NINPHA: Understanding the (3D) structure of hadrons and light nuclei

Francesco Murgia – INFN Sezione di Cagliari

TNPI 2023 – October 11-13, 2023 – Cortona, Italy

- Some history and facts about NINPHA
- Main research topics and interests
- Sinergies and complementarity
- Recent achievements and future prospects

National INitiative on the Physics of HAdrons

https://web.infn.it/CSN4/index.php/it/17-esperimenti/135-ninpha-home

Many thanks, in particular, to: M. Boglione, E. Santopinto, M. Radici, M. Rinaldi

Historical recollections...

Spin physics
Diffraction
Quarkonium decays

Y2008 — TO21 (TO, CA)

RN M. Anselmino

Y2009 — TO31 (TO, CA)

Spin physics
TMD approach
3D N structure

Y2013 — NINPHA

RN
M. Radici (2013-2016)
M. Boglione (2017-2023)
F. Murgia (2024-2026)

The many facets of nuclear and hadron physics

PI31 — GE, PG31, PV31, RM31, TN31

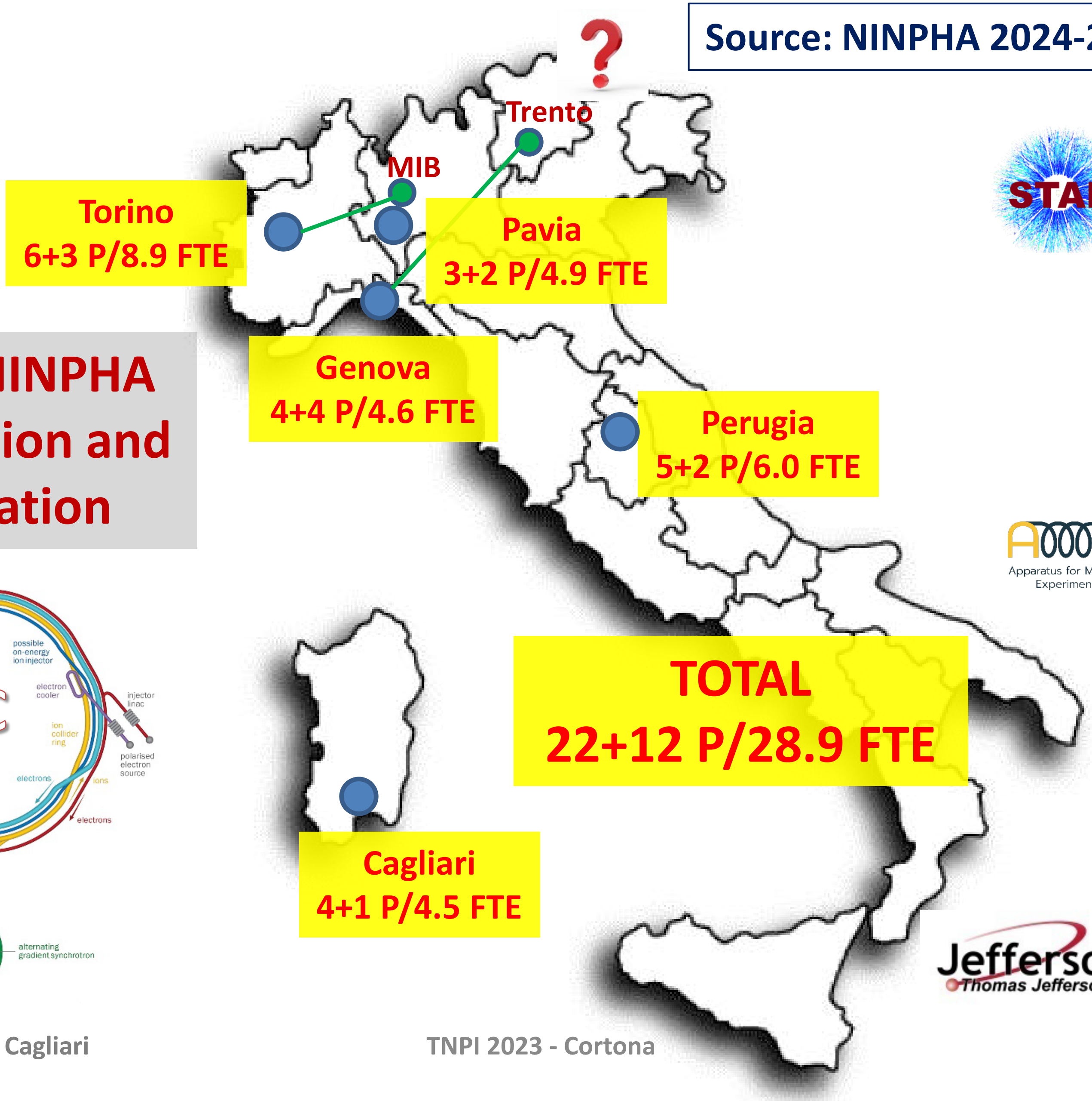
AD31

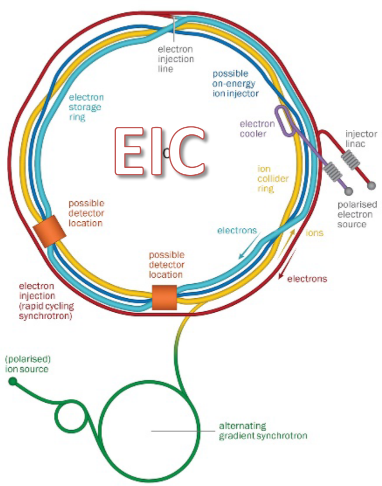
RN M. Radici

Spin & Hadron physics
3D nucleon structure & tomography
TMD PDFs & FFs, IFFs
DVCS, DVMP, GPDs, Form Factors,
Nucleon polarizabilities
Nonperturbative hadron models
Diquarks, Tetra&Pentaquarks, molecules
Three-body nuclear systems
Hadron Spectroscopy, exotics, hybrids
Multiparton interactions

Source: NINPHA 2024-2026 proposal

Present NINPHA configuration and organization





Participants by research units

Cagliari
Staff: G. Bozzi, U. D'Alesio, F. Murgia, C. Pisano
PhD&P.docs: S. Anedda, N. Kato

Genova
Staff: D. Binosi, A. Pilloni, E. Santopinto, P. Saracco
PhD&P.docs: I. Belov, H. G.-Tecocoatzi, A. R.-Acosta, Z.Q. Yan

Pavia
Staff: A. Bacchetta, B. Pasquini, M. Radici
PhD&P.docs: F. Delcarro, L. Rossi

Perugia
Staff: M. Alvioli, S. Pacetti, M. Rinaldi, G. Salmè, S. Scopetta
PhD&P.docs: F. Fornetti, O. Shekhovtsova

Torino
Staff: V. Barone, M. Boglione, O.J. G.-Hernandez, E.R. Nocera, P. Ratcliffe, A. Signori
PhD&P.docs: C. Flore, S. Tanishq, T. Yushkevych

Staff: 14 Univ, 6 INFN, 2 CNR, ECT*; PhD&P.docs: 10 Univ, 2 INFN, 1 ECT*

Main research topics and motivations

- **Development of a full three-dimensional (3D) tomographic picture of the nucleon and hadrons (Mainly CA, PV, TO, also PG)**

TMDs, IFFs, GPDs, GTMDs, Wigner functions, proton spin, Lambda polarization, nucleon polarizabilities, TMDs & GPDs for light nuclei, double parton scattering, pion TMDs,…

- **QCD spectroscopy and nonperturbative models for (excited) heavy and light hadrons (Mainly GE, also PG and PV)**

Exotics, hybrids, diquark models, tetra&pentaquarks, molecules, nonperturbative models, light front wavefunctions, holographic models, glueballs,…

- **Relativistic nonperturbative description of light nuclei and hadron dynamics (Mainly PG, also GE and PV)**

Hadron dynamics in Minkowsky space, BS equation, pion PDFs & Form Factors, quantum computing techniques, EMC effect for light nuclei,…

A (partial) selection of recent achievements and future prospects

See also next talks on

EMC effect for light nuclei [M. Rinaldi]

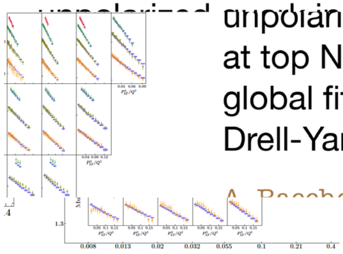
Global fits of unpol. TMD PDFs at N3LO [G. Bozzi]

Heavy Baryons & new IBFFM results [H.G. Tecocoatzi]

Homogeneous BS eq. & quantum annealer [F. Fornetti]

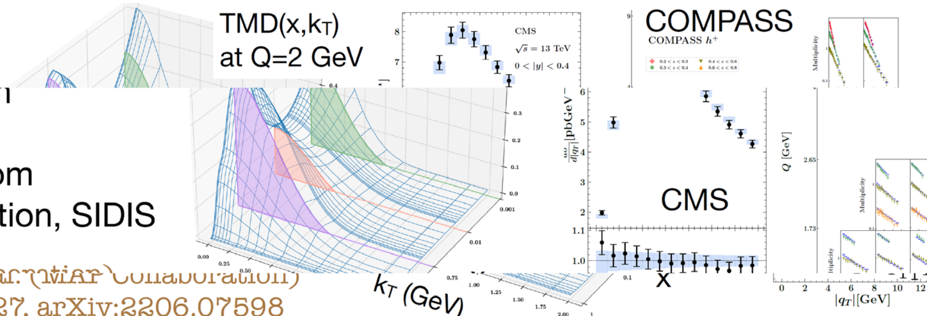
3He struct. Functions & LF Hamiltonian dynamics [E. Proietti]

NINPHA-PV at the forefront in many fields : phenomenology

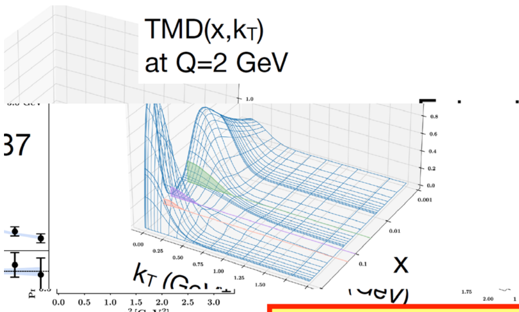


First extraction of TMD of unpolarized quark in proton at top N^{3}LL accuracy from global fit of ~ 2000 data from Drell-Yan, Z-boson production, SIDIS

A. Bacchetta et al. (MAP Collaboration)
JHEP **10** (22) 127, arXiv:2206.07598

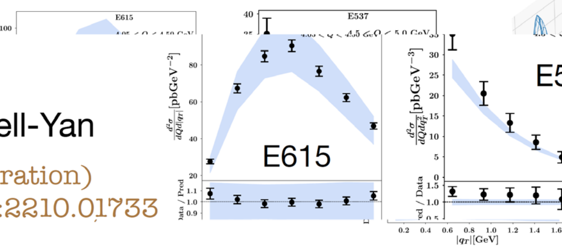


tomography of up quark in proton

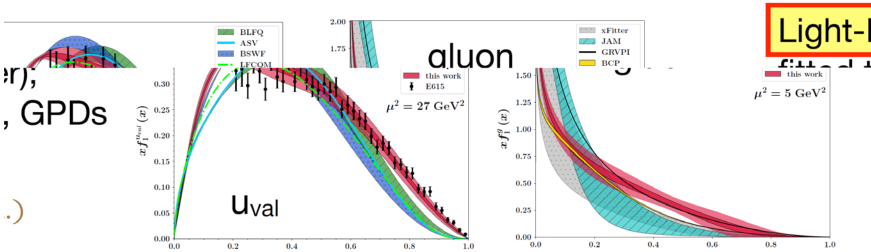


Extraction of TMD of unpolarized quark in pion at N^{3}LL accuracy from Drell-Yan

M. Cerutti et al. (MAP Collaboration)
P.R.D **107** (23) 014014, arXiv:2210.01733



tomography of up quark in pion



Light-Front Wave Functions of pion, parameters fitted to pion form factor and PDF (xFitter) can consistently build pion PDFs, TMDs for valence/sea quarks and gluons

B. Pasquini, S. Rodini, S. Venturini (MAP Coll
P.R.D **107** (23) 114023, arXiv:2303.01789

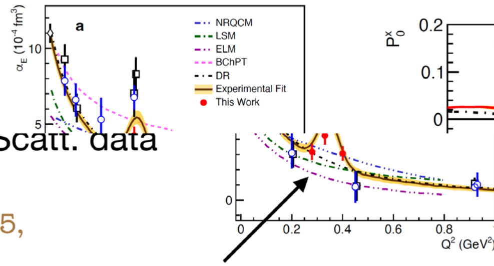
Slide by M. Radici

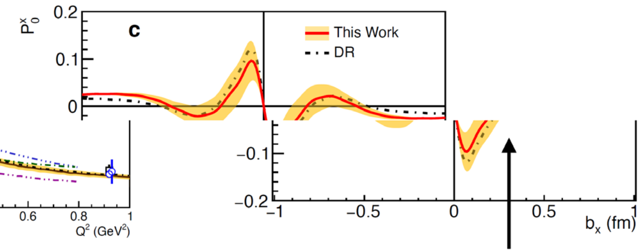
(continued)

Unexpected behavior of proton electric generalized polarizability

from Virtual Compton Scatt. data

R. Li,.., B. Pasquini et al. Nature **611** (22) 7935, 265, arXiv:2210.11461





.25-0.35 fm

not predicted by theory; new structure in induced polarization at 0

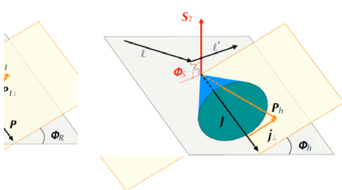
l properties

Pasquini, S. Rodini
3, arXiv:2212.12197

NINPHA-PV at the forefront in many fields : general

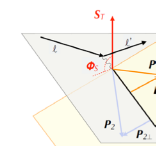
- Gravitational form factors of electron in QED at one loop: energy, angular momentum and mass radius

A. Freese, A. Metz, B. P
P.L. **B839** (23) 137768



- Formal analogies between di-hadron and hadron-in-jet fragmentation functions: new possibilities for the latter

A. Bacchetta, M. Radici, L. Rossi
P.R.D **108** (23) 014005, arXiv:2303.04314



modeling

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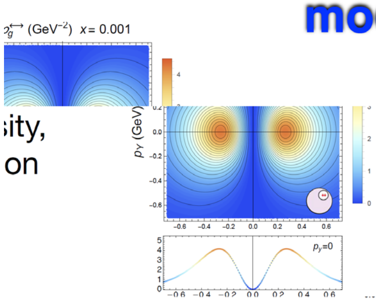
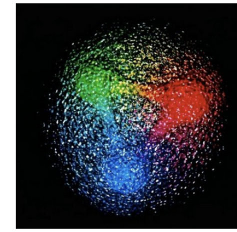


probability density of gluons linearly polarized in ⊥ plane in unpolarized proton

- **First tomography of T-odd gluon TMDs** in spectator model with mass spectral dens and applications to heavy-flavor producti

A. Bacchetta, F.G. Celiberto, M. Radici
arXiv:2206.07815, 2208.06252

NINPHA - TORINO main objectives

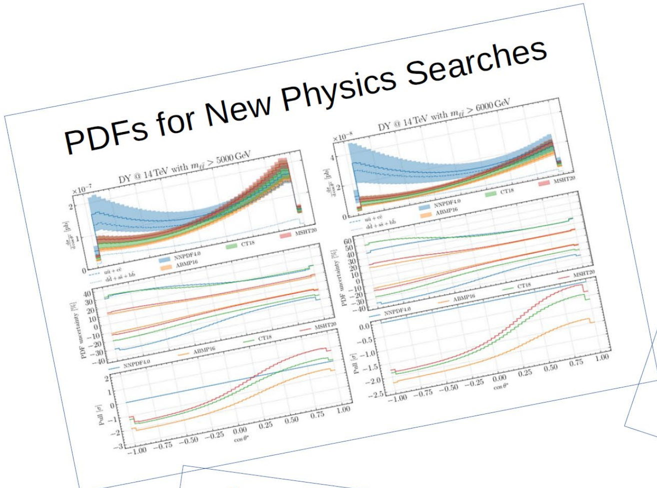


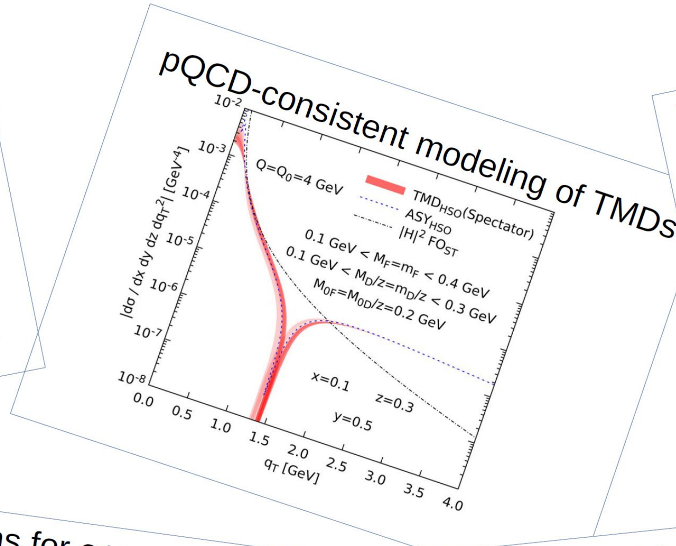
The activity of the Torino group focus on several aspects related to the study of the **inner structure of hadronic matter,** in the framework of QCD

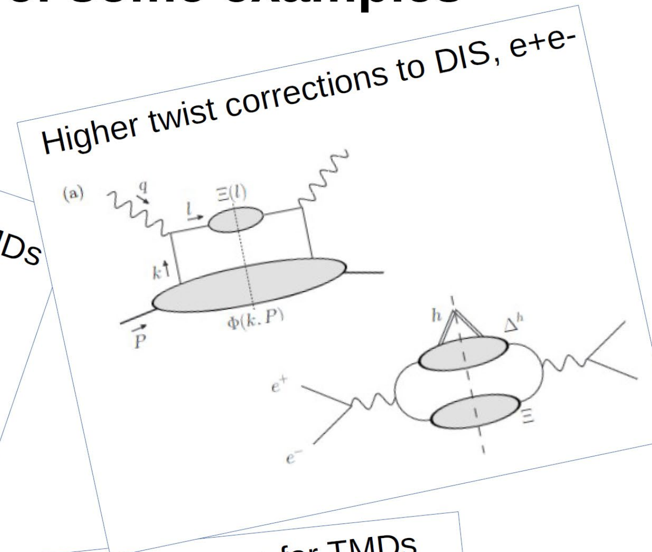
- **State of the art accuracy of collinear parton distribution functions (PDFs) of the proton**. We produce unpolarized and longitudinally polarized PDF sets accurate to (approximate) N3LO and NNLO, respectively. Extractions include uncertainty estimates of missing higher-order corrections
- **Quark-flavor dependence and intrinsic transverse momentum**. Global analyses of SIDIS and DY data are performed, to determine transverse-momentum dependent functions (TMDs) and their flavor dependence. Higher-twist contributions and mass corrections are also being explored
- **Consistency of factorization theorems and phenomenological applications**. Concrete recipes that exploit the relation of collinear and TMD factorization theorems are implemented into phenomenological analyses aiming at describing the entire transverse momentum spectrum of observables
- **Phenomenology of hadronization**. We study the factorization properties of single inclusive hadron production in e+e- annihilation $e^+ e^- \to h\, X$ data, which allow the direct extraction of one isolated TMD fragmentation function and the separation of its soft content from the collinear part of the TMD.
- **Partonic interpretations in proton-proton collisions.** We study the consistency of a partonic interpretation of pion production in pp scattering. We explore new reweighting techniques for the estimate of reliable theoretical uncertainties in the study of universality in SIDIS, e^+e^- annihilations and pp collisions processes. This allows us to assess factorization breaking effects from a phenomenological perspective.

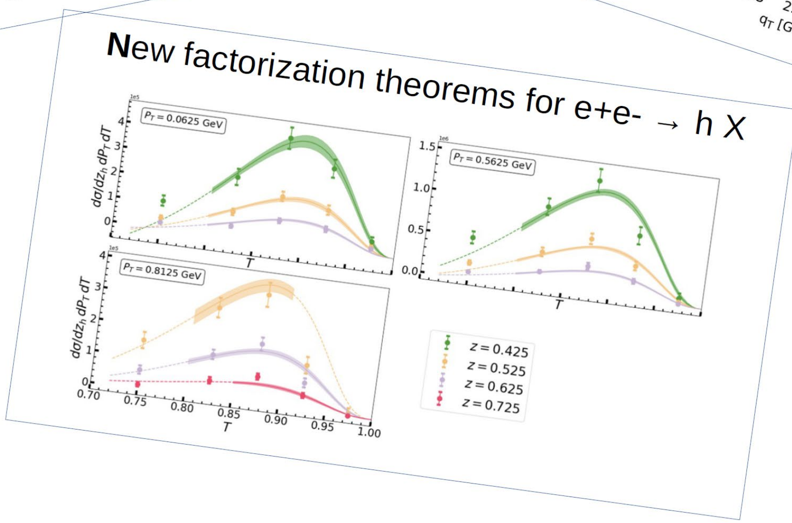
Slide by M. Boglione

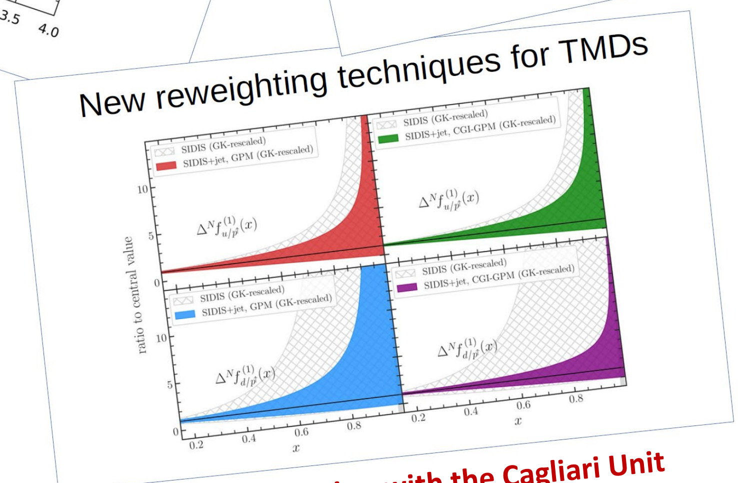
A closer look to the 3D nucleon structure: some examples







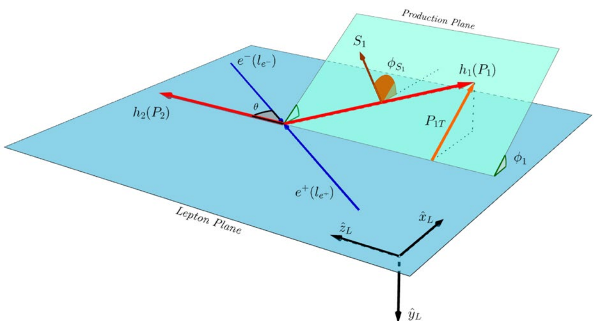


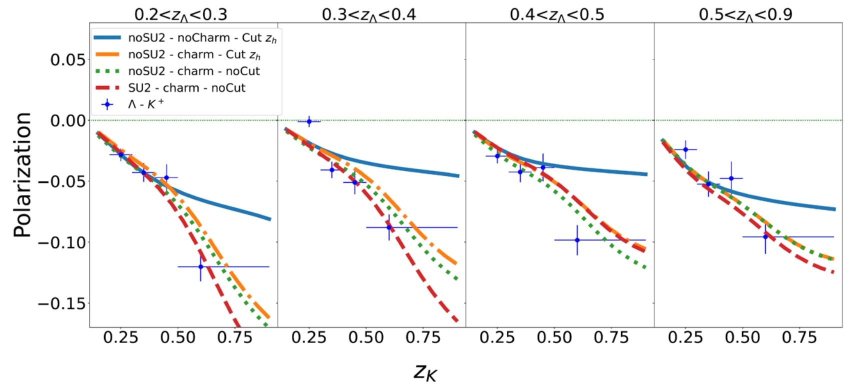


In collaboration with the Cagliari Unit

NINPHA –CA : TMDs, Polarization, Quarkonium, Lambda, global fits,...

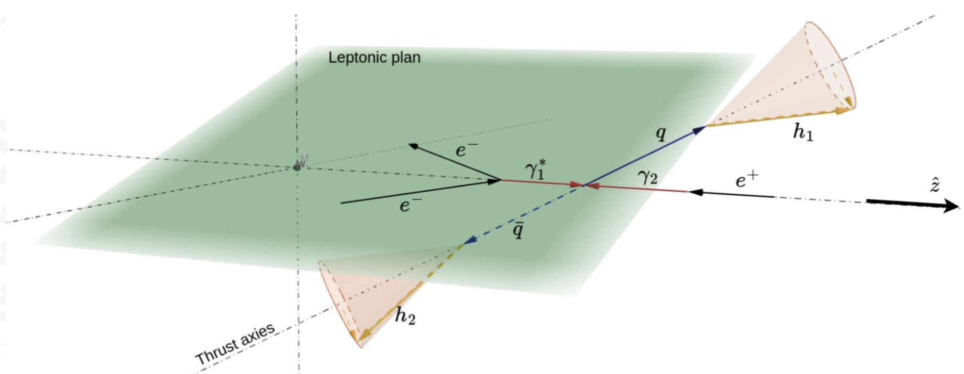
Transverse Lambda polarisation in pp, e+e- and SIDIS collisions – polarizing TMD FF
Two almost back-to-back hadron production in e+e- annihilations and TMD FFs





U. D'Alesio, FM, M. Zaccheddu
PRD 102, 054001 (2020);
JHEP 10, 078 (2021)
U. D'Alesio, L. Gamberg, FM, M. Zaccheddu
JHEP 12, 074, (2022), PRD accepted (2023)

Two hadron production in photon-photon collisions:
future lepton circular and linear colliders as effective gamma-gamma colliders
Ultra-peripheral collisions



$$d\sigma \propto \sum_q \sum_{\{\lambda\}} \rho^{\gamma_1}_{\lambda_1,\lambda_1'} \rho^{\gamma_2}_{\lambda_2,\lambda_2'} \hat{M}_{\lambda_q,\lambda_{\bar{q}};\lambda_1,\lambda_2} \hat{M}^*_{\lambda_q',\lambda_{\bar{q}}';\lambda_1',\lambda_2'} \hat{D}^{\lambda_{h_1},\lambda_{h_1}}_{\lambda_q,\lambda_q'} \hat{D}^{\lambda_{h_2},\lambda_{h_2}}_{\lambda_{\bar{q}},\lambda_{\bar{q}}'}$$

...many many calculations later...

$$d\sigma \propto \sum e_q^4 \Big[A(\Delta\phi)\mathcal{D}_{h_1/q}\mathcal{D}_{h_2/\bar{q}} + B(\Delta\phi, \Delta\psi)\Delta^N\mathcal{D}_{h_1/q^\uparrow}\Delta^N\mathcal{D}_{h_2/\bar{q}^\uparrow} \Big]$$

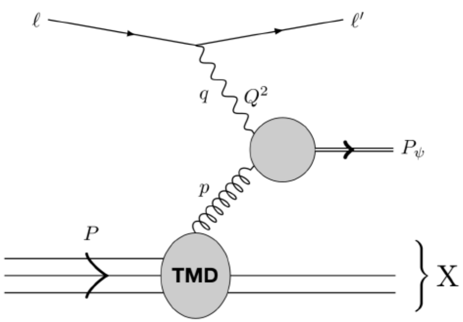
S. Anedda, G. Bozzi, U. D'Alesio, FM, C. Pisano, work in progress

Slide by C. Pisano

Smearing effects in quarkonium production are encoded in the *shape functions* $\Delta^{[n]}$ (TMD generalizations of NRQCD LDMEs)

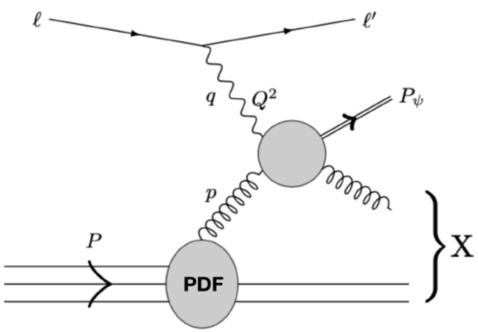
Echevarria, JHEP 10 (2019)
Fleming, Makris, Mehen, JHEP 04 (2020)

TMD



$\boldsymbol{q}_T^2 \ll Q^2$

Collinear



$\Lambda_{\rm QCD}^2 \ll \boldsymbol{q}_T^2$

Its perturbative tail is obtained by Imposing the matching of the TMD and collinear results in the overlapping region $\Lambda_{\rm QCD}^2 \ll \boldsymbol{q}_T^2 \ll Q^2$:

Boer, D'Alesio, Murgia, Pisano, Taels, JHEP 09 (2020)
D'Alesio, Maxia, Murgia, Pisano, Rajesh, JHEP 037 (2022)
Boer, Bor, Maxia, Pisano, Yuan, JHEP 08 (2023)

Independent of J/ψ polarization and CO quantum numbers

Slide by C. Pisano

C-even quarkonium production

η_Q, χ_{Q0}, χ_{Q2}

Structure of the cross section for the doubly polarized process $p(S_A) + p(S_B) \to \mathcal{Q}\,X$

$$\frac{\mathrm{d}\sigma[\mathcal{Q}]}{\mathrm{d}y\,\mathrm{d}^2\boldsymbol{q}_T} = F_{UU}^{\mathcal{Q}} + F_{UL}^{\mathcal{Q}}\,S_{BL} + F_{LU}^{\mathcal{Q}}\,S_{AL} + F_{UT}^{\mathcal{Q},\sin\phi_{S_B}}\,|\boldsymbol{S}_{BT}|\sin\phi_{S_B} + F_{TU}^{\mathcal{Q},\sin\phi_{S_A}}\,|\boldsymbol{S}_{AT}|\sin\phi_{S_A}$$
$$+F_{LL}^{\mathcal{Q}}\,S_{AL}\,S_{BL} + F_{LT}^{\mathcal{Q},\cos\phi_{S_B}}\,S_{AL}\,|\boldsymbol{S}_{BT}|\cos\phi_{S_B} + F_{TL}^{\mathcal{Q},\cos\phi_{S_A}}\,|\boldsymbol{S}_{AT}|\,S_{BL}\cos\phi_{S_A}$$
$$+|\boldsymbol{S}_{AT}||\boldsymbol{S}_{BT}|\left[F_{TT}^{\mathcal{Q},\cos(\phi_{S_A}-\phi_{S_B})}\cos(\phi_{S_A}-\phi_{S_B}) + F_{TT}^{\mathcal{Q},\cos(\phi_{S_A}+\phi_{S_B})}\cos(\phi_{S_A}+\phi_{S_B})\right]$$

Kato, Maxia, Pisano, Pitzalis (in preparation)

Single spin asymmetries for different quarkonia are sensitive to different TMDs

$$F_{UT}^{\eta_Q,\sin\phi_{S_B}} \propto -f_1^g \otimes f_{1T}^{\perp g} + h_1^{\perp g} \otimes h_1^g - h_1^{\perp g} \otimes h_{1T}^{\perp g}$$
$$F_{UT}^{\chi_{Q0},\sin\phi_{S_B}} \propto -f_1^g \otimes f_{1T}^{\perp g} - h_1^{\perp g} \otimes h_1^g + h_1^{\perp g} \otimes h_{1T}^{\perp g}$$
$$F_{UT}^{\chi_{Q2},\sin\phi_{S_B}} \propto -f_1^g \otimes f_{1T}^{\perp g}$$

Such observables are in principle measurable at the planned LHCspin experiment

The distributions f_1^g and $h_1^{\perp g}$ can be extracted separately by looking at the same process, where both protons are unpolarized

Boer, Pisano, PRD 86 (2012)

2/2

Slide by E. Santopinto

Genoa node:

Multiquark States (pentaquarks and tetraquarks)

Heavy baryons for LHC

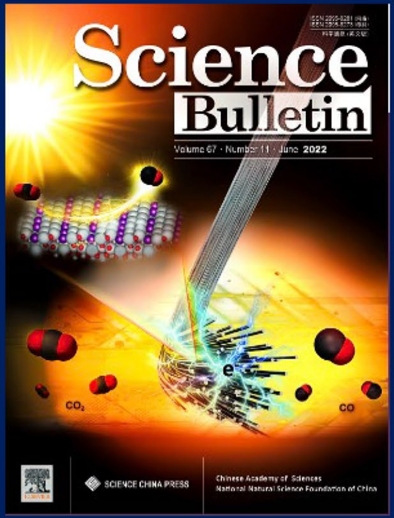
Solving of Theoretical problems for Analysis at LHC and Jlab

Planning of future hadron experiments including EIC

IBM calculation for NUMEN (see talk by Hugo Garcia Tecocoatzi)

XYZ at. LHC

Predictions of exotic strange hidden charm tetraquark and pentaquarks, published on **Science Bulletin July 2022, just confirmed by LHC**



The new Pcs.4459.; Zcs.3985.; Zcs.4000. and Zcs.4220. and the possible emergence of flavor pentaquark octets and tetraquark nonets

J. Ferretti, E. Santopinto (July 2022)
Science Bulletin 67 (2022) 1209–1212
doi.org/10.1016/j.scib.2022.04.010

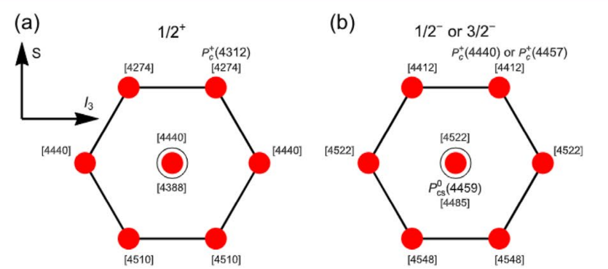
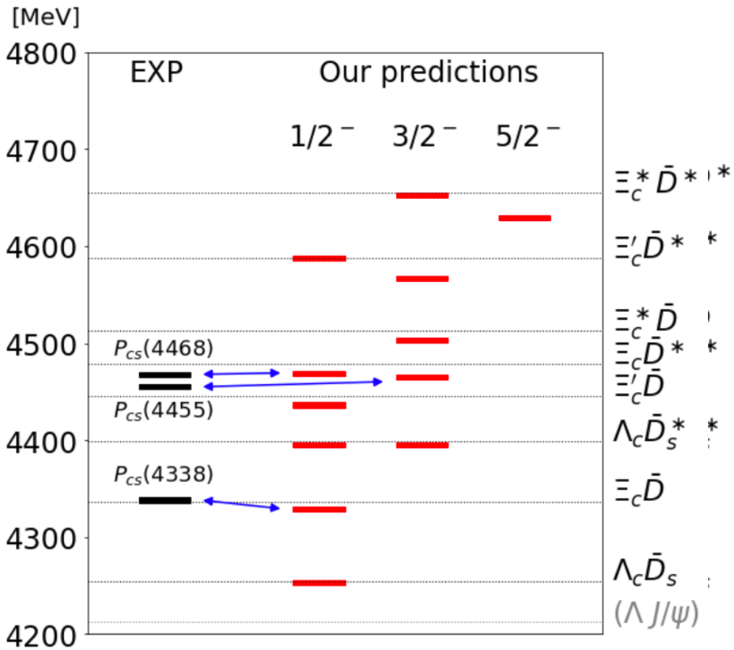


Fig. 2. (Color online) $J^P = \frac{1}{2}^+$ pentaquark octet, made up of the bound states of octet baryons plus the $\chi_{c0}(1P)$ (a), and $J^P = \frac{1}{2}^-$ or $J^P = \frac{3}{2}^-$ pentaquark octet, made up of the bound states of octet baryons plus the $\psi(2S)$ (b). The predicted hadro-charmonium masses are reported inside square brackets, the experimental ones are inside round brackets. See the Supplementary materials for more details.

In [1] a coupled-channel model was constructed for the hidden-charm pentaquarks with strangeness whose quark content is $uds c\bar{c}$, P$_{cs}$, described as $\Lambda_c \bar{D}_s^{(*)}$, $\Xi_c^{(\prime,*)} \bar{D}^{(*)}$ molecules coupled to the five-quark states. The meson baryon interactions satisfy heavy quark and chiral symmetries. It reproduces the experimental mass and quantum numbers J^P of Pcs(4338) for which LHCb has just announced the discovery. We make other predictions for new Pcs states as molecular states near threshold regions that can be studied by LHCb.

Comparing EXP with the predicted masses

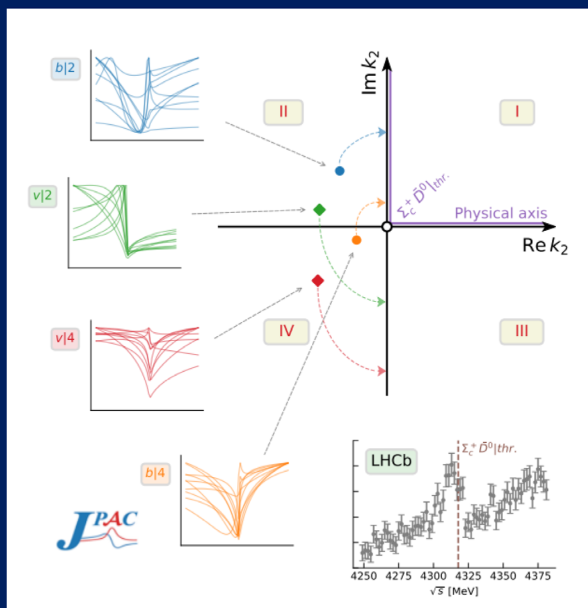


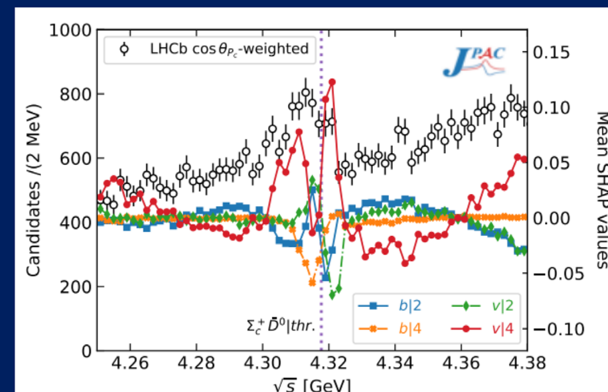
[1] A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, Y.Y, arXiv:2209.10413 [hep-ph] accepted by PRD2023, in press

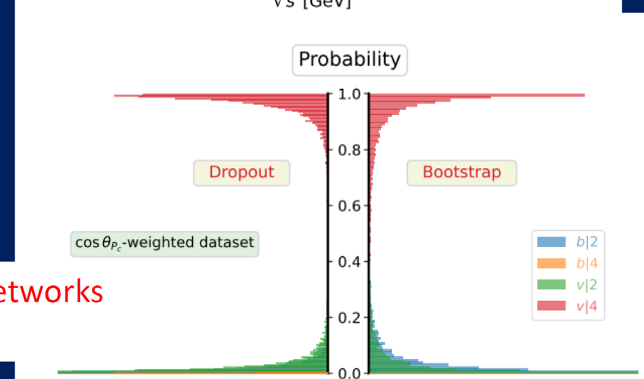
- Consistence with the two-peak structure hypothesis by LHCb, $P_{cs}(4468)$ and $P_{cs}(4455)$

Lineshape studies

The nature of the states can be determined from detailed studies of the lineshape
Esposito, Maiani, Pilloni, Polosa, Riquer, PRD 105 (2022) 3, L031503

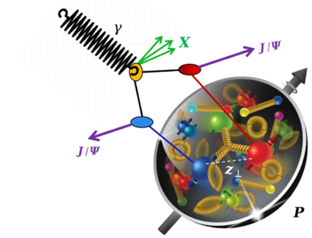






Model discrimination can be done with Neural Networks
Ng, *et al.* (JPAC), PRD 105, L091501

Double Parton Scattering at the Electron Ion Collider?



We calculated the single and double parton scattering contributions to:

1) photo-production of 4 jets. **M. R. and F. A. Ceccopieri PRD 105 (2022) 1, L011501**

$$\sigma_{DPS} > 30\,\%\,\sigma_{tot}$$

From ZEUS coll. from HERA data

Nucl. Phys B 792 1 (2008)

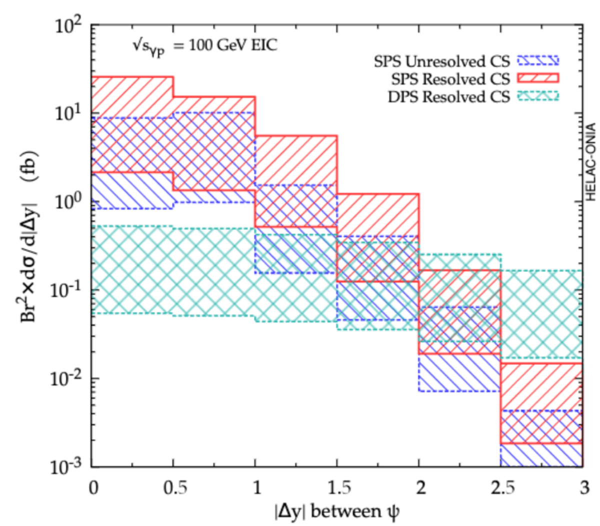
we prove that an experimental observable is related to the mean transverse distance between two partons inside the proton (unknown and extremely important to unveil new information on the non-perturbative structure of the proton):

$$\left[\sigma_{\rm eff}^{\gamma p}(Q^2)\right]^{-1} = \sum_n C_n(Q^2)\langle z_\perp^n \rangle_p$$

Mean value of the transverse distance

2) photo-production fo double J/ψ

R. Sangem, F. A. Ceccopieri, J.P. Lansberg, M. R. and H. S. Shao, in prep.

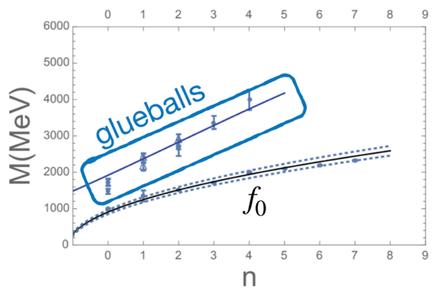


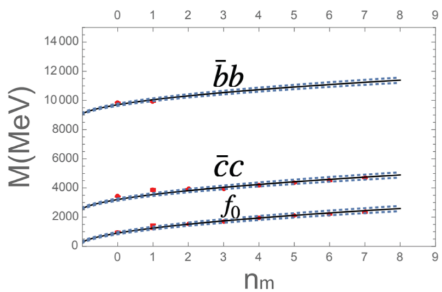
A holographic model for glueballs and mesons

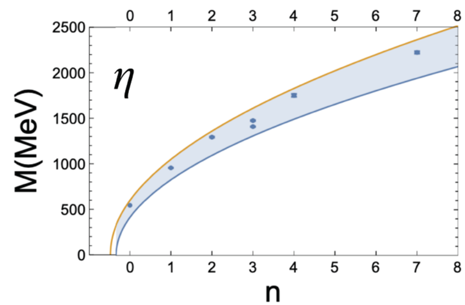
We proposed that duals to mesons and glueballs could be fields and graviton propagating in deformed AdS space:

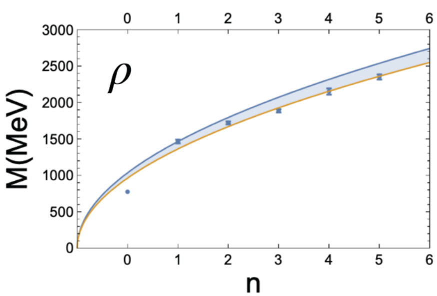
$$ds^2 = \frac{R^2}{z^2} e^{\alpha k^2 z^2} (dz^2 + \eta_{\mu\nu} dx^\mu dx^\nu)$$

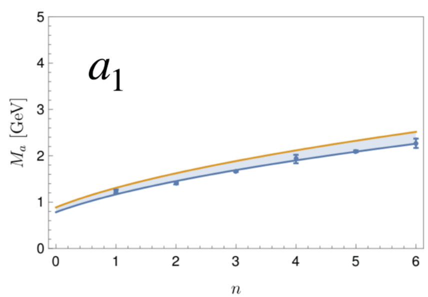
only 2 fixed parameters for all observables











M.R. and V. Vento, EPJA 54 (2018) 151

M.R. and V. Vento, J. Phys. G 47 (2020) 5, 055104

M.R. and V. Vento, J. Phys. G 47 (2020) 12, 125003

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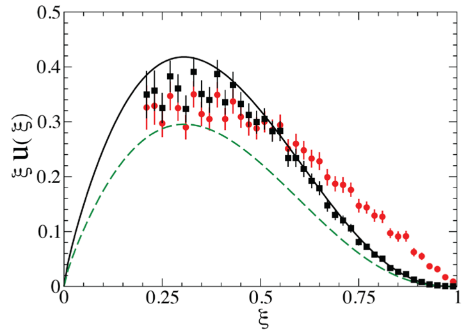
M.R., F. A. Ceccopieri and V. Vento, EPJC 82 (2022) 7,636 ⟶ PION

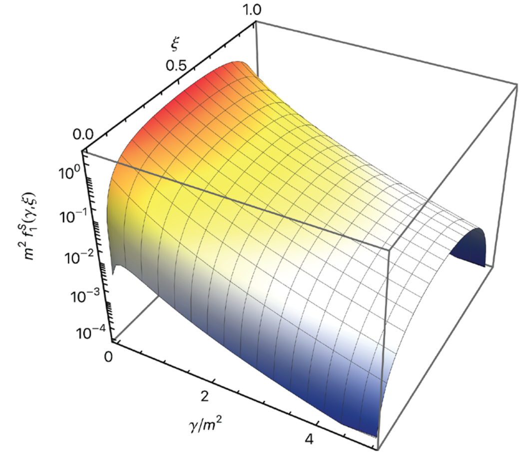
M.R. and V. Vento, ArXiv:2304.01793
M.R. and V. Vento, EPJC 82 (2022), 2 140
} Temperature dependence of the glueball spectrum

Slide by M. Rinaldi

Insights into the Pion Minkowskian dynamics via the Bethe-Salpeter Equation

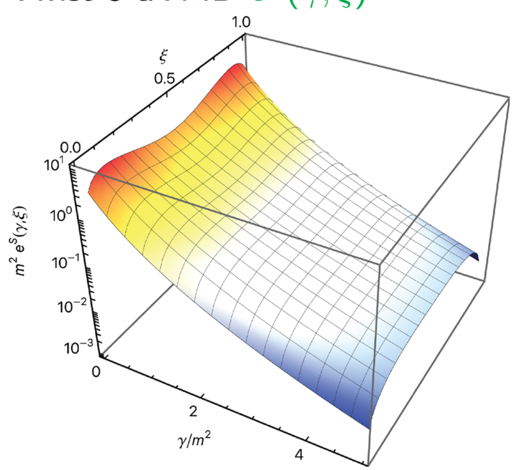
Pion Parton Distribution.
Solid line & squares



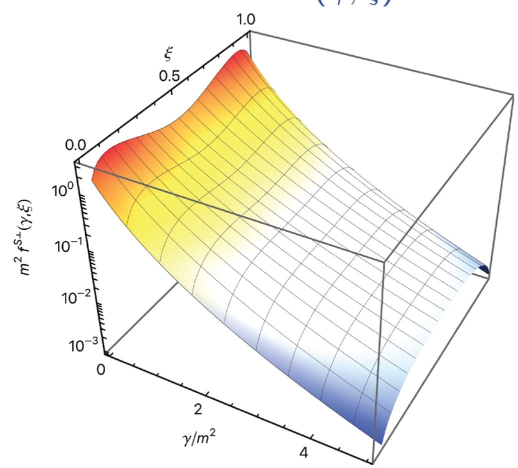


Twist-2 unpolarized $k_\perp$-dependent distribution (uTMD) $f_1^S(\gamma,\xi)$, with $\gamma = k_\perp^2$ and

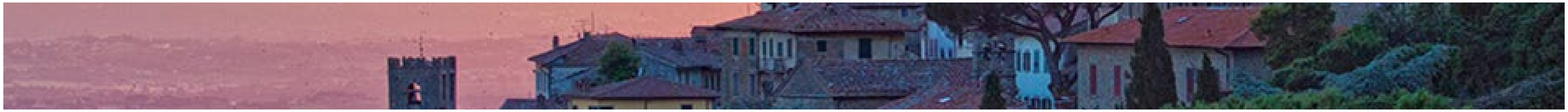
Twist-3 uTMD $e^S(\gamma,\xi)$



Twist-3 uTMD $f^{\perp S}(\gamma,\xi)$



Giovanni Salmè (INFN-Rome) Insights into the pion dynamics in Minkowski 1 / 1



Many thanks for your attention!

XYZ at JLab (solving of theoretical problems for the analysis) and EIC (planning of future experiments)

Predictions based on VMD for semi-inclusive Z production Winney *et al.* (JPAC) PRD106, 094009
VMD and factorization tests at GlueX (Jlab) need further scrutiny Winney *et al.* (JPAC) PRD108, 054018