Theoretical Physics in Bicocca

Risultati recenti e prospettive delle ricerche nel Dipartimento di Fisica “G. Occhialini”

presented by Paolo Nason for the Theory Group

December 18, 2018

Preamble: Fundamental Interactions in 2018

- Newborn (2012): The Higgs particle!
- The Standard Model is (almost) complete, in the sense that (almost) all that could be there, is there. Still missing:
  - (Perhaps) full understanding of neutrino sector;
  - Strong CP, axions and the like
- But, don't forget: the Higgs is young!
  - We must study it: LHC, HLLHC.
  - Is it really IT? (precision SM physics at LHC, HLLHC).
  - Is there anything nearby? (HELHC? FCC? ILC? CLIC? Muon Colliders?)

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- Missing stuff: large scale observation in conflict with small-scale observation: missing dark matter.
- Simple but cumbersome: $>$ 19 parameters

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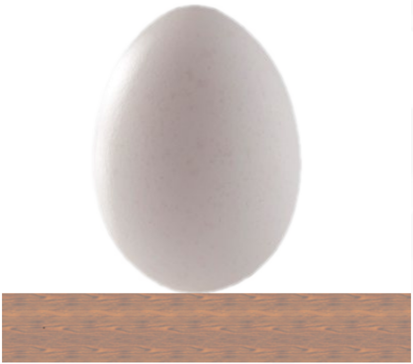

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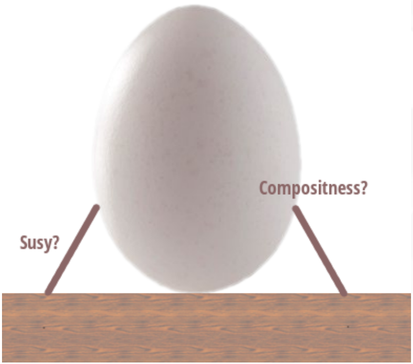

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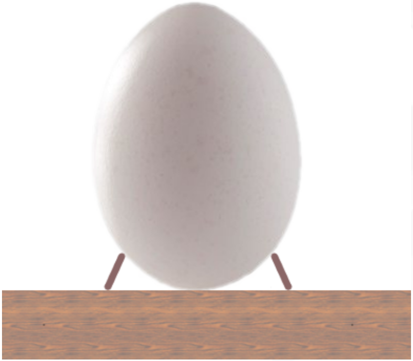

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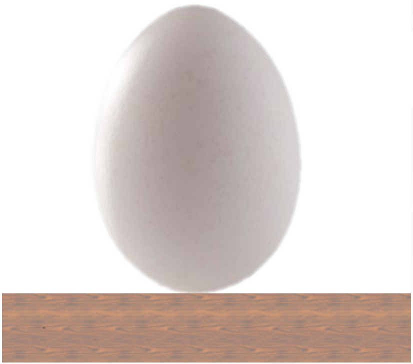

- As it is, it needs fine tuning!
- We expected to see what stabilizes it at the LHC.
- We haven't seen it. Is it there at shorter distances?
- Or is it too far to be seen? Or it is some magic mechanism that we don't yet understand?

Open problems: low scales

- Quantum Chromo Dynamics is strongly interacting (*and thus hard to treat!*) at long distances ($\gtrsim 1\,\mathrm{fm}$).
- Paradoxical situation: we measure α_s at high energy, where IT IS SMALLER!
- Low energy QCD uncertainties propagates into many important observables.
- In flavour physics it modifies and mixes the expectation values of weak operators over hadronic states.
- A particularly instructive example is in the muon $g-2$, that display a 4σ deviation from Standard Model predictions. The main uncertainty in its calculation comes from the hadronic contribution to the electromagnetic vacuum polarization and to the light-by-light scattering.

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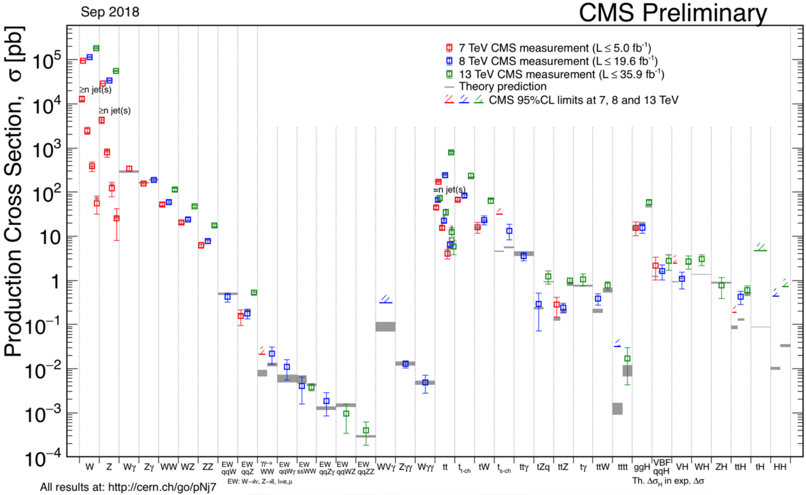
Theory Research Directions in Bicocca

Collider Physics Phenomenology

Field Theories on a Lattice

String Theory

Collider Phenomenology



Summary of the most important CMS measurements at 7, 8 and 13 TeV, compared with theoretical predictions.

Collider Phenomenology: theory predictions

- Must provide an accurate prediction for the
  - INTERESTING part of the process (for example the production of the Higgs boson)
  - but also an accurate description of common associated processes (the production of associated jets of hardrons),
  - plus a global description of the production of all accompanying particles (several hundreds): Event generators
- The formalism to perform these calculations has been developed since the discovery of QCD and up to now. Buzzwords: parton density evolution, Altarelli-Parisi equations, Factorization theorems, NLO, NNLO corrections, soft gluon resummation, Shower Algorithms, etc.

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Our group:

The POsitive Weights Hardest Emission Generator project.

- POWHEG (UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA, INFN): a method for building accurate event generators for hadronic collisions.
  born in 2004 in Bicocca. Very successful ...
- Milestones:
  - 2006: first processes implemented (ZZ production)
  - 2007: Fully general formulation of the method
  - 2010: Automated framework for the generation of processes (POWHEG BOX, http://powhegbox.mib.infn.it) (with Alioli and Re)
  - Many processes implemented in Bicocca + several in other institutions worldwide using the POWHEG BOX
- Recent work:
  - dilepton + Higgs (SM-EFT) in POWHEG;
  - HW, HZ + 1 jet in POWHEG (with Federico Granata);
  - $t\bar{t}$ production and decay in POWHEG BOX RES; study of top mass sensitive observables (with Silvia Ferrario Ravasio)

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Other recent work, not related to POWHEG:

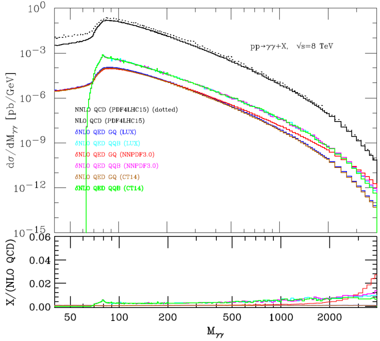
- Non perturbative effects (renormalons) in top mass sensitive observables (with Silvia Ferrario Ravasio)
- Phenomenological Studies: Z' at LHC;
- Higgs at Next-to-Next-to-Next-to leading order in QCD
- Master integrals for heavy-to-light quark decays
- Z transverse momentum distribution, QCD+QED effects
- Diphotons at the LHC
- Photon density in the proton

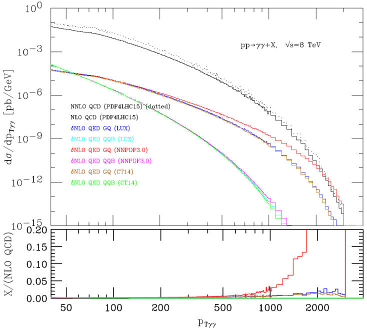
All what we do ends in a plot:

NLO QED CORRECTIONS FOR $\gamma\gamma$

$\sqrt{s} = 8$ TeV
$p_{T\gamma}^{\rm hard} \geq 40$ GeV, $p_{T\gamma}^{\rm soft} \geq 30$ GeV
$|y_\gamma| < 1.37$ and $1.56 < |y_\gamma| \leq 2.37$, $R_{\gamma\gamma}^{\rm min} = 0.4$,
$R = 0.4$ and $E_{T\ max} = 11$ GeV.

- Merging of photons included
- Myy and pTyy defined with the two hardest photons
- All the channels included (also qy)

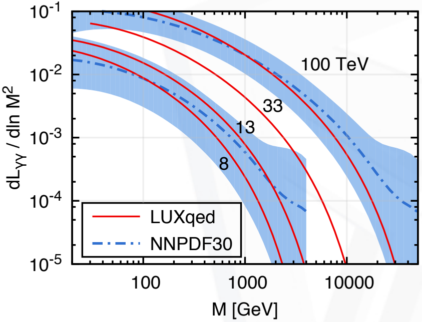




Cieri, Ferrera, Sborlini, in preparation

NLO QED corrections implemented in 2γNNLO

Some very successful



Fast protons behave as broad band beams of constituent particles. They also contain γ's, that can collide at LHC. LUXqed is a result that brought the photon content of the proton from essentially unknown to perfectly known.

What we do

We are part of a large physics community of experimentalists and theorists worldwide.
We talk to our experimentalists colleagues, we seek areas where improvements are needed, and build up theoretical projects to meet the challenges.
We are constantly involved in debates on what can be done and what should not be done, both in theory and experiments, on how to realistically assess the errors in the theoretical results.
We answer e-mails (tons of them) regarding our calculations and generators.
We have responsibilities in

- the PDG (particle data group) reviews;
- HXSWG: Higgs cross section working group
- HLHELHC (High Luminosity and High Energy LHC) workshop
- TopLHCWG (The top LHC working group)

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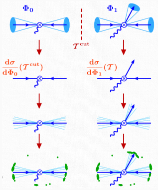
We are:

- Professors: C. Oleari, S.Alioli (ERC), P.Nason
- Postdocs: L.Cieri, L.Rottoli, A.Broggio, S.Kallweit, M.Lim
- Doctoral students:
  - Silvia Ferrario Ravasio (now Postdoctor in Duhram, UK)
  - Marco Rocco

Alioli's ERC project:

REINVENT: A new approach to event generation

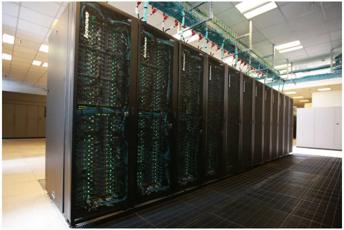
Key idea: Replace parton-shower evolution with higher-logarithmic resummation. Not "yet another Monte Carlo", but a new approach to Monte Carlo event generation. **How to do it?**



1. Slice phase space with physical resolution parameters, resummable at high-accuracy ($\mathcal{T}_N^{\rm cut}$).
2. Calculate differential cross-sections, resum down to small $\mathcal{T}_N^{\rm cut} \sim \mathcal{O}(1 \text{ GeV})$
3. Shower events without spoiling perturbative accuracy. Shower used now only where good approximation.
4. Hadronize, add MPI and decays without restrictions.

ERC-2016-StG **REINVENT** *Simone Alioli* 6

Non-perturbative quantum field theory and computational physics



Group: Dalla Brida, Destri, Giusti, Harris, Pepe, Rapuano

Physics: Quantum Chromodynamics (QCD), Flavour Physics, Dark Matter

Methodology: Non-perturbative quantum field theory on the lattice, numerical simulations, High Perf. Computing (HPC) (up to $4 \cdot 10^{11}$ integration variables on 10^5 processors)

Running projects:
INFN national proj. QCDLAT - L. Giusti national coordinator (PI)
High Performance Data Network, 13.5 M€, 450 K€ at Bicocca
PRACE & ISCRA (160M core hours in the last 4 years)

International collaborations: CERN, DESY, Berna, Dublino, Edinburg, CLS (founding member),...

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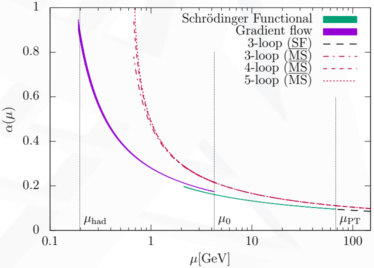
Coupling constant of Quantum Chromodynamics

Goal: Determining $\alpha_s(M_z^2)$ at 0.5% level from **first principles**

Motivation: fundamental parameter of Standard Model, crucial for LHC physics and to discover new phenomena

Key idea: Schrödinger Functional to relate non-perturbatively $\alpha_s(M_Z^2)$ to simple hadronic quantities (m_N, $f_\pi, \ldots$)

Status: Precision of 0.7% achieved. To be compared with the PdG World average $\alpha_s(M_Z^2) = 0.1181(11)$ (0.9%). Simulations running to reach 0.5%, the most precise determination of this fundamental constant



$\boldsymbol{\alpha_s(M_Z^2) = 0.1185(8)}$

Dalla Brida et. al. Phys. Rev. D95 (2017)
Dalla Brida et. al. Phys. Rev. Lett. 117 (2016)
Dalla Brida et. al. Phys. Rev. Lett. 119 (2017)
(Editor suggestion on home page of PRL)

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Thermal Quantum Chromodynamics

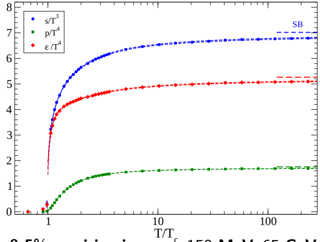
Goal: Non-perturbative determination of the Equation of State (EoS) of QCD from **first principles**, transport coefficients, topology (Axions),. . .

Motivation: particle physics, heavy ions, astrophysics

Key Idea: Simulating plasma in a moving reference frame. Computing entropy s, energy ε and pressure p highly simplified

Status: Running QCD with 3 flavours with T in the range 150 MeV-65 GeV (state of the art $T \leq 1.5$ GeV!)

Gauge sector (Tc=296 MeV)



0.5% precision in range 150 **MeV–65 GeV**

L. Giusti, M. Pepe Phys. Rev. Lett. 113 (2014)
L. Giusti, M. Pepe Phys. Rev. D91 (2015)
L. Giusti, M. Pepe Phys. Lett. B769 (2017)

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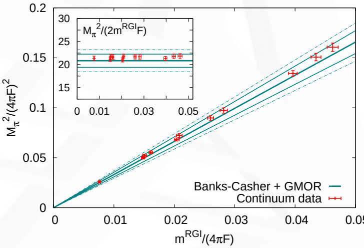
Spontaneous Symmetry breaking in QCD

Goal: Numerical proof of spontaneous symmetry breaking in QCD.
Explicit verification of GellMann-Oakes-Renner (GMOR) formula

$$f_\pi^2\, m_\pi^2 = (m_u + m_d)\langle q\bar{q}\rangle$$

Motivation: Theory, determination of light quark masses

Key Idea: Demonstration in QCD of renormalizability of spectral density of Dirac operator⇒ order parameter (condensate) computed by counting low modes of Dirac operator!



$[\Sigma^{\mathrm{RGI}}]^{1/3}/F = 2.77(2)(4)$

Status: Completed. Condensation of low modes proven, GMOR verified, chiral condensate with 1.5% precision. Best worldwide determination, see FLAG 2017.

L. Giusti, M. Lüscher JHEP 0903 (2009) 013
L. Giusti et al. Phys. Rev. Lett. 114 (2015)
(Editor suggestion on home page of PRL)
L. Giusti et al. Phys.Rev. D91 (2015)
(Editor suggestion on home page PRD)
Opening Plenary talk at Lattice 2015

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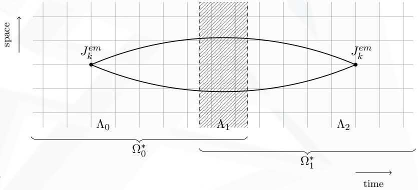
Muon anomalous magnetic moment

Goal: Computing from **first principles** the hadronic contribution to the muon anomalous magnetic moment a_μ with an overall precision (0.5%), 4 times better than state of the art

Motivation: Theory for a_μ deviates by $\sim 4\sigma$ from experiments. New E989 experiment at FNAL expected to release final results by 2021. By then a_μ may be the only observable deviating from its SM value by more than 5σ

Key Idea: A new paradigm in numerical lattice QCD: multi-level Monte Carlo integration in the presence of fermions (applicable to B semileptonic decays as well).



Dalla Brida, Giusti, Harris, Pepe in preparation
M. Cè et al., Phys.Rev. D95 (2017)
M. Cè et al., Phys.Rev. D93 (2016)
Plenary talk at Lattice 2017, opening session
2017 Sergio Fubini Prize for best Ph.D thesis

Status: R & D almost completed. Preparing for the first large scale simulation

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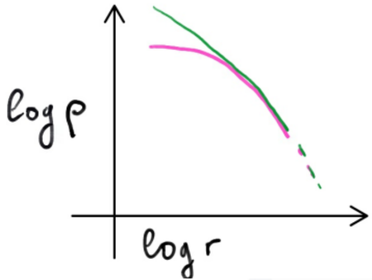
Numerical work on Structure Formation

- C. Destri, Cored density profiles in the DARKexp model, JCAP05(2018)010.
- C. Destri, Cored DARKexp systems with finite size:numerical results, JCAP05(2018)010.

Work on problem related to Dark Matter and structure formation;

- Problem: (quasi-)equilibrium states of relaxed DM halos
- Results: cores are favoured over cusps in the DARKexp model



- ρ is the mass density
- r is the distance from the center of the galaxy

String Theory

Proposed in the mid 80's as a theory containing everything we need (and more): gravity, gauge theories, chiral fermions.

Developed in unexpected directions:

- Duality:
  - Different theories related to each other by duality;
  - Strongly coupled systems dual to weakly coupled one: (can compute one for the other);
  - Quantum effects in one system corresponding to classical ones in the other
  - It can provide some insight in properties of QCD at low energy.
- AdS/CFT duality conjecture, (duality between theories in different space-time dimensions): a string theory in an Anti-de-Sitter space is dual to a Conformal Field Theory on its (flat) boundary. (the symmetry properties of the AdS space map into the conformal symmetry on the boundary).

AdS/CFT is an example of Holography.

Thermodynamics, Quantum Gravity and Holography

Mysterious connection between
Quantum Gravity, Thermodynamics, and the
Holographic principle (t'Hooft, Susskind): what happens inside a volume is determined by what happens on the boundary

Examples:

- Hawking's radiation from black holes:
  The black hole entropy is proportional to its surface, with the number of microstates $\propto R^2/l_p^2$ (l_p is the Planck length).
- Entropic (or emergent) gravity (Verlinde)
  emergent phenomenon arising from the quantum entanglement of bits of spacetime information living on a holographic boundary.

Verlinde's theory has implications for Dark Matter.
These are interesting speculations. But in the framework of string theories they can be scrutinized in simplified models.

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Our Group:

Not only strings. Also:
Strongly coupled field theory
from string inspired methods (duality, holography)
but also from:

- Localization: A technique to compute exactly the Path Integral of (supersymmetric) field theory.
- Integrability: exactly solvable theories.
- Bootstrap: techniques to formulate CFTs;
  Notice: field theories formulated without a Lagrangian.

Recent results of the group

Topic 1. Classification of conformal field theories (CFTs) in various spacetime dimensions

We recently found classification results for conformal theories in $d = 6$, which can also be used to generate new examples in $d = 4$

- CFTs arise in a number of physical systems near phase transition.
- Several CFTs are exactly solvable, yet non-trivial, toy models that can be used to study interesting physical systems
- Can be used to understand quantum gravity, such as microscopic descriptions of black holes, via the AdS/CFT correspondence

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Recent results of the group

Topic 2. Dualities between quantum field theories
We recently found a number of new dualities that lead to a better understanding of vacuum structures and operators of 3d CFTs

- Dualities can relate strongly coupled with weakly coupled systems, as well as quantum with classical phenomena.
- 3d CFT: solid state phenomena (in our case interest in relation to topological insulators).

Recent results of the group

Topic 3. The entropy of black holes
We recently solved the long-standing problem of explaining AdS black holes using quantum field theory (localization) and holography.

- Properties of black holes in string theories where studied before, but in (asymptotically) flat space (no holography).
- In AdS, the (weakly coupled) gravity solution is mapped to a strongly coupled CFT on the boundary, that we solve using localization.
- Explaining the microscopic origin of this entropy has become one of the fundamental quest in quantum gravity. Our work is a step in this direction.

Recent results of the group

Topic 4. Wilson loops, amplitudes, and integrability

- We recently contributed to unveil integrability in the AdS4/CFT3 version of the correspondence
- Using localization, we computed exactly physical quantities in CFT3, confirming AdS/CFT predictions
- We developed new localizing techniques to compute exactly physical quantities of 3d CFT theories with defects of interest for condensed matter.

Members of the group

Permanent members

Noppadol Mekareeya, Sara Pasquetti (ERC), Silvia Penati, Alessandro Tomasiello (ERC), Alberto Zaffaroni

Postdocs

Francesco Aprile	Vladimir Bashmakov	Kate Eckerle
Chiung Hwang	Andrea Mauri	Daniël Prins
Valentin Reys	Yegor Zenkevich	

PhD students

Francesco Azzurli	Stefano Baiguera	Lorenzo Coccia
G.Bruno De Luca	Ivan Garozzo	Carolina Gomez
Nicola Gorini	Andrea Legramandi	Gabriele Lo Monaco