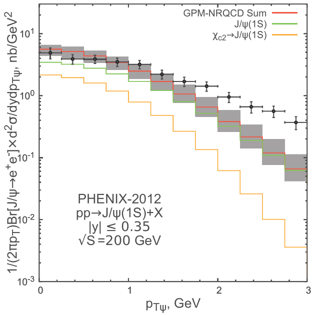
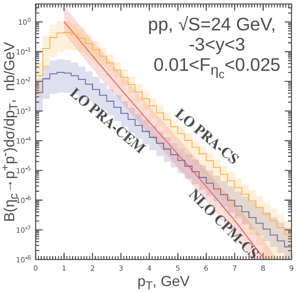


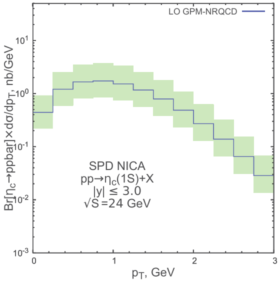
Figure 4 : Differential cross-section of prompt J/ψ production as function of transverse momentum at $\sqrt{s} = 200$ GeV, $|y| \leq 0.35$. The theoretical results are obtained in GPM with $\langle q_T^2 \rangle = 1$ GeV^2. Left panel: NRQCD-factorization prediction with only color-singlet channels included. Right panel: ICEM-prediction. In the left panel, non-zero contributions from decays $\chi_{c0} \to J/\psi$ and $\psi(2S) \to J/\psi$ are not shown. Experimental data are from the Ref. [A. Adare *et al.* [PHENIX], Phys. Rev. D **85**, 092004 (2012)].

Charmonium production

Predictions for η_c transverse momentum spectra

Predictions in NLO CPM CSM[Kniehl, Butenshön], LO PRA ICEM and LO PRA CSM shown in the left plot. Right plot – LO GPM CSM (with $\langle k_T \rangle = 1$ GeV). Cross-section$\times B(\eta_c \to p\bar{p})$:



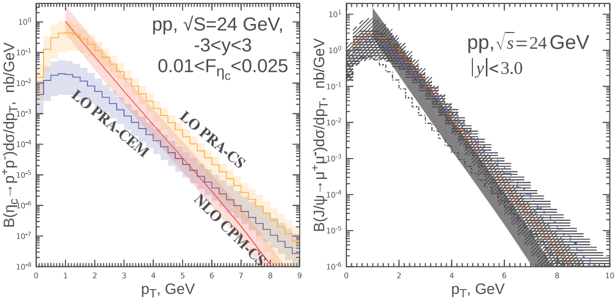


LO PRA CSM: $\sigma \times B(\eta_c \to p\bar{p}) = 0.61^{+0.76}_{-0.43}$ nb.

Charmonium production

Predictions for η_c transverse momentum spectra

Predictions in NLO CPM CSM[Kniehl, Butenshön], LO PRA ICEM and LO PRA CSM shown in the left plot. Cross-section$\times B(\eta_c \to p\bar{p})$:



Cross section is ~ 0.1 compared with the $J/\psi \times B(J/\psi \to \mu^+\mu^-)$.

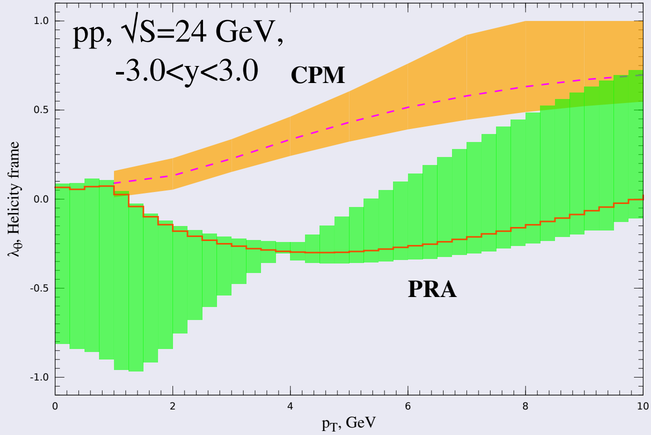
Charmonium production

Production of η_c as golden probe for gluon structure

- Any measurement of η_c production, even with large errors, is useful for development of heavy-quarkonium production theory
- If CS-model is valid (all existing data support this conclusion), η_c is the golden probe for proton structure. Couples to gluons, TMD-factorization is valid. One can study spin-asymmetries etc.

Charmonium production

J/ψ polarization in unpolarized pp-collisions



Transverse Single Spin Asymmetry (TSSA) in Charmonium production

$p^{\uparrow}p \to \mathcal{C}X$ $\mathcal{C} = J/\psi, \chi_c, \psi(2S), \eta_c$

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{d\Delta\sigma}{2d\sigma}.$$

The numerator and denominator of A_N have the form:

$$d\sigma \propto \int dx_1 \int d^2q_{1T} \int dx_2 \int d^2q_{2T} F_g(x_1, q_{1T}, \mu_F) F_g(x_2, q_{2T}, \mu_F) d\hat{\sigma}(gg \to \mathcal{C}X),$$

$$d\Delta\sigma \propto \int dx_1 \int d^2q_{1T} \int dx_2 \int d^2q_{2T} [\hat{F}_g^{\uparrow}(x_1, \mathbf{q}_{1T}, \mu_F) - \hat{F}_g^{\downarrow}(x_1, \mathbf{q}_{1T}, \mu_F)] \times F_g(x_2, q_{2T}, \mu_F) d\hat{\sigma}(gg \to \mathcal{C}X), \quad (1)$$

where $\hat{F}_g^{\uparrow,\downarrow}(x, q_T, \mu_F)$ is the distribution of unpolarized gluon (or quark) in polarized proton.
The gluon Sivers function (GSF) can be introduced as

$$\Delta\hat{F}_g^{\uparrow}(x_1, \mathbf{q}_{1T}, \mu_F) \equiv \hat{F}_g^{(\uparrow)}(x_1, \mathbf{q}_{1T}, \mu_F) - \hat{F}_g^{(\downarrow)}(x_1, \mathbf{q}_{1T}, \mu_F) \quad (2)$$

Transverse Single Spin Asymmetry (TSSA) in Charmonium production

CGI-GPM approach [L. Gamberg and Z. B. Kang, Phys. Lett. B 696, 109 (2011)]

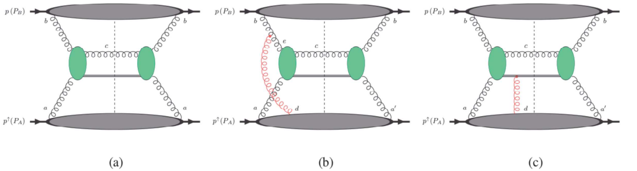


Figure 2 : LO diagrams for the process $p^\uparrow p \to J/\psi X$, assuming a color-singlet production mechanism, within the GPM (a) and the CGI-GPM (b), (c). It turns out that only initial state interactions depicted in (b) contribute to the SSA. Figure is from [D'Alesio *et.al.*, Phys. Rev. D **96**, 036011 (2017)].

Transverse Single Spin Asymmetry (TSSA) in Charmonium production

$A_N^{J/\psi}(x_F)$, prompt J/ψ

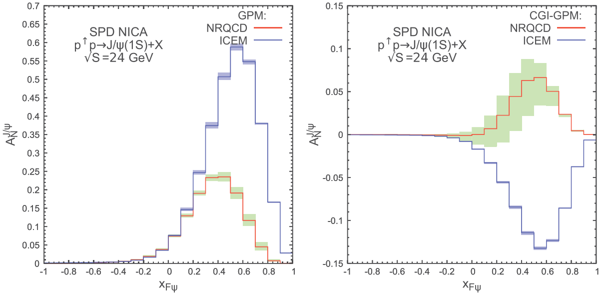


Figure 11 : Comparison of predictions for SSA $A_N^{J/\psi}$ as function of x_F at $\sqrt{s} = 24$ GeV in NRQCD (solid histogram) and ICEM (dashed histogram) approaches. Left panel: GPM-prediction. Right panel: CGI-GPM-prediction. The SIDIS1 parametrisation of GSFs is used.

Transverse Single Spin Asymmetry (TSSA) in charmonium production

$A_N^{J/\psi}(p_T)$, prompt J/ψ

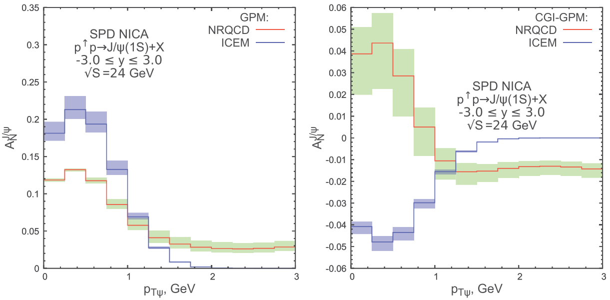


Figure 12 : Comparison of predictions for SSA $A_N^{J/\psi}$ as function of p_T at $\sqrt{s} = 24$ GeV in NRQCD (solid histogram) and ICEM (dashed histogram) approaches. Left panel: GPM-prediction. Right panel: CGI-GPM-prediction. The SIDIS1 parametrisation of GSFs is used.

Longitudinal double-spin asymmetries in charmonium production

$A_{LL}^{J/\psi}(p_T)$, prompt J/ψ

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Delta\sigma}{\sigma},$$

Collinear Parton Model + NRQCD-factorization:

$$\Delta\sigma = \sum_n \langle \mathcal{O}^X[n] \rangle \sum_{i,j} \Delta f_i \otimes \Delta f_j \otimes \Delta\hat{\sigma}_{ij}[n],$$

$$\sigma = \sum_n \langle \mathcal{O}^X[n] \rangle \sum_{i,j} f_i \otimes f_j \otimes \hat{\sigma}_{ij}[n].$$

Possible observables:

- p_T**-dependent** (and y-dependent) asymmetry:
  - $2 \to 2$: $\boxed{i + j \to c\bar{c}[n] + k}$ processes at LO $\Rightarrow$ **NLO-complicated**
  - scale $\mu \sim \sqrt{M^2 + p_T^2}$, CPM valid for $p_T > M$
- p_T**-integrated**, y-dependent asymmetry
  - $2 \to 1$: $\boxed{i + j \to c\bar{c}[n]}$ processes at LO $\Rightarrow$ **NLO-simple** (but not done yet...)
  - scale $\mu \sim M$

Longitudinal double-spin asymmetries in charmonium production

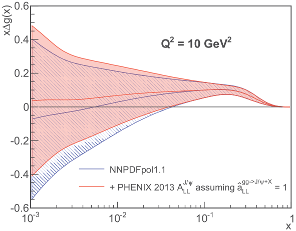
$A_{LL}^{J/\psi}(p_T)$. Some references

- Un-polarized partonic cross-sections $\hat{\sigma}_{ij}[n]$ are well-known at LO.
- p_T**-dependent** asymmetry first studied at LO in [Teryaev, Tkabladze, Phys.Rev.D 56 (1997) 7331-7340], but expressions for $\Delta\hat{\sigma}_{ij}[n]$ are not given
- LO results for $\Delta\hat{\sigma}_{ij}[n]$ are written in [Klasen, Kniehl, Steinhauser, Phys.Rev.D **68** (2003) 034017, hep-ph/0306080], however I have some issues with this results, they need to be checked. In the present analysis **only gluon-gluon channels** are included, which I have reproduced.
- p_T**-dependent** asymmetry was studied at NLO in [Feng, Zhang, JHEP **11** (2018) 136]
- p_T**-integrated** asymmetry first studied in [Gupta, Mathews, Phys.Rev.D **55** (1997) 7144-7151]
- NLO results for **un-polarized** p_T**-integrated** partonic cross-sections had been obtained in closed form in [Petrelli, Cacciari, Greco, Maltoni, Mangano, Nucl.Phys.B **514** (1998) 245-309]

Longitudinal double-spin asymmetries in charmonium production

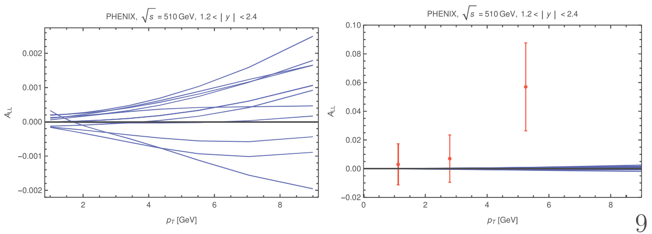
Validation: PHENIX data. Plot from hep-ex/1606.01815

LO LDMEs from [Braaten, Kniehl, Lee, Phys.Rev.D**62** (2000) 094005] together with NNPDF30_nlo_as_0119_nf_6 PDF set and NNPDFpol11_100 polarized PDF set.



Longitudinal double-spin asymmetries in charmonium production

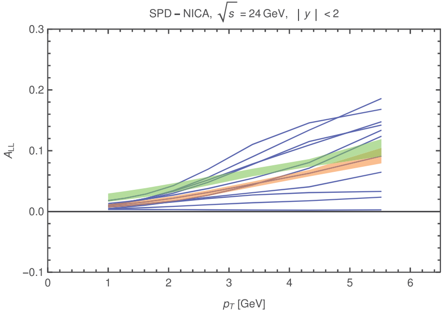
Validation: PHENIX data.



Longitudinal double-spin asymmetries in charmonium production

$A_{LL}^{J/\psi}$ for ten replicas of Δg, bands scale and LDME-variation

A_{LL} for ten replicas of Δg, bands – scale and LDME-variation :



Longitudinal double-spin asymmetries in charmonium production

$A_{LL}^{J/\psi}(p_T)$. Outlook.

- A_{LL} up to 10% for J/ψ at NICA is consistent with latest NNPDF parametrization for Δg
- At LO, LDME and scale uncertainties look small, but this may be misleading
- Estimates in color-evaporation model should be done
- LDME sets predicting different polarization of quarkonium at high-p_T lead to significantly different asymmetry at RHIC. Impact for NICA is not clear...
- if color-singlet model for η_c is correct, then there is no LDME-set problem for this state!

$D-$meson production at SPD NICA

Massive scheme ($m_c = 1.2 - 1.5$ GeV) with nonperturbative fragmentation function $D_{c\to D}(z)$ or $D_{c\to D}(z, \vec{q}_T, \mu^2)$

$$z = \frac{E_D + p_D}{E_c + p_c}$$

$D-$meson cross sections at SPD NICA

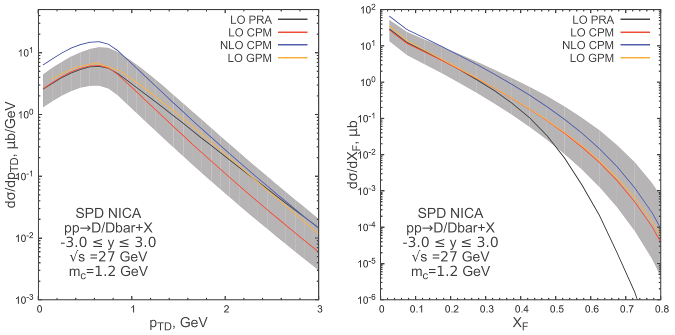


Figure 4 : Predictions for differential cross sections $d\sigma/dp_T$ and $d\sigma/dx_F$ on SPD

$D-$meson production at SPD NICA

$A_N^D(p_T)$

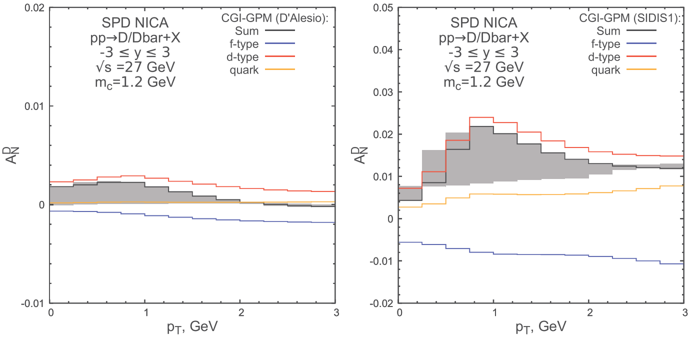


Figure 6 : Predictions for SSA on SPD NICA as function of p_T within the CGI-GPM and parametrizations of D'Alesio (*et. al.*) (left) and SIDIS1 (right). Phenomenological fragmentation function of Peterson with $\epsilon = 0.06$ and $N = f(c \to D^0) + f(c \to D^+) + f(c \to D_s^+) = 0.859$ is used.

$D-$meson production at SPD NICA

$A_N^D(x_F)$

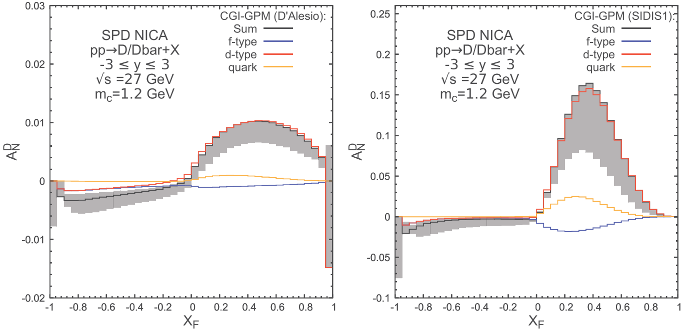


Figure 7 : Predictions for SSA on SPD NICA as function of x_F within the CGI-GPM and parametrizations of D'Alesio (*et. al.*) (left) and SIDIS1 (right). Phenomenological fragmentation function of Peterson with $\epsilon = 0.06$ and $N = f(c \to D^0) + f(c \to D^+) + f(c \to D_s^+) = 0.859$ is used.

Prompt photon production

Prompt = Direct + Fragmentation or "Isolated photons" could be better ?

It is well known that at high energies and large photon p_T so called Isolation Criteria (ISO) can be used:

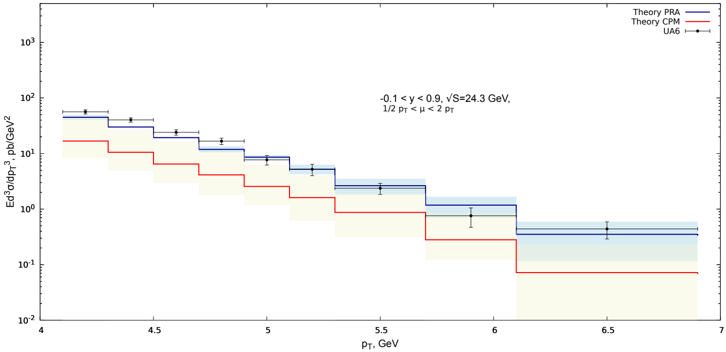
$$r = \sqrt{\Delta\phi^2 + \Delta y^2} > R$$

At first, ISO with $R = 0.4$ and $E_{ISO} = 10$ GeV (for LHC data with $p_T \geq 50$ GeV, strongly suppress fragmentation contribution for isolated photon production.
At second, ISO with Frixione receipt ("Frixione cone condition") help to estimate fragmentation contribution without knowledge on $D_{q\to\gamma}(z,\mu)$. It makes HO calculations more simple

My question for experimentalists: "*Is it possible to formulate Isolation Criteria for photon with* $p_T = 3-6$ *GeV ?* "

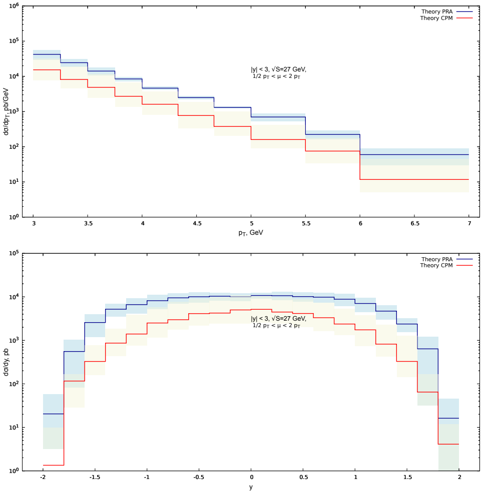
Prompt photon production

Transverse momentum spectrum in LO CPM and in PRA (it is coincide with NLO*).
Data from UA6 Collaboration (1987).



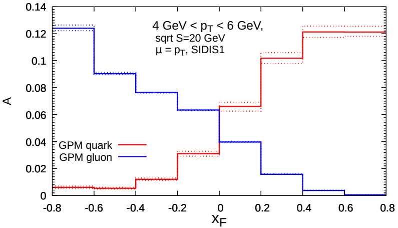
Prompt photon production

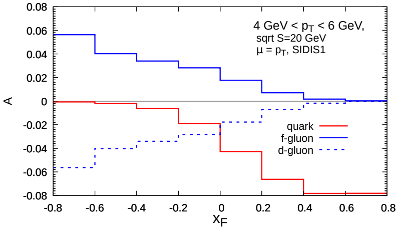
Prediction for SPD NICA, LO CPM and PRA (NLO*)



Prompt photon production, TSSA

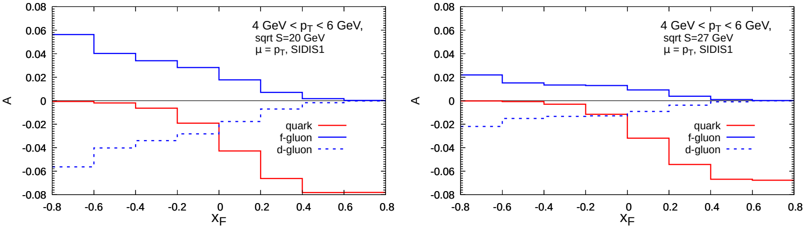
$A_N^\gamma(x_F)$, GPM versus CGI-GPM





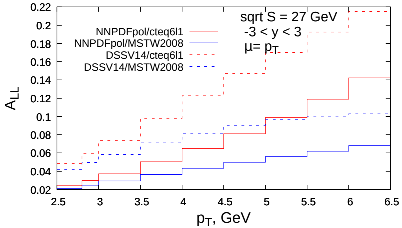
Prompt photon production, TSSA

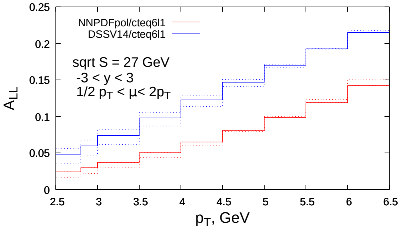
$A_N^\gamma(x_F)$, CGI-GPM, at $\sqrt{s} = 20$ and $\sqrt{s} = 27$ GeV



Prompt photon production, A_{LL}

$A^{\gamma}_{LL}(x_F)$,





Future plans

1. Charmonium production
    - $p + p \to J/\psi + \gamma$: test of NRQCD and CEM, azimuthal correlations, ...
    - Polarized J/ψ production in polarized proton collisions
    - A_N, A_{LL} in η_c production
2. $D-$meson production
    - $D\bar{D}$ azimuthal correlation
    - Large p_T production for study $g_p(x, \mu^2)$ at large x at NLO CPM and PRA
    - A_{LL} in $D-$meson production
3. Prompt photon production
    - Prompt photon production at large p_T in NLO CPM
    - Estimation for $\gamma\gamma$ production
4. **All suggestions are welcome !**