

Resurrecting LEP

Ian Moulton
Yale



Electron-Positron Colliders

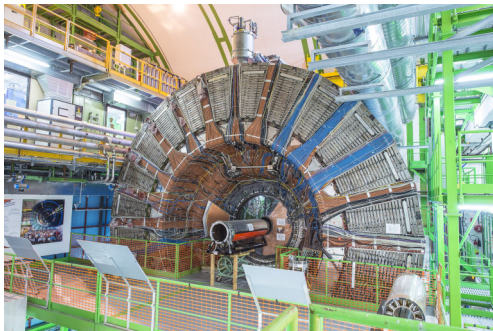
- Multiple proposals for high energy e^+e^- colliders (FCC-ee, CEPC, ...).
- Large time gap since last Z-pole collider (LEP is now a tourist exhibition). Many new theory/ AI techniques never tested on real data.

Retired DELPHI Detector

which better year than 2009 to publish a book describing the history of LEP? At the time of writing these lines the LEP experiments are going to publish their last scientific papers eight years after the end of data taking and more than thirty years after the first studies for a large electron-positron collider which eventually became LEP. It is now the right time to look back how everything has started and how this scientific project made its way so successfully from its birth to its last, scientifically dramatic years. And who else would be better placed to write the story, and not only the history, of LEP than Professor Herwig Schopper, Director General of CERN from 1981 to 1988, who not only obtained the approval of LEP but also brought its construction to a successful end during his term of office. With all his insights into the scientific, technical, political, financial and managerial aspects and challenges of such an endeavour he does not forget the human aspects; and the personal recollections and anecdotes expressed by the author help to understand the reader what it means to carry such a project through. Without LEP, we would not have the same knowledge of particle physics to day. LEP has had a strong impact on the experimental 'discovery' of the Standard Model. But LEP has not only pushed the frontier of knowledge, it also advanced the frontier of technology, of computing and of worldwide collaboration. This book is also a reminder to everybody about the duration of our projects, about the stability needed to carry them through, but also about the excitement they give to us! The exciting times of LEP which shaped generations of physicists, are over – but more are ahead of us with the turn-on of the Large Hadron Collider (LHC). LEP has been making way for this new global project of particle physics at CERN, which will push further ahead our knowledge of the microcosm and of the early universe. But LEP will live on in physics text books and as a model for international collaboration beyond all political boundaries. As stated by the author, with LEP and its international exploitation, CERN has become a laboratory serving the worldwide community of elementary particle physicists. This book addresses the specialists as well as the interested public, you don't have to know particle physics but you will learn much. Enjoy reading as much as I did.

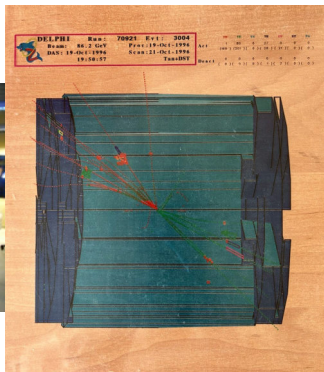
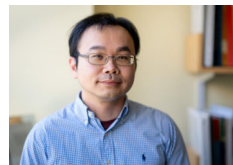
CERN, February 2009

Rolf-Dieter Heuer
Director-General CERN



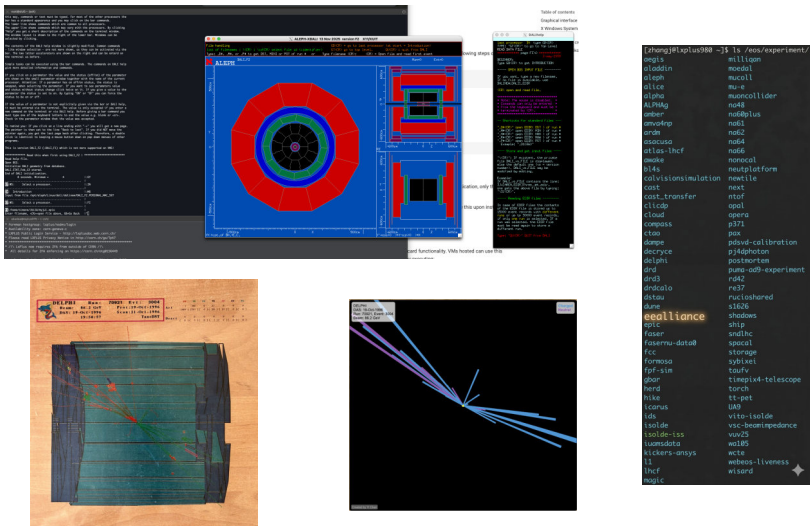
LEP Archival Data

- ALEPH and DELPHI invested significantly in data preservation.
- In 2017, YenJie Lee initiated a project to resurrect the LEP data.



Resurrected LEP Datasets

- ALEPH and DELPHI datasets retrieved!



Resurrected LEP Datasets

- After heroic efforts there are modernized ALEPH and DELPHI datasets: QCD ALEPH LEP-I dataset is 28GB!
- Rapidly growing experimental effort focused on LEP archival data.

e^+e^- alliance



Janice Chen (MIT)



Austin Baty (UIC)



Chris McGinn (MIT)



Michael Peters (MIT)



Hannah Bossi (MIT)



Tzu-An Sheng (MIT)



Luna Chen
(Vanderbilt)



Jesse Thaler
(MIT)



Jingyu Zhang
(Vanderbilt)



Luke Lu
(Vanderbilt)



Anthony Badea
(UChicago)



Yen-Jie Lee (MIT)



Gian Michele
Innocenti (MIT)



Marcello
Maggi (INFN)



Paoti Chang (NTU)



Ben Nachman
(Stanford/SLAC)



SanDisk 32GB
Ultra USB 3....

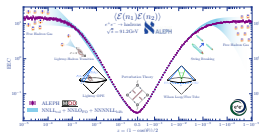
\$8.20

Amazon.com

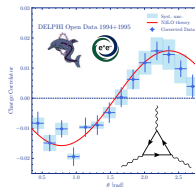
An Opportunity

- Archival LEP datasets, combined with modern theory and data analysis techniques, present a tremendous opportunity for

- Precision QCD Measurements



- Precision Electroweak Measurements



- Searches for Physics Beyond the Standard Model



Energy Correlators from Partons to Hadrons

Energy Correlators from Partons to Hadrons: Unveiling the Dynamics of the Strong Interactions with Archival ALEPH Data

Hannah Bossi,¹ Yi Chen,² Yu-Chen Chen,¹ Max Jaarsma,^{3,4} Yibei Li,⁵ Jingyu Zhang,²
Ian Mould,⁶ Wouter Waalewijn,^{3,4} Hua Xing Zhu,^{7,8} Anthony Badea,⁹ Austin Baty,¹⁰
Christopher McGinn,¹ Gian Michele Innocenti,¹ Marcello Maggi,¹¹ and Yen-Jie Lee¹

Which better year than 2009 to publish a book describing the history of LEP? At the time of writing these lines the LEP experiments are going to publish their last scientific papers eight years after the end of data taking and more than thirty years after the first studies for a large electron-positron collider which eventually became LEP. It is now the right time to look back how everything has started and how this scientific project made its way so successfully from its birth to its last, scientifically dramatic years. And who else would be better placed to write the story, and not only the history, of LEP than Professor Herwig Schopper, Director General of CERN from 1981 to 1988, who not only obtained the approval of LEP but also brought its construction to a successful end during his term of office. With all his insights into the scientific, technical, political, financial and managerial aspects and challenges of such an endeavour he does not forget the human aspects, and the personal reflections and anecdotes expressed by the author help to understand the reader what it means to carry such a project through. Without LEP, we would not have the same knowledge of particle physics to day: LEP has had a strong impact on the experimental 'discovery' of the Standard Model. But LEP has not only pushed the frontier of knowledge, it also advanced the frontier of technology, of computing and of worldwide collaboration. This book is also a reminder to everybody about the duration of our projects, about the stability needed to carry them through, but also about the excitement they give to us! The exciting times of LEP which shaped generations of physicists, are over – but more are ahead of us with the turn-on of the Large Hadron Collider (LHC). LEP has been making way for this new global project of particle physics at CERN, which will push further ahead our knowledge of the microcosm and of the early universe. But LEP will live on in physics text books and as a model for international collaboration beyond all political boundaries. As stated by the author, with LEP and its international exploitation, CERN has become a laboratory serving the worldwide community of elementary particle physicists. This book addresses the specialists as well as the interested public, you don't have to know particle physics but you will learn much. Enjoy reading as much as I did.

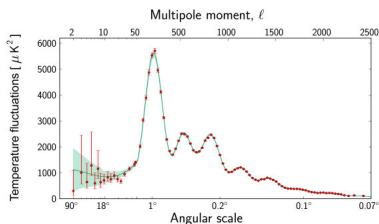
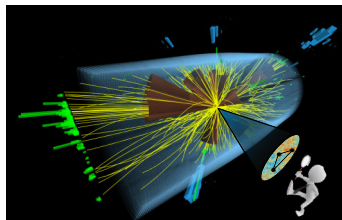
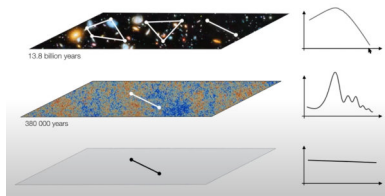
CERN, February 2009

Rolf Dieter Hauer
Director-General CERN



The CMB of QCD

- LHC re-ignited a decades long quest to achieve a precision description of energy flux in the “little bangs” of QCD collisions.

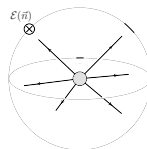


50 Years of Energy Flux in Yang-Mills

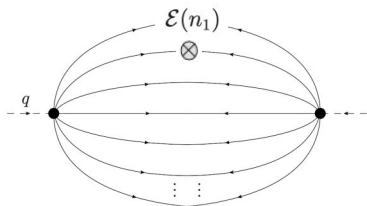
- The expectation value of energy flux, $\langle \mathcal{E}(\vec{n}_1) \rangle$, at a fixed angle on the celestial sphere is calculable in perturbation theory.
(Sterman, Dec 1975)

states. To make this idea more quantitative we define for any state $\underline{a}$, an "angular energy current" in the e^+e^- CM frame:

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



George Sterman



$$\int d^4x e^{iQ \cdot x} \langle 0 | J(x) \mathcal{E}(\hat{n}) J(0) | 0 \rangle$$

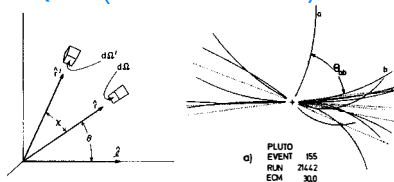
- "Energy Flux Becomes the Focus of Calculability"

Energy Correlators

- Correlators of energy flow operators $\langle \mathcal{E}(\vec{n}_1) \cdots \mathcal{E}(\vec{n}_k) \rangle$ characterize the final state in collider experiments in QCD (Ellis et al. 1977)



Stephen Ellis



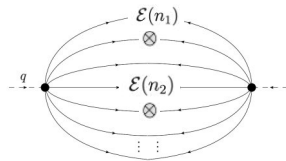
Energy Correlations in electron - Positron Annihilation: Testing QCD

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

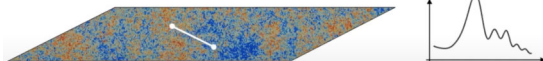
13 pages
Published in: *Phys.Rev.Lett.* 41 (1978) 1585
DOI: 10.1103/PhysRevLett.41.1585
Report number: RLO-1388-759
View in: OSTI Information Bridge Server, ADS Abstract Service

cite claim

reference search 454 citations

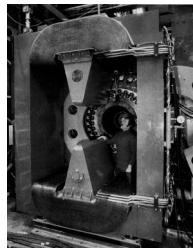
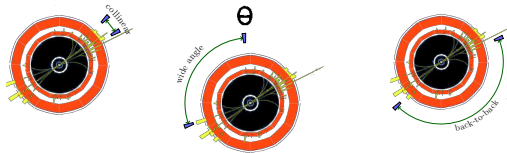
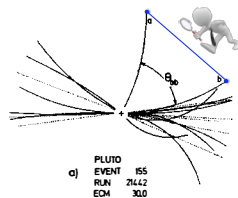
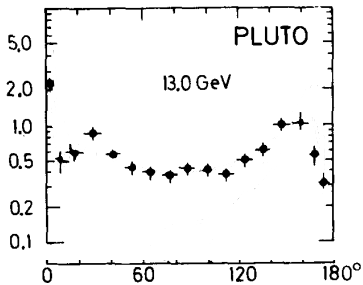


- Analogous to correlators in the CMB.



Energy Correlators at PLUTO

- First measurement of the energy correlator by PLUTO (1979).

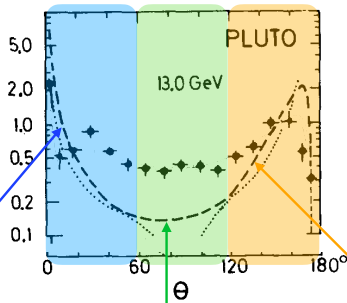
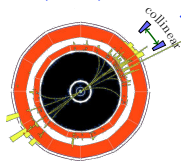


Theory Meets Data

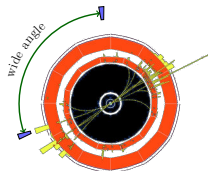
- First calculation of energy flux correlations from the microscopic QCD Lagrangian:



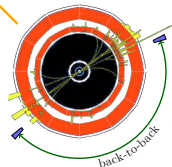
Konishi, Ukawa, Veneziano



Basham, Brown, Ellis, Love



Parisi, Petronzio



Energy Correlators: Beyond QCD

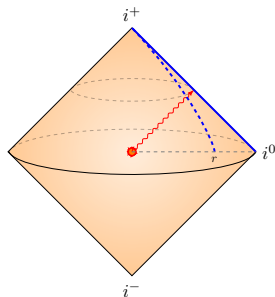
- Energy Correlators are interesting observables for characterizing generic quantum theories. (Hofman, Maldacena, 2008)

Conformal collider physics: Energy and charge correlations

Diego M. Hofman^a and Juan Maldacena^b



$$\begin{aligned}\text{Hammer} &= \sum_i h_i \mathcal{O}_i \\ \text{Camera} &= \sum_j c_j \mathcal{D}_j\end{aligned}$$

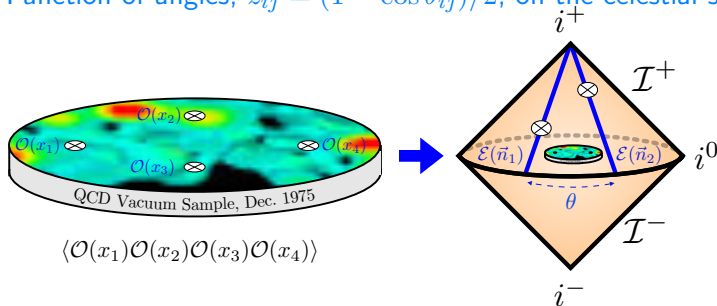


$$\text{Camera} \longleftrightarrow \mathcal{E}(\vec{n}) = \lim_{r \rightarrow \infty} r^2 \int_0^\infty dt \, n^i T_{0i}(t, r\vec{n})$$

- Cleanly relates correlations in asymptotic energy flux with properties of the microscopic field theory.

Energy Correlators

- Provides a direct relation between correlation functions of local operators, and measurements of asymptotic fluxes.
- Function of angles, $z_{ij} = (1 - \cos \theta_{ij})/2$, on the celestial sphere.

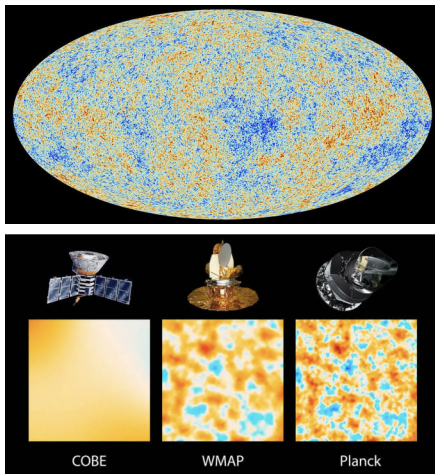


$$\int d^4x e^{iq \cdot x} \langle \mathcal{O}(x) \mathcal{E}(n_1) \mathcal{E}(n_2) \mathcal{O}(0) \rangle$$

- Can use insights from simpler theories to sharpen our understanding of real world QCD at colliders.

A Fundamental Limitation

- Correlator measurements fundamentally limited by detector resolution.



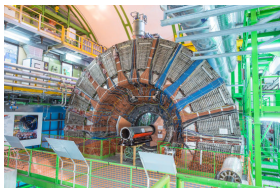
- How can we do better without a new detector?

Enhancing LEPs Resolution

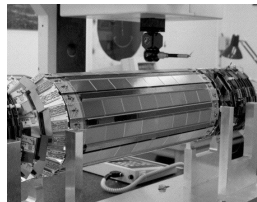
- Charged particles (tracks) can be measured with exceptional resolution, neutral particles cannot.



=



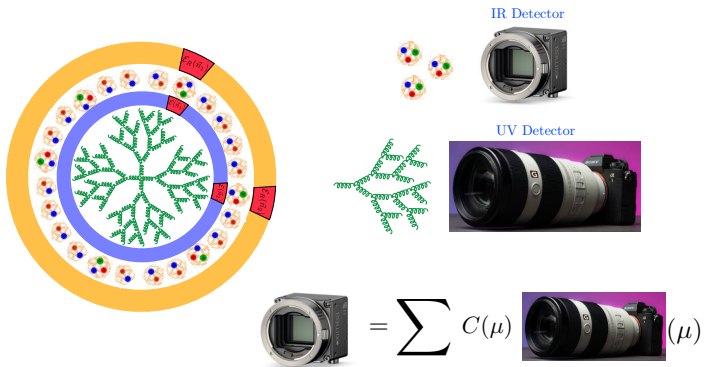
=



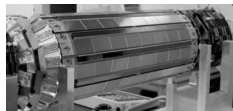
- Kinoshita-Lee-Nauenberg theorem requires sum over all states to achieve an infrared finite answer: “The expectation value of energy flux, $\langle \mathcal{E}(\vec{n}_1) \rangle$, is calculable in perturbation theory.”

Enhancing LEPs Resolution

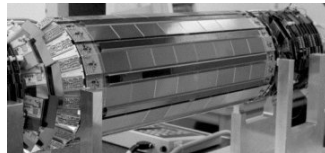
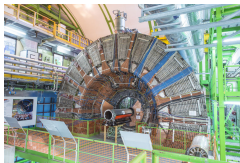
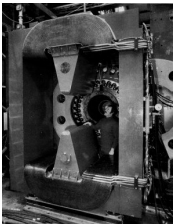
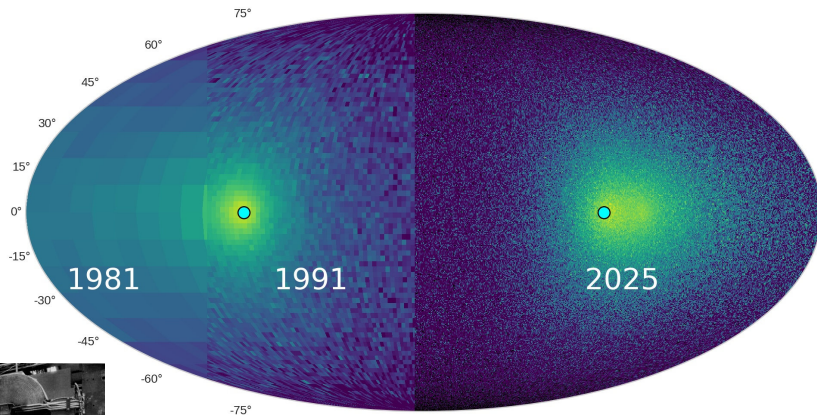
- Modern Effective Field Theory techniques enable systematic matching between UV detectors (quarks/ gluons) and IR detectors (hadrons).



- Enables precision theoretical calculations for measurements with tracking detectors.



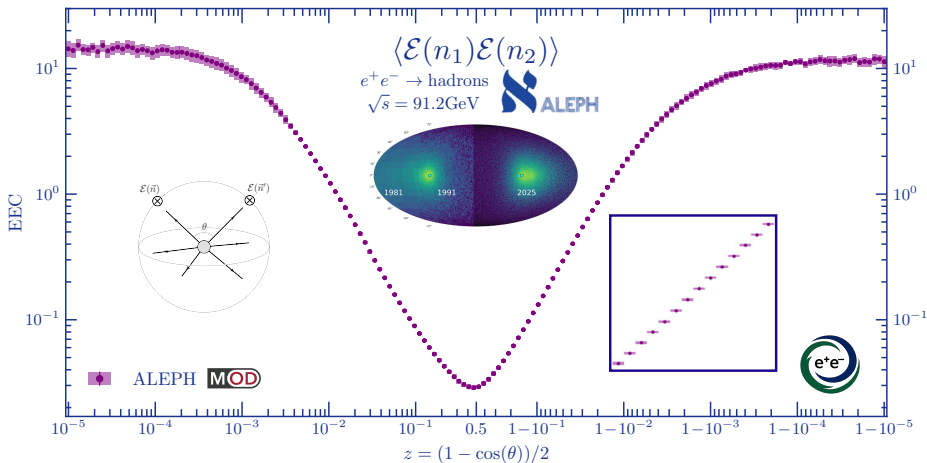
QCD Comes into Focus



QCD in Focus

Energy Correlators from Partons to Hadrons: Unveiling the Dynamics of the Strong Interactions with Archival ALEPH Data

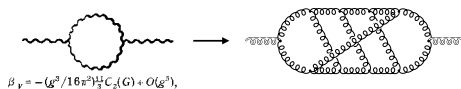
Hannah Bossi,¹ Yi Chen,² Yu-Chen Chen,¹ Max Jaarsma,^{3,4} Yibei Li,⁵ Jingyu Zhang,²
Ian Mould,⁶ Wouter Waalewijn,^{3,4} Hua Xing Zhu,^{7,8} Anthony Badea,⁹ Austin Baty,¹⁰
Christopher McGinn,¹ Gian Michele Innocenti,¹ Marcello Maggi,¹¹ and Yen-Jie Lee¹



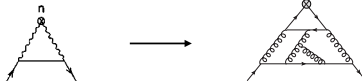
50 Years of Advances in Perturbative QCD



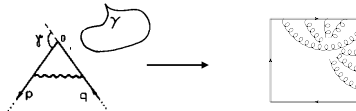
- β functions



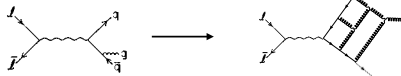
- Twist-2 operators



- Cusped Wilson loops

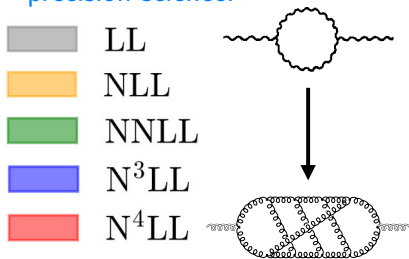


- Scattering Amplitudes



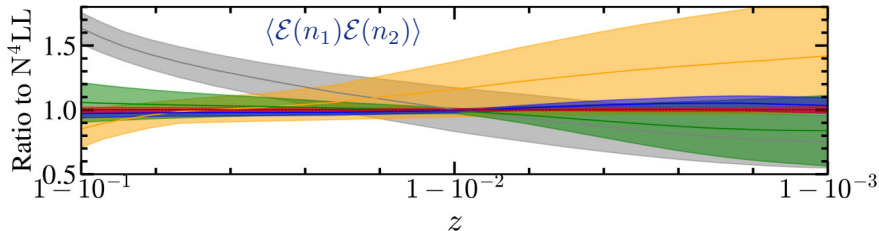
50 Years of Advances in Perturbative QCD

- Transforms theoretical predictions from a qualitative description to a precision science.



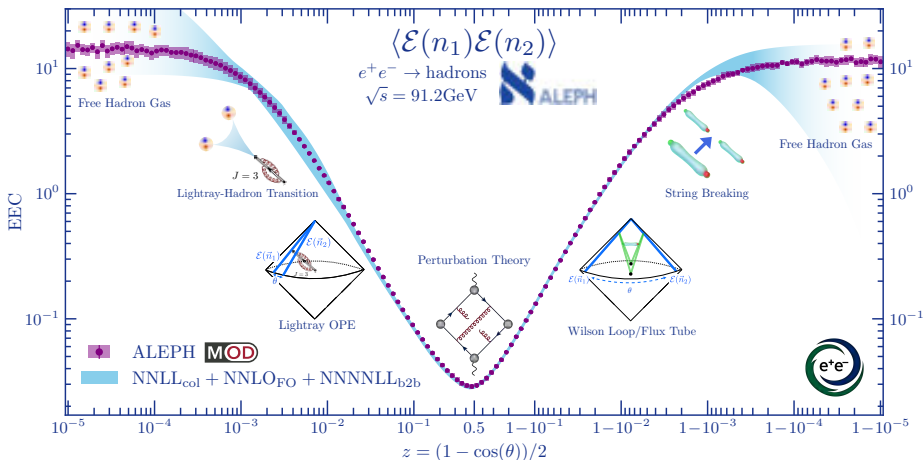
$$\beta_V = -(g^3/16\pi^2) \frac{11}{3} C_2(G) + O(g^5),$$

$$A_s = C_2^2 \left(\frac{8056205}{3008} - \frac{1659}{81} \zeta_3 + \frac{121}{6} \zeta_4 - \frac{1045}{18} \zeta_5 \right) + \frac{g^{\mu\nu} g^{\rho\sigma}}{N_A} C_2 \left(\frac{514}{3} - \frac{19716}{9} \zeta_3 - \frac{568}{3} \zeta_4 + \frac{15400}{3} \zeta_5 \right) + C_2^2 T_F n_f \left(\frac{5048059}{972} + \frac{35955}{81} \zeta_3 - \frac{783}{3} \zeta_4 + \frac{11200}{3} \zeta_5 \right) + C_2^2 C_F T_F n_f \left(\frac{6140395}{9384} + \frac{146}{3} \zeta_3 - \frac{862}{3} \zeta_4 + \frac{8720}{3} \zeta_5 \right) + C_2^2 C_F T_F n_f \left(\frac{548732}{81} - \frac{58561}{27} \zeta_3 - \frac{484}{3} \zeta_4 + \frac{12020}{3} \zeta_5 \right) + C_2 C_F^2 T_F n_f \left(\frac{5717}{3} - \frac{7596}{3} \zeta_3 - \frac{7440}{3} \zeta_4 + \frac{4172}{3} \zeta_5 + 128 \zeta_6 \right) + C_2 C_F^2 T_F n_f \left(\frac{261}{N_A} - \frac{20732}{9} \zeta_3 + \frac{352}{3} \zeta_4 - \frac{4000}{9} \zeta_5 \right) + \frac{g^{\mu\nu} g^{\rho\sigma}}{N_A} C_2 n_f \left(\frac{1531}{8} - \frac{127736}{9} \zeta_3 + \frac{2288}{3} \zeta_4 + \frac{67380}{9} \zeta_5 \right) + \frac{g^{\mu\nu} g^{\rho\sigma}}{N_A} C_F n_f \left(-\frac{320}{3} - \frac{1280}{3} \zeta_3 + \frac{6400}{3} \zeta_4 \right) + C_2^2 T_F^2 n_f^2 \left(\frac{843867}{1080} - \frac{16446}{45} \zeta_3 - \frac{104}{3} \zeta_4 - \frac{2280}{3} \zeta_5 \right) + C_2^2 T_F^2 n_f^2 \left(\frac{5701}{720} - \frac{26452}{27} \zeta_3 - \frac{844}{3} \zeta_4 + \frac{1680}{3} \zeta_5 \right) + C_2^2 C_F T_F^2 n_f^2 \left(\frac{31543}{18} - \frac{26528}{27} \zeta_3 - \frac{1144}{3} \zeta_4 - \frac{6480}{3} \zeta_5 \right) + C_2^2 T_F^2 n_f^2 \left(\frac{2055}{9} - \frac{2514}{3} \zeta_3 + \frac{112}{3} \zeta_4 \right) + C_2^2 T_F^2 n_f^2 \left(\frac{2055}{9} - \frac{2514}{3} \zeta_3 + \frac{112}{3} \zeta_4 \right) + \frac{g^{\mu\nu} g^{\rho\sigma}}{N_A} T_F n_f^2 \left(\frac{3690}{9} - \frac{40160}{9} \zeta_3 - \frac{832}{3} \zeta_4 - \frac{1280}{9} \zeta_5 \right) + \frac{g^{\mu\nu} g^{\rho\sigma}}{N_A} C_2 n_f^2 \left(\frac{7154}{3} - \frac{48536}{9} \zeta_3 - \frac{704}{3} \zeta_4 + \frac{2240}{9} \zeta_5 \right) + C_2^2 T_F^2 n_f^2 \left(\frac{4160}{N_A} - \frac{5120}{3} \zeta_3 + \frac{12800}{3} \zeta_4 \right) + C_2^2 T_F^2 n_f^2 \left(\frac{2055}{9} - \frac{2514}{3} \zeta_3 + \frac{112}{3} \zeta_4 \right) + C_2 C_F T_F^2 n_f^2 \left(\frac{736}{81} - \frac{5680}{81} \zeta_3 + \frac{224}{3} \zeta_4 \right) + C_2^2 T_F^2 n_f^2 \left(\frac{6080}{9} - \frac{70360}{9} \zeta_3 - \frac{352}{3} \zeta_4 \right) + C_2^2 T_F^2 n_f^2 \left(\frac{3520}{3} - \frac{26528}{3} \zeta_3 + \frac{256}{3} \zeta_4 + \frac{1280}{3} \zeta_5 \right) + C_2 T_F^2 n_f^2 \left(\frac{205}{243} - \frac{648}{81} \zeta_3 - \frac{806}{243} \zeta_4 + \frac{128}{27} \zeta_5 \right).$$



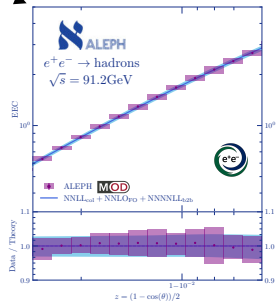
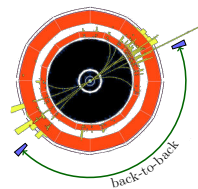
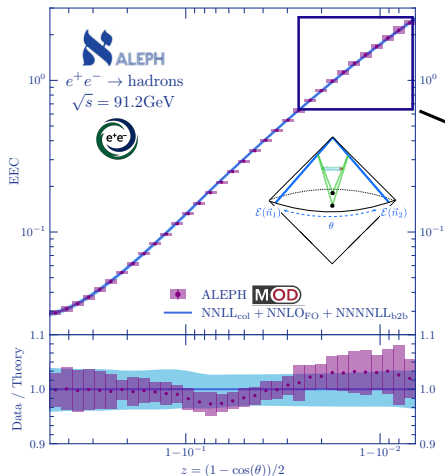
Energy Correlators from Partons to Hadrons

- Most precise image ever made of correlations in QCD energy flux.



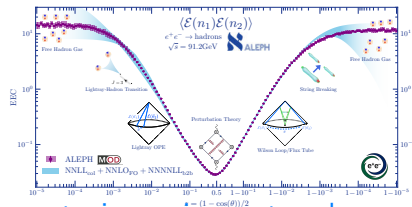
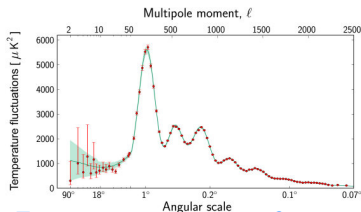
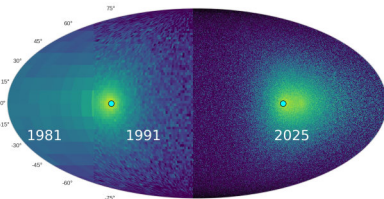
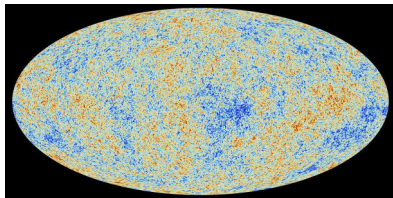
Precision QCD

- Percent level understanding of QCD energy flux.



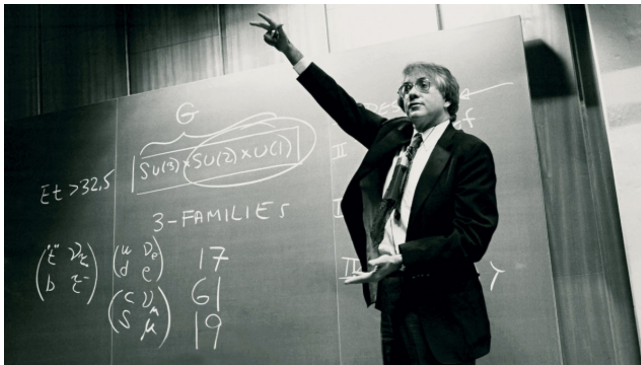
A New Era of Theory-Data Comparison

- Achieves a description of the QCD analog of the “CMB” for the simplest e^+e^- “little bangs”.



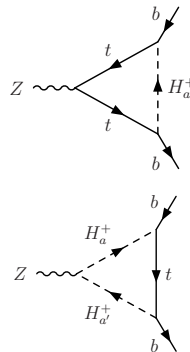
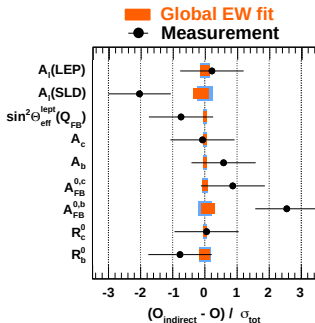
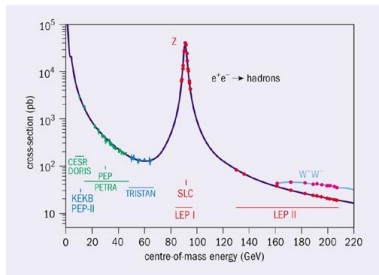
- Exciting opportunity for α_s measurements, improving parton showers, and sharpening our understanding of gauge theory phenomena.

Reviving the Precision Electroweak Program



Electroweak Precision

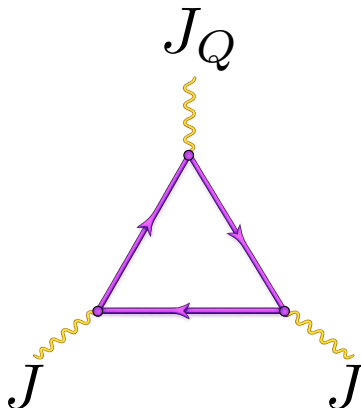
- The lack of explicit new physics at the LHC has shifted attention to precision measurements.
- Precision Electroweak data still dominated by LEP
 $\Rightarrow$ uncertainties dominated by QCD.



- Archival data combined with new theoretical techniques presents an opportunity to modernize the precision electroweak program.

Anomalies

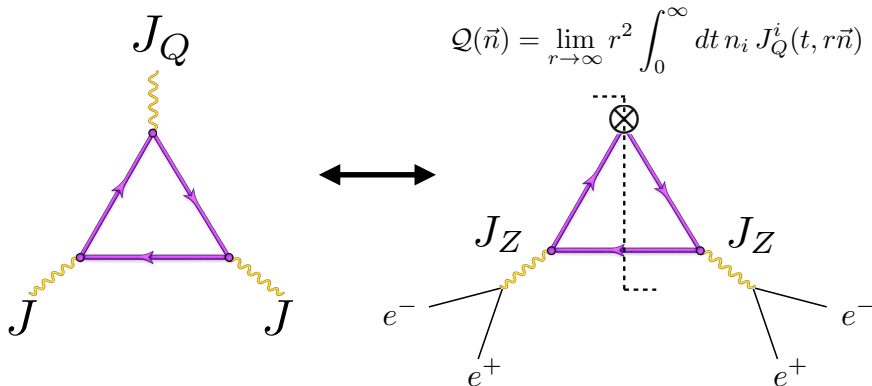
- Anomalies are fundamental aspects of quantum field theories



- Do they have a macroscopic impact at colliders?

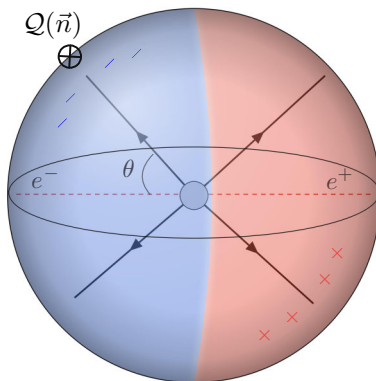
Anomalies and Charge Correlators

- Triangle diagram can be directly accessed by the measurement of a charge correlator on the Z-pole.



Anomalies and Forward-Backward Asymmetries

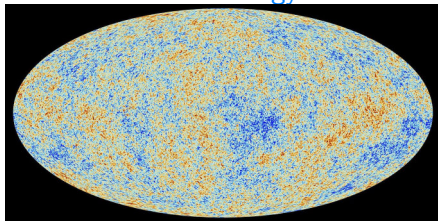
- Anomalies generate asymmetries in charge flux.



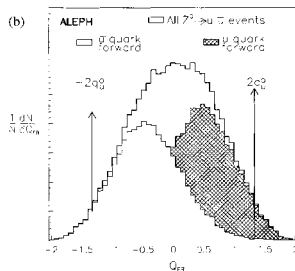
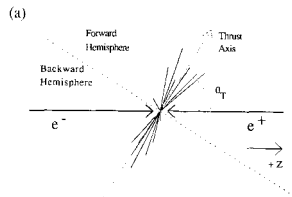
$$\langle J Q(\vec{n}) J \rangle \sim i \epsilon_{jlk} \epsilon_j^* \epsilon_l n_k \sim \cos \theta$$

Charge Correlators

- Recent push to transition from jets to correlators has been very successful for energy flux.



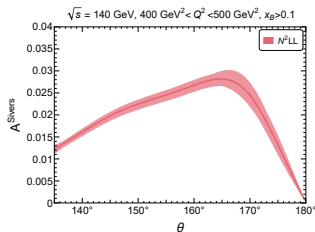
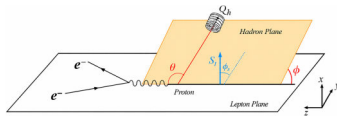
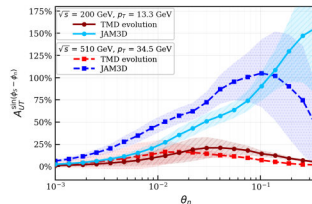
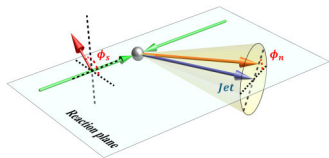
- The charge of jets has been measured starting with LEP.



- Can correlations in charge actually be measured in experiment?

Other Applications of Charge Correlators

- Many recent proposals to use charge correlators in nuclear physics (See talk by Dingyu Shao).



- Would like to show experimental feasibility of charge correlators.

First Measurement of Charge Flux

**First measurement of the one-point charge correlator
in e^+e^- collisions at $\sqrt{s} = 91.2$ GeV with DELPHI
Open Data**

Jingyu Zhang,^a Yi Chen,^a Kyle Lee,^b Ian Moul,^c Cristian Baldenegro,^d Hannah Bossi,^d Yen-Jie Lee^d

^a*Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee, USA*

^b*High Energy Physics Division, Argonne National Laboratory, Lemont, IL, USA*

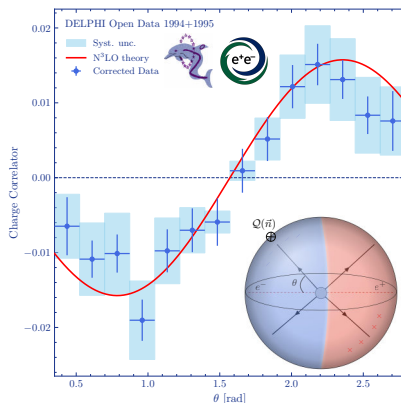
^c*Department of Physics, Yale University, New Haven, CT 06511, USA*

^d*Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*

- Extends connection between theory and experiment in the “correlator program”.

Anomalous Charge Flux

- First measurement of charge correlator.

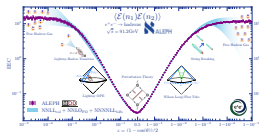


- Newly achieved precision in QCD calculations + archival data
⇒ opens the door to a re-imagined precision electroweak program.

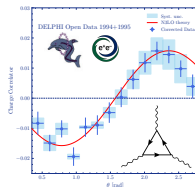
An Opportunity

- Archival LEP datasets, combined with modern theory and data analysis techniques, present a tremendous opportunity for

- Precision QCD Measurements



- Precision Electroweak Measurements



- Searches for Physics Beyond the Standard Model



Thanks!