

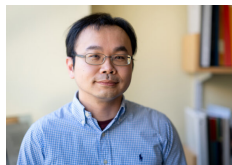
Resurrecting LEP

Ian Moutl
Yale



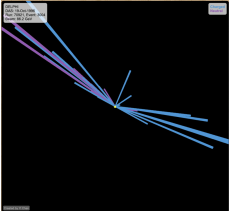
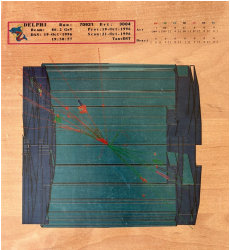
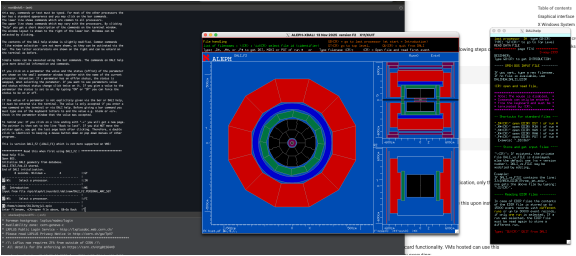
LEP Archival Data

- 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!



```
[zhong]@leplus980 ~$ ls /eos/experiment/
aegis
aladdin
aleph
alice
amuoncollider
ALPHAg
amber
amv4trp
arcs
asacusa
atlas-lhcf
awake
bl4s
collisionsimulation
cost
cost_transfer
clickap
cloud
compass
ctao
dampc
decryce
pj4photon
postmortem
pms-a09-experiment
r642
rdcalo
dstau
rucioshared
dune
ealliance
epic
faser
fasermu-data0
fcc
Formosa
fpf-sin
gbar
herd
hike
lcanus
lds
lsole
lsole-ss
luansdata
klickers-ansys
l1
lhcf
magic
million
muoncoll
mu8
naucollider
na48
na60plus
na61
na62
na64
na66
nanocal
neutplatform
newtile
next
ntof
opal
opera
p371
pix
pdsvd-calibration
pj4photon
postmortem
pms-a09-experiment
r642
re37
rucioshared
s1626
shadows
spic
sndlhc
spocal
storage
sybixnet
taufy
timepix4-telescope
torch
ti-pet
l00
vito-1solde
vsc-beamimpedance
vuv25
wa185
wcte
wboos-liveness
wisard
```

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)



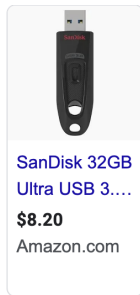
Marcello Maggi (INFN)



Paoti Chang (NTU)



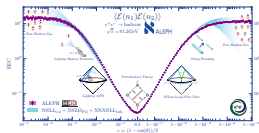
Ben Nachman (Stanford/SLAC)



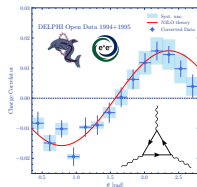
An Opportunity

- 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 recollections expressed by the author help us 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.

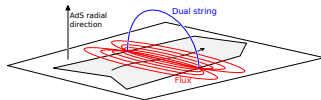
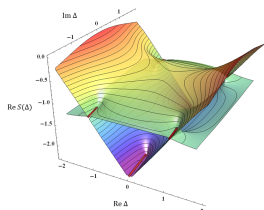
CERN, February 2009

Rolf Dieter Heuer
Director-General CERN



Phenomena in Gauge Theories

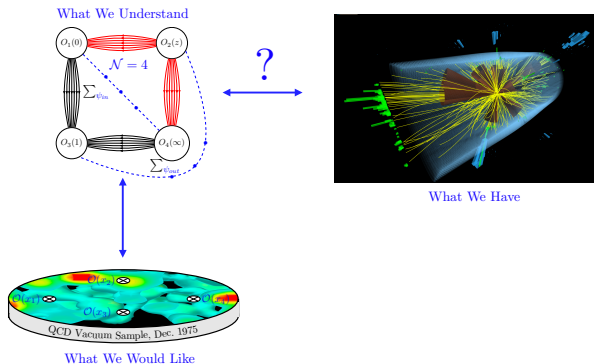
- Tremendous progress in the understanding of gauge theories from simplified theories.
- Has led to a qualitative, and sometimes quantitative, understanding of many observables (spectrum, Wilson loops, ...)



- Despite this progress, sharpening this picture for real world QCD remains an extraordinary challenge.

QCD in the Real World

- The beautiful aspect of QCD is that it is real
 \implies we can (in principle) access all its phenomena experimentally.



- Challenging to identify microscopic phenomenon in QCD experiments
 \implies link between experiment and recent progress in field theory lost.

Energy Correlators: Beyond QCD

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

Conformal collider physics:
Energy and charge correlations

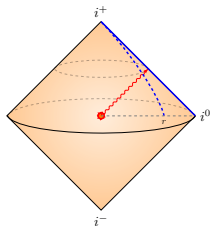
Diego M. Hofman^a and Juan Maldacena^b



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

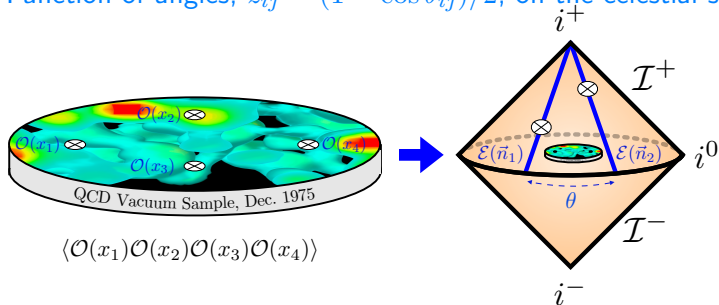


$$\mathcal{E}(\vec{n}) = \lim_{r \rightarrow \infty} r^2 \int_0^\infty dt n^i T_{0i}(t, r\vec{n})$$



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.

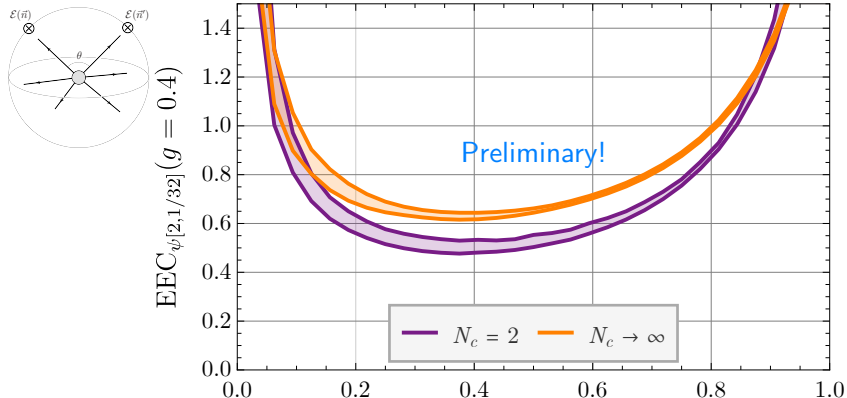


- Can use insights from simpler theories to sharpen our understanding of real world QCD at colliders.

Energy Correlator in $\mathcal{N} = 4$ SYM

- The energy correlator can be computed non-perturbatively in $\mathcal{N} = 4$ SYM using the numerical conformal bootstrap + integrability.

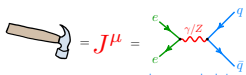
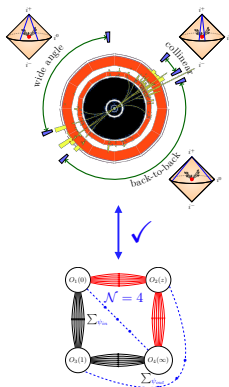
[Dempsey, Karlsson, Pufu, Zhiboedov, Zahraee]



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

Energy Correlators in Experiment

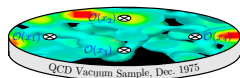
- We can directly measure the $\langle J\mathcal{E}(n_1)\mathcal{E}(n_2)J \rangle$ from angular correlations in e^+e^- collisions:



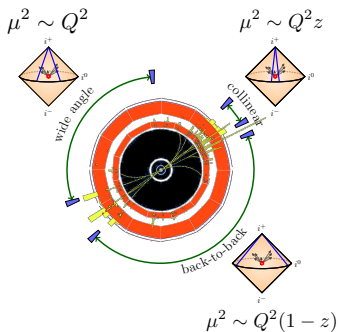
- Provides a sharp relation between experimental observables and the $\langle JTTJ \rangle$ four-point function.

Studying Confinement with Energy Correlators

- The measurement of the energy correlators probes the dynamics of QCD at the scale $Q^2 z$ or $Q^2(1-z) \implies$ probe the theory over multiple orders of magnitude for a fixed collider energy.



$$\mu^2 \sim \frac{1}{(x_i - x_j)^2}$$

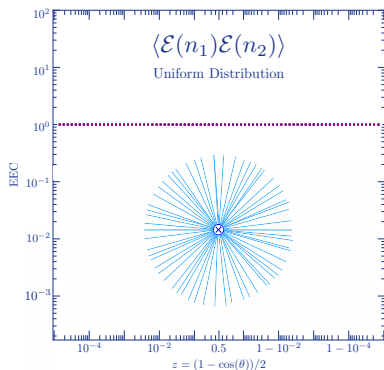


- Given sufficient angular resolution, one can achieve sub-confinement resolution, and observe the transition from partons to hadrons.

Toy Worlds

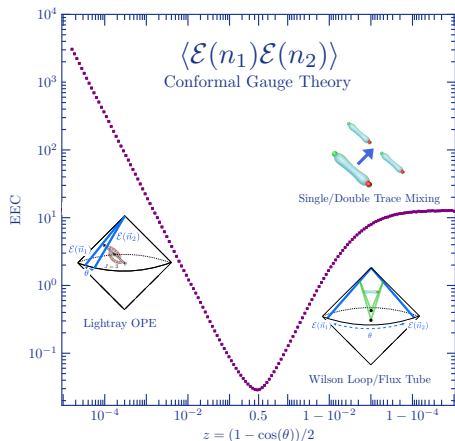
- We can first consider “data” in toy worlds.
- Free theory with a large charge operator: ϕ^k

$$\langle \mathcal{E}(\hat{n}_1) \mathcal{E}(\hat{n}_2) \rangle_{\phi^k} = 1 + \frac{1}{k} \left(\frac{3}{2} \delta(z) + (9z - 6) \right) + \mathcal{O}(1/k^2)$$



Toy Worlds

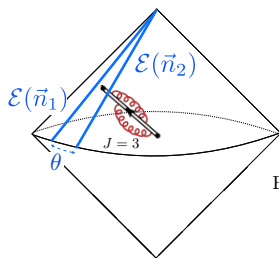
- Conformal gauge theory at (weakish) coupling.
- Kinematic limits cleanly probe the low spin ($J = 3$) and high spin ($J \rightarrow \infty$) limits of twist-2 operators.



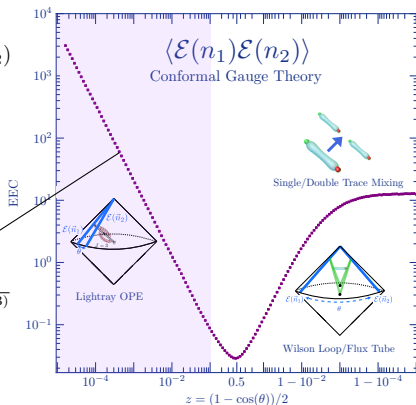
Toy Worlds

- The small-angle limit is governed by the “light-ray” OPE.
- Exhibits power law scaling with lowest twist spin-3 operator.

$$\mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2) = \sum_i (n_1 \cdot n_2)^{\frac{\tau_i-4}{2}} C_i \mathbb{O}_i^{[J=3]}(\vec{n}_2)$$

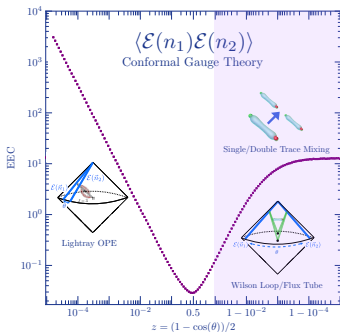
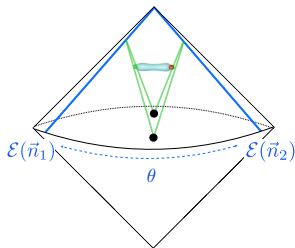


$$EEC_{z \rightarrow 0} = \frac{C(\lambda)}{z^{1-\gamma(3)}}$$



Toy Worlds

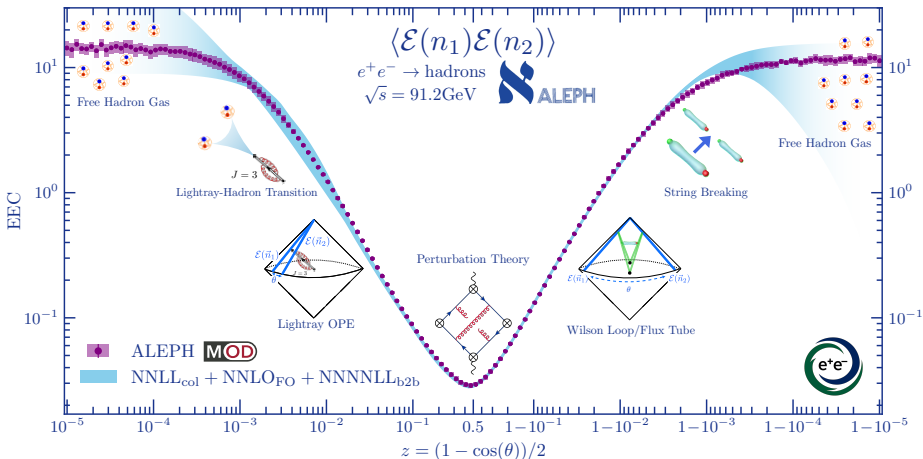
- Back-to-back limit ($z \rightarrow 1$) sensitive to conserved gauge flux, large spin limit of twist-2 operators: $J \sim 1/(1-z)$
- Logarithmic growth of anomalous dimensions, $\Delta - J = 2 + \Gamma_{\text{cusp}}(\lambda)(\log J + \gamma_E) + B_\delta(\lambda) + \mathcal{O}(1/J)$



$$EEC_{z \rightarrow 1} = \frac{H(\lambda)}{8(1-z)} \int_0^\infty db b J_0(b) \exp \left[-\frac{1}{2} \Gamma_{\text{cusp}}(\lambda) \ln^2 \left(\frac{e^{2\gamma_E} b^2}{4(1-z)} \right) + 2B_\delta(\lambda) \ln \left(\frac{e^{2\gamma_E} b^2}{4(1-z)} \right) \right]$$

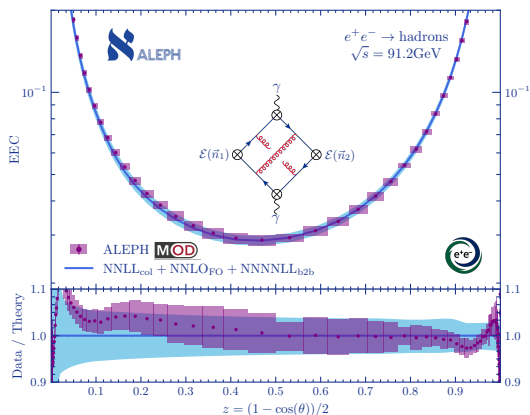
Energy Correlators from Partons to Hadrons

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



Perturbation Theory

- In the bulk ($z \sim 1/2$) region, no single state in any OPE dominates.
- Perform a perturbative expansion in partonic Fock states.

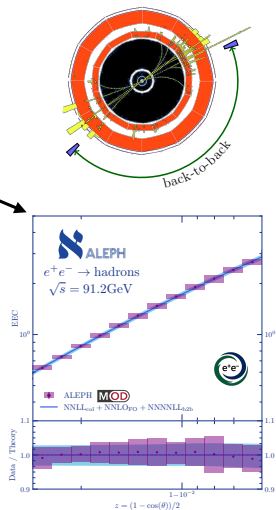
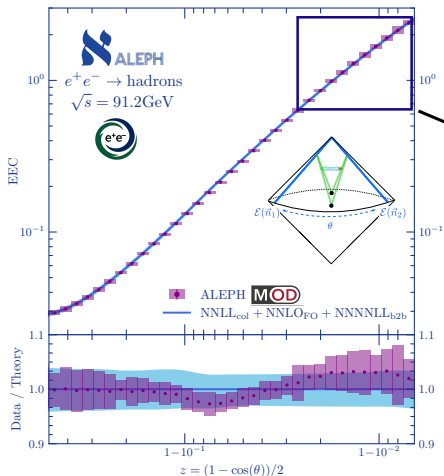


- Incorporates:

- $|q\bar{q}\rangle$
- $|q\bar{q}g\rangle$
- $|q\bar{q}gg\rangle$
- $|q\bar{q}q\bar{q}\rangle$
- $|q\bar{q}q\bar{q}g\rangle$
- $|q\bar{q}ggg\rangle$

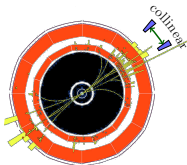
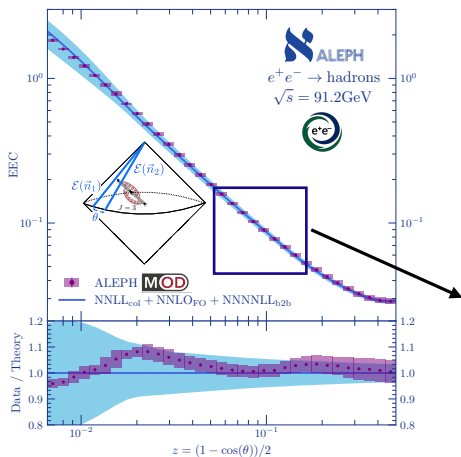
Sudakov Resummation

- $z \rightarrow 1$ limit provides a sensitive probe of the $\log(J)$ growth of anomalous dimensions.

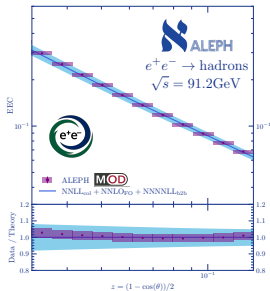


Collinear Resummation

- Percent level understanding of QCD energy flux.

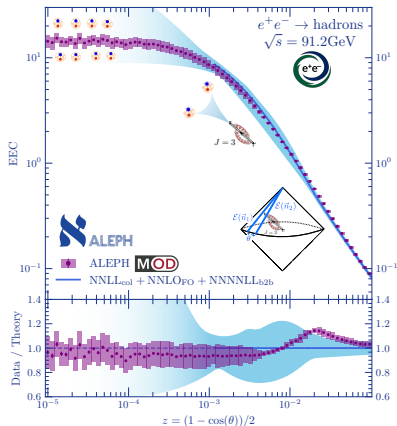
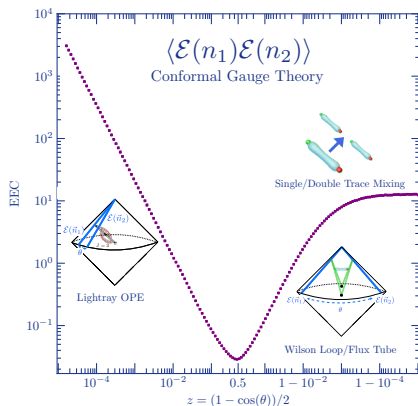


$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \sim \frac{1}{\theta^{2-\gamma(3)}} \mathcal{D}_{\tau=2}^{n=3}(\hat{n}_1) + \dots$$



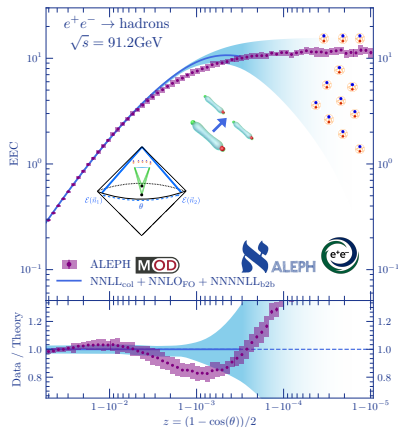
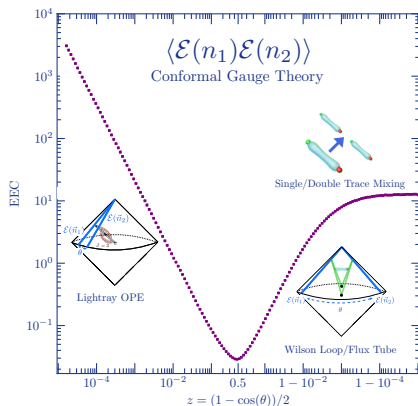
Collinear Confinement Transition

- Confinement in the collinear limit clearly imprinted as transition to free hadron scaling.



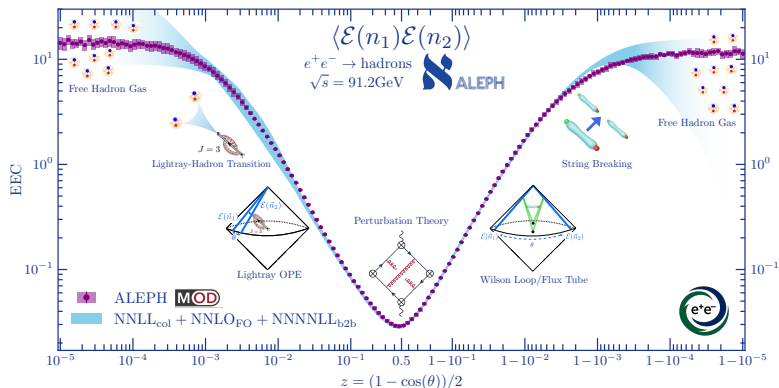
Sudakov Confinement Transition

- Perturbative flux tube enables smooth transition with confining behavior.



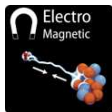
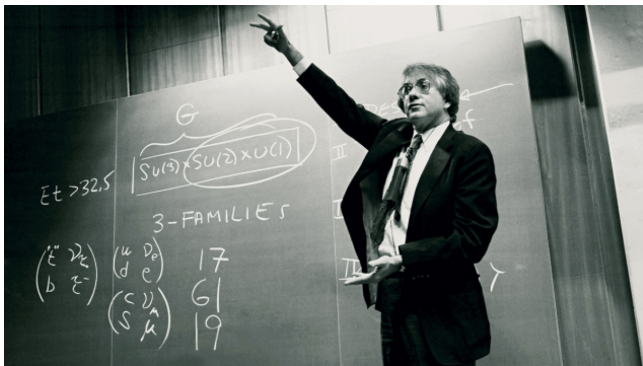
A New Era of Theory-Data Comparison

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



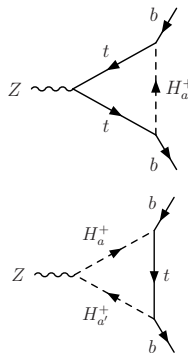
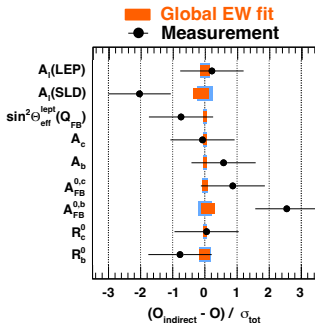
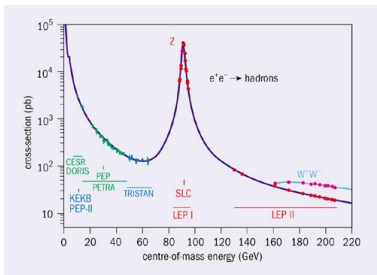
- Comparison with finite coupling results in conformal gauge theories will elucidate differences.

Reviving the Precision Electroweak Program



Electroweak Precision

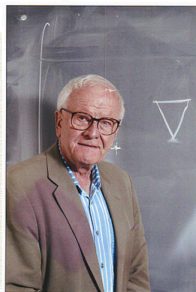
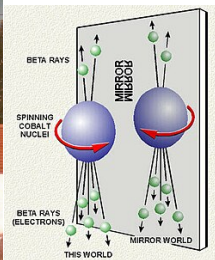
- The lack of explicit new physics at the LHC has shifted attention to precision measurements.
- Precision Electroweak data still dominated by LEP
 \implies uncertainties dominated by QCD.



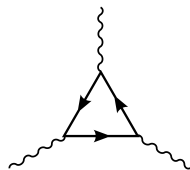
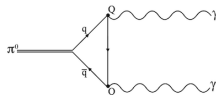
- Archival data combined with new theoretical techniques presents an opportunity to modernize the precision electroweak program.

$SU(2) \times U(1)$

- The Electroweak Theory is famously chiral
 \implies Exciting new field theoretic phenomena!



Romen Jaclain

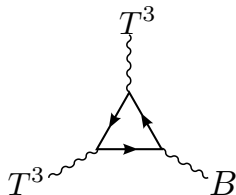
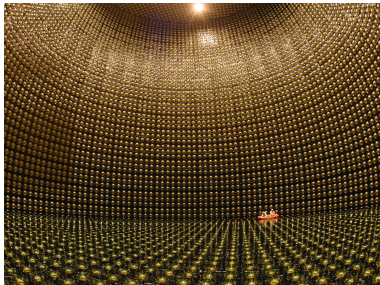


Baryon Number Violation Through Anomalies

- One of the most famous predictions is the violation of Baryon number through mixed electroweak anomalies.

Symmetry Breaking through Bell-Jackiw Anomalies*

G. 't Hooft
Department of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 22 March 1976)



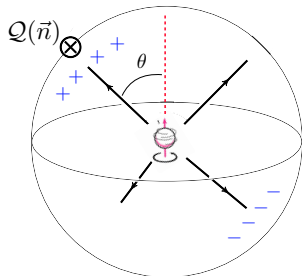
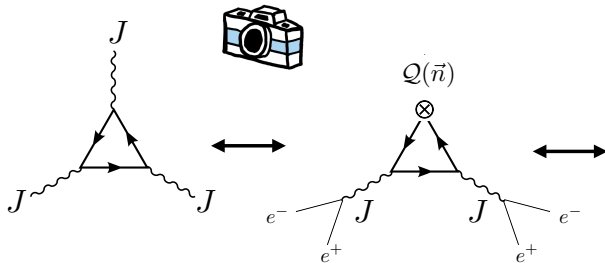
- Can we measure its magnitude without observing explicit baryon number violation?

Anomalous Fluxes

- Anomalies can be directly accessed in colliders using charge detectors.

$$Q(\vec{n}) = \lim_{r \rightarrow \infty} \int_0^{\infty} dt n^i j_i(t, r\vec{n})$$

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



- In the real world:

$$= -e \tan \theta_w \text{Tr} YYB + e \cot \theta_w \text{Tr} T_3^L T_3^L B$$

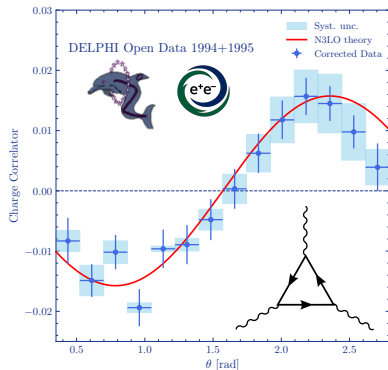
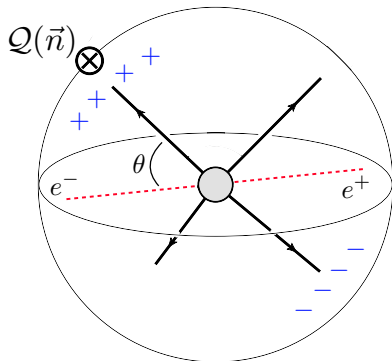
The diagram shows a triangle loop with three external lines: a photon γ on the left, a Z boson on the right, and a top quark Q at the top. Below the diagram is the corresponding mathematical expression for the anomaly contribution.

Kyle Lee



Anomalous Charge Flux

- First direct measurement of baryon number anomaly coefficients.
- Control over percent level fluctuations in QCD fluxes.

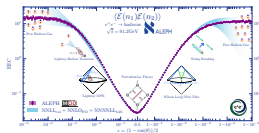


- Newly achieved precision in QCD calculations + archival data
⇒ opens the door to a re-imagined precision electroweak program.

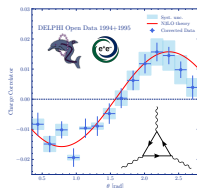
An Opportunity

- 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!