Calculational techniques in Particle Theory

Marc Riembau
CERN

EPS-HEP, Marseille, 11th July 2025

Dear Marc,

We are contacting you with some unusual last-minute invitation. […]

Yael Shadmi was supposed to give the talk **Calculational techniques in particle theory**.

However, she has to cancel. […] you would be available and willing to give this talk instead

Thank you very much for the invitation. I'm not sure about the title of the talk, I would think to ask [list of people], they might be able to give a better and broader talk...

I can talk about energy correlators, has some overlap with the title [...]

We are delighted to hear that you can make it!

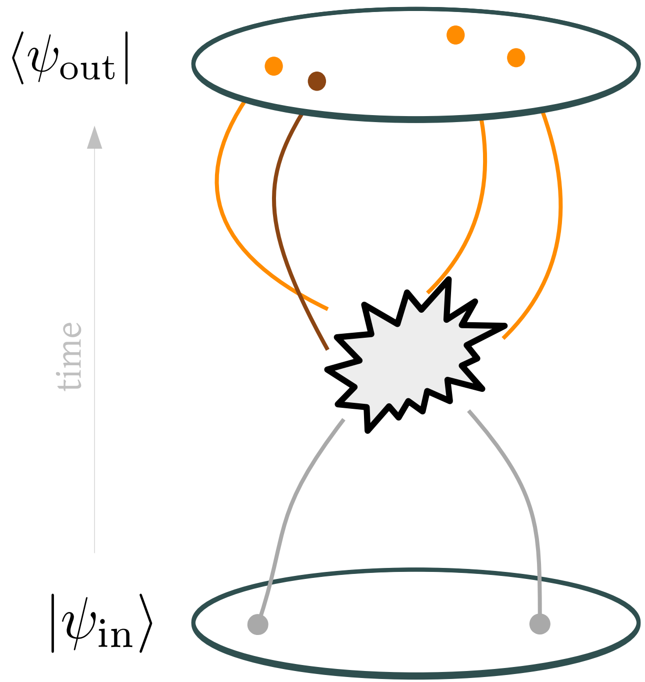
[…] the topic you propose is fine. However, it is very important that you make an effort to be very pedagogical with a generous introduction

👌 🚀

Calculational techniques in Particle Theory (a focus on Correlator Observables)

Marc Riembau
CERN

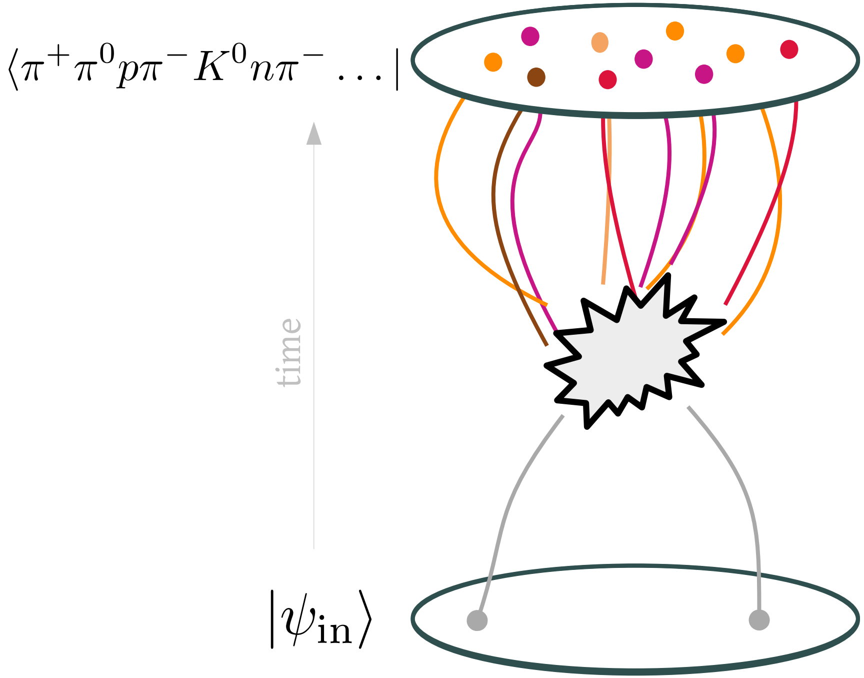
EPS-HEP, Marseille, 11th July 2025



Collider experiments transform an initial state, e.g. pp, into a final state.

(Almost) all we know is based on the different production rates of different states.

Fine for theories with a mass gap and suppressed multiparticle production.



Collider experiments transform an initial state, e.g. pp, into a final state.

(Almost) all we know is based on the different production rates of different states.

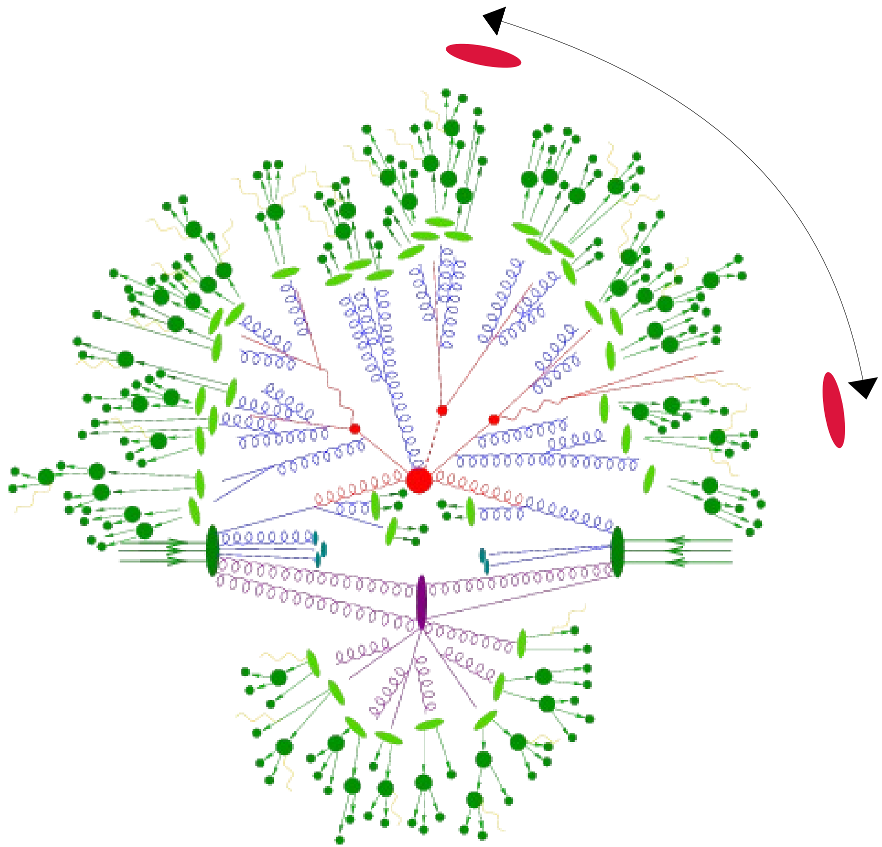
Fine for theories with a mass gap and suppressed multiparticle production.

Not the case of real world at high energy or high accuracy!

Need to “coarse grain” your Hilbert space into jets... matching, merging...

Worse at high energies: what does “diboson” means at √s=10TeV?

An alternative question to the experiments: what is the correlation among energy fluxes?



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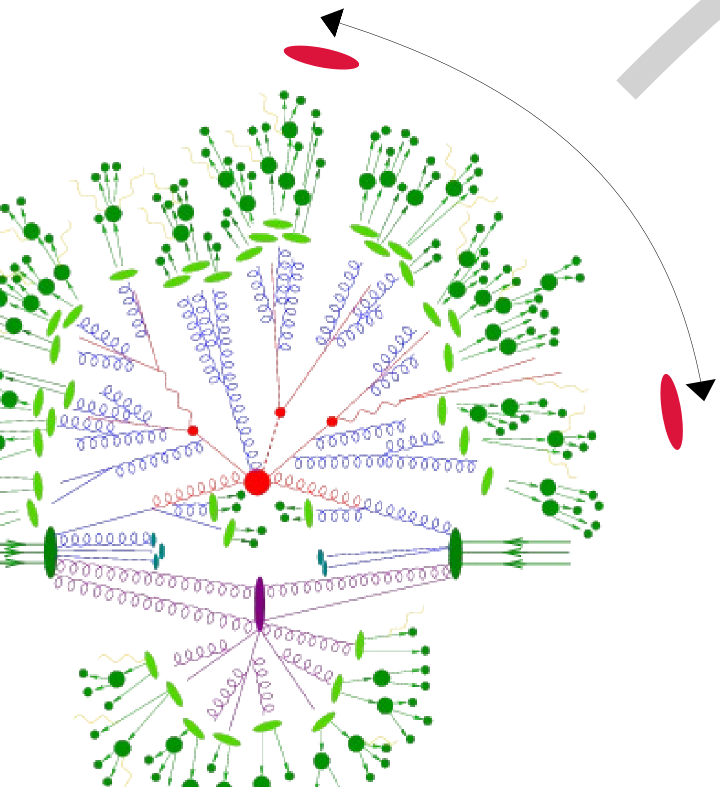
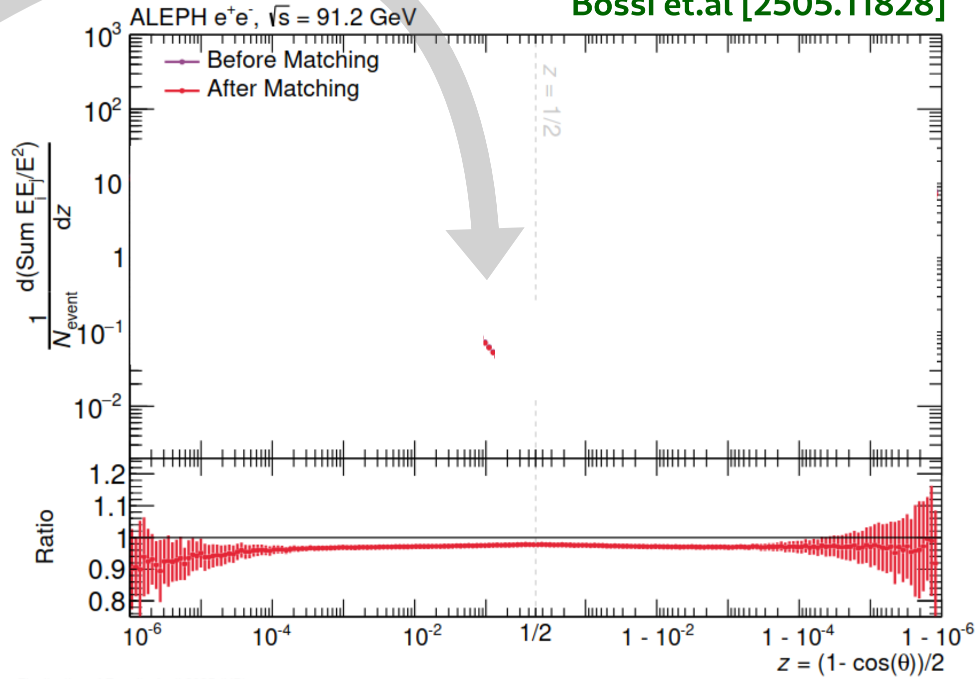


Bossi et.al [2505.11828]



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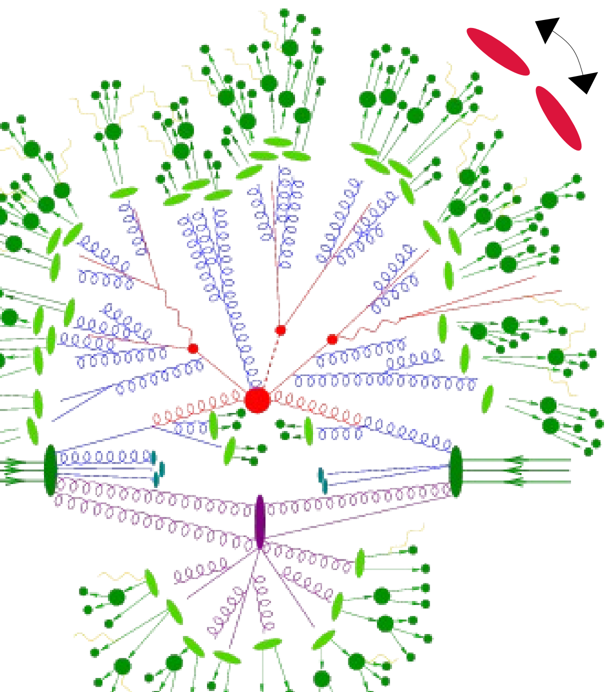

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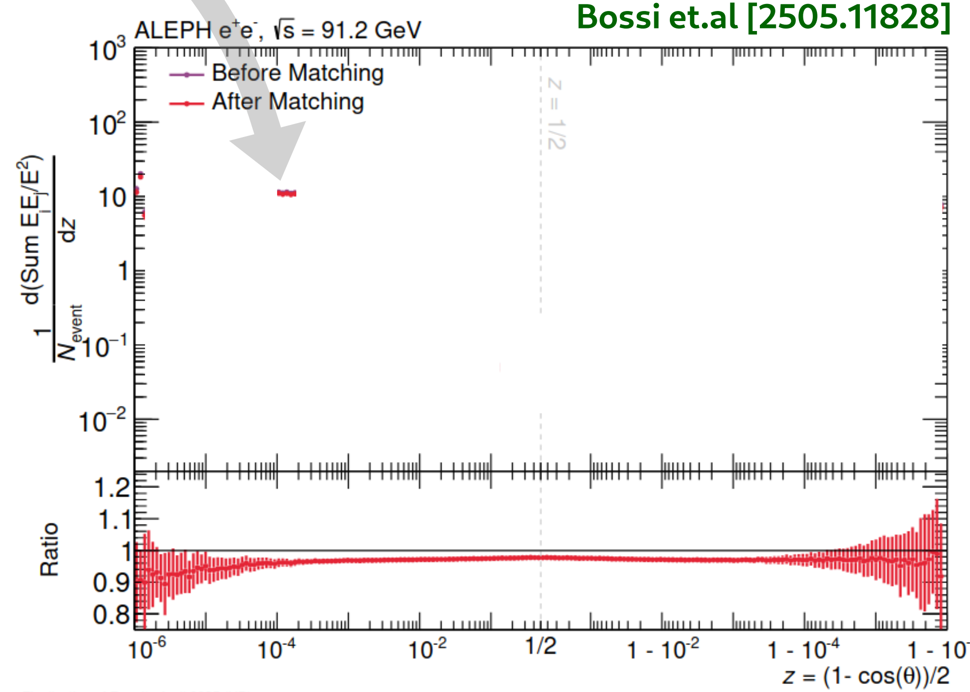

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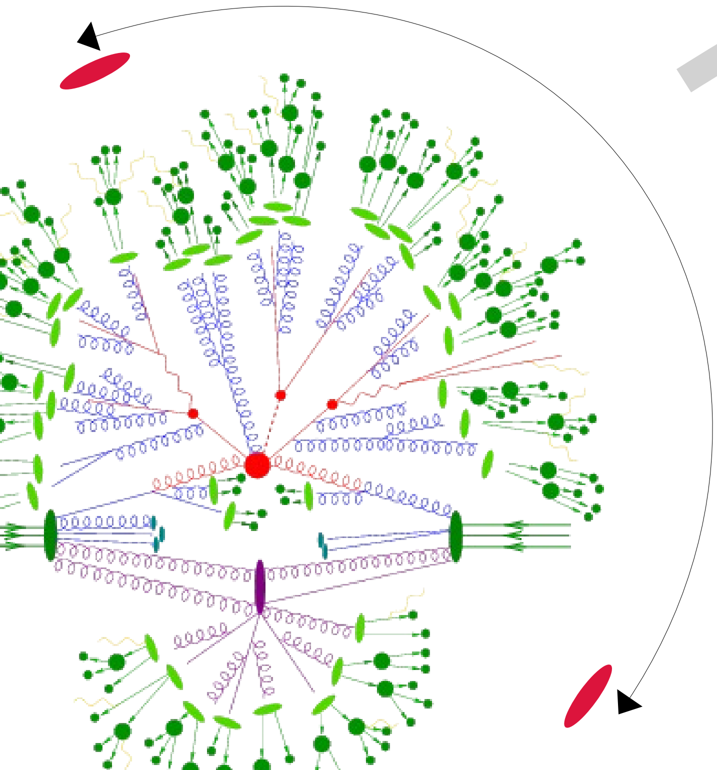

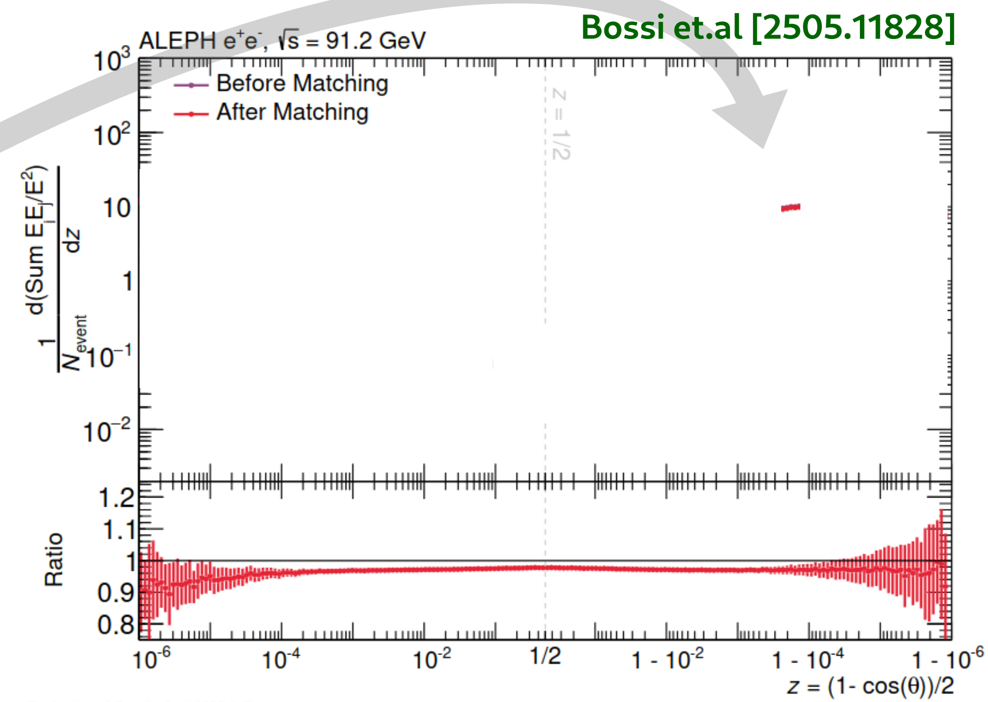

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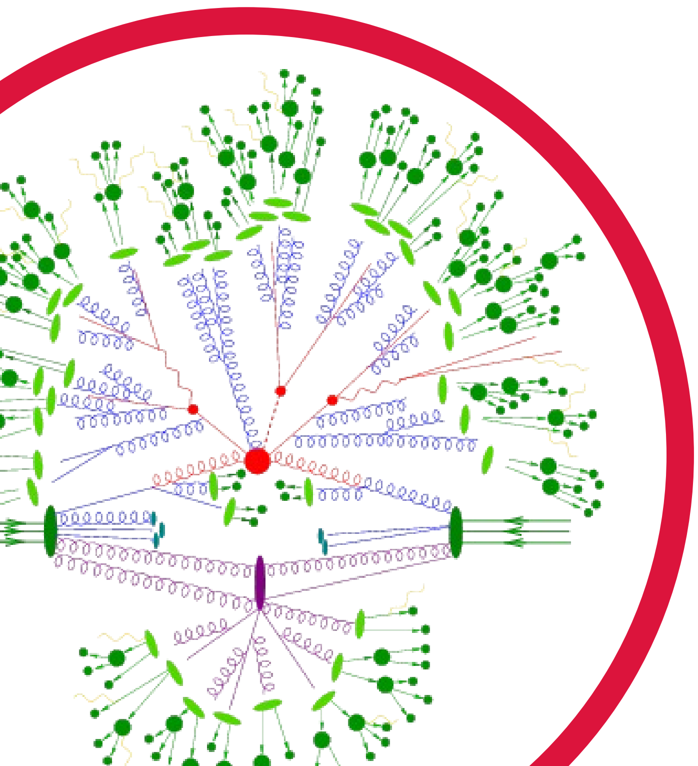

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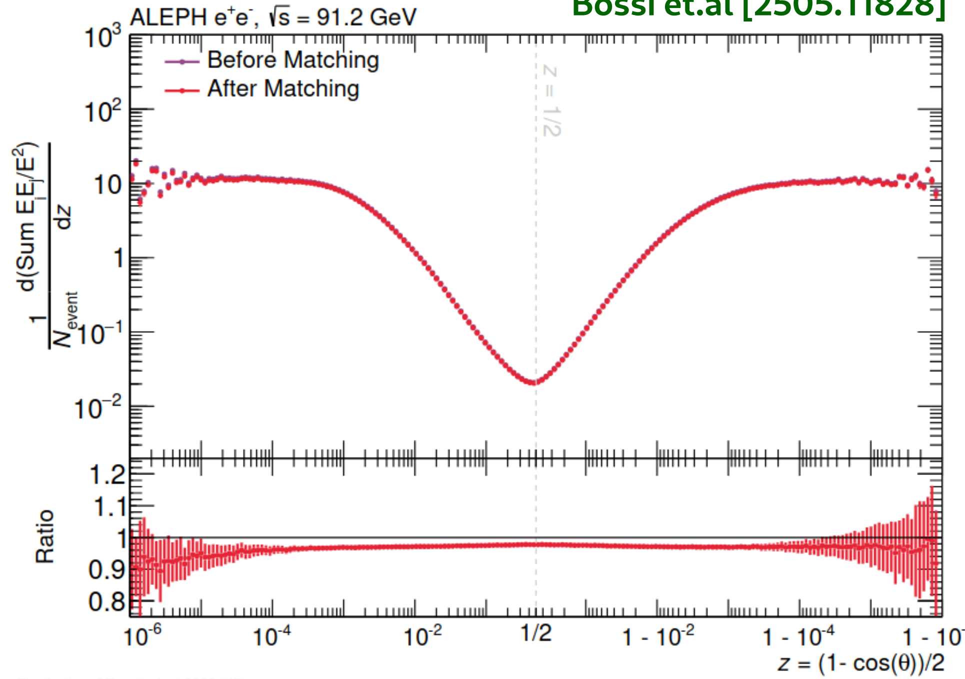
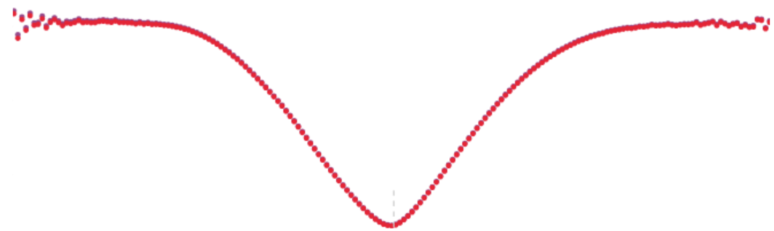


Recent progress in computing the two-point correlator:



Collinear region:	Hard region:	Back-to-back region:
Hofman, Maldacena '08	Dixon et.al '18	Kardos et.al. '18
Dixon et.al. '19		Moult, Zhu '18
Kologlu et.al '21		Duhr et.al. '22
Korchemsky '20		Aglietti, Ferrera '24

Basham, Brown, Ellis, Love '78

$$\langle \mathcal{E}_{n_1} \dots \mathcal{E}_{n_N} \rangle = \frac{1}{\sigma} \int d\sigma(\alpha \to \beta) \sum_{i_1 \dots \in \beta} (E_{i_1} \dots E_{i_N}) \delta^{(2)}(\Omega_{i_1} - \Omega_{n_1}) \dots \delta^{(2)}(\Omega_{i_N} - \Omega_{n_N})$$

Basham, Brown, Ellis, Love '78

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Energy weights have an operatorial definition

Sveshnikov, Tkachov '95

$$\mathcal{O}_n = \lim_{r \to \infty} \int dt r^2 n_i T_{i0}(t, r\hat{n}) \quad \Rightarrow \quad \mathcal{O}_n \sim \int d^4k \delta(k^2) \delta^{(2)}(\Omega_{\vec{k}} - \Omega_{\vec{n}})\, k^0\, a_k^\dagger a_k$$

These act as "detectors" or "calorimeters": Extract the energy of particles along detector's direction.

$$\mathcal{O}_{\hat{n}_i} |\alpha\rangle = \sum_i E_i \delta(\hat{p}_i - \hat{n}_i) |\alpha\rangle$$

In hindsight, this was a breakthrough. As long as the operator is well defined, as is the case of the energy operator, this gives a perfectly robust definition of observables in a gauge theory (and gravity), avoiding the theoretical nuance of defining an S-matrix for a gauge theory (and gravity).

Energy weights have an operator product expansion

Hoffman, Maldacena '08

$$\mathcal{E}(n_1)\mathcal{E}(n_2) = \frac{1}{\theta_{12}^{2+\gamma}}\mathcal{O}^{[J=3]} + \mathcal{O}(\theta^4)$$

Calorimeters getting closer

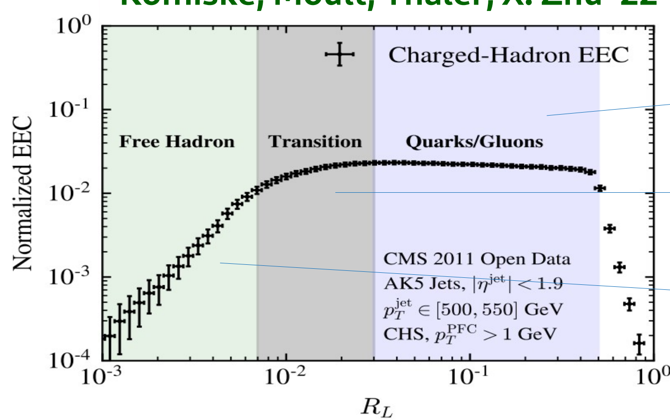
Scaling fixed by dilatations and boosts

New operator that measures ~energy squared

Higher twist suppressed

Scaling measured in CMS open data:

Komiske, Moult, Thaler, X. Zhu '22

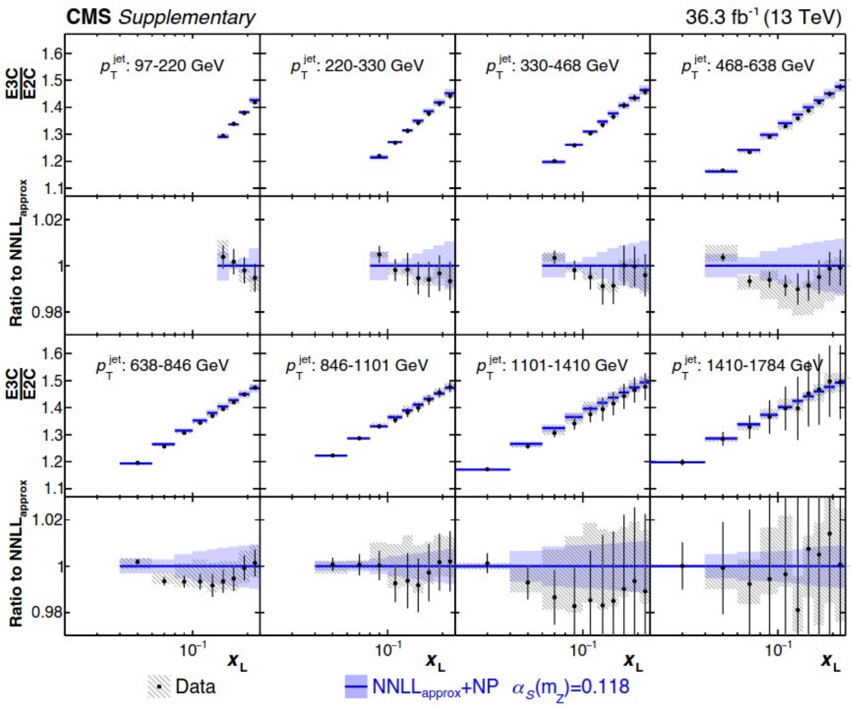


$1 \gg \theta \gg \Lambda_{QCD}/E_{jet}$

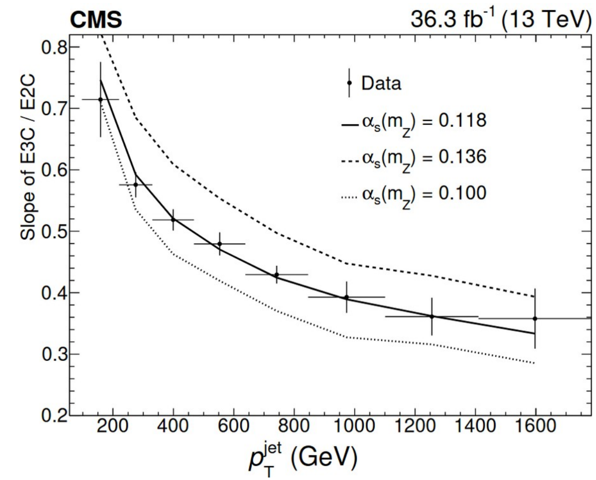
$\theta \sim \Lambda_{QCD}/E_{jet}$

$\Lambda_{QCD}/E_{jet} \gg \theta$

Now used for strong coupling measurement inside jets



Chen, Gao, Li, Xu, Zhang, X. Zhu '23
CMS [2402.13864]



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

$$= 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$$

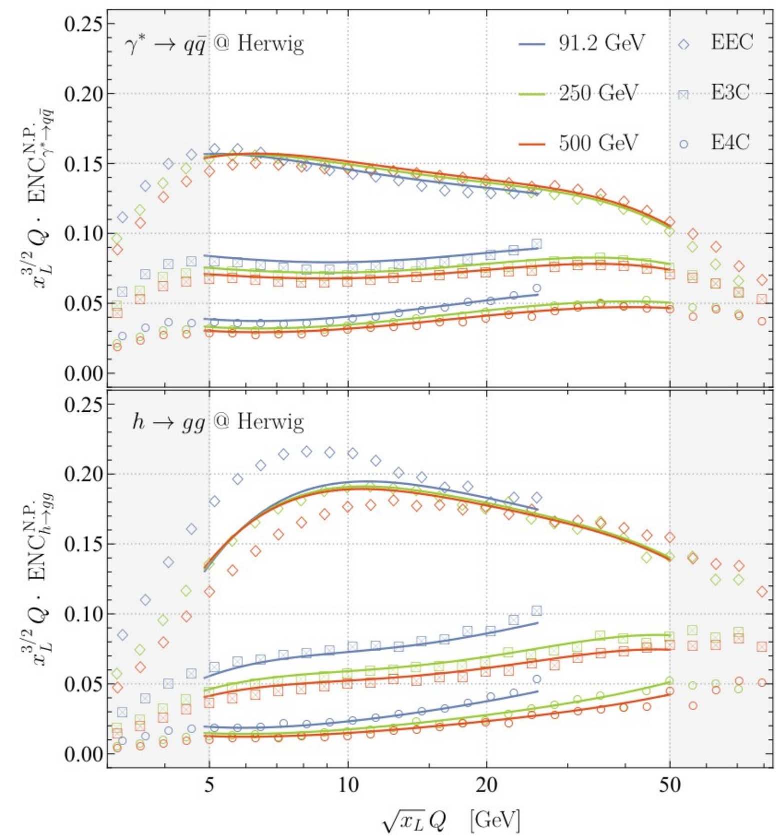
Best determination of α_s using jet substructure

Power corrections to the scaling regime:

Schindler, Stewart, Sun '23
Lee, Pathak, Stewart, Sun '24
Chen, Monni, Xu, X. Zhu '24

$$\lim_{n_1 \to n_2} \mathcal{E}(n_1)\mathcal{E}(n_2) = \frac{1}{x_L} \vec{C} \cdot \vec{\mathbb{O}}^{[J=3]}_{\tau=2}(n_2) + \frac{\Lambda_{\rm QCD}}{x_L^{3/2}} \vec{D} \cdot \vec{\mathbb{O}}^{[J=2]}_{\tau=2}(n_2) + \cdots$$

$$\mathrm{ENC}^{\rm N.P.}_{\Psi_q}(x_L, Q) \equiv \mathrm{ENC}_{\Psi_q}(x_L, Q) - \mathrm{ENC}^{\rm P.T.}_{\Psi_q}(x_L, Q)\,,$$



OPE structure predicts scaling of

nonperturbative corrections,

which can be matched across different scales

The theoretical robustness of these observables has induced a recent interest on correlators

The following is a (rather short) list of works exploring phenomenological opportunities.

For a more theoretical perspective, see Sasha's talk Tuesday

For a more complete list see the recent review

Moult, Zhu [2506.09119]

Energy Correlators: A Journey From Theory to Experiment

Ian Moult[1,*] and Hua Xing Zhu[2,3,†]

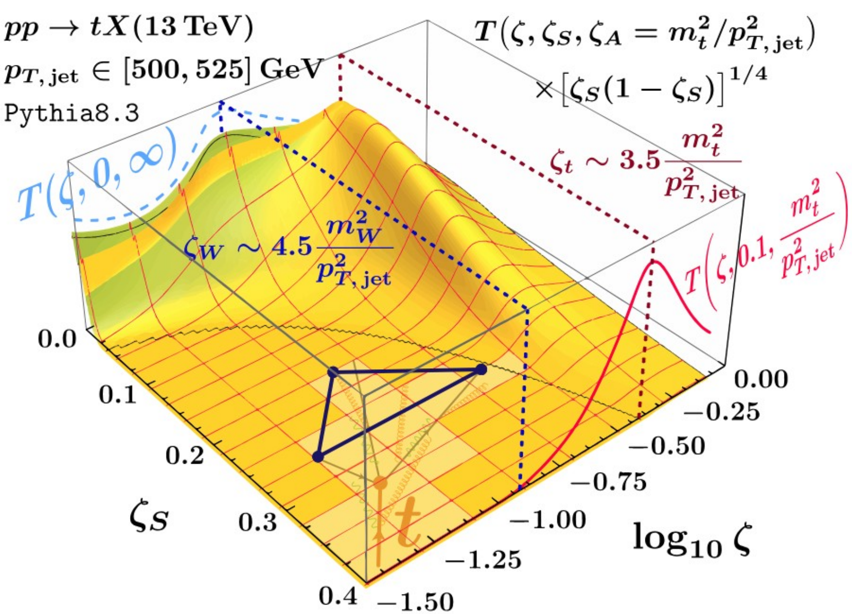
[1] *Department of Physics, Yale University, New Haven, CT 06511*

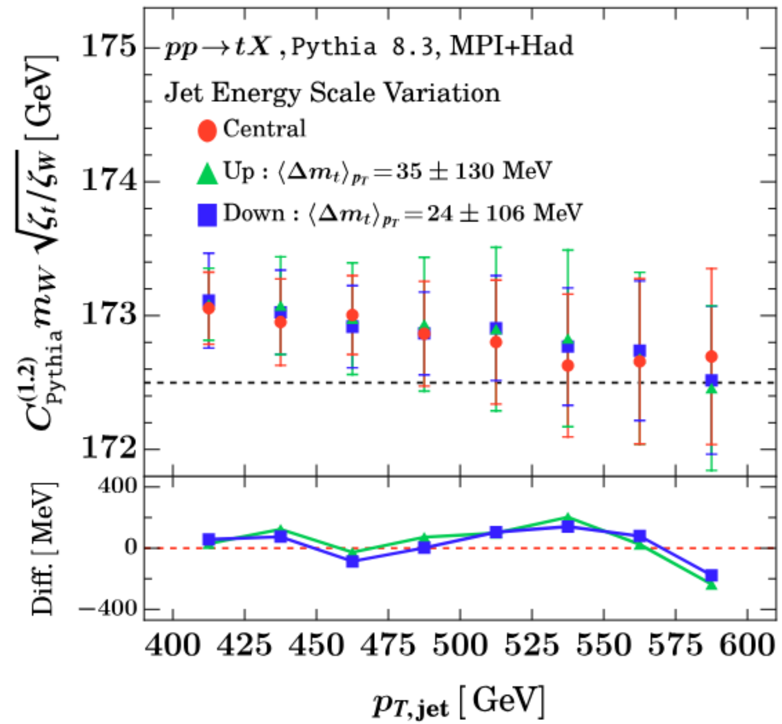
[2] *School of Physics, Peking University, Beijing, 100871, China*

[3] *Center for High Energy Physics, Peking University, Beijing 100871, China*

Energy correlation for studying top quark substructure:

Holguin et.al '24

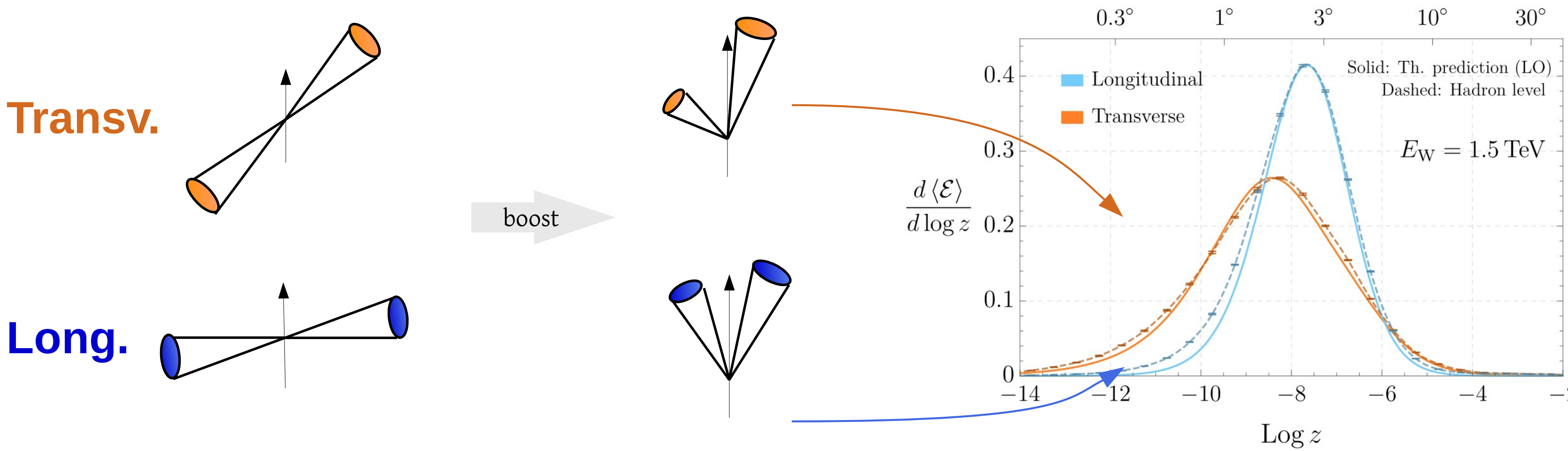




Three-point energy correlations inside a top quark can be used to extract its mass

Energy correlations as a probe of spin structure of electroweak bosons:

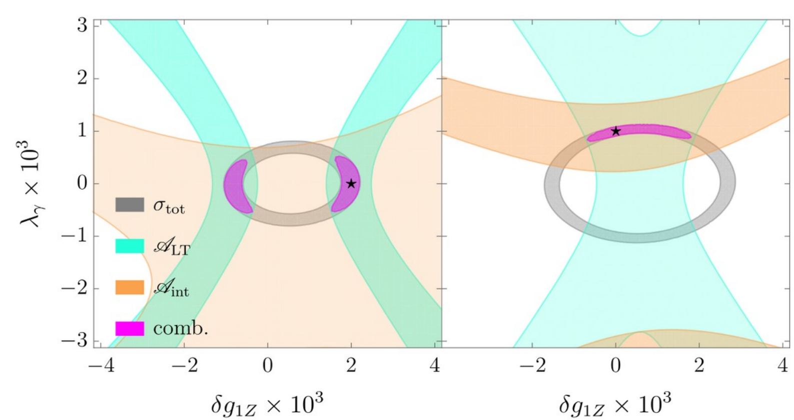
Ricci, MR '22



$$\mathcal{A}_+ \propto e^{i\phi} x \qquad \mathcal{A}_0 \propto \sqrt{x(1-x)} \qquad \mathcal{A}_- \propto e^{-i\phi}(1-x)$$

The energy fraction x is in one-to-one with the distance to the center z

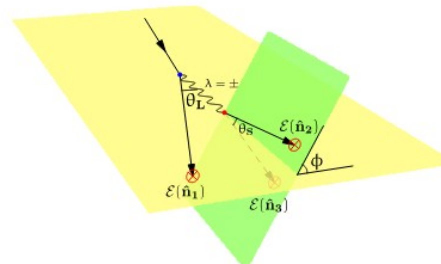
Can be used to characterize an excess:

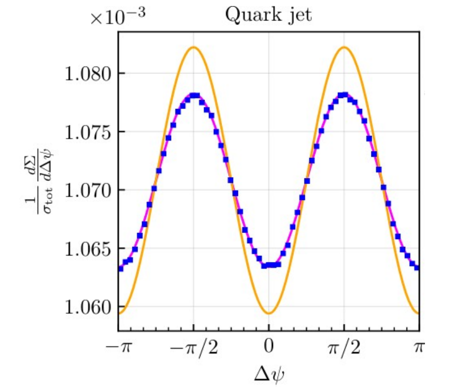


Chen, Moult, Zhu '21
Karlberg, Salam, Scyboz, Verheyen '21

Sensitivity to helicity structure:

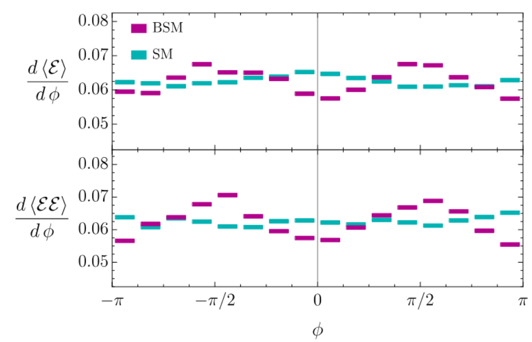
Interference in the parton shower

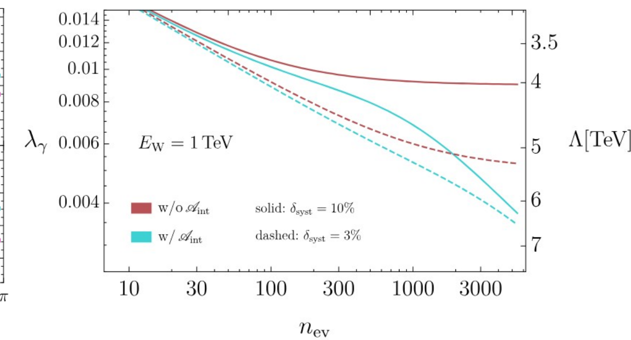




Ricci, MR '22

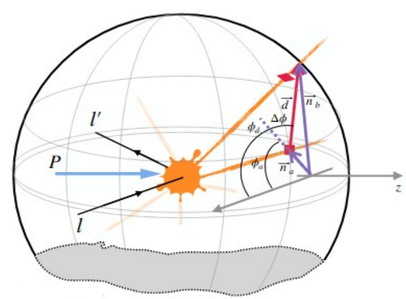
Interference of
W boson polarizations:

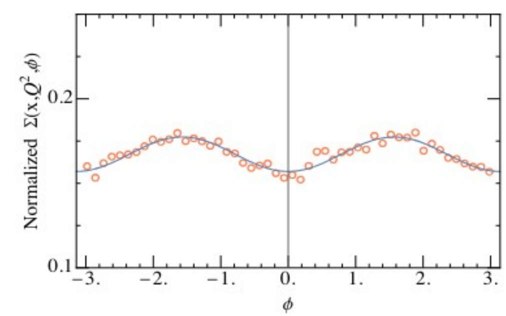




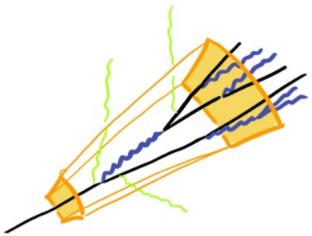
Li, Liu, Yuan, Zhu '23

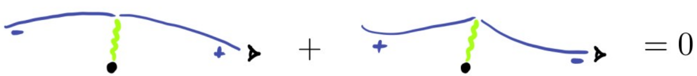
Gluon polarization in DIS



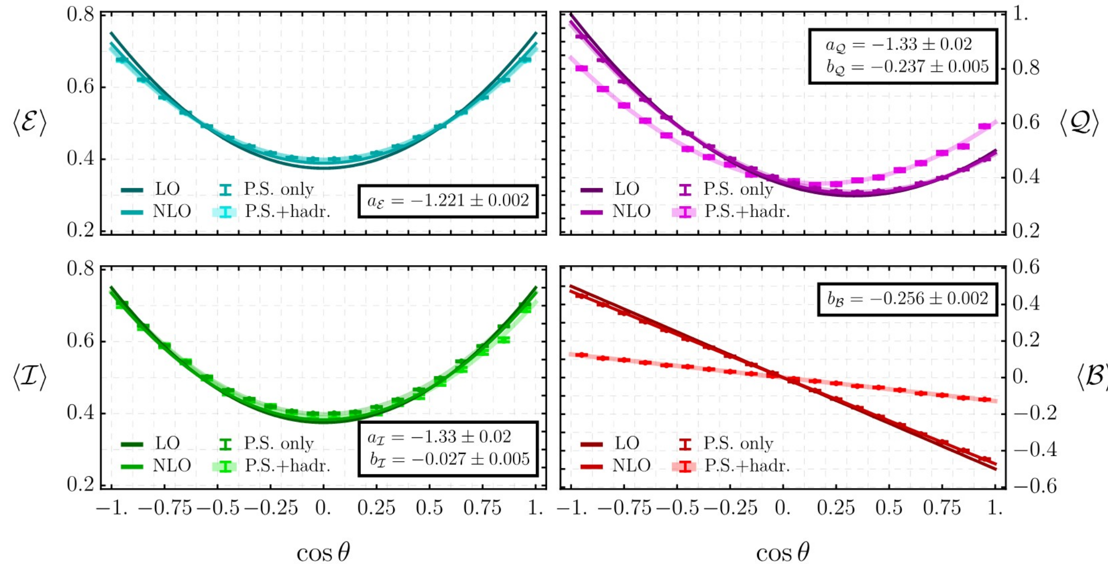


Correlators of conserved charges might be IR-safe, some one point:





MR, Son '24



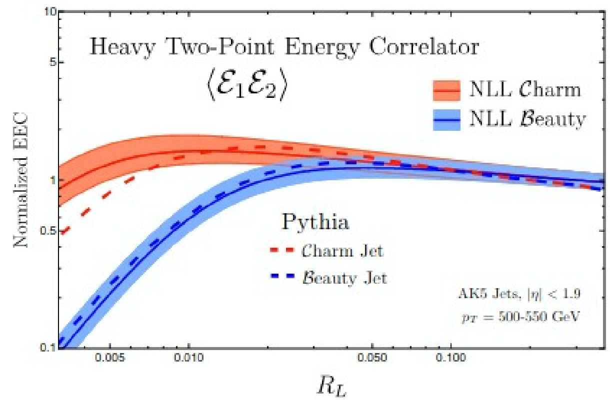
... and some higher point:

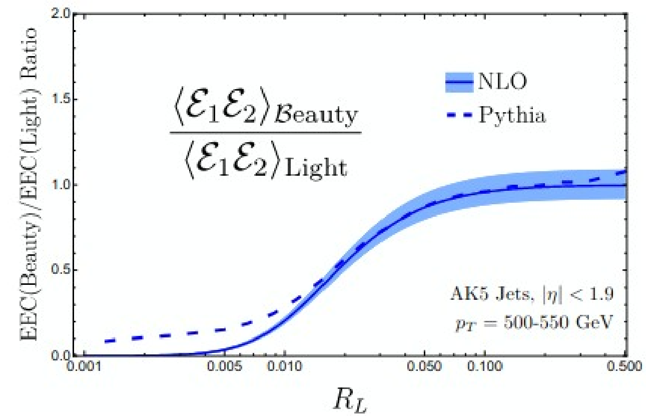
$\langle \mathcal{Q}_{n_1} \mathcal{Q}_{n_2} \rangle$ ✗ $\langle \mathcal{E}_{n_1} \mathcal{Q}_{n_2} \rangle$ ✓ $\langle \mathcal{E}_{n_1} \mathcal{E}_{n_2} \mathcal{Q}_{n_3} \rangle$ ✓

$\langle \mathcal{I}_{n_1} \mathcal{B}_{n_2} \rangle$ ✗ $\langle b_{n_1} \mathcal{B}_{n_2} \rangle$ ✓

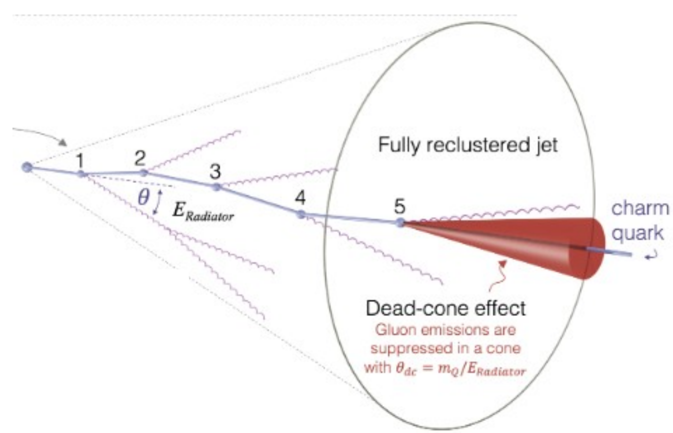
Jets of heavy flavour have different collinear behaviour due to finite mass effects

Craft, Lee, Mecaj, Moult '22



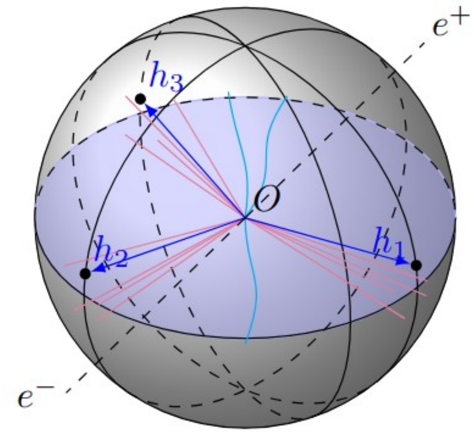


Equivalent to deadcone effect

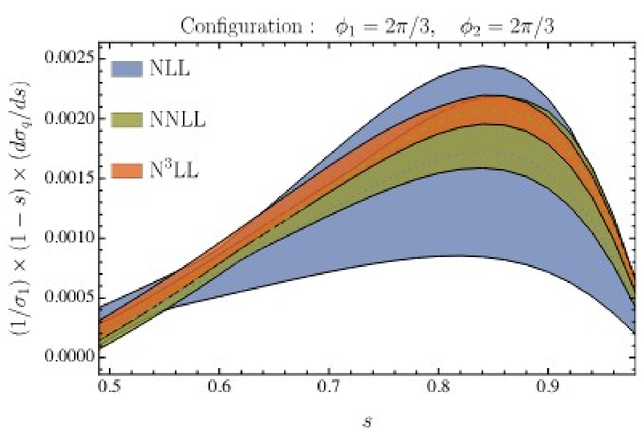


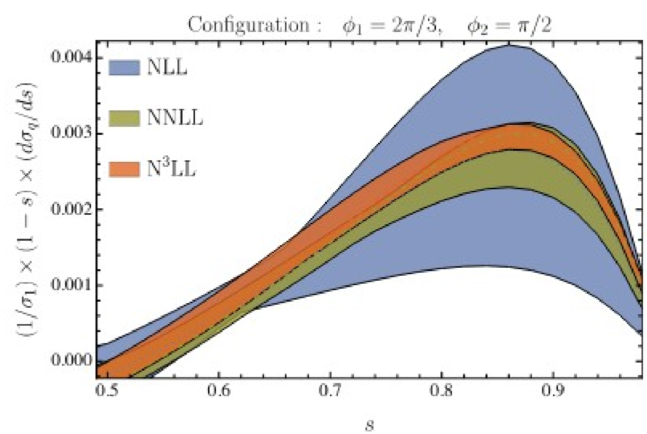
Exponentiation of the back-to-back regime is an instance of a broader phenomenon:

Coplanar limit of three-point dominated by similar dynamics:



Gao, Yang, Zhang '24

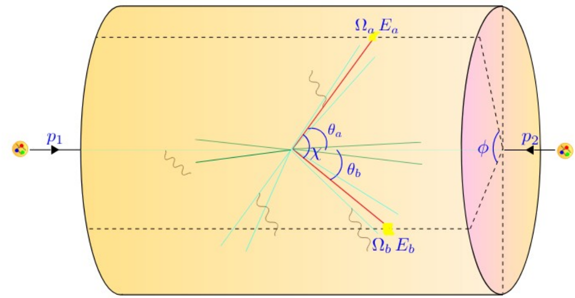


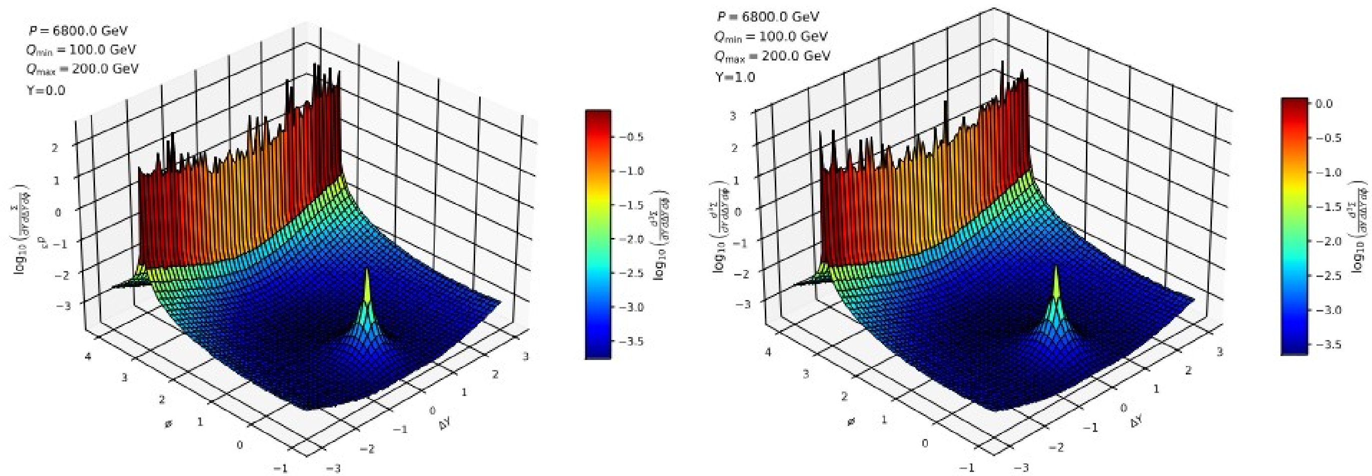


Energy correlators as global observables in hadron colliders:

Gao, Li, Moult, Zhu ‘19

Chen, Ruan, Zhu ‘25

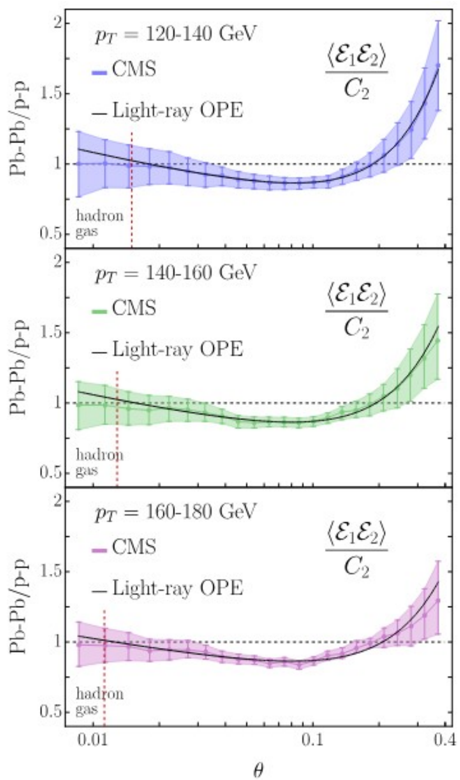




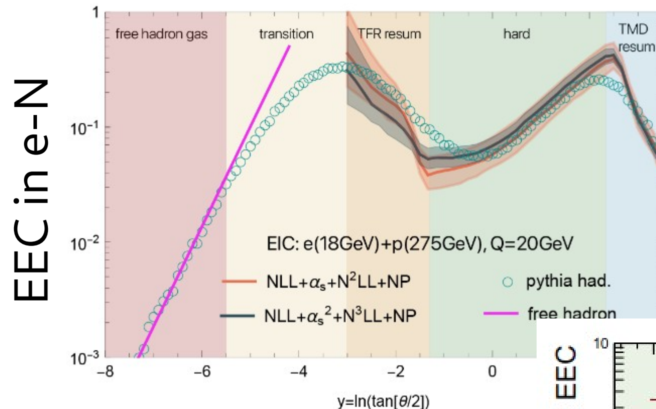
Decomposition of the observable in conformal blocks.

Energy correlators are the natural probe for the behaviour of many physical systems

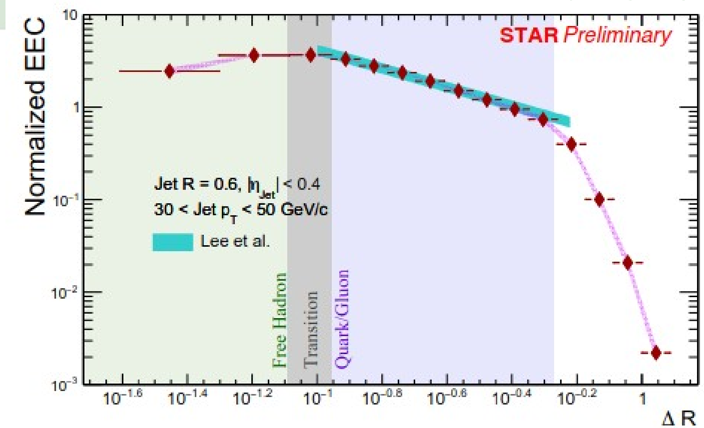
Andres et.al. '24



Cao et.al. '23



Tamis '23



For a complete, comprehensive recent discussion of phenomenological implementations, see **Moult, Zhu [2506.09119]**

Conclusions

Conclusions

Correlator observables are inherently interesting;

theoretically, phenomenologically and experimentally.

It is an interdisciplinary area of study,

with plenty of new challenges and opportunities.