XVIII Conference on Theoretical Nuclear Physics in Italy

TNPI2021, November 23rd

NINPHA
Theoretical activities on QCD and hadronic structure

Francesco Giovanni Celiberto

ECT*/FBK Trento & INFN-TIFPA

ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

FBK FONDAZIONE BRUNO KESSLER FUTURE BUILT ON KNOWLEDGE

TIFPA Trento Institute for Fundamental Physics and Applications

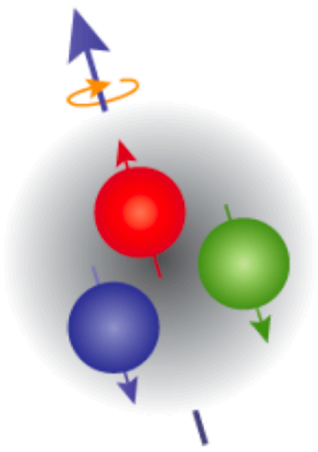
HAS QCD HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

NINPHA and the hadron structure

The main goals of NINPHA

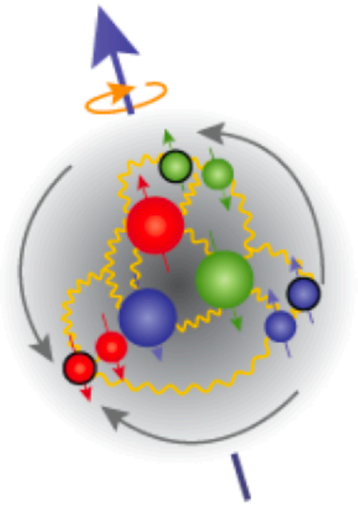
- QCD confinement $\leftrightarrow$ **detailed map** of *nonlinear* dynamics of partons inside hadrons
- Internal structure of hadrons $\rightarrow$ **parton distributions** in **3D** mom. and coord. space
- Innovative way to look at the **nucleon** $\rightarrow$ revealing properties otherwise inaccessible
- Original methodology $\rightarrow$ addressing **mass**, **spin** and **orbital angular momentum** quests
- **Hadron structure** $\leftarrow$ **PDFs**, **FFs**, spectrum of **excited** and **exotic** hadrons
- Advanced **nonperturbative** and **perturbative** techniques requested
- Different *kinds* of factorization $\rightarrow$ PDF **universality**, **evolution** equations

The proton spin crisis



quarks helicity

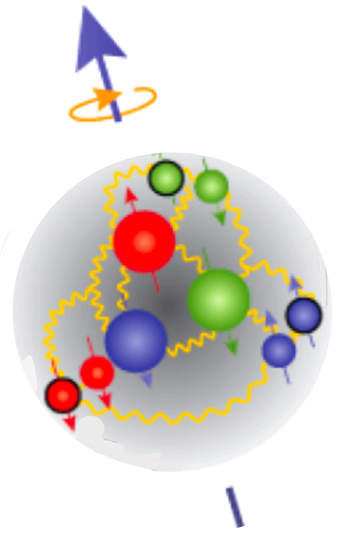
~ 30 %



orbital angular momentum

unknown!

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



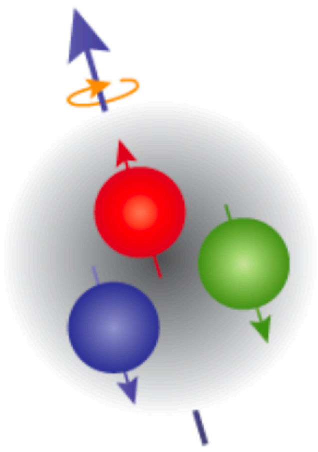
gluons helicity

~ 20% – 50 % **?**

Total spin carried by quarks and gluons does not amount to 1/2, one needs orbital angular momentum, then a 3D description…

🔗 (proton spin crisis) [EMC Collaboration, CERN (1987)]

The proton spin crisis



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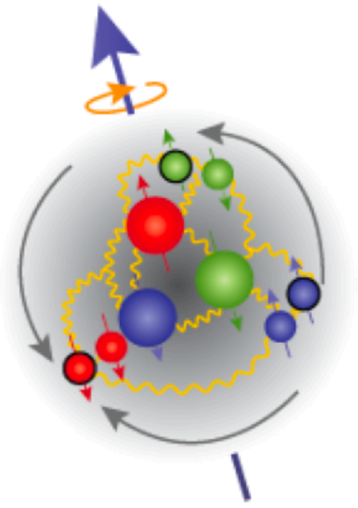

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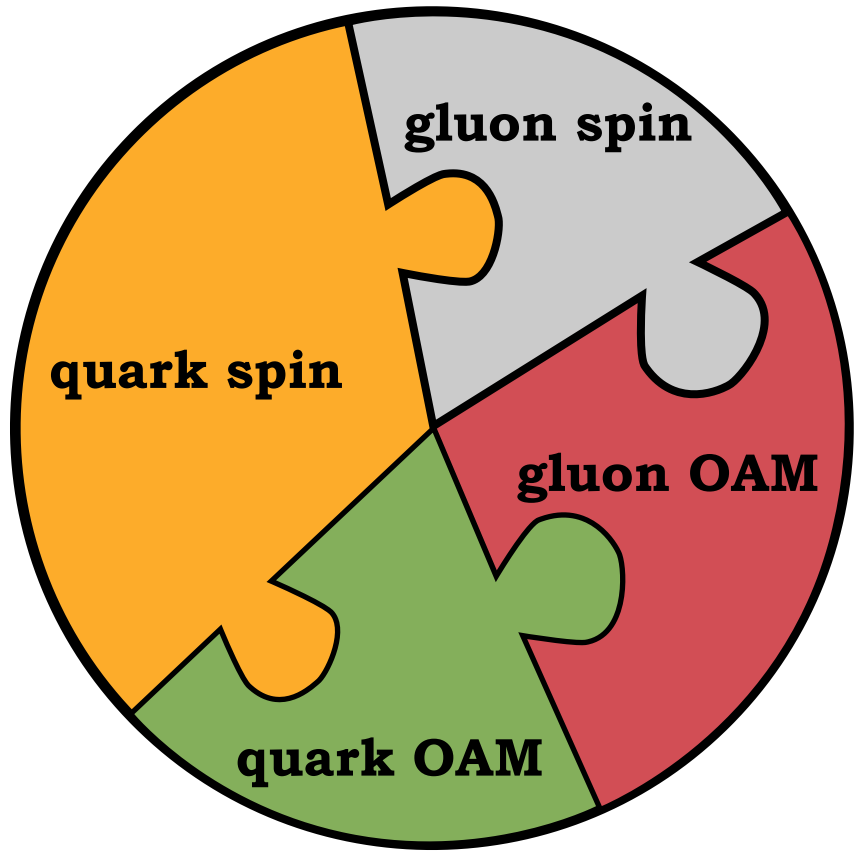

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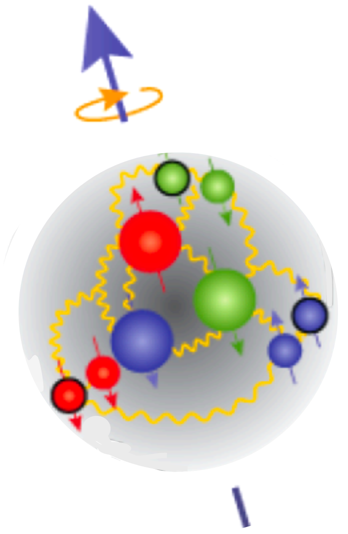

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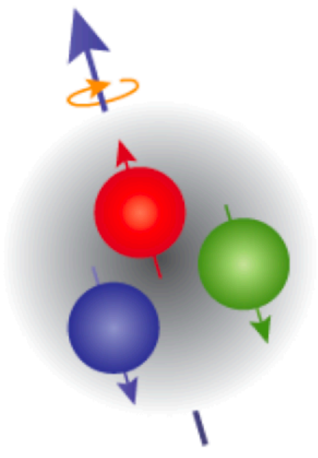
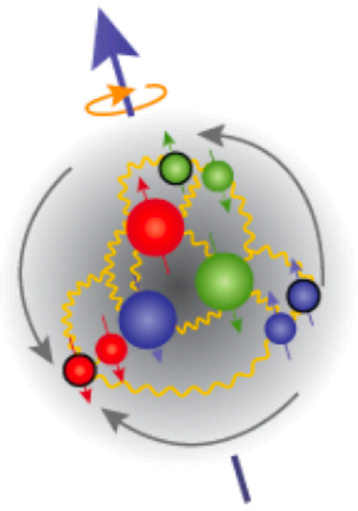


quarks helicity

$\sim 30\,\%$

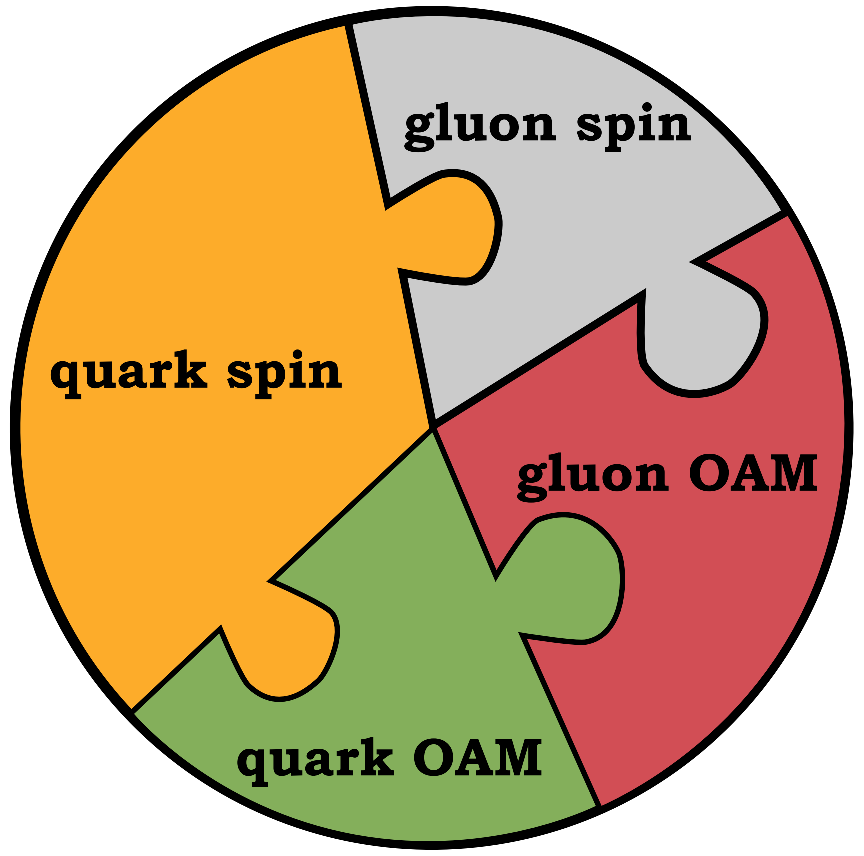


orbital angular momentum

unknown!

...many other effects in hadronic interactions cannot be understood in the purely collinear approach

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



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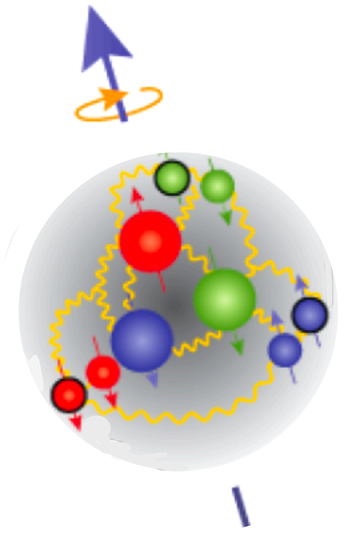

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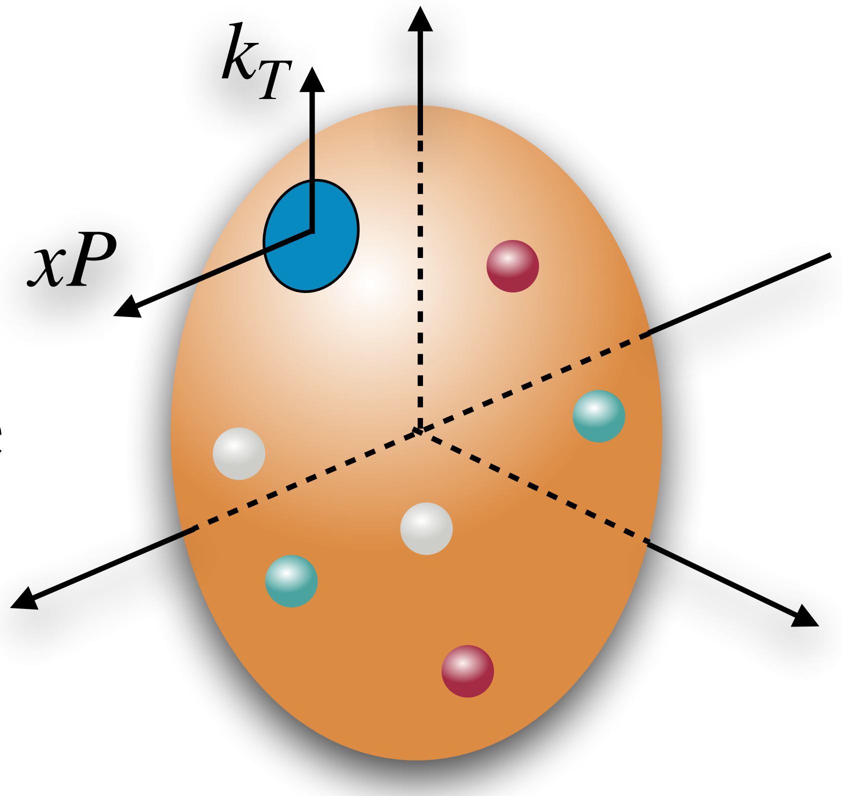
Parton densities: an incomplete family tree

3D

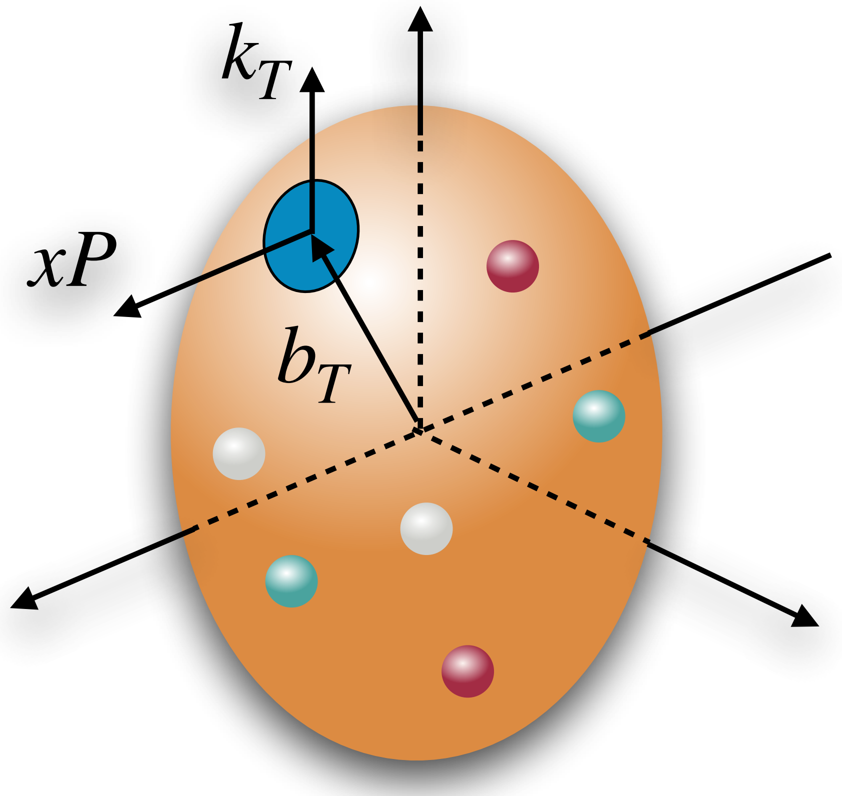
TMDs

(semi-)inclusive



5D

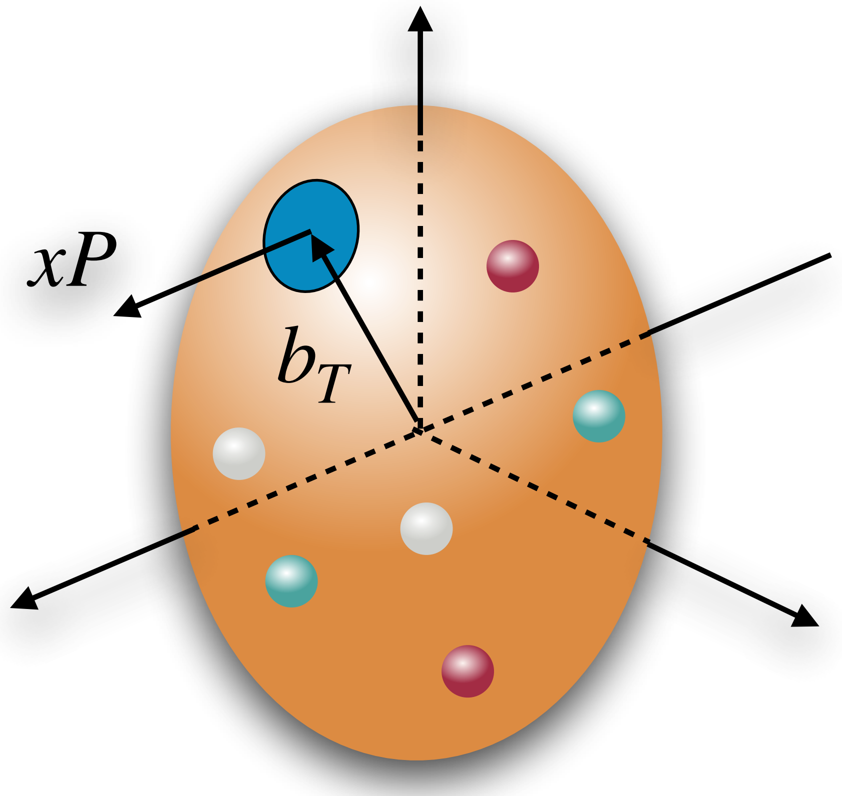
Wigner distributions



3D

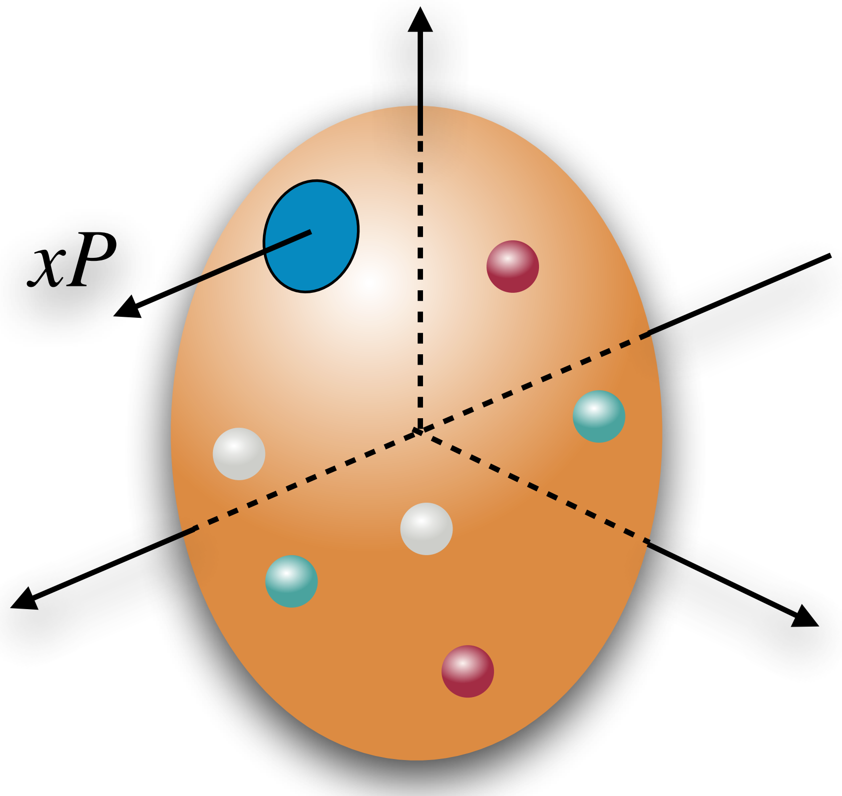
FT of GPDs

exclusive



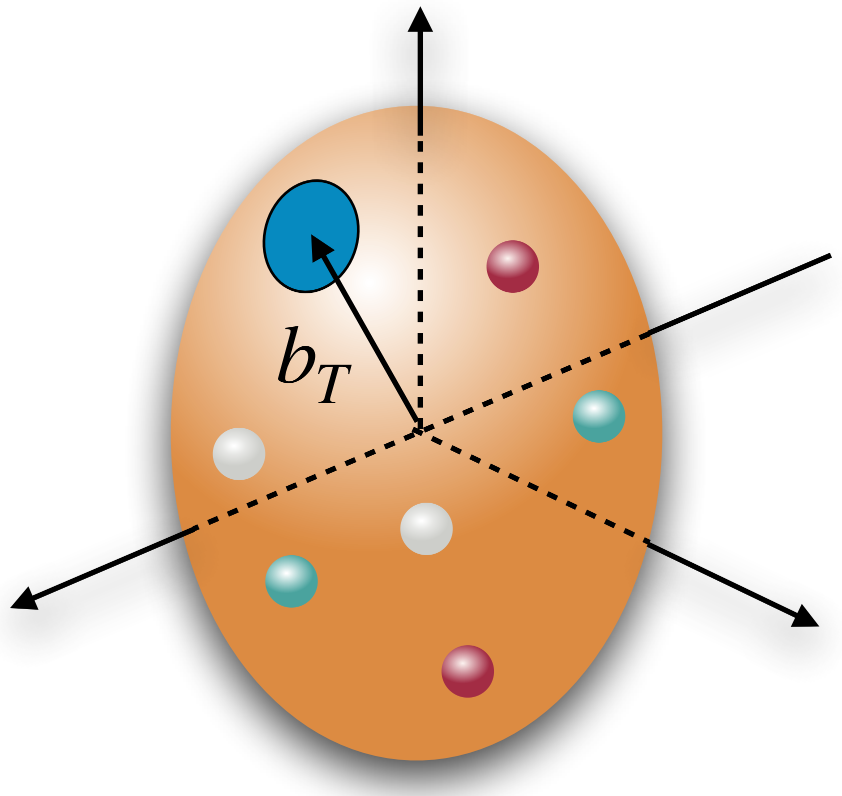
PDFs

(semi-)inclusive



1D

FT of Form Factors



2D

$\vec{b}_\perp$ dependence

$\vec{k}_\perp$ dependence

these two variables are NOT Fourier conjugate

NINPHA experimental connections

NINPHA activities are connected the following international experimental collaborations:

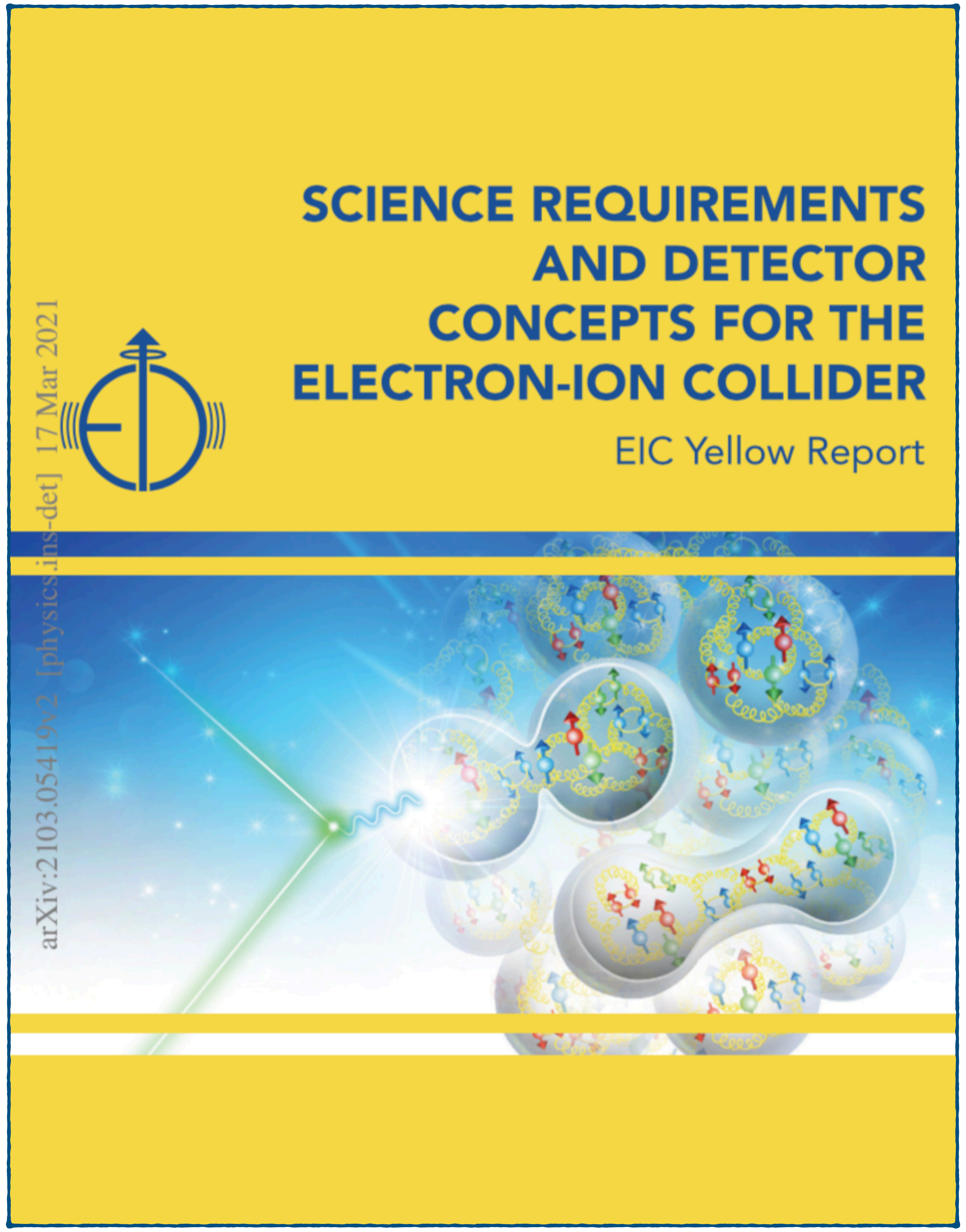
- Alice,CMS, Atlas, LHCb - LHC - CERN - Geneva (Switzerland)
- COMPASS - CERN - Geneva (Switzerland)
- HERMES - DESY - Hamburg (Germany)
- MAMBO (Mainz-Bonn)
- NUMEN INFN-LNS
- CLAS, Hall A, Hall B, Hall C - Jefferson Laboratories (JLab) - (VA) USA
- STAR, Phenix - Brookhaven National Laboratories (BNL) - (NY) USA
- CDF, DØ- Tevatron - Fermi National Accelerator Laboratory - (IL) USA
- BaBar - SLAC National Accelerator Laboratory - (CA) USA
- BELLE - KEK - Tokio – Japan
- BESIII - Beijing – China
- NICA-SPD – JINR - Dubna - Russia
- In the last two years NINPHA has been deeply involved in the planning and design work of a brand new, dedicated facility, the **Electron Ion Collider** (EIC). All members have co-authored the EIC Yellow Report, which was published earlier this year.

slide adapted from M. Boglione, NuPECC

The EIC Yellow Report

"The Yellow Report represents a year-long superb effort of the EIC community. This community spans the world, with crucial contributions coming from many scientists in many countries, underscoring that we all work together as one community toward shared science goals."

🔗 [from the BNL website]



🔗 [EICUG [arXiv:2103.05419]]

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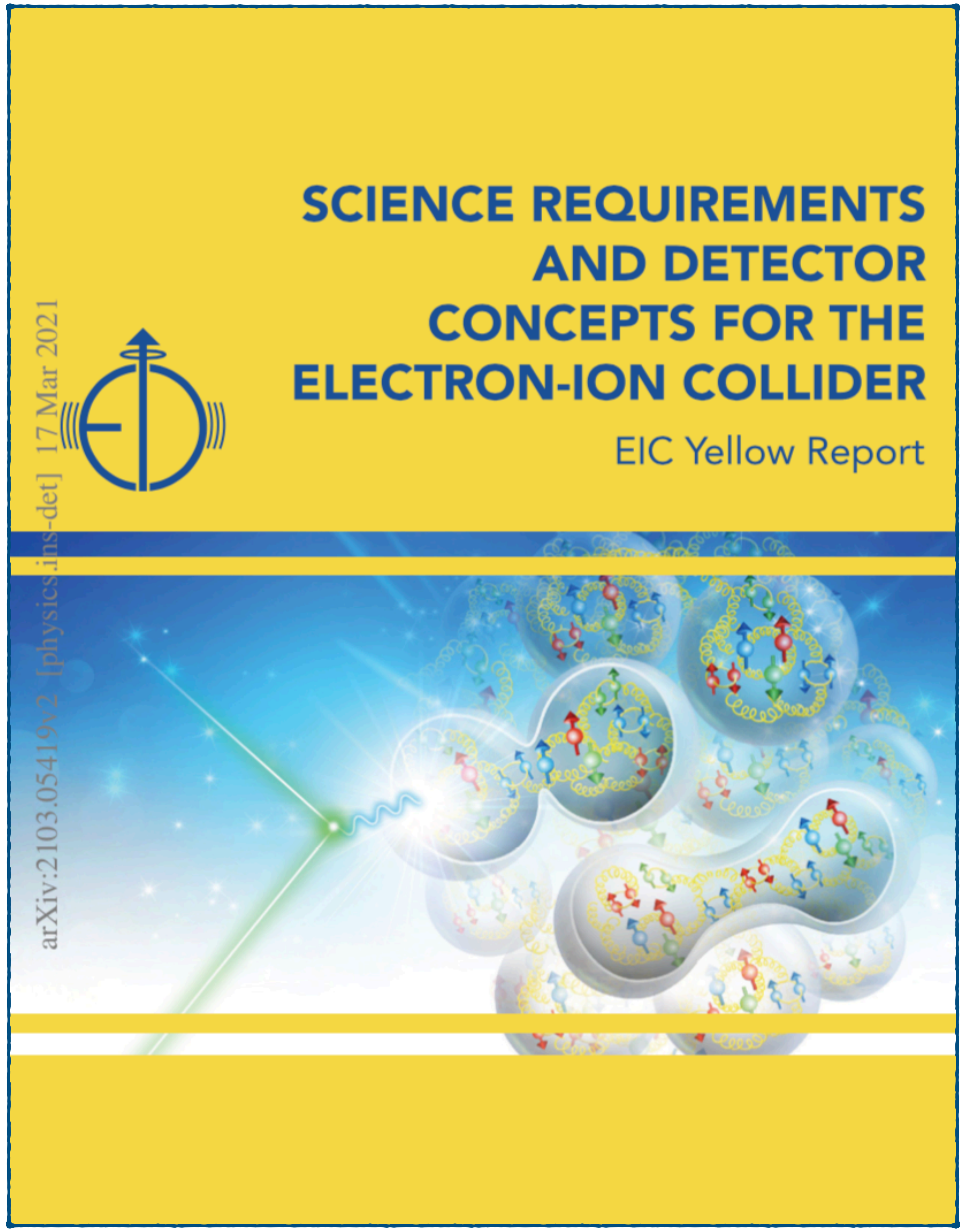
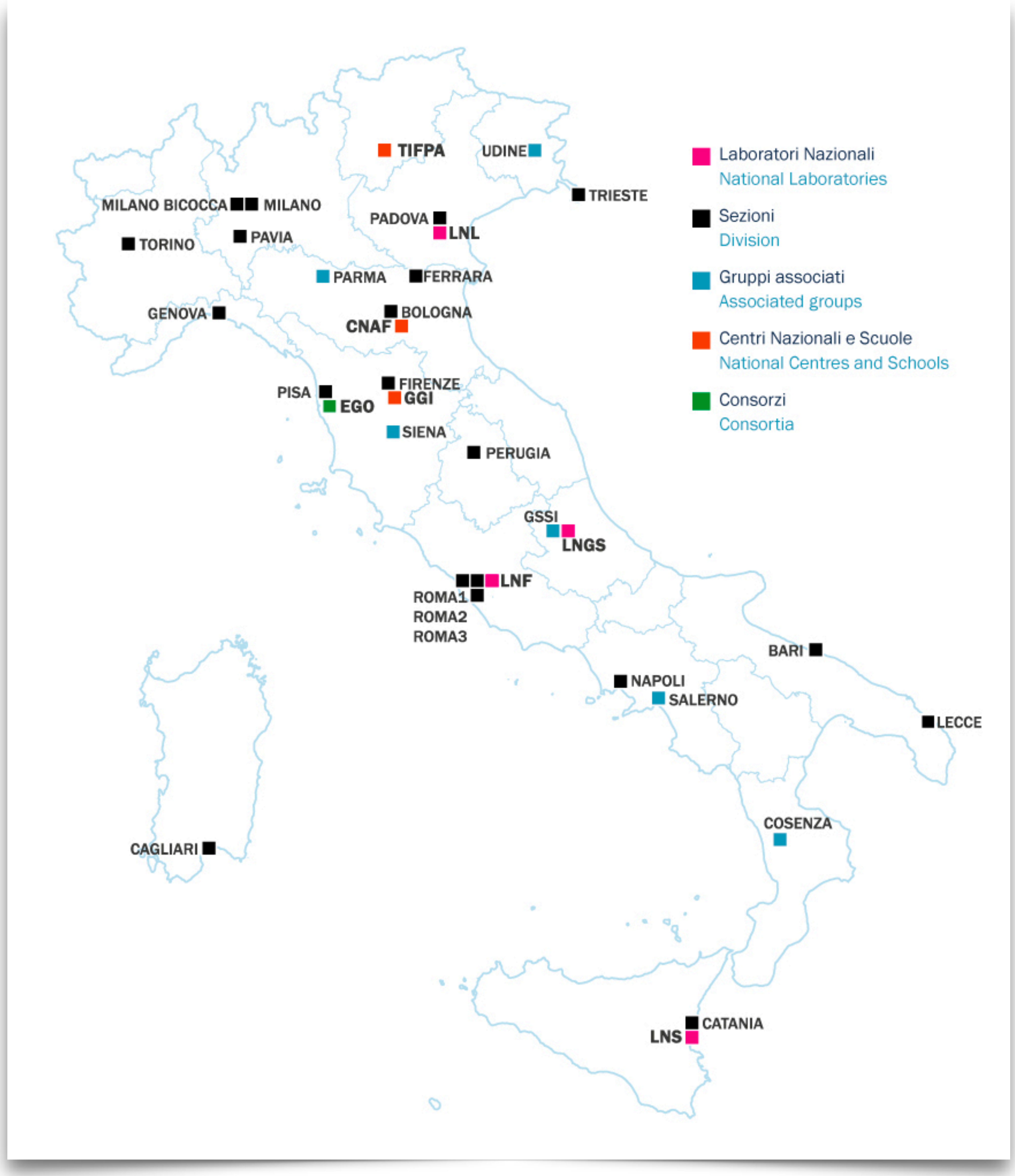


- Result of a **year-long** preparation
- **902** pages, **414** authors, **121** institutions
- **M. Radici** (Pavia), co-editor
- **B. Pasquini** (Pavia), co-convener of Exclusive WG
- NINPHA took part in **all** the Physics WGs

[EICUG [arXiv:2103.05419]]

NINPHA activities at Local Units

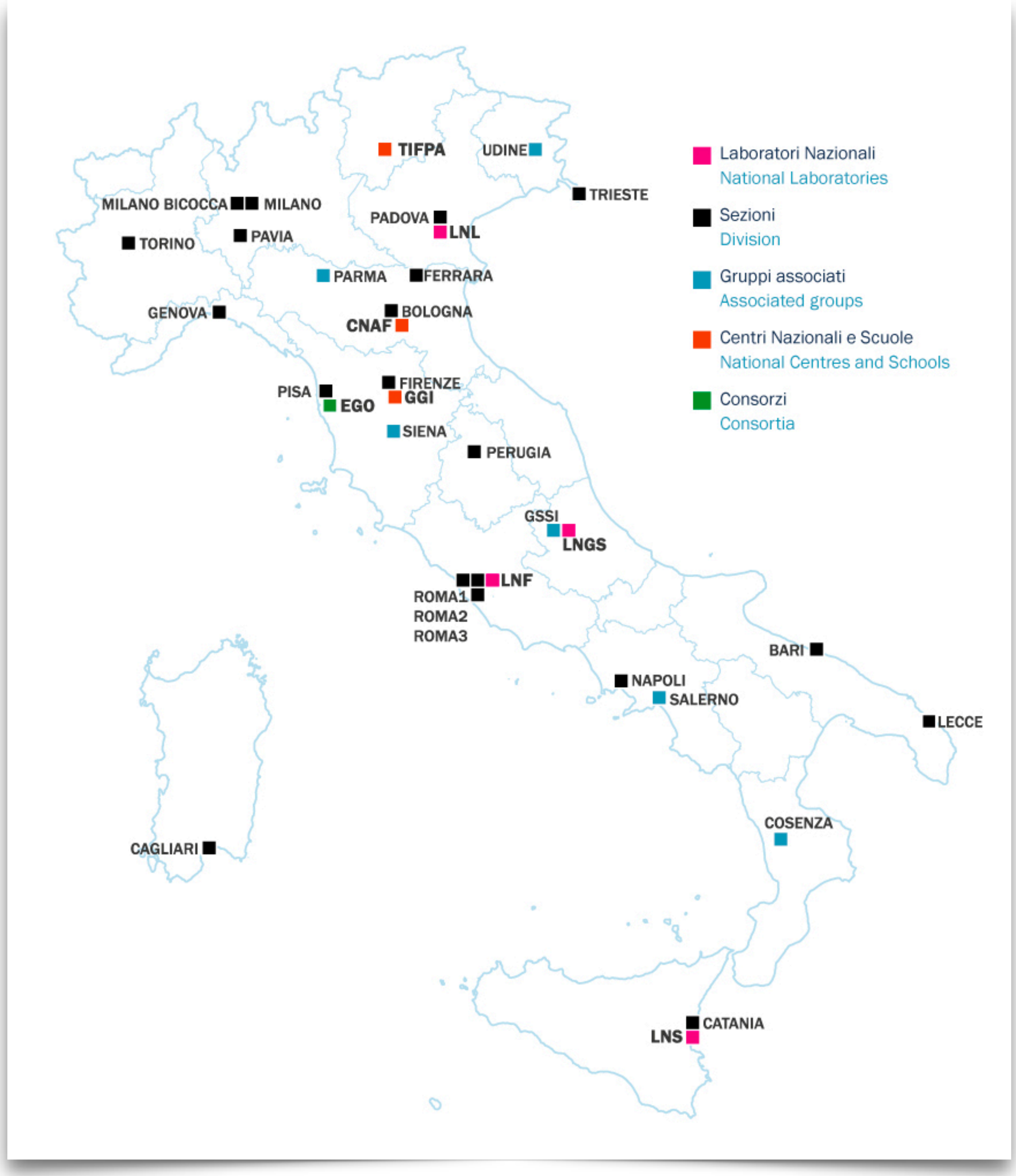
National INitiative in Physics of HAdrons



National INitiative in Physics of HAdrons

6 Research Lines

- Field and String Theory
- Phenomenology of Elementary Particles
- Nuclear and Hadronic Physics
- Mathematical Methods
- Astroparticle Physics
- Statistical Physics and Applied Field Theory



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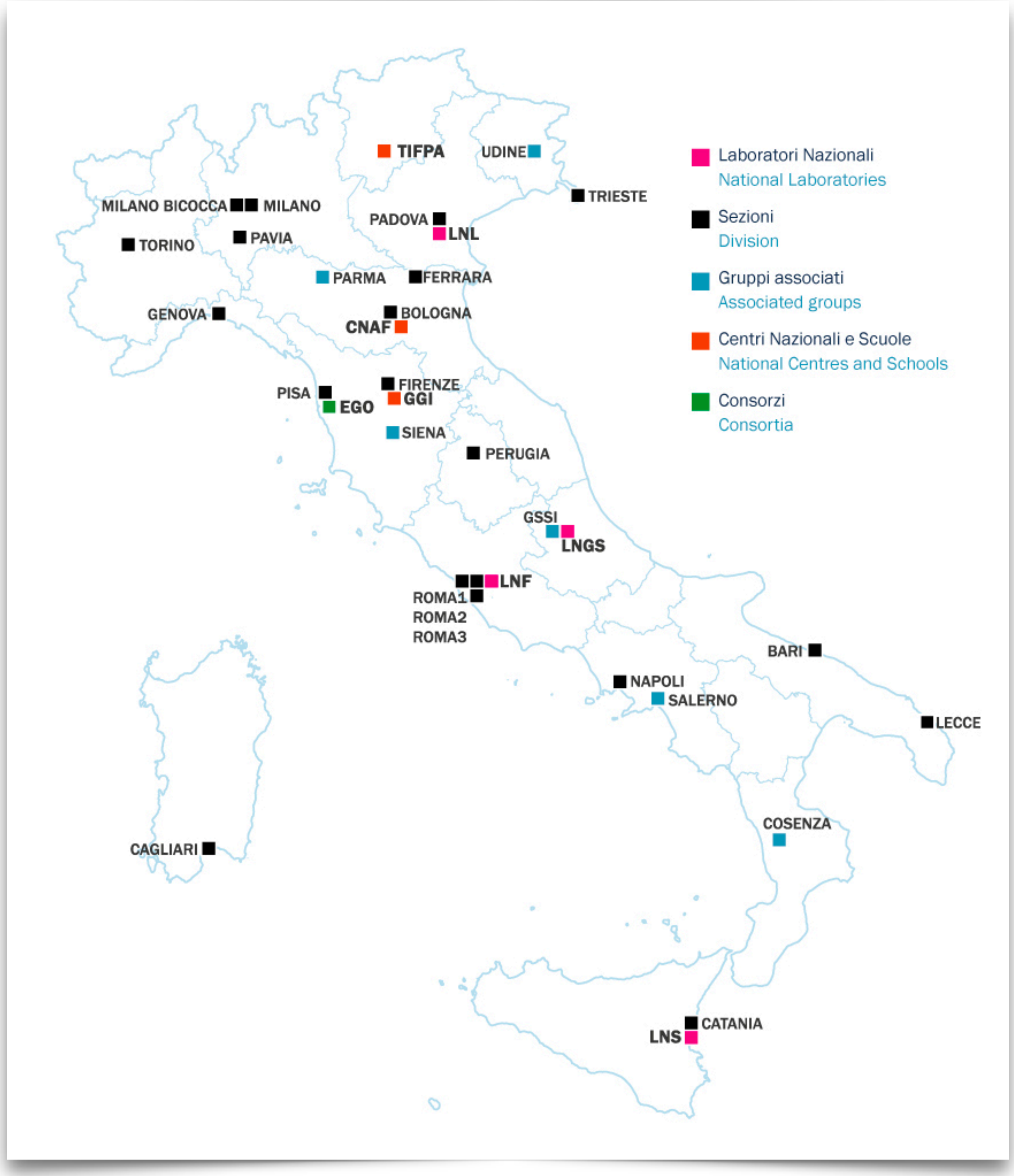
4 Initiatives

NINPHA



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- Field and String Theory
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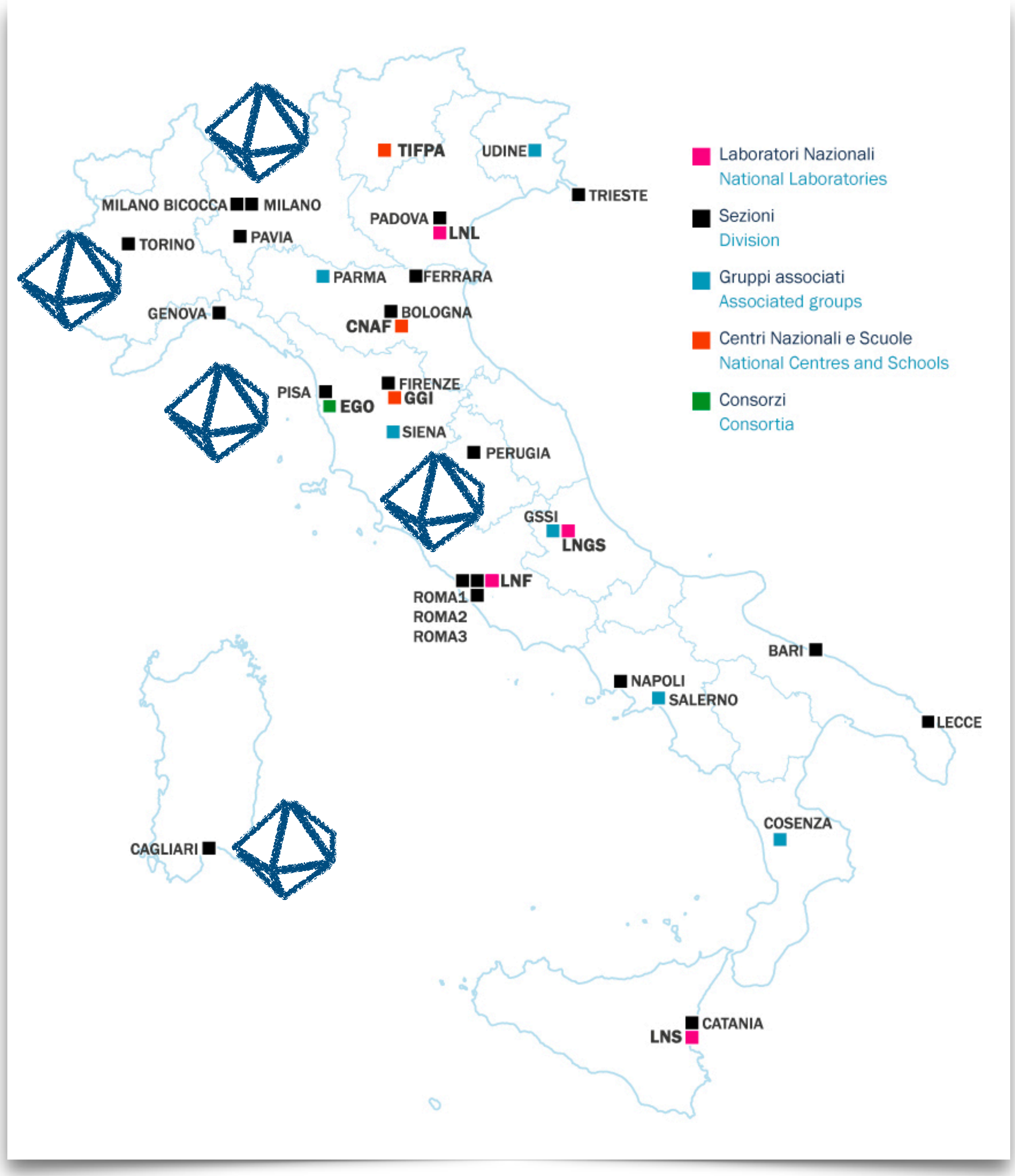
4 Initiatives

NINPHA

National Coordinator: **Marielena Boglione** (Torino)

5 Local Units: **Cagliari**, **Genova**, **Pavia**, **Perugia**, **Torino**

>**30** Associates, ~**90** papers, ~**45** talks (2020)



INFN Unit: Cagliari

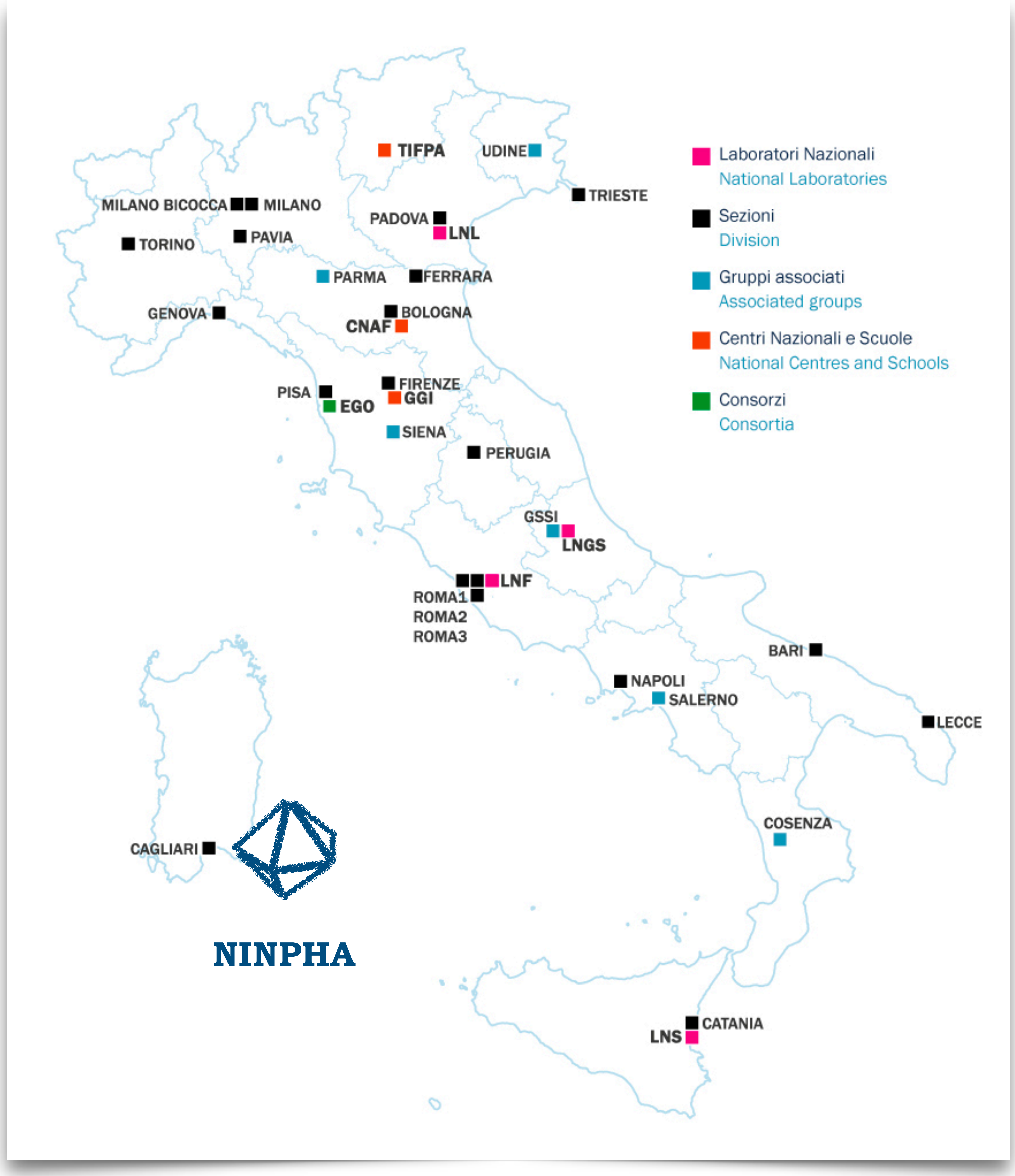
Staff members

Umberto D’Alesio, U. Cagliari, Associate Professor, <u>CSN4 Local Coordinator</u>

Francesco Murgia, INFN, First Researcher

Cristian Pisano, U. Cagliari, Associate Professor

Giuseppe Bozzi, U. Cagliari, Researcher



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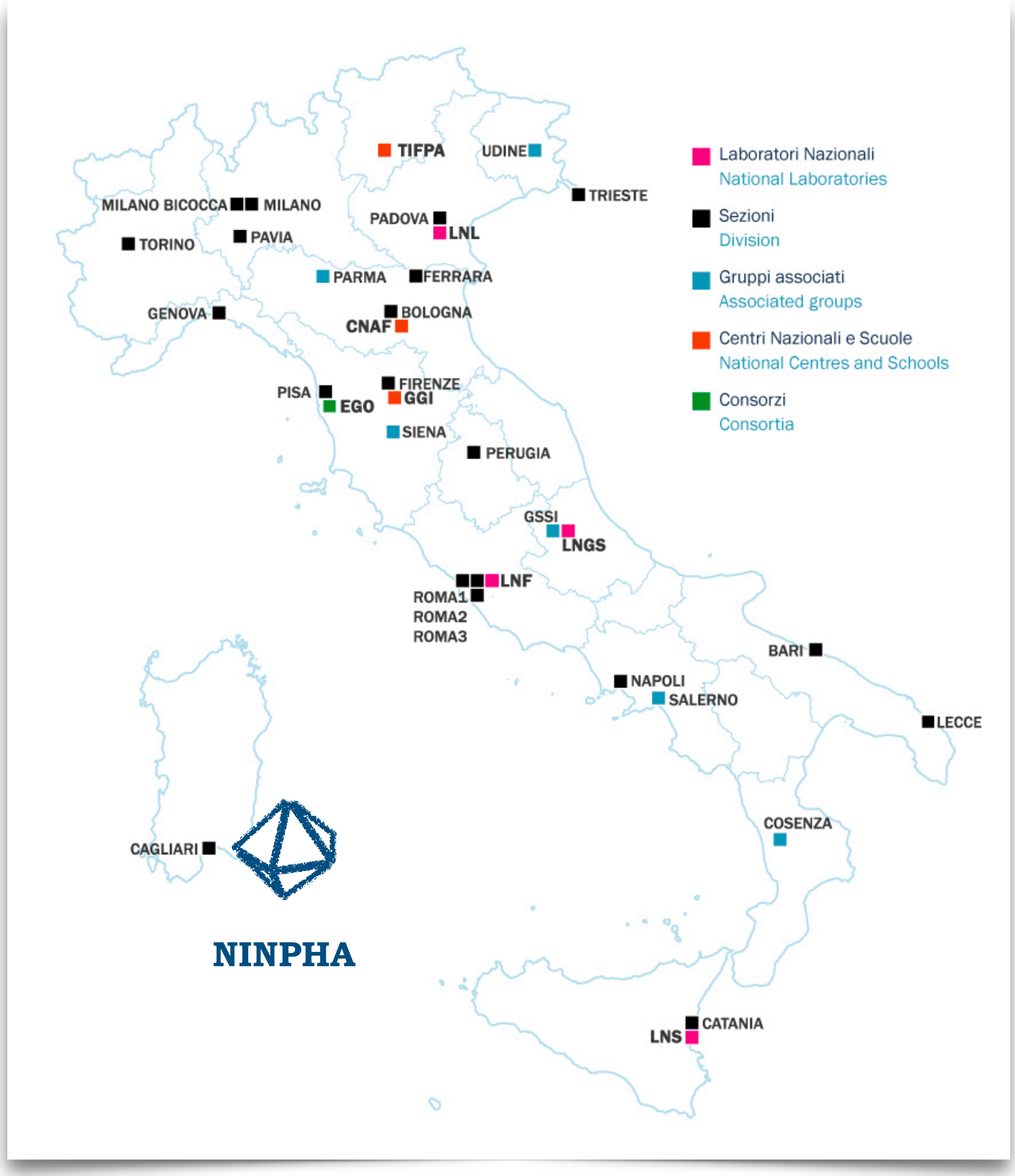
Other Participants

Luca Maxia, U. Cagliari, PhD Student

Marco Zaccheddu, U. Cagliari, PhD Student

Carlo Flore, IJCLab (Paris), Post-doc, External Collaborator

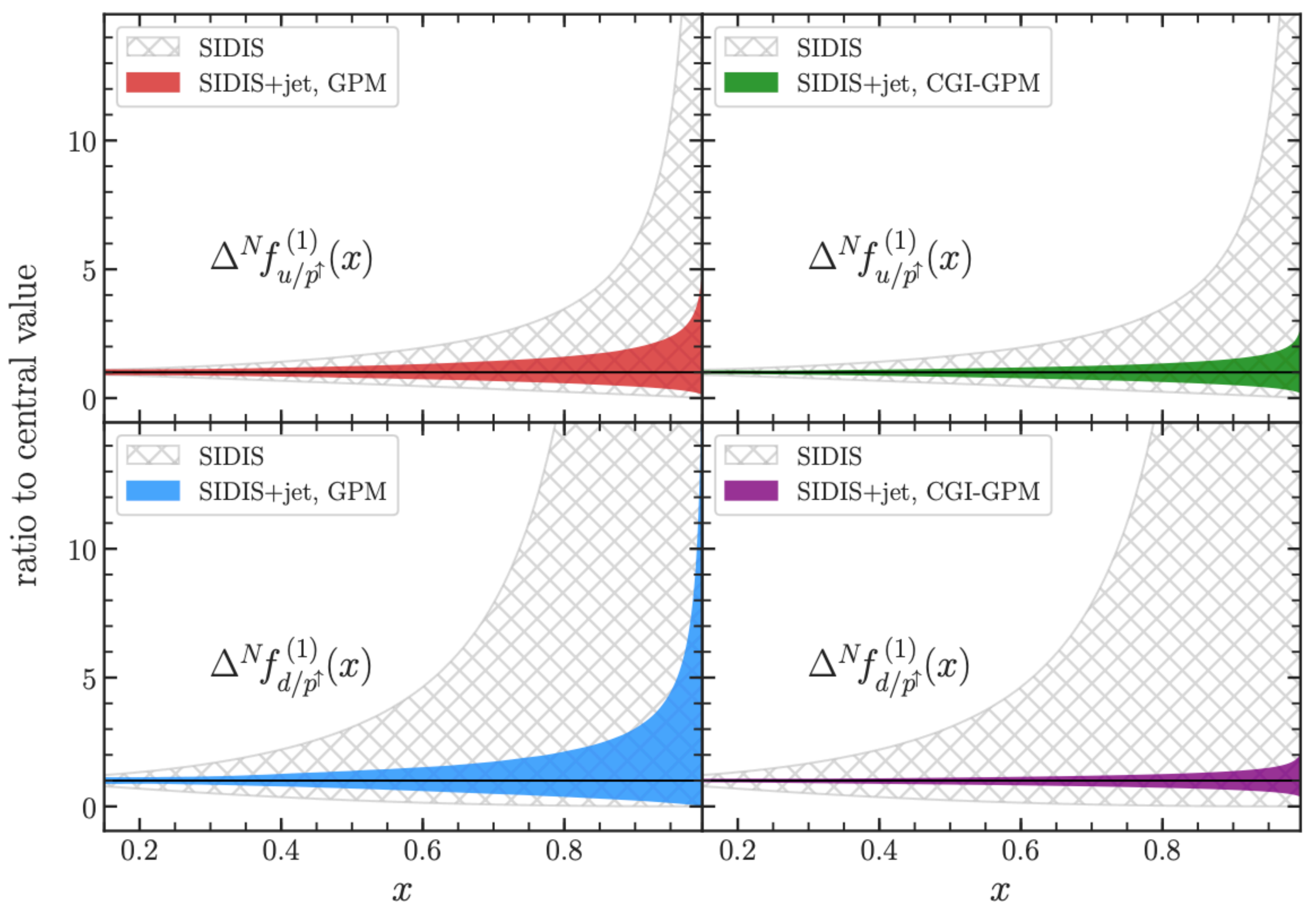


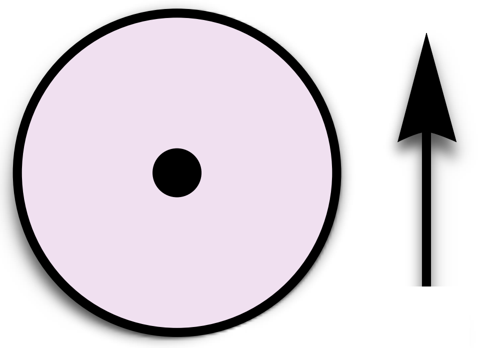
Quark Sivers and J/Ψ production in SIDIS

* Reweighting of quark Sivers with jet at *pp* STAR

  NINPHA/**Cagliari** + NINPHA/**Torino** + JLab

  STAR data to costrain quark Sivers at large-x



 $\Leftrightarrow$ Quark contribution to nucleon spin

[M. Boglione *et al.* (2021)]

Quark Sivers and J/Ψ production in SIDIS

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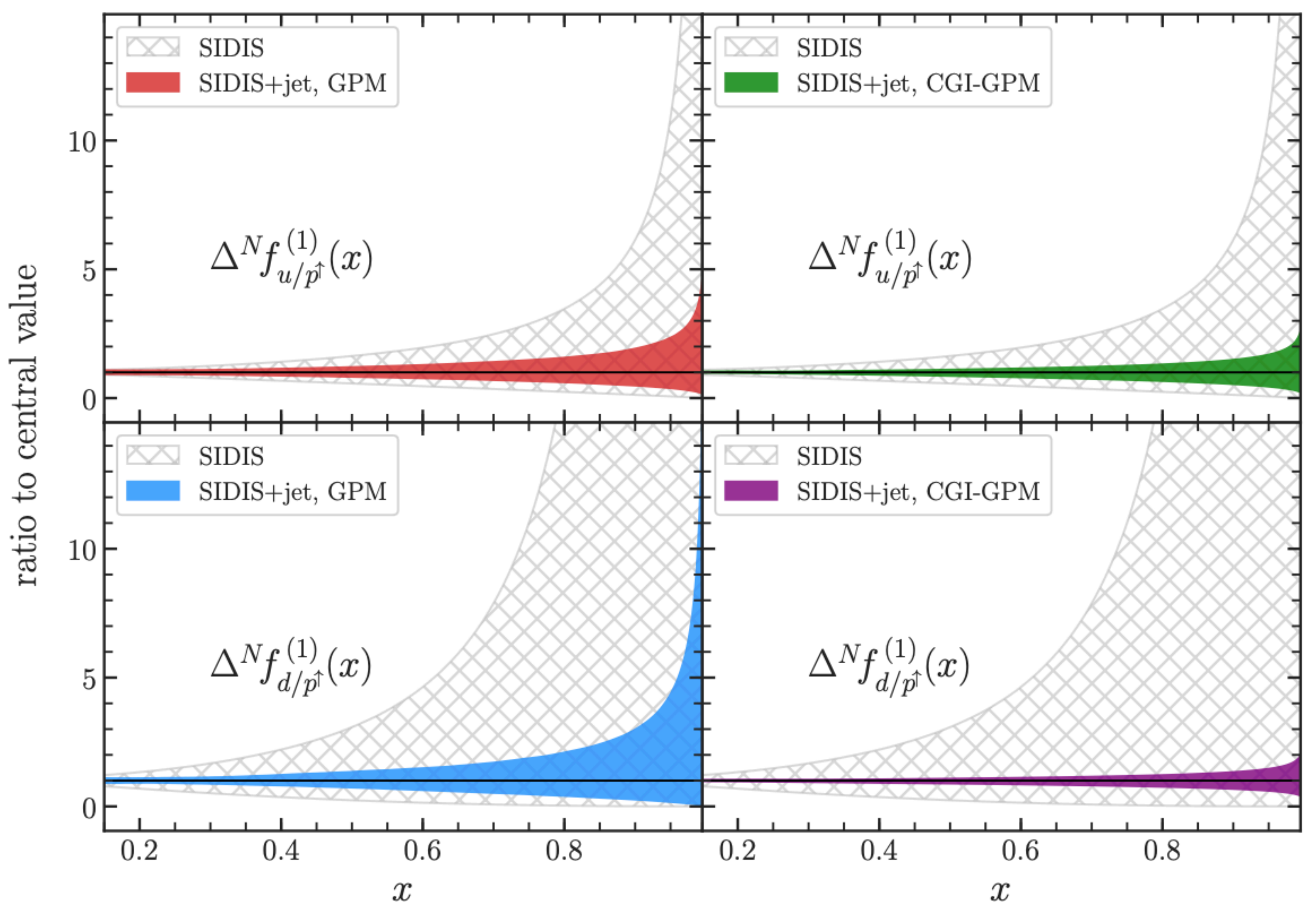

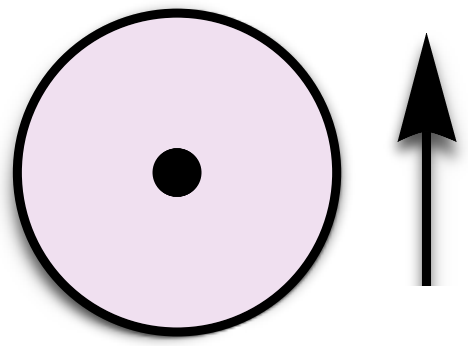

⇔ Quark contribution to nucleon spin

🔗 [M. Boglione *et al.* (2021)]

- ✱ NLO large-p_T J/Ψ in SIDIS at HERA and **EIC**
  🔗 [C. Flore *et. al.* (2020)]
- ✱ J/Ψ in SIDIS: matching low and high p_T
  🔗 [D. Boer *et al.* (2020)]
- ✱ Extracting SIDIS J/Ψ NRQCD-CO at the **EIC**
  🔗 [D. Boer, C. Pisano, P. Taels (2021)]
- ✱ J/Ψ pol., gluon TMDs and shape functions
  🔗 [U. D'Alesio *et al.* (2021)]

TMD FFs in e^+e^- annihilations

- First extraction of Λ polarizing TMD FF $\qquad e^+e^- \rightarrow$ TMD factorization proven

Puzzle: spontaneous transverse polarization

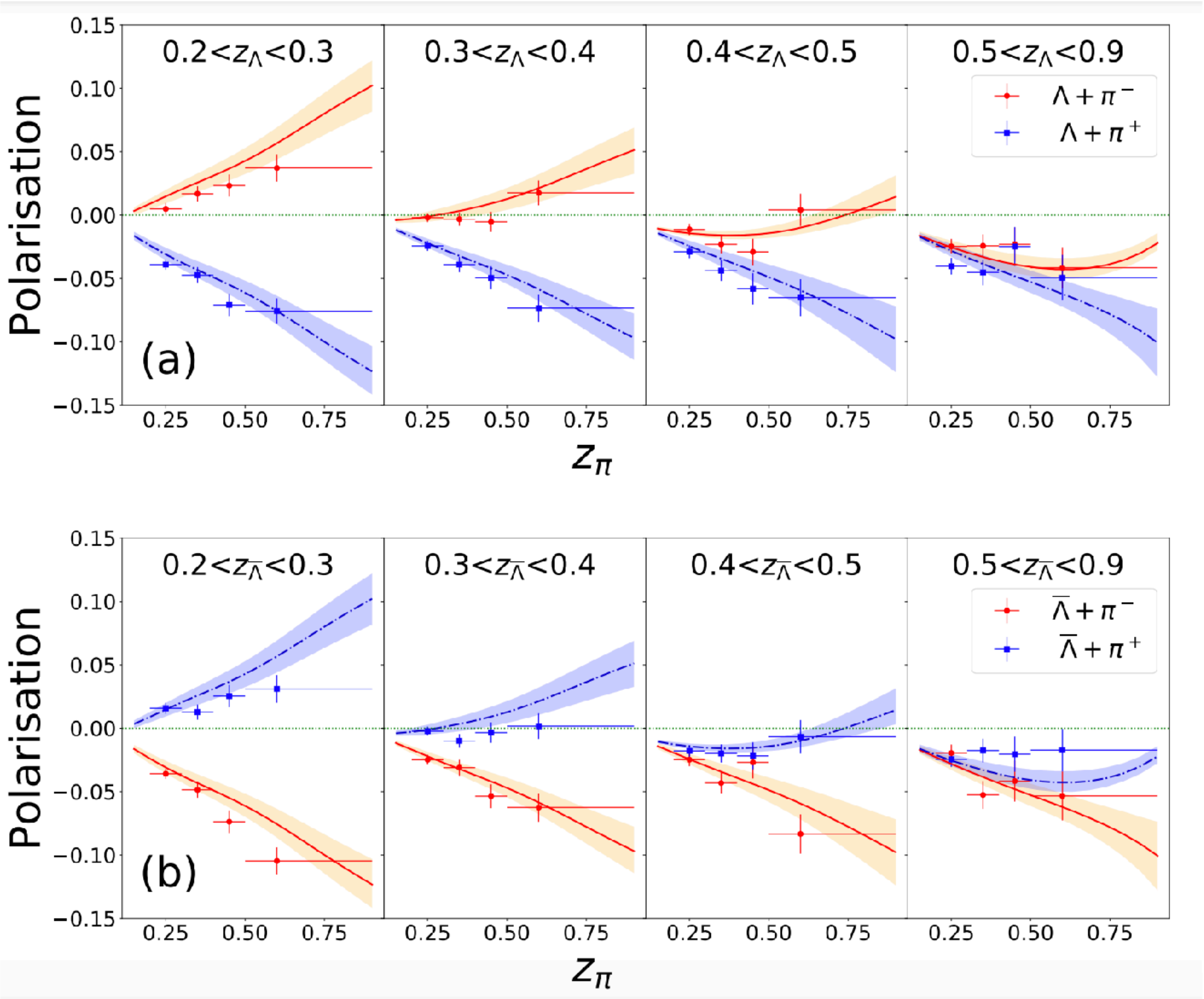

FIG. 2. Best-fit estimates of the transverse polarisation for Λ and $\bar{\Lambda}$ production in $e^+e^- \to \Lambda(\bar{\Lambda})h + X$, for $\Lambda\pi^\pm$ (a), $\bar{\Lambda}\pi^\pm$ (b), $\Lambda K^\pm$ (c), $\bar{\Lambda}K^\pm$ (d), as a function of z_h (of the associated hadron) for different z_Λ bins. Data are from Belle [11]. The statistical uncertainty bands, at 2σ level, are also shown. Notice that data for $z_{\pi,K} > 0.5$ are not included in the fit.

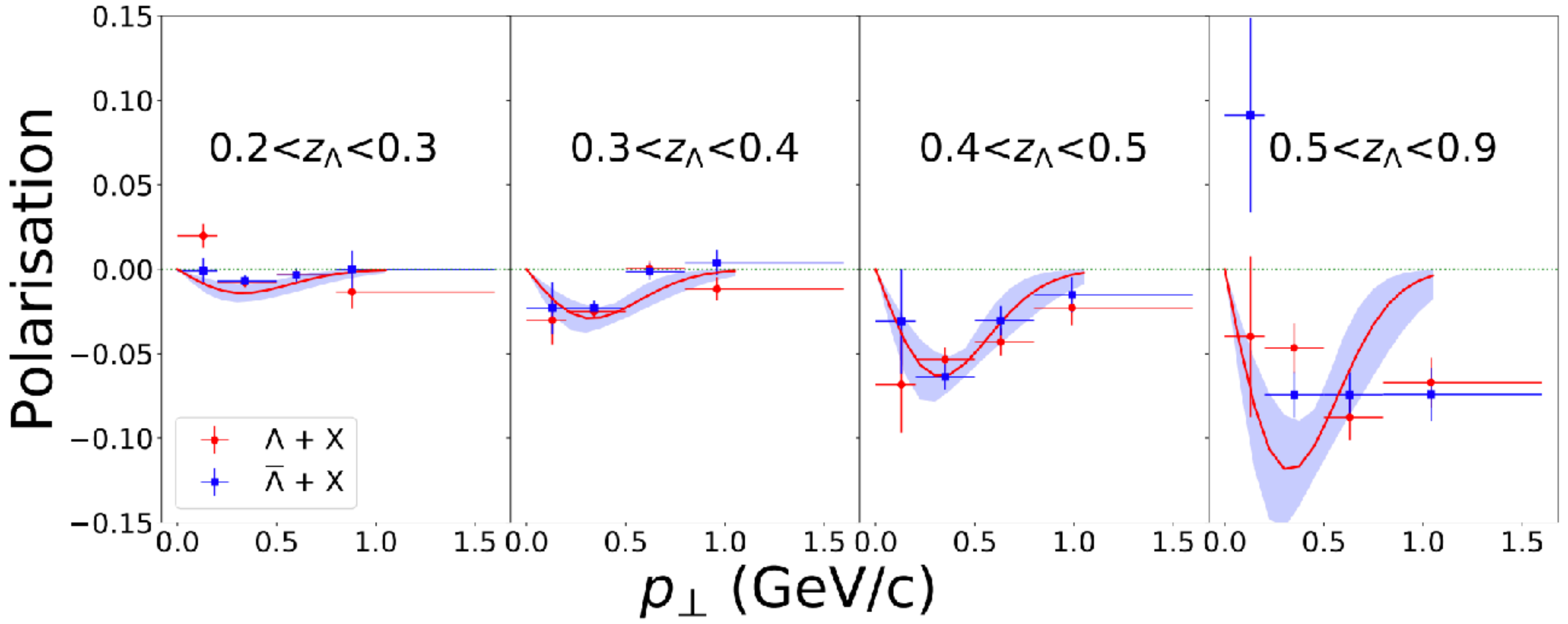

FIG. 1. Best-fit estimates of the transverse polarisation for inclusive Λ and $\bar{\Lambda}$ production in $e^+e^- \to \Lambda(\text{jet}) + X$ (thrust-plane frame) as a function of $p_\perp$ for different z_Λ bins (energy fractions), compared against Belle data [11]. The statistical uncertainty bands, at 2σ level, are also shown. Notice that curves for Λ and $\bar{\Lambda}$ coincide and that data in the rightmost panel are not included in the fit.

🔗 [U. D'Alesio, F. Murgia, M. Zaccheddu (2020)]

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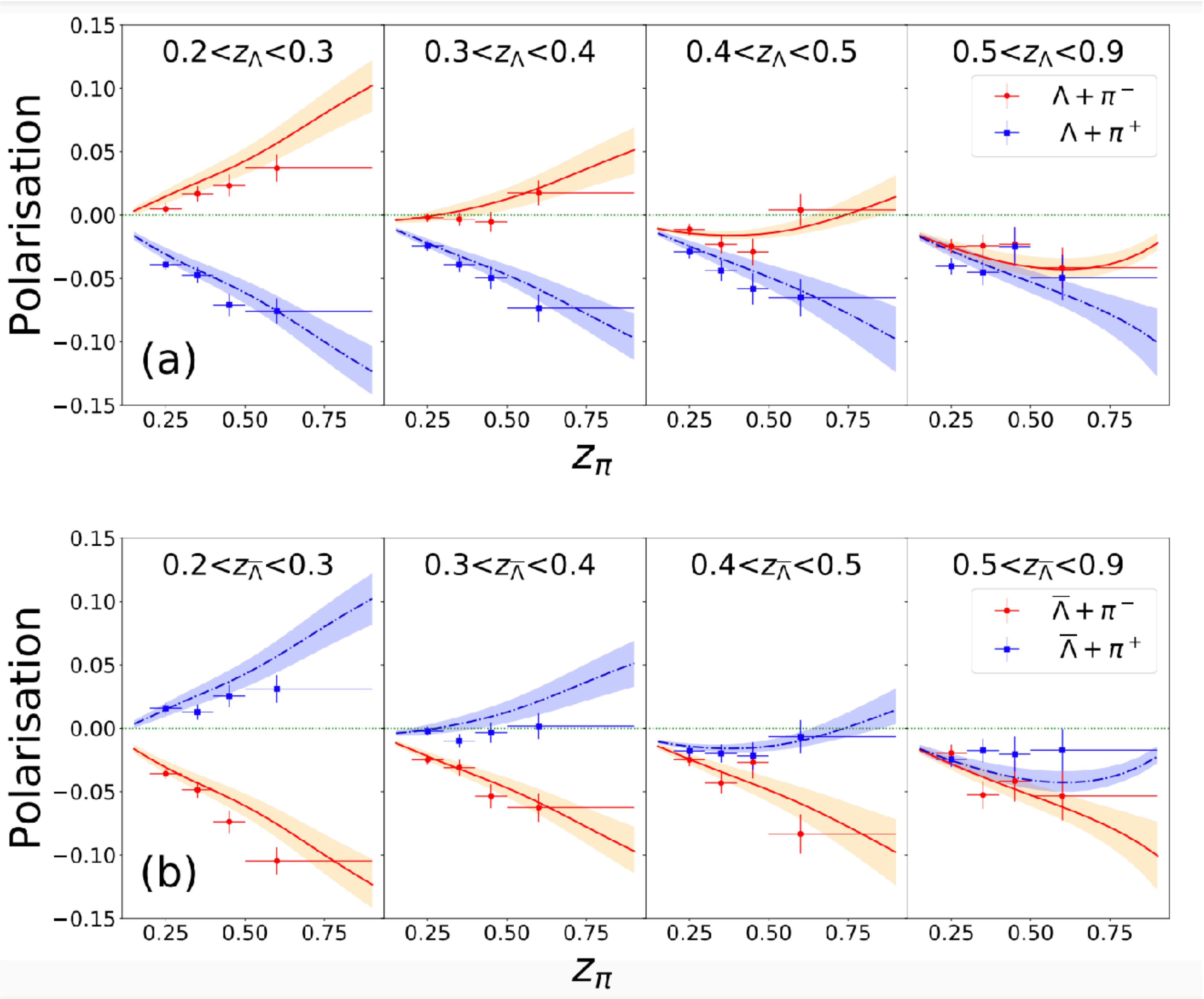

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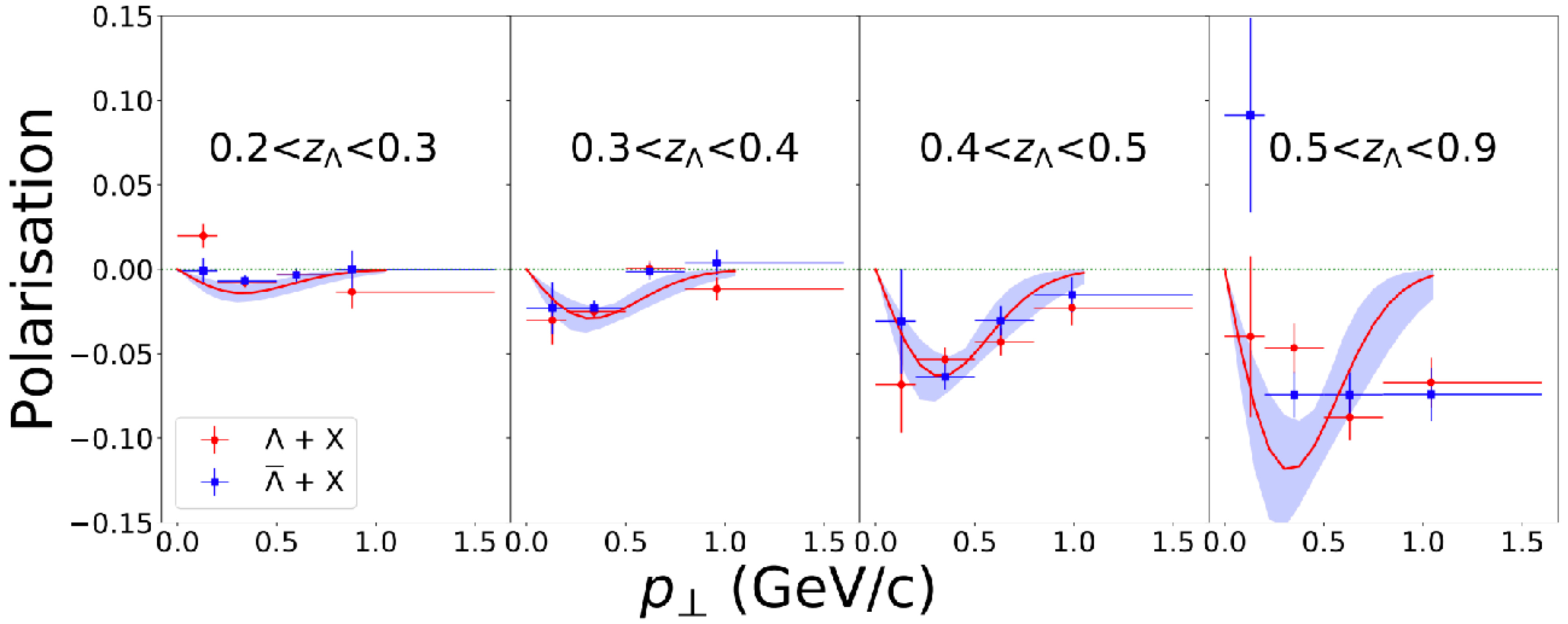

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🔗 [U. D'Alesio, F. Murgia, M. Zaccheddu (2020)]

* TMD FFs via the helicity formalism

$$e^+e^- \to h_1 h_2 + X$$

🔗 [U. D'Alesio, F. Murgia, M. Zaccheddu (2021)]

Gluon Sivers effect in quarkonium production

* Gluon distribution via onium production, *pp* and semi-inclusive DIS (SIDIS) $\leftarrow$ TMD $\otimes$ NRQCD

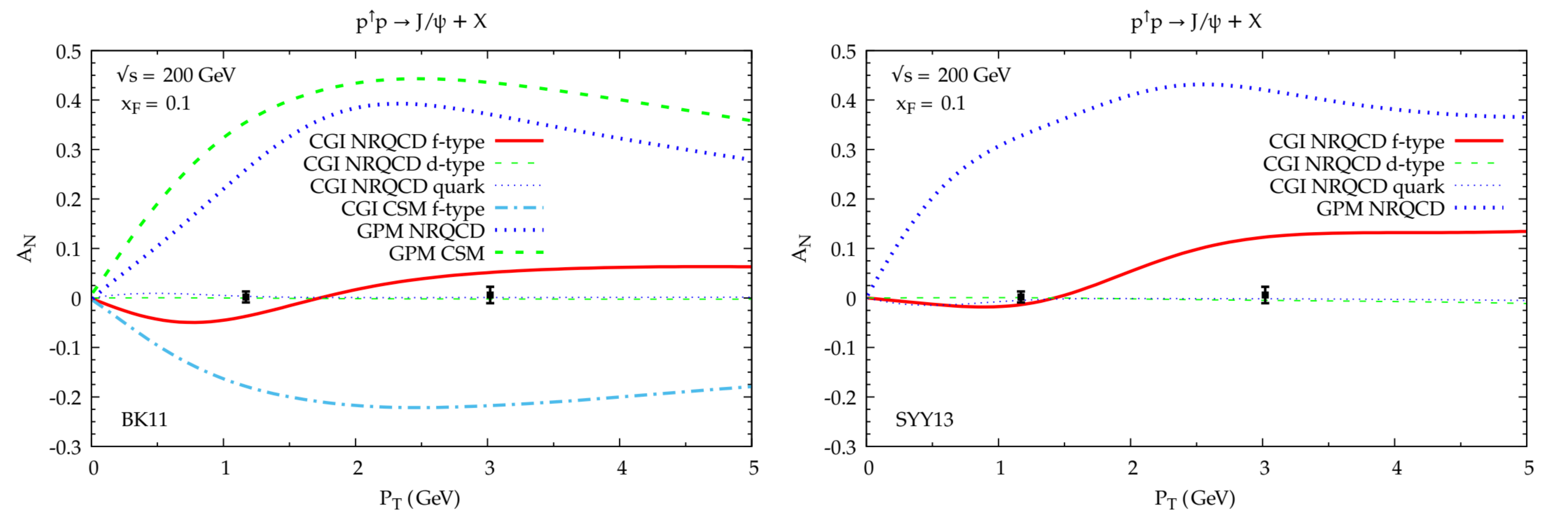
$$p^{\uparrow}p \to J/\psi + X$$

$$A_N \equiv \frac{\mathrm{d}\sigma^{\uparrow} - \mathrm{d}\sigma^{\downarrow}}{\mathrm{d}\sigma^{\uparrow} + \mathrm{d}\sigma^{\downarrow}} \equiv \frac{\mathrm{d}\Delta\sigma}{2\mathrm{d}\sigma}$$

CGI-GPM $\otimes$ NRQCD-CO

Gauge link $\Rightarrow f_{1T}^{\perp(f)} \gg f_{1T}^{\perp(d)}$

🔗 [U. D'Alesio *et al.* (2020)]



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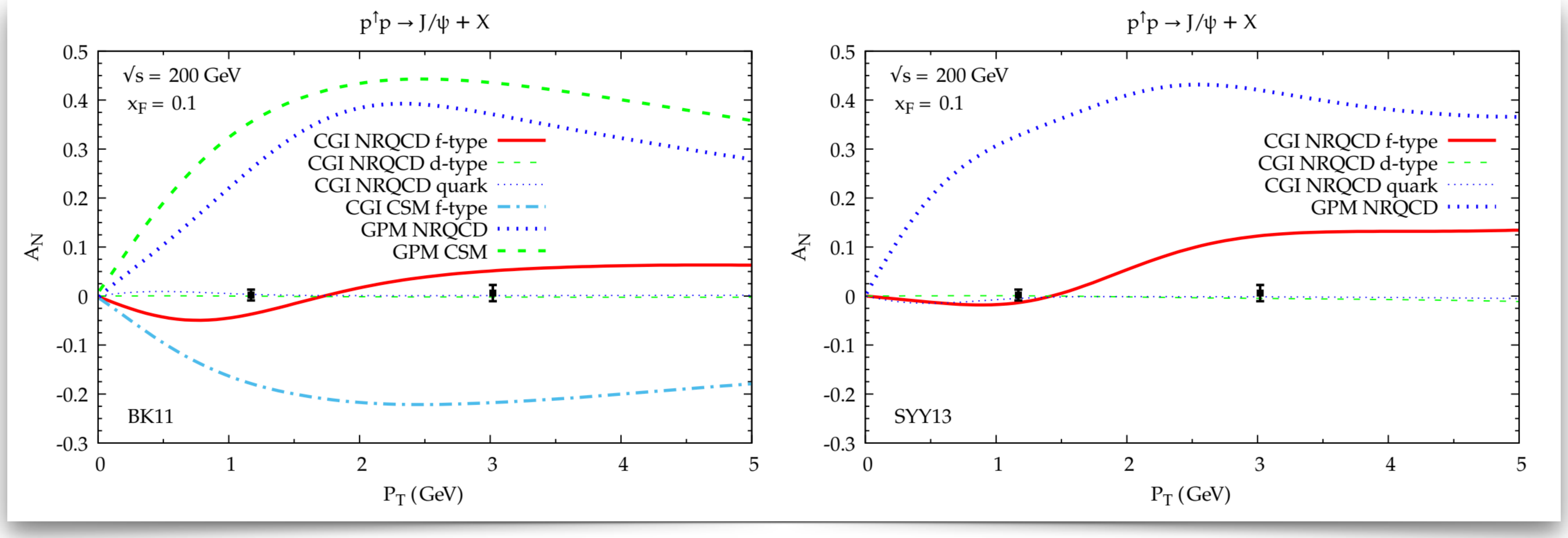
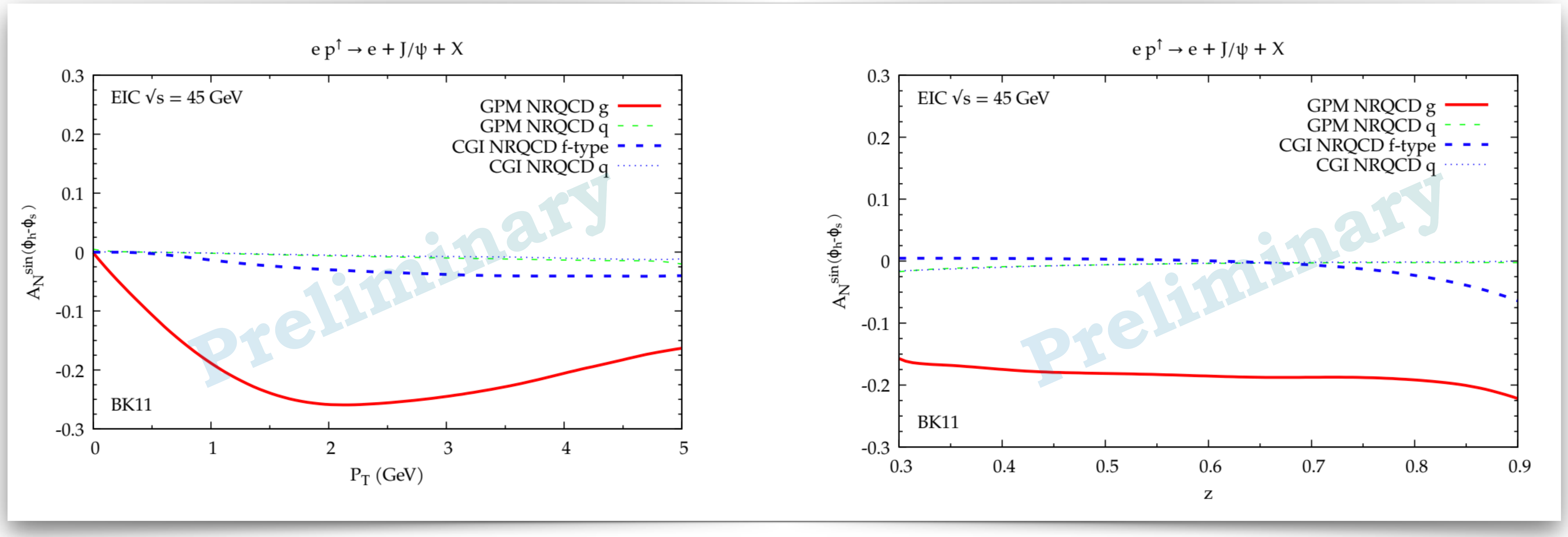


$$ep^{\uparrow} \to e + J/\psi + X$$

Gluon Sivers $\gg$ quark Sivers

Role of **EIC** $\rightarrow$ gluon Sivers

🔗 [S. Rajesh *et al.* (2021)]

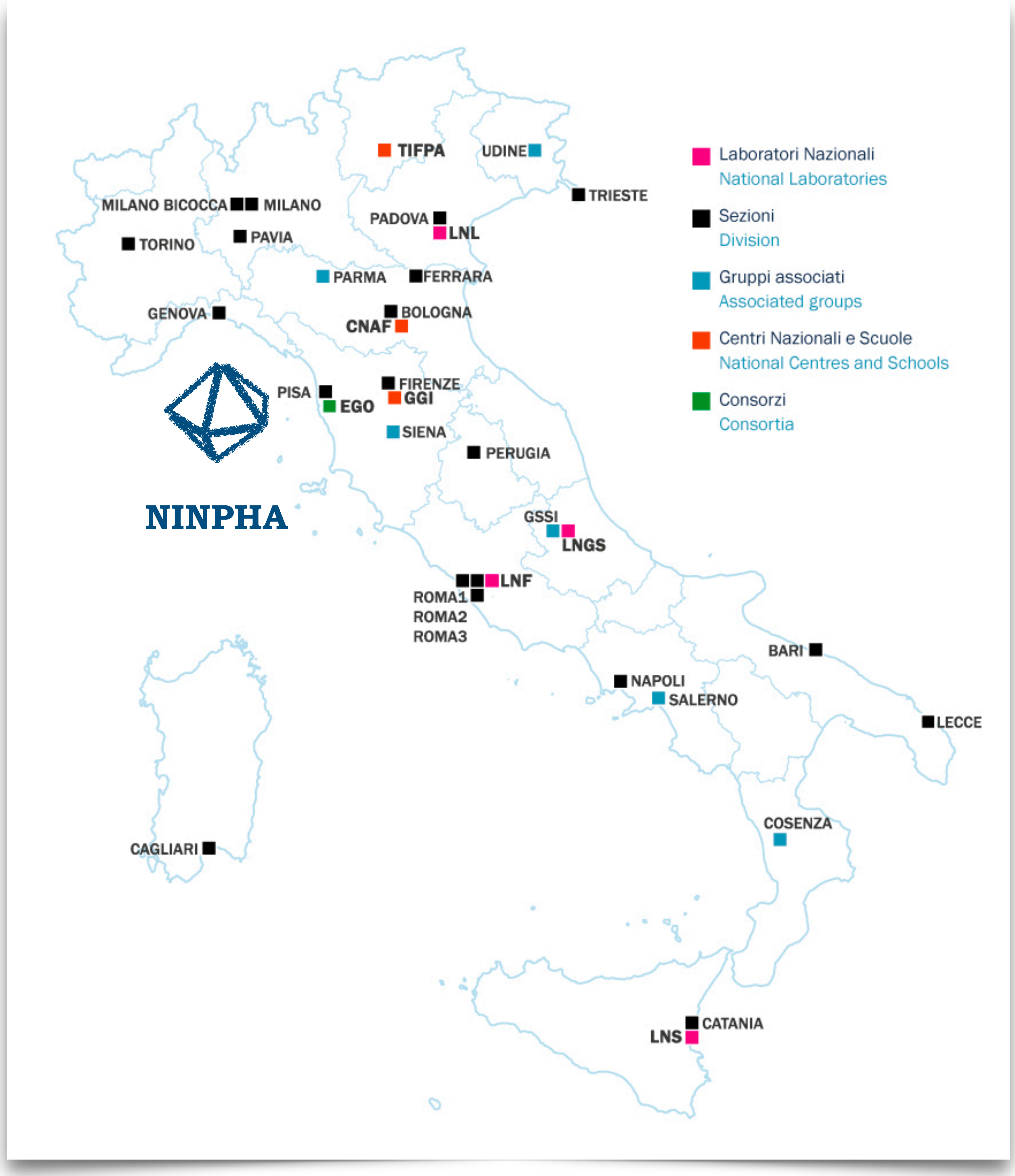


INFN Unit: Genova

Staff members

Elena Santopinto, INFN, First Researcher

Paolo Saracco, INFN, Researcher



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Staff members

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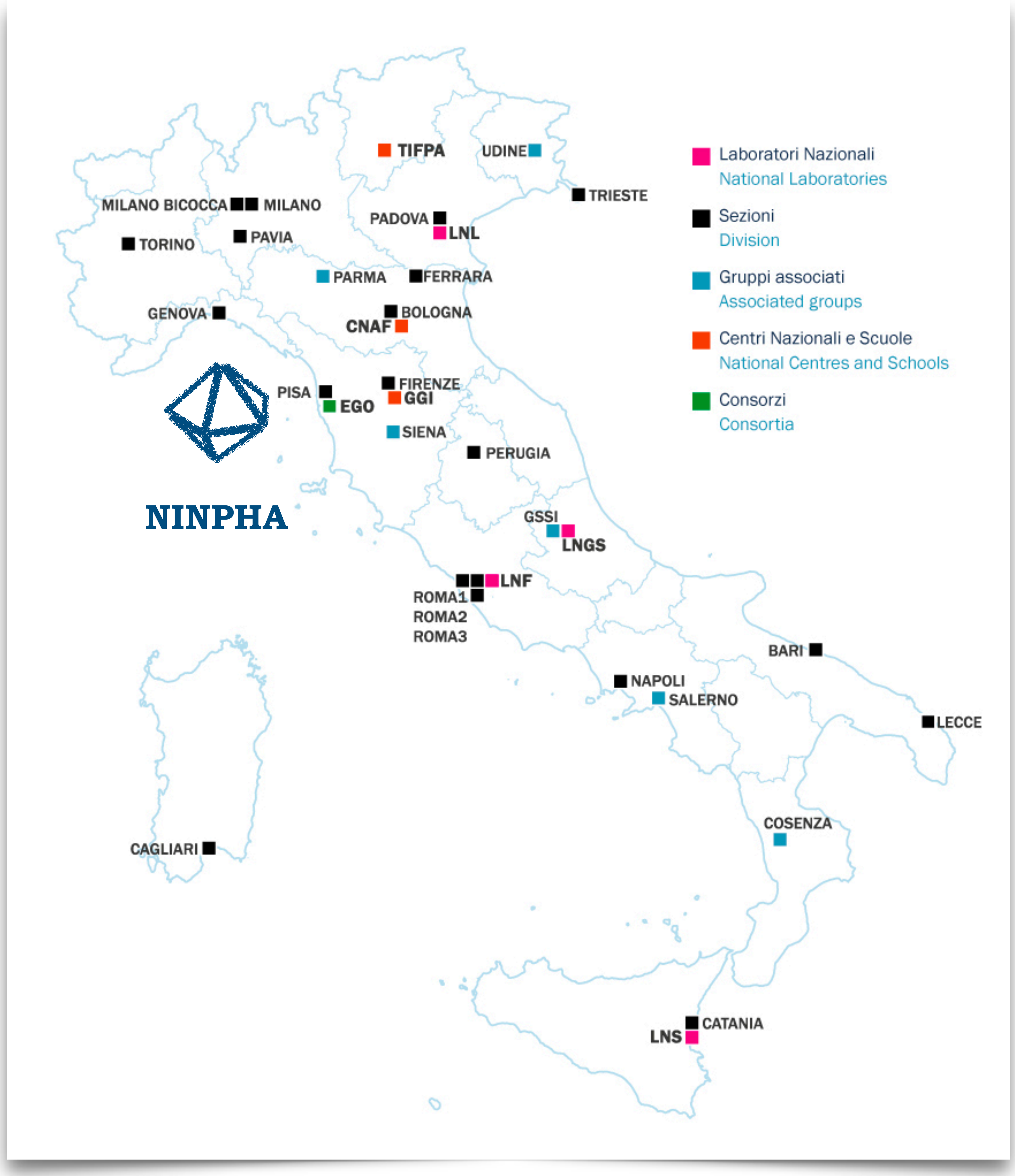
Paolo Saracco, INFN, Researcher

Other Participants

Ruslan Magaña Vsevolodovna, U. Genova, Post-doc

Many external collaborators:

Europe, China, Japan, USA and Latin America



INFN Unit: Genova

* *Systematic* study of **heavy-hadron spectroscopy**

* **Tetraquarks/Pentaquarks/Hybrids** $\rightarrow$ *Exotics*

* **Prediction** before *detection* (LHCb) of new Ω_b states

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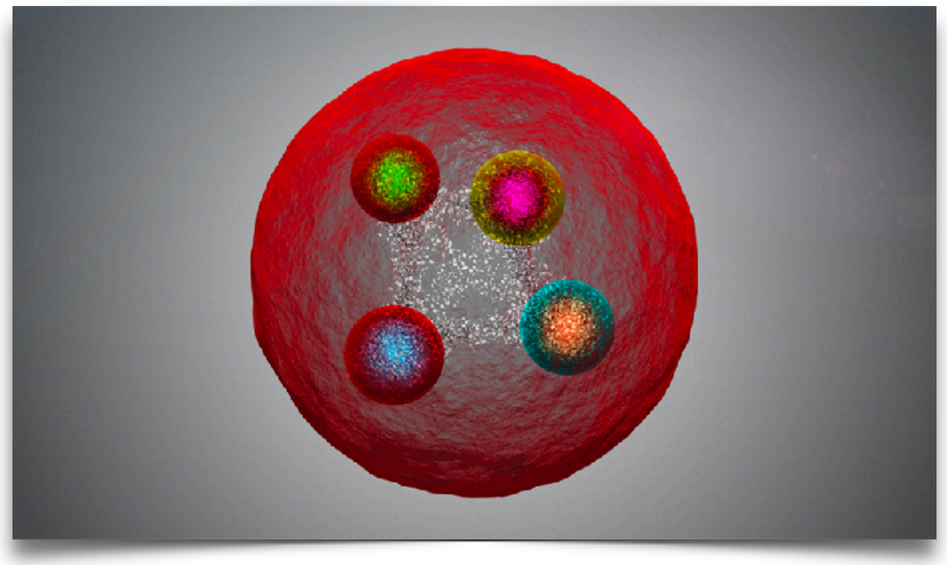

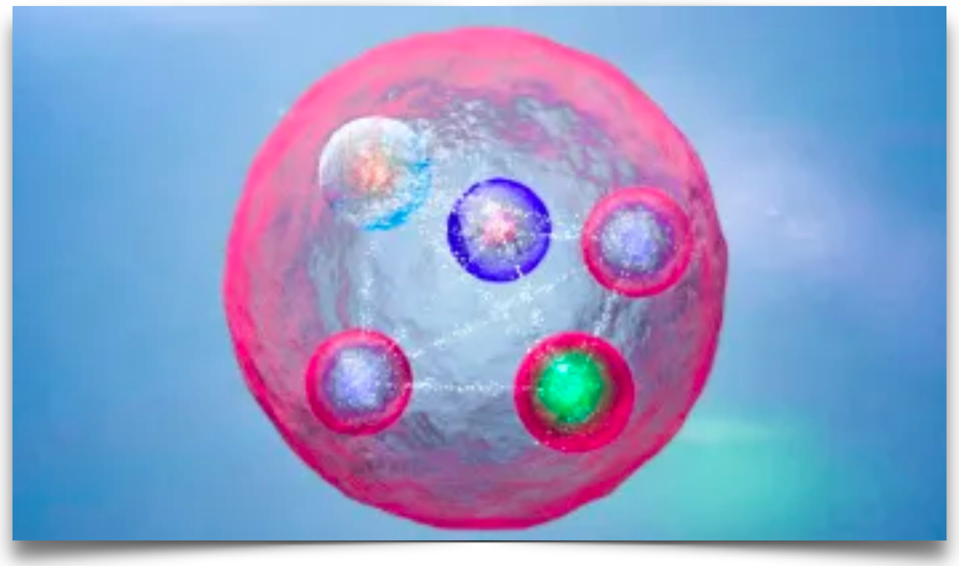

- NINPHA/**Genova** + NINPHA/**Perugia**
- Relativistic description of 3-body bound systems
- **Tools** for GPD/TMD modeling at the **EIC**

INFN Unit: Genova

* *Systematic* study of **heavy-hadron spectroscopy**
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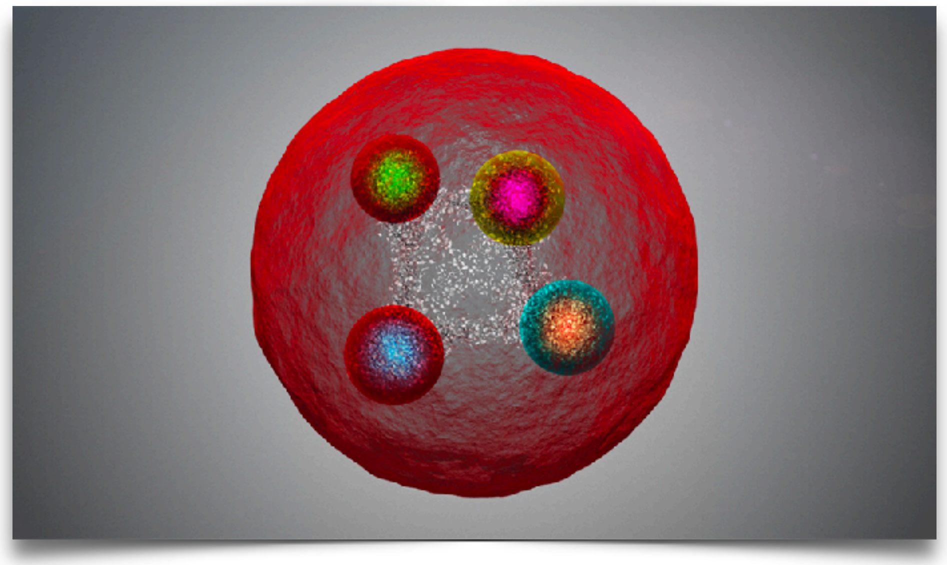
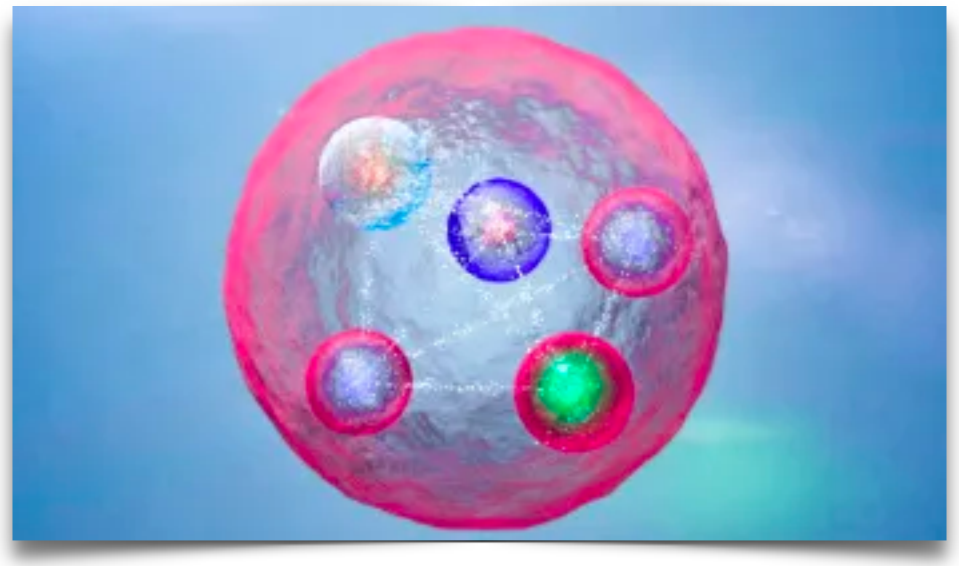
* **Prediction** before *detection* (LHCb) of new Ω_b states

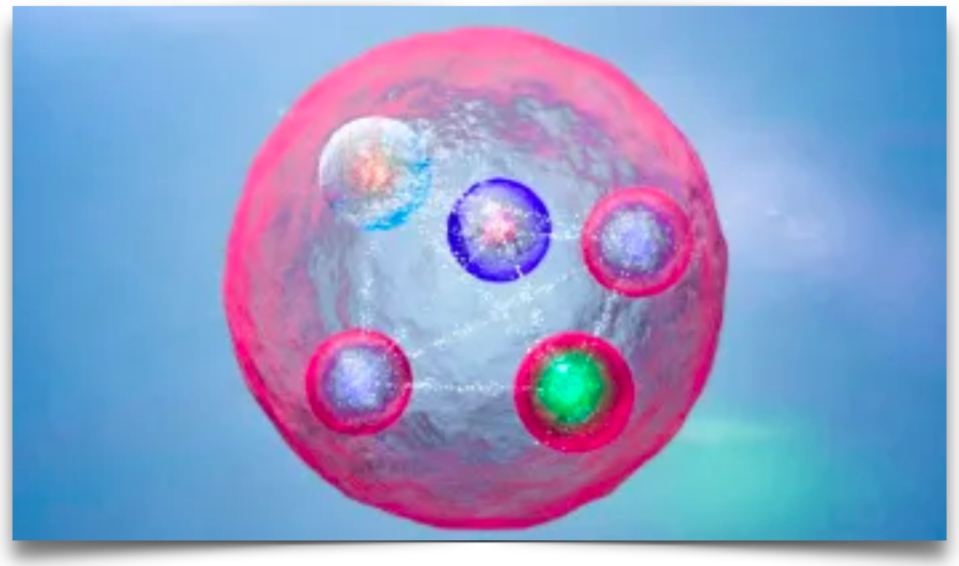


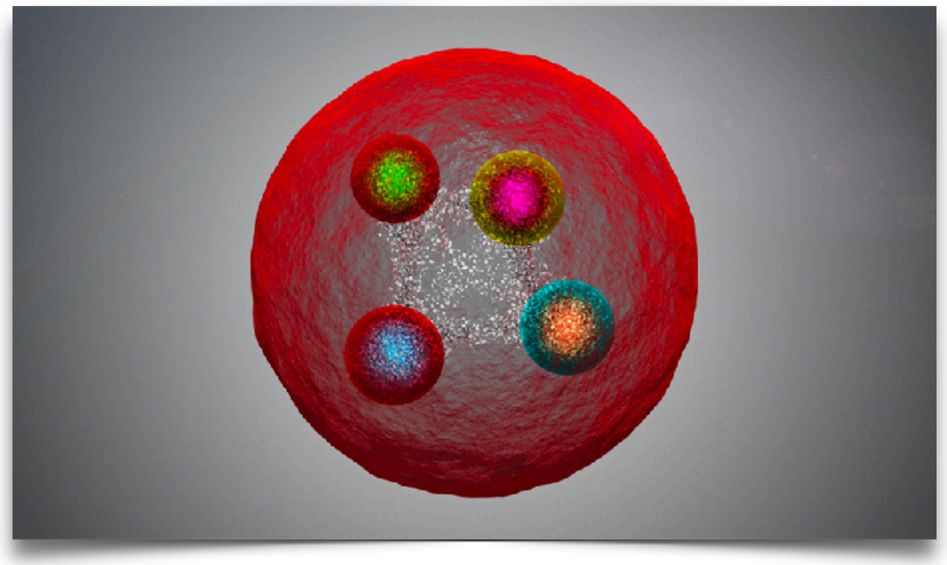


* NINPHA/**Genova** + NINPHA/**Perugia**
* Relativistic description of 3-body bound systems
* **Tools** for GPD/TMD modeling at the **EIC**

* **Interdisciplinary** connections
* Exotic hadrons as *candidates* for **dark matter**
* Exotic matter inside **neutron stars**

INFN Unit: Genova





- *Systematic* study of **heavy-hadron spectroscopy**
- **Tetraquarks/Pentaquarks/Hybrids** $\rightarrow$ *Exotics*
- **Prediction** before *detection* (LHCb) of new Ω_b states

- Compact pentaquarks structures

  🔗 [E. Santopinto, A. Giachino (2017)]

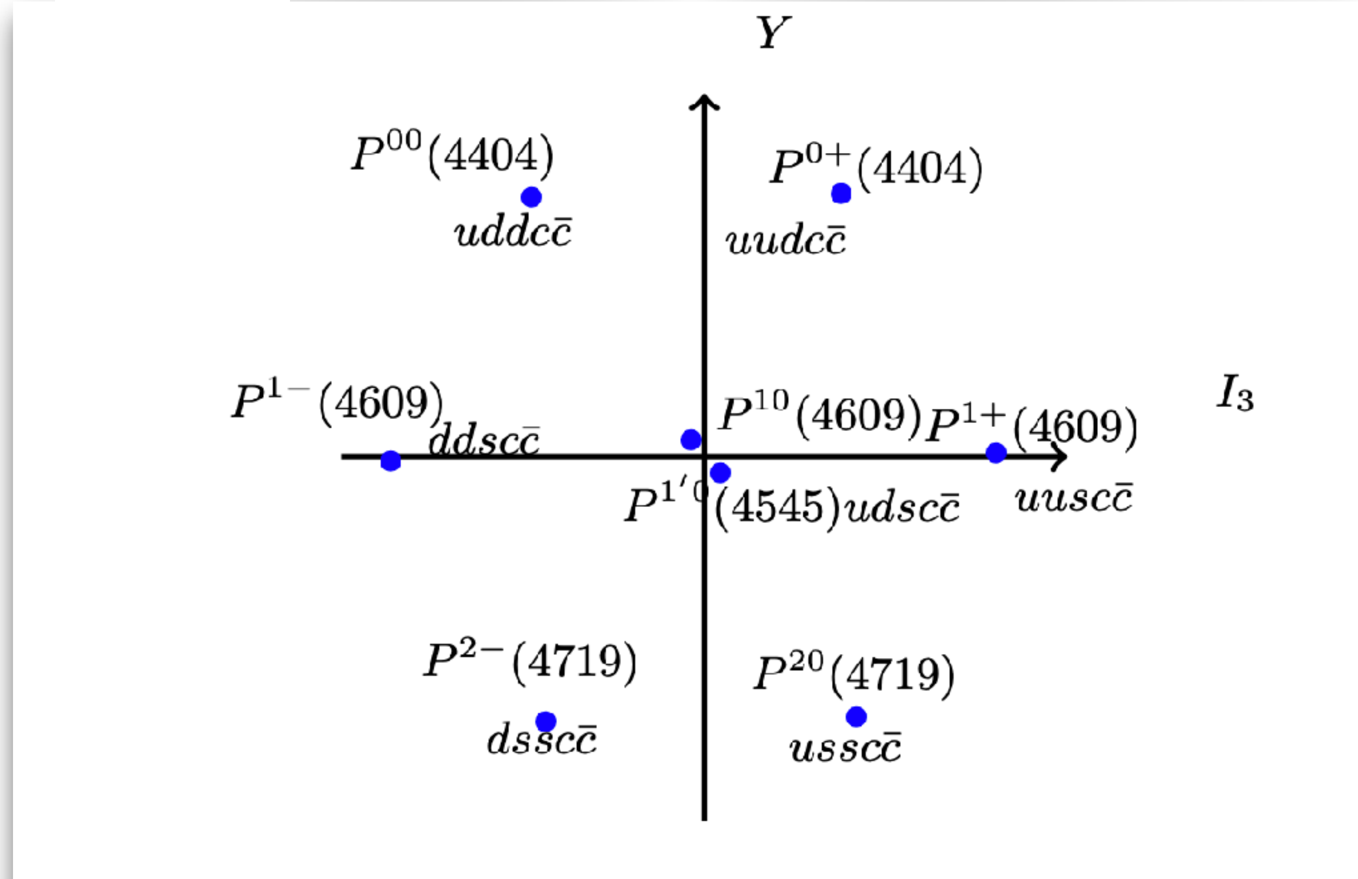


FIG. 3: octet of the charmonium pentaquark states: each state is labelled with $P^{ij}(M)$, where $i = 0, 1, 2$ is the number of strange quarks of a given pentaquark state, $j = -, 0, +$ is the pentaquark's electric charge, and M the predicted mass.

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INFN Unit: Genova

* $cc\bar{c}\bar{c}$ TQ decays in 4μ or $D^{(*)}\bar{D}^{(*)}$ at the LHC

  🔗 [C. Becchi *et al.* (2020)]

* Fully-heavy TQs, diquark+antidiquark

  🔗 [A. Bedolla *et al.* (2020)]

* Triply-heavy TQs, relativized quark model

  🔗 [Q.-F.. Lü *et al.* (2021)]

* Hidden-c PQs, chiral tensor, quark dynamics

  🔗 [Y. Yamaguchi *et al.* (2020)]

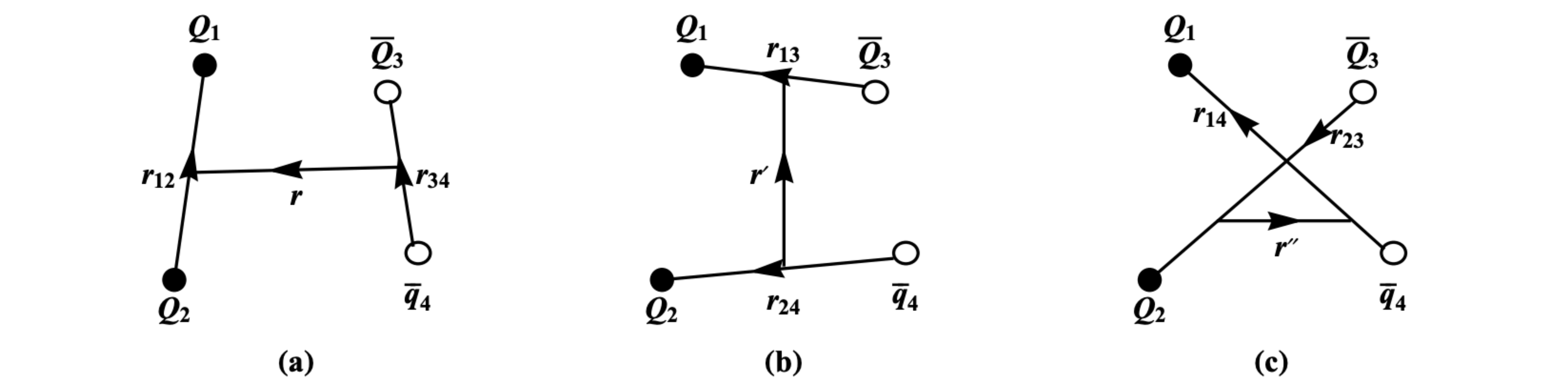


FIG. 1: The $Q_1Q_2\bar{Q}_3\bar{q}_4$ tetraquark state in Jacobi coordinates. (a) combination $(Q_1Q_2)(\bar{Q}_3\bar{q}_4)$ with relative coordinates $\boldsymbol{r}_{12}$, $\boldsymbol{r}_{34}$, and $\boldsymbol{r}$, (b) combination $(Q_1\bar{Q}_3)(Q_2\bar{q}_4)$ with relative coordinates $\boldsymbol{r}_{13}$, $\boldsymbol{r}_{24}$, and $\boldsymbol{r}'$, (c) combination $(Q_1\bar{q}_4)(Q_2\bar{Q}_3)$ with relative coordinates $\boldsymbol{r}_{14}$, $\boldsymbol{r}_{23}$, and $\boldsymbol{r}''$.

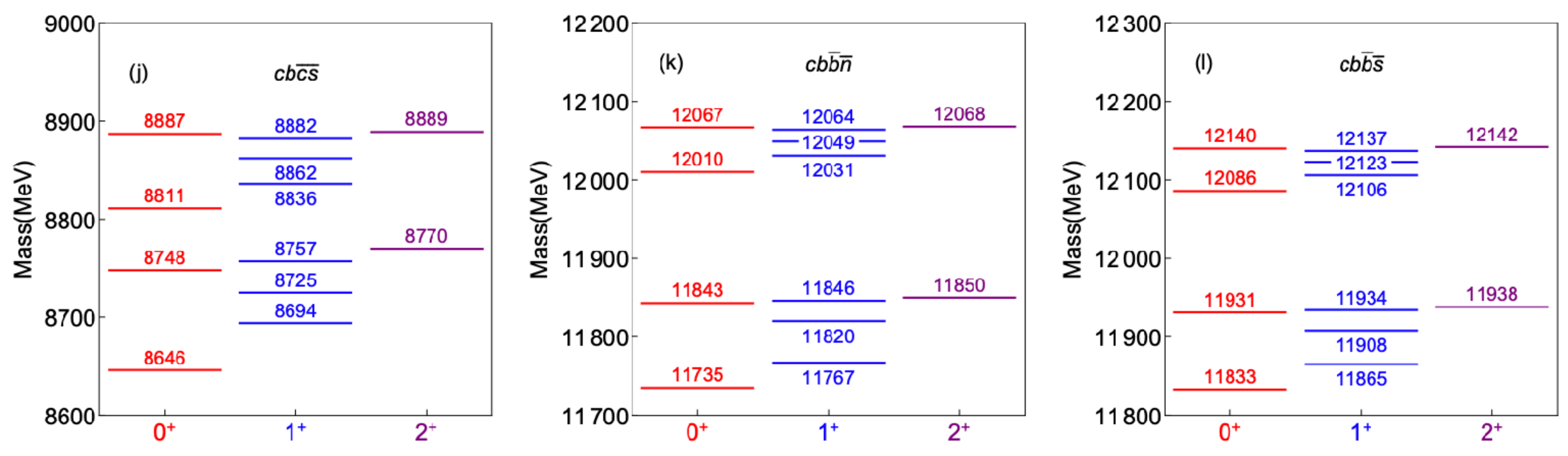


FIG. 4: The predicted mass spectra of triply heavy tetraquarks. (a)-(l) correspond to the mass spectra of $cc\bar{c}\bar{n}$, $cc\bar{c}\bar{s}$, $cc\bar{b}\bar{n}$, $cc\bar{b}\bar{s}$, $bb\bar{c}\bar{n}$, $bb\bar{c}\bar{s}$, $bb\bar{b}\bar{n}$, $bb\bar{b}\bar{s}$, $cb\bar{c}\bar{n}$, $cb\bar{c}\bar{s}$, $cb\bar{b}\bar{n}$, and $cb\bar{b}\bar{s}$ states, respectively.

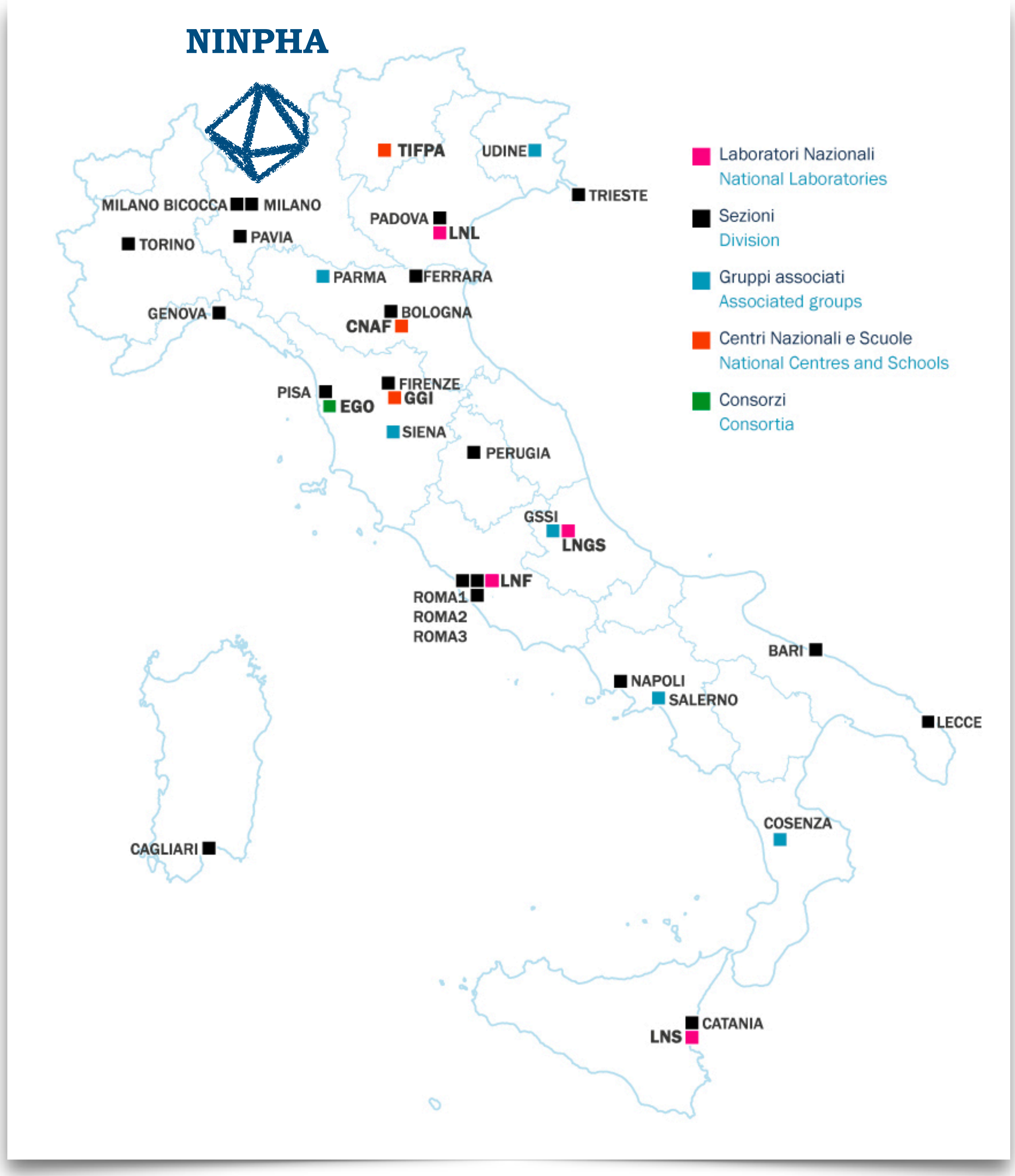
INFN Unit: Pavia

Staff members

Alessandro Bacchetta, U. Pavia, Full Professor

Barbara Pasquini, U. Pavia, Associate Professor

Marco Radici, INFN, First Researcher



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Other Participants

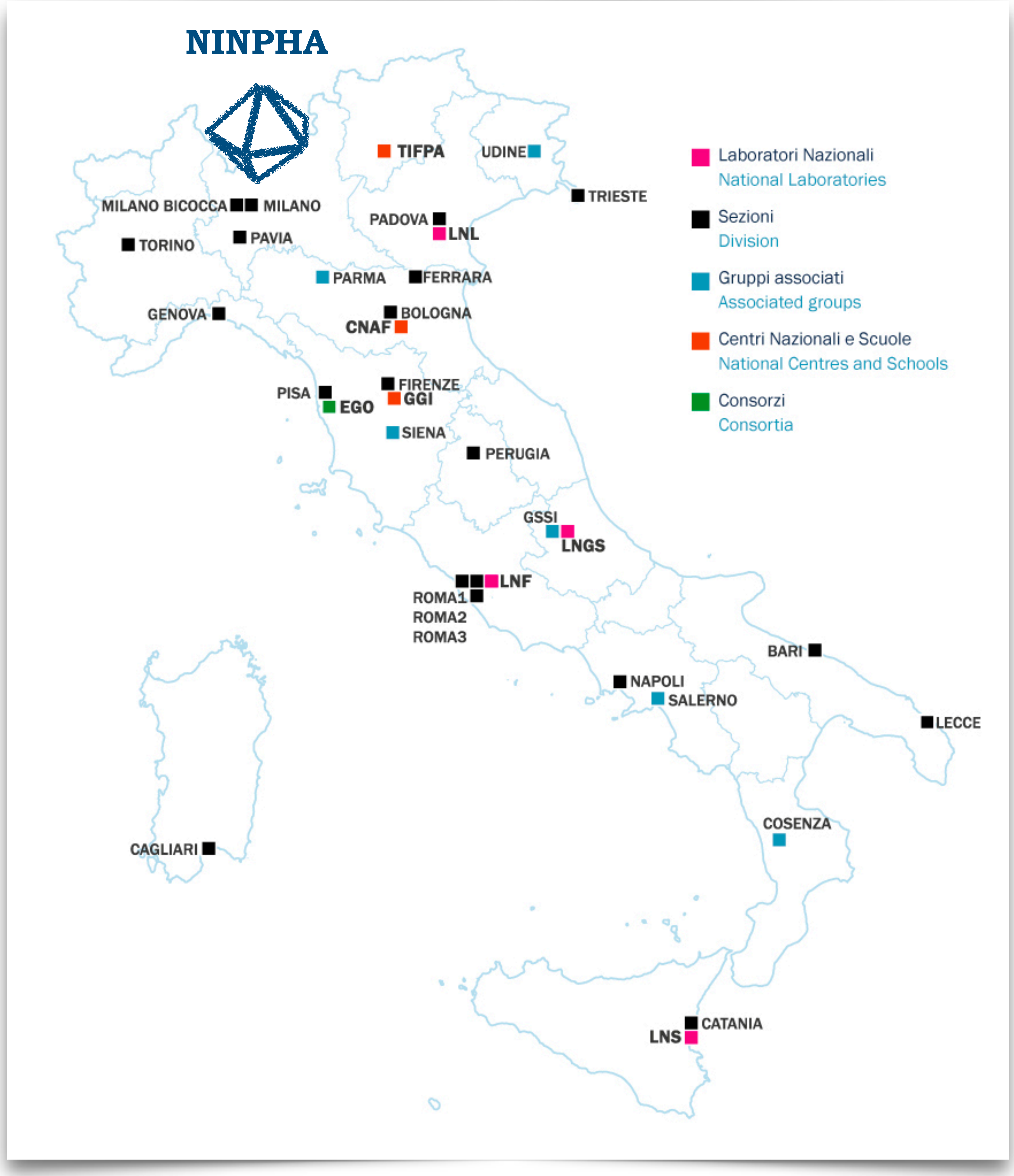
Francesco Giovanni Celiberto, ECT*/FBK Trento, Researcher

Andrea Signori, JLab & U. Pavia, Marie Curie Global Post-doc

Matteo Cerutti, Simone Venturini, Lorenzo Rossi, U. Pavia, PhD Students

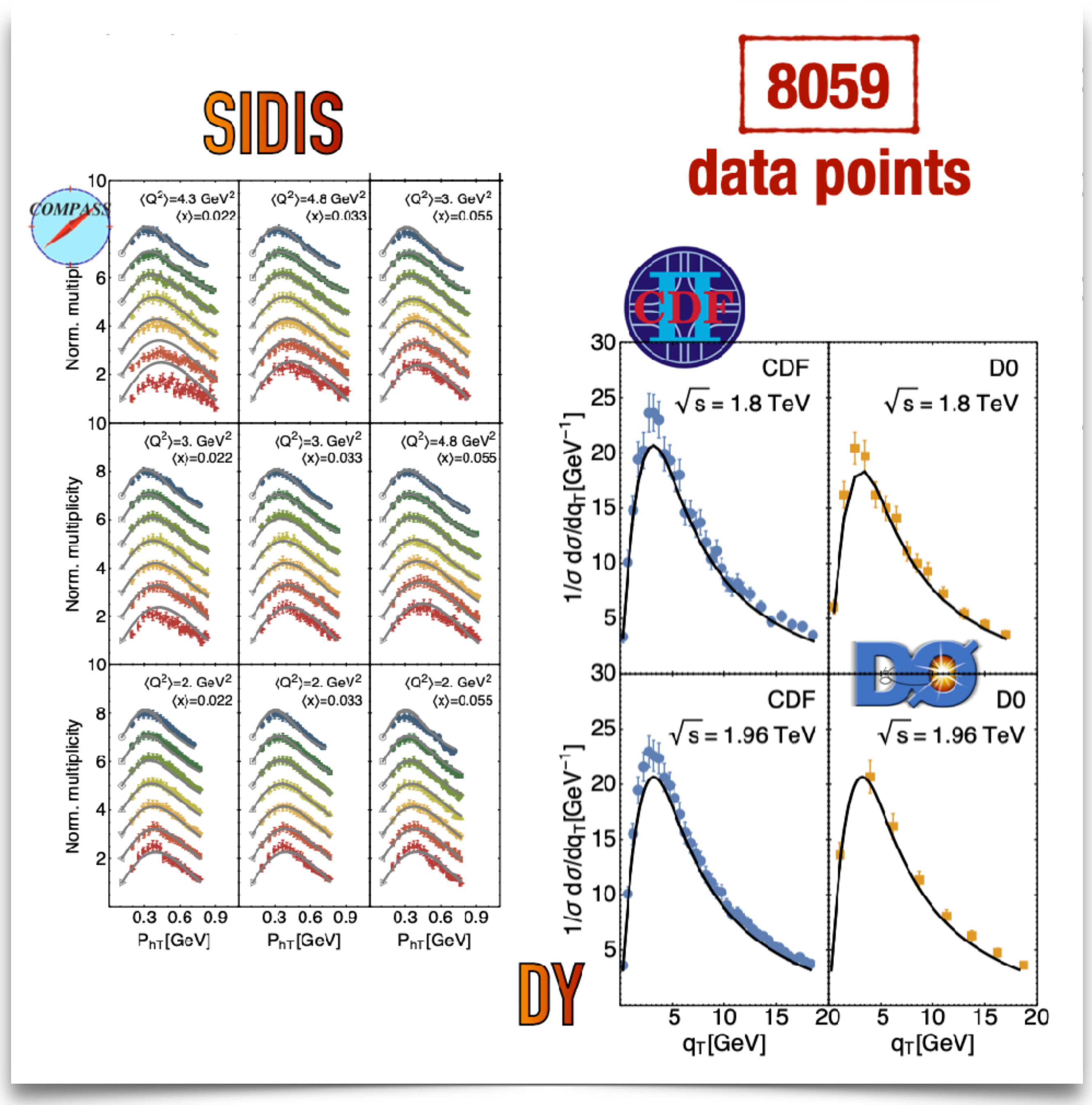
Many former PhD students, now post-docs:

Argonne, JLab, Regensburg



3D proton tomography: unpolarized quark studies

* Global extraction of f_1 [DY+SIDIS]
  - 🔗 [A. Bacchetta *et al.* (2017)]



$$\chi^2/N_{\mathrm{dat}} = 1.55$$

8059 points

with normalization coefficients

slide adapted from C. Bissolotti

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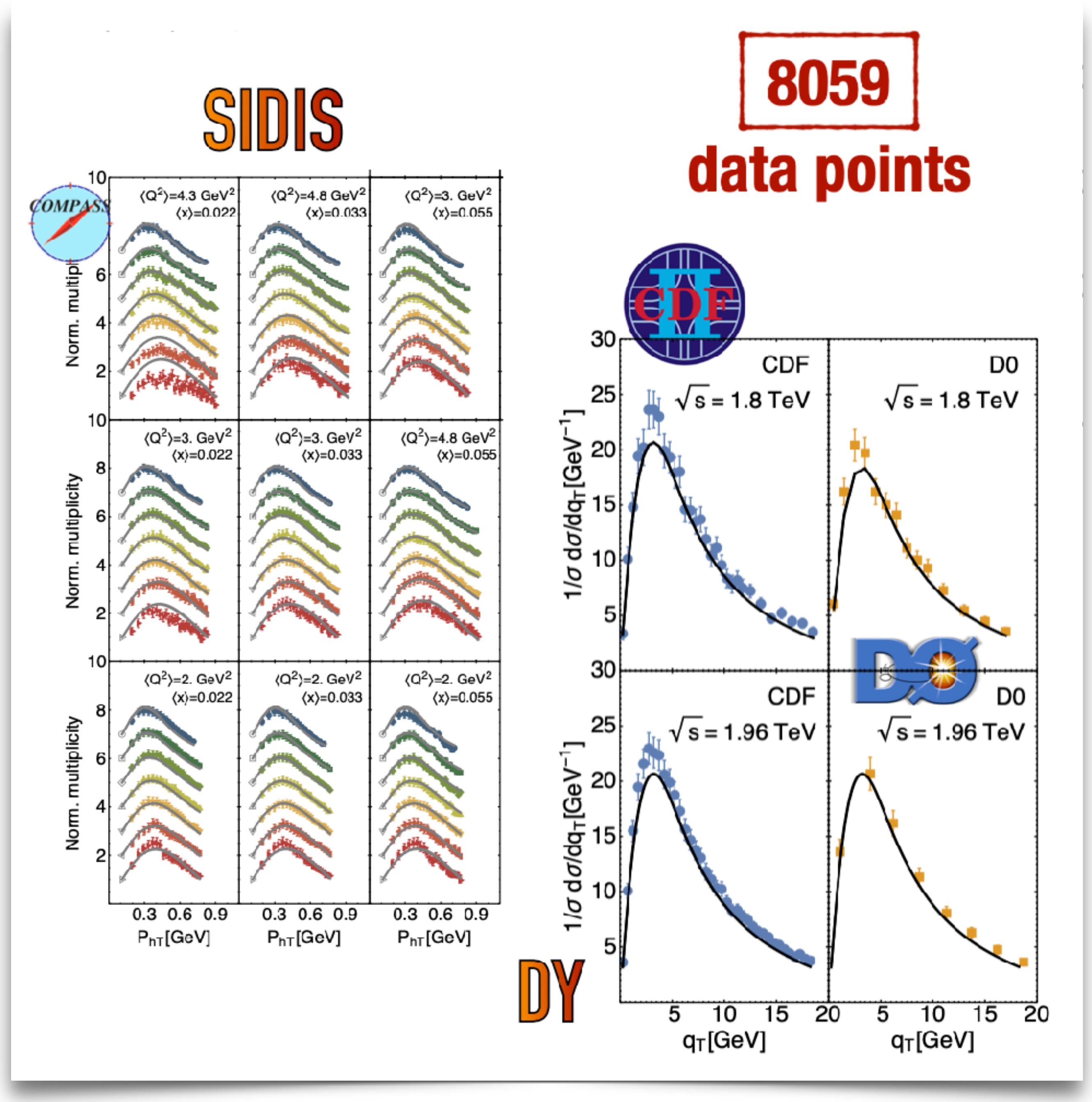

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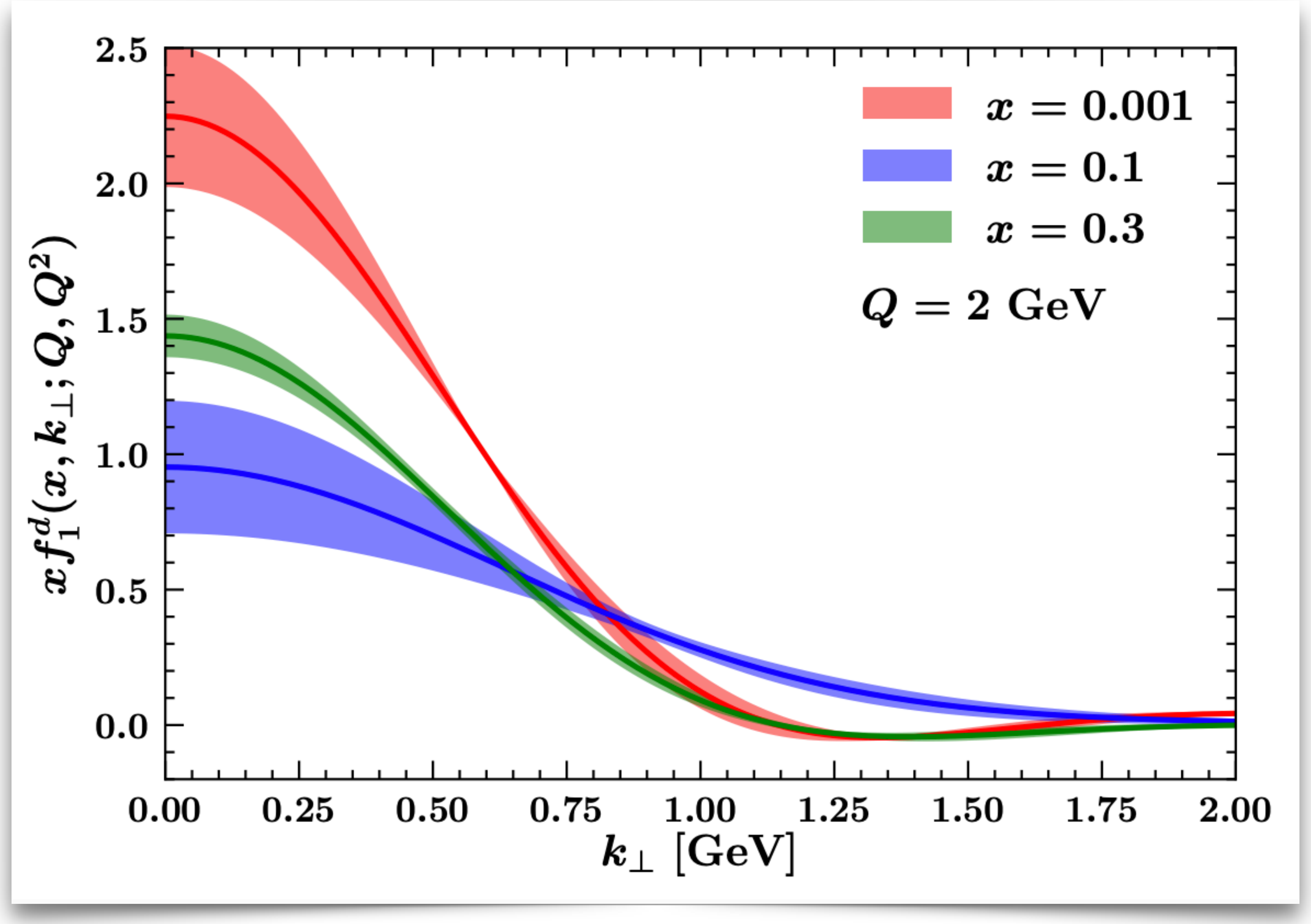

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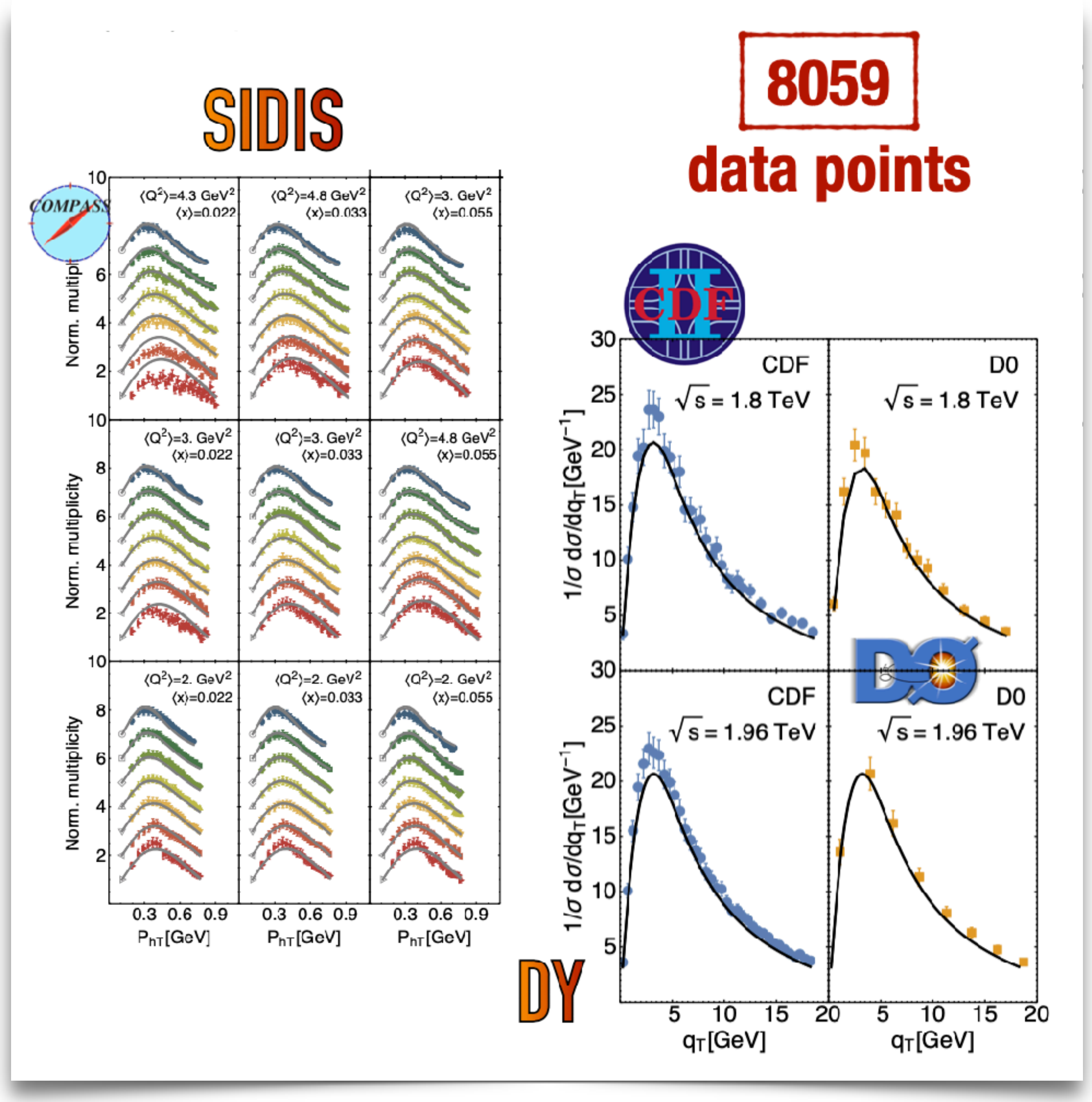

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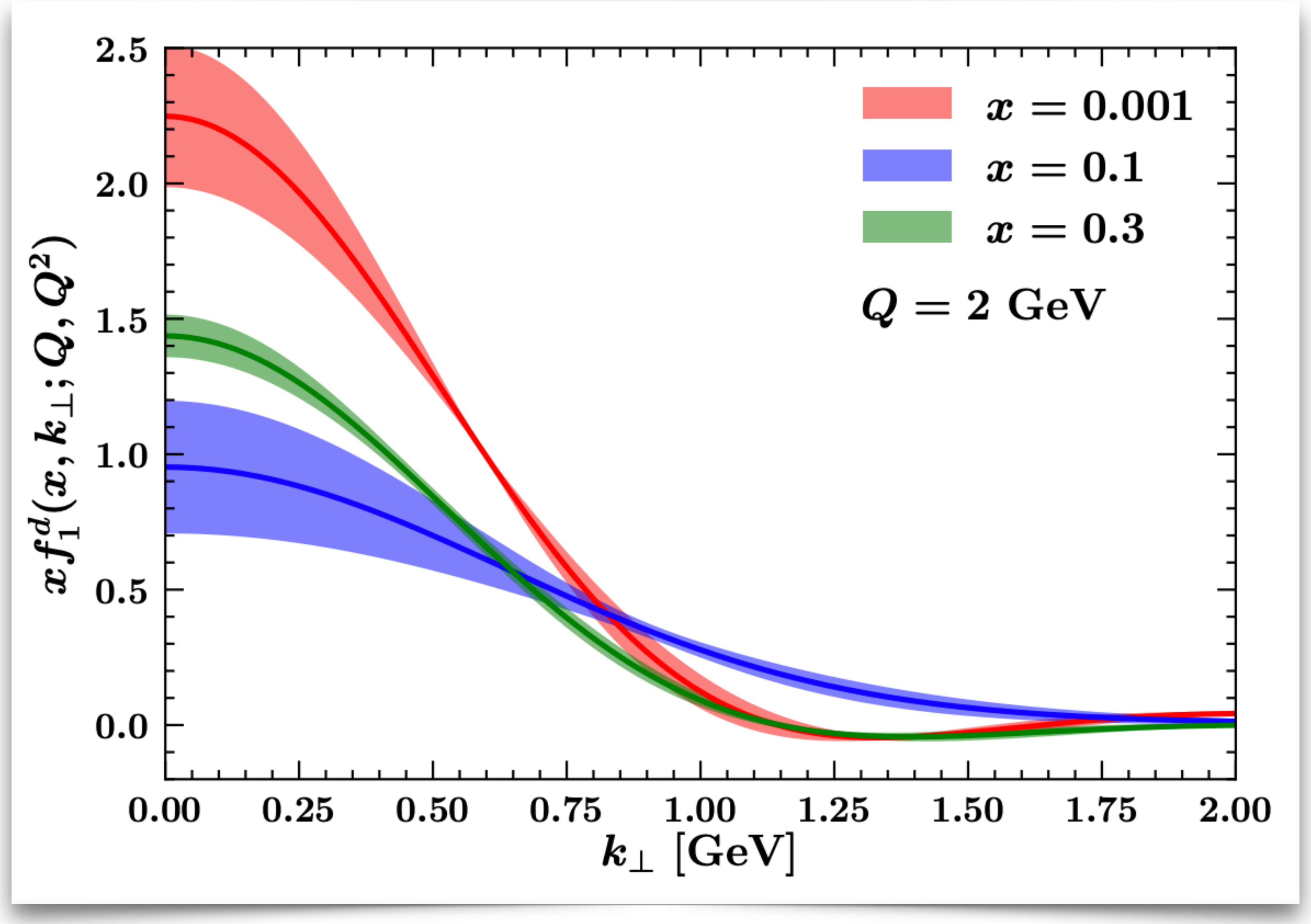

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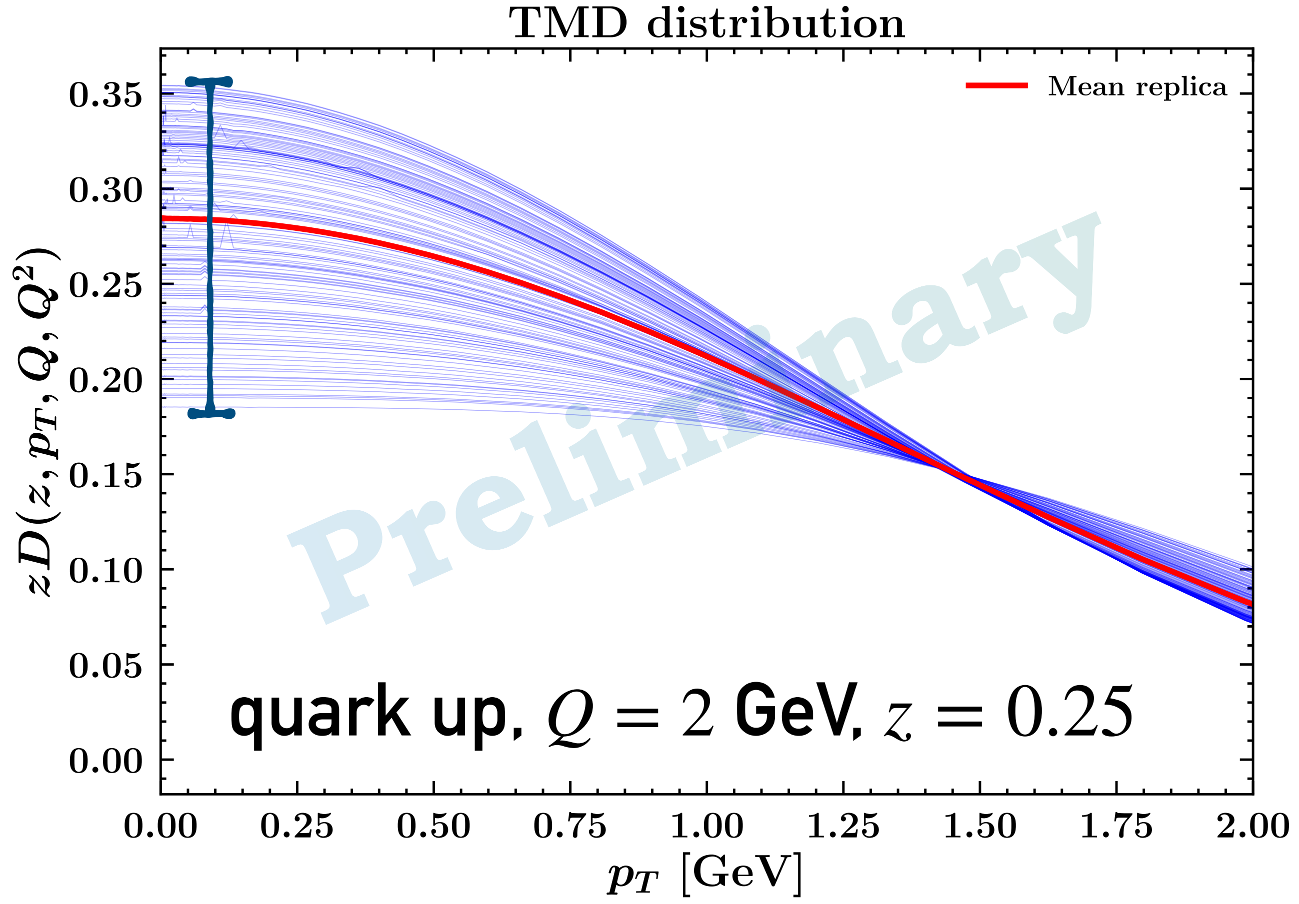
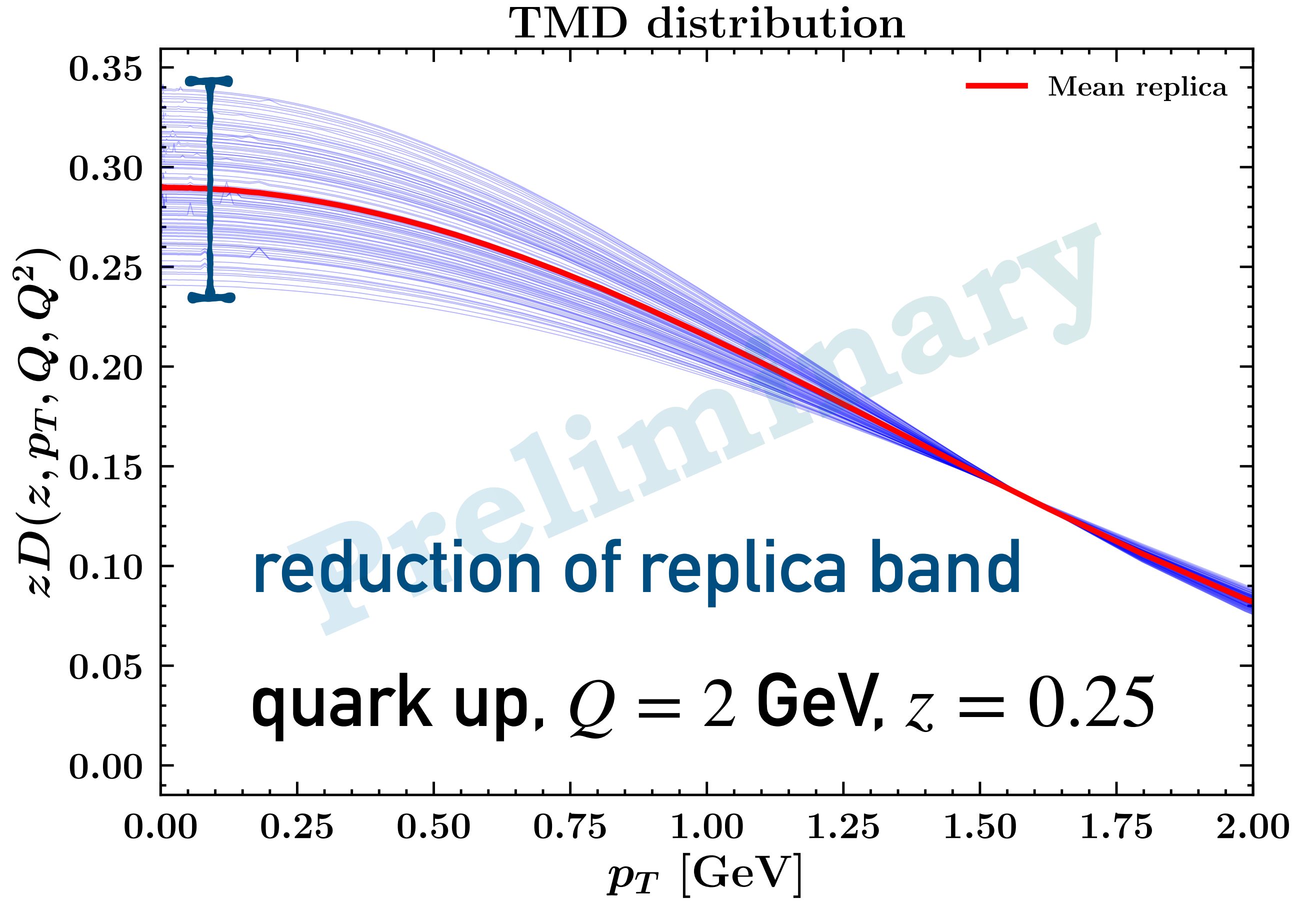
* **EIC** impact on TMD FFs

PV17 baseline



PV17baseline + EIC

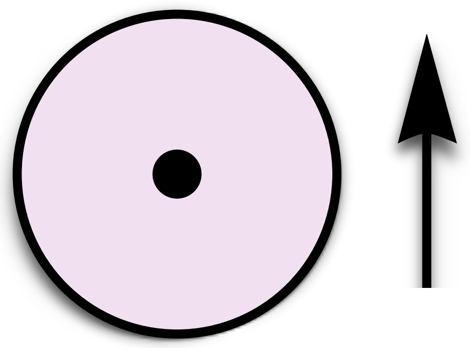


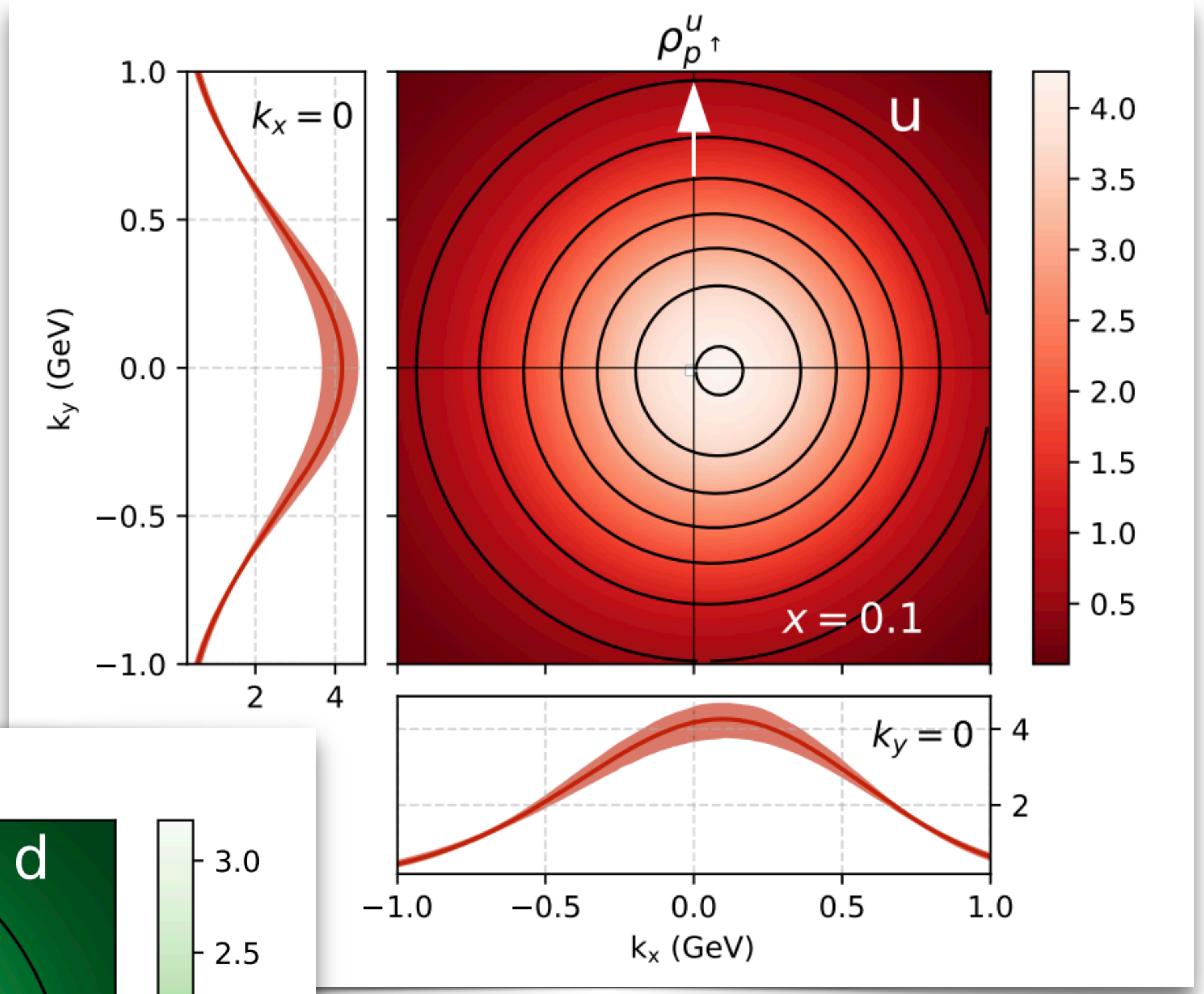
slide adapted from C. Bissolotti

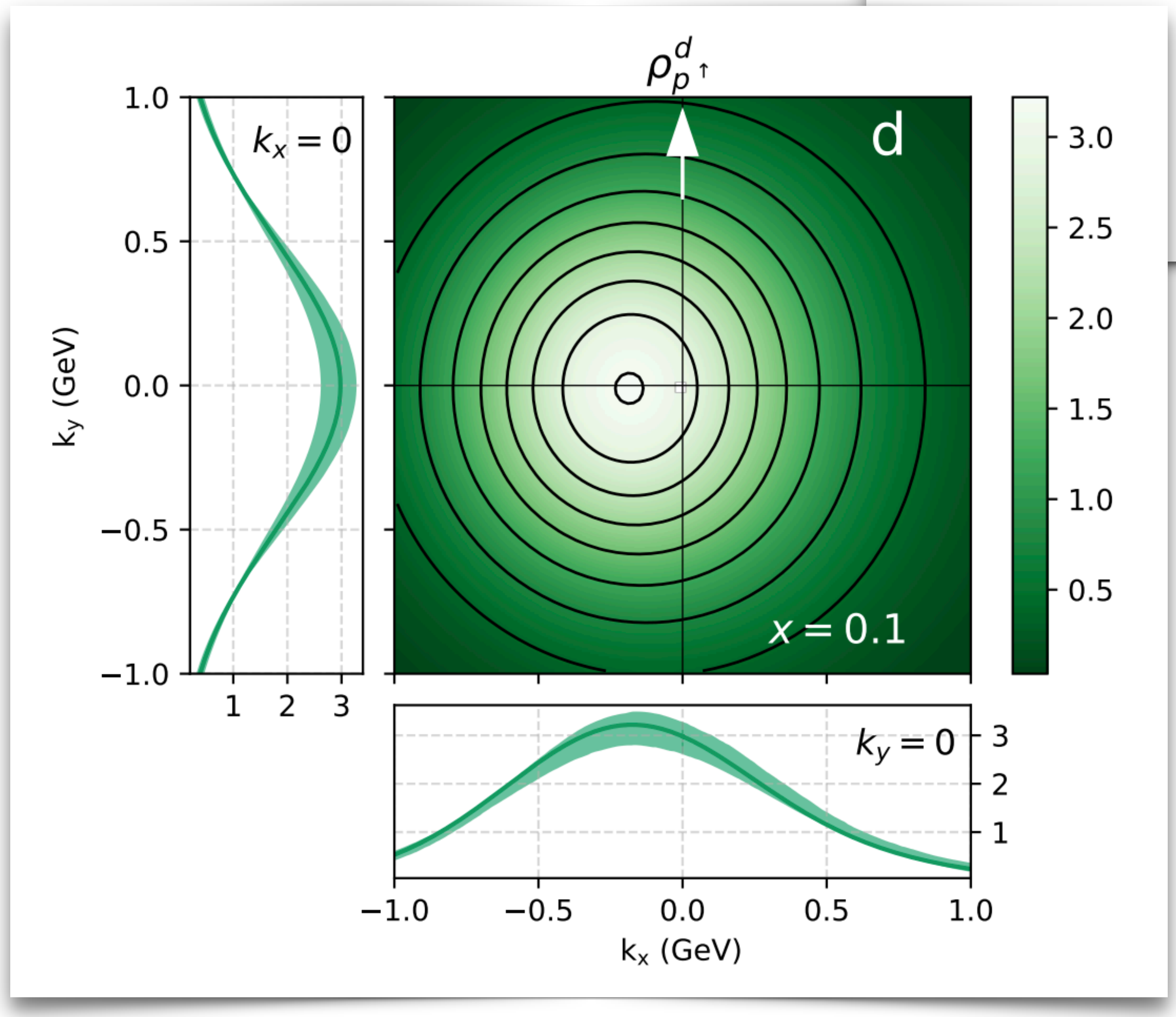
3D proton tomography: quark polarization studies

* NLL Sivers effect from SIDIS

[A. Bacchetta *et al.* (2021)]







Different distortion

between

u and d quarks

3D proton tomography: quark polarization studies

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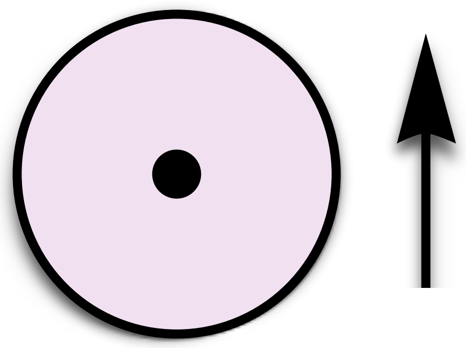

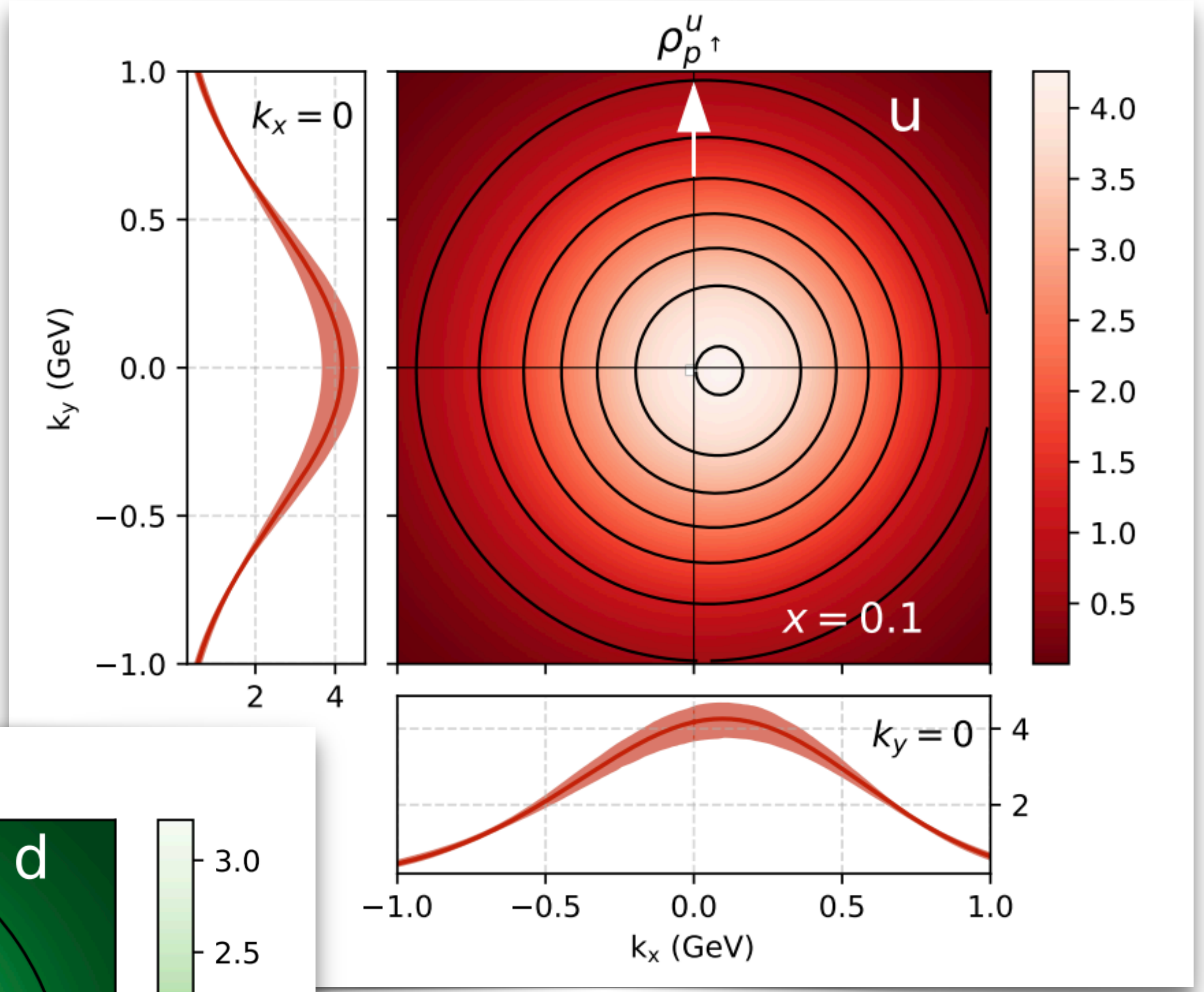

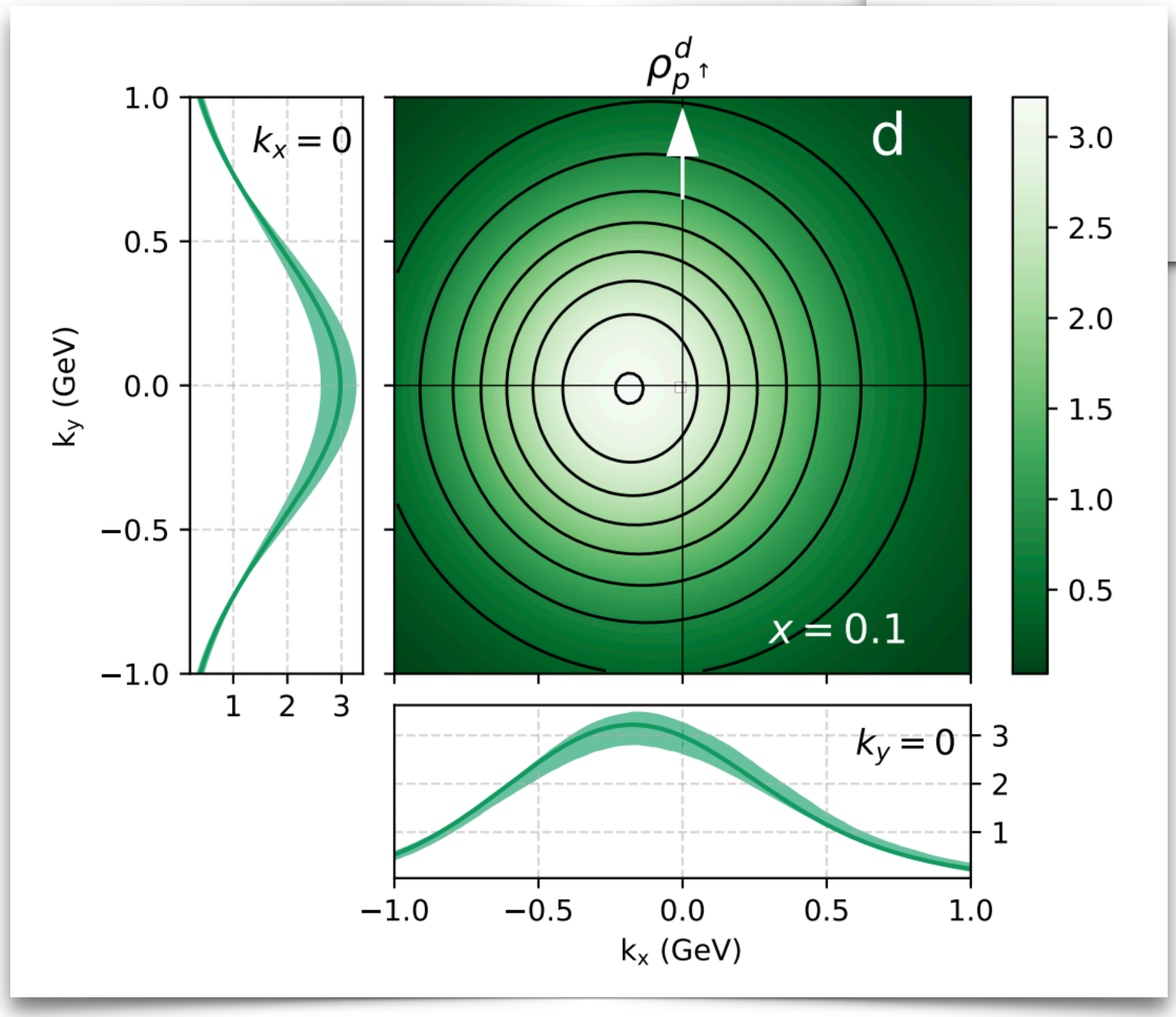

Different distortion

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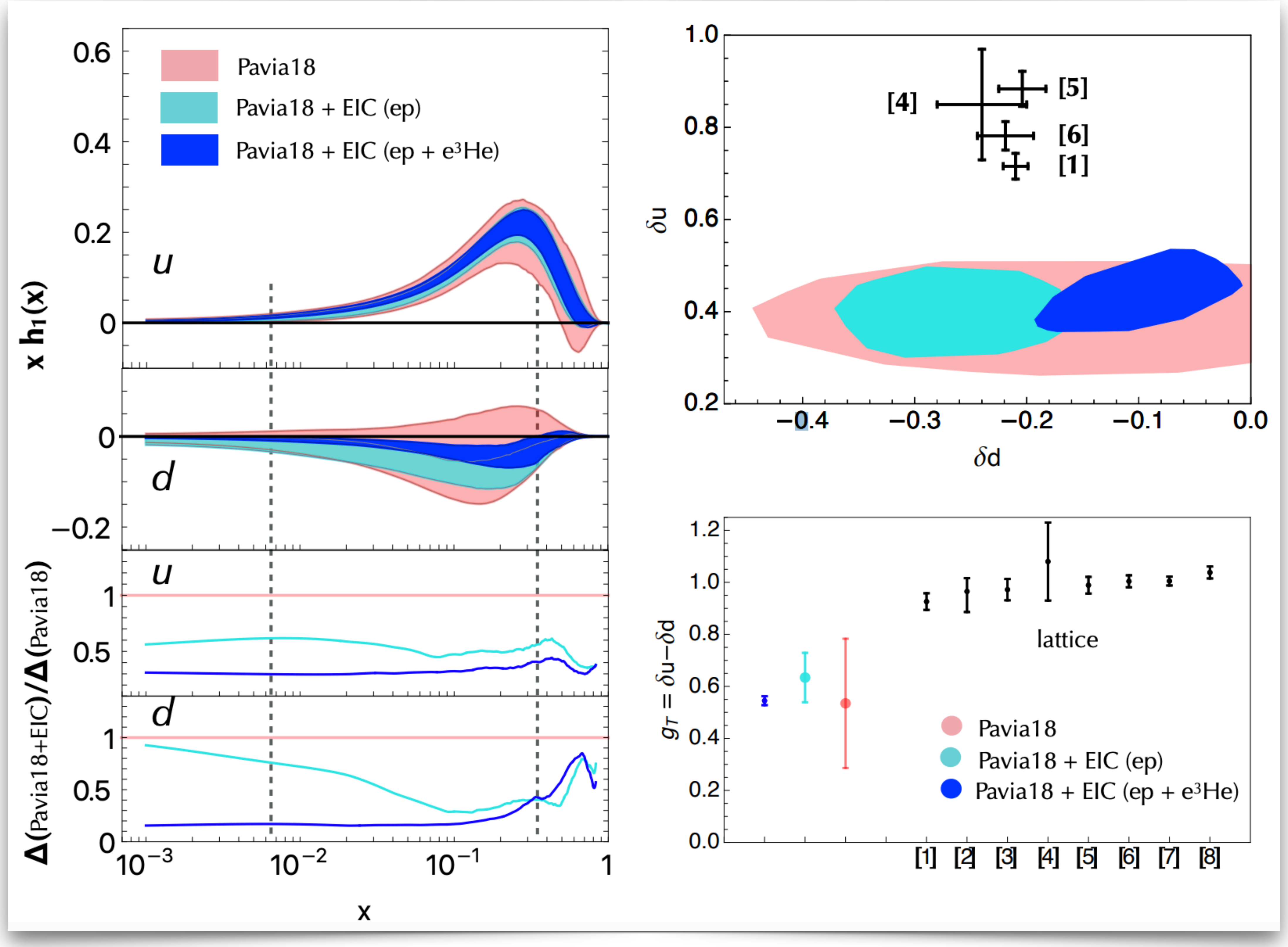
u and d quarks

* **EIC**: transversity PDF + tensor charge

🔗 [EIC Yellow Report (2021)]

EIC impact $\Rightarrow$ accuracy to lattice level or better!

BSM EFT applications $\Rightarrow$ strong $\cancel{CP}$, nN β-decay



3D proton tomography via TMD gluon distributions

* **Spectator model** approach + spectral-mass function

* Calculation of twist-2 ***T*-even** gluon TMDs done

  🔗 [A. Bacchetta, F.G.C., M. Radici, P. Taels (2020)]

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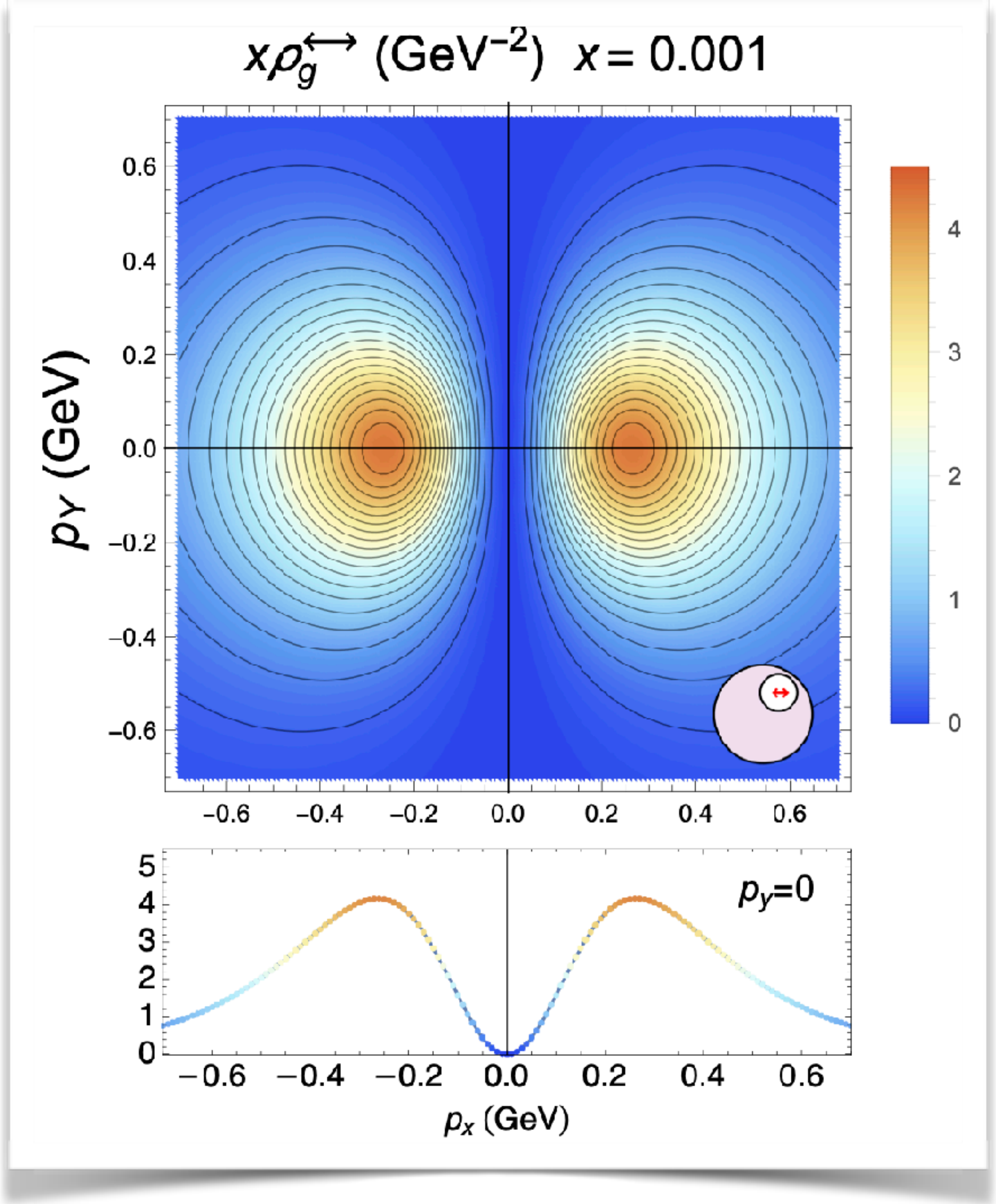

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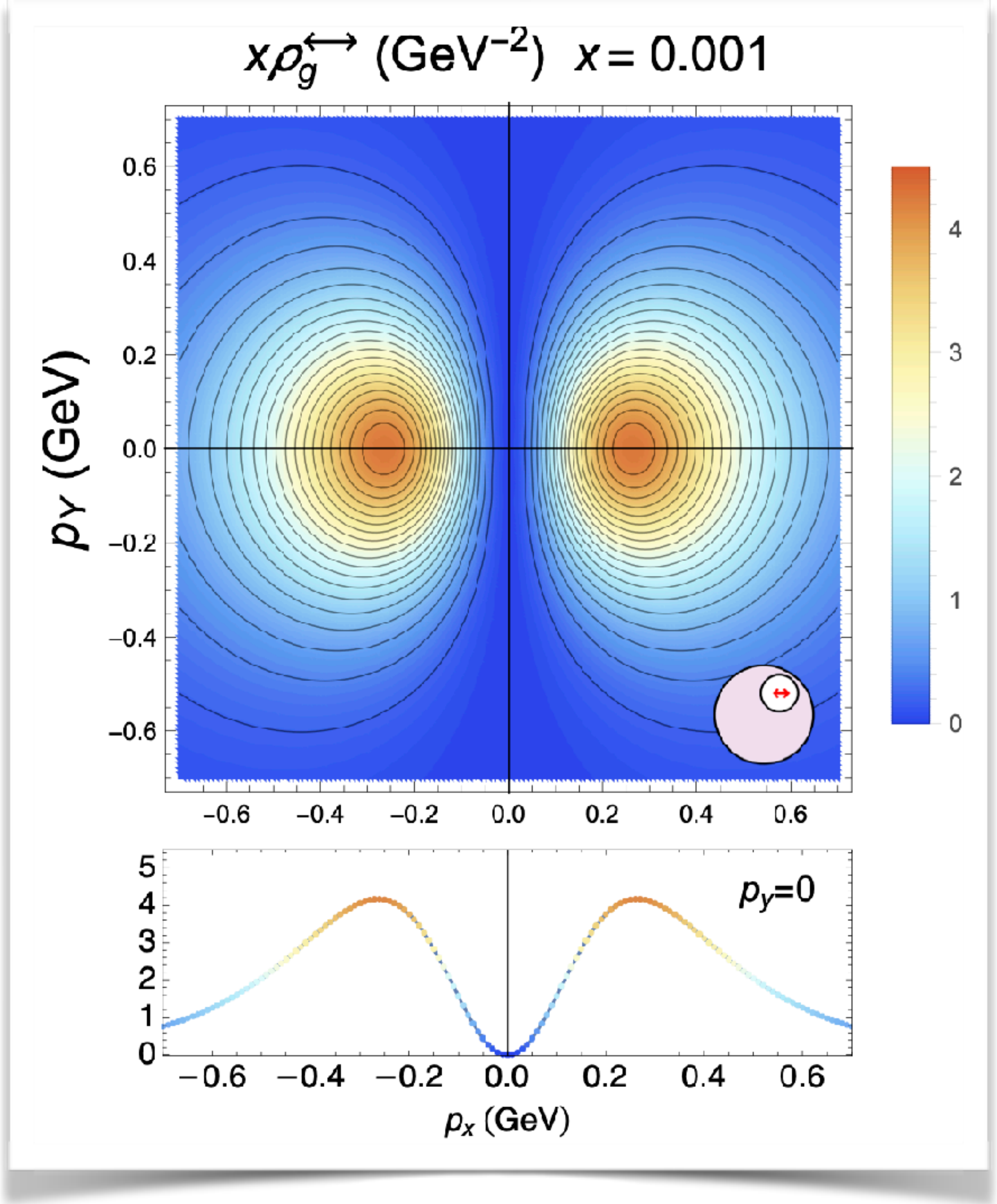
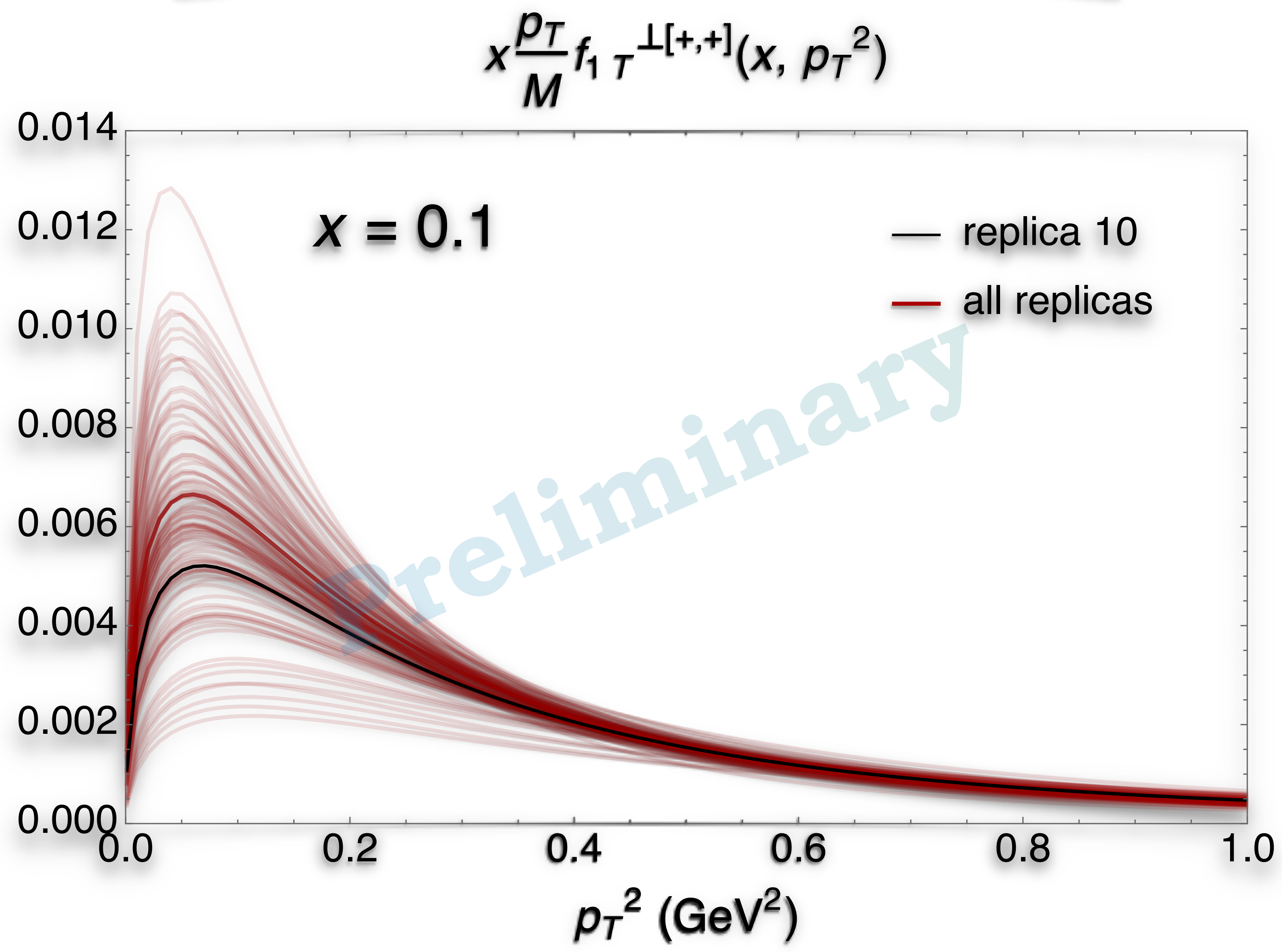


* Twist-2 ***T*-odd** gluon TMDs almost ready!
* Gluon **Sivers** effect via **heavy flavor** at the **EIC**

NINPHA/**Pavia** + NINPHA/**Cagliari**



GPD-TMD lensing, Pion Drell-Yan, Wigner, jets

* GPD-(T-odd TMD) lensing function in SIDIS

  🔗 [B. Pasquini, S. Rodini, A. Bacchetta (2019)]

* Properties of the EMT, $T^{\mu\nu}$

  1-loop QED: e^- gravitation form factor

  3-loop QCD: mass decomp., Tr anom., σ term

  🔗 [A. Metz, B. Pasquini, S. Rodini (2021)]

  🔗 [C. Lorcé, A. Metz, B. Pasquini, S. Rodini (2021)]

* P generalized polarizabilities from **JLab12** VCS

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  🔗 [B. Pasquini, M. Vanderhaegen (2021)]

* Modeling pions and nucleons TMDs in DY

  🔗 [S. Bastmi, ..., B. Pasquini, *et. al.* (2021)]

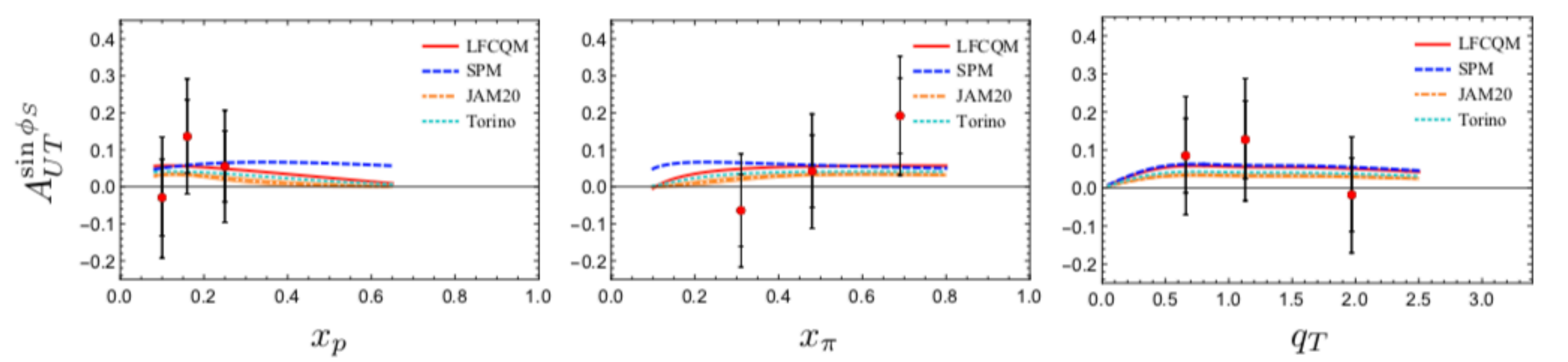


Figure 5. $A_{UT}^{\sin\phi}$ as a function of x_p (left), x_π (middle) and q_T (right) vs COMPASS data [46].

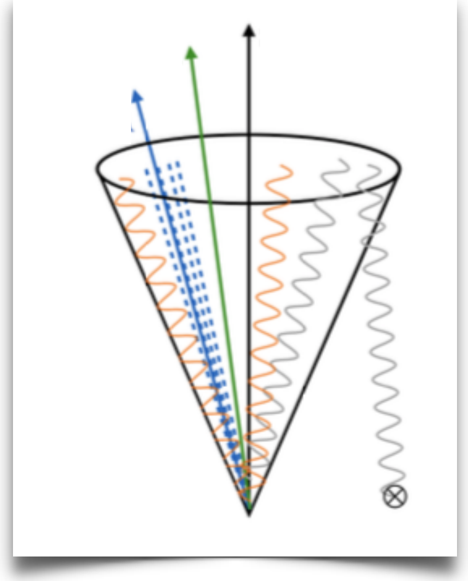
* Polarized quark Wigner distributions

  🔗 [B. Pasquini, C. Lorcé (2021)]

* Inclusive jets, hadrons in jets

  🔗 [A. Accardi, A. Signori (2020)]

  [HASQCD Pavia, in progress]



INFN Unit: Perugia

Staff members

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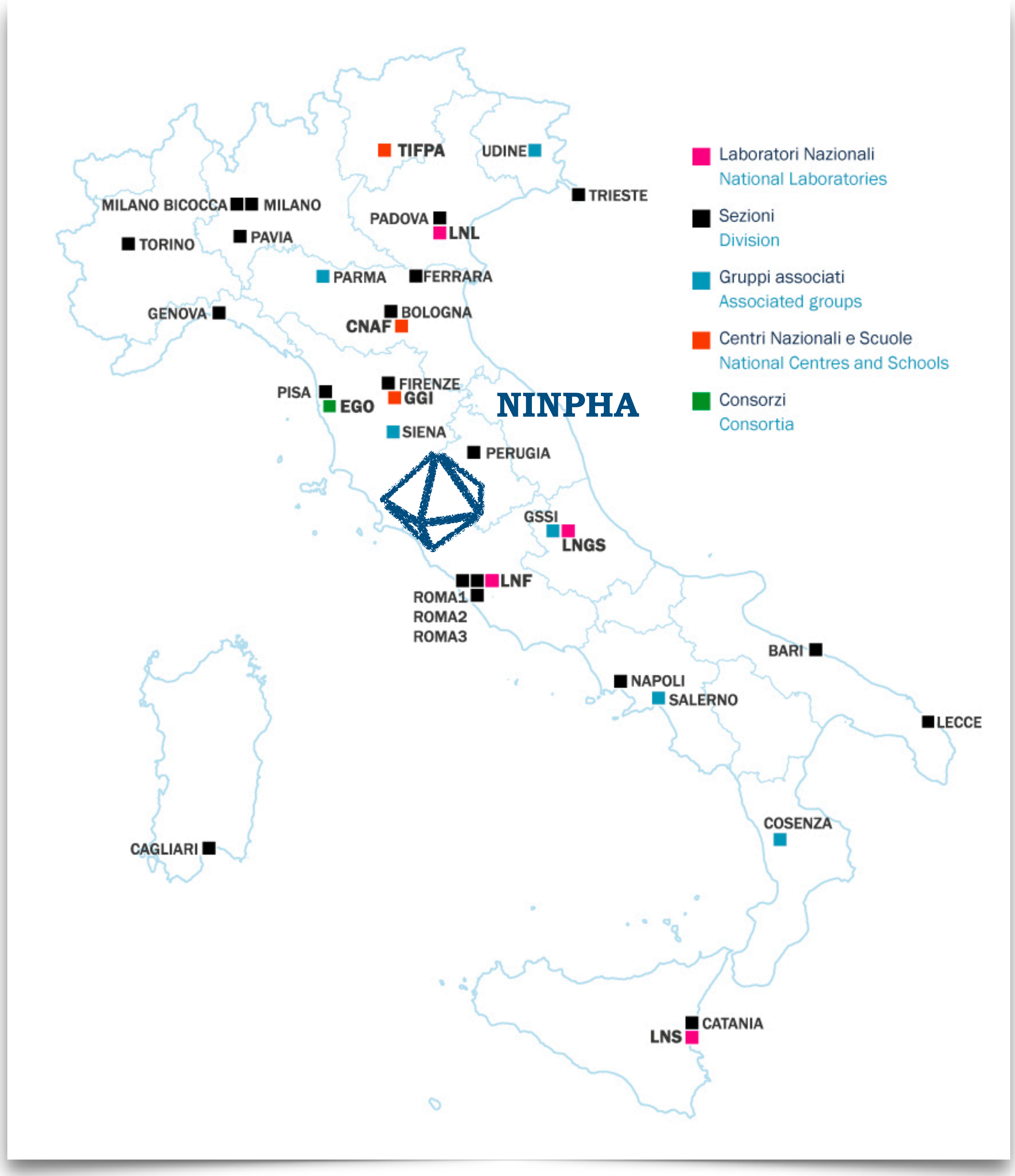
Simone Pacetti, U. Perugia, Associate Professor

Matteo Rinaldi, U. Perugia, Researcher

Sergio Scopetta, U. Perugia, Associate Professor



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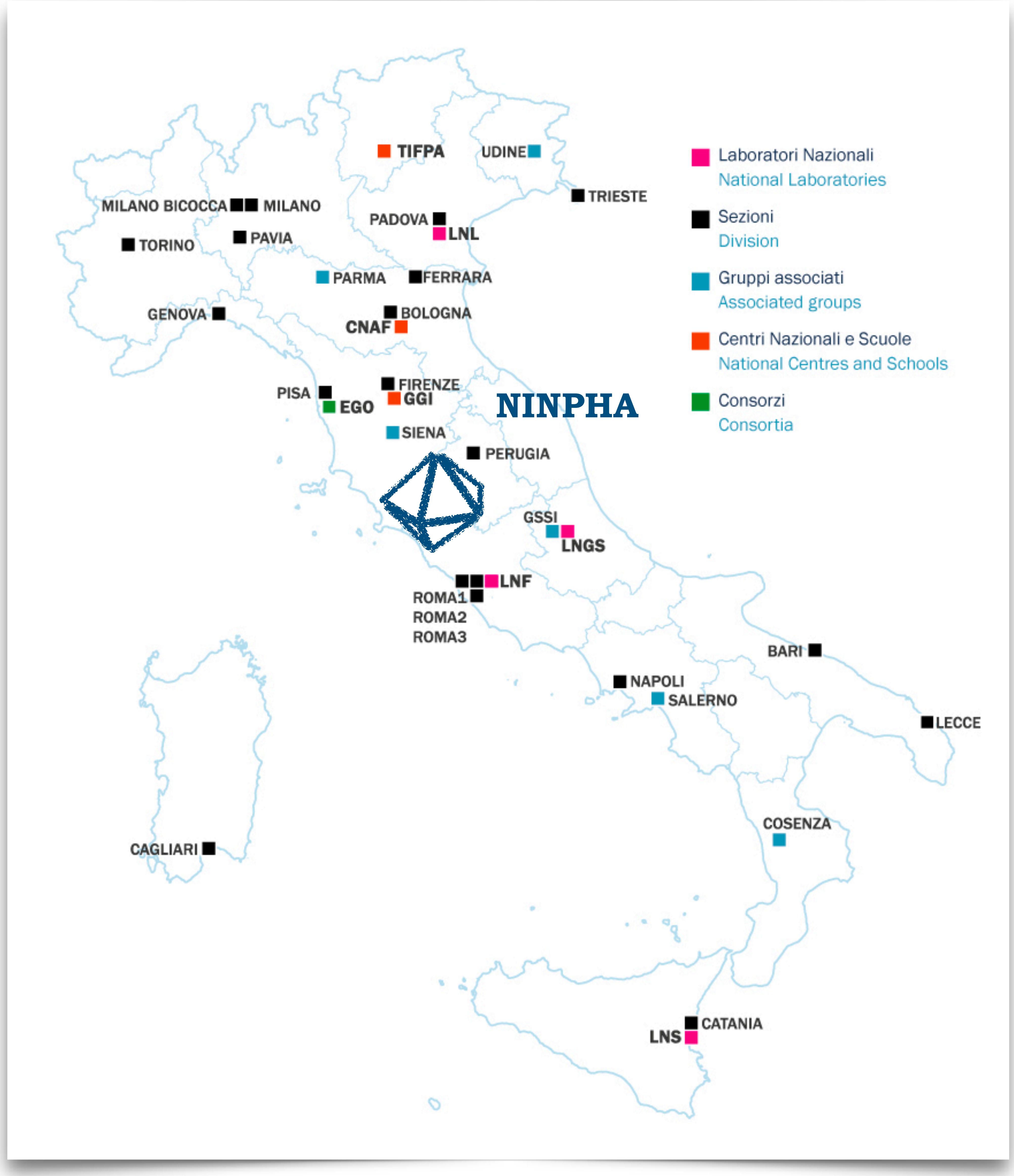
Other Participants

Alessio Mangoni, INFN, Post-doc

Rajesh Sangem, INFN, Post-doc

Giovanni Salmè, INFN-Roma, First Researcher (Senior)



Multi-particle interactions, diquark correlations

* HAS via **multi-particle interactions** (**MPIs**), link to light-front wave functions (LFWFs)

  Double PDFs (**dPDFs**) carry information on transverse distance of partons; dPDFs $\Leftrightarrow$ GPDs (?)

  Hadronic structure and New Physics $\Leftarrow$ **JLab12**, BESIII, **HL-LHC**, **EIC**

🔗 [M. Rinaldi, S. Scopetta, M.C. Traini, V. Vento (2016)]

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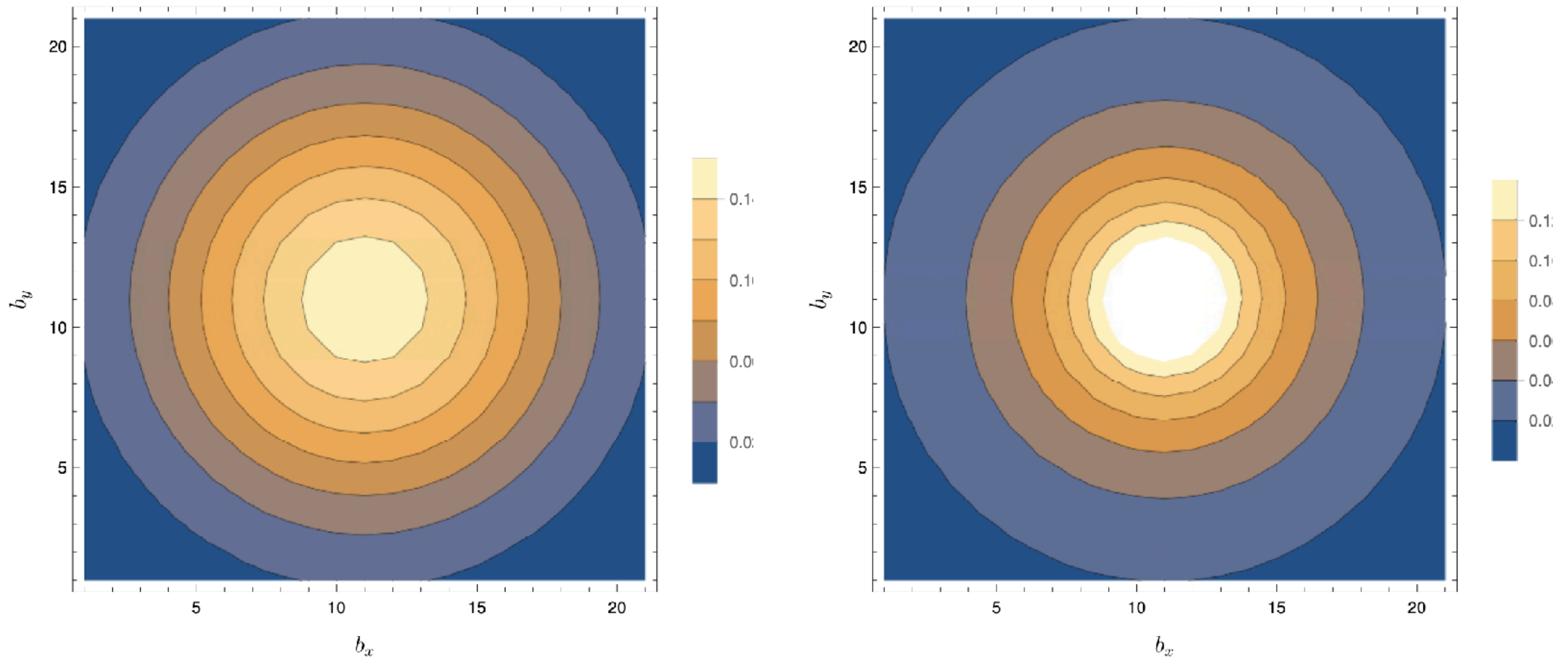

Figure 1. The digluon distribution $\tilde{F}_{gg}(x_1 = 10^{-4}, x_2 = 10^{-2}, b_\perp, Q^2 = m_H^2)$. Left panel: calculation within the HO model. Right panel: calculation within the HP model. Partonic distance expressed in [GeV^{-1}].

(in this slide, LHC double parton scattering) [M. Rinaldi, F. Ceccopieri (2019)]

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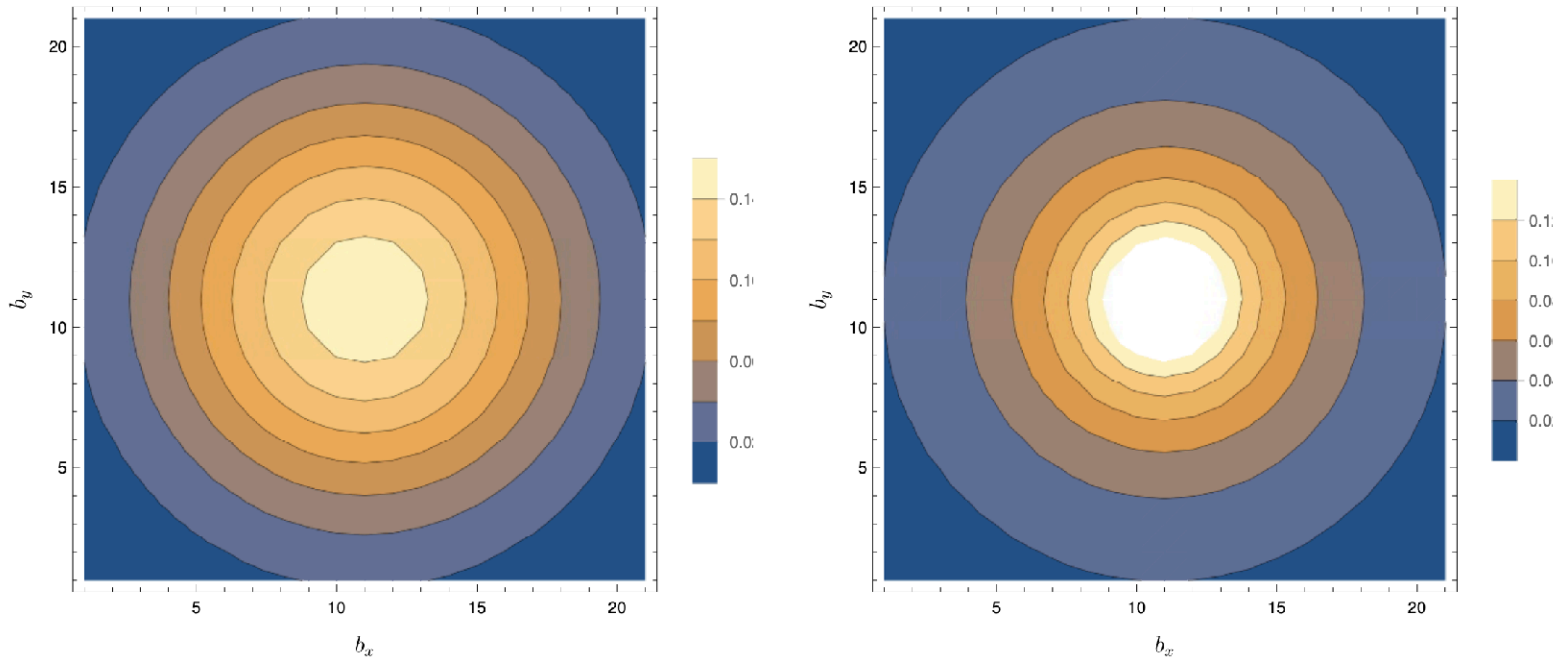

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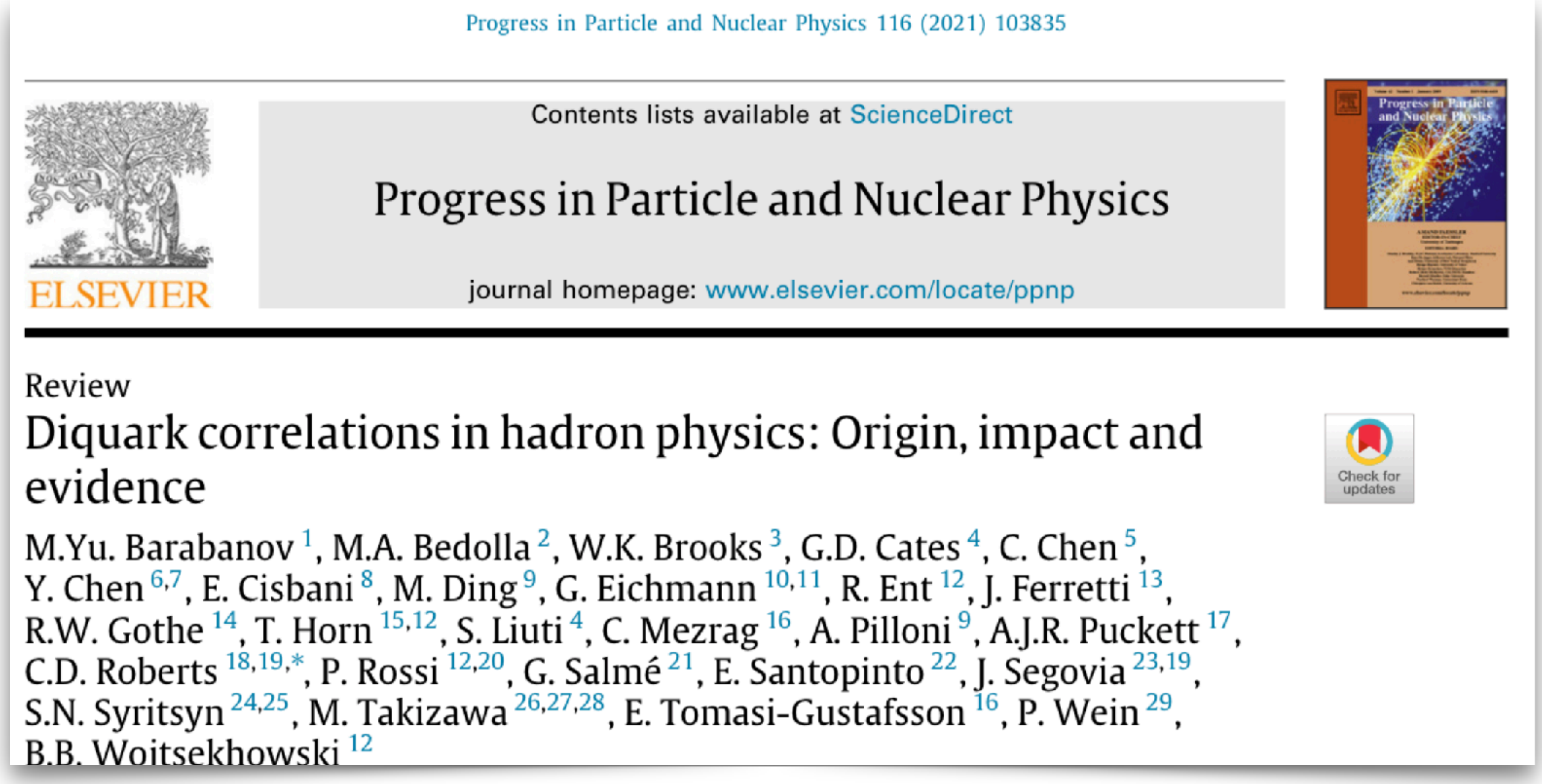
* Review: NINPHA/**Perugia** + NINPHA/**Genova**

  Diquark correlations $\Leftrightarrow$ exotics, PDFs



Progress in Particle and Nuclear Physics 116 (2021) 103835

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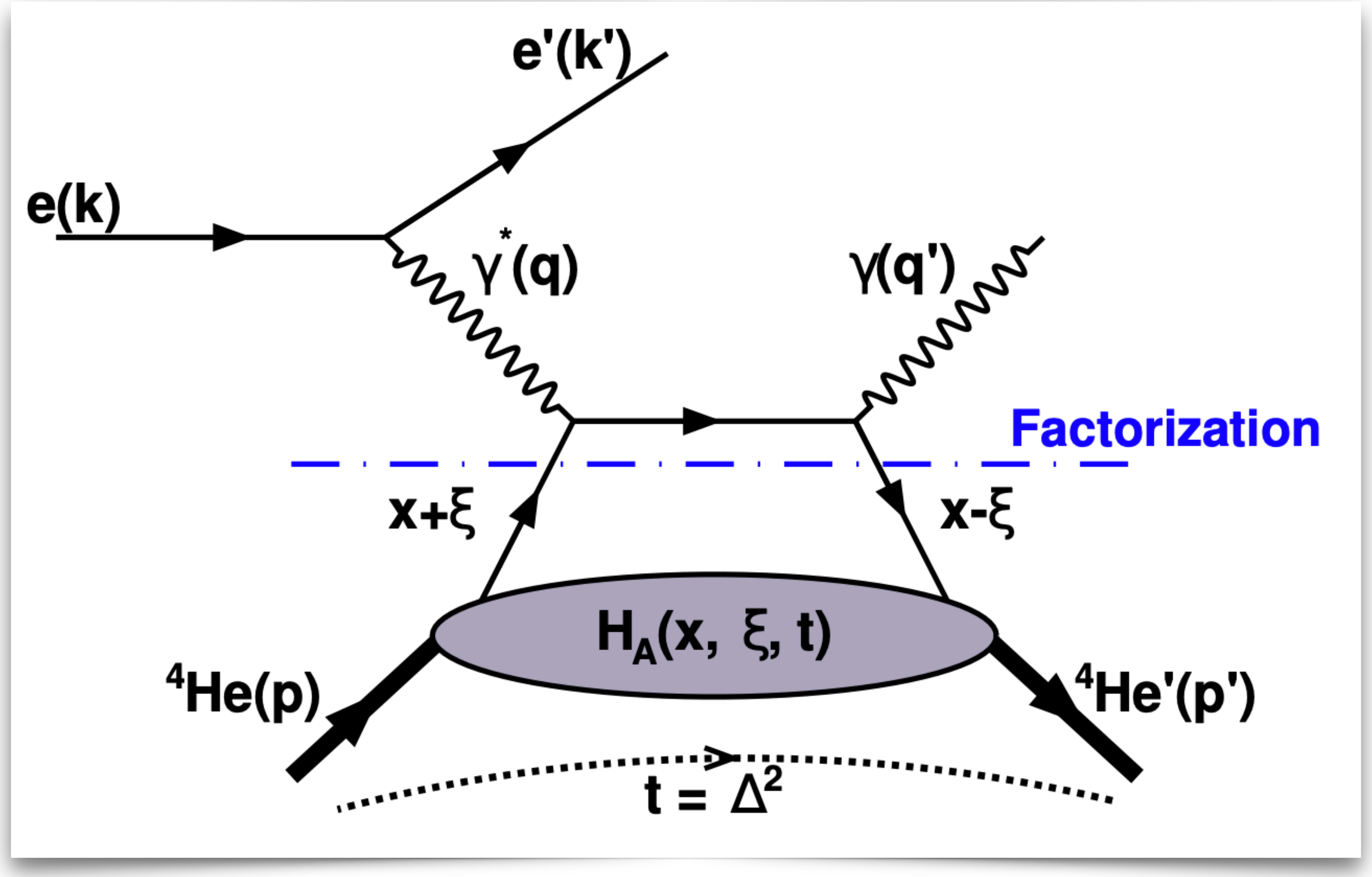
Review

Diquark correlations in hadron physics: Origin, impact and evidence

M.Yu. Barabanov [1], M.A. Bedolla [2], W.K. Brooks [3], G.D. Cates [4], C. Chen [5], Y. Chen [6,7], E. Cisbani [8], M. Ding [9], G. Eichmann [10,11], R. Ent [12], J. Ferretti [13], R.W. Gothe [14], T. Horn [15,12], S. Liuti [4], C. Mezrag [16], A. Pilloni [9], A.J.R. Puckett [17], C.D. Roberts [18,19,*], P. Rossi [12,20], G. Salmé [21], E. Santopinto [22], J. Segovia [23,19], S.N. Syritsyn [24,25], M. Takizawa [26,27,28], E. Tomasi-Gustafsson [16], P. Wein [29], B.B. Woitsekhowski [12]

DVCS, GPDs, nuclear collisions, baryons

* $^{3(4)}$He DVCS and GPDs at **JLab12** and **EIC**



🔗 [S. Fucini, M. Rinaldi, S. Scopetta (2018)]

🔗 [S. Fucini, S. Scopetta, M. Viviani (2020)]

🔗 [S. Fucini, M. Hattawy, M. Rinaldi, S. Scopetta (2021)]

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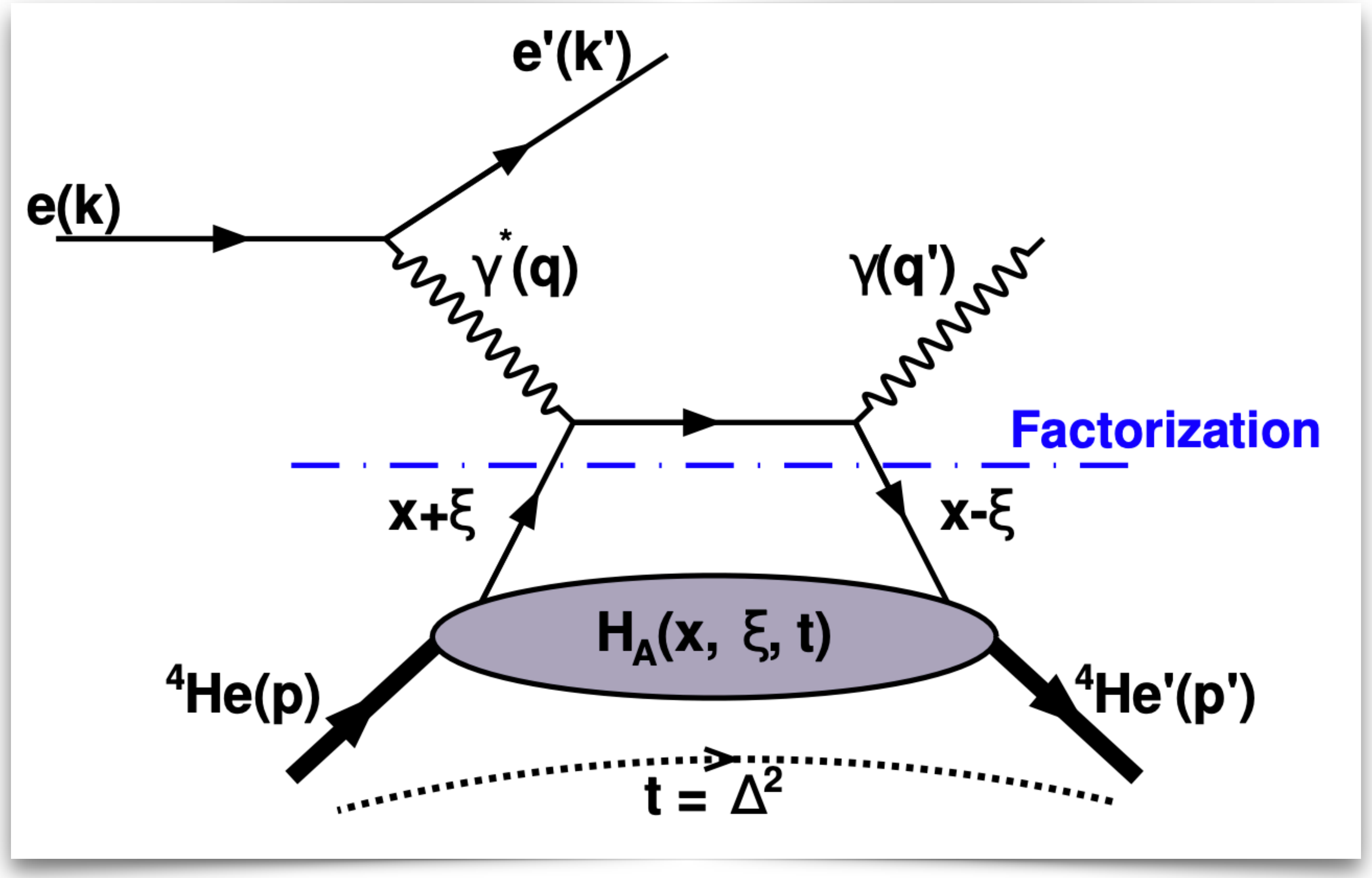

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🔗 [S. Fucini, M. Hattawy, M. Rinaldi, S. Scopetta (2021)]

* Color fluctuations in pN and D^+N, RHIC and LHC

🔗 [M. Alvioli, L. Frankfurt, D. Perepelitsa, M. Strikman (2018)]

* Neutron-skin effect at RHIC nuclear collisions

🔗 [J. Hammelmann, ..., M. Alvioli *et al.* (2020)]

* Amplitude separation in $\Psi(2S) \to$ baryons

🔗 [R. Ferroli, A. Mangoni, S. Pacetti, K. Zhu (2021)]

* Electromagnetic structure of the neutron

🔗 [BESIII Collaboration (2021)]

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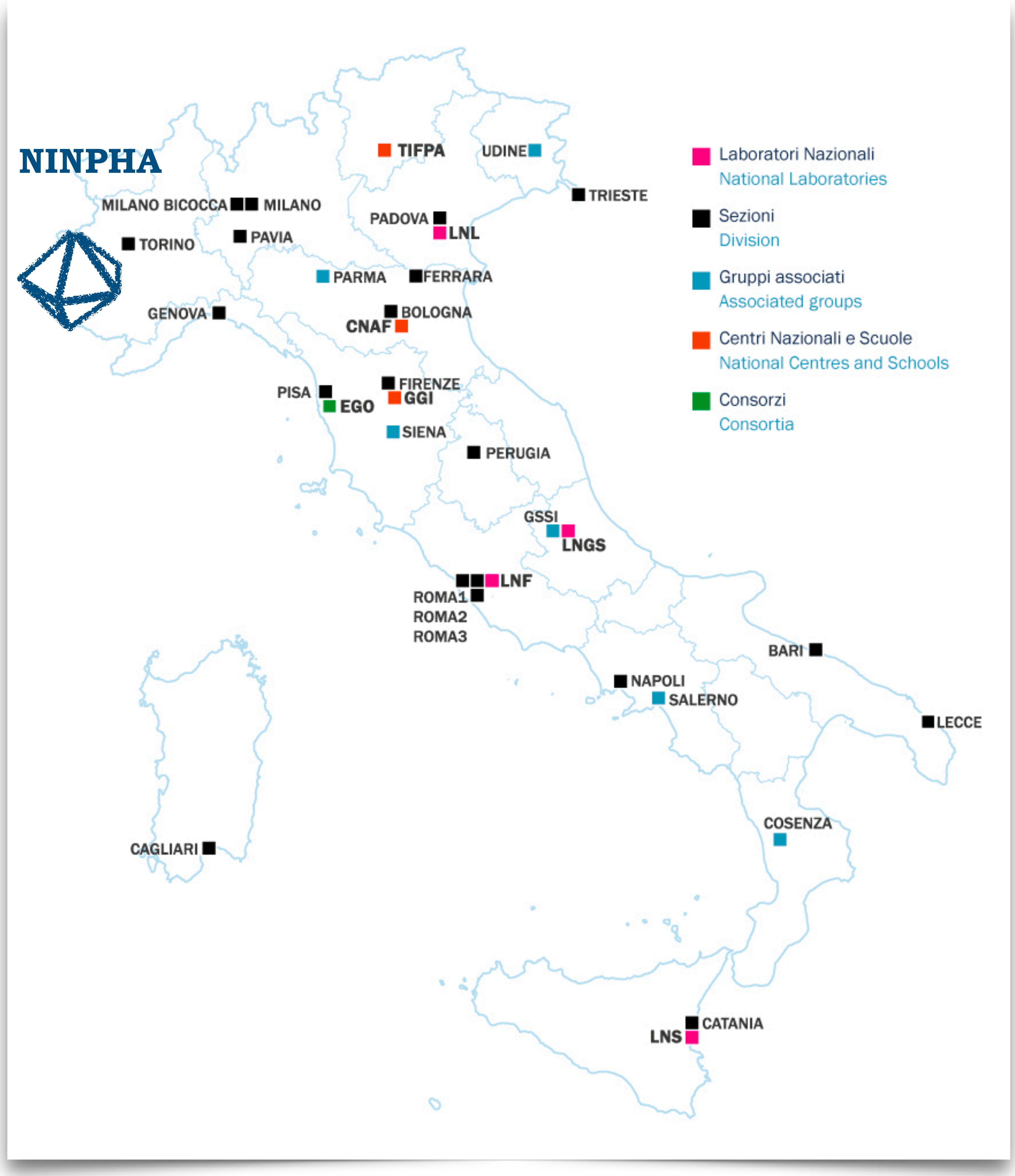
Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO



Staff members

Vincenzo Barone, U. Piemonte Orientale, Associate Professor

Mariaelena Boglione, U. Torino, Associate Professor, NINPHA Coordinator

José Osvaldo Gonzalez-Hernandez, U. Torino, Researcher

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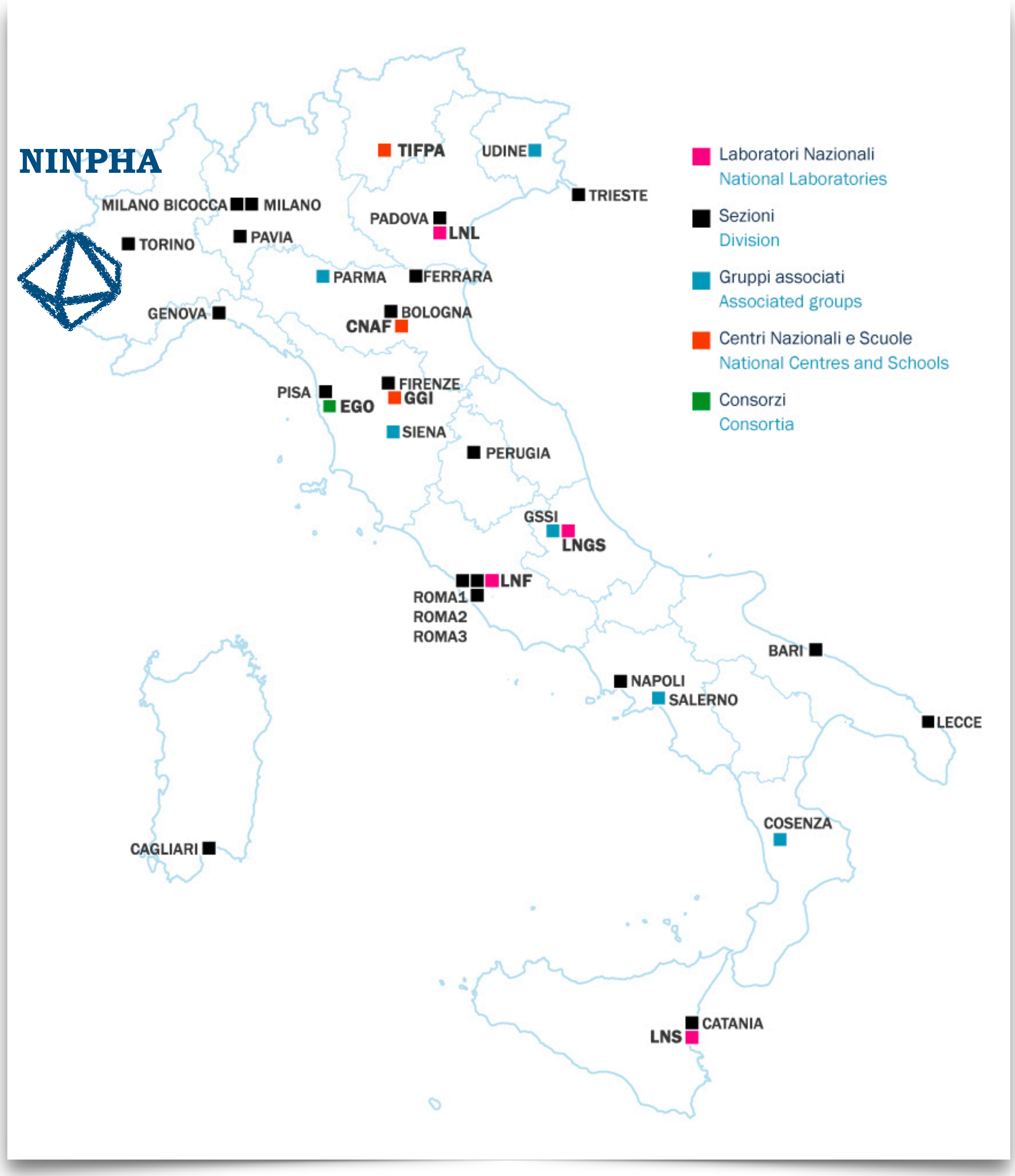
Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO



Staff members

Vincenzo Barone, U. Piemonte Orientale, Associate Professor

Mariaelena Boglione, U. Torino, Associate Professor, NINPHA Coordinator

José Osvaldo Gonzalez-Hernandez, U. Torino, Researcher

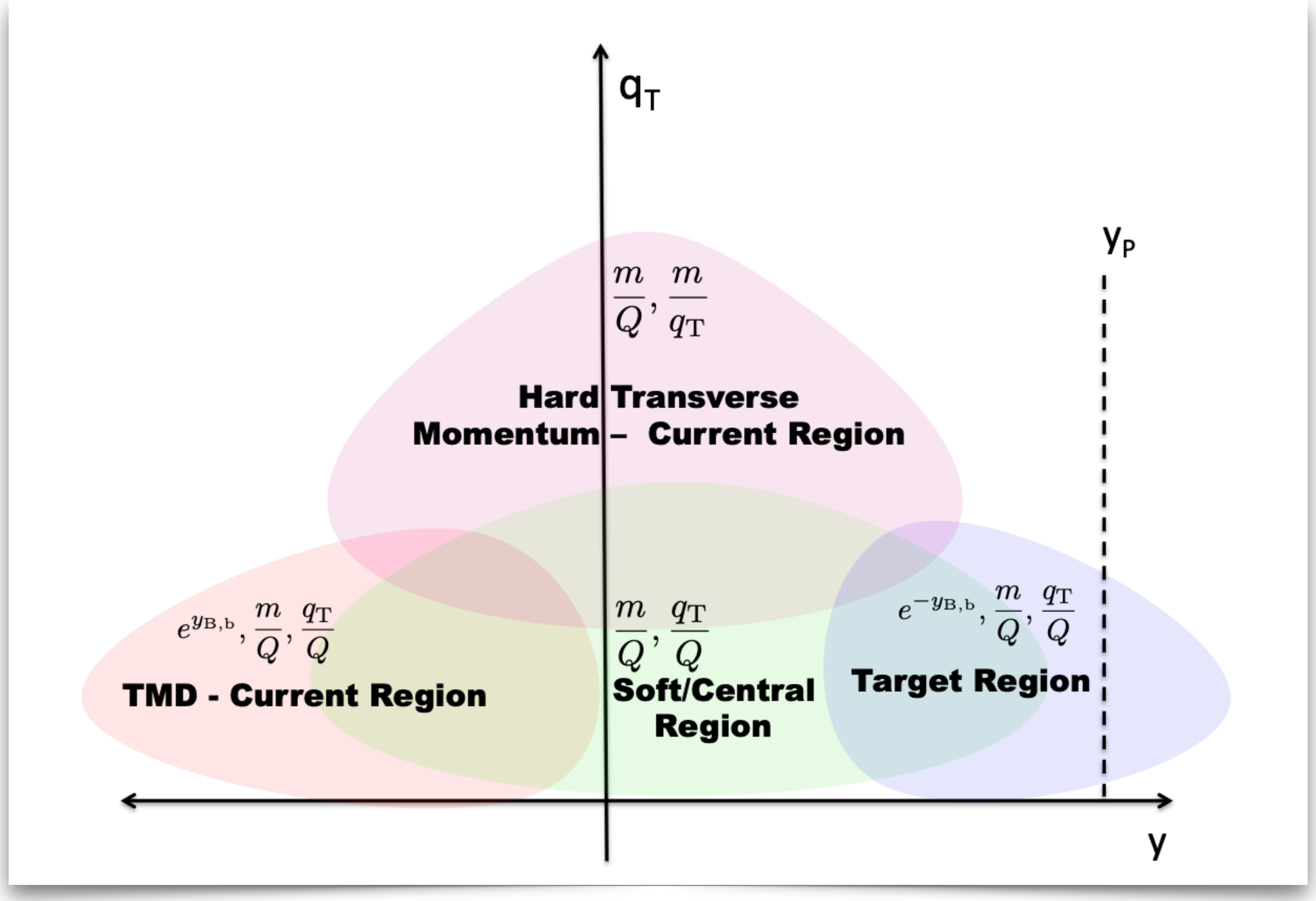
Other Participants

Mauro Anselmino, U. Torino, Full Professor (Senior)

Andrea Simonelli, INFN, Post-doc

Mapping kinematic regimes of SIDIS

* SIDIS production and TMD factorization



[M. Boglione *et al.* (2019)]

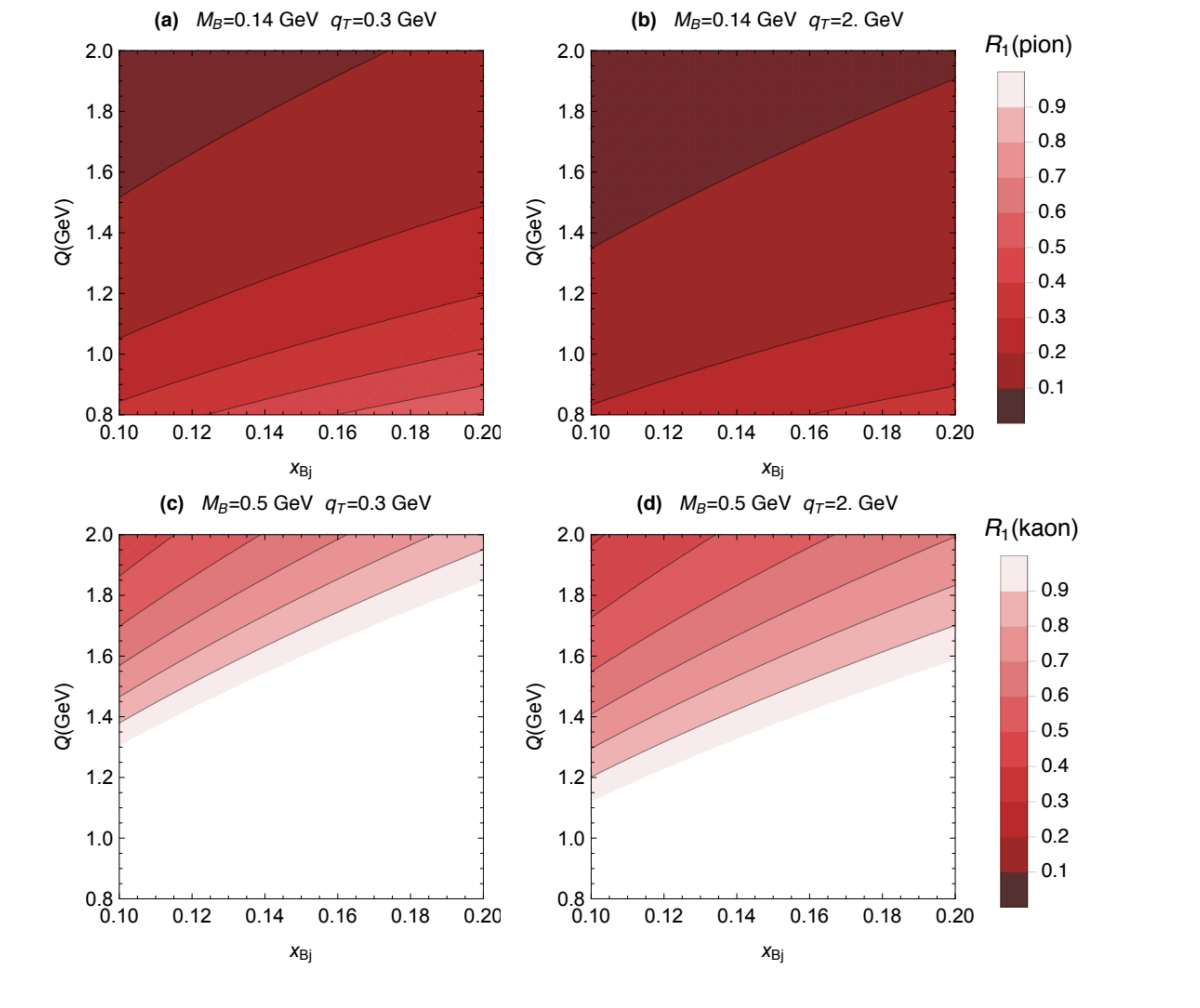


Figure 10: Collinearity (R_1 from Eq. (8.15) for fixed $z_h = 0.25$, $\zeta = 0.3$ and $\xi = 0.2$. Top panels show the ratio for $M_B = m_\pi$ at (a) small transverse momentum ($q_T = 0.3$ GeV) and (b) $q_T = 2.0$ GeV. Similar cases for $M_B = m_K$ are shown in the bottom panels, (c) and (d).

Collinearity. Similar plots for transverse-hardness and spectator-virtuality ratios

Jets and TMD FFs in e^+e^- annihilations

- TMD factorization, benchmark processes:
  1. Drell-Yan, l^+l^- almost back-to-back
  2. SIDIS, small p_T
  3. $e^+e^- \to H_1 + H_2 + X$, almost back-to-back

Same structure for the cross section:

$$\frac{d\sigma}{dq_T} = \mathcal{H}_{\text{proc.}} \int \frac{d^2\vec{b}_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{b}_T}\, F(b_T)\, S(b_T)\, D(b_T)$$

First Hadron

No direct experimental probe

Second Hadron

Factorization definition for F and D

Jets and TMD FFs in e^+e^- annihilations

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First Hadron

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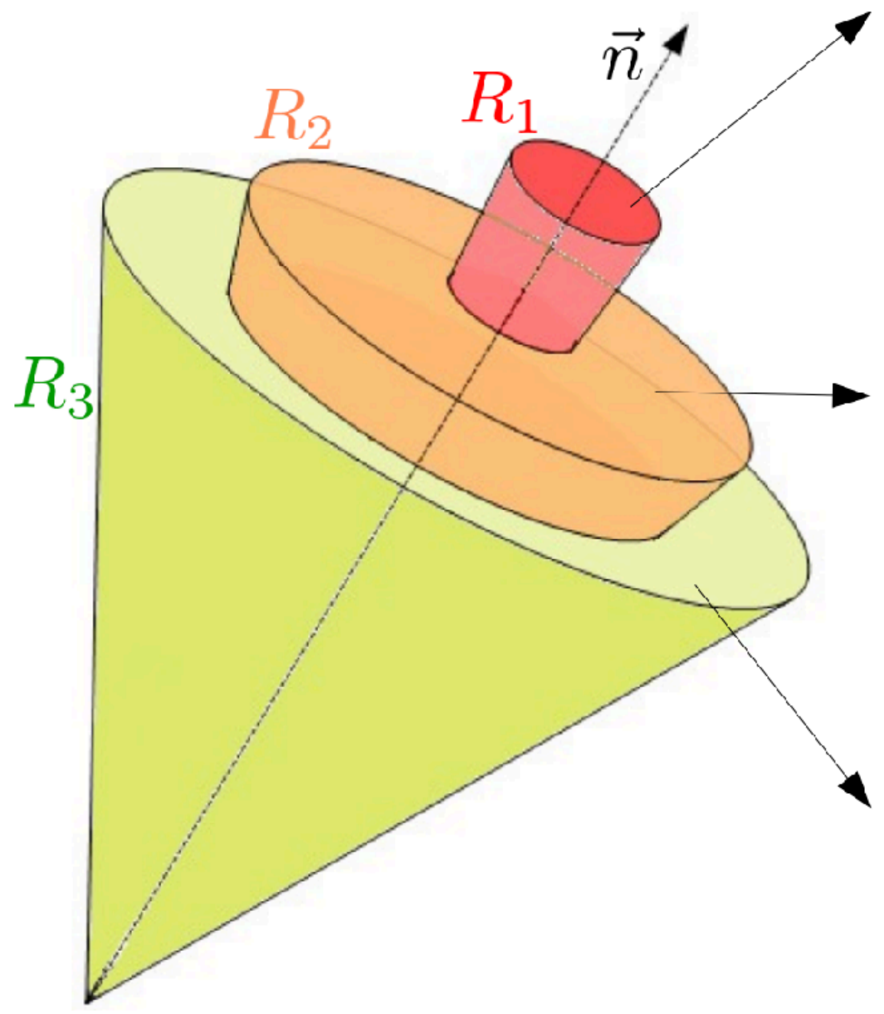
Second Hadron

Factorization definition for F and D

slide adapted from A. Simonelli, Sar Wors 2021

- Beyond benchmark: $e^+e^- \to H + X$

Sensitivity to **thrust**, rapidity cut-offs



TMD Factorization (similar to benchmarks).

TMD FFs are contamined by soft radiation as in the **square root definition**. Access to:

$M_S, \quad M_D, \quad g_K$

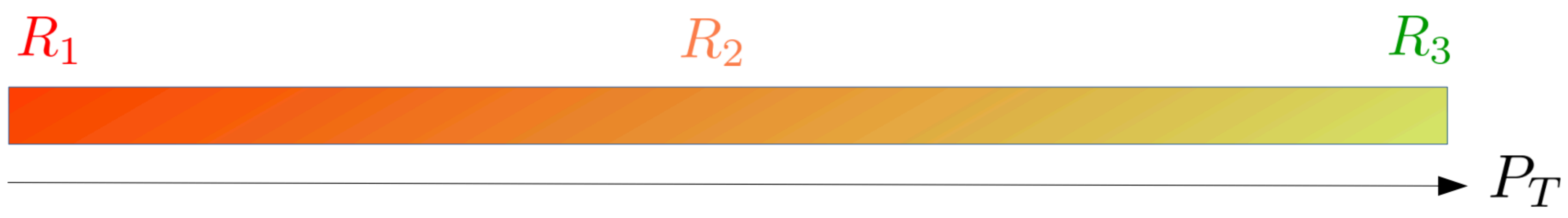
collinear-TMD Factorization NEW!

TMD FFs are pure collinear objects, defined through the **factorization definition**. Access to:

$M_D, \quad g_K$

Generalized collinear Factorization

The hadronization is described by GFJFs, which depend explicitly on thrust.



(Universality breaking) [M. Boglione, A. Simonelli (2020)]

(Factorization, 2-jet limit) [M. Boglione, A. Simonelli (2021)]

(Factorization, kinematics) [M. Boglione, A. Simonelli (2021)]

Sivers and Collins functions, SIDIS at large p_T

* Unpol. TMD PDFs/FFs and SSAs

  🔗 [M. Anselmino *et al.* (2018)]

* TMD signals of the quark Sivers effect

  NINPHA/**Torino** + NINPHA/**Cagliari**

  Extraction from HERMES/JLab/COMPASS

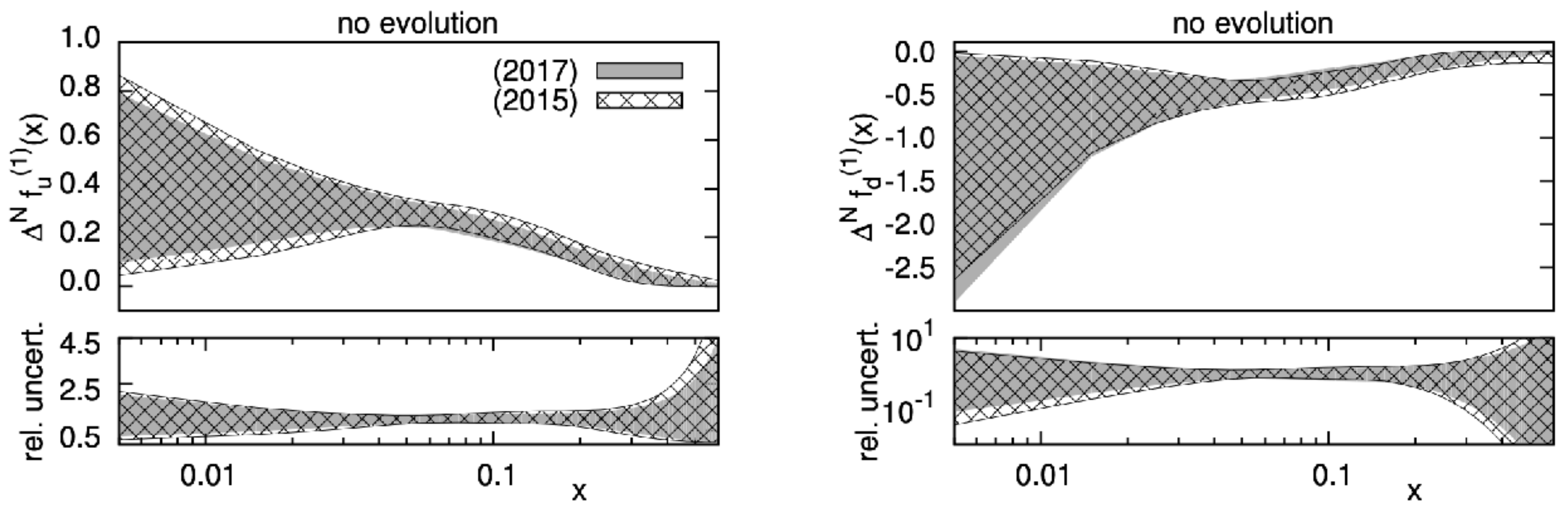


FIG. 8: Uncertainties on the first moments of the Sivers distribution for $u = u_v + \bar{u}$ (left panel) and $d = d_v + \bar{d}$ (right panel). The shaded bands correspond to our estimate of 2σ C.L. error for α-fit case. In both panels, the gray bands correspond to the fit which includes the new COMPASS-2017 data [9] for h^+ and h^- production off NH_3 target, while the meshed areas correspond to the uncertainties obtained when the COMPASS-2015 data from the older analysis [33] are included. The lower panels show the relative errors, given by the ratio between the upper/lower border of the uncertainty bands and the best-fit curve for the reference fit.

🔗 [M. Boglione *et al.* (2018)]

Sivers and Collins functions, SIDIS at large p_T

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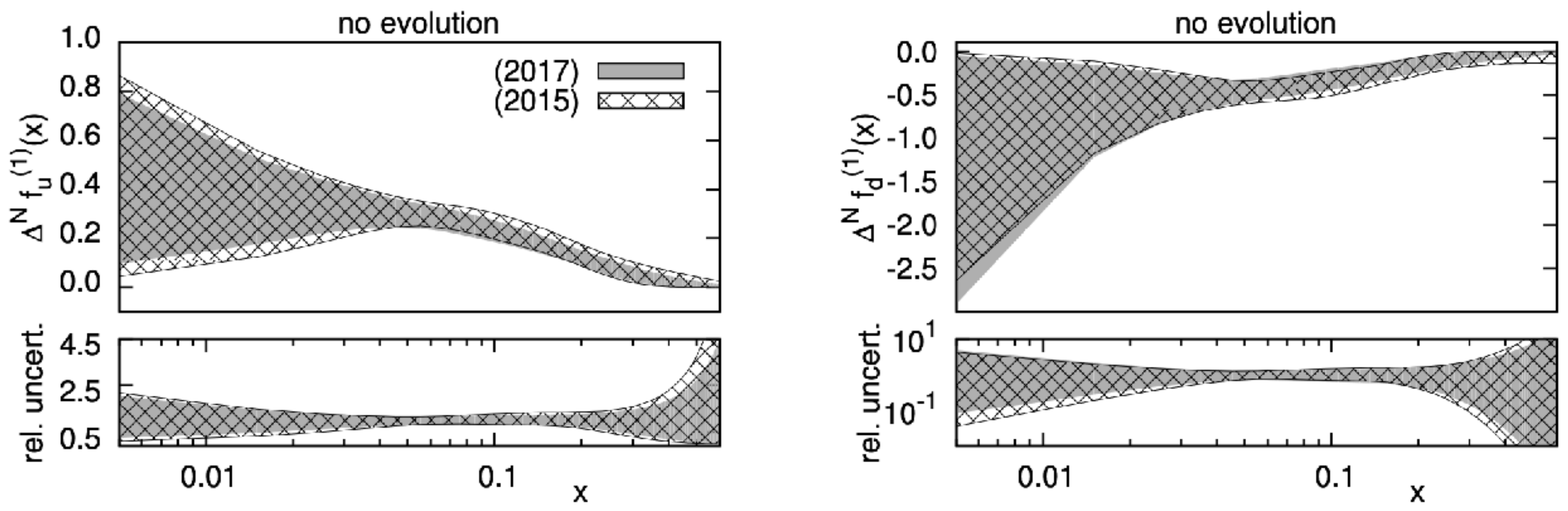

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🔗 [M. Boglione *et al.* (2018)]

* Large p_T behavior in SIDIS

  NINPHA/**Torino** + JLab + Zhejiang (China)

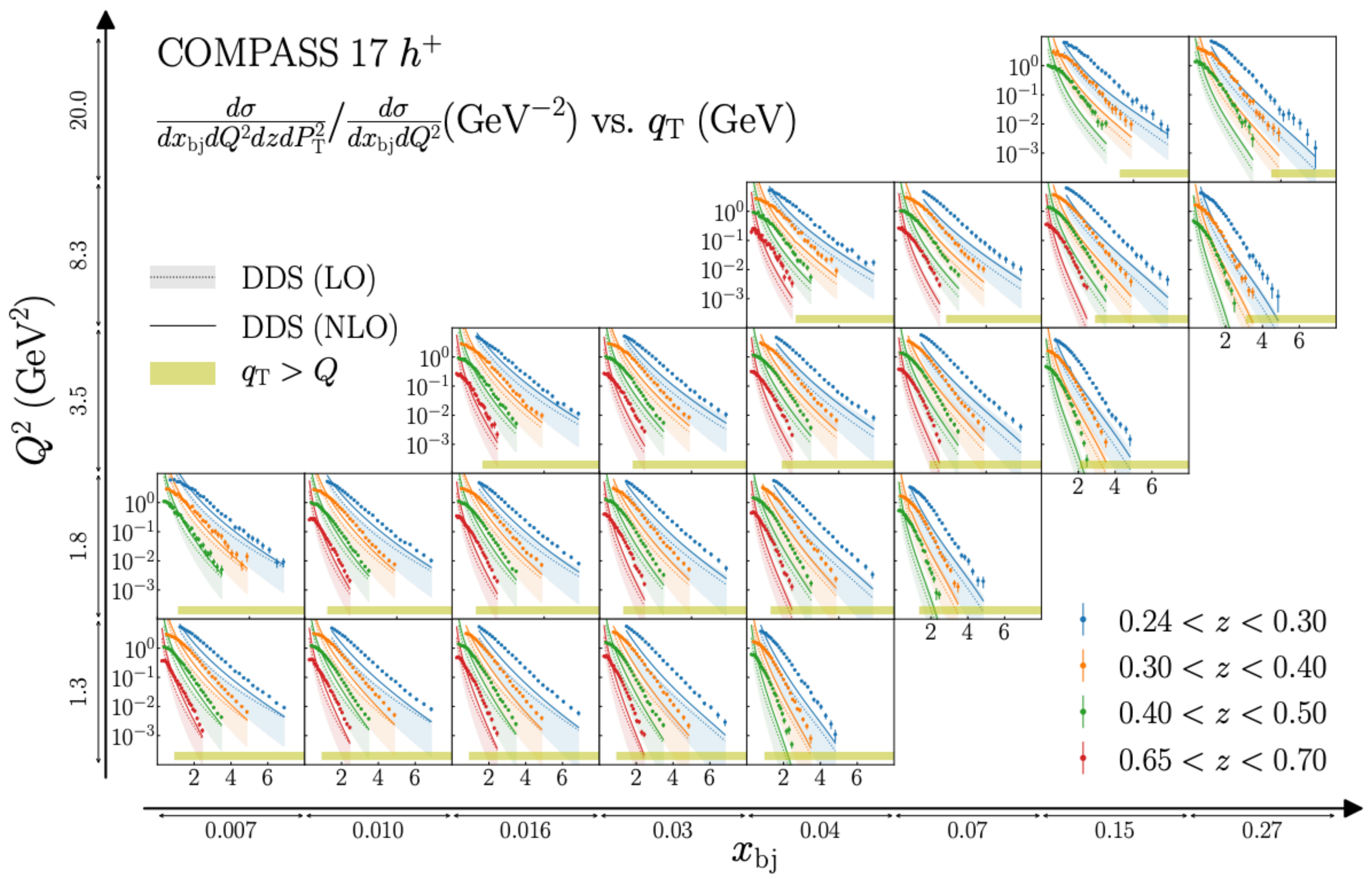
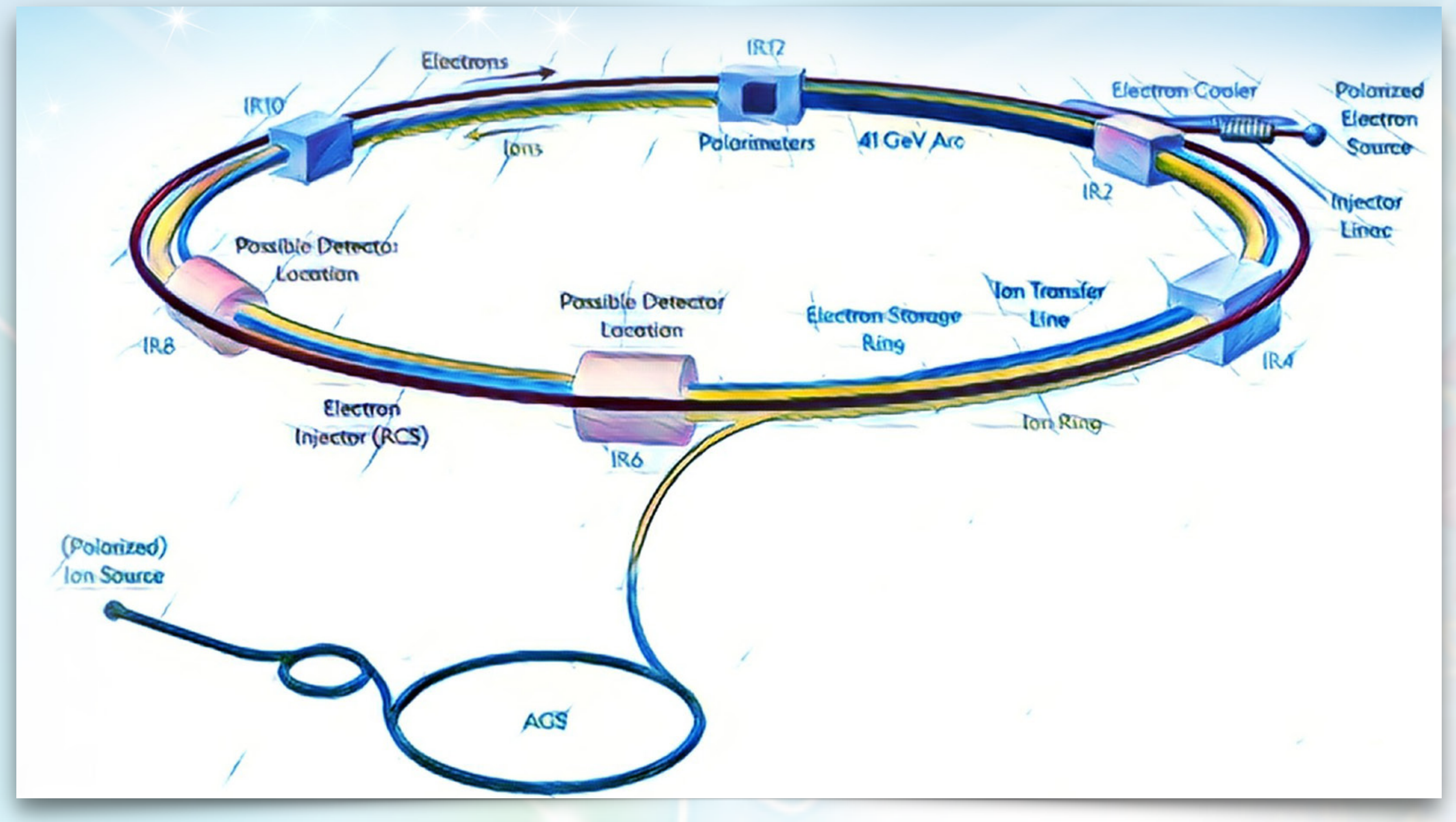


FIG. 4. Calculation of $O(\alpha_s)$ and $O(\alpha_s^2)$ transversely differential multiplicity using code from [24], shown as the curves labeled DDS (for Daleo-de Florian-Sassot). The bar at the bottom marks the region where $q_T > Q$. The PDF set used is CJNLO [31] and the FFs are from [32]. Scale dependence is estimated using $\mu = ((\zeta_Q Q)^2 + (\zeta_{q_T} q_T)^2)^{1/2}$ where the band is constructed point-by-point in q_T by taking the min and max of the cross section evaluated across the grid $\zeta_Q \times \zeta_{q_T} = [1/2, 1, 3/2, 2] \times [0, 1/2, 1, 3/2, 2]$ except $\zeta_Q = \zeta_{q_T} = 0$. The red band is generated with $\zeta_Q = 1$ and $\zeta_{q_T} = 0$. A lower bound of 1 GeV is place on μ when $Q/2$ would be less than 1 GeV.

🔗 [J.O. Gonzalez-Hernanded *et al.* (2018)]

Future perspectives

3D proton tomography at new-generation colliders

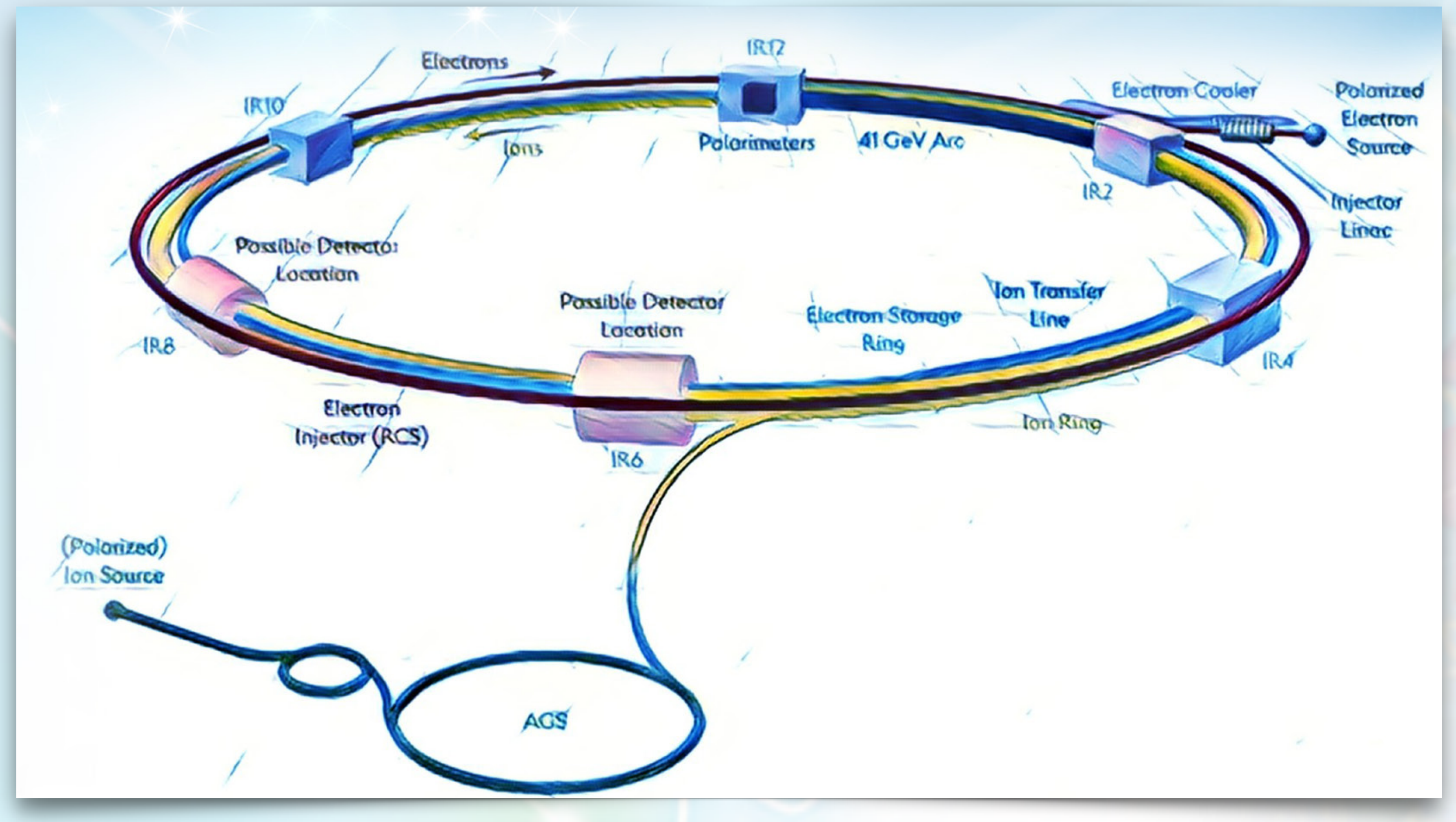


EIC

EIC Yellow Report 🔗 [EICUG [arXiv:2103.05419]]

Accessing the proton content

3D proton tomography at new-generation colliders



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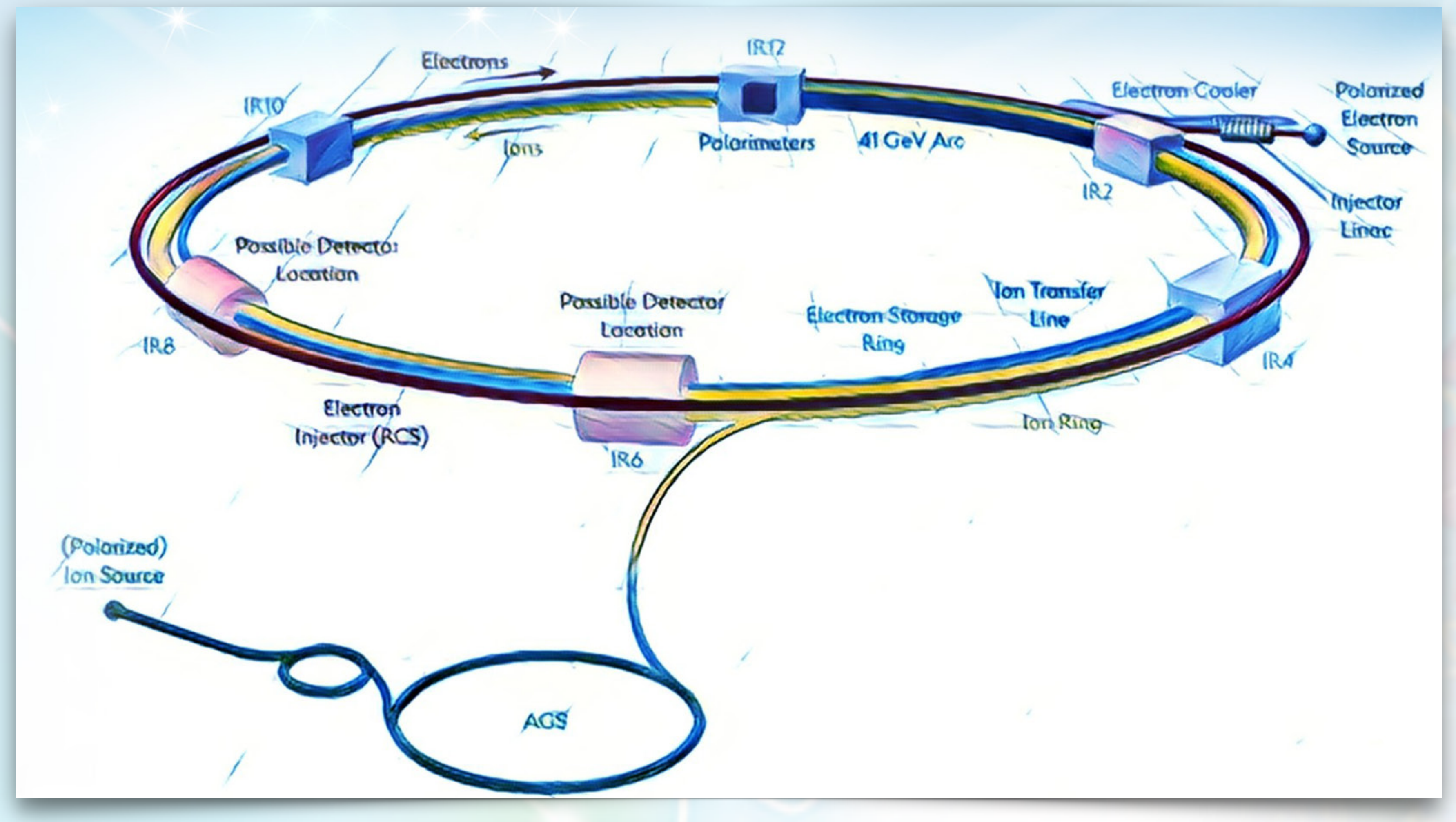
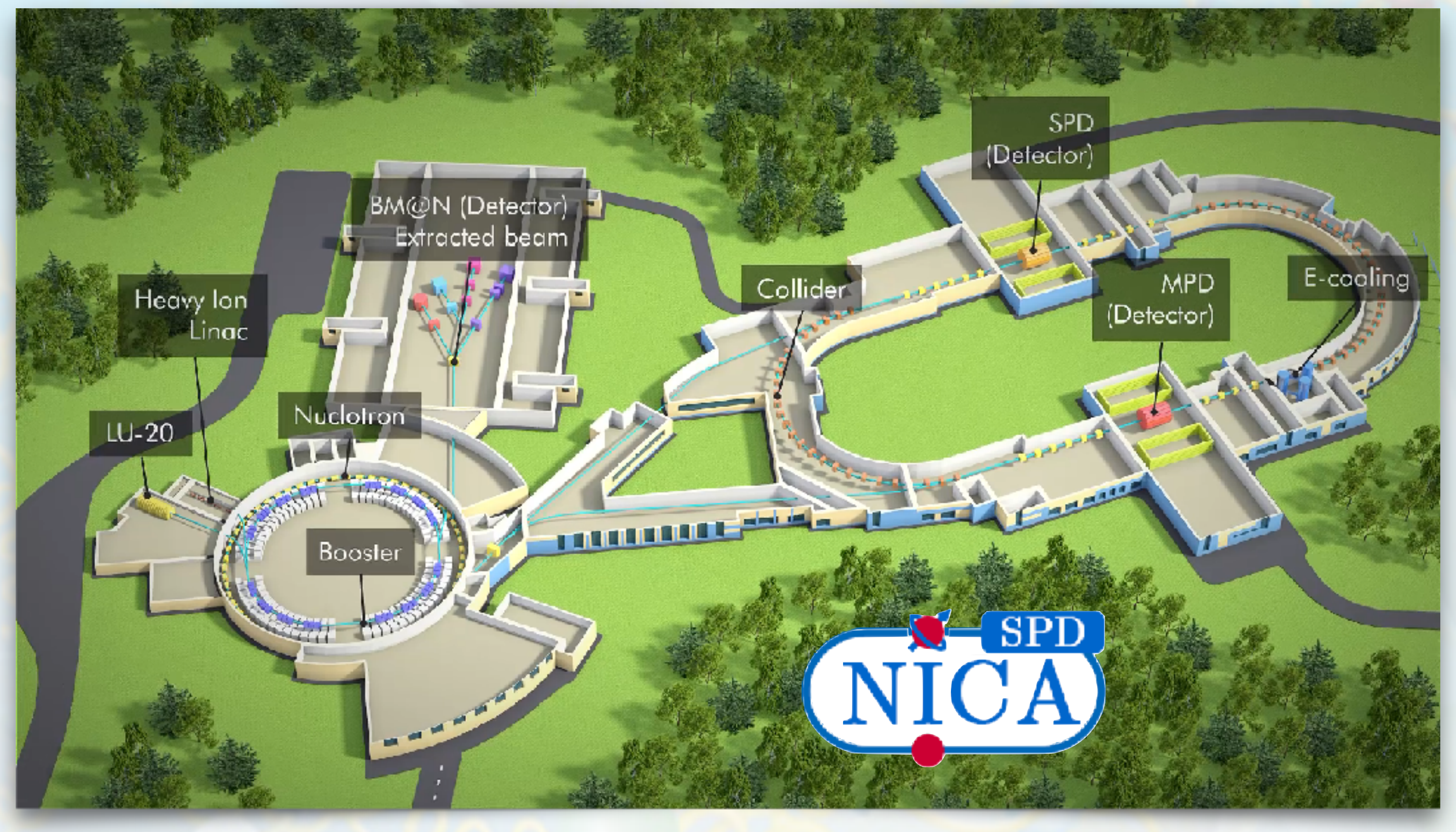
Accessing the proton content

Core sector of **EIC** analyses

3D proton tomography at new-generation colliders





EIC

NICA-SPD

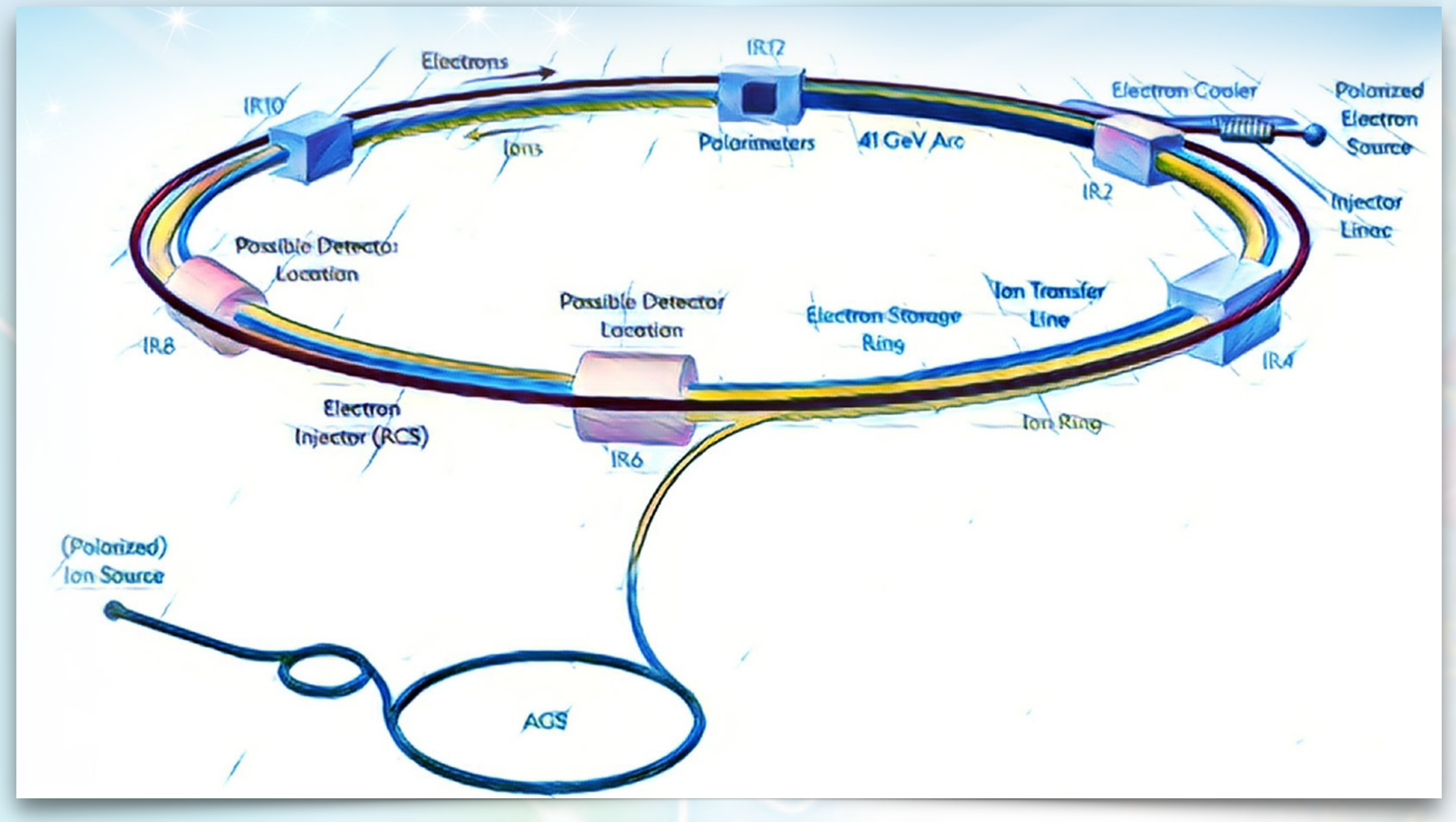
EIC Yellow Report 🔗 [EICUG [arXiv:2103.05419]]

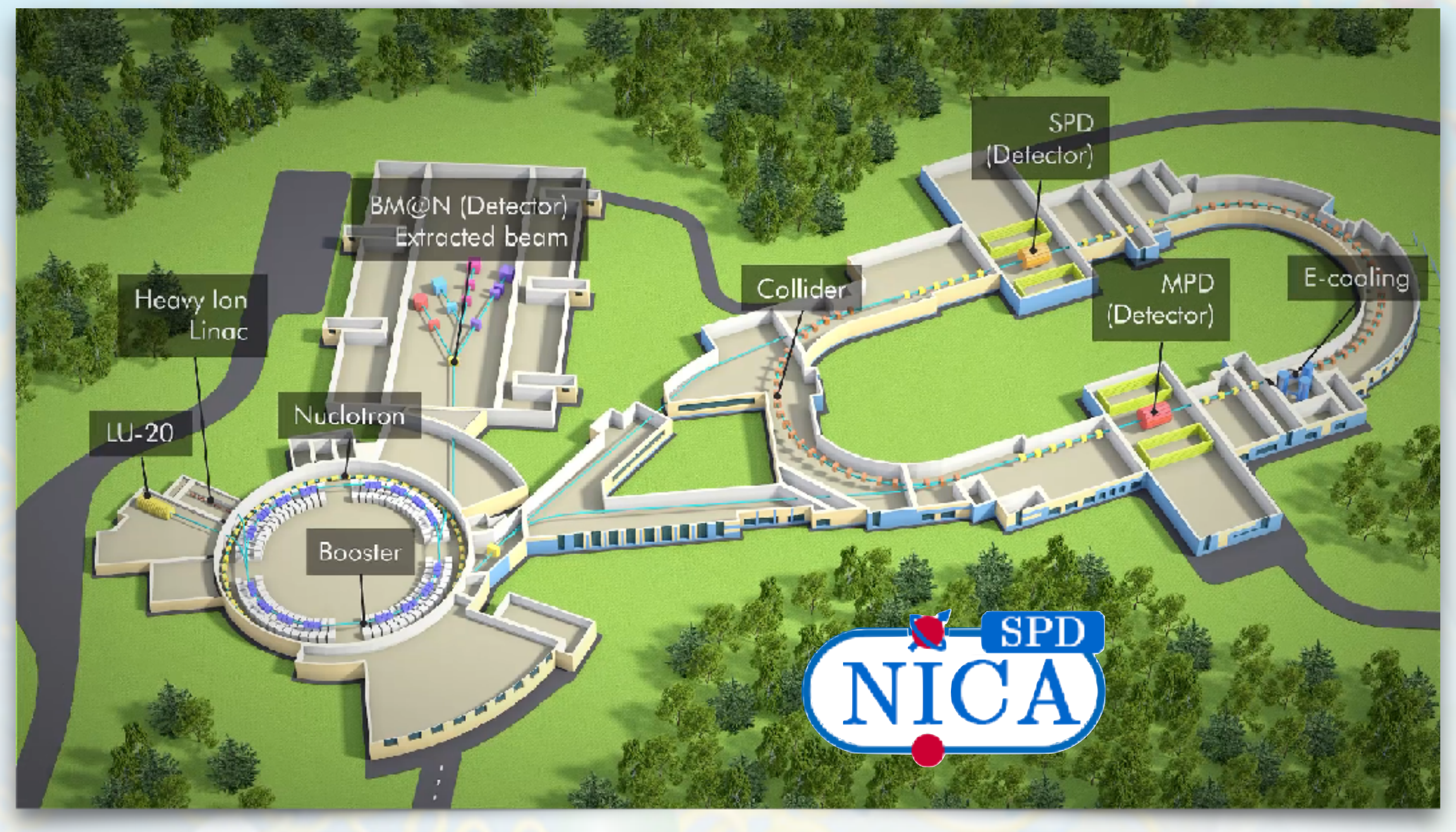
Gluon content at **NICA-SPD** 🔗 [NICA [arXiv:2011.15005]]

Accessing the proton content

- *Core* sector of **EIC** analyses
- *Significance* of large-x studies at **NICA-SPD**

3D proton tomography at new-generation colliders





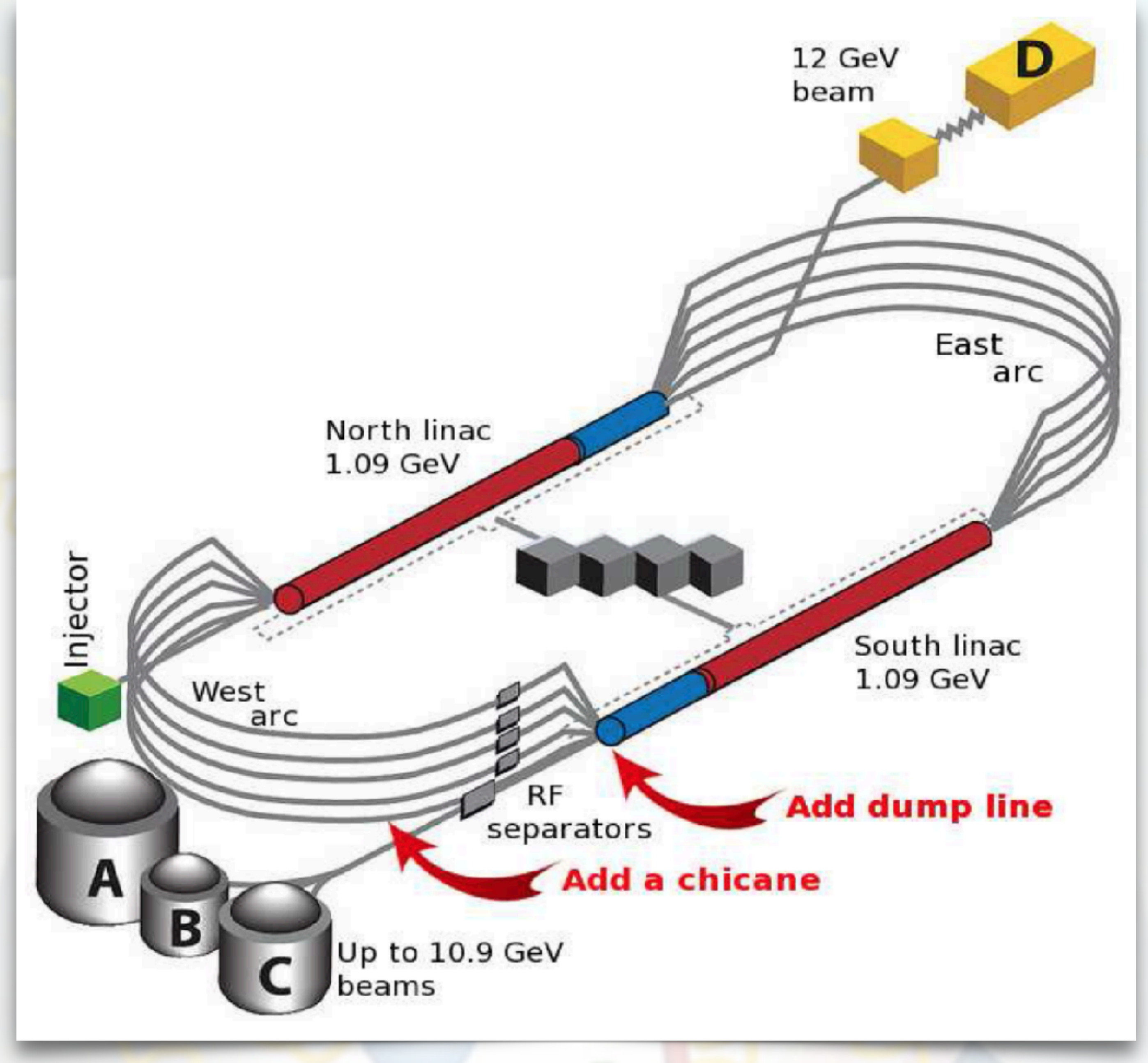
EIC

NICA-SPD

JLab12

EIC Yellow Report 🔗 [EICUG [arXiv:2103.05419]]

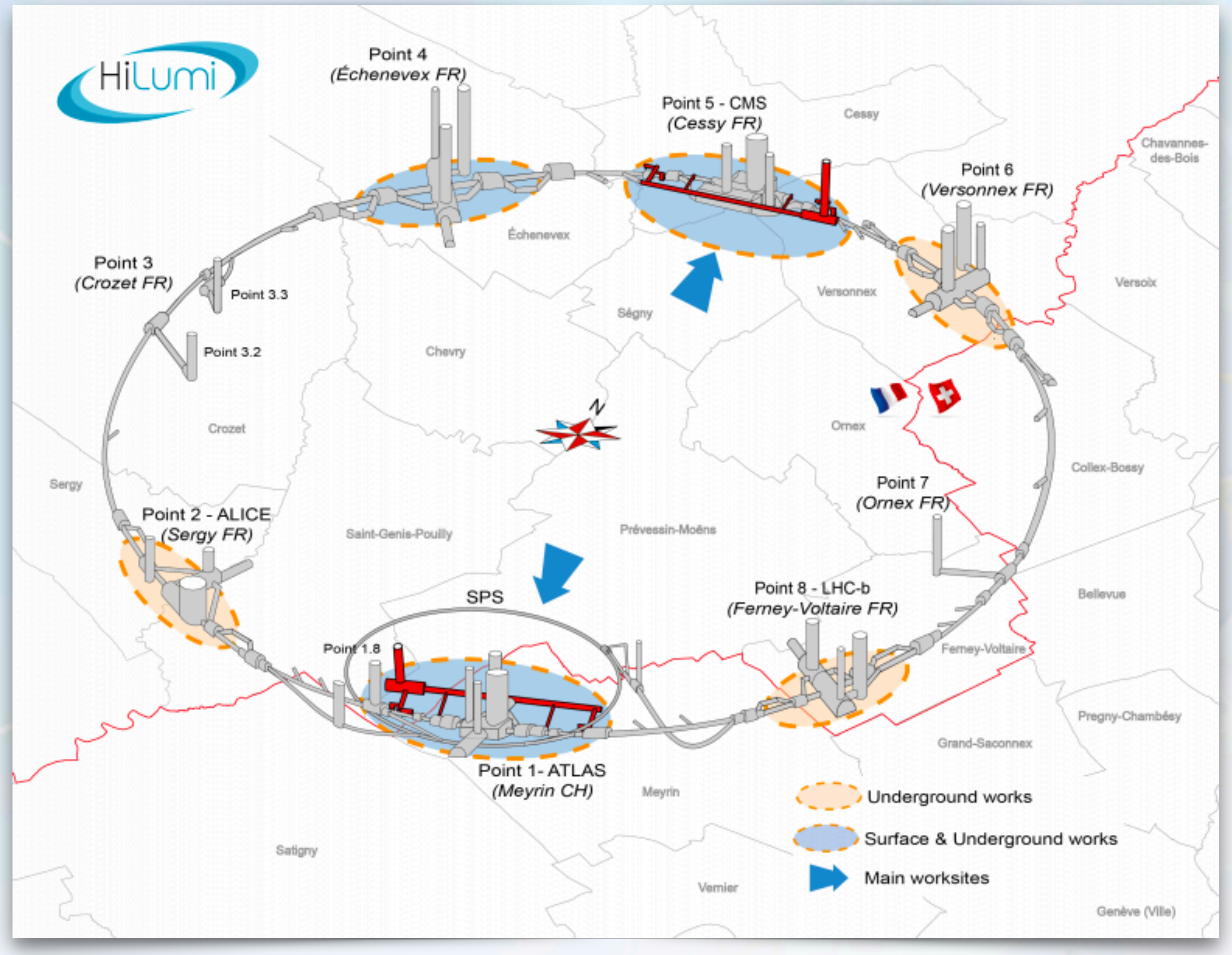
Gluon content at **NICA-SPD** 🔗 [NICA [arXiv:2011.15005]]



Accessing the proton content

- *Core* sector of **EIC** analyses
- *Significance* of large-x studies at **NICA-SPD**
- *All* NINPHA nodes *involved* in **JLab12** physics

Connections with high-energy physics

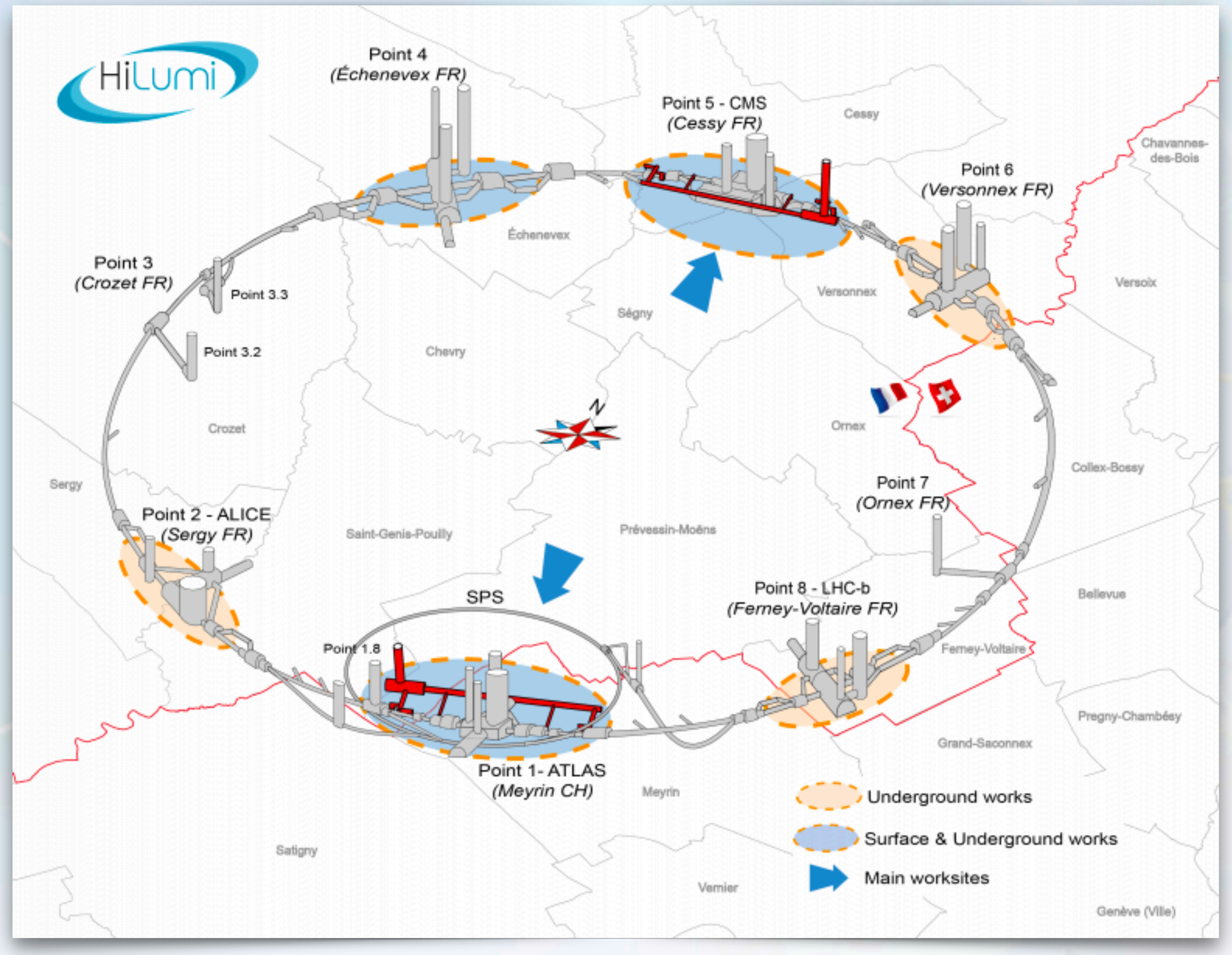


HL-LHC

Quarkonium studies at **HL-LHC** 🔗 [QAT [arXiv:2012.14161]]

Hadronic structure at high energies

Connections with high-energy physics



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Intrinsic effect of gluon polarization in **unpolarized** *pp* collisions

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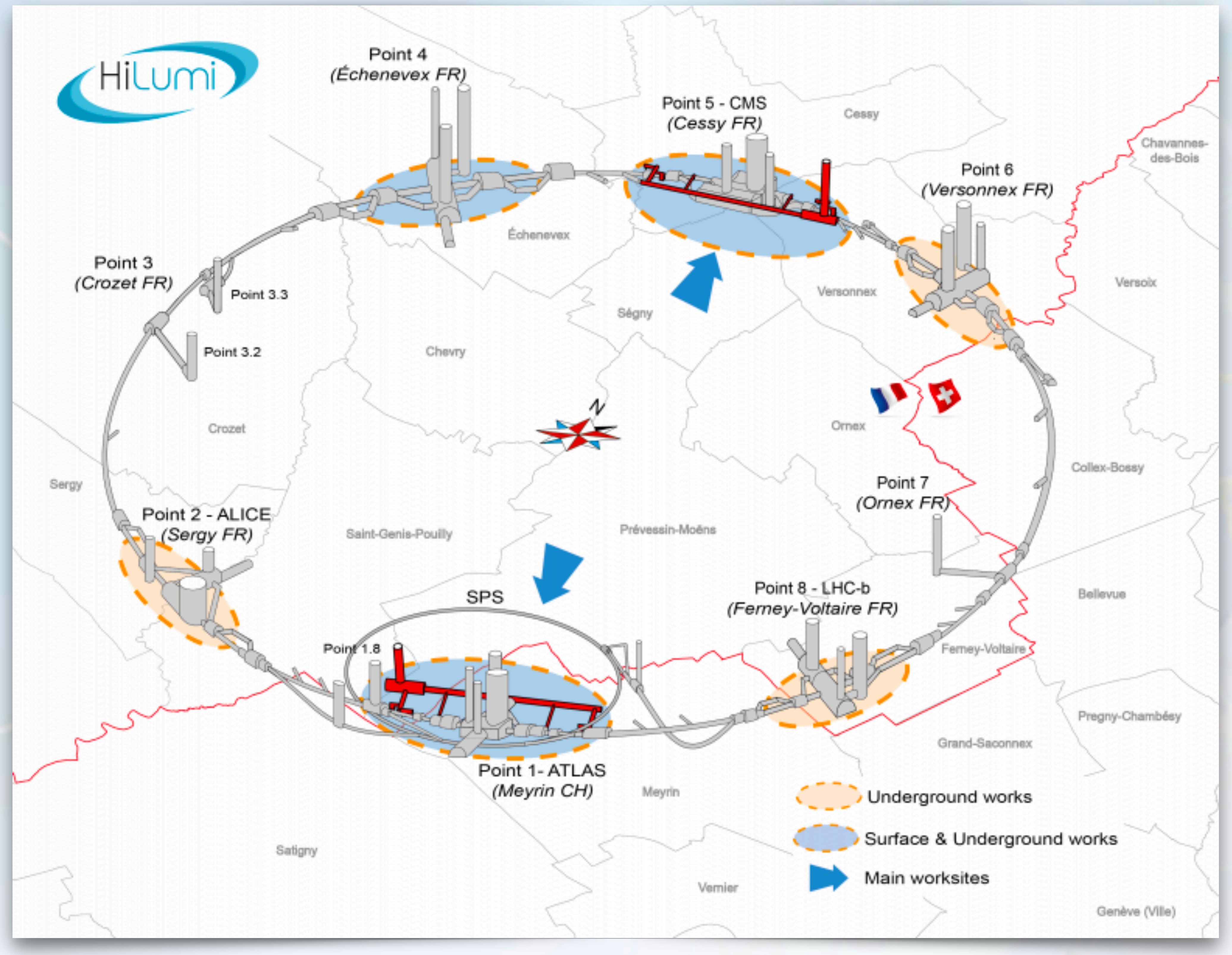
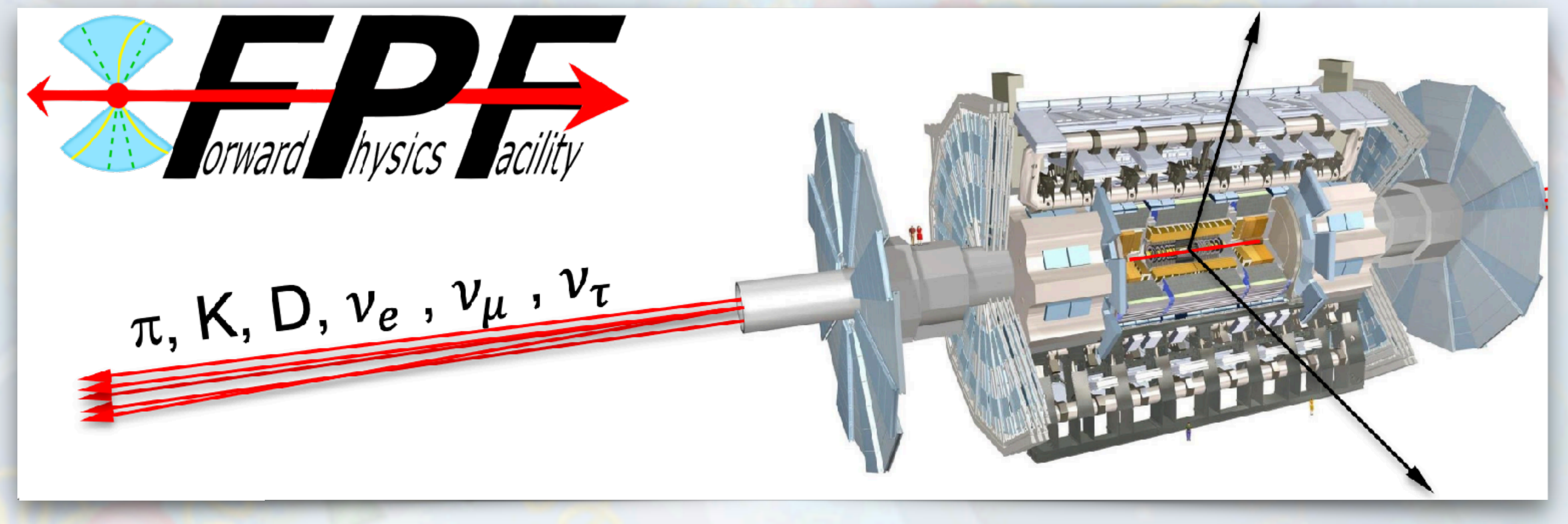




HL-LHC

Forward Physics Facility

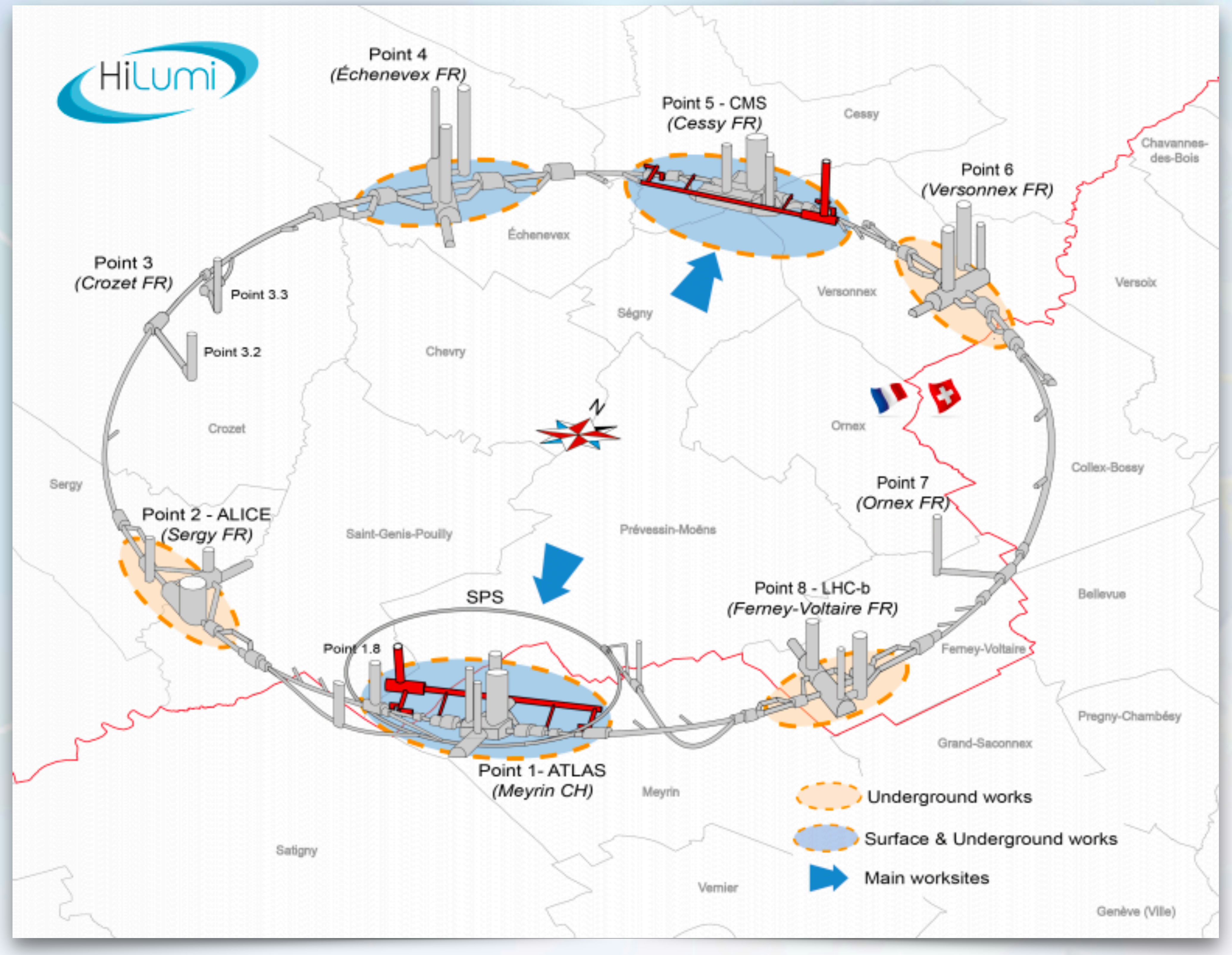
Quarkonium studies at **HL-LHC** [QAT [arXiv:2012.14161]]

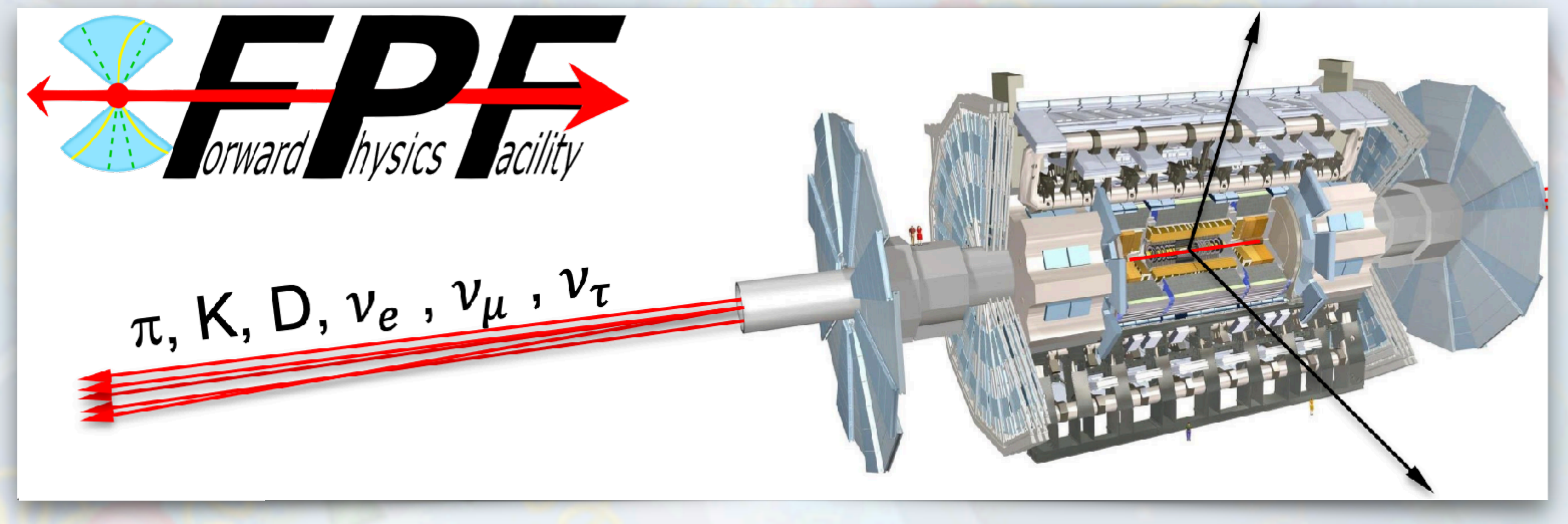
The Forward Physics Facility (**FPF**) [FPF [arXiv:2109.10905]]

Hadronic structure at high energies

- *Intrinsic* effect of gluon polarization in **unpolarized** *pp* collisions
- *Precision* studies of proton structure via **natural stability** of high-energy resummation

Connections with high-energy physics





HL-LHC

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The Forward Physics Facility (**FPF**) [FPF [arXiv:2109.10905]]

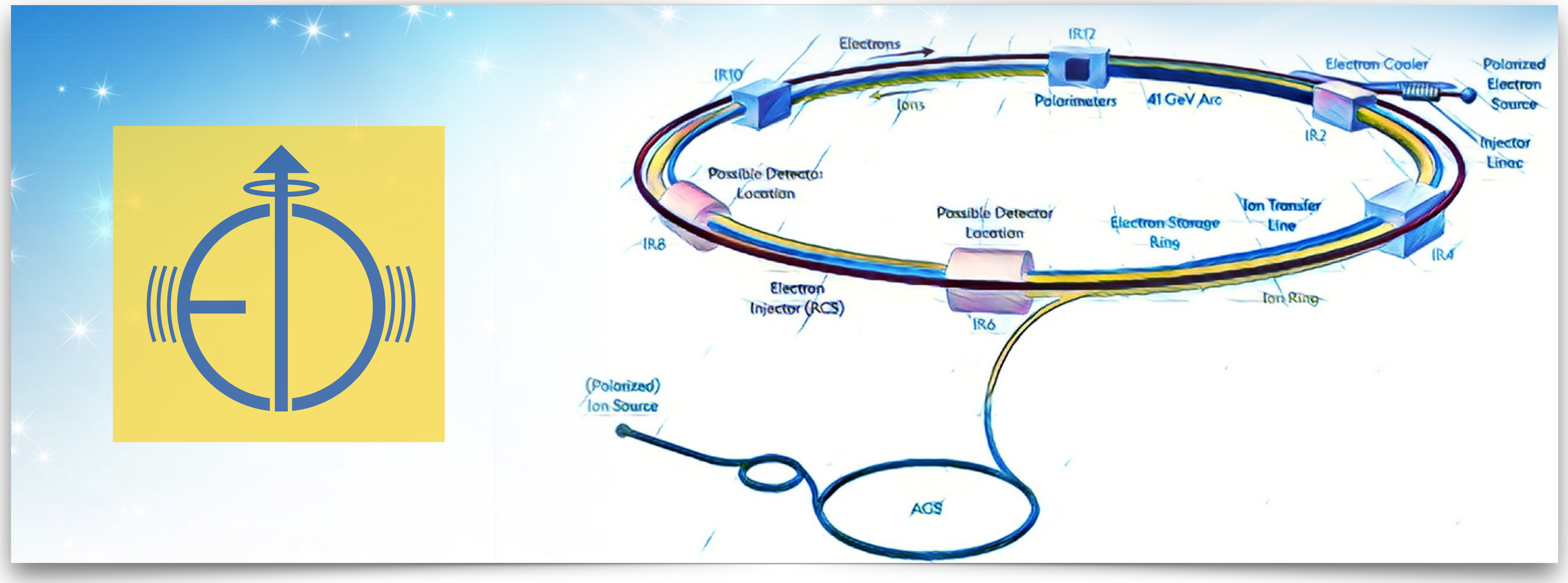
Hadronic structure at high energies

...two high-energy collaboration papers signed by NINPHA members!

- *Intrinsic* effect of gluon polarization in **unpolarized** *pp* collisions
- *Precision* studies of proton structure via **natural stability** of high-energy resummation

Challenges and new opportunities

HAS at new-generation colliders



Challenges and new opportunities

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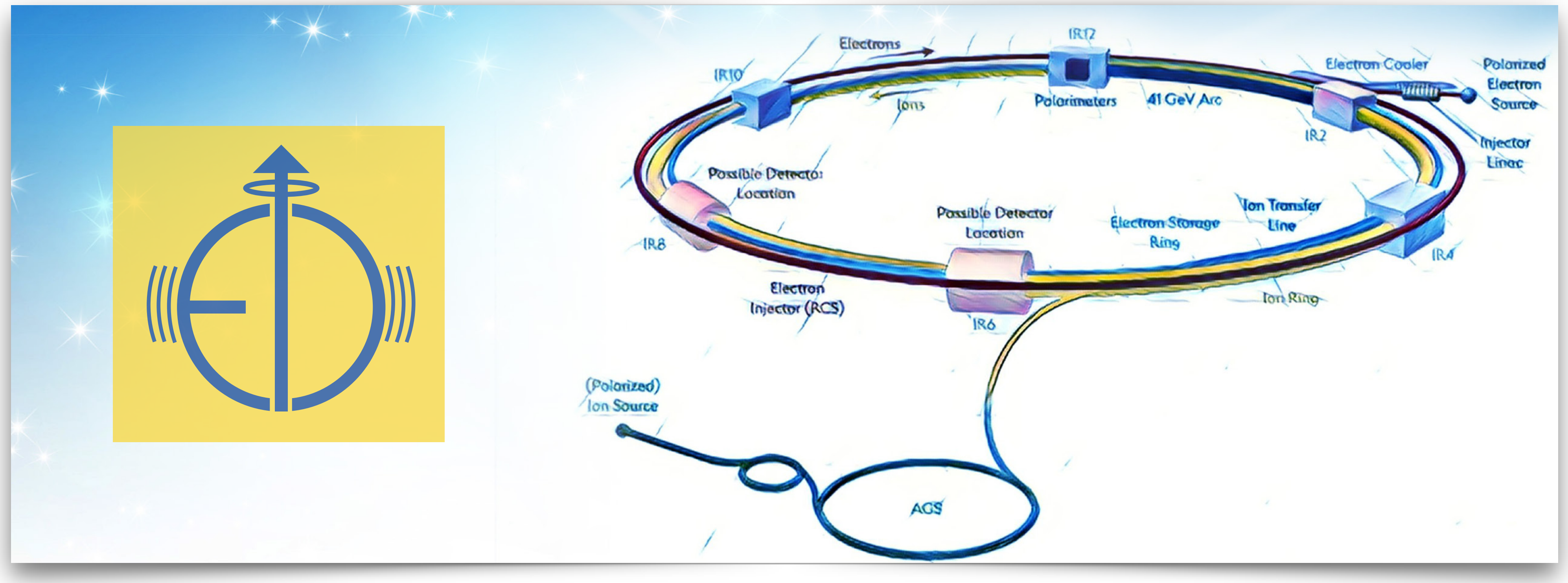
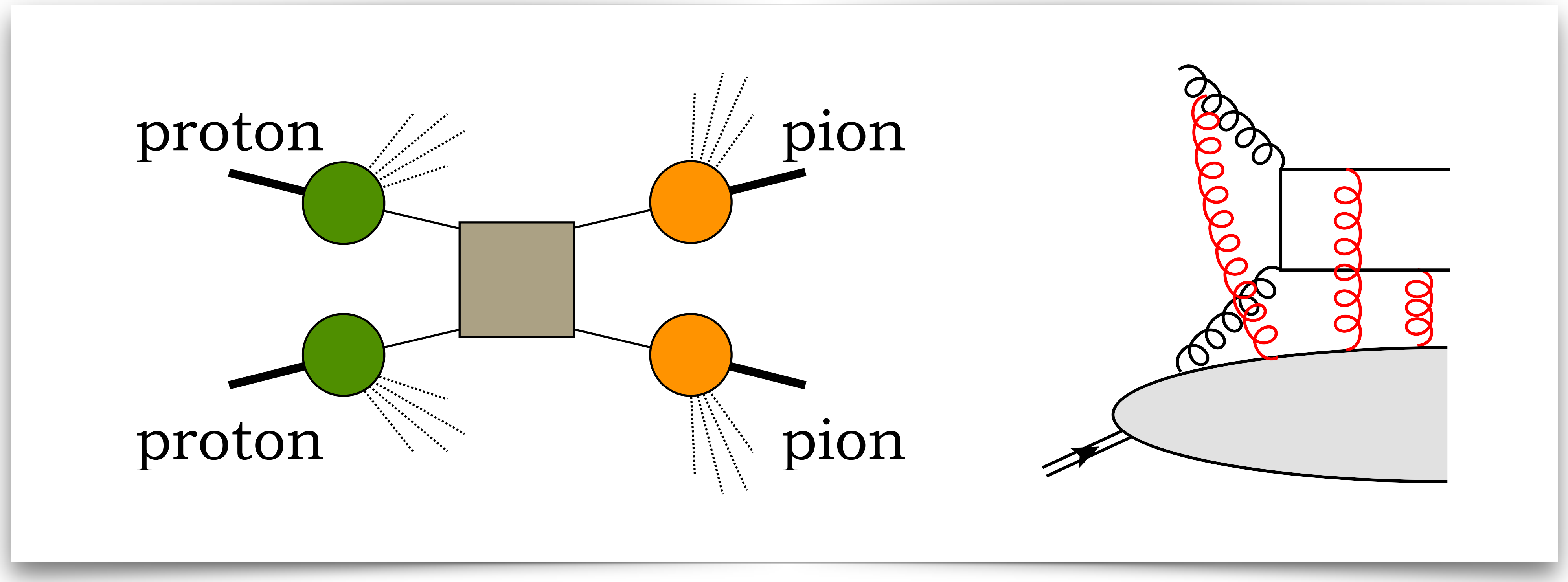


Assessing TMD factorization violation



Challenges and new opportunities

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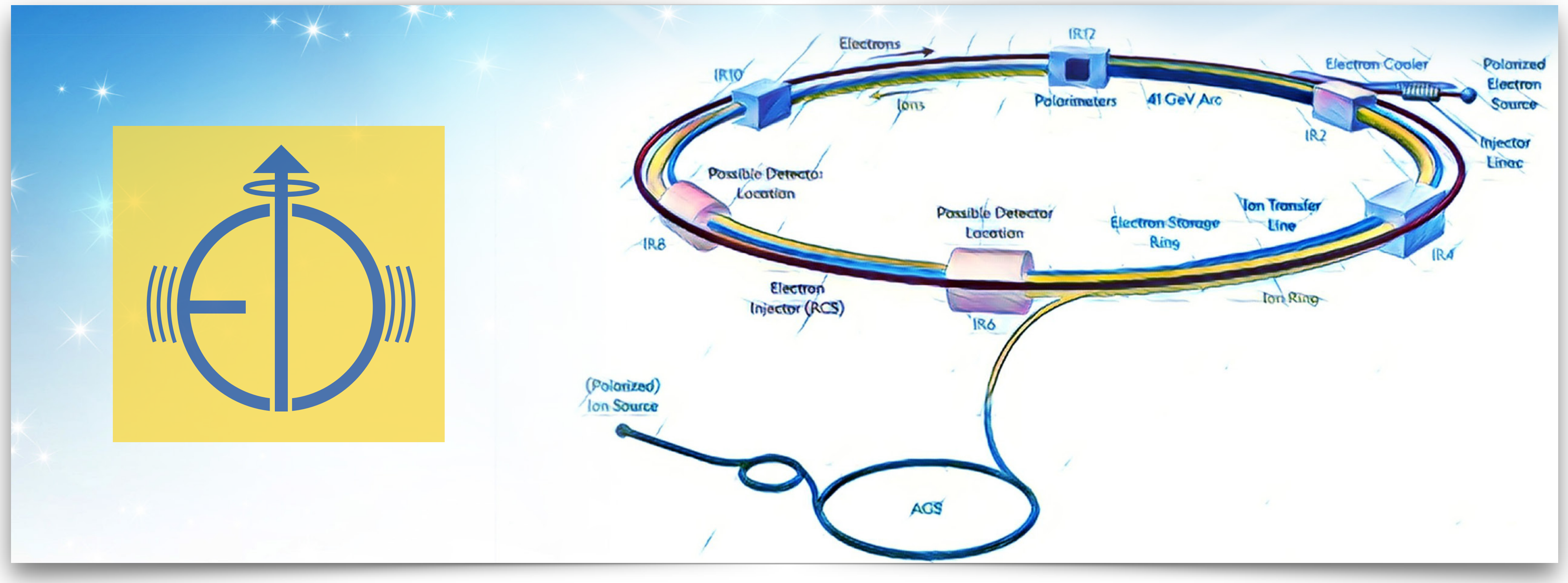

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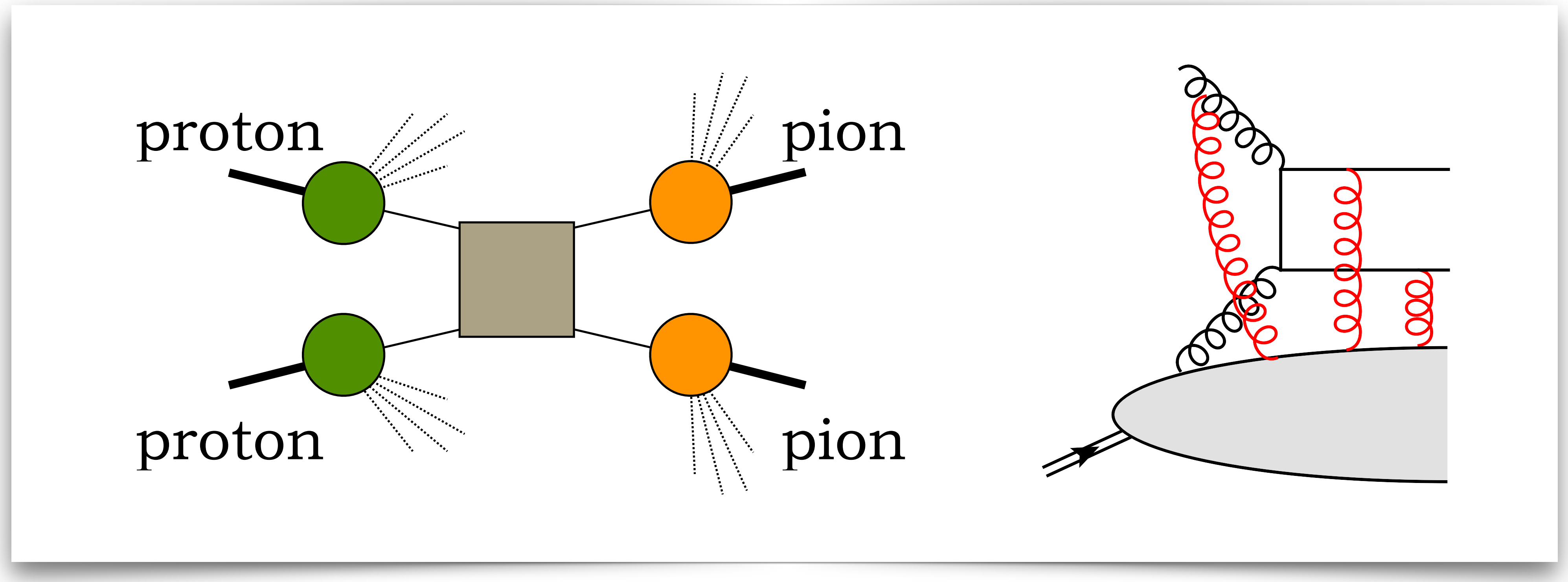
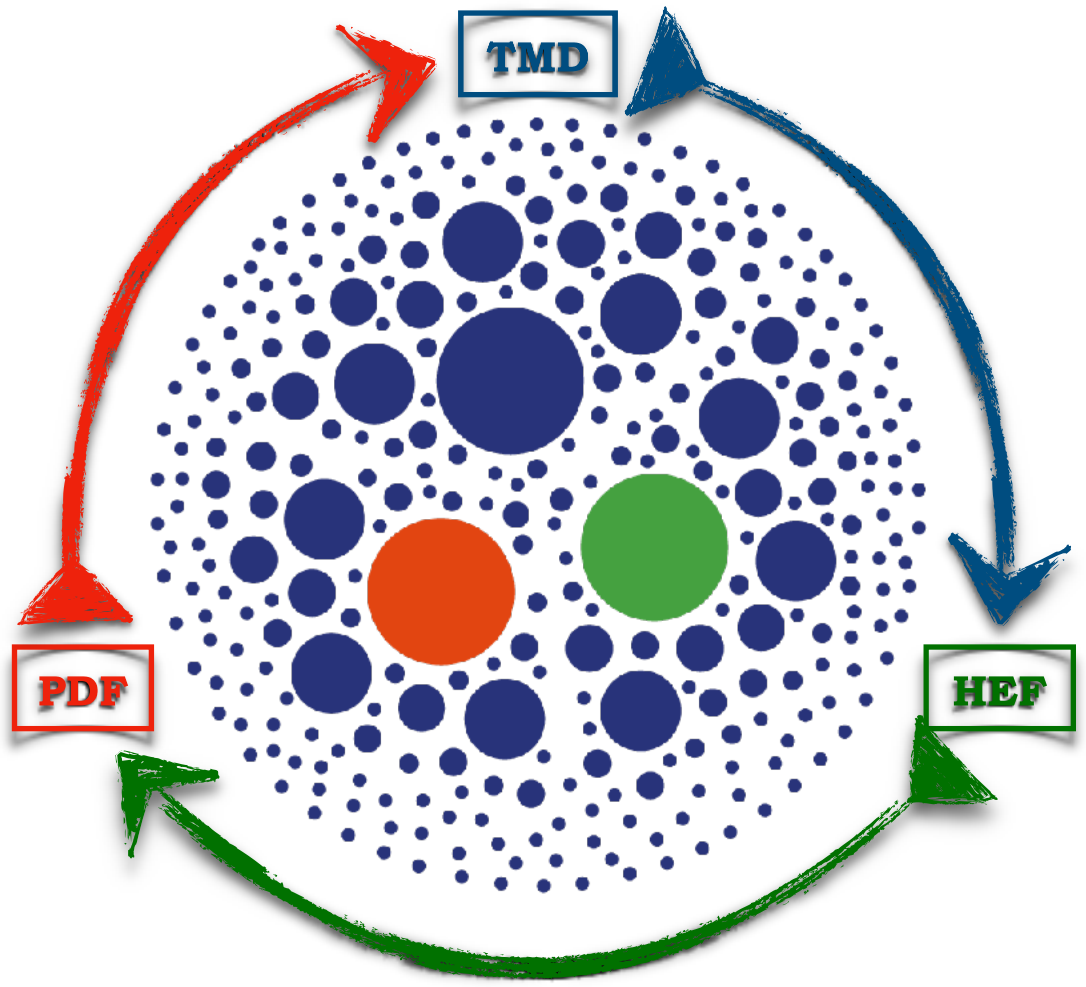


Interplay of different factorizations



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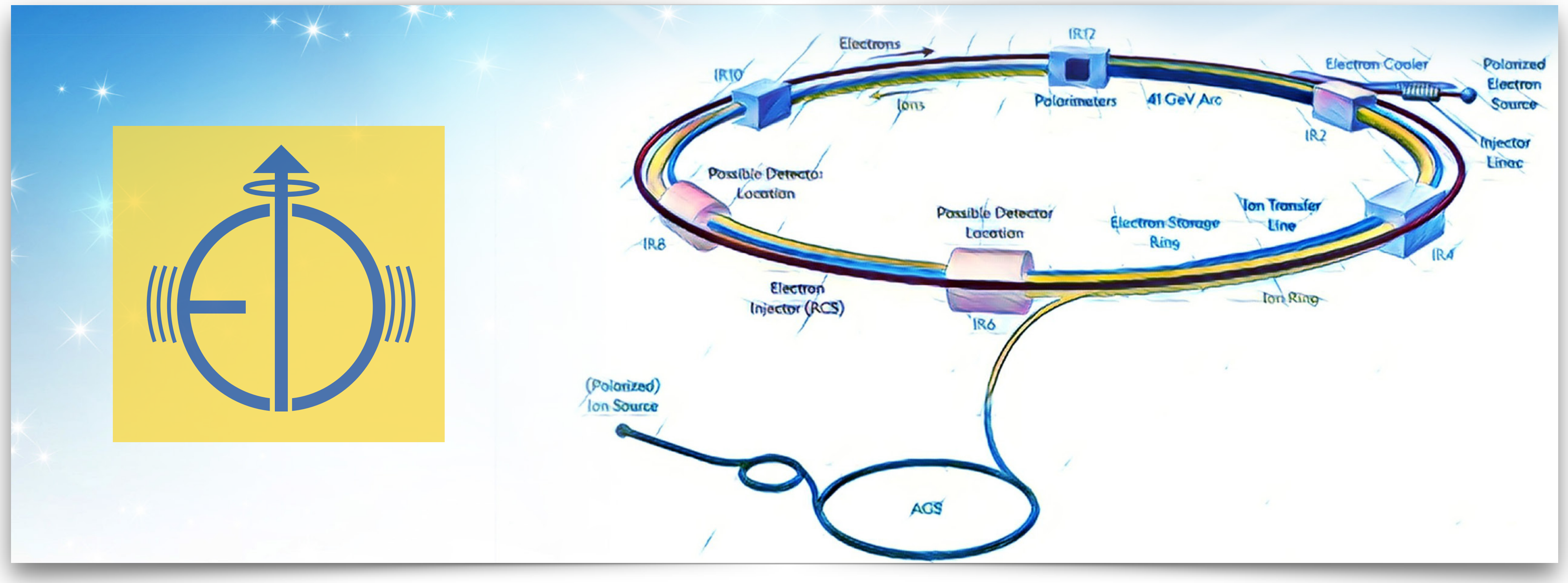

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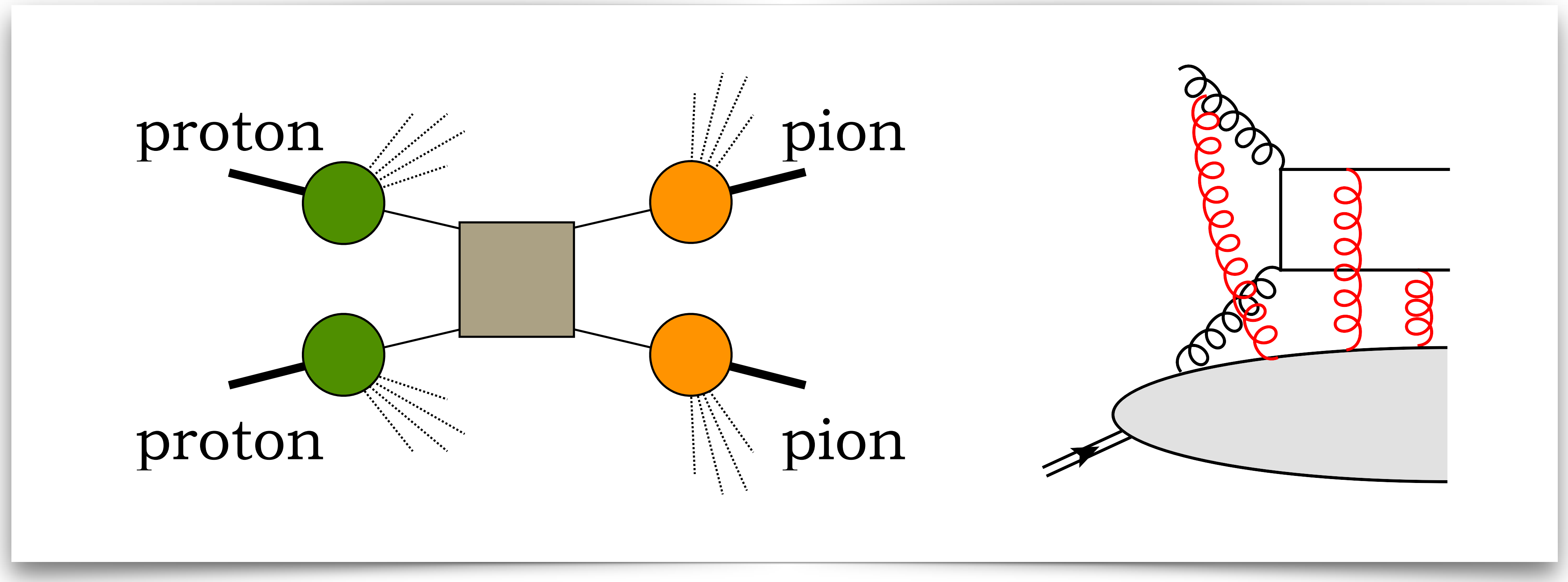

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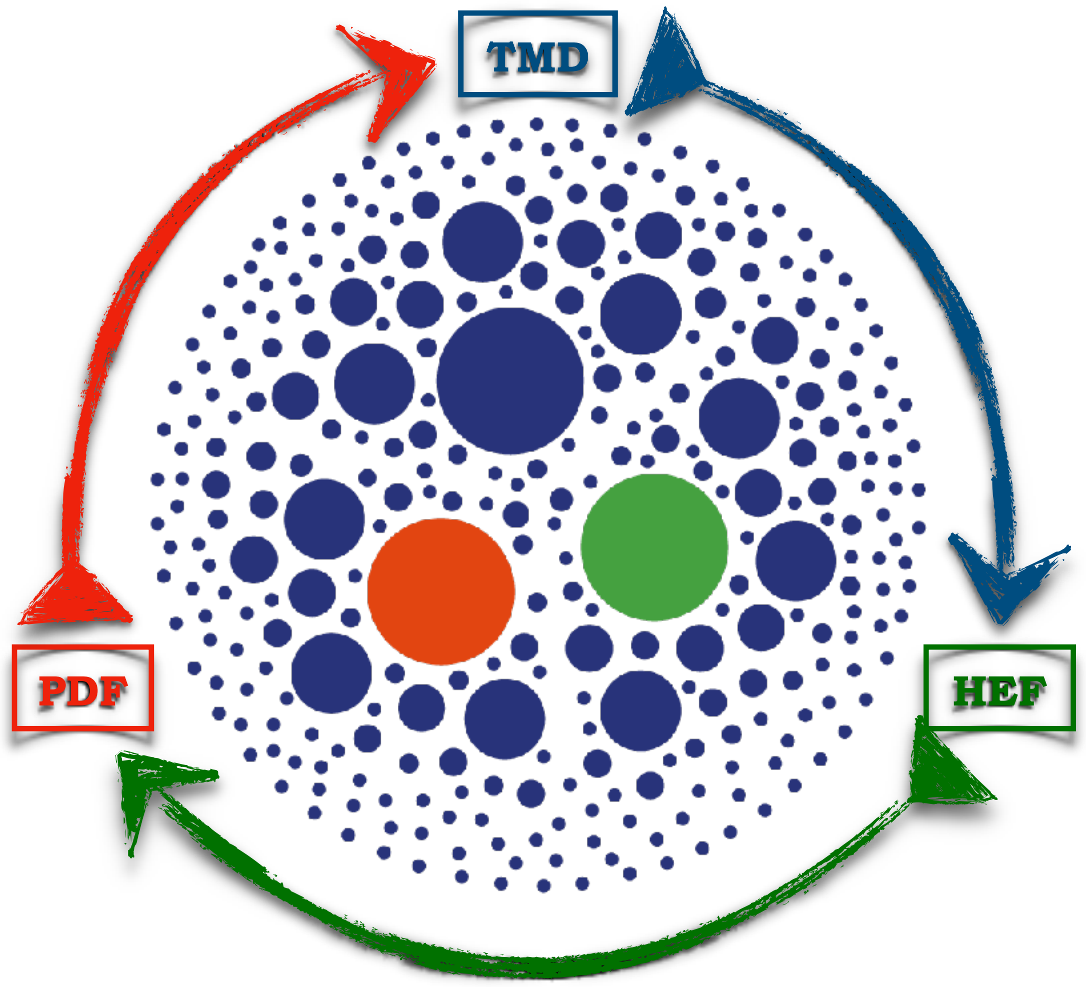
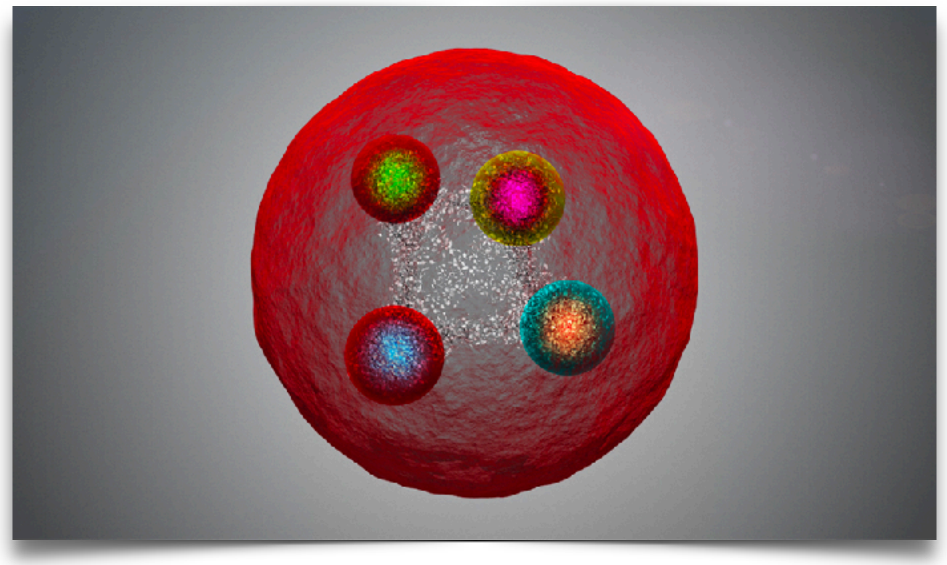
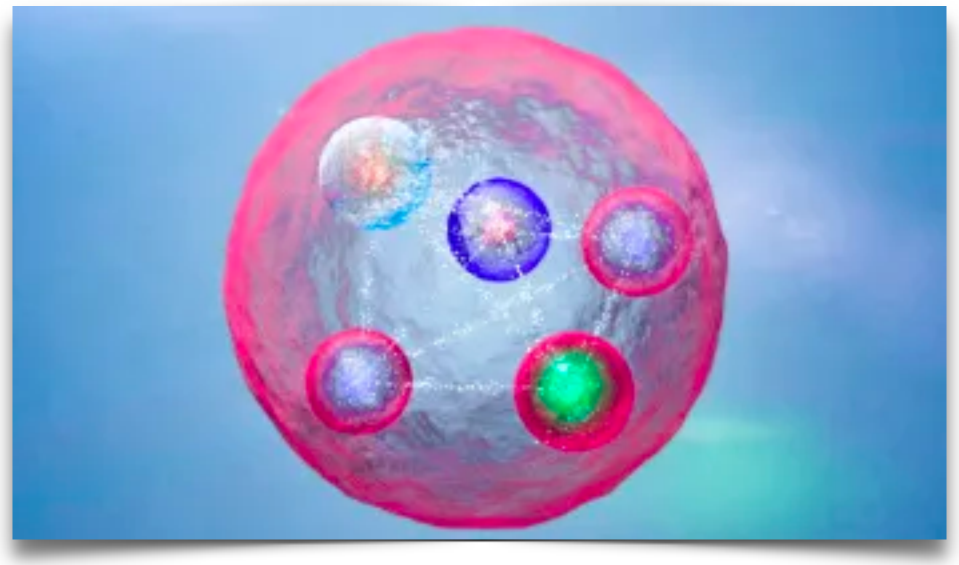


Heavy-hadron spectroscopy





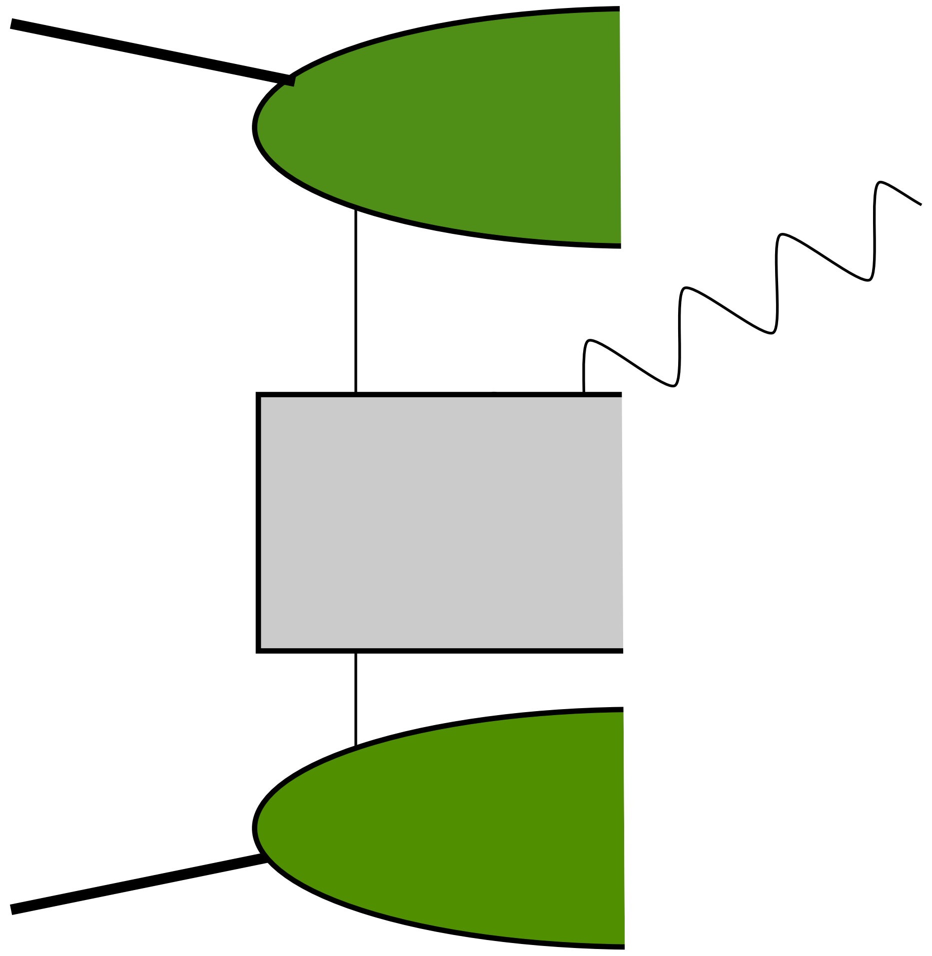
Present and future of NINPHA

- **Hadron structure** → extremely varied and complex research line, *different viewpoints* needed
- **All** NINPHA nodes → **fundamental role** in their *area of expertise*
- *Variety* of approaches → *consolidation* of **coherence** and **homogeneity** of our research lines
- **Collaboration** between NINPHA nodes → *deep* and *historical* **roots**
- Main effort in the *conceptual development* of a new **EIC** detector → 🔗 **EIC Yellow Report**
- **Sardinian Workshop on Spin studies and related issues (Sar WorS)**, Cagliari (2019, 2021)
- **Link** with *high-energy* physics ← *precision* calculations **assume** knowledge of hadronic matter
- **Strength** of our metodology → **synergy** toward *future challenges*

Backup slides

Factorization and universality

Drell-Yan



Backup

Factorization and universality

SIDIS

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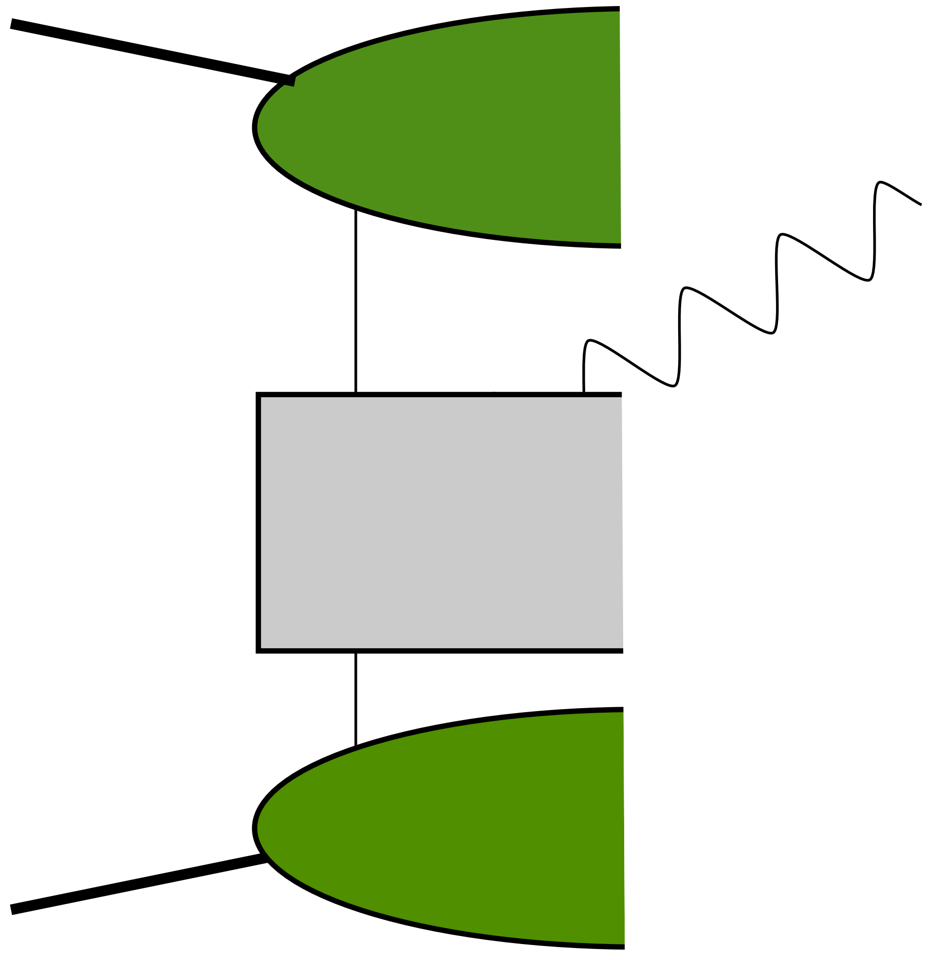

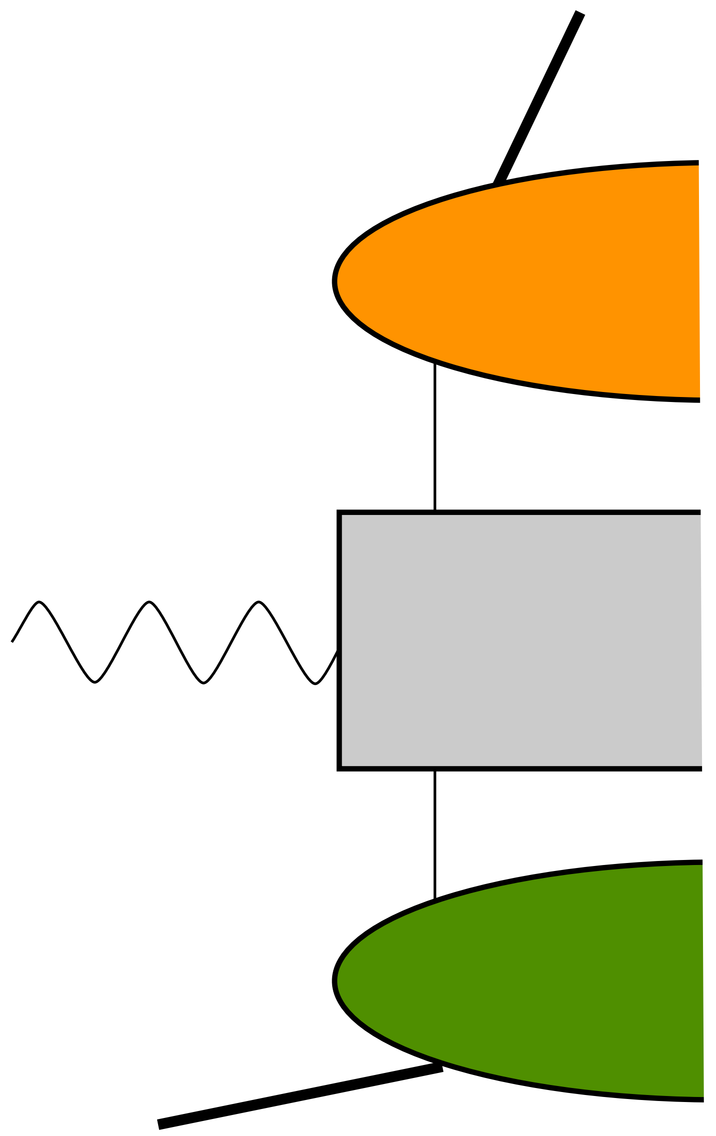

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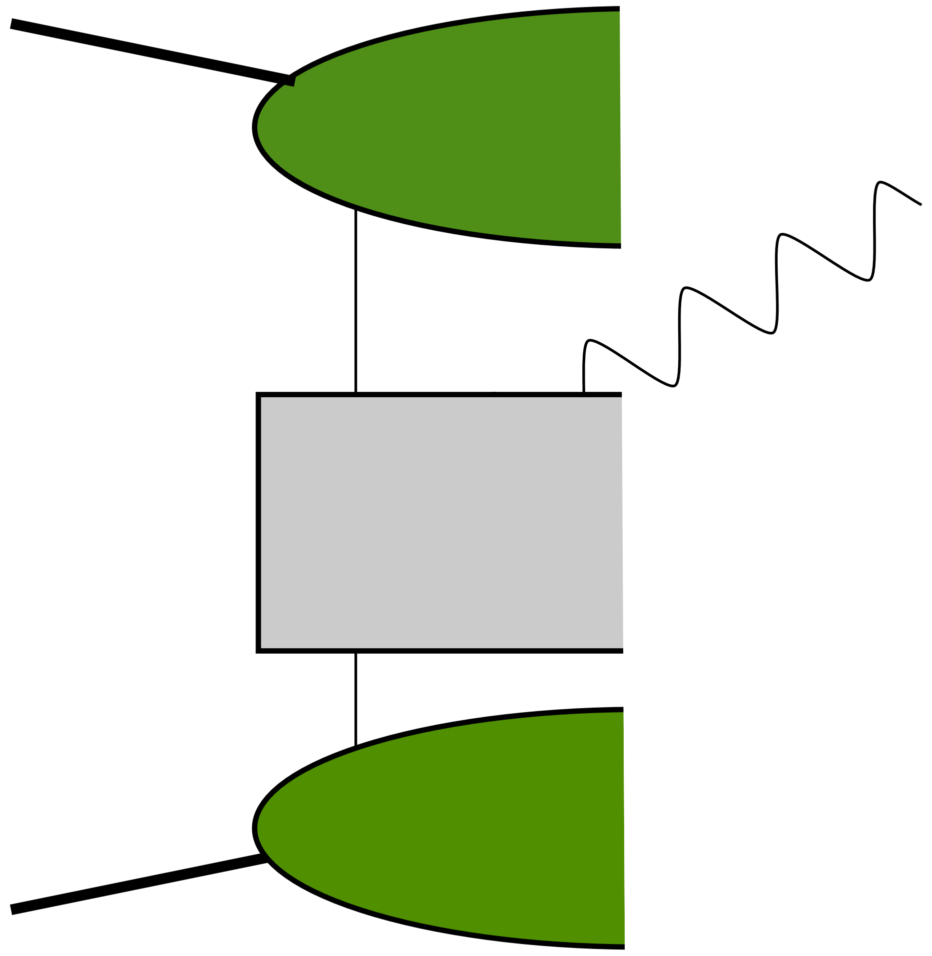

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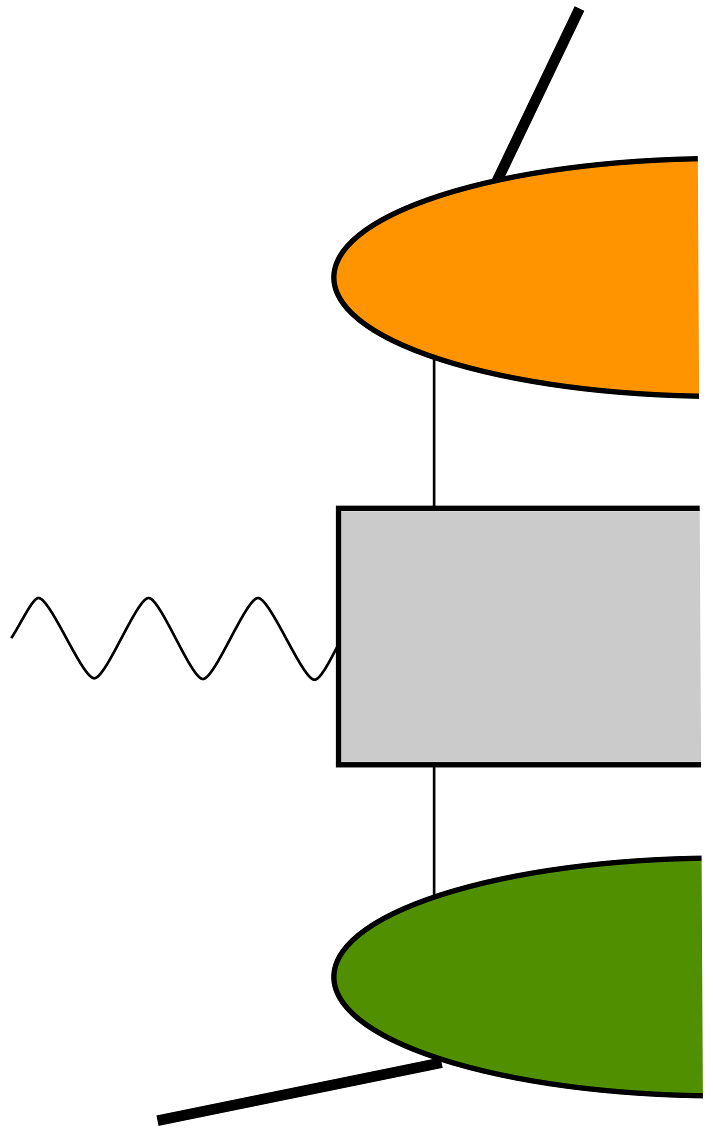
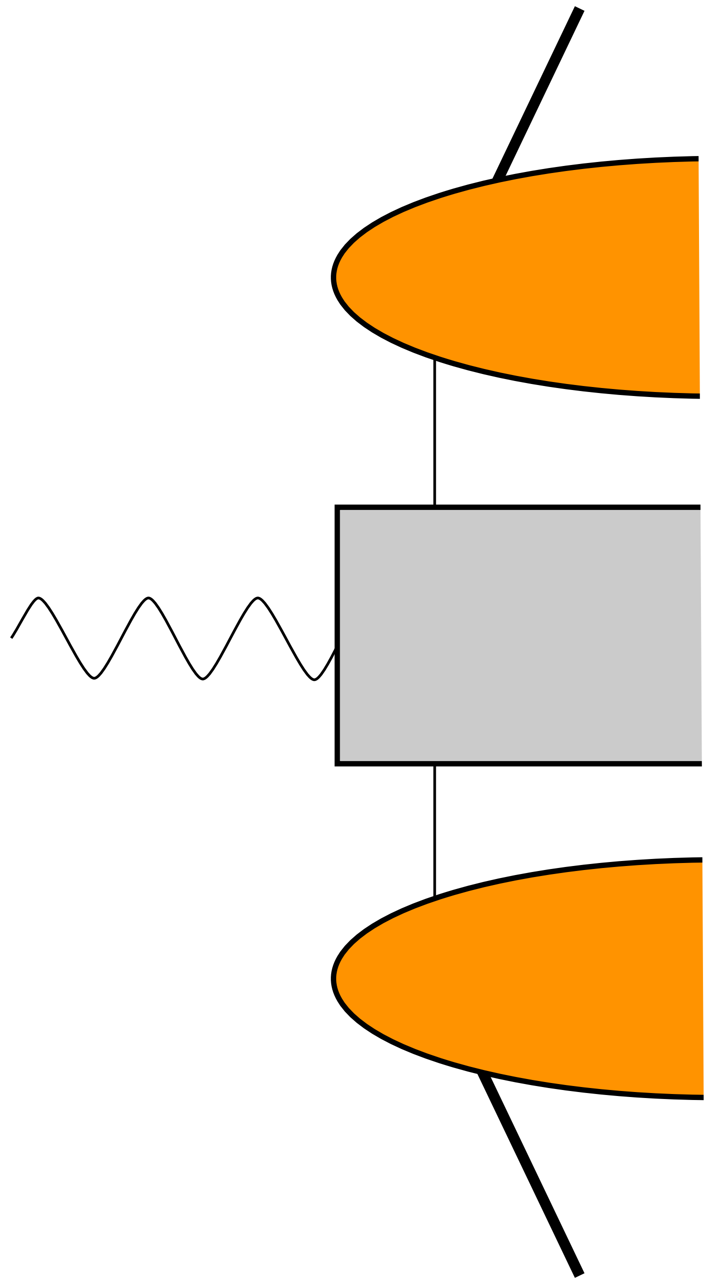


$e^+ + e^- \rightarrow$ **hadrons**



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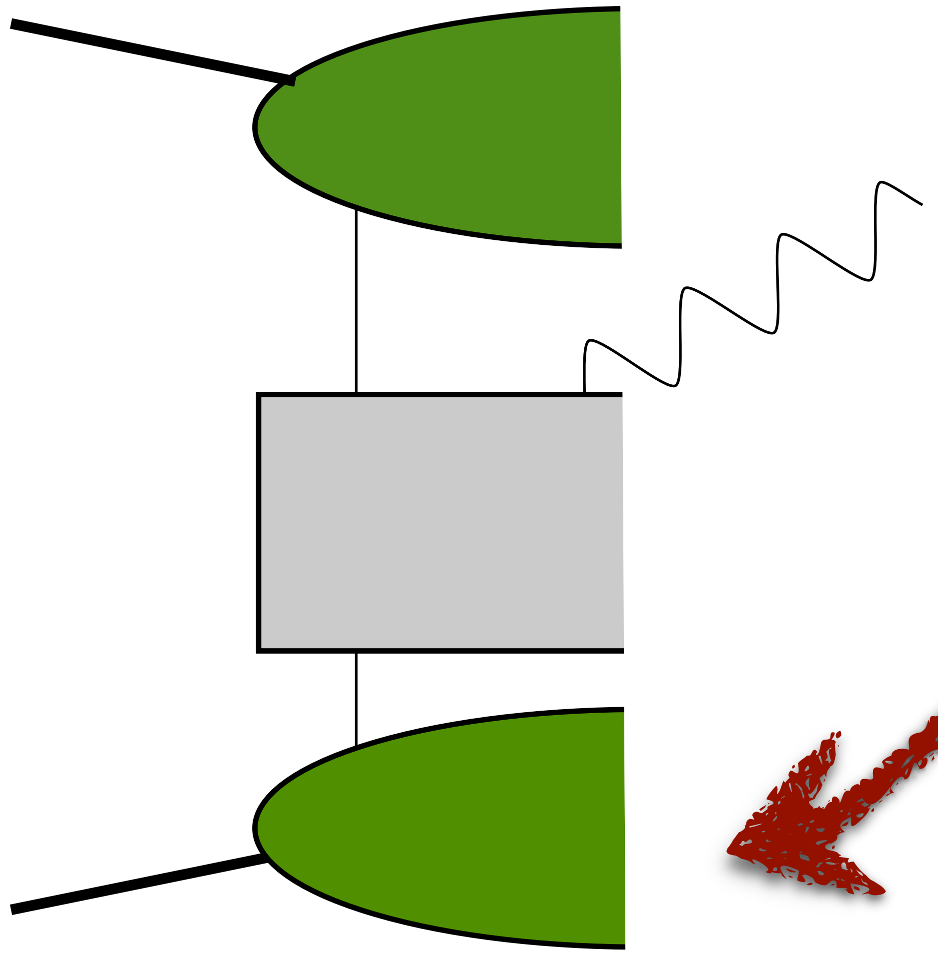
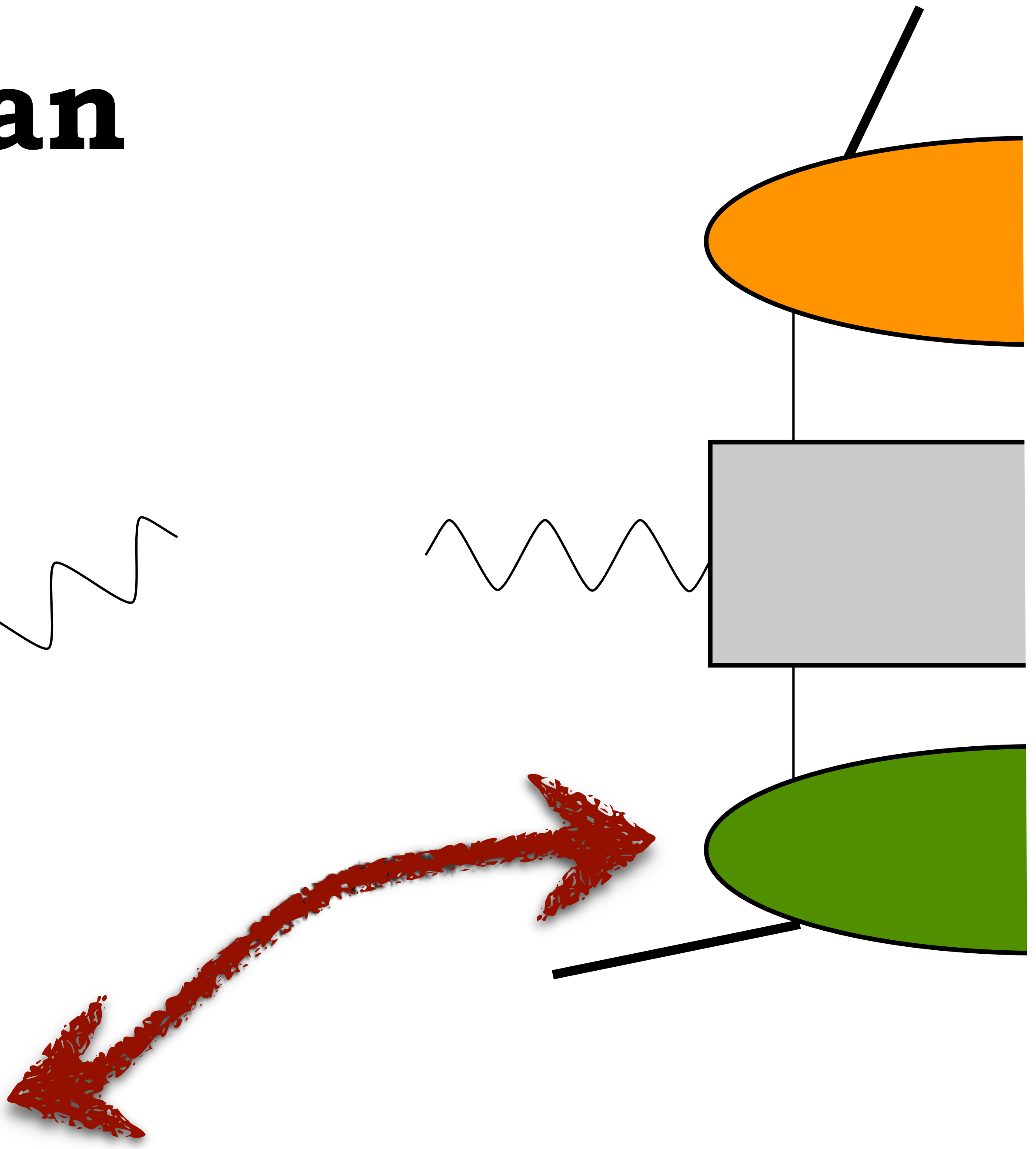
Factorization and universality

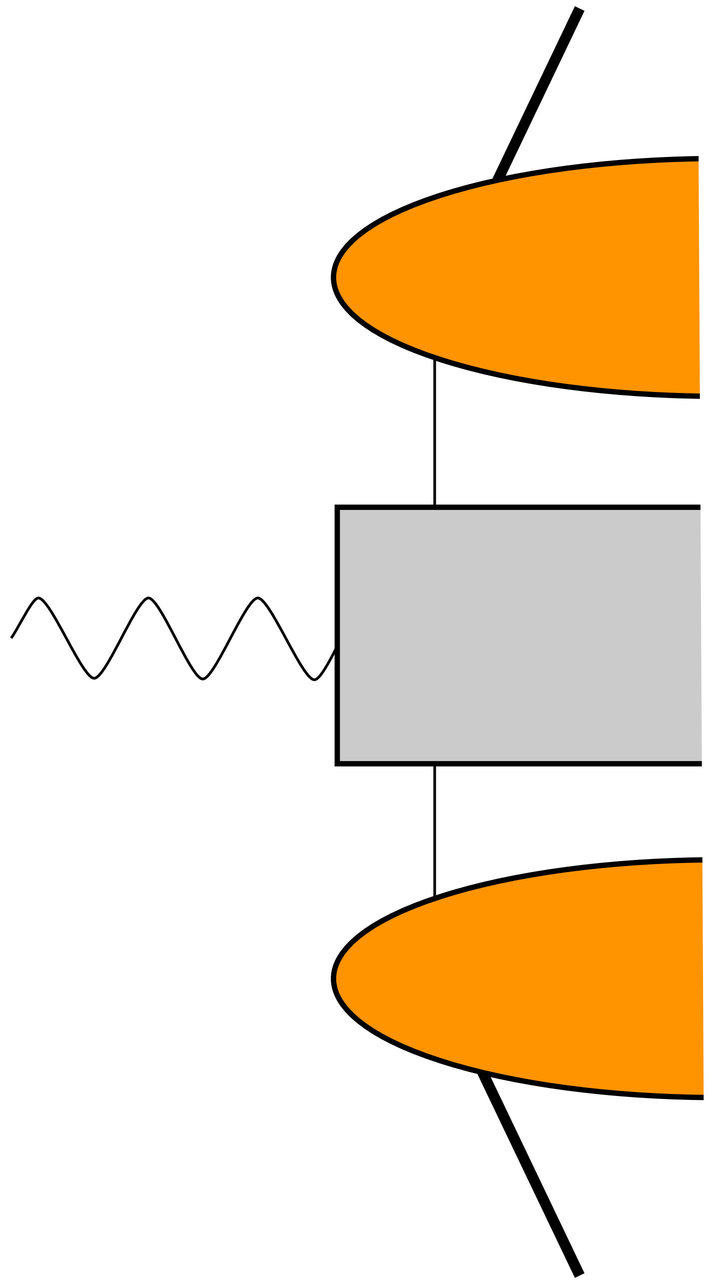
$e^+ + e^- \to$ **hadrons**

SIDIS

Drell-Yan







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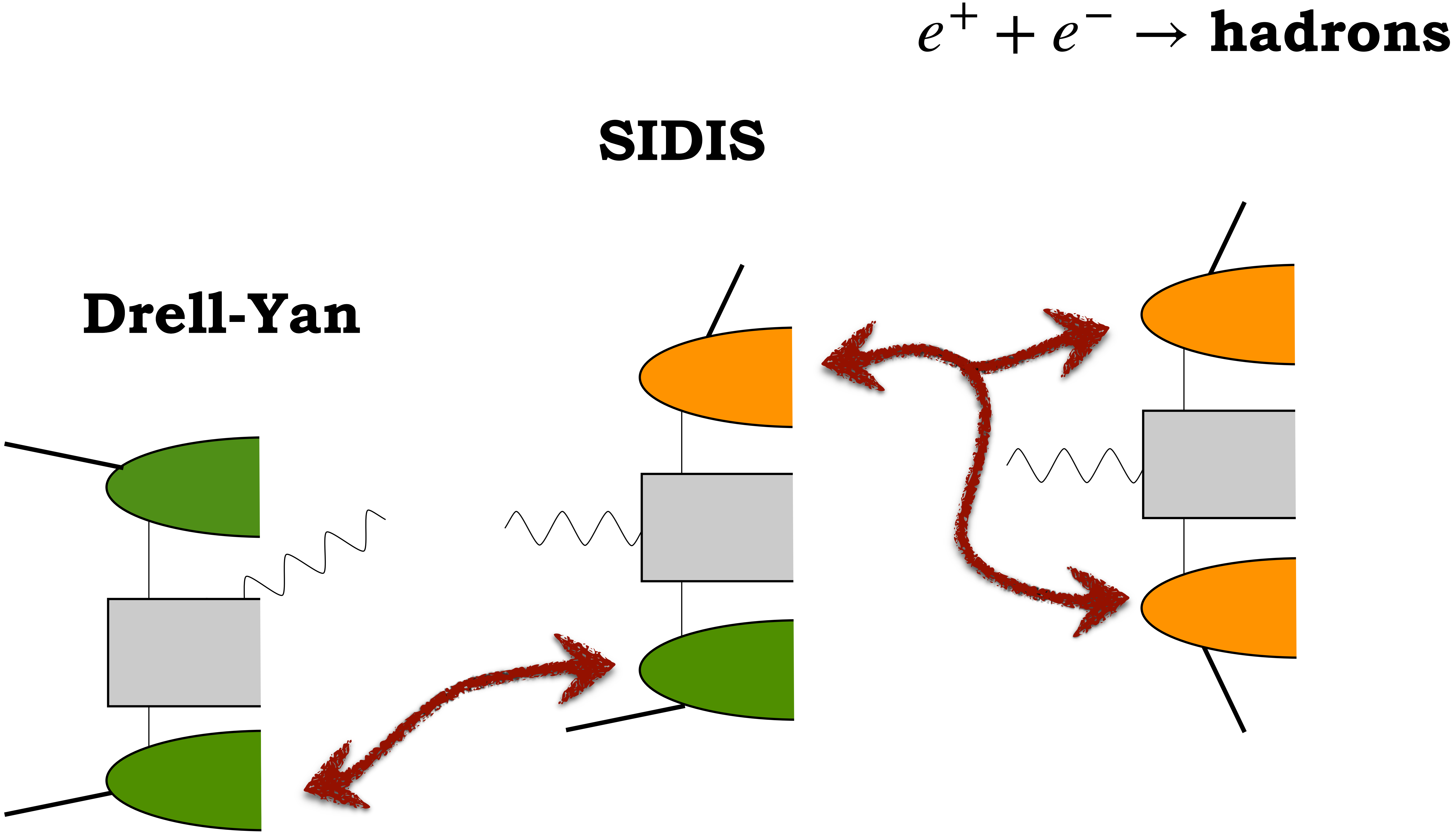
Factorization and universality



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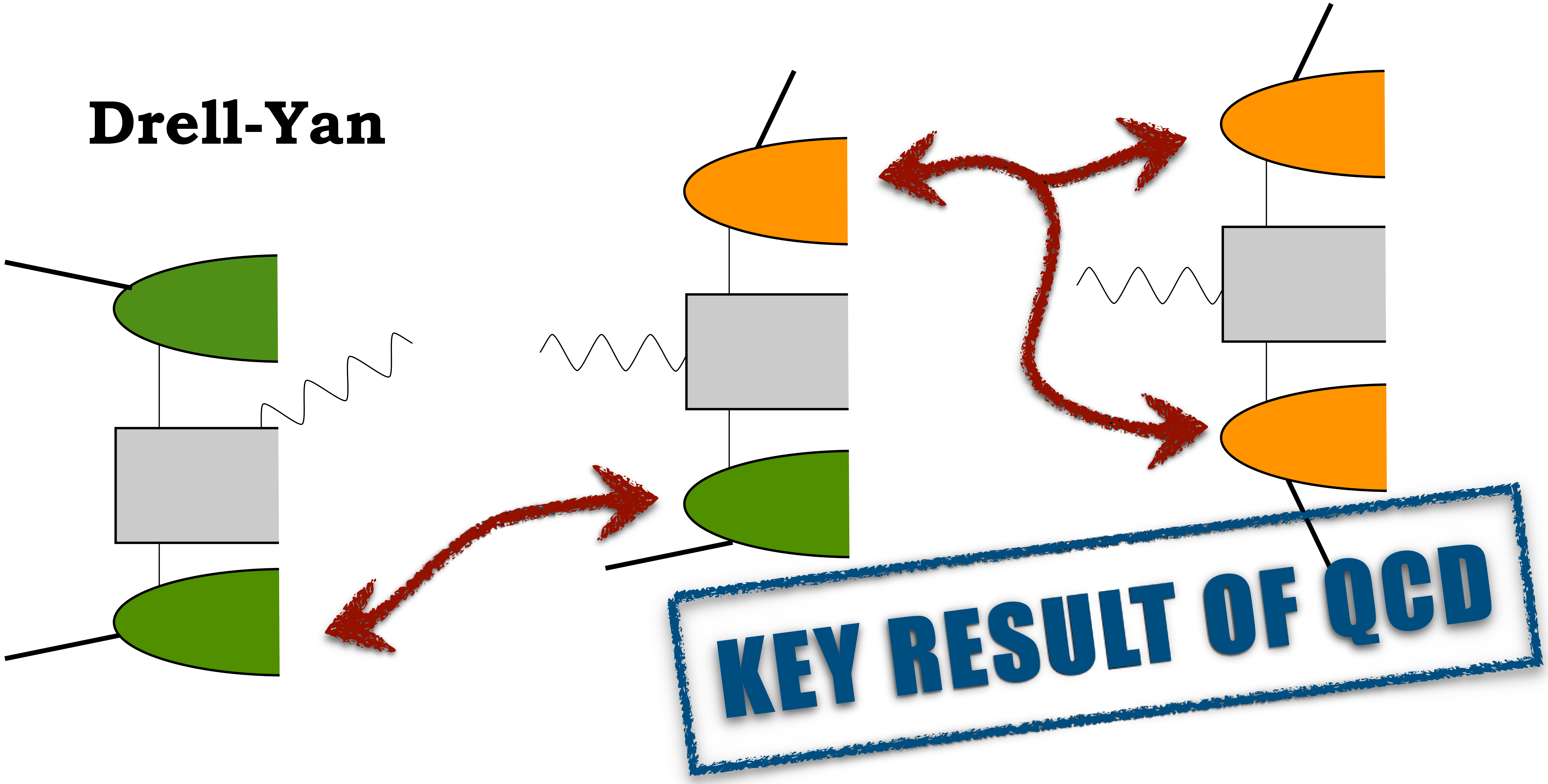
SIDIS

Drell-Yan



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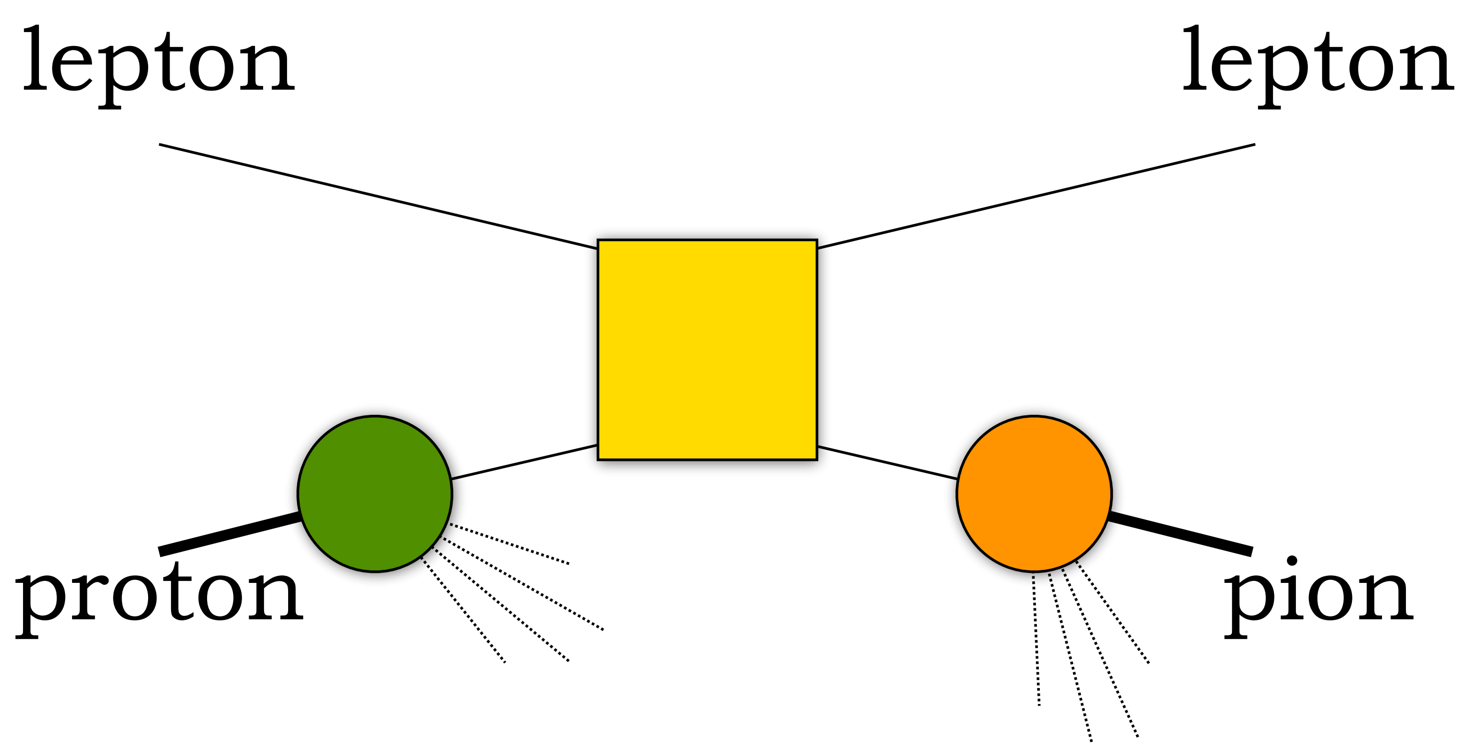
Factorization and universality

SIDIS



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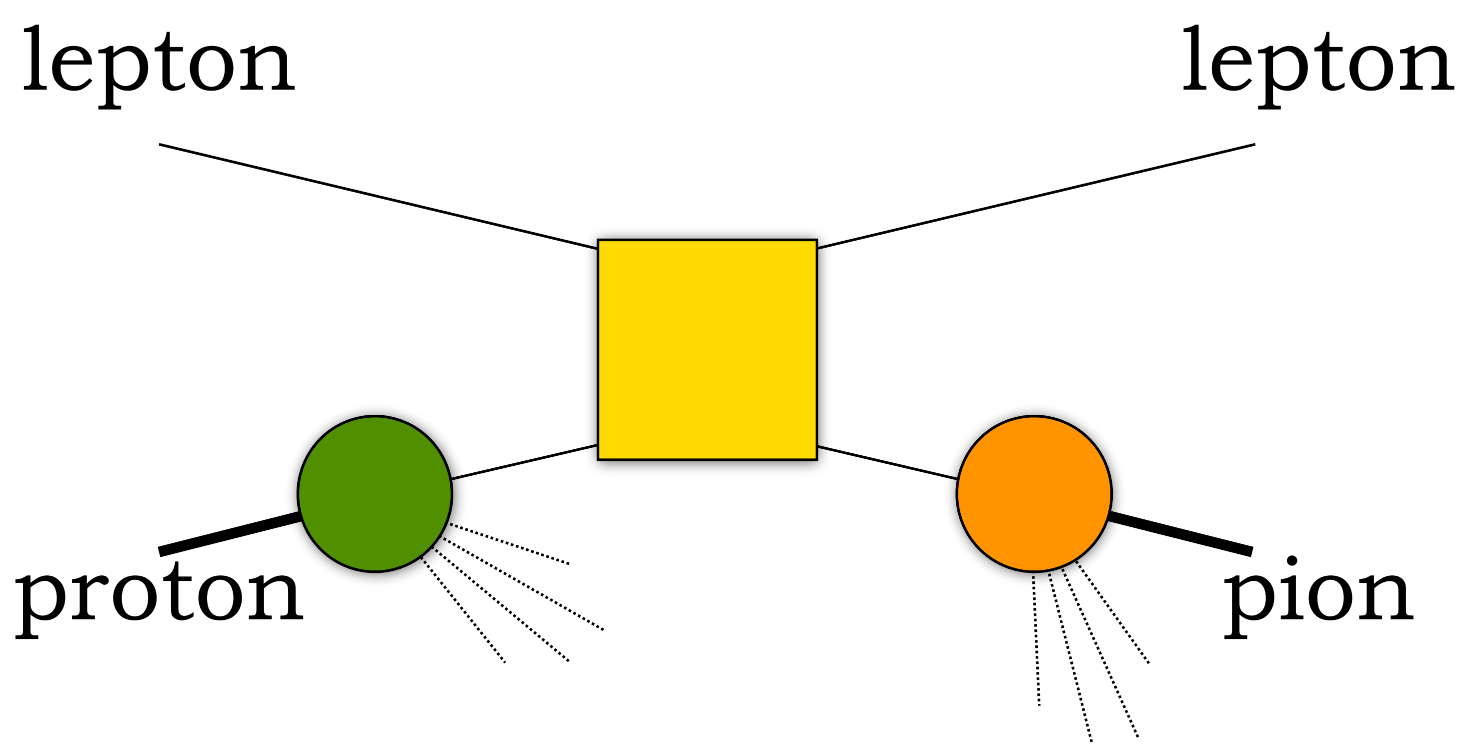
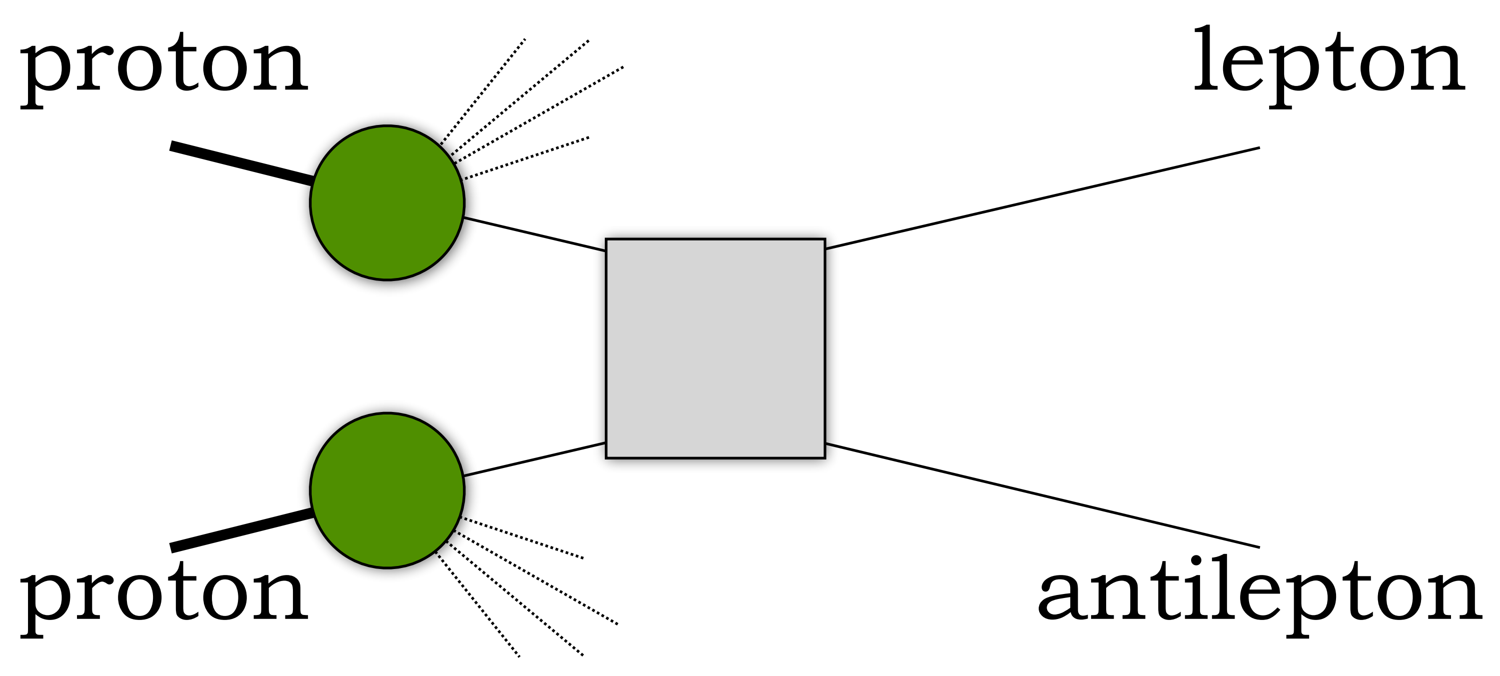


Drell-Yan



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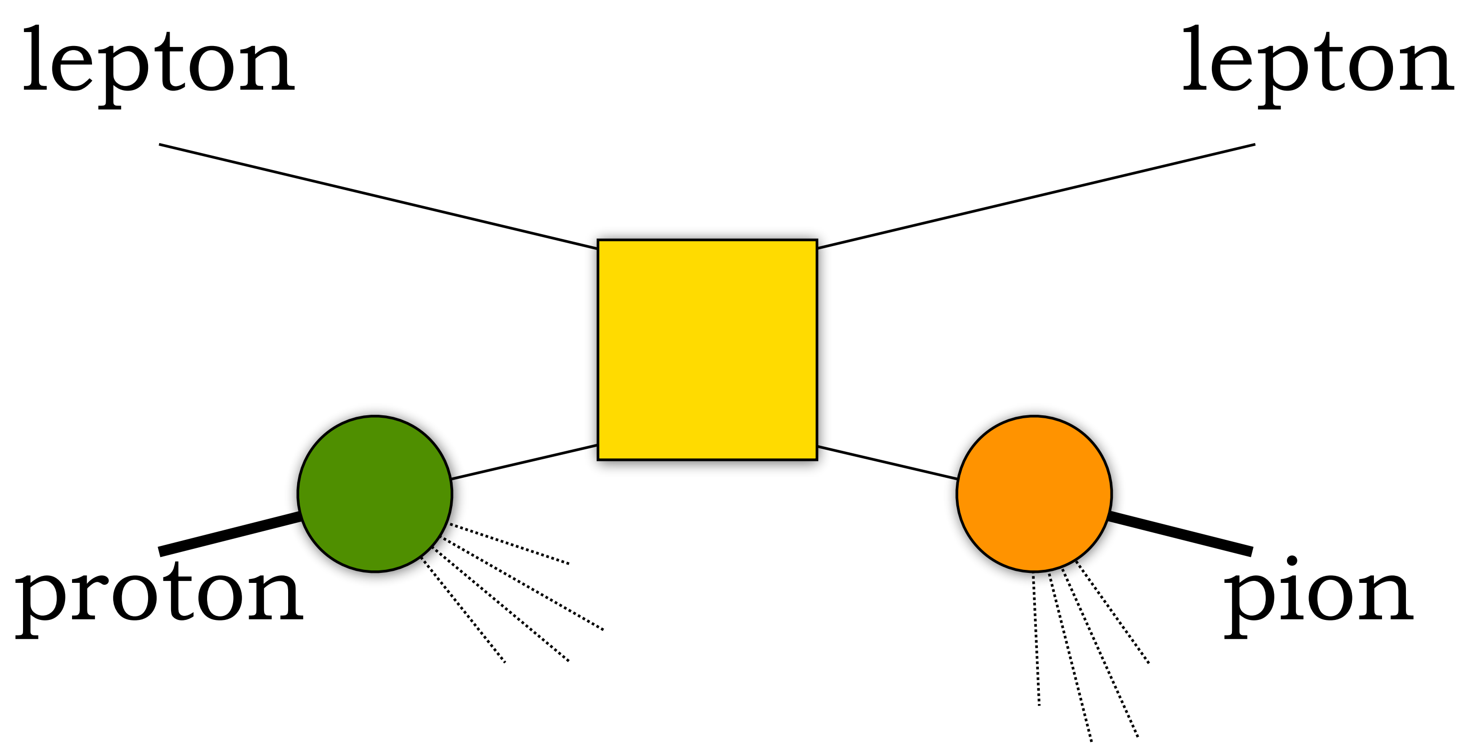
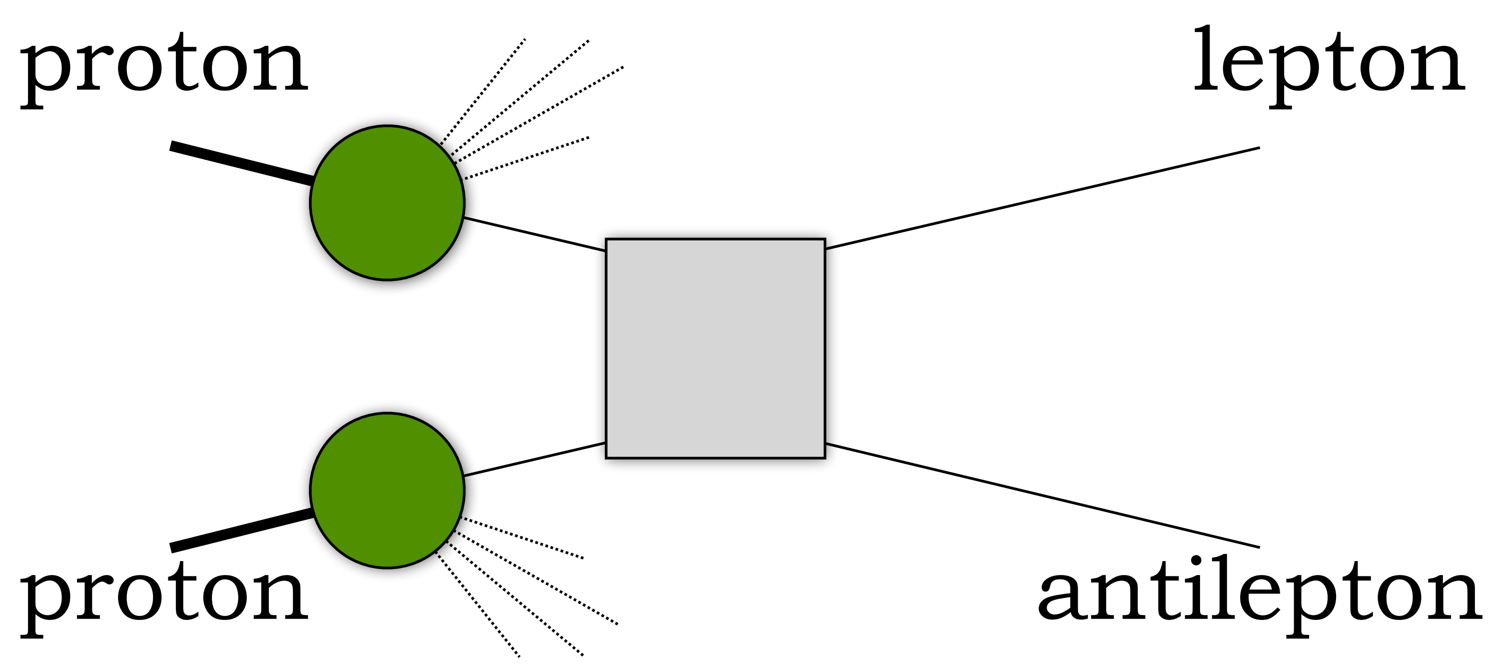
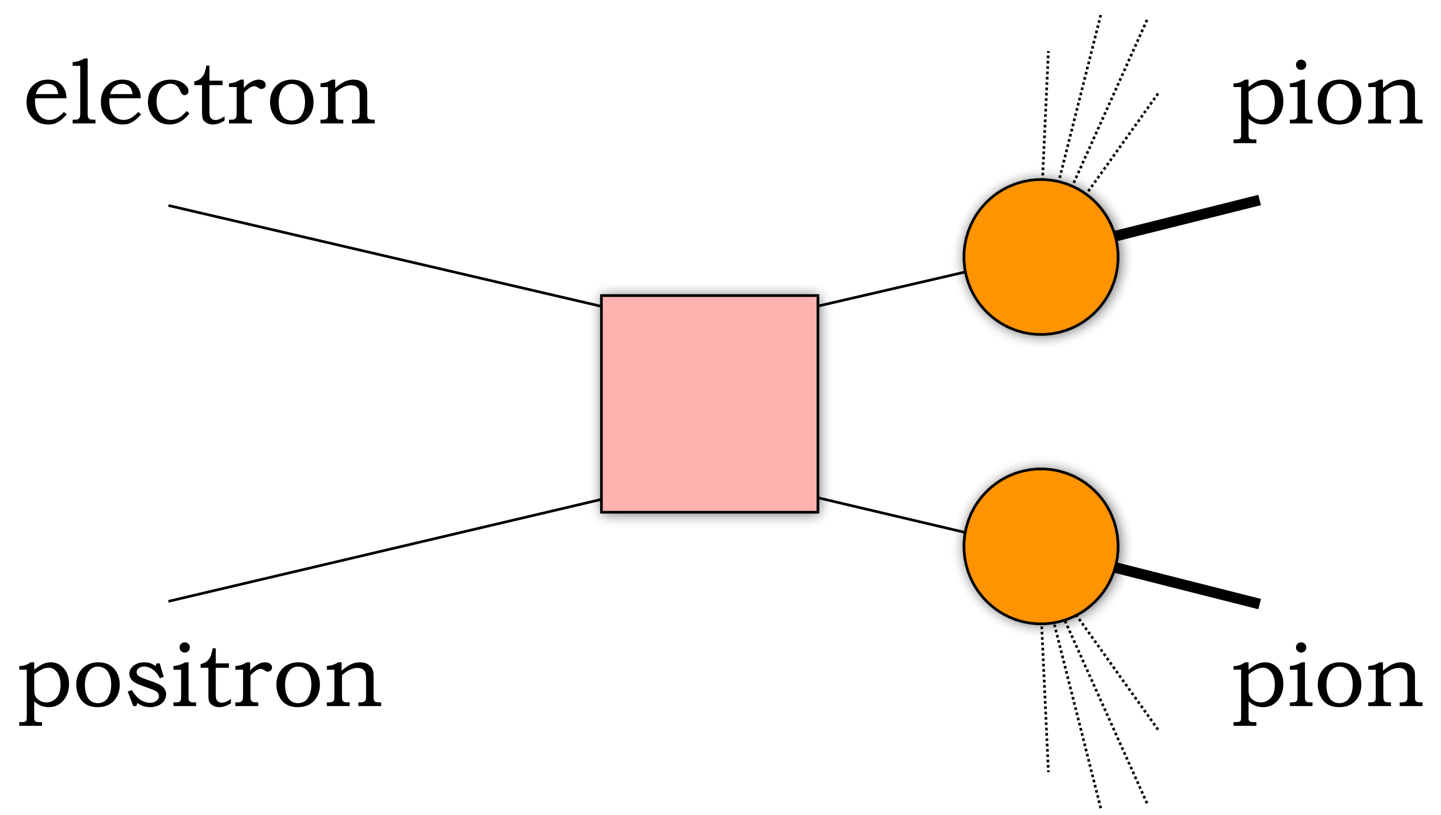


Drell-Yan





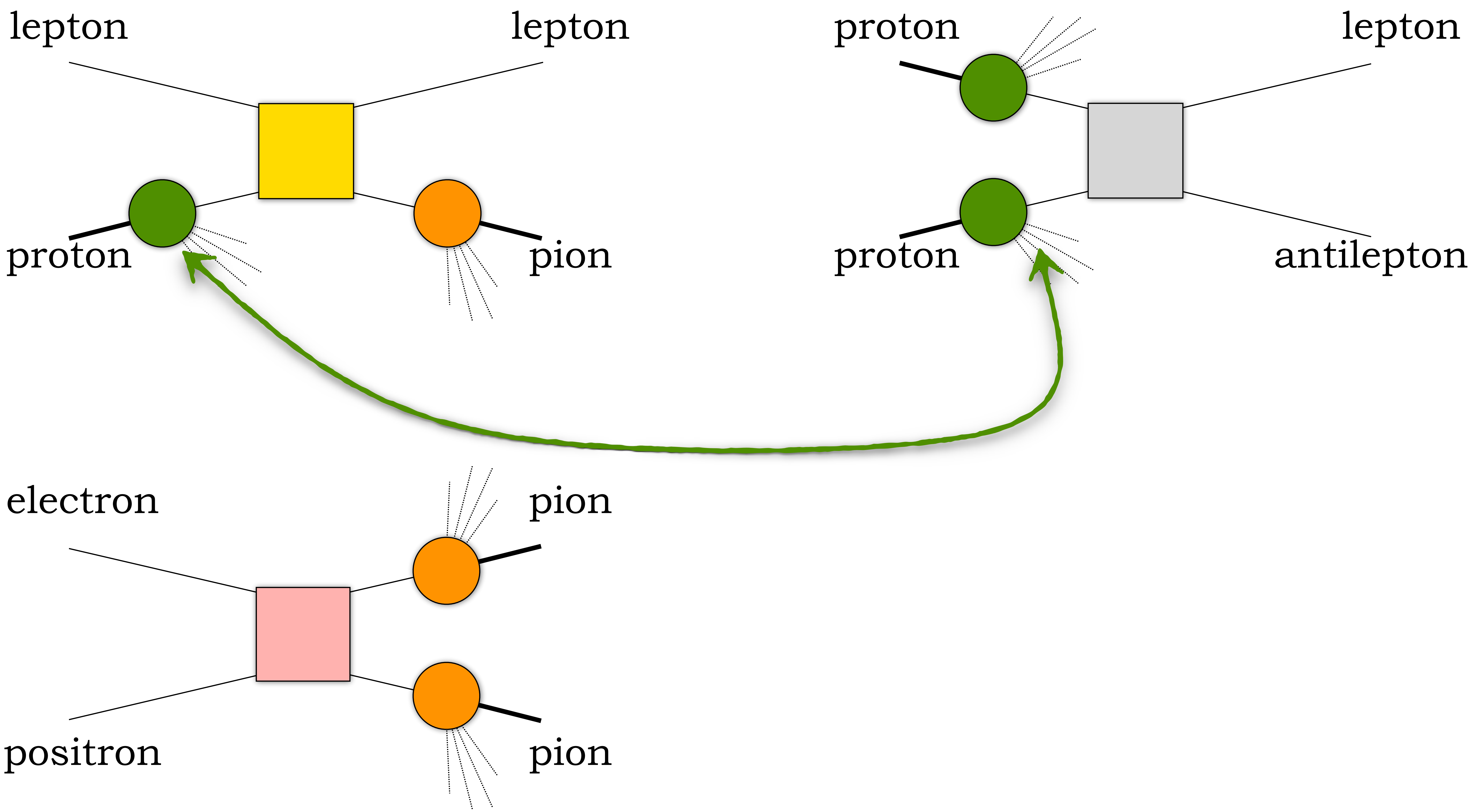
$e^+ + e^- \rightarrow$ **hadrons**

Backup

Factorization and universality

SIDIS

Drell-Yan

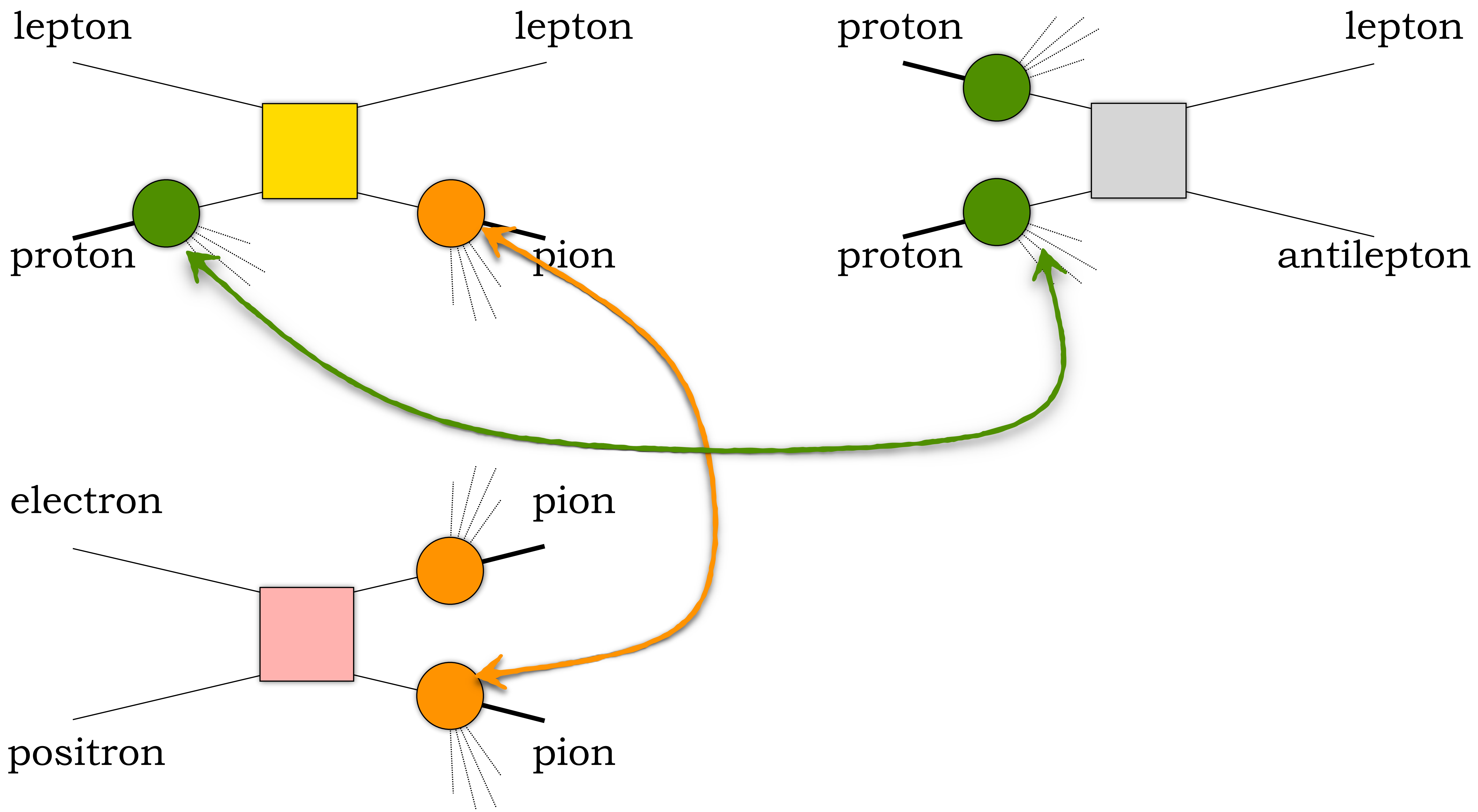


$e^+ + e^- \to$ **hadrons**

Backup

Factorization and universality

SIDIS **Drell-Yan**



$e^+ + e^- \rightarrow$ **hadrons**

Backup

Factorization and universality

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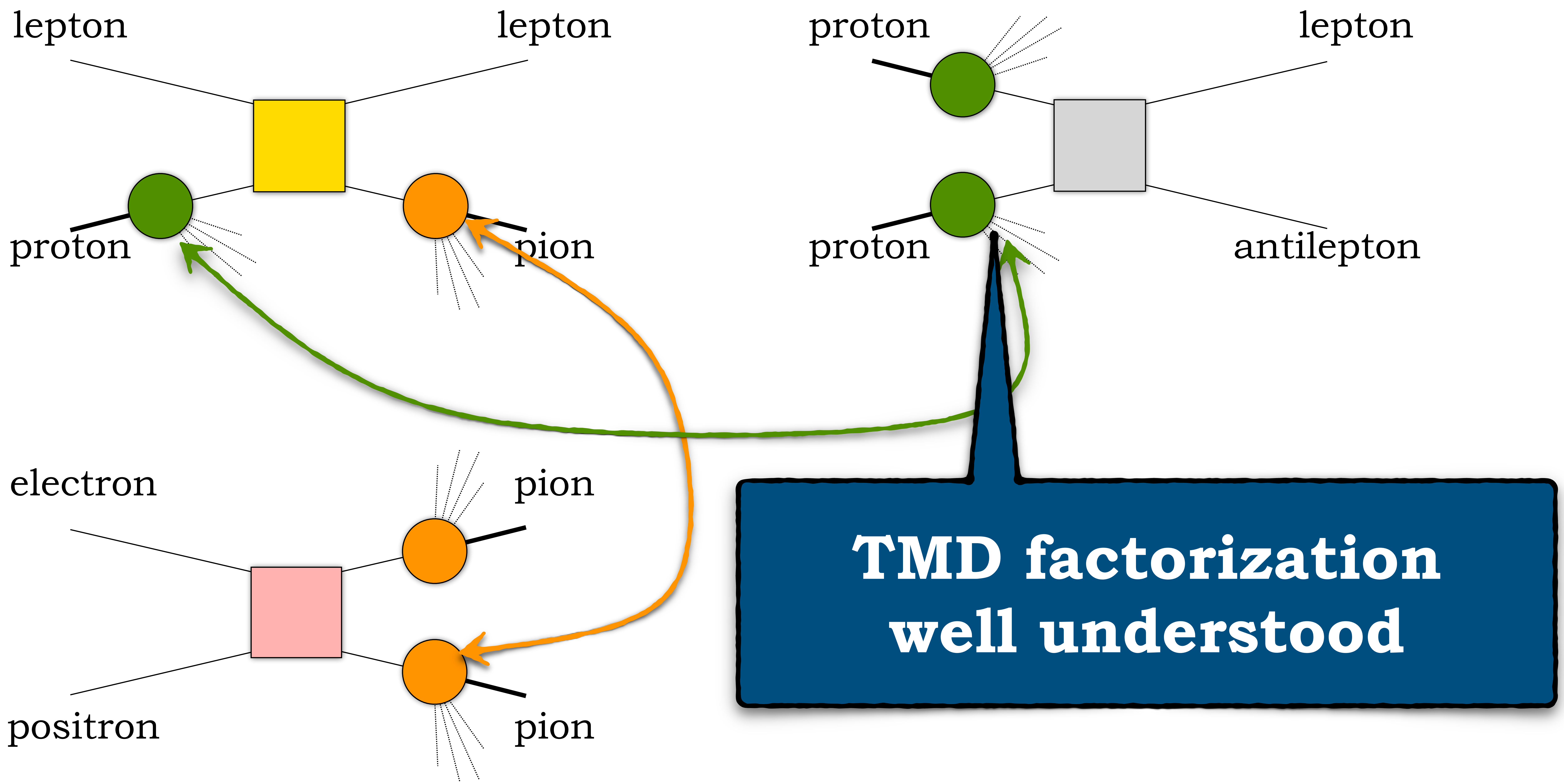

$e^+ + e^- \rightarrow$ **hadrons**

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Factorization and universality

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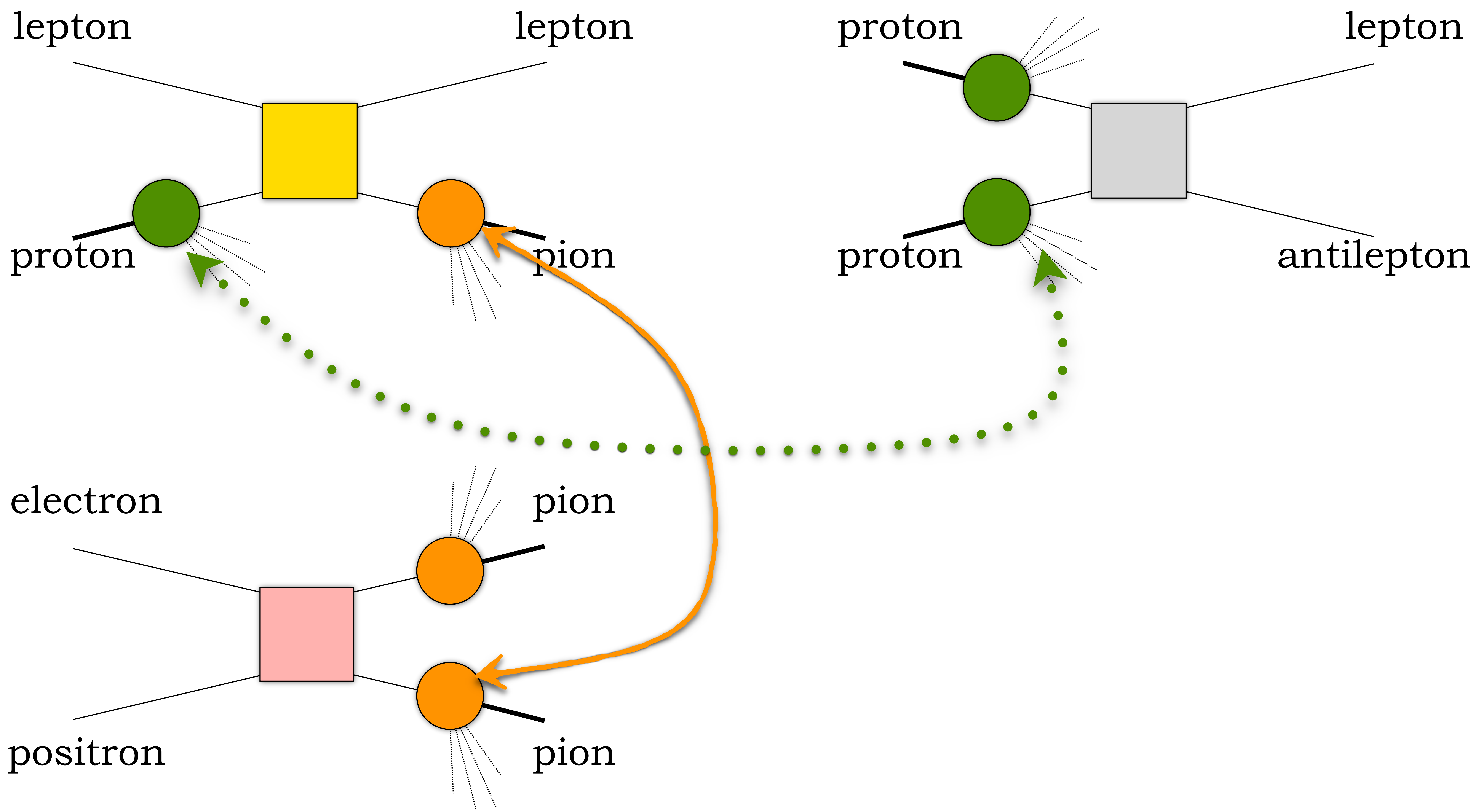
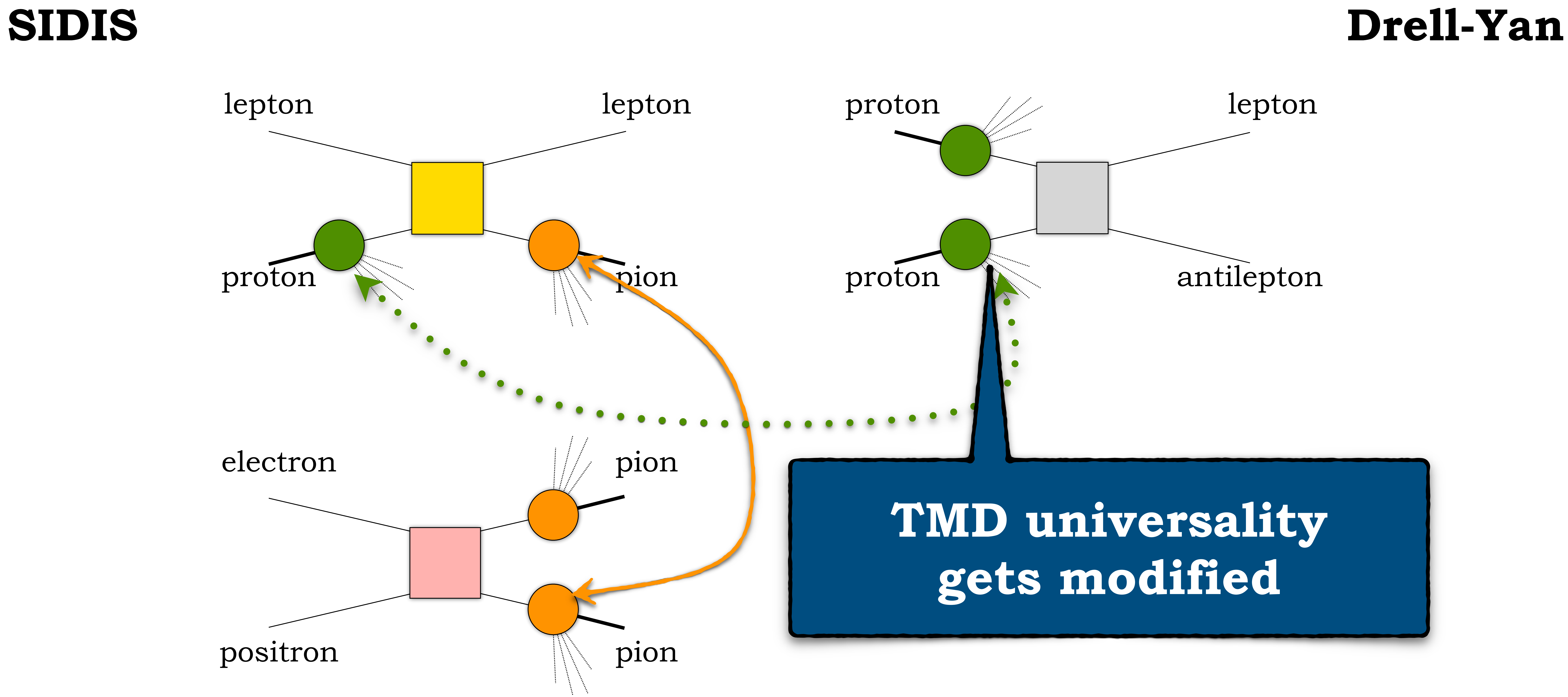


$e^+ + e^- \to$ **hadrons**

Backup

Factorization and universality



TMD universality gets modified

$e^+ + e^- \to$ **hadrons**

Backup

Factorization and universality

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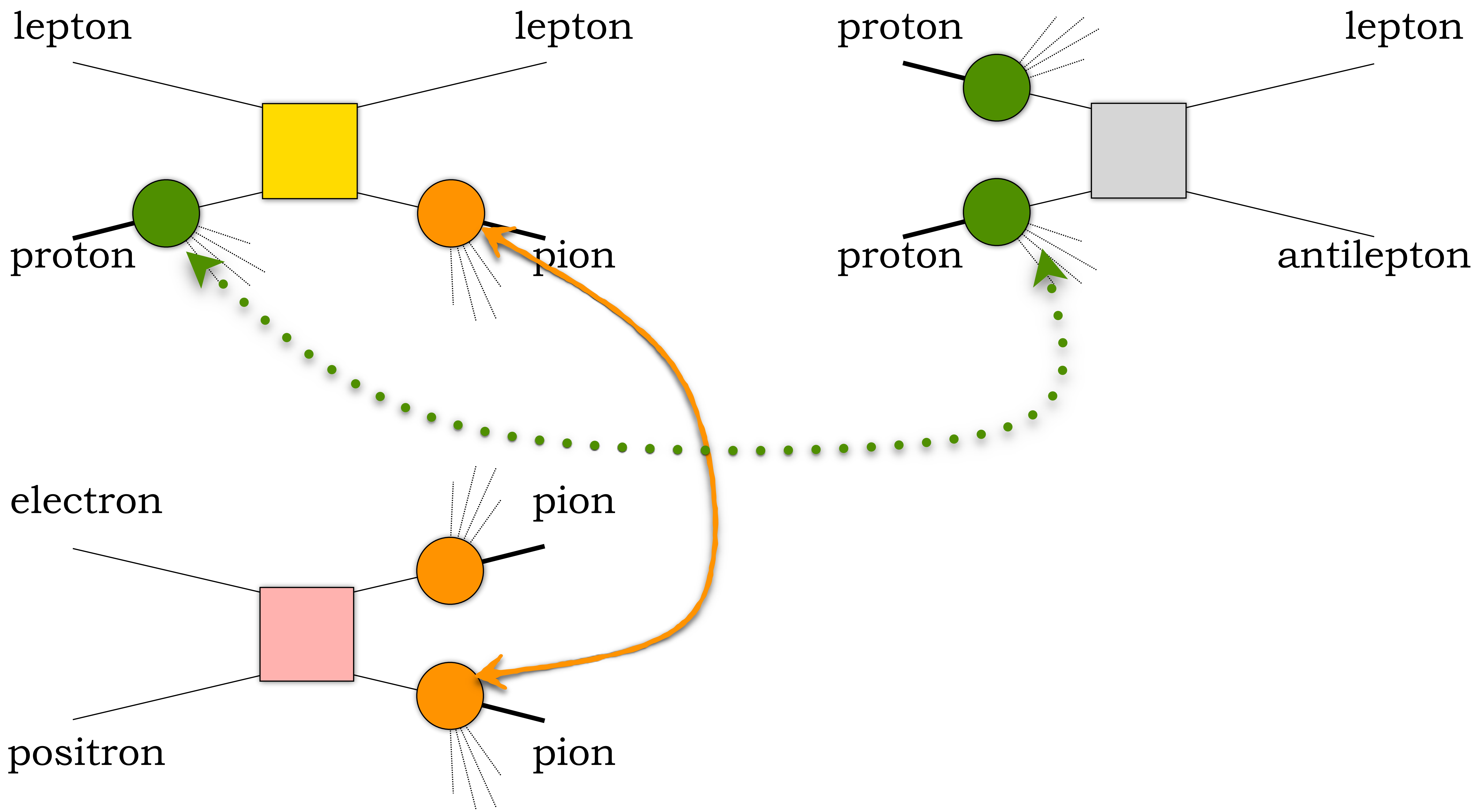
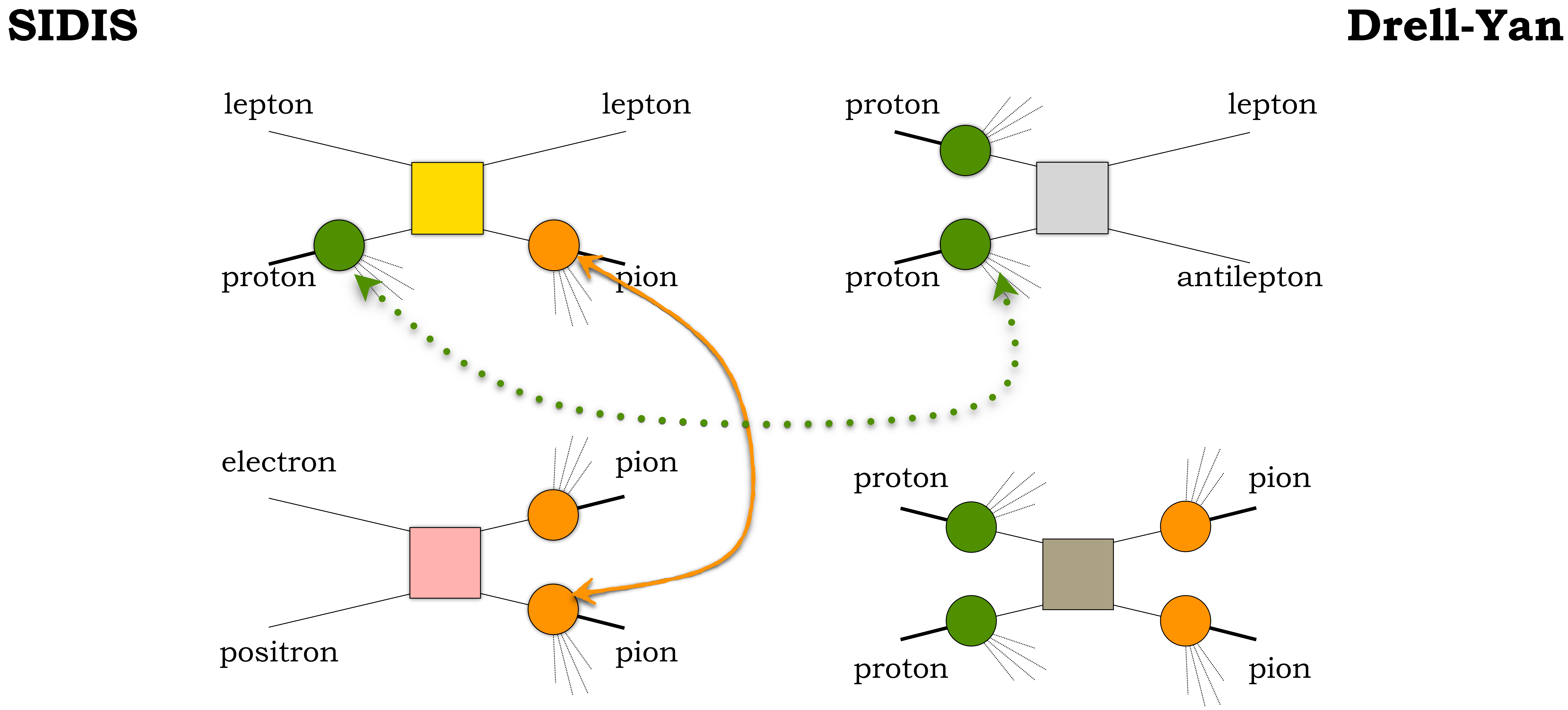


$e^+ + e^- \to$ **hadrons**

Backup

Factorization and universality



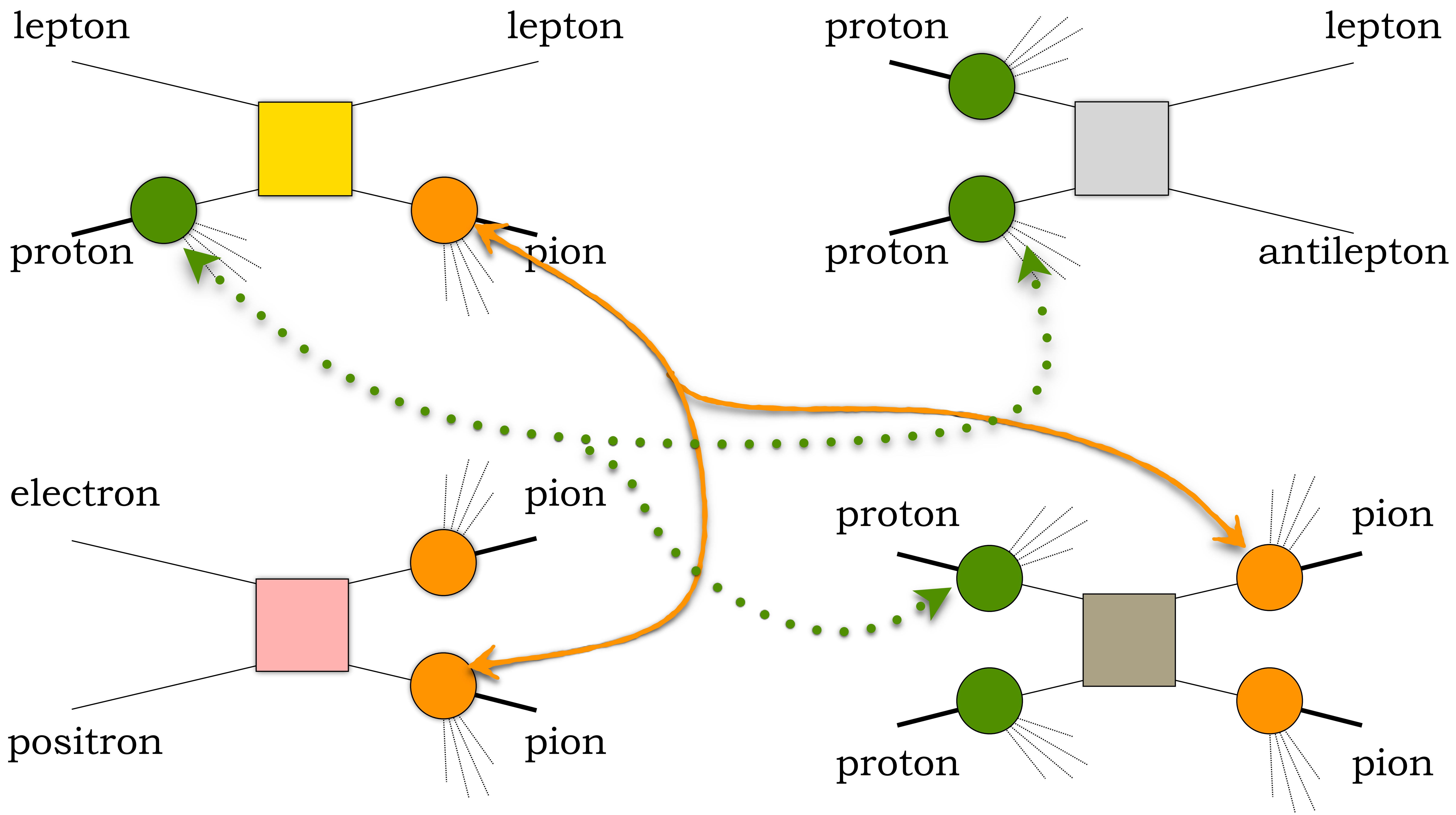
$e^+ + e^- \to$ **hadrons**

$p + p \to$ **hadrons**

Backup

Factorization and universality

SIDIS **Drell-Yan**

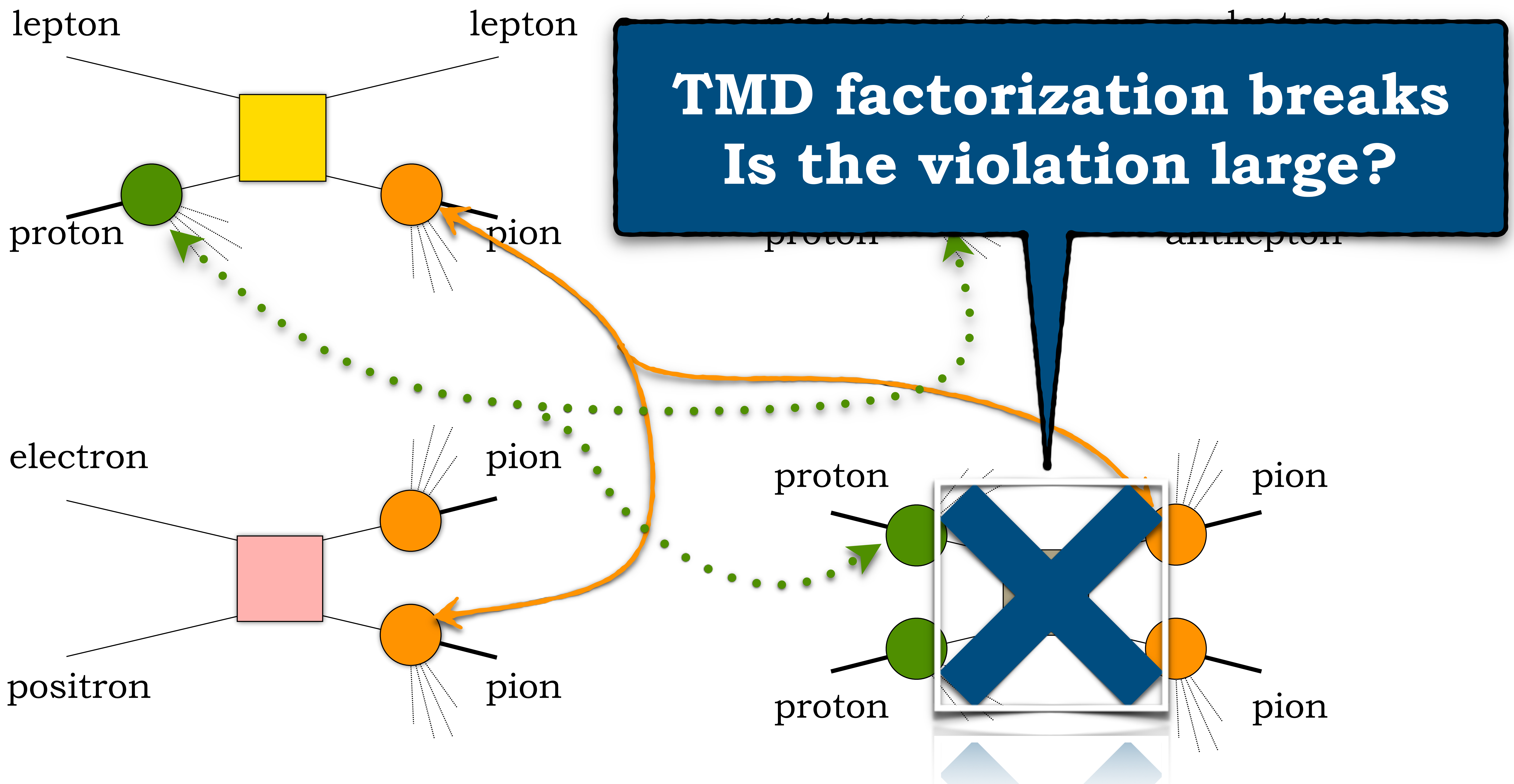


$e^+ + e^- \rightarrow$ **hadrons** $p + p \rightarrow$ **hadrons**

Backup

Factorization and universality

SIDIS **Drell-Yan**



$e^+ + e^- \rightarrow$ **hadrons** $p + p \rightarrow$ **hadrons**

Backup

Exclusive forward ρ-meson production at the EIC

Common ground between **TMD** and **HEF** factorization

NINPHA/**Pavia** + QFT@Colliders/**Cosenza** + IFJ **Krakow**

🔗 [A.D. Bolognino, F.G.C., D.Yu. Ivanov, A. Papa, W. Schäfer, A. Szczurek (2021)]

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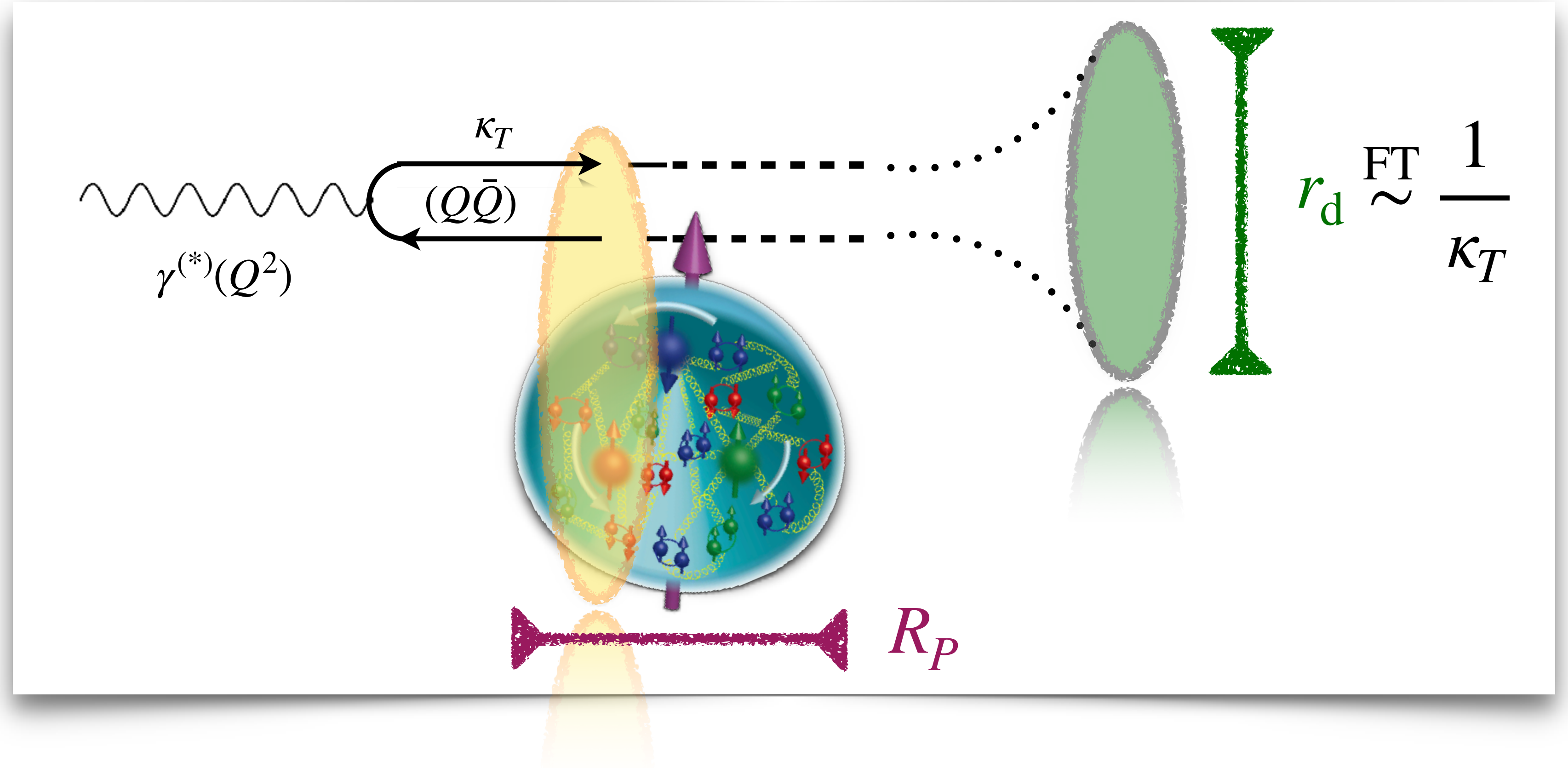

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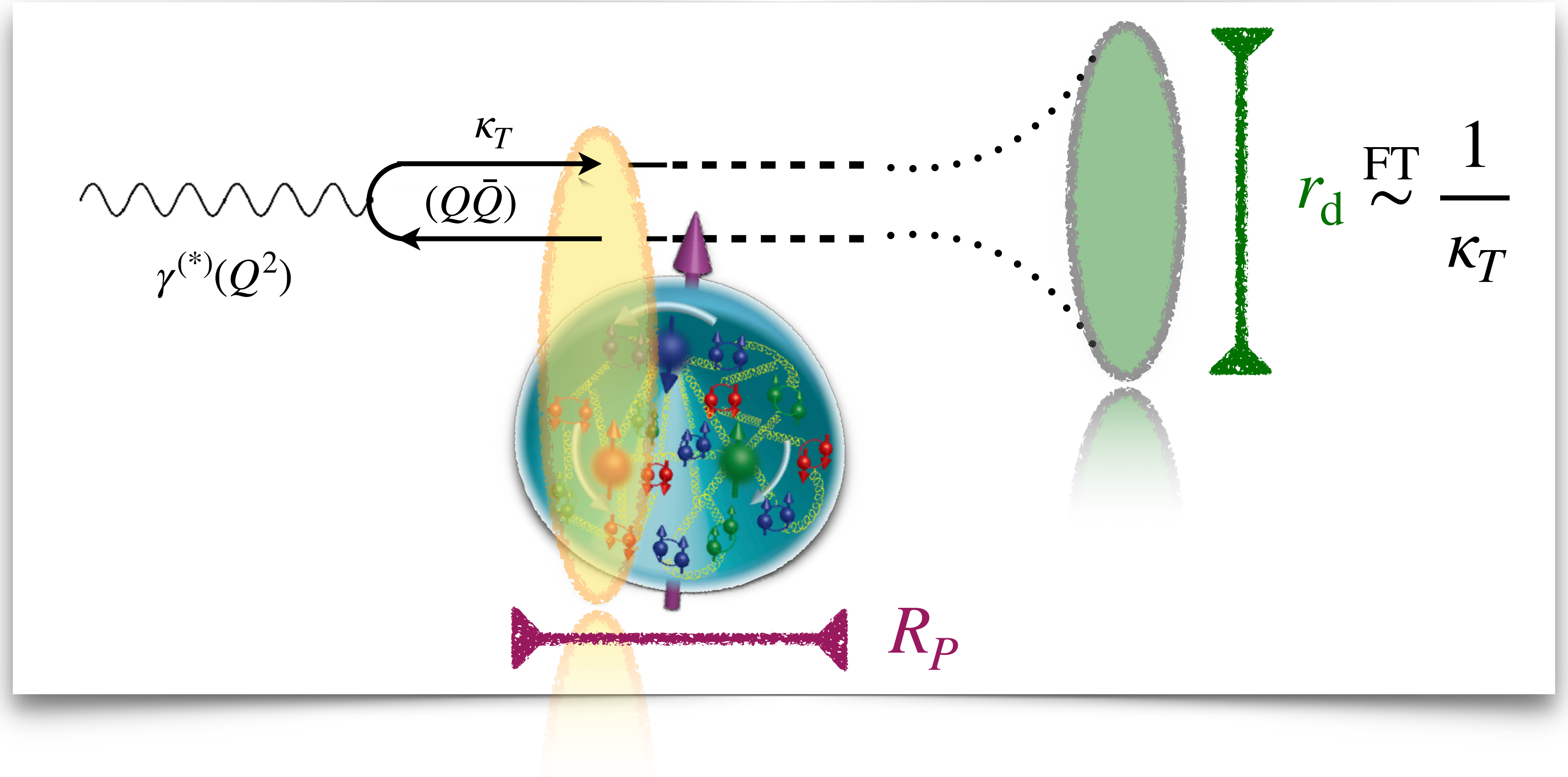

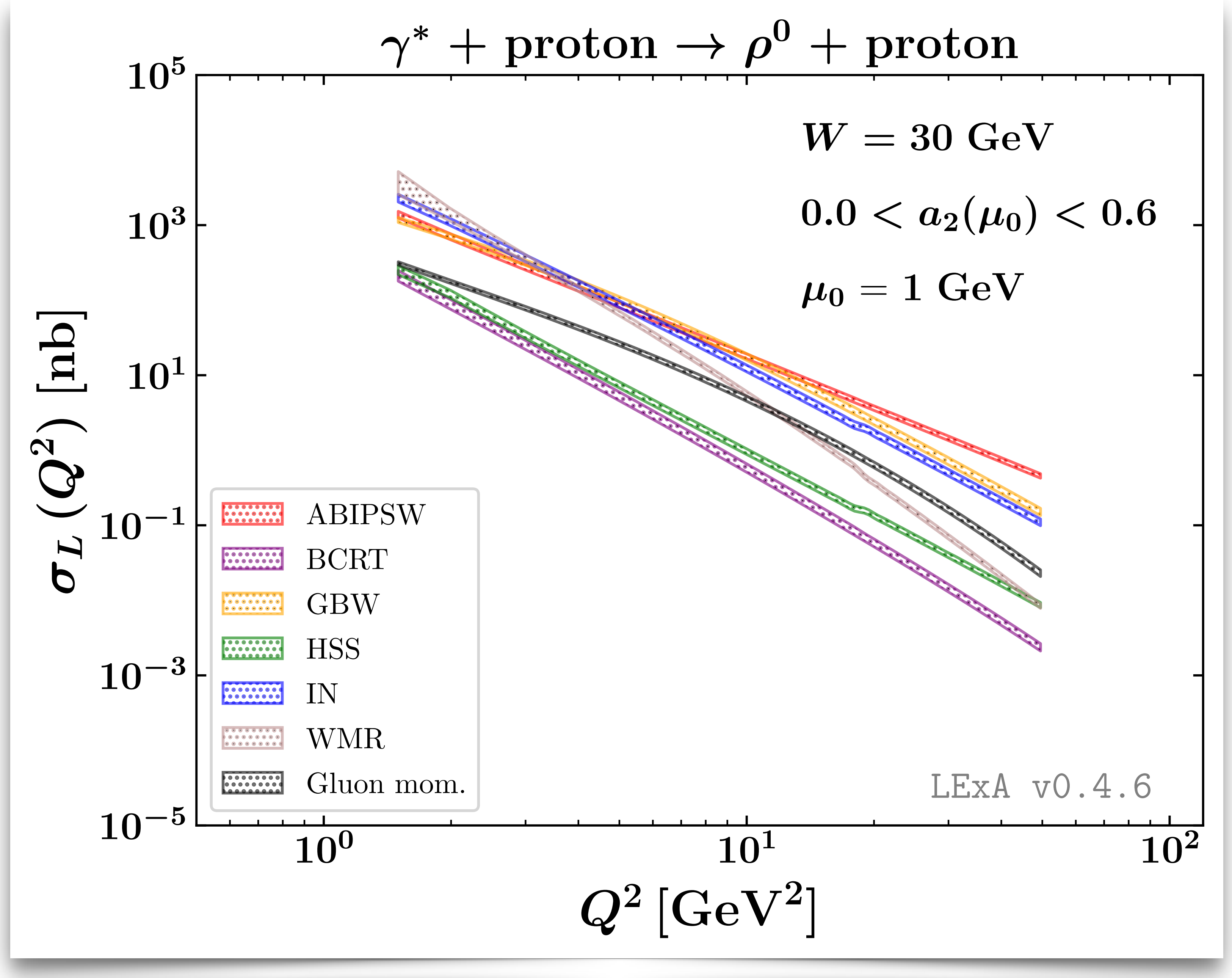

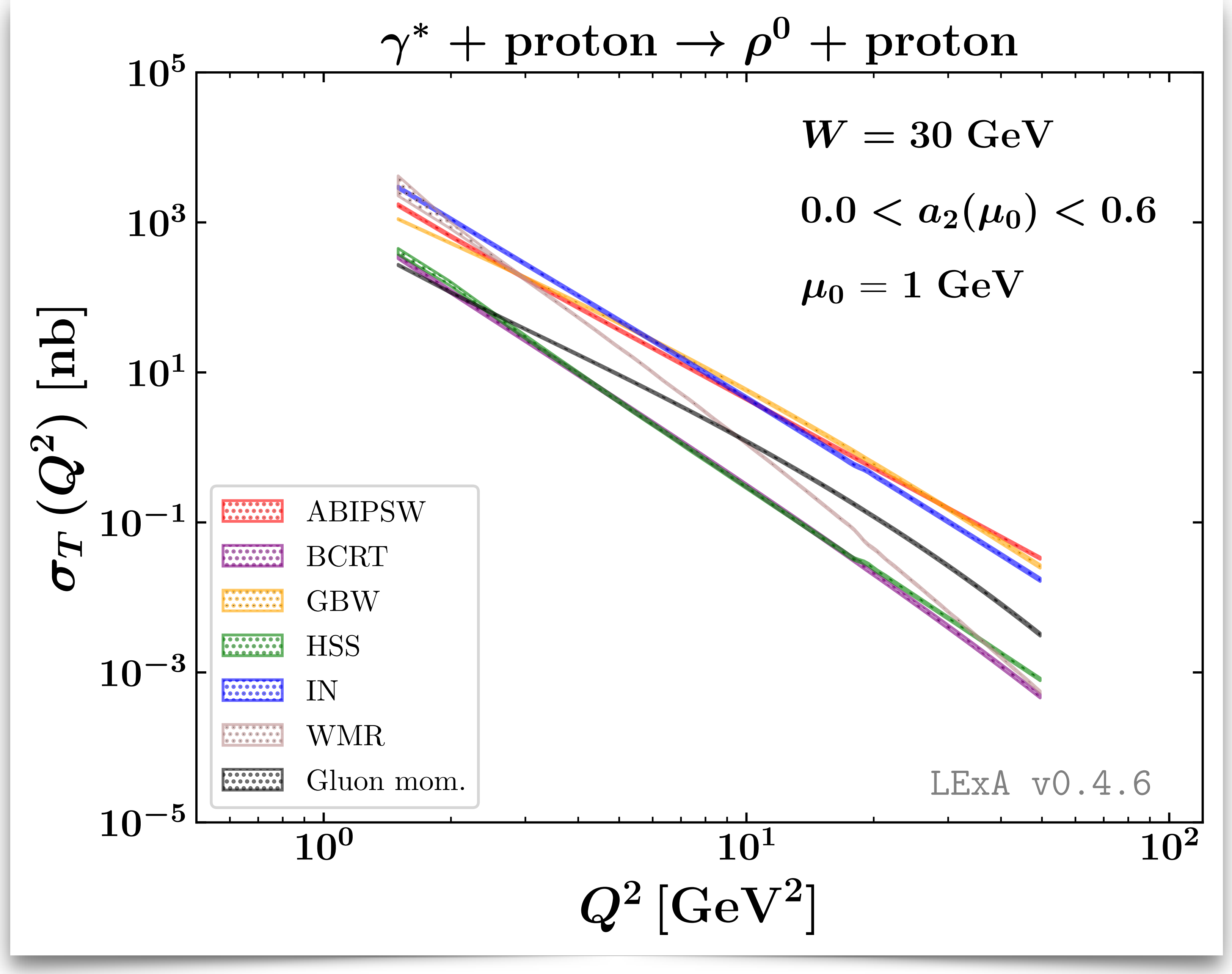

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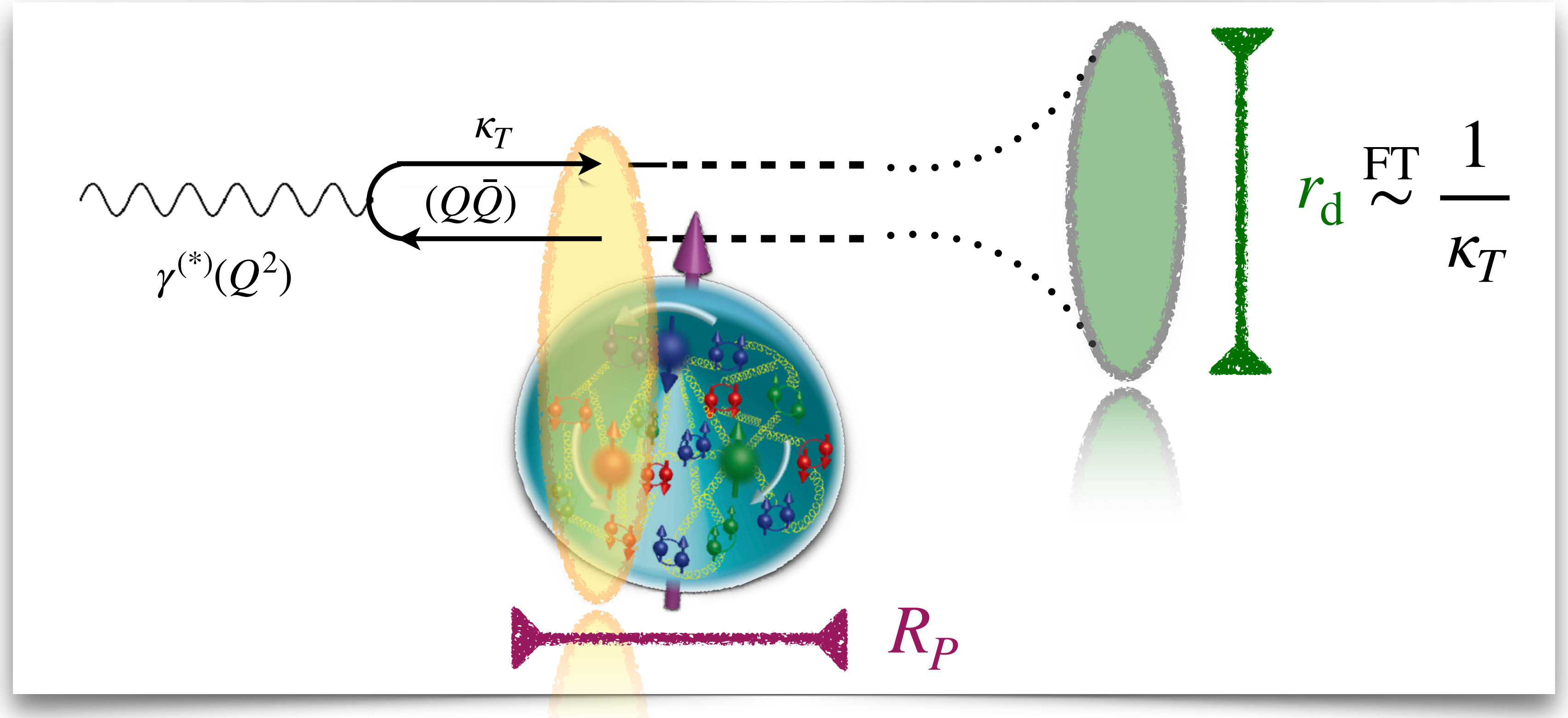
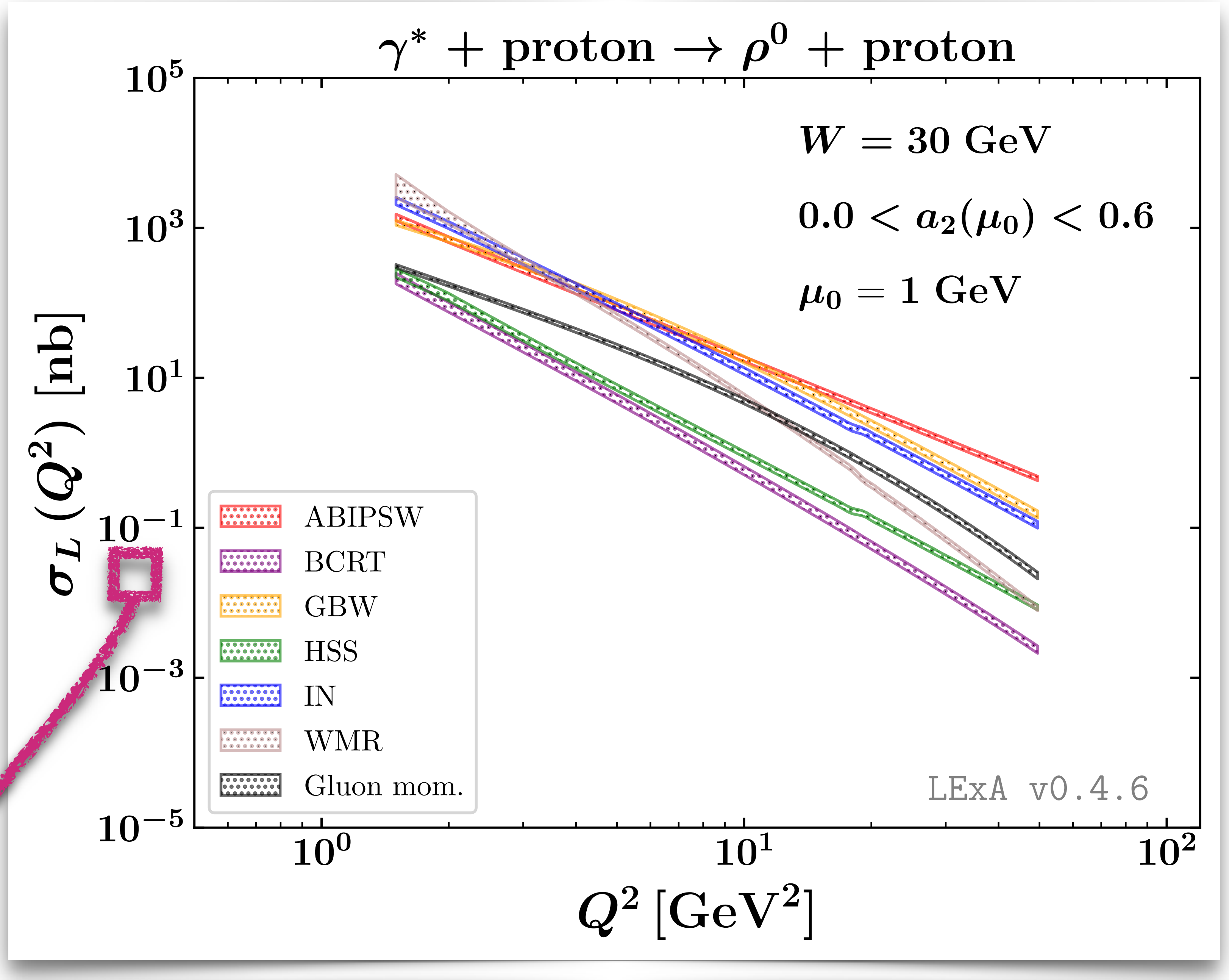
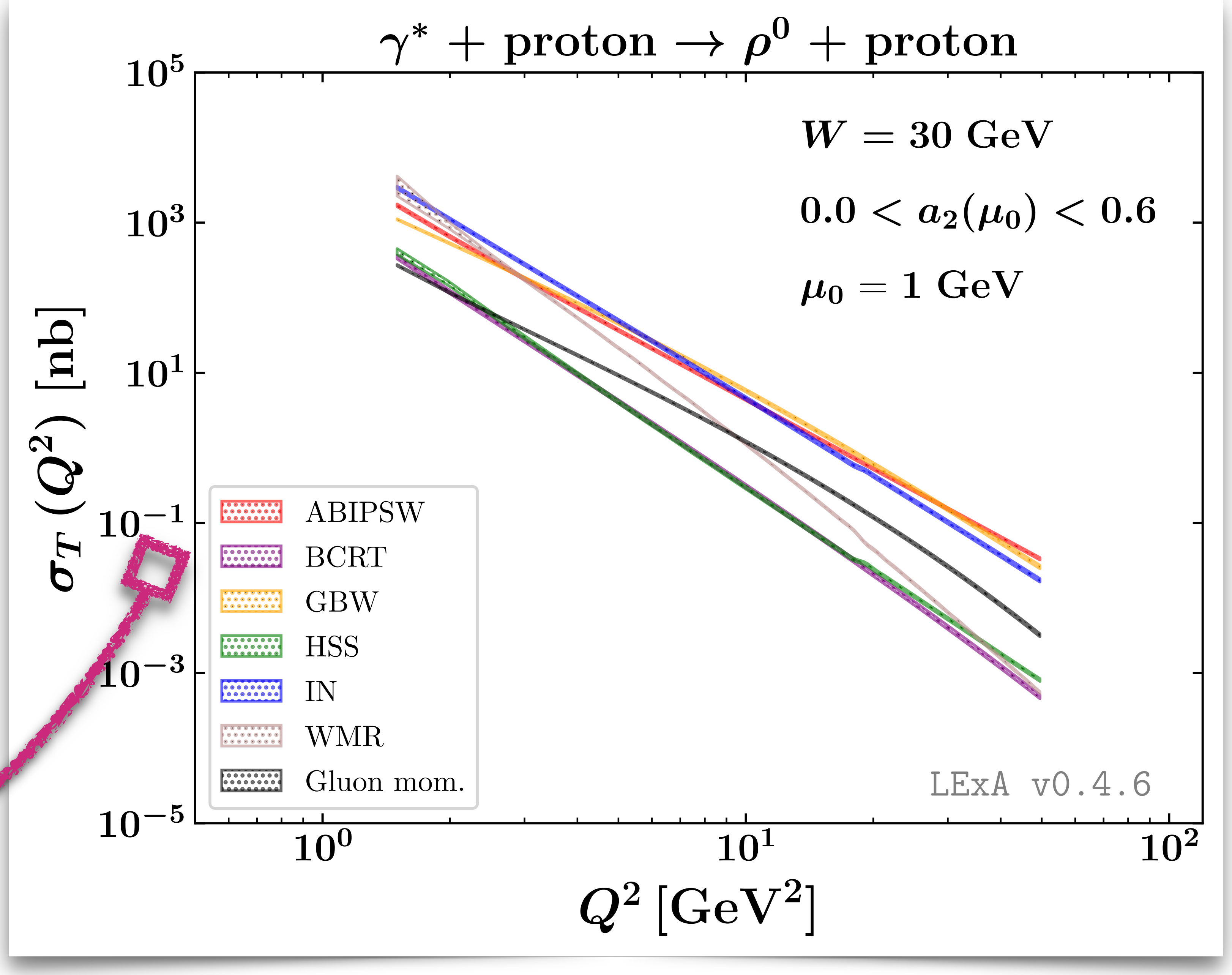


- Small-x $\Rightarrow$ **HEF**
- $\Im(\mathscr{A}) = \Phi(\kappa^2, Q^2) \otimes \mathscr{F}_g(x, \kappa^2)$
- Pavia gluon **TMD** as a small-x **UGD**?





Backup