**Template JRA**

|  |  |  |  |
| --- | --- | --- | --- |
| **Work package number** | WP22 | **Start date** | 01/06/2019 |
| **Activity Type** | Joint Research Activity | | |
| **Work package acronym** | JRA4-TMD-neXt | | |
| **Work package title** | 3D structure of the nucleon in momentum space | | |

1. Work carried out and overview of progress
   1. **Project objectives**

*[Please give an overview of the project objectives for the third reporting period (June 2022 – July 2024), with regard to the overall objectives as described in the Annex 1 of the Grant Agreement and summarized below.]*

The exploration of the internal structure of hadrons is one of the core missions of hadronic physics. TMD-neXt will join together a network of experimentalists and theorists with the aim of mapping the distributions of partons inside hadrons in momentum space, including their dependence on spin. The complete three-dimensional information on these distributions is encoded in Transverse-Momentum Dependent Parton-Distribution Functions (TMD PDFs). In experimental observables, they are often combined with Transverse-Momentum Dependent Fragmentation Functions(TMD FFs).

TMD-neXt will open the way to the next-generation extractions of Transverse-Momentum Distributions (TMDs).

In the envisaged four years’ running of the work package, TMD-neXt plans to:

- increase the amount of data available for TMD studies,

- test the validity and limits of applicability of the TMD framework,

- extract TMDs from available data,

- extend the formalism in particular to gluon-dominated processes.

* 1. **Progress made during the reporting period towards the objectives**

*[Please describe the progress made during the third reporting period in line with your Gantt chart and the project overall tasks as described in the Annex 1 of the Grant Agreement and summarized below.]*

***Table 1.2: Progress made during the reporting period towards objectives***

|  |
| --- |
| ***Task 1: Analysis of Drell-Yan (DY) data. The COMPASS collaboration will analyze unpolarized and polarized DY data,suitable for the study of unpolarized TMDs and the Sivers polarized TMD in the range 4 GeV < Q < 9 GeV. Of particular importance is the experimental verification of the sign-reversal property of the Sivers function in polarized Drell-Yan processes, which is a crucial test of the validity of TMD factorization.*** |
| * 1. COMPASS: The analysis of transverse spin asymmetries from 2015 and 2018 data taking in the dimuon high mass range (4.3 GeV/c2 - 8.5 GeV/c2) has been published (arxiv.org/abs/2312.17379). The Sivers asymmetry is found to be one standard deviation above zero, which is in agreement with the sign-change hypothesis.  Drell-Yan unpolarized cross sections have been measured in ammonia, aluminum and tungsten. Preliminary results were shown at SPIN 2023, 24-29 September 2023   2. CMS: The final analysis of DY transverse-momentum spectra measured by CMS was published in Eur.Phys.J.C 83 (2023) 7, 628. |
| ***Task 2: Analysis of semi-inclusive DIS data*** |
| 2.1) At COMPASS the analysis of unidentified hadrons off proton target is near to completion and preliminary results have been presented at international conferences. Progress has been achieved on the analysis of data with identified hadrons using the RICH detectors.  2.2) At COMPASS, the data taking with transversely polarized target has been performed in 2022 and results published in Phys.Rev.Lett. 133 (2024) 10, 101903.  2.3) At CLAS, the longitudinal polarized target has been installed and data was taken in 2022-2023. The analysis is in progress and preliminary data have been presented at conferences (see, e.g., <https://agenda.infn.it/event/38132/contributions/234391/>). Progress with the RICH detector have been documented in Nucl.Instrum.Meth.A 1057 (2023) 168758. |
| ***Task 3: Analysis of electron-positron data*** |
| 3.1) The analysis of Belle e+e− is slowly progressing. Most of the intermediate analysis steps have been cross-checked. A framework for tuning Pythia MC generator was developed and published, with the aim of reducing strong Pythia model dependence of systematics. |
| ***Task 4: Quark TMD extractions*** |
| The MAP22 extraction of pion TMDs from Drell-Yan data has been published (e-Print: 2210.01733 [hep-ph]).  The ART23 extraction of unpolarized proton TMDs at N4LL has been published (e-Print: 2305.07473 [hep-ph]).  The MAP24 extraction of unpolarized proton TMDs and unpolarized fragmentation functions, including their flavor dependence, was published (e-Print: 2405.13833 [hep-ph])  A parametrization of unpolarized TMD fragmentation functions was published (e-Print: 2306.02937 [hep-ph]).  Apart from these improved extractions of quark TMD PDFs and FFs, several other related achievements took place:  Benchmarking of available codes, especially for Drell-Yan precision physics (see CERN EW precision working group)  Global reweighting of Sivers, transversity, and Collins functions from azimuthal asymmetries (arxiv.org/abs/2402.12322)  Alternative approach to TMD parametrization (HSO) (arxiv.org/abs/2401.14266)  Study of transverse momentum with parton branching approach (arxiv.org/abs/2312.08655, arxiv.org/abs/2404.04088) |
| ***Task 5: Gluon TMD studies*** |
| 5.1) The TMD shape functions for J/ψ production in SIDIS have been studied (arxiv.org/abs/2304.09473).  The gluon transverse-momentum-dependent fragmentation function (TMDFF) at next-to-leading order (NLO) into heavy quarkonium was computed (https://arxiv.org/abs/2308.12356v3) Matching coefficients of gluon TMDs have been calculated (arxiv.org/abs/2306.15052)  5.2) A model calculation of T-odd gluon TMDs was completed (arxiv.org/abs/2402.17556). This can help to make predictions for experimental observables.  5.3) A detailed phenomenological study of *J*/*ψ* polarization in semi-inclusive deep inelastic scattering processes has been published (arXiv:2301.11987 [hep-ph]). An analysis of single and double spin asymmetries for C-even quarkonium production was performed (arxiv.org/abs/2403.20017). |

**1.3 Highlights of significant results**

*[Include an overview of the project results towards the objectives in line with the structure of the Annex 1 to the Grant Agreement*.*]*

New data suitable for TMD studies have been collected in all processes of interest (Drell-Yan, semi-inclusive DIS, for e+e− annihilation to hadrons) and almost all published. At COMPASS and CLAS, polarized targets have been installed and data taking has been performed in 2022-2023.

New extractions of TMD distribution and fragmentation functions (unpolarized and polarized) have been completed and published. The results have been made available through the TMDlib interface (https://arxiv.org/abs/2103.09741)

Several theoretical and phenomenological studies of gluon TMDs have been published.

Overall, all tasks have been completed, with the exception of Tasks 3.1 and 3.2.

1. Critical Implementation risks and mitigation actions

**2.1 Risk materialization**

*[Provide the information on the project risks described in Annex 1 to the Grant Agreement*.*]*

1. Failure to obtain the expected experimental data (low)

The risk has not materialized

1. Insufficient resources to carry out all foreseen analyses (low)

This risk has partially materialized: the analysis of e+e− multiplicities at Belle (Task 3.1) has been progressing very slowly, as one of main analyzers, formerly Bilbao, left the Belle collaboration. The Bilbao unit received money for about 6 person-months, however it has proven to be difficult to find a researcher with the necessary qualifications.

1. Failure of theoretical framework (medium)

The risk has not materialized

**2.2 Risk-mitigation measures applied**

*[Please indicate whether the risk-mitigation plan described in Annex 1 to the Grant Agreement and corresponding to the risk number was applied in the reporting period*.*]*

1. The involvement of different experiments will guarantee that a sufficient amount of measurements will be available

Not needed

1. Focus on the observables that appear to be more relevant, seek an increase in support from experimental collaborations

Partially. Senior members of the Belle collaboration devoted more of their time to this analysis. And we tried to raise awareness among the Belle collaboration about the importance of finalizing this analysis. However, the workforce was lacking and the experimental collaboration focused on different observables, less relevant to the goals of our initiative..

1. Interaction with other WPs to improve hardware and to improve treatment of systematic errors through MC simulations

Not needed

1. Increase in theoretical efforts and interactions will lead to an improved understanding of the framework. Continue with considering observables where framework holds

Not needed

**2.3 Comments/new risk-mitigation measures proposed**

*[Provide any significant comments on the risks encountered and the mitigation plan applied. Give any unforeseen risks encountered during the reporting period and not mentioned above*.*]*

3. Deviations from Annex 1 (Description of Action) and Annex 2 (Estimated budget for Action) (if applicable)

**3.1 Deviations from planned objectives and tasks, and their impact on the progress of the work package**

*[Explain the reasons for deviations, the consequences and the proposed corrective actions.]*

Overall, the WP has progressed according to plans.

The only significant deviation was the failure to complete task 3 (analysis of e+e− multiplicities). This deviation has not prevented us from completing all other tasks on time, thanks to the wealth of data . However, for a future, more precise determination of TMD fragmentation functions (and, indirectly, also TMD distribution functions), data on e+e− multiplicities will be very useful.

**3.2 Deviations between actual and planned person months**

*[Explain deviations between actual and planned person-months. If applicable, propose corrective actions.]*

During the project, there have been some delays in the opening and filling of researcher positions, partially due to the Covid-19 emergency. However, in the end, all positions have been filled.

1. Deliverables and milestones tables

**4.1 Deliverables**

*[Please list all the deliverables due in this reporting period, as indicated in Annex I.*

*Deliverables must also be accompanied by a short report (deliverable description and technical documentation, such as photo, list of publications, etc.), so that the European Commission has a record of their existence.]*

***Table 4.1 List of deliverables***

| **Deliverable No.** | **Deliverable name** | **Lead Beneficiary** | **Nature** | **Dissemination level[[1]](#footnote-1)** | **Delivery month from Annex I** | **Delivered**  **(yes/no)** | **Actual delivery month** | **Comments** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| D22.1 | TMD data from DY,  SIDIS, e+e− | 30 - INFN | Report | PU | 54 | yes | 54 | Less data than expected for e+e− , but more than expected in the other experiments, also thanks to extension |
| D22.2 | Parametrizations of TMD  PDFs and FFs | 30 - INFN | Report | PU | 54 | yes | 54 | Many results with increasing degree of accuracy and increasing data |
| D22.3 | Estimates of quarkonium  production in SIDIS | 33 - RUG | Report | PU | 54 | yes | 42 | Several observables have been investigated |

*In case a deliverable has been delivered in the reporting period and a report exists in the Participant Portal, you can indicate “uploaded report” in correspondence of a deliverable*

**4.2 Milestones**

*[Please complete the table if milestones are specified in Annex I.*

*Milestones will be assessed against specific criteria and performance indicators as defined in Annex I.]*

***Table 4.2 List of milestones***

| **Milestone number** | **Milestone name** | **Lead beneficiary** | **Delivery month from Annex I** | **Delivered**  **(yes/no)** | **Actual delivery month** | **Comments** |
| --- | --- | --- | --- | --- | --- | --- |
| MS42 | Implementation of polarized  target at CLAS12 | 30 - INFN | 38 | yes | 30 | The polarized target has been commissioned, and data-taking started in May 2022 |

**4.3 Deliverable Reports**

*[Please provide, per each deliverable listed in Table 4.1, a brief description, including if possible some technical documentation (photos, list of publications, etc.). Use as many pages as needed per each report.]*

**D22.1-TMD data from DY, SIDIS, e+e−**

Publications containing data from DY

[CMS] Eur.Phys.J.C 83 (2023) 7, 628, e-Print: 2205.04897 [hep-ex]

[COMPASS DY unpol] Pion-induced Drell-Yan cross section [Paper in drafting. Results were shown at SPIN 2023, 24-29 September 2023]

[COMPASS DY transverse] Phys.Rev.Lett. 133 (2024) 7, 071902; e-Print: 2312.17379 [hep-ex]

Publications containing data from SIDIS

[CLAS A\_LU] Phys.Rev.Lett. 130 (2023) 2, 022501; e-Print: 2208.05086 [hep-ex]

[COMPASS]  Int.J.Mod.Phys.A 37 (2022) 07, 2240005; DOI: 10.1142/s0217751x2240005x

[COMPASS A\_UT] Phys.Rev.Lett. 133 (2024) 10, 101903; e-Print:2401.00309 [hep-ex]

Publications containing data from e+e-

[BELLE] Phys. Rev. D 100 (2019) 9, 092008; e-Print: 1909.01857 [hep-ex]

**D22.2 Parametrizations of TMD PDFs and FFs**

Publications containing parametrizations of TMD PDFs

[PDF bias] JHEP 10 (2022) 118; e-Print: 2201.07114 [hep-ph]

[PionTMDs] Phys.Rev.D 107 (2023) 1, 014014; e-Print: 2210.01733 [hep-ph]

[ART 23] JHEP 05 (2024) 036; e-Print: 2305.07473 [hep-ph]

[PV Sivers] Phys.Lett.B 827 (2022) 136961; e-Print: 2004.14278 [hep-ph]

Publications containing parametrizations of FFs

[TO1] Phys.Rev.D 106 (2022) 7, 074024; e-Print: 2206.08876 [hep-ph]

[TO2] JHEP 09 (2023) 006; e-Print: 2306.02937 [hep-ph]

Publications containing parametrizations of both

[SV 20] JHEP 06 (2020) 137; e-Print: 1912.06532

[MAP 22] JHEP 10 (2022) 127; e-Print: 2206.07598 [hep-ph]

[MAP 24] JHEP 08 (2024) 232; e-Print: [2405.13833](https://arxiv.org/abs/2405.13833) [hep-ph]

**D22.3 Estimates of quarkonium production in SIDIS**

Publications containing estimates of quarkonium production in SIDIS

[Dijet] JHEP 03 (2022) 047; e-Print: 2111.03703 [hep-ph]

[J/Psi] Phys.Rev.D 106 (2022) 1, 014030; e-Print: 2204.01527 [hep-ph]

[J/Psi pol] Phys. Rev. D 107 (2023), 114001, e-Print: 2301.11987 [hep-ph]

1. PU = Public

   PP = Restricted to other programme participants (including the Commission Services).

   RE = Restricted to a group specified by the consortium (including the Commission Services).

   CO = Confidential, only for members of the consortium (including the Commission Services). [↑](#footnote-ref-1)