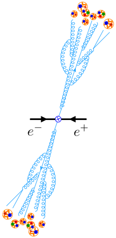
The Rise of Jet Substructure

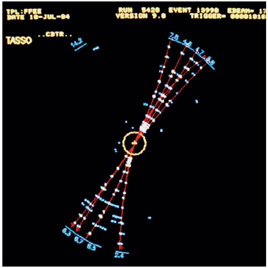
Ian Moult
Yale

Jets

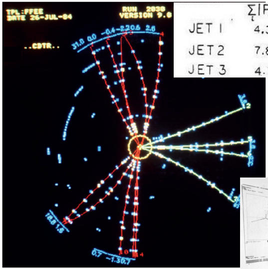
- Jets play a central role in colliders as proxies for quarks and gluons
  $\Longrightarrow$ long distance manifestation of microscopic interactions.



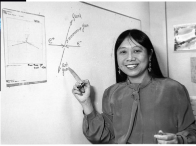
2-Jet Event

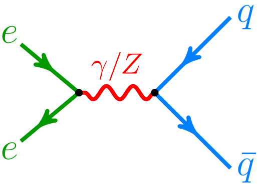


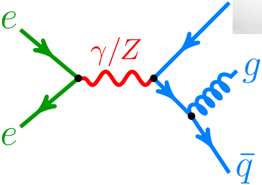
3-Jet Event



	$\sum_i \lvert P_i \rvert_{\text{CHARGE}}$	TOTAL ENERGY
JET 1	4.3 GEV	7.4 GEV
JET 2	7.8	8.9
JET 3	4.1	11.1



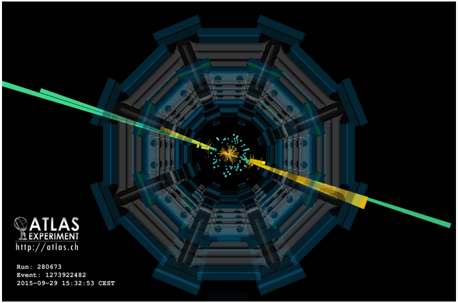




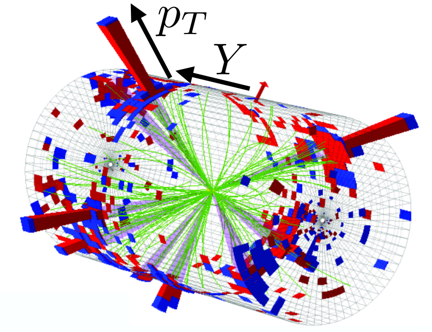
Jets at the Large Hadron Collider

- The LHC produces jets with unprecedented energy and multiplicity.

$p_T = 3.2$ TeV



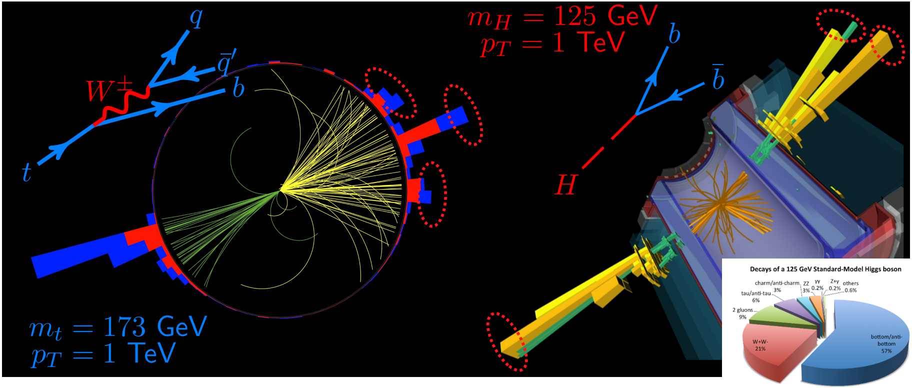
9 Jet Event



- Provides a rich dataset for exploring the dynamics of QCD.

Jet Substructure

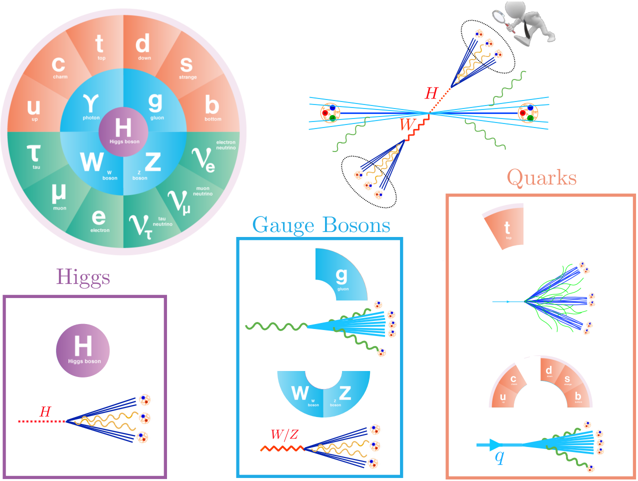
- The LHC is the first collider where electroweak scale particles appear boosted inside jets $\Longrightarrow$ The SM in a new regime.



- Electroweak scale dynamics imprinted in energy flow of jets $\Longrightarrow$ jets have substructure!

The Standard Model of Jets

- Jets are the long distance manifestation of Standard Model dynamics.



- Understanding QCD jets takes on a central role.

Jet Substructure

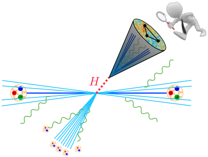
- Jet Substructure uses the internal structure of jets to provide qualitatively new ways to study the SM and Beyond.

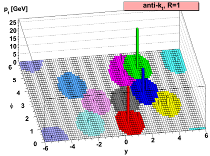
The anti-k_t jet clustering algorithm

Matteo Cacciari (Paris, LPTHE), Gavin P. Salam (Paris, LPTHE), Gregory Soyez (Brookhaven)
Feb, 2008

12 pages
Published in: *JHEP* 04 (2008) 063
e-Print: 0802.1189 [hep-ph]
DOI: 10.1088/1126-6708/2008/04/063
Report number: LPTHE-07-03
View in: HAL Science Ouverte, ADS Abstract Service

pdf cite claim reference search 9,616 citations





Jet substructure as a new Higgs search channel at the LHC

Jonathan M. Butterworth (University Coll. London), Adam R. Davison (University Coll. London), Mathieu Rubin (Paris, LPTHE), Gavin P. Salam (Paris, LPTHE)
Feb, 2008

4 pages
Published in: *Phys.Rev.Lett.* 100 (2008) 242001
e-Print: 0802.2470 [hep-ph]
DOI: 10.1103/PhysRevLett.100.242001
View in: HAL Science Ouverte, ADS Abstract Service

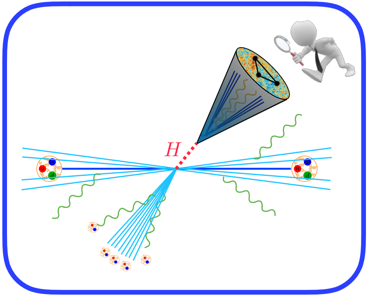
pdf cite claim reference search 1,207 citations

- Tremendous Influence: Reinvigorated the study of jets in QCD.

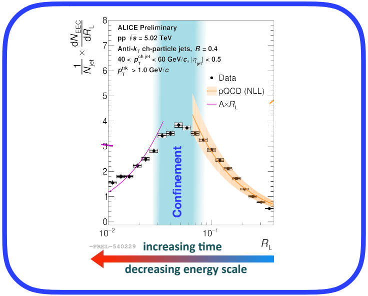
Jet Substructure

- Jet substructure has emerged as a central new technique at the LHC:

Innovative Search Techniques



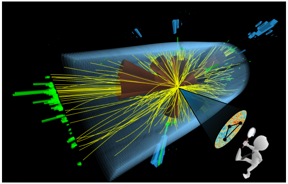
Novel Probes of QCD Dynamics



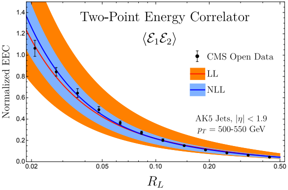
- Has evolved well beyond its origin to have a large impact on BSM, SM, high energy QCD and nuclear physics.

Outline

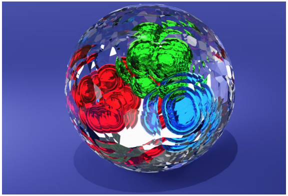
- Decoding Energy Flux



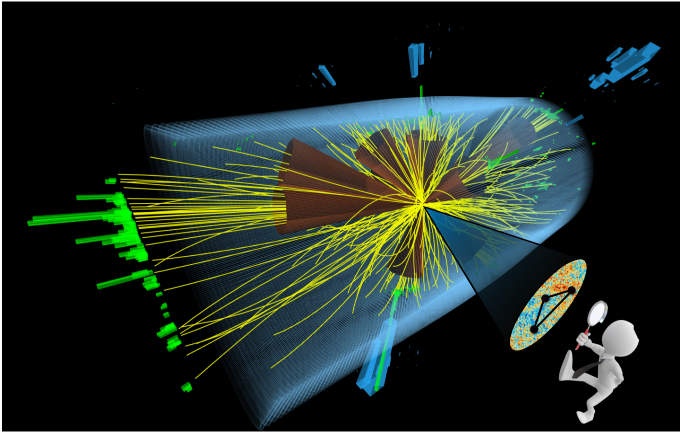
- Asymptotic Scaling of Quarks and Gluons



- Imaging Intrinsic and Emergent Scales of the Standard Model

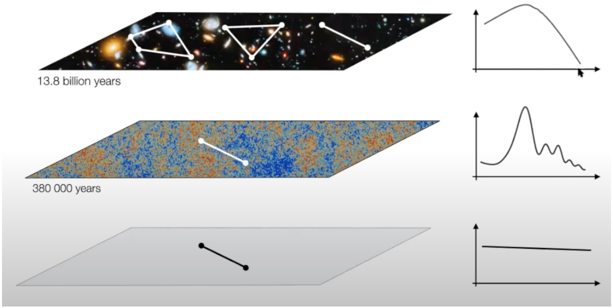


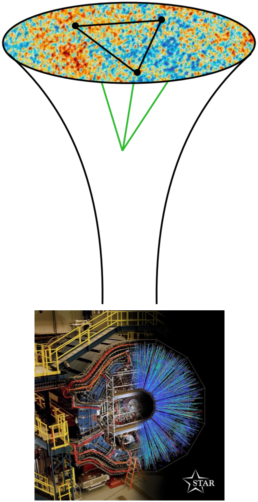
Decoding Energy Flux



Decoding Energy Flux

- In condensed matter physics or cosmology we decode the underlying dynamics using correlation functions.



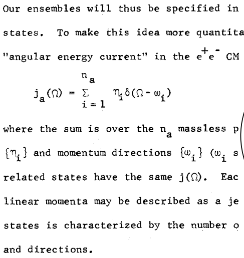


- What is the analog for collider physics?

Energy Flux

- Expectation value of energy flux at specific angles on the celestial sphere is calculable in perturbation theory.

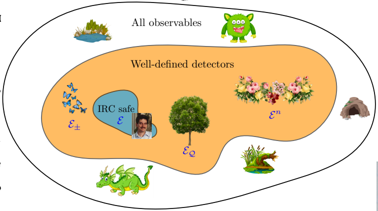
Energy flow becomes the focus of computability.



Our ensembles will thus be specified in terms of sets of jet-related states. To make this idea more quantitative we define for any state a, an "angular energy current" in the e^+e^- CM

$$j_a(\Omega) = \sum_{i=1}^{n_a} \eta_i \delta(\Omega - \omega_i)$$

where the sum is over the n_a massless p
$\{\eta_i\}$ and momentum directions $\{\omega_i\}$ (ω_i s
related states have the same $j(\Omega)$. Eac
linear momenta may be described as a je
states is characterized by the number o
and directions.

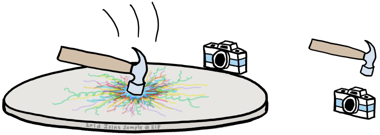


$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty} r^2 \int_0^\infty dt\; n^i T_{0i}(t, r\vec{n})$$

[Korchemsky, Sterman], [Sveshnikov, Tkachov], [Hofman, Maldacena],[Korchemsky, Sokatchev, Zhiboedov,...]

A Modern Perspective

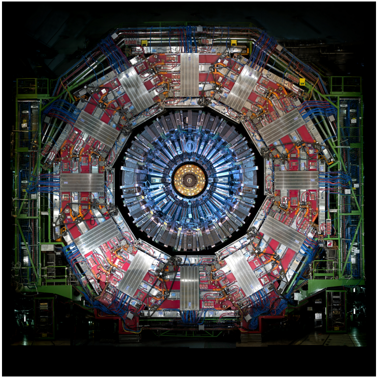
- What is a detector?



$$= \sum_i h_i \mathcal{O}_i$$

$$= \sum_j c_j \mathcal{D}_j$$

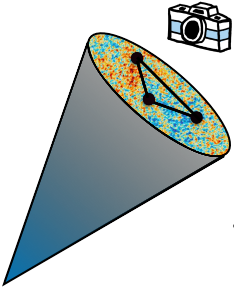
[Caron Huot, Kologlu, Kravchuk, Meltzer, Simmons Duffin]



- To be able to understand subtle signals in energy flux, we must understand what a detector is in Quantum Field Theory.

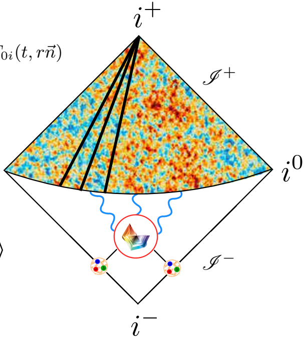
Calorimeter Cells in Field Theory

- Calorimeter cells can be given a field theoretic definition in terms of light-ray operators. [Hofman, Maldacena] [Korchemsky, Sterman] [Ore, Sterman] [Basham, Brown, Ellis, Love]



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

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



- Provides a sharp link between experimentally measurable observables and the underlying QFT.

Energy Correlators: History

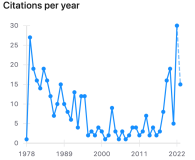
- Proposed 45 years ago (The first jet substructure!):

Energy Correlations in electron - Positron Annihilation: Testing QCD

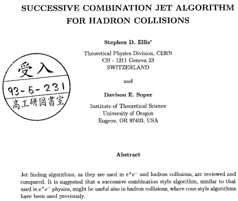
C.Louis Basham (Washington U., Seattle), Lowell S. Brown (Washington U., Seattle), Stephen D. Ellis (Washington U., Seattle), Sherwin T. Love (Washington U., Seattle)

Aug, 1978

13 pages
Published in: *Phys.Rev.Lett.* 41 (1978) 1585
DOI: 10.1103/PhysRevLett.41.1585
Report number: RLO-1388-759
View in: OSTI Information Bridge Server, ADS Abstract Service



Abstract: (APS)
An experimental measure is presented for a precise test of quantum chromodynamics. This measure involves the asymmetry in the energy-weighted opening angles of the jets of hadrons produced in the process e+e−→hadrons at energy W. It is special for several reasons: It is reliably calculable in asymptotically free perturbation theory; it has rapidly vanishing (order 1W2) corrections due to nonperturbative confinement effects; and it is straightforward to determine experimentally.


SUCCESSIVE COMBINATION JET ALGORITHM FOR HADRON COLLISIONS

Stephen D. Ellis*
Theoretical Physics Division, CERN
CH - 1211 Geneva 23
SWITZERLAND

and

Davison E. Soper
Institute of Theoretical Science
University of Oregon
Eugene, OR 97403, USA

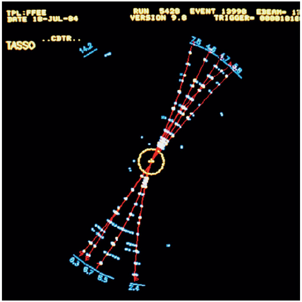
Abstract

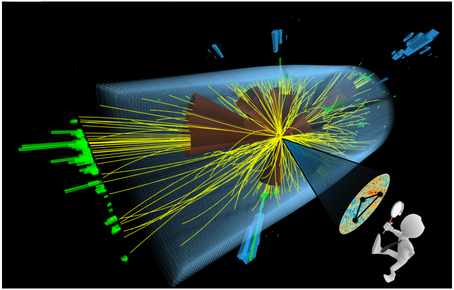
Jet finding algorithms, as they are used in e^+e^- and hadron collisions, are reviewed and compared. It is suggested that a successive combination style algorithm, similar to that used in e^+e^- physics, might be useful also in hadron collisions, where cone style algorithms have been used previously.

- Large resurgence of interest due to LHC dataset and improvement in our understanding of perturbative QCD.

Jets at the LHC

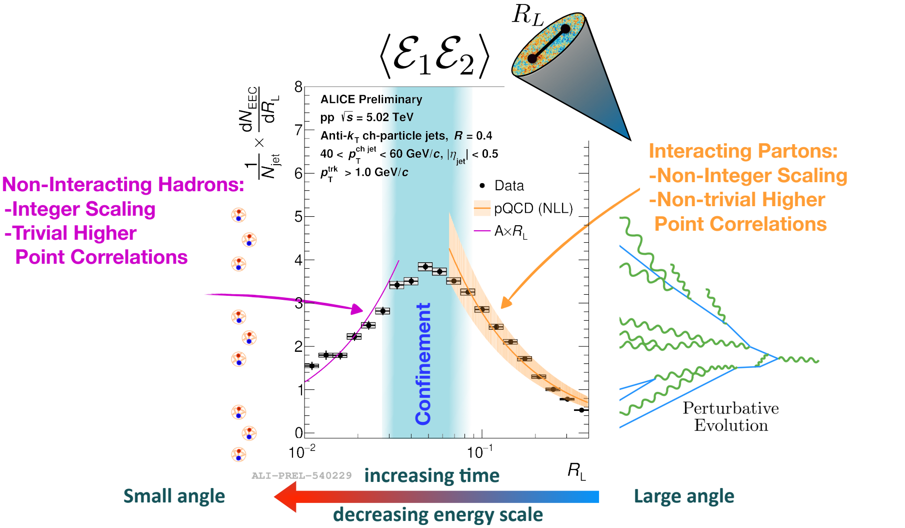
- Transition from GeV$\to$ TeV Jets transforms the questions we can understand using perturbation theory.
- Move from exclusive amplitudes to the study of correlations $\langle\Psi|\mathcal{E}(\hat{n}_1)\cdots\mathcal{E}(\hat{n}_k)|\Psi\rangle$ on high multiplicity states
  $\implies$ A new regime of QCD!





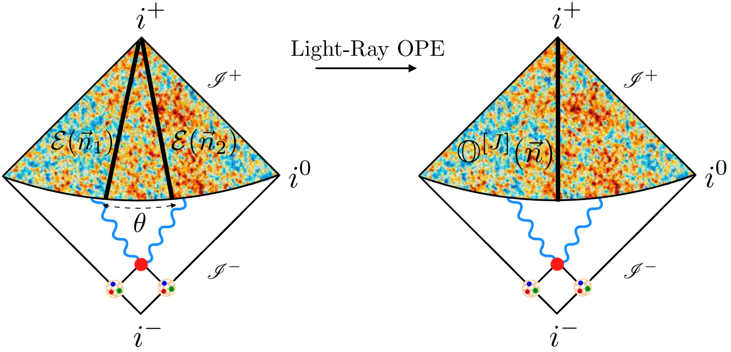
Energy Correlators: Present

Figure: Wenqing Fan



- Asymptotic Freedom and Confinement in one plot!

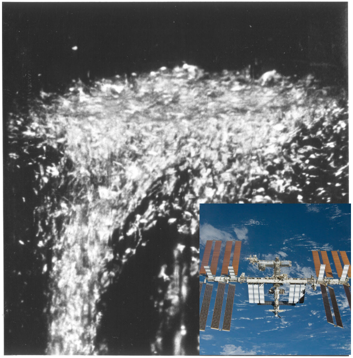
Asymptotic Scaling of Quarks and Gluons

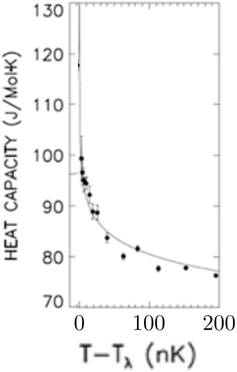


Scaling Behavior in QFT

- Scaling behavior in Euclidean regime well understood.

λ-point of Helium

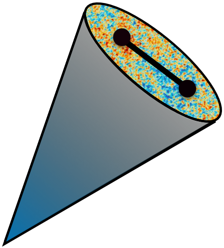


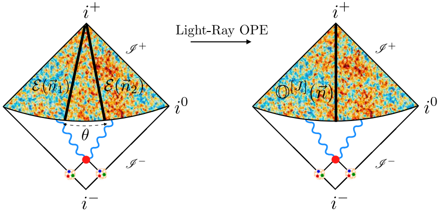


$$\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i$$

The OPE Limit of Lightray Operators

- Energy flow operators admit a Lorentzian OPE: “the lightray OPE”





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

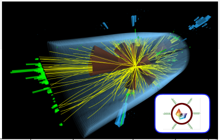
[Hofman, Maldacena]
[Chang, Kologlu, Kravchuk, Simmons Duffin, Zhiboedov]
QCD: [Dixon, Moult, Zhu]

- Predicts universal scaling behavior in correlations of energy flux at energies $E \gg \Lambda_{\text{QCD}}$.

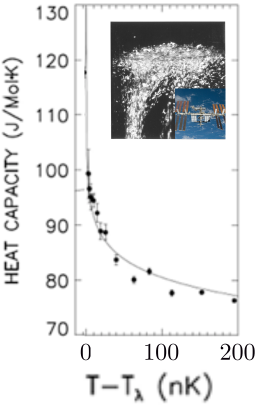
See early work by [Konishi, Ukawa, Veneziano]

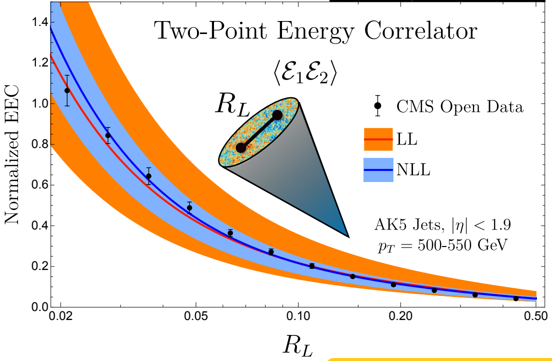
Scaling Behavior in Jets

[Komiske, Moult, Thaler, Zhu]
[Dixon, Moult, Zhu]
[Lee, Mecaj, Moult]



- The $\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2)$ OPE inside high-energy jets!





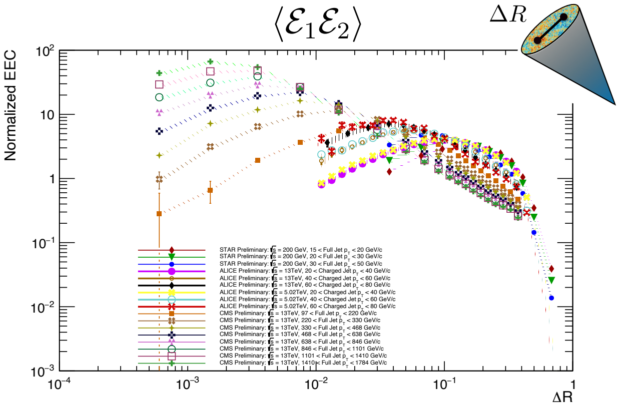
$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4} \mathbb{O}_i(\hat{n}_1)$$

- Beautiful scaling behavior in energy flux, even in complicated hadronic environment!

Scaling Behavior in Jets

Thanks to Helen Caines, Meng Xiao, ChenFeng Lu, Andrew Tamis, Ananya Rai.

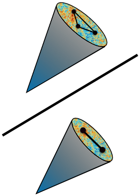
- Measurements from ALICE, CMS and STAR from 15 GeV to 1784 GeV released last week!



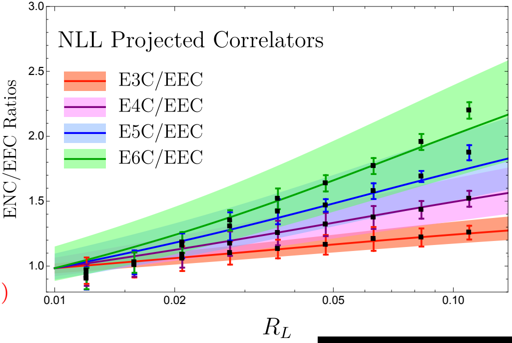
- Dominated by classical scaling. Can we accurately measure anomalous scaling?

The Spectrum of a Jet

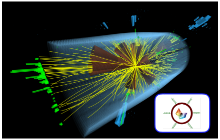
- The light-ray OPE predicts that the N-point correlators develop an anomalous scaling that depends on N.



$$\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \cdots \mathcal{E}_{J-1} \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \rangle} \sim \frac{\langle \mathbb{O}^{[J]} \rangle}{\langle \mathbb{O}^{[3]} \rangle} \sim R_L^{\gamma(J)-\gamma(3)}$$



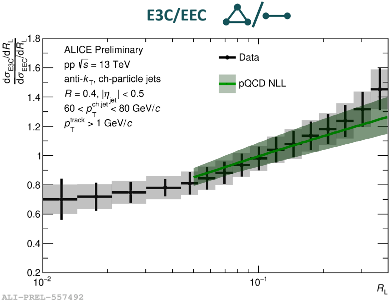
- Directly probes the spectrum of (twist-2) lightray operators from asymptotic energy flux.

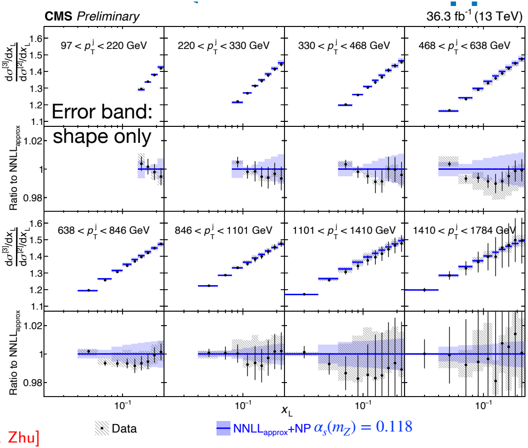


Anomalous Scaling of 3/2 Ratio

- Anomalous scaling measured from 15 GeV to 1784 GeV!

$$\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \mathcal{E}_3 \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \rangle} \sim \frac{\langle \mathbb{O}^{[3]} \rangle}{\langle \mathbb{O}^{[3]} \rangle} \sim R_L^{\gamma(4)-\gamma(3)}$$

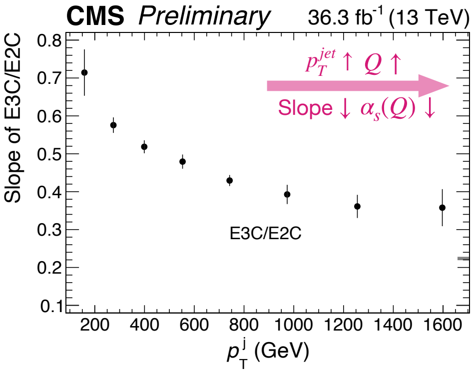


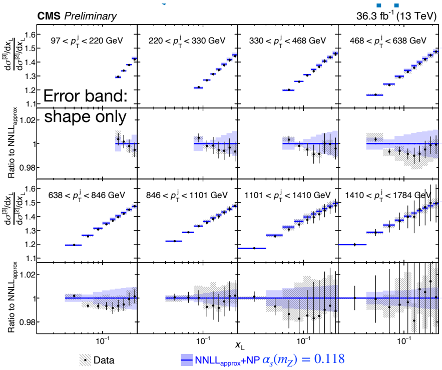


Using [Lee, Mecaj, Moult], [Chen, Gao, Li, Xu, Zhang, Zhu]

Asymptotic Freedom

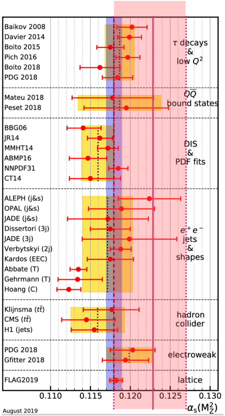
- Scaling exponents are proportional to $\alpha_s \implies$ run with p_T.
- Asymptotic Freedom by eye!

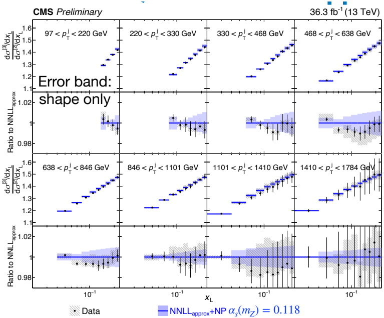




The Strong Coupling

- Proof of principle α_s can be extracted from jet substructure in complicated hadron collider environment: 4% accuracy.
- Hope to use high energies of the LHC to resolve previous tensions in α_s extractions.





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

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

Jet Substructure: Factorization

- Any quantitative result at colliders relies crucially on the seminal factorization theorems of Collins, Soper, Sterman.

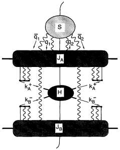
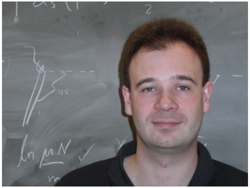
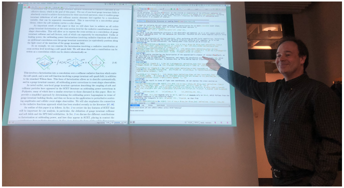
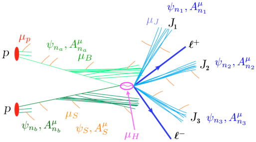


Fig. 1. General graphical contribution to the Drell-Yan cross section, corresponding to eq. (2.1). In the corresponding region in momentum space, each propagator or cut line falls into one of the subgraphs.

- Greatly extended to more differential jet substructure observables using Soft Collinear Effective Theory.

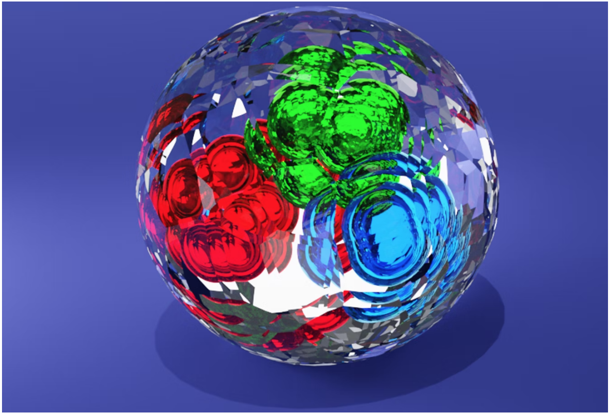






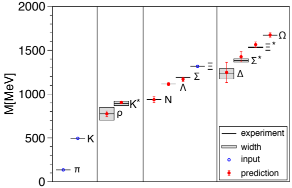
- Forms the theoretical backbone of the jet substructure program.

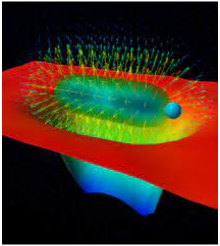
Imaging the Confinement Transition

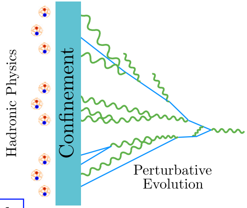


Dynamics of Hadronization

- What are the dynamics of the hadronization process?



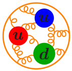


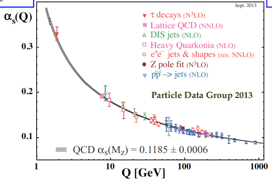


Long Time Scale
Low Energy

$\alpha_s(Q)$ ←

Short Time Scale
High Energy



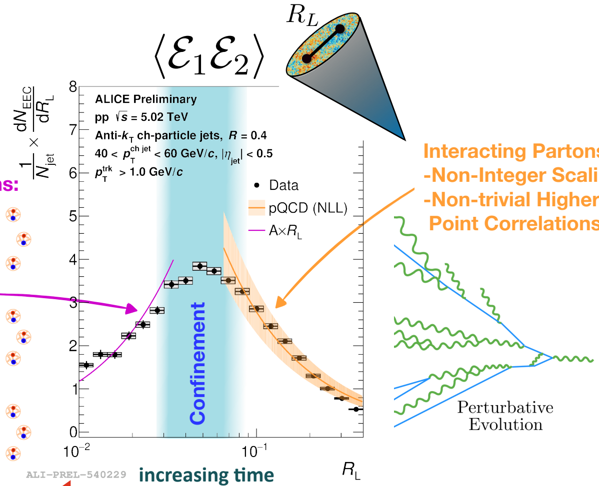


$$\hat{O} = \alpha_s + \alpha_s^2 + \cdots$$

- Can it be directly imaged in asymptotic energy flux?

The Confinement Transition

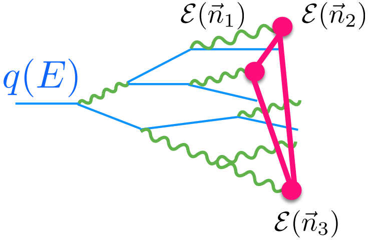
Non-Interacting Hadrons:
- Integer Scaling
- Trivial Higher Point Correlations

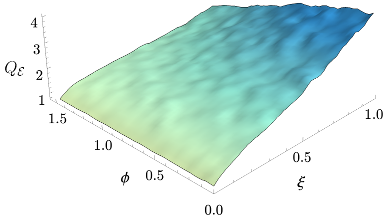


Interacting Partons:
- Non-Integer Scaling
- Non-trivial Higher Point Correlations

Small angle — increasing time — decreasing energy scale — Large angle

Non-Gaussianities in Energy Flux

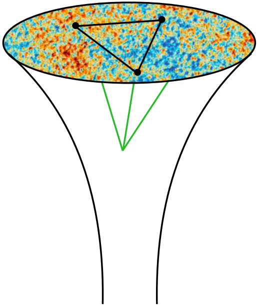


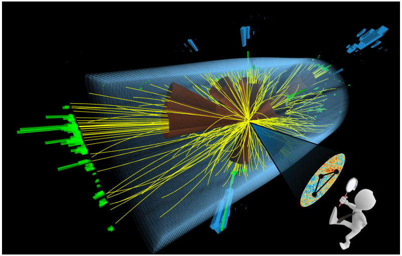


[Chen, Moult, Thaler, Zhu]

Non-Gaussianities

- Higher-point correlators probe more detailed aspects of interactions.
- e.g. Non-Gaussianities allow one to distinguish models of inflation.



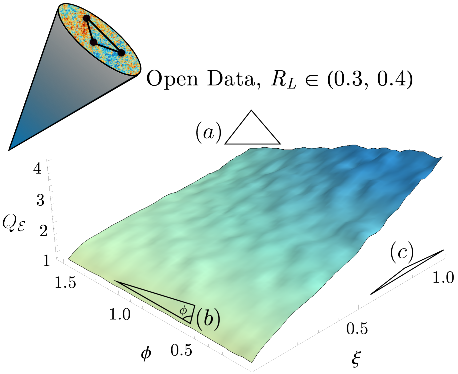


- What is the structure of higher-point functions of energy flux?

Shape Dependence of Non-Gaussianities

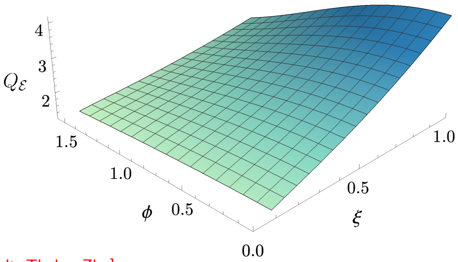
- Can directly study non-gaussianities inside high energy jets.

Open Data, $R_L \in (0.3,\, 0.4)$



$$G_{\mathcal{N}=4}(z) = \frac{1+u+v}{2uv}(1+\zeta_2) - \frac{1+v}{2uv}\log(u) - \frac{1+u}{2uv}\log(v) - (1+u+v)(\partial_u+\partial_v)\Phi(z) + \frac{(1+u^2+v^2)}{2uv}\Phi(z) + \frac{(z-\bar{z})^2(u+v+u^2+v^2+u^2v+uv^2)}{4u^2v^2}\Phi(z) + \frac{(u-1)(u+1)}{2uv^2}D_2^+(z) + \frac{(v-1)(v+1)}{2u^2v}D_2^+(1-z) + \frac{(u-v)(u+v)}{2uv}D_2^+\left(\frac{z}{z-1}\right)$$

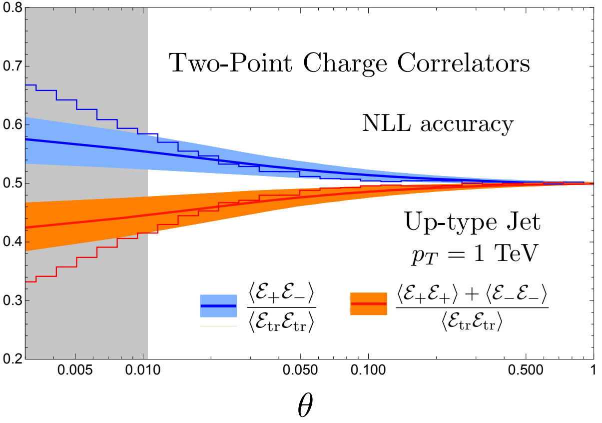
LL + LO prediction, $R_L = 0.35$



[Chen, Moult, Thaler, Zhu]

- Illustrates theoretical control over multi-point correlations!

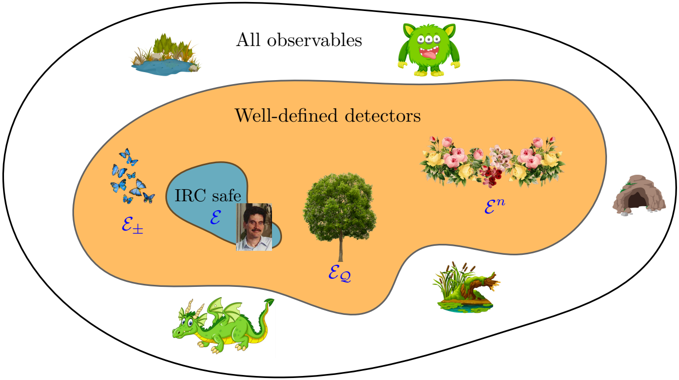
Beyond Energy Flux



[Lee, Moult]

The Space of Detectors

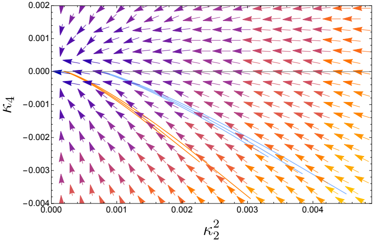
- Details of the hadronization process are encoded in the quantum numbers (charge, flavor, ...): By definition, energy flux is insensitive!
- What is the space of detectors over which we can gain theoretical control?

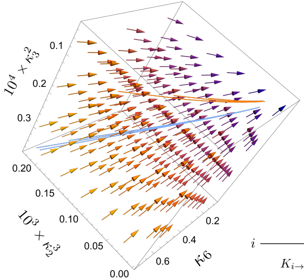


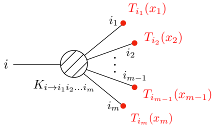
Factorization

[Chen, Jaarsma, Li, Moult, Waalewijn, Zhu]

- More general observables can be calculated by combining factorization into universal matrix elements, with the Renormalization Group.
- Tremendous recent progress in understanding renormalization group evolution of functions characterizing correlations in the hadronization process (beyond DGLAP).



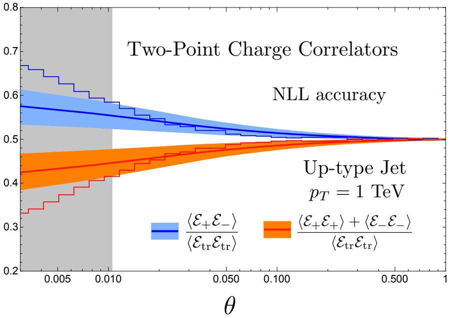


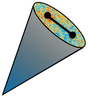


- Enables the calculation of correlations on energy flux carried by hadrons of specific quantum numbers: e.g. $\langle\Psi|\mathcal{E}_+(\hat{n}_1)\cdots\mathcal{E}_-(\hat{n}_k)|\Psi\rangle$

Charged Energy Flux

- Opposite sign hadrons exhibit enhanced small angle correlations relative to like sign hadrons.
- Not electromagnetic in nature: generated by hadronization!

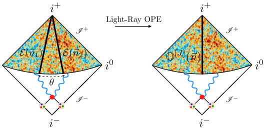




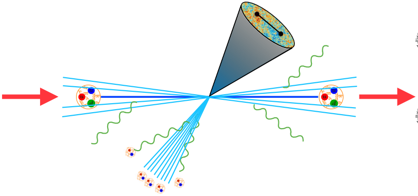
- How far can we push into the confinement transition? Experimental measurements will be crucial.

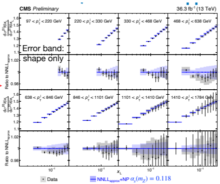
From Theory and Experiment

- In the last decade jet substructure has provided a new way of studying QCD: rapid evolution of new techniques from theory to experimental reality.



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





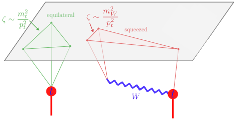
$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

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

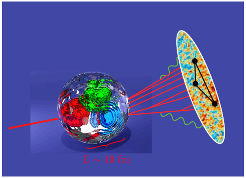
- Now we can begin to use jets as calibrated probes of more complicated systems!

Three Examples

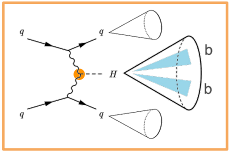
- Weighing the Top Quark



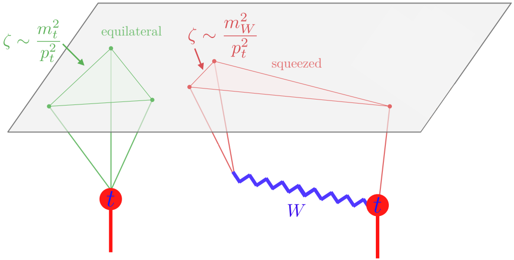
- Resolving the Scales of the Quark Gluon Plasma



- New Particles and Interactions



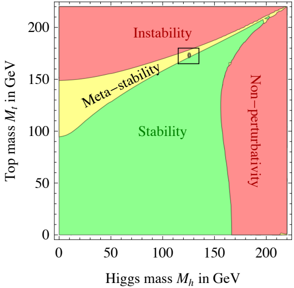
Weighing the Top Quark

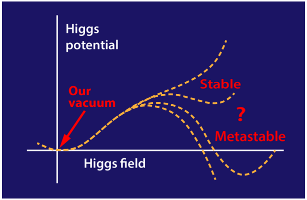


[Holguin, Moult, Pathak, Procura, Schofbeck, Schwarz]

Top Quark Mass

- 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.

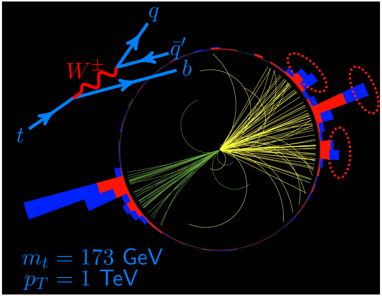


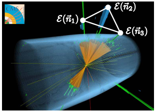


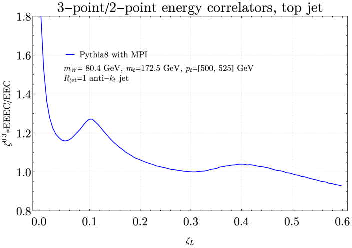
- The top quark mass is one of the most important parameters of the SM. e.g. electroweak vacuum stability/criticality, electroweak fits, etc.
- Precision extraction from experiment requires detailed understanding of QCD.

Boosted Top Quarks

- Large samples of highly boosted top quarks produced at the LHC.

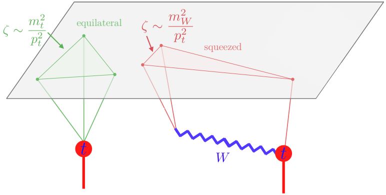


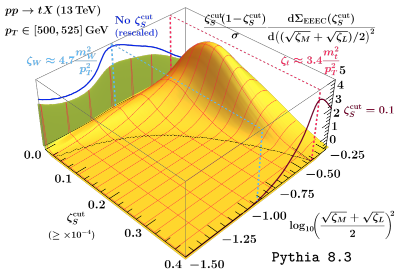


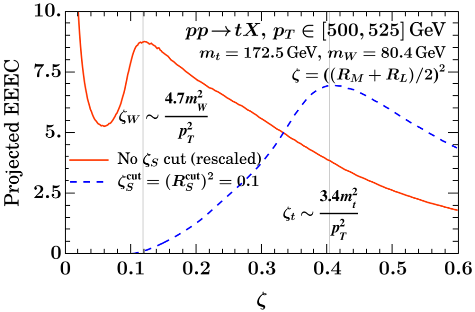


- Imprint their structure into three-point energy correlators.

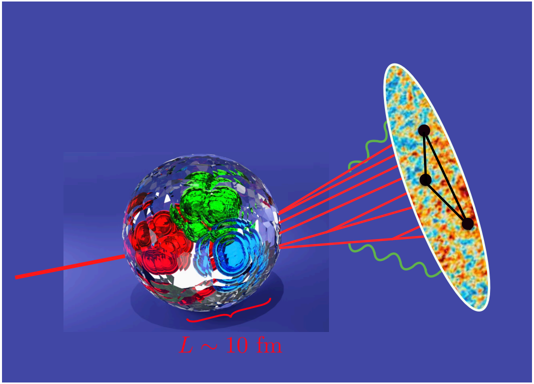
Top Quark Mass Measurement Proposal







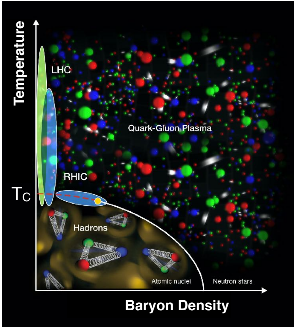
Resolving the Scales of the Quark Gluon Plasma

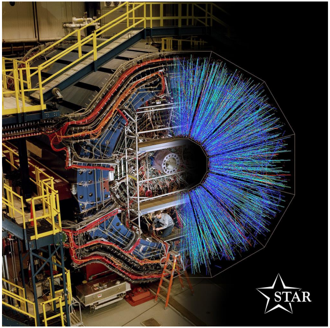


[Andres, Dominguez, Holguin, Kunnawalkam Elayavalli, Marquet, Moult]

The Quark Gluon Plasma

- Understanding extreme states of QCD matter, “the condensed matter physics of QCD”, is important for many problems ranging from early universe cosmology to neutron star mergers.

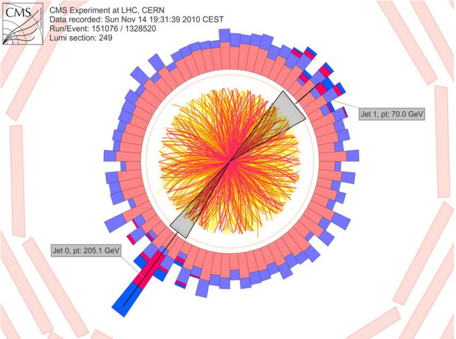


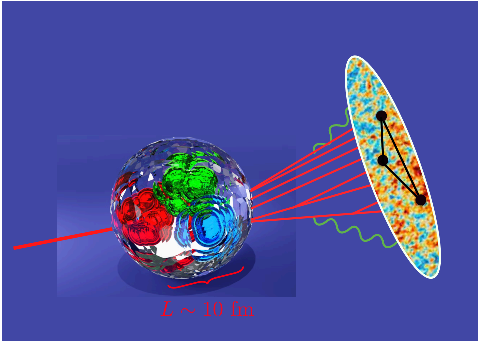


- The QGP can be produced and studied in high energy colliders, providing a primary target for new jet substructure techniques.

Imaging the Plasma

- Energetic quarks and gluons produced in the collisions shoot through the plasma, much like the classic Rutherford experiment.

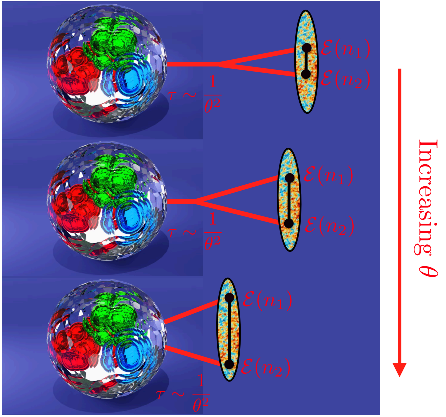


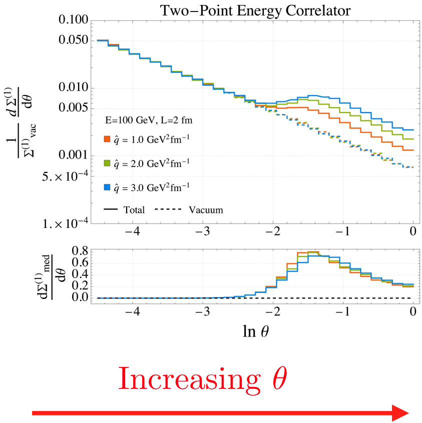


- How can we see there was a 10^{-14}m ball of plasma at the center?

Resolving the Scales of the QGP

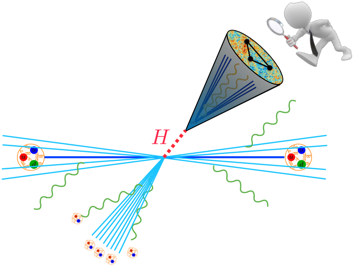
- QGP scales cleanly imprinted in two-point correlation!

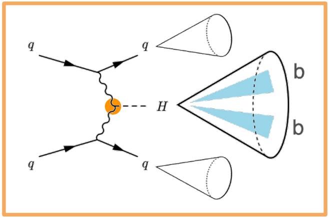




- Detailed behavior and higher point correlators probe transport, etc.
- Measurements public soon!

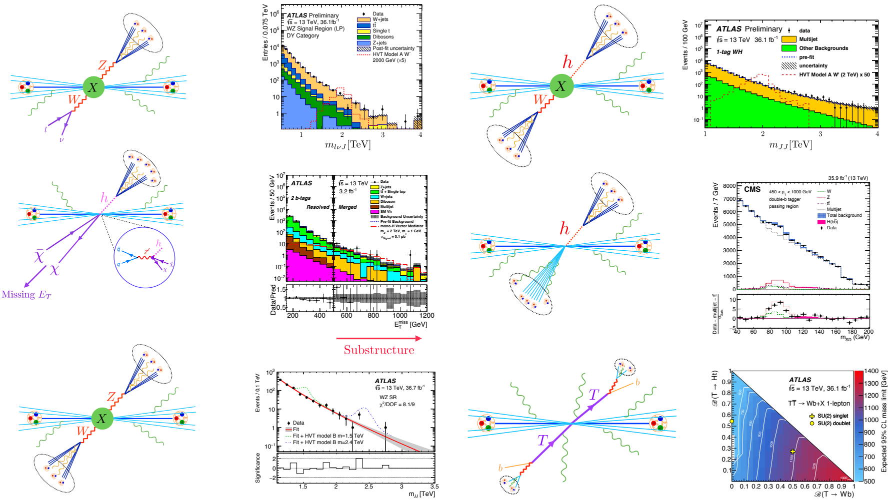
New Particles and New Interactions





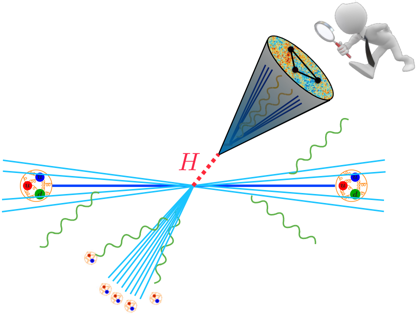
Searches at the LHC

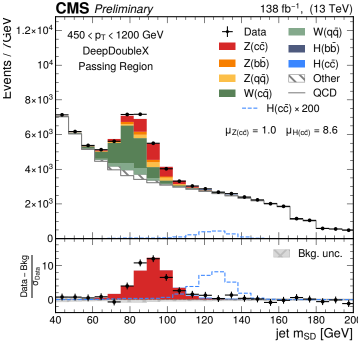
- Tremendous impact on (B)SM searches:



Charm Yukawa

- 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, $1.1 < \kappa_c < 5.5$.

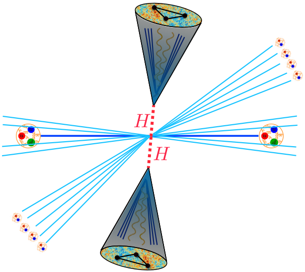


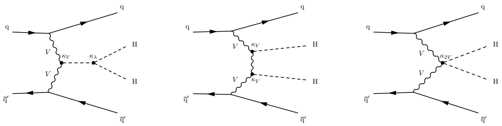


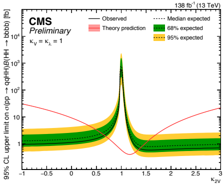
- Matches the original projected sensitivity with $3000\ \text{fb}^{-1}$!

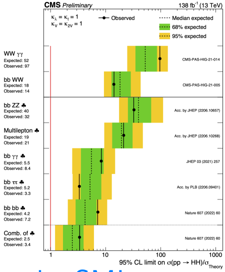
Higgs Self Interactions

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





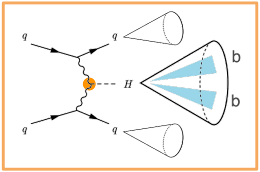


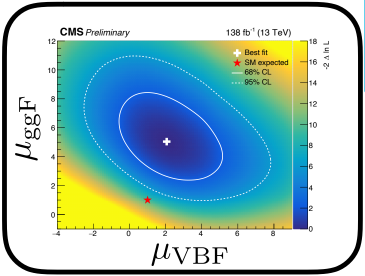


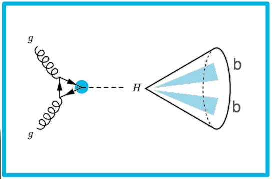
- First observation of the $VV \to HH$ coupling in the SM!

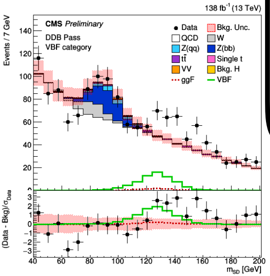
Boosted Higgs

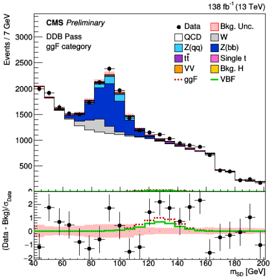
- Searches for modifications of Higgs couplings at high p_T.





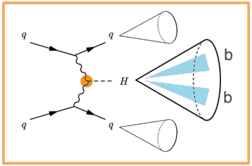




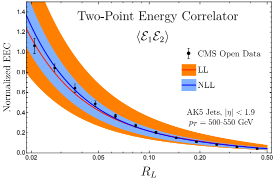


Summary

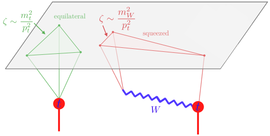
- The spectacular understanding of QCD developed over the past 50 years is being used to study the SM in new ways.

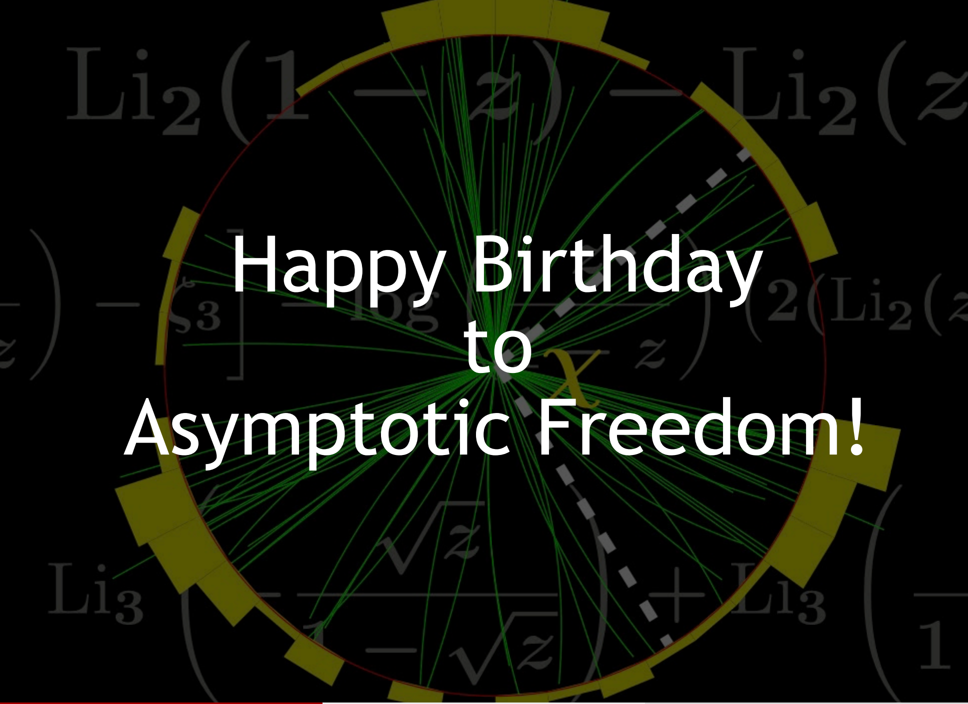


- Jet Substructure is rapidly evolving into a precision science enabling *quantitative* new ways to study the strong force.



- With the rich experimental program from HEP to nuclear physics, expect many exciting developments in the next 50!





Happy Birthday to Asymptotic Freedom!