Jets Meet CFT at the CEPC

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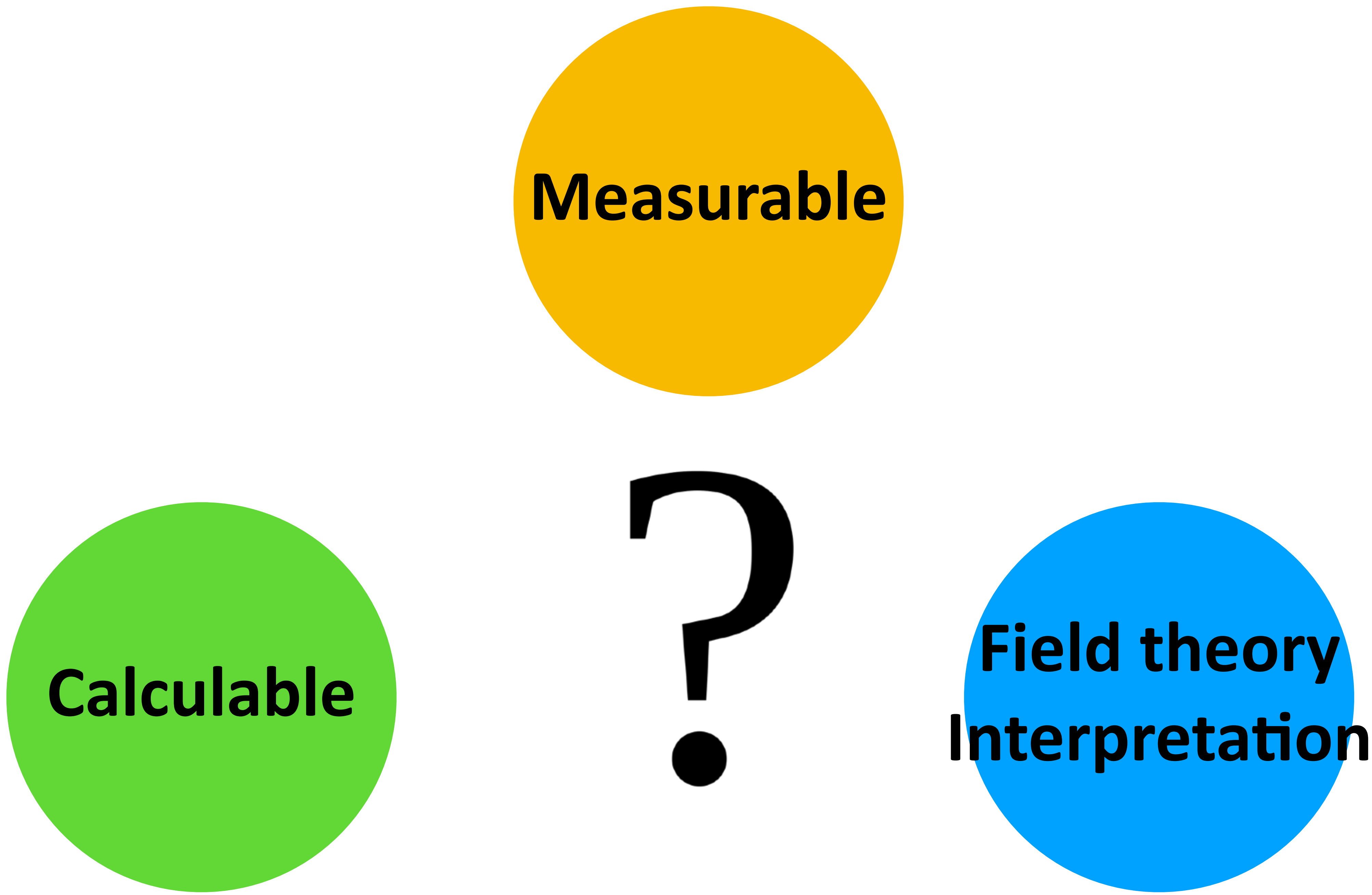
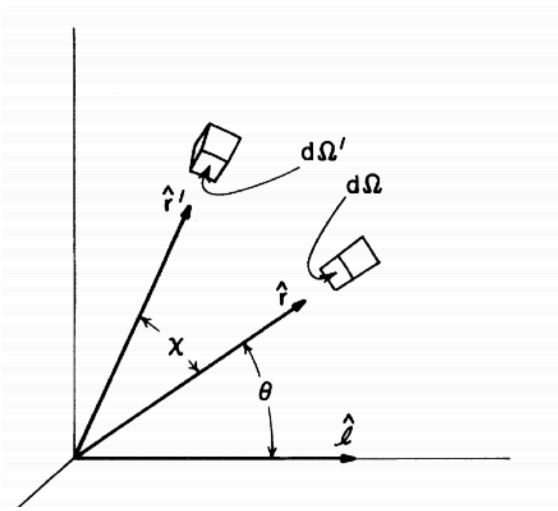
2021年4月16日，扬州

Rethinking Jets physics



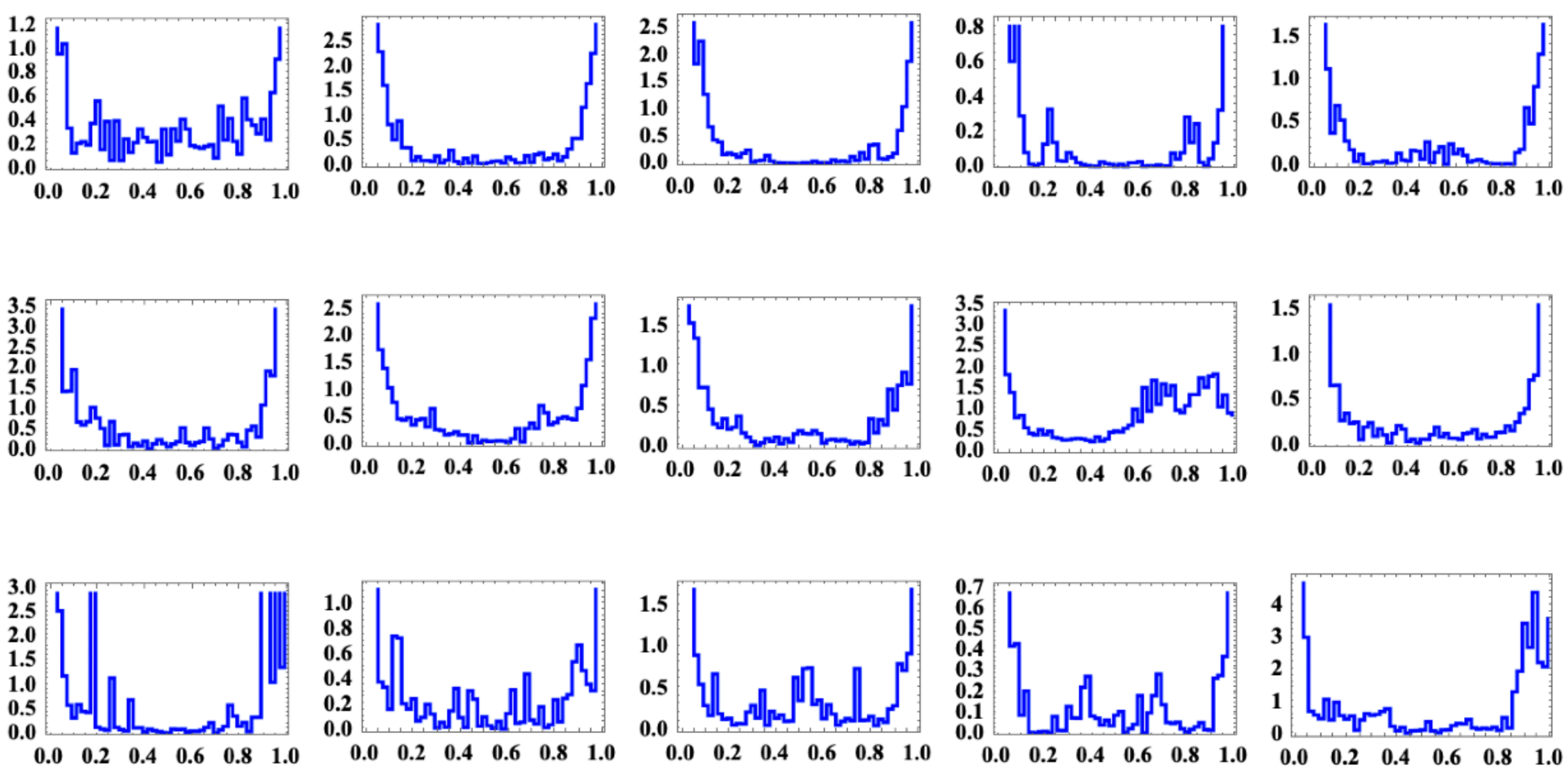
Energy Correlators

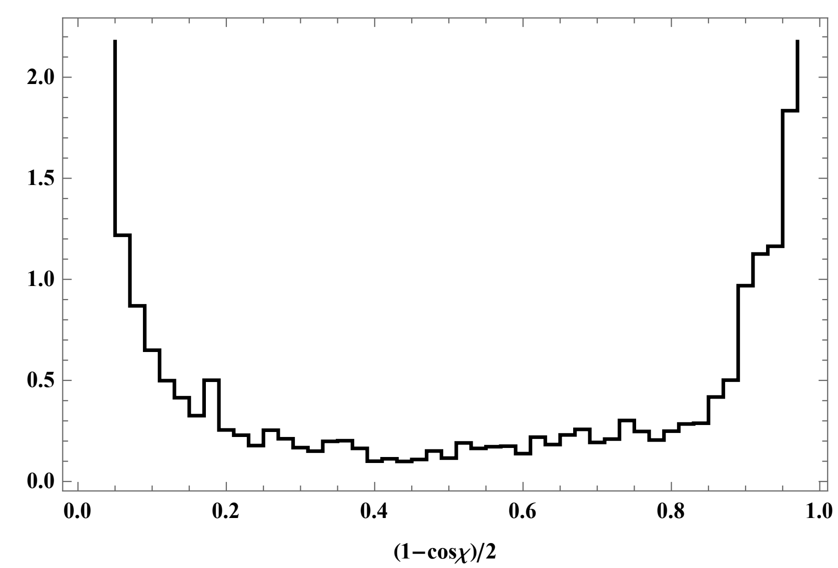
Basham, Brown, Ellis, Love, 1978



Two-point energy correlation

$$\mathrm{EEC}(\chi) = \frac{1}{N}\sum_{\text{events}}^{N}\sum_{i,j}^{N_{\text{particles}}}\frac{E_iE_j}{E_{\text{tot}}^2}\left(\frac{1}{\Delta\chi}\int_{\chi-\Delta\frac{\chi}{2}}^{\chi+\Delta\frac{\chi}{2}}\delta(\chi'-\chi_{ij})d\chi'\right)$$





Measured on a single event

Average over events

What's new about energy correlators?

Conformal collider physics: Energy and charge correlations

Diego M. Hofman (Princeton U.), Juan Maldacena (Princeton, Inst. Advanced Study)

Mar, 2008

72 pages

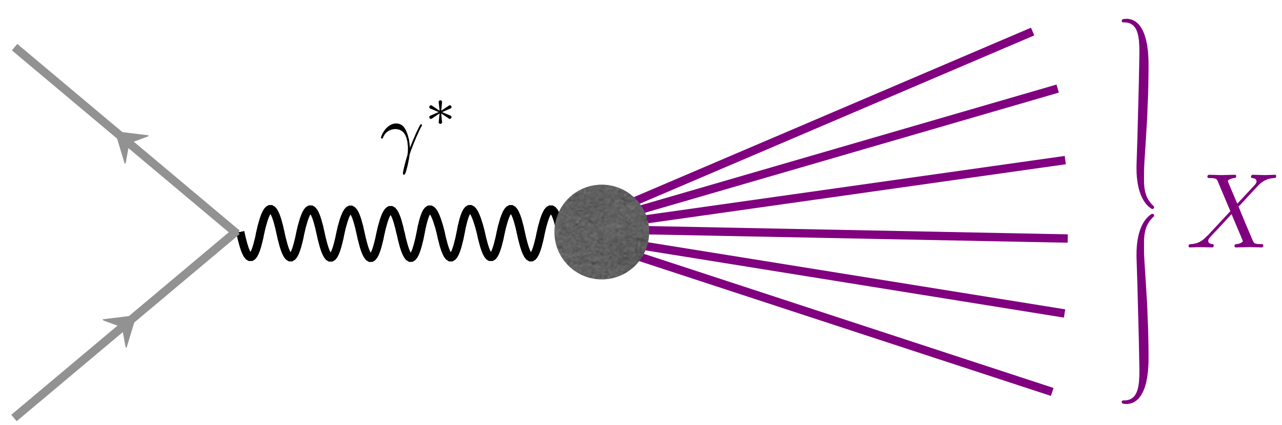
Published in: *JHEP* 05 (2008) 012

e-Print: 0803.1467 [hep-th]

DOI: 10.1088/1126-6708/2008/05/012

View in: ADS Abstract Service

$$\langle O'(-q)|\mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\ldots|O(q)\rangle$$



Recent progress in energy correlators

- Analytic calcualtion in N=4 SYM at NLO and NNLO

Belitsky, S. Hohenegger, G. P. Korchemsky, E. Sokatchev, and A. Zhiboedov ; J. M. Henn, E. Sokatchev, K. Yan, and A. Zhiboedov; D. Chicherin, J. M. Henn, E. Sokatchev, and K. Yan

- Analytic calculation in QCD at NLO

L. J. Dixon, M.-X. Luo, V. Shtabovenko, T.-Z. Yang, and H. X. Zhu; M.-x. Luo, V. Shtabovenko, T.-Z. Yang, and H. X. Zhu; J. Gao, V. Shtabovenko, and T.-Z. Yang

- Numerical calculation in QCD at NNLO

V. Del Duca, C. Duhr, A. Kardos, G. Somogyi, and Z. Tr´ocs´anyi; V. Del Duca, C. Duhr, A. Kardos, G. Somogyi, Z. Sz˝or, Z. Tr´ocs ´anyi, and Z. Tulip´ant

- Resummation in the back-to-back limit at N3LL

I. Moult and H. X. Zhu; M. A. Ebert, B. Mistlberger, and G. Vita

- Resummation in the collinear limit at NNLL and jet substructure

L. J. Dixon, I. Moult, and H. X. Zhu; M. Kologlu, P. Kravchuk, D. Simmons-Duffin, and A. Zhiboedov; Korchemsky; H. Chen, I. Moult, X. Zhang, and H. X. Zhu; H. Chen, M.-X. Luo, I. Moult, T.-Z. Yang, X. Zhang, and H. X. Zhu

- Generalization to pp and ep collision

A. Gao, H. T. Li, I. Moult, and H. X. Zhu; H. T. Li, I. Vitev, and Y. J. Zhu; H. T. Li, Y. Makris, and I. Vitev

- Power corrections in the back-to-back limit

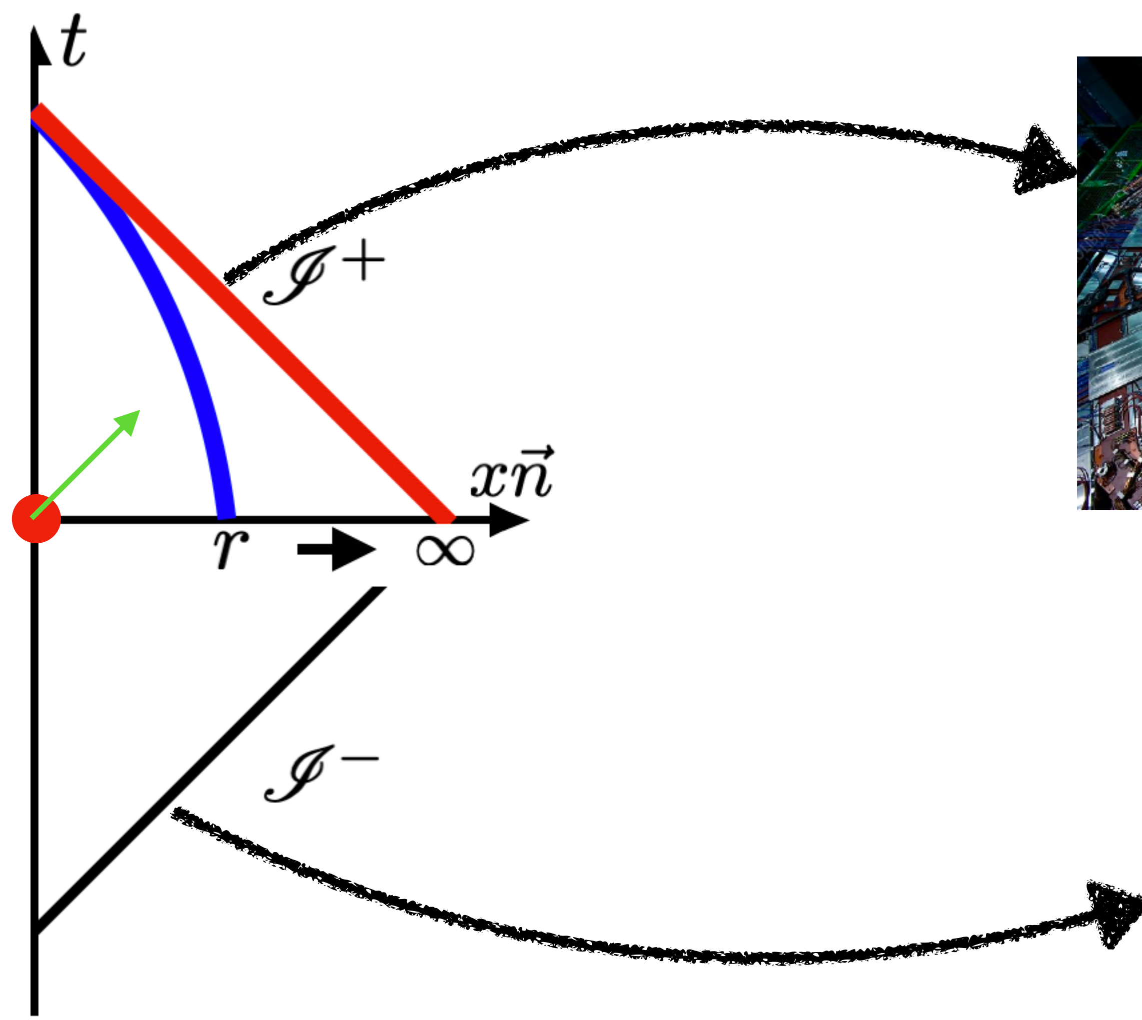
I. Moult, G. Vita, K. Yan

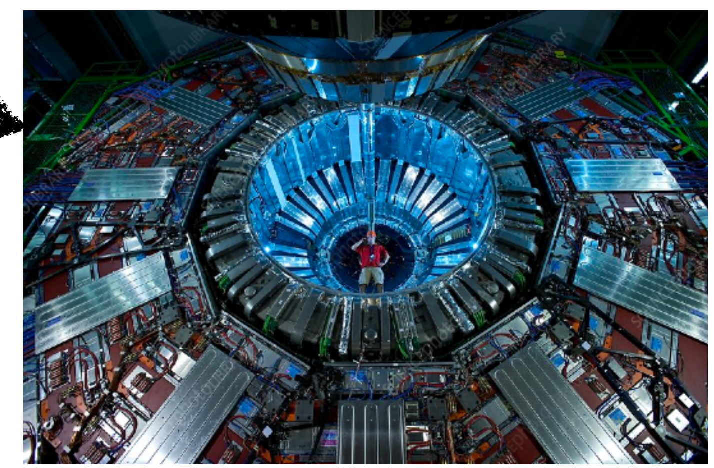
Energy flow operator

Theorist's energy detector

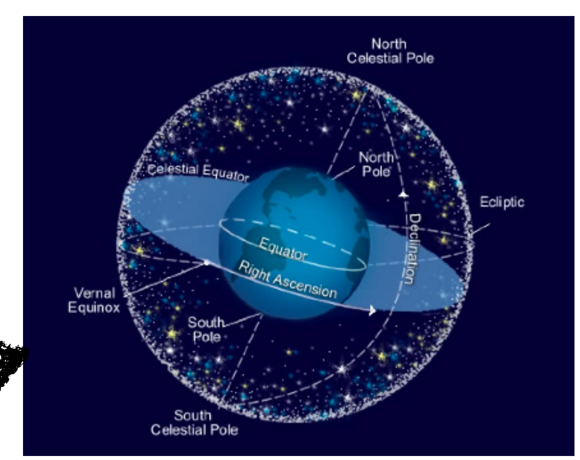
$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty} r^2 \int_0^\infty dt\ \vec{n}_i T^{0i}(t, r\vec{n})$$

Application in other areas:
CFT bootstrap, modular Hamilton, ANEC, gravitational shockwave, …





Detector celestial sphere

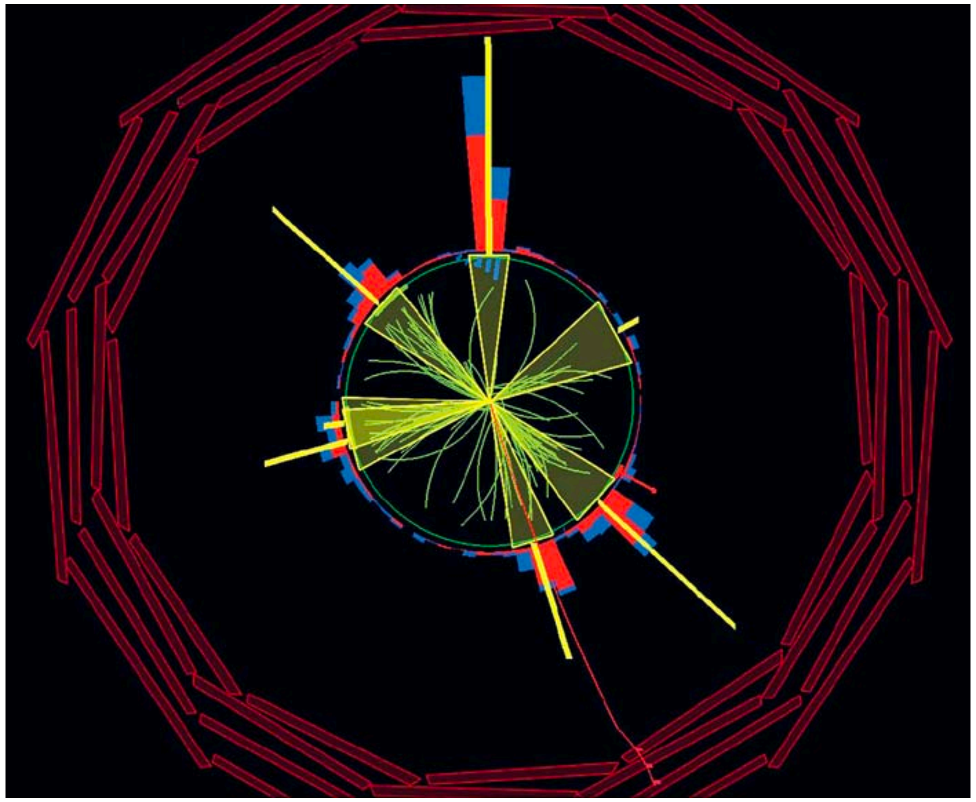


Celestial sphere

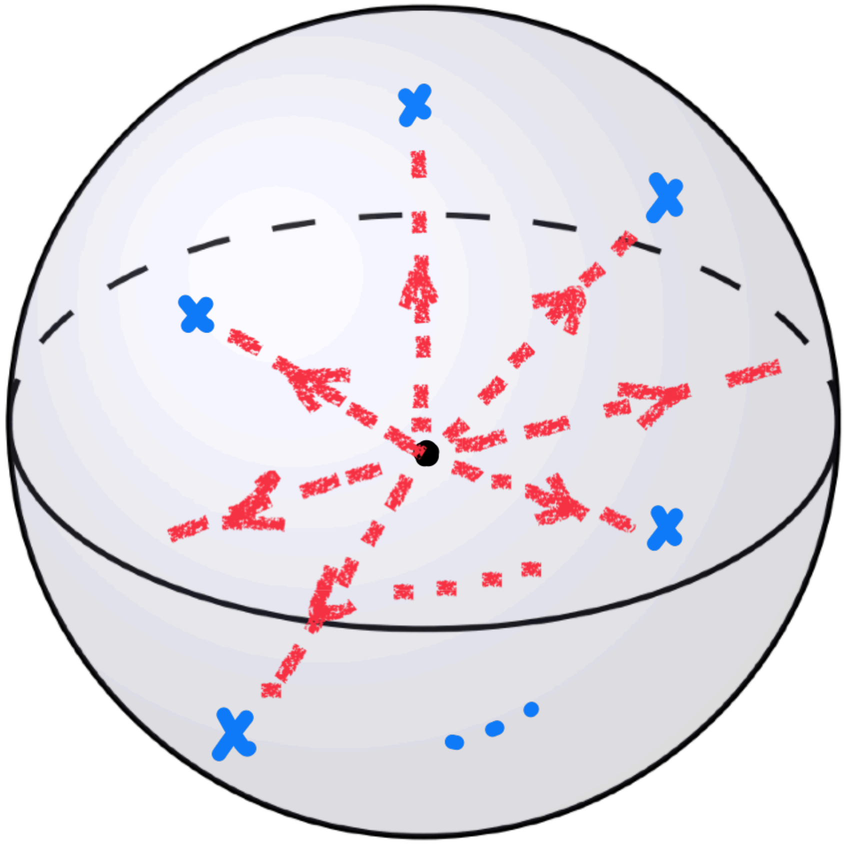
Penrose diagram for Minkowski space-time

Experiment v.s. Theory

What experimentalist measure

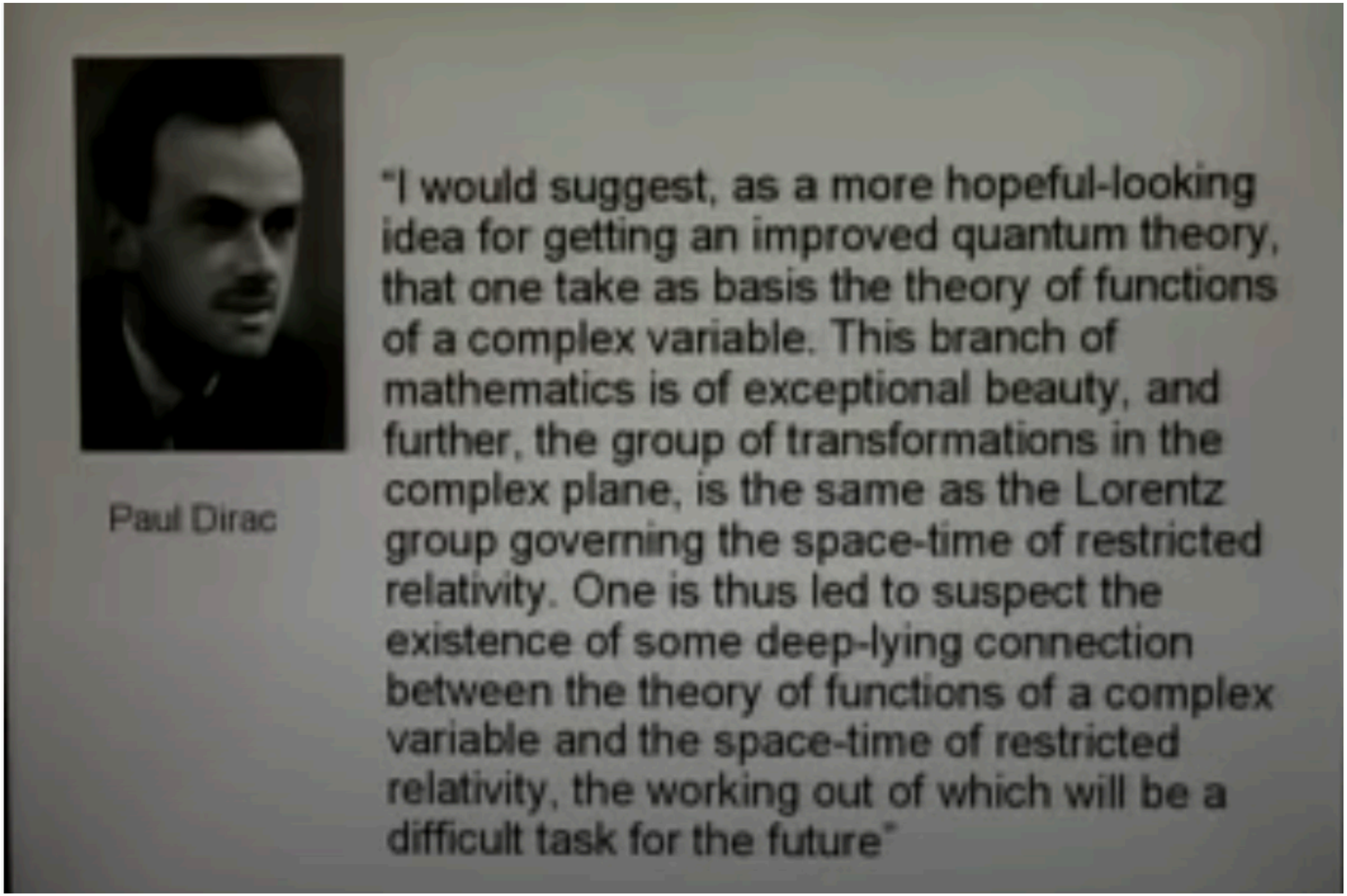


What theorist can calculate



There is one-to-one correspondence between experimental measurement and theory calculation.
No intermediate jet algorithm involves: calculation significantly simplified.

Dirac's dream

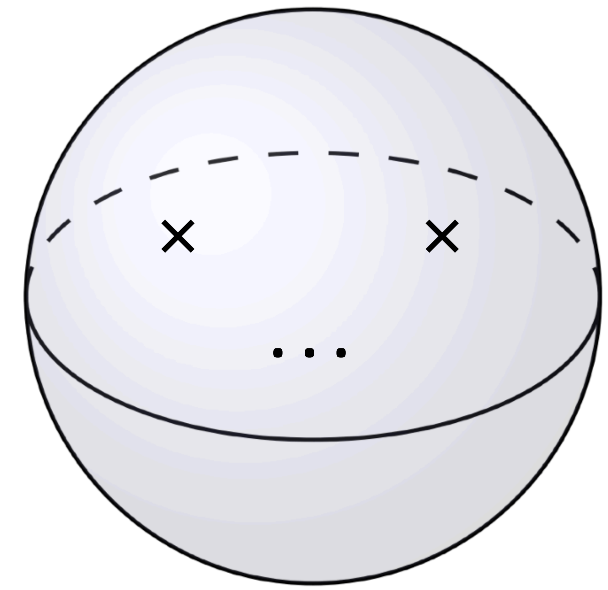


From Atiyah's talk

Theory interpretation: correlator of a fiducial 2D Euclidean field theory

Only angular information is retained.
No notion of time.

$$\langle O'(-q)|\mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\ldots|O(q)\rangle$$



Remarkably, the Lorentz symmetry SO(3,1) ~ SL(2,C) of 4D space-time is realized as conformal symmetry on the celestial sphere.

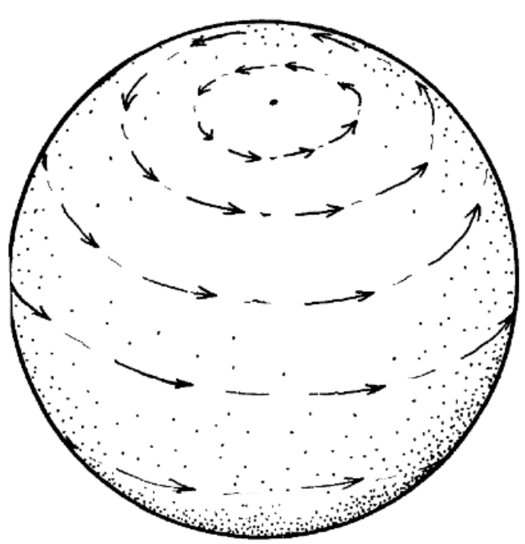


Fig. 1-6. The effect of a rotation on S^+.

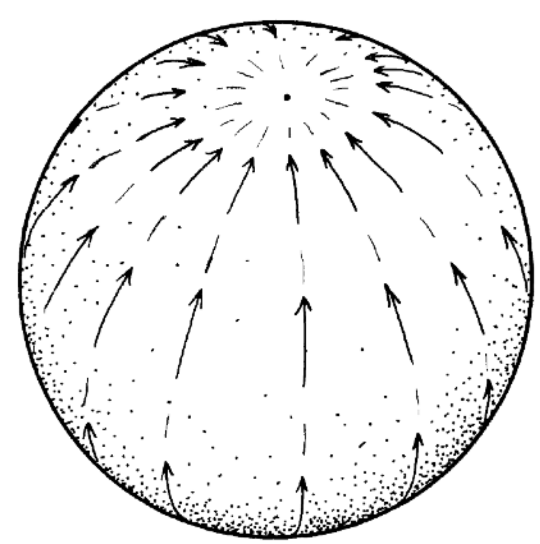


Fig. 1-7. The effect of a boost on S^+.

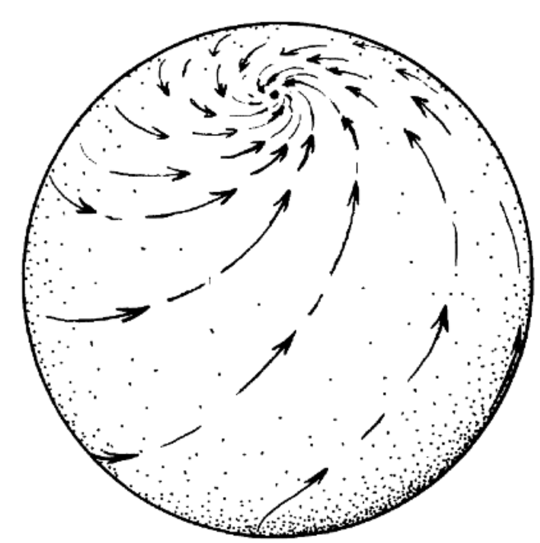
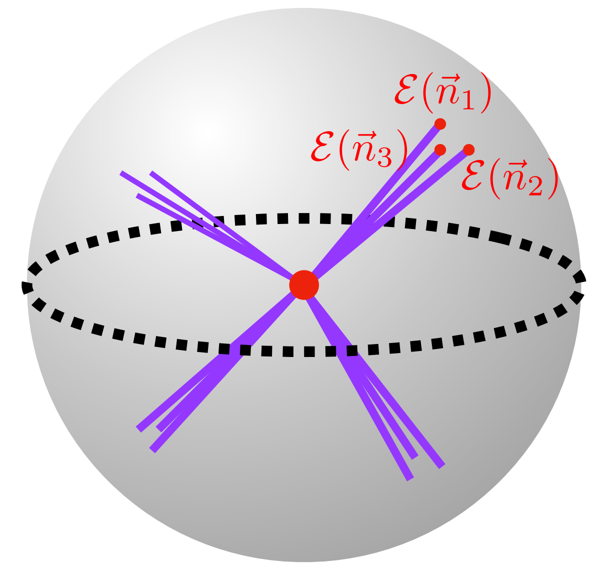


Fig. 1-8. The effect of a four-screw on S^+.

Application of conformal symmetry on the celestial sphere

The conformal symmetry has practical implication: allows the resummation of family of perturbative power corrections into conformal block. M. Kologlu, P. Kravchuk, D. Simmons-Duffin, and A. Zhiboedov; H. Chen, I. Moult, H.X. Zhu



$$
\begin{aligned}
\widetilde{G}_q(w) = C_F n_f T_f \Bigg\{ & \frac{1}{|w|^2}\left[\frac{13}{4800} - \frac{1}{720}\cos(2\phi)\right] + \left[-\frac{\cos(4\phi)}{1680} + \frac{37\cos(2\phi)}{10080} - \frac{\pi^2}{3} + \frac{111199}{33600}\right] \\
& + |w|^2 \left[-\frac{67}{105}\log(2|w|) - \frac{\cos(6\phi)}{3024} + \frac{331\cos(4\phi)}{151200} - \left(\frac{46}{3}\pi^2 - \frac{22853623}{151200}\right)\cos(2\phi) - \frac{28\pi^2}{3} + \frac{21468341}{235200}\right] \\
& + |w|^4 \Bigg[\left(-\frac{2996}{495}\cos(2\phi) - \frac{12317}{1155}\right)\log(2|w|) - \frac{\cos(8\phi)}{4752} + \frac{53\cos(6\phi)}{36960} - \left(110\pi^2 - \frac{32817971}{30240}\right)\cos(4\phi) \\
& \quad - \left(\frac{464}{3}\pi^2 - \frac{83514316033}{54885600}\right)\cos(2\phi) - 83\pi^2 + \frac{41787326893}{51226560}\Bigg]\Bigg\} \\
& + C_F^2 \Bigg\{\frac{1}{20|w|^2} + \left[\frac{13}{180}\cos(2\phi) + \frac{59}{360}\right] \\
& + |w|^2 \left[-\frac{4}{21}\cos(2\phi)\log(2|w|) + \frac{23}{350}\cos(4\phi) + \frac{6529\cos(2\phi)}{22050} - \frac{29}{3150}\right] \\
& + |w|^4 \Bigg[\left(-\frac{208}{315}\cos(2\phi) - \frac{88}{315}\cos(4\phi) - \frac{4}{15}\right)\log(2|w|) \\
& + \frac{44153\cos(2\phi)}{396900} + \frac{102983\cos(4\phi)}{396900} + \frac{79\cos(6\phi)}{1260} + \frac{6613}{37800}\Bigg]\Bigg\}
\end{aligned}
$$

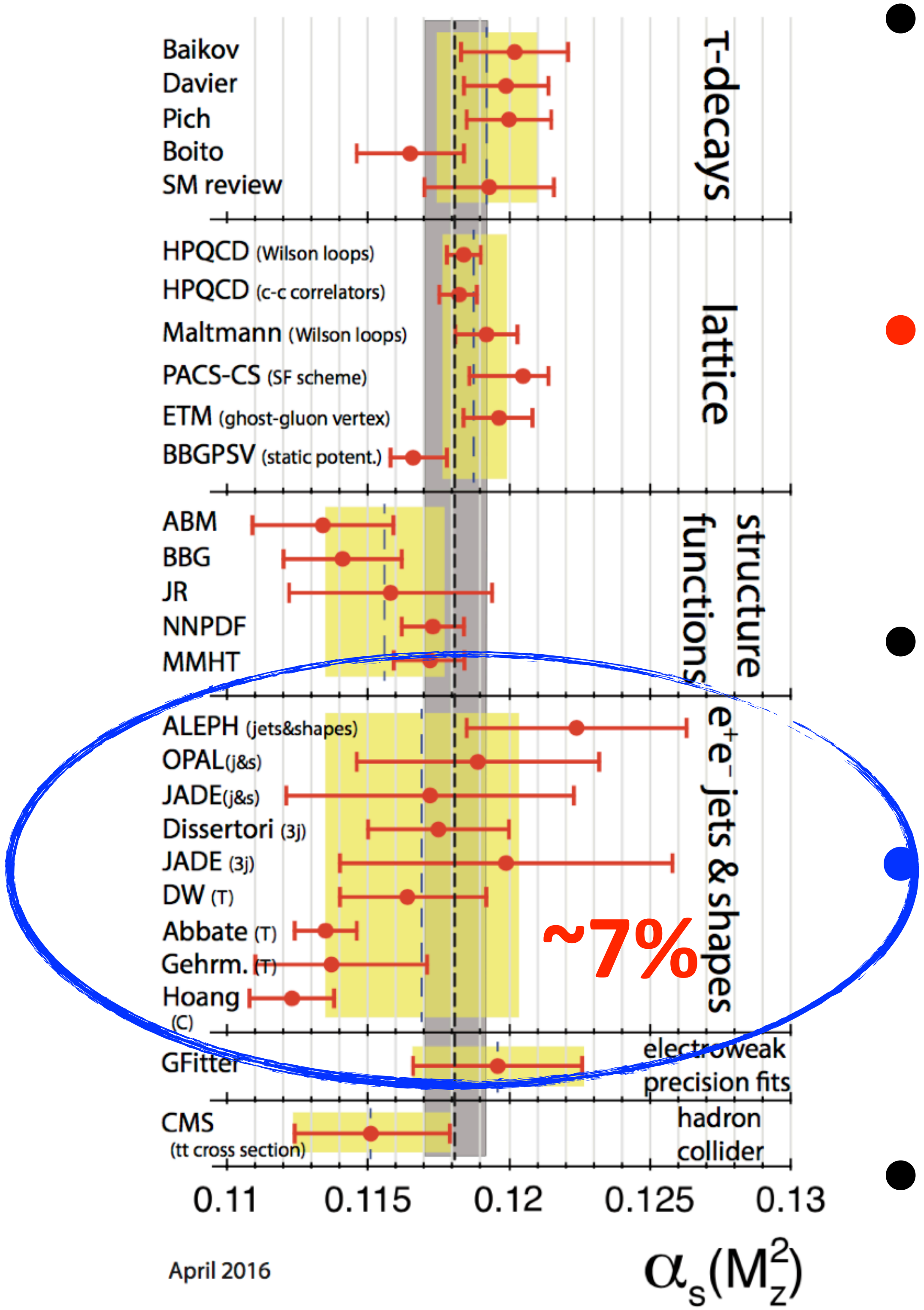
Highest harmonics resummed into blocks

$$
\frac{1}{\bar{w}^2}\,{}_2F_1\left[1, \frac{3}{2}, \frac{7}{2}, w^2\right] + \frac{1}{w^2}\,{}_2F_1\left[1, \frac{3}{2}, \frac{7}{2}, \bar{w}^2\right] = \frac{\cos 2\phi}{|w|^2} + \frac{3}{7}\cos 4\phi + |w|^2 \frac{5}{21}\cos 6\phi + |w|^4 \frac{5}{33}\cos 8\phi + \cdots
$$

H. Chen, I. Moult, H.X. Zhu

Phenomenology

Precision α_s measurement



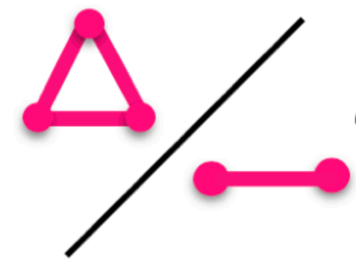
- The muon g-2 teach us a good lesson that the SM might not work that good if we compare theory and experimental at high precision.
- A long standing puzzle from LEP measurement is the tension between jet/event shape determination from other approaches.
- An important physical goal of the CEPC resolve this tension.
- **The uncertainty in the jet/event shape determination dominated QCD theory: non-perturbative power corrections.**
- Require novel theoretical motivated observable to suppress non-perturbative QCD contributions!

Ratio of (projected)energy correlators

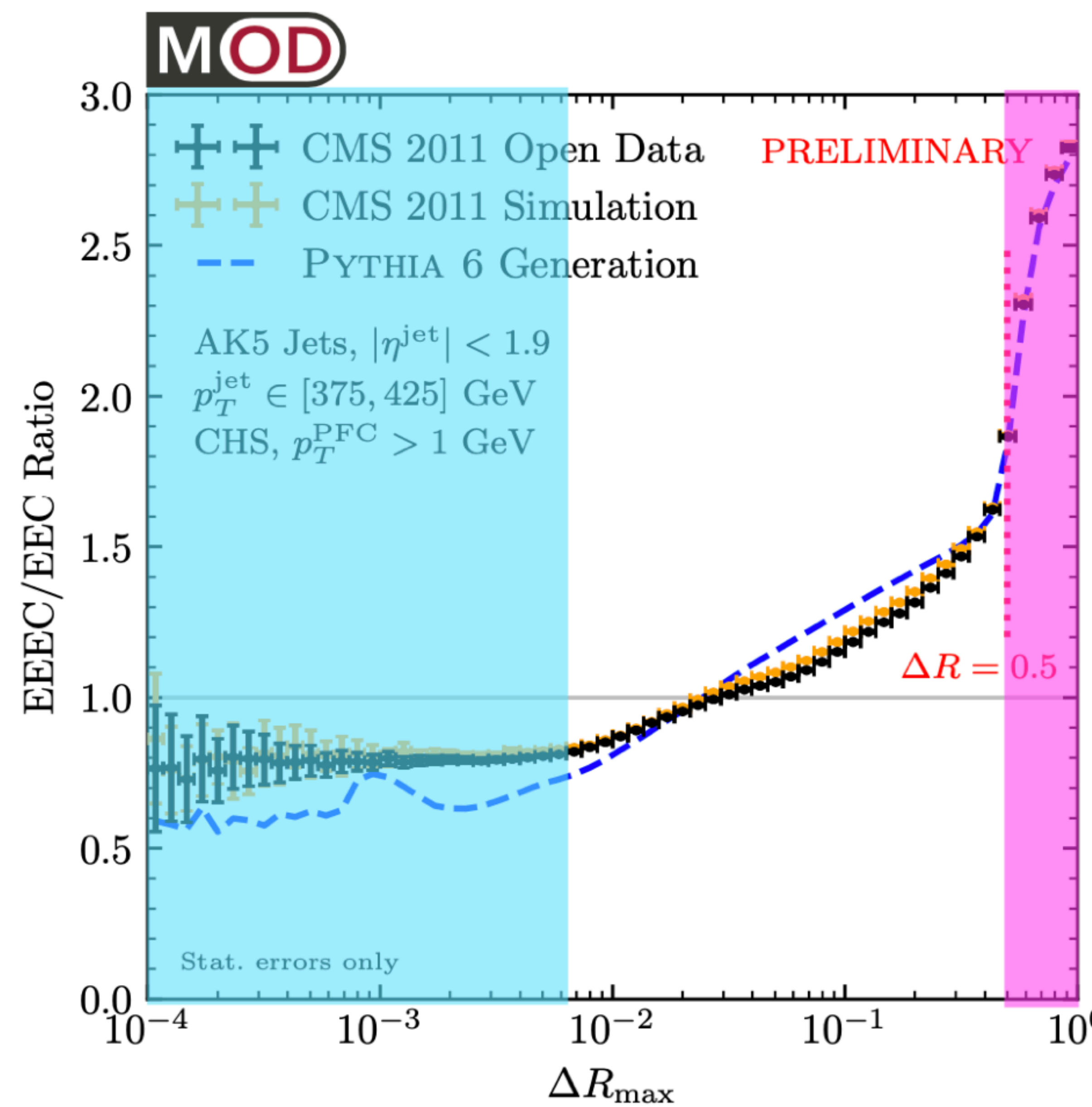
- A large class of ratio observables can be constructed from energy correlators.

H. Chen, I. Moult, X. Zhang, and H. X. Zhu

- Exhibit nice perturbative scaling in a large phase space.
- In a free theory (α_s =0), the ratio would be identically 1.
- The slope in the perturbative region is directly sensitive to α_s: a clean observable for α_s determination!

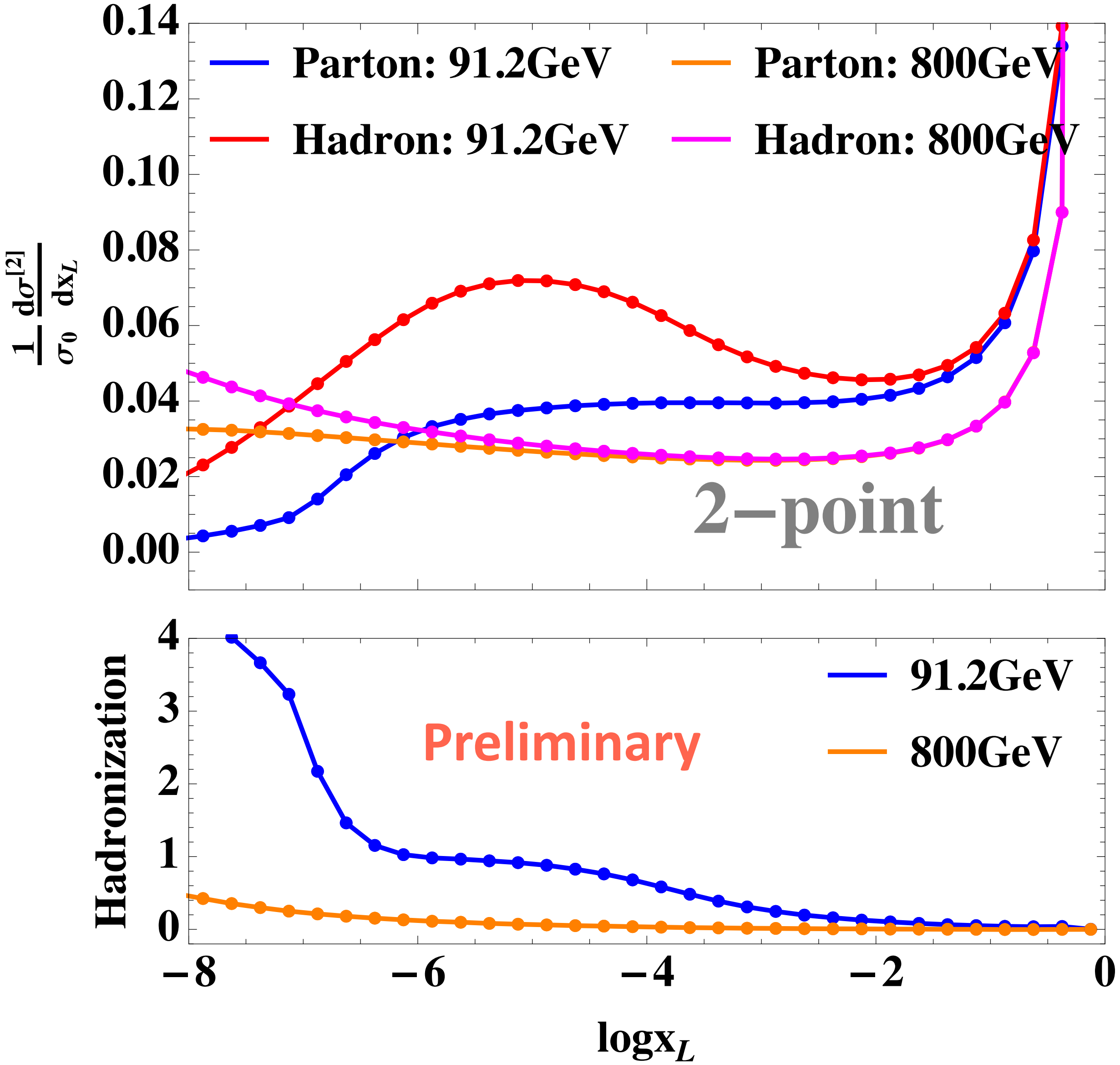


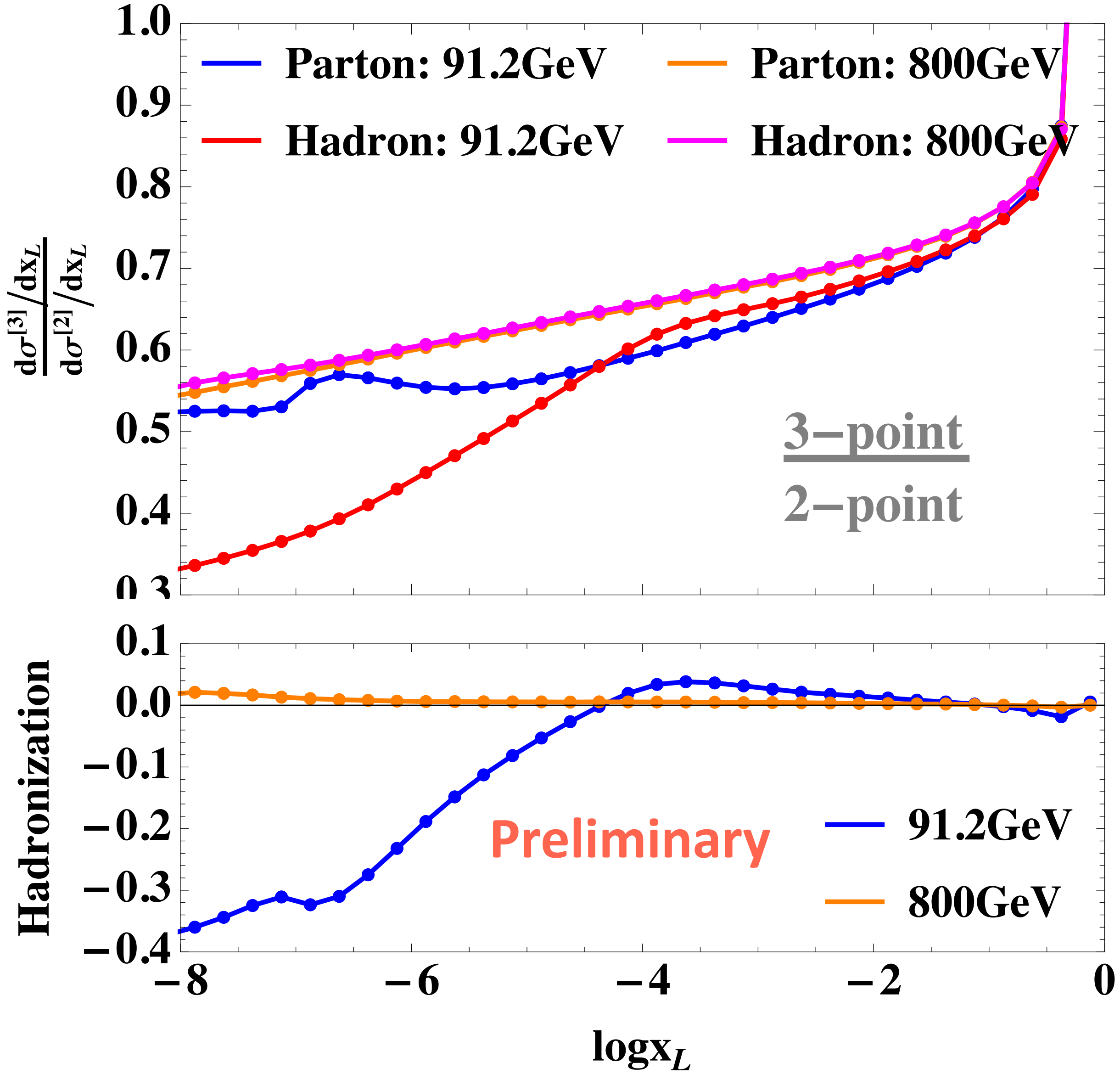
$$\sim \Delta R^{(\gamma_4-\gamma_3)/2}$$



P. Komiske, I. Moult, J. Thaler, and H. X. Zhu, in preparation

Remarkable cancellation of non-perturbative power corrections in ratio observables



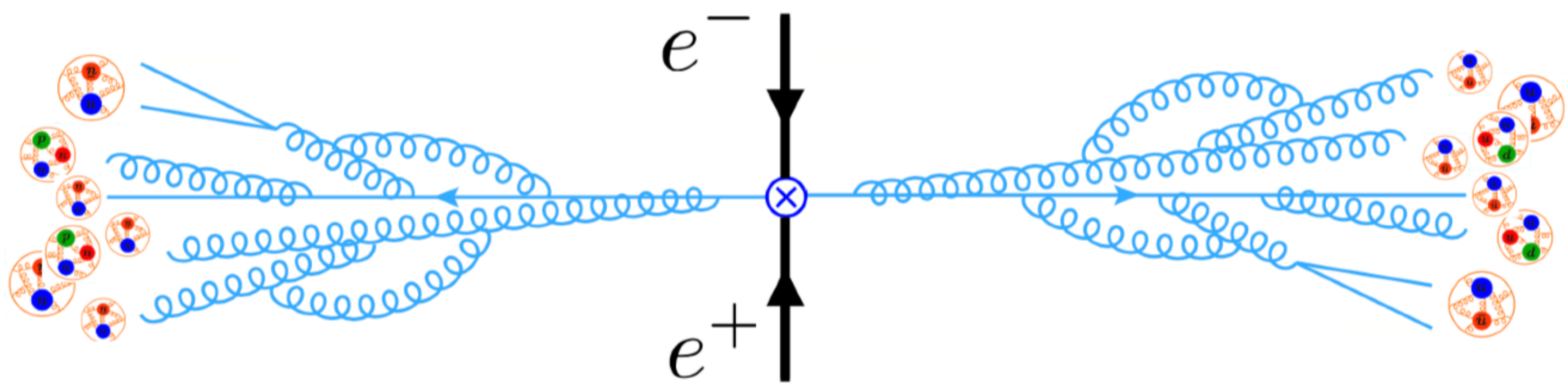


At the CEPC@250 GeV, the NP power corrections can be reduced to 1 ~ 2%. (further study required)

Then it's conceivable that final precision from jet/event shape can be bring to the same level. If the discrepancy with other measurements persists, then it would be a very interesting.

Looking for novel quantum phenomenon at hadron collider

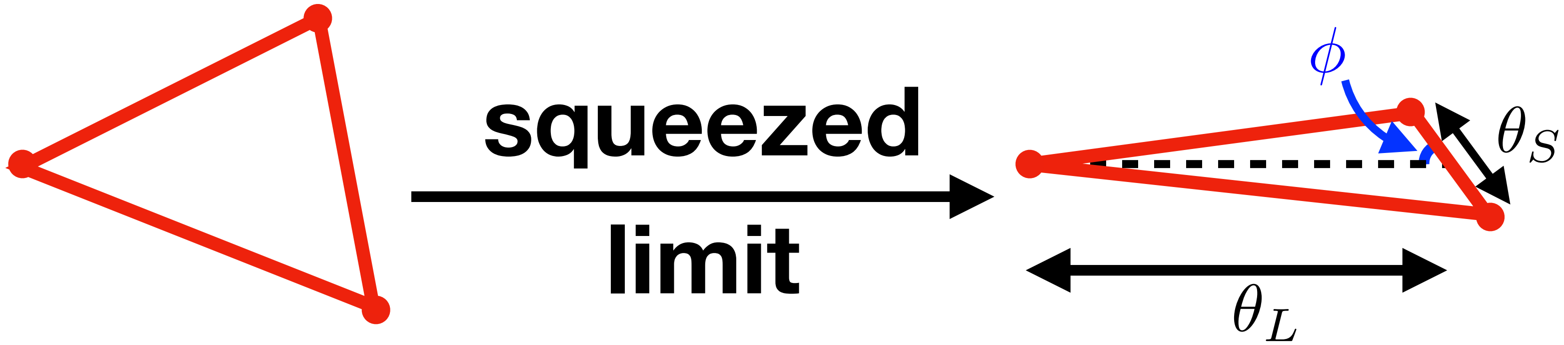
- Monte Carlo Event generator provides an excellent description of collider (after tuning).
- However, we should keep in mind that most current event generator (such as Pythia) are only correct at leading logarithmic approximation — semi classical!

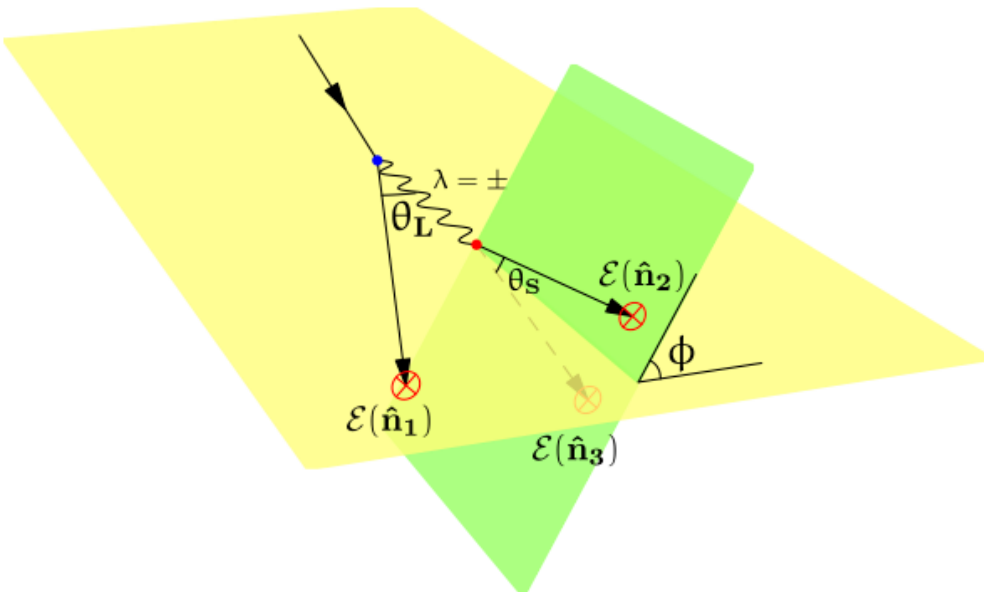


- In particular, interference between different stage of fragmentation are absent in Pythia!
- Can new physics hidden in such interference effects? Probably not, **but we should not let any stone unturned.**
- Looking for such quantum effects are also interesting by itself: test our understanding of the SM and quantum mechanics!

Quantum interference from EEEC

H. Chen, I. Moult, H.X. Zhu



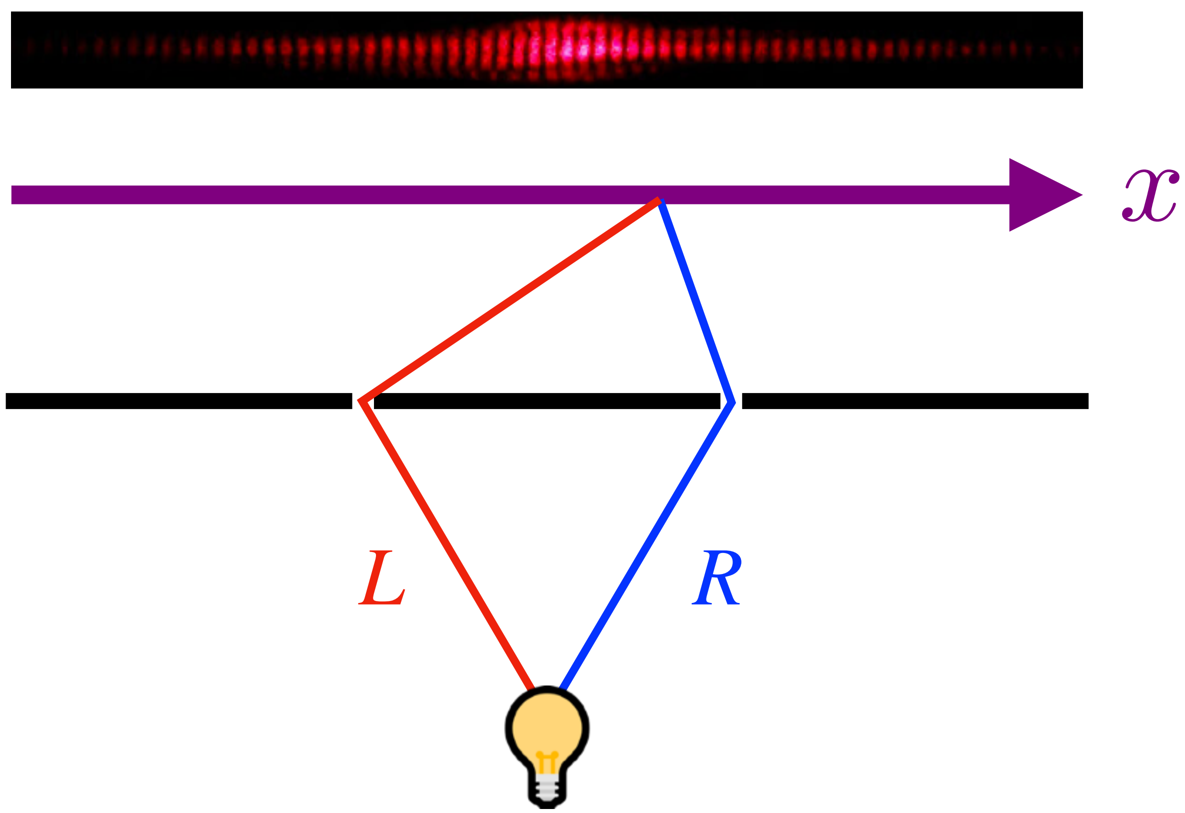


$$\frac{d^3\Sigma_i}{d\theta_L^2\, d\theta_S^2\, d\phi} \simeq \frac{1}{\pi}\left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\mathrm{Sq}_i^{(0)}(\phi)}{\theta_L^2\,\theta_S^2} + \cdots$$

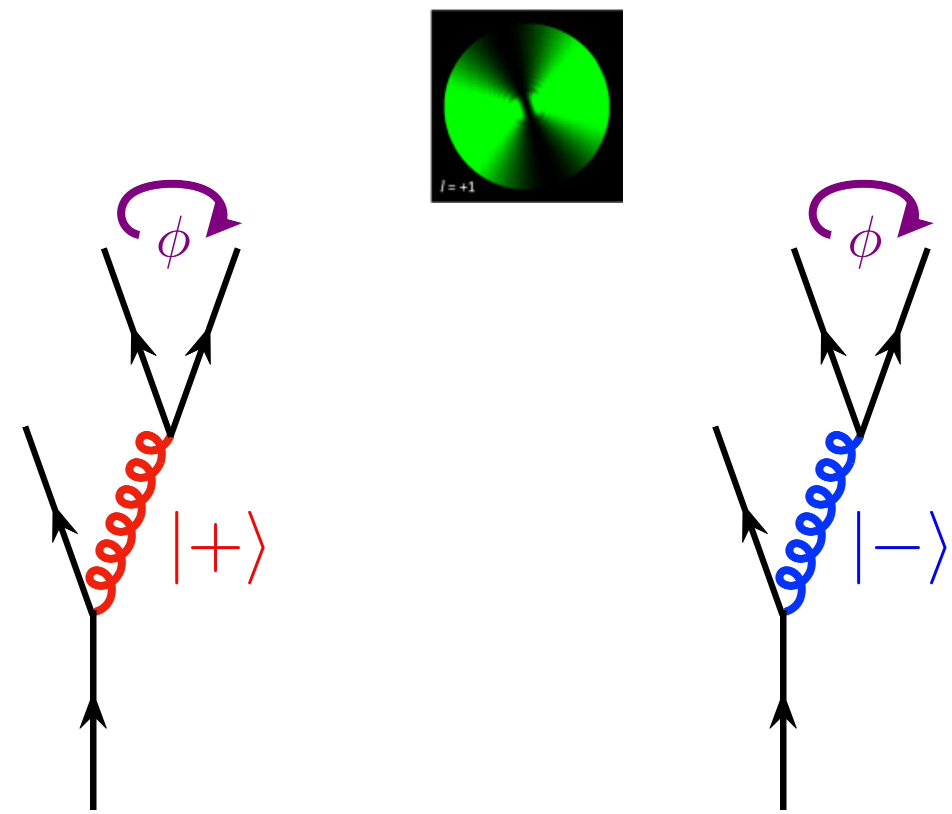
$$\mathrm{Sq}_q^{(0)}(\phi) = C_F n_f T_F \left(\frac{39 - 20\cos(2\phi)}{225}\right) + C_F C_A \left(\frac{273 + 10\cos(2\phi)}{225}\right) + C_F^2 \frac{16}{5}$$

$$\mathrm{Sq}_g^{(0)}(\phi) = C_A n_f T_F \left(\frac{126 - 20\cos(2\phi)}{225}\right) + C_A^2 \left(\frac{882 + 10\cos(2\phi)}{225}\right) + C_F n_f T_F \frac{3}{5}$$

Interpretation as double slit experiment in gluon spin space



Coherent source



incoherent source

Spin Space Interference leads to $\cos 2\phi$ pattern

Precision prediction

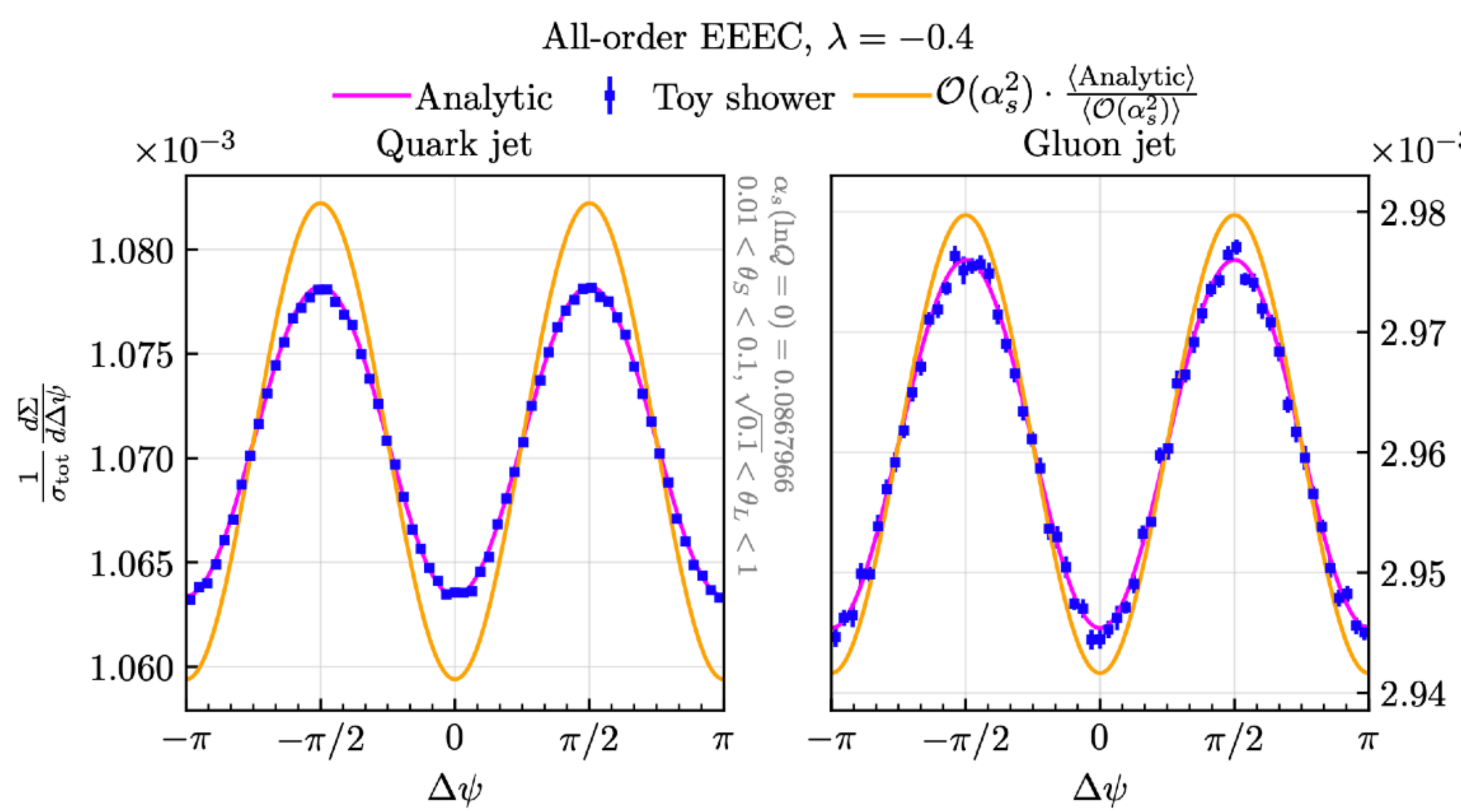
- Spin interference effects can be predicted with Light-ray OPE techniques. Analytic leading logarithmic prediction (can be improved to higher precision in the future)

H. Chen, I. Moult, H.X. Zhu

$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2)\mathcal{E}(\hat{n}_3)$$

$$=\frac{1}{(2\pi)^2}\frac{2}{\theta_S^2}\frac{2}{\theta_L^2}\vec{\mathcal{J}}\left[\widehat{C}_{\phi_S}(2)-\widehat{C}_{\phi_S}(3)\right]\left[\frac{\alpha_s(\theta_L Q)}{\alpha_s(\theta_S Q)}\right]^{\frac{\widehat{\gamma}(3)}{\beta_0}}\left[\widehat{C}_{\phi_L}(3)-\widehat{C}_{\phi_L}(4)\right]\left[\frac{\alpha_s(Q)}{\alpha_s(\theta_L Q)}\right]^{\frac{\widehat{\gamma}(4)}{\beta_0}}\vec{\mathbb{O}}^{[4]}(\hat{n}_1)$$

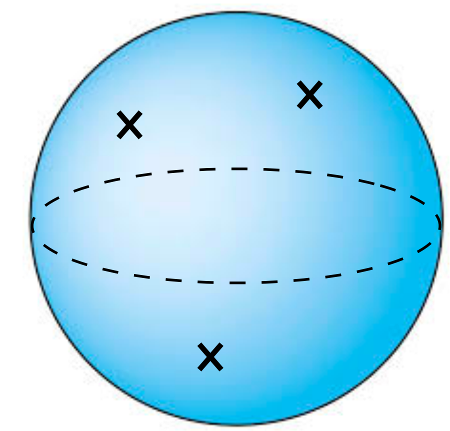
- Recently the spin interference has been confirmed by a newly implemented Monte Carlo algorithm PanScale
- Interesting interplay between analytic resummation and Parton shower
- The observation of this effect will be a direct measurement of gluon spin!

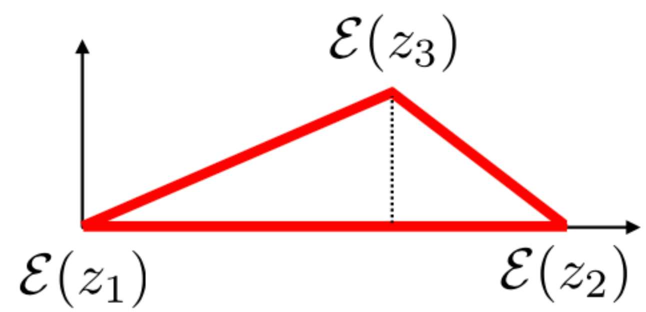


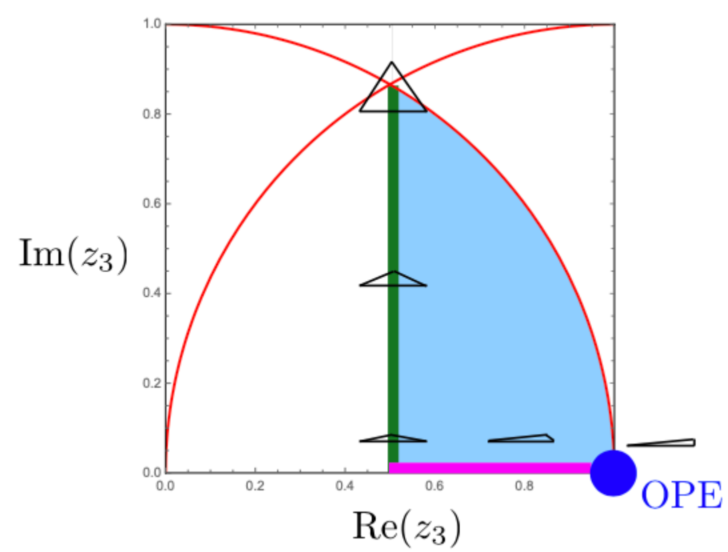
A. Karlberg, G. Salam, L. Scyboz, R. Verheyen

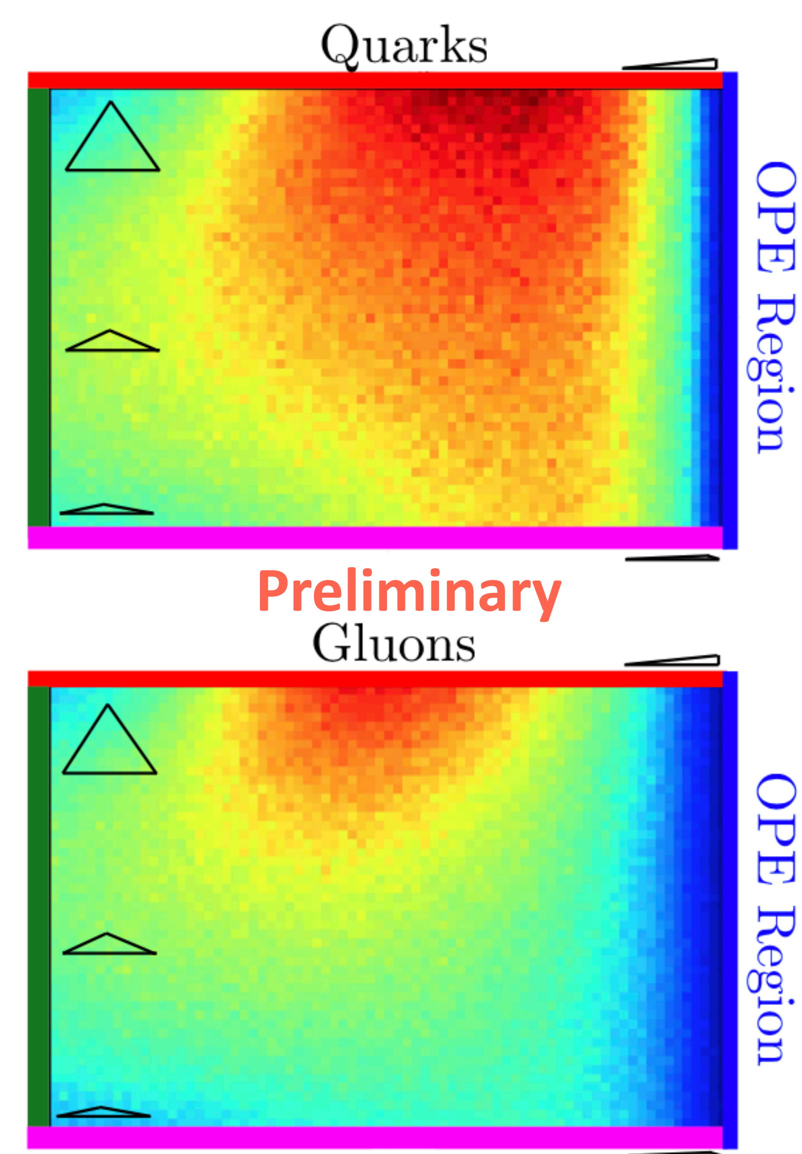
Towards more differential measurement: three-point energy correlator

- More differential observables have the potential to reveal more significant deviation between experiment and the SM prediction (e.g., Pythia + MadGraph).
- A good candidate is three-point correlator in e+e- (has not been measured before at LEP).
- A three-point correlator can be parameterized by three spherical angle. In the small angle limit reduced to a triangle. How do we visualize a three dimensional distribution?





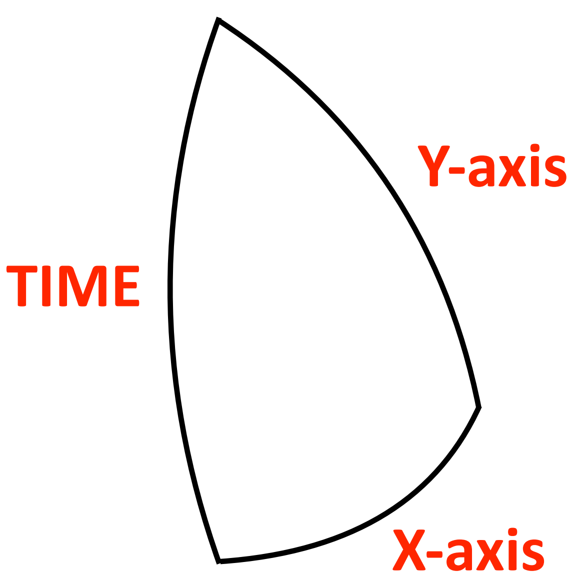


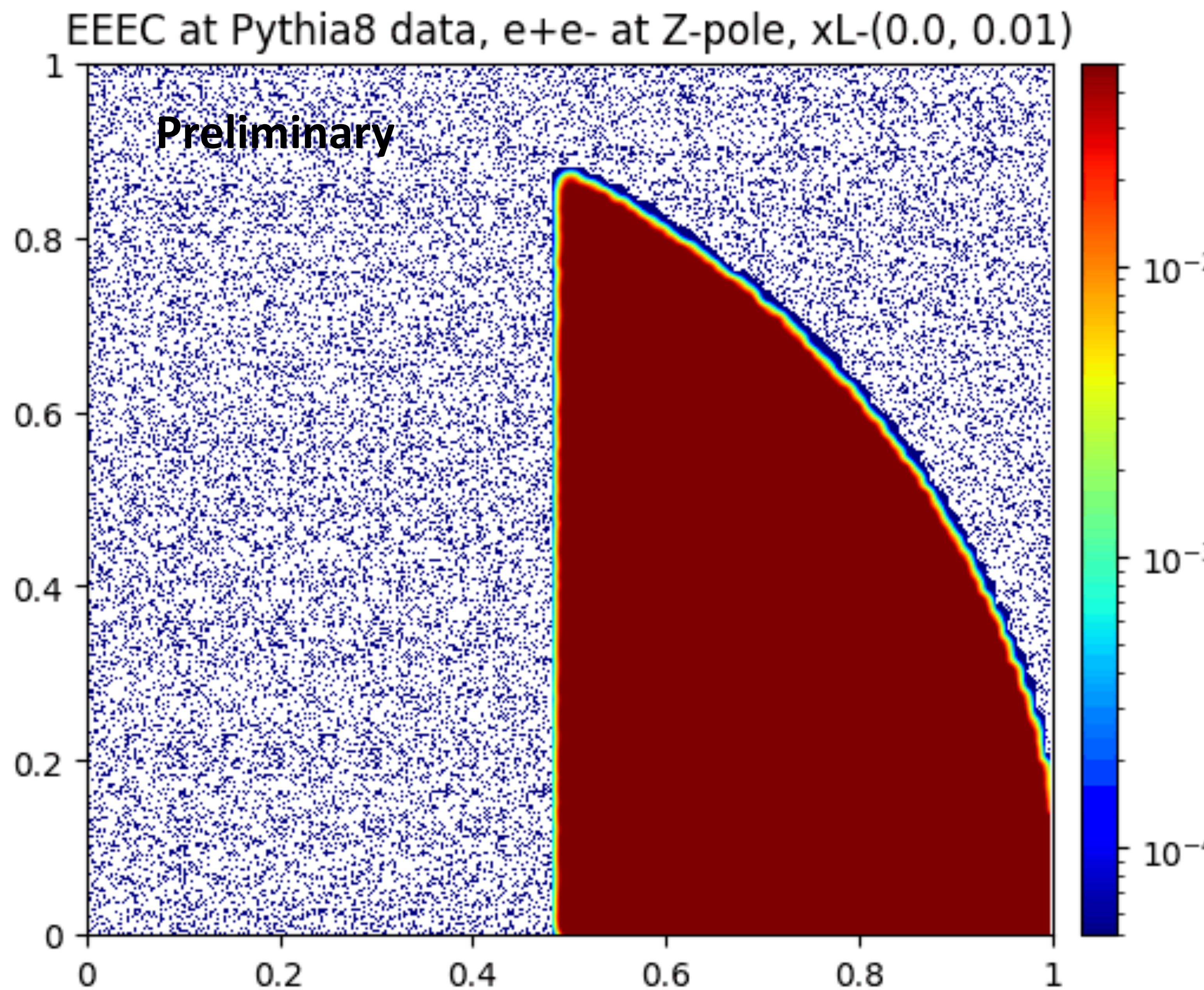


A collinear slice of three-point energy correlator

Adding in the third dimension

- To visualize the full three dimensional data, we can add one more TIME dimension.





A comparison between real experimental data, fixed QCD prediction, and Parton shower would be very interesting!

A movie of how quark and gluon from hard scattering evolve to hadrons!

Summary

- Energy correlators emerge as a new class of observables for collider physics, which have nice theoretical property.
- Experimental measurement on the detector sphere can be interpreted as measuring correlation function in a fictitious 2D Euclidean field theory.
- Ready for phenomenology application once data are available:
  - Precision α_s determination.
  - Novel quantum interference phenomena. More to explore.
  - Comparison/visualization of higher dimensional data/theory to look for deviation from the Standard Model.