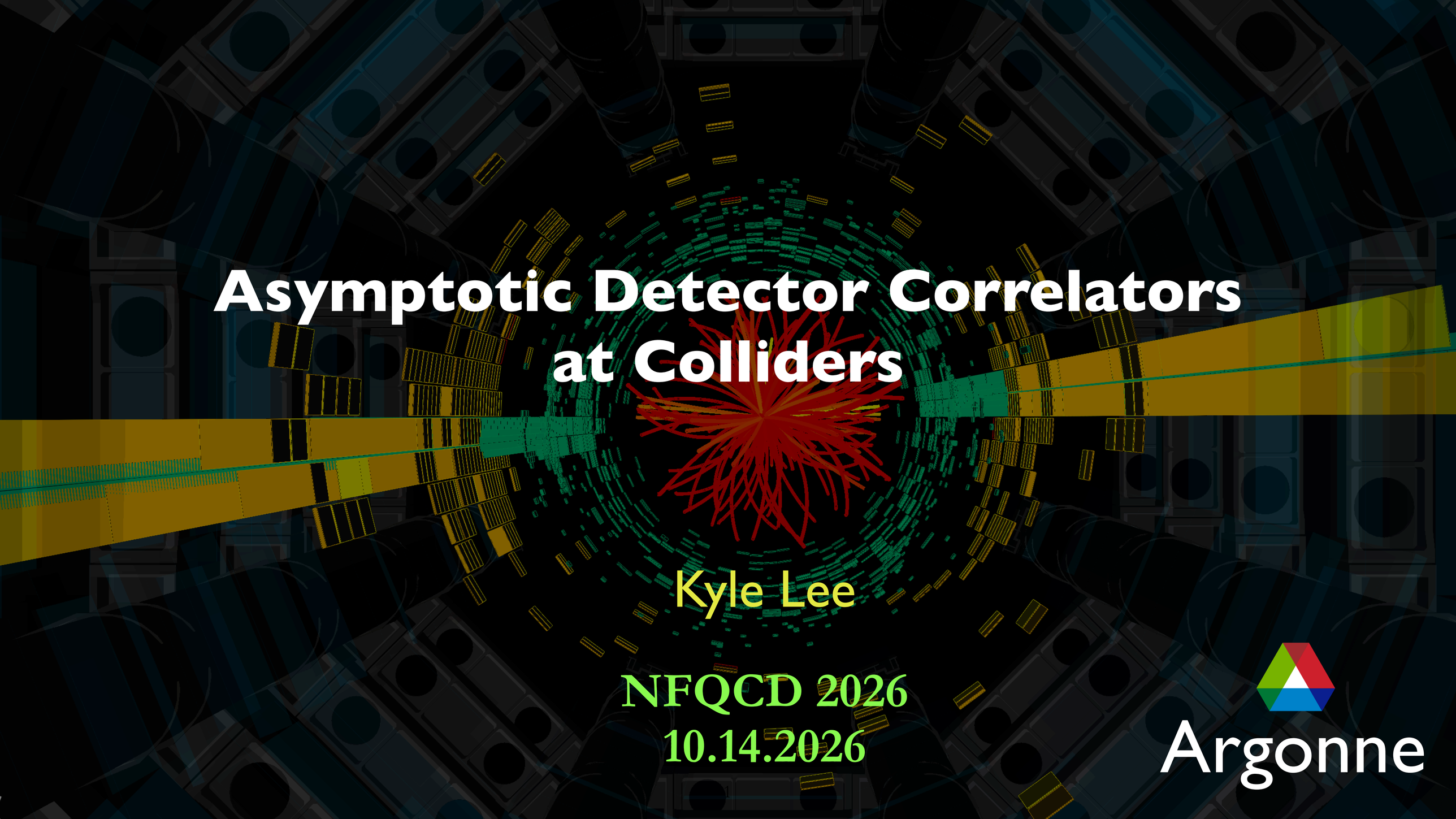


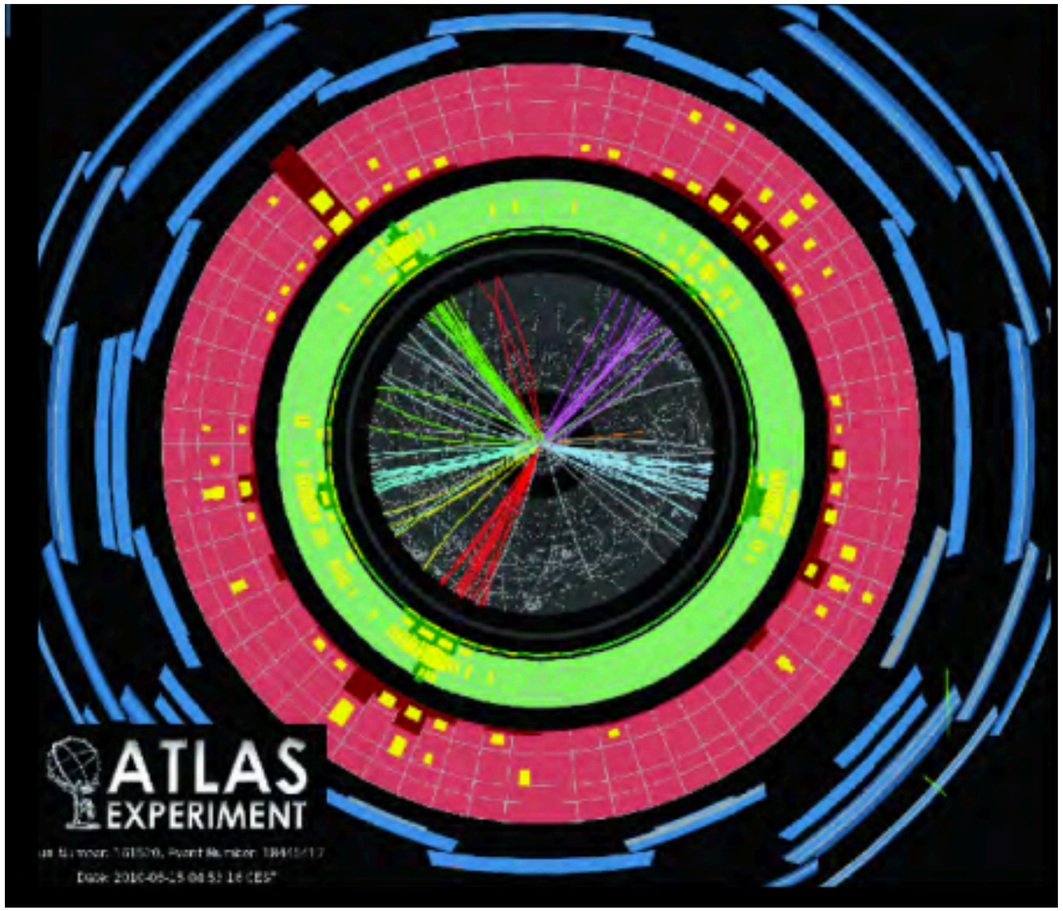
Asymptotic Detector Correlators at Colliders

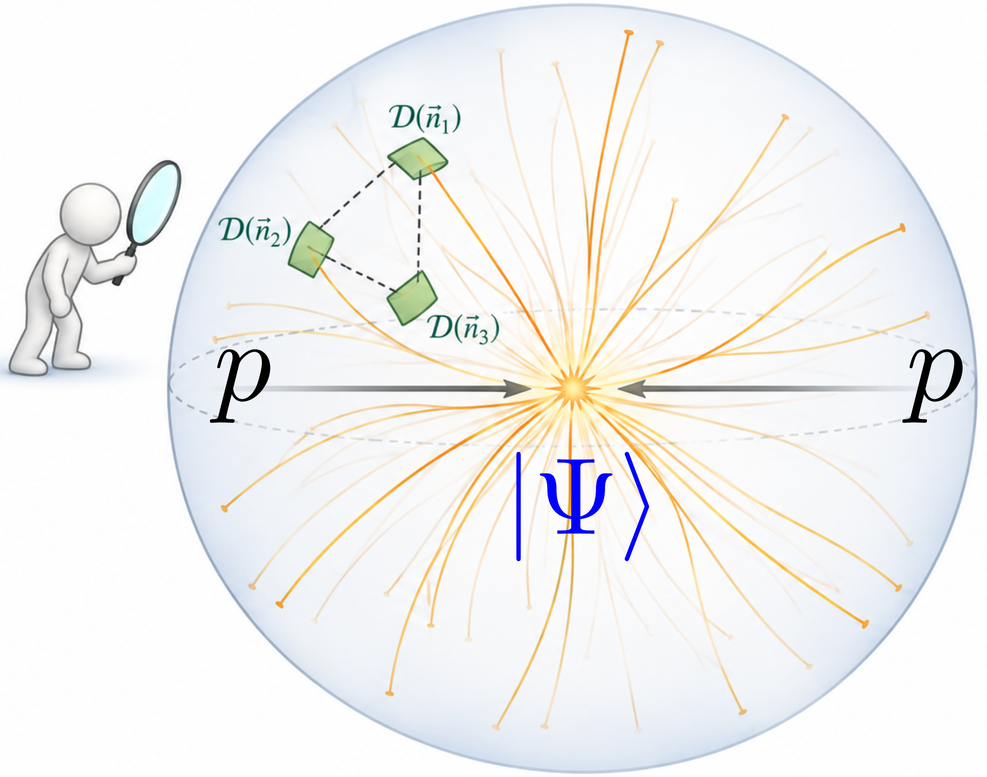
Kyle Lee

NFQCD 2026
10.14.2026

Argonne

ASYMPTOTIC DETECTOR CORRELATORS

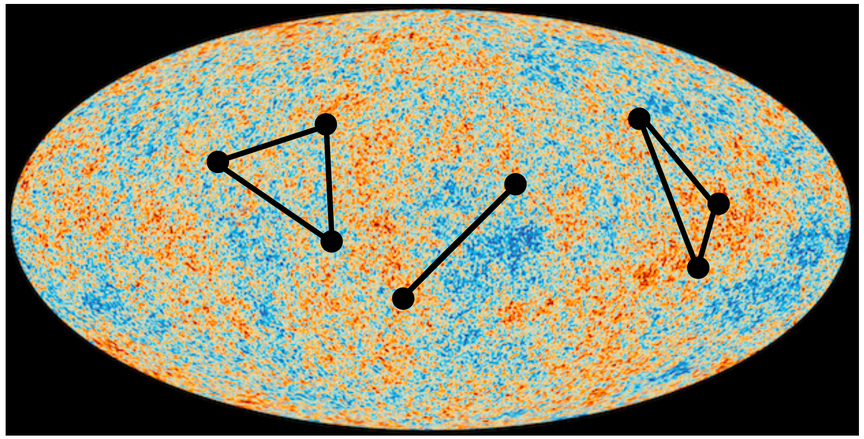


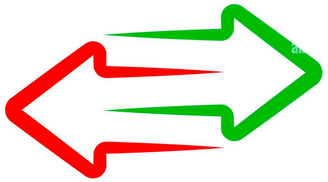


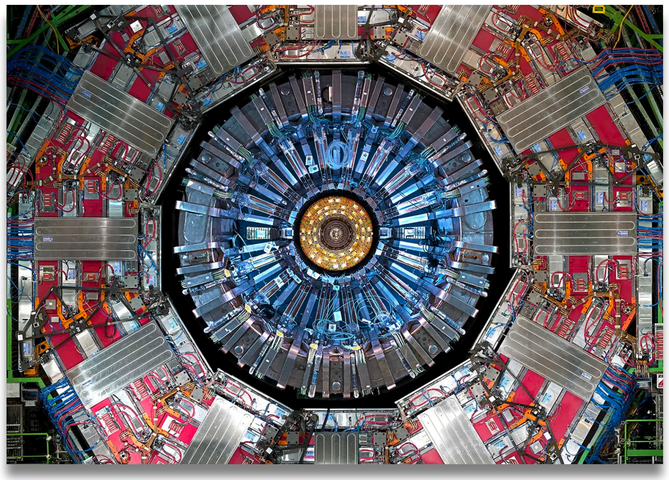
$$\langle \Psi | \mathcal{D}(\vec{n}_1)\mathcal{D}(\vec{n}_2)\mathcal{D}(\vec{n}_3) | \Psi \rangle$$

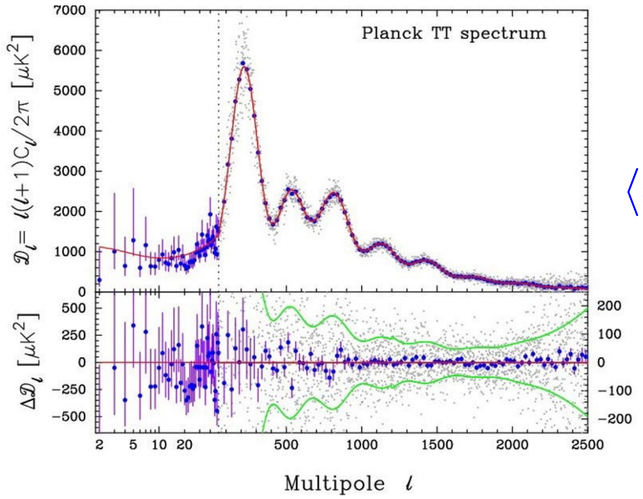
At colliders, microscopic dynamics of quantum field theory of nature is imprinted on macroscopic asymptotic flux measured at experimental detectors.

DECODING ASYMPTOTIC ENERGY FLUX IN COLLIDERS









$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \cdots \zeta_{\vec{k}_n} \rangle$

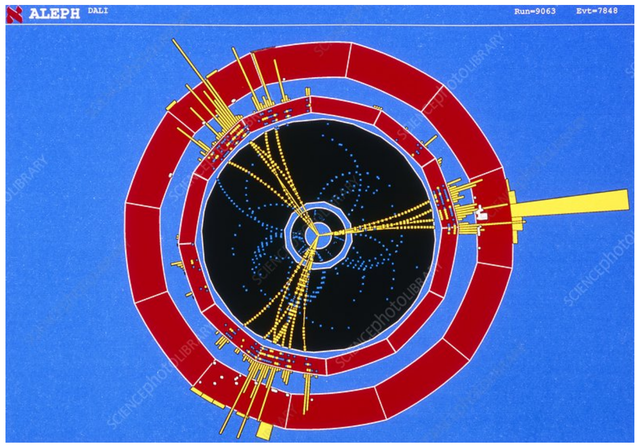
We probe primordial perturbations by analyzing correlations in the CMB

Much like cosmology, we infer microscopic (early time) physics from asymptotic (late time) **detector flux**

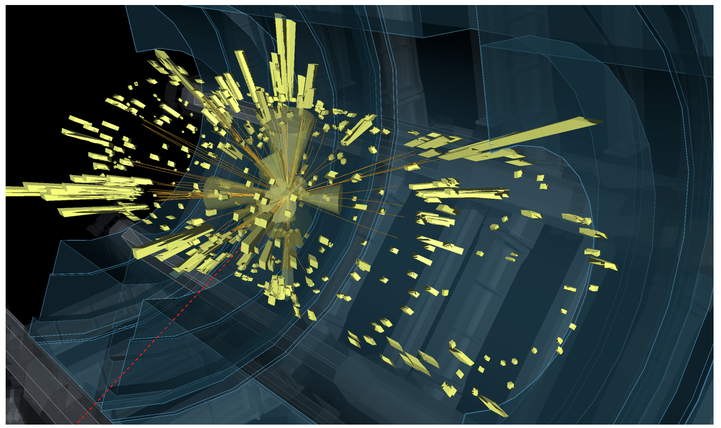
From **QFT** point of view, **what field theoretic observables** describe this patterns of **detector flux**?

MANY COLLIDER "COSMOLOGIES"

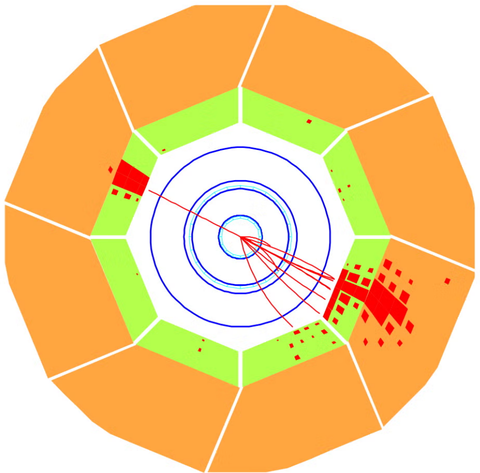
e^+e^-



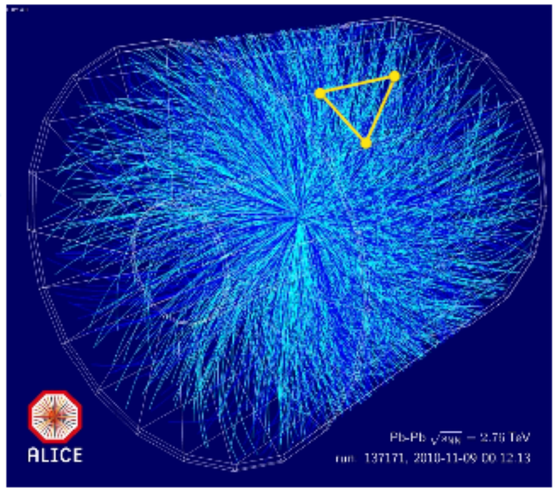
pp



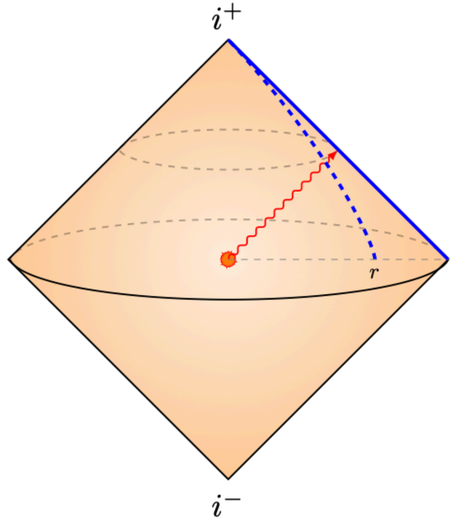
ep



Pb-Pb



ENERGY FLOW OPERATOR

$T_{0i} \leftrightarrow$ 

$=$ 

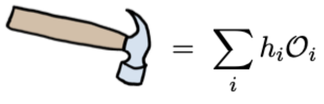
From QFT point of view, what is a detector?

Energy Flow Operators 

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

$$\mathcal{E}(\hat{n})|X\rangle = \sum_a E_a \delta^{(2)}\left(\Omega_{\vec{p}_a} - \Omega_{\hat{n}}\right)|X\rangle$$

- Generic field theories with stress-energy tensors can have a corresponding energy flow operators.


$= \sum_i h_i \mathcal{O}_i$


$= \sum_j c_j \mathcal{D}_j$



$\left\langle \text{hammer} \middle| \text{camera}(\hat{n}_1) \cdots \text{camera}(\hat{n}_N) \middle| \text{hammer} \right\rangle$

Caron-Huot, Kologlu, Kravchuk, Meltzer, Simmons-Duffin`22

From the perspective of QFT, collider processes are study of correlation functions of energy flow operators.

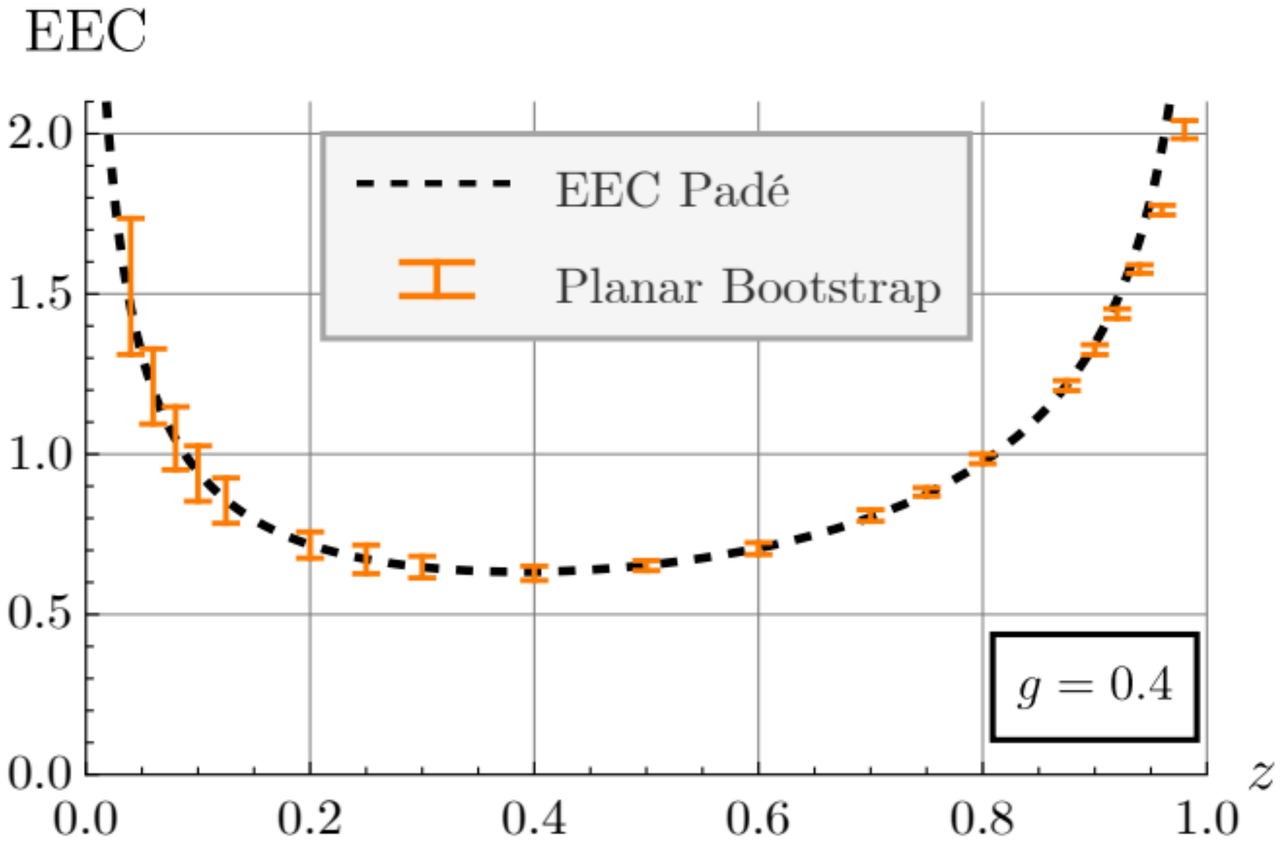
= energy correlators!

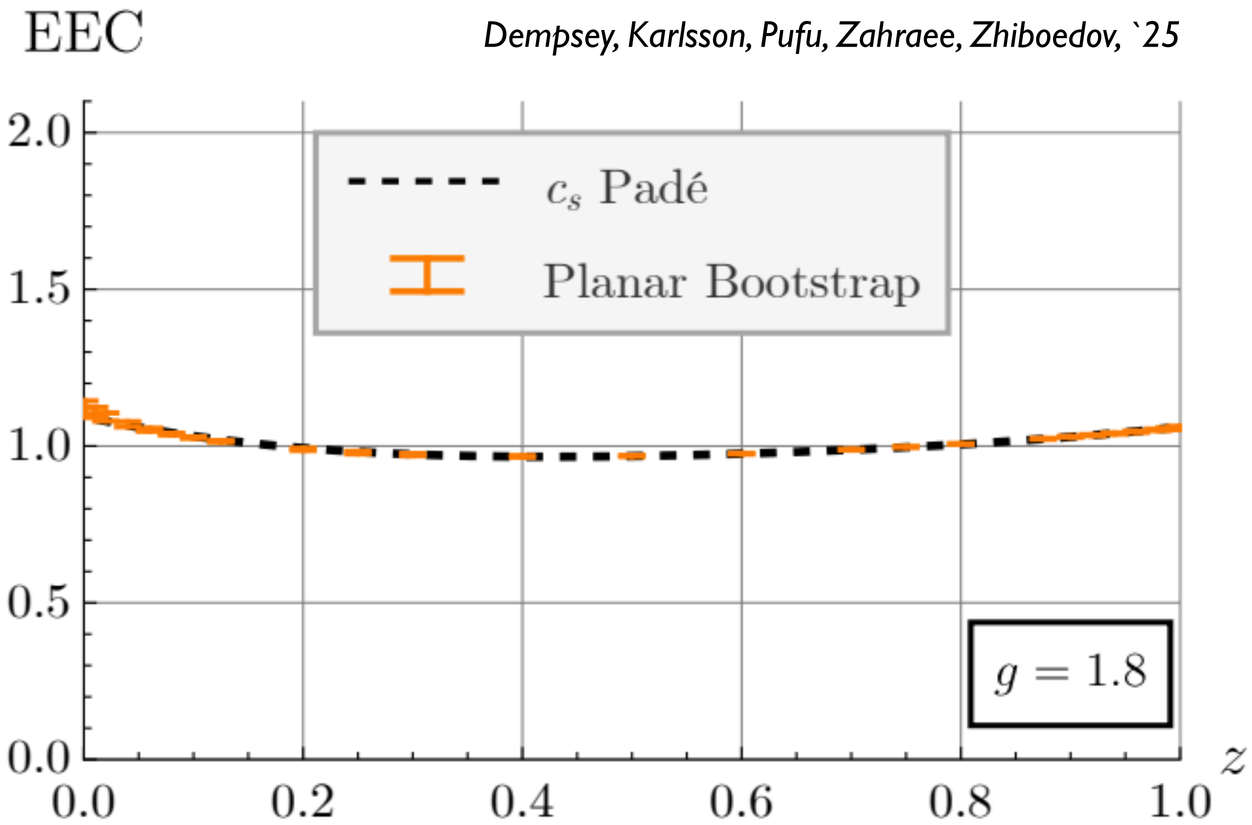
$$\langle \mathcal{E}(\hat{n}_1) \cdots \mathcal{E}(\hat{n}_N) \rangle \equiv \langle \Psi | \mathcal{E}(\hat{n}_1) \cdots \mathcal{E}(\hat{n}_N) | \Psi \rangle$$

"Conformal collider physics" *Hofman, Maldacena `08*

EEC: FIRST *NONPERTURBATIVELY COMPUTED* COLLIDER OBSERVABLES

Conformal collider bootstrap in $\mathcal{N} = 4$ SYM





Dempsey, Karlsson, Pufu, Zahraee, Zhiboedov, `25

"We use a combination of perturbation theory, holography, supersymmetric localization, integrability, and numerical conformal bootstrap methods to constraint EEC in $\mathcal{N} = 4$ SYM at finite coupling"

ASYMPTOTIC DETECTOR OPERATORS $\mathscr{D}(\vec{n})$

From QFT point of view, what are the operators describing asymptotic flux measured in experiments?

Gonzaelz, KL, Moult `26

Energy Flow Operators



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

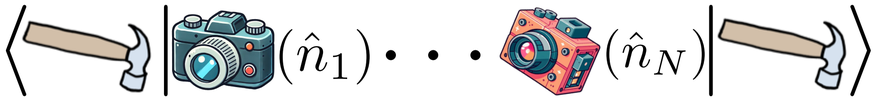
Charge Operators



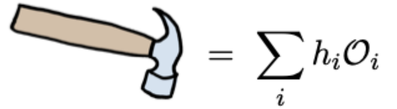
$$= \mathcal{Q}(\vec{n}) = \int_0^\infty dt \lim_{r\to\infty} r^2 n^i J_i(t, r\hat{n})$$

Correlations of general asymptotic detectors





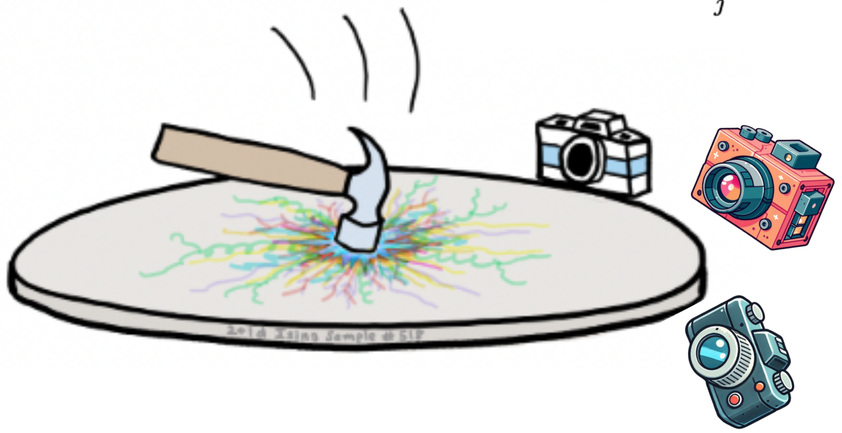
Correlations of detector operators
are well-defined field theoretic objects



$$= \sum_i h_i \mathcal{O}_i$$



$$= \sum_j c_j \mathcal{D}_j$$



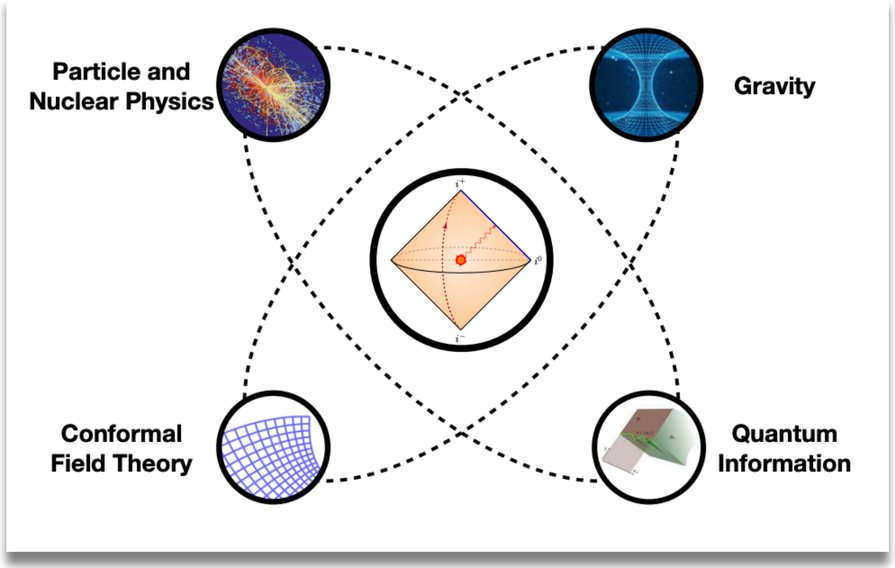
BRINGING IDEAS FROM FORMAL THEORY, PHENOMENOLOGY, AND EXPERIMENTALISTS

UC SANTA BARBARA
Kavli Institute for Theoretical Physics

Energy Correlators: From Theory to Experiment

Coordinators: Kyle Lee, Ian Moult, and David Simmons-Duffin

Feb 1, 2027 - Feb 4, 2027



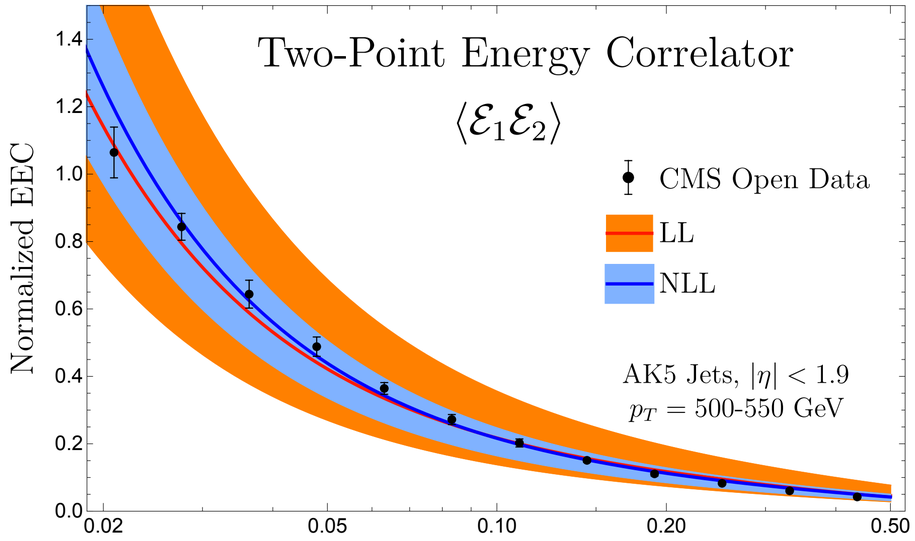
Asymptotic Detectors are fundamental objects of Lorentzian Field Theories!

…***This conference will bring together formal theorists, phenomenologists, and experimentalists to advance the use of energy flow observables across collider physics and formal quantum field theory.***

MACROSCOPIC CONSEQUENCES OF MICROSCOPIC DYNAMICS

Phenomenological Applications

Microscopic dynamics $\Longleftrightarrow$	Macroscopic consequences
$\gamma,\ \alpha_s$	Angular power laws
Confinement	Turnover from partonic scaling
Particle mass M_Q	Characteristic angle
Resonance $M_H,\ M_Z$	Angular peak
Spin interference	Azimuthal modulation
Anomaly	Charge asymmetry
Non-Gaussianities	Shape dependence
Hadronic structure	Nucleon EEC
QGP medium scale	Twist-4 scaling

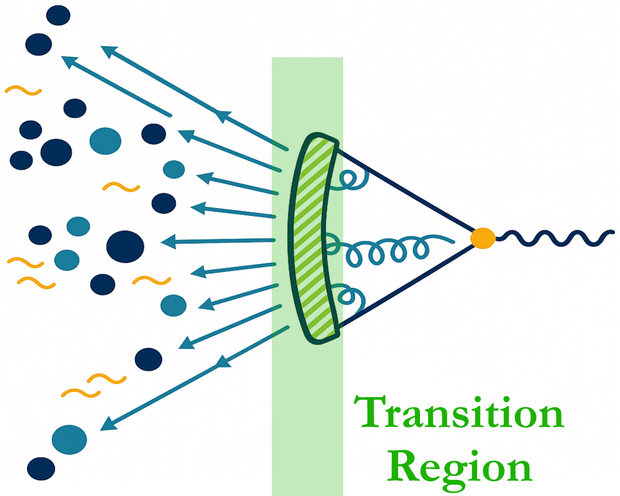


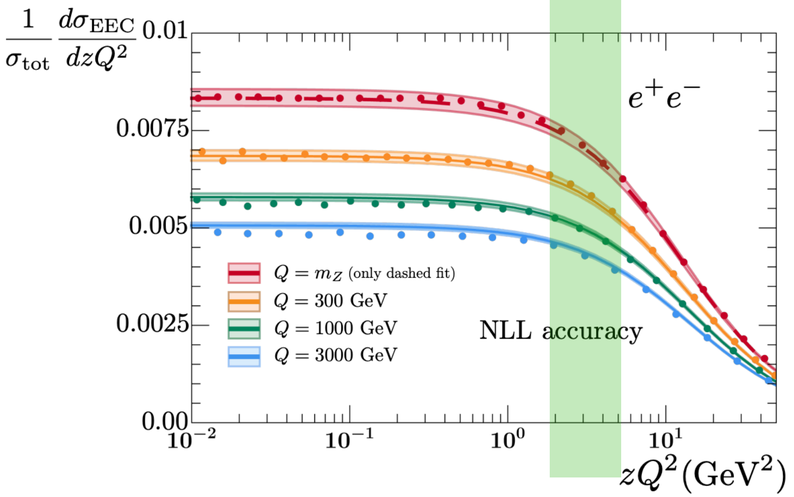
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$$\theta \sim \frac{\Lambda_{\rm QCD}}{p_T}$$

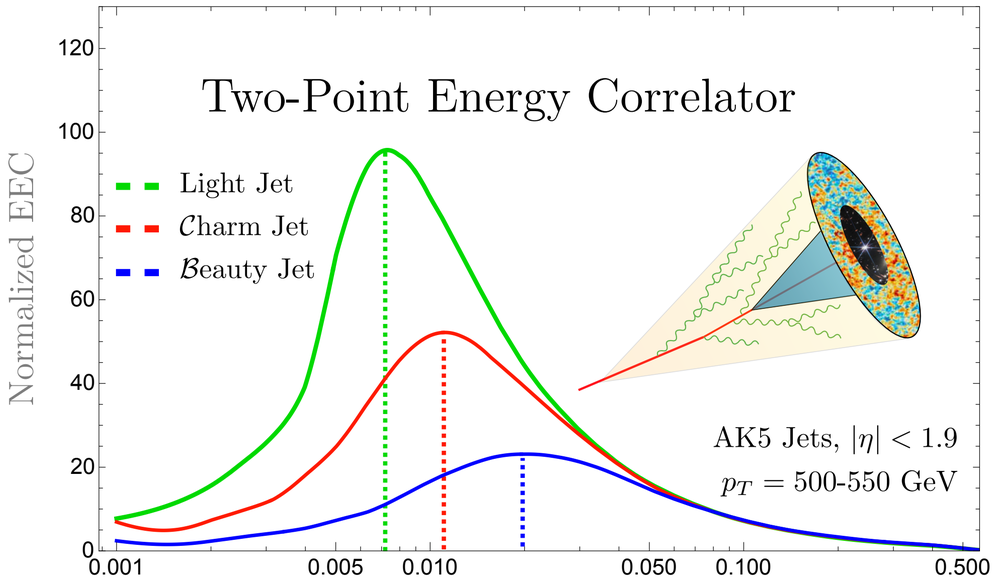




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Phenomenological Applications

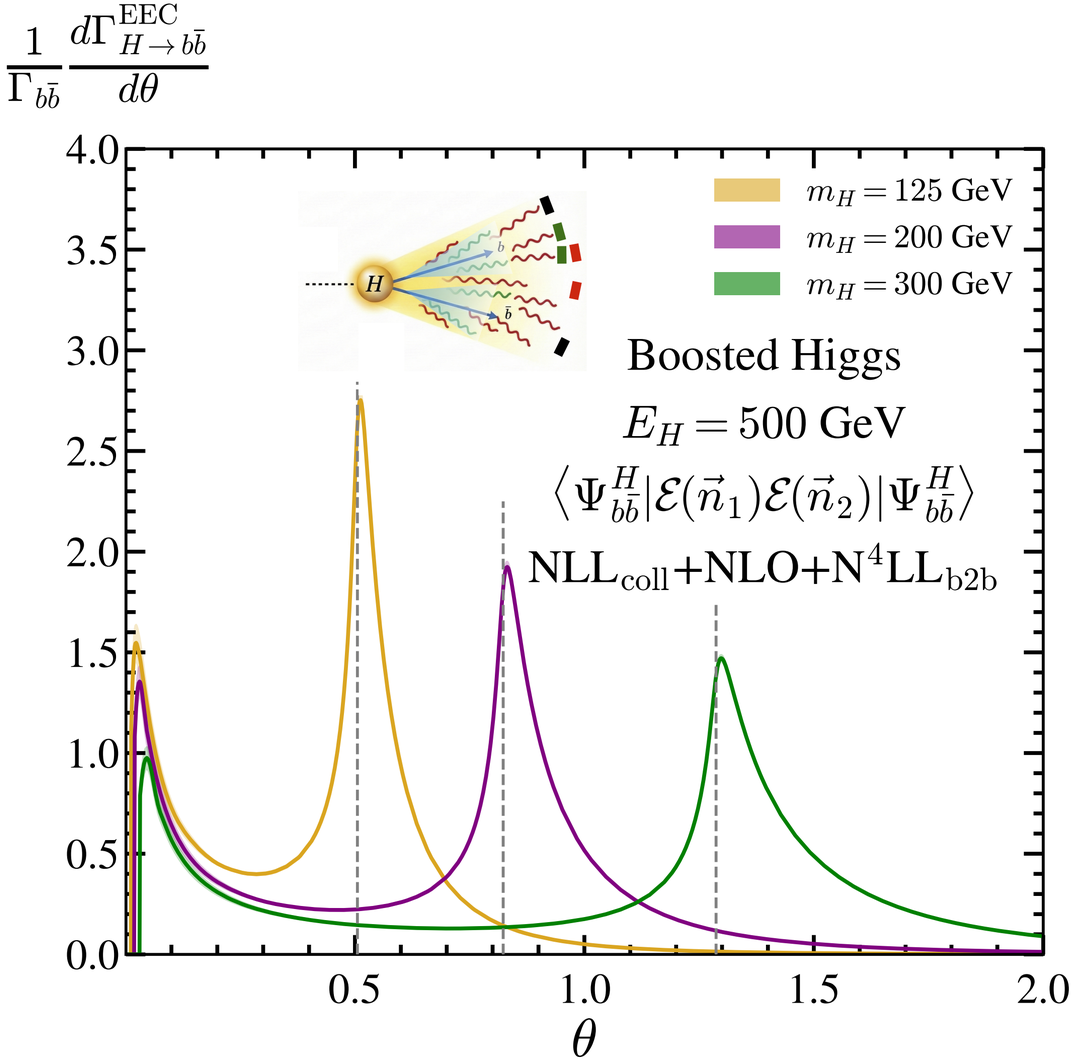
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Phenomenological Applications

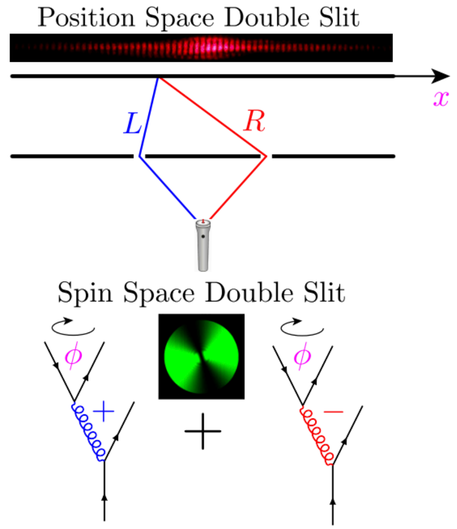
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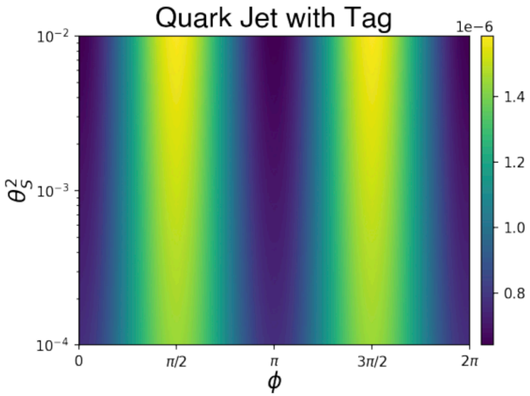


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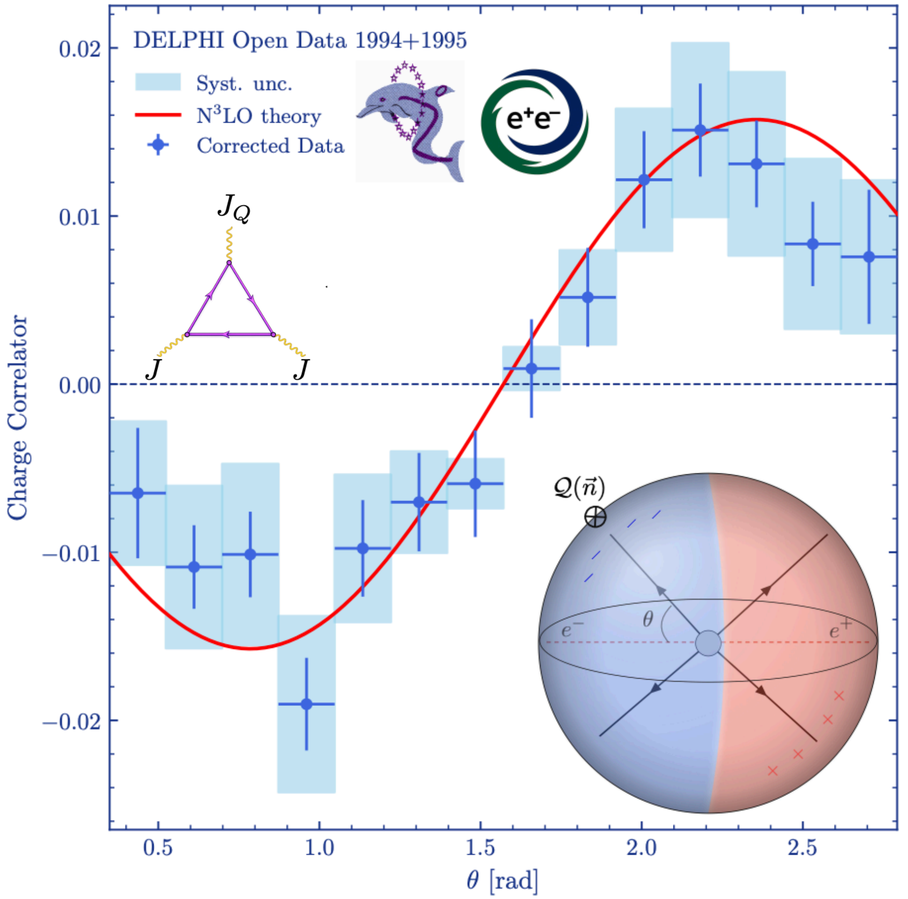




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Phenomenological Applications

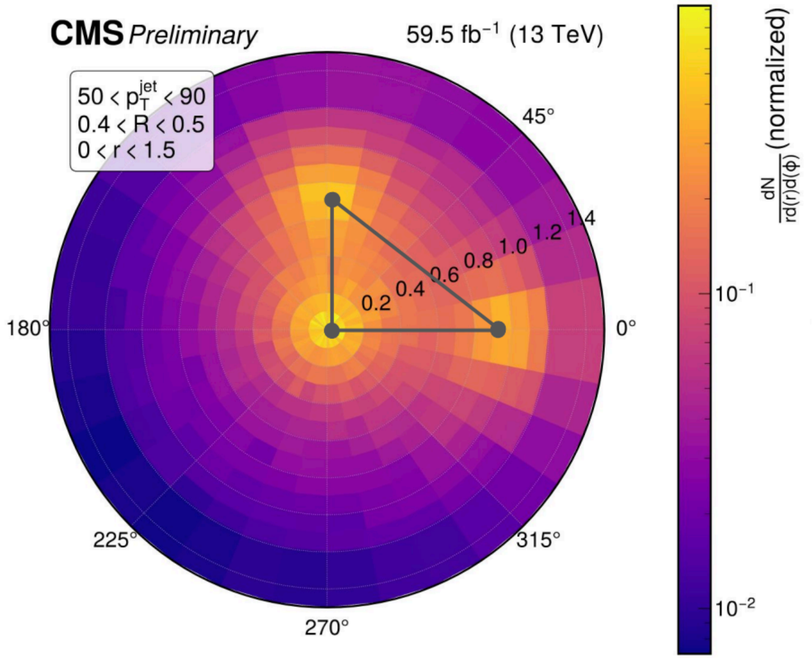
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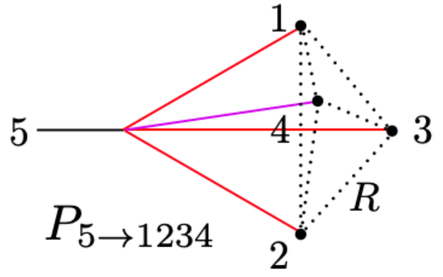


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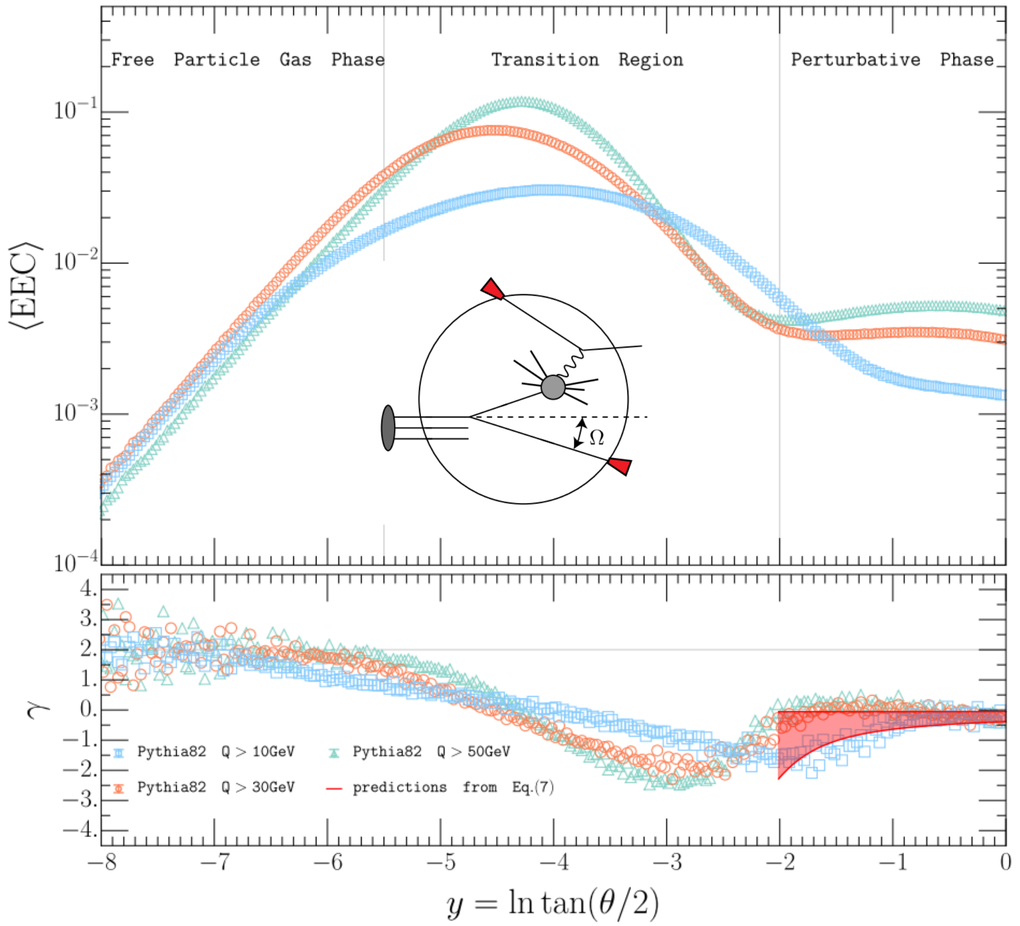




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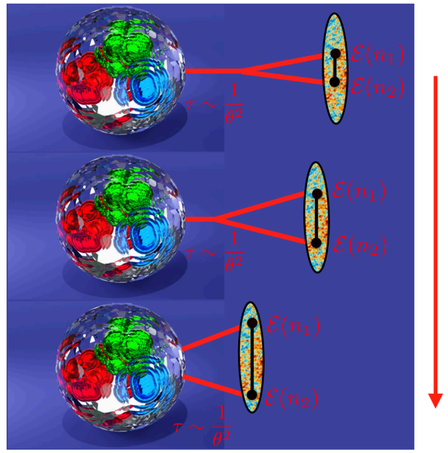
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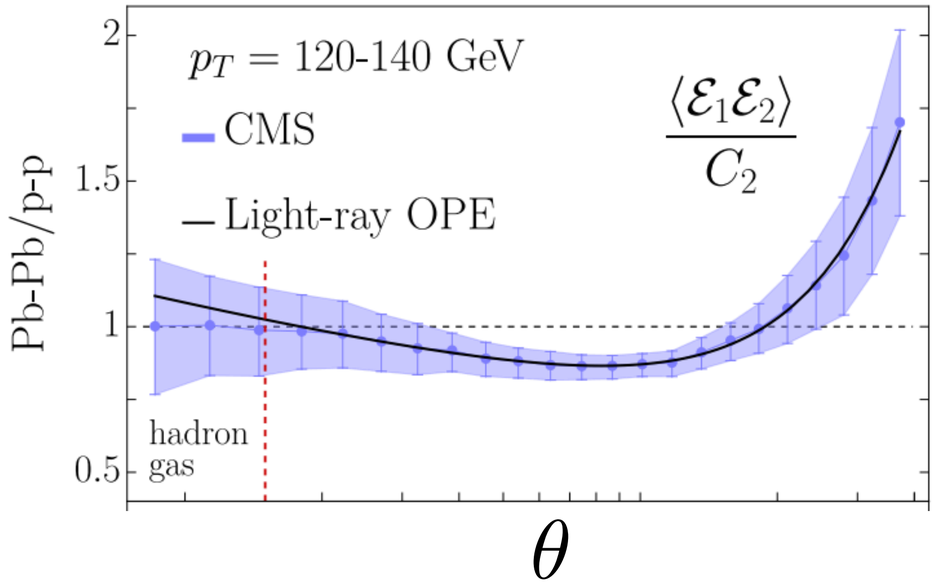


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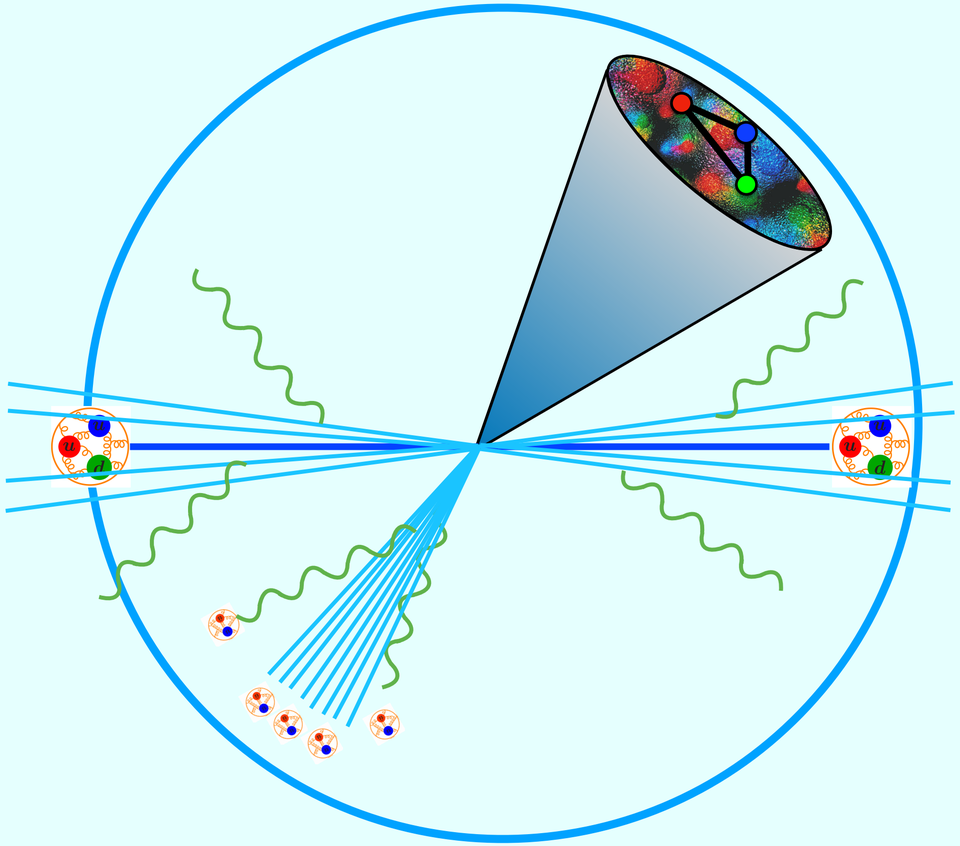
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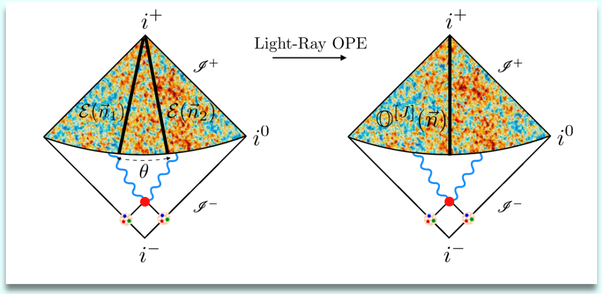


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Universal Scaling
In The Collinear Limit of Detectors

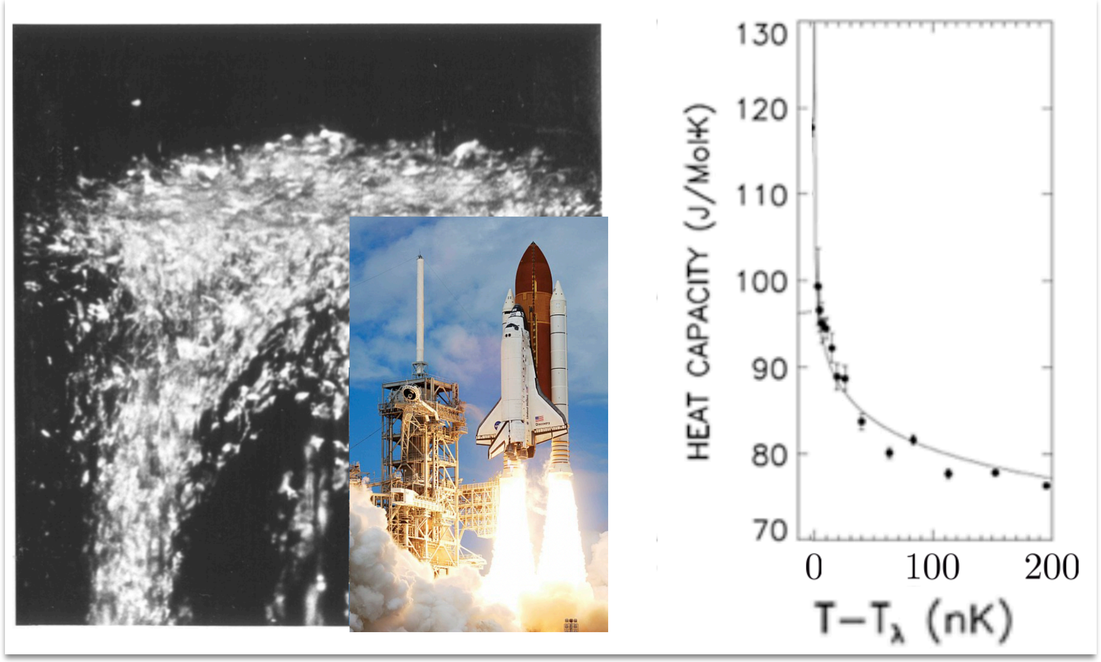


SCALING BEHAVIOR IN QFT

- **Why is the study of jet substructure of interest in QFT?**
- **QFTs display universal scaling behaviors when operators approach one another**



Wilson `70



Euclidean Operator Product Expansion

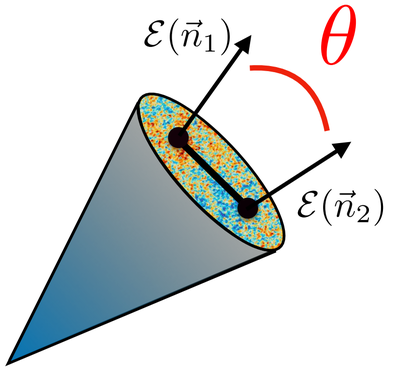
$$\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i$$

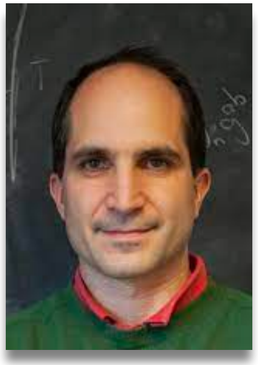
- **Critical phenomena give us access to universal scaling behavior as Euclidean operators are brought together**

UNIVERSAL LORENTZIAN SCALING WITHIN JETS

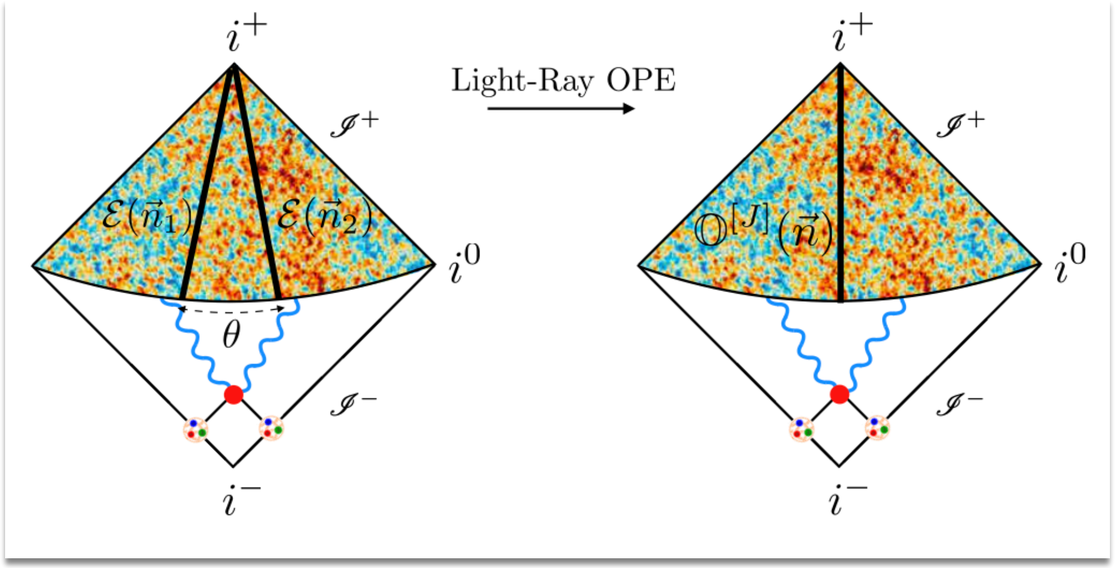
- **Jet substructure describes the limit where energy flow operators are brought together, thus probing the OPE limit of Lorentzian operators**

$\Longrightarrow$ **Profound field theory predictions within jets!**





Hofman, Maldacena `08



Light-ray Operator Product Expansion

$$\mathcal{E}(\hat{n}_1)\,\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\gamma(3)-2}\mathbb{O}_i(\hat{n}_1)$$

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

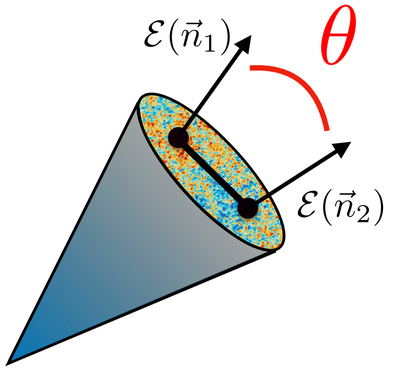
$$\mathcal{E}(\hat{n})|X\rangle = \sum_a E_a \delta^{(2)}\left(\Omega_{\vec{p}_a} - \Omega_{\hat{n}}\right)|X\rangle$$

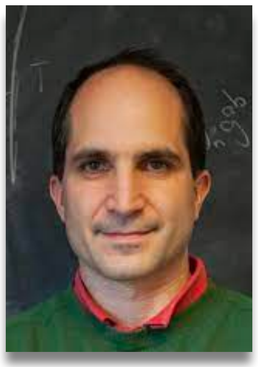
- **Light-ray Operator Product Expansion predicted universal scaling within jets within the context of conformal field theory**

UNIVERSAL LORENTZIAN SCALING WITHIN JETS

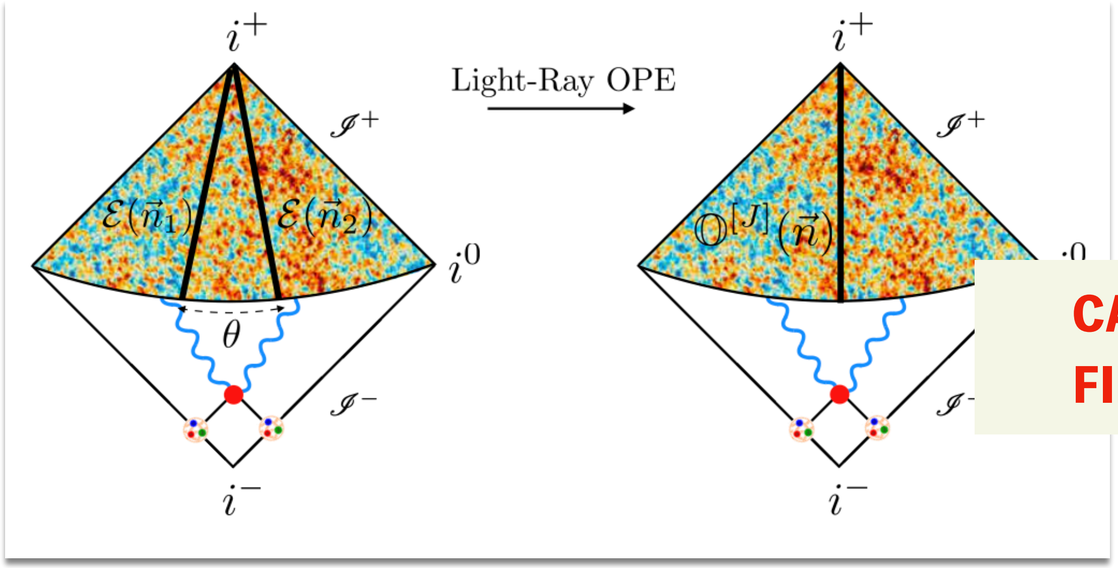
- **Jet substructure describes the limit where energy flow operators are brought together, thus probing the OPE limit of Lorentzian operators**

$\Longrightarrow$ **Profound field theory predictions within jets!**





Hofman, Maldacena `08



Light-ray Operator Product Expansion

$$\mathcal{E}(\hat{n}_1)\,\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\gamma^{(3)}-2}\mathbb{O}_i(\hat{n}_1)$$

CAN THIS UNIVERSAL SCALING OF THE FIELD THEORY BE OBSERVED IN JETS???

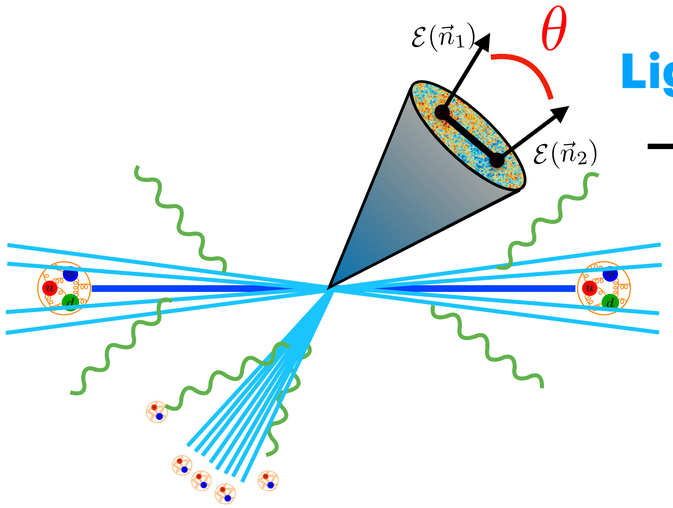
$$\mathcal{E}(\hat{n})|X\rangle = \sum_a E_a \delta^{(2)}(\Omega_{\vec{p}_a} - \Omega_{\hat{n}})\,|X\rangle$$

- **Light-ray Operator Product Expansion predicted universal scaling within jets within the context of conformal field theory**

UNIVERSAL SCALING BEHAVIOR IN JETS!

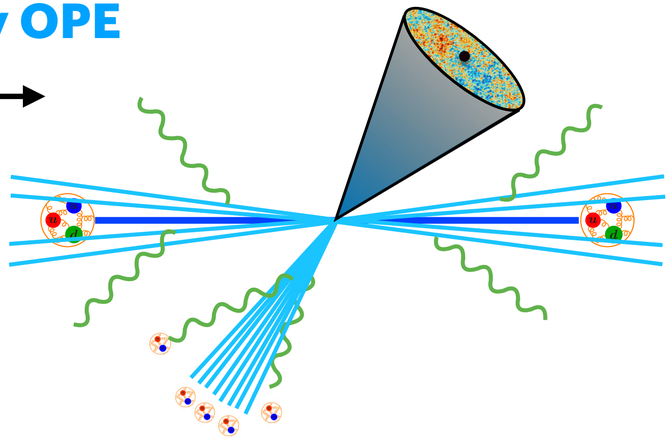
- **In QCD, we developed the proper framework to observe the universal scaling behavior within jets!**

$$\langle\psi|\mathcal{E}(\vec{n}_1)\,\mathcal{E}(\vec{n}_2)|\psi\rangle$$



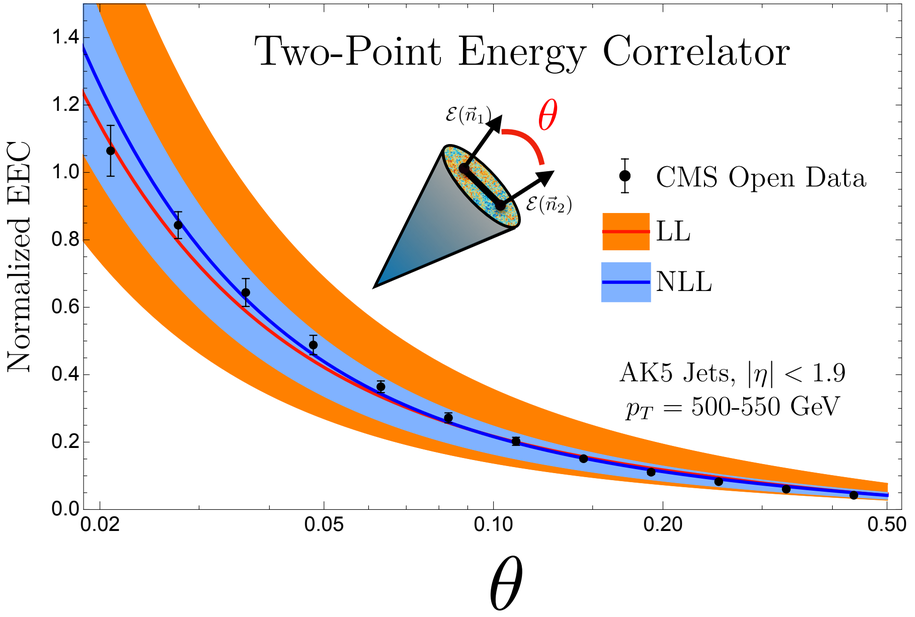
Light-ray OPE

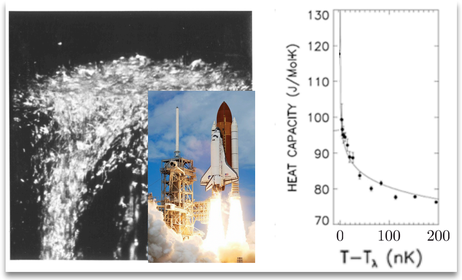
$$\langle\psi|\mathbb{O}^{[3]}(\vec{n})|\psi\rangle$$



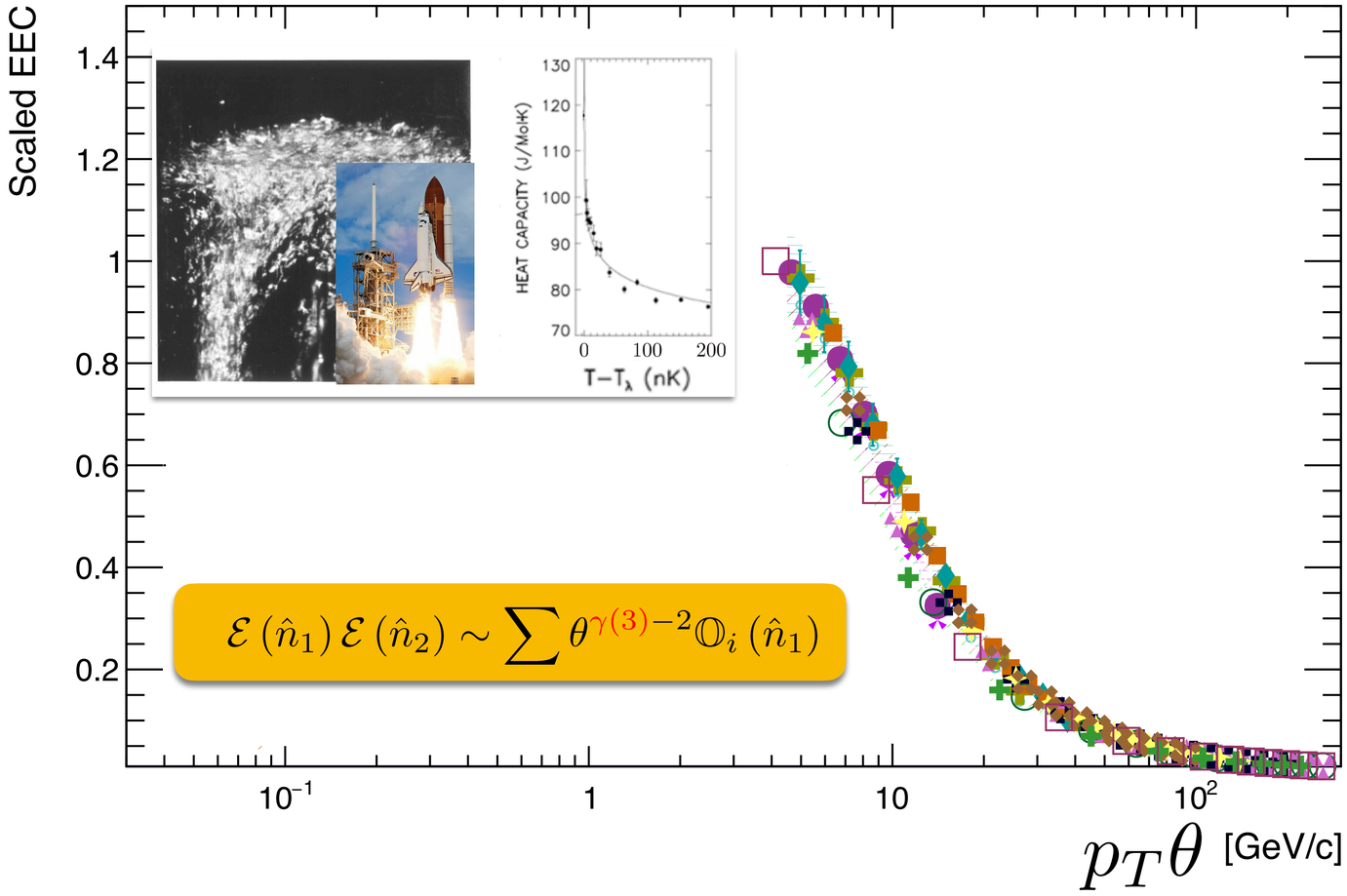
KL, Meçaj, Moult `22
KL, Moult, Zhang `24

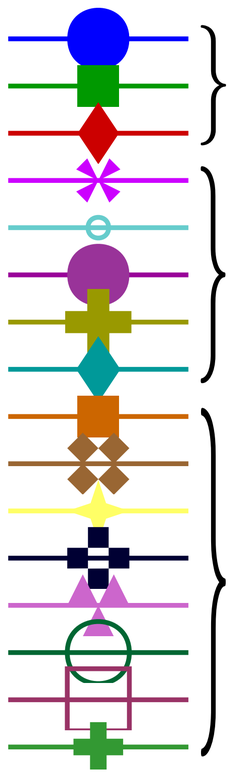
Dixon, Moult, Zhu `19
Chen `23
KL, Stewart `25





SCALING FROM 15 GEV TO 2 TEV IN DATA!





STAR from 15 - 50 GeV

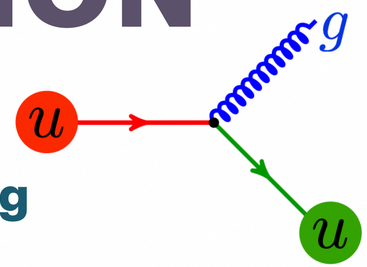
ALICE from 20 - 80 GeV

CMS from 97 - 1784 GeV

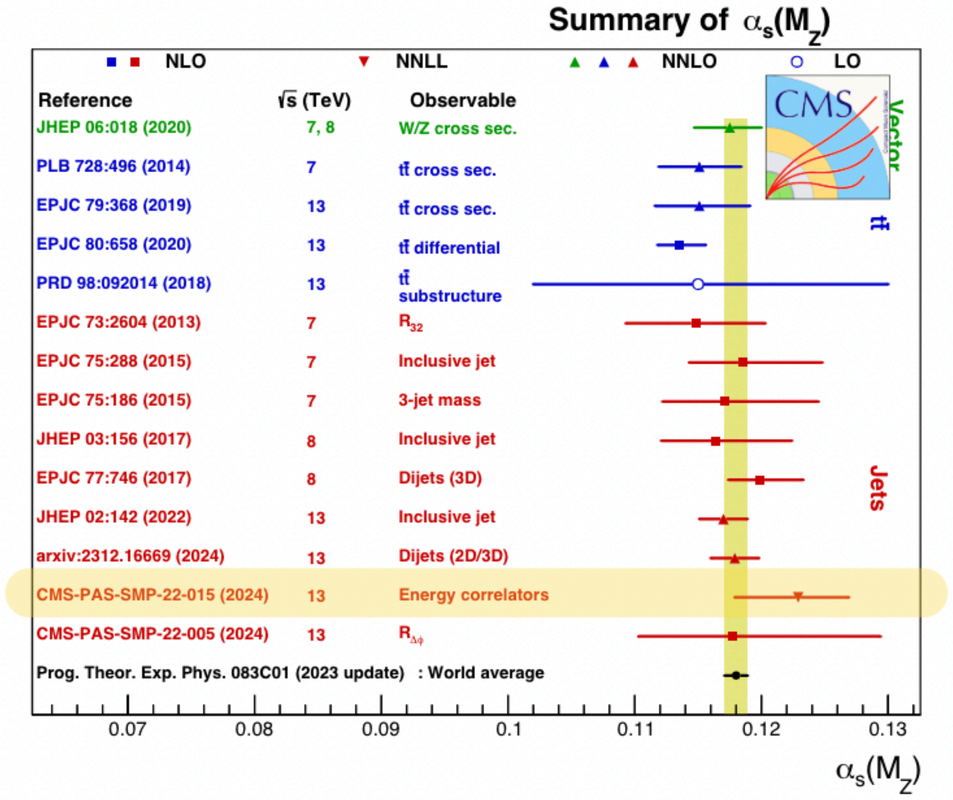
- **Universal scaling of QCD operators revealed in data from STAR, ALICE, and CMS, from 15 GeV to 1784 GeV!**

STRONG COUPLING DETERMINATION

- **How strong is the Strong Force?** In comparison, EM coupling: $\alpha_e = 0.00729735256 93(11)$



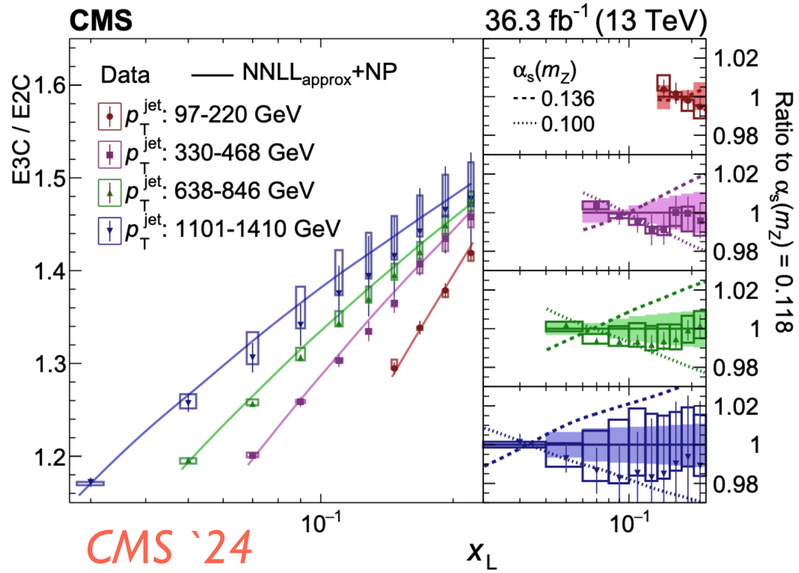
Quarks are never free, and thus it is very hard to measure their coupling



CMS collaboration carried out most precise determination of the strong coupling constant for jet substructure

$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050} \Longrightarrow$$ 4% uncertainty

Energy Correlators in Jet



QCD FACTORIZATION FRAMEWORK OF JET SUBSTRUCTURE

$$\frac{d\sigma}{dp_T d\eta\, d\theta_L} = \sum_{i,j,k,l} f_{i/P} \otimes f_{j/P} \otimes H_{ij}^{k} \otimes \mathcal{J}_{kl} \otimes \left[J_l \otimes T \right] + \text{fixed order}$$

PDFs — Parton Hard Scattering — Jet Production — Substructure Measurement — FFs

KL, Moult, Zhang `24

See also Kang, Ringer, Vitev `16

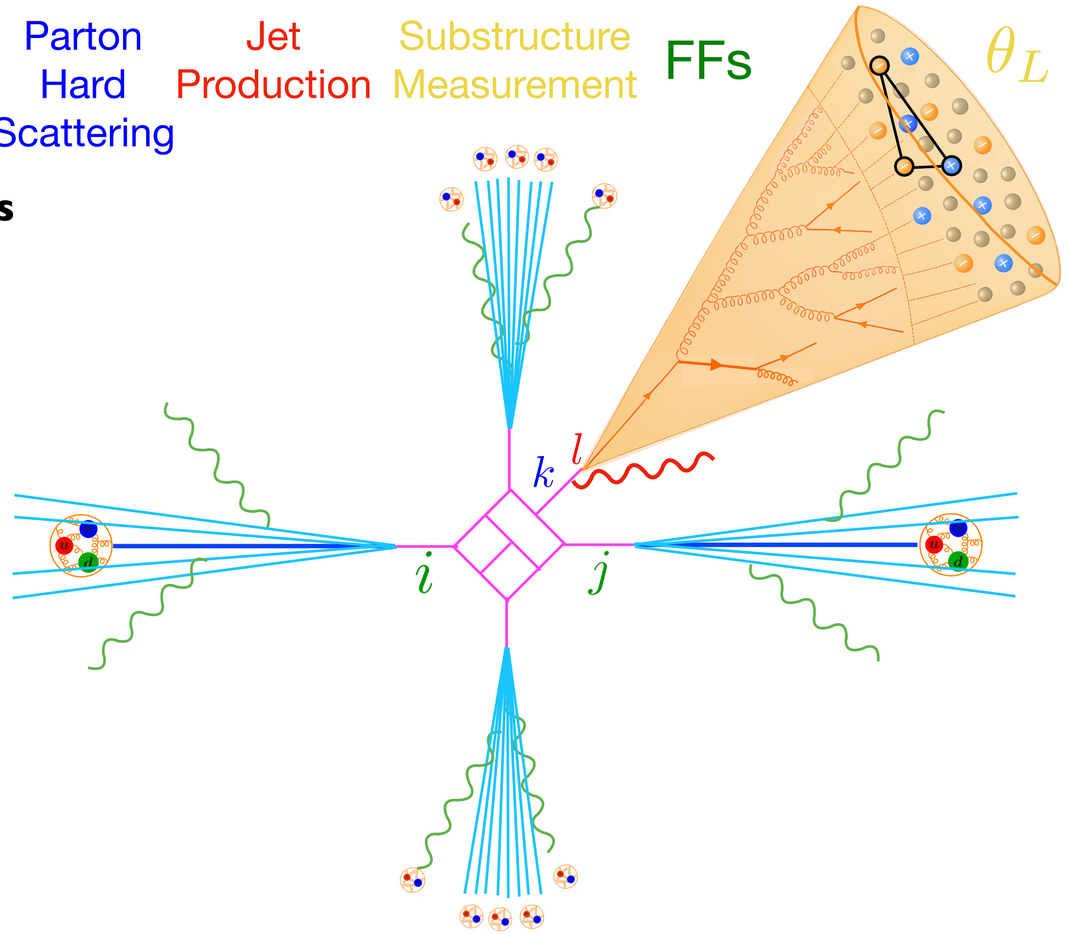
Energy scales

Hard Scale $p_T \sim 500\,\text{GeV}$

Jet Scale $p_T R \sim 100\,\text{GeV}$

Substructure Scale $p_T \theta \sim 30\,\text{GeV}$

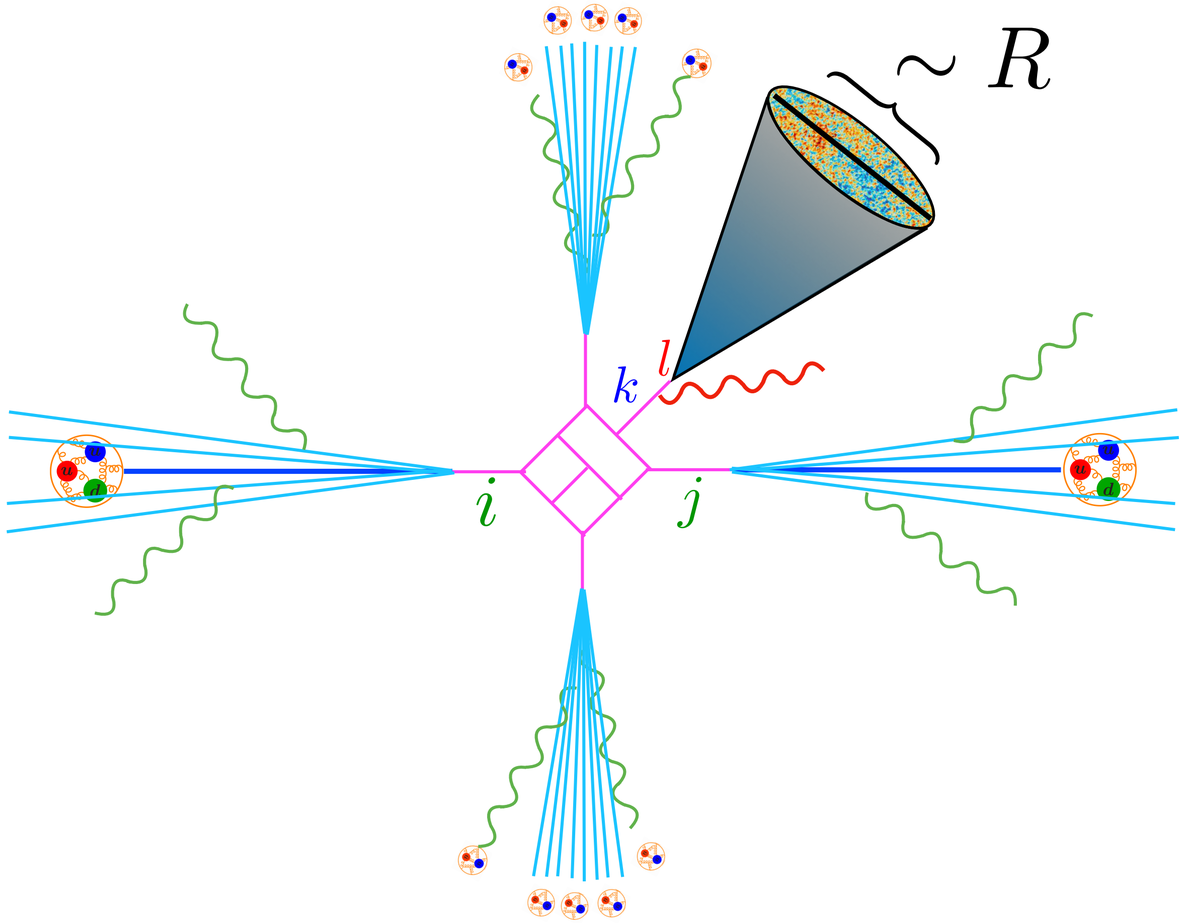
Nonperturbative Scale $\Lambda_{\text{QCD}} \sim 1\,\text{GeV}$

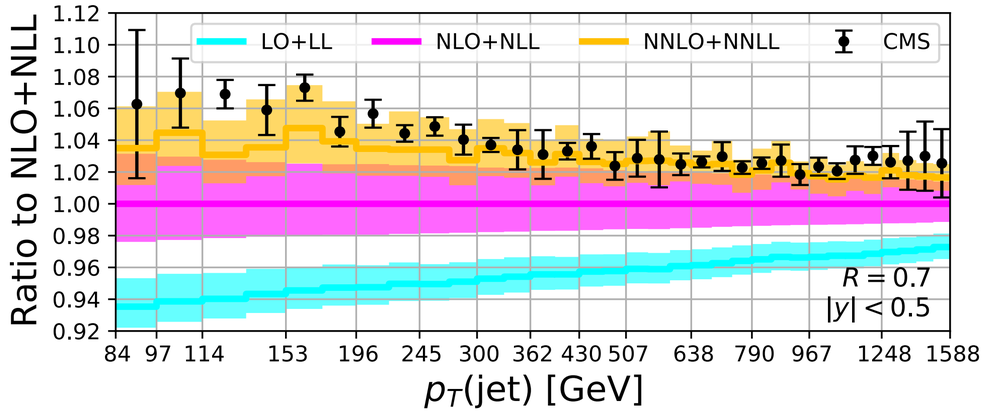


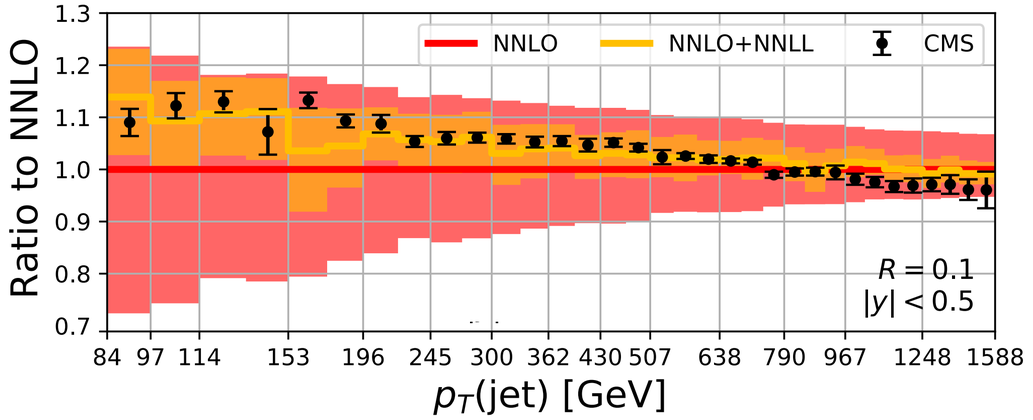
- **Precision understanding of this scaling requires QCD factorization of multiple scales present in jet processes**

JET PRODUCTION AT THE LHC

Hard ⊗ Jet + FO



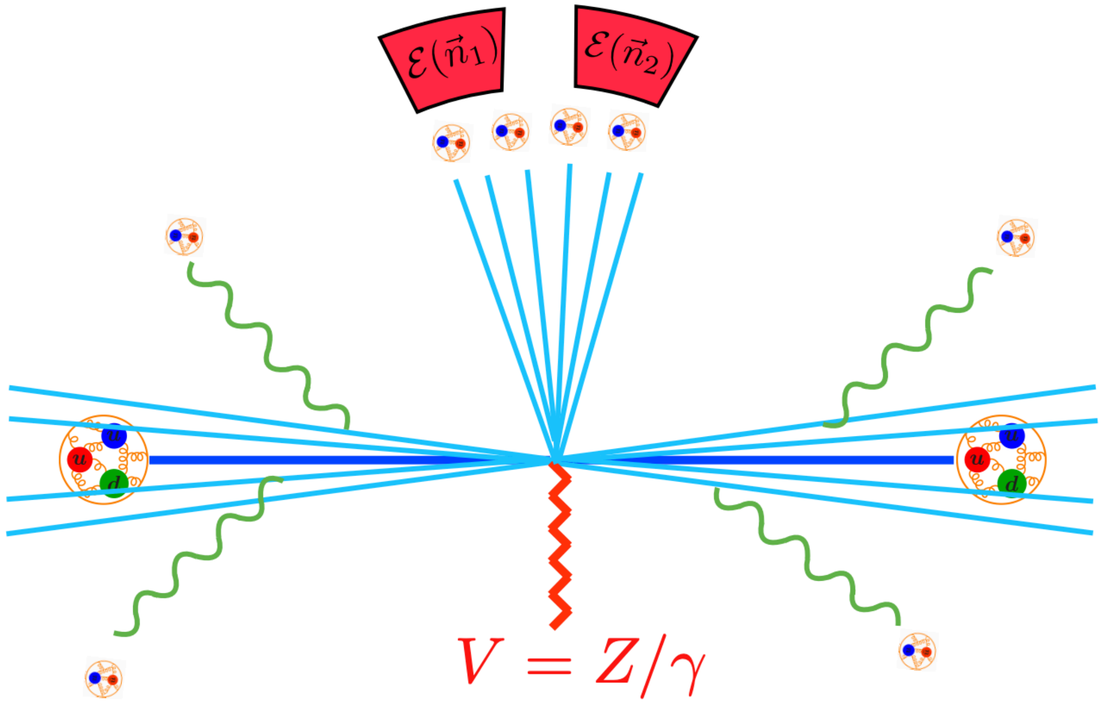




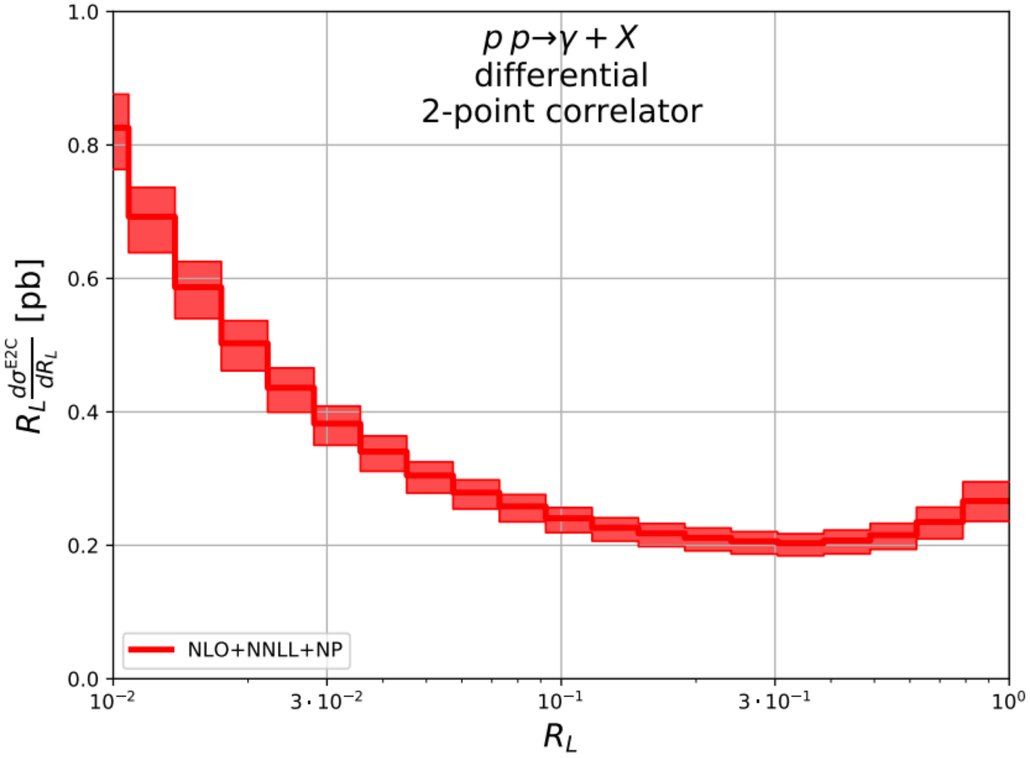
Generet, KL, Moult, Poncelet, Zhang `25

Combining the **hard function** with **jet function**, we describe the **jet production at the LHC** at **NNLO + NNLL**

MEASUREMENT ON RECOIL OF BOSON PRODUCTION

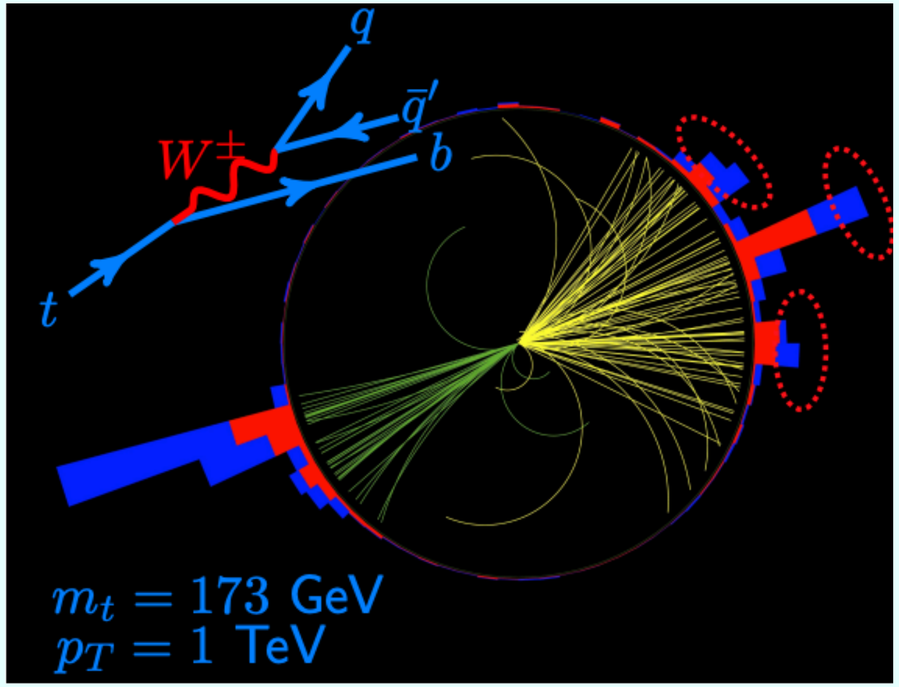






Generet, KL, Moult, Poncelet, Zhang `26

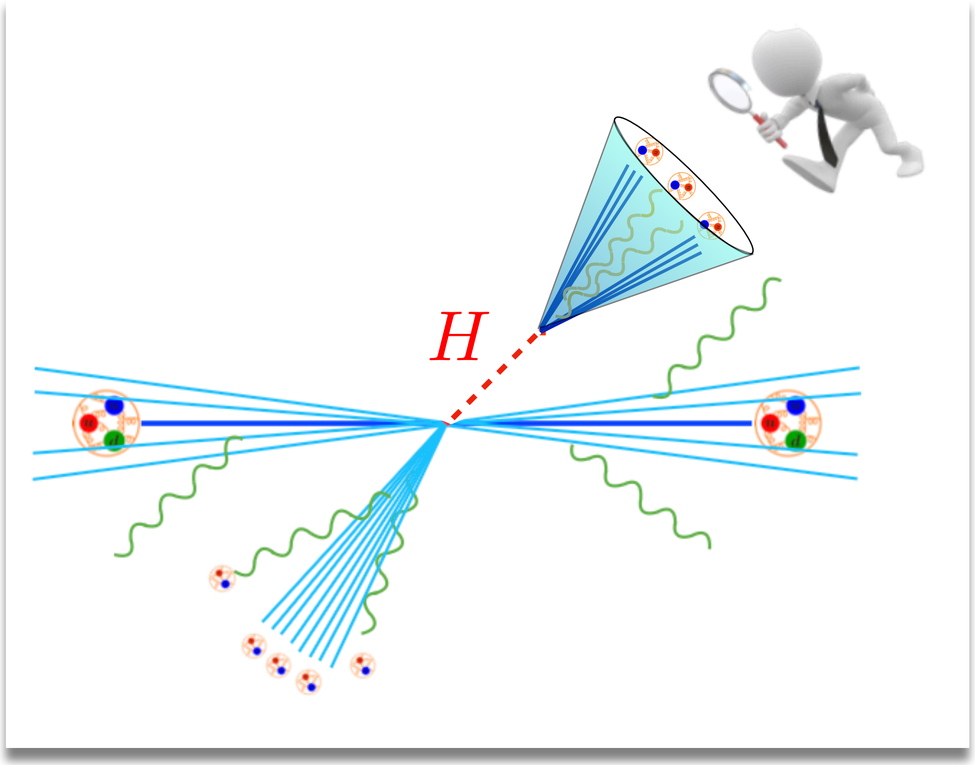
Measurement of EEC on hadronic recoils of Higgs production may give sensitivity to Yukawa!

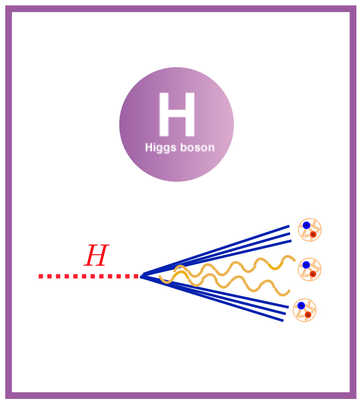


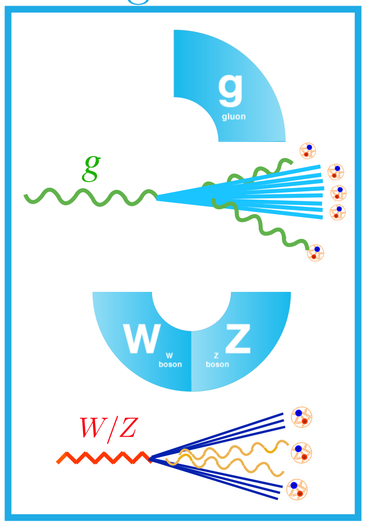
Probing Boosted Structure

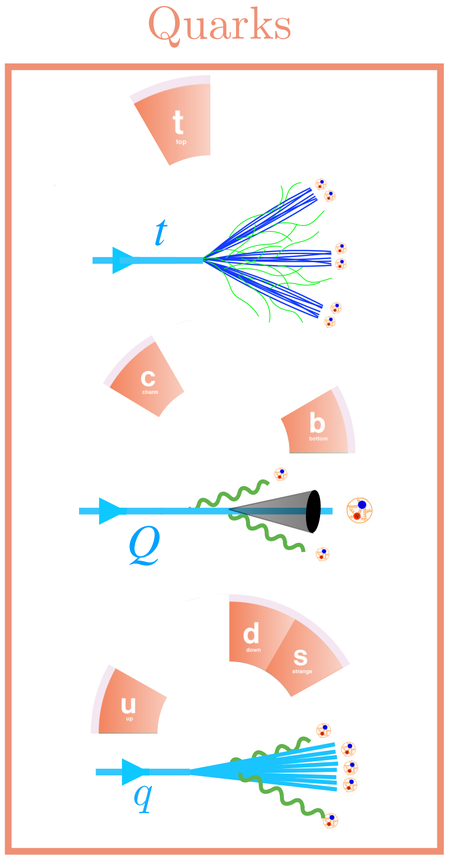
JET SUBSTRUCTURE: STUDYING ENERGY FLOW INSIDE JETS

- Beyond massless QCD jets, highly energetic colliders (the LHC and proposed future colliders) produce boosted H/W/Z bosons and top quarks whose multi-body decays appear as jets.





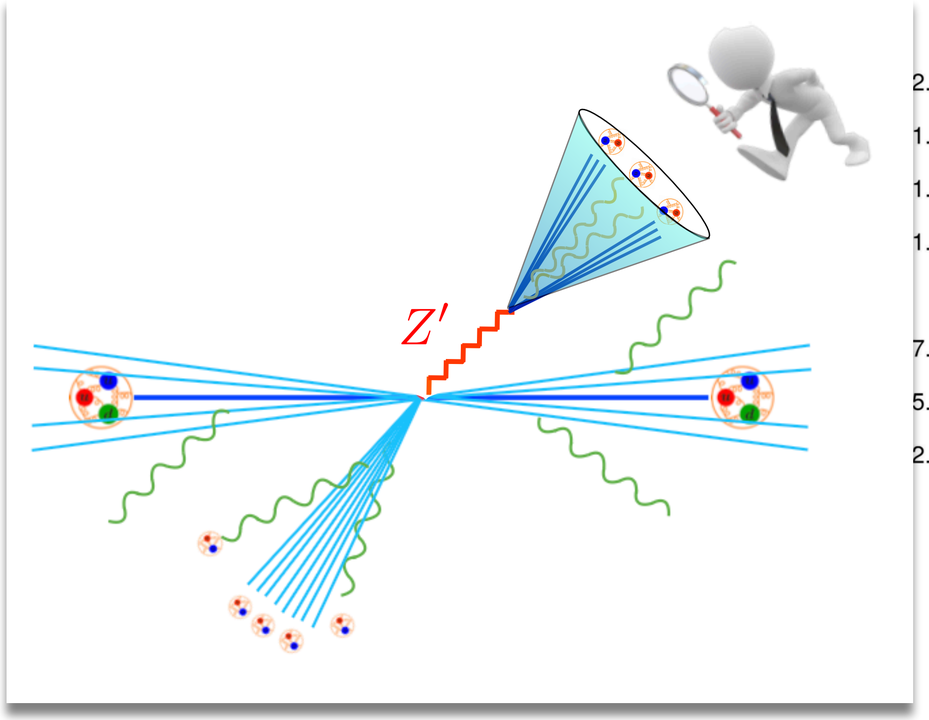


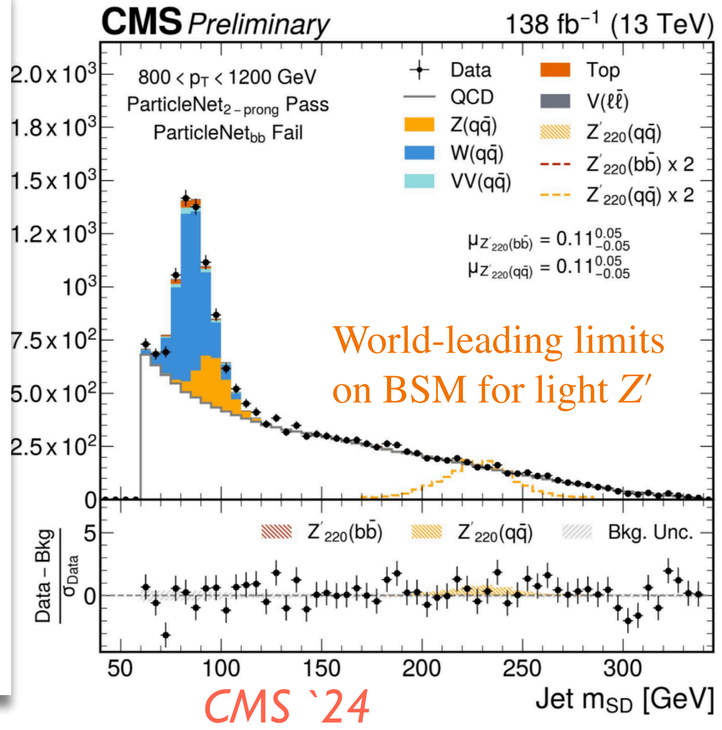


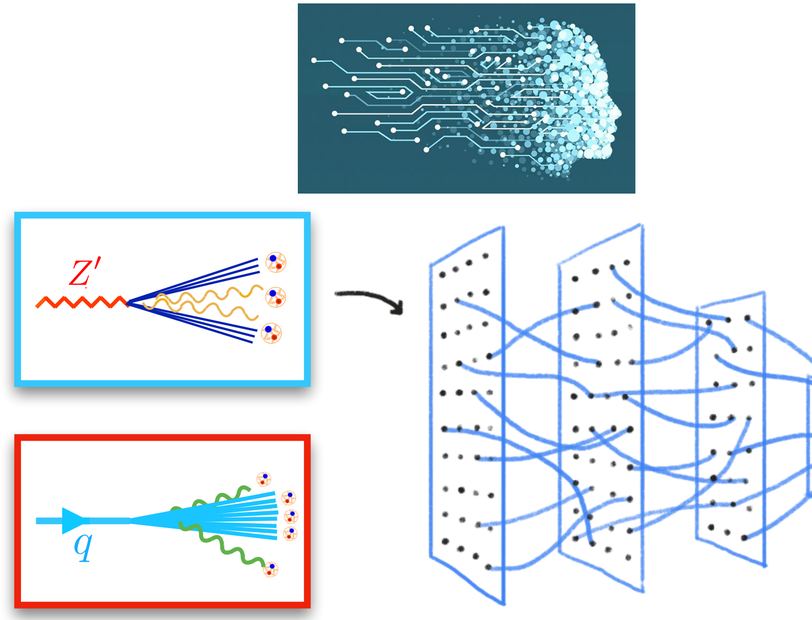
- Since its introduction in 2008 by Butterworth, Davison, Rubin, and Salam for Higgs reconstruction, jet substructure has provided a novel way to probe the vast LHC jet data by analyzing energy patterns within jets.

JET SUBSTRUCTURE: STUDYING ENERGY FLOW INSIDE JETS

- This has had a tremendous impact on carrying out new physics searches and the need to study energy flux in QCD.



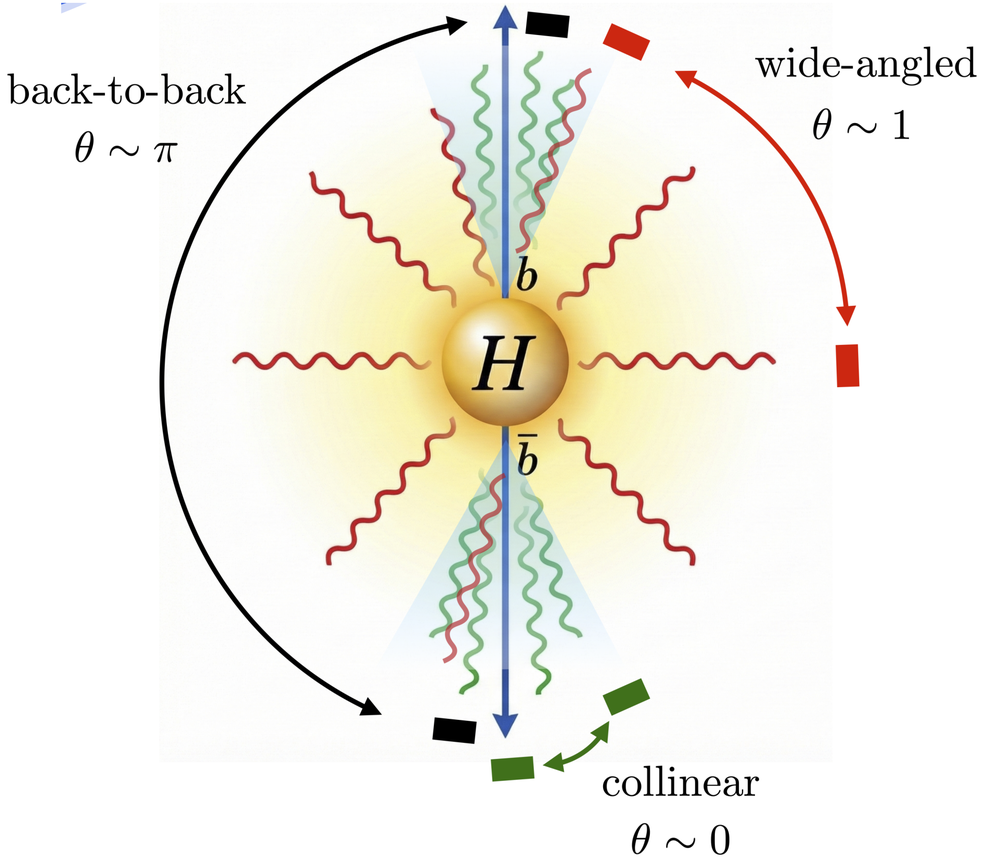




- Therefore, important Standard Model and BSM questions are also encoded in the energy flow inside jets. This motivates a dedicated, precision theoretical program and tools to decode the energy flow inside jets.

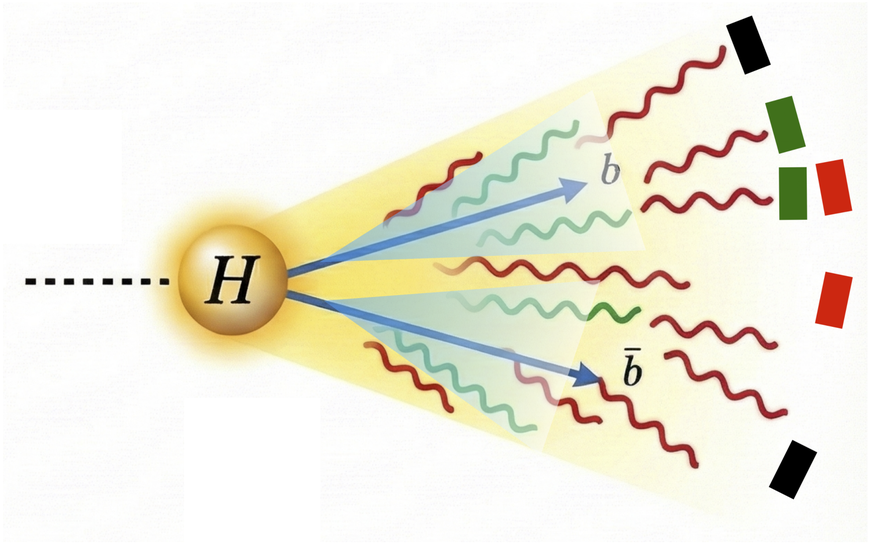
new theory insight needed!

BOOSTED HIGGS JETS



Large Boost

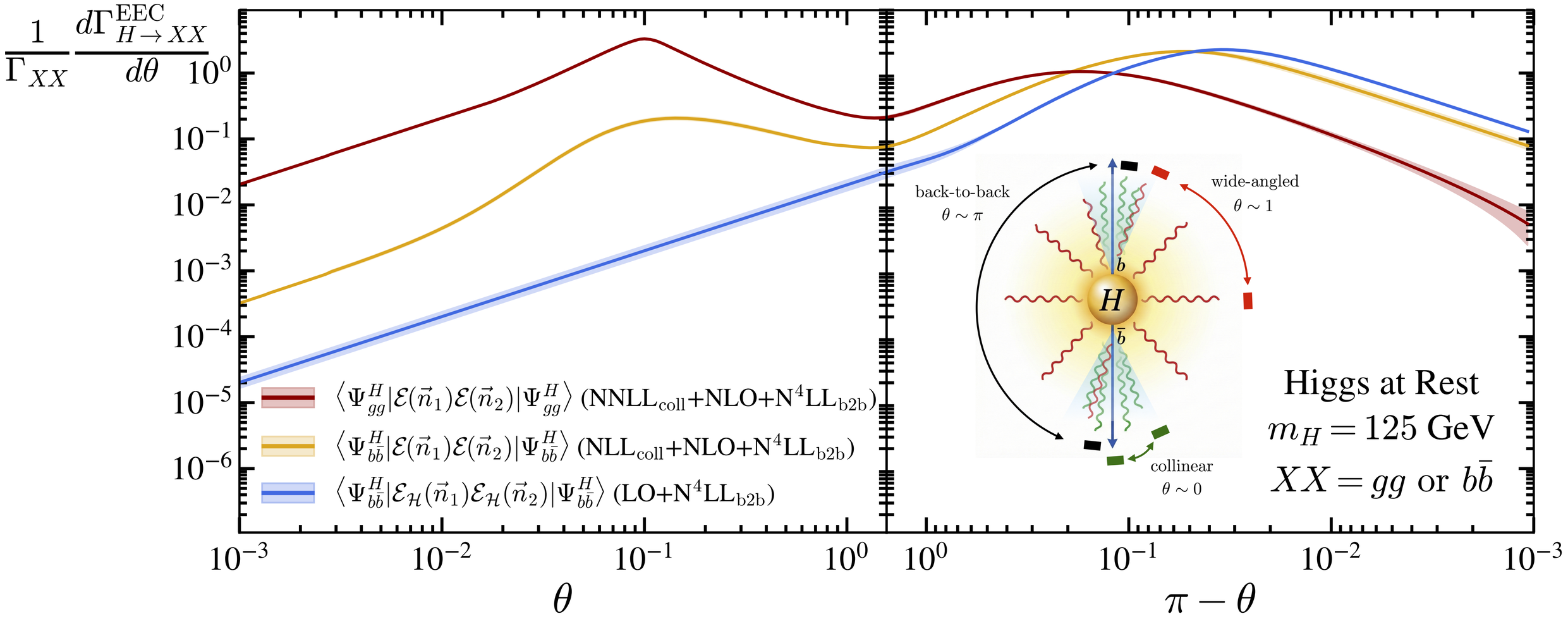
$E \gg m_H$



- Can we understand the structure of the Higgs decay in the boosted Higgs jets?

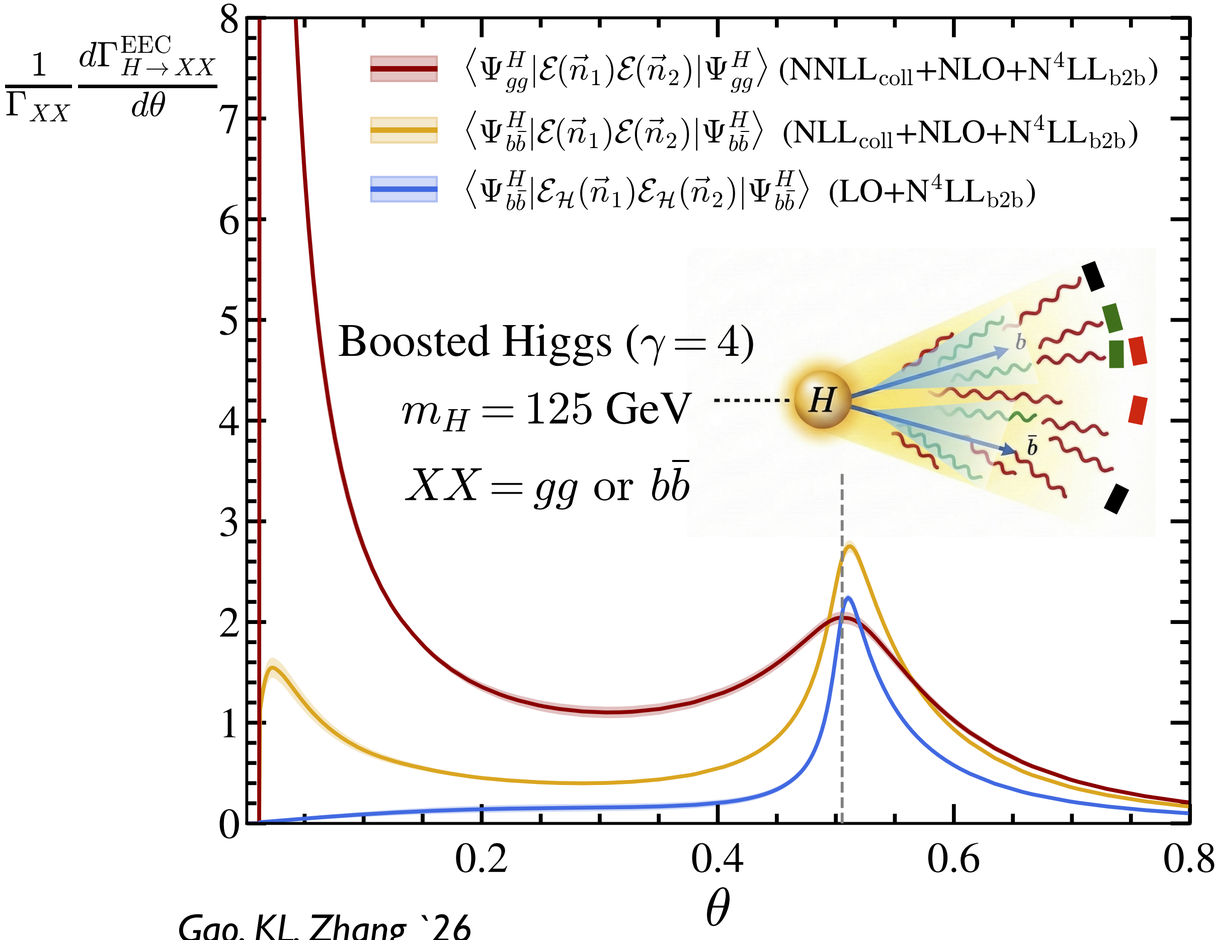
HIGGS AT REST

Gao, KL, Zhang `26
See also Holguin, Moult, Pathak, Procura, Sule `26

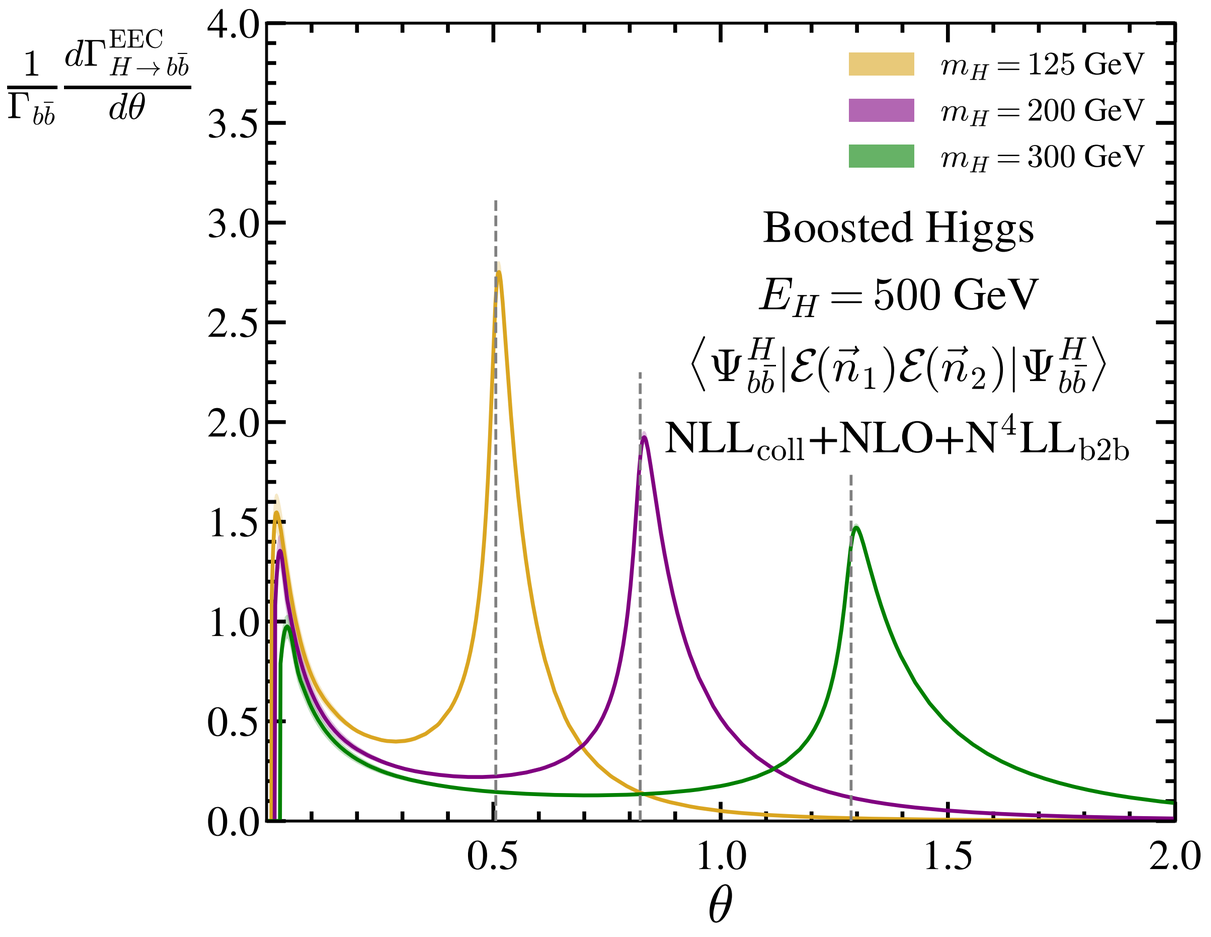


- Using "heavy flavor detector" vs "inclusive energy detector" clearly discriminates back-to-back region vs collinear emissions within b-jets.

BOOSTED HIGGS JETS

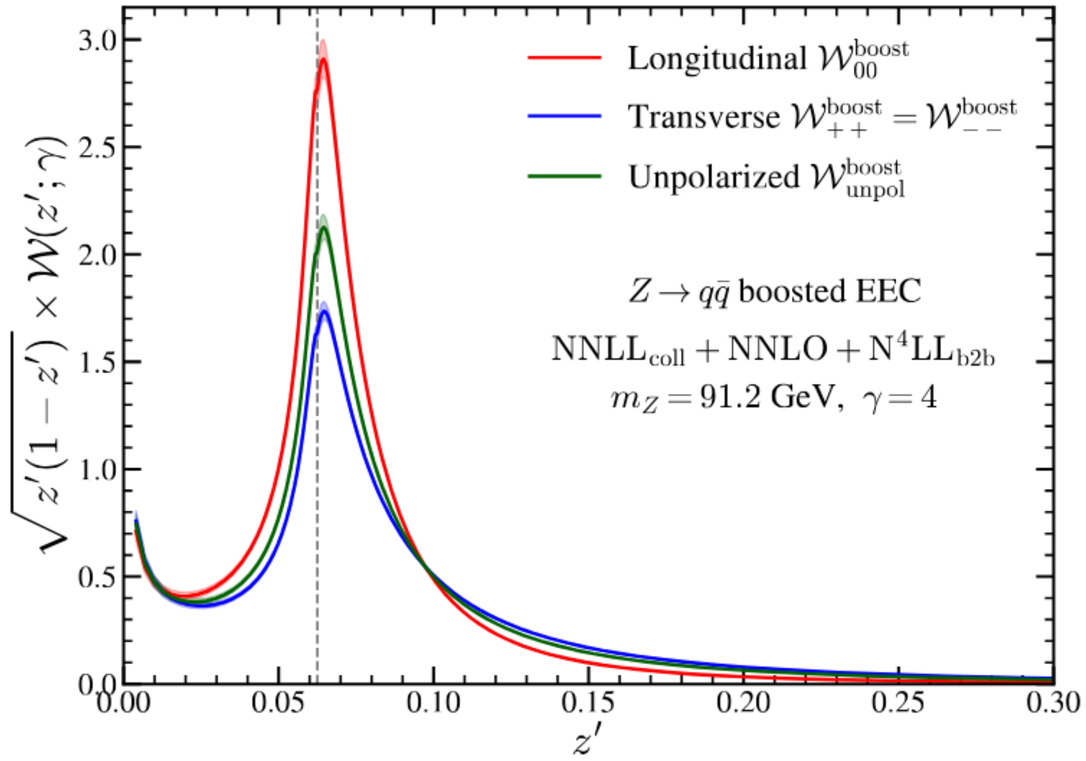


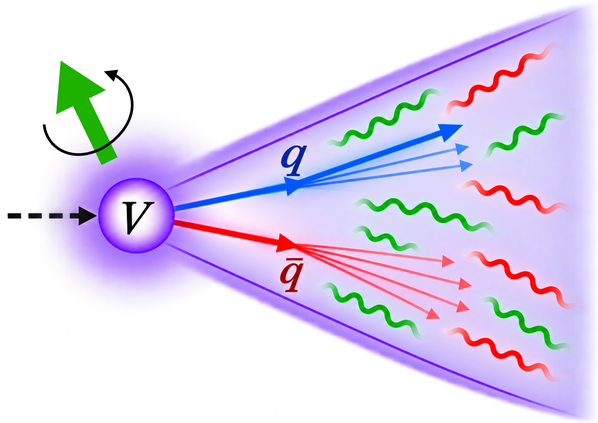
Gao, KL, Zhang `26



- The peak structure associated with the boost factor allows resolving of the scalar mass scale!

BOOSTED VECTOR BOSON





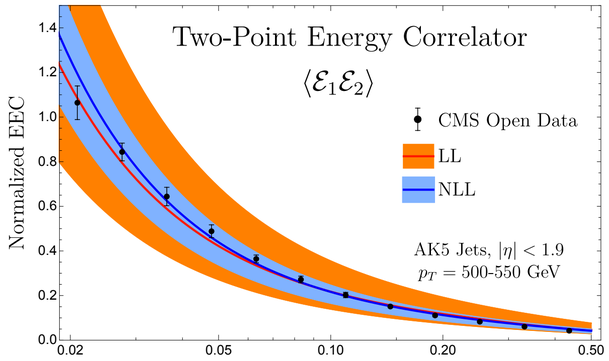
Gao, KL, Zhang `26

- Vector bosons have polarization that one needs to account for. It is also produced a lot more than Higgs!

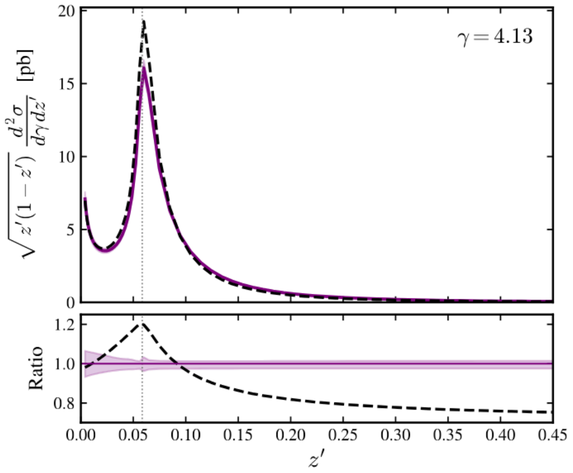
BOOSTED VECTOR BOSON

QCD jets

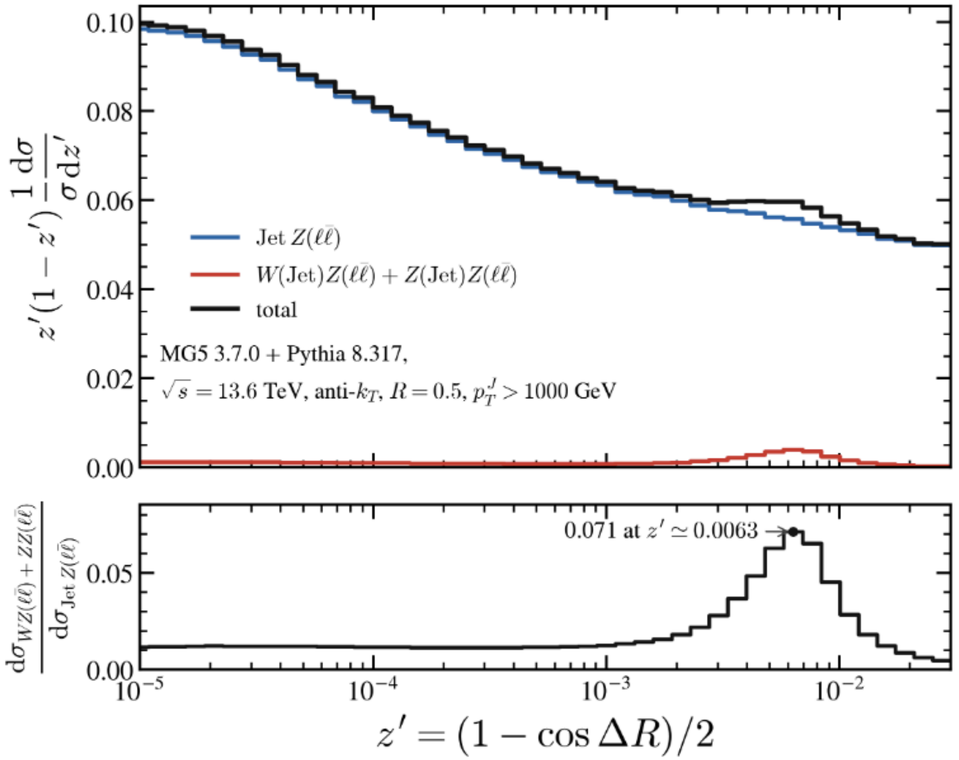
Boosted vector boson jets



+



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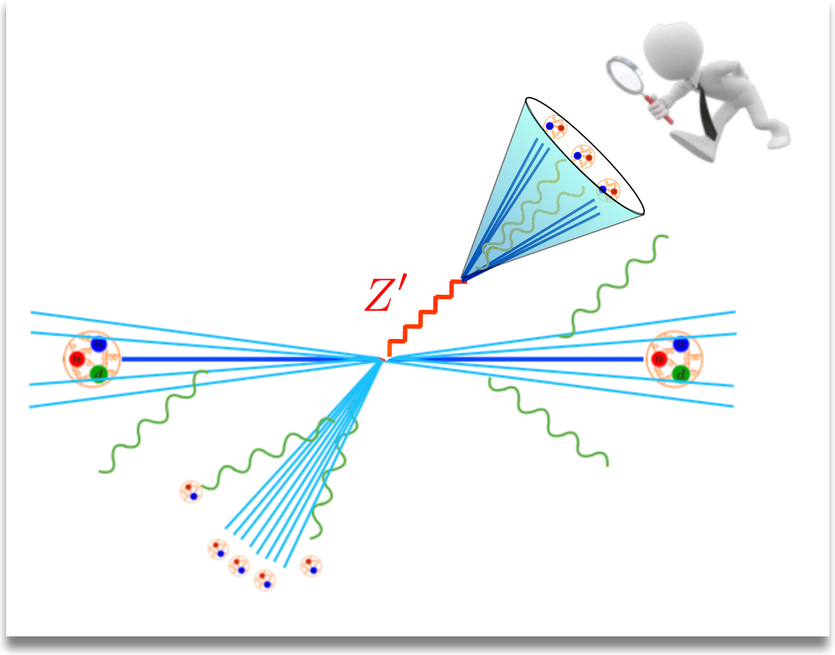


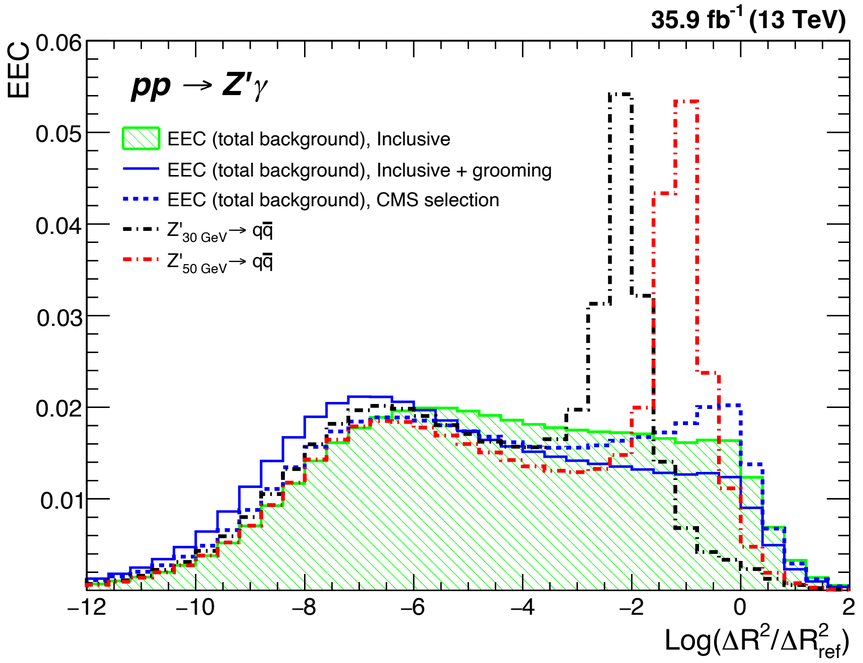
W/Z bump on QCD jets

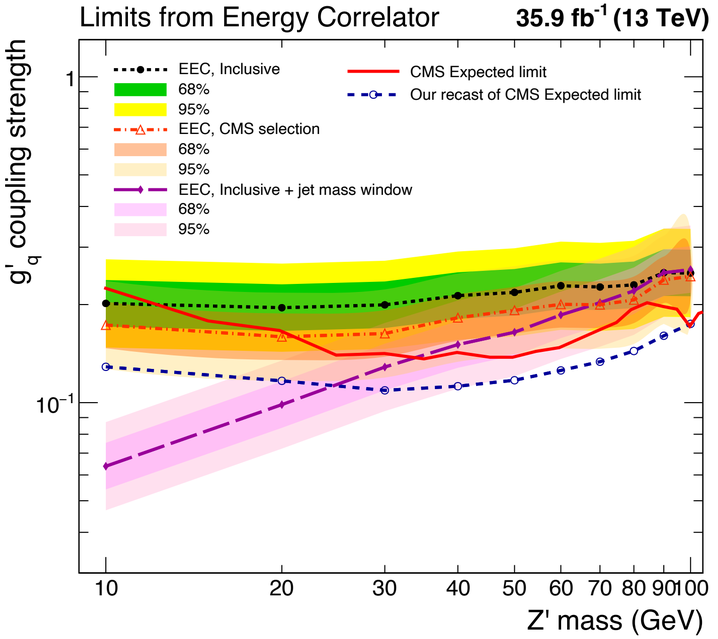
Gao, KL, Zhang `26

- Even without any tagging or cuts, one can literally see the imprint of boosted boson jets as a bump on the clean QCD background

LIGHT Z' RESONANCES

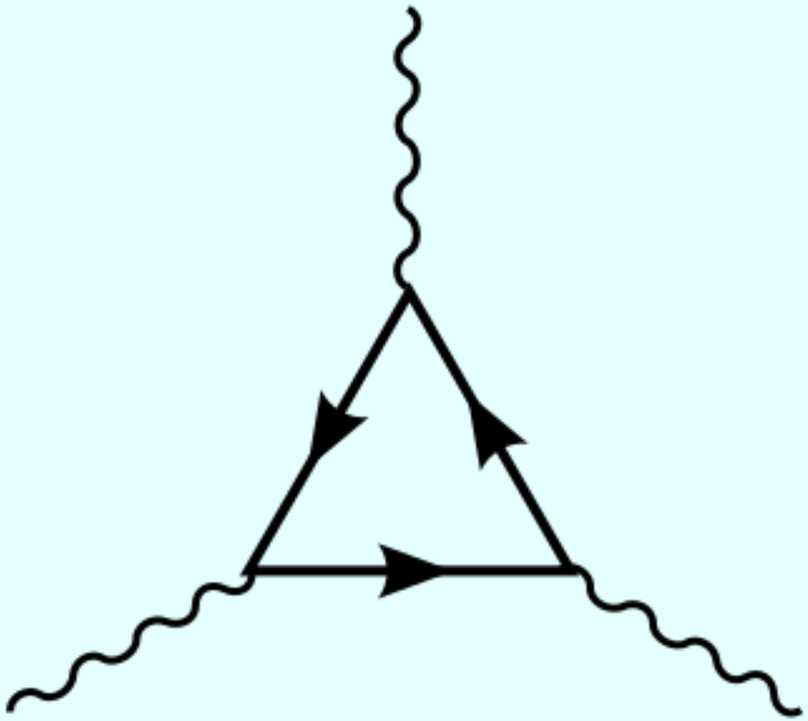






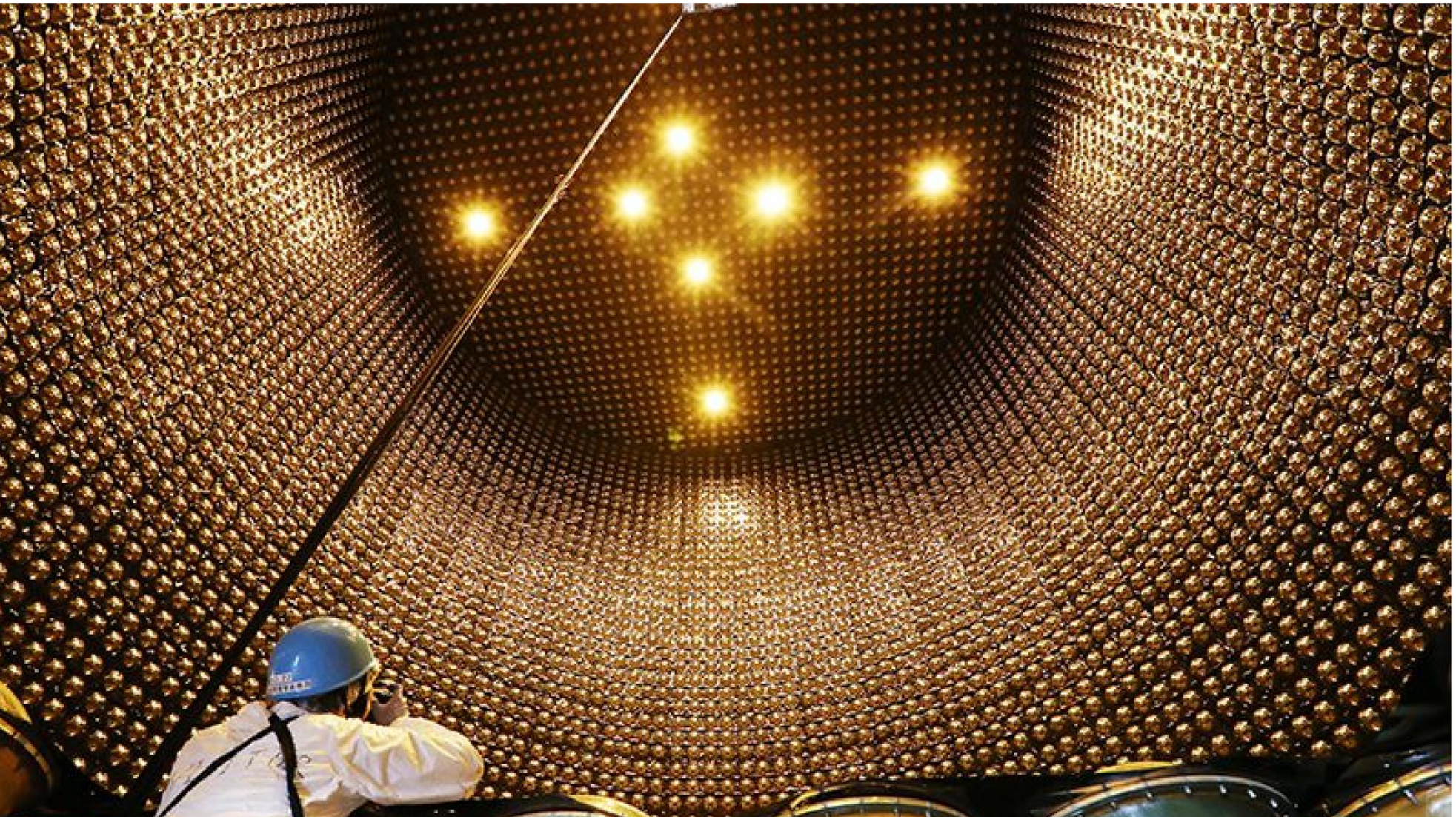
Ricci, Riembau, Son `26

New physics light Z' resonances that hadronically decay will appear as a signal in the EEC scaling region



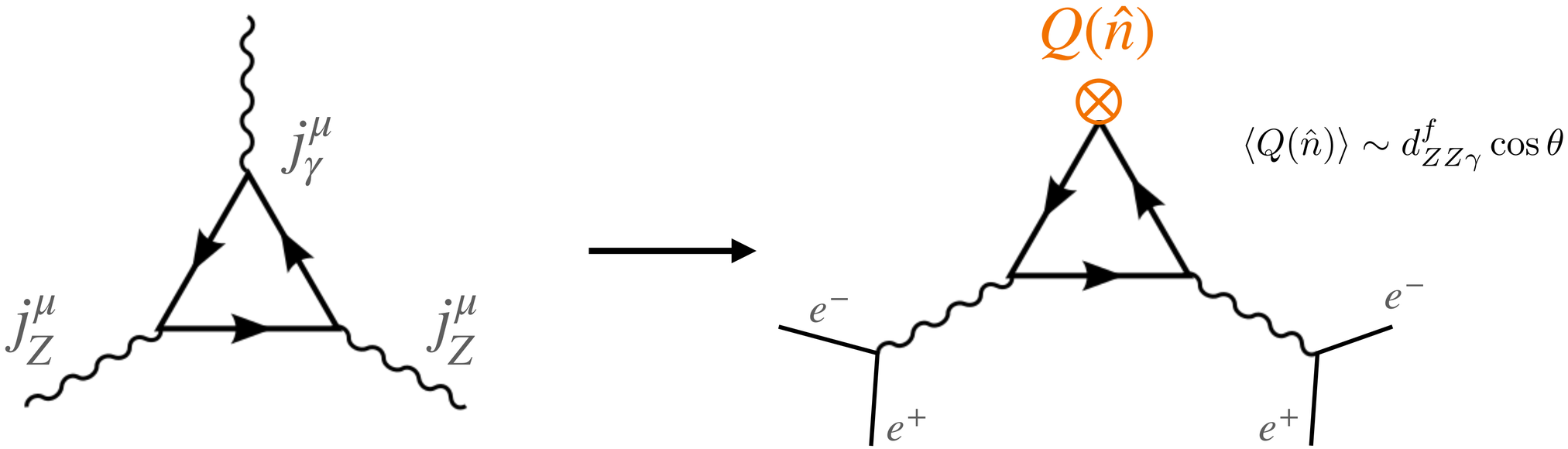
Probing SM anomaly

BARYON/LEPTON NUMBER DETECTORS



Super-Kamiokande searching for a proton decay

MIXED ANOMALY BETWEEN BARYON NUMBER AND ELECTROWEAK



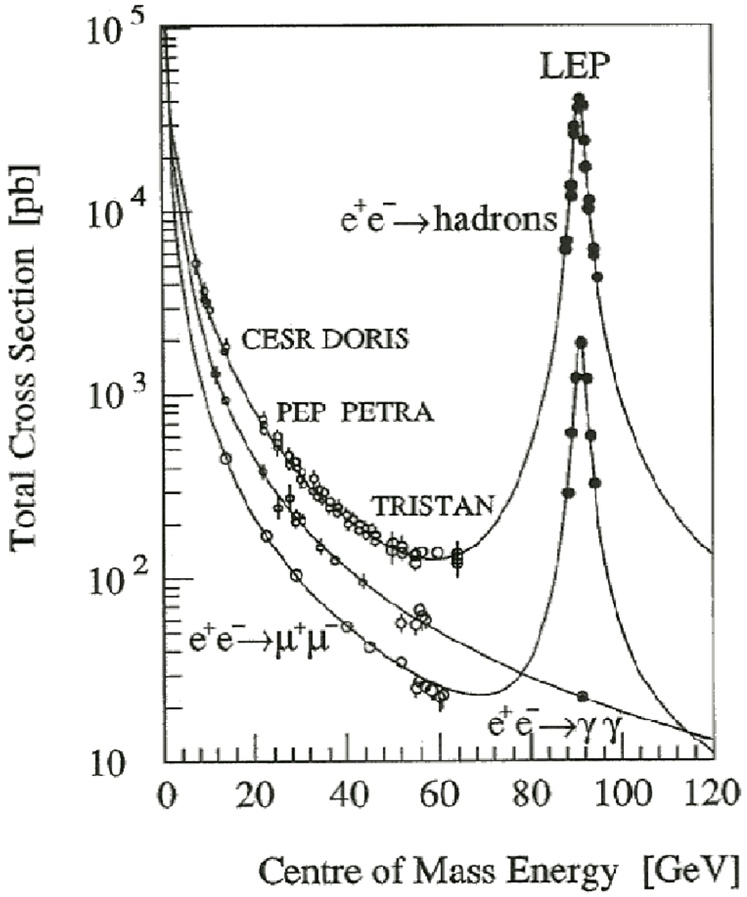
Baryon / lepton number current has mixed anomalies with the electroweak sector

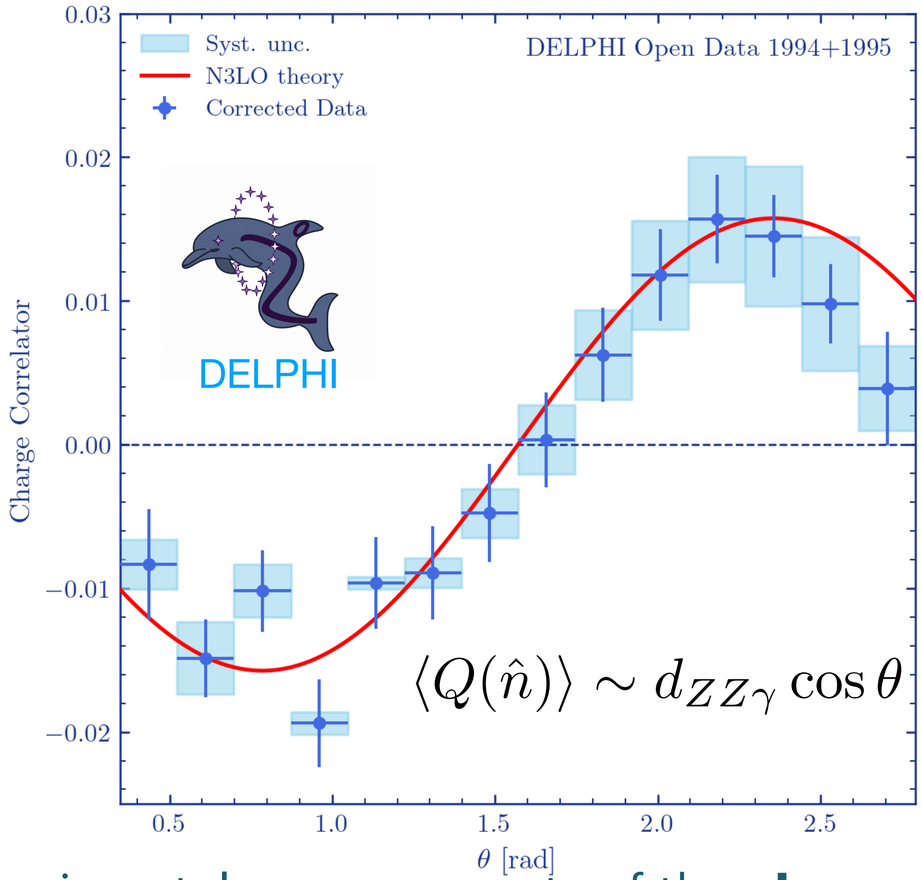
$$\partial_\mu J_B^\mu \sim d_{BT_3T_3} W^3_{\mu\nu}\widetilde{W}^{3\mu\nu} + d_{BYY} B_{\mu\nu}\widetilde{B}^{\mu\nu} + \ldots$$

e^+e^- collisions provide access to direct probe of baryon-number 1-point function with Z currents as backgrounds.

$$\sim \epsilon^*_\mu \epsilon_\nu \langle j_Z^\mu \mathcal{B}(\vec{n}) j_Z^\nu \rangle \sim \cos\theta \left[\cos\theta_W^4 d_{BT_3^2} + \sin\theta_W^4 d_{BY^2}\right]$$

MIXED ANOMALY BETWEEN BARYON NUMBER AND ELECTROWEAK

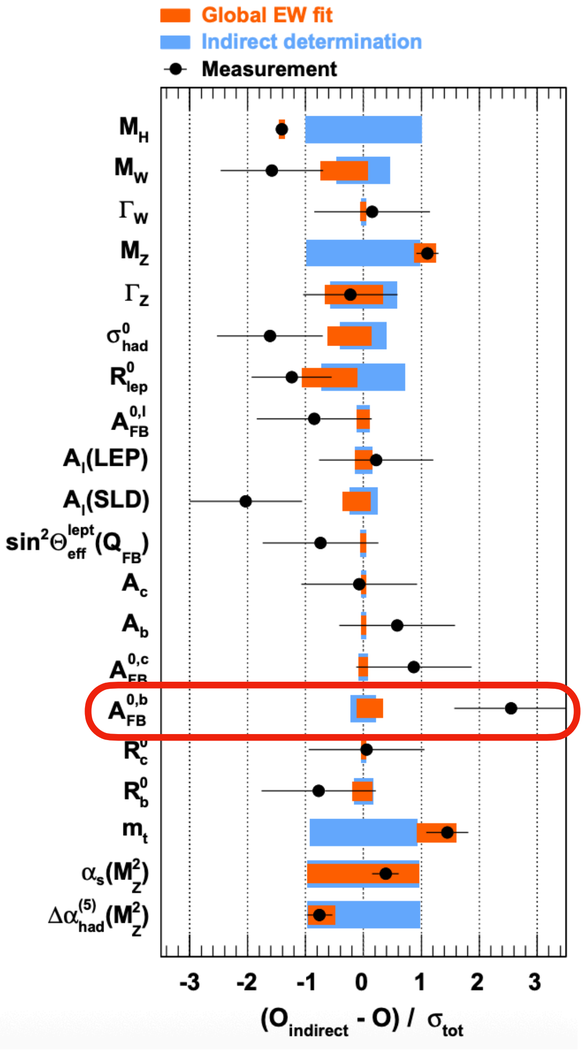


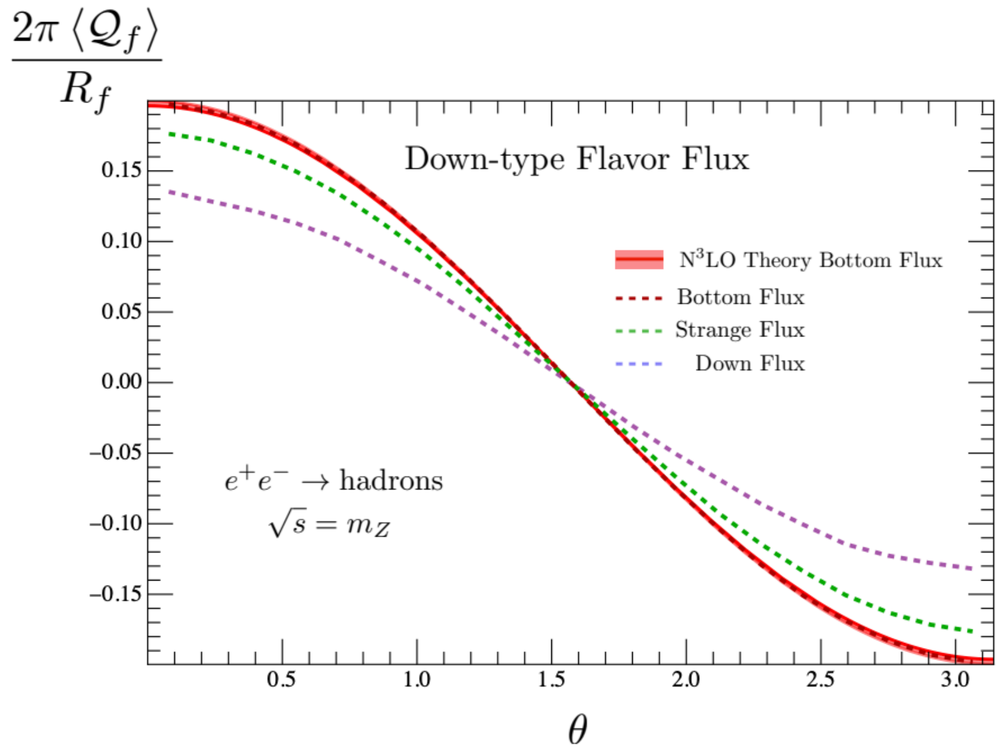


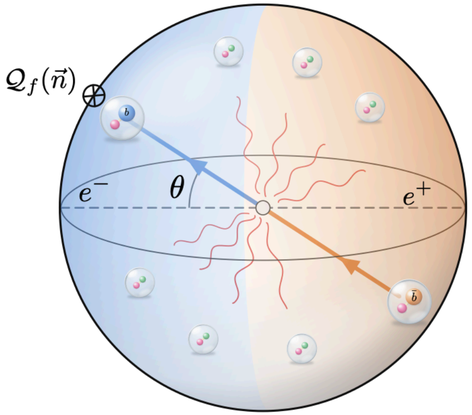
- Modern reanalyses techniques allow experimental measurements of the **charge flow**
- Robustness of anomaly gives very small perturbative QCD corrections, opening possibilities for precision electroweak measurements as well as new physics searches!

Zhang, KL, Moult, Chen, Lee `26

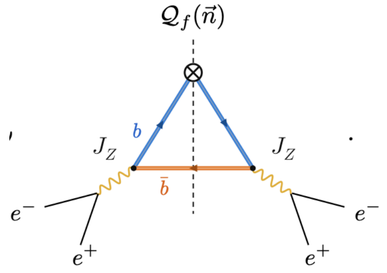
MIXED ANOMALY BETWEEN BARYON NUMBER AND ELECTROWEAK



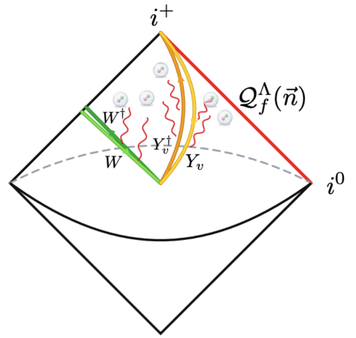




$\sim$



$\mu \sim \sqrt{s}$

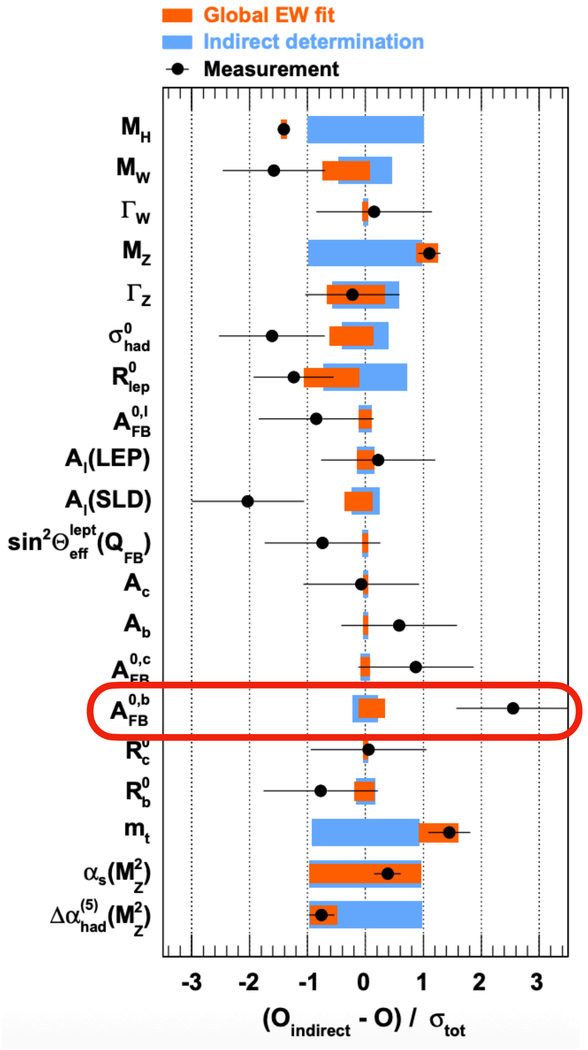


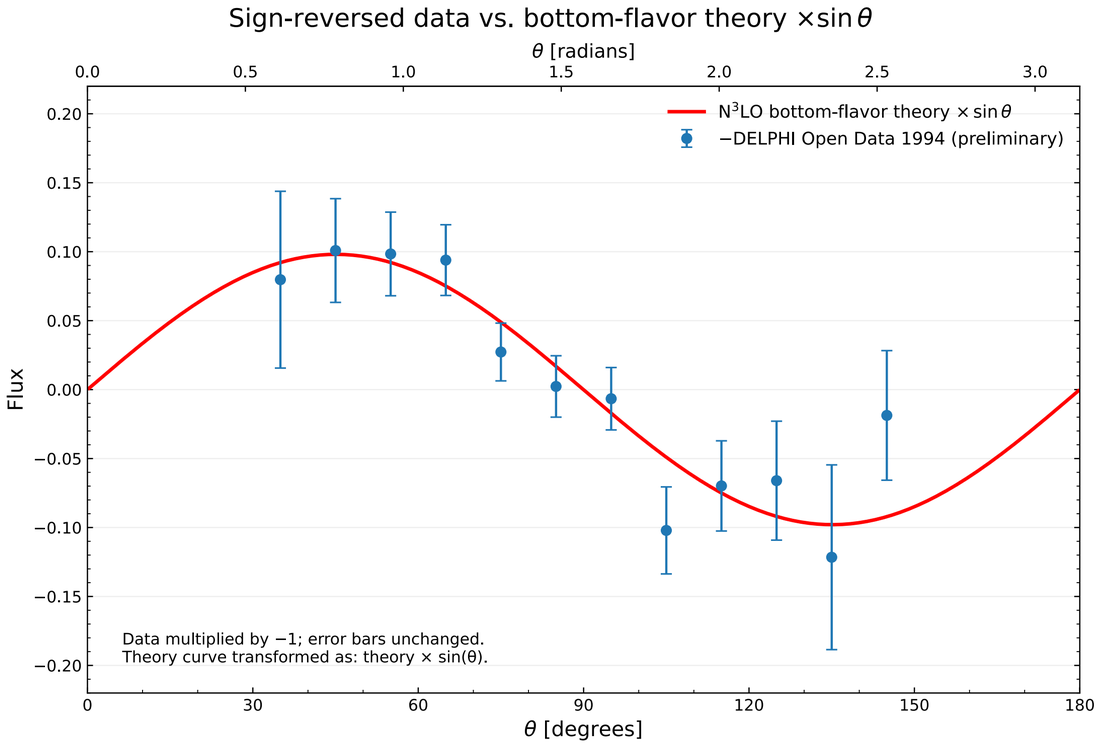
$\mu \sim \Lambda_{\rm QCD}$

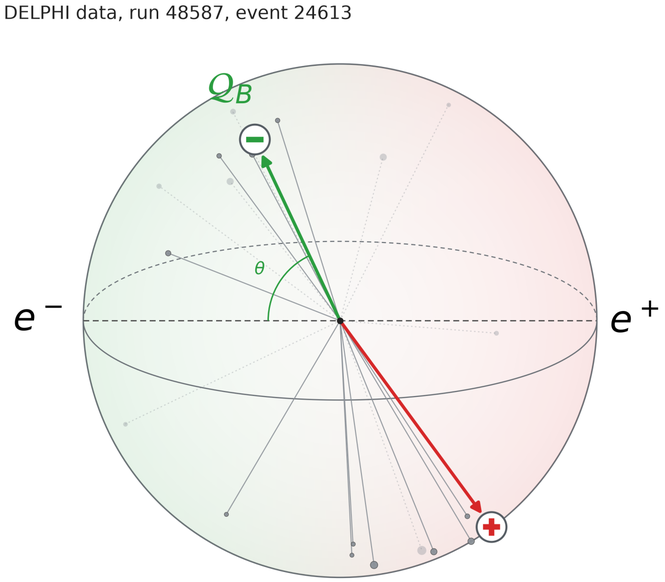
- Incredibly well-controlled perturbative AND nonperturbative corrections, providing potentials for **resolving** the largest tension in global EW fit and **strong constraints** for new physics

KL, Moult `26

MIXED ANOMALY BETWEEN BARYON NUMBER AND ELECTROWEAK



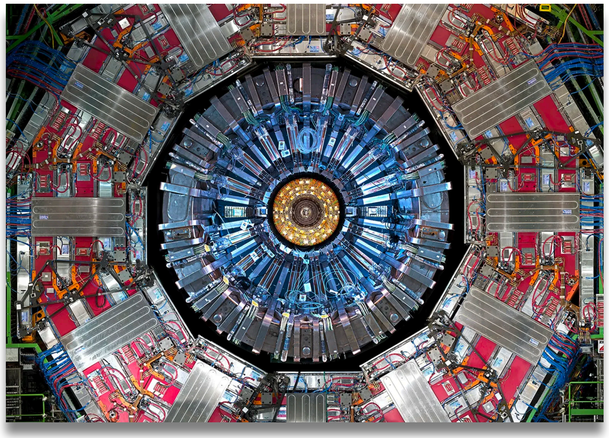




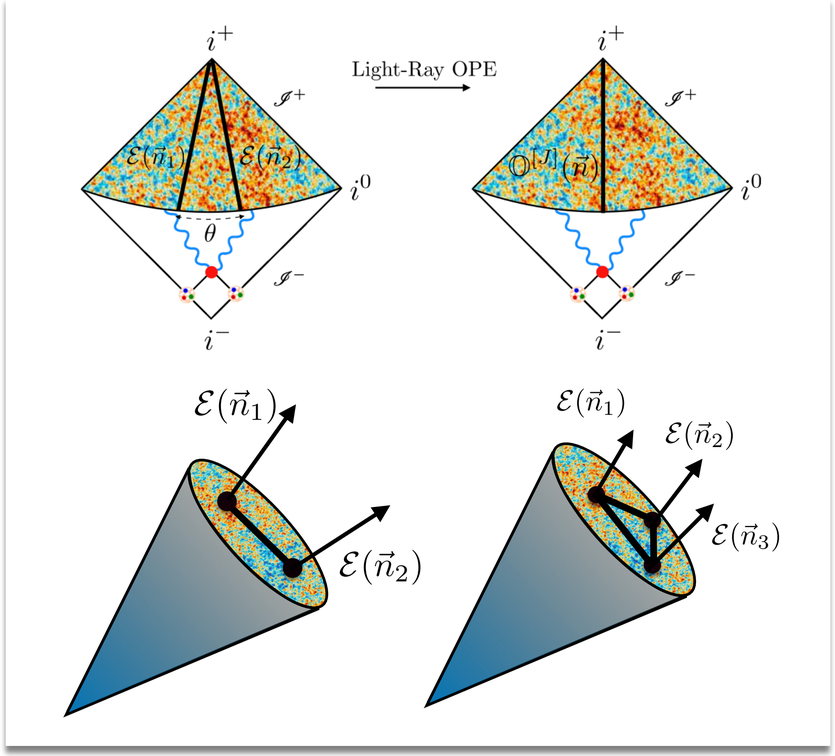
Ko, KL, Moult, Qian, Zhang `[In progress]

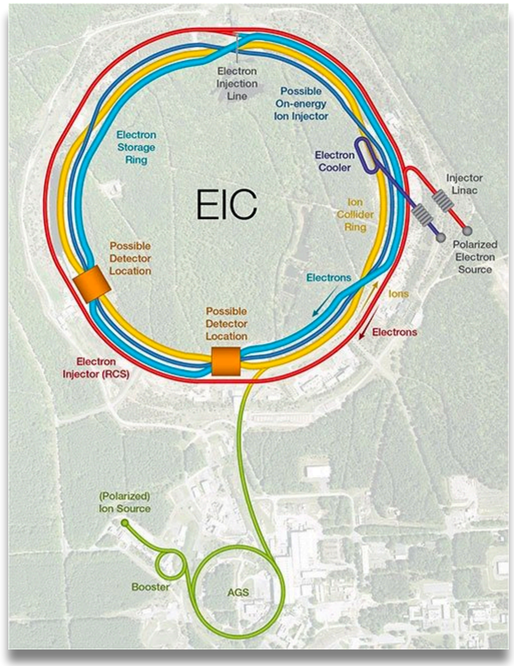
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KL, Moult `26

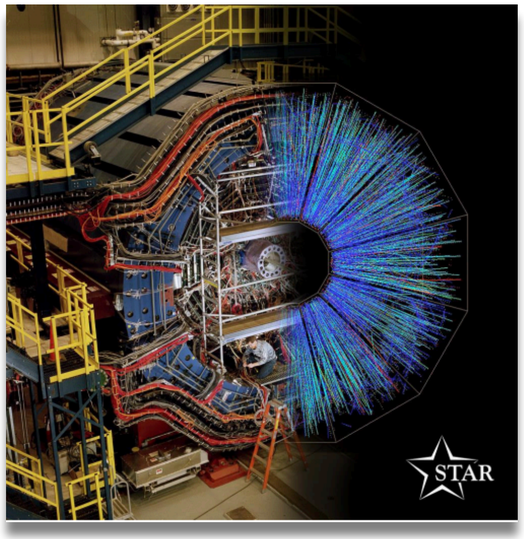


LHC



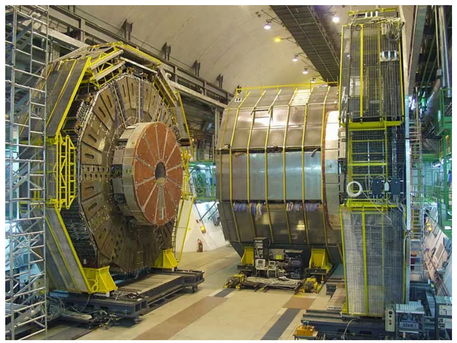


EIC



RHIC

Detector correlators provide sharp link between underlying field theory and real world!



LEP