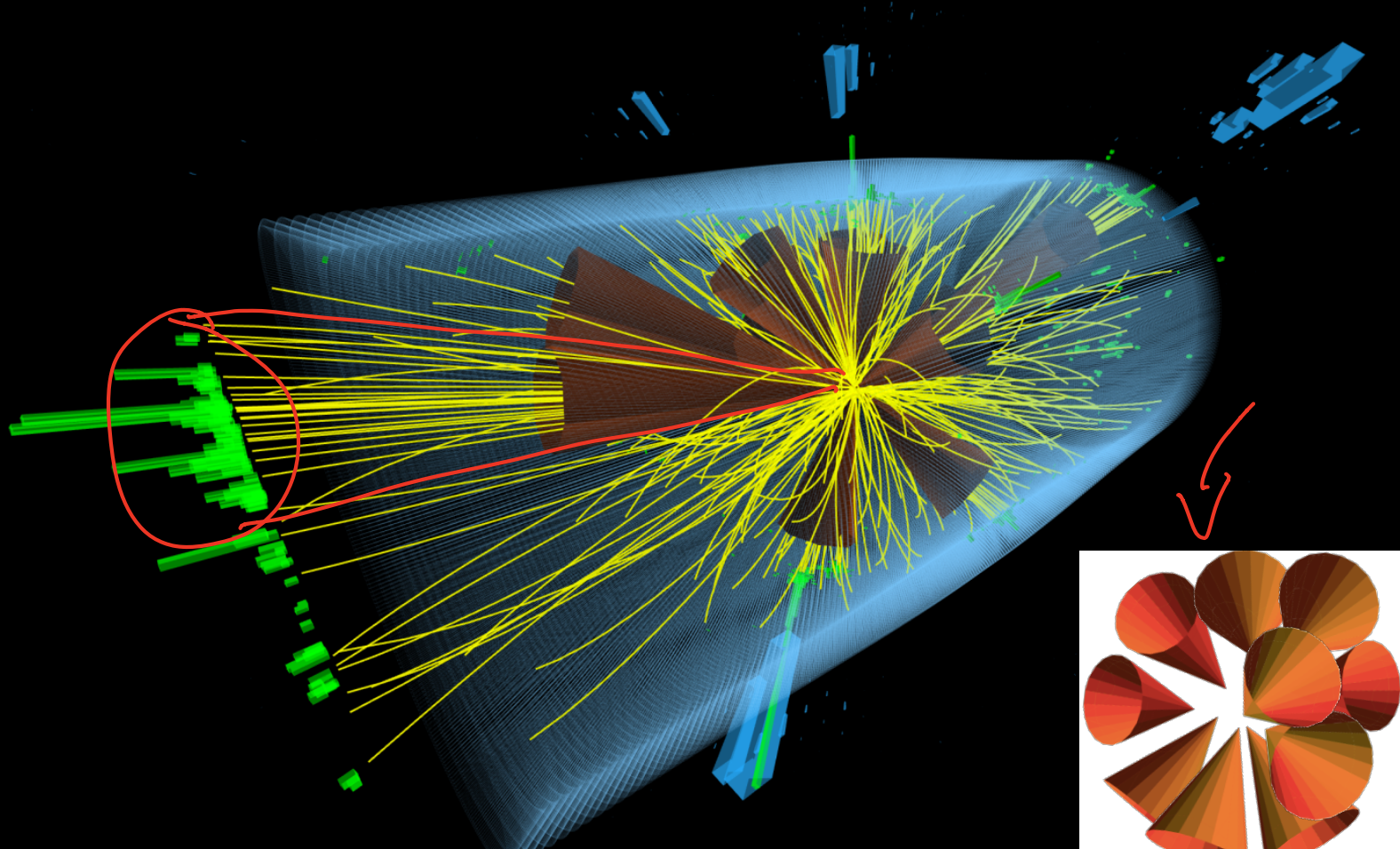


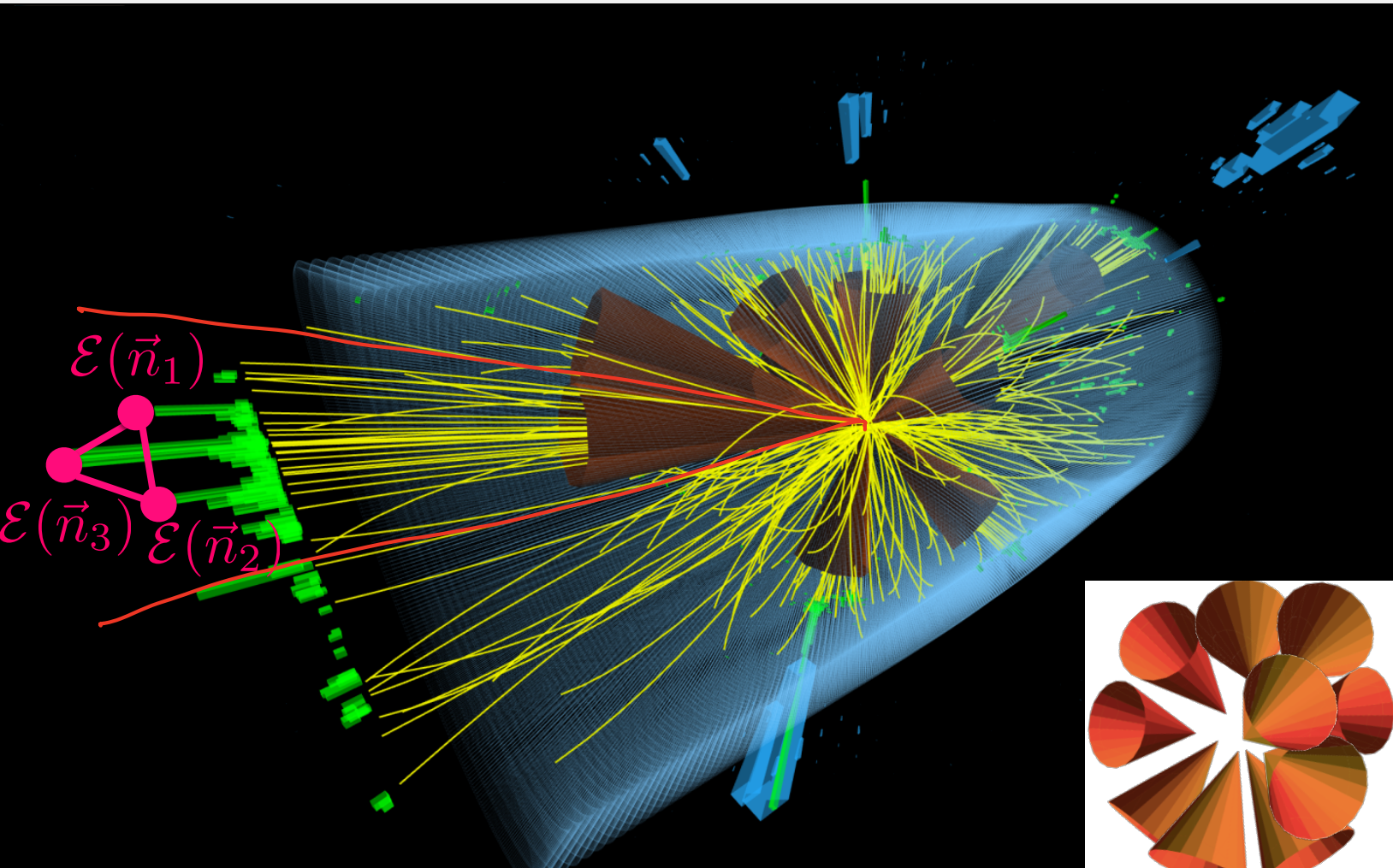
Ian Moulton
SLAC

Jet Substructure, Lightray Operators, and Spinning Gluons

Jets!

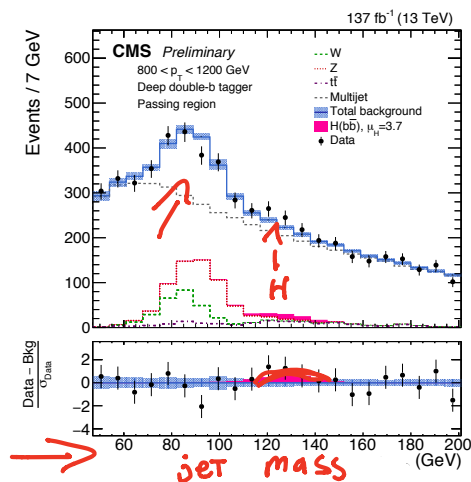
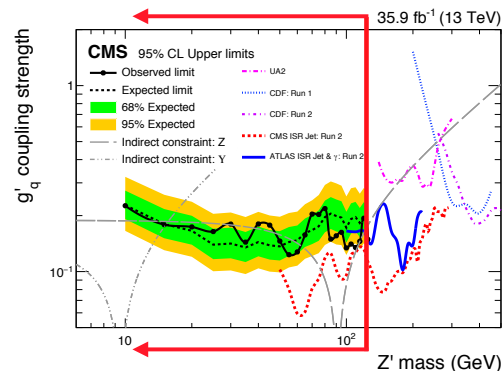
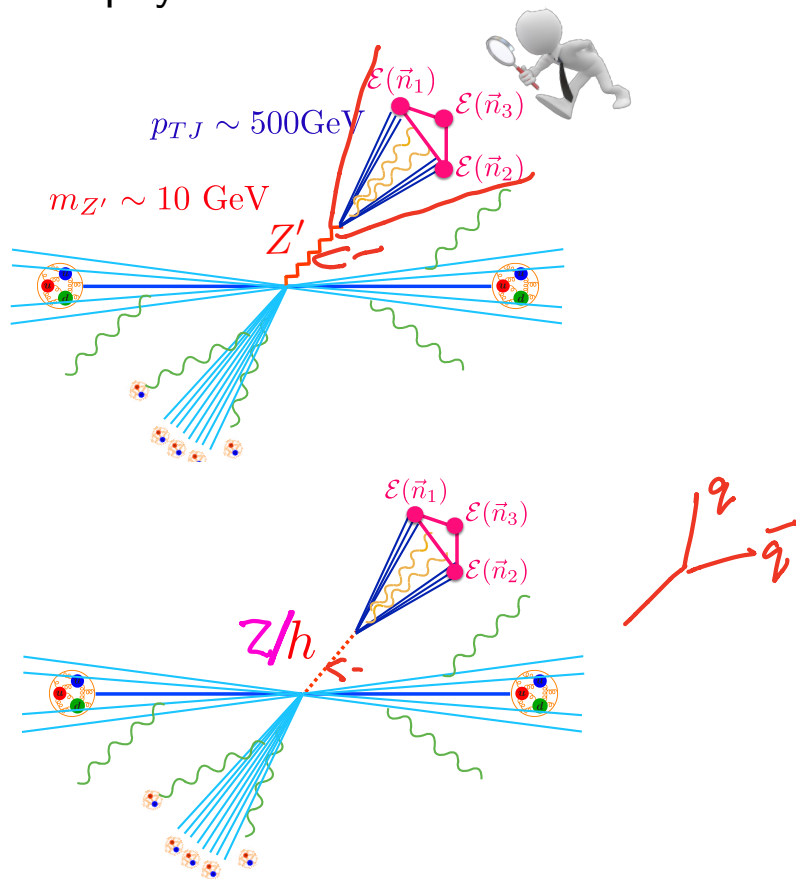


Jets!



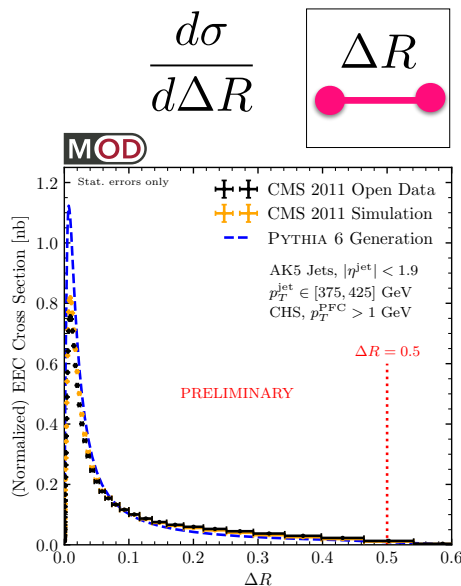
Jet Substructure: Searches

- **Jet Substructure** provides **qualitatively new** ways to search for new physics at the LHC:

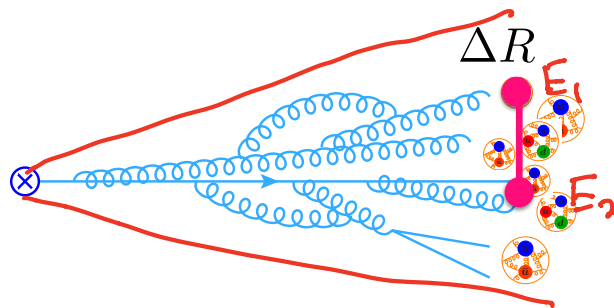


Jet Substructure: Understanding QCD

- Recent years have seen a rise of interest in using jet substructure to study the dynamics of QCD on the lightcone.



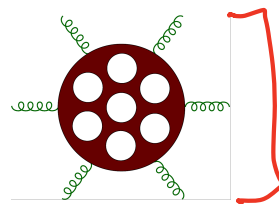
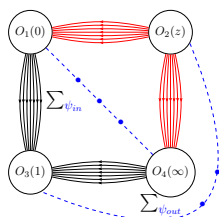
Two-Point
Energy Correlator



- Extends the classic study of “event shapes” in e^+e^- colliders.

Motivation

- There has been significant progress understanding correlation functions and scattering amplitudes, driven by enhanced symmetries, behavior in kinematic limits and functional/analytic properties.



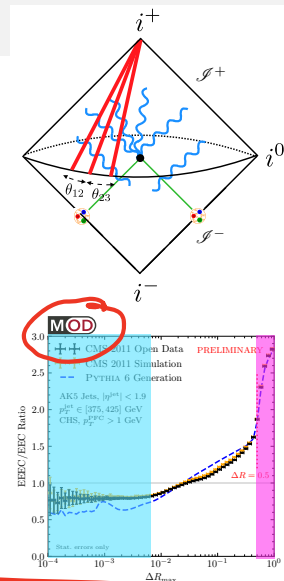
- Cross section level observables that measure the flow of energy in jets are another class of field theoretic observables, but have received much less attention.

Goal of this work is to formulate jet substructure in a manner such that formal developments can have a direct impact on precision QCD.

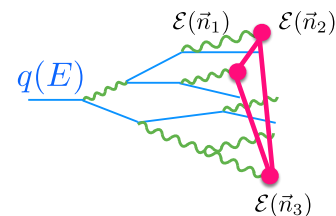
Outline

- Energy Flow and Correlation Functions

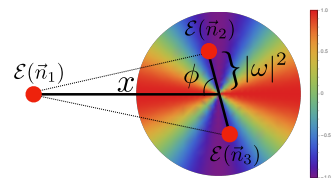
- Experimental Results on Energy Correlators



- The Three Point Correlator :



- Spin Structure of the Squeezed Limit



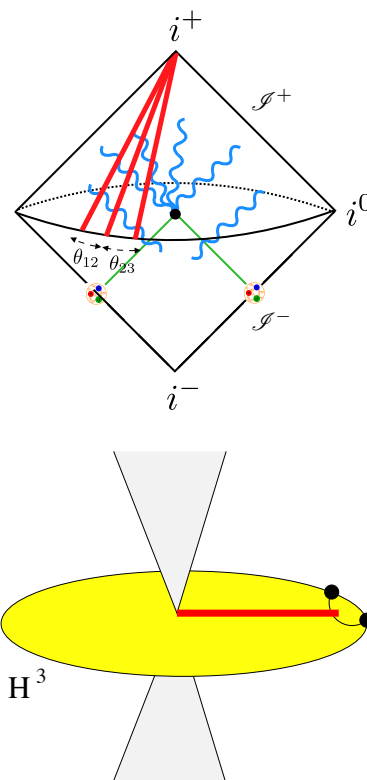
References

- Directly based on:

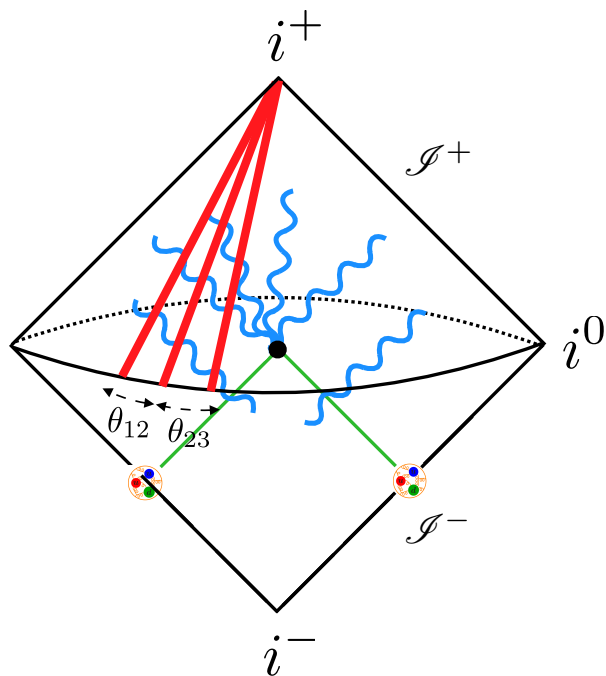
- Dixon, Moulton, Zhu, [arXiv:1905.01310](#)
- Chen, Luo, Moulton, Yang, Zhang, Zhu, [arXiv:1912.11050](#)
- Chen, Moulton, Zhang, Zhu, [arXiv:2004.11381](#)
- Komiske, Moulton, Thaler, Zhu [Forthcoming](#)
- Chen Moulton, Zhu, [arXiv:2011.02492](#)
- Chen, Moulton, Sandor, Zhu, [Forthcoming](#)

- See also/ Thanks to perspectives from:

- Hofman, Maldacena
- Korchensky, Sokatchev, Zhiboedov, Belitsky, ...
- Korchensky
- Caron Huot
- Kravchuk, Simmons Duffin
- Kologlu, Simmons Duffin, Kravchuk, Zhiboedov
- Henn, Sokatchev, Yan, Zhiboedov
- Chicherin, Henn, Sokatchev, Yan

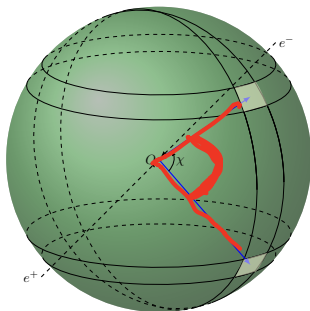


Energy Flow and Correlation Functions



The Choice of Observable

- Many observables have been proposed over the years to measure flow of energy in colliders:
 - Thrust
 - C-parameter
 -
- These all involve some “human” definition. Is there an observable that is intrinsically an object in the field theory?
- Such an observable was introduced in the early days, the Energy-Energy Correlator, although it was not appreciated why it holds a special place compared to other observables.



[Basham, Brown, Ellis, Love]

$$\frac{d\sigma}{dz} = \sum_{i,j} \int d\sigma \frac{\overline{E_i E_j}}{Q^2} \delta \left(z - \frac{1 - \cos \chi_{ij}}{2} \right)$$



$$E_1 E_2 \delta(z - \cos \chi_{12})$$

$$E_1 E_3$$

$$E_2 E_3$$

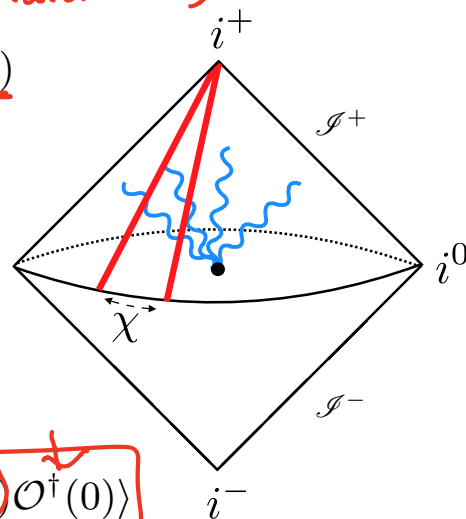
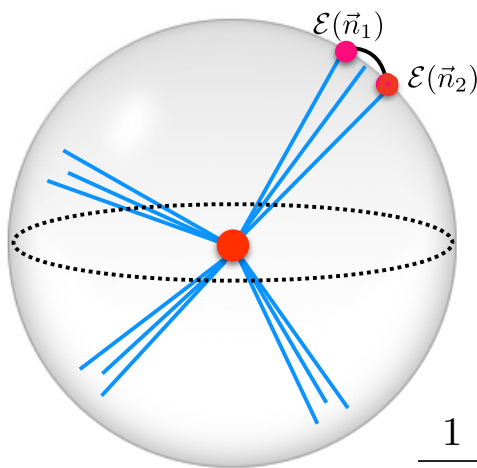
Energy Flow Operators

- Energy Correlators admit a representation as an N-point correlation function of Energy Flow operators (not true for other observables such as thrust):

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

(Korchemsky
Hofman, Maldacena)

Light ray operator

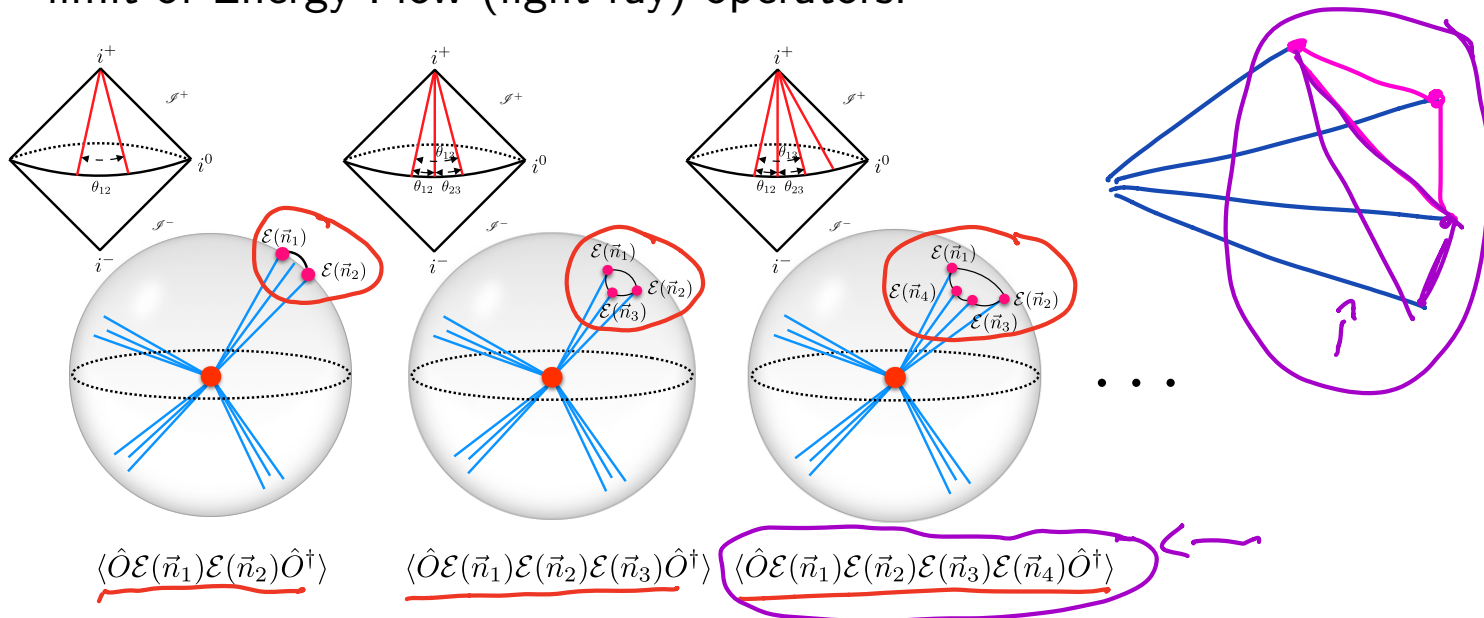


$$\frac{1}{\sigma_{\text{tot}}} \frac{d\sigma}{dz} = \frac{\int d^4x e^{iq \cdot x} \langle \mathcal{O}(x) \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) \mathcal{O}^\dagger(0) \rangle}{\int d^4x e^{iq \cdot x} \langle \mathcal{O}(x) \mathcal{O}^\dagger(0) \rangle}$$

- Simplest extension of N-point correlation functions of local operators.
- Recent interest in the context of the conformal bootstrap.

Jet Substructure as Energy Correlators

- Theoretically, jet substructure is the study of the small angle (OPE) limit of Energy Flow (light ray) operators:

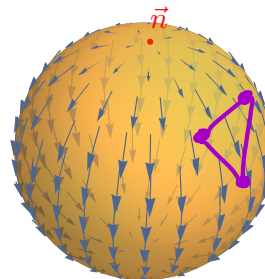
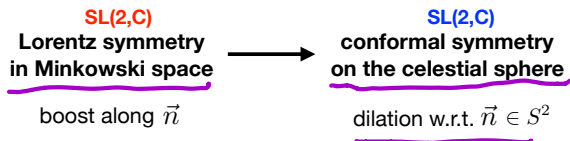


- Forms a bridge between QCD phenomenology and the OPE limit of
lightray operators.

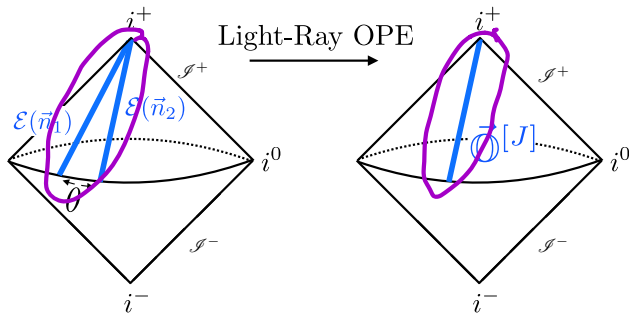
Jet Substructure as Energy Correlators

- Matrix elements of lightray ops are amenable to powerful techniques:

- Symmetry: Lightray operators are labelled by points on the celestial sphere, on which Lorentz symmetry acts as (global) conformal symmetry.



- Operator product expansions: The lightray OPE is a power expansion about the small angle limit, whose leading term gives the small angle asymptotic behavior.



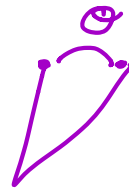
$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) = \theta^{\gamma_i} \sum \mathbb{O}_i(\hat{n}_1)$$

Jet Substructure as Energy Correlators

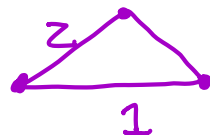
- Combined, these make Energy Correlators behave similarly to correlation functions of local operators:

- Two-point correlator: $\frac{d\sigma}{d\theta} \sim \theta^{\gamma(3)-1}$

$\gamma(n)$
Twist Spin- n
anomalous



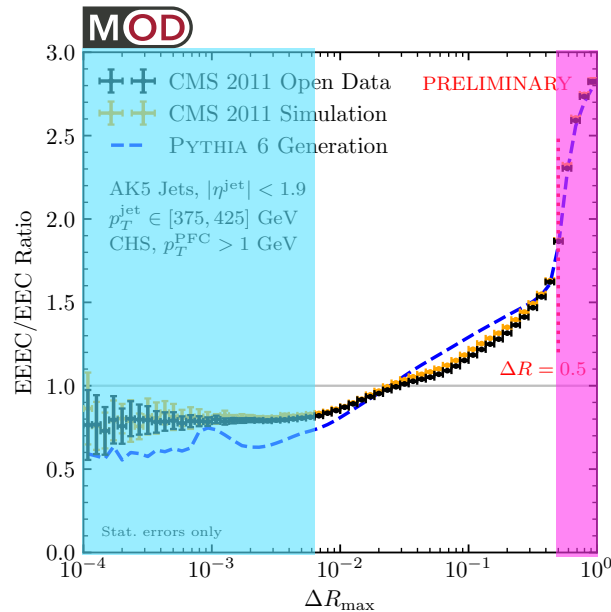
- Three-point correlator: $\frac{d\sigma}{d\theta dz d\bar{z}} \sim \theta^{\gamma(4)-1} G(z, \bar{z})$



- N-point correlator: $\frac{d\sigma}{d\theta \prod dz_i d\bar{z}_i} \sim \theta^{\gamma(N+1)-1} G(z_i, \bar{z}_i)$

- This is nice, but can we really observe this at colliders?

Experimental Results on Energy Correlators

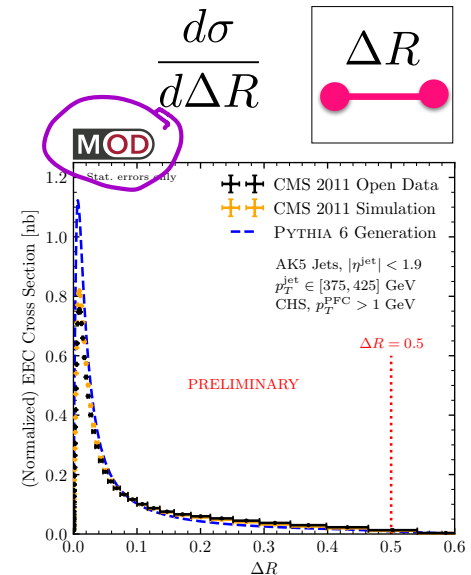


Komiske, Moul, Thaler, Zhu (forthcoming)

CMS Open Data

- CMS has released a sample of high quality data for public use.
⇒ Perfect for jet studies.

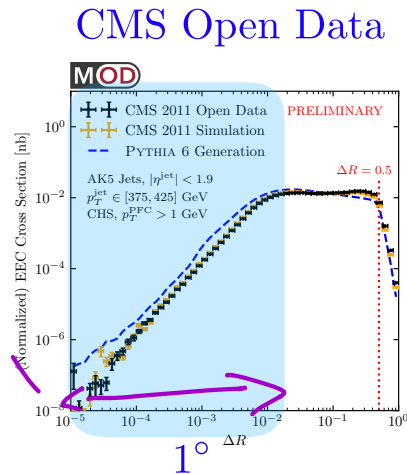
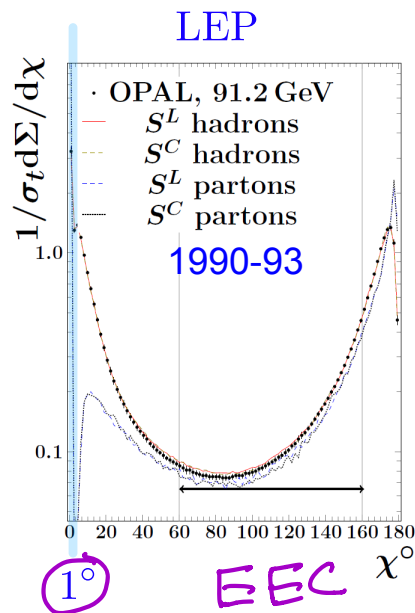
- Packaged in “MIT Open Data”:



- Provided by Jesse Thaler and Patrick Komiske.
- Ideal for rapid testing of new theory ideas. Measurements can then be done more carefully in proper experimental analyses.

Compared to LEP

- Lightcone dynamics corresponds experimentally to small angles.
- **Better resolution calorimeters** completely transforms the ability to study these regions.



- Allows us to measure the **scaling and shape dependence of multipoint correlators** of lightray operators.

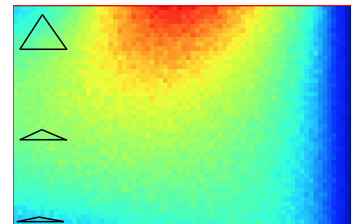
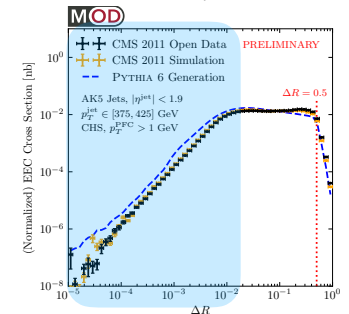
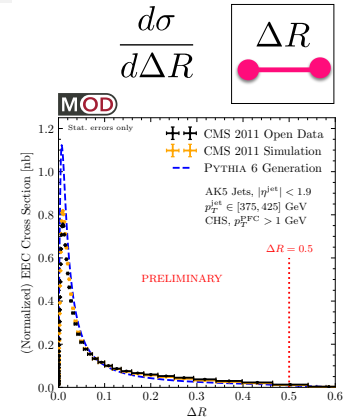
Goals

- We would like to illustrate that we can measure:

① Perturbative scaling behavior.

② The effect of the transition to confined hadrons.

③ The shape dependence of higher point correlators.

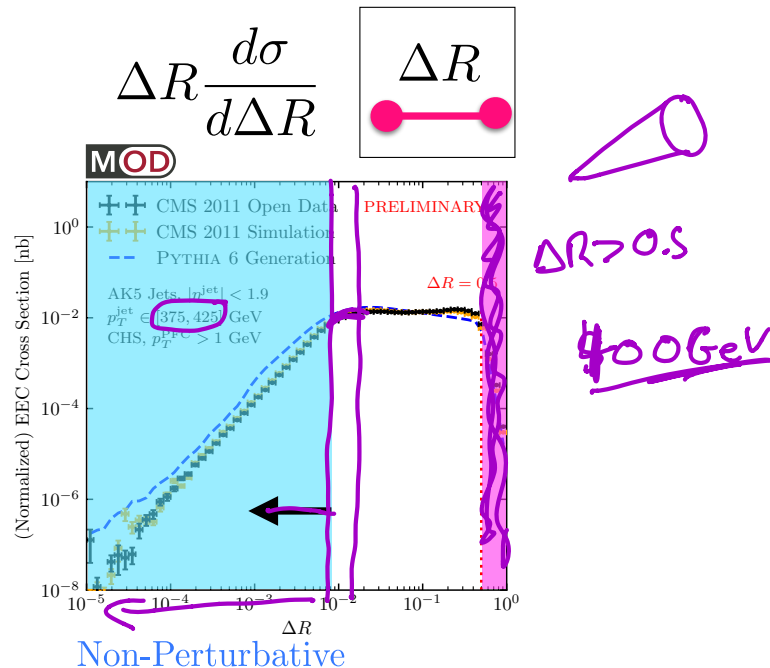
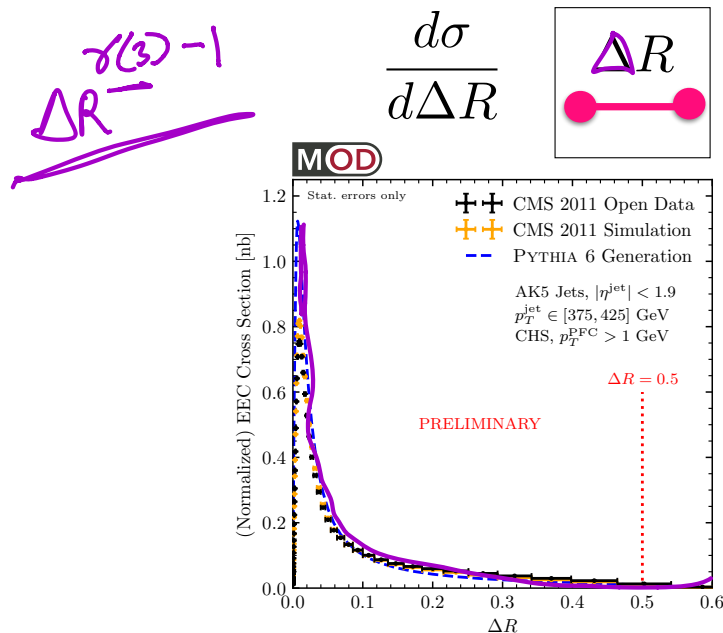


Experimental Results on Energy Correlators:

Scaling Behavior

Two-point Correlator with Open Data

- Scaling of two-point correlator:

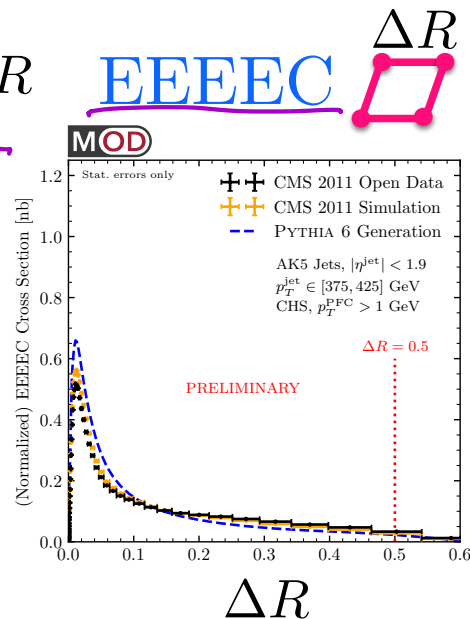
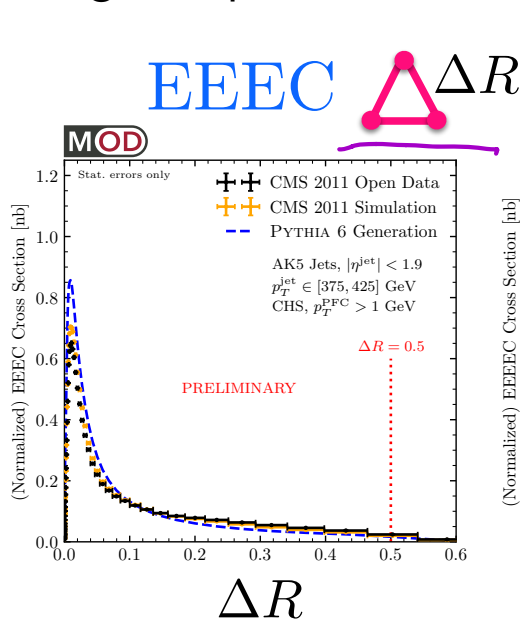
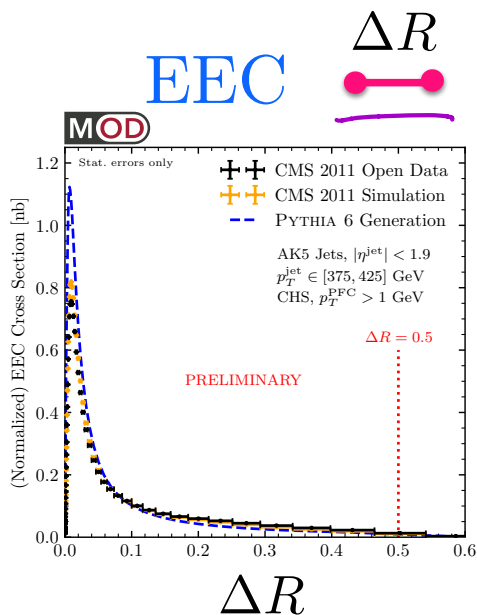


- Can measure over a remarkable dynamic range including both perturbative and non-perturbative regimes.



Scaling of Higher Point Correlators

- We can probe these scalings in open data:



- First probes of multipoint correlators in data.
- In a linear plot, these are dominated by the classical $1/\Delta R$ scaling.

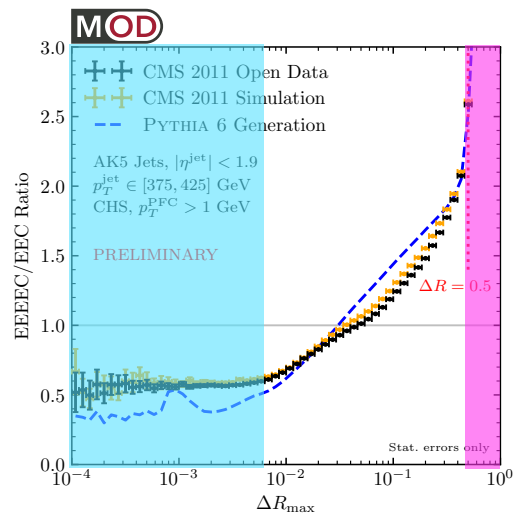
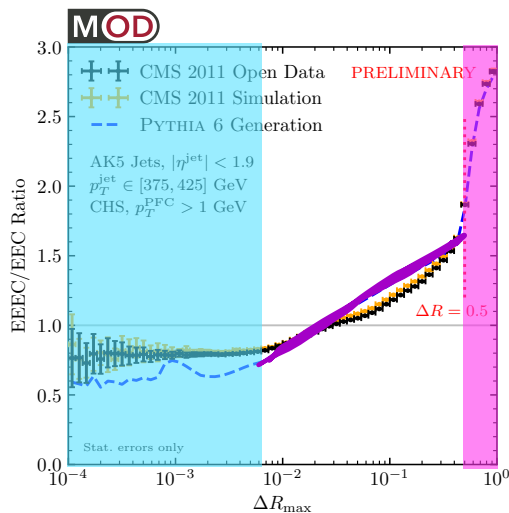
Scaling in Data

- Anomalous scaling can be clearly seen by considering ratios:

Scaling Behavior ✓

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

$$\Delta R \square / \text{---} \sim \Delta R^{(\gamma_5 - \gamma_3)/2}$$



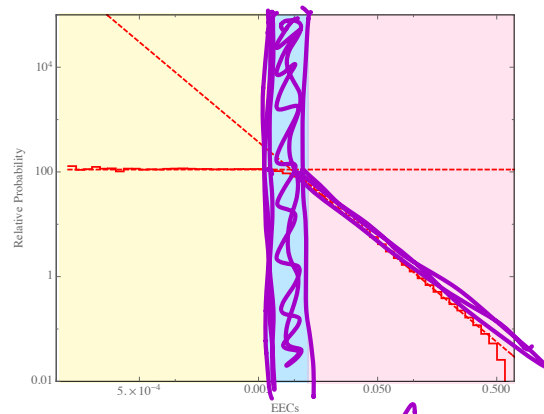
- Slope is directly proportional to α_s .

Experimental Results on Energy Correlators:

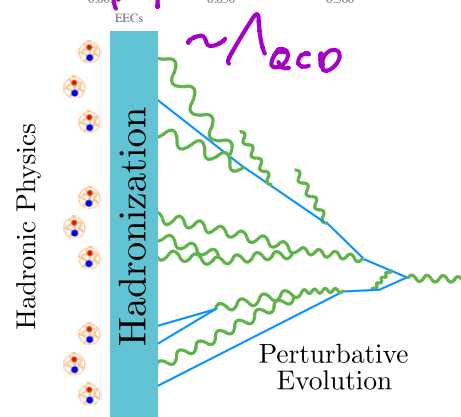
Hadronization

Hadronization in QCD

- Perturbative scaling only valid above confinement scaling.
- Observe a rapid transition to uniformly distributed hadrons!!

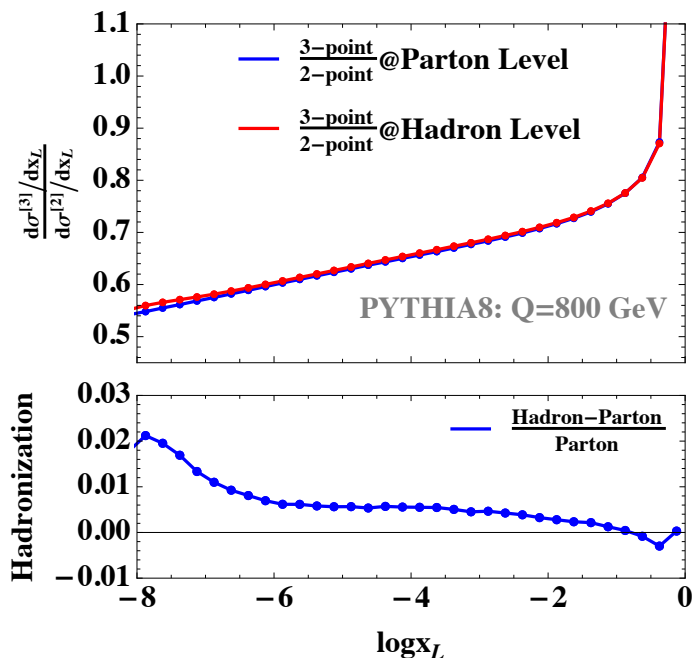
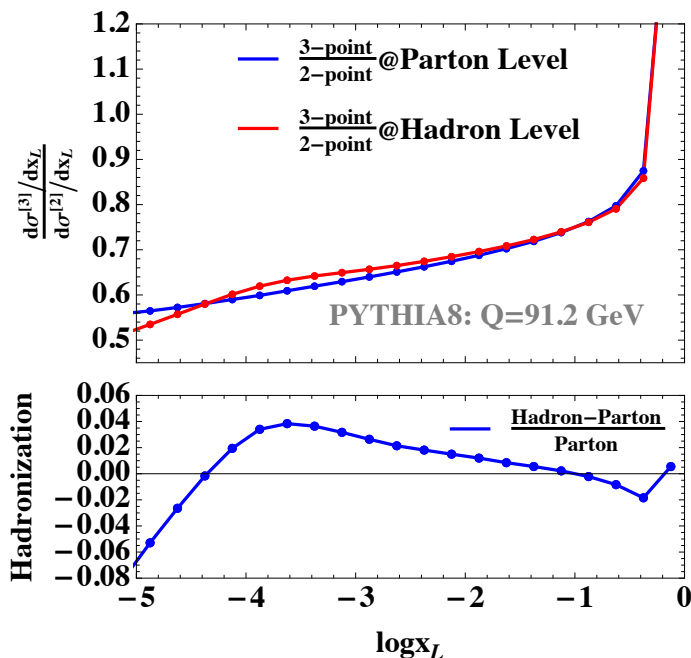


$$\frac{g^{\tau(2)-1}}{g^{\tau(2)-1}}$$



Excellent Non-Perturbative Behavior

- Simple behavior of hadronization implies that it is largely removed by taking ratios: Ratios of projected correlators have $\leq$ percent level NP corrections.



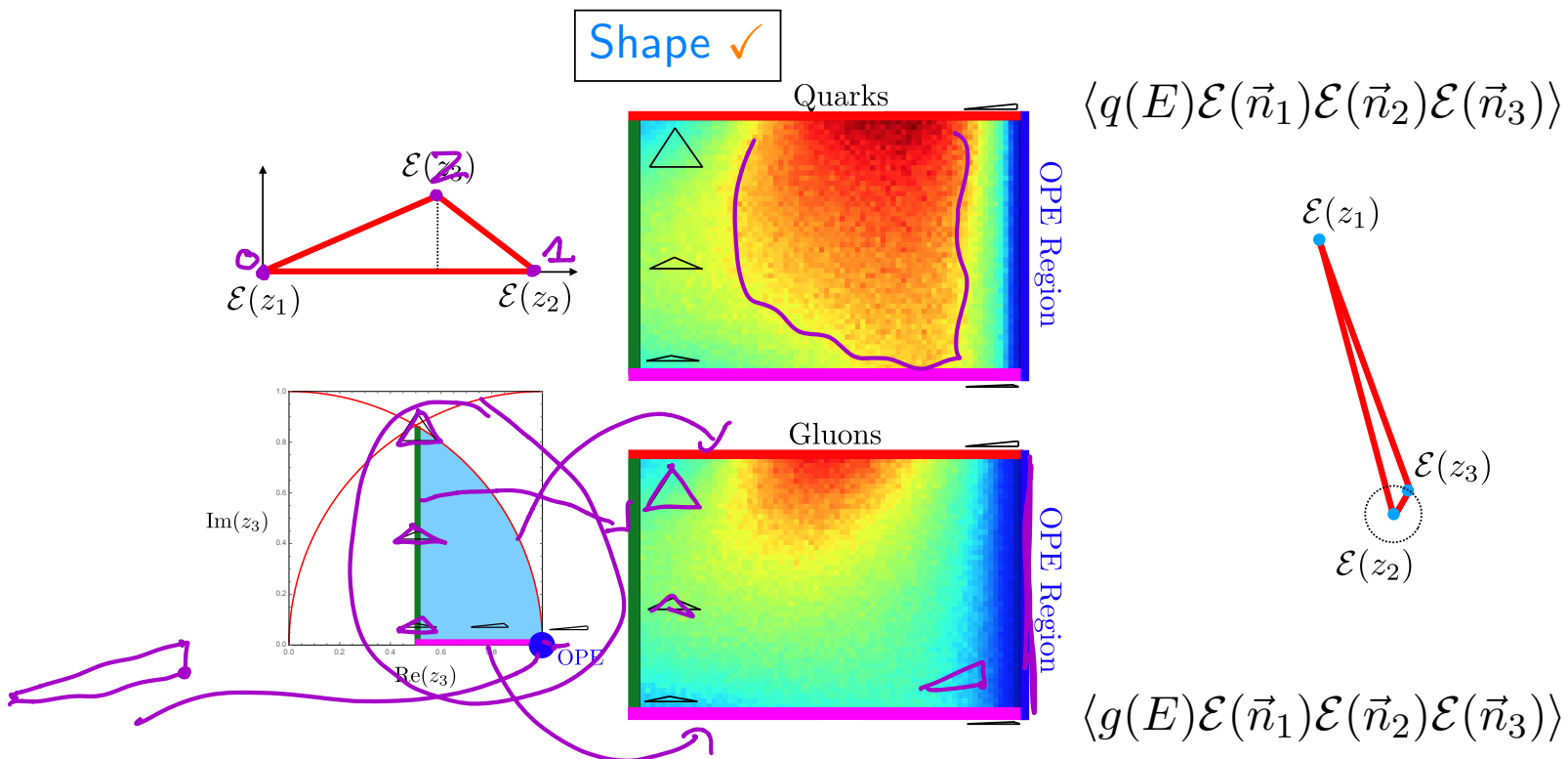
- Promising for precision extraction of α_s from jet substructure data.

Experimental Results on Energy Correlators:

Shape Dependence

Shape Dependence

- Can directly measure shape of higher point correlators in LHC data.

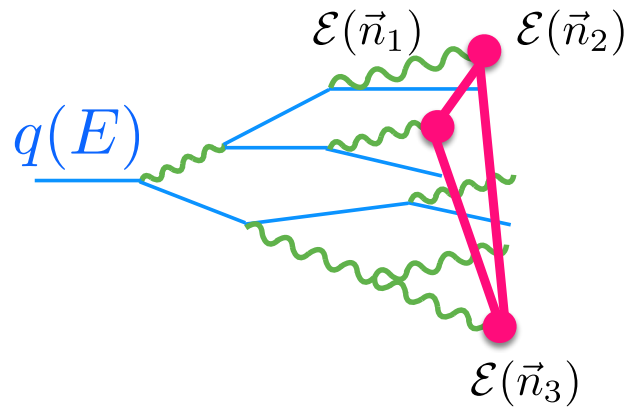


- Remarkable probe of QCD, well beyond standard event shapes!

A Wealth of New Data

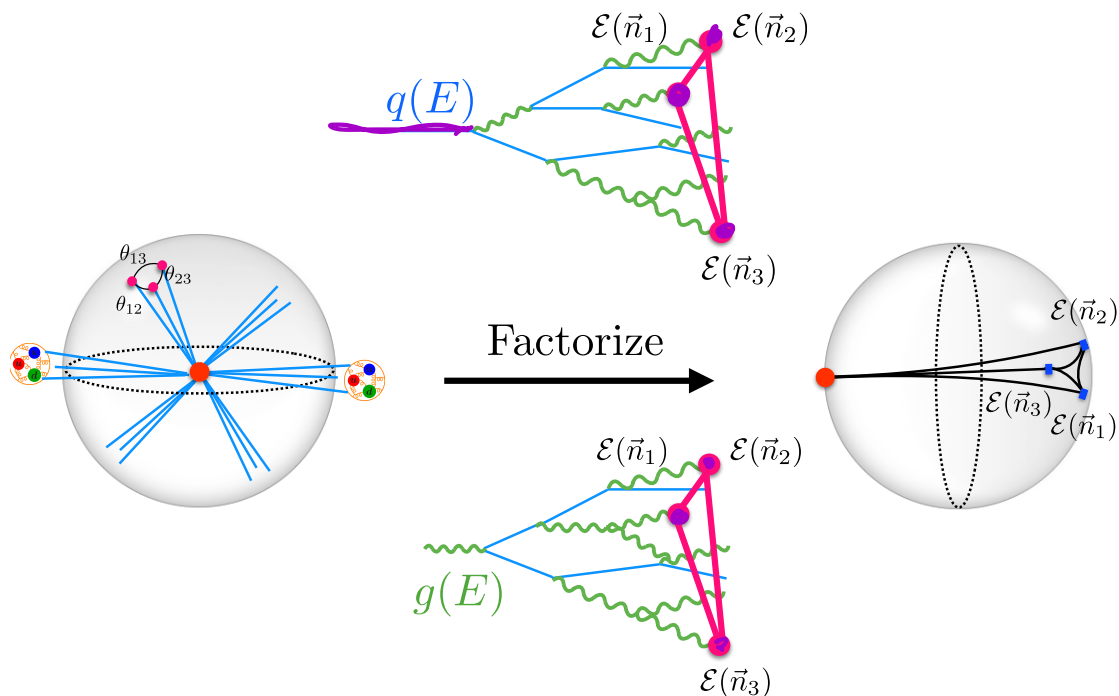
- Remarkable dataset from the LHC enables precision measurements of shapes and scaling behavior of multipoint correlators of energy flow operators.
- Opportunity for studying rich dynamics of QCD on the lightcone.
- Level of detail goes well beyond previous measurements of event shapes $\implies$ new theory tools/calculations needed!
- Theoretically clean nature of these observables enables exciting interplay with techniques recently developed in the context of Conformal Field Theory for the study of lightray operators.

The Three Point Correlator



Three Point Correlator in Collinear Limit

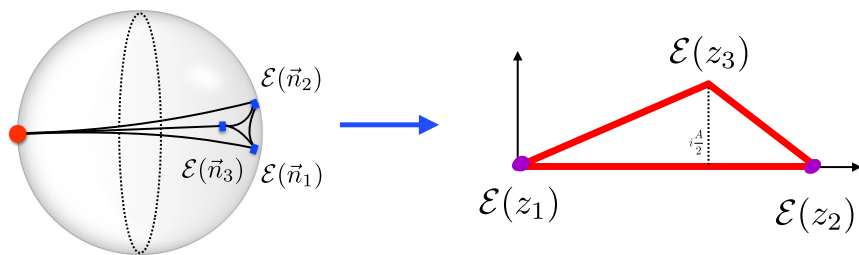
- First non-trivial behavior arises at three-points.
- Shape dependence of multi-point correlators described by universal [jet functions](#).



- No previous analytic calculations. Do they have a nice structure?

Parametrization

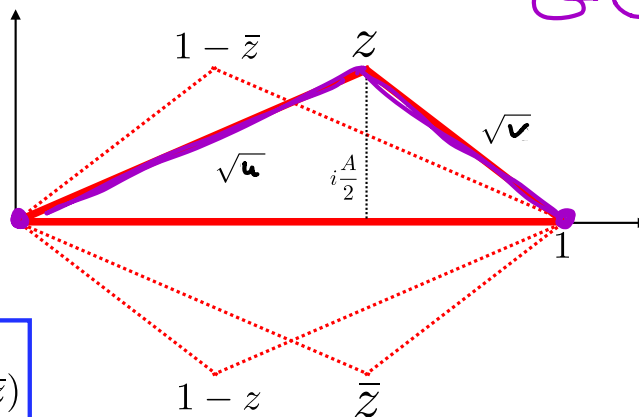
- In collinear limit, three point function depends on a single complex variable z , and a scaling variable x .
- Use standard parameterization for a CFT 4 point function.



$S_3 \times \mathbb{Z}_2$ Symmetry:

$$\begin{aligned} z &\rightarrow 1 - z & z &\rightarrow 1 - \frac{1}{z} \\ z &\rightarrow \frac{1}{z} & z &\rightarrow \frac{z}{1 - z} \\ z &\rightarrow \frac{1}{1 - z} & z &\rightarrow \bar{z} \end{aligned}$$

$$\begin{aligned} \underline{u} &= z\bar{z} \\ \underline{v} &= (1 - z)(1 - \bar{z}) \end{aligned}$$



$$G(z, \bar{z})$$

Result in $\mathcal{N} = 4$ Super Yang-Mills

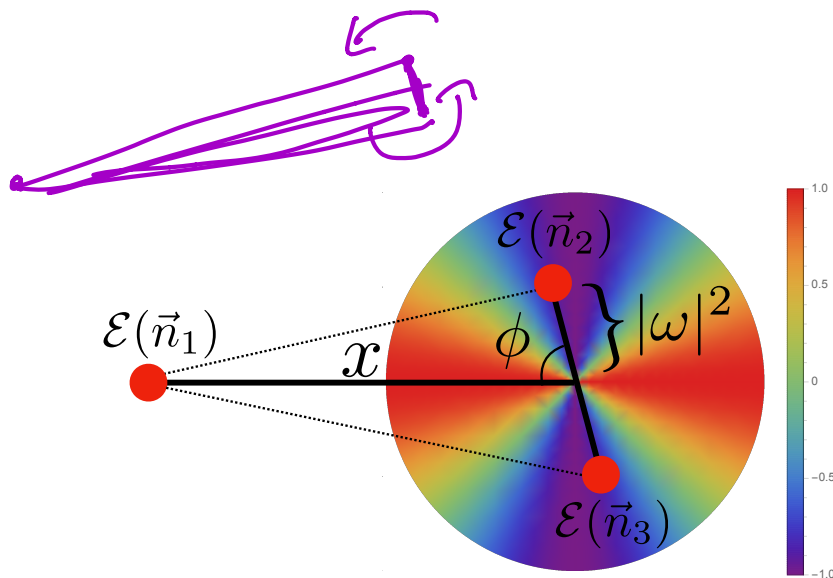
- To get an intuition for the result, we can first compute it in $\mathcal{N} = 4$.
- We find that it can be written in a simple form, similar to standard correlation functions of local operators.

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


- It is expressed in terms of rational prefactors and two weight-2 polylogarithmic functions

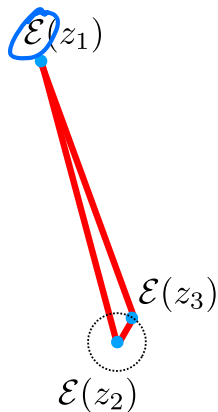
$$\Phi(z) = \frac{1}{z-\bar{z}} (2\text{Li}_2(z) - 2\text{Li}_2(\bar{z}) + (\log(1-z) - \log(1-\bar{z})) \log(z\bar{z})) , \\ D_2^+(z) = \text{Li}_2(1-|z|^2) + \frac{1}{2} \log(|1-z|^2) \log(|z|^2)$$

Spin Structure of the Squeezed Limit



The OPE Limit

- A particularly interesting limit of the multipoint correlator is the OPE limit, where two detectors are brought together:

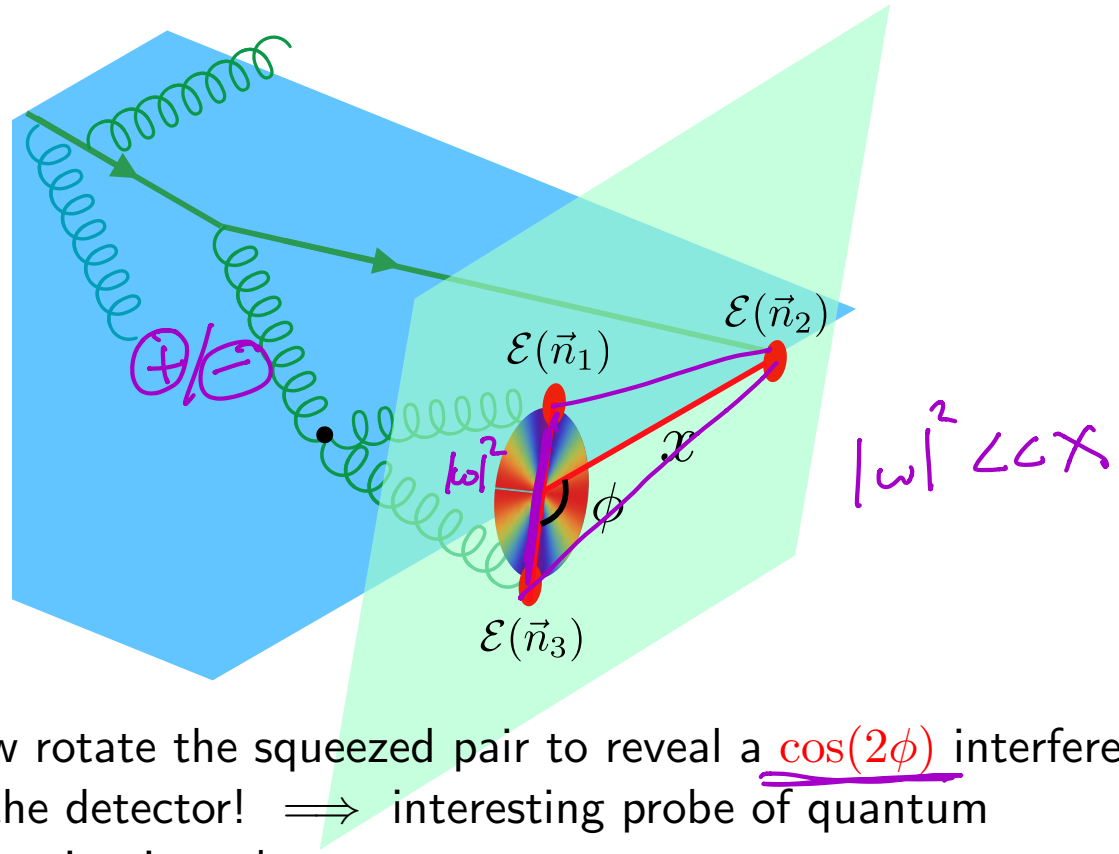


→ Korchemsky
Sokatchev
Yan
Henn
Chicherin

- Turns out to be non-trivial in QCD due to the presence of spin correlations.
- We will show how this limit can be efficiently analyzed using the lightray OPE.

Seeing Quantum Interference with Spinning Gluons

- In the squeezed limit, the intermediate gluon is nearly on-shell: It has two polarizations, $\pm$, which can interfere with each other.



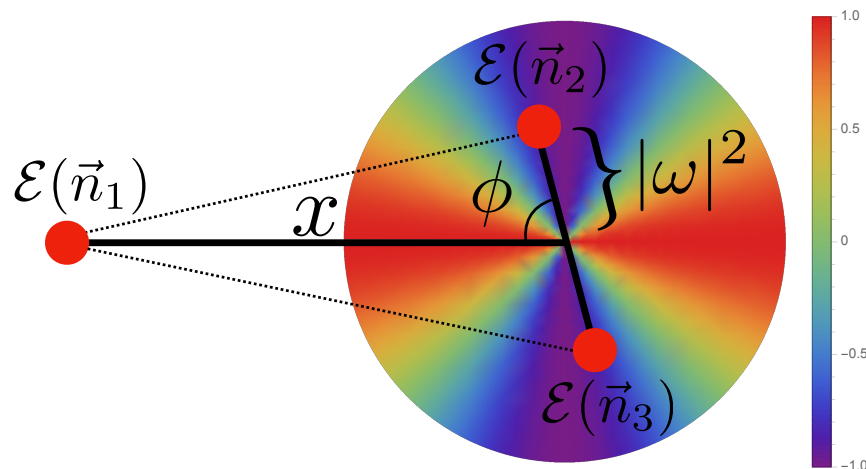
- We can now rotate the squeezed pair to reveal a $\cos(2\phi)$ interference pattern in the detector! $\Rightarrow$ interesting probe of quantum interference using jet substructure.

The OPE Limit

- Using our analytic result for the three point correlator, we can extract the squeezed limit at fixed order:

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

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



$$x^2 \frac{1}{\sigma_{\text{tot}}} \frac{d^3 \Sigma}{dx dz d\bar{z}} \simeq \left(\frac{\alpha_s}{4\pi} \right)^2 \frac{\text{Sq}^{(0)}}{x |\omega|^2} + \dots,$$

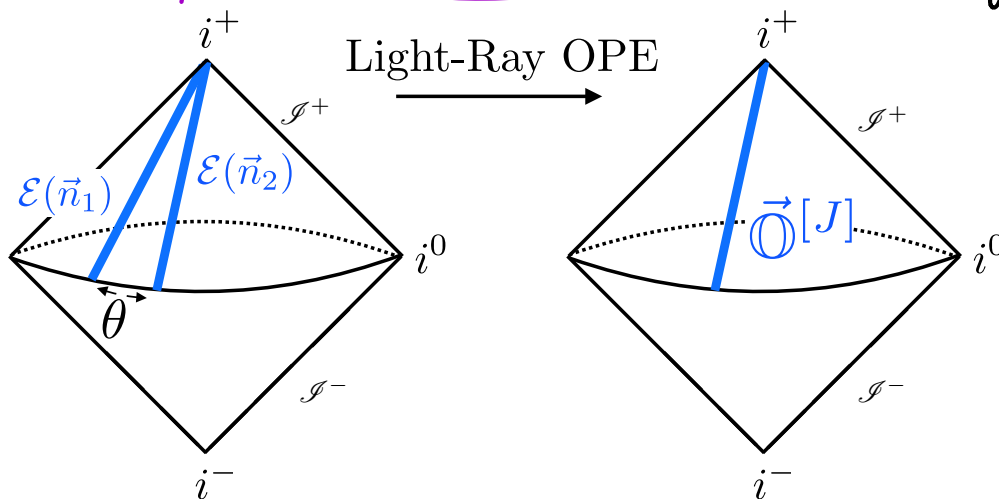
- At higher powers (twists) in the OPE expansion, get $\cos(2n\phi)$.

Lightray OPE

- We would now like to understand how to perform the leading logarithmic, leading twist resummation in the squeezed limit using an iterative lightray OPE.

$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) = \theta^{\gamma_i} \sum \mathbb{O}_i^{[J]}(\hat{n}_1)$$

(Hofman, Maldacena)
(Simmons Duffin,
Kologlu, Kravchuk,
Zhiboedov)



- Need to understand what operators appear in the OPE in QCD.

Twist-2 Lightray Operators

- In the iterative OPE of lightray operators, we will find twist-2 lightray operators at positive $J = 3, 4, 5, \dots$.
- These operators have a long history in QCD. Much interest in the $J \rightarrow 1$ (Regge limit). Analyticity in J then provides an interesting connection to the Regge limit. (Balitsky et al.)
- Jet substructure provides another interesting problem of physical interest governed by these operators.

Local Operators

transverse spin-0

$$\begin{cases} \mathcal{O}_q^{[J]} = \frac{1}{2^J} \bar{\psi} \gamma^+ (iD^+)^{J-1} \psi \\ \mathcal{O}_g^{[J]} = -\frac{1}{2^J} F_a^{\mu+} (iD^+)^{J-2} F_a^{\mu+} \end{cases}$$

transverse spin-2

$$\mathcal{O}_{g,\lambda}^{[J]} = -\frac{1}{2^J} F_a^{\mu+} (iD^+)^{J-2} F_a^{\nu+} \epsilon_{\lambda,\mu} \epsilon_{\lambda,\nu}$$

helicity $\pm$

$\xrightarrow{\lim_{r \rightarrow \infty} r^2 \int_0^\infty dt}$

$\vec{\mathcal{O}}^{[J]}(\vec{n}) =$

$\mathbb{O}_q^{[J]}(\vec{n})$
 $\mathbb{O}_g^{[J]}(\vec{n})$

unpolarized

$\mathbb{O}_{g,+}^{[J]}(\vec{n})$
 $\mathbb{O}_{g,-}^{[J]}(\vec{n})$

polarized

(Balitsky, Braun)

(Hofman, Maldacena)

(Balitsky, Kozlov)

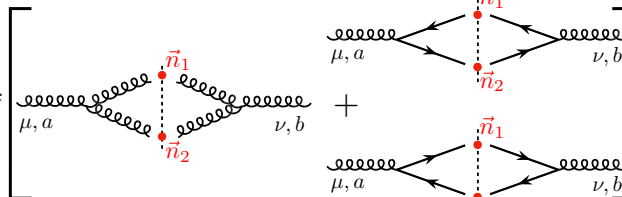
Mode Expansion

$$\begin{aligned} \mathbb{O}_q^{[J]}(\vec{n}) &= \sum_s \int \frac{d^3 p}{(2\pi)^3 2E} \delta^{(2)}(\hat{p} - \vec{n}) E^{J-1} (b_{\vec{p},s}^\dagger b_{\vec{p},s} + d_{\vec{p},s}^\dagger d_{\vec{p},s}) \\ \mathbb{O}_g^{[J]}(\vec{n}) &= \sum_{\lambda,c} \int \frac{d^3 p}{(2\pi)^3 2E} \delta^{(2)}(\hat{p} - \vec{n}) E^{J-1} a_{\vec{p},\lambda,c}^\dagger a_{\vec{p},\lambda,c} \\ \mathbb{O}_{g,\lambda}^{[J]}(\vec{n}) &= - \sum_c \int \frac{d^3 p}{(2\pi)^3 2E} \delta^{(2)}(\hat{p} - \vec{n}) E^{J-1} a_{\vec{p},\lambda,c}^\dagger a_{\vec{p},-\lambda,c} \end{aligned}$$

Matching Calculation

- Using the mode expansion, we performed a lowest order matching calculation to determine the required OPE coefficients.

$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) = -\frac{1}{2\pi}\frac{2}{\theta^2}\vec{\mathcal{J}}\left[\hat{C}_\phi(2) - \hat{C}_\phi(3)\right]\vec{\mathcal{O}}^{[3]}(\hat{n}_1) + \dots,$$

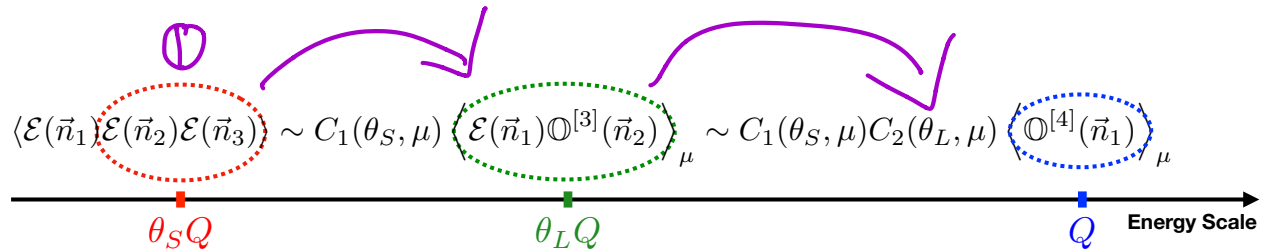
$$\vec{\mathcal{O}}^{[J]}(\hat{n}_1)\mathcal{E}(\hat{n}_2) = -\frac{1}{2\pi}\frac{2}{\theta^2}\left[\hat{C}_\phi(J) - \hat{C}_\phi(J+1)\right]\vec{\mathcal{O}}^{[J+1]}(\hat{n}_1) + \dots$$


- These take the form of a matrix that is an analytic function of J

$$\hat{C}_\phi(J) = \begin{pmatrix} \gamma_{qq}(J) & 2n_f\gamma_{qg}(J) & 2n_f\gamma_{q\tilde{g}}(J)e^{-2i\phi/2} & 2n_f\gamma_{q\tilde{g}}(J)e^{2i\phi/2} \\ \gamma_{gq}(J) & \gamma_{gg}(J) & \gamma_{g\tilde{g}}(J)e^{-2i\phi/2} & \gamma_{g\tilde{g}}(J)e^{2i\phi/2} \\ \gamma_{\tilde{g}q}(J)e^{2i\phi} & \gamma_{\tilde{g}g}(J)e^{2i\phi} & \gamma_{\tilde{g}\tilde{g}}(J) & \gamma_{\tilde{g}\tilde{g},\pm}(J)e^{4i\phi} \\ \gamma_{\tilde{g}q}(J)e^{-2i\phi} & \gamma_{\tilde{g}g}(J)e^{-2i\phi} & \gamma_{\tilde{g}\tilde{g},\pm}(J)e^{-4i\phi} & \gamma_{\tilde{g}\tilde{g}}(J) \end{pmatrix}$$

Resummation

- In QCD, one needs to incorporate the running coupling by solving a renormalization group equation.



transverse spin-0	$\mathcal{O}_q^{[J]} = \frac{1}{2^J} \bar{\psi} \gamma^+ (iD^+)^{J-1} \psi$ $\mathcal{O}_g^{[J]} = -\frac{1}{2^J} F_a^{\mu+} (iD^+)^{J-2} F_a^{\mu+}$
transverse spin-2	$\mathcal{O}_{g,ij}^{[J]} = -\frac{1}{2^J} F_a^{(i+} (iD^+)^{J-2} F_a^{j)+}$ $\left[\mathcal{O}_{g,\lambda}^{[J]} = -\frac{1}{2^J} F_a^{\mu+} (iD^+)^{J-2} F_a^{\nu+} \epsilon_{\lambda,\mu} \epsilon_{\lambda,\nu} \right]$

CANNOT MIX

RG equation:

$$\frac{d}{d \ln \mu^2} \vec{\mathcal{O}}^{[J]} = -\hat{\gamma}(J) \cdot \vec{\mathcal{O}}^{[J]}$$

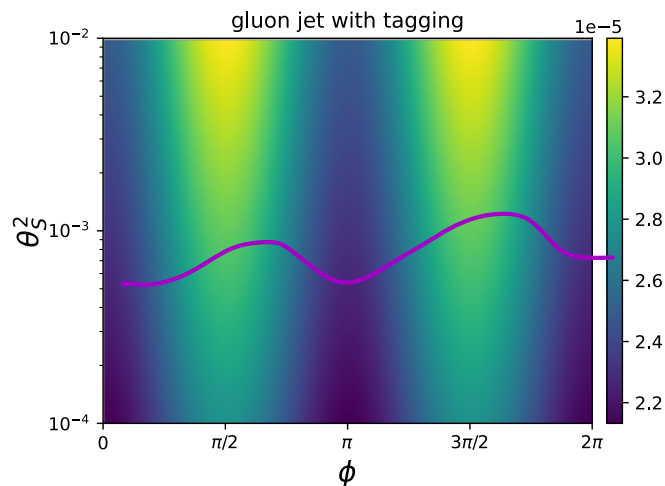
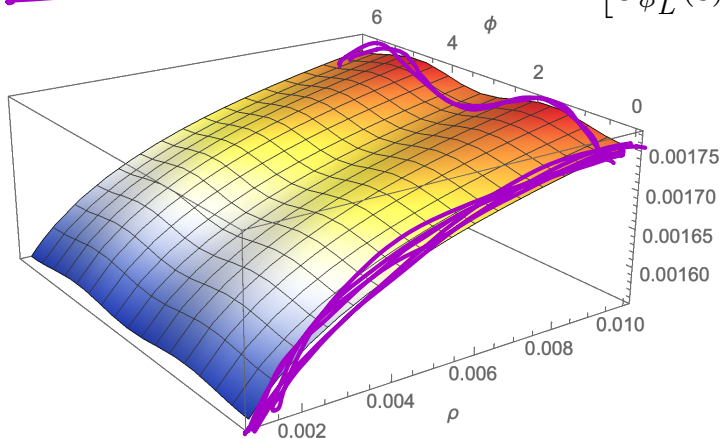
$$\hat{\gamma}(J) = \begin{pmatrix} \gamma_{qq}(J) & 2n_f \gamma_{qg}(J) & 0 \\ \gamma_{gq}(J) & \gamma_{gg}(J) & 0 \\ 0 & 0 & \gamma_{\bar{g}\bar{g}}(J) \mathbf{1} \end{pmatrix}$$

Lightray OPE

- Combining all pieces, we obtain the final resummed result. It exhibits an angular “ripple” on top of a power law.

$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2)\mathcal{E}(\hat{n}_3) = \frac{1}{(2\pi)^2} \frac{2}{\theta_S^2} \frac{2}{\theta_L^2} \vec{\mathcal{J}} \left[\hat{C}_{\phi_S}(2) - \hat{C}_{\phi_S}(3) \right] \left[\frac{\alpha_s(\theta_L Q)}{\alpha_s(\theta_S Q)} \right]^{\frac{\hat{\gamma}^{(0)}(3)}{\beta_0}} \cdot \left[\hat{C}_{\phi_L}(3) - \hat{C}_{\phi_L}(4) \right] \left[\frac{\alpha_s(Q)}{\alpha_s(\theta_L Q)} \right]^{\frac{\hat{\gamma}^{(0)}(4)}{\beta_0}} \vec{\mathcal{O}}^{[4]}(\hat{n}_1) + \dots$$

Handwritten notes: A purple squiggle with an arrow points to the first part of the equation. A blue circle highlights the ratio of coupling constants in the first term, with an arrow pointing to it from above. A large blue bracket on the right side groups the entire equation.



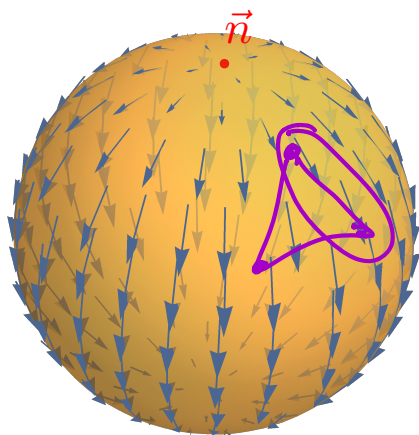
- Hope to observe in LHC data!

Higher Twist Contributions



$$\frac{\cos 2\phi}{\omega^2} + \cos 4\phi + \cos 6\phi \frac{\omega^2}{\omega^2} + \dots$$

- In a standard OPE, higher twist contributions arising from descendants of a primary operator can be summed into "blocks" associated with a particular symmetry. In this case, the $SL(2, C)$ on the celestial sphere.
- We can also do this for lightray operators!
- This can be efficiently achieved by solving a quadratic Casimir differential equation (following Dolan and Osborn) for the symmetries acting on the celestial sphere.



$$(C_2 - [\Delta(\Delta - d) + l(l + d - 2)])g = 0$$

$$C_2 = -\frac{1}{2}L_{\mu\nu}L^{\mu\nu}$$

$$L^{\mu\nu} = z_1^\mu \frac{\partial}{\partial z_1^\nu} - z_1^\nu \frac{\partial}{\partial z_1^\mu} + (1 \leftrightarrow 2)$$

Collinear Lightray Blocks

- Skipping some steps, one eventually finds the result for the required blocks

$$G_{h,\bar{h}}(\omega, \bar{\omega}) = F_h(\omega) F_{\bar{h}}(\bar{\omega})$$

$$F_h(\omega) = w^{h-3} {}_2F_1\left(\frac{h-1}{2}, \frac{h}{2}, \frac{1}{2} + h; w^2\right)$$

$$F_{\bar{h}}(\bar{\omega}) = \bar{w}^{\bar{h}-3} {}_2F_1\left(\frac{\bar{h}-1}{2}, \frac{\bar{h}}{2}, \frac{1}{2} + \bar{h}; \bar{w}^2\right)$$

- Note that the result exhibits “holomorphic factorization”, as expected since the celestial sphere is 2 dimensional.

Handwritten notes:

$$\mathcal{H} = \sum_j c_j P_j(\cos\theta)$$

for j $c_j \frac{(1 + \cos\theta)^j}{R}$

sol(3)

$$\Delta(\Delta - 2) + l^2 = 2h(h - 1) + 2\bar{h}(\bar{h} - 1),$$

$$h = \frac{\Delta + l}{2}, \quad \bar{h} = \frac{\Delta - l}{2}$$

Collinear Lightray Blocks

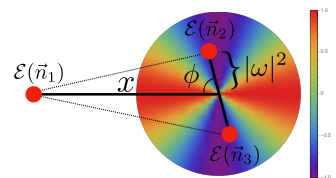
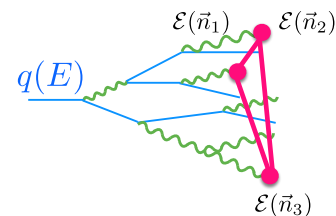
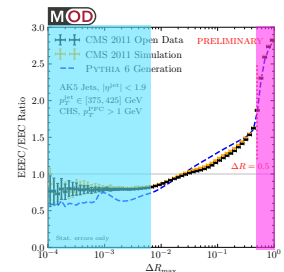
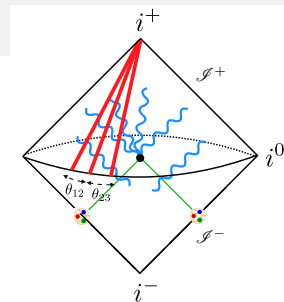
- As a test, one can show that the terms with highest azimuthal dependence at each twist are uncontaminated by higher twist primaries, and arise only from the descendants of the leading twist operators. They are resummed by the block

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

- Agrees exactly with the expansion of the full result for the three-point correlator!
- Here we have barely scratched the surface. Opens the door to the use of many powerful techniques for studying jet substructure.
- Sophisticated technical machinery developed for studying conformal blocks in CFTs can be exploited.

Outline Summary

- Energy Correlators are a theoretically nice observable formulated as matrix elements of lightray operators.
- Shapes and scalings of Energy Correlators can be measured precisely at the LHC.
- Multipoint correlators can be analytically computed.
- Squeezed limits exhibit interesting spin interference effects which can be analyzed using the lightray OPE and collinear blocks.



Thanks!