Energy-Energy Correlators in pp and AA

Simon Rothman (MIT)
for the
CMS Collaboration
ALICE Collaboration
STAR Collaboration

A thought experiment

How does physics work in your universe?

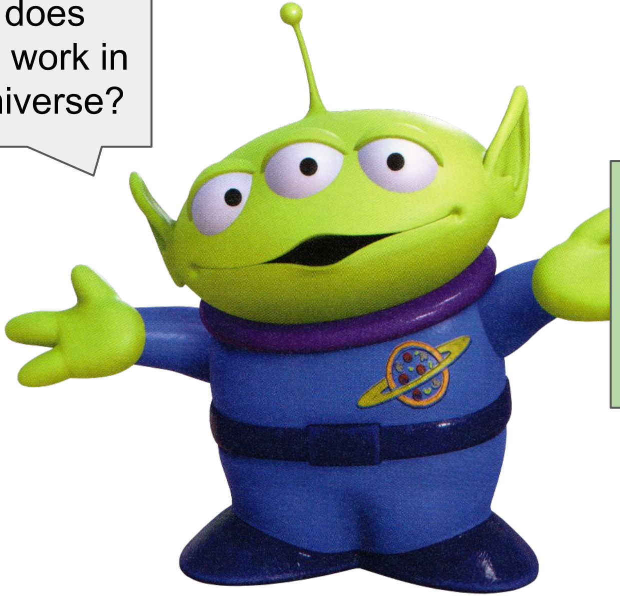
PhD
Conformal Field Theory

Alien U

A thought experiment

$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2s_w^2A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\overline{\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa} + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_jC_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_jC_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{G}^a\partial^2G^a + g_sf^{abc}\partial_\mu\bar{G}^aG^bg^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \\
\partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \\
\partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \\
\partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \\
\partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right).
\end{gathered}
$$

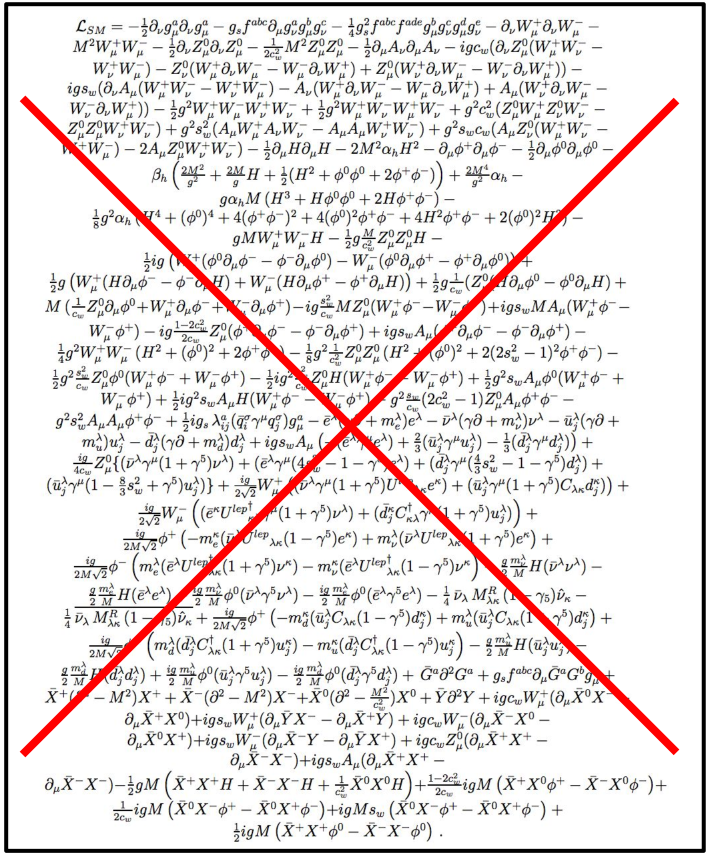
How does physics work in your universe?



PhD Conformal Field Theory

Alien U

A thought experiment



How does physics work **experimentally** in your universe?

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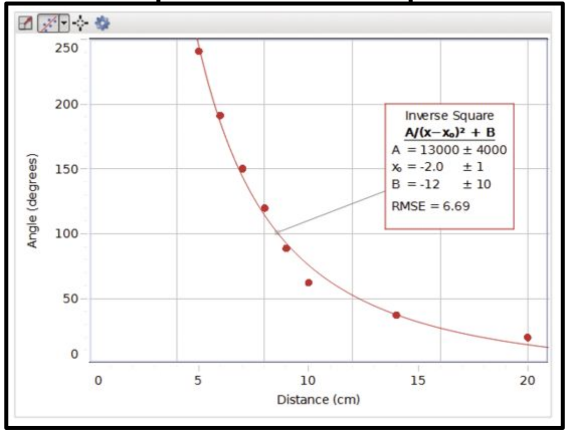
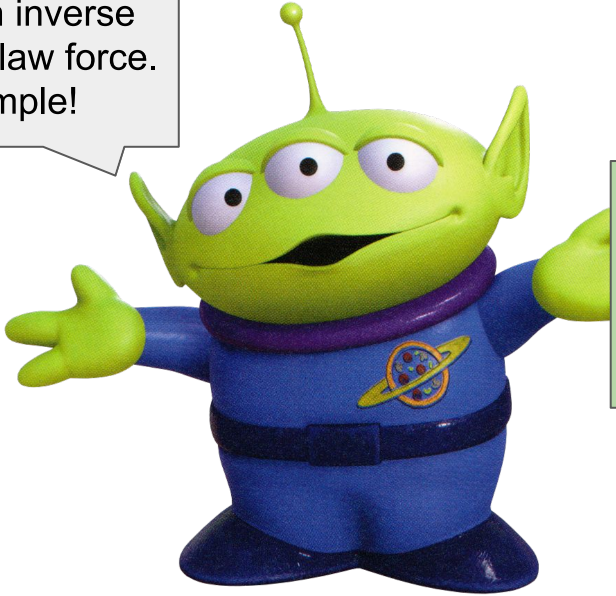
A thought experiment

Electric Force



Ah, an inverse square law force. Simple!



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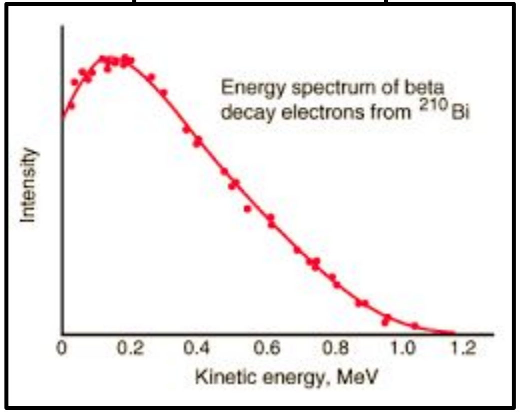
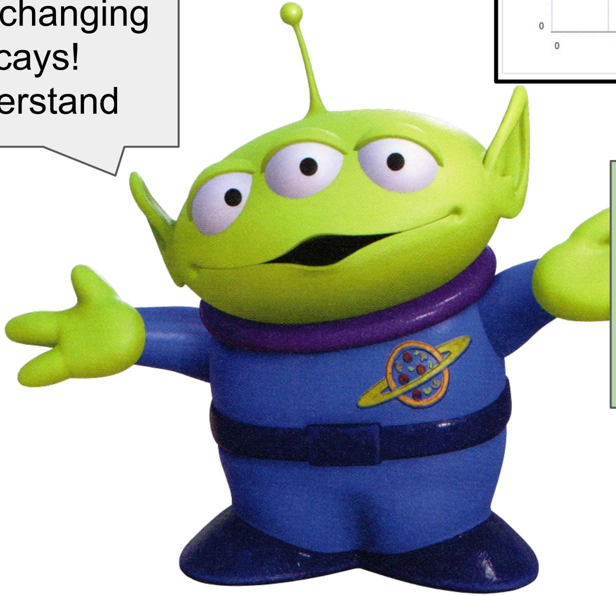
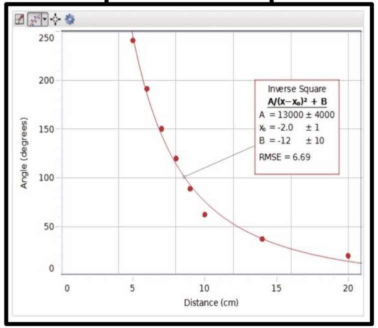
Weak Force



Flavor-changing decays!
I understand



Electric Force



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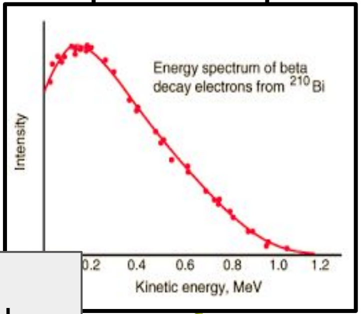
Strong Force

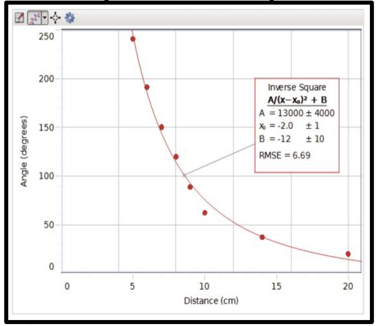
????

What experiment can we do that will **directly** reveal features of QCD??

Weak Force



Electric Force



What about the strong force?

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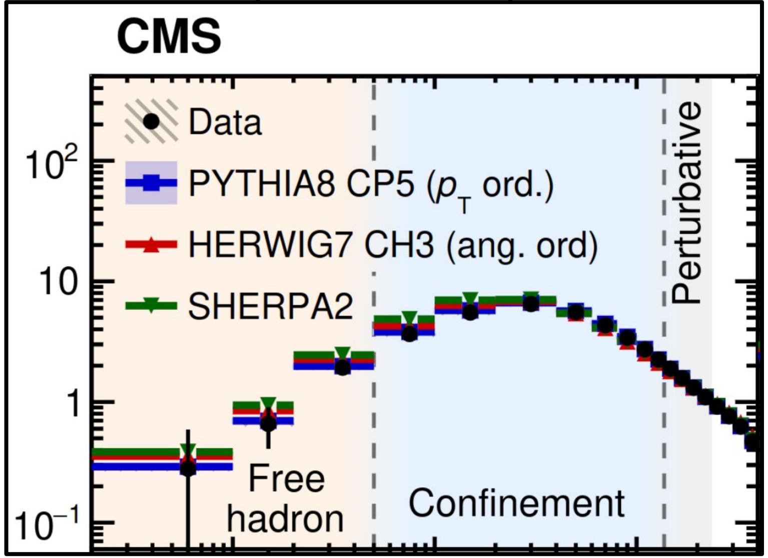
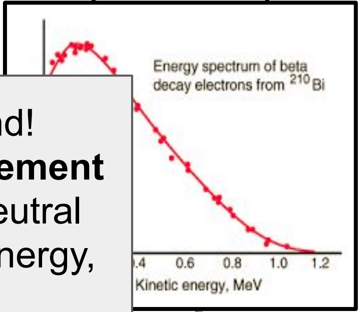
Strong Force



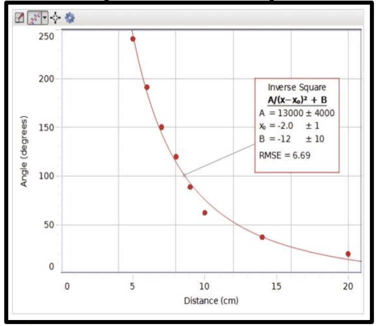
CMS-SMP-22-015 (in press)

Energy-Energy Correlators

Weak Force



Electric Force



I understand!
There's **confinement** into charge-neutral states at low energy, and
Asymptotic freedom at high energy!

PhD Conformal Field Theory

Alien U

Outline

1. What are energy-energy correlators, and why are they so important?
2. Technical challenges (unfolding, statistical relationships, …)
3. Existing measurements
4. Future directions

Outline

1. **What are energy-energy correlators, and why are they so important?**
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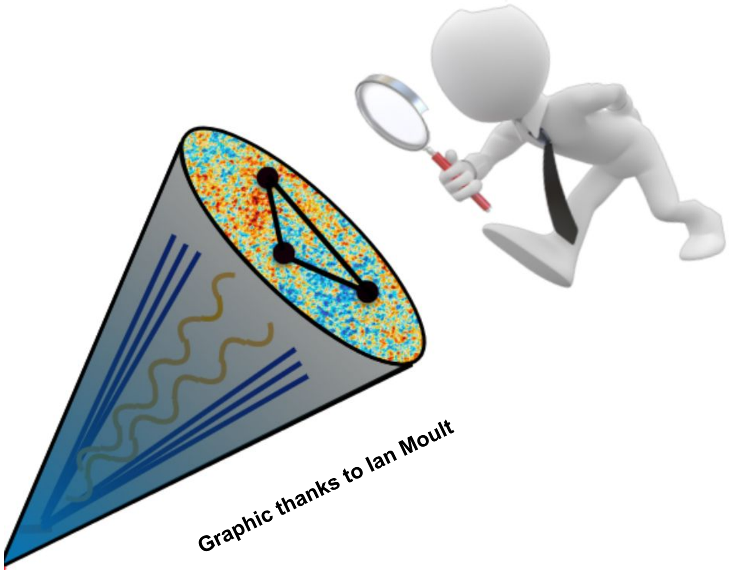
QCD experiment according to a CFT theorist

- Fundamental object of field theory is energy flow operator

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

- Flow of energy through idealized calorimeter cell located at infinity
- **From QFT perspective, jet substructure is the study of correlation functions of energy flow operators**



Phys. Rev. D 102, 054012 (2020)

Energy-energy correlators

- **Traditional observables are based on infinite sum of correlators**
  - Root of technical issues with perturbative calculations
  - Implies need for infinite moments of nonperturbative track etc functions
- Instead, we can **just measure the straightforward theoretical objects:**

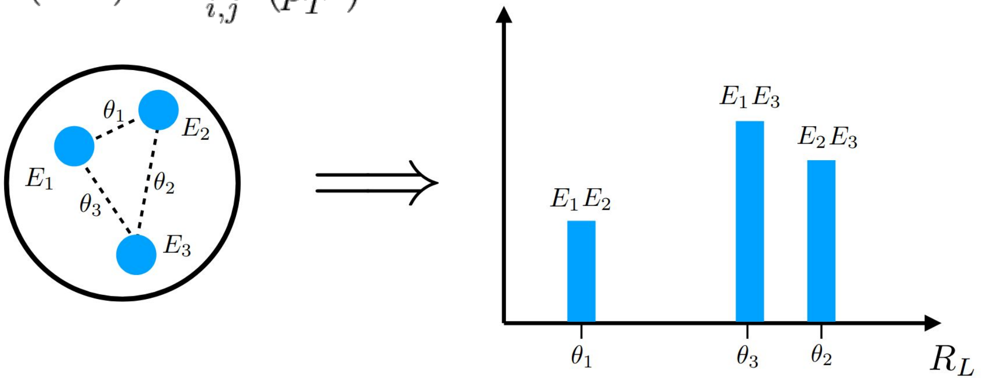
$$\langle \Psi | \mathcal{E}(\hat{n}_1) \cdots \mathcal{E}(\hat{n}_k) | \Psi \rangle$$

- **These are the energy energy correlators**
- Advantages:
  - Clean theoretical structure allows perturbative calculations to high order
  - Need only first few integer moments of relevant nonperturbative functions
  - Allows direct view of underlying QCD structure and dynamics
  - Rapidly emerging excitement and expertise growing in theory community

Measuring energy-energy correlators

- N-point correlation function measured as energy-weighted N-way correlation between configurations of particles
- **Each jet contributes a distribution in configuration space**
  - Configuration space can be projected onto longest axis for single scaling variable
- Ex: 2-point correlator depends only on angular separation between pair

$$\frac{d\Sigma}{d(\Delta R)} = \sum_{i,j} \frac{p_T^i p_T^j}{(p_T^{jet})^2} \delta(\Delta R_{ij} - \Delta R)$$



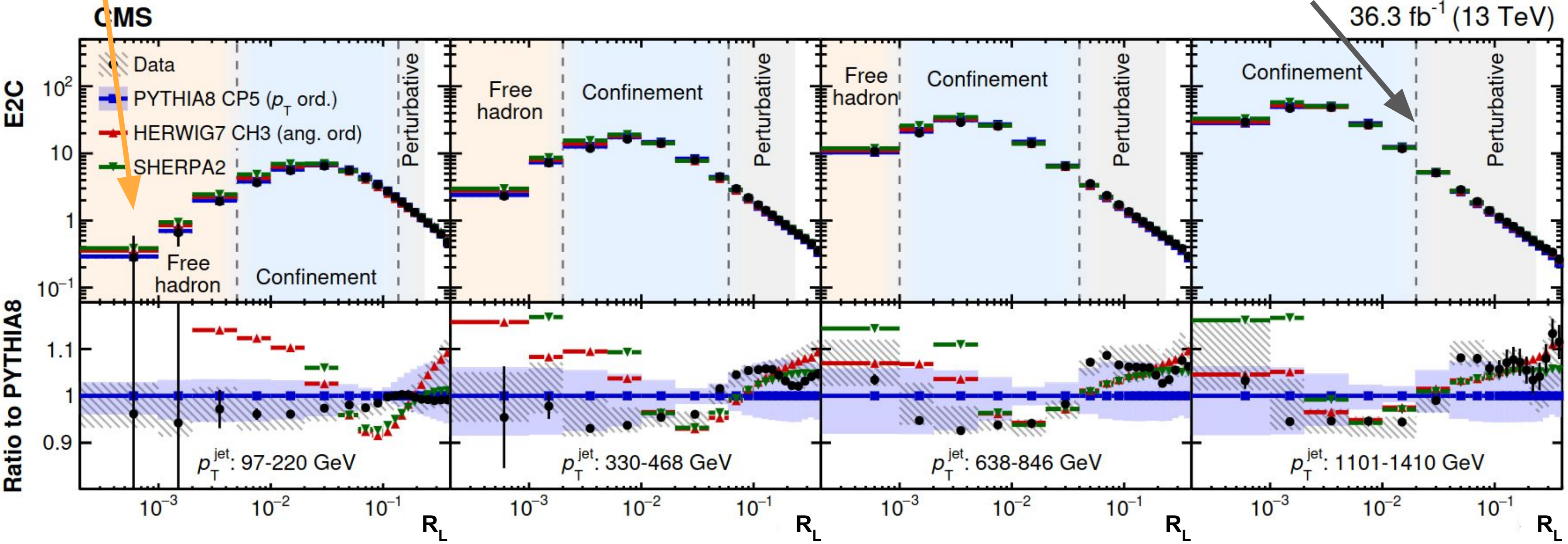
Understanding energy-energy correlators

x_L ~ splitting p_T
~ $1/t_{formation}$

Small angle
E2C ~ R_L -> uniform distribution
-> free particles

Intermediate angle
Crossover between two regimes
Confinement transition

Large angle
E2C ~ $R_L^{\text{anomalous dimension}}$
~ asymptotically free partons



Confinement transition ~ Λ_{QCD} / p_T

CMS-SMP-22-015

Outline

1. What are energy-energy correlators, and why are they so important?
2. **Technical challenges (unfolding, statistical relationships, …)**
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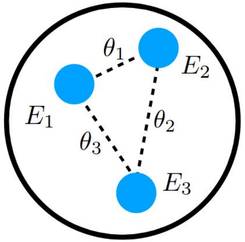
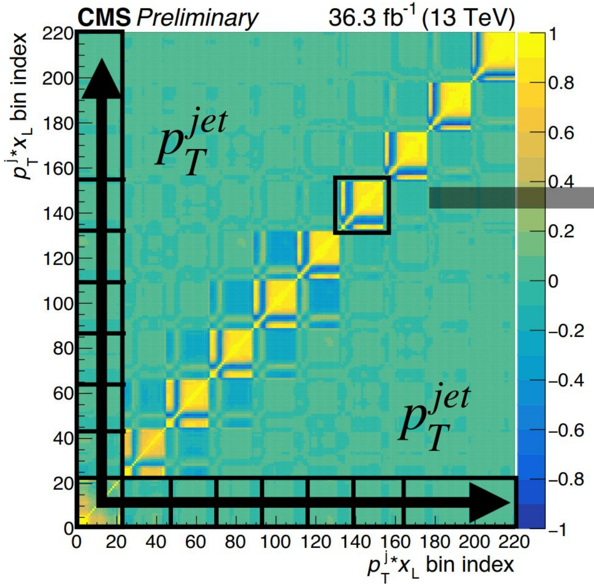
Statistical correlations

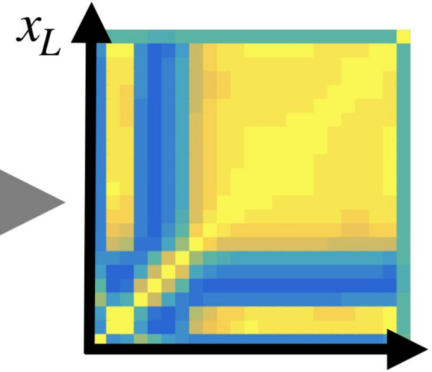
Every bin of every observable is statistically related to every other bin of every other observable



$\Longrightarrow$



E2C correlation matrix



R$_L$

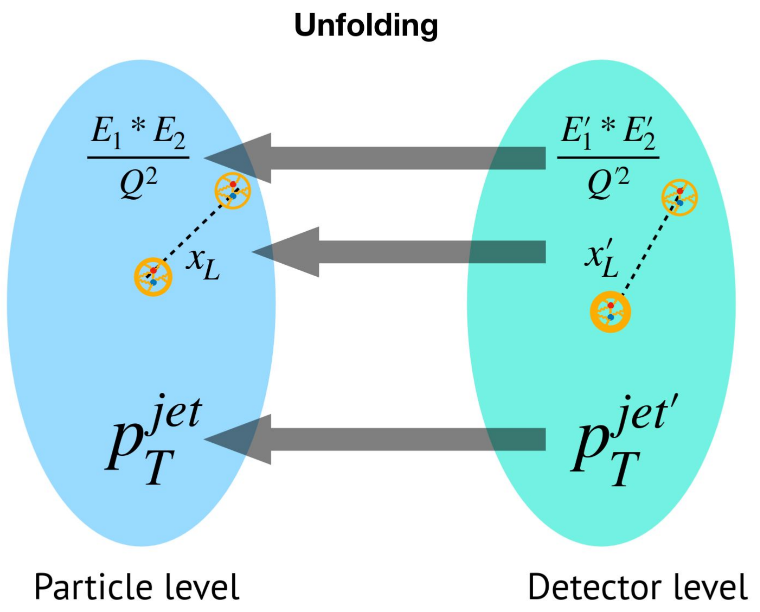
R_L bins in a p_T^{jet} region

Correlation: 80%

Figures from Meng Xiao's alphas workshop talk

Unfolding complications

- Each jet contributes distribution, rather than single number
  - Not sufficient to simply match jets from particle to detector level
  - Must account for reconstruction of **individual final-state particles**
- Most complicated for neutrals, where particle-level to detector-level mapping can be many-to-many



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Overview of current measurements

The second-order correlator has been measured at three different scales:

Experiment	Collision energy	Jet p_T range	Track only?	Citation
STAR	200 GeV	15 - 50 GeV	Yes	arXiv:2309.05761
ALICE	5.02 TeV	20 - 80 GeV	Yes	https://alice-figure.web.cern.ch/node/26341
CMS	13 TeV	97 - 1784 GeV	No	CMS-SMP-22-015

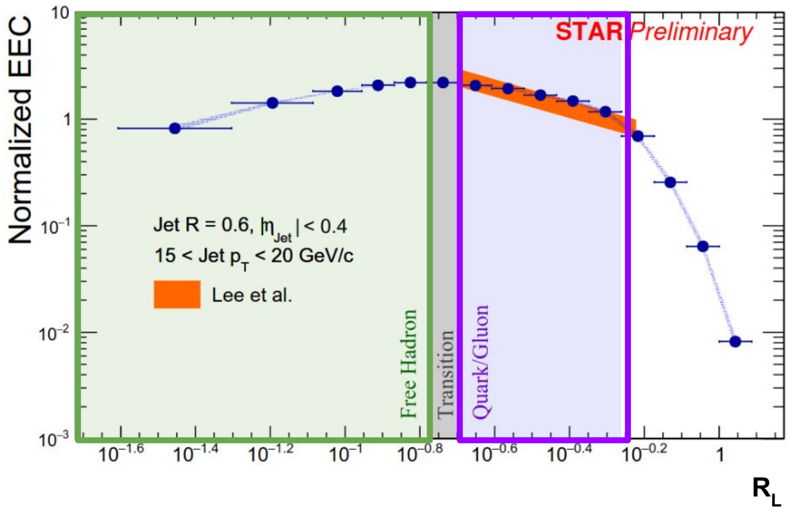
In addition, the CMS measurement also includes the third order correlator and its ratio to the second-order correlator, allowing extraction of the strong coupling

$$\frac{d\Sigma}{d(\Delta R)} = \sum_{ijk} \frac{p_T^i p_T^j p_T^k}{(p_T^{jet})^3} \delta\left(\max[\Delta R_{ij}, \Delta R_{ik}, \Delta R_{jk}] - \Delta R\right)$$

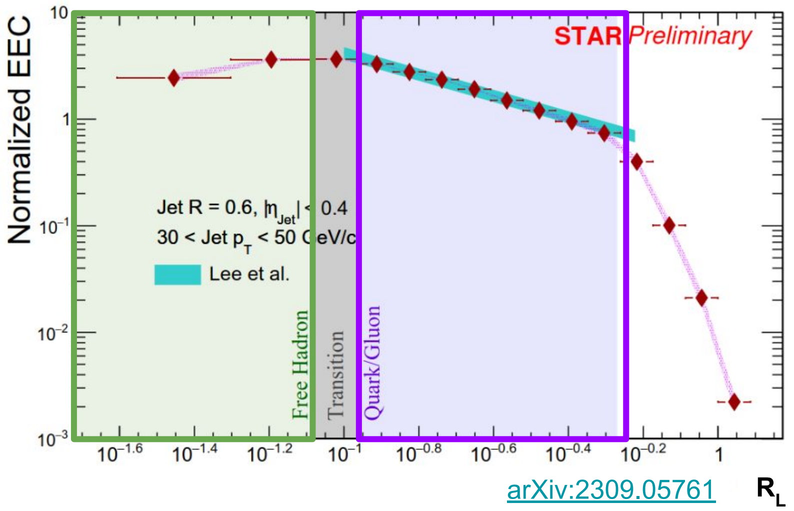
EECs at STAR

- Unfolding is performed in jet p_T, but not in R_L
- Same **free hadron**, **transition**, and **free parton** regimes as expected
- Measurement agrees beautifully with QCD calculations in perturbative regime

15 < p_T [GeV] < 20



30 < p_T [GeV] < 50



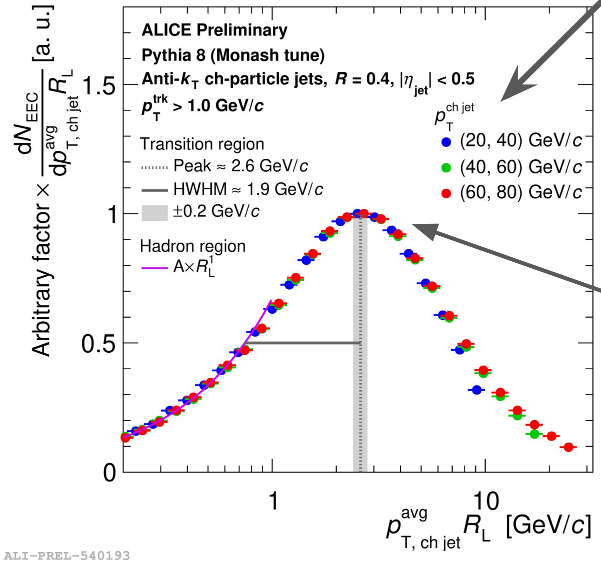
arXiv:2309.05761

EECs at ALICE

Same **free hadron** and **free parton** regimes

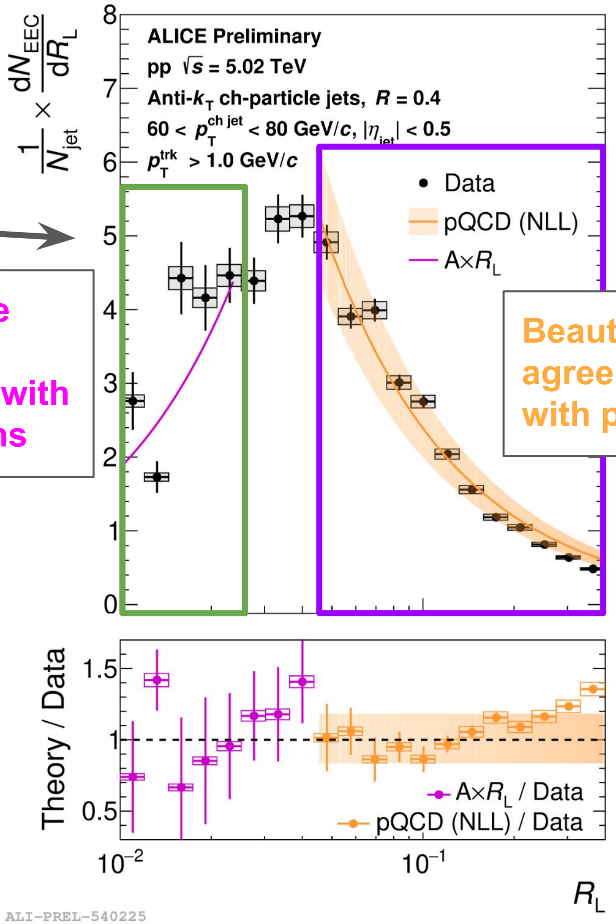
Explicit comparison with theory

Demonstration of scaling with jet p_T



Confinement at $\Delta R \sim \Lambda_{QCD} / p_T$

Small angle behavior consistent with free hadrons

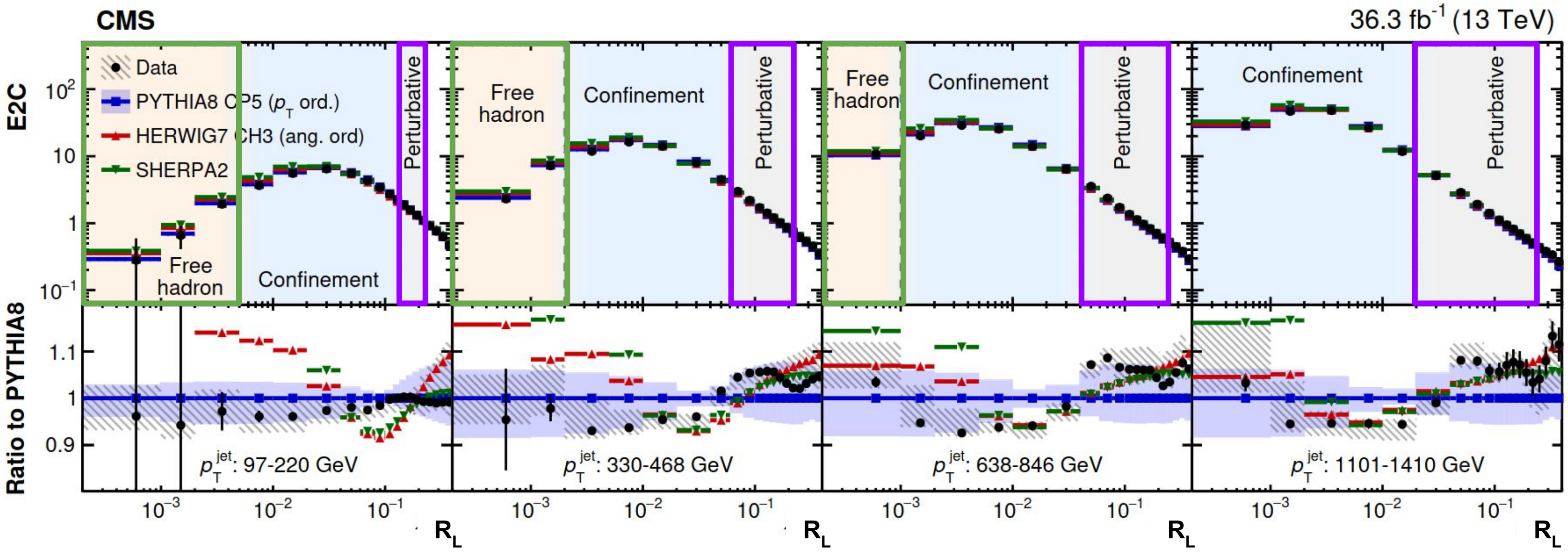


Beautiful agreement with pQCD

EECs at CMS

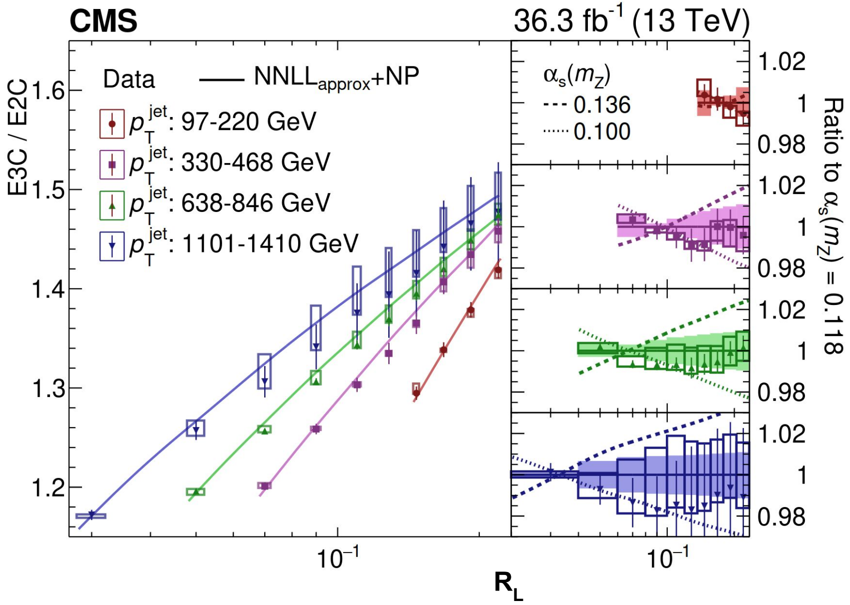
Same free hadron and free parton regimes

- Fully-unfolded in jet p_T **and** ΔR
- Agreement with Pythia8 predictions remarkably good
- Herwig7 agreement much worse (angular ordering)



Strong coupling from EECs

- Take ratio to cancel systematics
- Slope in perturbative region linear function of alpha$_S$
- Comparison with calculations at NLO + NNLL$_{approx}$ + NP allows extraction of alpha$_S$
- Most precise extraction of α_S from jet substructure to date



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

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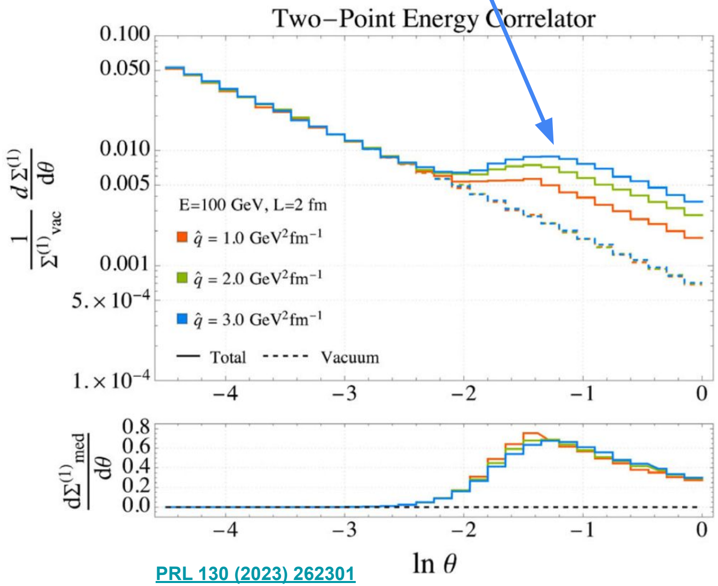
But what about "and AA"?

- pp measurements are just the first step!

- Will be sensitive to:
  - Jet wake (PRL 132 (2024) 01190)
  - Color coherence (PRL 130 (2023) 262301, JHEP 09 (2023) 088)
  - Modification of jet shapes due to medium interactions (arXiv:2308.01294)

Medium scales clearly imprinted in correlator!

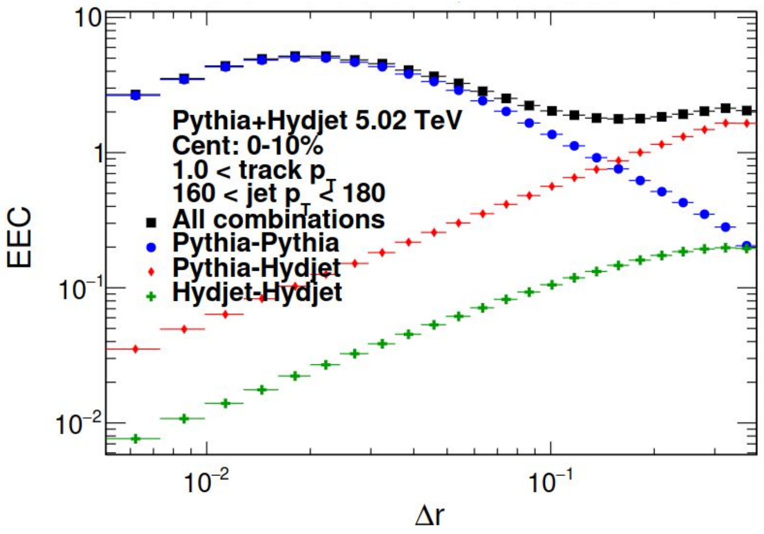


PRL 130 (2023) 262301

The challenges in HI

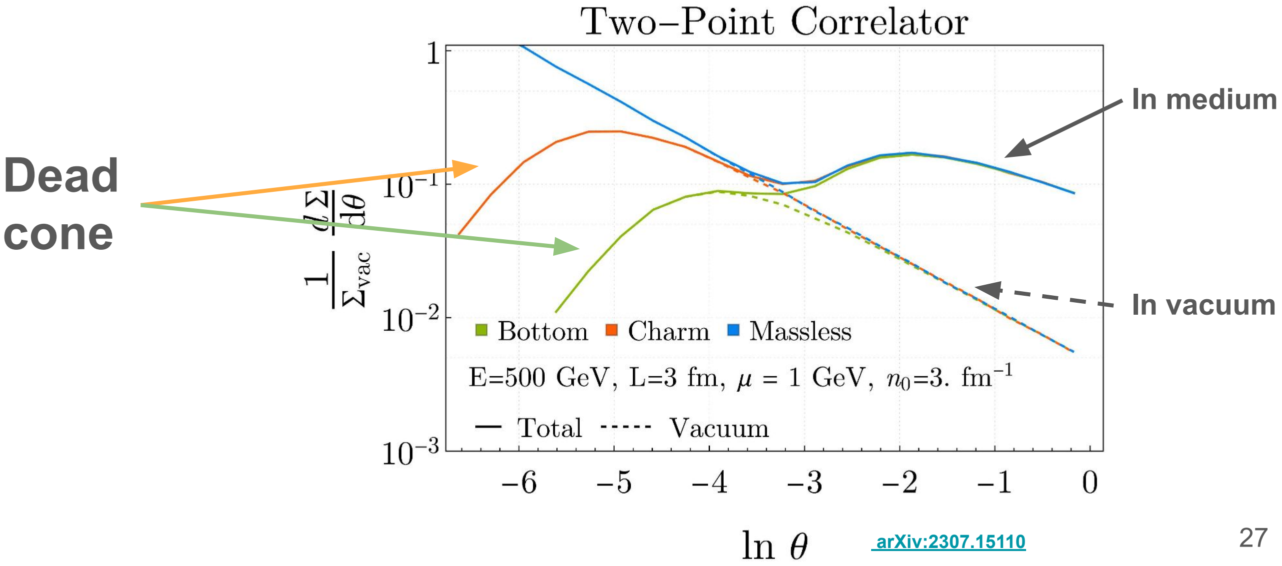
- Lots of additional complications in HI collisions:
  - Jet quenching can lead to weird biases in jets from dijet triggers
  - **Huge additional background from underlying event**
- Need to estimate and subtract these backgrounds, and handle them appropriately in the unfolding

From Jussi Viinikainen's talk at the Winter Workshop on Nuclear Dynamics 2024



Other exciting possibilities

- **Heavy flavor jets** expose mass effects
  - Requires understanding and unfolding of b-jet tagging and influence on the EEC distributions
  - Directly sensitive to dead cone effect (arXiv:2307.15110)
  - Could be most interesting in HI collisions



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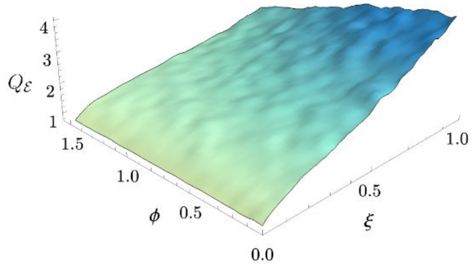
  - Can be resolved in the larger configuration space to see shape-dependencies
  - Sensitive to non-gausianities (arXiv:2205.02857), interference effects from gluon spin (arXiv:2011.02492)

CMS Open Data, $R_L \in (0.3, 0.4)$



(a) arXiv:2205.02857

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  - Sensitive to non-gausianities (arXiv:2205.02857),
    interference effects from gluon spin (arXiv:2011.02492)
- **Measurements with EM initial states** probe much cleaner environment
  - Can have little-to-no background from UE, PU
  - Allows access to back-to-back limit, event topology analysis
  - Can be seen in e.g. UPC collisions at LHC, e+e- collisions at ALEPH (see their poster)

Conclusions

- Energy-energy correlators are a powerful tools for high-precision experimental QCD with strong theoretical interpretability
- Multiple HEP collaborations (STAR, ALICE, CMS) have undertaking measurements of these observables in pp collisions, which are already sensitive to important features of QCD
- Lots of exciting possibilities on the horizon
  - HI collisions
  - Heavy flavor jets
  - Shape dependencies in higher-order correlators
  - Collisions with EM initial states

Backup

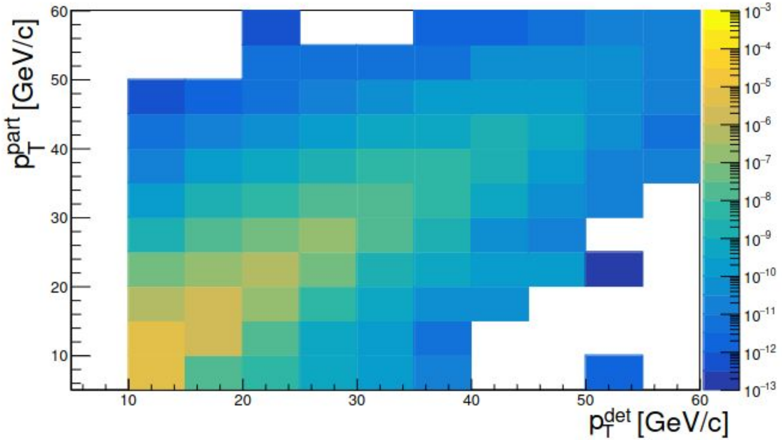
More details about the STAR measurement

Measurement is unfolded in jet pT

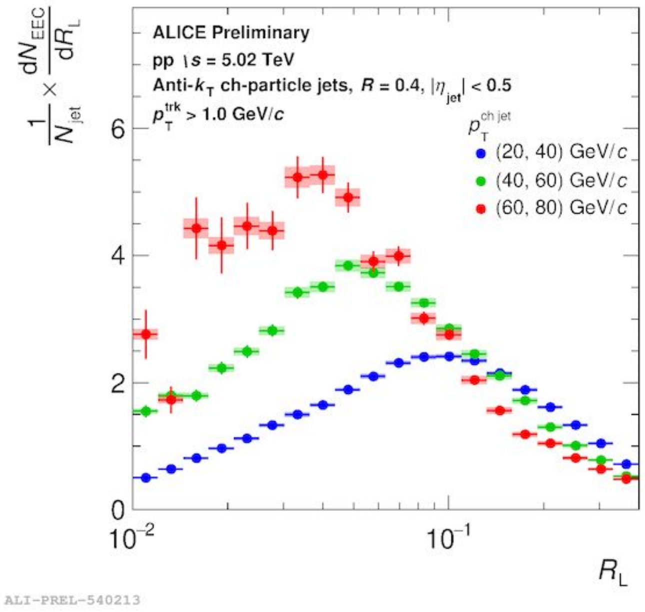
Systematics include

- Tracking efficiency
- Detector simulation parameters
- Energy corrections
- Maximum difference between matching jets at truth-level and detector-level thanks to unmodeled effects in R_L, particle energies

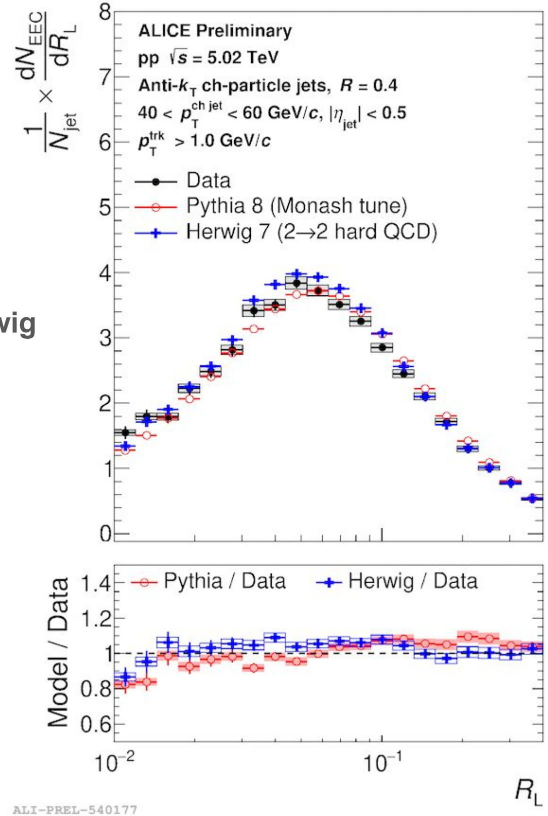
Dominant systematic (~5%)



More details about ALICE measurement



Pythia, Herwig modeling remarkably good



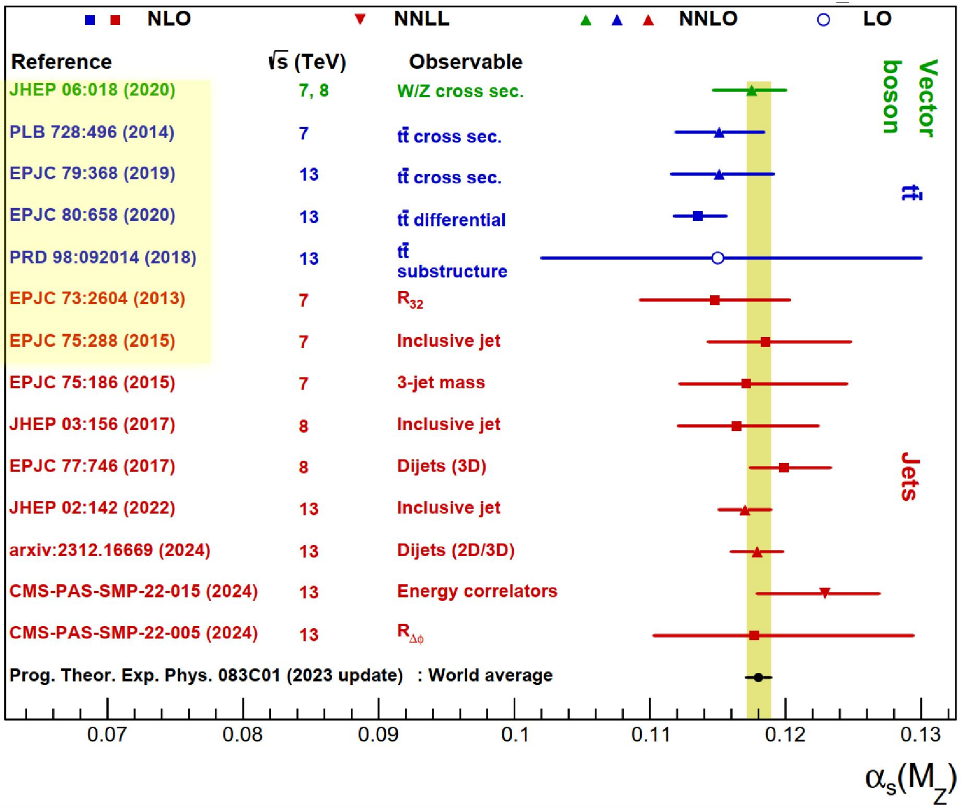
More details about CMS measurement (1)

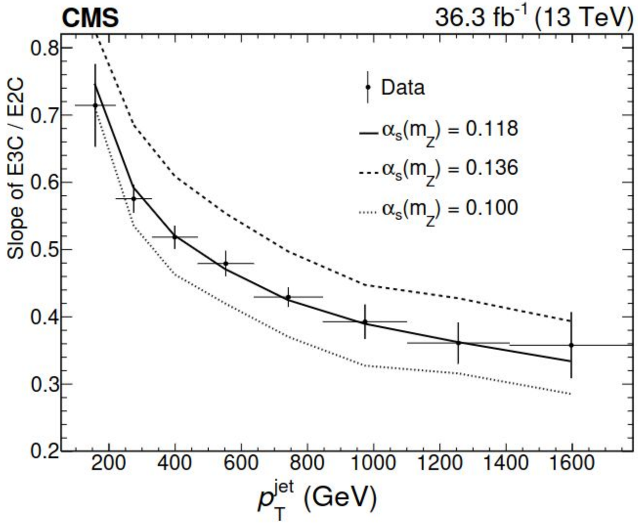
Systematics include

- Theoretical uncertainties (factorization scale, PS, UE scales, PDFS, …)
- Experimental uncertainties (particle energy scales, tracking efficiency, …)
- Modeling uncertainty in construction of response matrix

Dominant uncertainty is from pythia vs herwig modeling in construction of response matrix

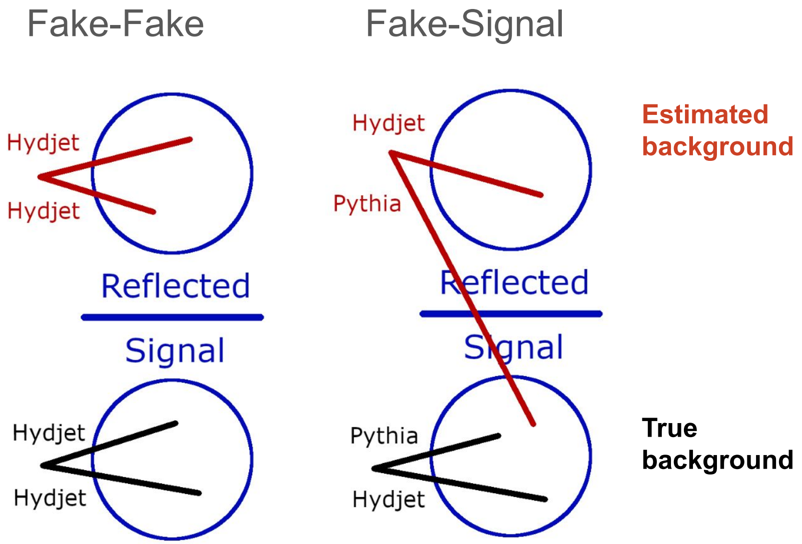
More details about CMS measurement (2)





Handling UE backgrounds in HI events

- Use reflected eta cone to characterize UE
- Two kinds of background



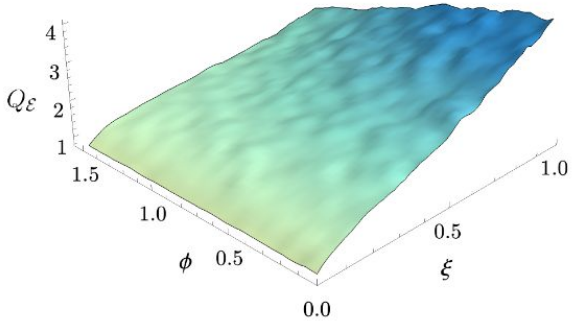
Background can be handled by appropriate thresholds in jet p_T

For more details, see Jussi Viinikainen's talk at the Winter Workshop on Nuclear Dynamics 2024

Higher-order correlators

- Higher-order correlators probe higher-order QCD dynamics
  - They can be resolved in configuration space to see shape-dependence in QCD
- Sensitive to:
  - non-gaussianities (arXiv:2205.02857)
  - Interference effects from gluon spin (arXiv:2011.02492)
  - …
- Higher-dimensional objects pose additional challenges in unfolding, this is in progress
  - Need to carefully handle detector effects for all particles in configuration, and propagate to EEC
  - Many more bins -> additional technical challenges

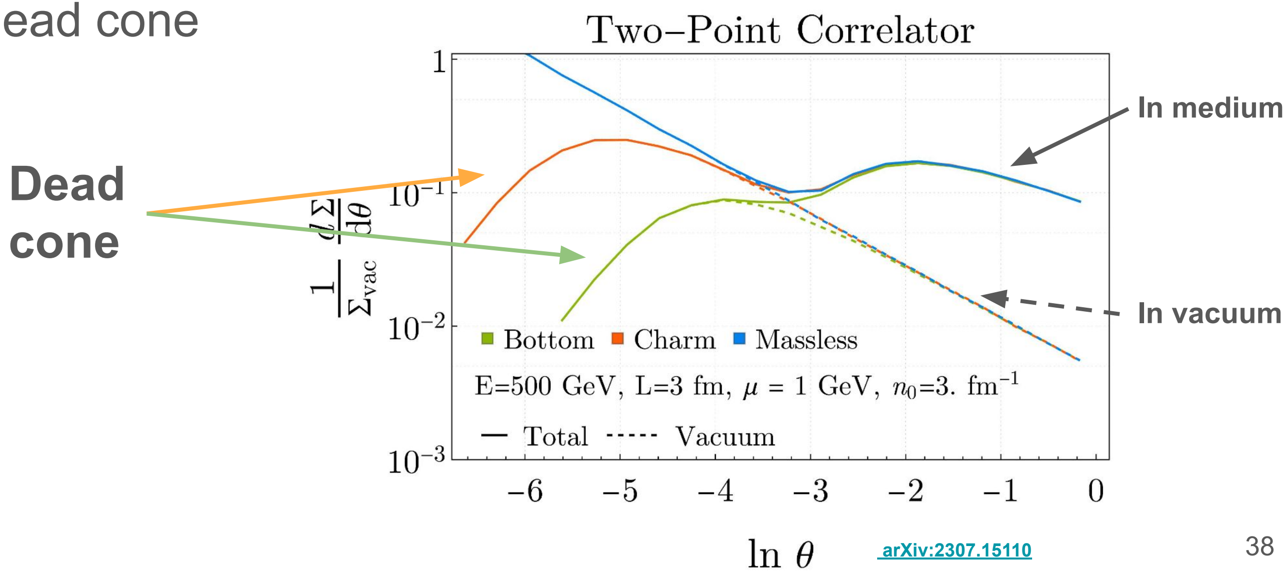
CMS Open Data, $R_L \in (0.3, 0.4)$



(a) arXiv:2205.02857

Mass effects

- Energy-energy correlators are sensitive to mass effects in heavy jets
- Should directly show dead cone effect
- Mass effects in HI collisions will be particularly interesting, as medium effects will partially fill the dead cone

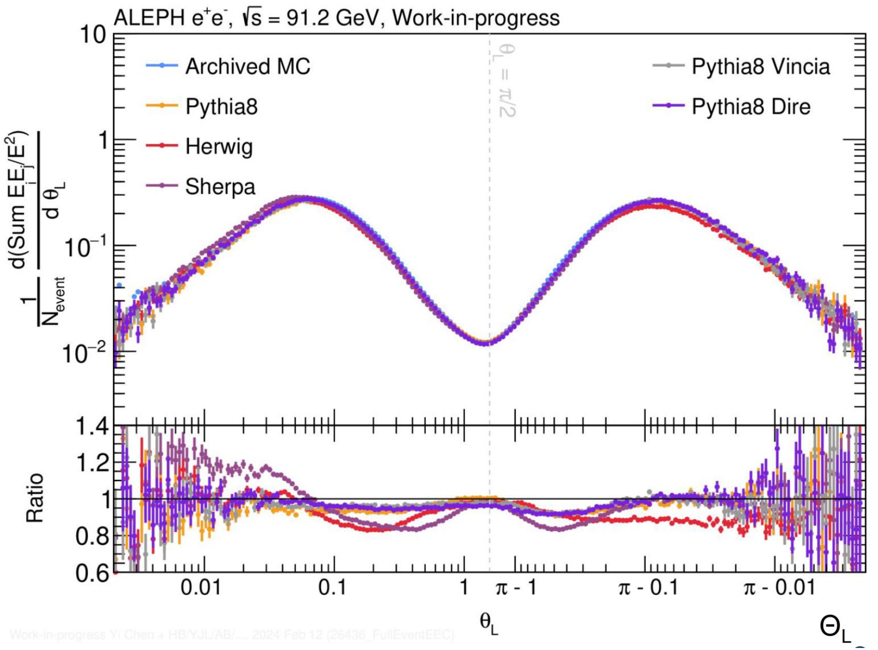


arXiv:2307.15110

Other initial states

- Addition of new triggers for ultra-peripheral PbPb collisions in CMS Run 3 allow running the CMS experiment as a photon-photon collider
- This data could have three major benefits:
  - Little to no background from UE and PU
  - Enhancement in heavy flavor
  - Access to the back-to-back limit, event topology analysis
- Similar benefits can also be seen in an analysis in e^+e^- data

E+e- simulation



x-axis goes all the way to back-to-back!