

# Power jets: A more global way to study jets

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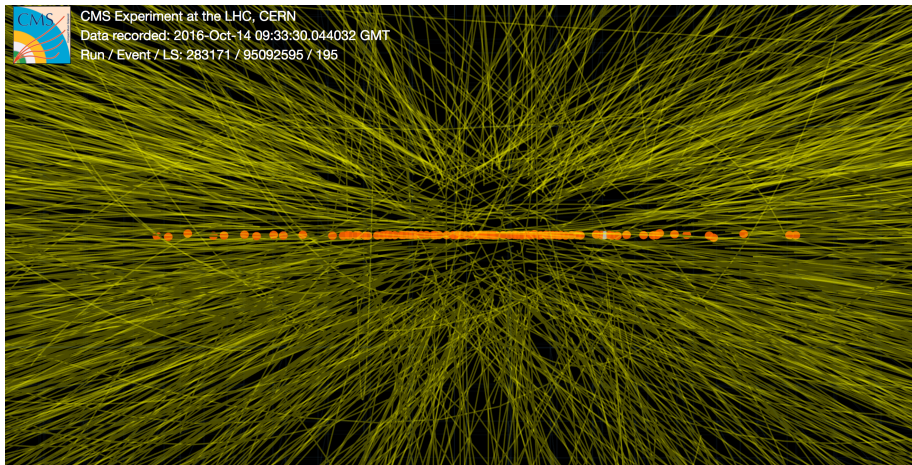
In collaboration with Zack Sullivan, IIT

Ref: arXiv:2312.08627

# Outline

- 1 Motivation
- 2 The QCD power spectrum
- 3 The extensive particle
- 4 Power jets
- 5 Conclusion

# Motivation: QCD is high multiplicity!



- The high luminosity of the LHC leads to **significant** pileup.
- At 13.6 TeV  $\rightarrow \langle N_{PU} \rangle = \mathcal{O}(70)$ !

# QCD power spectrum: Construction

Project an event's normalized, energy-density onto  $S^2 \implies \rho(\hat{r}) = \rho(\theta, \phi)$

Decompose into spherical harmonics

$$\rho(\hat{r}) = \sum_{l=0}^{\infty} \sum_{m=-l}^l \rho_l^m Y_l^m(\hat{r}) \quad \iff \rho_l^m = \int d\Omega Y_l^{m*}(\theta, \phi) \rho(\theta, \phi)$$

Construct dimensionless **power spectrum**

$$H_l \equiv \int_{\Omega} d\Omega \int_{\Omega'} d\Omega' \rho(\hat{r}) \rho(\hat{r}') P_l(\hat{r} \cdot \hat{r}') = \frac{4\pi}{2l+1} \sum_{m=-l}^l |\rho_l^m|^2$$

For a finite sample of  $N$  discrete particles, each with an energy fraction

$$f_i \equiv \frac{E_i}{E_{\text{tot}}}$$

$$\rho(\hat{r}) = \sum_{i=1}^N f_i \delta^2(\theta_i, \phi_i) \implies H_l = \sum_{i,j}^N f_i f_j P_l(\cos \theta_{ij})$$

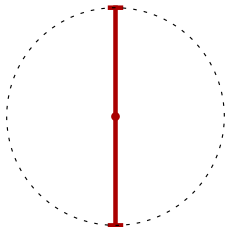
# QCD power spectrum: $e^+ e^-$ annihilation

## Two-parton final state

$$(e^+ e^- \rightarrow q \bar{q})$$

Every kinematic depiction is back-to-back in CMF.

Every power spectrum  $H_I$  is the same.

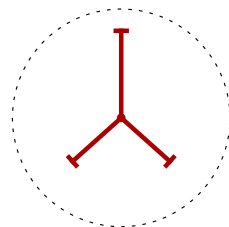
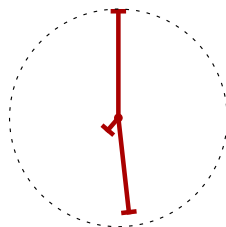


## Three-parton final state

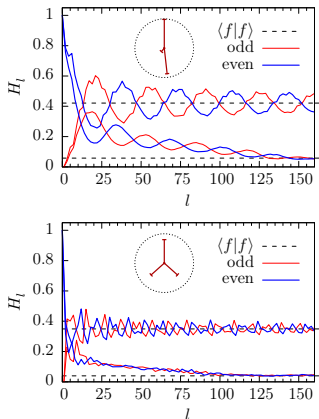
$$(e^+ e^- \rightarrow q \bar{q} g)$$

Every kinematic depiction is *not* the same.

2-jet-like vs. 3-jet-like.



# QCD power spectrum: $e^+ e^- \rightarrow q \bar{q} g \rightarrow \text{hadrons}$



- **Correlations are global:** information is spread across *all moments*
- $N \neq n$ : The spectra for  $N$  measurable particles and  $n$  originating partons are *not* the same.
- $H_l$  plateaus:

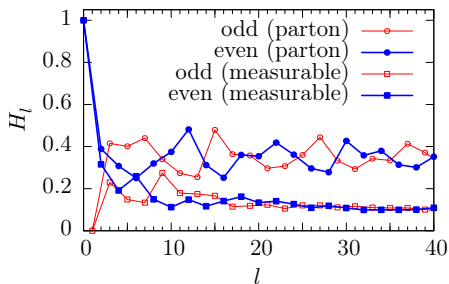
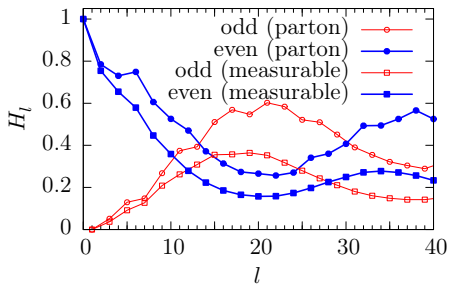
$$H_l \sim \sum_i f_i^2 \propto \frac{1}{N}$$

# QCD power spectrum: $N \neq n$

$$H_l = \sum_{i,j}^N f_i f_j P_l(\cos \theta_{ij})$$

$$\xi \equiv \frac{2\pi}{l} \implies \xi_{\min} = \frac{2\pi}{l_{\max}}$$

- spectral **correspondence** at **low  $l$**
- spectral **divergence** at **high  $l$**



# The extensive particle: Shape function

$$H_l \equiv \int_{\Omega} d\Omega \int_{\Omega'} d\Omega' \rho(\hat{r}) \rho(\hat{r}') P_l(\hat{r} \cdot \hat{r}')$$

- The asymptotic plateau is caused by the  $\delta^2(\hat{r} - \hat{p}_i)$  distributions
- Replace point particles with extensive particles described by a **shape function**

$$\rho(\hat{r}) = \sum_{i=1}^N f_i \delta^2(\hat{r} - \hat{p}_i) \implies \rho(\hat{r}) = \sum_{i=1}^N f_i h_i(\hat{r})$$

We need an  $h_i(\hat{r})$ :

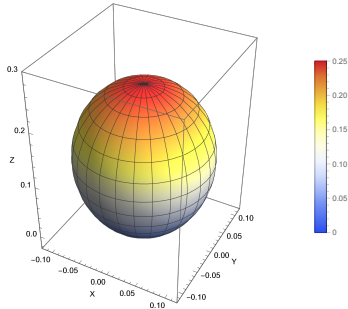
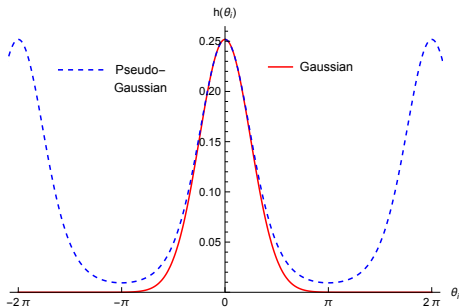
- That is square-integrable
  - Distributes energy flux azimuthally symmetrically
  - Gaussian-like
  - Periodic
- Solves the infinite-power problem
  - Makes sense



# The extensive particle: Pseudo-Gaussian

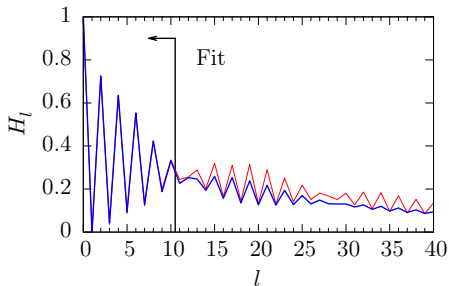
$$h_i(\hat{r}) = \frac{1}{2\pi\lambda^2(1 - e^{-2/\lambda^2})} \exp\left(-\frac{(1 - \hat{r} \cdot \hat{p}_i)}{\lambda^2}\right)$$

$$\lim_{\theta_i \rightarrow 0} h_i(\hat{r}) \stackrel{\lambda \ll 1}{\approx} \frac{1}{2\pi\lambda^2} \exp\left(-\frac{\theta_i^2}{2\lambda^2}\right) \implies \text{Reduces to Gaussian.}$$

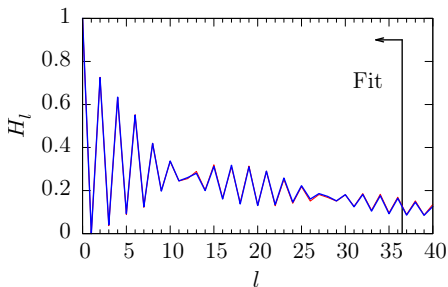


# Power jets: Two-jet-like event

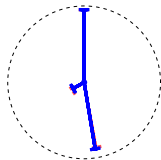
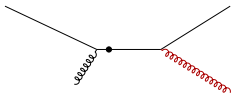
## 3-prong fit



## 4-prong fit

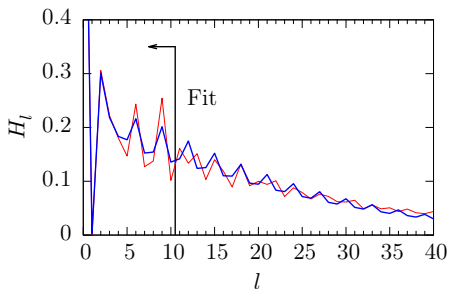


The 3-prong model doesn't well fit for  $l > 10$ . We add another prong.

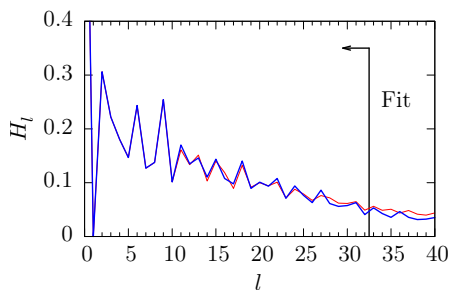


# Power jets: Three-jet-like event

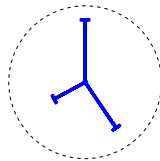
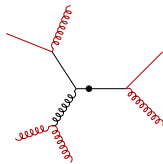
3-prong fit



6-prong fit



For a three-jet-like event, we make a 6-prong fit.

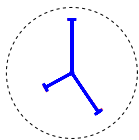
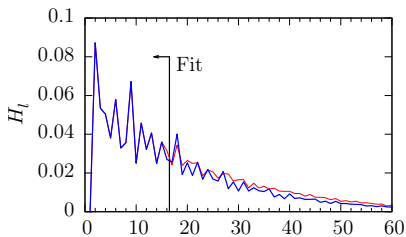


# Power jets: Anti- $k_t$ comparison

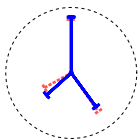
Power jet energies and angles are stable to high pileup.

Anti- $k_t$  jets become sensitive to pileup subtraction procedure.

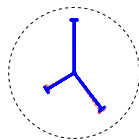
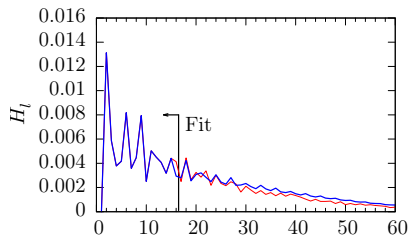
$$S/N = 1 \quad (f_{\text{PU}} = 0.5)$$



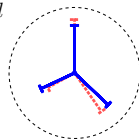
power jets

anti- $k_t$ 

$$S/N = 1/5 \quad (f_{\text{PU}} = 0.8)$$



power jets

anti- $k_t$

# Conclusion

- Identified key features of the QCD power spectrum
- Addressed the divergence in total power
- Formalism to extract all accessible correlations, with angular resolution built in
- Jet reconstruction algorithm without imposing an arbitrary cut
- Next step: extend the existing formalism to hadronic colliders

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**THANK YOU!**

**QUESTIONS?**

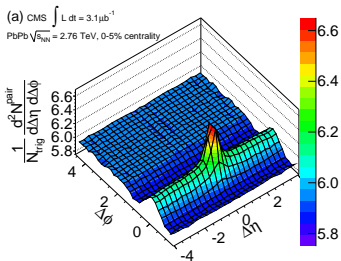
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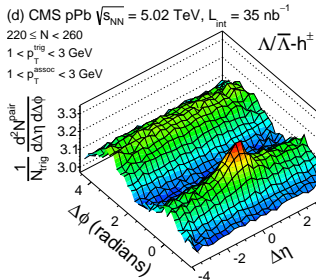
## Additional slides

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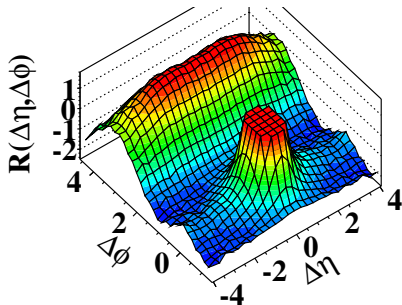
# Motivation: Long-range correlations



- Long-range, “ridge” correlation in  $p$ - $Pb$ ,  $Pb$ - $Pb$  collisions
- Same correlation seen in high-multiplicity  $pp$  collisions

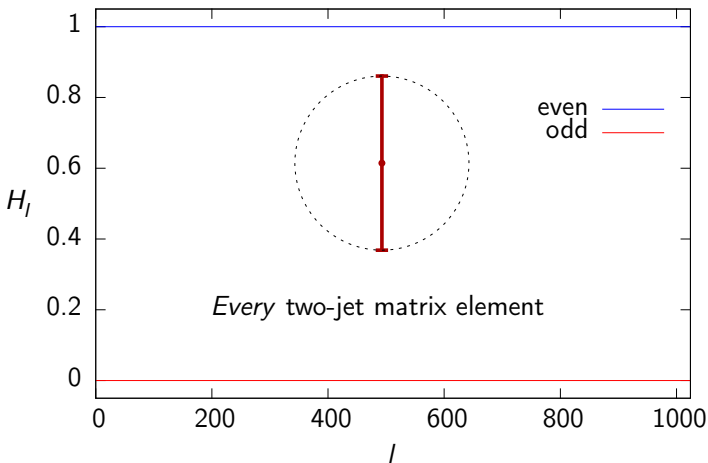


(d) CMS  $N \geq 110$ ,  $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



# QCD power spectrum: $e^+ e^- \rightarrow q \bar{q}$

$$H_l = f_1^2 P_l(\cos 0) + 2f_1 f_2 P_l(\cos \pi) + f_2^2 P_l(\cos 0) = \frac{1}{2}[P_l(1) \pm P_l(-1)]$$

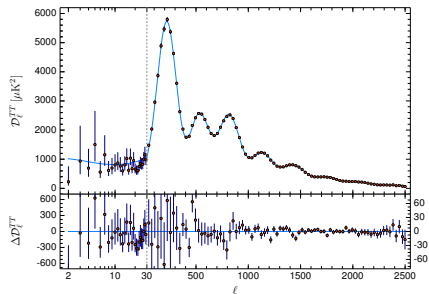




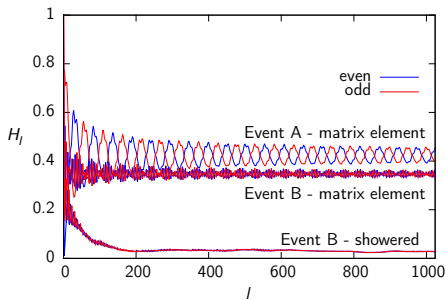
# QCD power spectrum: Correlations are global

$$H_l \equiv \int_{\Omega} d\Omega \int_{\Omega'} d\Omega' \rho(\hat{r}) \rho(\hat{r}') P_l(\hat{r} \cdot \hat{r}') \implies H_l = \sum_{i,j}^N f_i f_j P_l(\cos \theta_{ij})$$

- Difficult to fit **broad shapes**
- Every correlation appears at **every moment**



Power spectrum of the CMB

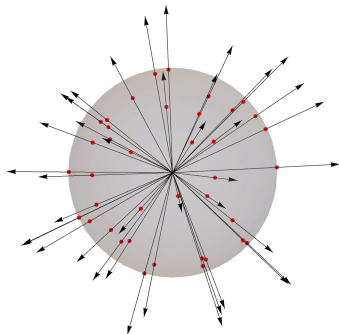


QCD power spectrum of two events

# QCD power spectrum: Asymptotic plateau

$$\rho(\hat{r}) = \sum_{i=1}^N f_i \delta^2(\theta_i, \phi_i) \implies \sum_l H_l \rightarrow \infty$$

$$H_\ell = \underbrace{\langle f|f \rangle}_{\text{self}} + \underbrace{\langle f| (P_\ell(|\hat{p}\rangle \cdot \langle \hat{p}|) - \mathbb{I}) |f \rangle}_{\text{inter-particle}}$$



# Power jets: Challenges in sequential jet-clustering (anti- $k_t$ )

$$d_i^2 = p_{T,i}^{-2}$$

cluster becomes a jet

$$d_{ij}^2 = \min(p_{T,i}^{-2}, p_{T,j}^{-2}) \frac{\Delta y_{ij}^2 + \Delta \phi_{ij}^2}{R^2}$$

merge two clusters

- 
- One correlation at a time
  - Uncertainties in pileup correction dominate over instrumental uncertainties for low- and medium- $p_t$  jets
  - Average pileup subtraction throws away some jet info

# Power jets: Reconstructed kinematics

Table: Reconstructed 3-jet kinematics for the 2-jet-like event.

(GeV)	$E_1$	$E_2$	$E_3$
parton	190.1	172.8	37.00
power jets	190.4(0)	174.2(1)	35.52(8)
error	0.1%	0.7%	-4%

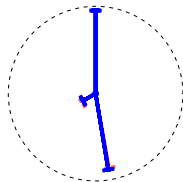


Table: Reconstructed 3-jet kinematics for the 3-jet-like event.

(GeV)	$E_1$	$E_2$	$E_3$
parton	163.0	143.5	93.56
power jets	162.0(1)	146.3(4)	91.68(4)
error	-0.6%	2.0%	-2.0%

