Table 1. Features of included articles

Article (year)/ description	Quant. eval. ?	Descr. proce--dures /"TLS"	Class--room disc.	Daily lives	Link knowl.	Expl. ans--wers	Expr--ess ideas	Group Work	Com--puter use	Plan exp./ cons-truct.	Conduct exp.	Inter--pret data	Present data	Observe phenom.	Use evidence to supp.	Watch demo. of exp.	Field work	Chall--enging exs.	Give feed--back
ATOMIC:																			
Savall-Alemany, F. et al. (2019) PBL atomic spectr.	Y	Y	X	X	X	X	X	X		X	X	X		X	X	X			X
Rodriguez, L. V. et al. (2020)Inquiry quantum.	Y	Y	X	X	X	X	X	X	X			X	X	X	X	X			X
Kontomaris, S. V. et al. (2020) Ionizing vs. non-ion. rad.	N	N		X	X														
Cziprok, C. et al. (2016) Vee heuristic, photoel. eff.	N	Y		X	X			X	X		X	X	X		X				
Cai, S. et al. (2020) AR, photoel. eff.	Y	Y						X	X		X	X		X					X
Woo, Y. et al. (2019) Constr. spectrometer	N	N							X	X			X						
Maftei, G. et al. (2011) Mosaic method, atom. spectra	N	Y	X		X	X		X				X	X	X	X				X
Salazar, R. et al.(2019) Modeling activities	Y	Y	X	X	X	X	X	X	X				X						X
Article/ activity	**Quant. eval. ?**	**Descr. proce--dures /"TLS"**	**Class--room disc.**	**Daily lives**	**Link knowl.**	**Expl. ans--wers**	**Expr--ess ideas**	**Group Work**	**Com--puter use**	**Plan exp./ cons-truct.**	**Conduct exp.**	**Inter--pret data**	**Present data**	**Observe phenom.**	**Use evidence to supp.**	**Watch demo. of exp.**	**Field work**	**Chall--enging exs.**	**Give feed--back**
NUCLEAR:																			
Bastos, R. O. et al. (2016) Experiments, low-cost.	N	N		X							X	X						X	
Tsuruta, T. et al. (2009) Exp., track detection	N	N		X								X		X		X	X		
De Cicco, F. et al. (2017) Radon exp., School-uni collab.	N	Y		X	X	X		X	X	X	X	X	X	X	X		X	X	X
Schibuk, E. (2015) Activities (Manhattan project)	N	Y	X	X	X	X	X	X	X										X
Sengdala, P. et al. (2014) NOS teaching, Nucl./peace.	N	Y	X	X	X	X	X	X					X						X
Shastri, A. (2007) Constr. Slide-rule comp., nuclear eff.	N	Y	X	X	X	X	X		X	X		X	X		X			X	
Brown, T. (2014) Exp., radioactive dating	N	Y		X	X				X		X	X		X					X
Kapon, S. (2013) Scientific text for students (Einst. E=mc^2)	N	Y	X	X	X	X	X	X							X			X	X
KRIŠŤÁK, Ľ. et al. (2013) Multimedia/ DVD activity	Y	Y	X	X	X	X		X	X		X	X			X	X			X
Elbanowska-Ciemuchowska, S. et al. (2011) *Many activities*	N	Y	X	X	X		X	X	X		X	X	X		X		X	X	X

Article/ activity	Quant. eval. ?	Descr. proce--dures /"TLS"	Class--room disc.	Daily lives	Link knowl.	Expl. ans--wers	Expr--ess ideas	Group Work	Com--puter use	Plan exp./ cons-truct.	Conduct exp.	Inter--pret data	Present data	Observe phenom.	Use evidence to supp.	Watch demo. of exp.	Field work	Chall--enging exs.	Give feed--back
PARTICLE:																			
Schramek, A. et al. (2019) Research-based teaching, Uni-school. Detectors	N	Y		X	X	X	X	X		X	X	X	X		X	X	X	X	X
Bressan, E. (2011) Research-based teaching, Uni-school, CR detection	N	Y		X					X	X	X	X	X		X		X	X	X
Bardeen, M. et al. (2018) Online tools, *QuarkNet*	Y	Y	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X
van den Berg, E. et al. (2006) Fast feedback, symmetries etc.	N	Y	X		X	X		X										X	X
Kourkoumelis, C. et al. (2014) Online tool, *HYPATIA*	N	Y	X		X				X			X	X	X	X			X	X
Goldader, J. D. et al. (2010) Constr. cheap CR detec.	N	N							X	X	X		X					X	
Brouwer, W. et al. (2009) Research-based. *ALTA* proj.	N	Y		X	X	X	X	X	X		X	X	X		X		X	X	
de Souza, V. et al. (2013) (re-) Constr. CR Impact point	N	Y			X					X		X	X		X			X	X
Badalà, A. et al. (2007) Data analysis, Simul. CR data	N	Y	X		X			X	X			X	X					X	

Article/ activity	Quant. eval. ?	Descr. proce--dures /"TLS"	Class--room disc.	Daily lives	Link knowl.	Expl. ans--wers	Expr--ess ideas	Group Work	Com--puter use	Plan exp./ cons-truct.	Conduct exp.	Inter--pret data	Present data	Observe phenom.	Use evidence to supp.	Watch demo. of exp.	Field work	Chall--enging exs.	Give feed--back
COMBINED /OTHER:																			
Bussani, A. (2020) Dice game, microsc. sys.	N	Y	X		X			X	X			X			X			X	
Kvita, J. et al. (2018) Particle camera for exp.	N	Y		X	X				X		X	X	X	X		X	X	X	
Keegans, J. D. et al. (2021), Outreach, Python, Nucleosynth.	Y	Y			X			X	X			X	X		X			X	X
Planinšič, G. et al. (2008), Constr. AF microscope model, Nano.	N	Y		X	X			X		X	X	X	X		X	X		X	
Laubach, T. A. et al. (2010), Quided inquiry, Nano.	N	Y		X	X	X			X		X	X	X		X			X	

Table 2. Trends

Frequency (out of 32 papers)	Variable		Frequency (out of 32 papers)
Describe procedures/ “TLS”	84%	Conduct experiment	50%
Link knowledge	81%	Classroom discussion Explain answers	47%
Interpret data	75%	Express ideas	34%
Daily lives	69%	Plan experiment/ construct something Observe phenomenon	31%
Present data, Computer Use	66%	Watch demonstration of an experiment	25%
Group work	63%	Quantitative evaluation Field work	22%
Challenging exercises Give feedback Use evidence to support	59%		

Table 3. Summary of proposed activities

Educational games
Duhdonium, competitive dice game. Microscopic systems. Bussani, A. (2020)
Specific instructional methods
Fast feedback method. Particle physics. van den Berg, E. *et al.* (2006)
Modelling method. Atomic models. Salazar, R. *et al.*.(2019)
Mosaic (Jigsaw). Atomic spectra. Maftei, G. *et al.* (2011)
Focus on analogies. Ionizing vs. non-ionizing radiation. Kontomaris, S. V. *et al.*. (2020)
Guided problem-based learning. Atomic spectra. Savall-Alemany, .F *et al.* (2019)
Many different methods. Nuclear physics. Elbanowska-Ciemuchowska, S. *et al.* (2011)
Reading a scientific text. Class discussions. Einstein’s paper on E=mc^2. Kapon, S. (2013)
Reading articles. NOS teaching. Nuclear physics and peace. Sengdala, P. *et al.* (2014)
Flipped classroom approach. Discussions. Studying the Manhattan project. Schibuk, E. (2015)
Experiments
=> Conduct
4 mystery vials with nano-solutions. Inquiry. Laubach, T. A. *et al.* (2010)
Particle camera MX-10: Particle and nuclear physics. Kvita, J. *et al.* (2018)
Photoelectric effect, using the Vee heuristic. Cziprok, C. *et al.* (2016)
Radioactive dating in the classroom, using Cobalt-60. Brown, T. (2014)
Nuclear track detection methods. Tsuruta, T. *et al.* (2009)
Nuclear experiments with low-cost instruments. Nuclear physics. Bastos, R. O. *et al.* (2016)
=> Plan/construct
Constructing an atomic force microscope model. Planinšič, G. *et al.* (2008)
Reconstruction of impact point and arrival direction of a CR particle. de Souza, V. *et al.* (2013)
Constructing a cheap cosmic ray detector. Goldader, J. D. *et al.* (2010)
Constructing detectors at a research center. Research-based teaching. Schramek, A *et al.* (2019)
Constructing a high-res 3D-printed smartphone spectrometer. Atomic. Woo, Y. *et al.* (2019)
Constructing a slide-rule computer. Effects of nuclear weapons. Shastri, A. (2007)
=> Data analysis
Extensive air showers of particles. Particle physics. Badalà, A. *et al.* (2007)
Online tools/applets/multimedia
HYPATIA. (ATLAS event data). Particle physics. Kourkoumelis, C. *et al.* (2014)
Go-Lab activities. Photoelectric effect sequence. Rodriguez, L. V *et al.* (2020)
Multimedia DVD - nuclear physics. KRIŠŤÁK, Ľ. *et al.* (2013)
Augmented reality (AR)
Photoelectric effect experiment using AR in groups. Cai, S. *et al.* (2020)
Outreach/Research program
ALTA study of cosmic ray bursts. Hypotheses in student projects. Brouwer, W. *et al.* (2009)
QuarkNet education program. Research, masterclasses, e-Labs. Bardeen, M. *et al.* (2018)
EEE (Extreme Energy Events) project: Cosmic ray detectors at schools. Bressan, E. (2011)
ENVIRAD - Radon measurements at schools and university. De Cicco, F *et al.* (2017)
ThaiPASS - Data analysis using Python. Astroparticle physics. Keegans, J. D. *et al.* (2021)

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APPENDIX: OVERVIEW OF EMPIRICAL EVALUATION

Article (Year)	Context of study/sample	Control group	Pre-test	Post-test	Statistical analysis	Results
Savall-Alemany, F. et al. (2019) PBL atomic spectr.	Assess learning achievement and identify student misconceptions. Experimental group (PBL): total of 74 students, 2 high schools. Control group (lectures+problem solving): total of 67 students. Teachers - over 10 year experience, incl. PBL.	Yes	Yes. No correct answers - exp. Or ctrl. group.	Yes. Included in appendix. Open-ended answers to three questions. Classification of student answers. High inter-rater reliability. 5 students who performed very well additionally interviewed to check knowledge.	Yes. Chi-square test. Fisher's *p*. Cohen's *h*.	Experimental group performed stat. signif. *better* in all 3 questions. Cohen's *h* suggests a large effect size. Discussion of observed student misconceptions.
Rodriguez, L. V. et al. (2020) Inquiry quantum.	Assess learning outcomes and identify student misconceptions. 114 students from four high schools.	No	No	Data collection through digital environment. MCQ and open-ended questions.	Correct answers reported as a %.	Majority of students understand critical concepts related to the photoelectric effect. Less successful in answering certain open-ended questions.
Cai, S. et al. (2020) Augmented reality, photoel. eff.	Assess student self-efficacy and conceptions of learning. Experimental group (AR): total of 49 students. Control group (flash-based): total of 49 students from one high school.	Yes	Yes. No significant differences.	Yes. SEOLP questionnaire, COLP questionnaire.	Yes. t-test analysis. ANCOVA.	AR group achieved significantly higher scores on physics learning self-efficacy compared to the Flash group. (4 out of 6 aspects showed improvement, namely *conceptual understanding*, *higher-order thinking skills*, *practical work* and *social communication*.) AR group scored higher in *applying*, *understanding* and *seeing in a new way*. (higher-level conception) They scored lower in *memorizing* and *calculating* (loverl-level conception).
Salazar, R. et al.(2019) Modeling activities	Assess learning outcomes (Hake's gain score). 20 students from one school.	No	Yes	Yes. Included in appendix.	Yes. Hake's normalized gain.	Most answers show a high conceptual gain (g>0.7). Only three questions still trouble students (g<0.3). Average gain for the 20 questions is high (g=0.72). Authors report student answers to activities.
KRIŠŤÁK, Ľ. et al. (2013) Multimedia/ DVD activity	Assess learning gains in area of: remembering, understanding, transfer of specific and non-specific knowledge (analysis, synthesis etc.). Experimental group (Multimedia DVD): 104 students. Control group ("traditional" teaching): 101 students. Students are from four high schools. Same teacher taught the students (for each school).	Yes	No	Yes. Included in appendix. Open-ended/MCQ.	Yes. F-test and t-test. Normal distribution verified for both groups.	Students using DVD multimedia scored significantly higher than students using "traditional" methods, in all three categories: specific and non-specific transfer, remembering and understanding.
Bardeen, M. et al. (2018) Online tools, *QuarkNet*	Assess increase in scientific literacy of students. Masterclass effectiveness - knowledge and attitude. 582 students.	No	Yes. Conceptual maps. Masterclass: Yes.	Yes. Conceptual maps. Masterclass: Yes.	Yes. However, analysis of effect sizes and stat.sig. differences only mentioned; no details included in paper.	Post-maps show a more sophisticated or scientifically literate understanding of the scientific process. Improvements for students with higher and with lower pre-program maps. Masterclasses: Positive attitude towards physics: 4.0 average out of 5. Increase student knowledge and skills.
Keegans, J. D. et al. (2021), Outreach, Python, Nucleosynthesis	Assess student attitude and skills. 60 students from 30 schools	No	No (2018 event). Yes (2019 event).	Yes. Questionnaire included in appendix.	No, however all student responses clearly shown on histogram.	(2018) Largely positive attitude towards the summer school. (2019)Self-assessment shows that students believe their programming and computer science skills have increased. Most students would pursue a STEM career. Perceived usefulness of Python, interest in nuclear astrophysics and STEM-career interest have increased (pre- to post-test).