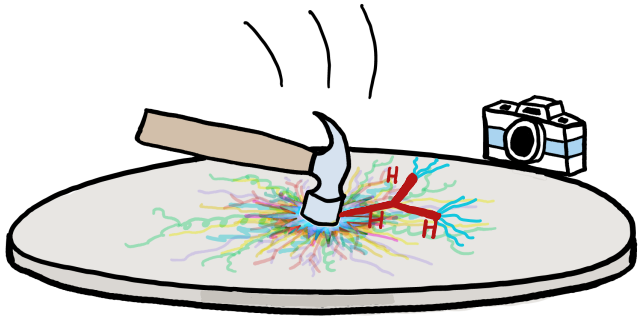
Theory Outlook

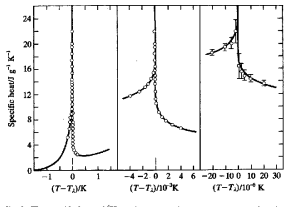
Ian Moult
Yale

Role of Theory

- Role of theory:
  - Determine the QFT describing a particular system.



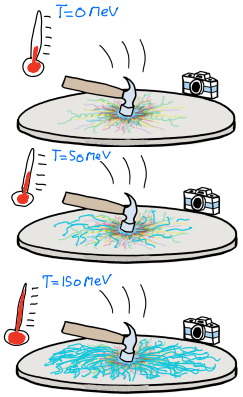
  - Extract the parameters of a QFT from measurements.

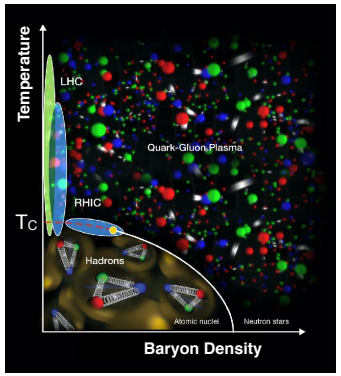


$$C \sim \left|1 - \frac{T}{T_c}\right|^{\alpha}$$

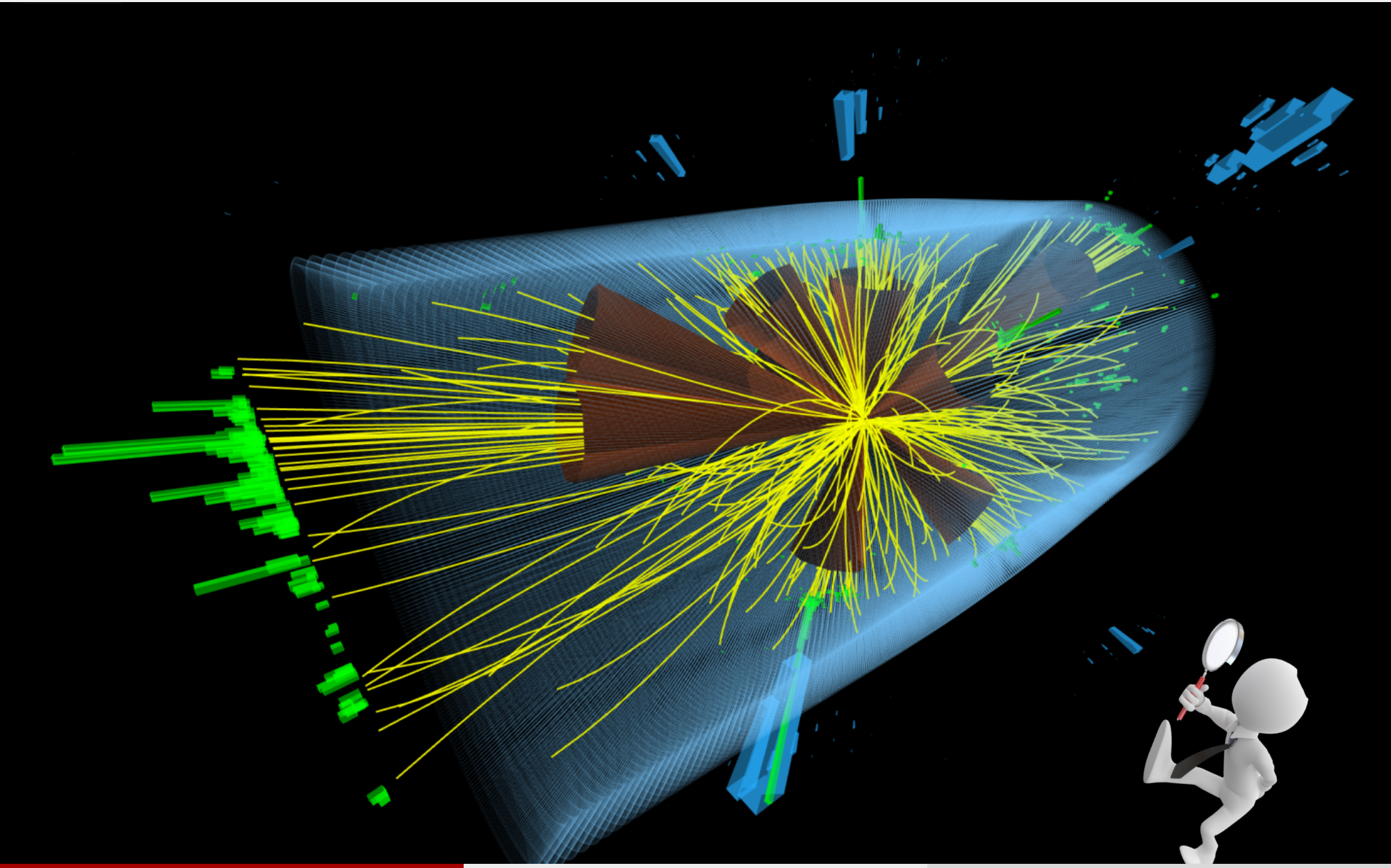
$$\alpha = 0.0127(3)$$

  - Understand the dynamics of a specific QFT (e.g. QCD).



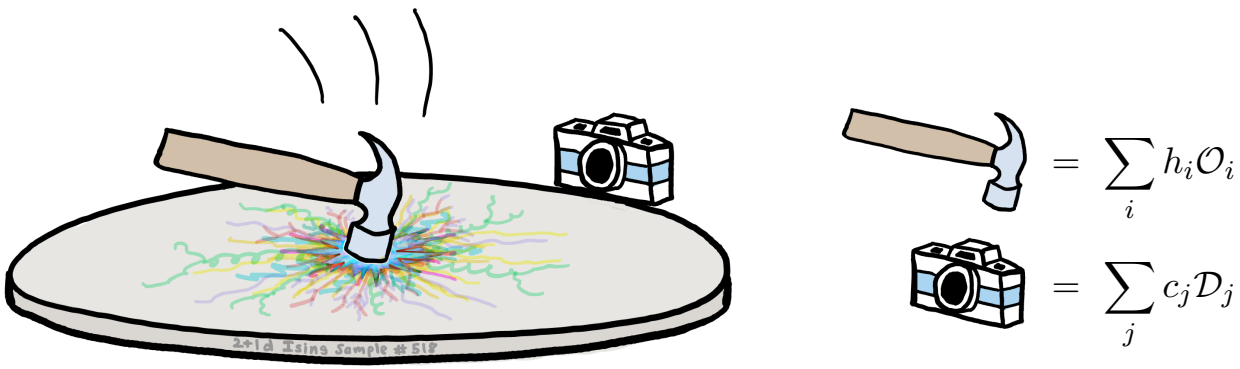


The Particular System We Have Chosen to Study:



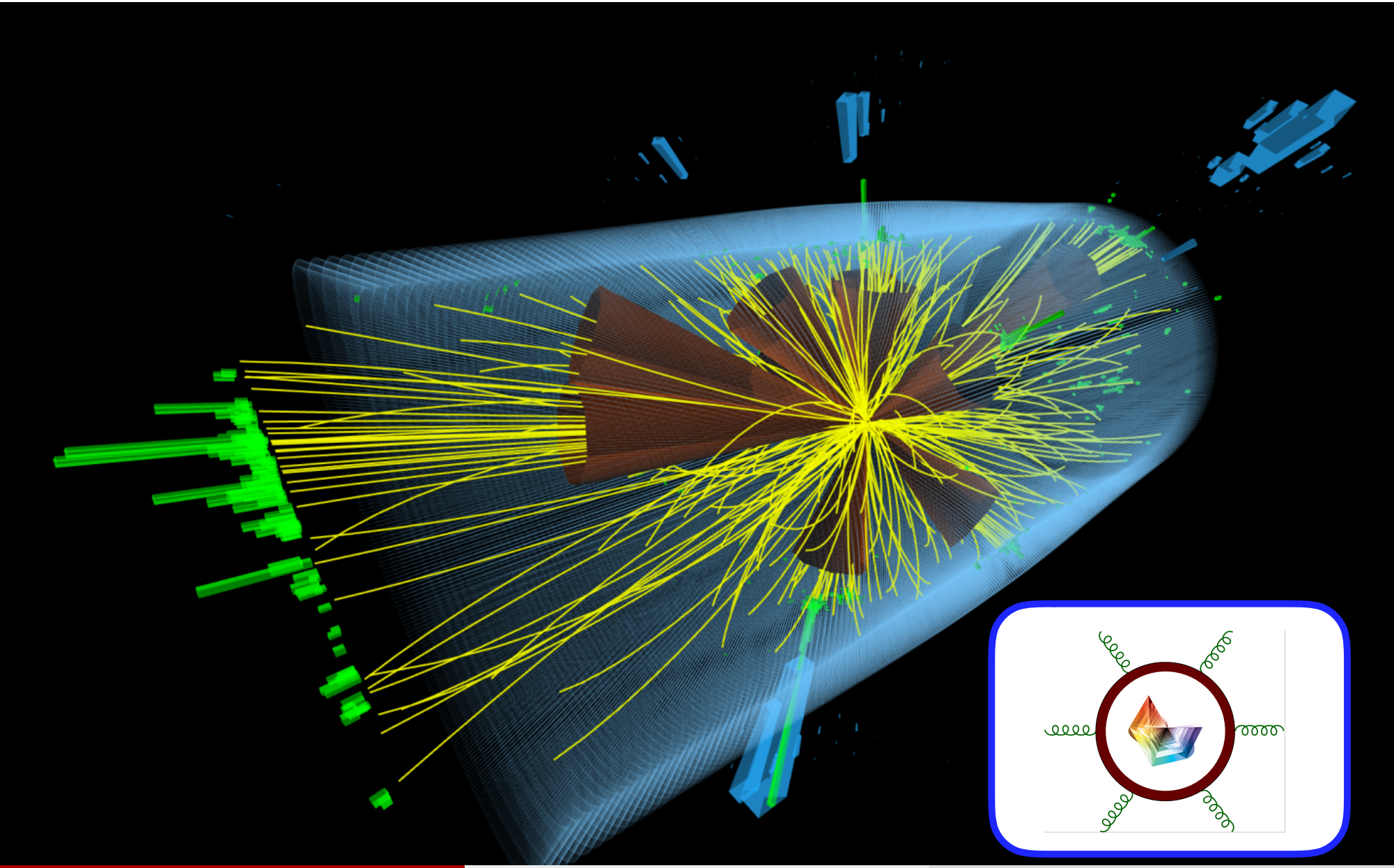
Jet Substructure

- What is the theoretical question we are trying to ask in Jet Substructure?
  "How do we characterize a quantum mechanical system using only asymptotic measurements?"



- This has proven to be a fruitful lens through which to study general aspects of QFT.
- Still have basic conceptual questions to understand.

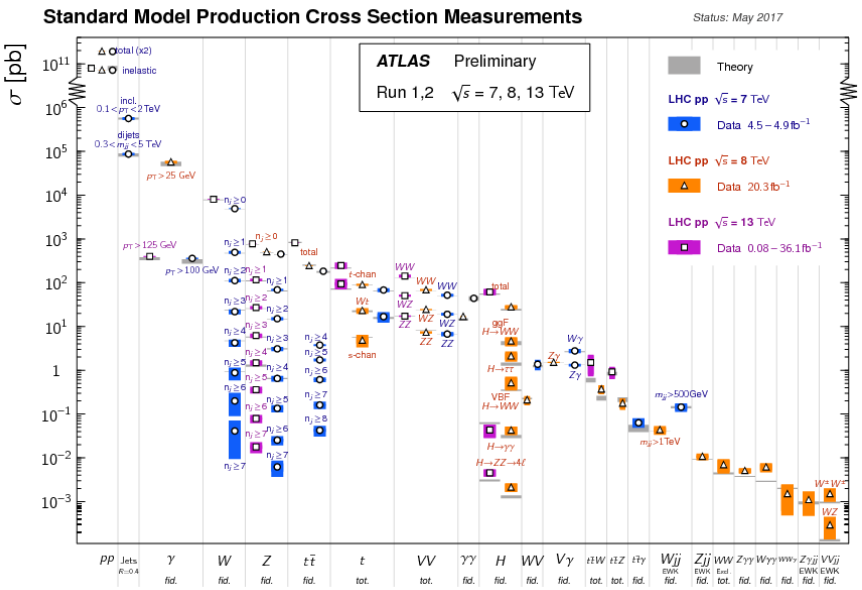
Jets!

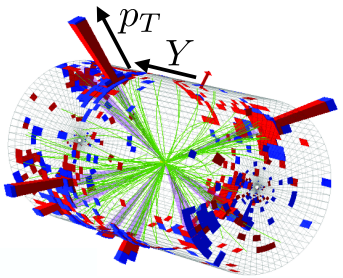


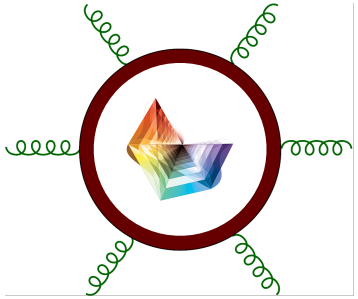
Amplitudes

- Obtaining a precise description of jet cross sections has been a significant driver of theory developments in Quantum Field Theory.

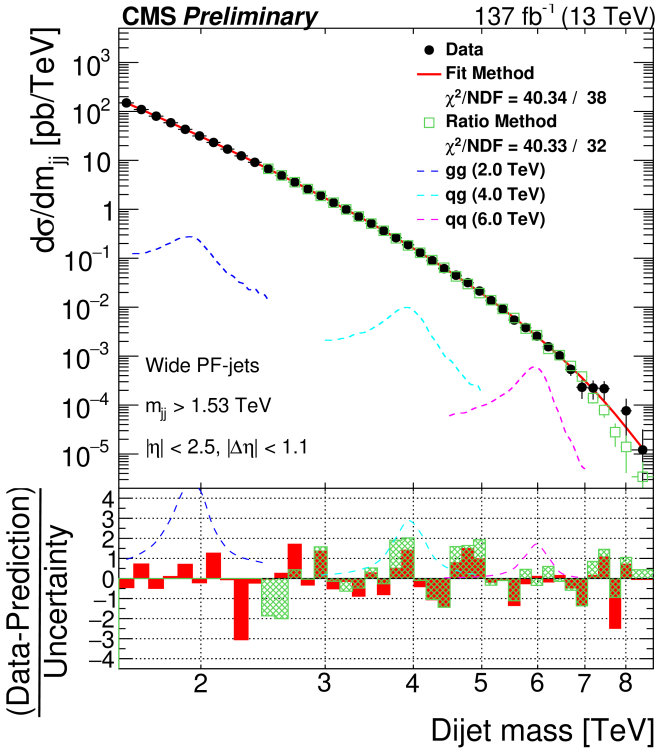
Jet Kinematic Distributions





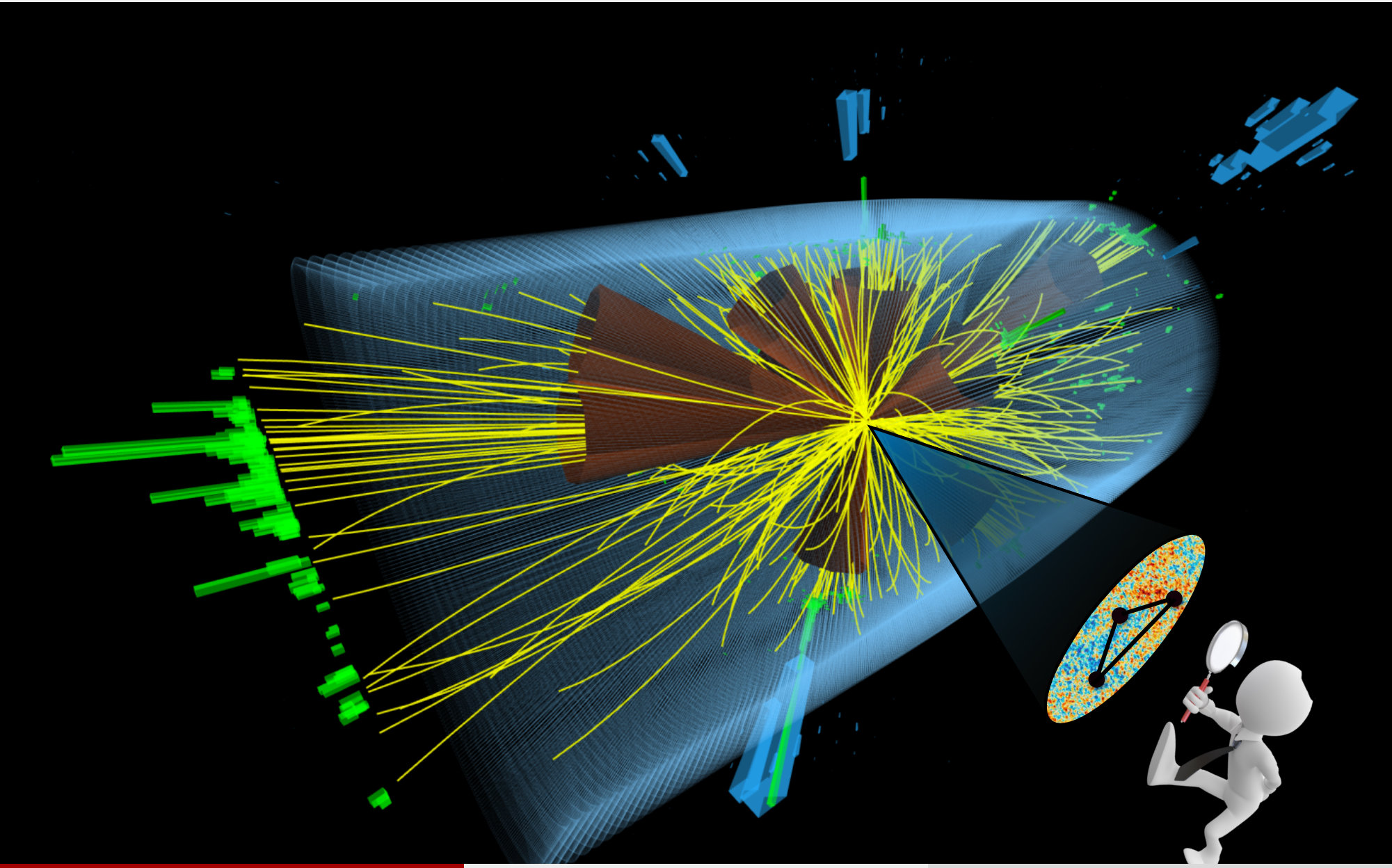


Dijet Mass



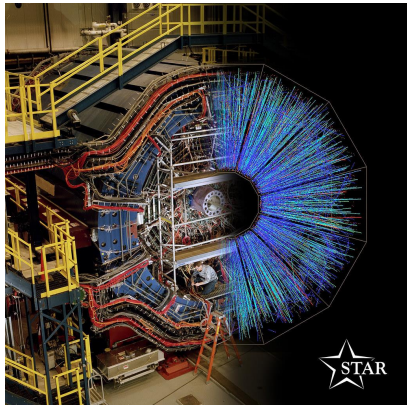
- Enables precision tests of QCD and searches for new physics.

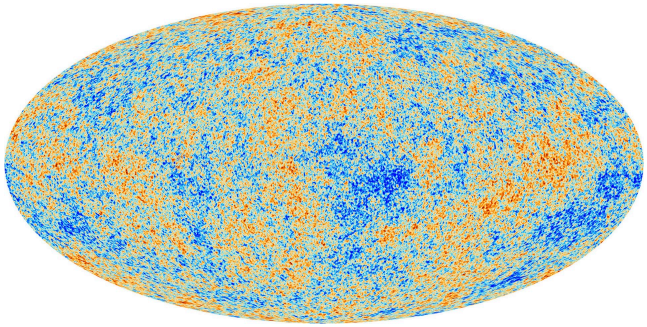
Jet Substructure!

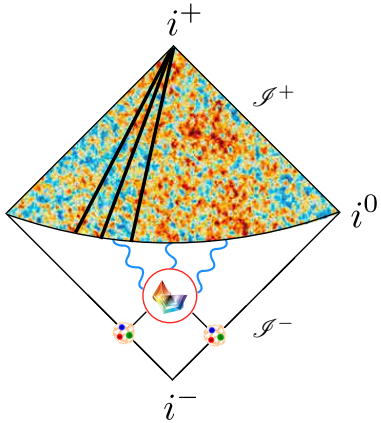


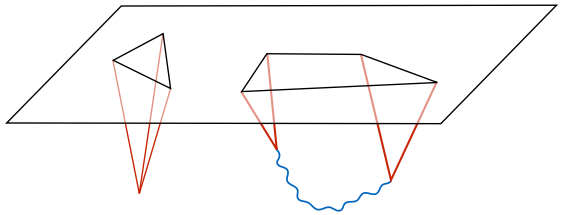
Decoding Energy Flux

- Requires development of field theoretic techniques to interpret subtle correlations in terms of the dynamics of the underlying field theory.





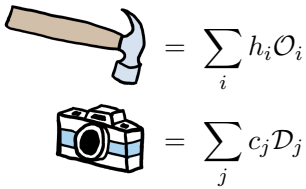




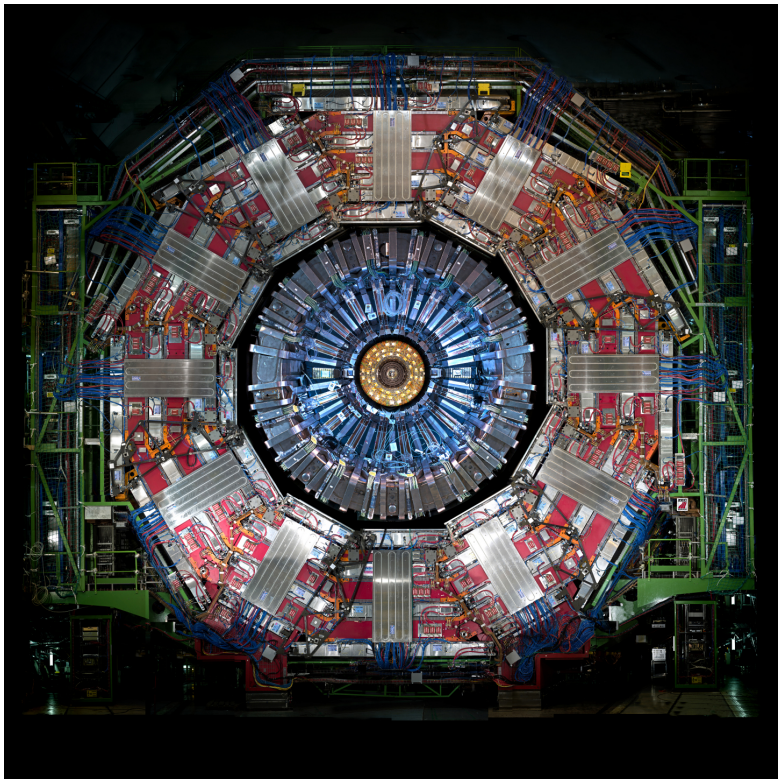
- Hope that the study of these questions combined with experimental data will lead to improved understanding of QFT.

Defining the Problem

- What is a detector?
- What correlators can measure?



[Caron Huot, Kologlu, Kravchuk, Meltzer, Simmons Duffin]



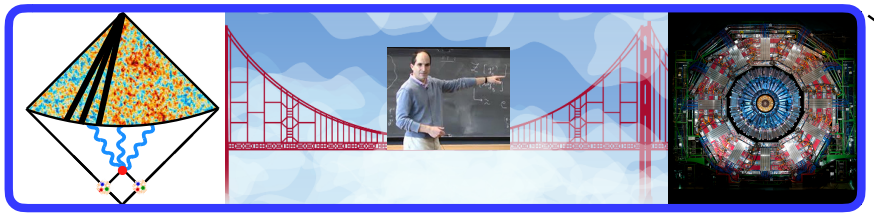
$$\langle \Psi | \mathcal{E}(\hat{n}_1) \cdots \mathcal{E}(\hat{n}_k) | \Psi \rangle$$

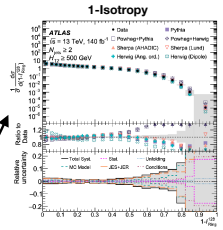
- To the rescue of JSS (Tkachov, Korchemsky, Sterman, Hofman, Maldacena)
- In our specific case:

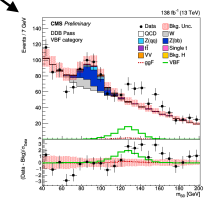
$$\longleftrightarrow \quad \mathcal{E}(\vec{n}) = \lim_{r\to\infty} r^2 \int_0^\infty dt \; n^i T_{0i}(t, r\vec{n})$$

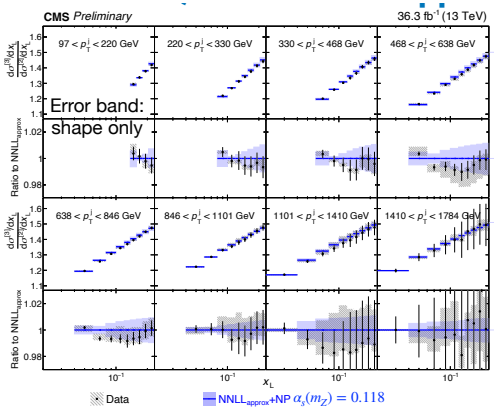
Finally....

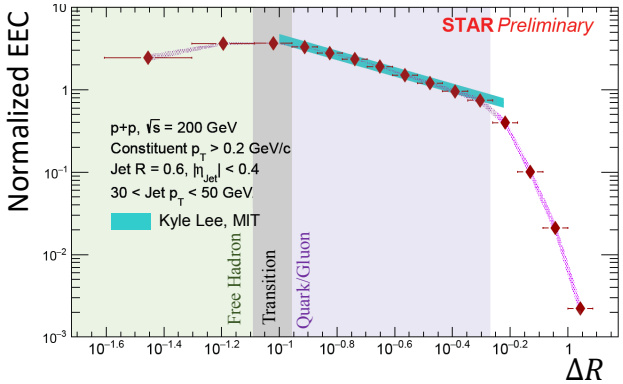
- A milestone in connecting jet substructure with QFT.
- Direct measurement of the underlying correlators.

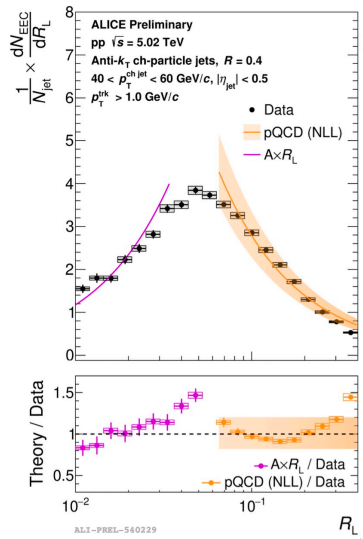








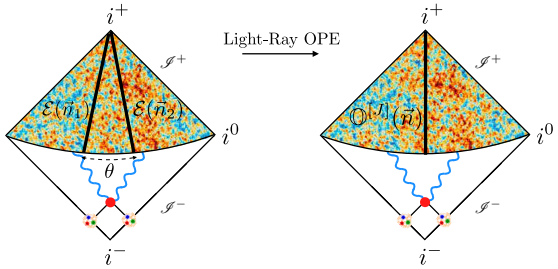




- We have learned how to do Jet Substructure in the proper language of QFT!

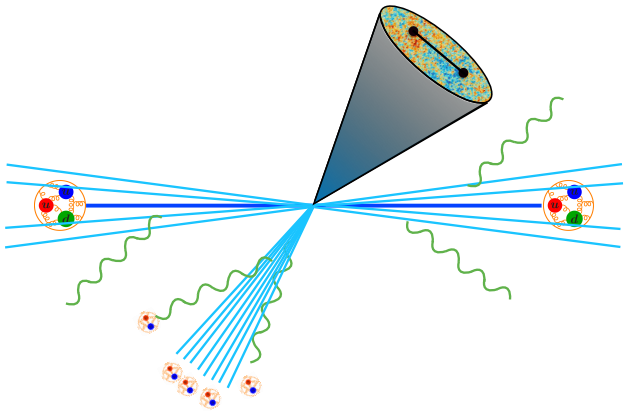
Connecting Theory and Experiment

- A beautiful example of combining progress in QFT with progress in experiment to learn something about the real world.

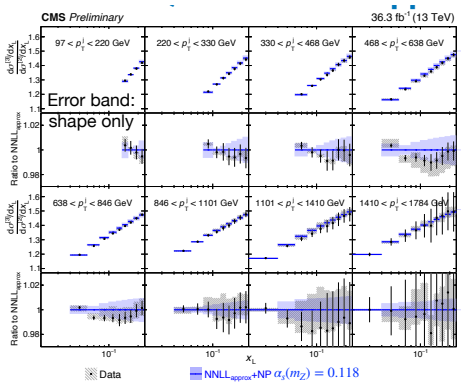


$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4}\mathbb{O}_i(\hat{n}_1)$$

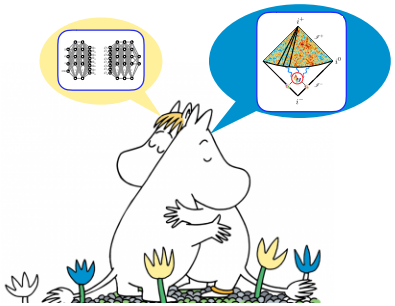
Understand Generic Field Theory Phenomena



Learn to calculate in a specific theory (QCD)



Measure to extract parameter and learn about the Real World



$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

$$= 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$$

- New ways of thinking

  $\Longrightarrow$ most precise α_s extraction from JSS. Lets make it even better!

- Congratulations to CMS for this spectacular achievement!

Connecting Fields

- Provides a direct connection between recent developments in formal field theory and real world collider physics!
- Jet substructure measurements have motivated formal theory studies.

Snowmass White Paper:
The Analytic Conformal Bootstrap

Thomas Hartman,[1] Dalimil Mazáč,[2] David Simmons-Duffin,[3] Alexander Zhiboedov[4]

Remarkably, the machinery of the OPE [49, 65, 71, 72] and crossing equations [24, 25] can be generalized to light-ray operators in a nontrivial way. The light-ray OPE has interesting applications in the study of jet substructure in QCD [73, 74]. Developing a better understanding of the space of light-ray operators and associativity of the light-ray OPE is an important open problem in our quest for understanding nonperturbative Lorentzian dynamics of CFTs.

arXiv:2306.14330v1 [hep-th] 25 Jun 2023

Energy correlations in heavy states

Dmitry Chicherin[a], Gregory P. Korchemsky[b,c], Emery Sokatchev[a], and Alexander Zhiboedov[d]

[a] *LAPTh-CNRS-USMB, 9 chemin de Bellevue, 74940, Annecy, France*
[b] *Institut de Physique Théorique[1], Université Paris Saclay, CNRS, F-91191 Gif-sur-Yvette, France*
[c] *Institut des Hautes Études Scientifiques, 91440 Bures-sur-Yvette, France*
[d] *CERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland*

Abstract: We study energy correlations in states created by a heavy operator acting on the vacuum in a conformal field theory. We argue that the energy correlations in such states exhibit two characteristic regimes as functions of the angular separations between the calorimeters: power-like growth at small angles described by the light-ray OPE and slowly varying, or "flat", function at larger angles. The transition between the two regimes is controlled by the scaling dimension of the heavy operator and the dynamics of the theory. We analyze this phenomenon in detail in the planar $\mathcal{N} = 4$ SYM theory both at weak and strong coupling. An analogous transition was previously observed in QCD in the measurement of the angular energy distribution of particles belonging to the same energetic jet. In that case it corresponds to the transition from the light-ray OPE, perturbative regime described in terms of correlations between quarks and gluons to the flat, non-perturbative regime described in terms of correlations between hadrons.

- Jet substructure "exists" in the formal theory world! Progress!

Finally...

- What was going on in the year the energy correlators were proposed...

Abstract

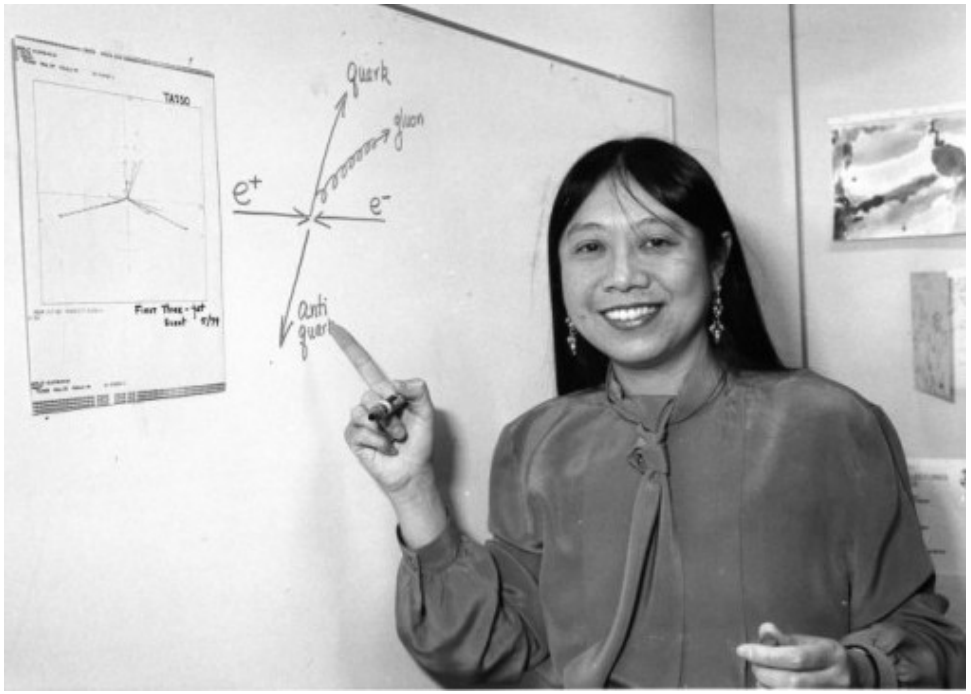
The possible role of gluons in hadronic processes as suggested by the quark-parton model and QCD is discussed and evaluated.

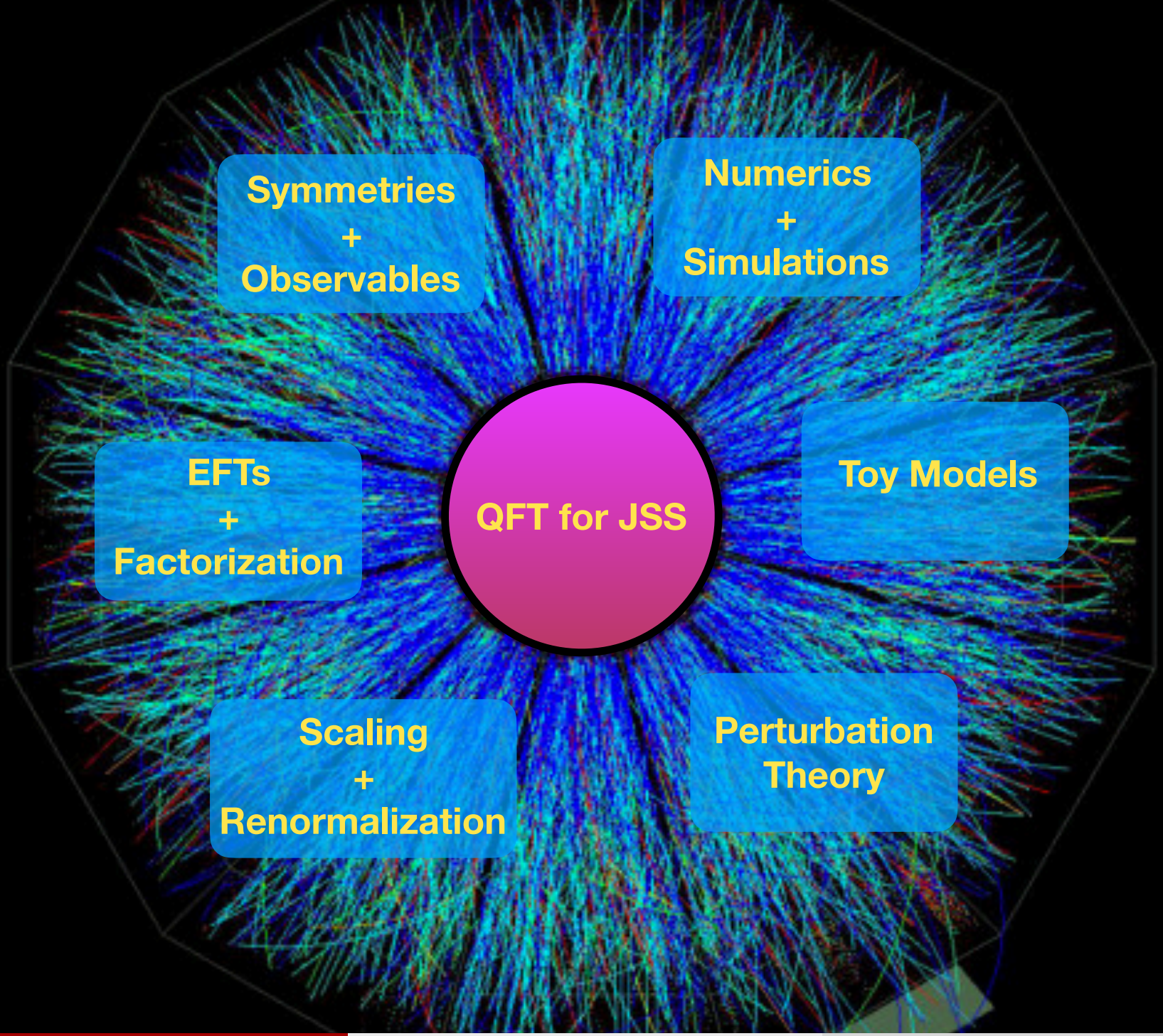
Introduction

The most dramatic and encouraging development in Strong Interaction physics in the past few years has been the emergence of a candidate field theory to describe these interactions. This situation is in sharp contrast to that which obtained ten years ago when, at least at one well known institution of higher learning, it was "taught" that field theory was irrelevant to Strong Interactions[1].

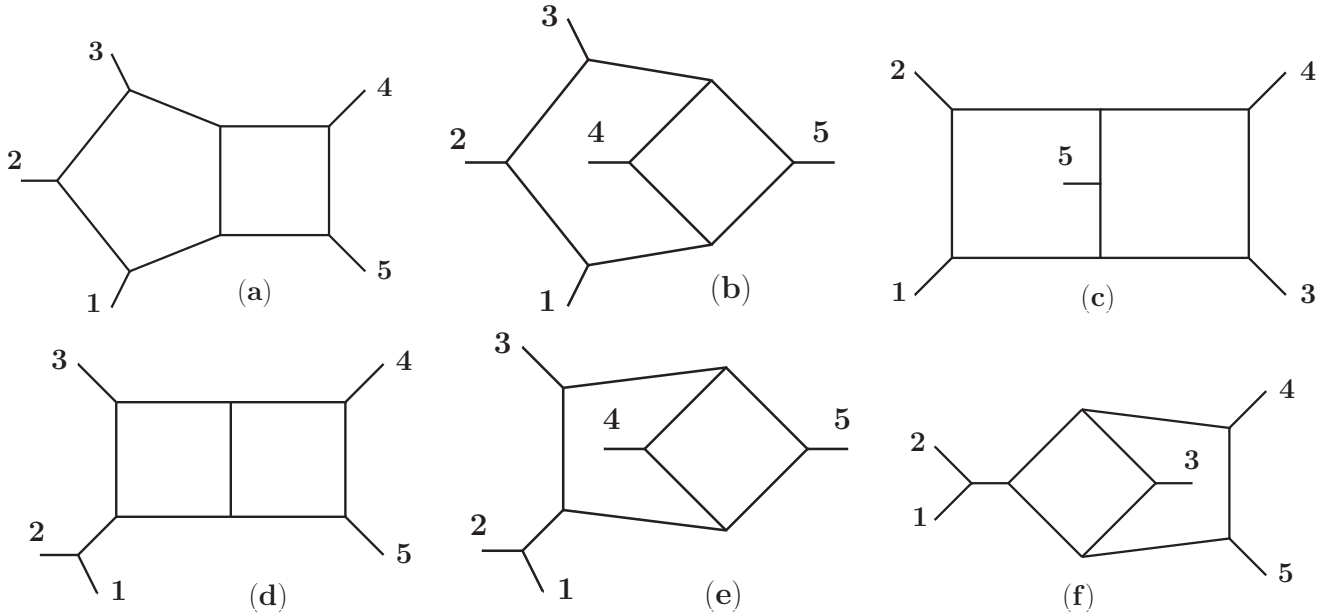
Footnote and References

1) Recollections of a Caltech graduate student, S. D. Ellis, unpublishable.




Symmetries
+
Observables
Numerics
+
Simulations
EFTs
+
Factorization
QFT for JSS
Toy Models
Scaling
+
Renormalization
Perturbation
Theory

Perturbation Theory



50 Years of Perturbative QCD

- At high energies, QCD admits a perturbative expansion in terms of interacting quarks and gluons.

RENORMALIZABLE LAGRANGIANS FOR MASSIVE YANG-MILLS FIELDS

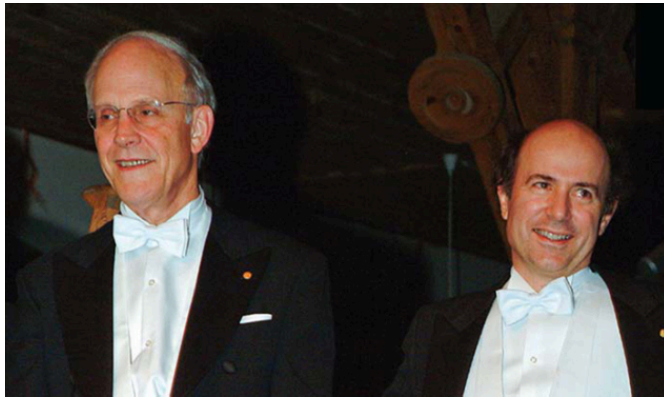
G.'t HOOFT
Institute for Theoretical Physics, University of Utrecht

Received 13 July 1971

Abstract: Renormalizable models are constructed in which local gauge invariance is broken spontaneously. Feynman rules and Ward identities can be found by means of a path integral method, and they can be checked by algebra. In one of these models, which is studied in more detail, local SU(2) is broken in such a way that local U(1) remains as a symmetry. A renormalizable and unitary theory results, with photons, charged massive vector particles, and additional neutral scalar particles. It has three independent parameters.

Another model has local SU(2)⊗U(1) as a symmetry and may serve as a renormalizable theory for ρ-mesons and photons.

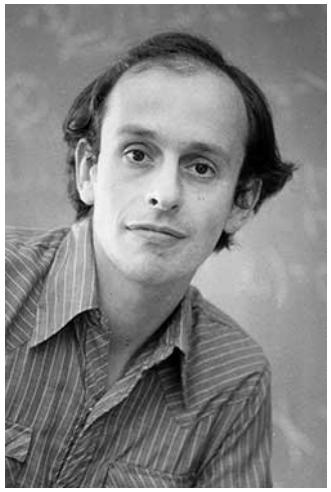
In such models electromagnetic mass-differences are finite and can be calculated in perturbation theory.



Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field–theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.



Reliable Perturbative Results for Strong Interactions?*

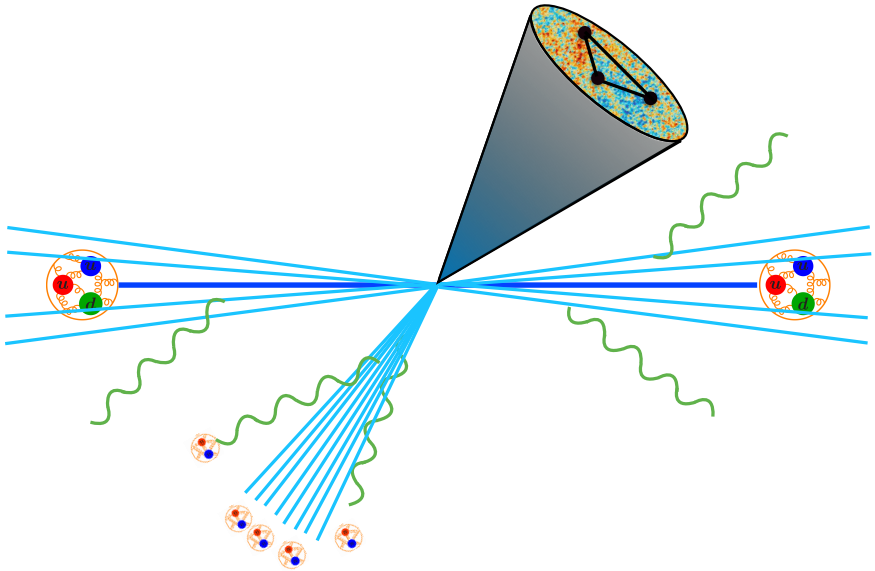
H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

- The study of perturbative QCD has progressed tremendously in the last 50 years.

Importance for Jet Substructure

- How do perturbative calculations help jet substructure? They enable an increasingly precise description of the *state* on which jet substructure observables are measured.
  1. Global state of the LHC collision.
  2. Internal structure of the Jet.



$$\langle \Psi | \mathcal{E}(\hat{n}_1) \cdots \mathcal{E}(\hat{n}_k) | \Psi \rangle$$

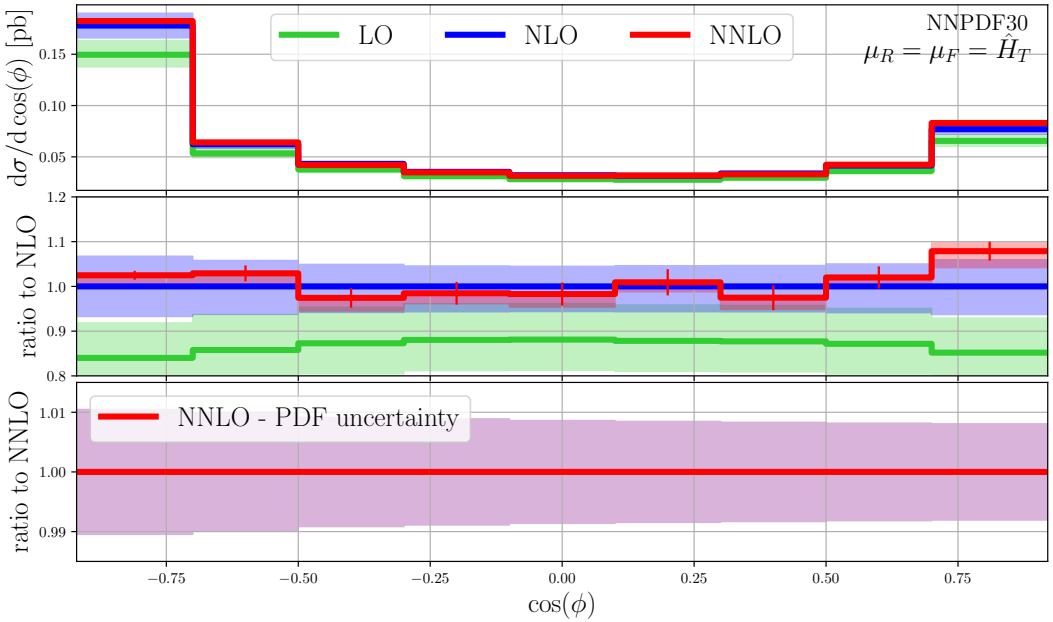
Three Jet Production at NNLO

- NNLO calculations of three-jet production are now available!

Tour de force in Quantum Chromodynamics:
A first next-to-next-to-leading order study of three-jet production at the LHC

Michał Czakon
Institut für Theoretische Teilchenphysik und Kosmologie,
RWTH Aachen University, D-52056 Aachen, Germany

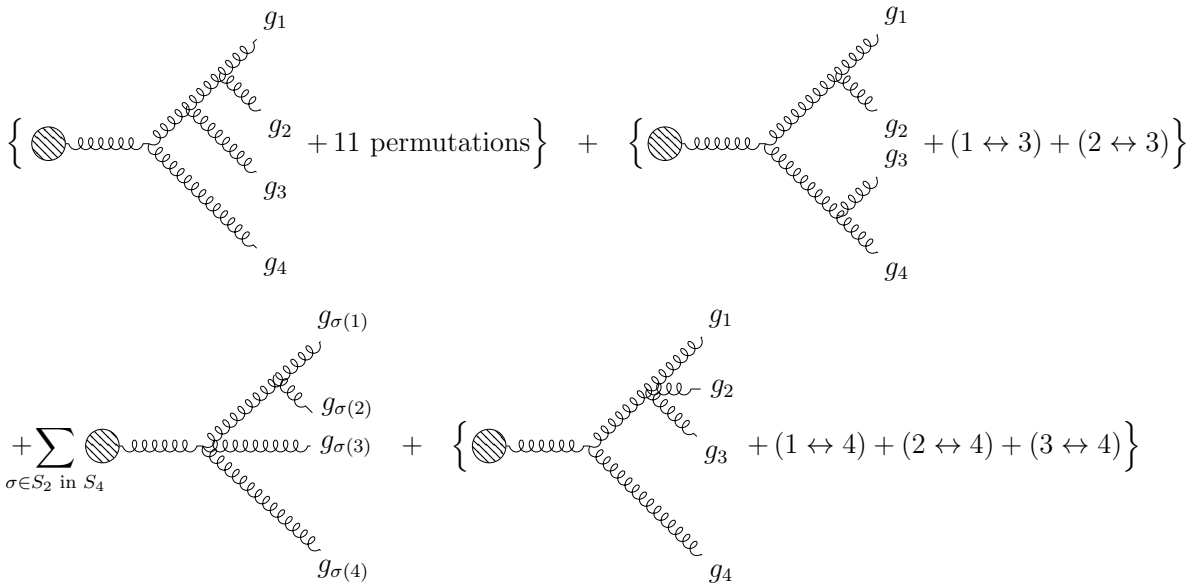
Alexander Mitov and Rene Poncelet
Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK
(Dated: August 30, 2022)



- Enables NNLO JSS. We need to have the corresponding ingredients ready on the JSS side.

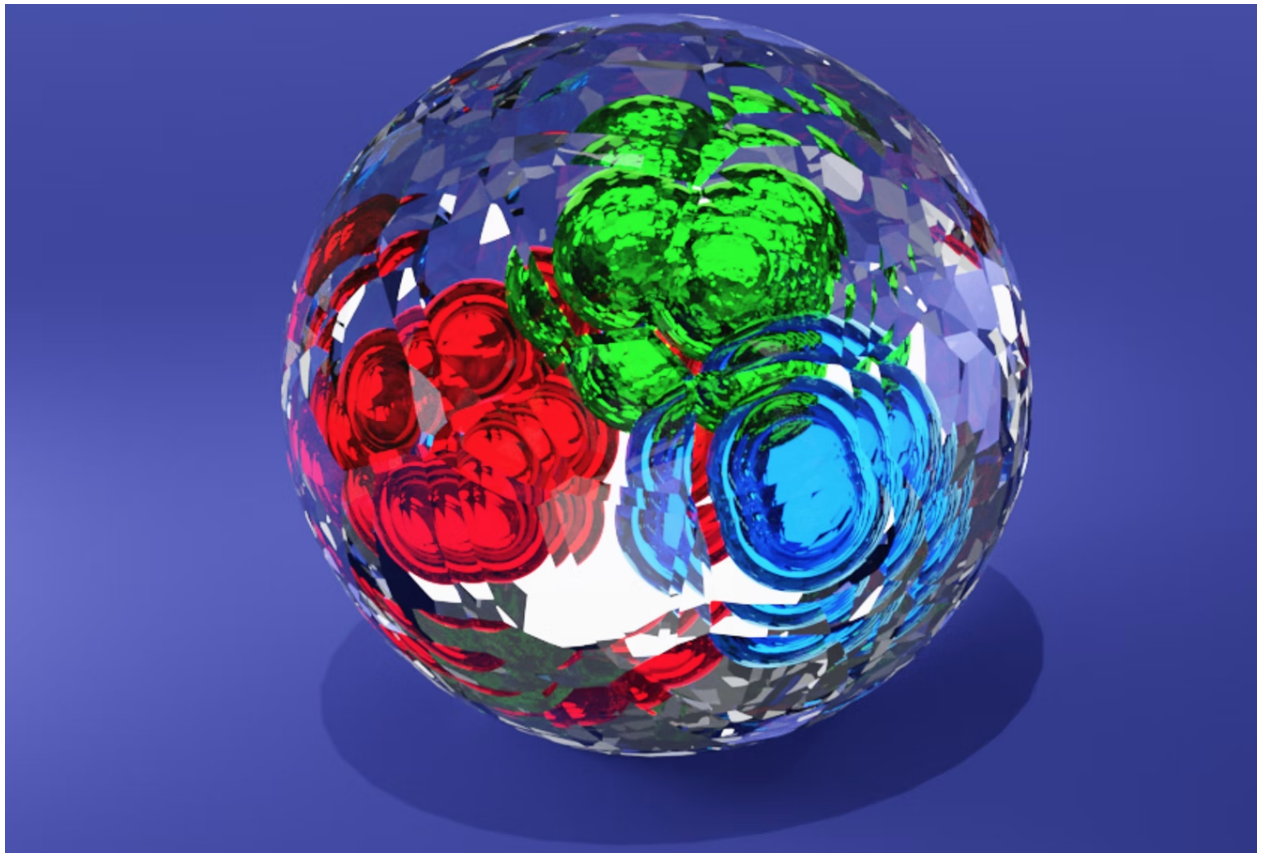
$1 \to 4$ Splitting Functions

- $1 \to 3$ splitting functions basis of modern jet substructure calculations.
- $1 \to 4$ splitting functions computed by Del Duca, Duhr, Haindl, Lazopoulos, Michel.



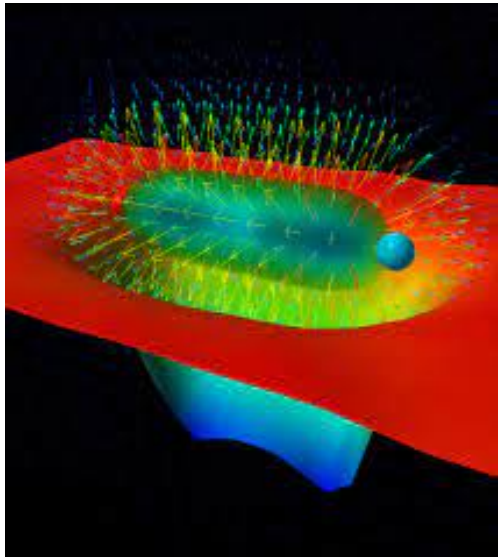
- Will push the boundary of the description of the internal structure of jets.

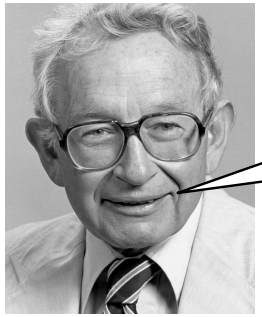
The Strong Coupling Regime

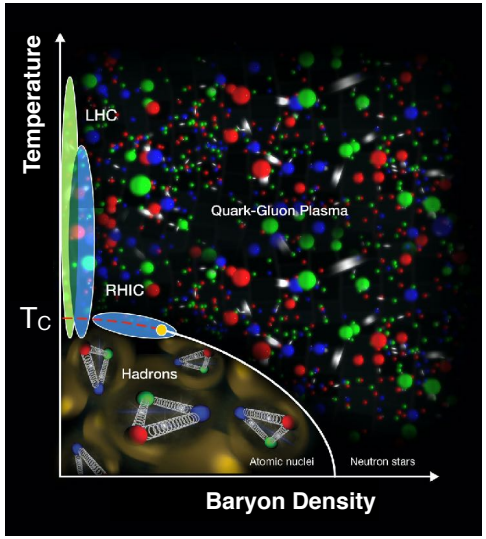


Role of Experiment

- "The purpose of experiments is to test the theory, or discover new phenomena that cannot be explained by existing theories, but if the theory is already a strictly solvable model, then there is no need to test it" -Yale Condensed Matter Faculty
- The dynamics of four dimensional gauge theories are rich and unexplored: expect new phenomena that theorists did not anticipate!

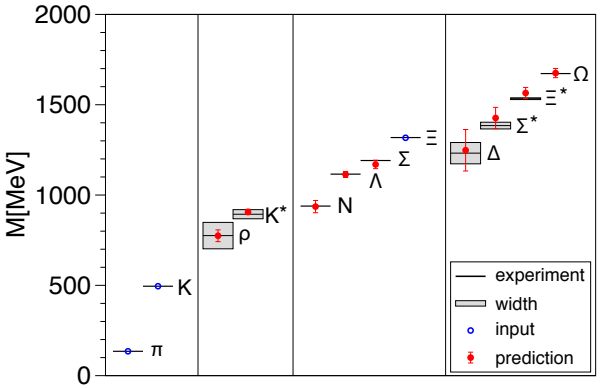


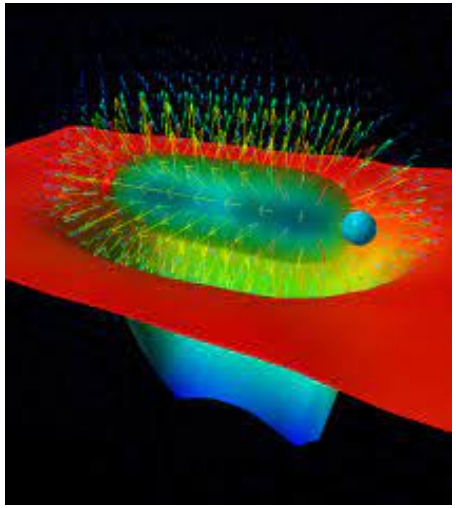


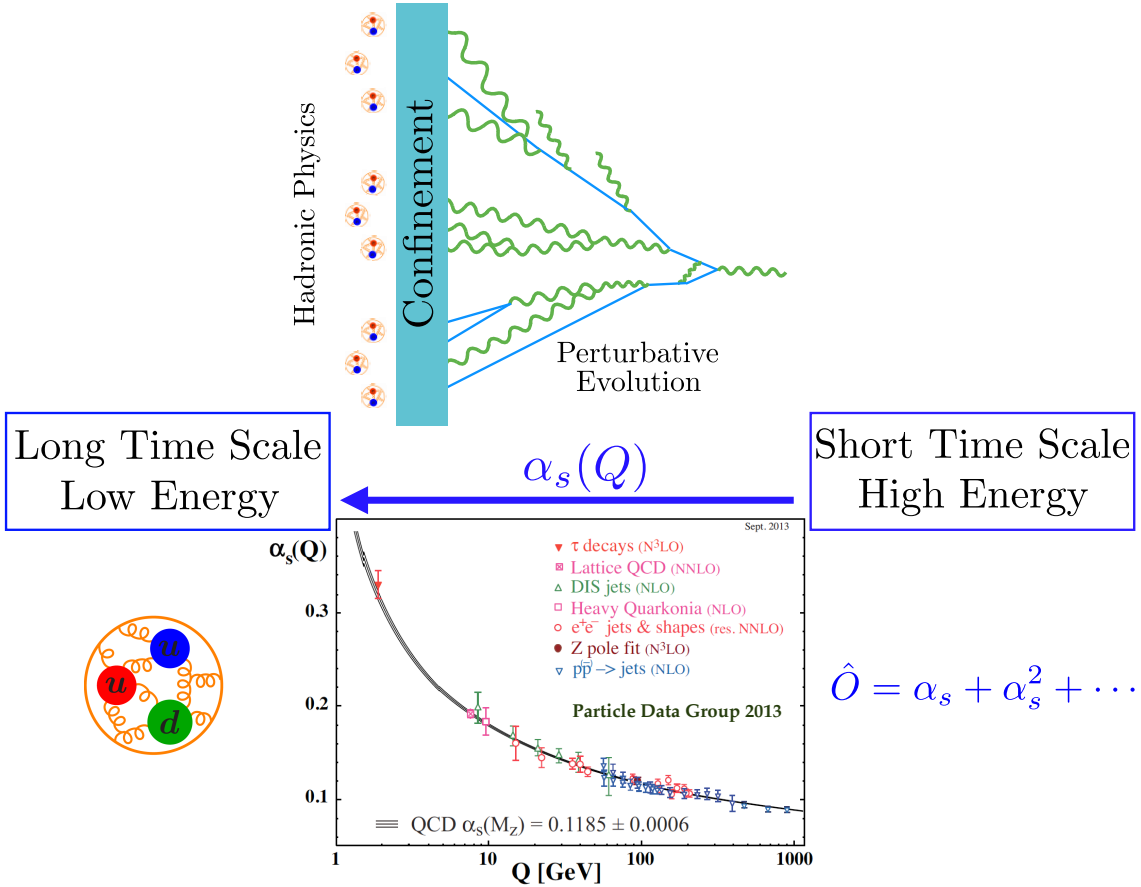


Dynamics of Hadronization

- What are the dynamics of the hadronization process?





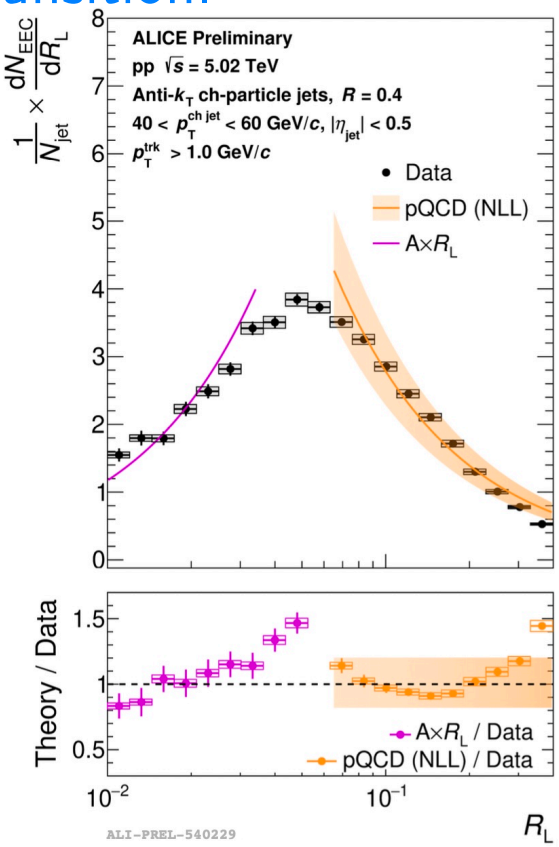


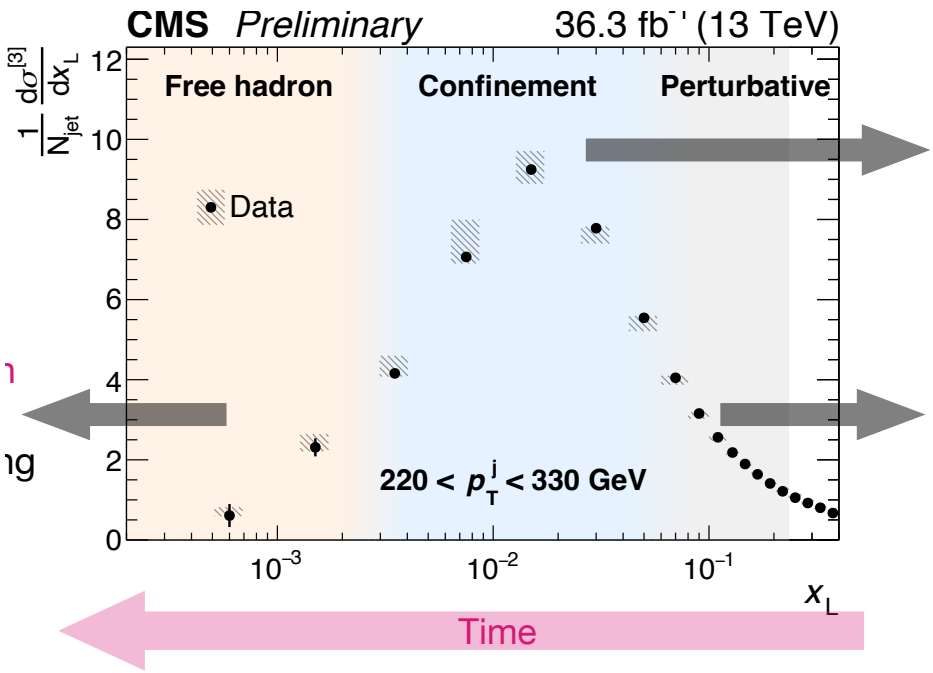
$$\hat{O} = \alpha_s + \alpha_s^2 + \cdots$$

- Can JSS contribute to the Simons Confinement Collaboration?

The Confinement Transition

- Beautiful recent measurements allow "imaging" of the confinement transition.

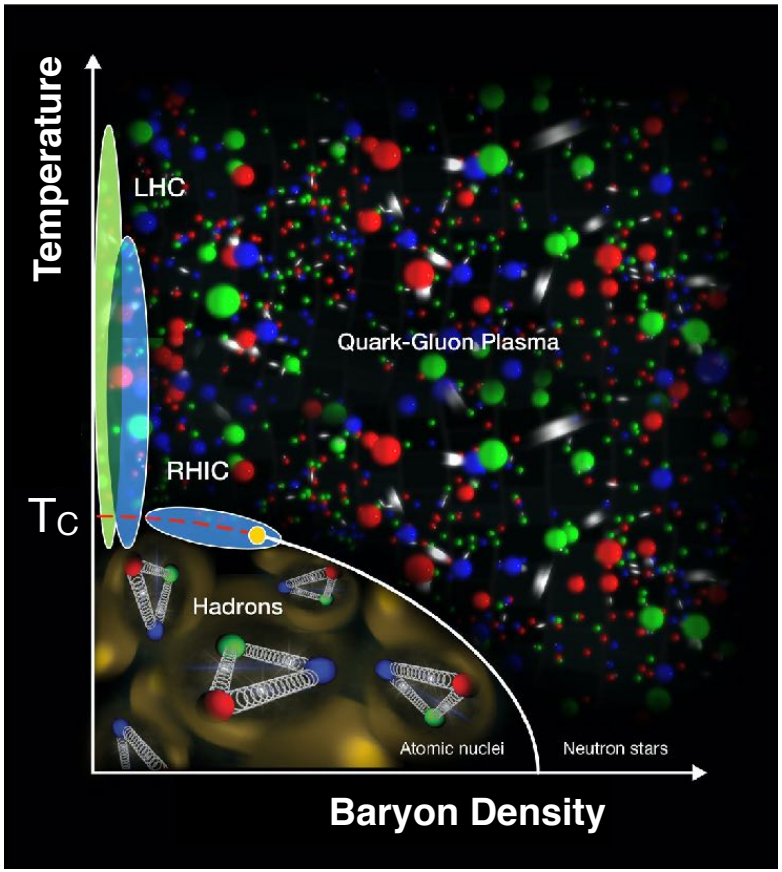


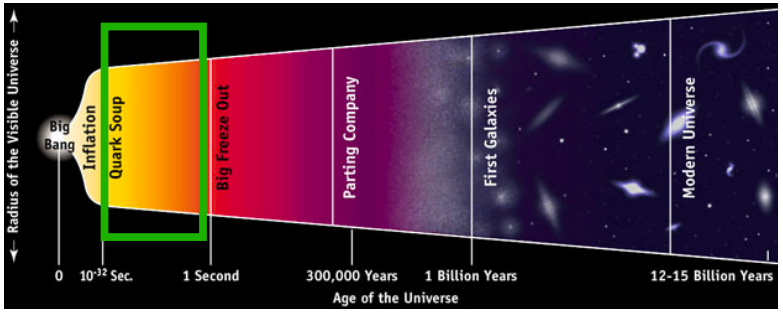


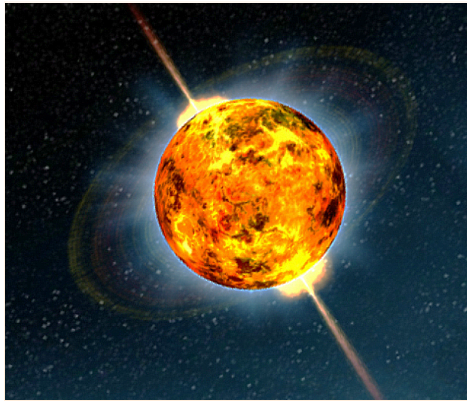
- Will be very interesting to measure in broader settings and interpret theoretically.

Extreme States of QCD Matter

- What are the phases of QCD matter?



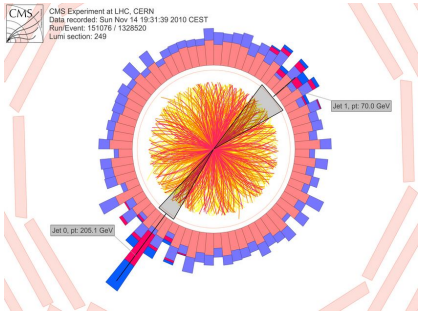


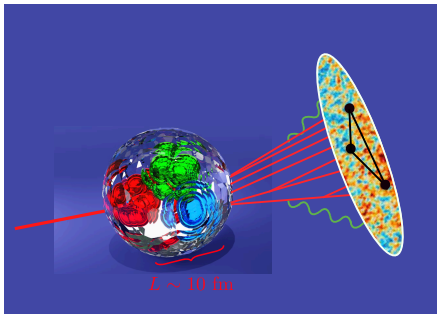


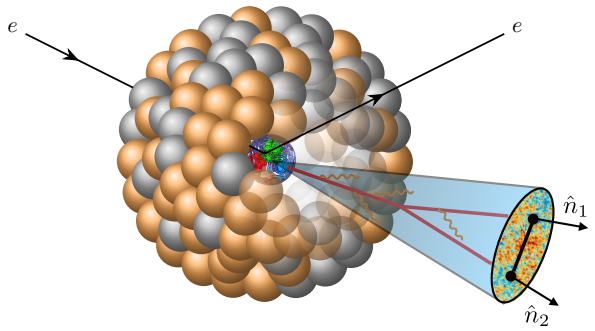
- Required to understand the dynamics of the early universe and the collisions of neutron stars.

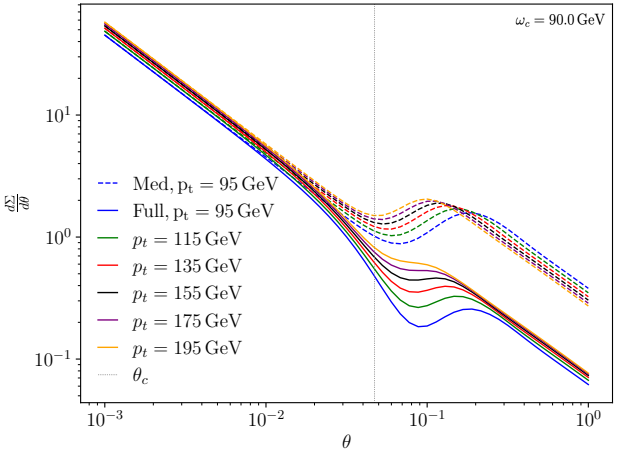
Dense and Hot QCD Matter

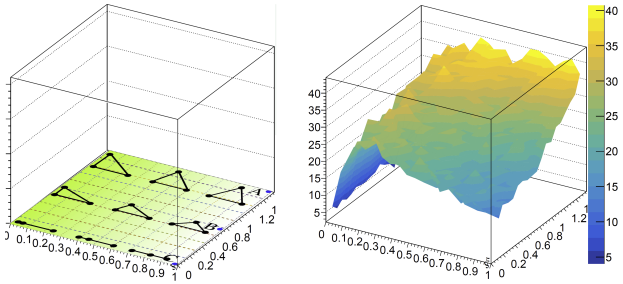
- Sharper connection between observables and field theory will facilitate measurements of hot and cold nuclear matter





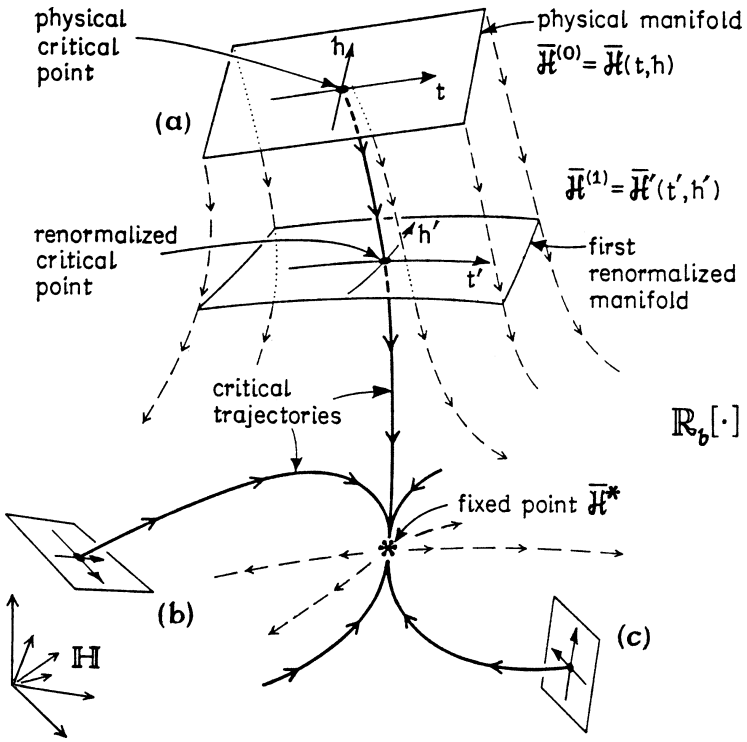






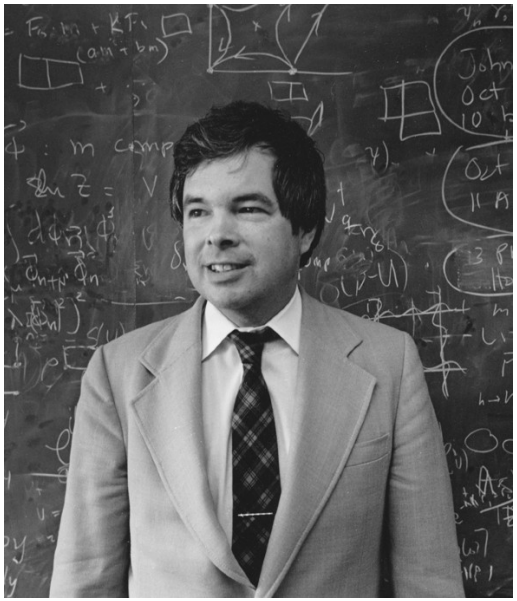
- Requires significant developments in our understanding of field theory at finite temperature and density.

Scaling and the Renormalization Group



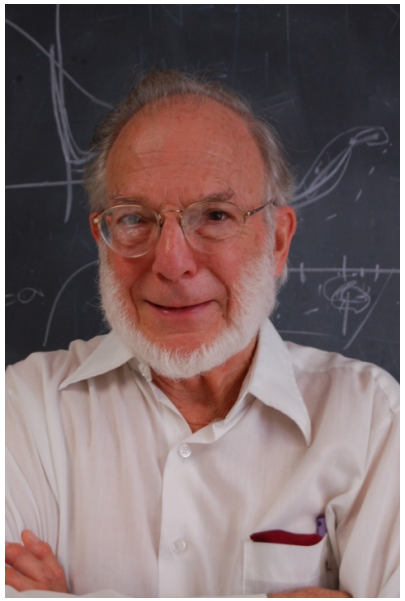
50 Years of the RG

- It is also the 50th Anniversary of the Renormalization Group:
  - Provides an organizing principle behind Quantum Field Theory
  - Provides a rare glimpse beyond perturbation theory.



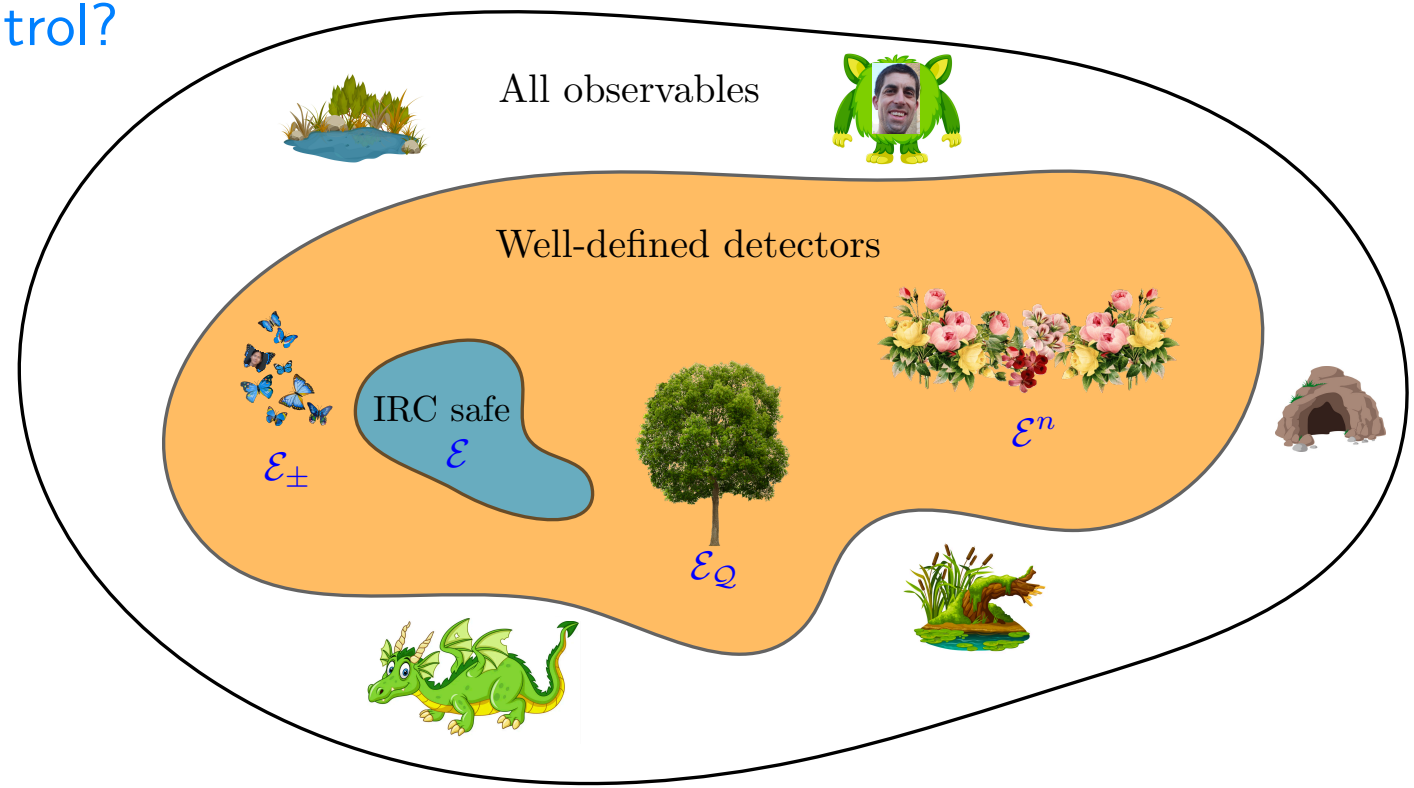
Renormalization Group and Strong Interactions

Kenneth G. Wilson
Phys. Rev. D **3**, 1818 – Published 15 April 1971



The Space of Detectors

- RG allows us to study the scale evolution of non-perturbative parameters controlling the hadronization process
- What is the space of detectors over which we can gain theoretical control?

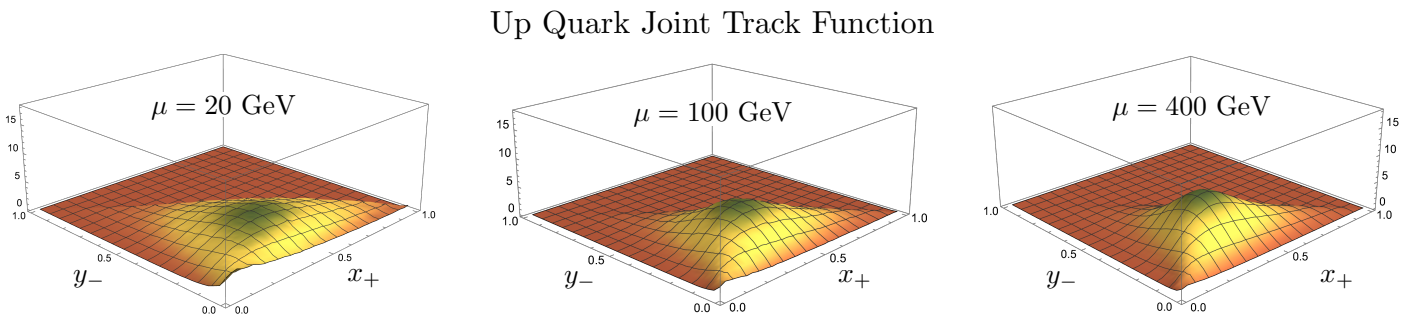


*Also a good metaphor for the conference atmosphere.

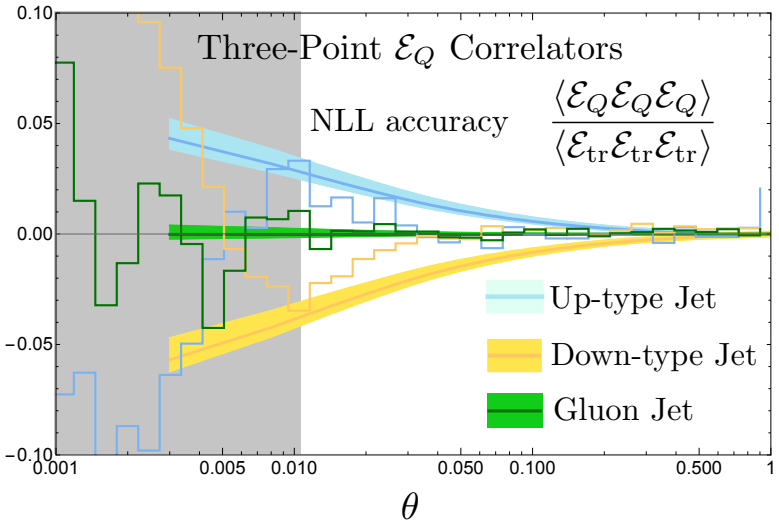
Lets make BOOST more welcoming for first time student speakers!

Deeper into the Parton → Hadron Transition

- Can study the parton → hadron transition by combining the factorization into universal matrix elements with the RG.
- Enables the calculation of the scale dependence of correlations in the hadronization process.

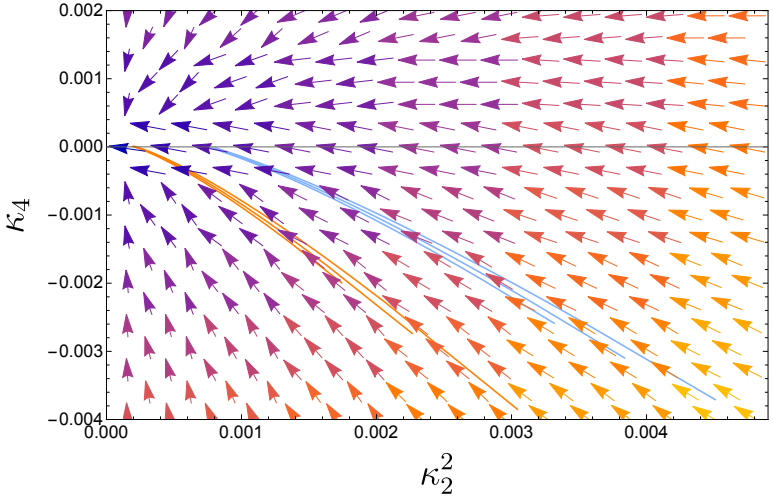


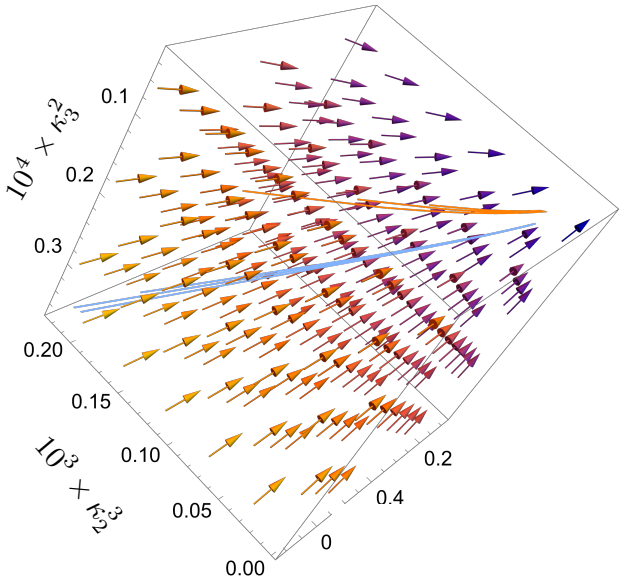
- How far can this be pushed?

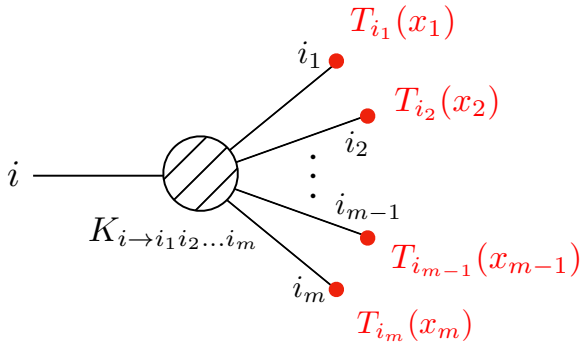


RG Flows in Jets

- Significant recent technical progress in describing non-linear RGs going beyond DGLAP.
- Can be directly measured using moments of track functions in high energy jets.

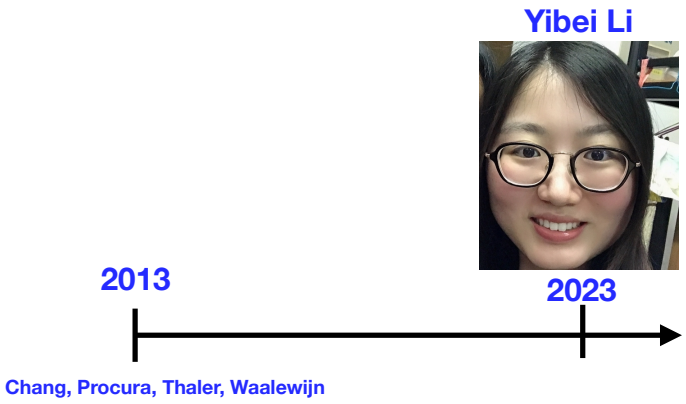


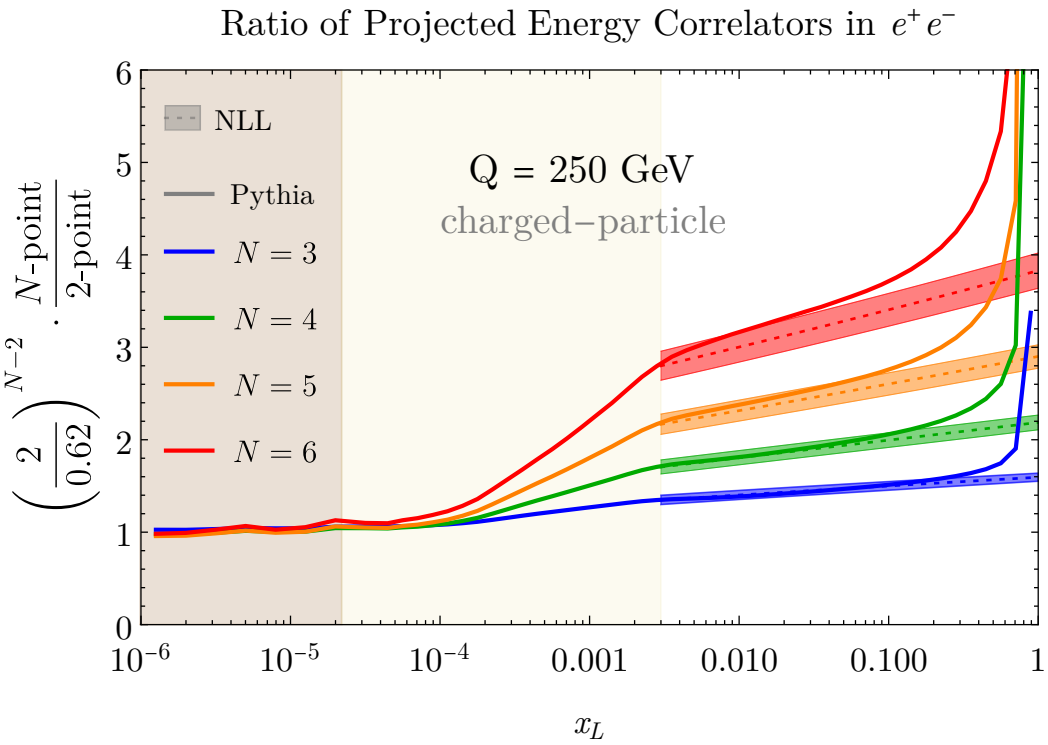




Track Based Jet Substructure

- Improved understanding of RG enables precision jet substructure on tracks (NLL collinear).
- Jet Substructure on Tracks Required Two Key Ingredients:
  1. Rethinking jet substructure in terms of detectors (energy correlators)
  2. Yibei Li





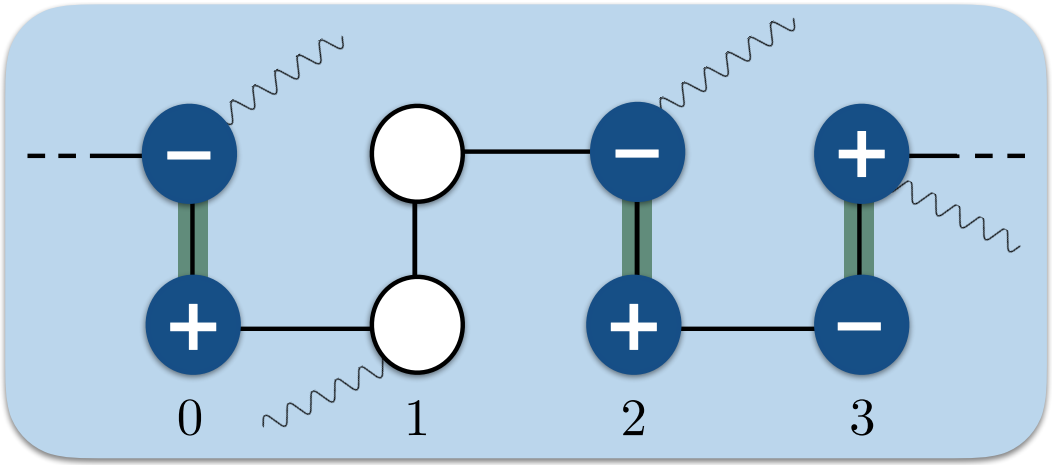
- Ready for track based jet substructure phenomenology at the LHC!

The Importance of Toy Theories

Importance of Toy Theories

- One should always find the simplest system that exhibits the behavior one is interested in. Almost certainly, that system is not QCD at a hadron collider.
- Toy models (AdS/CFT, SUSY, lower dimensions, ...) play a significant role in many other areas of theoretical physics.
- Rarely used in JSS:(Notable exceptions, e.g. Cesarotti, Strassler, Reece
- As we move towards more subtle questions (e.g. transport coefficients, confinement, non-standard BSM, etc) any intuition from simplified models could be invaluable.
- We have now developed to the stage of questions that are of general theoretical interest. We should not restrict to QCD in d=4.
- Wish there was more to say...

Numerics and Simulations



Parton Showers

- Much recent progress from various groups.

A new approach to QCD evolution in processes with massive partons

Benoît Assi and Stefan Höche
Fermi National Accelerator Laboratory, Batavia, IL, 60510

We present an algorithm for massive parton evolution which is based on the differentially accurate simulation of soft-gluon radiation by means of a non-trivial azimuthal angle dependence of the splitting functions. The kinematics mapping is chosen such as to to reflect the symmetry of the final state in soft-gluon radiation and collinear splitting processes. We compute the counterterms needed for a fully differential NLO matching and discuss the analytic structure of the parton shower in the NLL limit. We implement the new algorithm in the numerical code ALARIC and present a first comparison to experimental data.

A parton shower with higher-logarithmic accuracy for soft emissions

Silvia Ferrario Ravasio,[1] Keith Hamilton,[2] Alexander Karlberg,[1]
Gavin P. Salam,[3,4] Ludovic Scyboz,[3] and Gregory Soyez[1,5]
[1] *CERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland*
[2] *Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK*
[3] *Rudolf Peierls Centre for Theoretical Physics, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK*
[4] *All Souls College, Oxford OX1 4AL, UK*
[5] *IPhT, Université Paris-Saclay, CNRS UMR 3681, CEA Saclay, F-91191 Gif-sur-Yvette, France*

The accuracy of parton-shower simulations is often a limiting factor in the interpretation of data from high-energy colliders. We present the first formulation of parton showers with accuracy one order beyond state-of-the-art next-to-leading logarithms, for classes of observable that are dominantly sensitive to low-energy (soft) emissions, specifically non-global observables and subjet multiplicities. This represents a major step towards general next-to-next-to-leading logarithmic accuracy for parton showers.

Triple collinear emissions in parton showers

Stefan Höche[1] and Stefan Prestel[2]
[1] *SLAC National Accelerator Laboratory, Menlo Park, CA, 94025, USA*
[2] *Fermi National Accelerator Laboratory, Batavia, IL, 60510-0500, USA*

A framework to include triple collinear splitting functions into parton showers is presented, and the implementation of flavor-changing NLO splitting kernels is discussed as a first application. The correspondence between the Monte-Carlo integration and the analytic computation of NLO DGLAP evolution kernels is made explicit for both timelike and spacelike parton evolution. Numerical simulation results are obtained with two independent implementations of the new algorithm, using the two independent event generation frameworks PYTHIA and SHERPA.

- Will have significant impact on jet substructure program.

Quantum Simulations

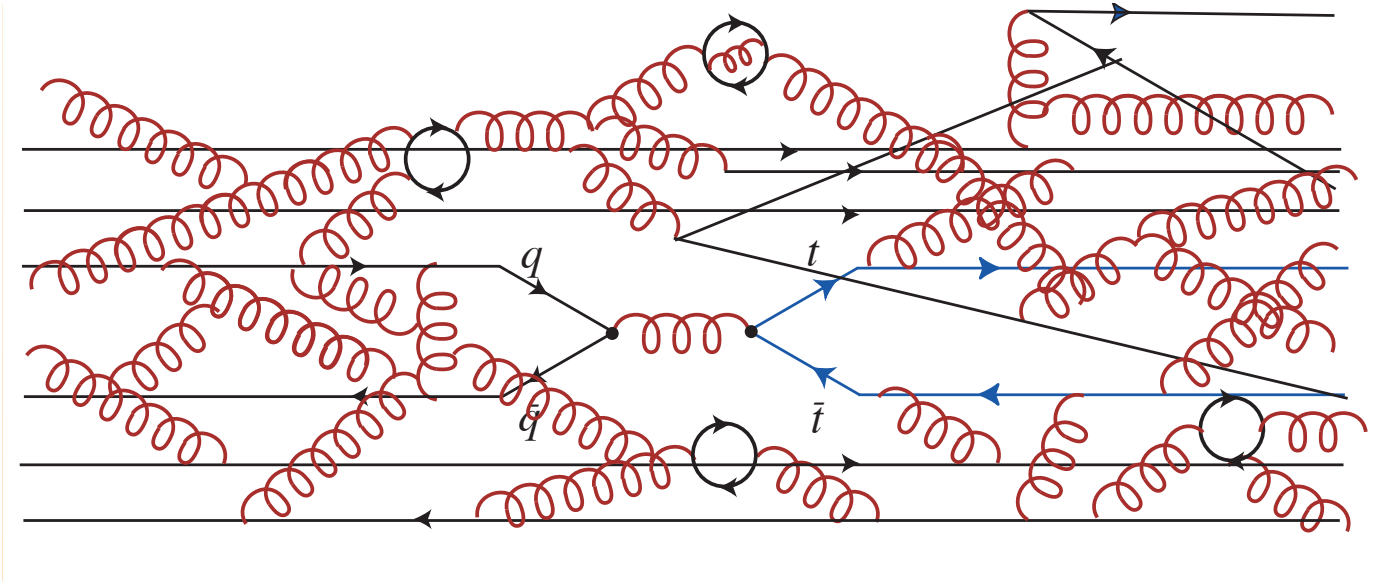
- Parton Showers are built on perturbation theory + modeling. We must ultimately move towards genuine simulations of non-perturvative QFT.
- Lorentzian nature of jet substructure makes this difficult with standard techniques.
- Having sharply defined field theoretic observables will be crucial.
- Goal: Non-perturbative calculation of fragmentation functions in any toy theory?

Simulating quantum field theory with a quantum computer

John Preskill*
Institute for Quantum Information and Matter
Walter Burke Institute for Theoretical Physics
California Institute of Technology, Pasadena CA 91125, USA
E-mail: preskill@caltech.edu

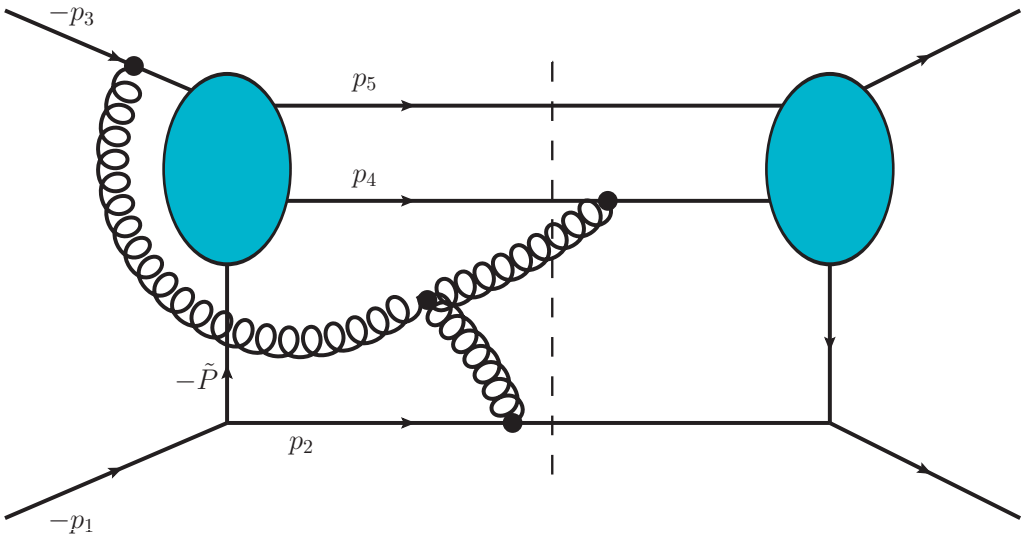
Forthcoming exascale digital computers will further advance our knowledge of quantum chromodynamics, but formidable challenges will remain. In particular, Euclidean Monte Carlo methods are not well suited for studying real-time evolution in hadronic collisions, or the properties of hadronic matter at nonzero temperature and chemical potential. Digital computers may never be able to achieve accurate simulations of such phenomena in QCD and other strongly-coupled field theories; quantum computers will do so eventually, though I'm not sure when. Progress toward quantum simulation of quantum field theory will require the collaborative efforts of quantumists and field theorists, and though the physics payoff may still be far away, it's worthwhile to get started now. Today's research can hasten the arrival of a new era in which quantum simulation fuels rapid progress in fundamental physics.

Effective Field Theories and Factorization



Factorization Theorems

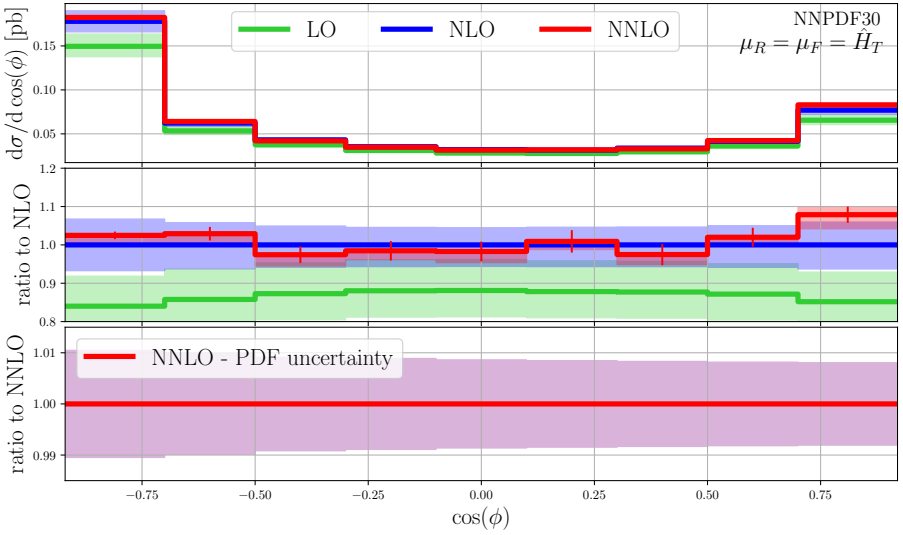
- The theoretical interpretation of any measurement at the LHC relies on the factorization theorems of Collins, Soper, Sterman into universal parton distribution functions, fragmentation functions, etc.
- These are only proven for a select set of processes (inclusive color singlet, inclusive hadron production, ...)

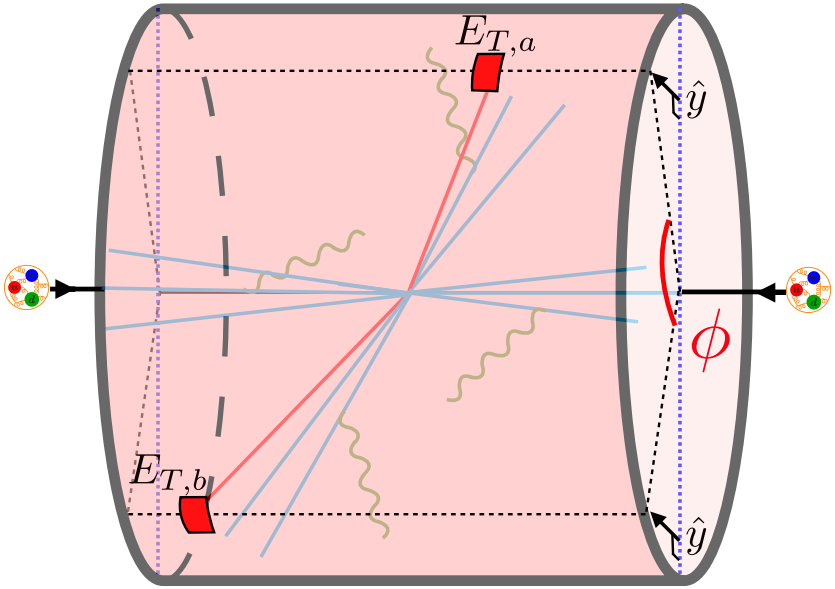


- Recent progress using EFT of Forward Scattering (Rothstein+Stewart).

Factorization Theorems

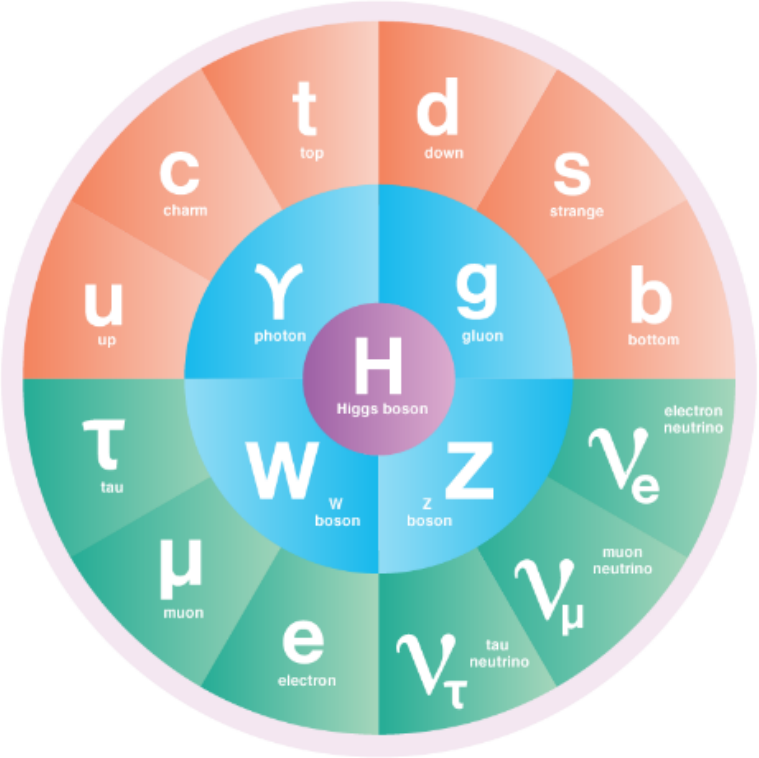
- This may seem academic, but we have now reached the boundary where such effects can (could) play an important role.
- e.g. Can we combine NNLO calculation of TEEC with N^{3}LL resummation? Not sure....





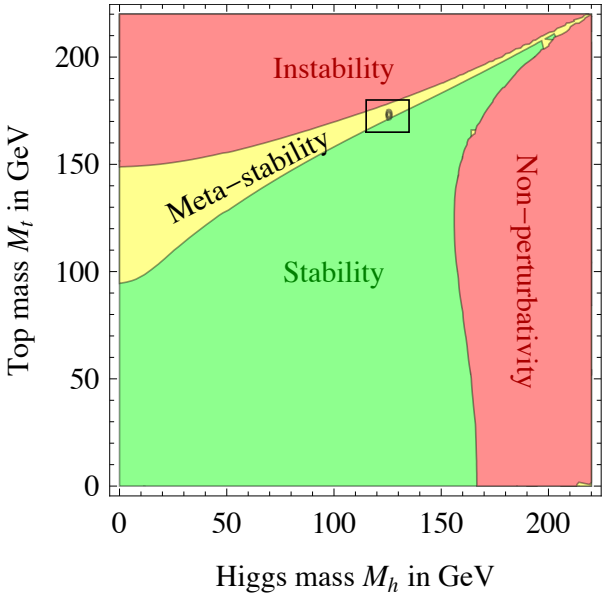
- We must further develop our understanding of factorization to go beyond current level of accuracy for hadron collider event/ jet shapes.

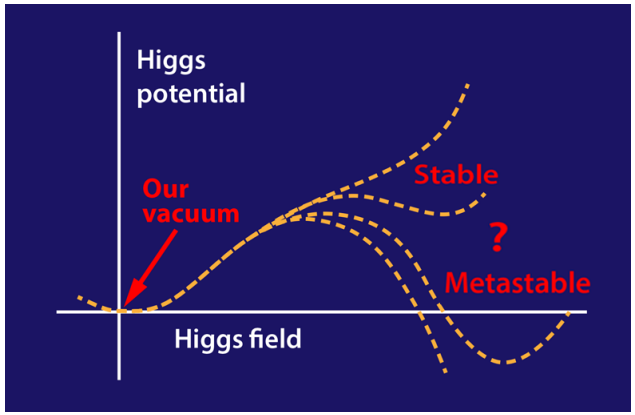
Exploring the Standard Model and Beyond



Clues for Beyond the Standard Model

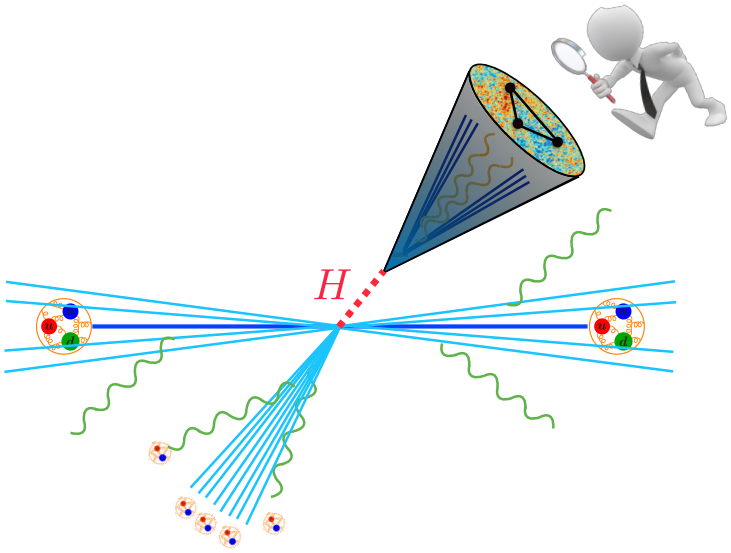
- In the absence of the direct observation of new physics, understanding the precise structure of the Standard Model and its extrapolation to high energies can provide clues.

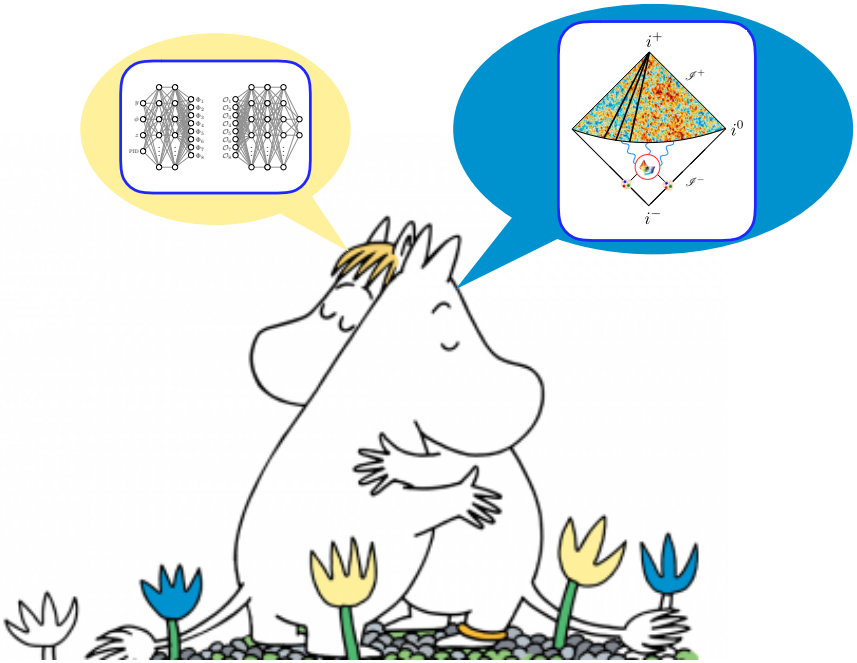




- We must:
  - Study all interactions.
  - Precisely measure all parameters.

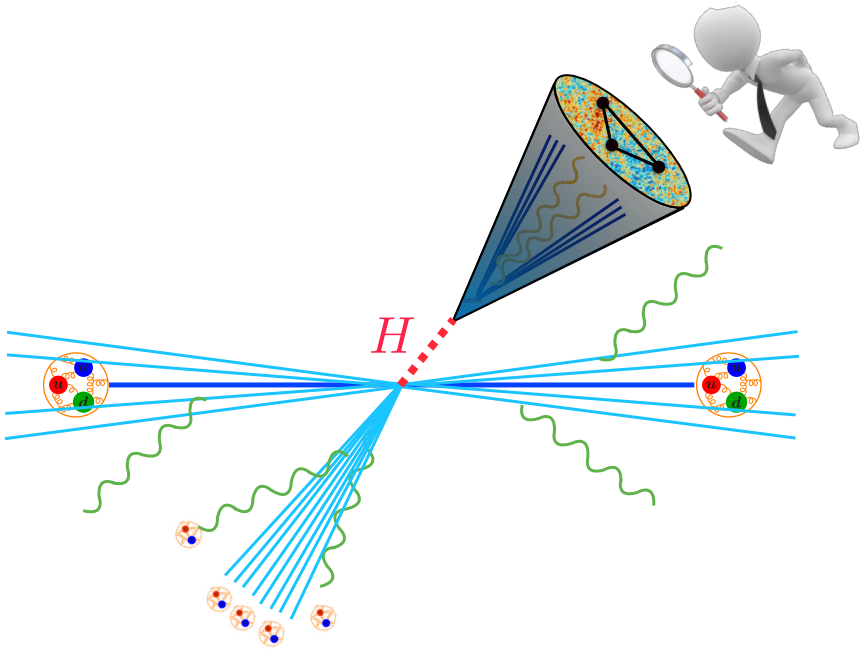
New Particles and New Interactions

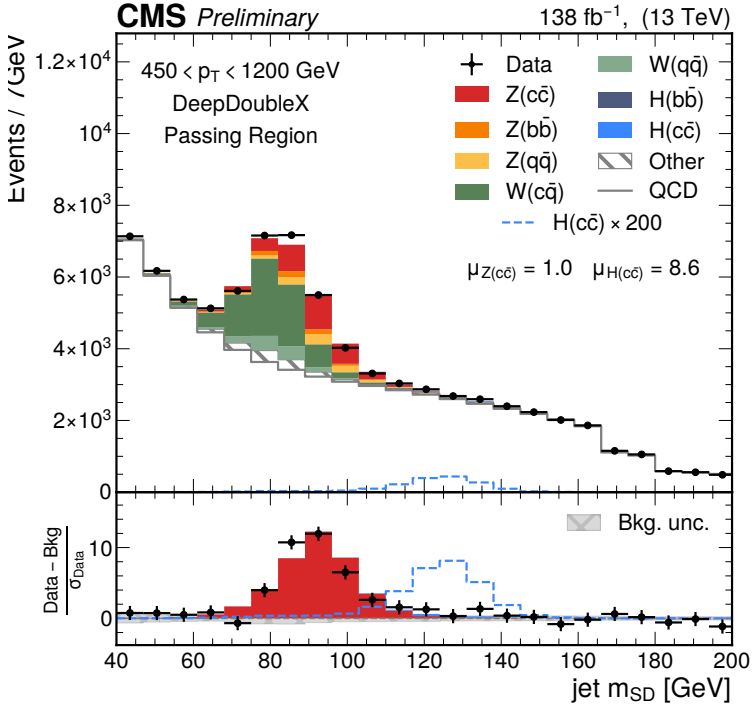




New Interactions

- Measurements of the Higgs couplings to light quarks provide a crucial test of the Yukawa sector of the SM.
- Jet substructure provides the current most stringent bound on the charm Yukawa, $1.1 < \kappa_c < 5.5$.

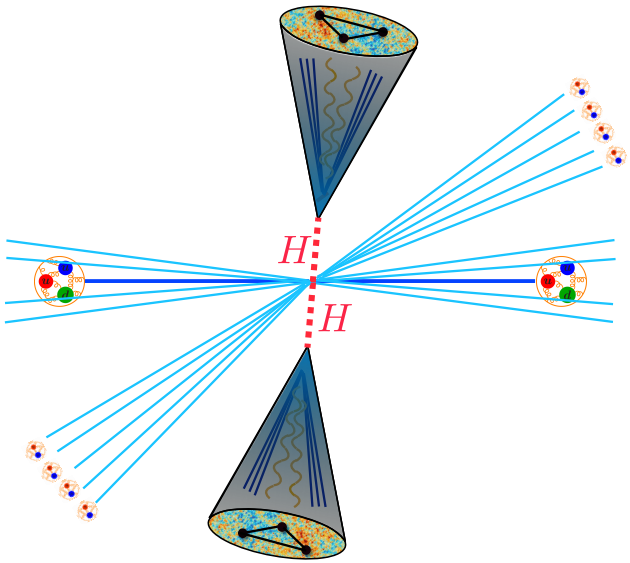


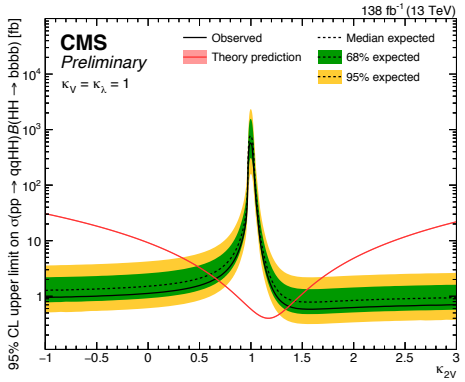


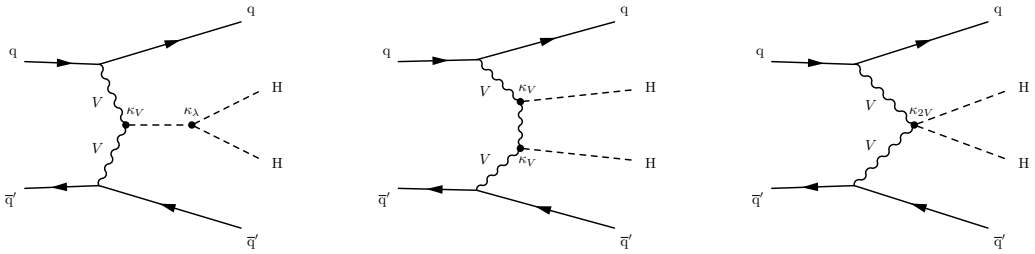
- Matches the original projected sensitivity with 3000 fb^{-1}!

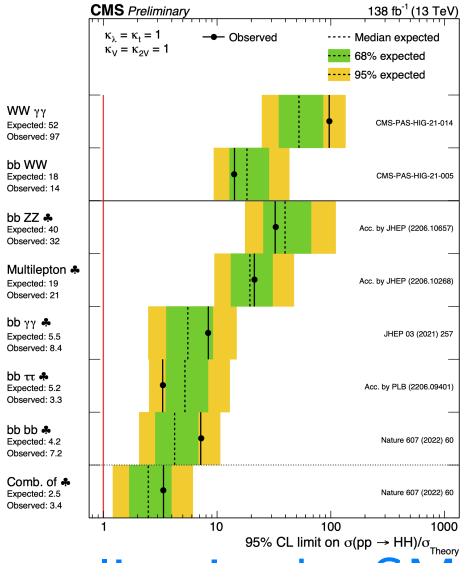
New Interactions

- The Higgs self interaction accesses the Higgs potential.
- Jet Substructure exploits the high branching ratio to b-quarks.





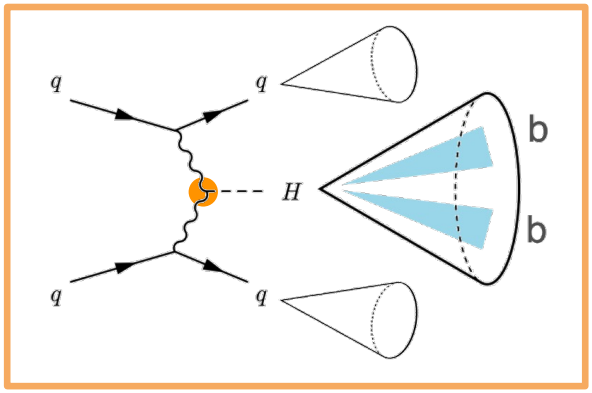


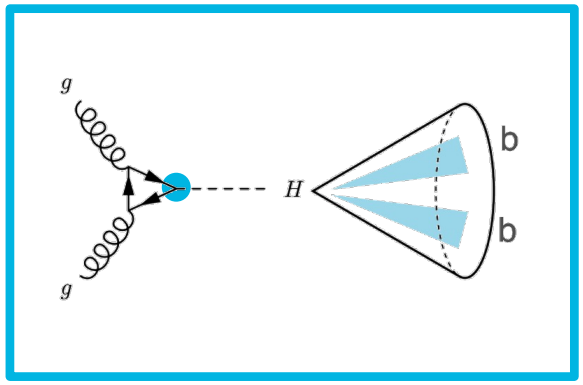


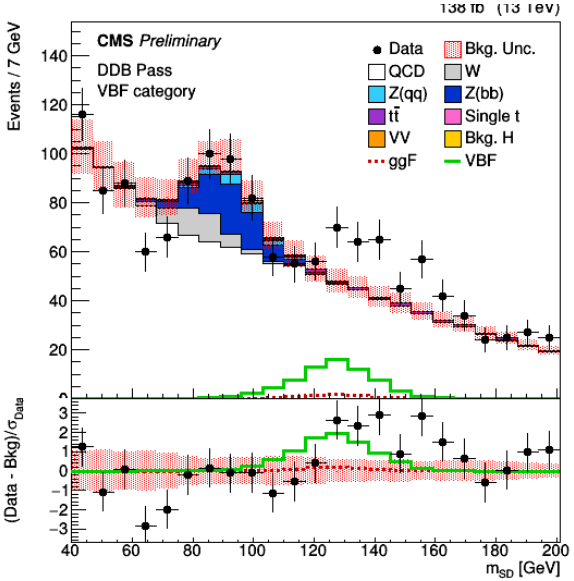
- First observation of the $VV \to HH$ coupling in the SM!

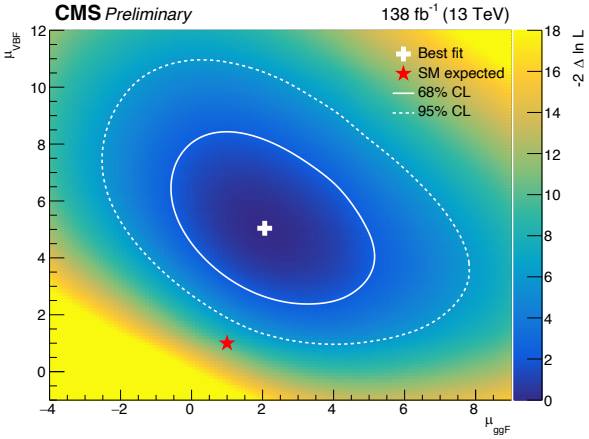
New Interactions

- Resolving Higgs Couplings at high p_T



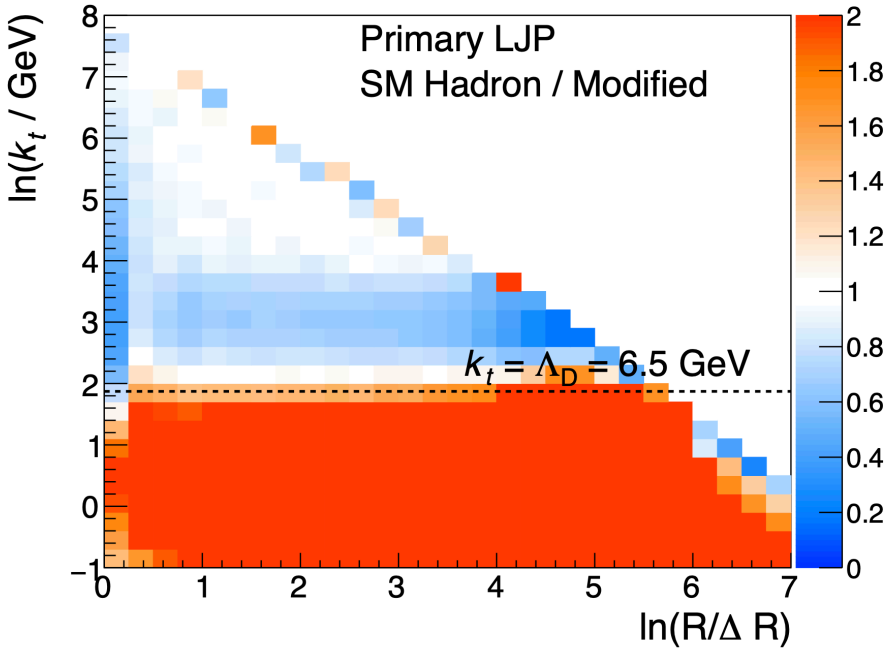


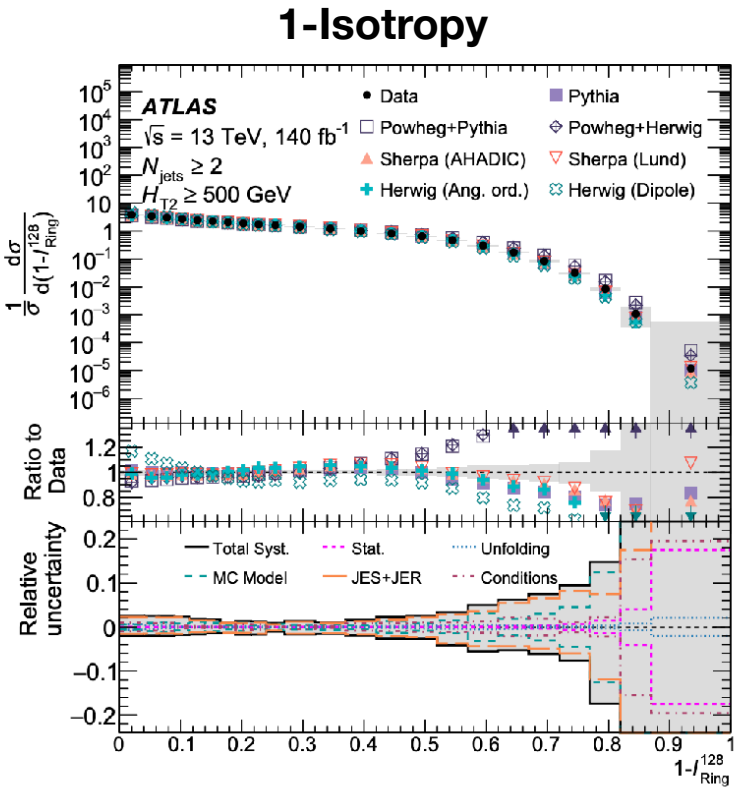




New Particles

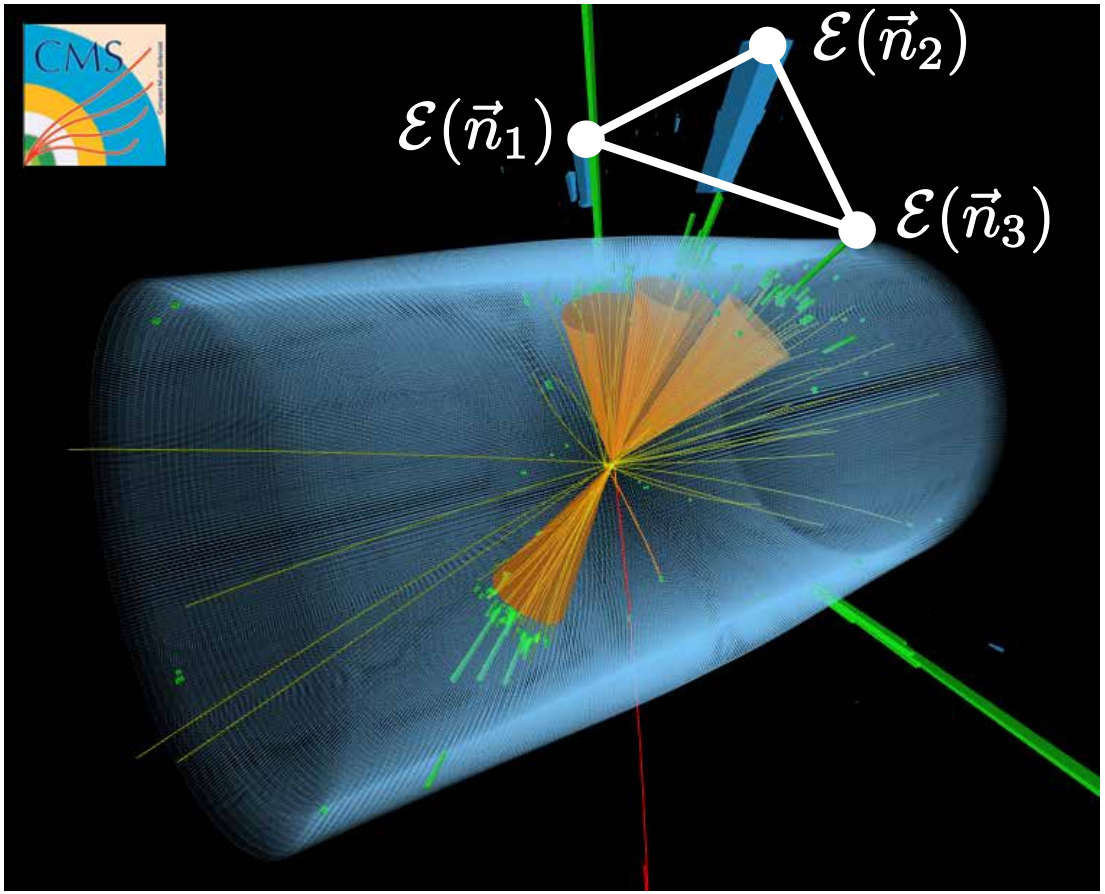
- Must continue to push innovative searches for more subtle phenomena that go beyond the standard paradigms.





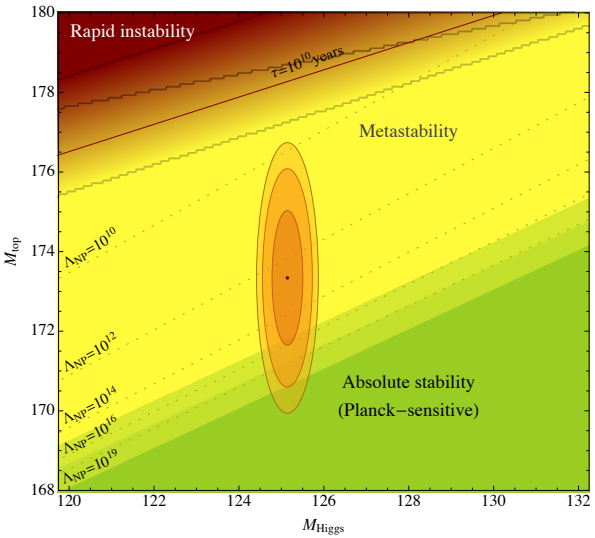
- Leave every stone unturned in forthcoming data sets.

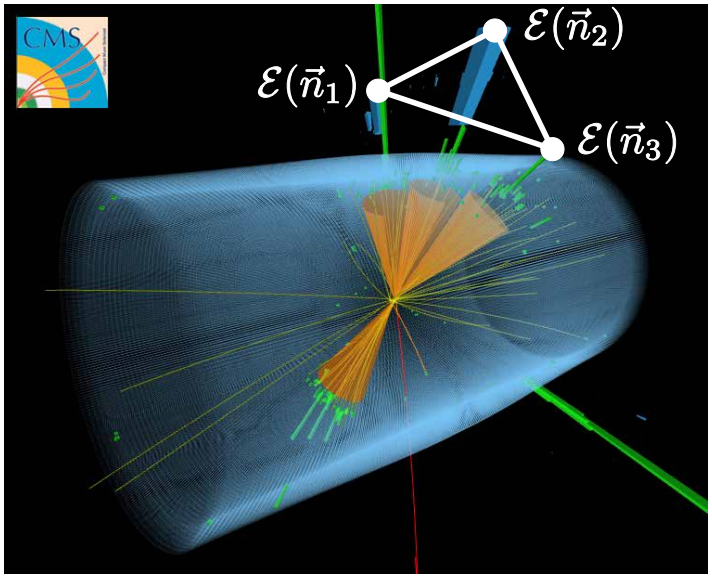
Weighing the Top Quark

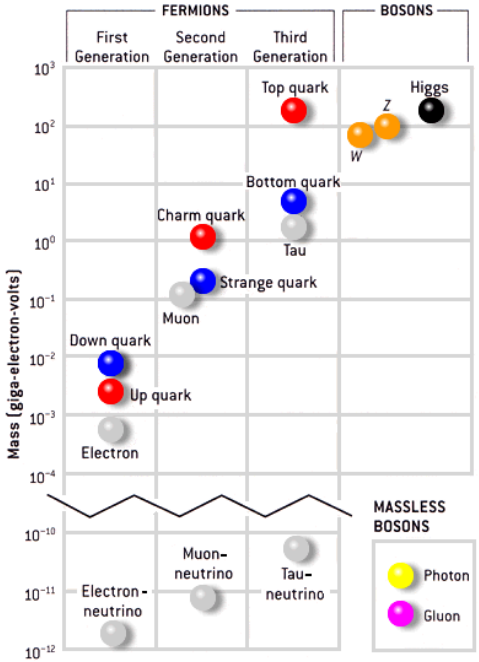


Top Quark Mass

- The top quark mass is one of the most important parameters of the SM.
- Need simple observables with top mass sensitivity that can be computed from first principles field theory: SD Mass, EEEC

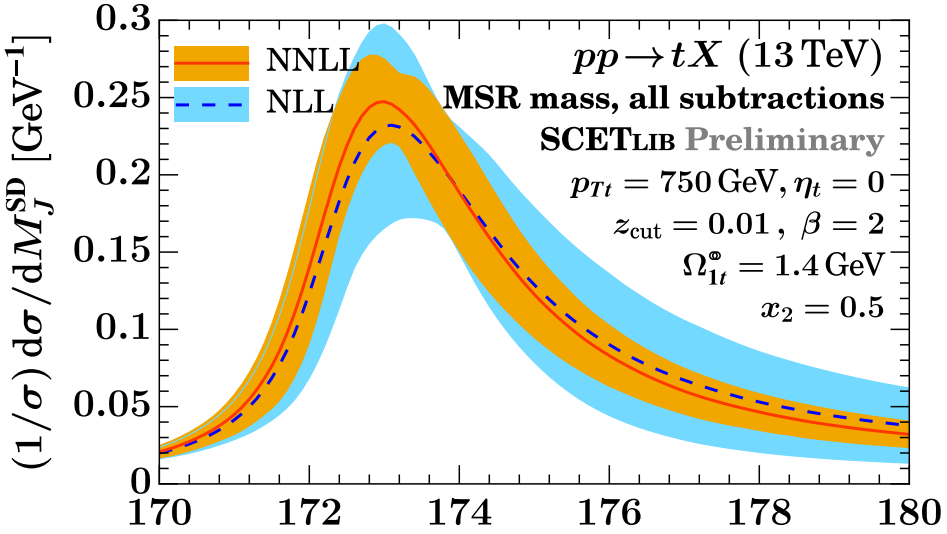






Top Quark Mass Measurement

- Nice progress towards higher order resummation, and MSR $\leftrightarrow$ MC mass conversions.

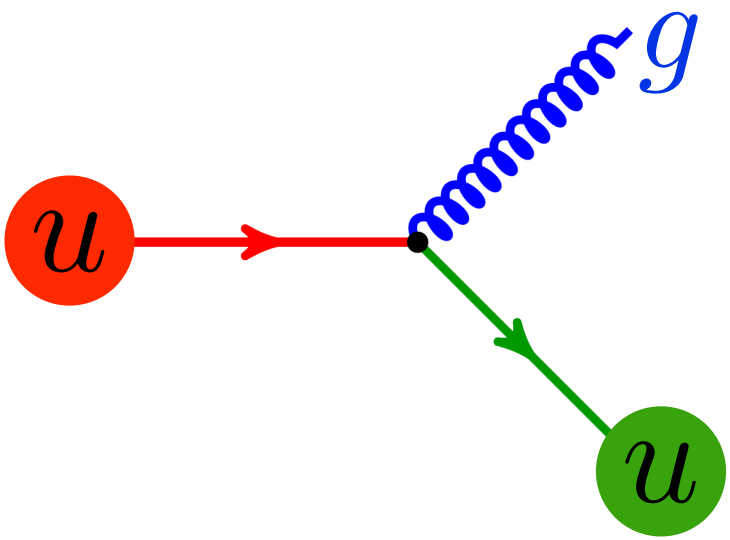


Mass relation of:

$$\Delta^{MSR} = m_t^{MC} - m_t^{MSR}(1\ \text{GeV}) = 320^{+97}_{-490}\ \text{MeV}$$

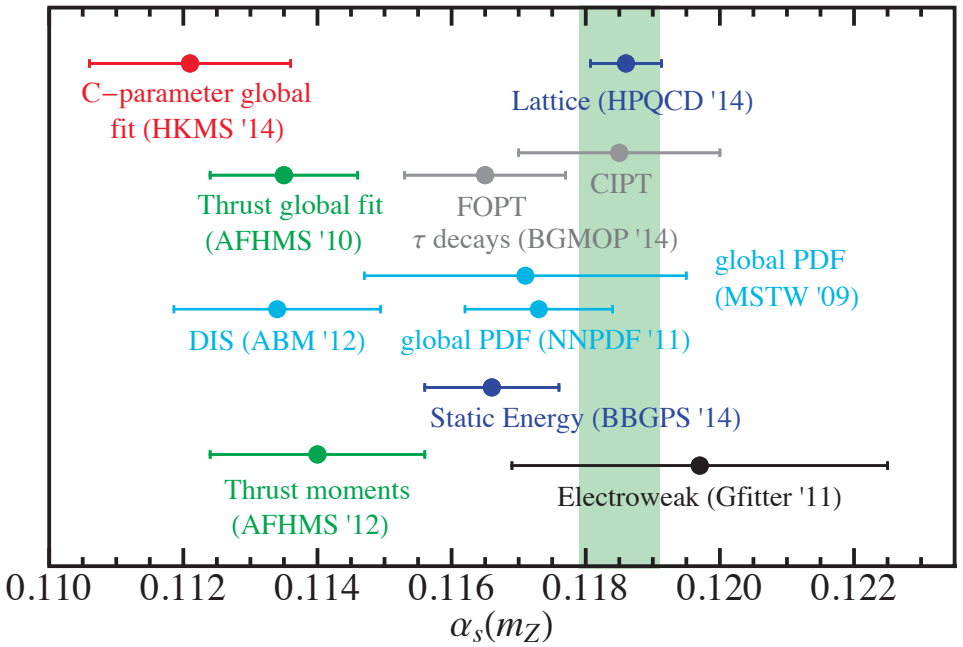
Uncertainty corresponding to the theoretical variations of the model.

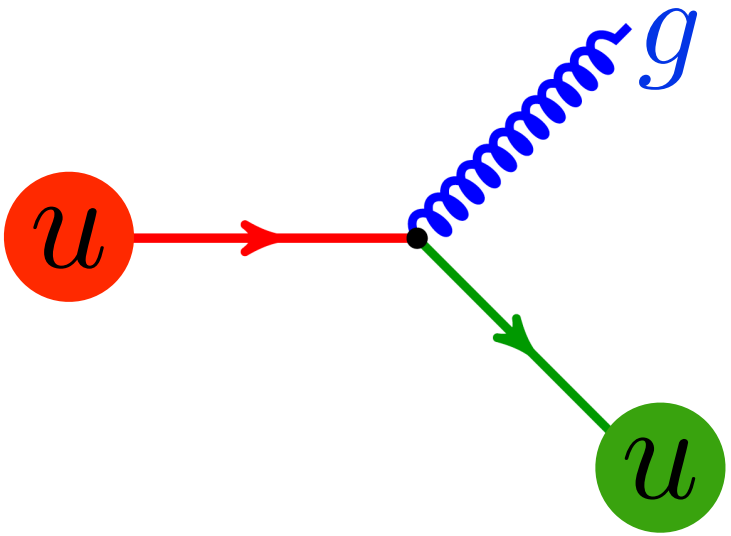
α_s with Jet Substructure



How Strong is the Strong Force?

- What is the value of the strong coupling constant?
- The electromagnetic coupling is one of the best known natural quantities $\alpha_e = 0.0072973525693(11)$.
- Quarks are never free $\implies$ very hard to measure their couplings!



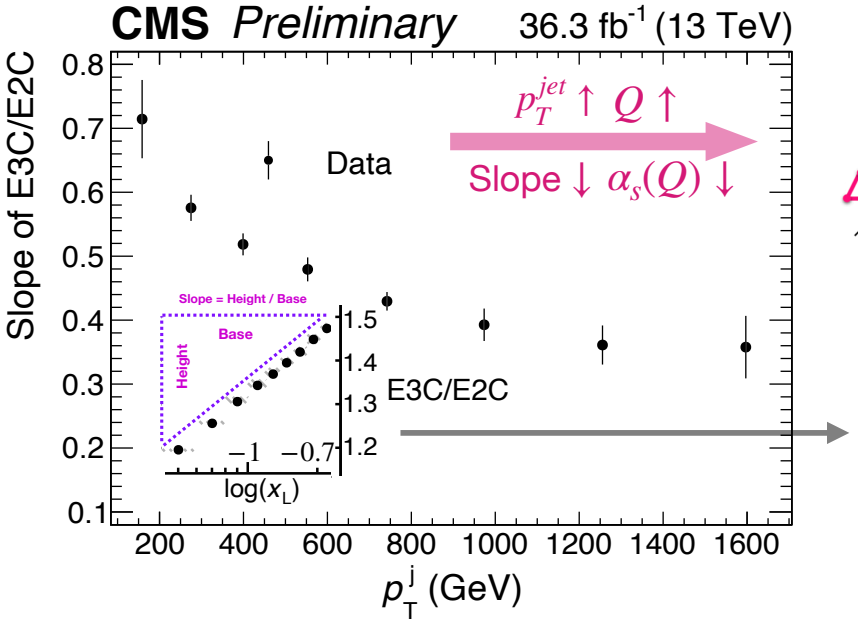


Strong Coupling

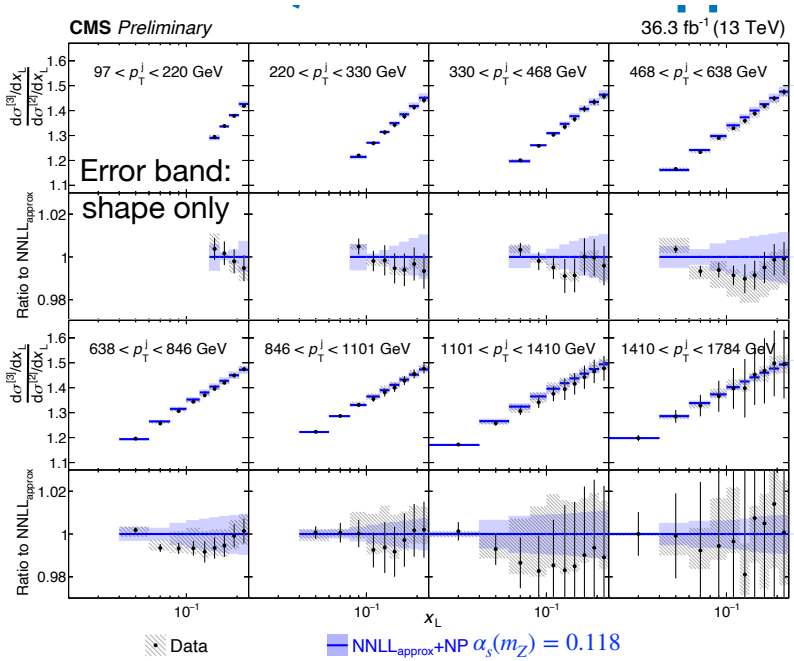
- There are two general approaches to measure a coupling in a QFT:

$$\mathcal{O} = C(\alpha_s) x^{\gamma(\alpha_s)}$$

- JSS offers the possibility to measure it as a scaling exponent.
- Which one will win? We must at least try...
- Milestone for jet substructure: $< 5\%$ accuracy

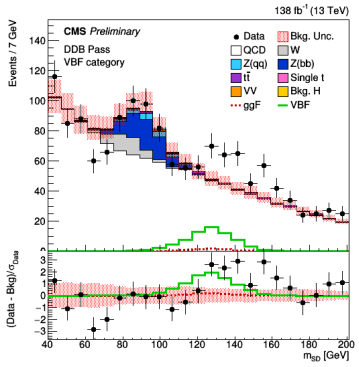


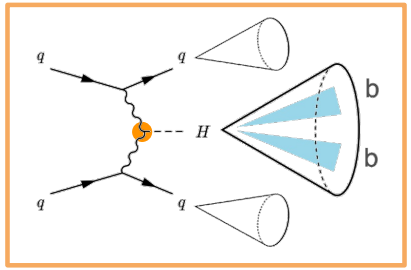
Data point: slope in a p_T^{jet} regio

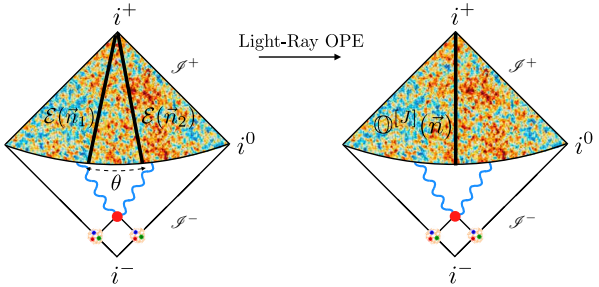


Outlook

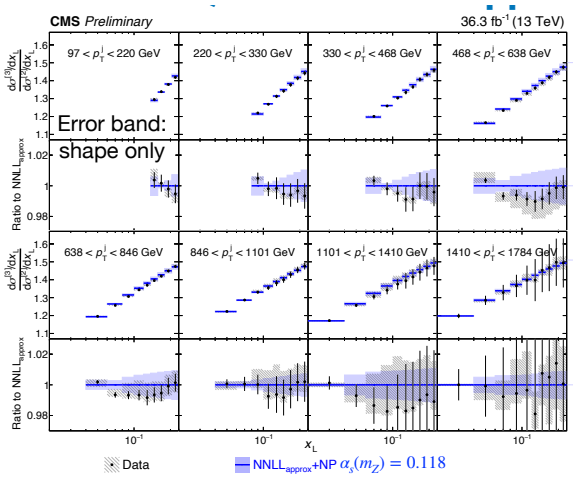
- Jet substructure provides one of the most exciting examples of connecting progress in QFT with data to learn something about the real world.

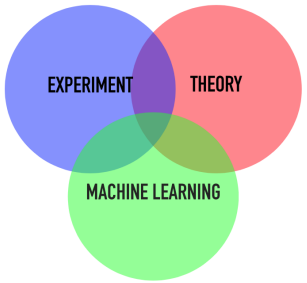






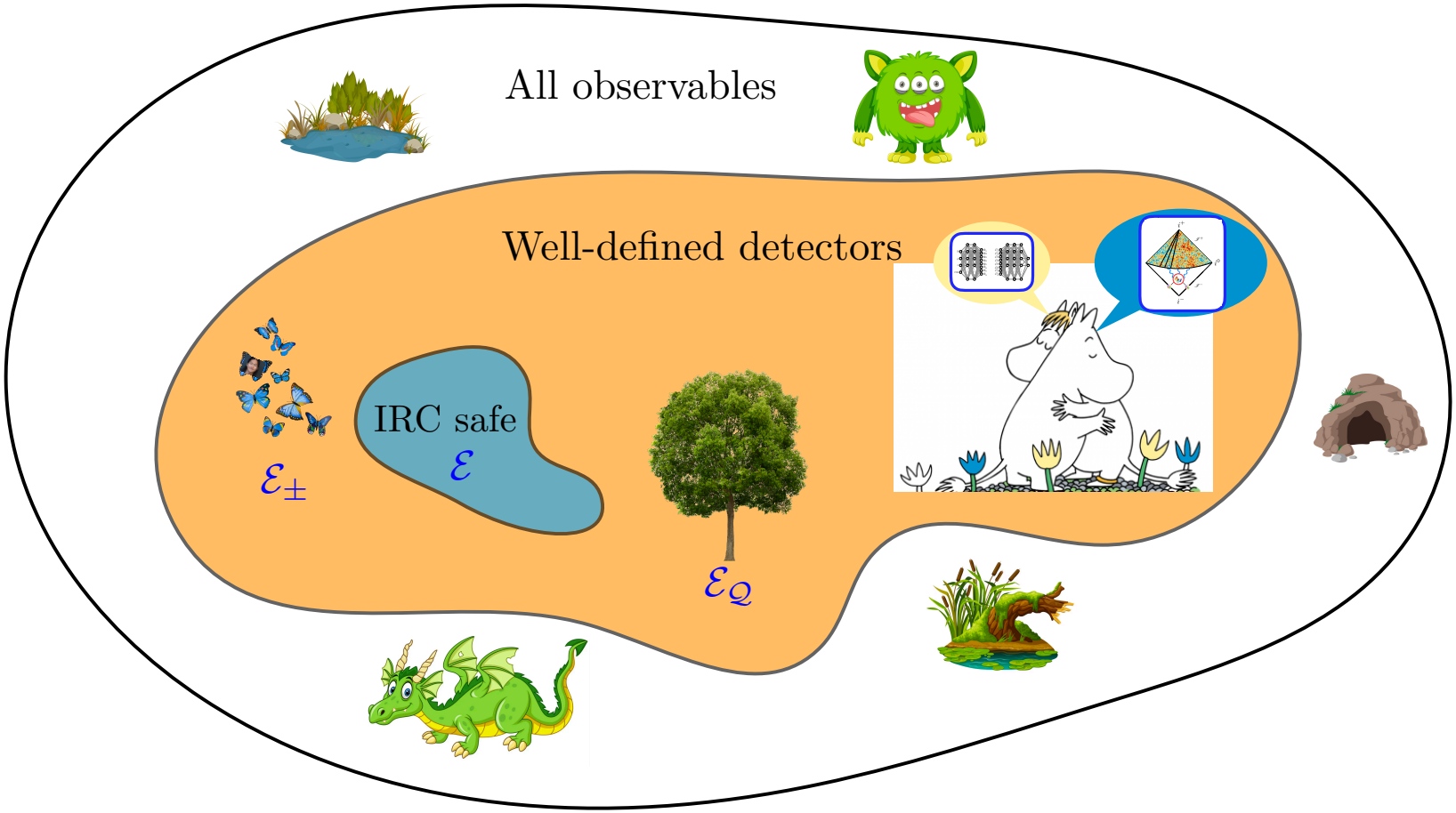
$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4}\mathbb{O}_i(\hat{n}_1)$$





- The fun is just beginning!

Thanks!


All observables
Well-defined detectors
IRC safe
$\mathcal{E}$
$\mathcal{E}_\pm$
$\mathcal{E}_Q$