Energy correlators and phenomenology

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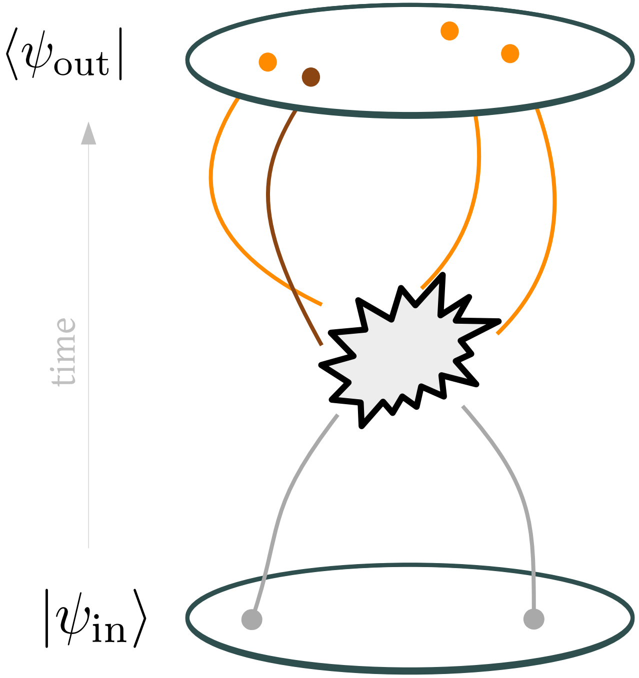
CERN & EPFL

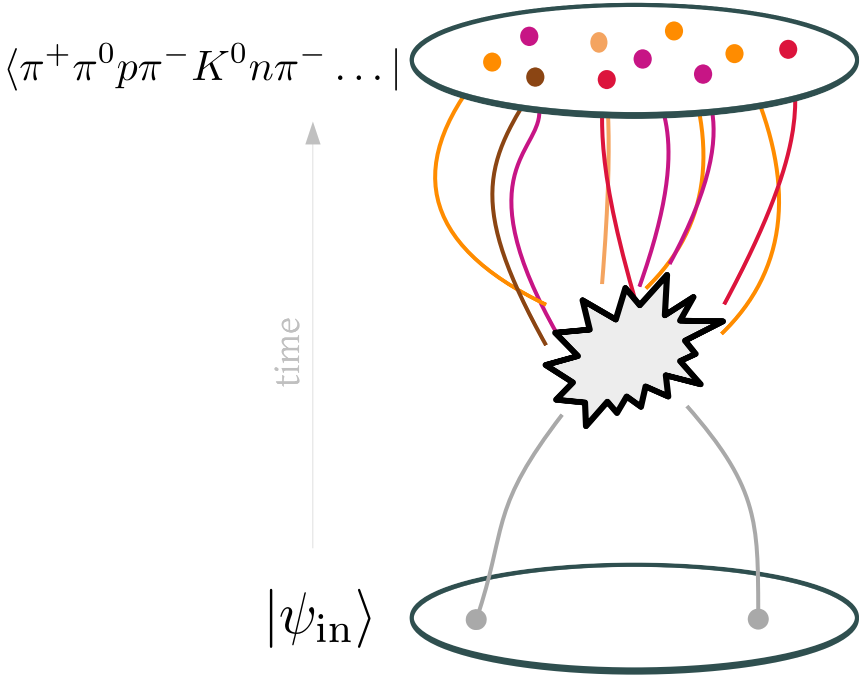
La Thuile, 5th March 2026



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.

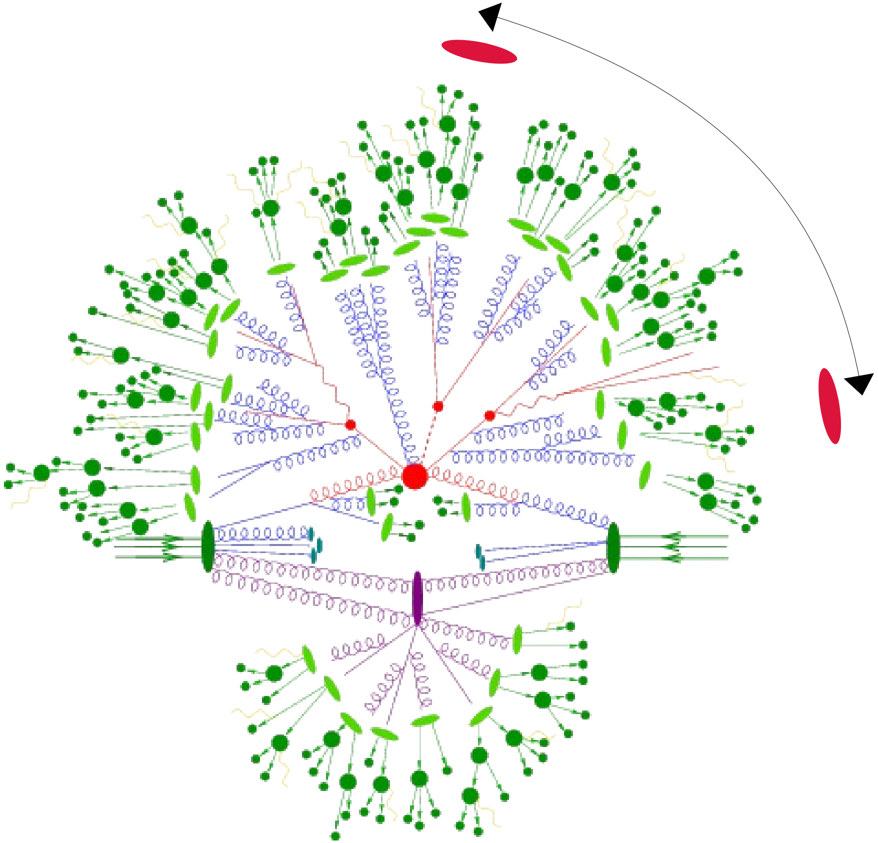
Fine for theories with a mass gap and suppressed multiparticle production.

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 $\sqrt{s}$=10TeV?

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



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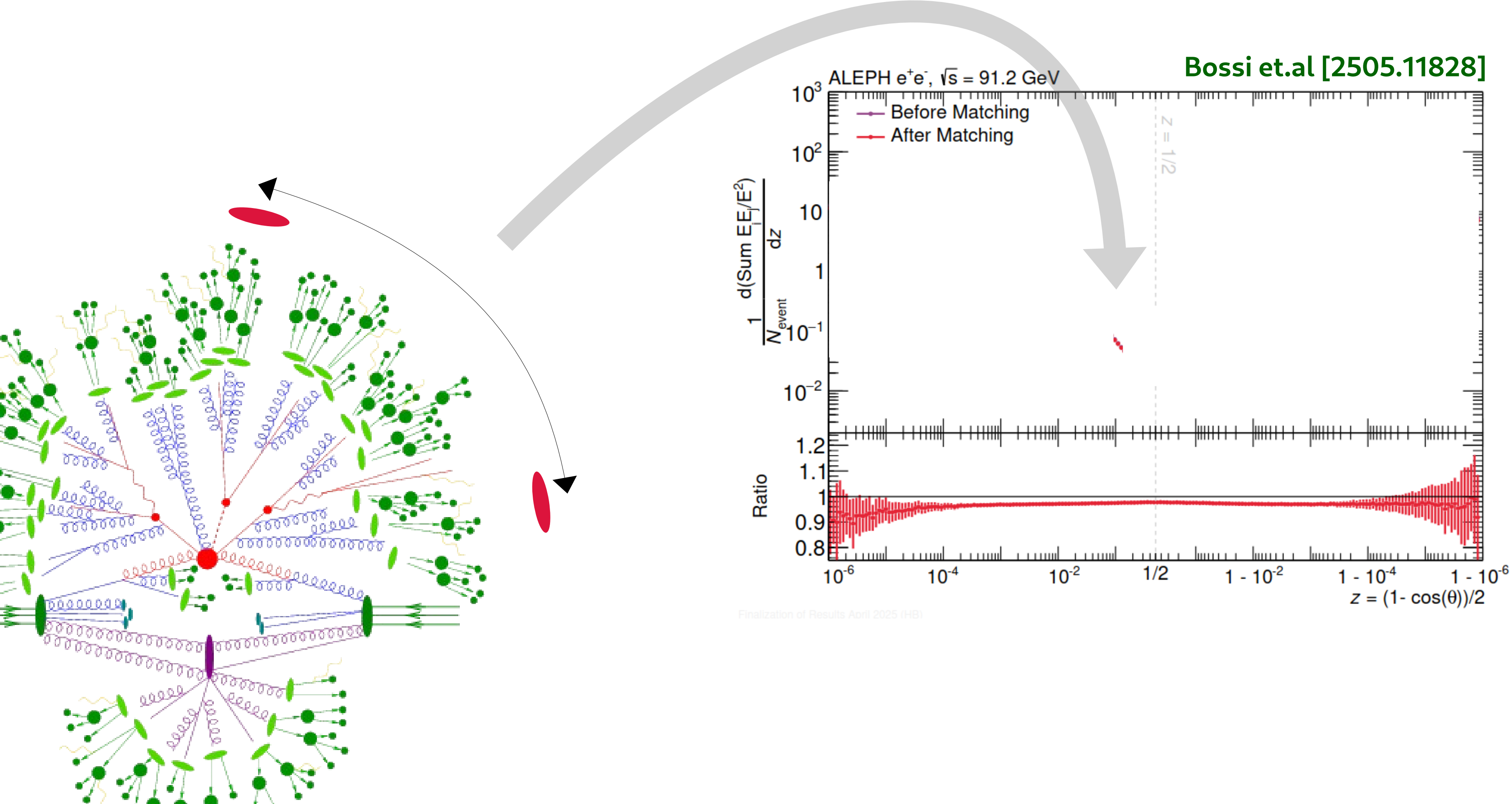

Bossi et.al [2505.11828]

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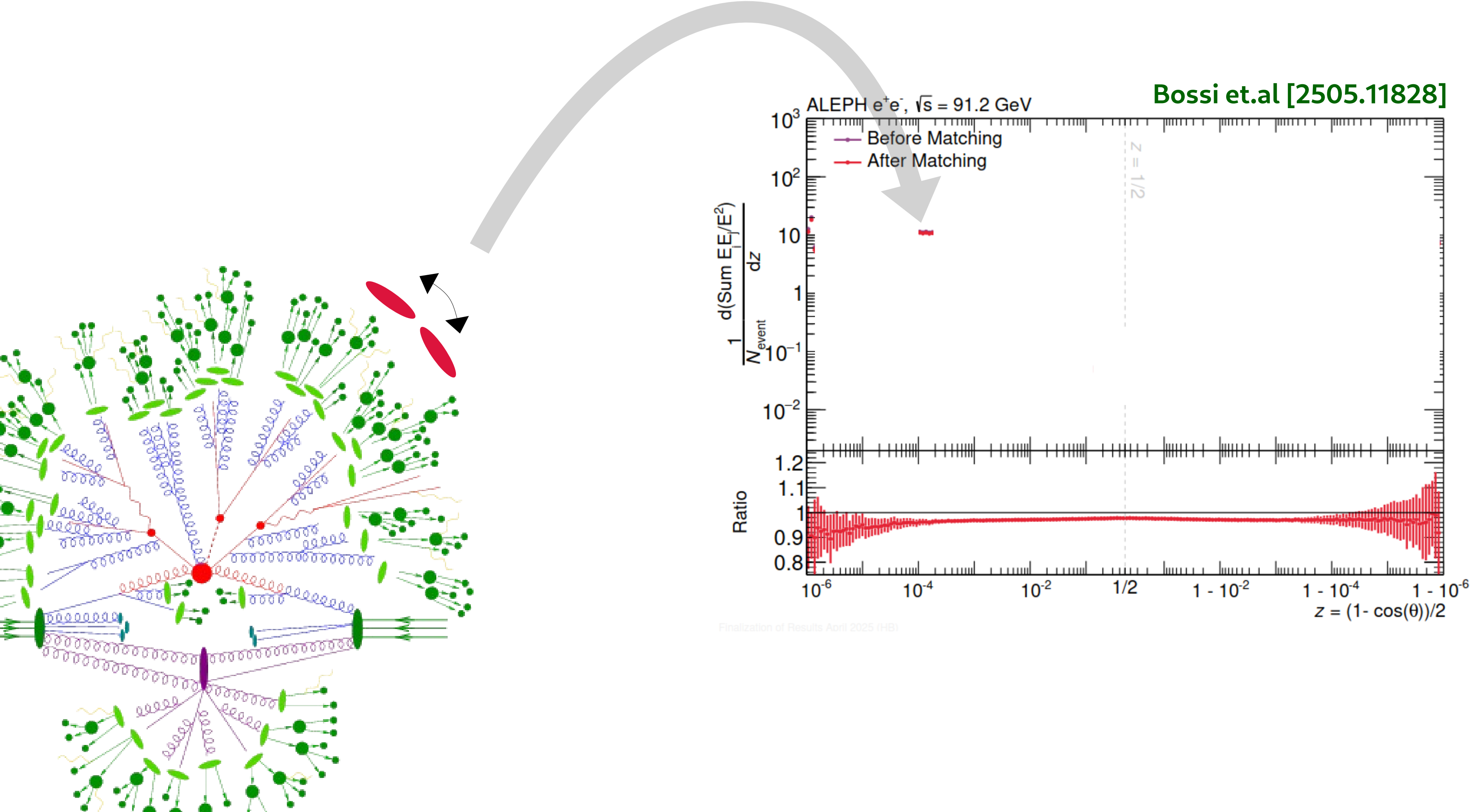

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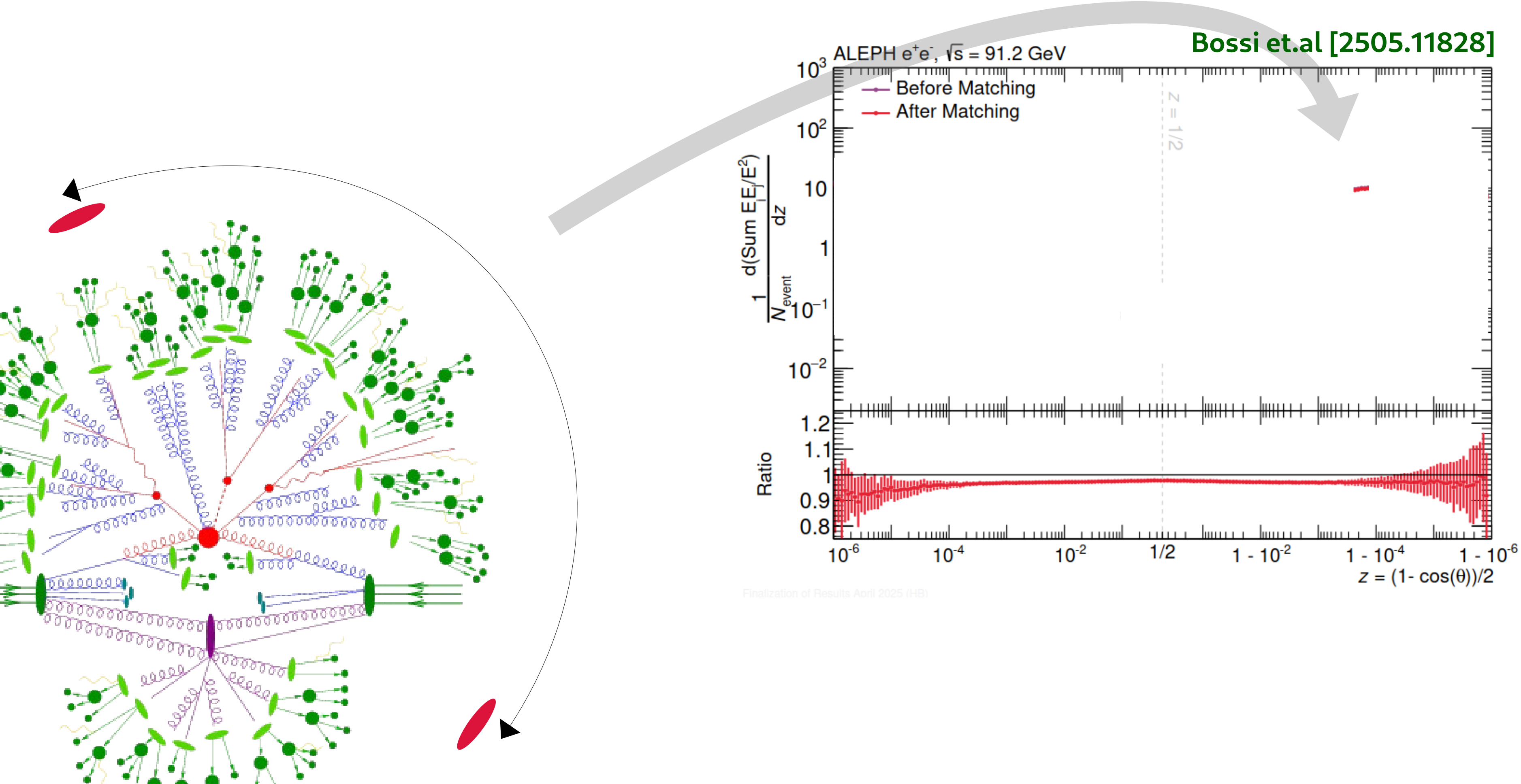

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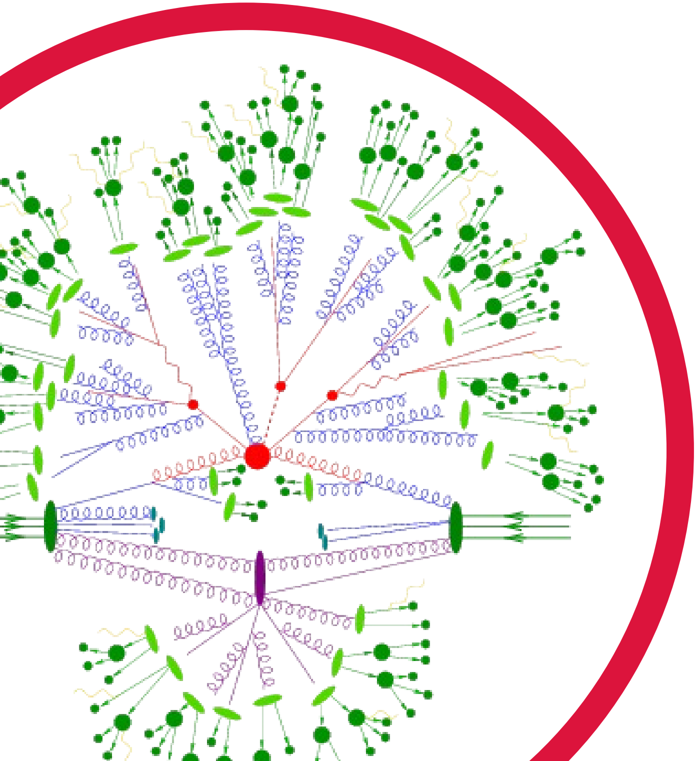

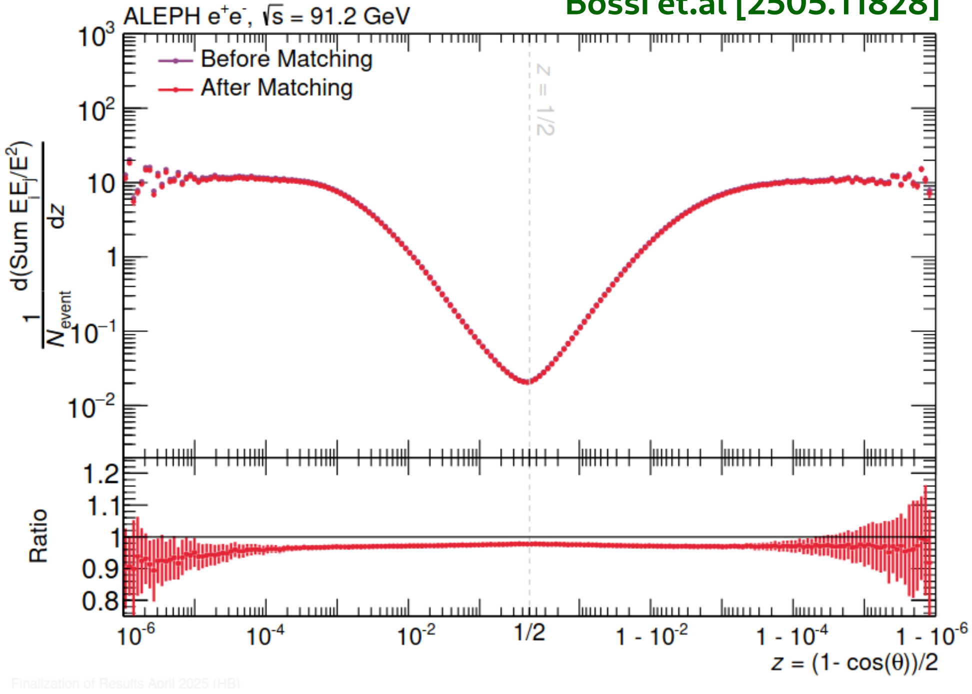

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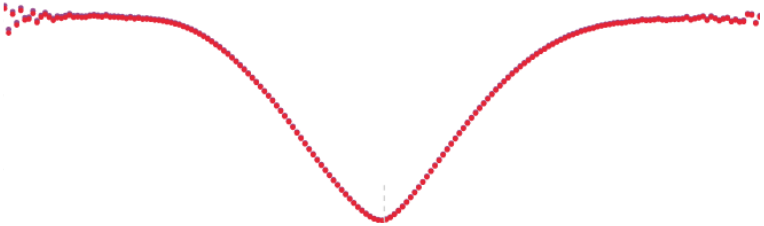
Recent progress in computing the two-point correlator:



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**

See a complete review of this calculation in **Jaarsma, Li, Moult, Waalewijn, Zhu [2512.11950]**

Basham, Brown, Ellis, Love '78

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

Basham, Brown, Ellis, Love ‘78

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

Energy weights have an operatorial definition

Sveshnikov, Tkachov ‘95

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

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

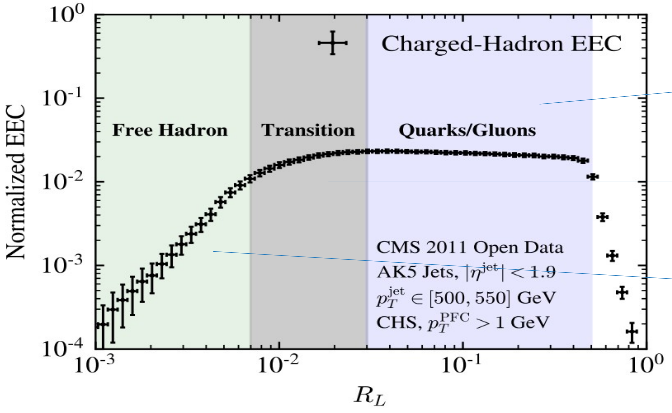
Scaling fixed by
dilatations and boosts

New operator that
measures ~energy squared

Higher twist
suppressed

Scaling measured in CMS open data:

Komiske, Moult, Thaler, X. Zhu '22

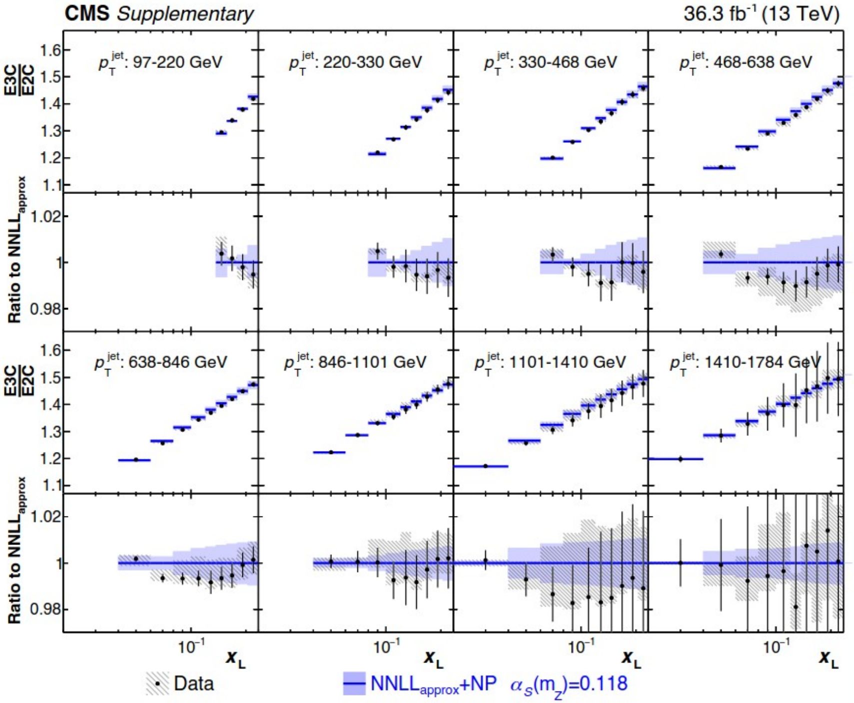


$$1 \gg \theta \gg \Lambda_{QCD}/E_{jet}$$

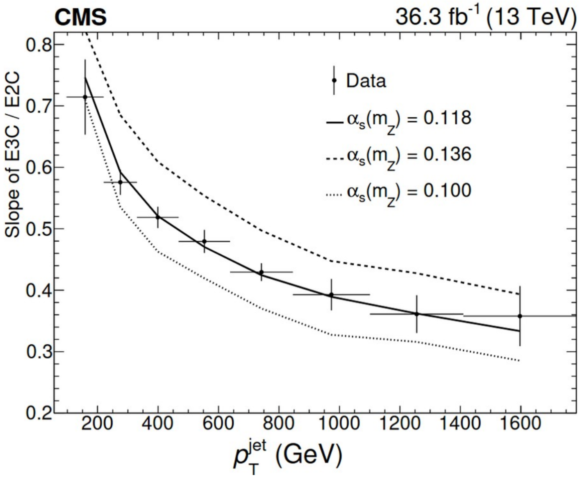
$$\theta \sim \Lambda_{QCD}/E_{jet}$$

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

Now used for strong coupling measurement inside jets



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



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

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

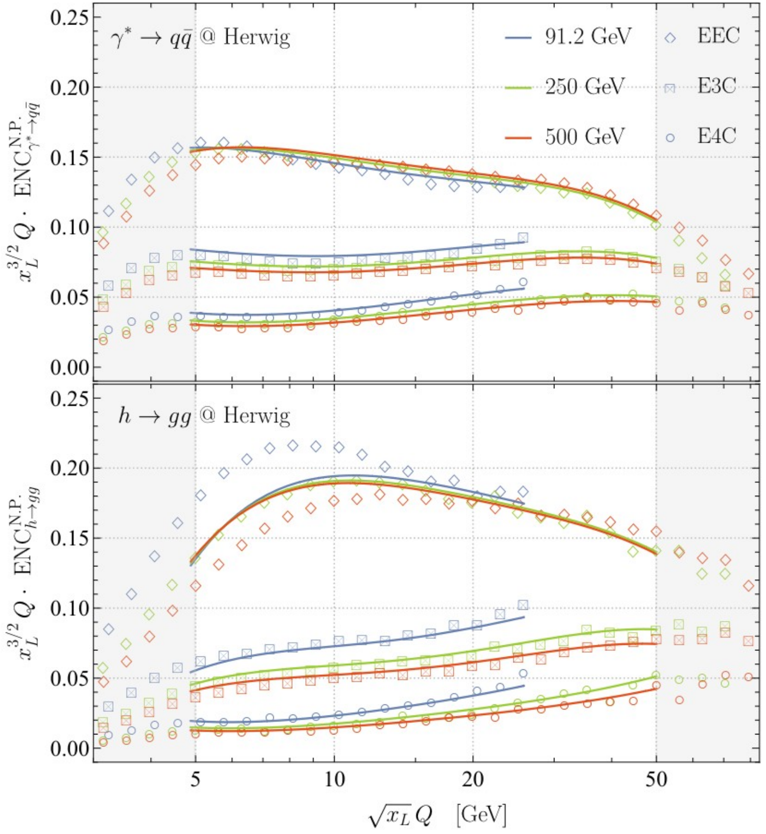
Best determination of α_s using jet substructure

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

Power corrections to the scaling regime:

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

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



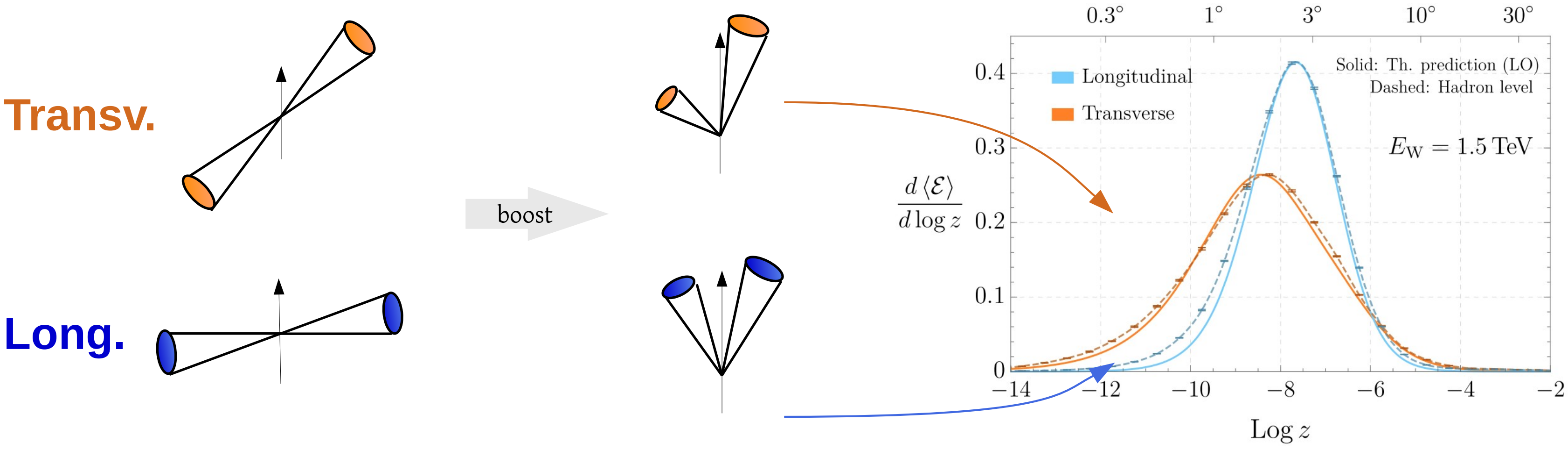
OPE structure predicts scaling of

nonperturbative corrections,

which can be matched across different scales

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

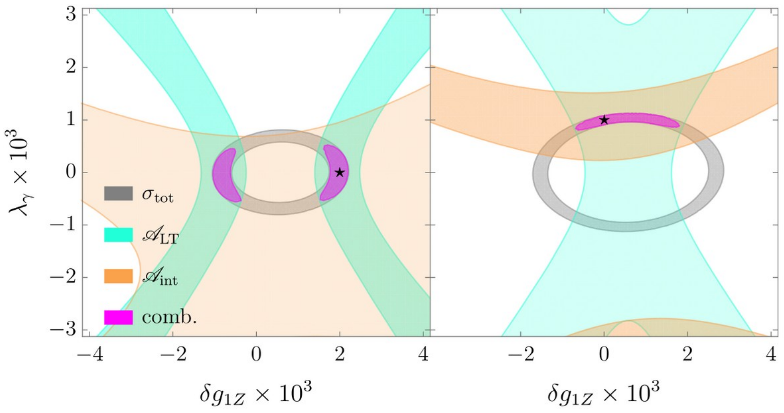
Ricci, MR ‘22



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

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

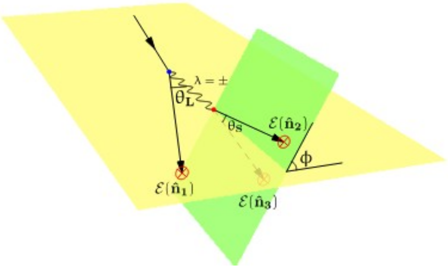
Can be used to characterize an excess:

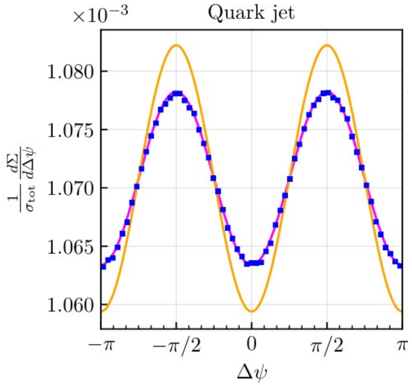


Sensitivity to helicity structure:

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

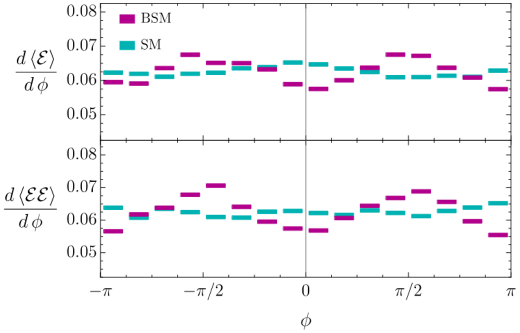
Interference in the parton shower

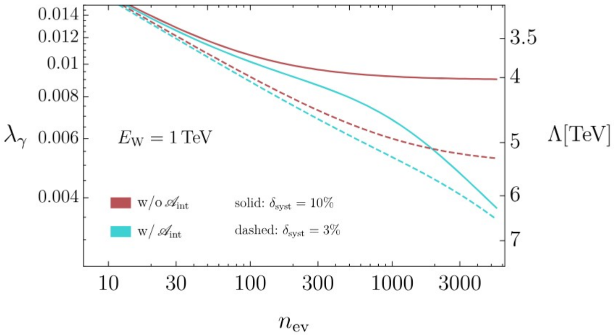




Ricci, MR '22

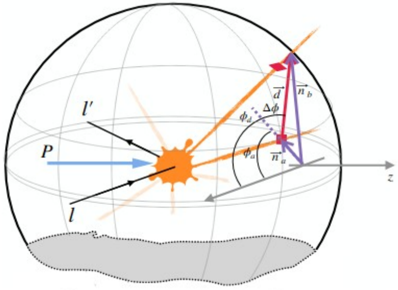
Interference of
W boson polarizations:

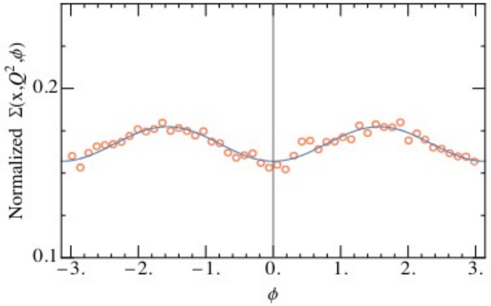




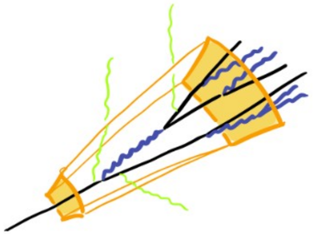
Li, Liu, Yuan, Zhu '23

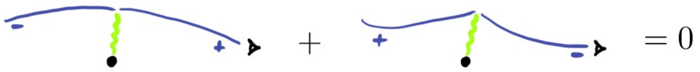
Gluon polarization in DIS



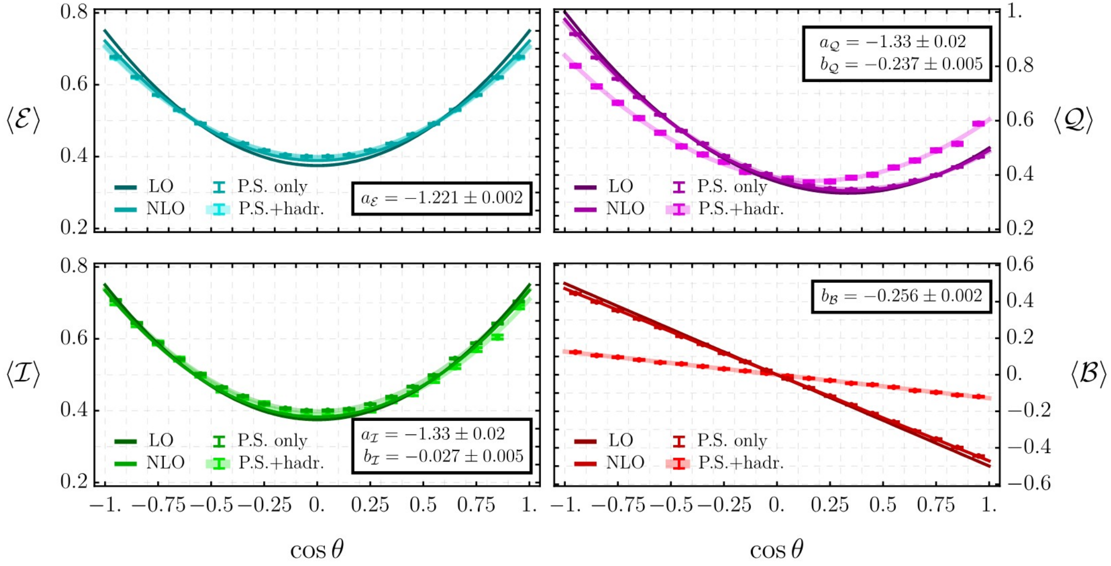


Correlators of conserved charges might be IR-safe, some one point:





MR, Son '24



... and some higher point:

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

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

Crucially, positivity and unitarity constrain the space of allowed correlators:

$$\langle \mathcal{E}_n \rangle = \frac{\langle \mathcal{E} \rangle}{4\pi} \left[1 + a_{\mathcal{E}} \left(\frac{3}{2} \sin^2 \theta - 1 \right) \right]$$

Hoffman, Maldacena '08

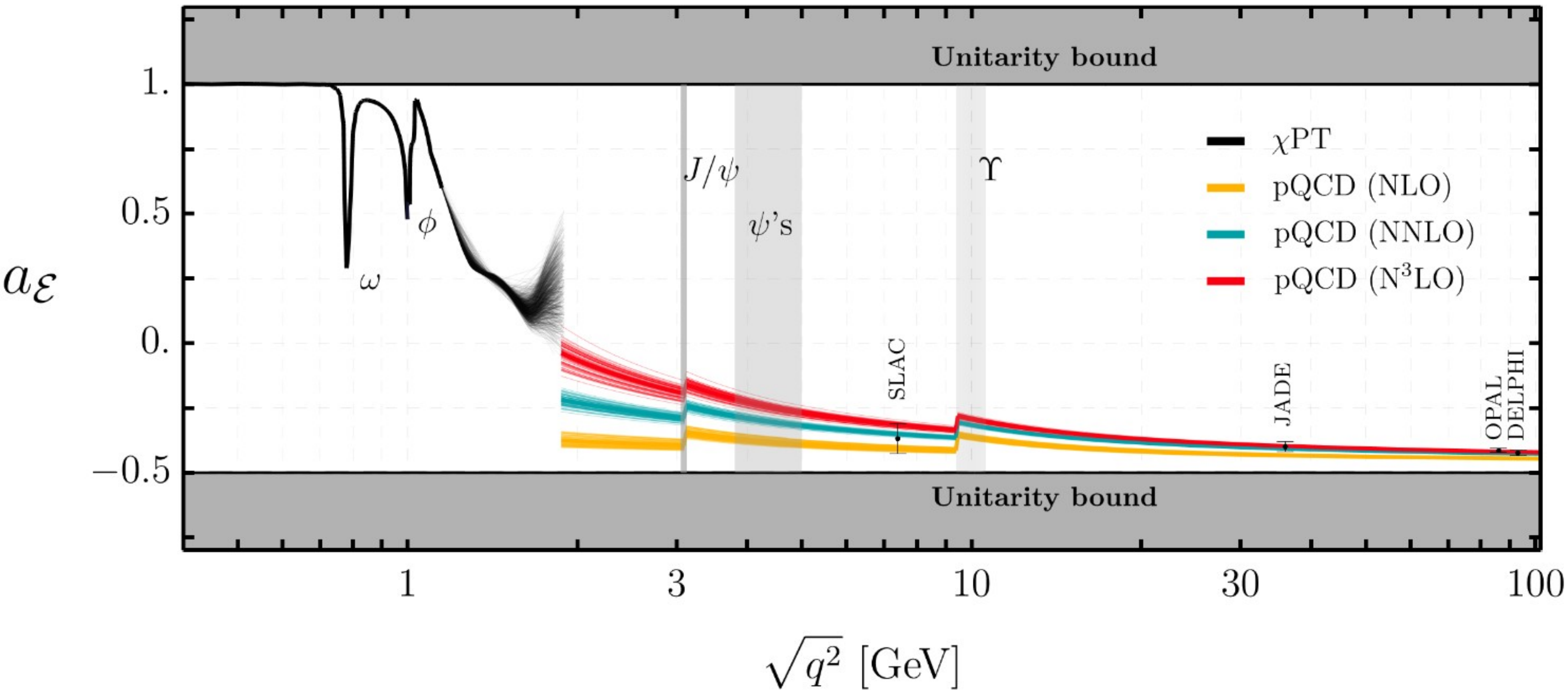
$$-1/2 \leq a_{\mathcal{E}} \leq 1$$

Saturated by a weakly coupled theory
with **fermionic** matter

Saturated by a weakly coupled theory
with **scalar** matter

QCD transitions between both regimes!

MR, Son [2509.02669]



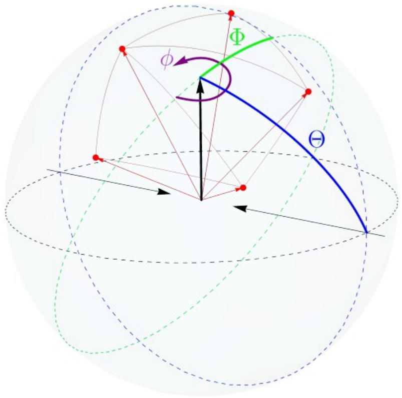
- QCD transitions between extremal correlators as it flows from UV to IR
- Future improvements on theoretical predictions at both high and low energies should be made to resolve the transition region around 2 GeV.
- The flow can be measured with currently existing data.

N-point kinematics & positivity

MR, Son [2512.16985]

- The density matrix of correlators can be written as

$$\langle \mathcal{E}_{n_1}\dots\mathcal{E}_{n_N}\rangle_{h'h} = \sum_{J=0}^{J=2}\sum_{\lambda,\lambda'} c^J(h,h',\lambda,\lambda')\ (H_{\mathcal{E}^{(N)}})_{\lambda'\lambda}(z_{ij})\ D^J_{h'-h,\lambda'-\lambda}(\Phi,\Theta,\phi)$$



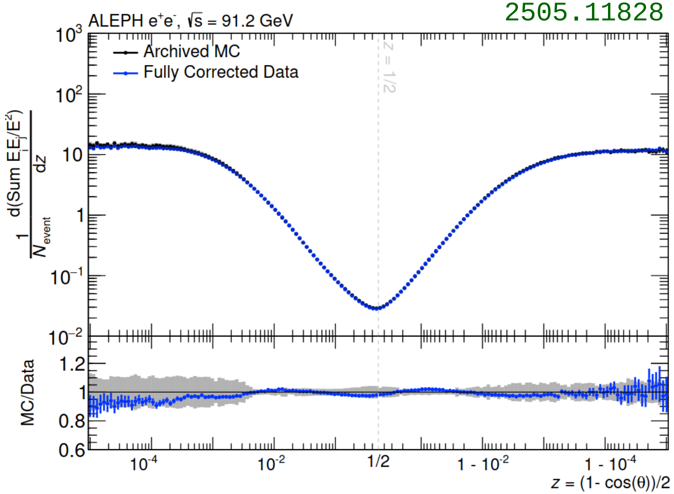
- Phase of the Wigner D-matrix depend on the polarization of the source and the polarization of the *rigid body* of detectors.
- Spinning part does depend nontrivially on the internal angles.
- Information lost for inclusive observables.

Two-point correlator

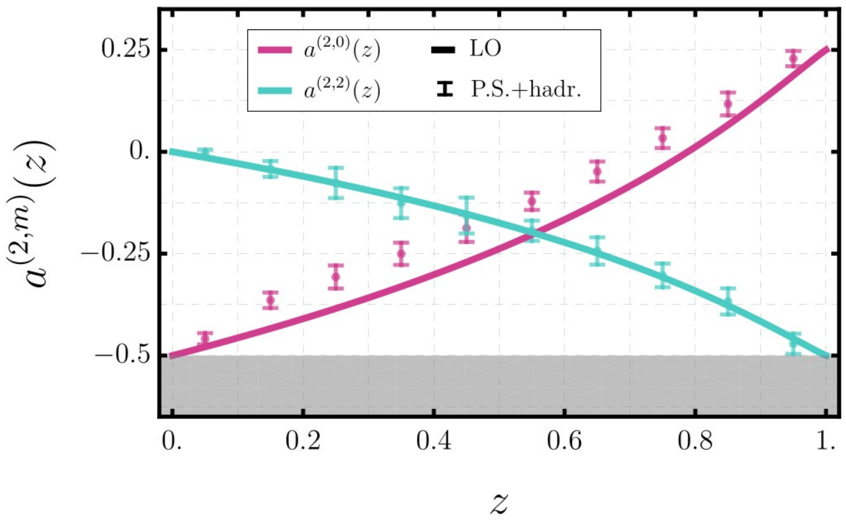
- For an unpolarized transverse source,

$$\langle \mathcal{E}_{n_1}\mathcal{E}_{n_2}\rangle = \frac{1}{4\pi}\mathrm{EEC}(z) \times \left[1 + a^{(2,0)}_{\mathcal{E}\mathcal{E}}(z)\left(\frac{3}{2}\sin^2\Theta - 1\right) - a^{(2,2)}_{\mathcal{E}\mathcal{E}}(z)\frac{3}{4}\sin^2\Theta\cos 2\phi\right]$$

2505.11828



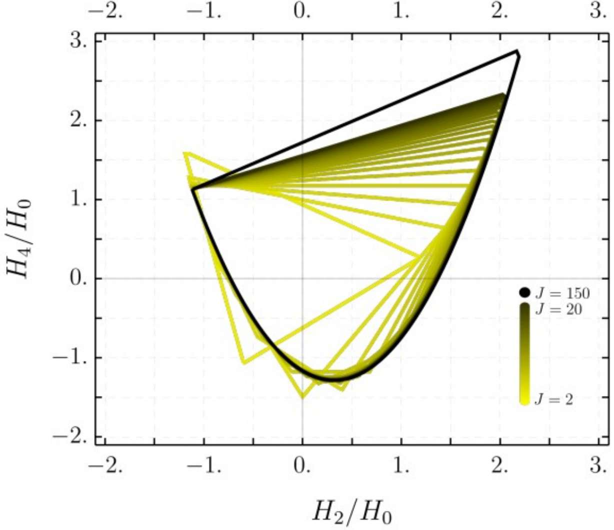
MR, M.Son, 2512.16985



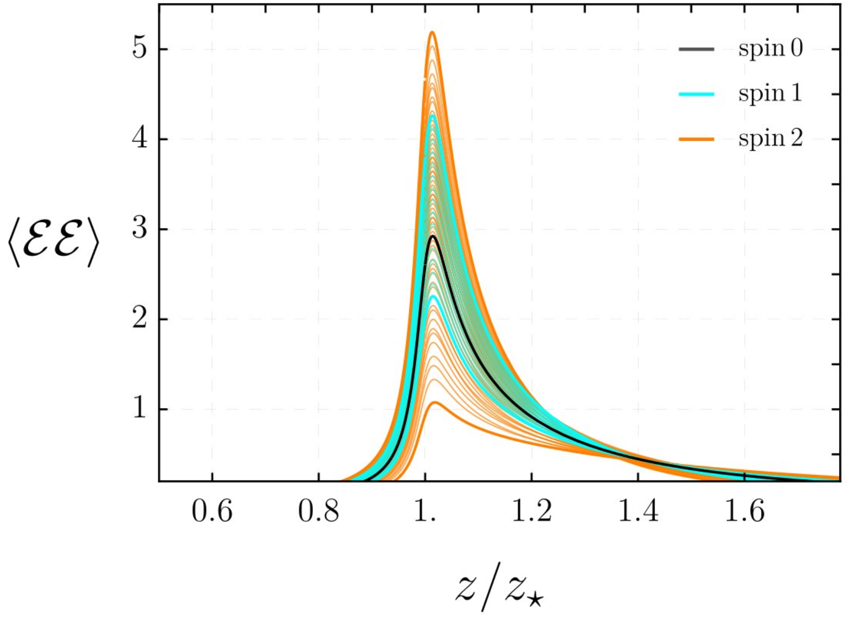
- Due to soft&coll. factorization, spinning correlators have no endpoint divergences. No need for resummation, direct probe of the hard scattering.
- Compared with the inclusive correlator, higher order and NP effects MUCH smaller. Better convergence of perturbative calculation.
- At the Z-pole, chiral structure can be recovered only via the spinning correlators.

- Positivity allows to systematically study, classify and constrain ALL space of BSM models that may leave a signal on jets

MR, Son [2512.16985]

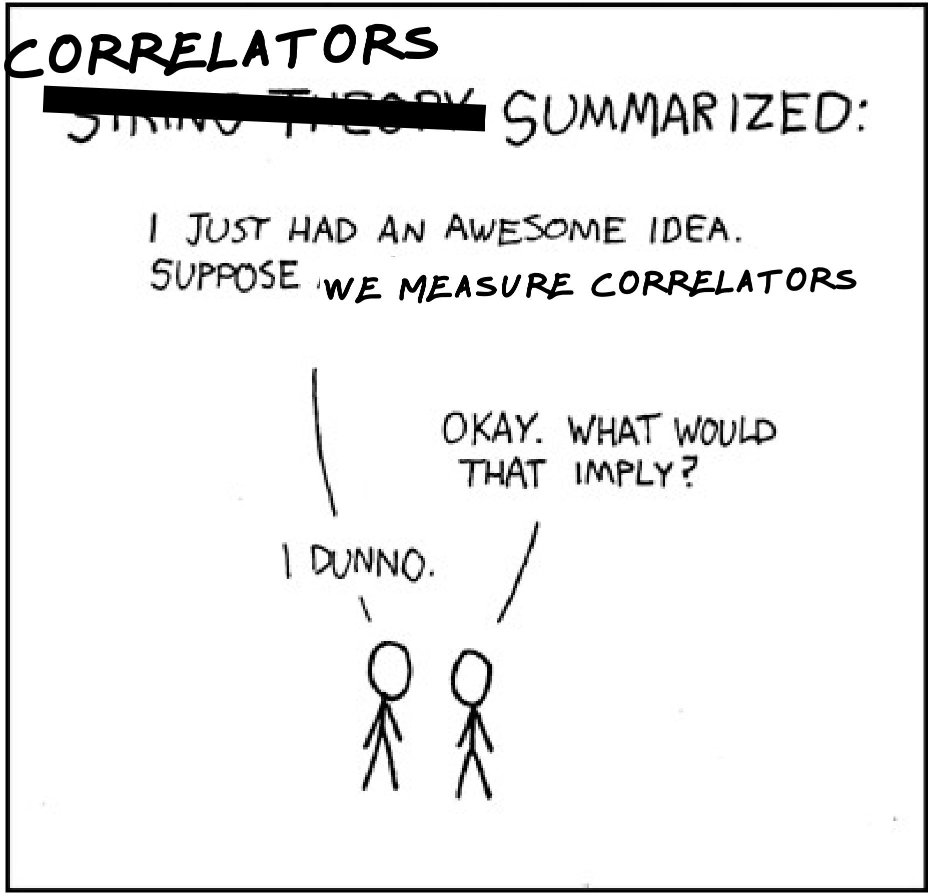


‘WIP



- Space of signals from light, boosted objects decaying to QCD fully classified via unitarity and positivity, in terms of the resonance’s mass.

Conclusions (~ early 2025)



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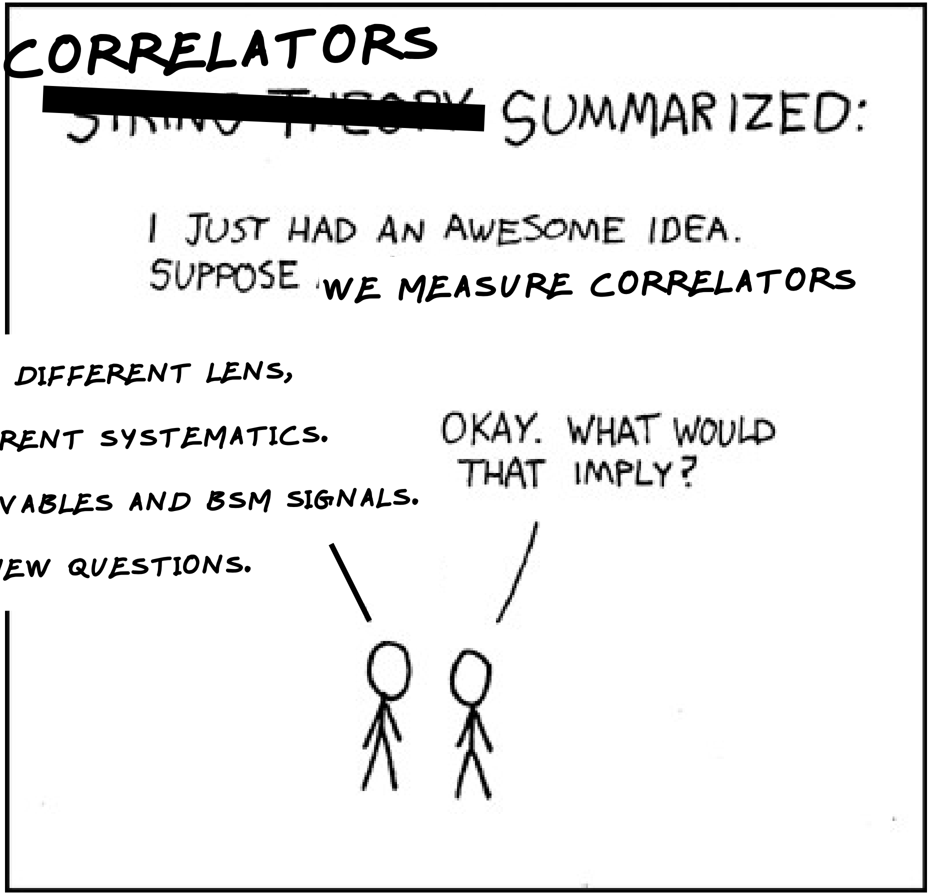

WE'LL LOOK AT COLLIDER DATA WITH A DIFFERENT LENS,

WITH DIFFERENT PREDICTIONS, DIFFERENT SYSTEMATICS.

FIRST PRINCIPLES TO CLASSIFY OBSERVABLES AND BSM SIGNALS.

GIVES THE OPPORTUNITY OF ASKING NEW QUESTIONS.