

# Energy correlators for collider phenomenology

Jack Holguin

# Outline

## **(1) A brief history of energy correlators**

- A popular new kid on the block and one of the oldest collider QCD observables?

## **(2) Links to fundamental theory**

- Energy correlators are not just collider observables...

## **(3) Recent developments and phenomenological applications**

- Probing the quark-gluon plasma
- Symmetries and jets formed from heavy decays

# Outline

## **(1) A brief history of energy correlators (before I was born)**

- A popular new kid on the block and one of the oldest collider QCD observables?

## **(2) Links to fundamental theory (I was in school)**

- Energy correlators are not just collider observables...

## **(3) Recent developments and phenomenological applications (I got involved)**

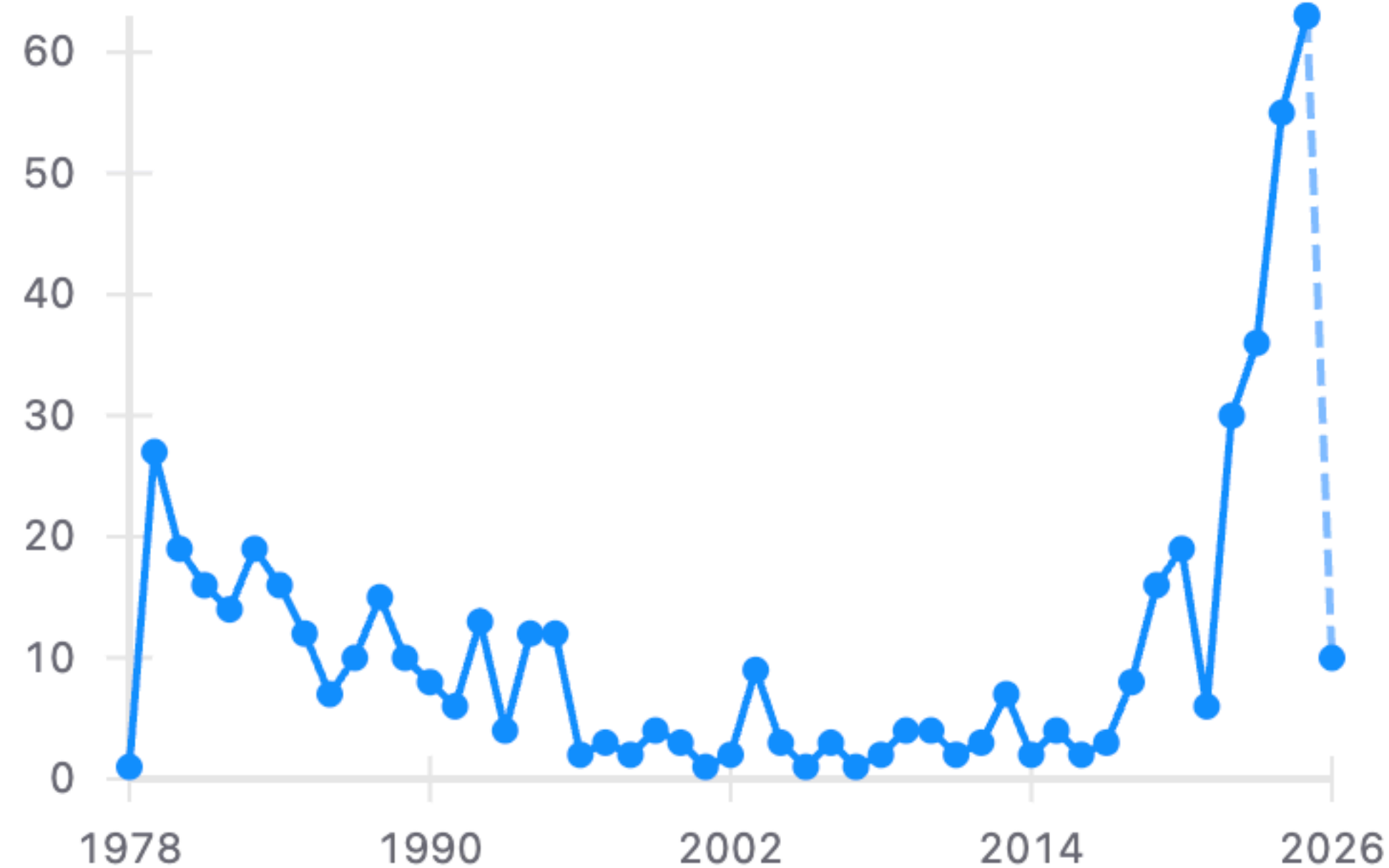
- Probing the quark-gluon plasma
- Symmetries and jets formed from heavy decays

# Outline

## (1) A brief history of energy correlators

- A popular new kid on the block and one of the oldest collider QCD observables?

Citations per year



Energy Correlations in  
electron - Positron  
Annihilation: Testing QCD

Basham, Brown, Ellis, Love '78

# A brief history of energy correlators

## The early years

The original energy correlator was proposed by [Basham, Brown, Ellis, Love '78](#)

$$\frac{d^2\Sigma}{d\Omega d\Omega'} = \sum_{N=2}^{\infty} \int \prod_{a=1}^N E_a^{-1}(d^3p_a) \frac{d^N\sigma}{E_1^{-1}(d^3p_1) \cdots E_N^{-1}(d^3p_N)} S_N \left[ \sum_{b,c=1}^N \frac{E_b E_c}{W^2} \delta(\Omega - \Omega_b) \delta(\Omega' - \Omega_c) \right]$$

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$$\frac{d\Sigma}{d\theta} = \int d\sigma_{ij} \frac{E_i E_j}{Q^2} \delta(\theta_{ij} - \theta)$$

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Energy of hadron i.  $\rightarrow$

Angle between hadrons (i,j)  $\rightarrow$

Inclusive cross section to produce two hadrons (i,j)  $\rightarrow$

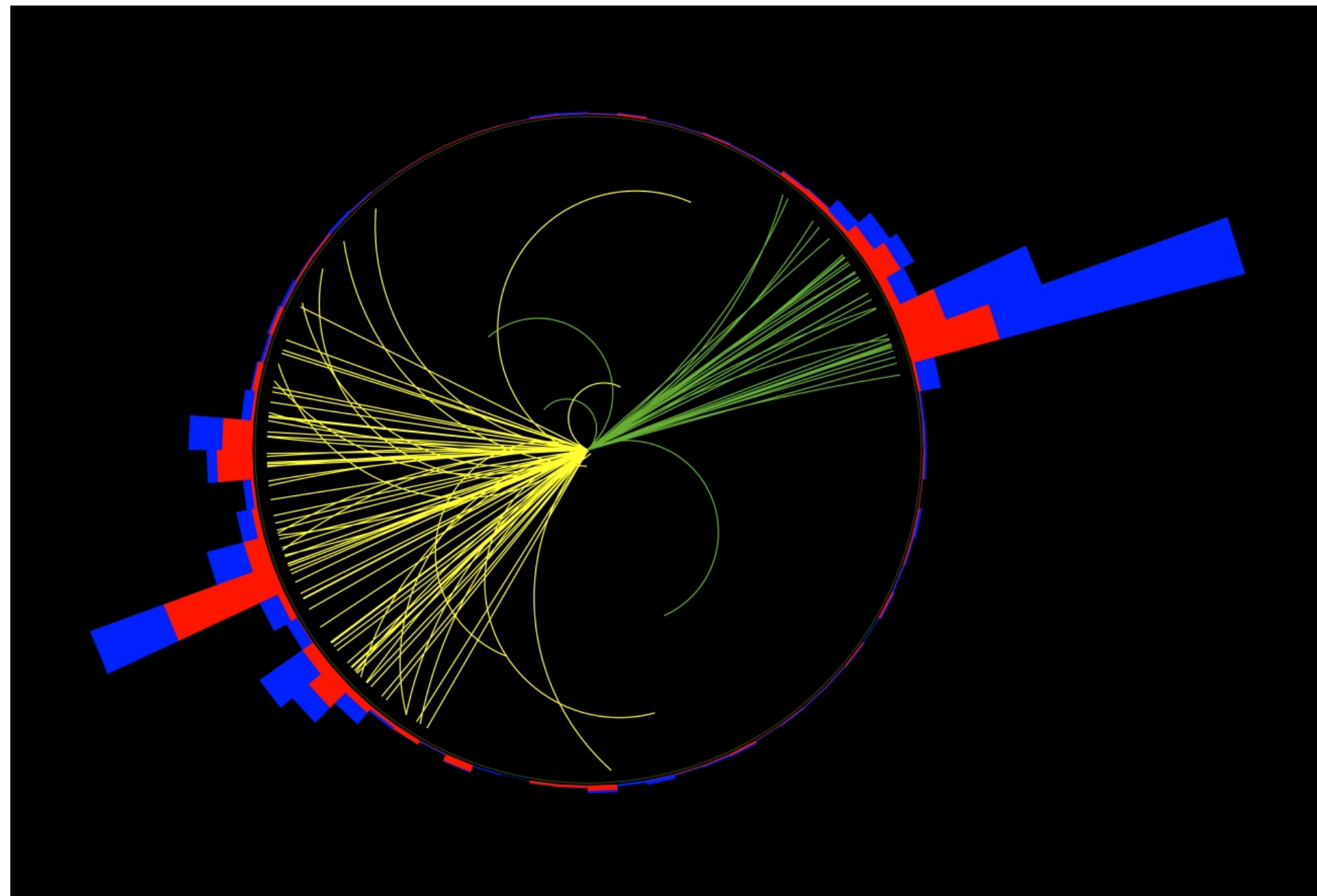
Hardscale  $\rightarrow$

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In an  $e^+e^-$  experiment:

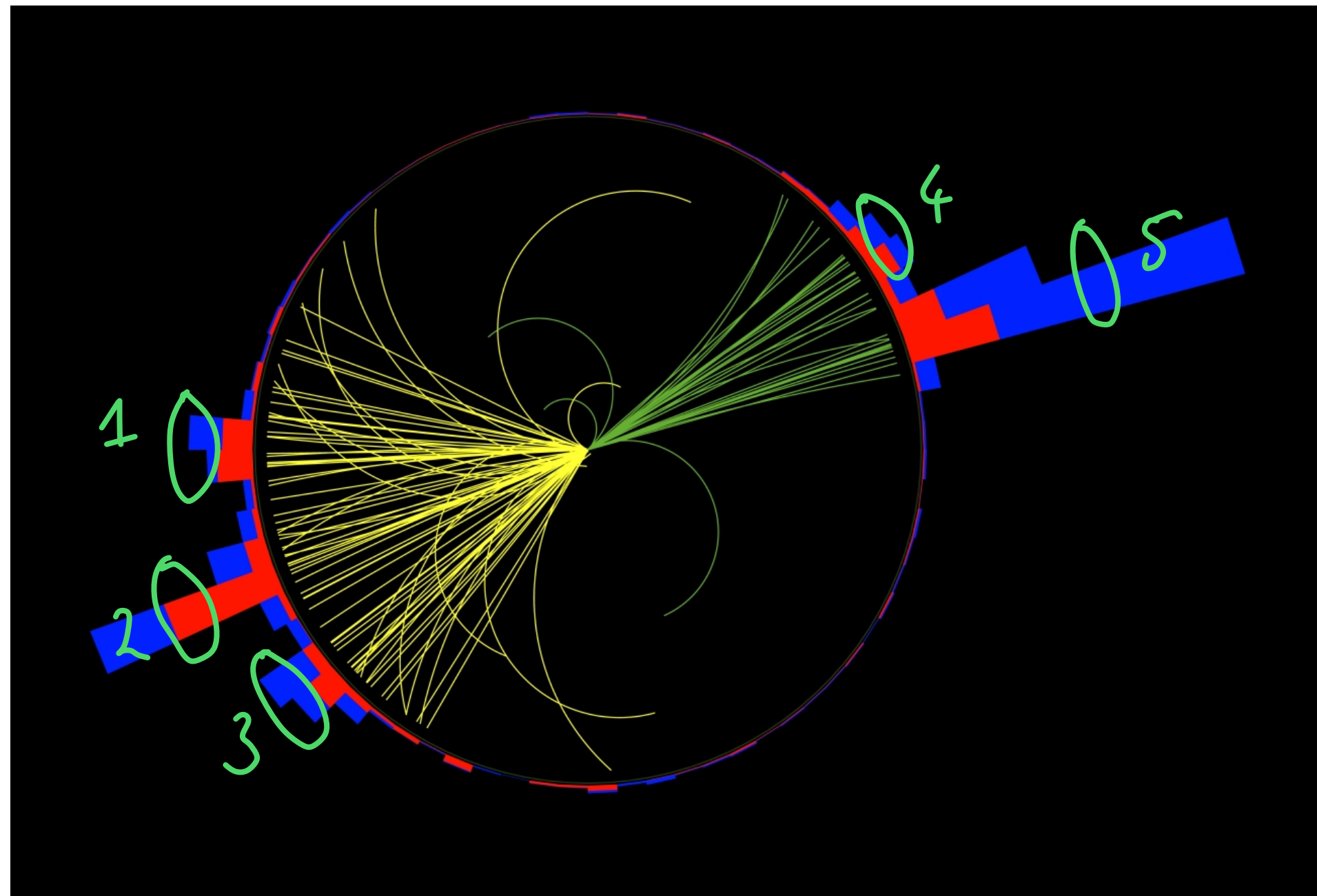


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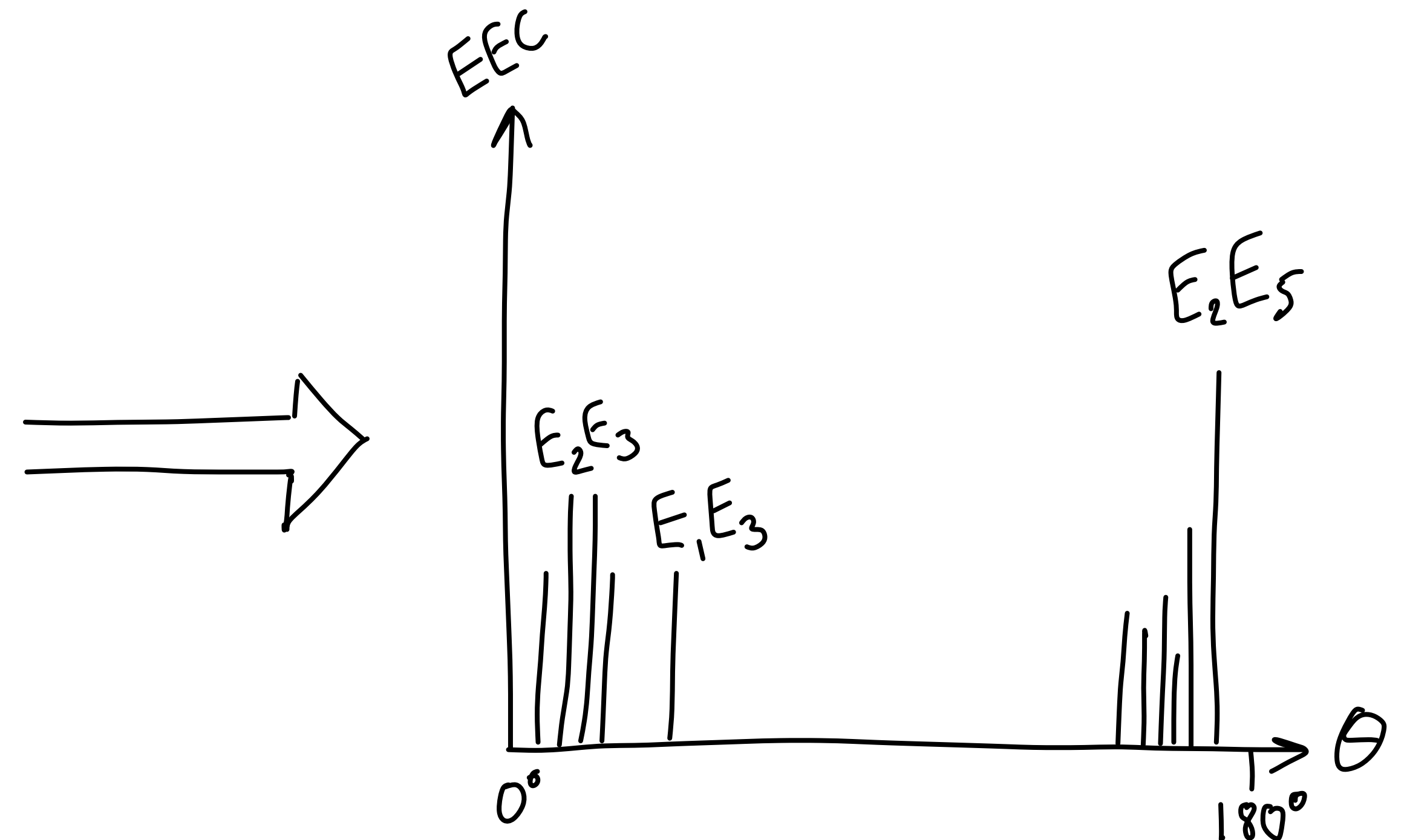
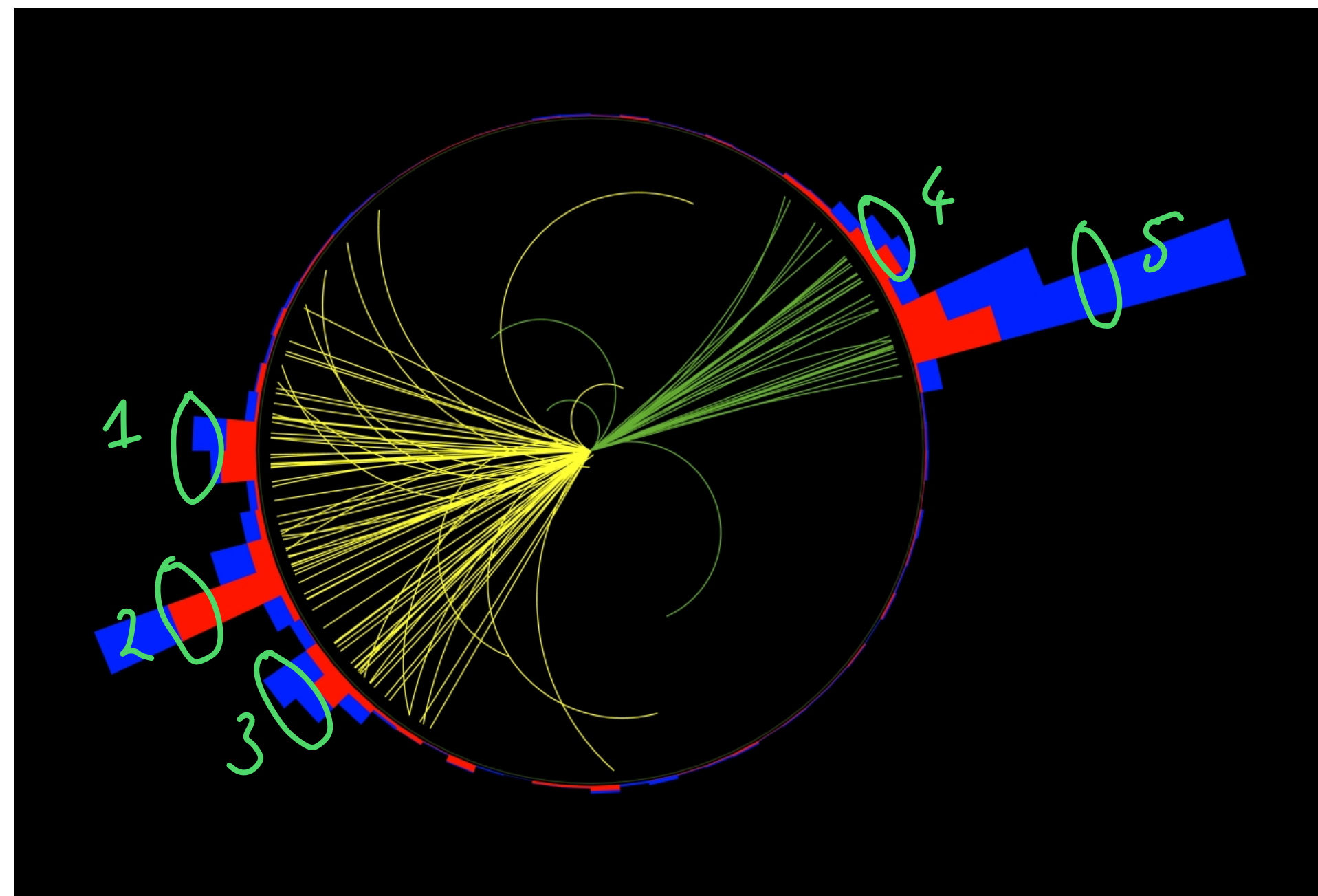


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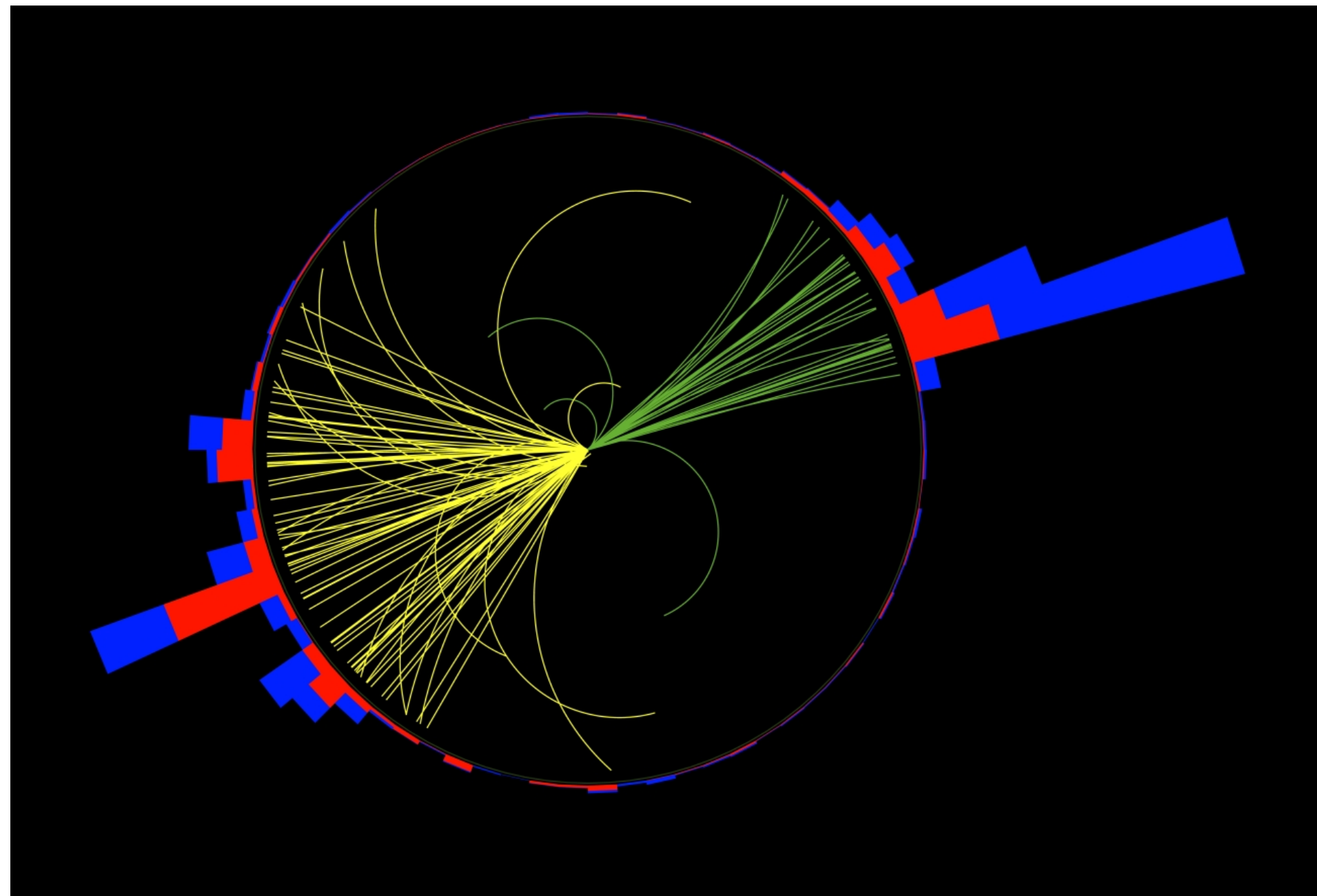


# A brief history of energy correlators

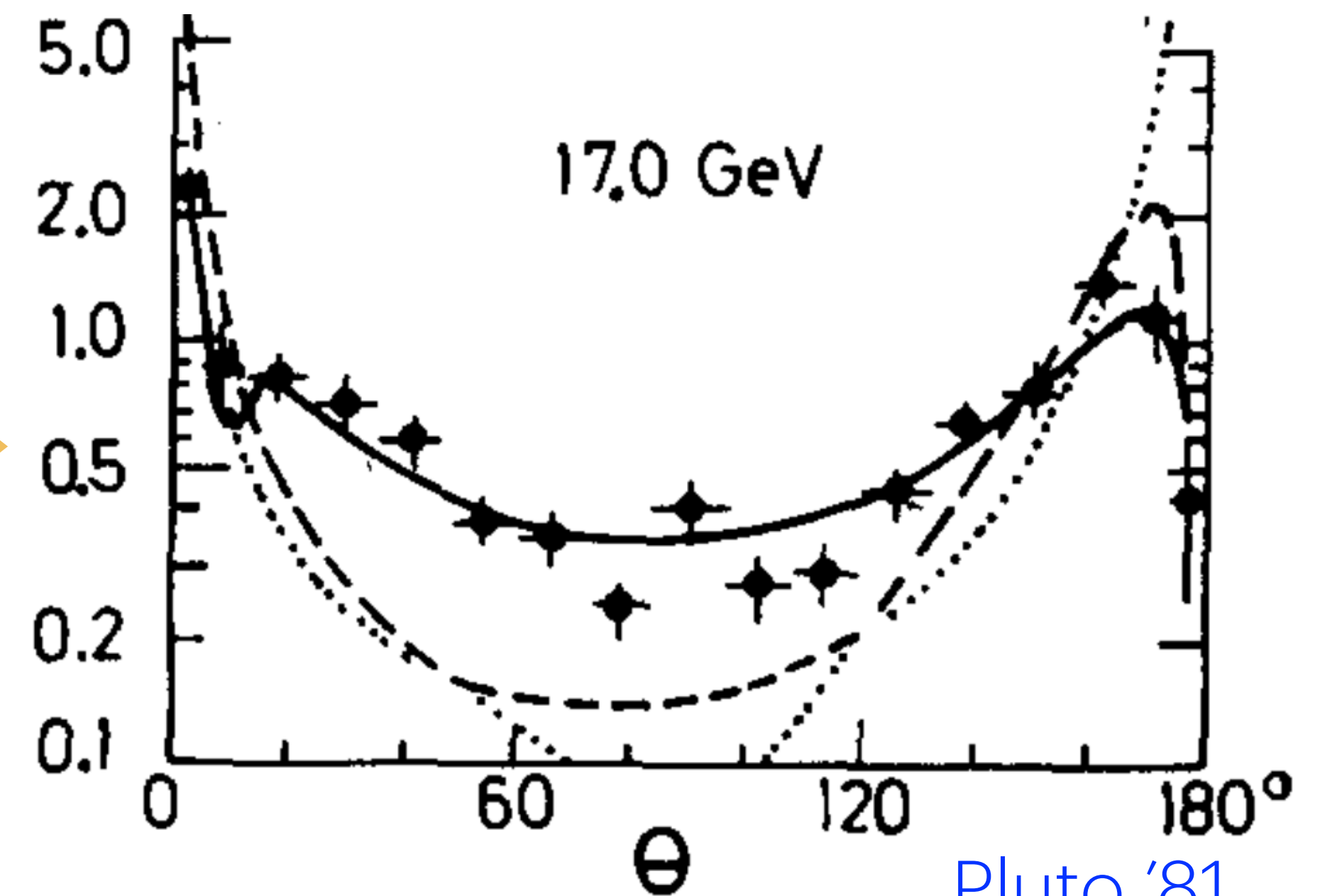
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In an  $e^+e^-$  experiment:



Sum over  
many  
events

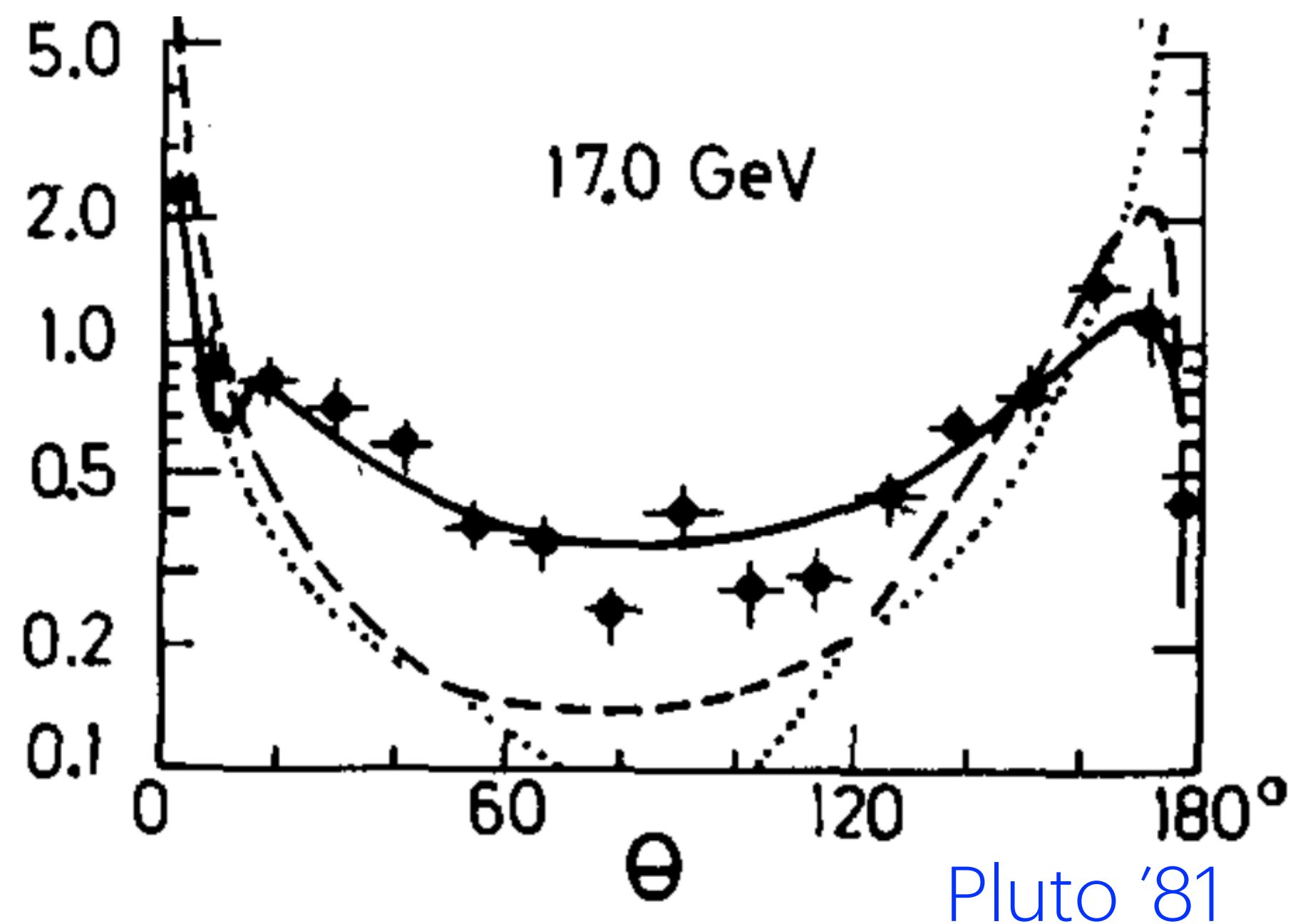


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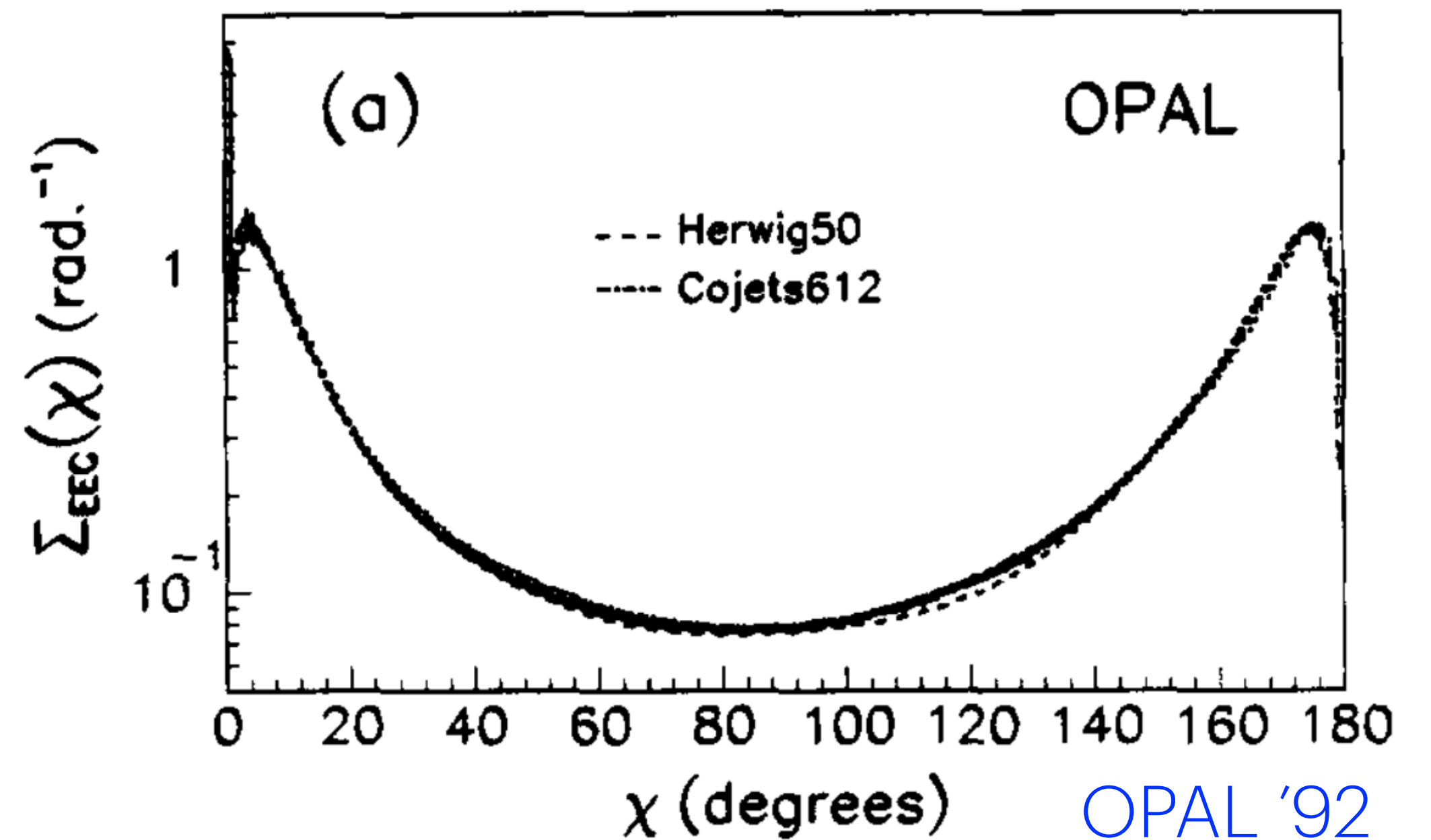
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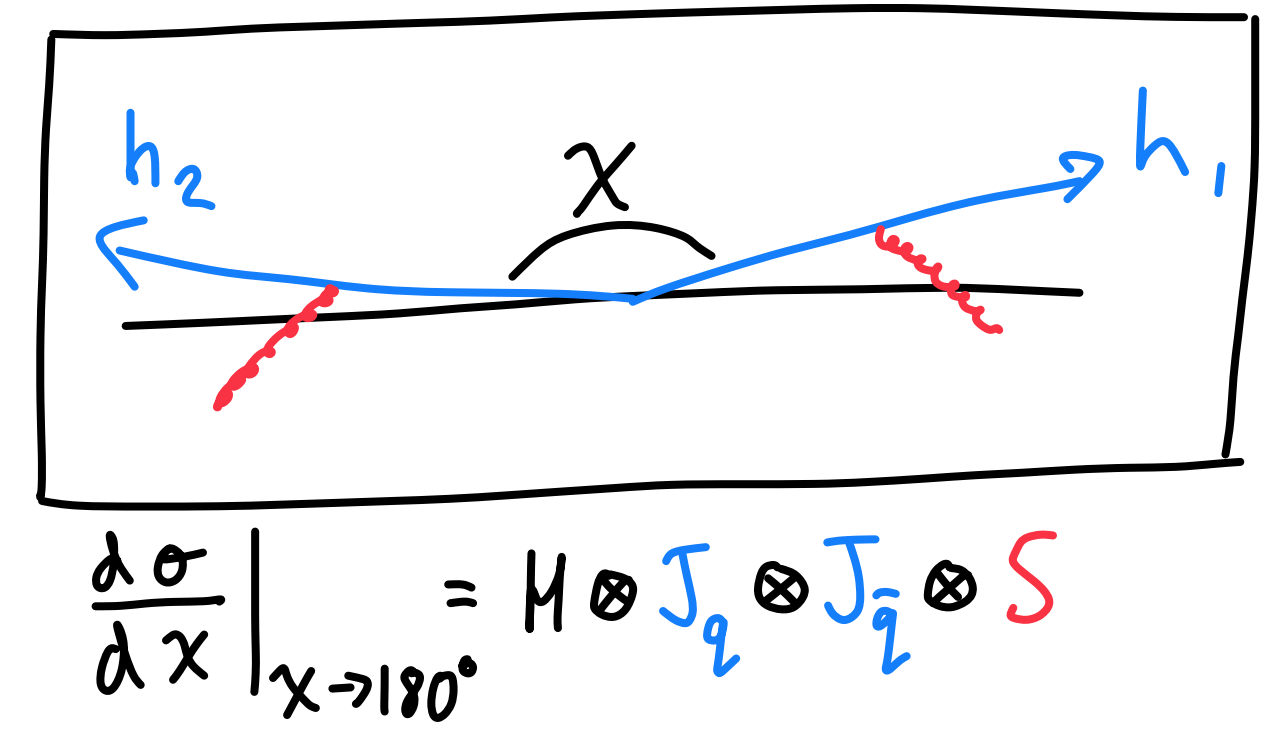
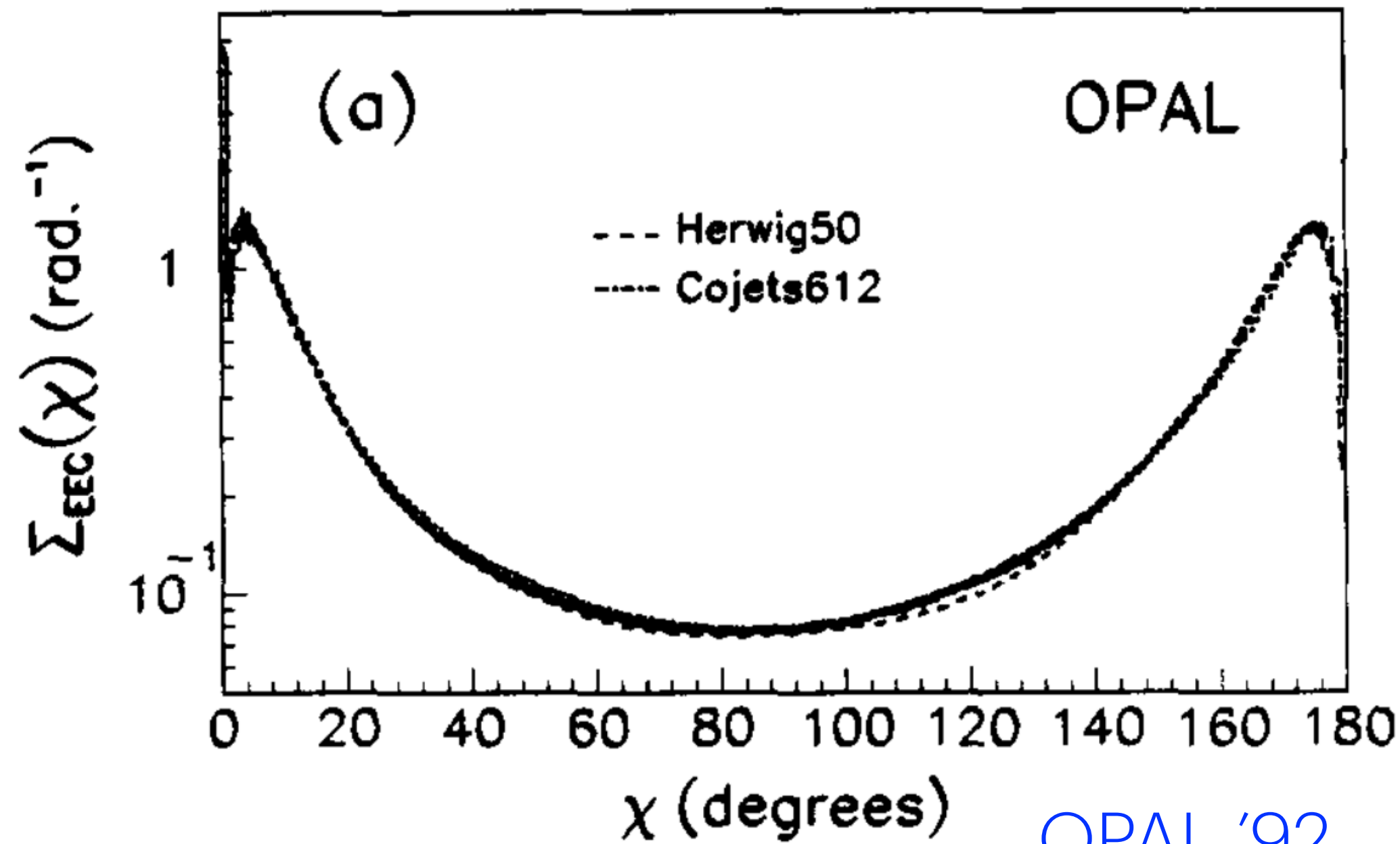
$$\alpha_s(M_{Z^0}) = 0.118 \pm 0.001 (\text{stat.}) \pm 0.003 (\text{exp. syst.}) \pm 0.009 (\text{theor. syst.})$$



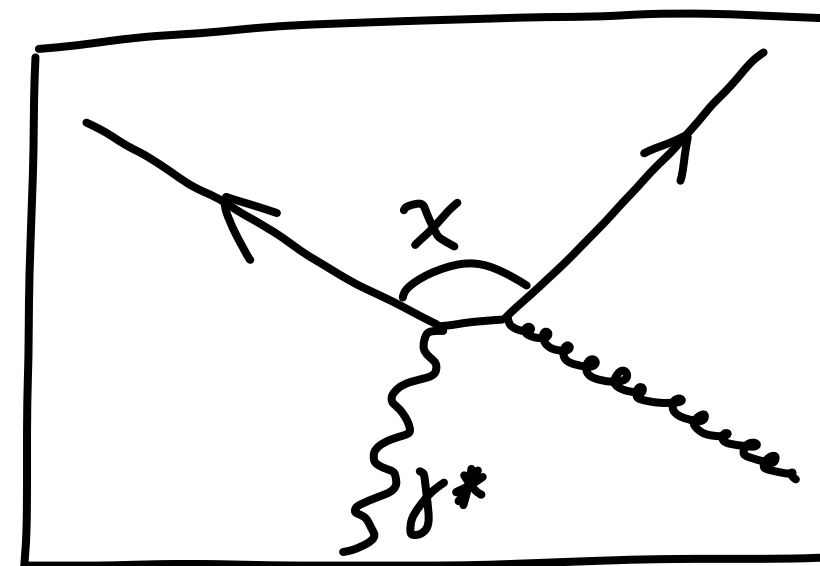
# A brief history of energy correlators

## The early years

Features of the  $e^+e^-$  EEC spectrum



LO  
 NLO  
 NNLO

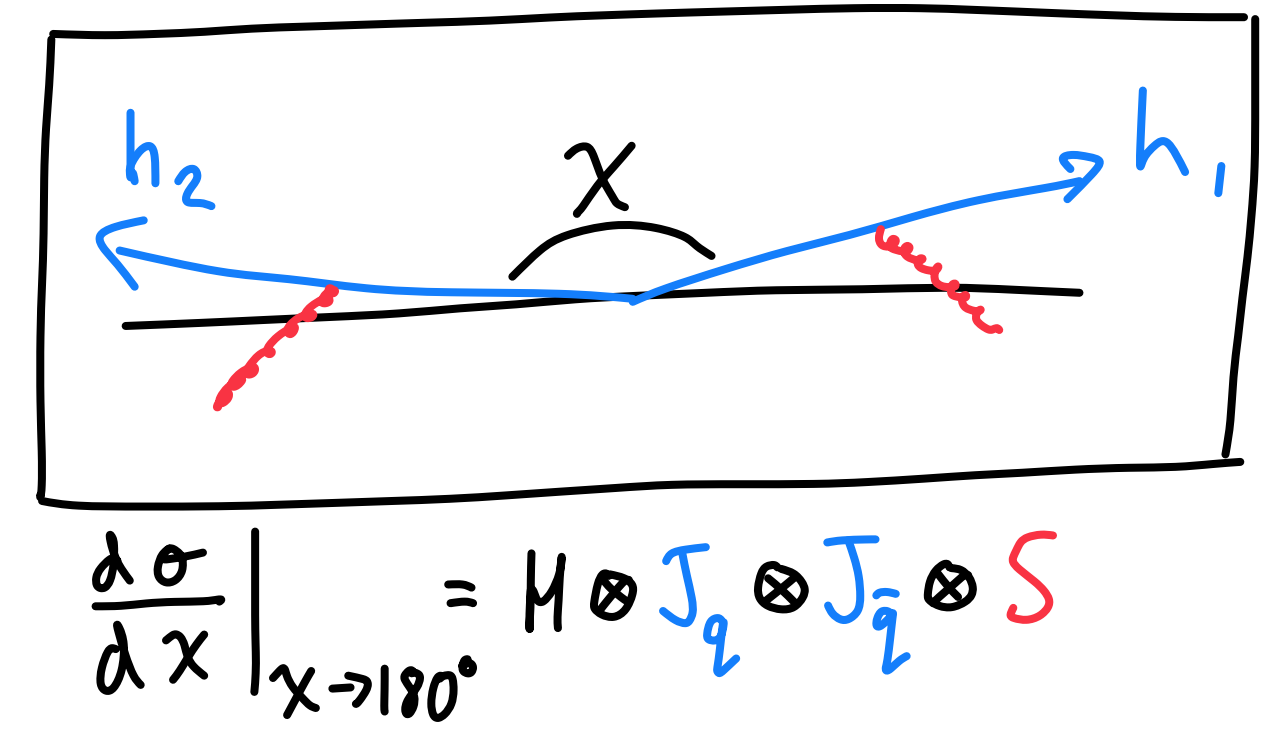
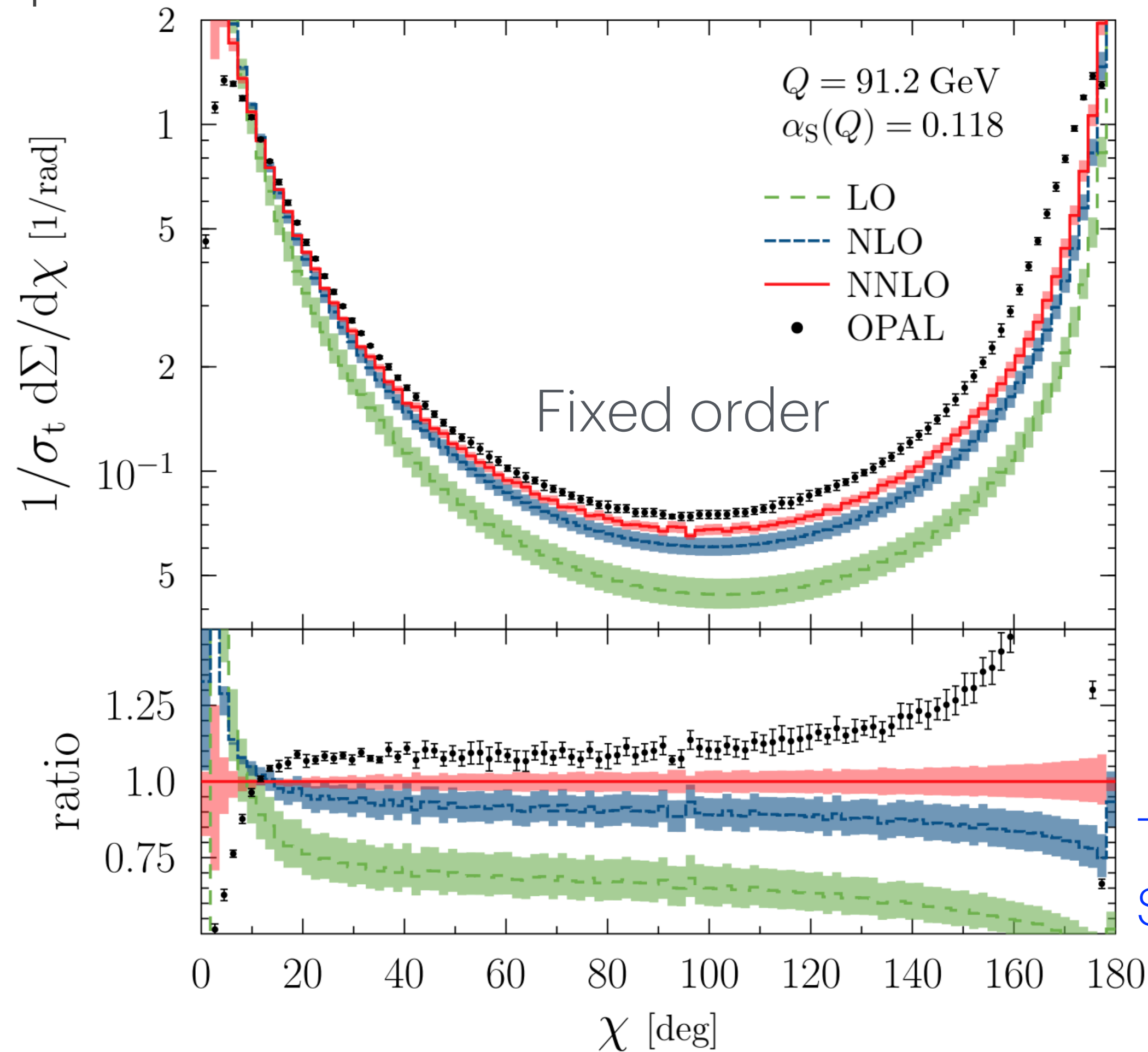


OPAL '92

# A brief history of energy correlators

## The early years

Features of the  $e^+e^-$  EEC spectrum



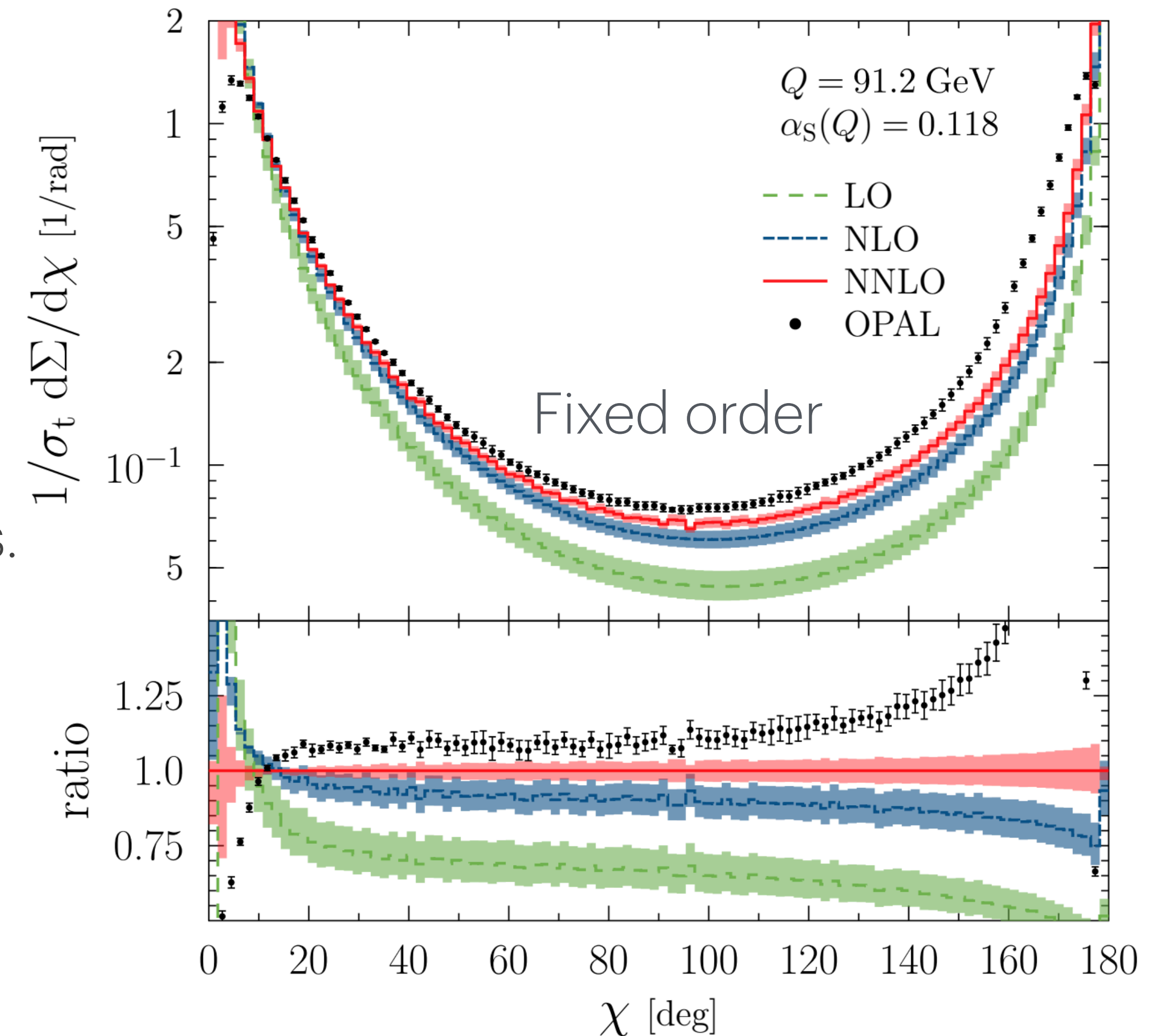
Tulipant, Kardos,  
Somogyi '17

# A brief history of energy correlators

## A changing of the guard

However, there was little phenomenological progress in the following 20 years for several key reasons:

- Notice the large difference between measurements and the NNLO predictions...
- Non-perturbative physics is crucial.
- The LHC was coming and these issues are big hurdles.
- In parallel, there was a huge amount of development into event-shapes and jet-observables.



# A brief history of energy correlators

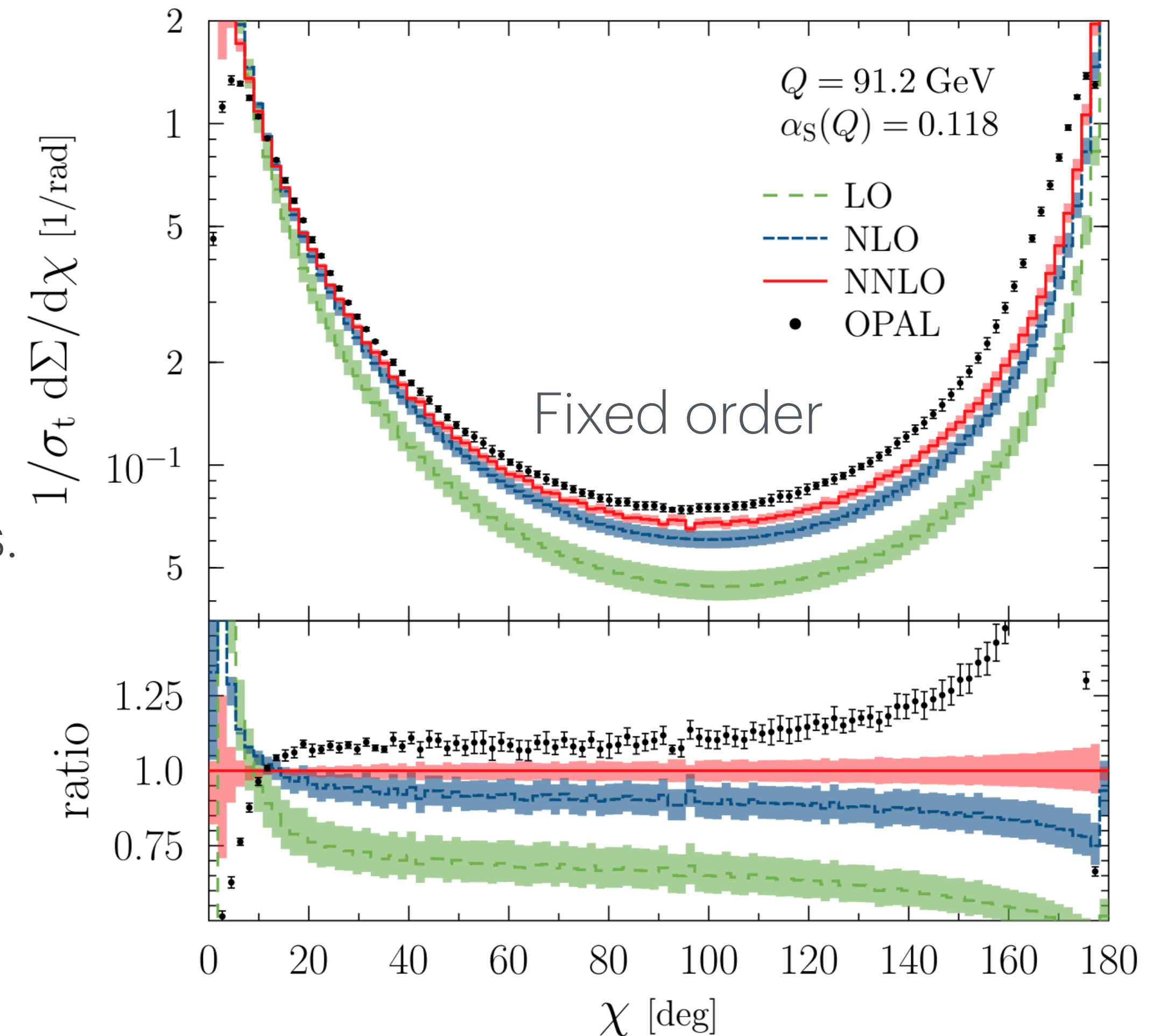
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A QCD Test for Jets  
Edward Farhi '77



# A brief history of energy correlators

## A changing of the guard

But whilst the phenomenologists were looking elsewhere, formal theory started to pay attention...

Consider an operator which projects out the energy of the particles measured in a detector:

$$\mathcal{E}(\vec{n}) |X\rangle = \sum_i E_i \delta^{(3)}(\vec{n} - \vec{p}_i/E_i) |X\rangle$$

With this, we can rewrite the energy correlator:

$$\begin{aligned} \frac{d\Sigma}{d\theta} &= \sum_X \int d\Phi_X \left| \langle \text{in} | X + i + j \rangle \right|^2 \frac{E_i E_j}{Q} \delta(\theta_{ij} - \theta) \\ &= \frac{1}{Q^2} \sum_X \int d\Phi_X \langle \text{in} | E_i E_j | X + i + j \rangle \langle X + i + j | \text{in} \rangle \delta(\theta_{ij} - \theta) \\ &= \frac{1}{Q^2} \int d\vec{n}_1 d\vec{n}_2 \langle \text{in} | \mathcal{E}(n_1) \mathcal{E}(n_2) | \text{in} \rangle \delta(\theta_{12} - \theta) \end{aligned}$$

# A brief history of energy correlators

## A changing of the guard

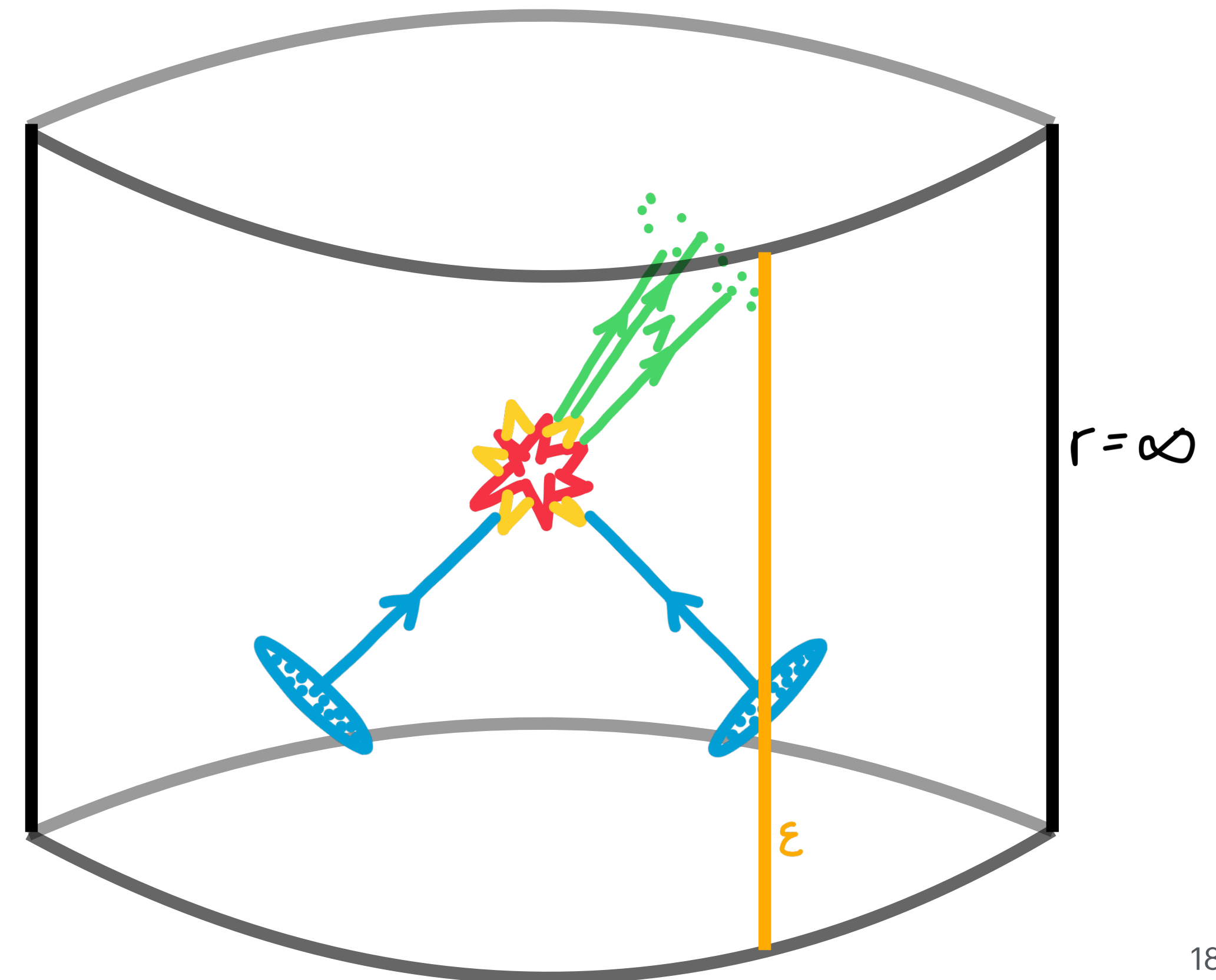
But whilst the phenomenologists were looking elsewhere, formal theory started to pay attention...

What is this “energy flow operator”?

$$\mathcal{E}(\vec{n}) |X\rangle = \sum_i E_i \delta^{(3)}(\vec{n} - \vec{p}_i/E_i) |X\rangle$$

Sveshnikov, Tkachov '96; Tkachov '97; Korchemsky, Sterman '99 demonstrated that it is determined by the energy-momentum tensor integrated along a light-ray.

$$\begin{aligned} \mathcal{E}(\vec{n}) &= \lim_{r \rightarrow \infty} \int_0^\infty dt r^2 \vec{n}_i T_{oi}(t, r\vec{n}) \\ &\equiv \lim_{x_+ \rightarrow \infty} \int_0^\infty dx_- x_+^2 T_{++}(x) \end{aligned}$$

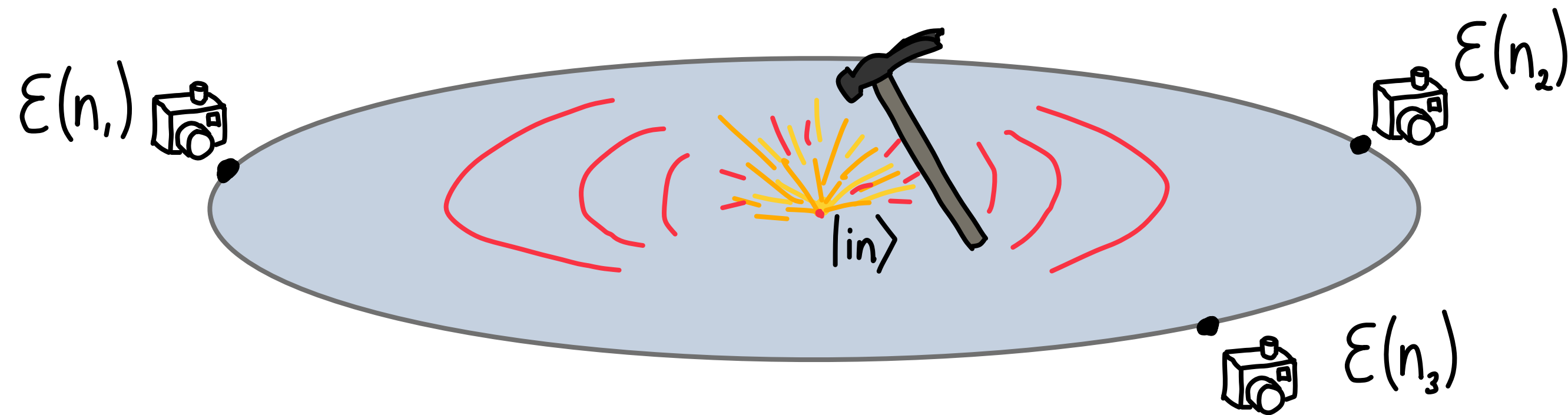


# Links to fundamental theory

## Energy correlators are not just collider observables

Studying n-point energy correlators amounts to studying correlation functions of the energy flow operator.

$$\langle \text{in} | \mathcal{E}(n_1) \dots \mathcal{E}(n_n) | \text{in} \rangle$$



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Additionally, these are fundamental field theoretic operators and relating to the average null energy condition:

$$\langle \text{in} | \mathcal{E}(n) | \text{in} \rangle \geq 0$$

in any Lorentzian field theory with  $d > 2$ . The ANEC (and its generalisations) can be crucial to determining the spectrum of conformal field theories and gravity theories.

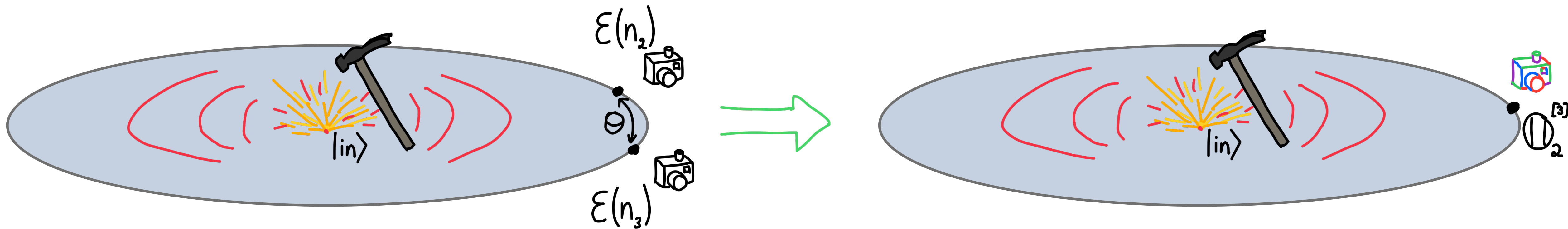
# Links to fundamental theory

Energy correlators are not just collider observables

This has resulted in a wealth of new techniques for computing energy correlators.

A landmark result was the introduction of the light-ray OPE by Hofman, Maldacena '08

$$\langle \text{in} | \mathcal{E}(n_1) \mathcal{E}(n_2) | \text{in} \rangle = \frac{C_2}{\theta^{2-\gamma(3)}} \langle \text{in} | \mathbb{O}_2^{[3]}(n_1) | \text{in} \rangle + \mathcal{O}(\theta^0)$$



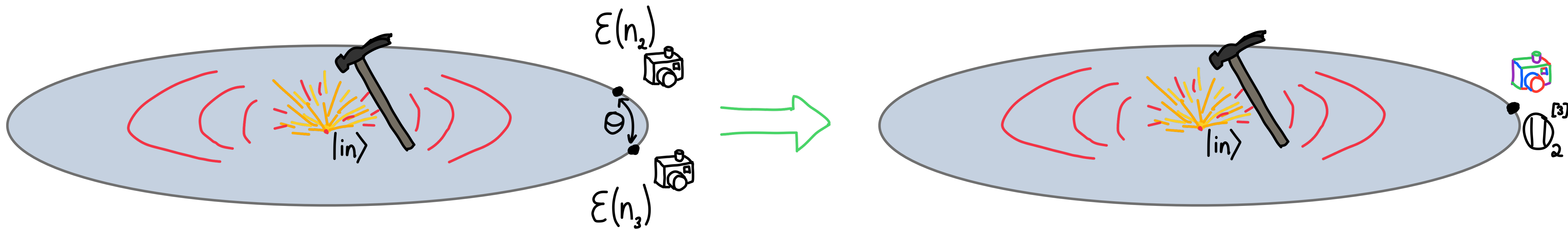
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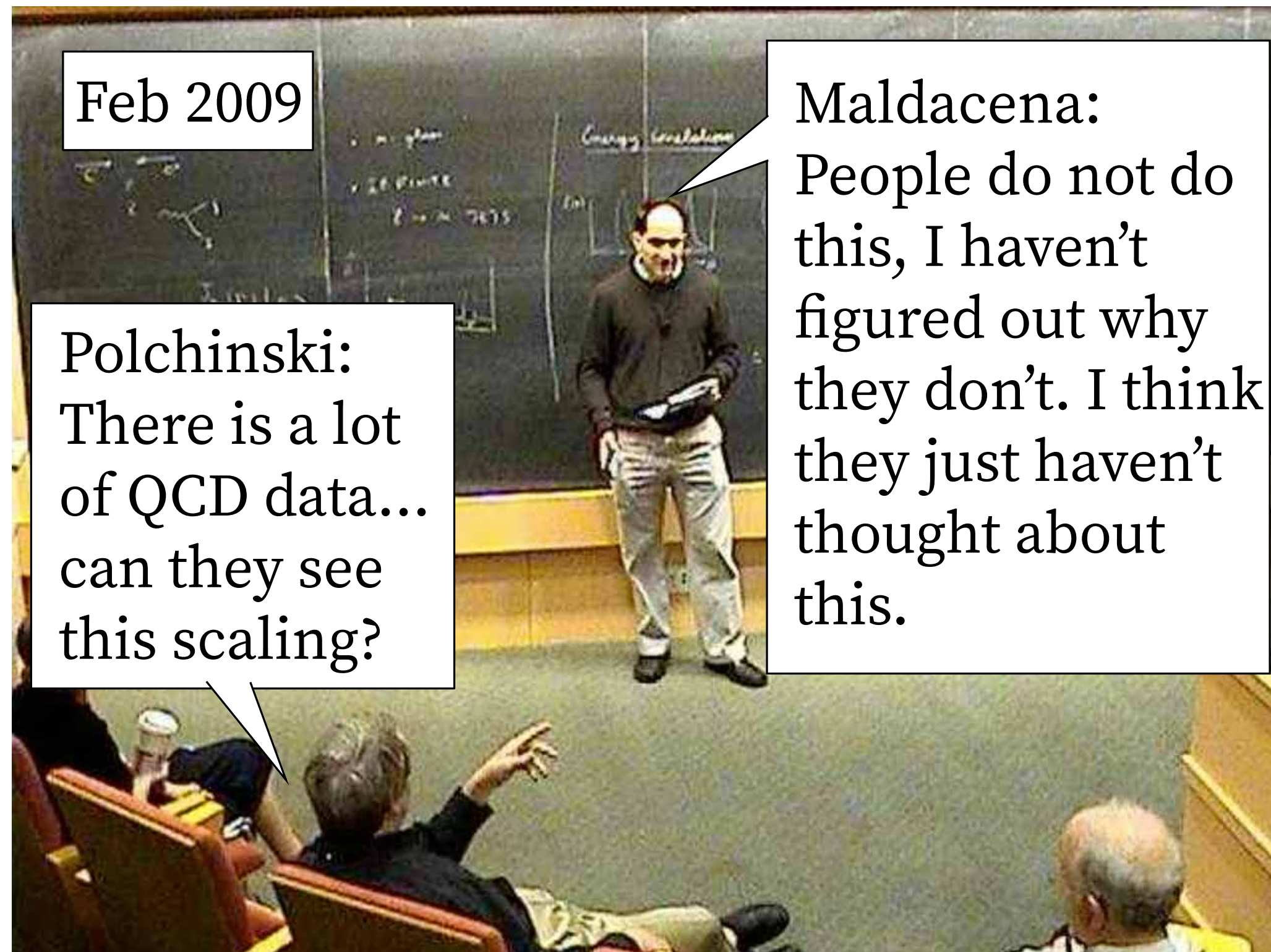
Lorentzian inversion    Integrability    Analyticity    etc.  
 Celestial Blocks    AdS/CFT    Effective theories

Belitsky, Hohenegger, Korchemsky, Sokatchev, Zhiboedov '14  
 Kravchuk, Simmons-Duffin '18  
 Koloğlu, Kravchuk, Simmons-Duffin, Zhiboedov '19  
 Plus many more

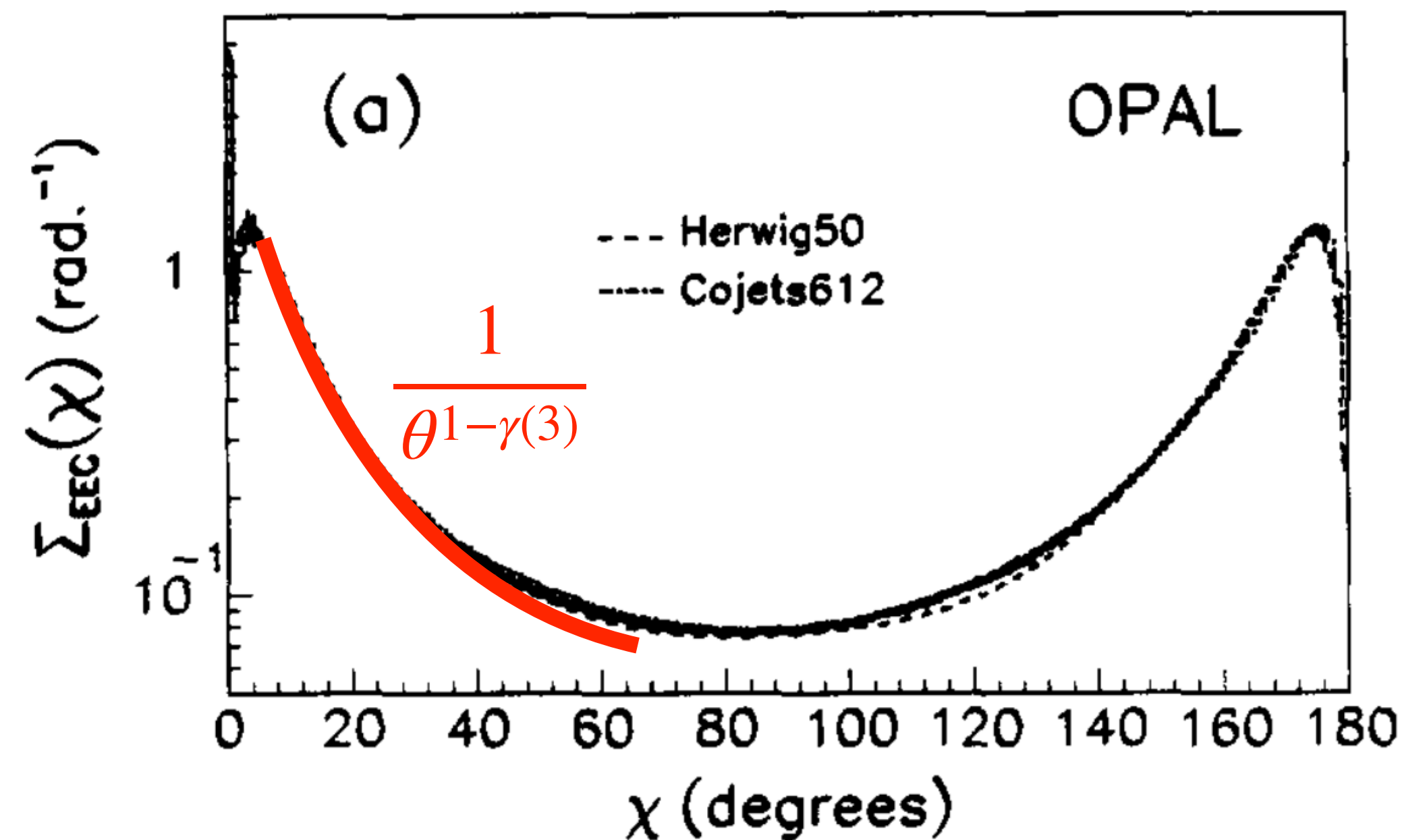
# Links to fundamental theory

## Energy correlators are not just collider observables

This wealth of development led to a now infamous exchange...



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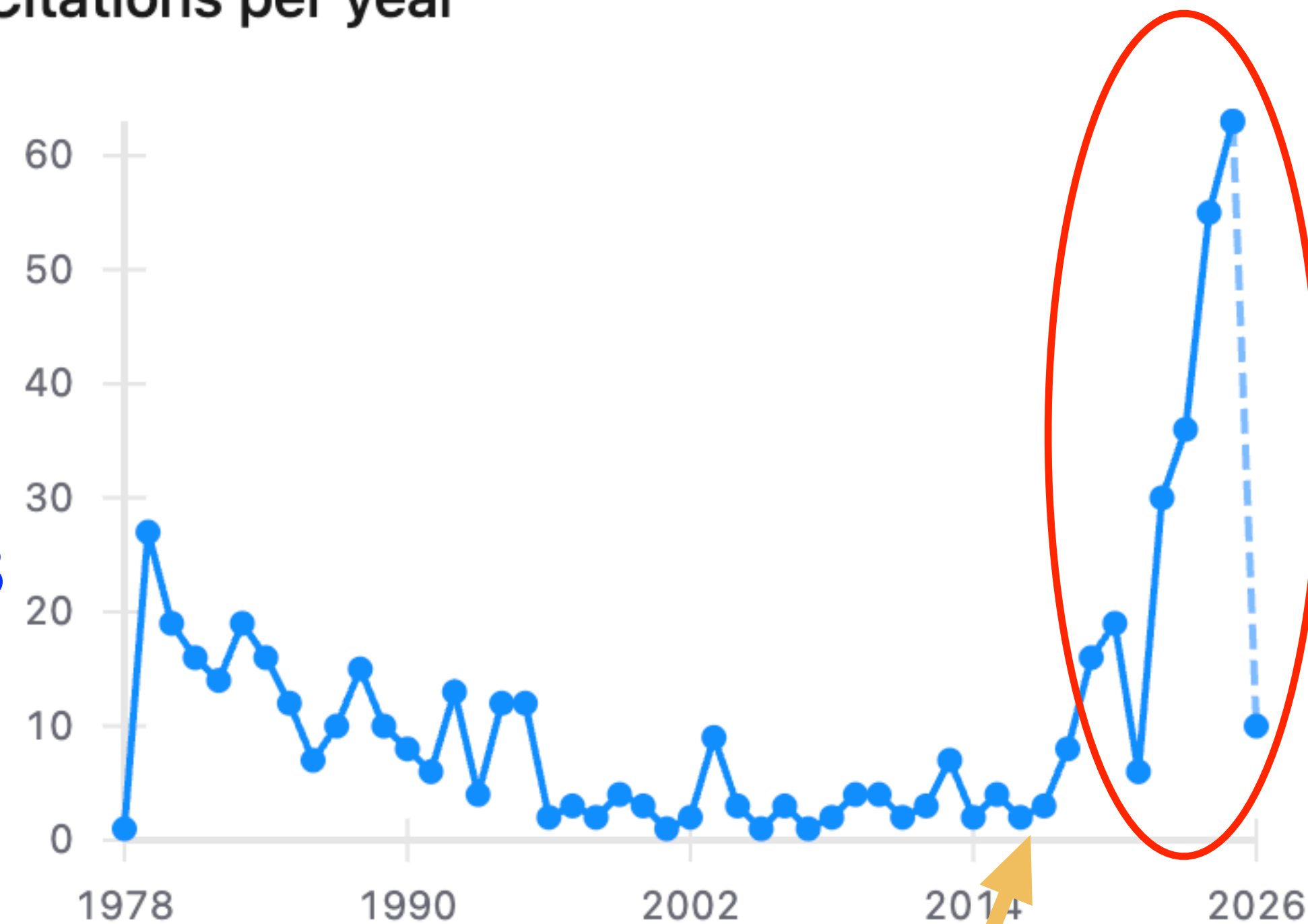
# Recent developments and phenomenological applications

## The modern day resurgence

Energy Correlations in  
electron - Positron  
Annihilation: Testing QCD

Basham, Brown, Ellis, Love '78

Citations per year

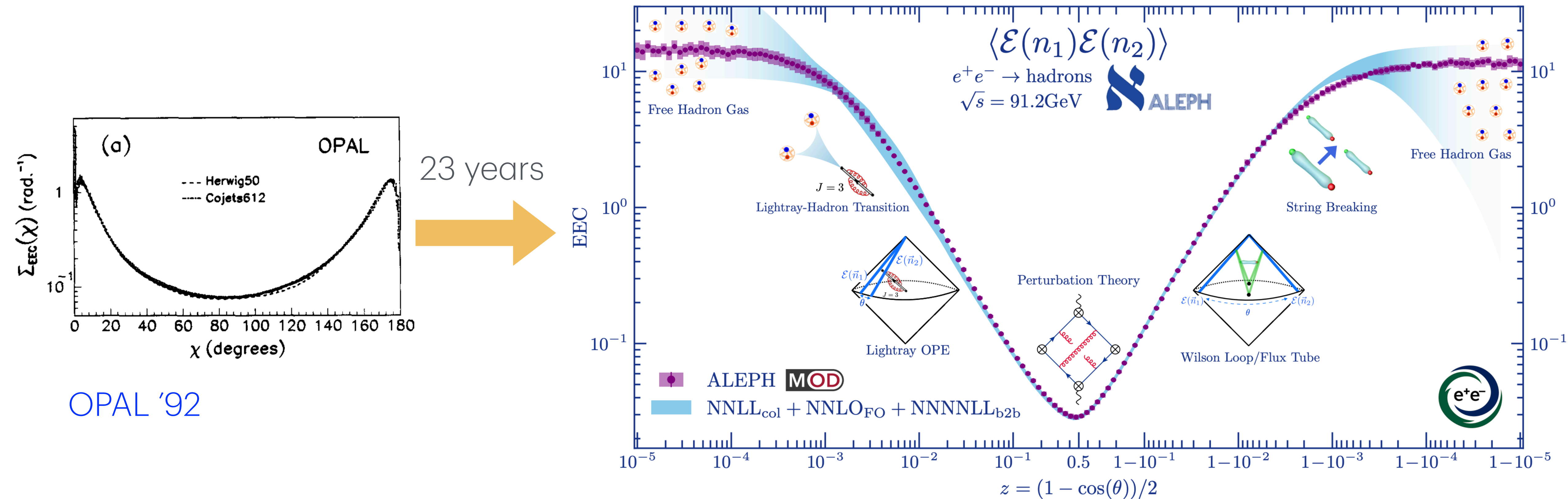


QCD theorists did pay attention once enough work had been done so that past hurdles could be overcome!

Belitsky, Hohenegger, Korchemsky, Sokatchev, Zhiboedov '14  
Kravchuk, Simmons-Duffin '18  
Koloğlu, Kravchuk, Simmons-Duffin, Zhiboedov '19  
Plus many more

# Recent developments and phenomenological applications

## The modern day resurgence



There is a Jacobian from the change  $\chi \rightarrow z$  which causes the peaks to become plateaux.

e+e- alliance '25

# Recent developments and phenomenological applications

But it is not just  $e^+e^-$

LHC process	Theory	Experiment
<b>Massless jets</b>	NNLL: Dixon, Moulton, Zhu '19 OPE + Spin correlations: Chen, Moulton, Sandor, Zhu '21-'23 Tracks: Jaarsma, Li, Moulton, Waalewijn, Zhu '23 Power corrections, OPE, NP: Chen et al. '21-'26	Strong coupling: CMS '24, Confinement: ALICE '24 Confinement: STAR '23
<b>Heavy boson jets</b>	Z jets N4LL: <b>JH</b> , Moulton, Pathak, Procura, Sule '26 Higgs jets N4LL: Gao, Lee, Zhang '26	-
<b>Heavy coloured jets</b>	b/c jets: Craft, Lee, Meçaj, Moulton '22 Top mass: <b>JH</b> , Moulton, Pathak, Procura '22 Top mass: <b>JH</b> , Moulton, Pathak, Procura, Schöffbeck, Schwarz '23-'26	D <sup>0</sup> -tagged jets: ALICE '24
<b>Proton-Ion collisions</b>	MC: Devereaux, Fan, Ke, Lee, Moulton '23 Twist: Fu, Müller, Sirimanna '24 OPE: Andres, Dominguez, <b>JH</b> , Marquet, Moulton '24 Barata, Kang, López, Penttala '24	p-Pb: ALICE '24
<b>Ion-Ion collisions</b>	Jet quenching: Andres, Dominguez, Elayavalli, <b>JH</b> , Marquet, Moulton '22 Predictions: Andres, Dominguez, <b>JH</b> , Marquet, Moulton '24 OPE: Andres, Aretz, Dominguez, <b>JH</b> , Lee, Marquet, Moulton '24-'26 Barata, Moulton, Sadofyev, Silva '25	Pb-Pb: CMS '24
<b>Forward processes/ small-x</b>	Nucleon ECs: Liu, Zhu '22-'23 CGC nucleon ECs: Liu, Liu, Pan, Yuan, Zhu '23	proposed for EIC
<b>Electro-weak physics</b>	Density matrix: Ricci, Riembau '22-'25	-
<b>Generalised detector correlators</b>	Charged and Energy weighted detectors: Lee, Moulton '23-'25 EWOCs: Alipour-fard, Waalewijn '25 Jet detectors: <b>JH</b> , Lee '26	track function moments: ATLAS '24

+ more

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Symmetries

OPE

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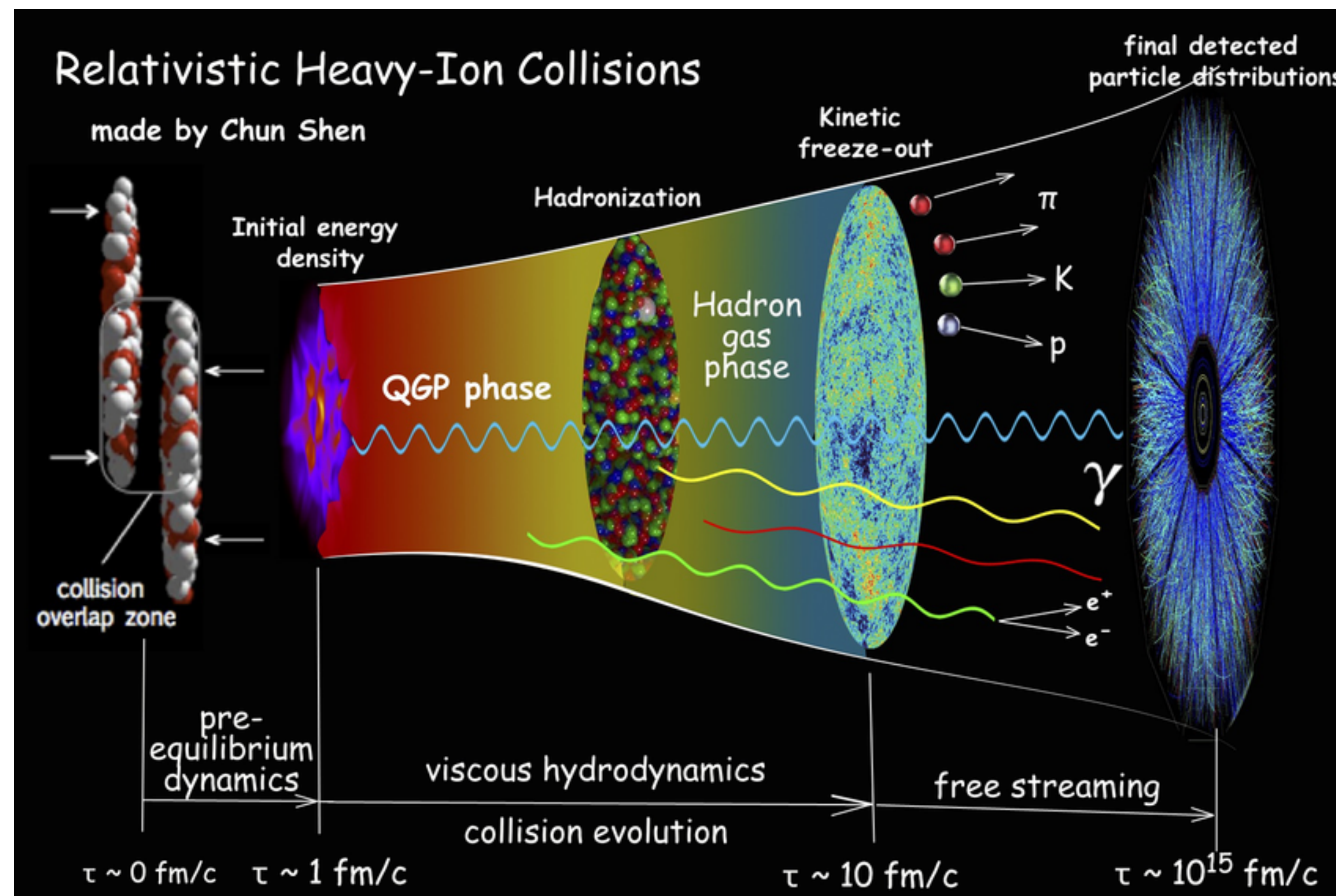
## Heavy ion jets

One of the core goals of HI collisions is studying the quark gluon plasma.

However, it's challenging at a fundamental level.

Jets and energetic particles are produced along with the plasma. This means both strongly coupled and weakly coupled dynamics.

Computing the S-matrix or cross-sections with precision is a present impossibility.



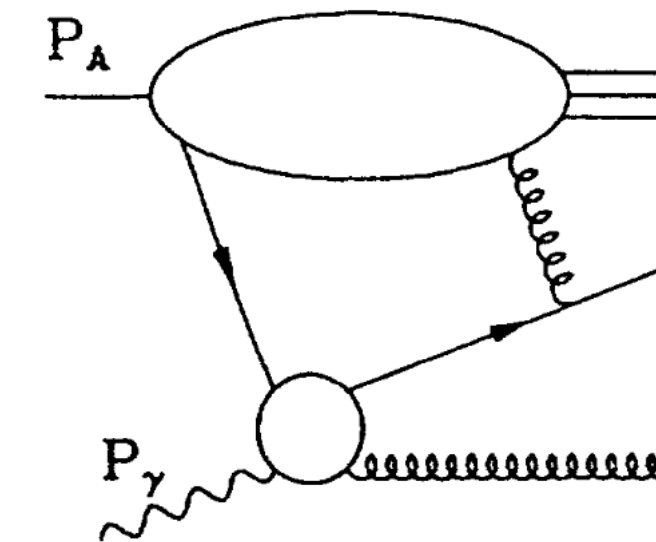
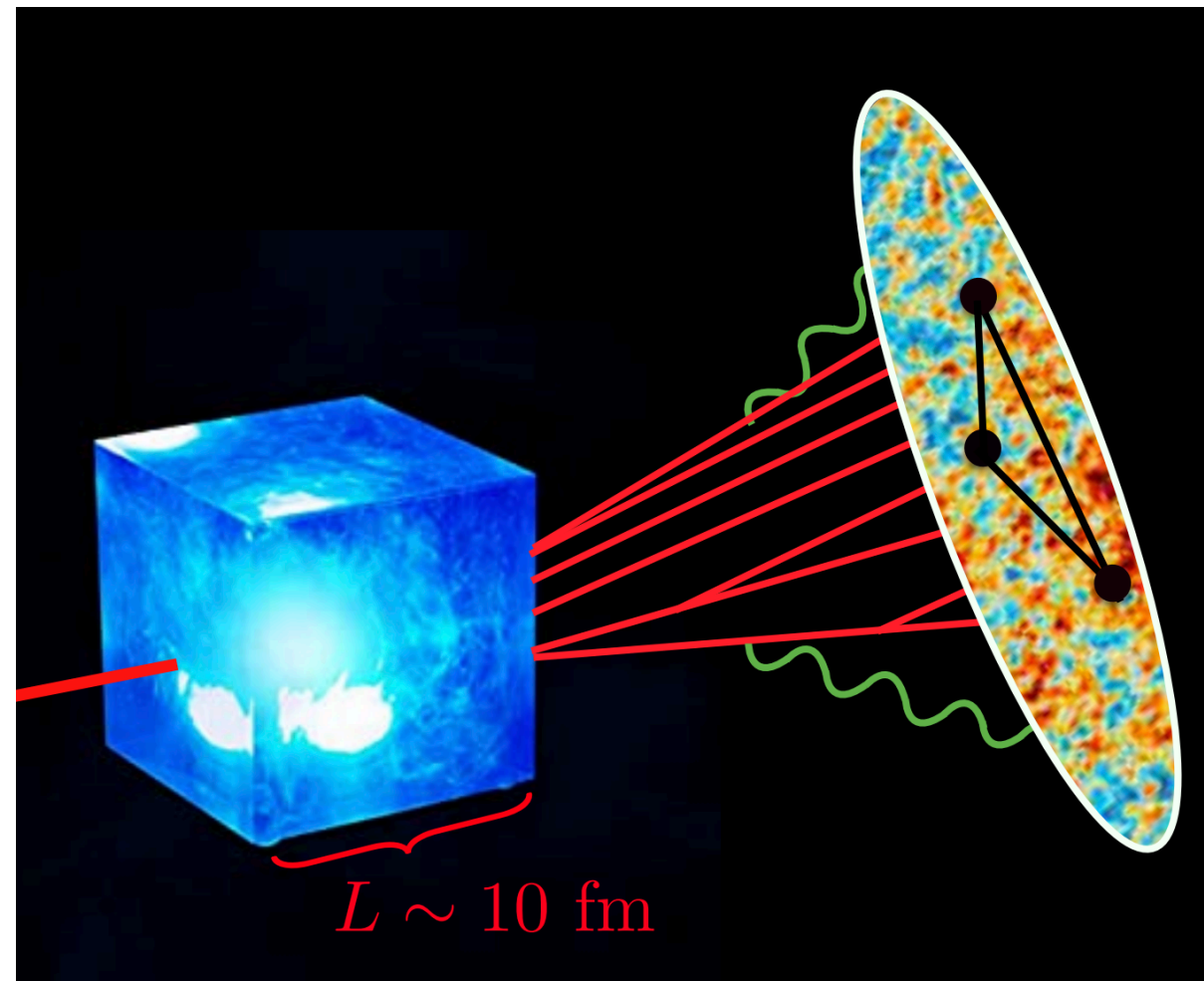
😞  $|\langle \text{Pb-Pb} | X + i + j \rangle|^2$  😏

# Recent developments and phenomenological applications

## Heavy ion jets

However, we can compute energy correlators inside heavy ion jets via the light-ray OPE!

$$\langle \text{Pb-Pb} | \mathcal{E}(n_1) \mathcal{E}(n_2) | \text{Pb-Pb} \rangle = \frac{C_2}{\theta^{2-\gamma(3)}} \langle \text{Pb-Pb} | \mathbb{O}_2^{[3]}(n_1) | \text{Pb-Pb} \rangle + \theta^{\gamma_4(3)} C_4 \langle \text{Pb-Pb} | \mathbb{O}_4^{[3]}(n_1) | \text{Pb-Pb} \rangle + \mathcal{O}(\theta^2)$$



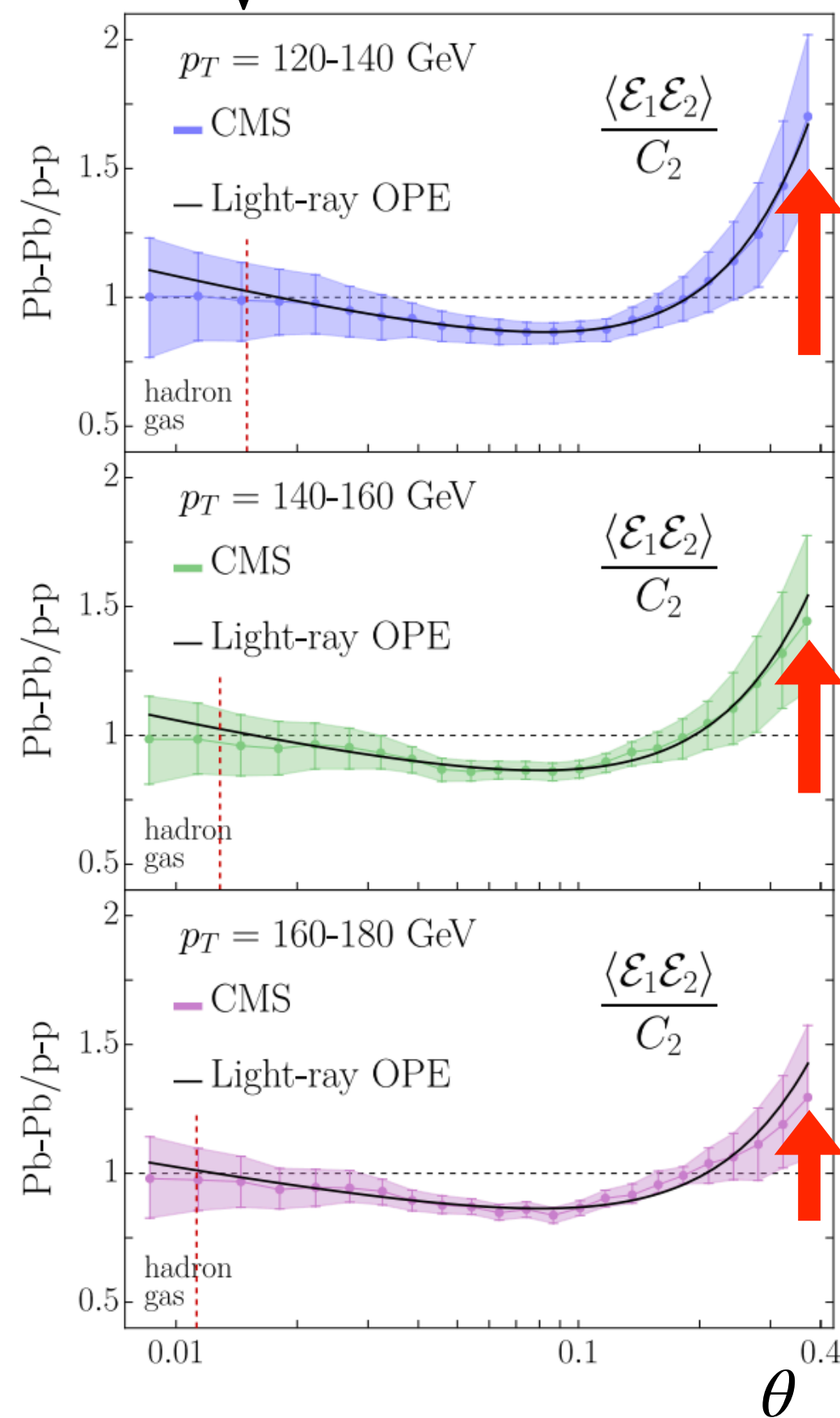
Luo, Qiu,  
Sterman '93

$$\frac{\text{Pb-Pb}}{\text{p-p}} \sim 1 + \langle \text{Pb-Pb} | \mathbb{O}_4^{[3]}(n_1) | \text{Pb-Pb} \rangle \theta^2$$

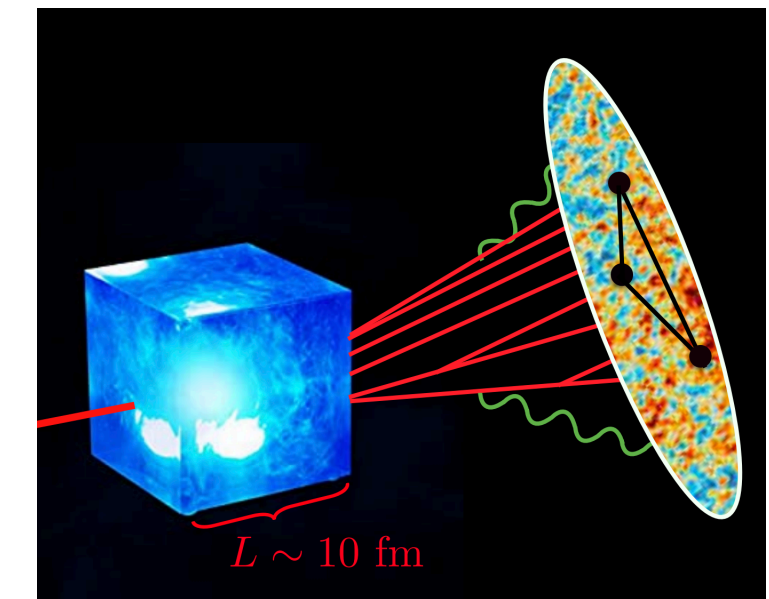
# Recent developments and phenomenological applications

## Heavy ion jets

Pb-Pb  $\sqrt{s_{NN}} = 5.02$  TeV 0-10 %



$\langle \text{Pb-Pb} | \mathbb{O}_4^{[3]}(n_1) | \text{Pb-Pb} \rangle$  is a one-point function that directly encodes the properties of the plasma (temperature, density, viscosity, etc).

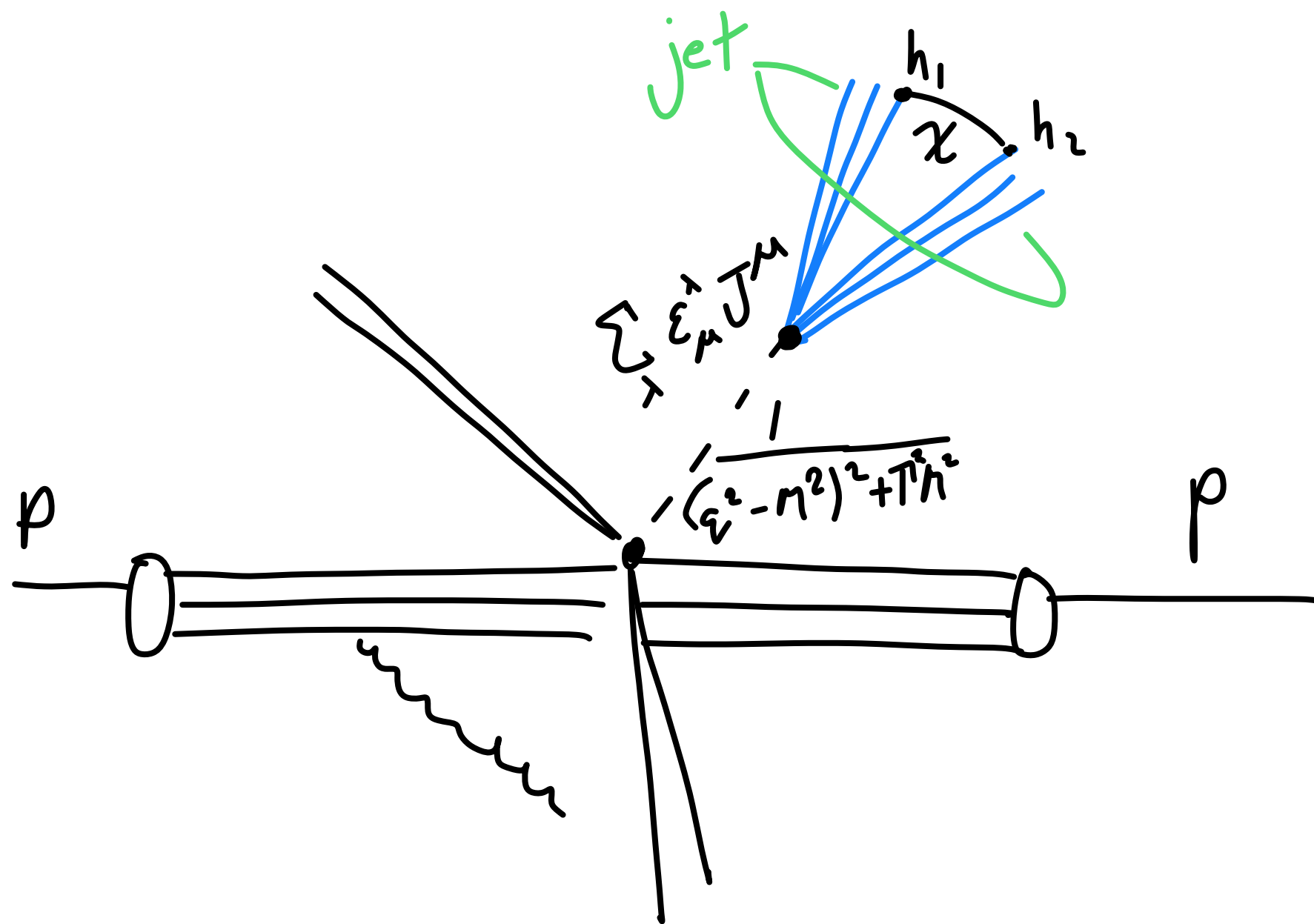


$$\langle \text{Pb-Pb} | \mathcal{E}(n_1) \mathcal{E}(n_2) | \text{Pb-Pb} \rangle = \frac{C_2}{\theta^{2-\gamma(3)}} \langle \text{Pb-Pb} | \mathbb{O}_2^{[3]}(n_1) | \text{Pb-Pb} \rangle + \theta^{\gamma_4(3)} C_4 \langle \text{Pb-Pb} | \mathbb{O}_4^{[3]}(n_1) | \text{Pb-Pb} \rangle + \mathcal{O}(\theta^2)$$

We find exceptional agreement with CMS measurement and ALICE measurements.

# Recent developments and phenomenological applications

## Heavy boson jets



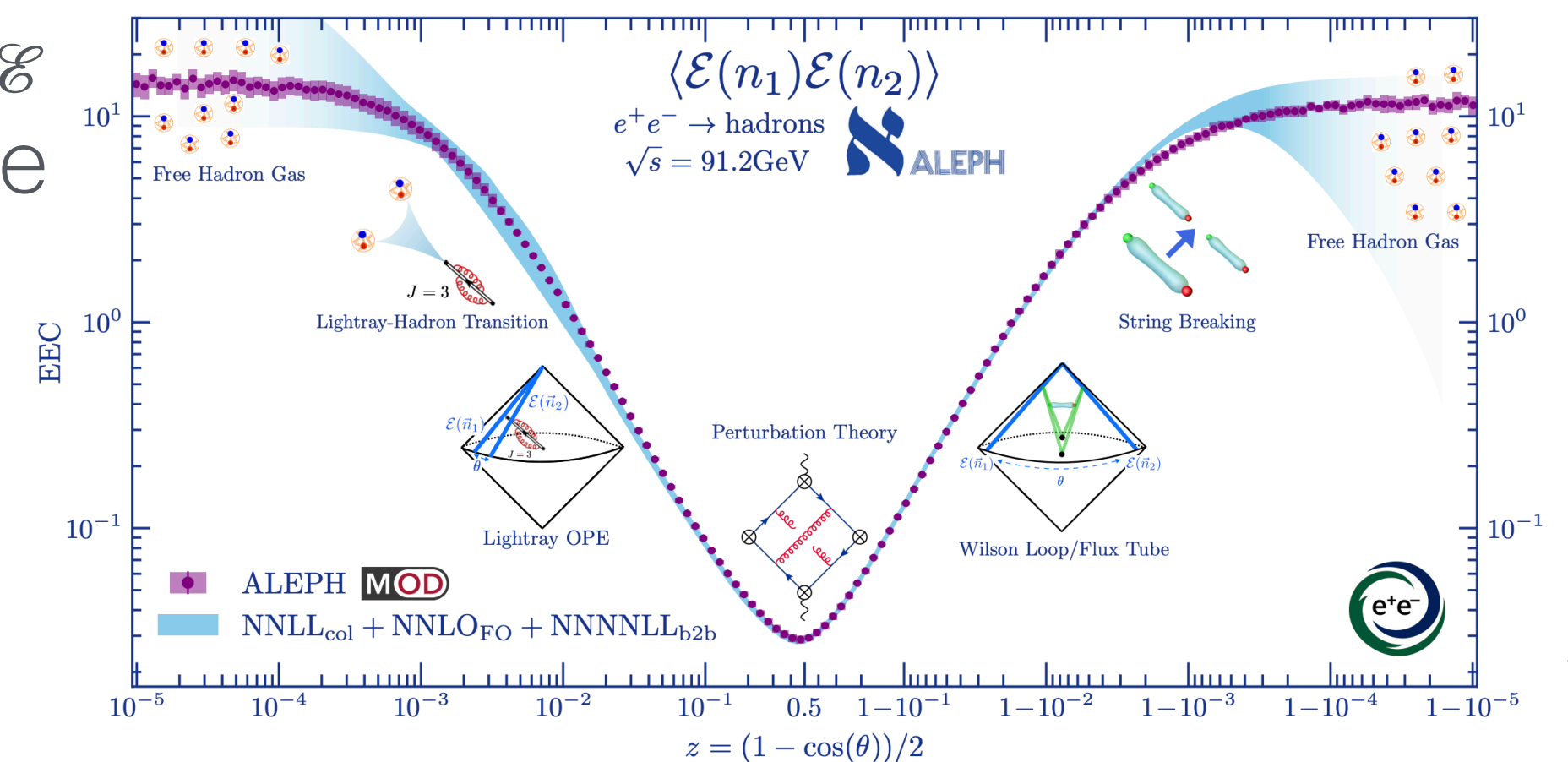
This measurement is determined by a Wightman function

$$\langle \mathcal{E}(n_1) \mathcal{E}(n_2) \rangle_q \equiv \frac{1}{\sigma_0} \left( \frac{q_\mu q_\nu}{M_Z^2} - g_{\mu\nu} \right) \int d^4x e^{iq \cdot x} \langle 0 | J_Z^\dagger(x) \mathcal{E}(n_1) \mathcal{E}(n_2) J_Z(0) | 0 \rangle$$

The Lorentz symmetries of the operators constrain this

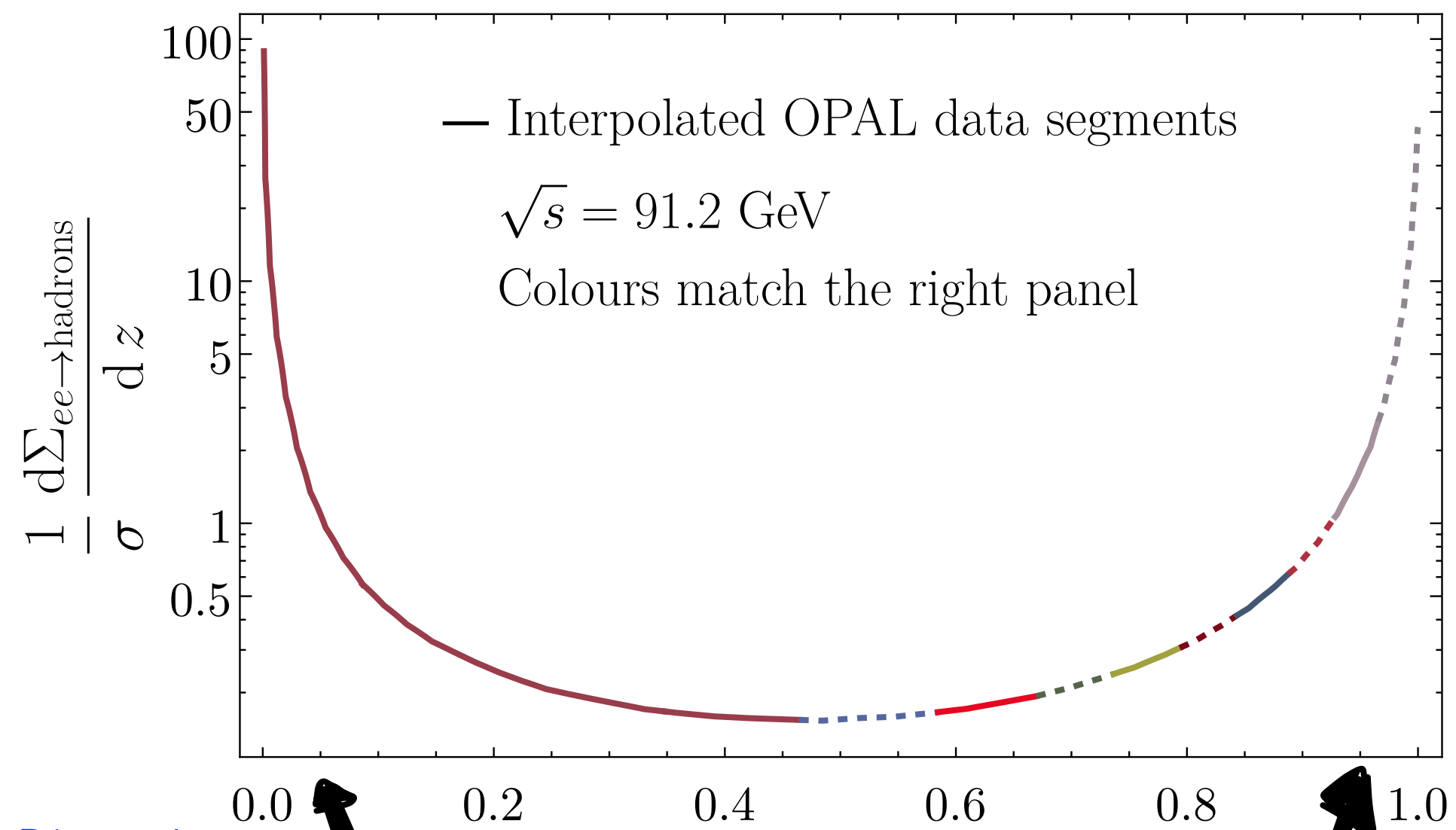
$$\langle \mathcal{E}(n_1) \mathcal{E}(n_2) \rangle_q = \frac{q^2 \mathcal{F}_{\mathcal{E}\mathcal{E}}(\bar{z}, M_Z^2/q^2, \Lambda_{\text{QCD}}^2/q^2)}{4\pi^2 (n_1 \cdot n_2)^3}$$

In turn, this function  $\mathcal{F}_{\mathcal{E}\mathcal{E}}$  is completely fixed by the energy correlator on  $e^+e^-$  at the  $Z$  pole.

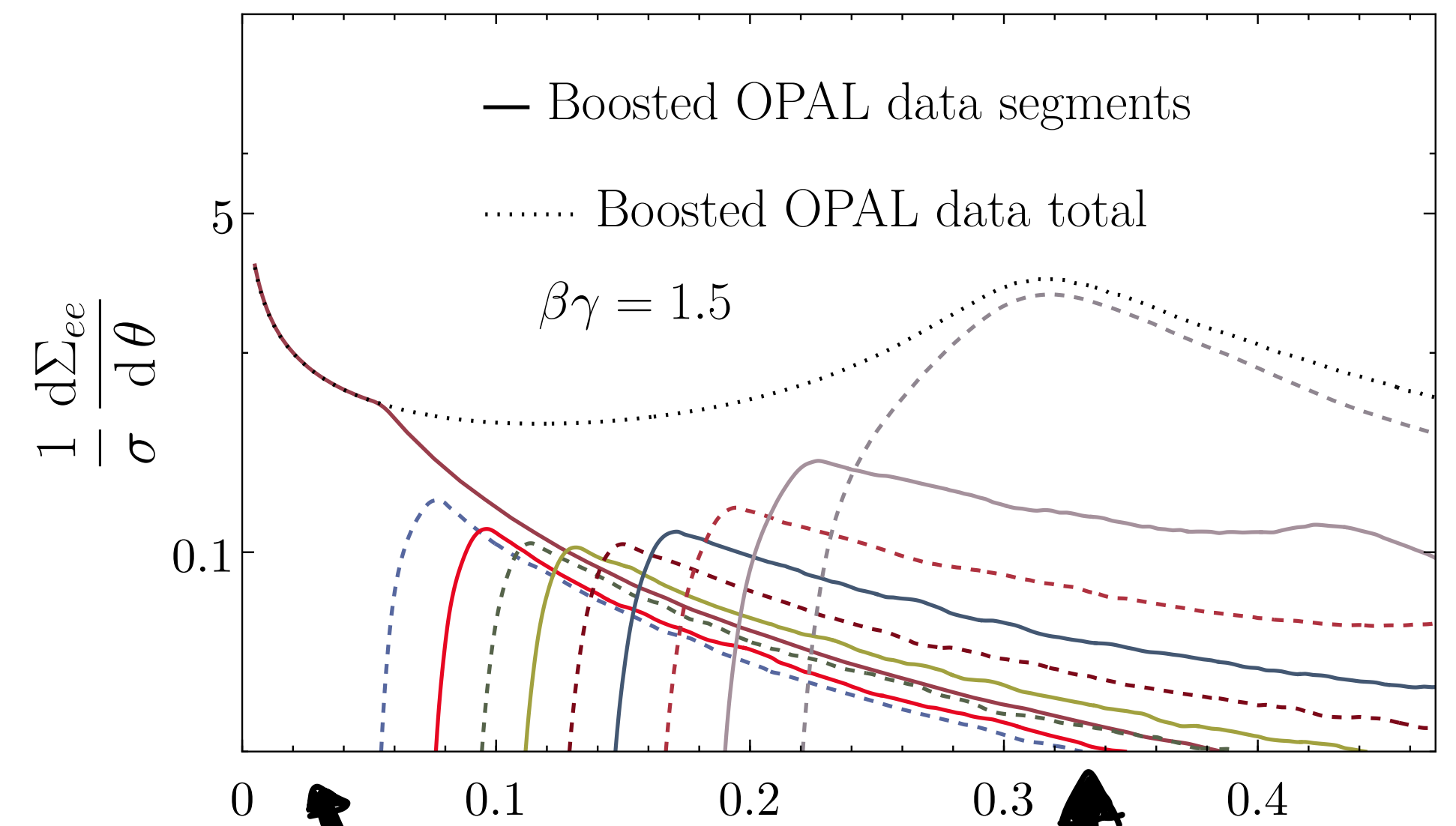


# Recent developments and phenomenological applications

## Heavy boson jets



Boosting  
→

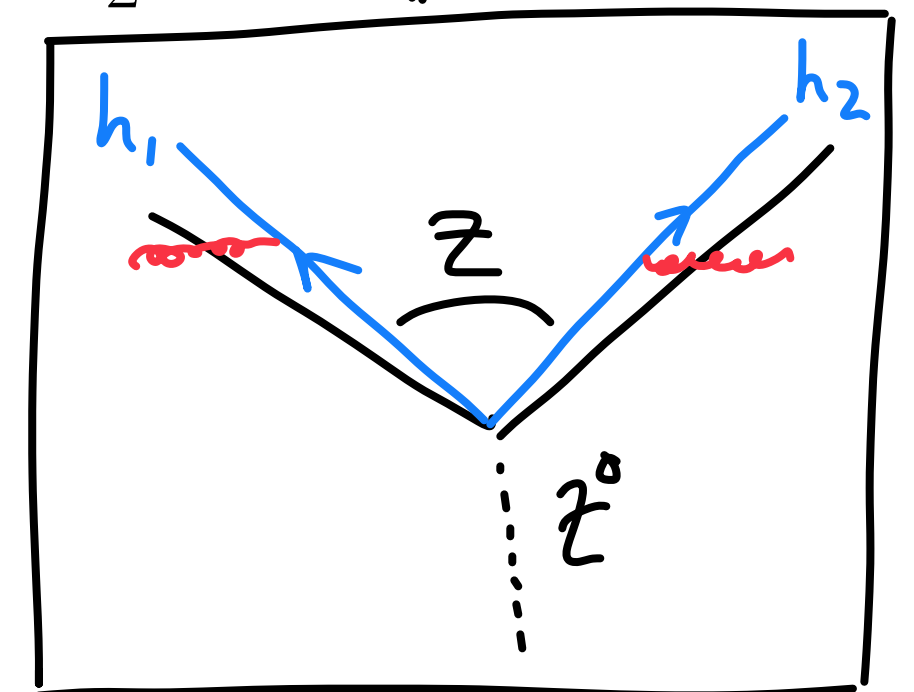
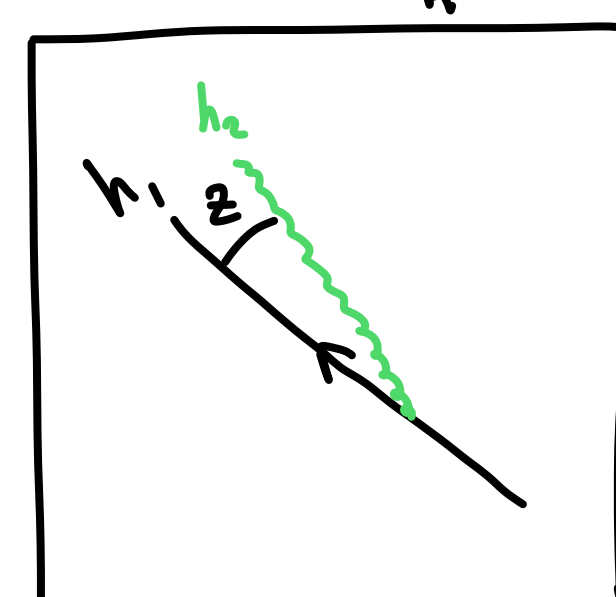
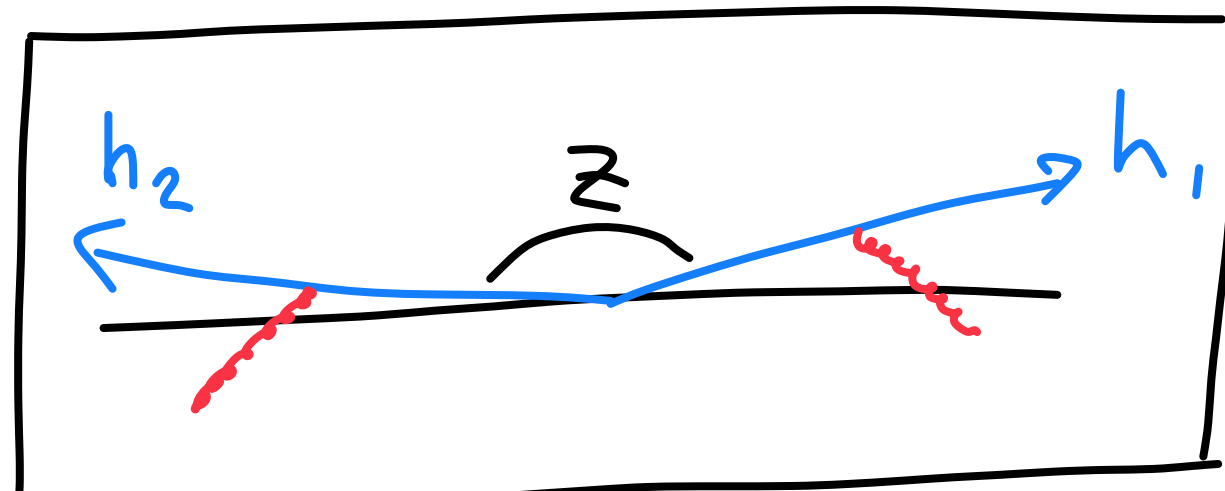
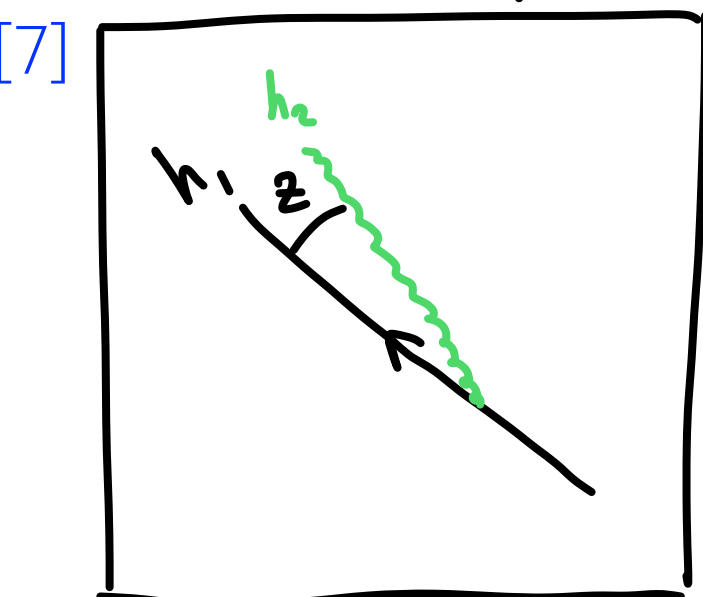


L. J. Dixon, I. Moul, H. Xing Zhu '19 [7]

I. Moul, H. Xing Zhu '18

$$z = \frac{1 - \cos \theta}{2}$$

$$z = \frac{1 - \cos \theta}{2}$$



$$\left. \frac{d\sigma}{dz} \right|_{z \rightarrow 0} = J_{GEC} \otimes H$$

$$\left. \frac{d\sigma}{dz} \right|_{z \rightarrow 1} = H \otimes J_q \otimes J_{\bar{q}} \otimes S$$

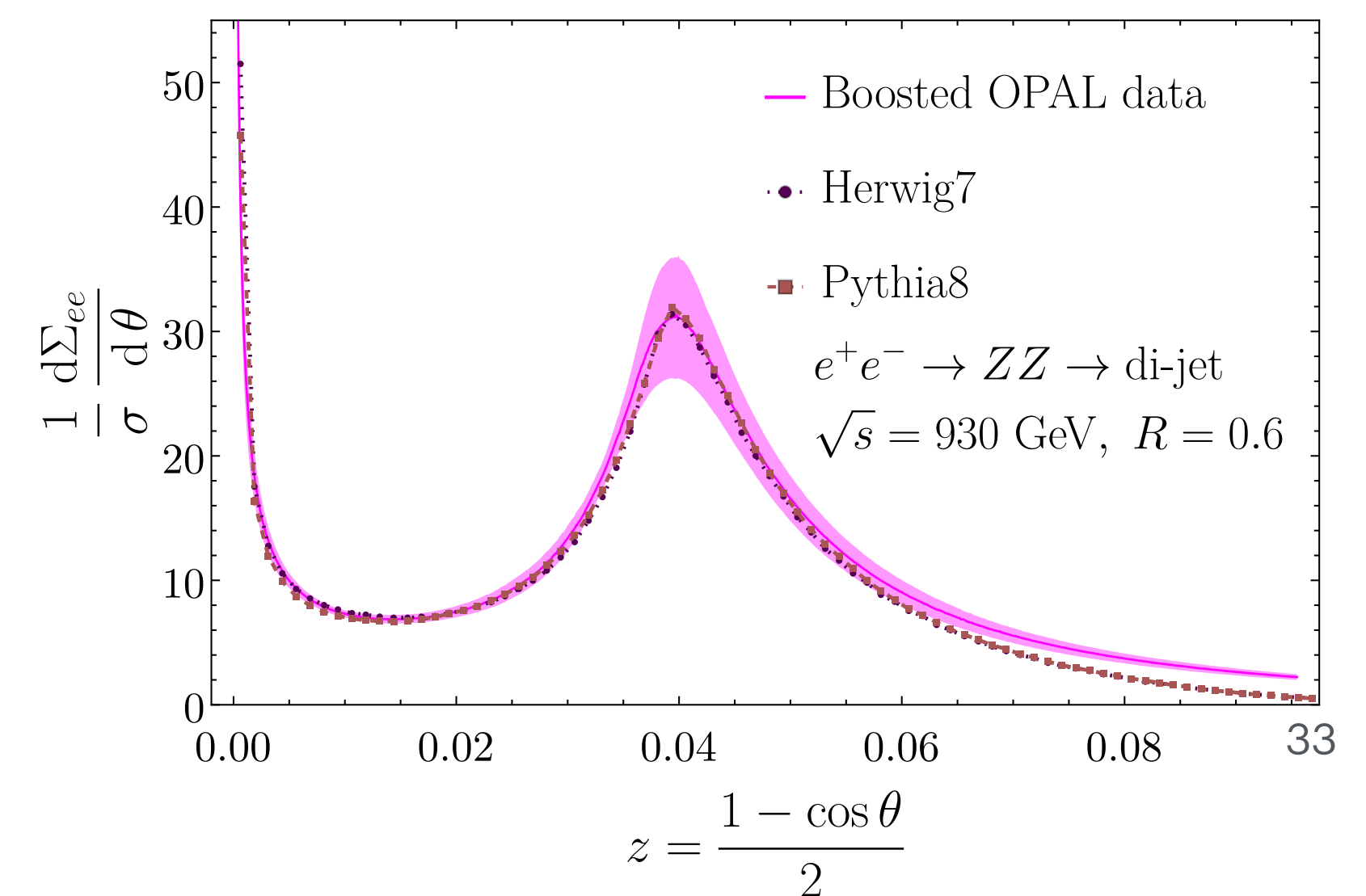
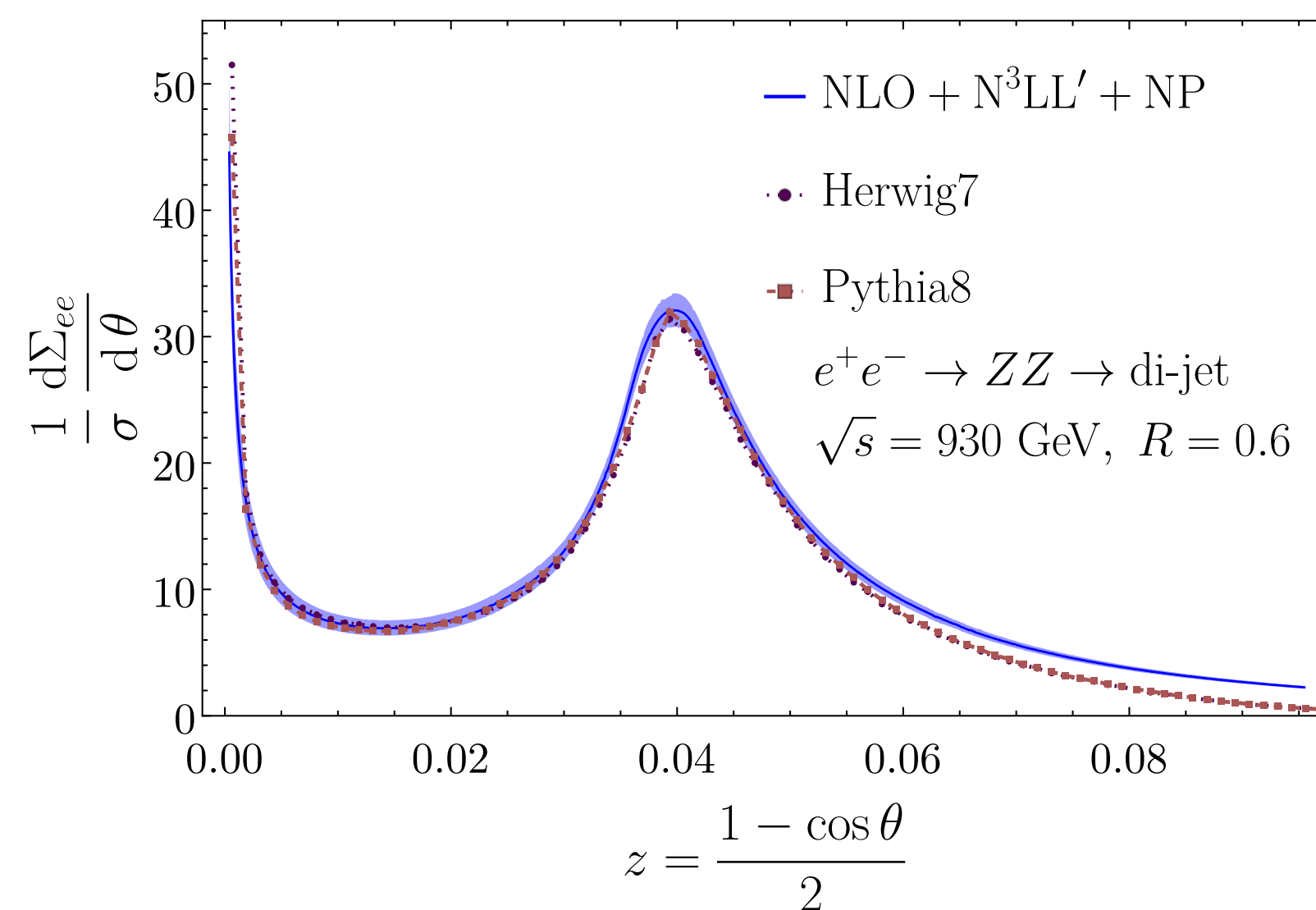
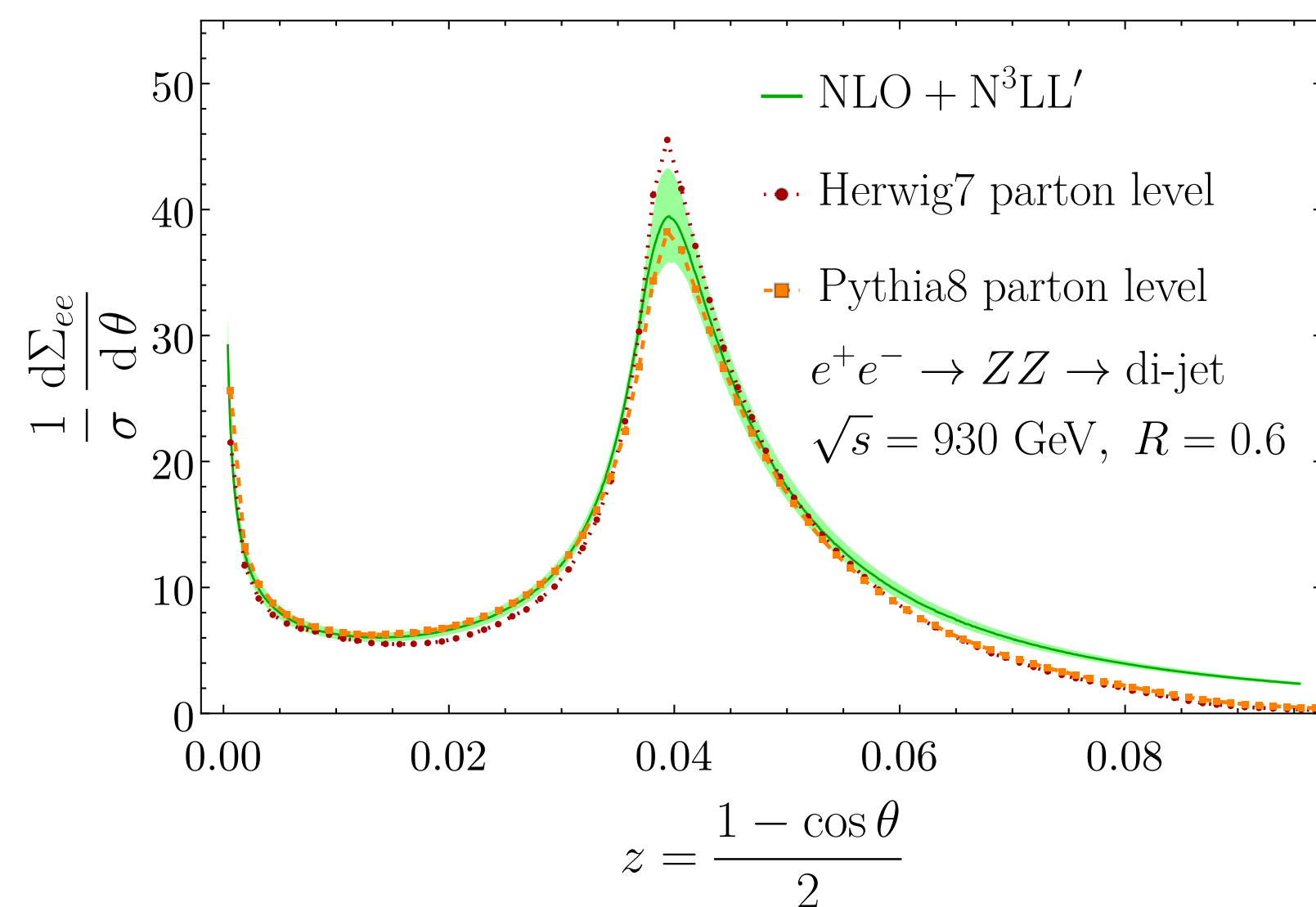
# Recent developments and phenomenological applications

## Heavy boson jets

Due to these symmetries constraining this measurement, the theory can be computed with extreme perturbative precision - N4LL+NNLO.

But, moreover, we can also compute the non-perturbative contributions. This leads to near perfect agreement between purely analytical theory and realistic tuned event generation.

And, we can directly boost the  $e^+e^-$  measurement to test consistency between collision systems.



# Conclusions

## Wrapping 48 years up in a single slide

- Energy correlators (EECs) have transitioned from collider QCD observables to fundamental objects in the study of field theory.
- Consequently, EECs and their generalisations are a kind of “theorists’ playground”.
- A huge variety of techniques now exist for the calculation of EECs, and with these, a vast amount of new phenomenology has been proposed.
- Presently, theory outpaces experiment. This is an open invitation to experimentalists.
- EECs offer a unique door to interdisciplinary work. Due to their fundamental nature, they can be studied in formal theory, collider phenomenology, tabletop solid state experiments, and cosmology.