THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

Division of Theoretical Physics (NO4)

Division Head: **dr hab. Sebastian Sapeta**

Scientific Departments:

- Department of Theory of Structure of Matter (NZ41)
- Department of Particle Physics (NZ42)
- Department of Complex Systems Theory (NZ44)

Permanent research staff: 17; Postdocs: 5; PhD Students: 5

10 doctoral theses defended in the years 2021-2024

Division of Theoretical Physics

Division of Theoretical Physics   Log In

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- Department of Theory of Structure of Matter (NZ41)
- Department of Particle Physics (NZ42)
- Department of Complex Systems Theory (NZ44)
- Jobs
- Useful Info
- Epiphany 2025
- QFT Lecture
- Declaration of accessibility

Division of Theoretical Physics of IFJ PAN

Forthcoming Division Seminars

The details and dates are available at INDICO
Seminars are held every Thursday at 14:00 in the room 4402 (4th floor, tower).
We warmly invite you to coffee 20 minutes before the Seminar.

Secretariate

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MAIN RESEARCH ACTIVITIES

The scientific activities of the Division of Theoretical Physics encompass a broad spectrum of **fundamental research** concerning the **structure and dynamics of matter from subatomic phenomena to those occurring at macro level**.

MAIN RESEARCH ACTIVITIES

- Perturbative QCD
- Parton distribution functions
- Monte Carlo generators
- Small-x physics
- Heavy ion physics
- Electroweak BSM
- Hadron spectroscopy
- Complex systems
- Mathematical physics
- Basics of Quantum Mechanics

MAIN RESEARCH ACTIVITIES

Perturbative QCD	Parton distribution functions	Monte Carlo generators	Small-x physics	Heavy ion physics
Electroweak BSM	Hadron spectroscopy	Complex systems	Mathematical physics	Basics of Quantum Mechanics

Systematic calculations of **higher-order corrections to key processes measured at colliders**, both in the central and forward regions of kinematic phase space.

MAIN RESEARCH ACTIVITIES

Perturbative QCD

Parton distribution functions

Monte Carlo generators

Small-x physics

Heavy ion physics

Basics of Quantum Mechanics

Continuous work on refining the modeling of (integrated and unintegrated) **parton distributions functions** in the proton and in nuclei.

MAIN RESEARCH ACTIVITIES

Perturbative QCD | Parton distribution functions | **Monte Carlo generators** | Small-x physics | Heavy ion physics

Electroweak BSM | Hadron Spectroscopy | Complex systems | Mathematical physics | Basics of Quantum Mechanics

- Many of our results are incorporated in **public Monte Carlo generators**:
  - KaTie
  - KKMC
  - KRKNLO
  - Tauola
  - TauSpinner
  - Therminator
  - MadGraph

MAIN RESEARCH ACTIVITIES

Perturbative QCD

Parton distribution functions

Monte Carlo generators

Small-x physics

Heavy ion physics

The rapid growth of gluon density inside a nucleon is suppressed by gluon recombination. We identify and study **signatures of saturation** of this density in hadron scattering data.

MAIN RESEARCH ACTIVITIES

Perturbative QCD

Parton distribution functions

Monte Carlo generators

Small-x physics

Heavy ion physics

We study the phenomenology of the **quark–gluon plasma** produced in relativistic heavy-ion collisions and develop effective theoretical models to describe its dynamics.

MAIN RESEARCH ACTIVITIES

Perturbative QCD

Monte Carlo generators

Small-x physics

Heavy ion physics

Exploration of **weak boson scattering** at high energies and emergence of weak bosons as partons of hadrons and leptons.
Collider tests of l**epton number and lepton flavor violation**.

Electroweak BSM

Hadron spectroscopy

Complex systems

Mathematical physics

Basics of Quantum Mechanics

MAIN RESEARCH ACTIVITIES

Studies of the spectrum of light mesons. Crucial in the search for **exotic mesons**.
CP symmetry violation studied in decays of heavy mesons (*B* and *D*).
Studies of **mechanical properties of hadrons** via form factors.

Perturbative QCD

Parton distribution functions

Heavy ion physics

Electroweak BSM

Hadron spectroscopy

Complex systems

Mathematical physics

Basics of Quantum Mechanics

MAIN RESEARCH ACTIVITIES

- Perturbative QCD
- Parton distribution functions
- Monte Carlo generators
- Small-x physics
- Heavy ion physics
- Electroweak BSM
- Hadron spectroscopy

CERN
ATLAS EXPERIMENT
LHCb
EIC
CMS
ALICE
Belle II
FCC hh ee he
RHIC relativistic heavy ion collider
HADES
FAIR
Jefferson Lab

MAIN RESEARCH ACTIVITIES

Our research explores areas, including quantitative linguistics, neuroscience and the development of multifractal formalism.

Electroweak BSM

Hadron spectroscopy

Complex systems

Mathematical physics

Basics of Quantum Mechanics

MAIN RESEARCH ACTIVITIES

Solving and analyzing differential-integral equations describing **memory-dependent transport phenomena**, *e.g.*, general diffusion and relaxation processes in disordered systems.

Electroweak BSM

Hadron spectroscopy

Complex systems

Mathematical physics

Basics of Quantum Mechanics

MAIN RESEARCH ACTIVITIES

We study **foundations of Quantum Mechanics**, where our work sheds light on the key questions related to **locality, entanglement and quantum information**.

Electroweak BSM

Hadron spectroscopy

Complex systems

Mathematical physics

Basics of Quantum Mechanics

MAIN RESEARCH ACTIVITIES

Perturbative QCD

Parton distribution functions

Monte Carlo generators

Small-x physics

Heavy ion physics

~70 publications per year

Electroweak BSM

Hadron spectroscopy

Complex systems

Mathematical physics

Basics of Quantum Mechanics

10 grants in the years 2021-2024

Current grants:

- ERC Starting grant, *Shower Thoughts About Precision LHC Event simulation*, 2026-2031, **Rene Poncelet**

- NCN Sonata, *High Precision Predictions to Probe the ElectroWeak-Symmetry Breaking*, 2025-2028, **Rene Poncelet**
- NCN Opus, *High Energy Structure of Protons and Nuclei*, 2024-2028, **Aleksander Kusina**
- APS-Simons Developement Grant, 2024-2026, **Richard Ruiz**
- NCN Opus, *Scattering Neutrinos on Atoms In the LHC*, 2024-2028, **Richard Ruiz**
- NCN Opus, *Extracting space-time energy and charge correlations in relativistic nuclear collisions from experimental observables*, 2024-2028, **Wojciech Broniowski**
- NCN Preludium Bis, *Generalized Cattaneo equation as a tool of describing anomalous diffusion with finite propagation speed*, 2021-2025, **Katarzyna Górska**
- NCN Opus, *Unveiling multidimensional partonic structure of hadrons*, 2020-2025, **Krzysztof Golec-Biernat**

“Our” conferences:

- Cracow Epiphany Conference (https://epiphany.ifj.edu.pl), 2021, 2023, 2024, 2025
- Polish Particle and Nuclear Theory Summit (2PiNTS), 2023, 2024
- International Symposium on Fractional Dynamics and Operational Methods, 2023, 2024

Conference series organization:

- Credo Workshops, January and June 2024
- Physics in Economy and Social Sciences, 1-3 July, 2024
- 38th Marian Smoluchowski Symposium on Statistical Physics 14-17 September 2025
- Cometa general meeting, 28-30 April 2025
- EIC-LHC Synergies, 22-24 September 2025

Networks:

- COMETA COST Action
- EIC Polish Community

Teaching and outreach

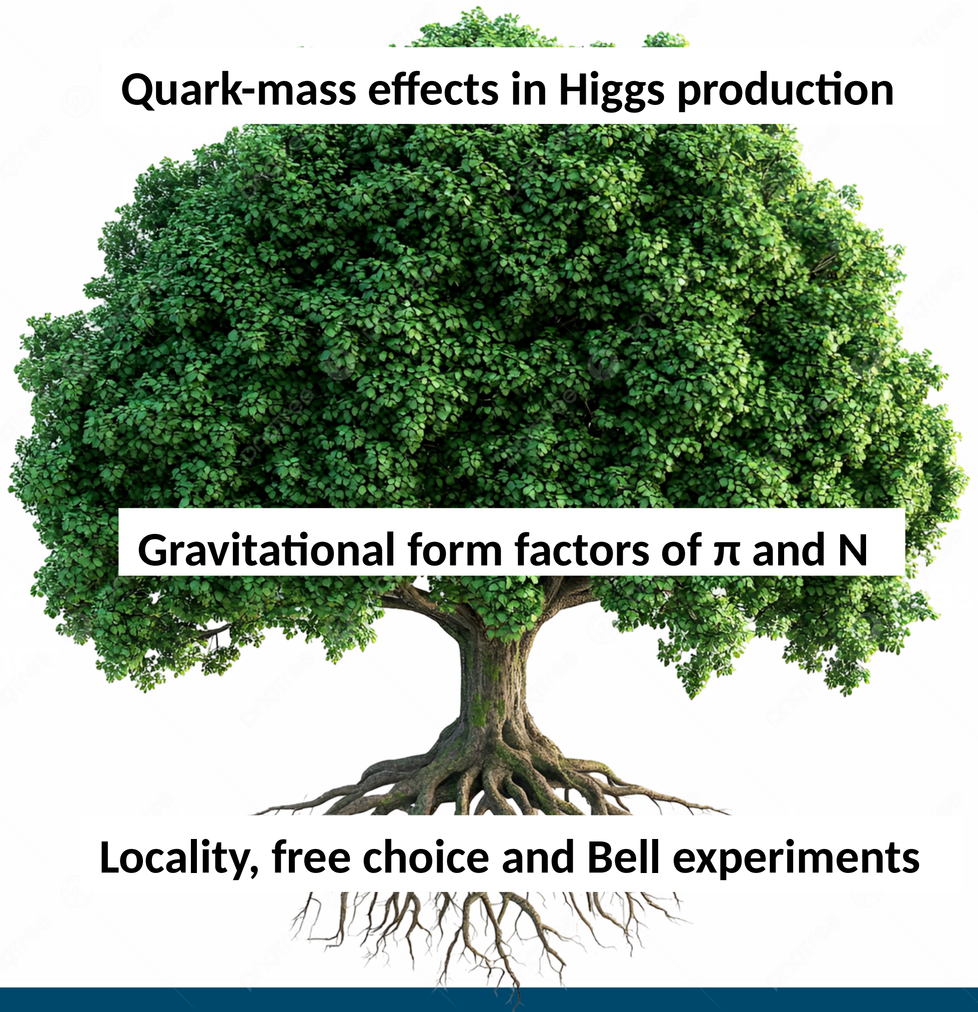
- Lectures for KISD KRAKOWSKA INTERDYSCYPLINARNA SZKOŁA DOKTORSKA students
- European Researchers' Night

  Małopolska Noc Naukowców
- CREDO THE QUEST FOR THE UNEXPECTED
- IFJ PAN Particle Physics Summer Student Program
- Internship
- Visits at schools

Selected recent achievements

Selected recent achievements

Energy



Quark-mass effects in Higgs production

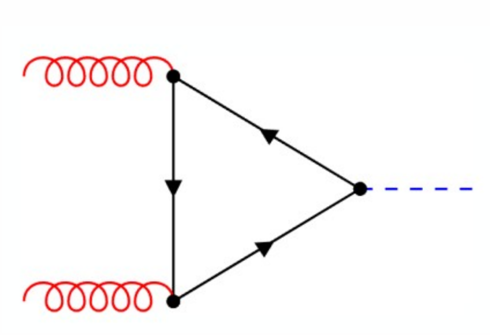
Gravitational form factors of π and N

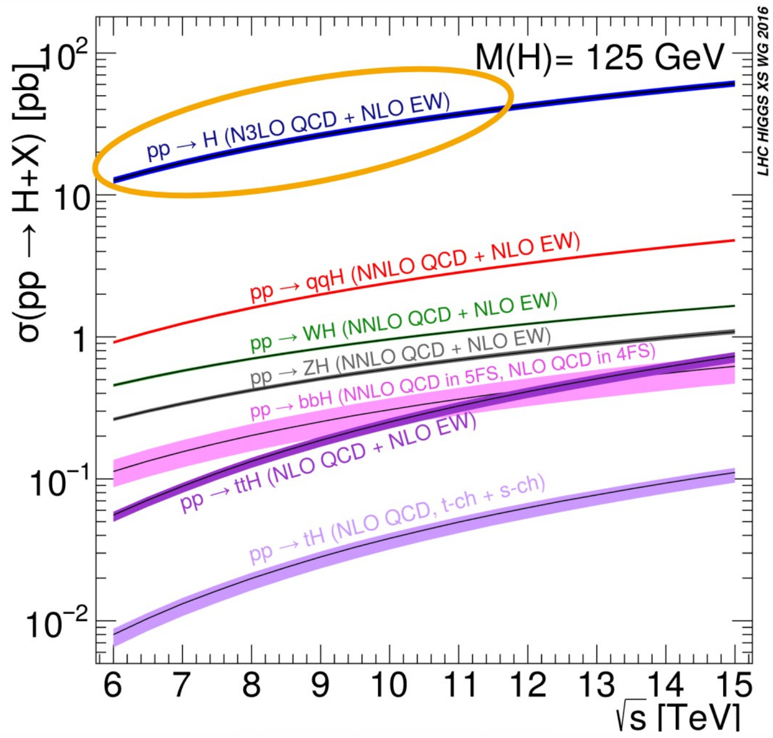
Locality, free choice and Bell experiments

Quark-mass effects in Higgs production

[Poncelet et al., Phys.Rev.Lett. 132 (2024) 21, 211902, JHEP 10 (2024) 210, EurekAlert!]

Higgs production is dominated by gluon fusion:





Cross section at 13 TeV:

experiment: $\sigma_{ggH} = 47.1 \pm 3.8\,\mathrm{pb}$

theory: $\sigma_{ggH} = 48.58^{+2.22}_{-3.27}\,\mathrm{pb}$

Quark-mass effects in Higgs production

[Poncelet et al., Phys.Rev.Lett. 132 (2024) 21, 211902, JHEP 10 (2024) 210, EurekAlert!]

Main theory uncertainties:

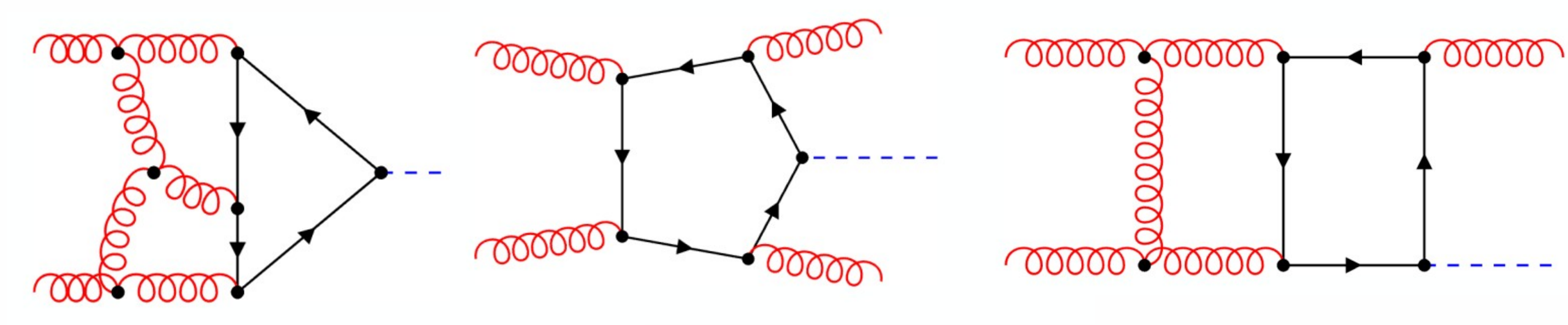
$\delta(\text{scale})$	$\delta(\text{trunc})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\boxed{\delta(t,b,c)}$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

- diagrams with heavy quarks
- mass renormalisation scheme

Quark-mass effects in Higgs production

[Poncelet et al., Phys.Rev.Lett. 132 (2024) 21, 211902, JHEP 10 (2024) 210, EurekAlert!]

Second-order corrections to top-bottom interference effects with full mass dependence!



Quark-mass effects in Higgs production

[Poncelet et al., Phys.Rev.Lett. 132 (2024) 21, 211902, JHEP 10 (2024) 210, EurekAlert!]

Bottom mass renormalization scheme:

Renorm. scheme	$\overline{\text{MS}}$	on-shell
$\mathcal{O}(\alpha_s^2)$	-1.11	-1.98
LO	$-1.11^{+0.28}_{-0.43}$	$-1.98^{+0.38}_{-0.53}$
$\mathcal{O}(\alpha_s^3)$	-0.65	-0.44
NLO	$-1.76^{+0.27}_{-0.28}$	$-2.42^{+0.19}_{-0.12}$
$\mathcal{O}(\alpha_s^4)$	$+0.02$	$+0.43$
NNLO	$-1.74(2)^{+0.13}_{-0.03}$	$-1.99(2)^{+0.29}_{-0.15}$

- significant reduction of scale uncertainties
- first agreement at NNLO between $\overline{\text{MS}}$ and on-shell scheme
- accurate assessment of bottom quark mass uncertainty
- will be included in LHCHiggsWG Yellow Report 5

Quark-mass effects in Higgs production

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- diagrams with heavy quarks
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Now: $\pm 0.3\,\%$

Gravitational form factors of π and N

[Broniowski, Ruiz Arriola, Phys. Lett. B 859 (2024) 139138, arXiv:2412.00848, arXiv:2503.09297]

Electromagnetic current	J^μ	$\partial_\mu J^\mu = 0$
Stress energy-momentum tensor	$\Theta^{\mu\nu}$	$\partial_\mu \Theta^{\mu\nu} = \partial_\nu \Theta^{\mu\nu} = 0$

Matrix elements:

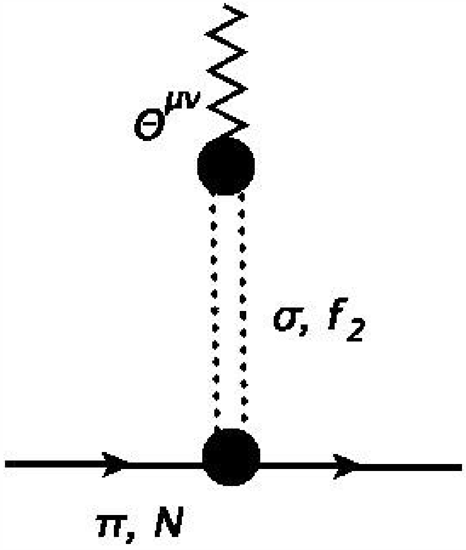
$$\langle p', s' | \Theta^{\mu\nu}(0) | p, s \rangle = \frac{1}{m_N} \bar{u}(p', s') \left[A(t) P^\mu P^\nu \; + J(t)\, i\, P^{\{\mu} \sigma^{\nu\}\rho} q^\rho + D(t)\, \frac{q^\mu q^\nu - g^{\mu\nu} q^2}{4} \right] u(p, s)$$

- Describes distribution of fundamental properties of hadrons: mass, energy, momentum, pressure, stress
- *p, p′, s, s′* - momenta and spins of a hadron
- *A(t), J(t), D(t)* – gravitational form factors: can be explained with Meson Dominance approach, from experiment (KEK-B, CLAS@TJLAB, Glue-X) or from lattice

Gravitational form factors of π and N

[Broniowski, Ruiz Arriola, Phys. Lett. B 859 (2024) 139138, arXiv:2412.00848, arXiv:2503.09297]

Meson Dominance



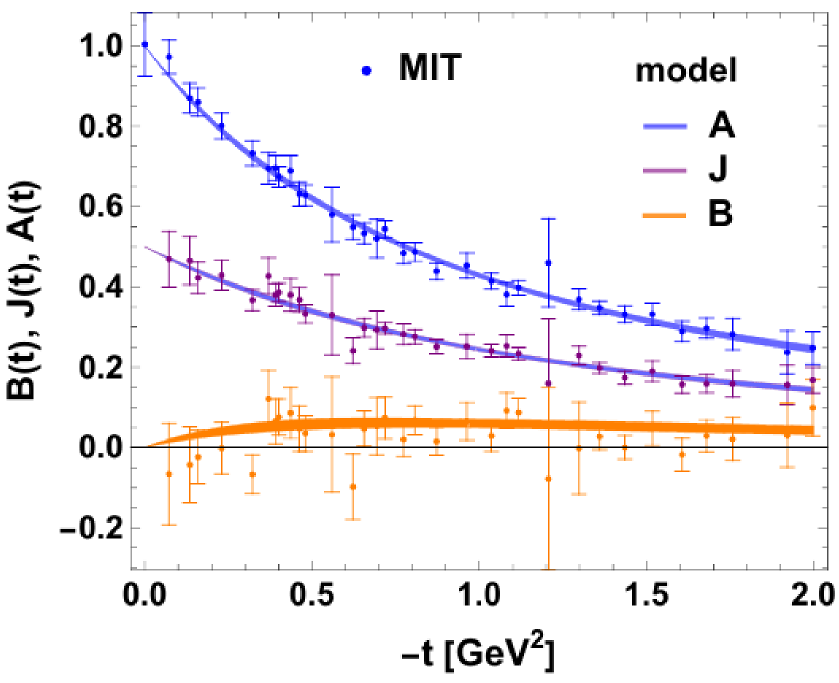
Form factors at moderate *t*:

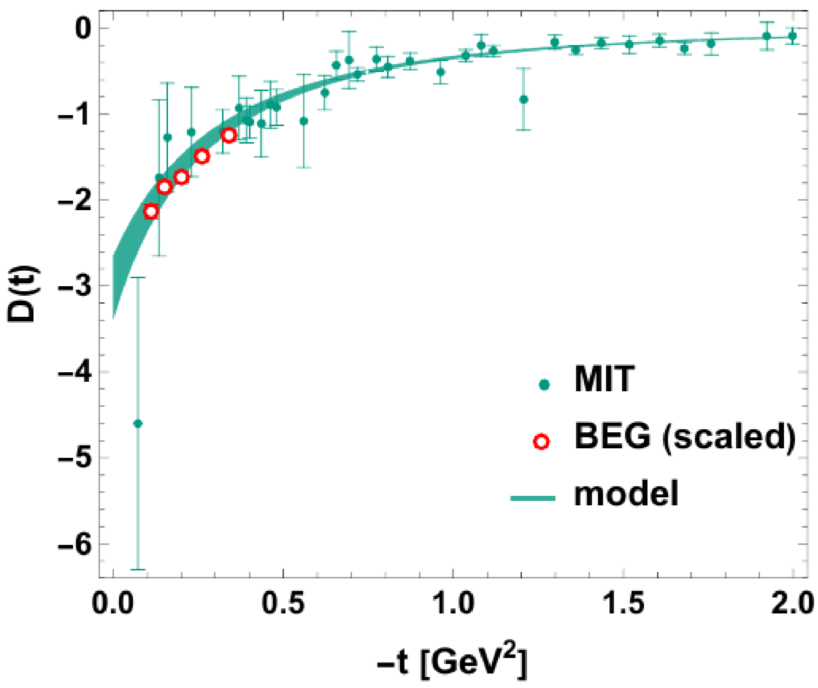
$$A(t), J(t), D(t) = \sum \frac{c_i}{m_i^2 - t}$$

- c_i – effective couplings
- m_i – masses of the resonances

Gravitational form factors of π and N

[Broniowski, Ruiz Arriola, Phys. Lett. B 859 (2024) 139138, arXiv:2412.00848, arXiv:2503.09297]



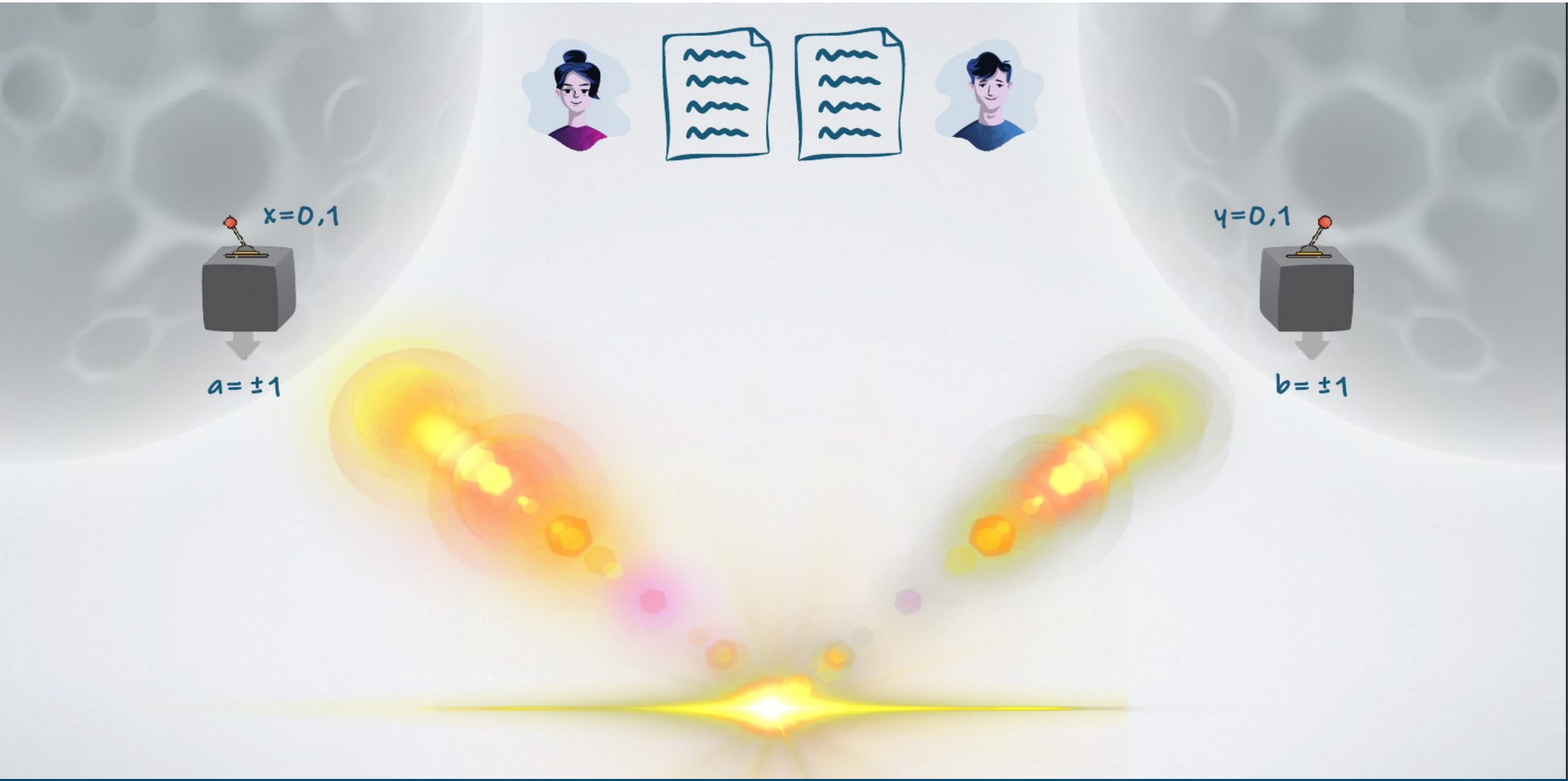


B = 2J -A

MIT: lattice data; BEG: experimental data from TJLab DVCS

Locality, free choice and Bell experiments

[Błasiak et al. PNAS 118 (17) e2020569118 (April 27, 2021), EurekAlert!]



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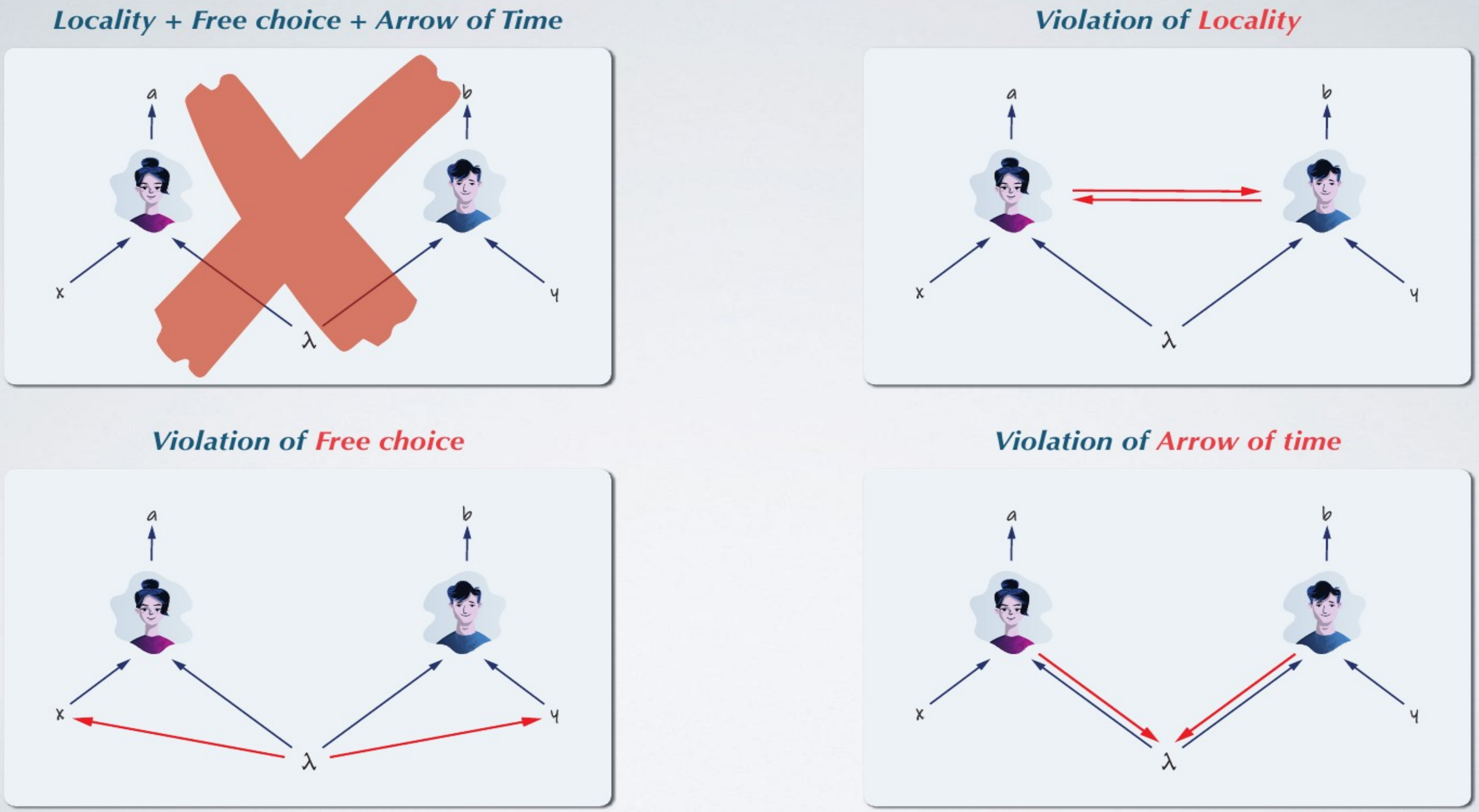

Locality, free choice and Bell experiments

[Błasiak et al. PNAS 118 (17) e2020569118 (April 27, 2021), EurekAlert!]

		Locality	Free choice	
Any statistics	any no. settings	$\mu_L = \mu_F$		**Theorem 1**
	non-signalling two settings	$\mu_L = \frac{1}{2}(4 - S_{max})$	$\mu_F = \frac{1}{2}(4 - S_{max})$	**Theorem 2**
Quantum statistics	Bell state infinite no. settings	$\mu_L \xrightarrow[M \to \infty]{} 0$ (*)	$\mu_F \xrightarrow[M \to \infty]{} 0$	**Theorem 3**
	two-qubit state any no. settings	$\mu_L = \cos\theta$ (*)	$\mu_F = \cos\theta$	**Theorem 4**

- Each type of violation (locality, free choice, arrow of time) requires the same cost
- In Bell experiment: $\mu_L = \mu_F = 59\,\%$
- For generalized Bell experiment: $\mu_L, \mu_R \to 0 \ \text{ for } \ n \to \infty$

Guiding principles and future directions:

- Stay at frontline of research defined by **major experiments** and **fundamental questions**
- Keep scientific **diversity** and **freedom**
- Attract and promote **talented young people**