Power jets: A more global way to study jets

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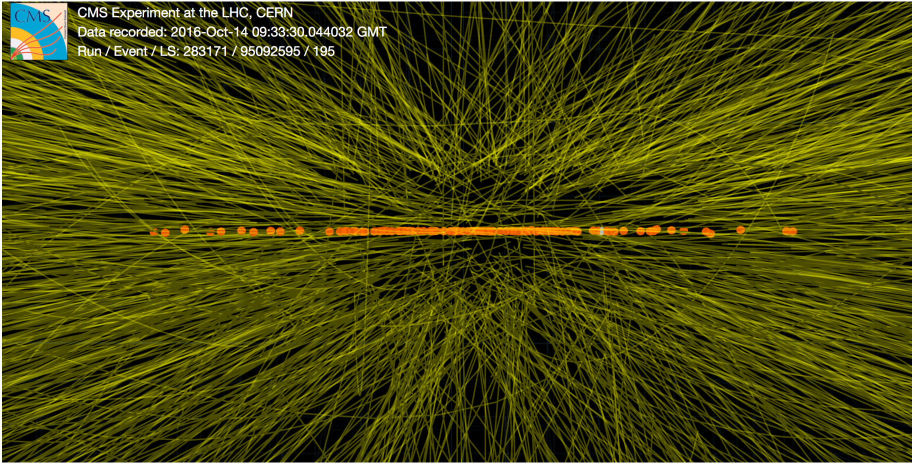
Outline

Motivation: QCD is high multiplicity!



- The "high luminosity" HL-LHC era anticipates **significant** pileup.
- At 13.6 TeV $\rightarrow$ $\langle N_{PU} \rangle = \mathcal{O}(70)$, and as high as **200**!

QCD power spectrum: Construction

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

Decompose into spherical harmonics

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

Construct dimensionless **power spectrum**

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

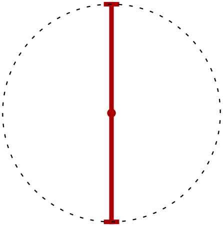
For a finite sample of N discrete particles, each with an energy fraction $f_i \equiv \frac{E_i}{E_{tot}}$

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

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

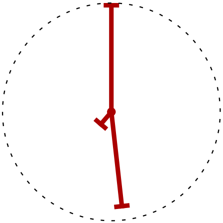
Two-parton final state
($e^+ e^- \to q\,\bar{q}$)

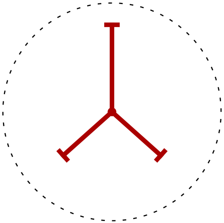
Every kinematic depiction is back-to-back in CMF.
Every power spectrum H_l is the same.



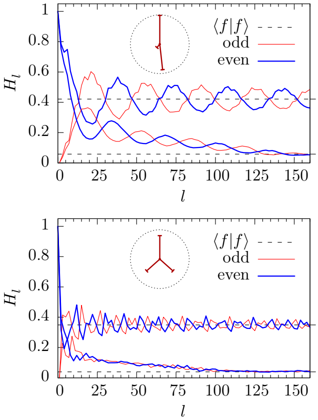
Three-parton final state
($e^+ e^- \to q\,\bar{q}\,g$)

Every kinematic depiction is *not* the same.
2-jet-like vs. 3-jet-like.





QCD power spectrum: $e^+ e^- \to q\,\bar{q}\,g \to$ hadrons



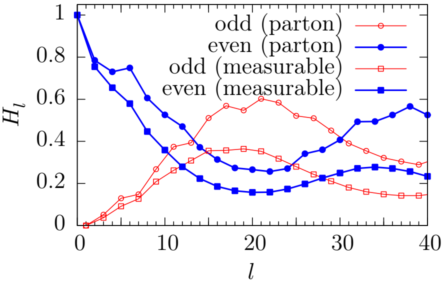
- **Correlations are global:** information is spread across *all moments*
- $N \neq n$**:** The spectra for N measurable particles and n originating partons are *not* the same.
- H_l **plateaus:**

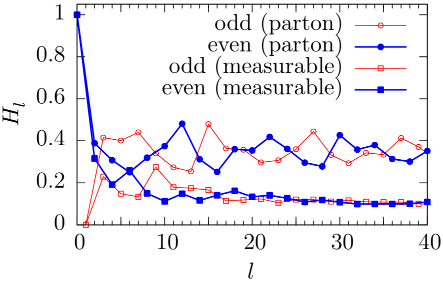
$$H_l \sim \sum_i f_i^2 \propto \frac{1}{N}$$

QCD power spectrum: $N \neq n$

$$H_l = \sum_{i,j}^{N} f_i f_j P_l(\cos\theta_{ij}) \qquad \xi \equiv \frac{2\pi}{l} \Longrightarrow \xi_{\text{min}} = \frac{2\pi}{l_{max}}$$

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





The extensive particle: Shape function

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

- 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**

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

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

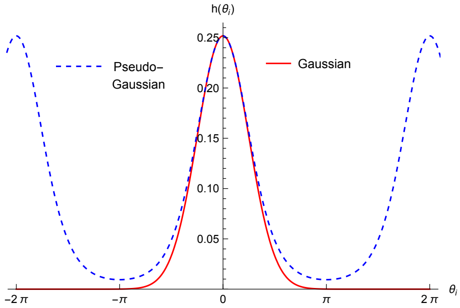
- That is square-integrable
- Distributes energy flux azimuthally symmetrically
- Gaussian-like
- Periodic

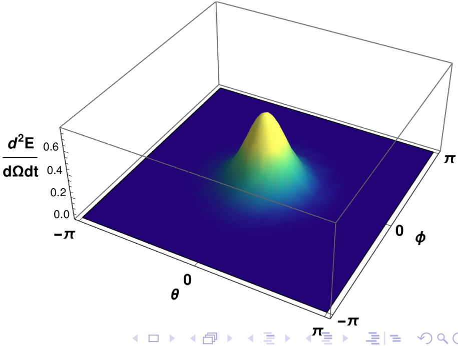
- Solves the infinite-power problem
- Makes sense

The extensive particle: Pseudo-Gaussian

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

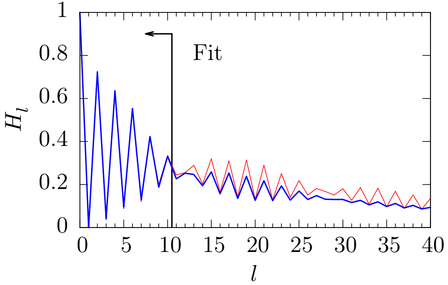
$$\lim_{\theta_i\to 0} h_i(\hat{r}) \overset{\lambda\ll 1}{\approx} \frac{1}{2\pi\lambda^2}\exp\left(-\frac{\theta_i^2}{2\lambda^2}\right) \implies \text{Reduces to Gaussian}\,.$$



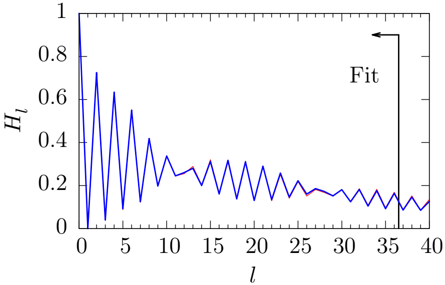


Power jets: Two-jet-like event

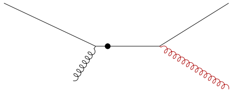
3-prong fit

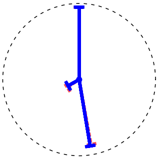


4-prong fit



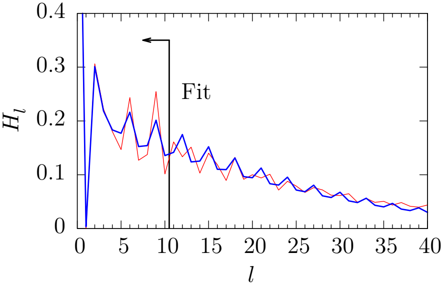
The 3-prong model doesn't well fit for $l > 10$. We add another prong.



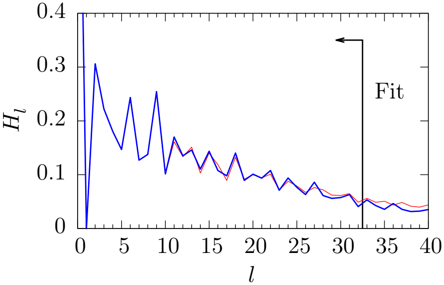


Power jets: Three-jet-like event

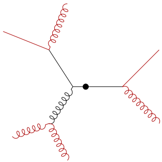
3-prong fit

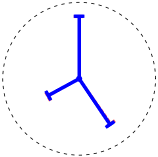


6-prong fit



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



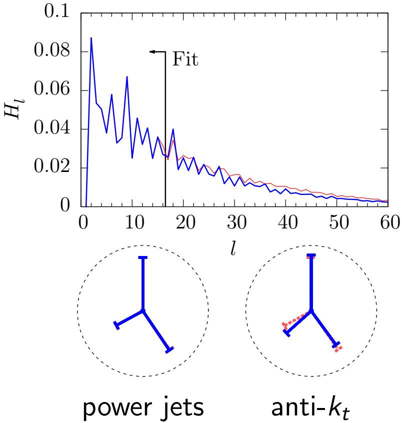


Power jets: Anti-k_t comparison

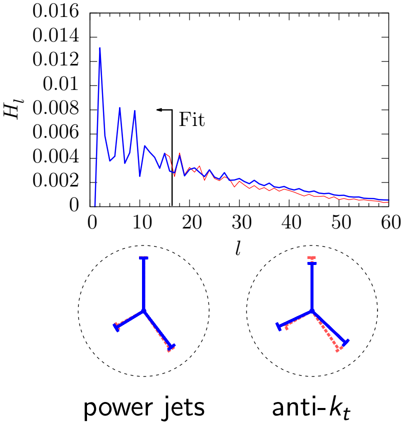
Power jet energies and angles are stable to high pileup.

Anti-k_t jets become sensitive to pileup subtraction procedure.

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



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



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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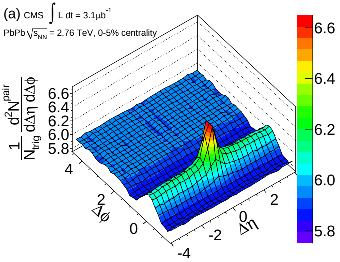
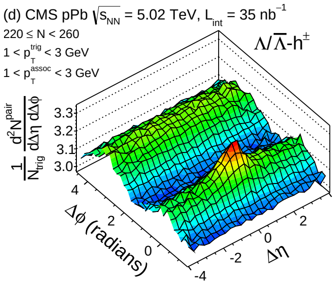
THANK YOU! **QUESTIONS?**

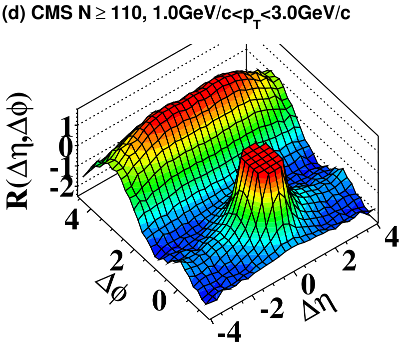
Additional slides

Motivation: Long-range correlations



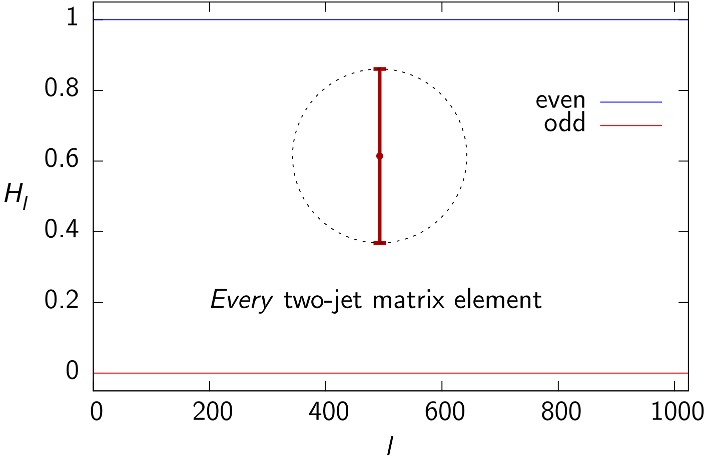


- Long-range, "ridge" correlation in *p-Pb*, *Pb-Pb* collisions
- Same correlation seen in high-multiplicity *p p* collisions



QCD power spectrum: $e^+ e^- \to q\,\bar{q}$

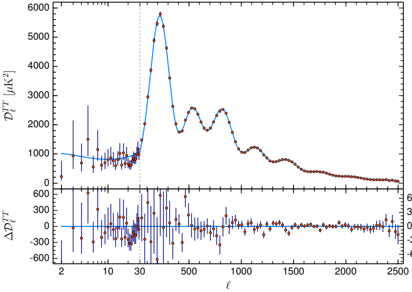
$$H_l = f_1^2 P_l(\cos 0) + 2 f_1 f_2 P_l(\cos\pi) + f_2^2 P_l(\cos 0) = \frac{1}{2}[P_l(1) \pm P_l(1)]$$



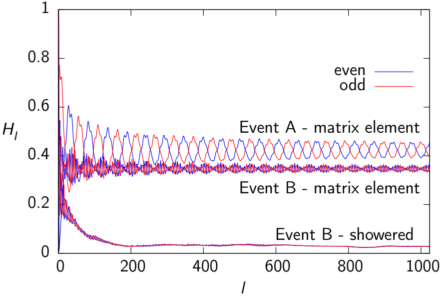
QCD power spectrum: Correlations are global

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

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



Power spectrum of the CMB

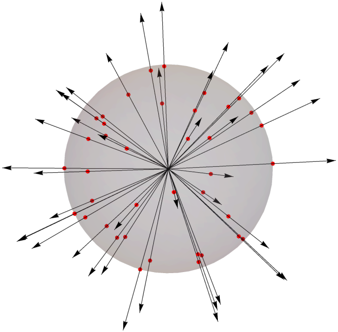


QCD power spectrum of two events

QCD power spectrum: Asymptotic plateau

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

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



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

$$d_i^2 = p_{T,i}^{-2} \qquad \text{cluster becomes a jet}$$

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

- 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%

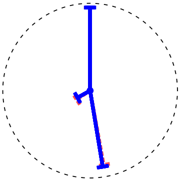


Table: Reconstructed 3-jet kinematics for the 3-jet-like event.

(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%