MC generator KaTie[1] for modeling of hard processes at the NICA

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Almaty

[1]A. Van Hameren, «KaTie: For parton–level event generation with k_T–dependent initial states», Comput.Phys.Commun 224 (2018);

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Outline

Introduction

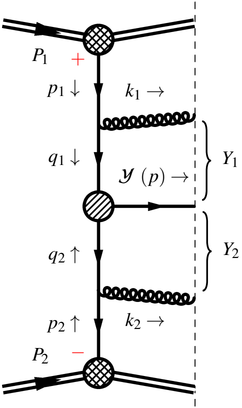
Gluon probes at NICA SPD:

- ***Different charmonia states production:*** $\eta_c[1S]$, $\psi[1S]$ (J/ψ), $\psi[2S]$.
  - Description of hadronization of $c\bar{c}$ pair is based on *phenomenological models: CSM, NRQCD, (I)CEM*;
  - Event generators:
    - `Pythia 6.,8.` ←-- *parton showers;*
    - `MadGraph5_aMC@NLO`[Alwall et.al. '14] ←-- *parton level* + *matching with parton showers;*
    - ...
- ***Open charm production:*** $D^0/\bar{D}^0$.
  - Usually description of hadronization of $c \to D^0/\bar{D}^0$ is based on *fragmentation mechanism*;
  - Calculations can be included in any pQCD event generator.
- ***Prompt photons:***
  - Fully perturbative process at parton level;
  - Event generators:
    - `Pythia 6.,8.` ←-- *parton showers;*
    - `Sherpa`[Gleisberg et.al. '09] ←-- *parton showers*;
    - `Jetphox`[Catani et.al. '02] ←-- *parton level*;
    - ...

- All of this generators use the ***collinear factorization approximation*** $\mu_F \sim p_T \gg \Lambda$.
- At the NICA kinematical range ***we plan to study TMD PDF's***.

Factorization approaches[3]

There are 3 **conventional factorization approaches** (in any case: $q_1^+ \gg q_1^-$ and $q_2^- \gg q_2^+$)**:**



- *Collinear Parton Model (CPM):* $|\mathbf{q}_{T_i}| \ll \mu$

$$d\sigma_{\rm CPM} = \left[f(x_1,\mu^2)\times f(x_2,\mu^2)\right]\otimes d\hat{\sigma}_{\rm CPM} + \mathcal{O}\left(\Lambda^2/\mu^2\right),$$

where $f(x_i,\mu^2)$ is *integrated over* $|\mathbf{q}_{T_i}|$ *(collinear) PDF's* ←-- ***DGLAP***;

- *Transverse Momentum Dependent (TMD)*[Collins '11]: $|\mathbf{q}_{T_i}| \ll \mu$

$$d\sigma_{\rm TMD} = \left[F(x_1,\mathbf{q}_{T_1},\mu^2,\mu_Y^2)\times F(x_2,\mathbf{q}_{T_2},\mu^2,\mu_Y^2)\right]\delta^{(2)}\left(\mathbf{q}_{T_1}+\mathbf{q}_{T_2}-\mathbf{p}_T\right)$$
$$\otimes d\hat{\sigma}_{\rm CPM} + \mathcal{O}\left(\Lambda^2/\mu^2, \mathbf{p}_T^2/\mu^2\right),$$

where $F(x_i,\mathbf{q}_{T_i},\mu^2,\mu_Y^2)$ is *TMD PDF's* ←-- ***Collins–Soper eq.***;

(See K. Shilyaev talk)

- *High Energy Factorization (HEF)*
a.k.a. k_T*–factorization*[Gribov et.al. '83; Catani et.al. '91]: $|\mathbf{q}_{T_i}| \sim \mu$ and $Y_i \gg 1$

$$d\sigma_{\rm HEF} = \left[\Phi(x_1,\mathbf{q}_{T_1},\mu^2)\times\Phi(x_2,\mathbf{q}_{T_2},\mu^2)\right]\otimes d\hat{\sigma}_{\rm HEF} + \mathcal{O}\left(\Lambda^2/\mu^2, \mu^2/s\right),$$

where $\Phi(x_i,\mathbf{q}_{T_i},\mu^2)$ is *unintegrated PDF's (uPDF's)* ←-- ***models***. **TMD ≠ HEF**

[3] We use *Sudakov notation* $\forall p:\ p = \left(p^+ n_- + p^- n_+\right)/2 + p_T$, so $y(p) = (1/2)\ln\left(p^+/p^-\right)$.

uPDF's

The uPDF's must include DGLAP evolution and small x effects:

PRA = Reggezied amplitudes + mKMRW uPDF's

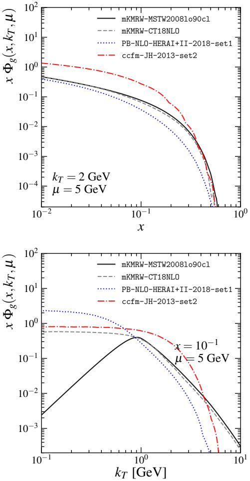
- We use uPDF's calculated in **modified Kimber–Martin–Ryskin–Watt model**[Nefedov, Saleev '20; KMR '01; MRW '03]:
  - `mKMRW-MSTW2008lo90cl` ←-- LO collinear input;
  - `mKMRW-CT18NLO` ←-- NLO collinear input;
  - Normalization condition holds exactly:

$$\int^{\mu^2} d\mathbf{q}_T^2\, \Phi(x,\mathbf{q}_T,\mu^2) = x f(x,\mu^2), \quad \forall x, |\mathbf{q}_T|$$

  - In the region $|\mathbf{q}_T| \ll \mu_F$:

$$\Phi(x,\mathbf{q}_T,\mu^2) \simeq F(x,q_T,\mu_F^2,\mu_Y^2=\mu_F^2) \to \mathbf{PRA} \simeq \mathbf{TMD} + O\left(\frac{\mathbf{p}_T^2}{\mu^2}\right)$$

- A large number (~ 30) of different uPDF's are collected in `TMDlib 2.x`[Jung et.al. '21]:
  - `PB-NLO-HERAI+II-2018-set1` ←-- Particle Branching method;
  - `ccfm-JH-2013-set2` ←-- Monte–Carlo CCFM equation solution.



KaTie overview

The main aspects of KaTie[Hameren '18]: **(see manual for details)**

- KaTie is a **parton level** event generator, i.e. without *parton showers*;
- On–shell initial states $|\mathbf{q}_T| \ll \mu$ ⇢ $f(x,\mu^2)$–standard tree–level CPM calculations:
  - Collinear PDF sets from LHAPDF[Buckley et.al. '14];
- Initial states can be off–shell $q^2 = -\mathbf{q}_T^2$ ⇢ $\Phi(x,\mathbf{q}_T,\mu^2)$ or $\Phi(x,\mathbf{q}_T)$–HEF calculations;
  - **uPDF's** from TMDlib 2.x[Jung et.al. '21] or **user grids with format**:

$$\ln(x) \quad \ln(|\mathbf{q}_T^2|) \quad x\Phi(x,|\mathbf{k}_T|) \qquad \text{or} \qquad \ln(x) \quad \ln(|\mathbf{q}_T^2|) \quad \ln(\mu^2) \quad x\Phi(x,|\mathbf{k}_T|,\mu)$$

  - **At $p_T \ll \mu$ KaTie may be used for TMD calculations with TMD PDF's**, f.e. with *Generalized PM* PDF's:

$$F(x,|\mathbf{q}_T|,\mu^2) = f(x,\mu^2)\times G(|\mathbf{q}_T|), \qquad G(|\mathbf{q}_T|) = \frac{1}{\pi\langle\mathbf{q}_T^2\rangle}\exp\left[-\frac{\mathbf{q}_T^2}{\langle\mathbf{q}_T^2\rangle}\right]$$

- **Fully numerical** method for calculating **gauge–invariant** amplitudes up to order $\mathcal{O}(e^n g^m)$, $n+m \leq 4$ ⇠ spinor amplitudes formalism and off–shell BFCW recurrence relations[Hameren et.al. '13] numerically equivalent to the PRA amplitudes[Nefedov, Saleev, Shipilova '13];
- A good tools for working with kinematics:
  - A FORTRAN like syntax in input file;
  - extra_cuts.f90 for FORTRAN code blocks;
- Output files in LHE format ⇢ connection with multipurpose generators like Pythia

and many more . . .

I. Charmonia production

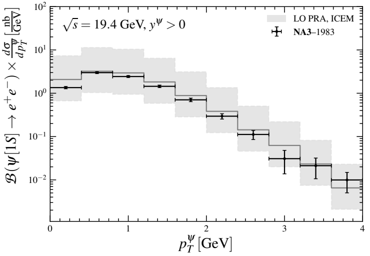
Improved Color Evaporation Model (ICEM)[Ma and Vogt '16]:

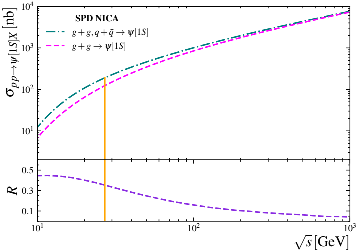
$$\frac{d\sigma_{\psi[1S]}}{d^3p} \simeq \mathcal{F}^{\psi} \times \int_{M_\psi}^{2M_D} dM\, d^3p'\, \delta^{(3)}\left(\mathbf{p} - \frac{M_\psi}{M}\mathbf{p}'\right) \frac{d\sigma_{c\bar{c}}}{dM\, d^3p'}$$

- Factor $\mathcal{F}^{\psi}$ is a *probability of hadronization*.

At NICA energies we obtained[A.C. and V. Saleev '22]:

$$R = \frac{\sigma_{q\bar{q}\to\psi[1S]X}}{\sigma_{gg\to\psi[1S]X} + \sigma_{q\bar{q}\to\psi[1S]X}} \simeq 30\%$$





`KaTie` **scheme:**

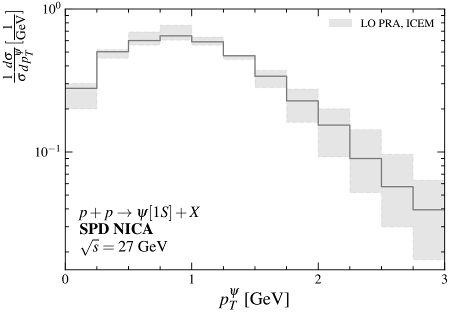
i. Calculate $c\bar{c}$ production with mass cut:

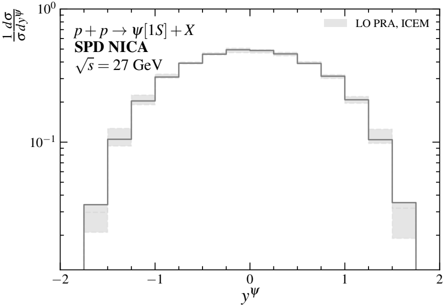
```
cut source = {mass|1+2|} < 3.74D0
cut source = {mass|1+2|} > 3.10D0
```

ii. Set transverse momentum cut:

```
cut source = if
((3.10D0/{mass|1+2|}*{pT|1+2|}).gt.4.0D0)
REJECT
```

Predictions for $\psi[1S]$ production at the SPD NICA





Also see talks by

- A. Karpishkov, *«Double longitudinal spin asymmetries in P–wave charmonium production at the NICA»*;
- K. Shilyaev, *«Small–p_T J/ψ production in the TMD parton model and NRQCD»*.

II. Open charm production (in this way we can also calculate fragmentation photons production)

Fragmentation approach:

$$\frac{d\sigma_D}{d^2 p_T^D\, dy^D} = \mathcal{D}(z) \otimes \frac{d\sigma_{c\bar{c}}}{d^2 p_T^c\, dy^c}, \quad z > z_{\rm cut} = \frac{M_D}{p_c^0 + |\mathbf{p}_c|},$$

we use *Peterson FF*:

$$\mathcal{D}(z) = \mathcal{N}\, \frac{z\,(1-z)^2}{[(1-z)^2 + \varepsilon\, z]^2}, \quad \int_0^1 dz\, \mathcal{D}_{c\to D}(z) = P_{c\to D},$$

with $\varepsilon = 0.06$, probabilities $P_{c\to D}$ from[Gladilin '99].

KaTie scheme:

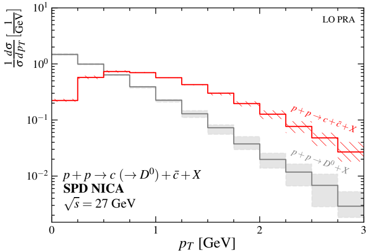
i. Calculate production of $c\bar{c}$ pair;

ii. Generate $z \leftarrow \mathcal{D}(z)$ or reweight events with $z \leftarrow \frac{1}{1-z_{\rm cut}}$:
$W_D = W_c \times P(c \to D) \times \mathcal{D}(z) \times (1 - z_{\rm cut})$;

iii. Apply *collinear massive fragmentation scheme*:

$$\frac{\mathbf{p}_c}{|\mathbf{p}_c|} = \frac{\mathbf{p}_D}{|\mathbf{p}_D|}, \qquad z = \frac{p_D^0 + |\mathbf{p}_D|}{p_c^0 + |\mathbf{p}_c|}.$$

Predictions for D^0 production at the SPD NICA



Also see

talk by A. Karpishkov at International Conefernce on Quantum Filed Theory, 21.07.2022, URL.

NLO* CPM calculations with KaTie

LO CPM $2 \to 2$: processes of order $\mathcal{O}(\alpha_S^2)$ are finite:

$$g + g \to c + \bar{c},$$
$$q + \bar{q} \to c + \bar{c}.$$

NLO* CPM $2 \to 3$: first α_S real correction of order $\mathcal{O}(\alpha_S^3)$:

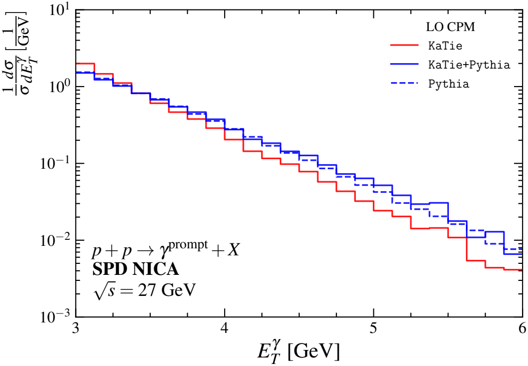
$$\left.\begin{array}{l} g + g \to c + \bar{c} + g \ (k'), \\ q + \bar{q} \to c + \bar{c} + g \ (k'), \\ g + q \to c + \bar{c} + q \ (k') \end{array}\right\} \quad \text{infrared diverge } |\mathbf{k}'_T| \to 0$$

Phenomenological cutoff at the lower limit and suppresion function:

$$\sigma_{ij \to c\bar{c}g}(\lambda) \sim \int_0^\infty d|\mathbf{k}'_T| \, F_{\text{sup}}(|\mathbf{k}'_T|; \lambda) \times \ldots, \qquad F_{\text{sup}}(|\mathbf{k}'_T|; \lambda) = \frac{|\mathbf{k}'_T|^4}{(|\mathbf{k}'_T|^2 + \lambda^2)^2}$$

- ***Suitable for describing data on charmonia production***[Cheung, Vogt '21]**;**
- ***Also can be applied to D mesons production***[Maciula, Szczurek '19]**.**

KaTie with parton showers from Pythia 8

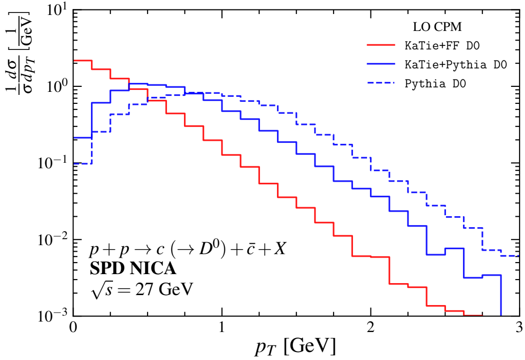


Pythia settings:

```
PartonLevel:ISR = on
PartonLevel:FSR = on
HadronLevel:Hadronize = on
HadronLevel:Decay = on

BeamRemnants:primordialKT = off
```

KaTie with parton showers from Pythia 8




```
Pythia settings:

PartonLevel:ISR = on
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HadronLevel:Hadronize = on
HadronLevel:Decay = on

BeamRemnants:primordialKT = off
```

Conclusions

- We have made a brief review of `KaTie` event generator;
- We have developed a scheme for calculating heavy quarkonia and D mesons production using `KaTie`;
- At the $p_T \ll \mu$ KaTie may be used for calculations in the TMD factorization;
- For the intermediate region $p_T \sim \mu$ we may use the PRA, which takes into account power corrections $\mathcal{O}\left(\mathbf{p}_T^2/\mu^2\right)$;
- **`KaTie` can be a powerful tool for calculating hard processes even at NICA energies**.

`KaTie` **can be found at** `Bitbucket/hameren/katie`

The efficiency of `KaTie` for calculating different hard processes at high energies was demonstrated in[A. van. Hameren et.al. '18–23] and some of our works[A. Chernyshev and V. Saleev '22–24].

A. Chernyshev and V. Saleev would like to thank A. van Hameren for helpful discussions on `KaTie` *program and H. Jung for help in* `TMDlib 2.x` *installation.*

Thank you for your attention!