

Conformal Colliders Meet the LHC

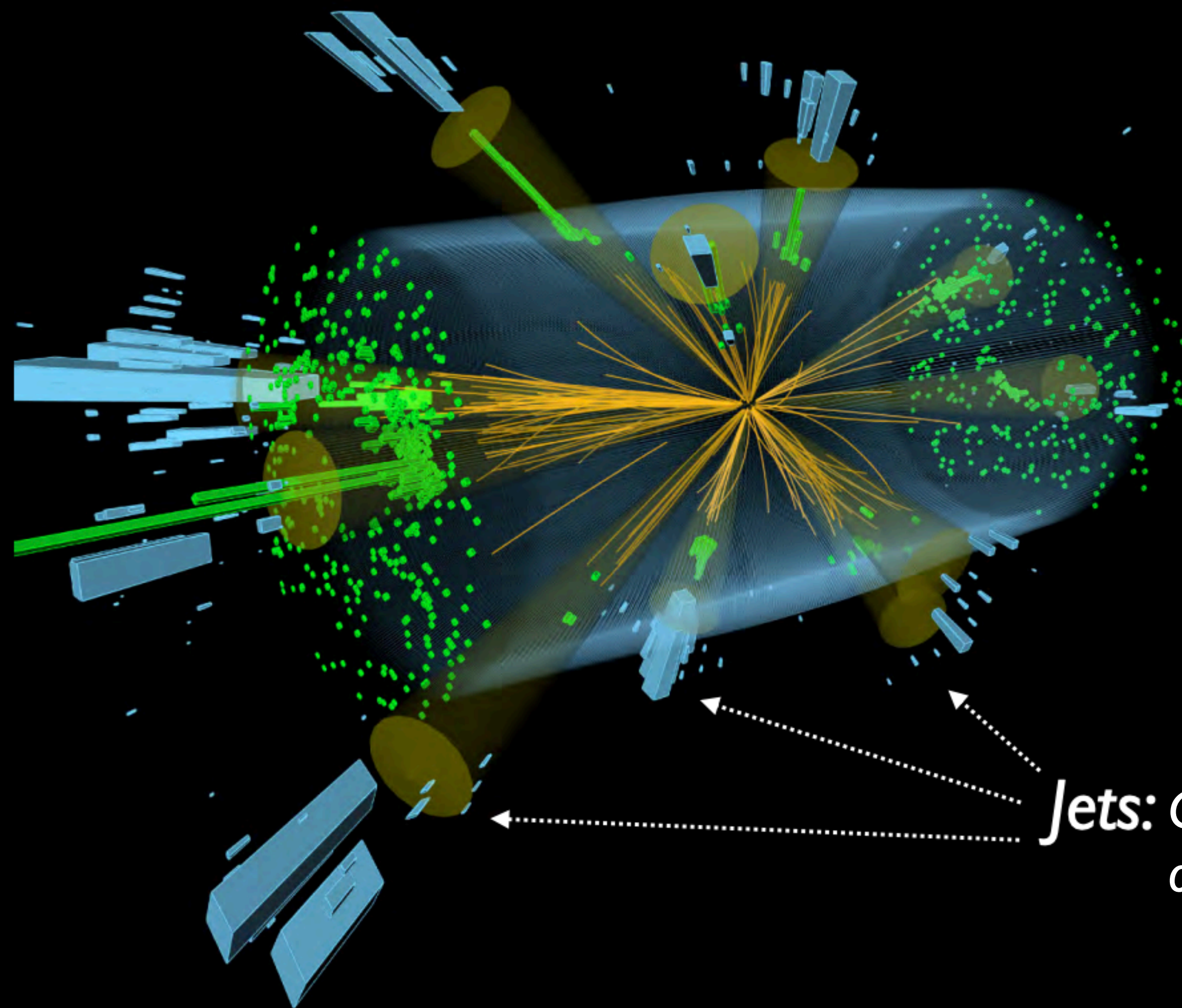
Kyle Lee

LoopFest XXIV
05.28.2026



Argonne

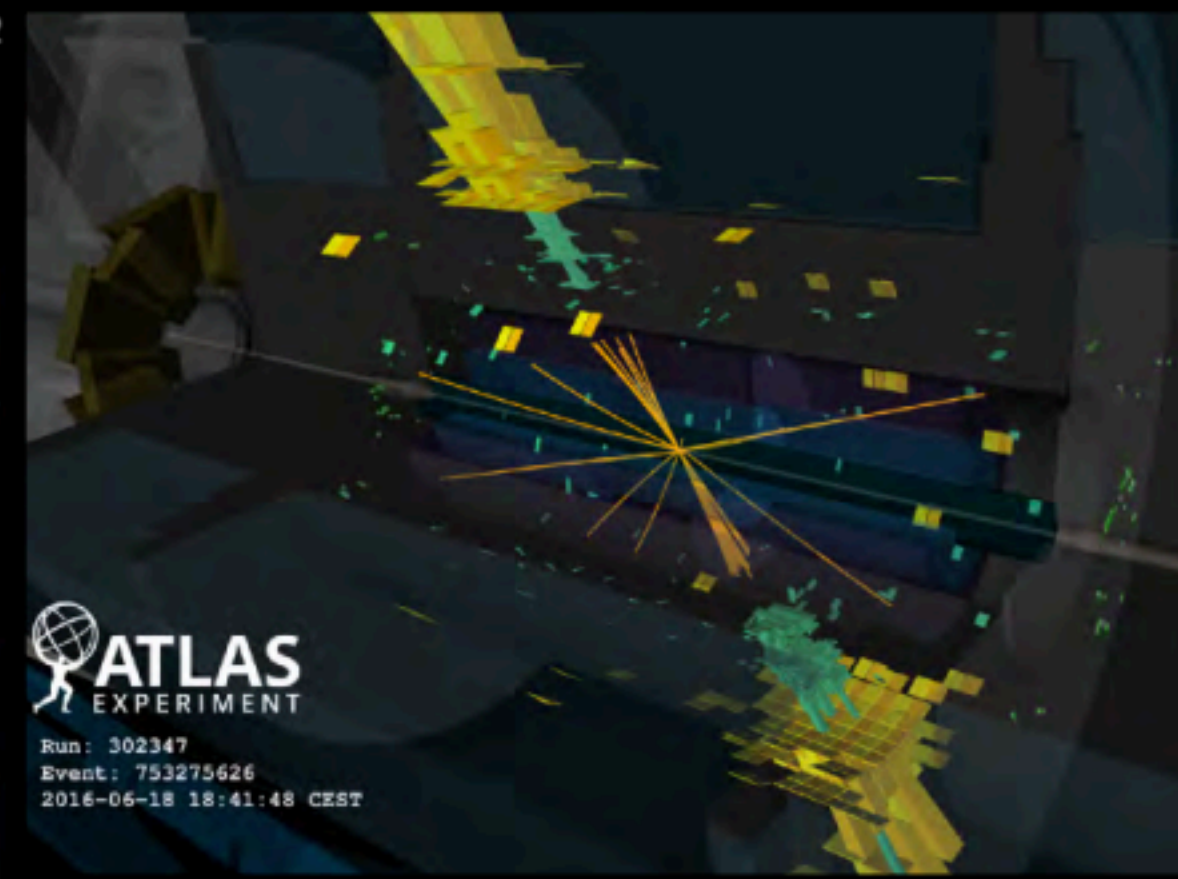
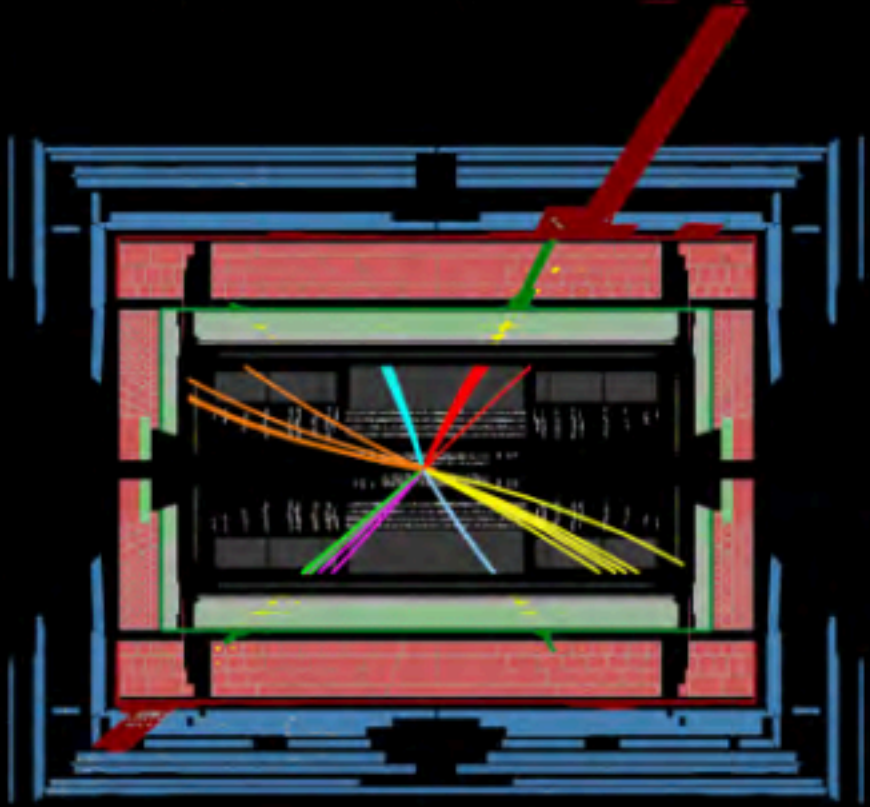
Collider Event



Jets: Collinear spray of Hadrons

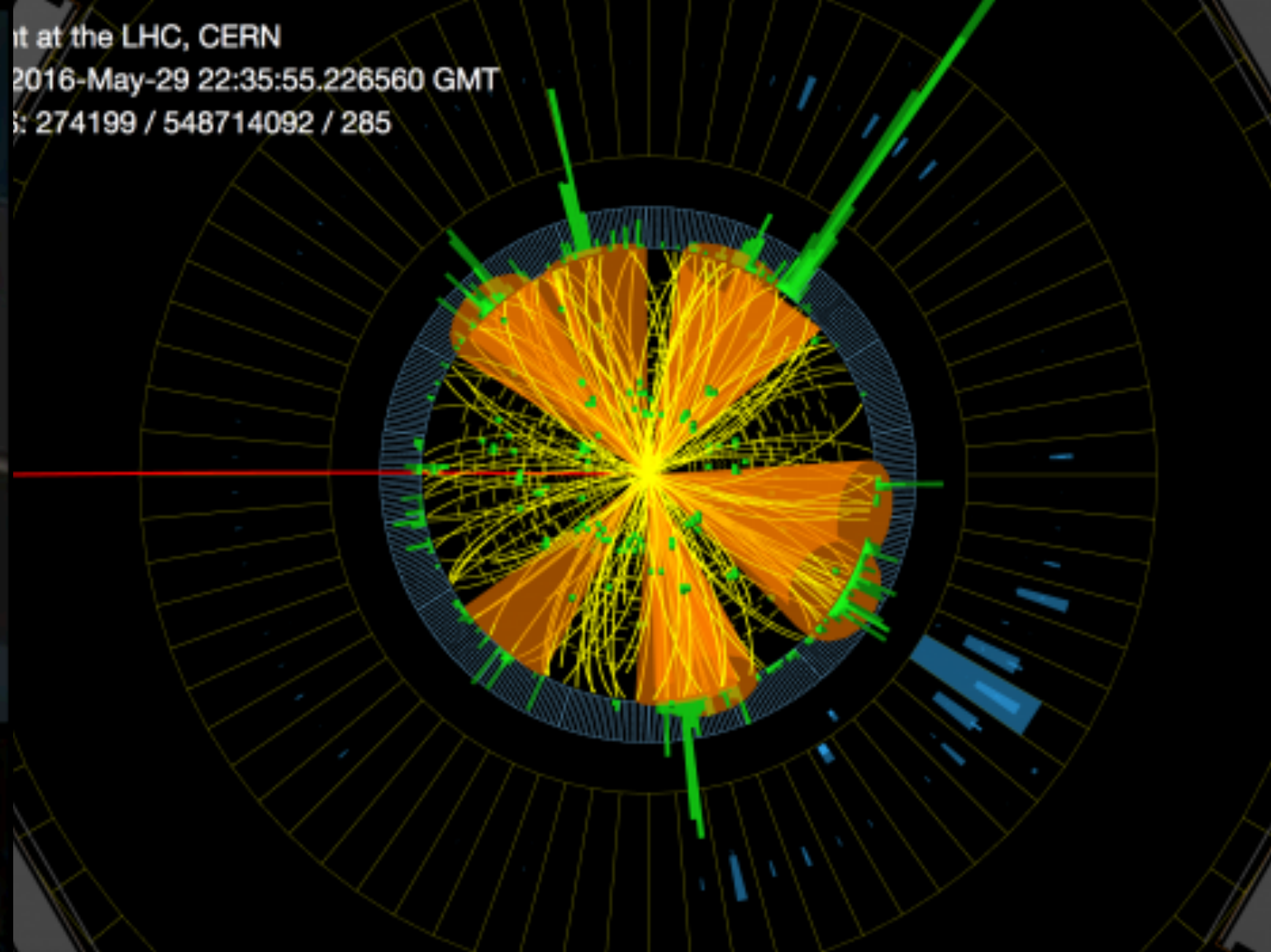
T	E	H	M	Symbol	Name	Category
	●			γ	photon	elementary
●	●			e^{\pm}	electron	
●	●	●	●	μ^{\pm}	muon	
●	●	●		π^{\pm}	pion	composite
●	●	●		K^{\pm}	kaon	
	●	●		K_L^0	K-long	
●	●	●		p/\bar{p}	proton	
	●	●		n/\bar{n}	neutron	

Run Number: 159224, Event Number: 3533152
Date: 2010-07-18 11:05:54 CEST

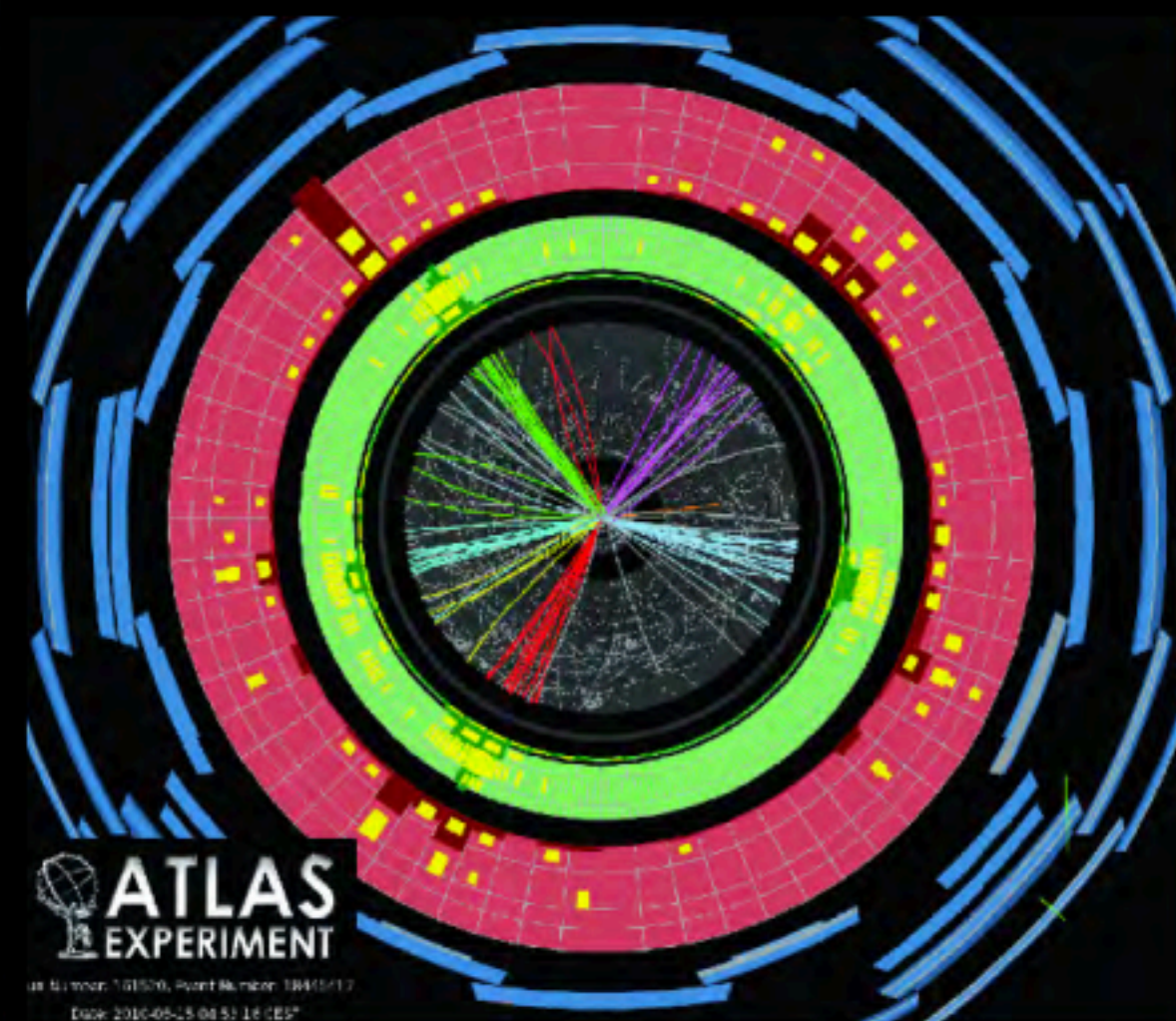
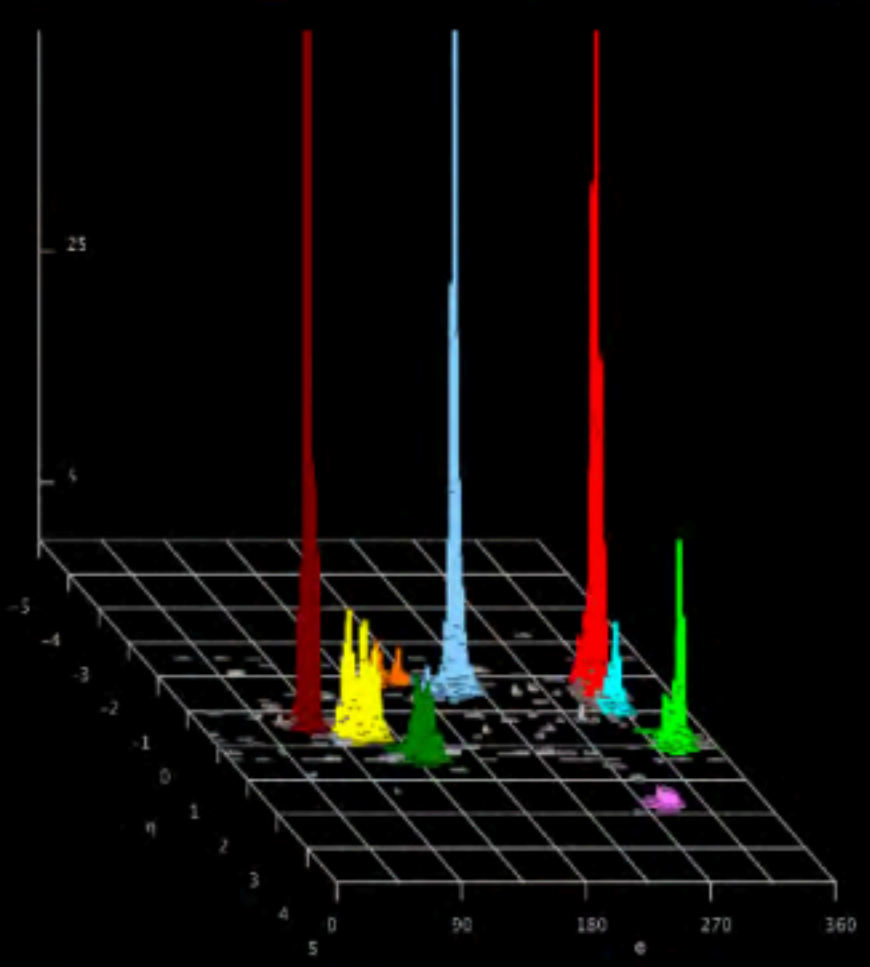
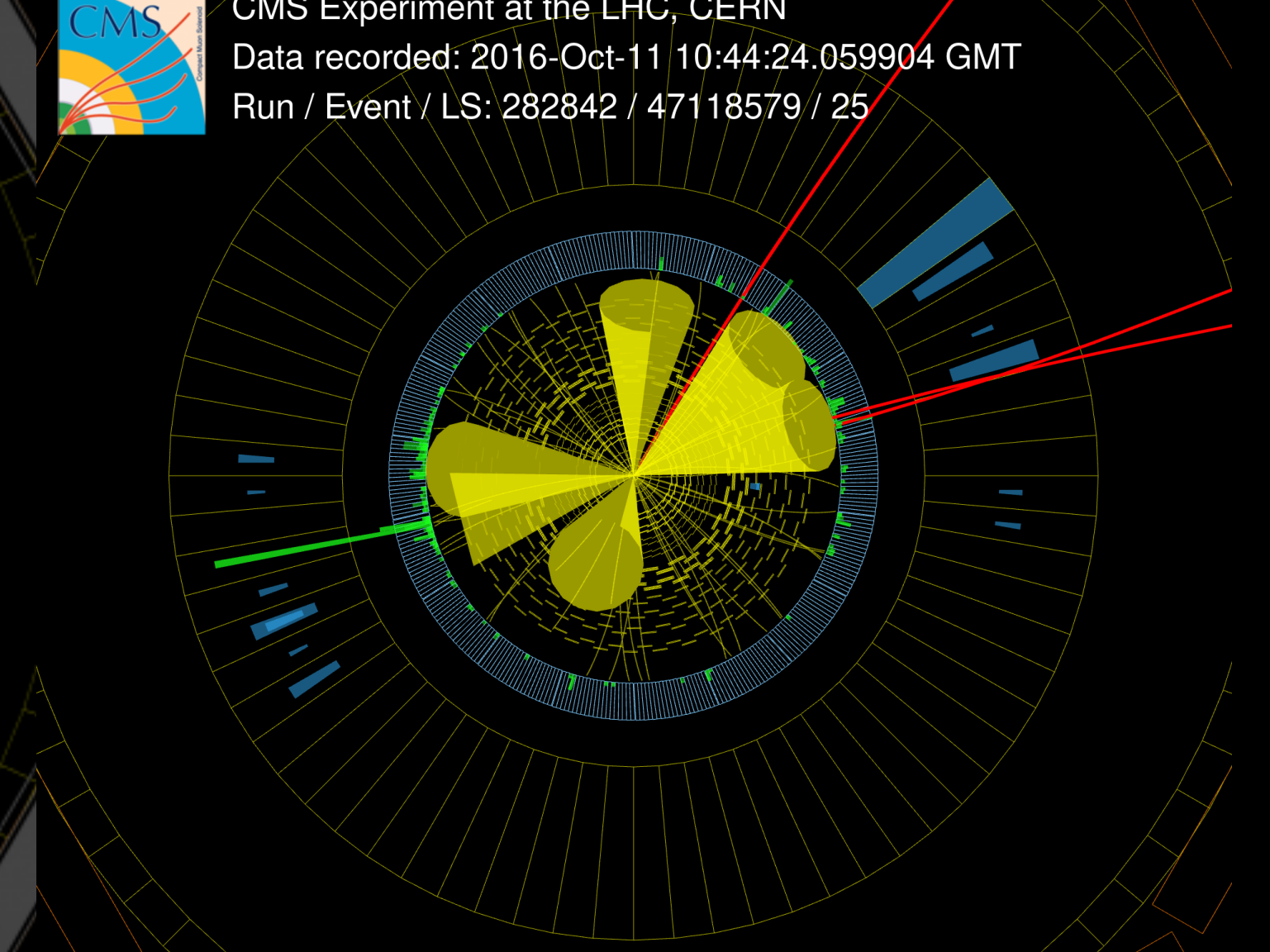


ATLAS
EXPERIMENT
Run: 302347
Event: 753275626
2016-06-18 18:41:48 CEST

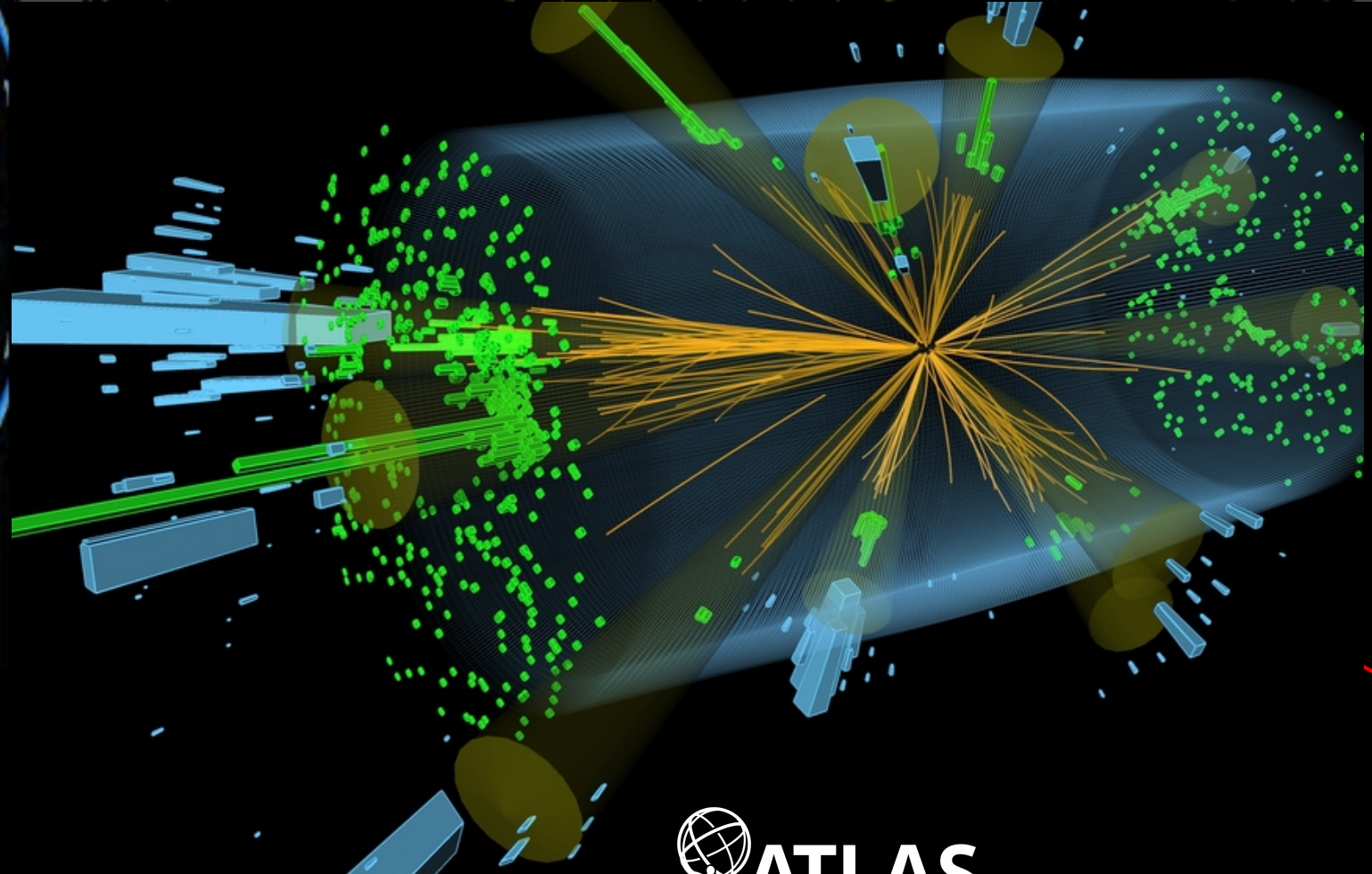
at the LHC, CERN
2016-May-29 22:35:55.226560 GMT
Run: 274199 / 548714092 / 285



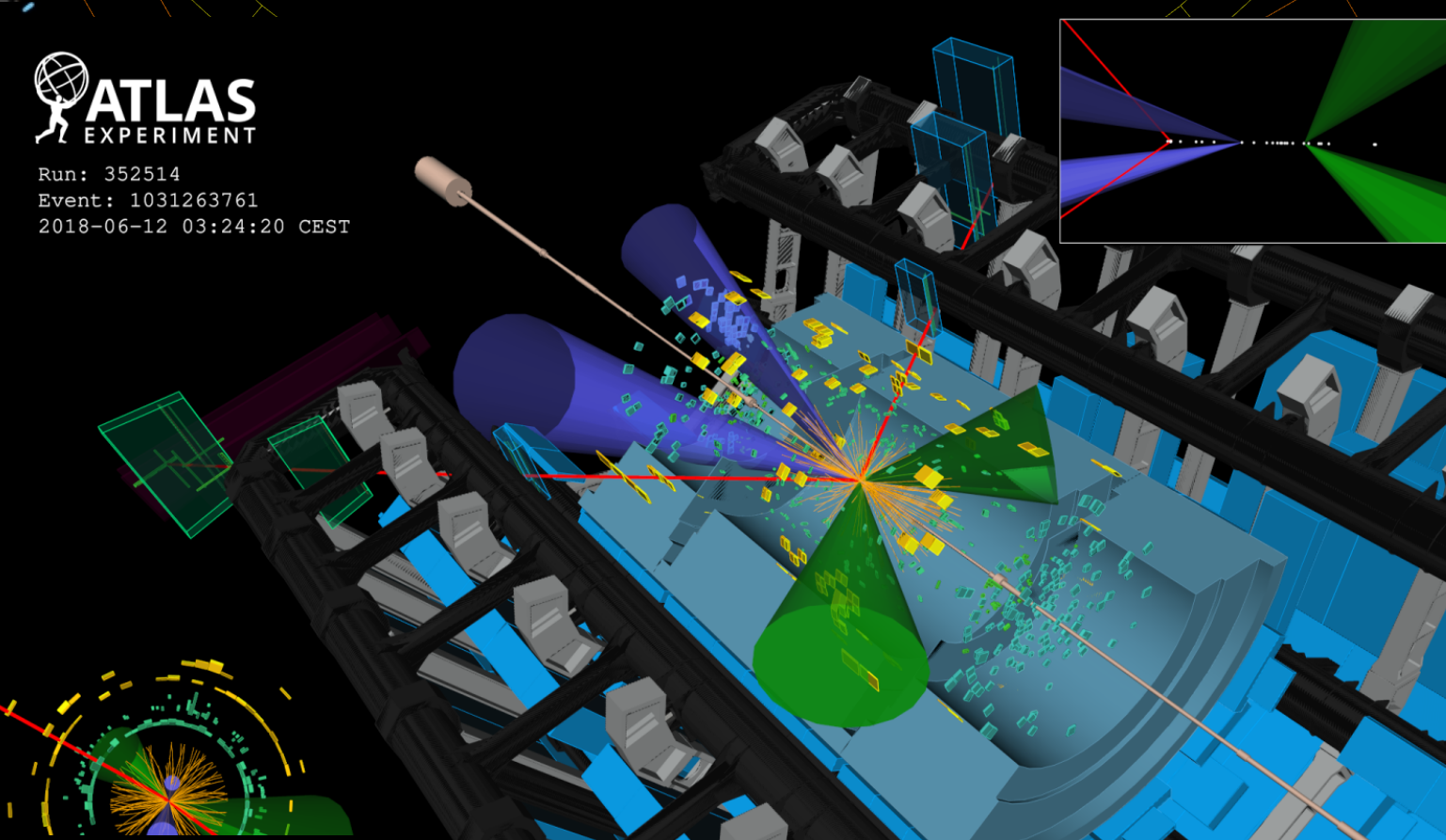
CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-11 10:44:24.059904 GMT
Run / Event / LS: 282842 / 47118579 / 25



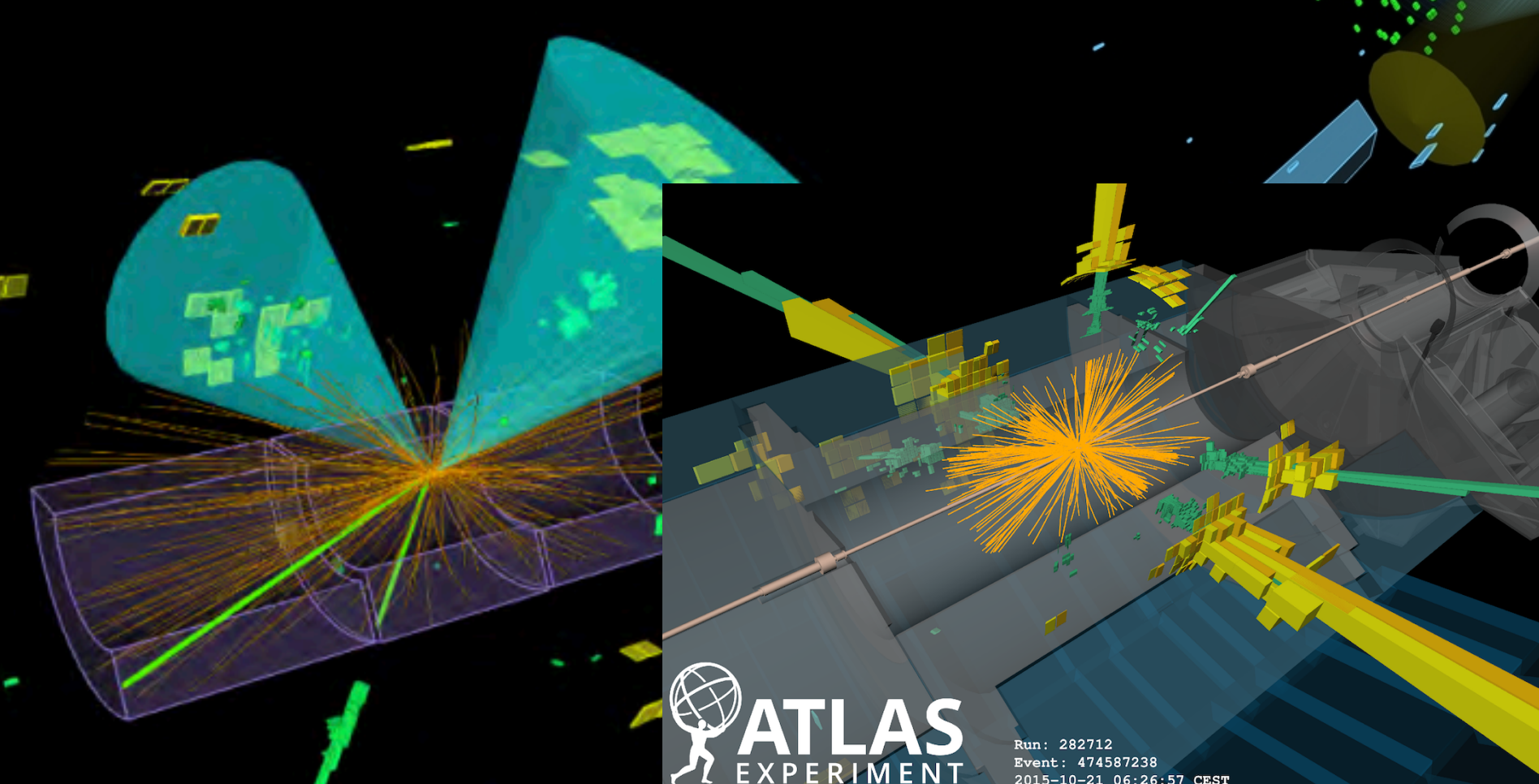
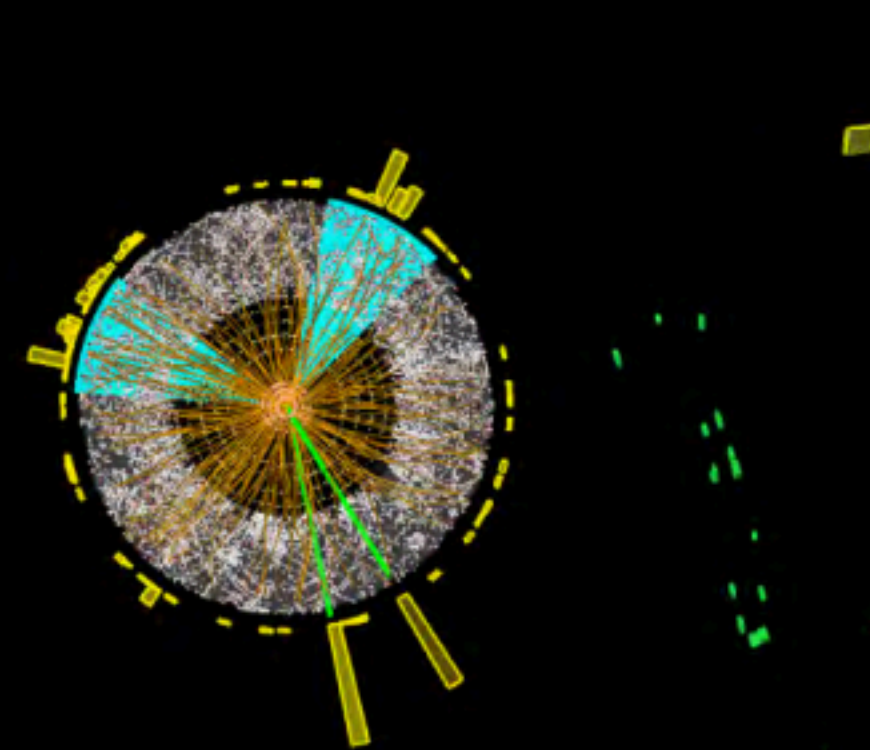
ATLAS
EXPERIMENT
Run: 101576, Event Number: 1845117
Date: 2010-09-15 04:51:18 CEST



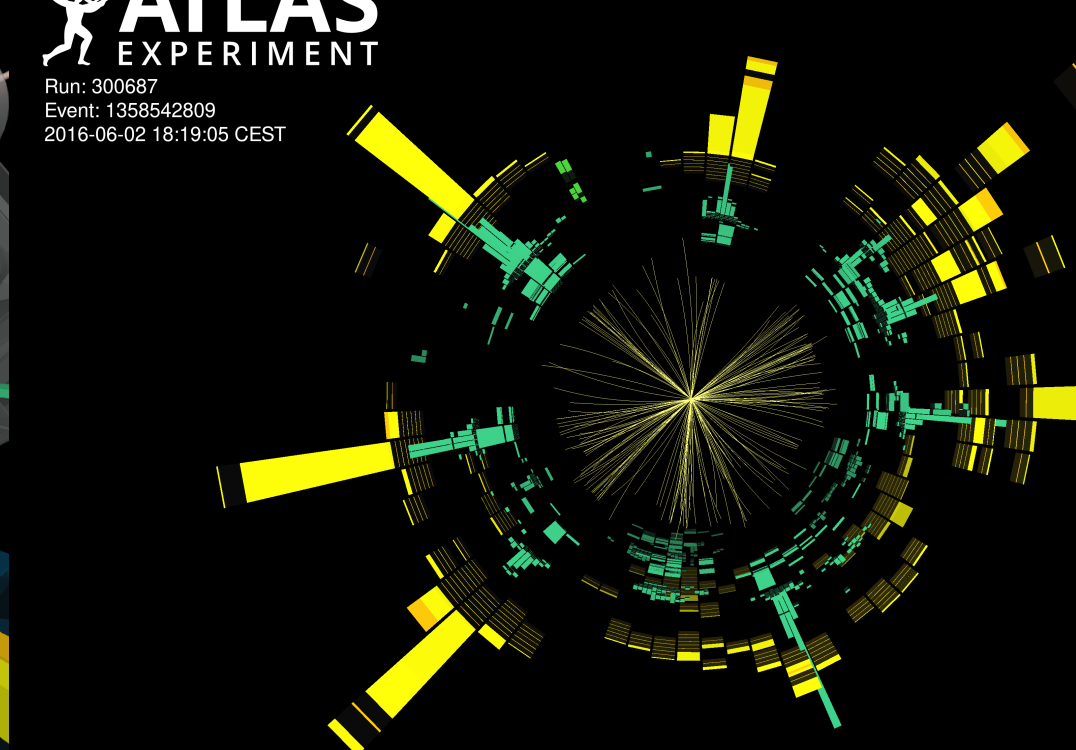
ATLAS
EXPERIMENT
Run: 352514
Event: 1031263761
2018-06-12 03:24:20 CEST



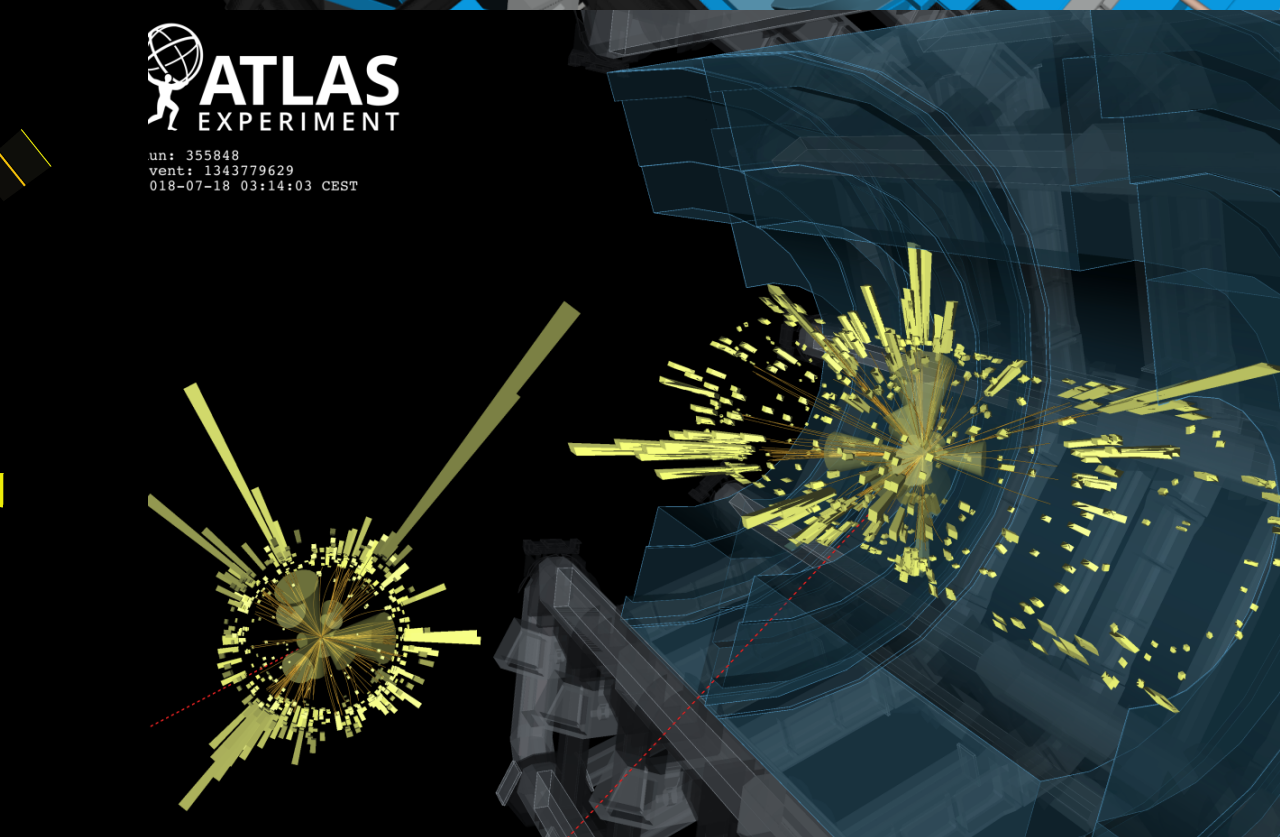
ATLAS
EXPERIMENT
<http://atlas.ch>



ATLAS
EXPERIMENT
Run: 300687
Event: 1358542809
2016-06-02 18:19:05 CEST



ATLAS
EXPERIMENT
Run: 355048
Event: 1343779629
018-07-18 03:14:03 CEST

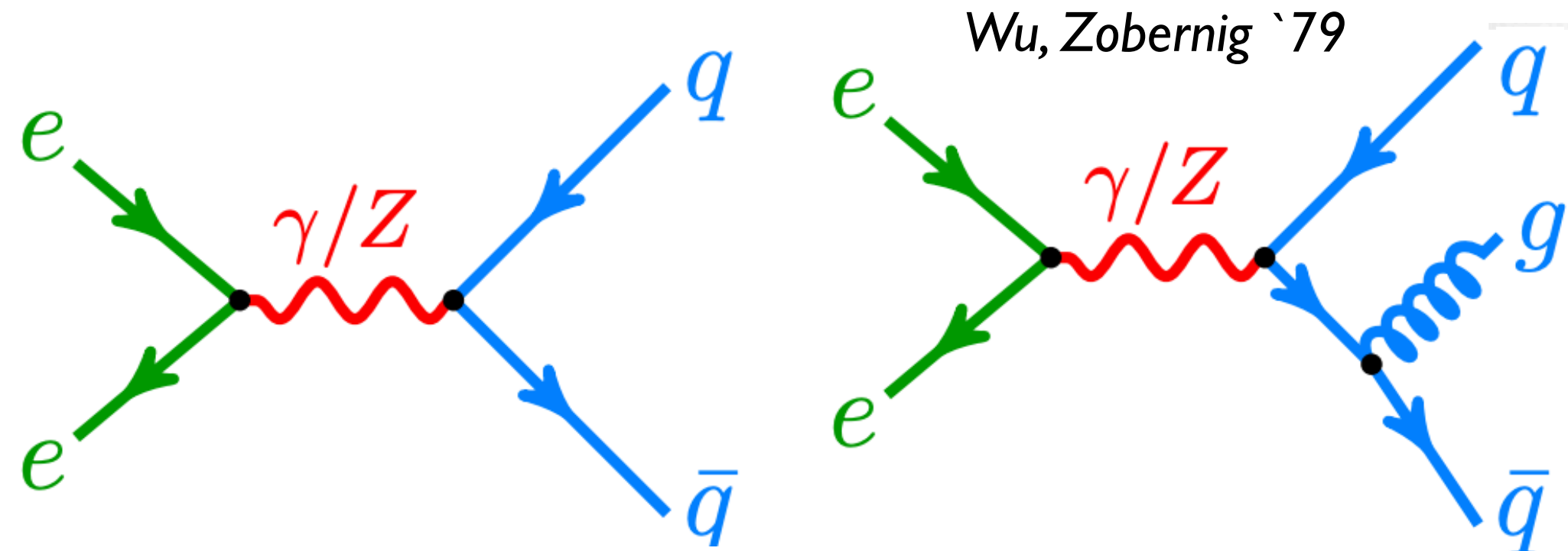
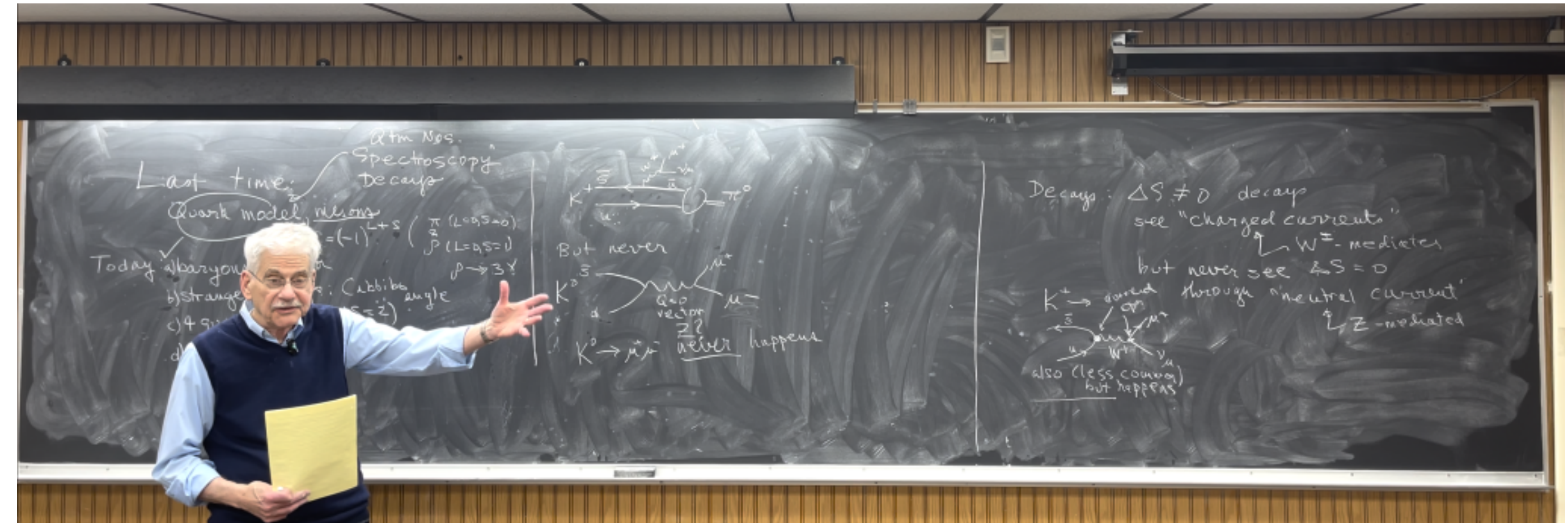
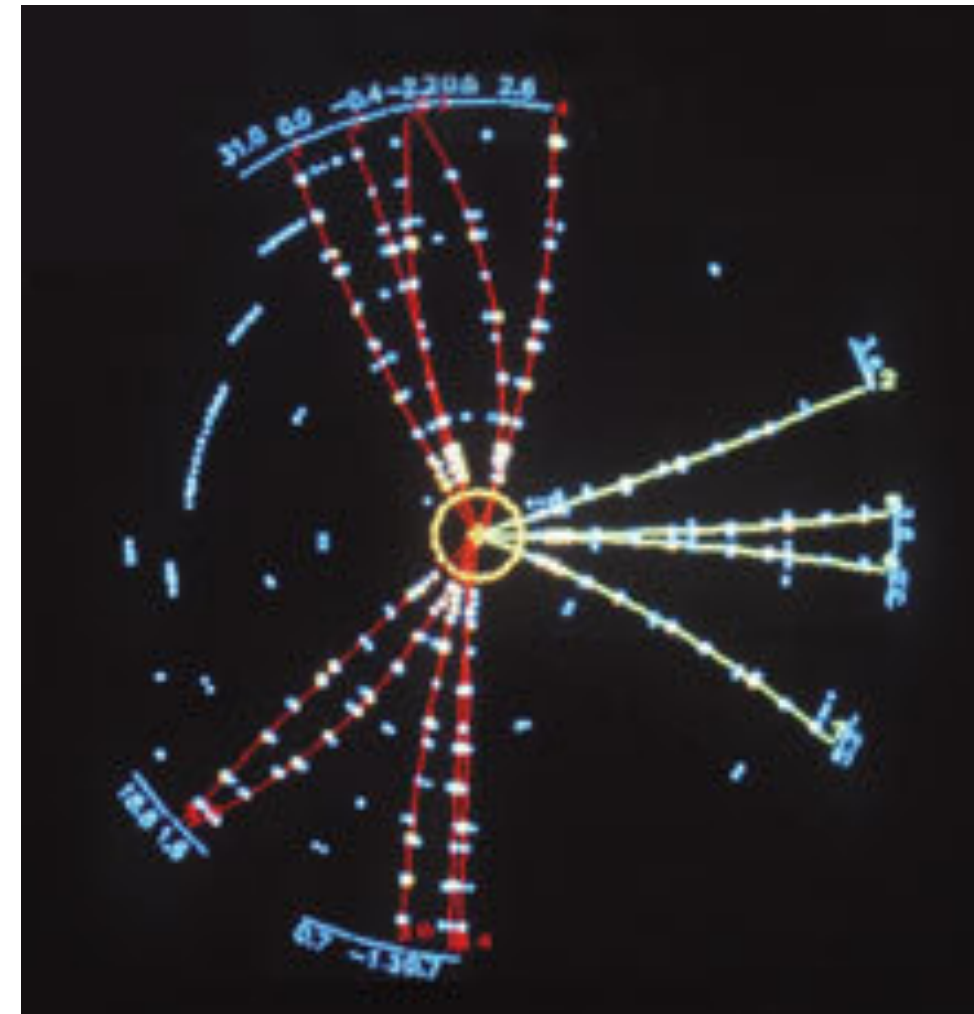
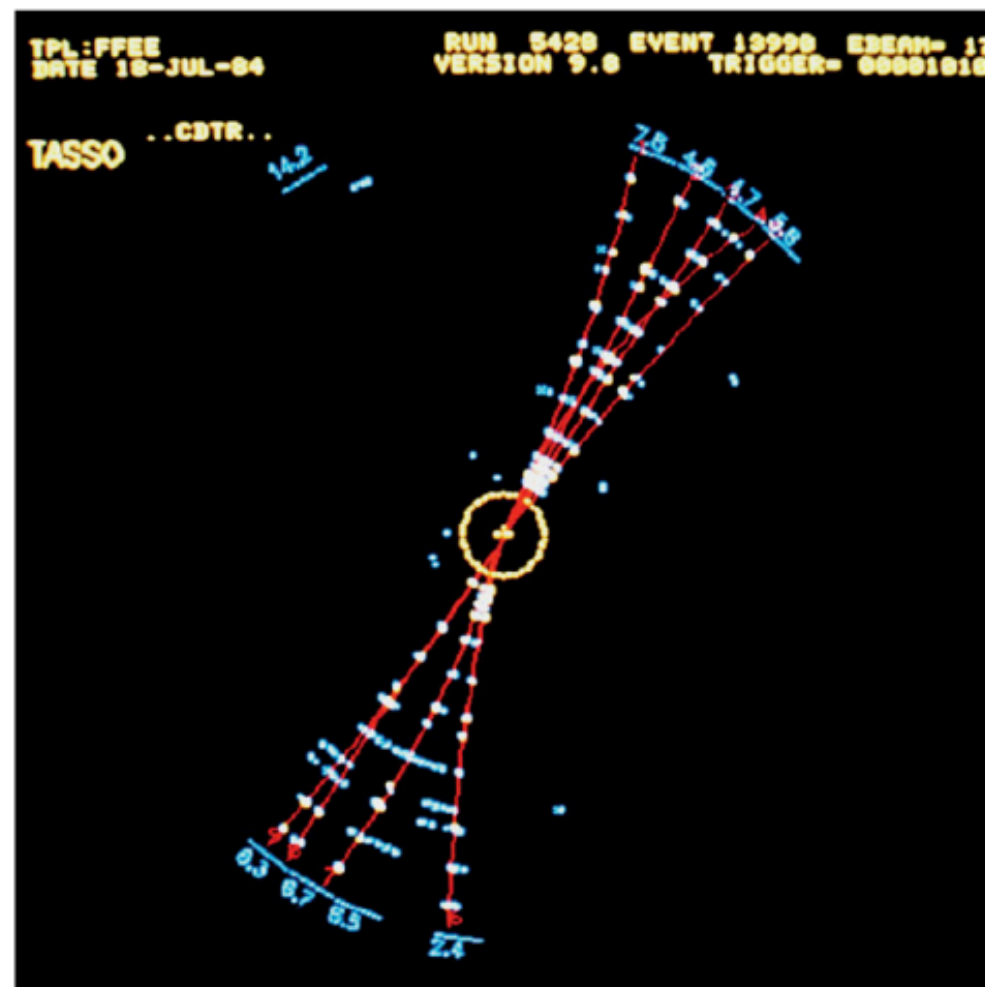


ATLAS
EXPERIMENT
Run: 282712
Event: 474587238
2015-10-21 06:26:57 CEST

THE DAWN OF QCD: FROM PARTONS TO JETS

2-jet event 3-jet event

50 Years of Jets :
 Celebrating the Science of George Sterman
 May 18-20, 2026



HUTP-77/A044

JETS FROM QUANTUM CHROMODYNAMICS

George Sterman*
 Institute for Theoretical Physics
 State University of New York at Stony Brook
 Stony Brook, New York 11790

and

Steven Weinberg[†]
 Lyman Laboratory of Physics
 Harvard University
 Cambridge, Massachusetts 02138

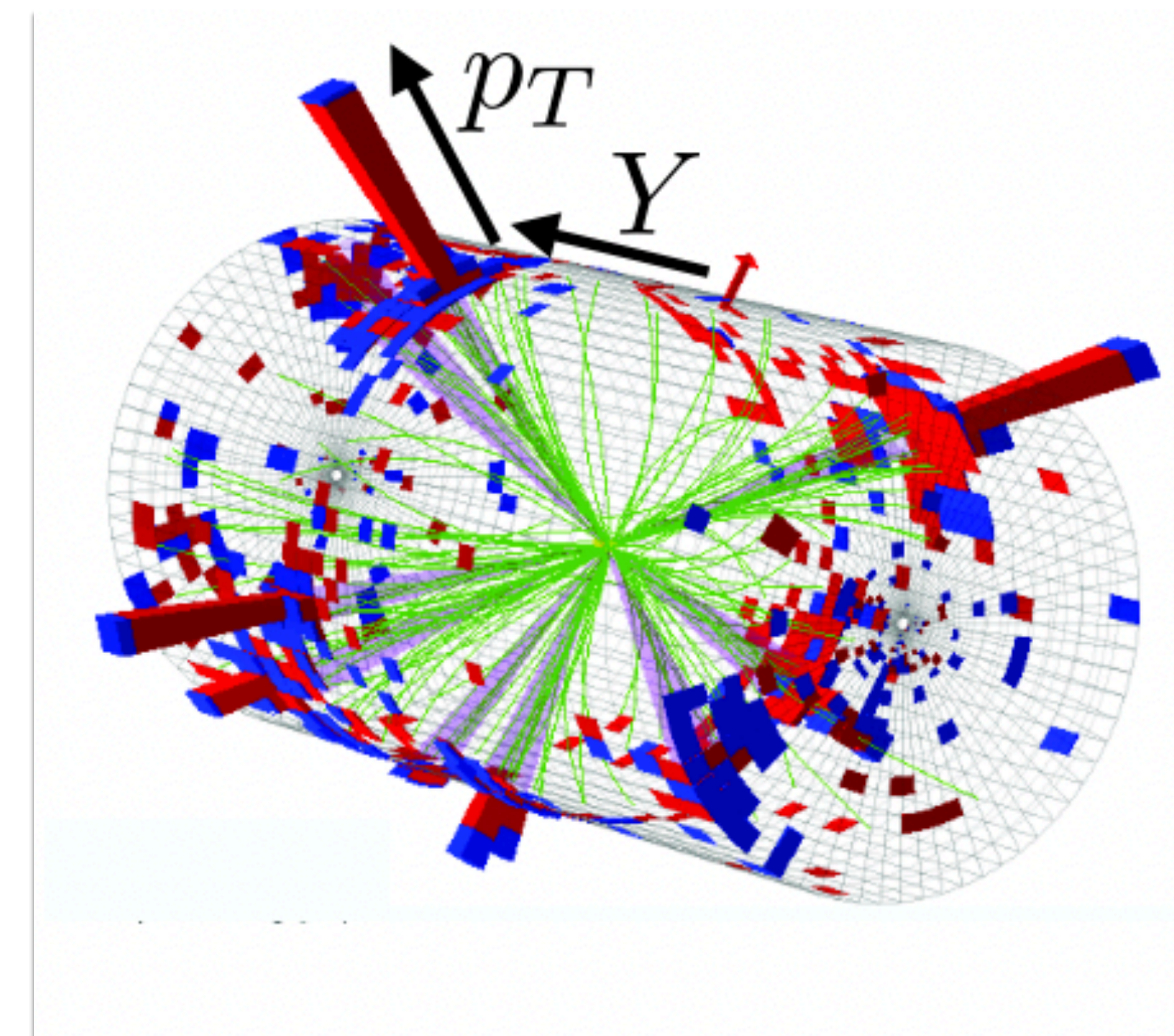
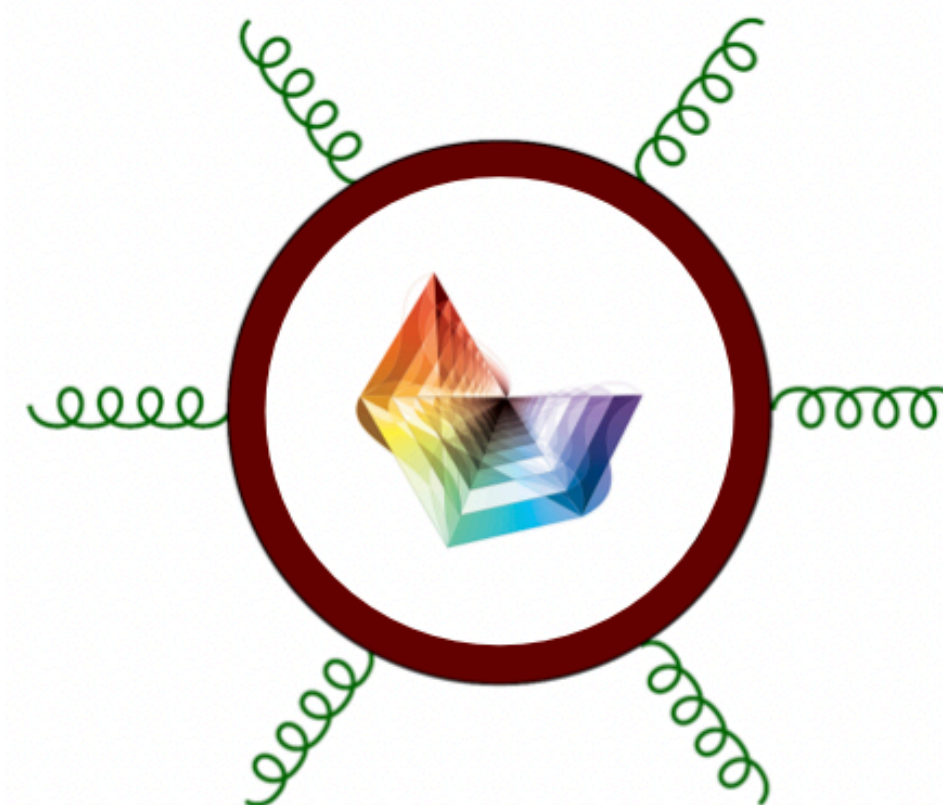
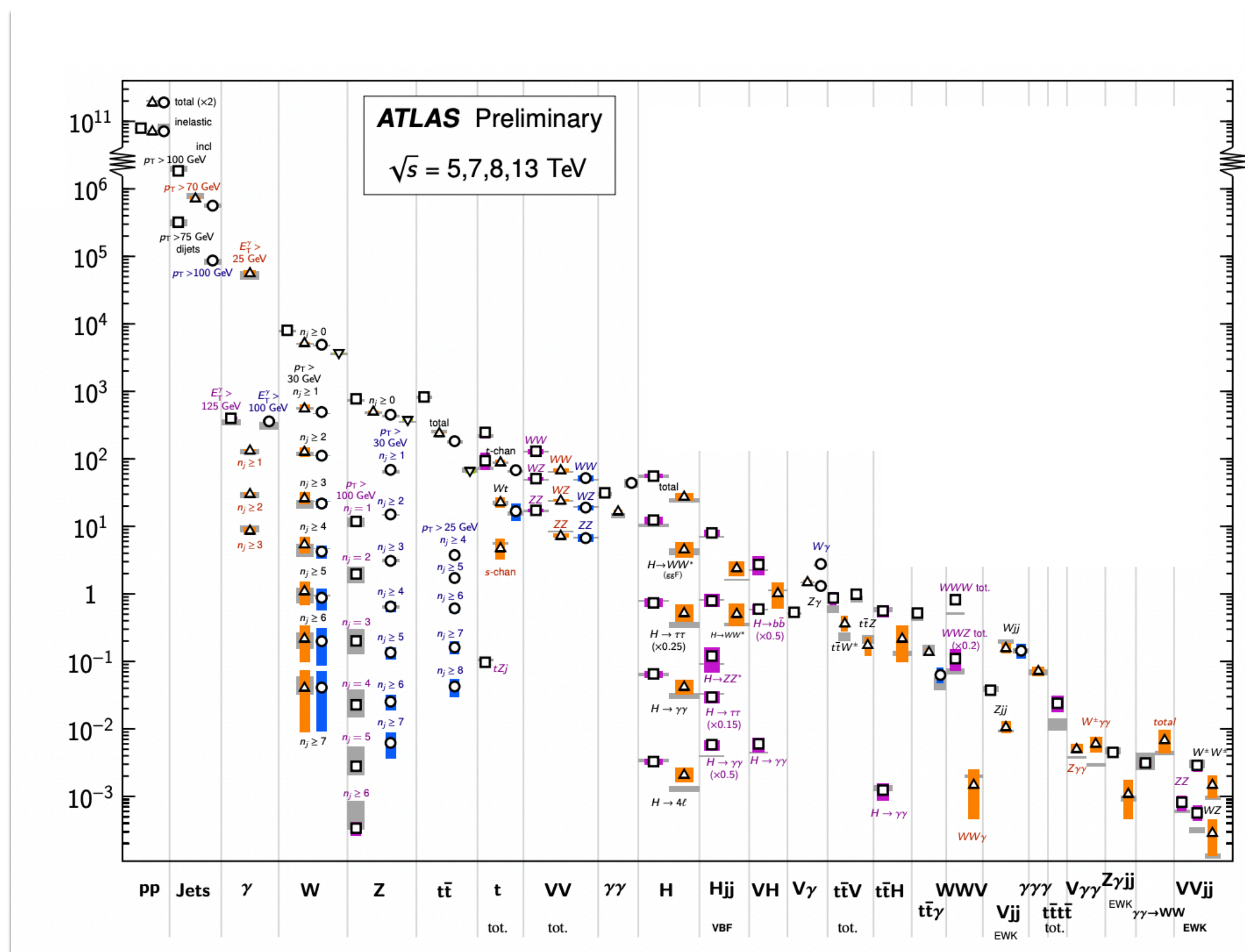
Sterman, Weinberg `77

Jets unveiled the partonic nature of QCD, playing an important role in the confirmation of QCD as the theory of strong interactions!

HIGH-MULTIPLICITY JETS AT COLLIDERS

- The effort to achieve precise predictions of jet cross sections has driven developments of **multi-loop calculations in Quantum Field Theory**

cross-section of SM processes



9-jet event at the LHC

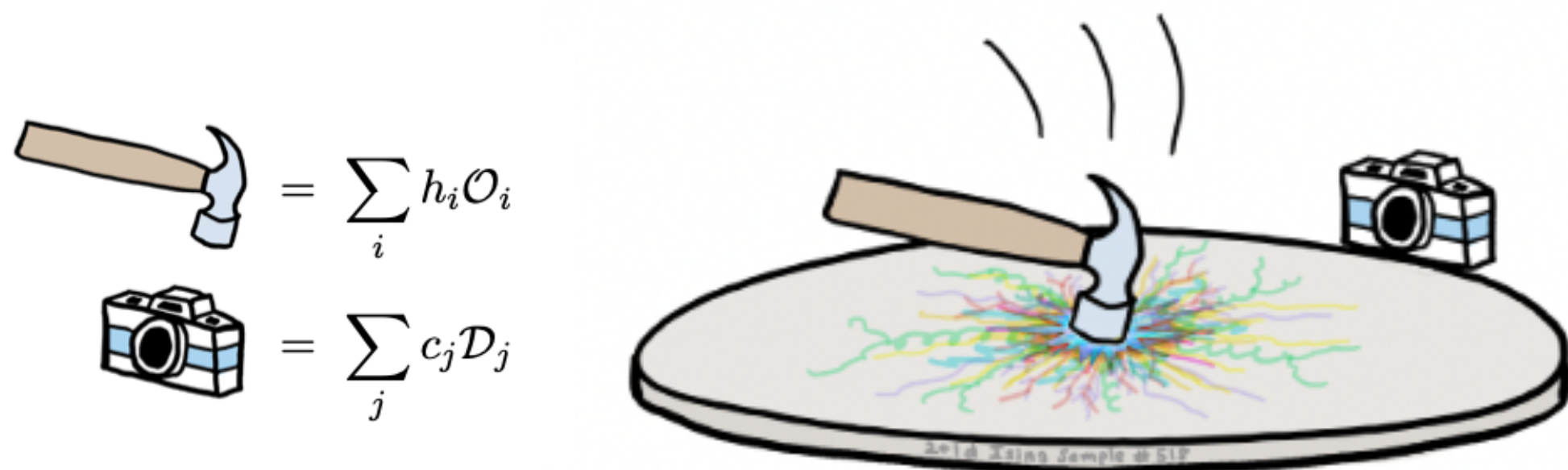
JET SUBSTRUCTURE: STUDYING ENERGY FLOW INSIDE JETS

From **QFT** point of view, **what is a detector?**

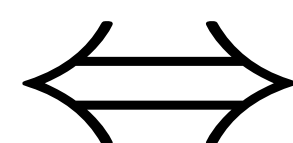
Energy Flow Operators *Sterman '75*

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

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

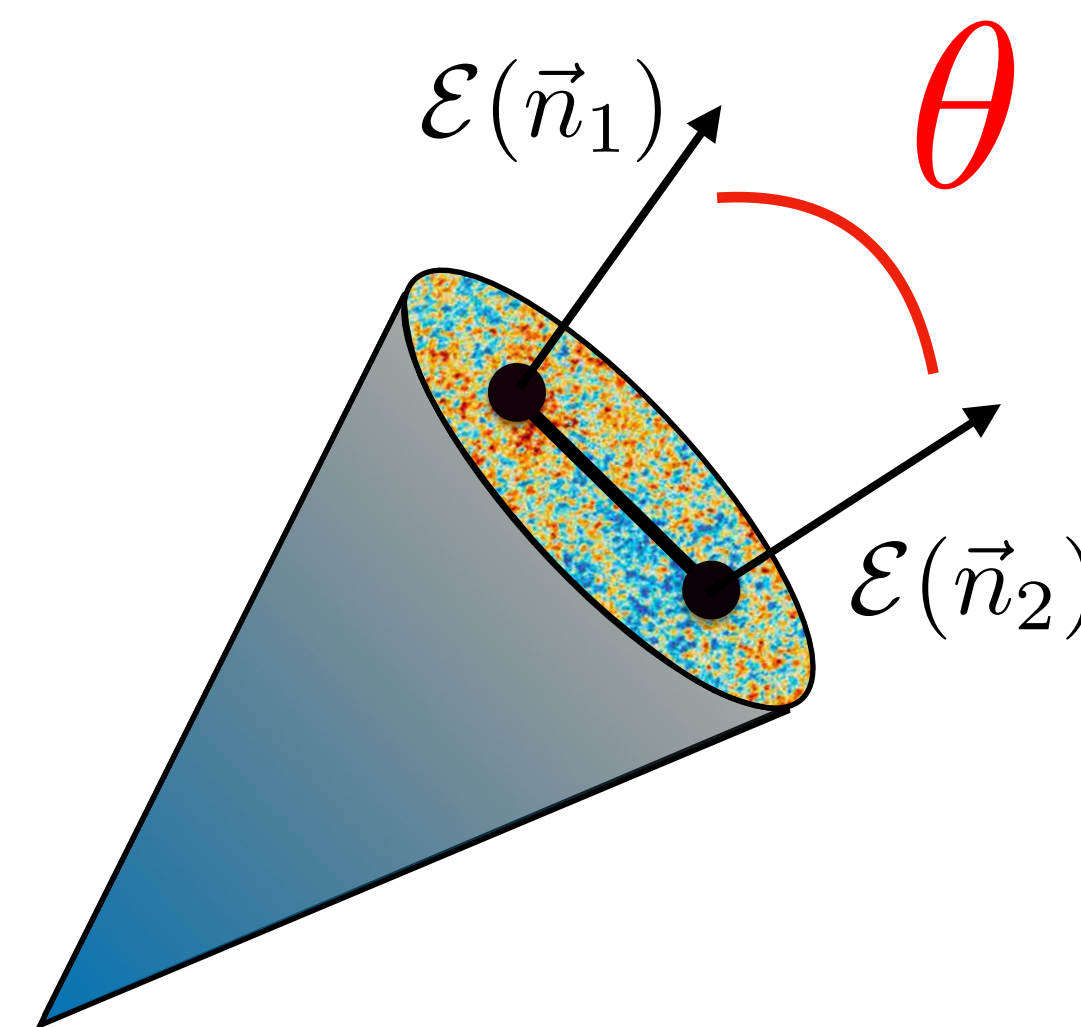


$$\langle \text{hammer} | \text{camera}(\hat{n}_1) \cdots \text{camera}(\hat{n}_N) | \text{hammer} \rangle$$



$$\langle \Psi_{\text{Jet}} | \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) | \Psi_{\text{Jet}} \rangle$$

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

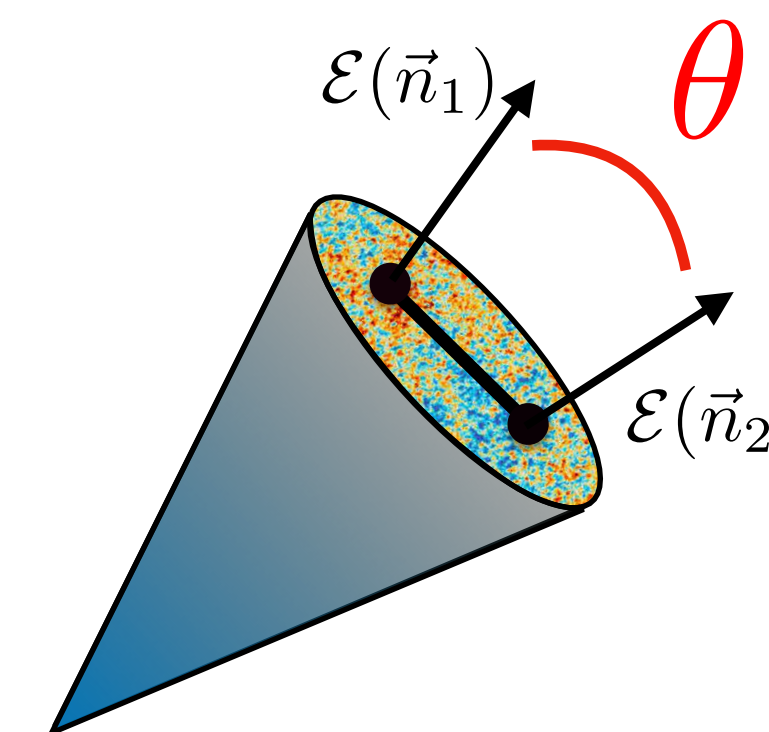
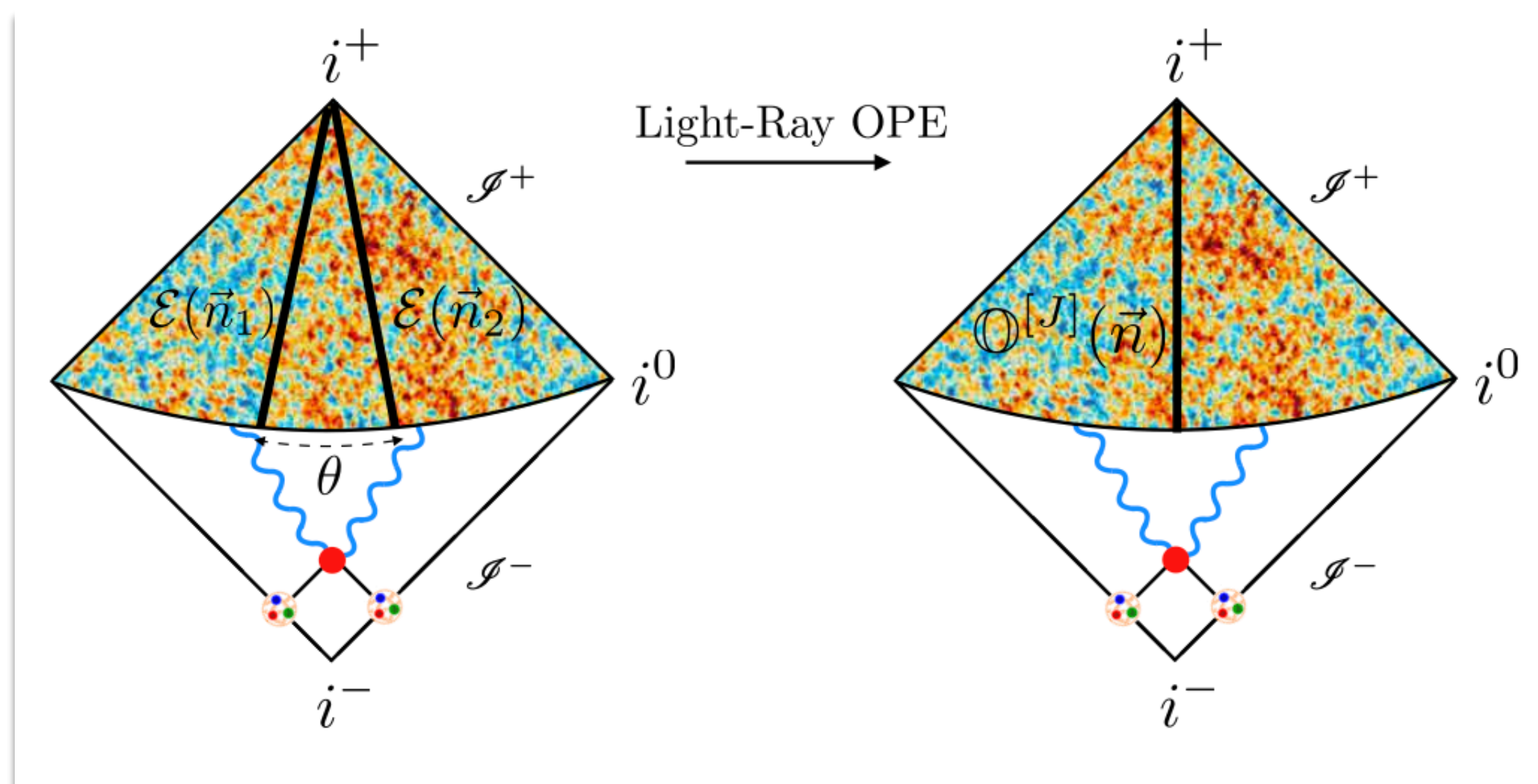


We infer microscopic (**early time**) physics from asymptotic (**late time**) **energy flux measured on detectors**

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**

⇒ **Profound field theory predictions within jets!**

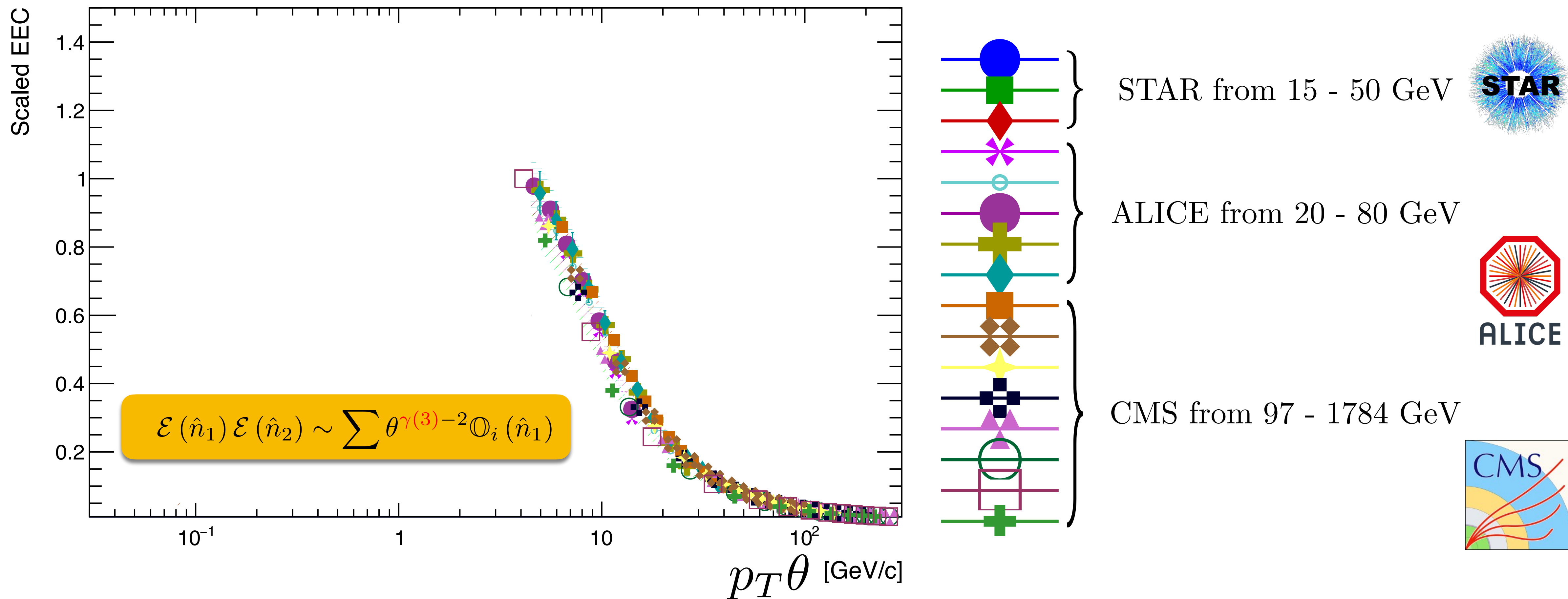


Light-ray Operator Product Expansion

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

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

SCALING FROM 15 GEV TO 2 TEV IN DATA!



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

QCD FACTORIZATION FRAMEWORK OF JET SUBSTRUCTURE

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

KL, Moutl, Zhang `24

See also Kang, Ringer, Vitev `16

PDFs

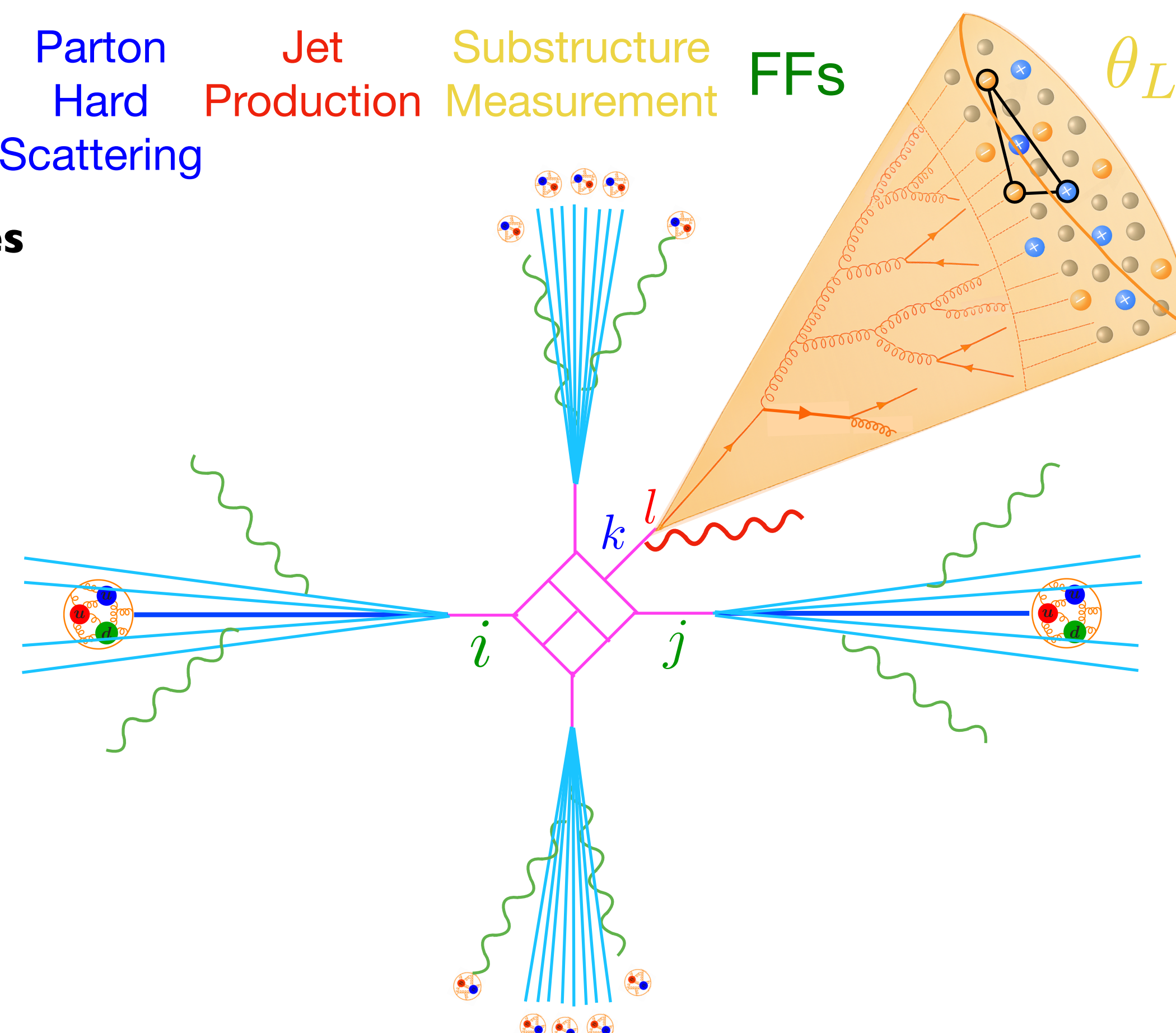
Parton
Hard
Scattering

Jet
Production

Substructure
Measurement

FFs

θ_L



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

$$\Lambda_{\text{QCD}} \sim 1 \text{ GeV}$$

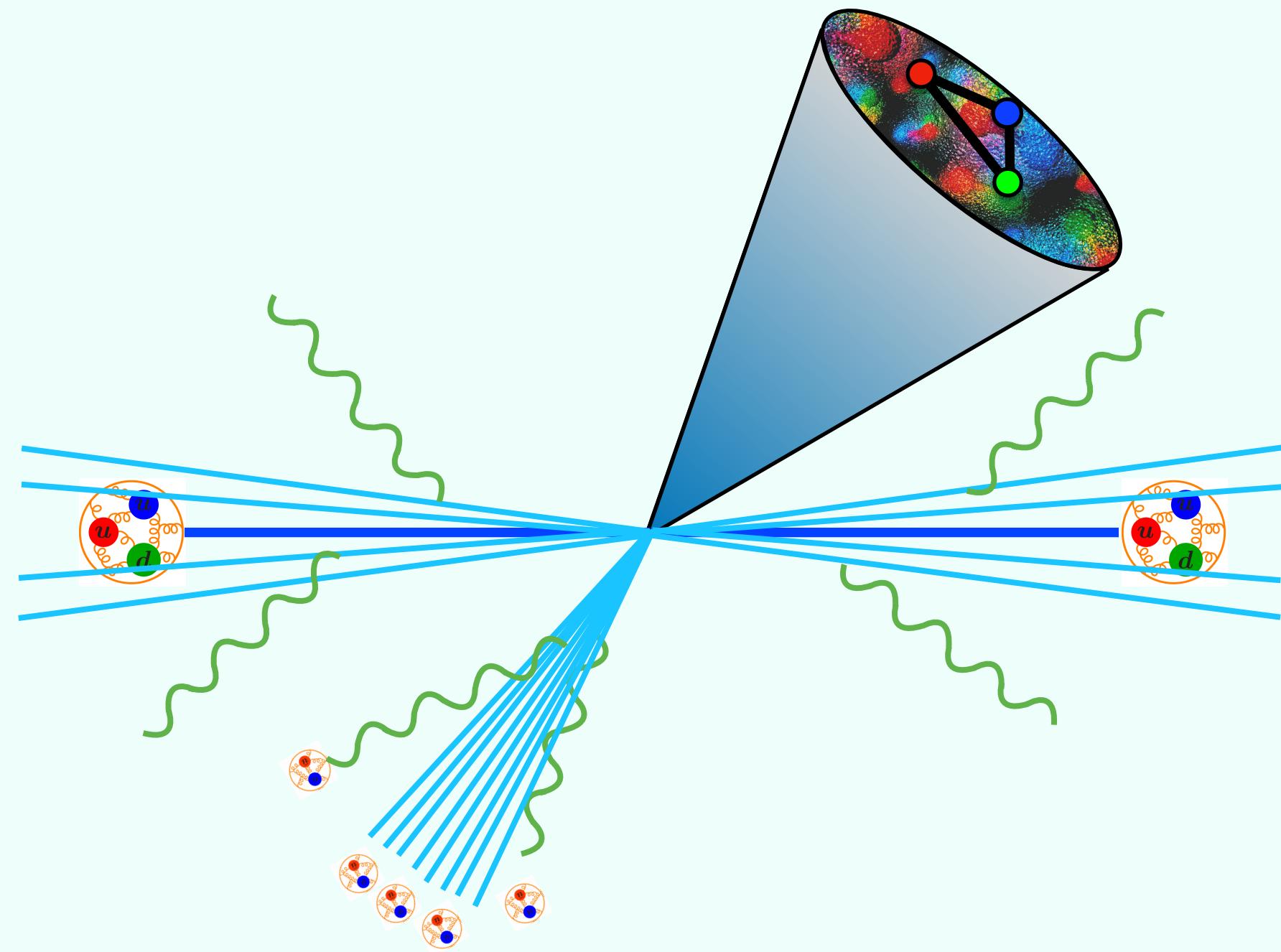
Ian Moutl

Xiaoyuan Zhang



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

Outline.



1. Hard Scale

$$p_T \sim 500 \text{ GeV}$$

2. Jet Scale

$$p_T R \sim 100 \text{ GeV}$$

1+2. NNLL + NNLO

3. Substructure Scale

$$p_T \theta \sim 30 \text{ GeV}$$

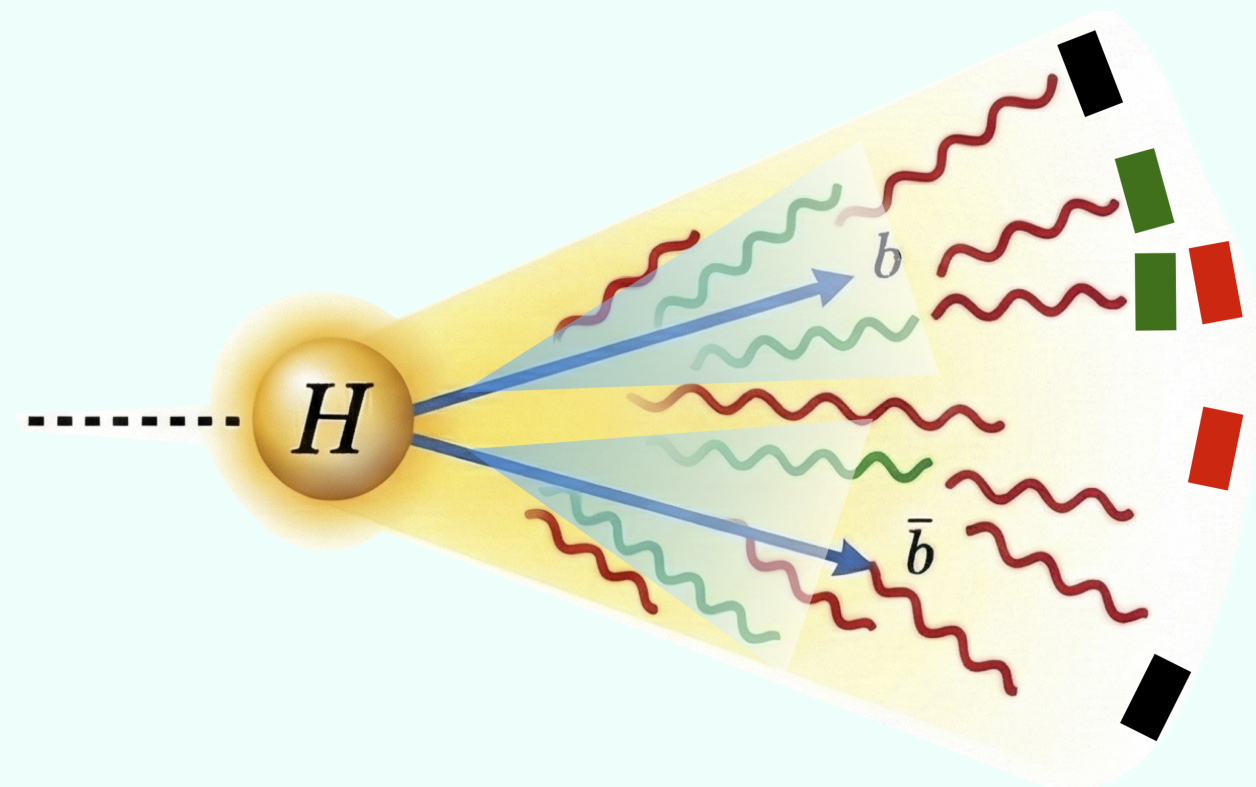
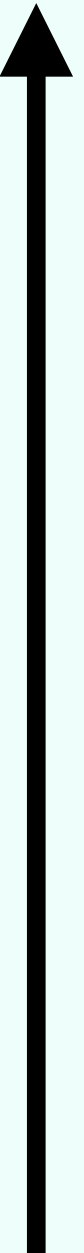
1+2+3. NLL

4. Nonperturbative Scale

$$\Lambda_{\text{QCD}} \sim 1 \text{ GeV}$$

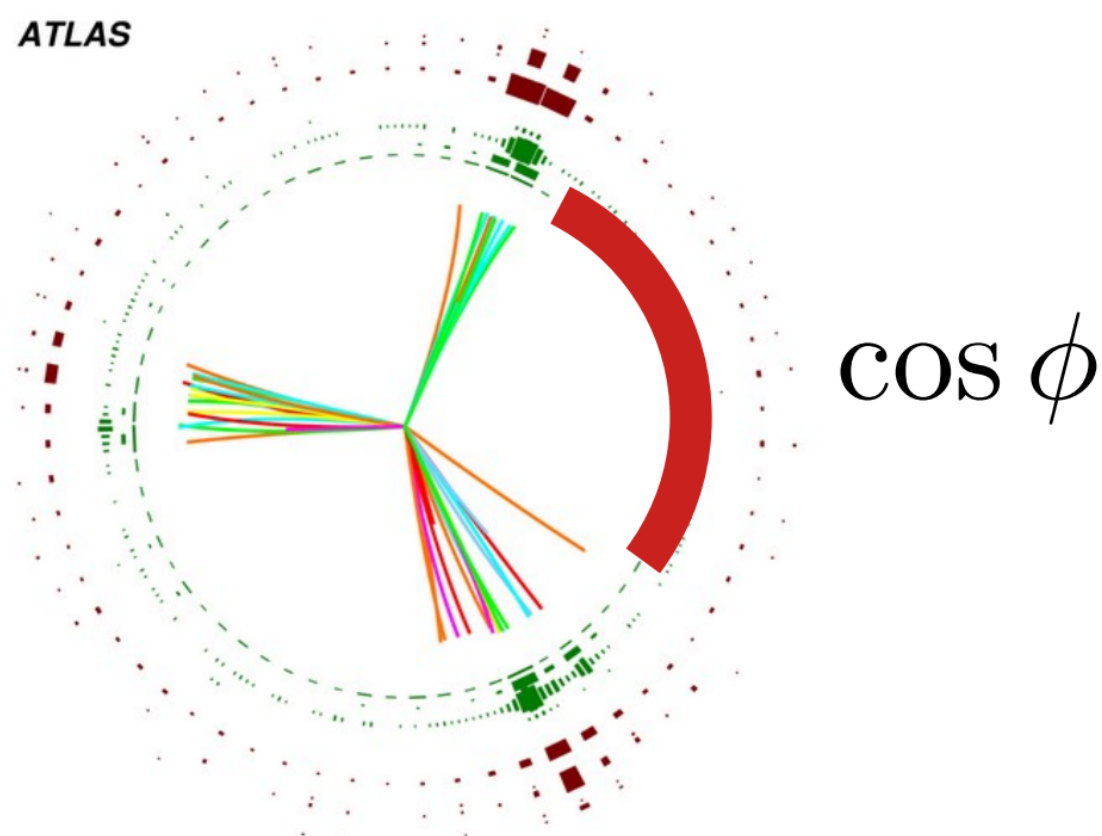
1+2+3+4. NLL

Energy scales

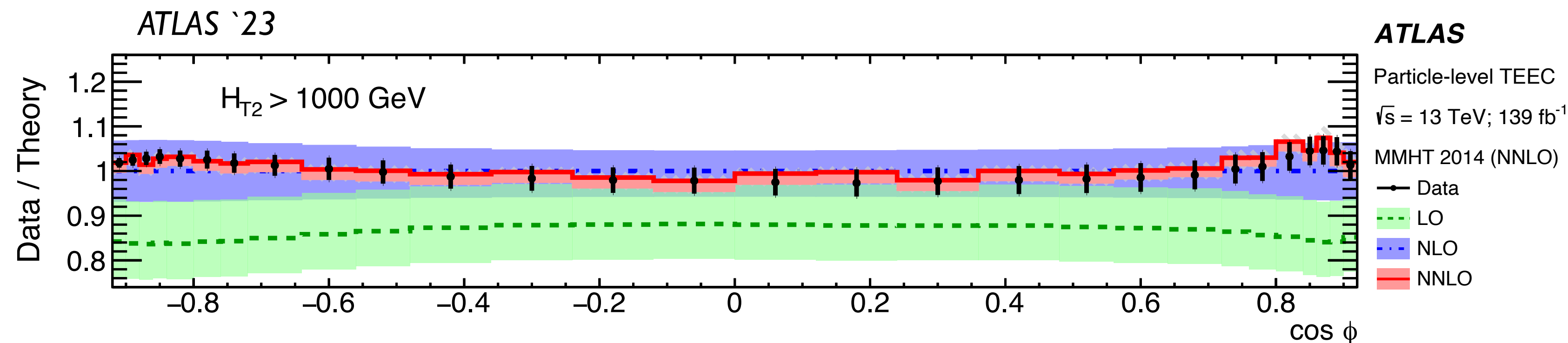


5. Electroweak Jets and New Physics

FRAGMENTING PARTON PRODUCTION



I. Hard Scale, FO calculation

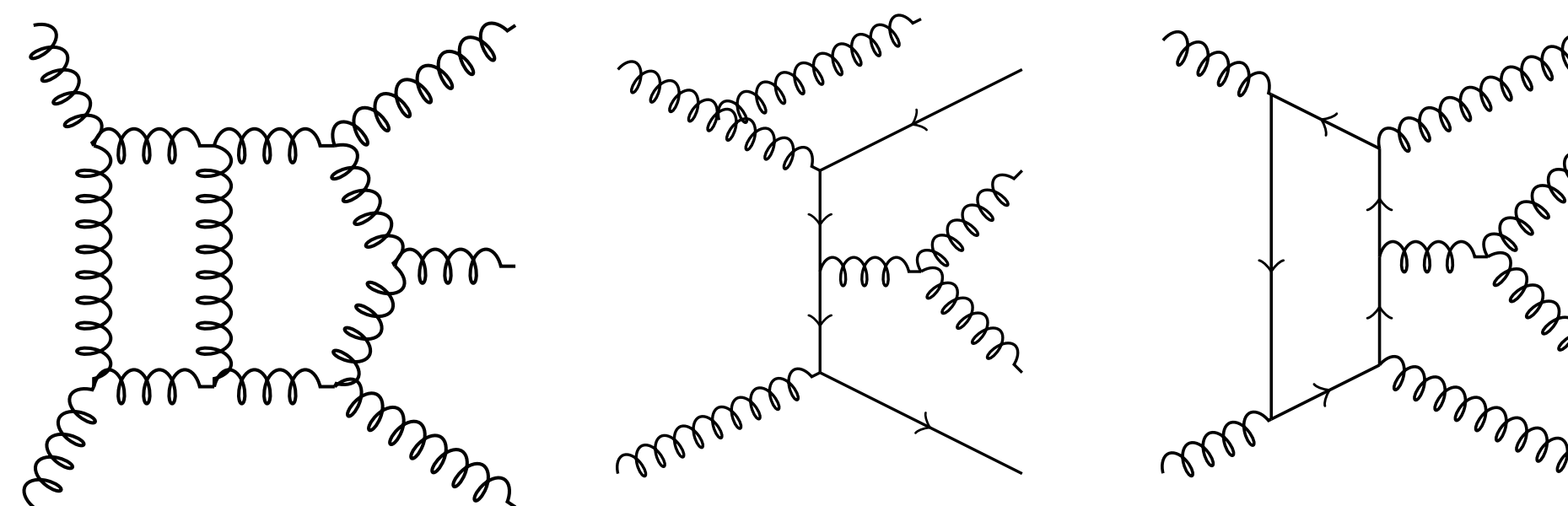


$$\frac{1}{\sigma} \frac{d\Sigma}{d \cos \phi} = \frac{1}{N} \sum_{A=1}^N \sum_{ij} \frac{E_{Ti}^A E_{Tj}^A}{\left(\sum_k E_{Tk}^A\right)^2} \delta(\cos \phi - \cos \phi_{ij})$$

Two impressive theoretical achievements:

1. Computation of 5-point two-loop amplitudes

Abreu, Buccioni, Gambuti, Gehrmann, Henn, ... et al '18-23



2. **STRIPPER formalism**: IR subtraction and phase space integrations

Czakon '10

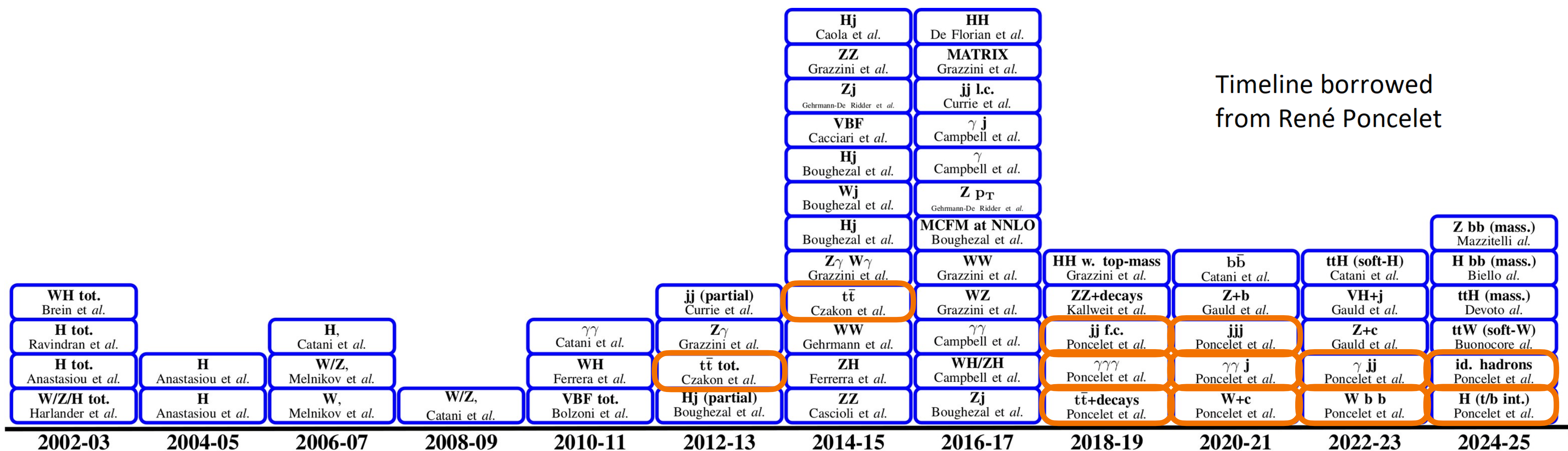
Czakon, Mitov, Poncelet '21

Czakon, Generet, Mitov, Poncelet '21,24

FRAGMENTING PARTON PRODUCTION

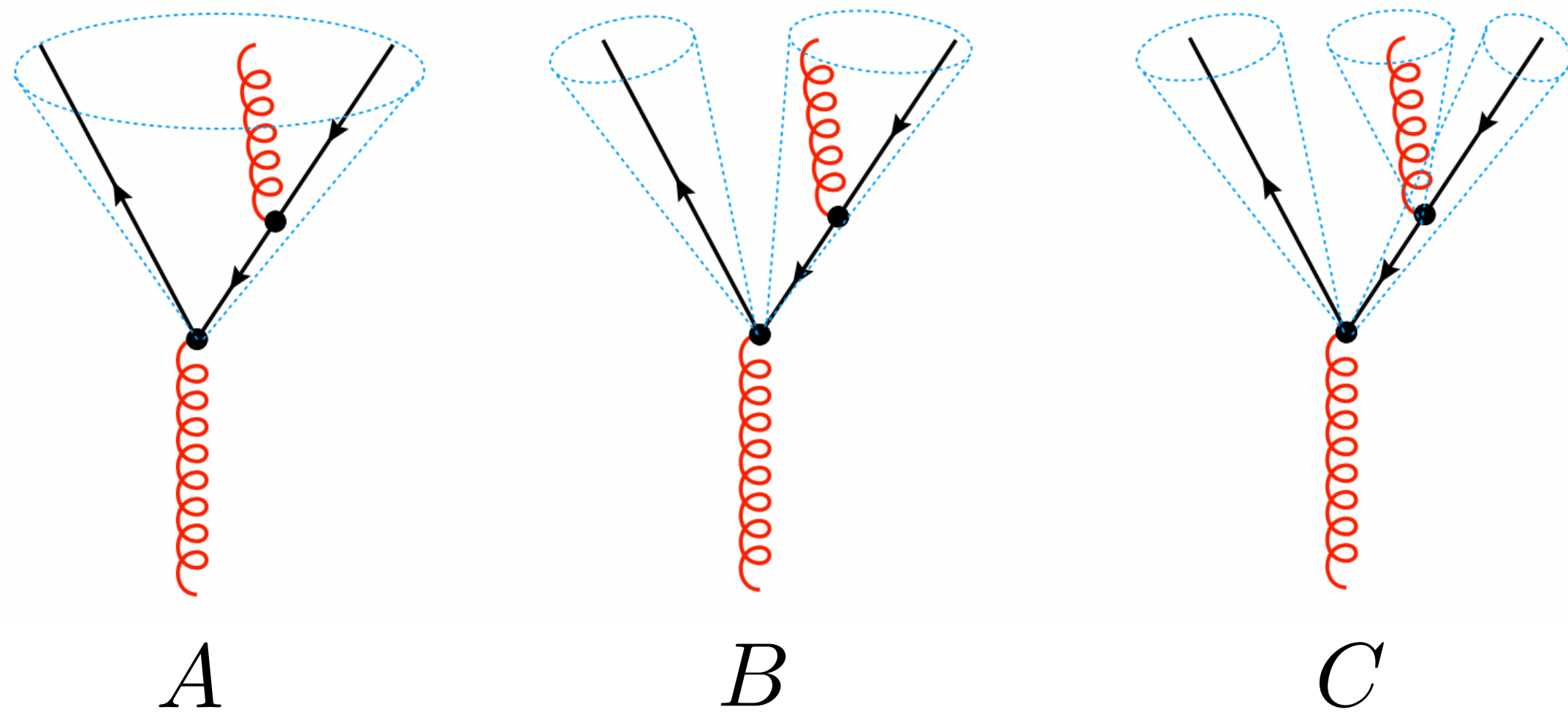
I. Hard Scale, FO calculation

Stripper Formalism automates IR subtraction at **NNLO order** allowing computation of many NNLO processes beyond **massless limit** and **color-singlet processes**



JET PRODUCTION

2. Jet Scale



\tilde{s}_{ik} = angle between i and k

z_i = momentum fraction of i

$$\begin{aligned} \mathcal{M}_{3,ijk}^{\text{AI}} &= \theta \left(\tilde{s}_{ij} < \left(\frac{x_j}{x_k} \right)^{2\alpha} \tilde{s}_{jk} \right) \theta \left(\tilde{s}_{ij} < \left(\frac{x_j}{x_k} \right)^{2\alpha} \tilde{s}_{ik} \right) \\ &\quad \times \theta \left(\frac{x_i}{x_j} \tilde{s}_{ik} + \tilde{s}_{jk} < 1 + \frac{x_i}{x_j} + \frac{x_i}{x_i + x_j} \tilde{s}_{ij} \right) \theta_{ijk} \\ \mathcal{M}_{3,ijk}^{\text{AII}} &= \left[1 - \theta \left(\tilde{s}_{ij} \leq \left(\frac{x_j}{x_k} \right)^{2\alpha} \tilde{s}_{ik} \right) \right] \theta(\tilde{s}_{ik} < 1) \theta(\tilde{s}_{ik} \leq \tilde{s}_{jk}) \\ &\quad \times \theta \left(\frac{x_i}{x_k} \tilde{s}_{ij} + \tilde{s}_{jk} < 1 + \frac{x_i}{x_k} + \frac{x_i}{x_i + x_k} \tilde{s}_{ik} \right) \theta_{ijk} \\ \mathcal{M}_{3,ijk}^{\text{AIII}} &= \left[1 - \theta \left(\tilde{s}_{ij} \leq \left(\frac{x_j}{x_k} \right)^{2\alpha} \tilde{s}_{jk} \right) \right] \theta(\tilde{s}_{jk} < 1) \theta(\tilde{s}_{jk} \leq \tilde{s}_{ik}) \\ &\quad \times \theta \left(\frac{x_j}{x_k} \tilde{s}_{ij} + \tilde{s}_{ik} < 1 + \frac{x_j}{x_k} + \frac{x_j}{x_j + x_k} \tilde{s}_{jk} \right) \theta_{ijk} \end{aligned}$$

KL, Mout, Zhang '24

Two-loop small-R jet function calculations describe complicated dynamics of IR-safe jet algorithms

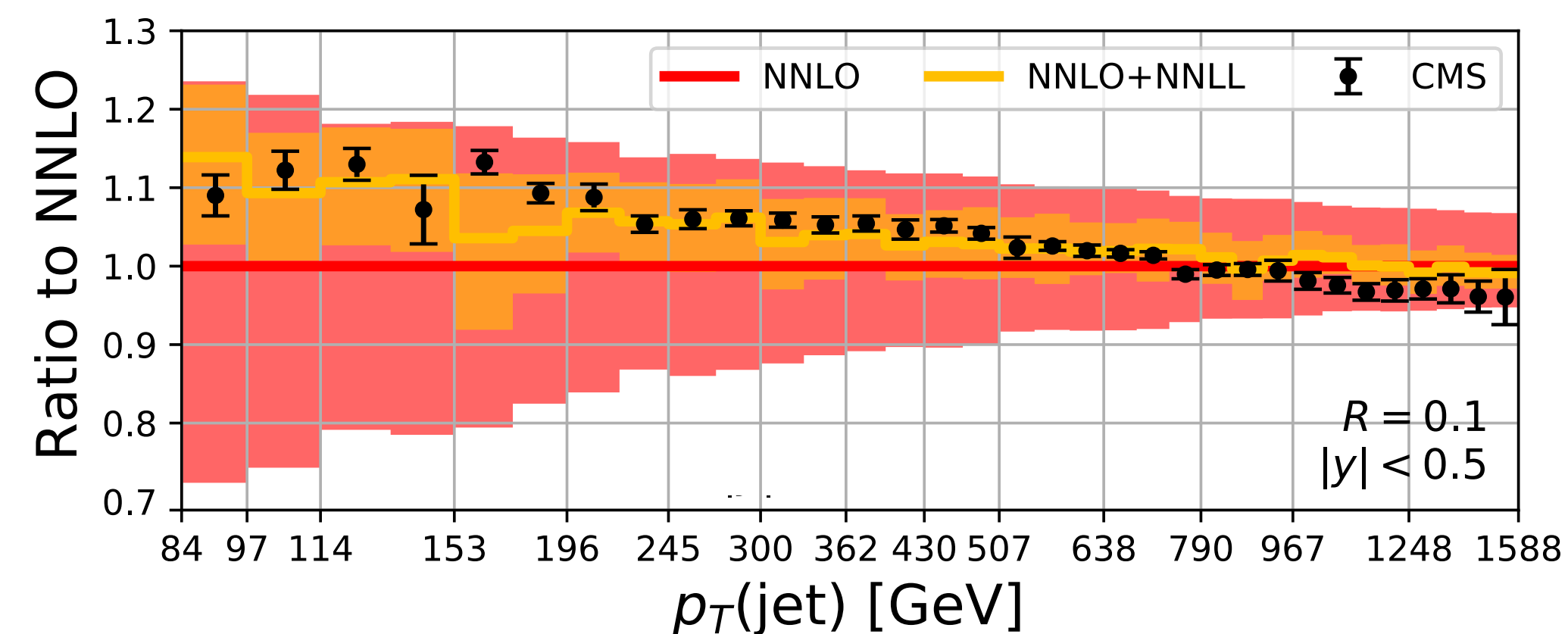
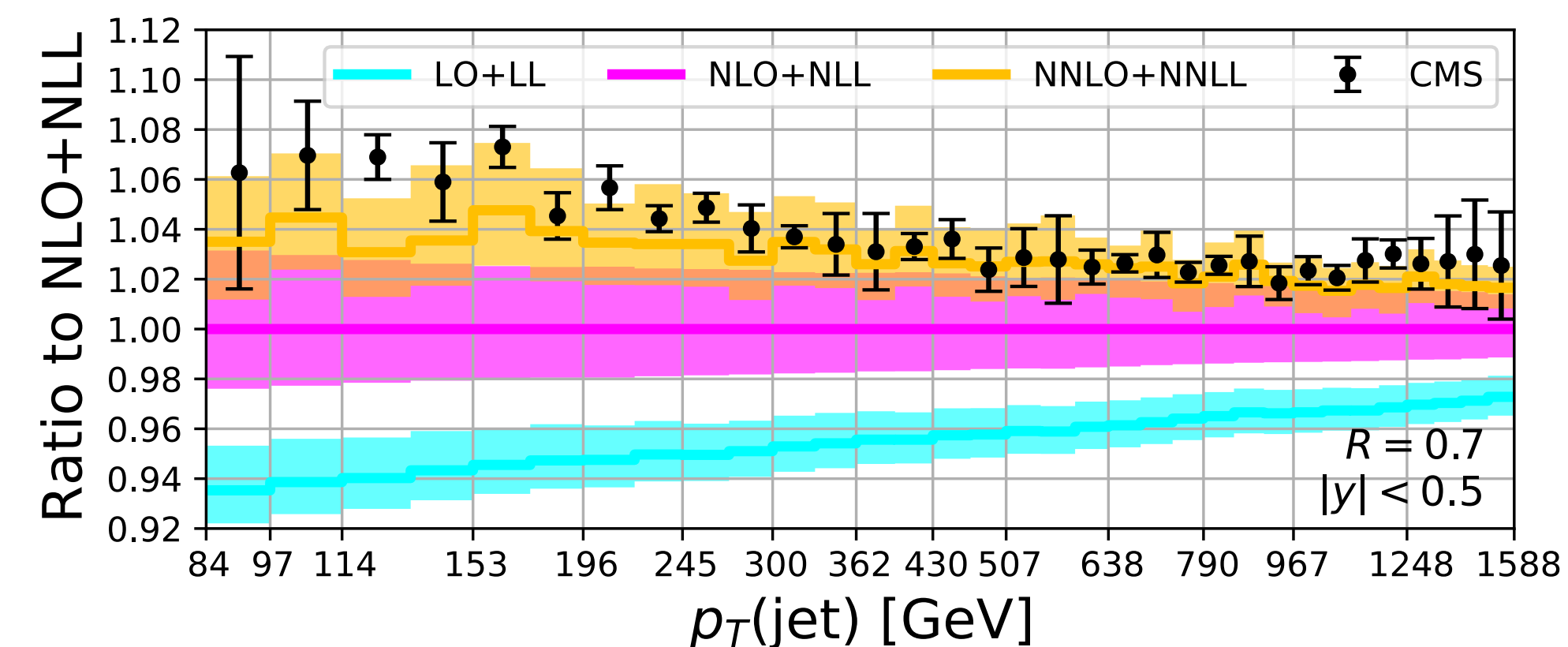
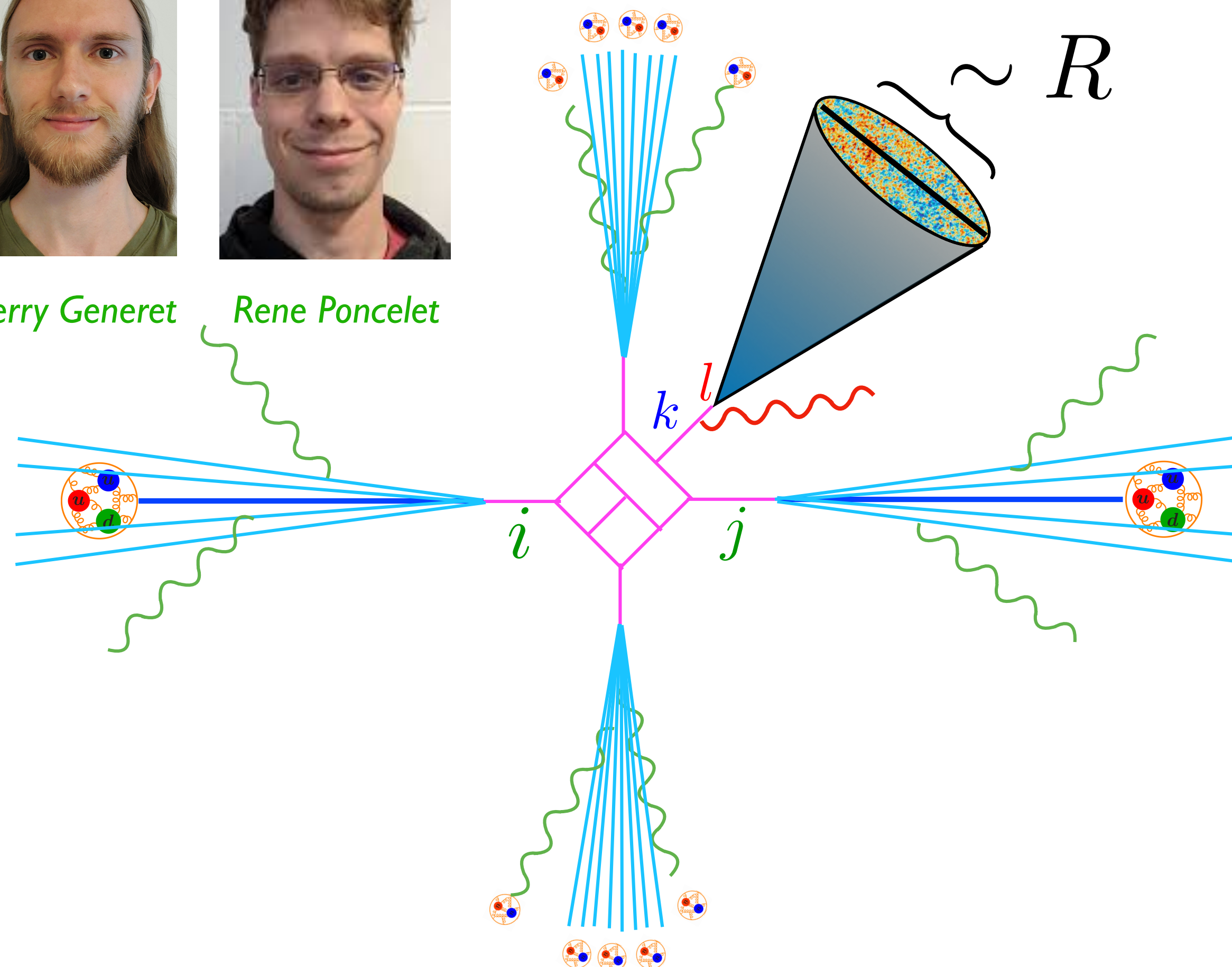
JET PRODUCTION AT THE LHC

I+2 Hard \otimes Jet + FO



Terry Generet

Rene Poncelet



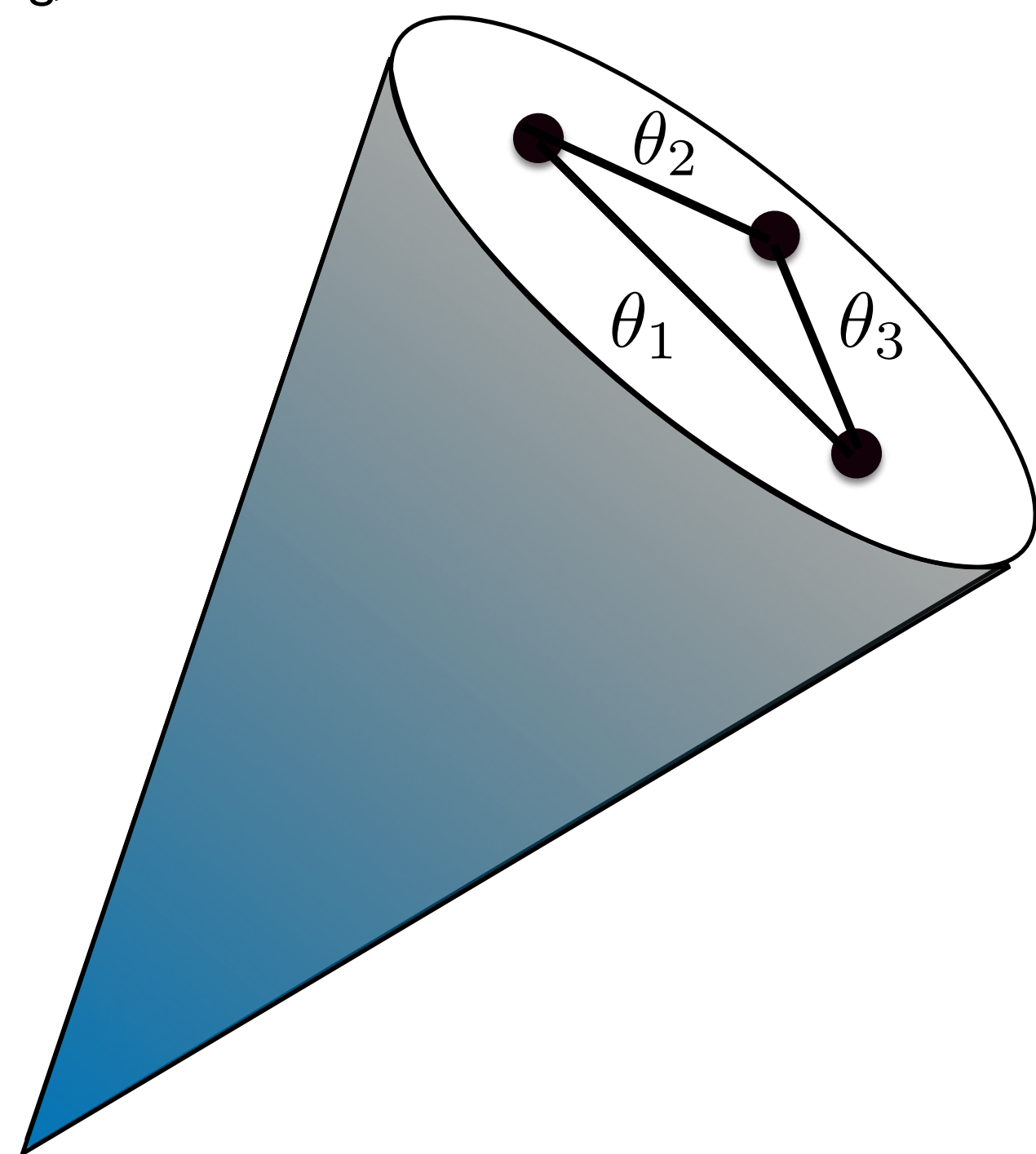
Generet, KL, Mout, Poncelet, Zhang '25

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

PROJECTED N-POINT ENERGY CORRELATORS

Chen, Moul, Zhang, Zhu '20

3. Substructure Scale



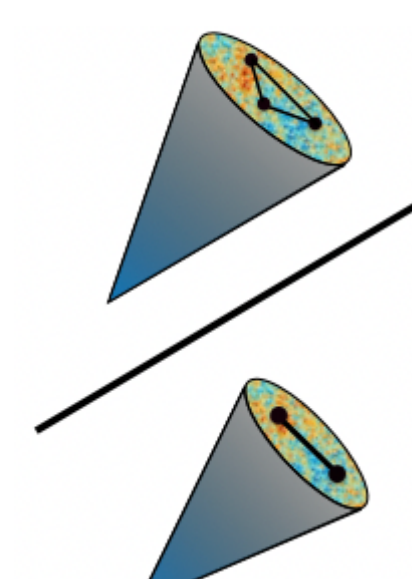
$\theta_L \equiv$ Largest Angle

$\theta_L = \theta_1$

$$\langle \Psi_{\text{Jet}} | \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) \cdots \mathcal{E}(\vec{n}_N) | \Psi_{\text{Jet}} \rangle \Big|_{\theta_L}$$

$$\mathcal{E}_1 \cdots \mathcal{E}_N \sim \theta_L^{\gamma(N+1)-2} \mathbb{O}_i^{[N+1]}$$

↑ quantum
↑ classical



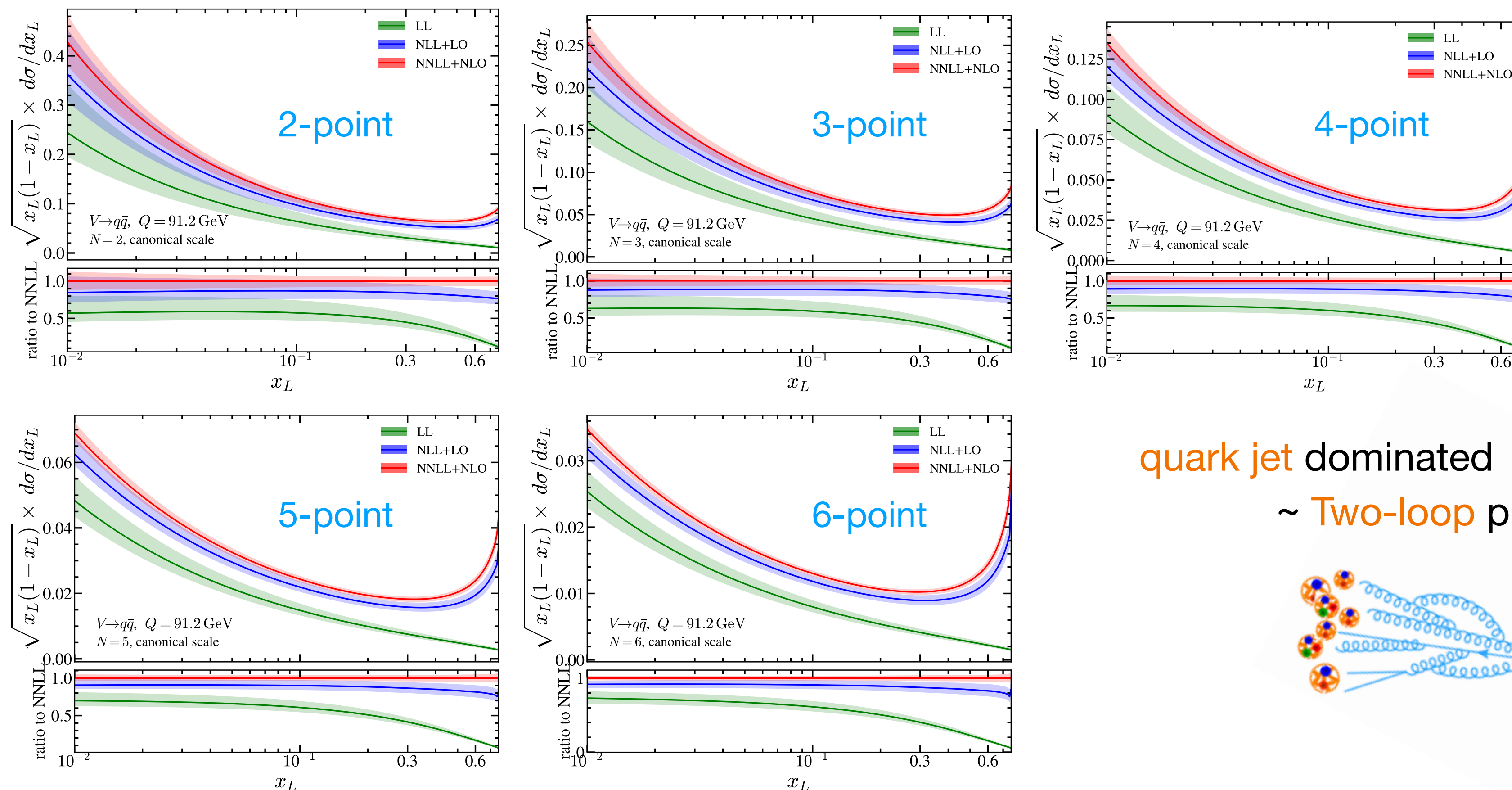
$$\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \cdots \mathcal{E}_N \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \rangle} \sim \theta_L^{\gamma(N+1)-\gamma(3)}$$

$$\gamma(N) \propto \alpha_s$$

Projected energy correlators “projects” higher-point energy correlators to its **largest angle**, giving access to **higher-spin twist-2 anomalous operators**

COLLINEAR LIMIT OF ENERGY CORRELATORS

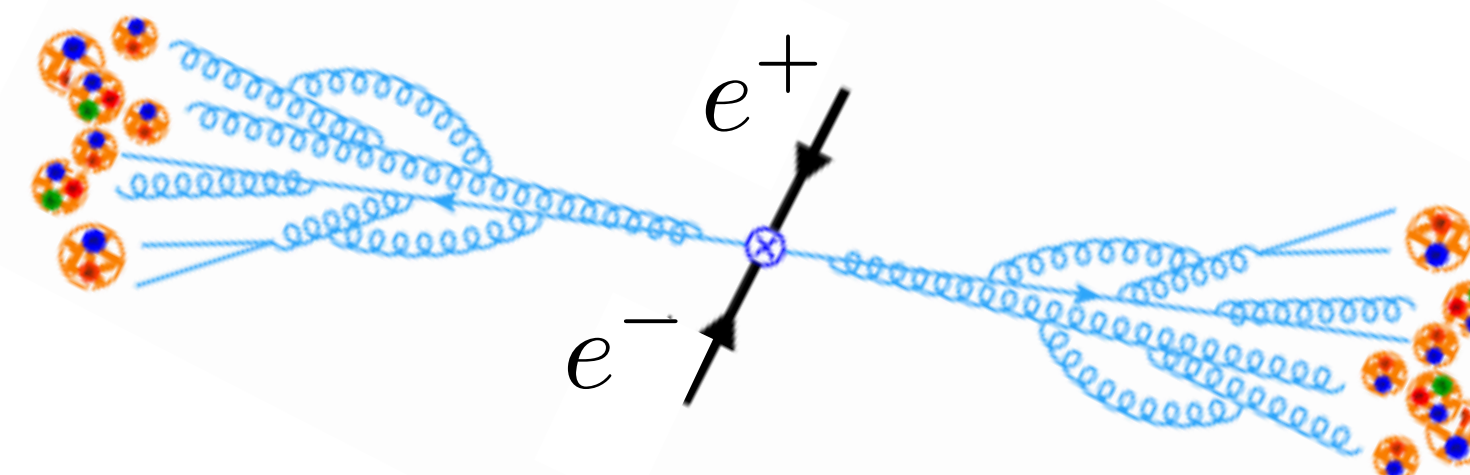
3. Substructure Scale



$$\mathcal{E}_1 \cdots \mathcal{E}_N \sim \theta_L^{\gamma(N+1)-2} \mathbb{O}_i^{[N+1]}$$

quark jet dominated

~ Two-loop projected N-point quark jet function

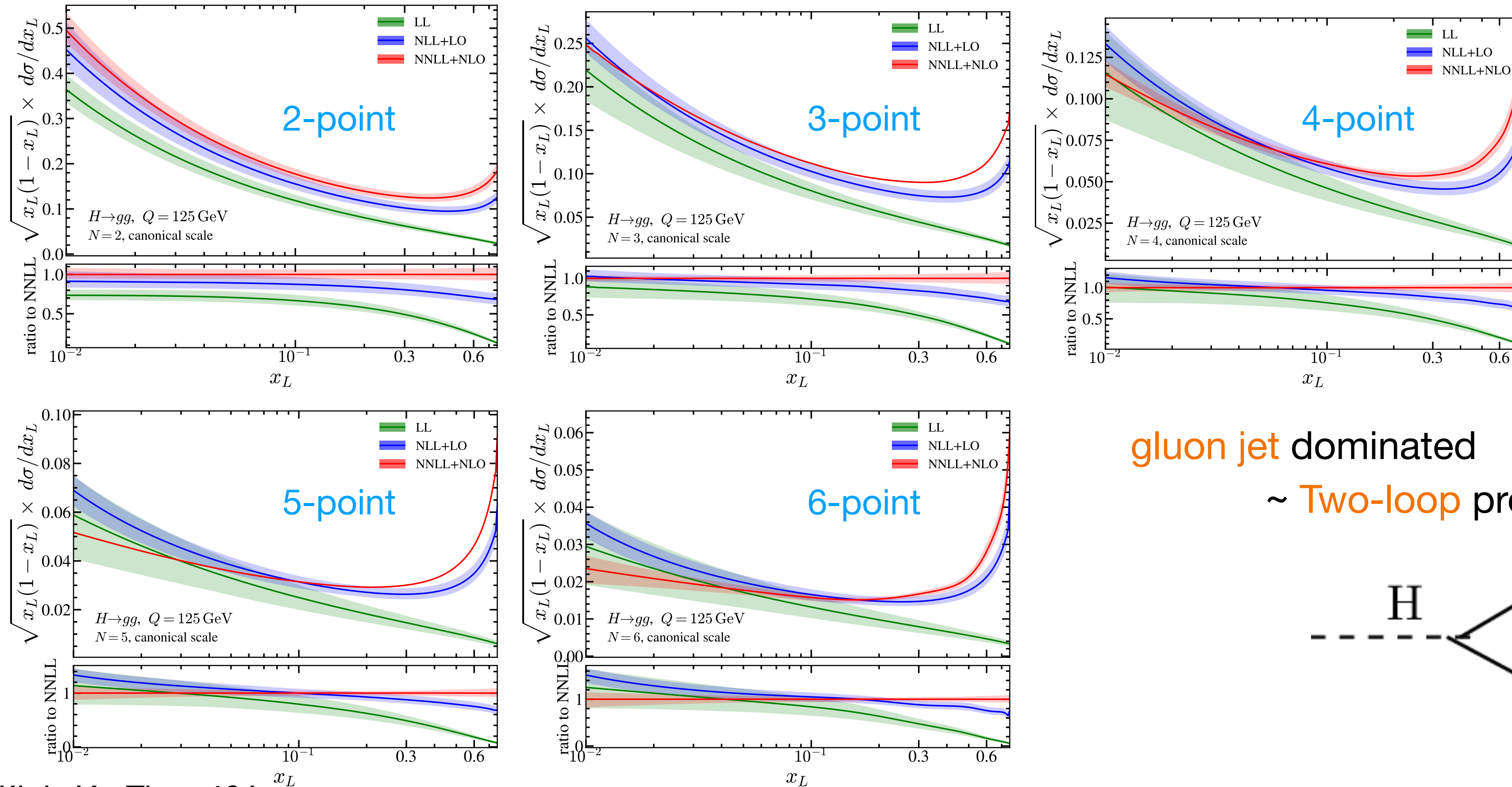


KL, Li, Xu, Zhang '26

- **NNLL calculations** of projected N-point energy correlators as a function of largest angle $x_L = (1 - \cos \theta_L)/2$

COLLINEAR LIMIT OF ENERGY CORRELATORS

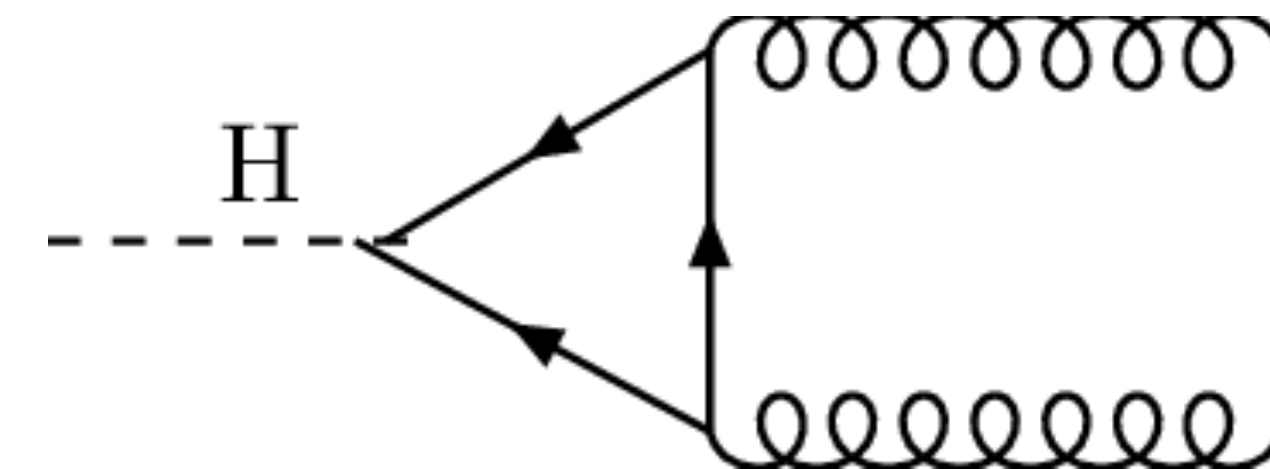
3. Substructure Scale



$$\mathcal{E}_1 \cdots \mathcal{E}_N \sim \theta_L^{\gamma(N+1)-2} \mathbb{O}_i^{[N+1]}$$

gluon jet dominated

~ Two-loop projected N-point gluon jet function

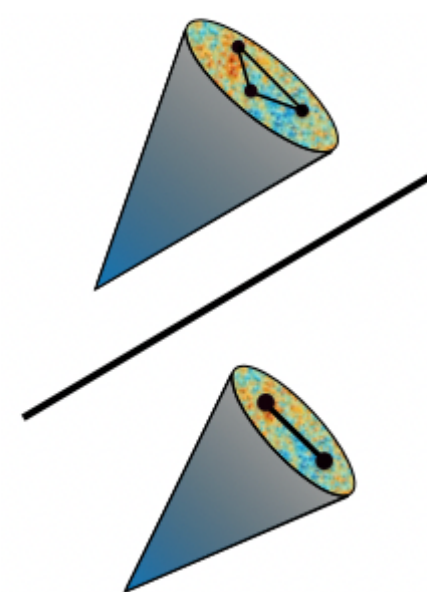
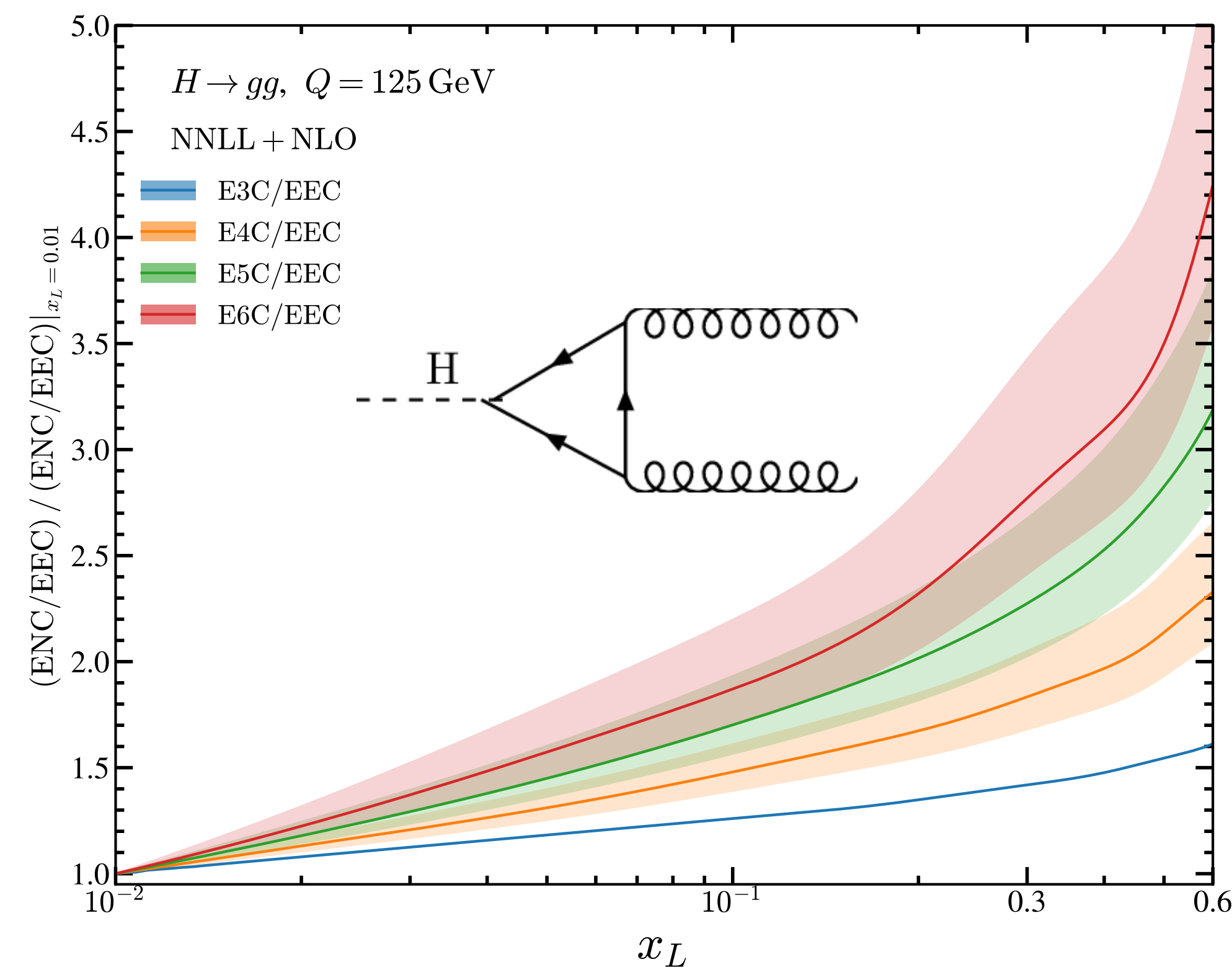
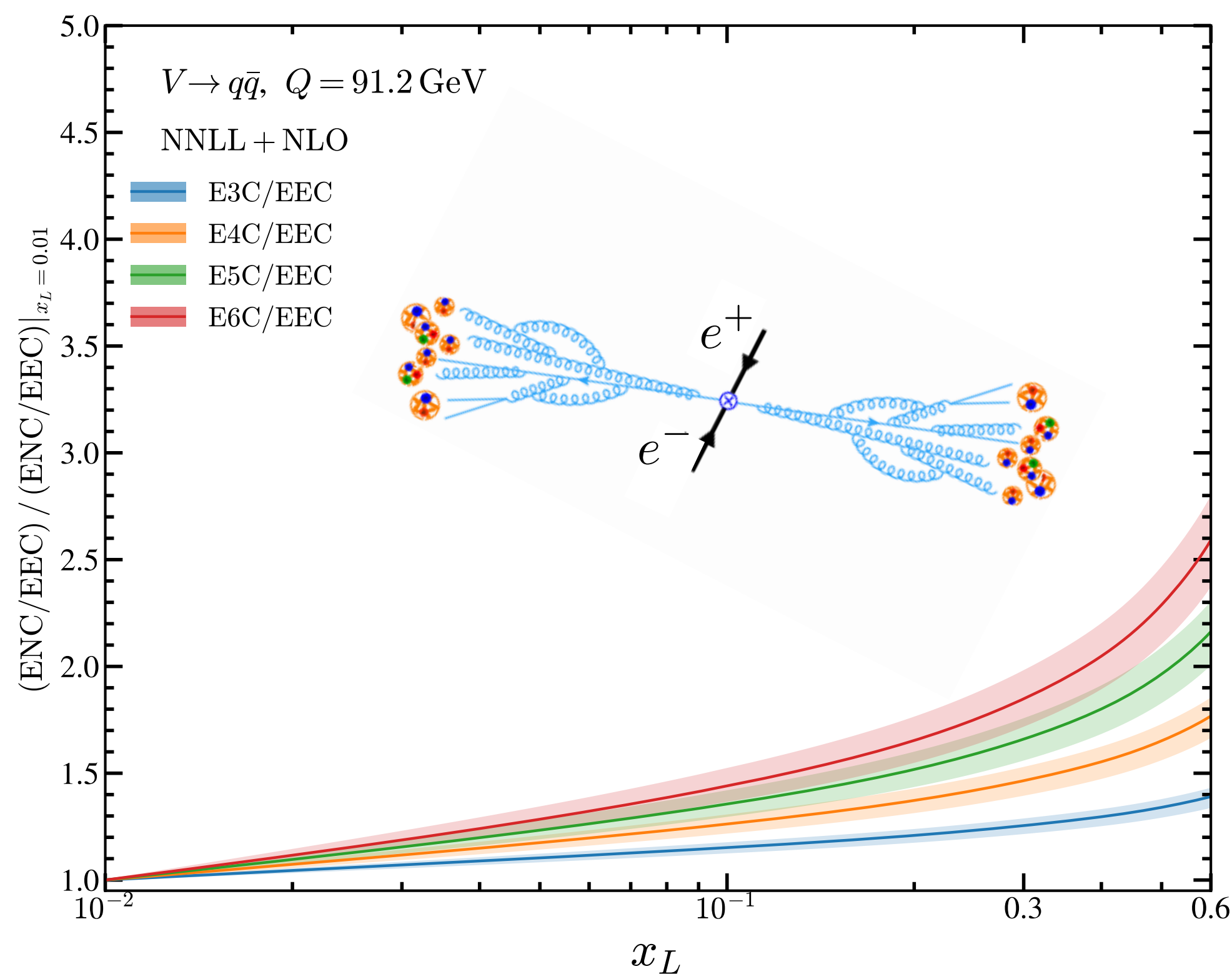


KL, Li, Xu, Zhang '26

- **NNLL calculations** of projected N-point energy correlators as a function of largest angle $x_L = (1 - \cos \theta_L)/2$

RATIO OF PROJECTED ENERGY CORRELATORS

3. Substructure Scale



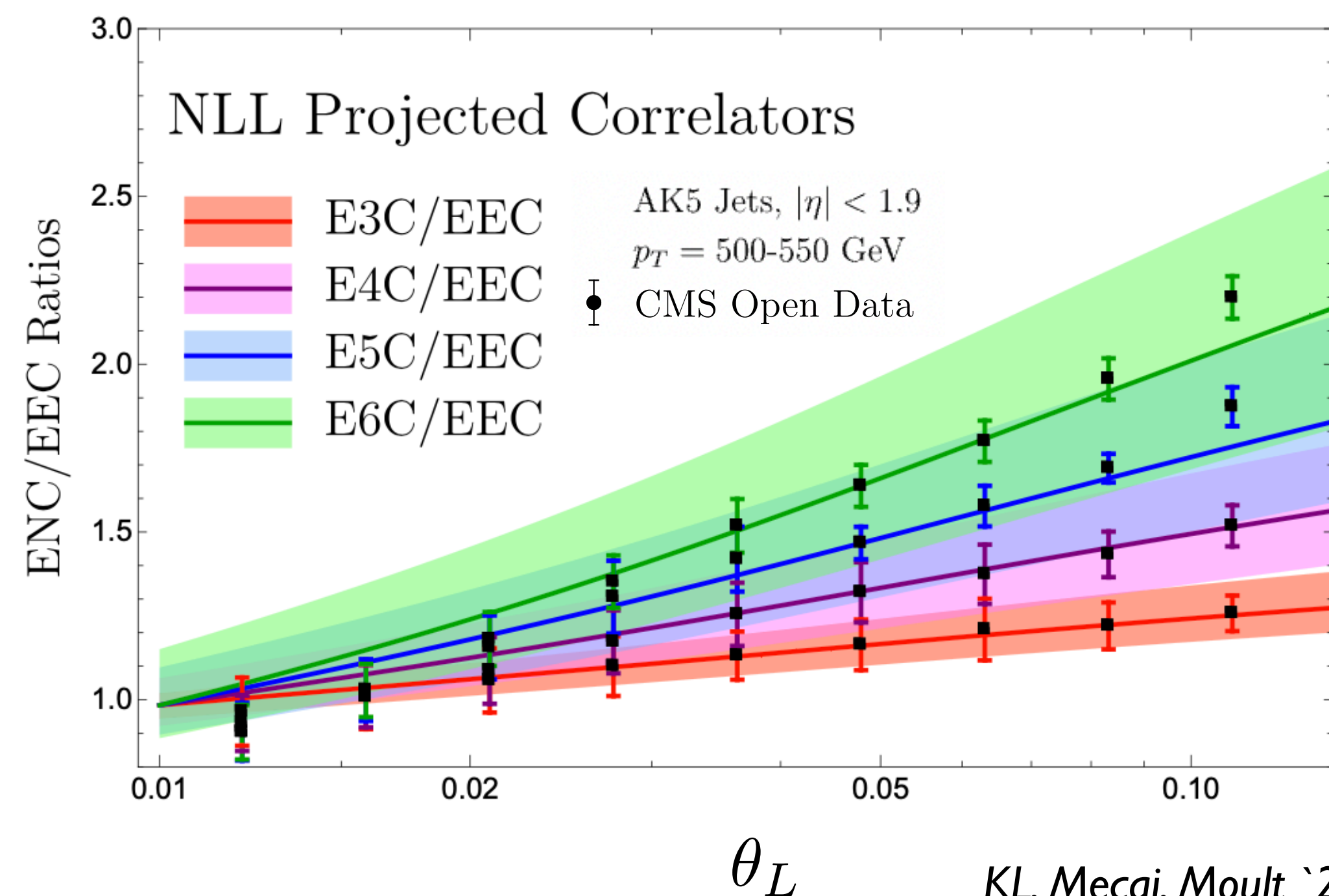
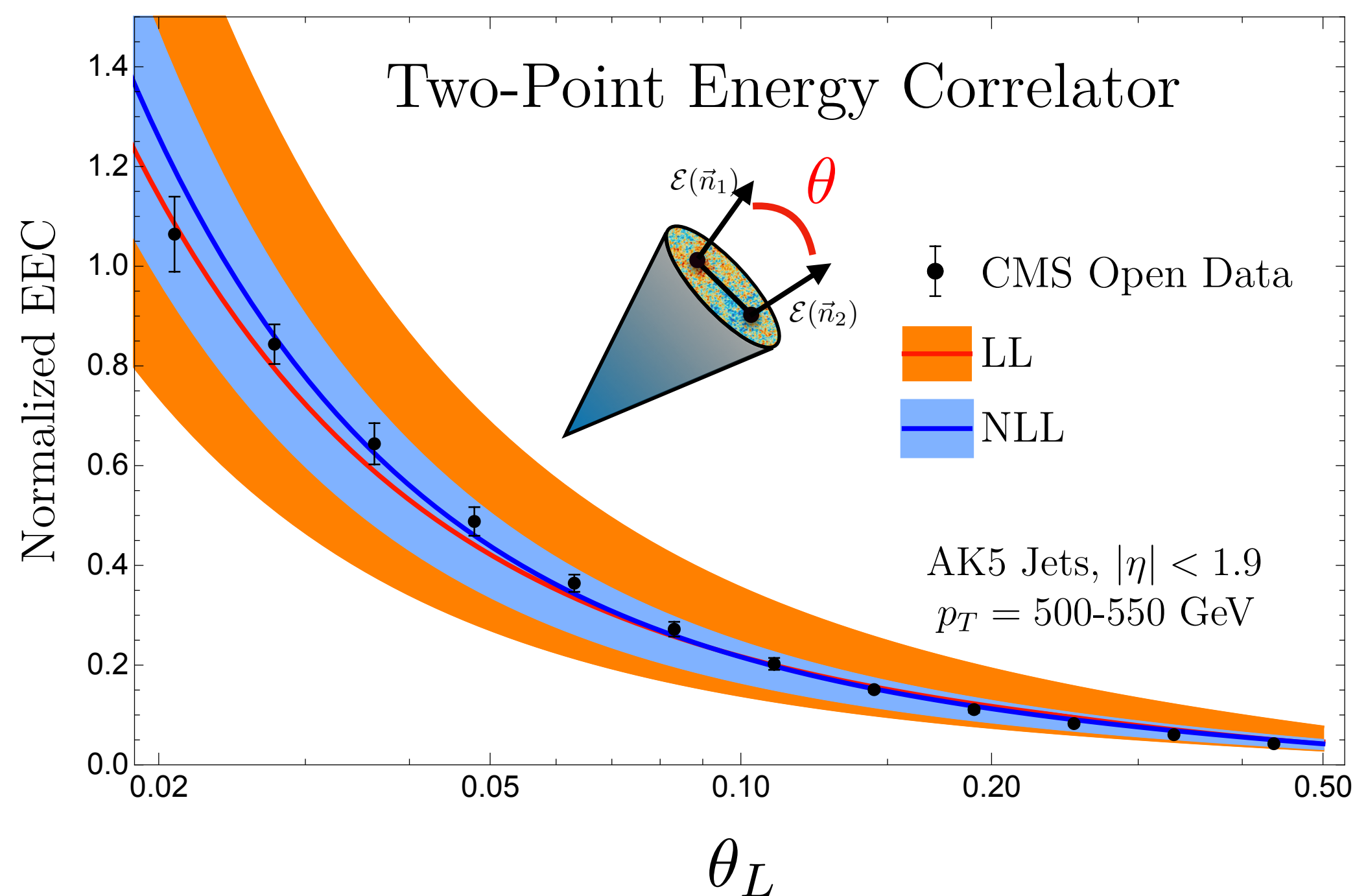
$$\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \cdots \mathcal{E}_N \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \rangle} \sim \theta_L^{\gamma(N+1) - \gamma(3)}$$

$$\gamma(N) \propto \alpha_s$$

- As expected, we observe that **anomalous dimension increases with spin-N** and is **larger for gluon than quark**

ENERGY CORRELATORS AT THE LHC

1+2+3 Hard ⊗ Jet ⊗ Substructure



KL, Meçaj, Moutl `22

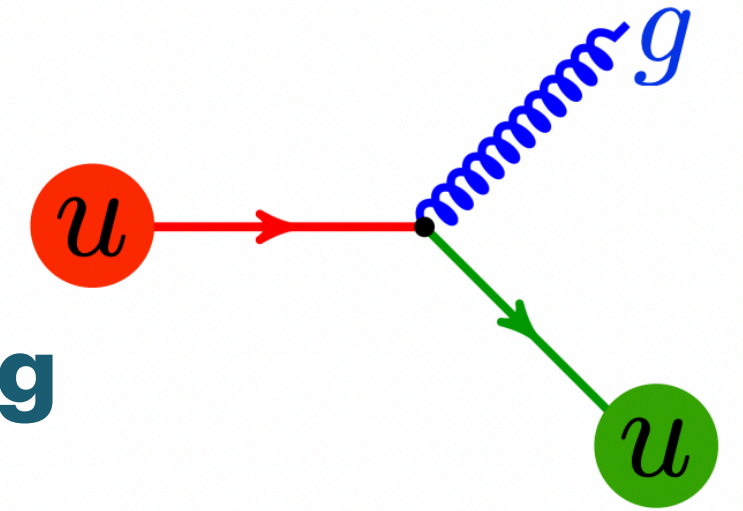
See also Chen, Gao, Li, Xu, Zhang `23

Combining the functions of the **hard + jet + projected ENC jet** scales, we can study **projected correlators at the LHC!**

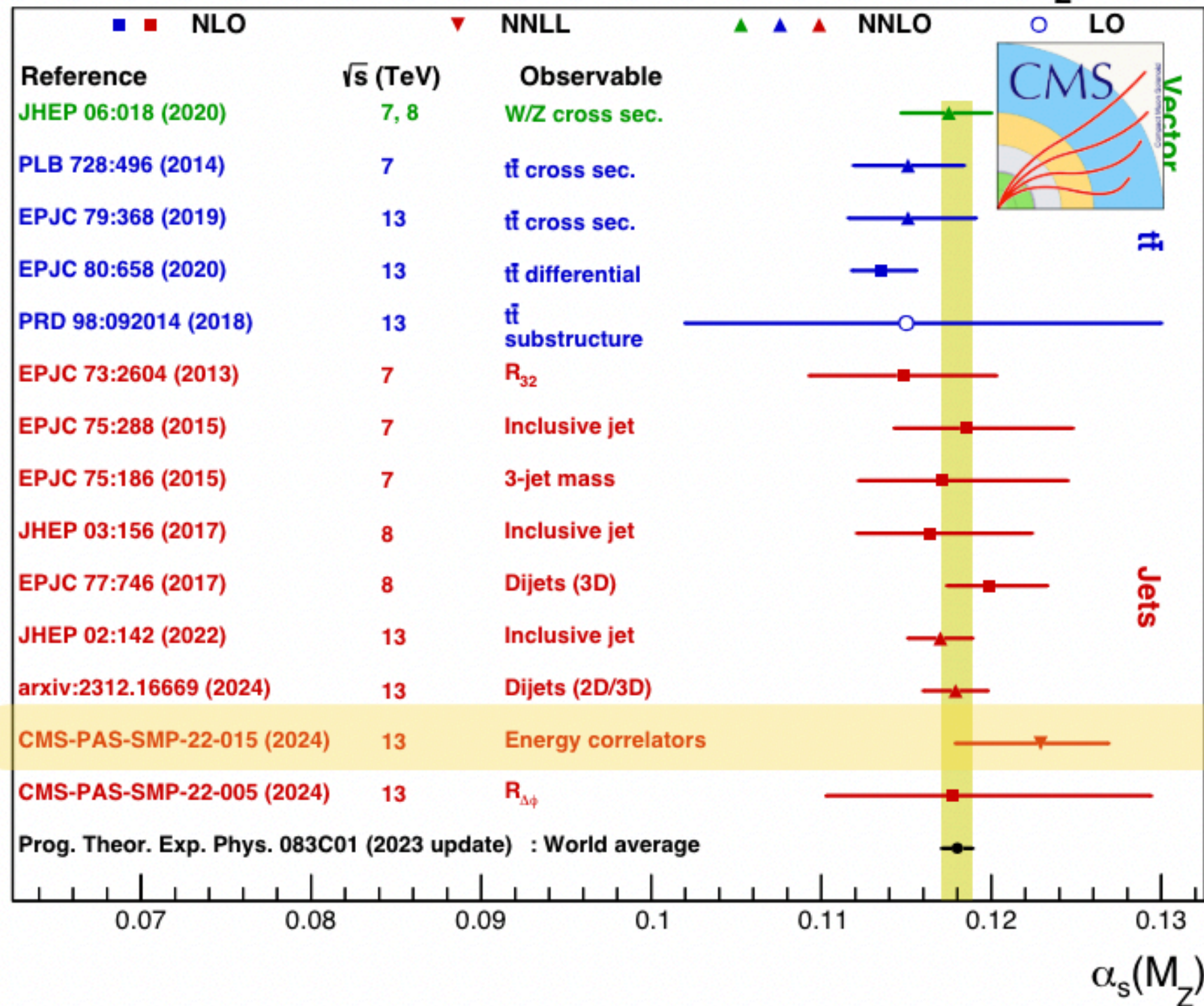
STRONG COUPLING DETERMINATION WITH RATIO OF ENERGY CORRELATORS

- **How strong is the Strong Force?** In comparison, EM coupling: $\alpha_e = 0.0072973525693(11)$

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



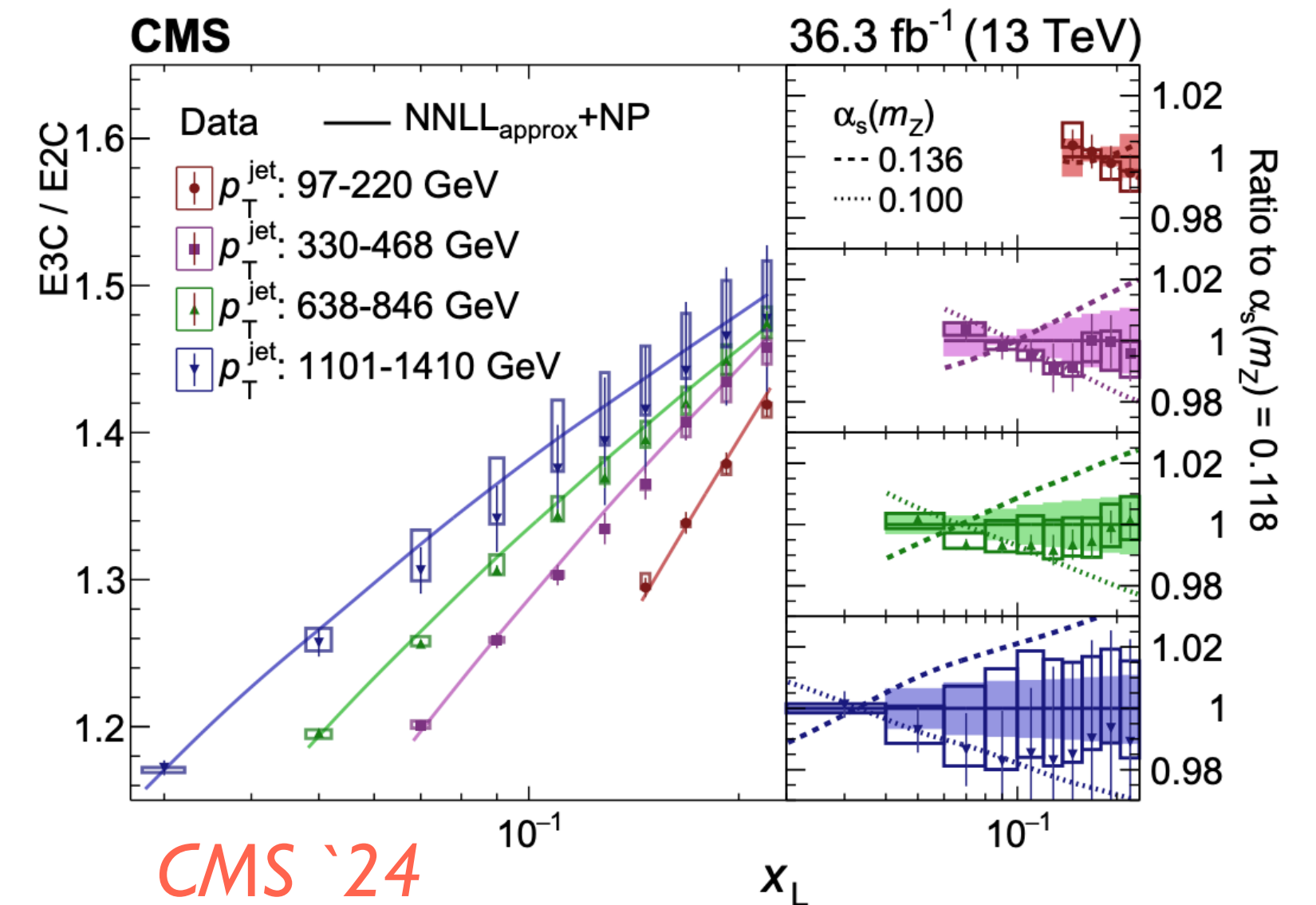
Summary of $\alpha_s(M_Z)$



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

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

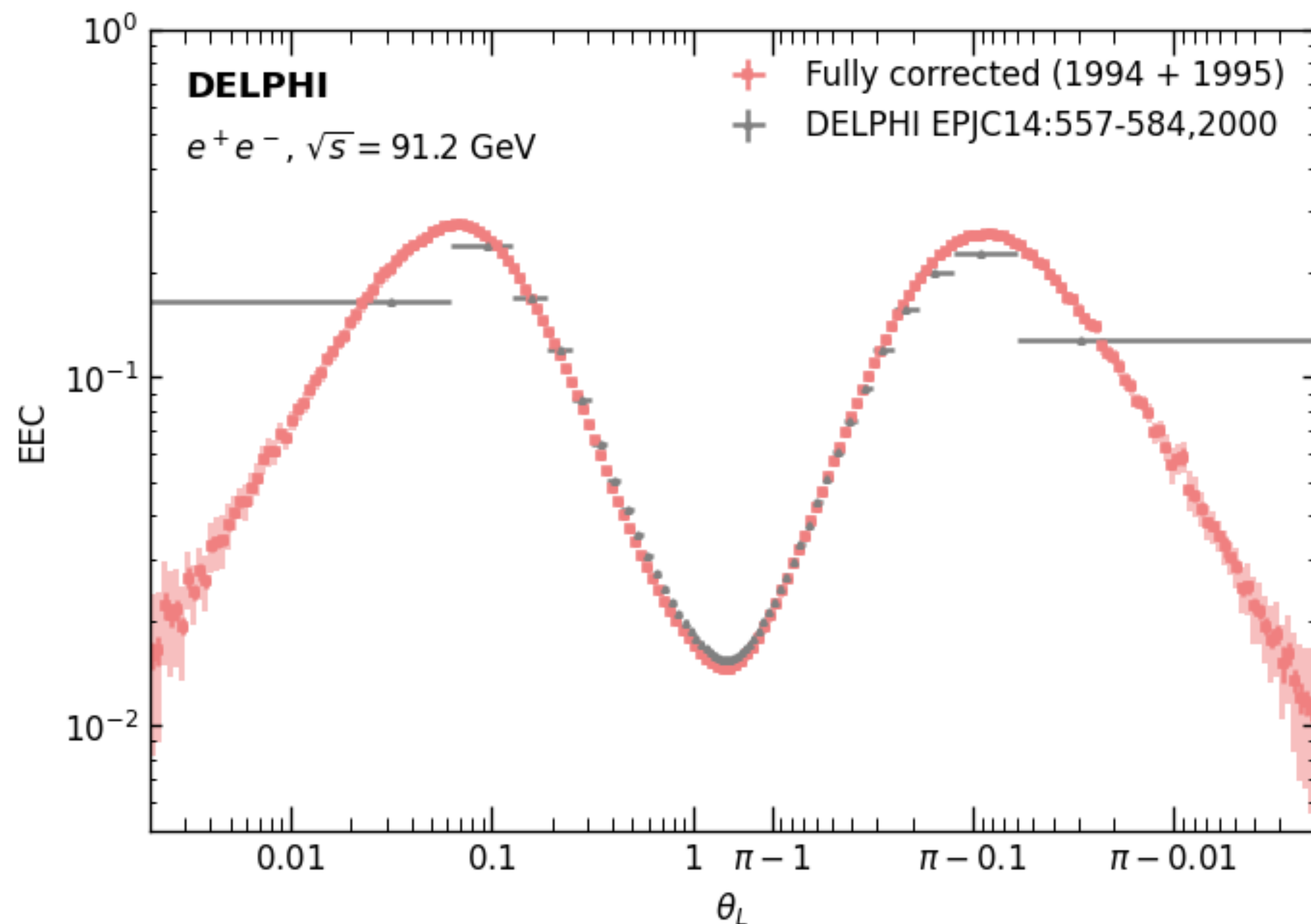
Energy Correlators in Jet



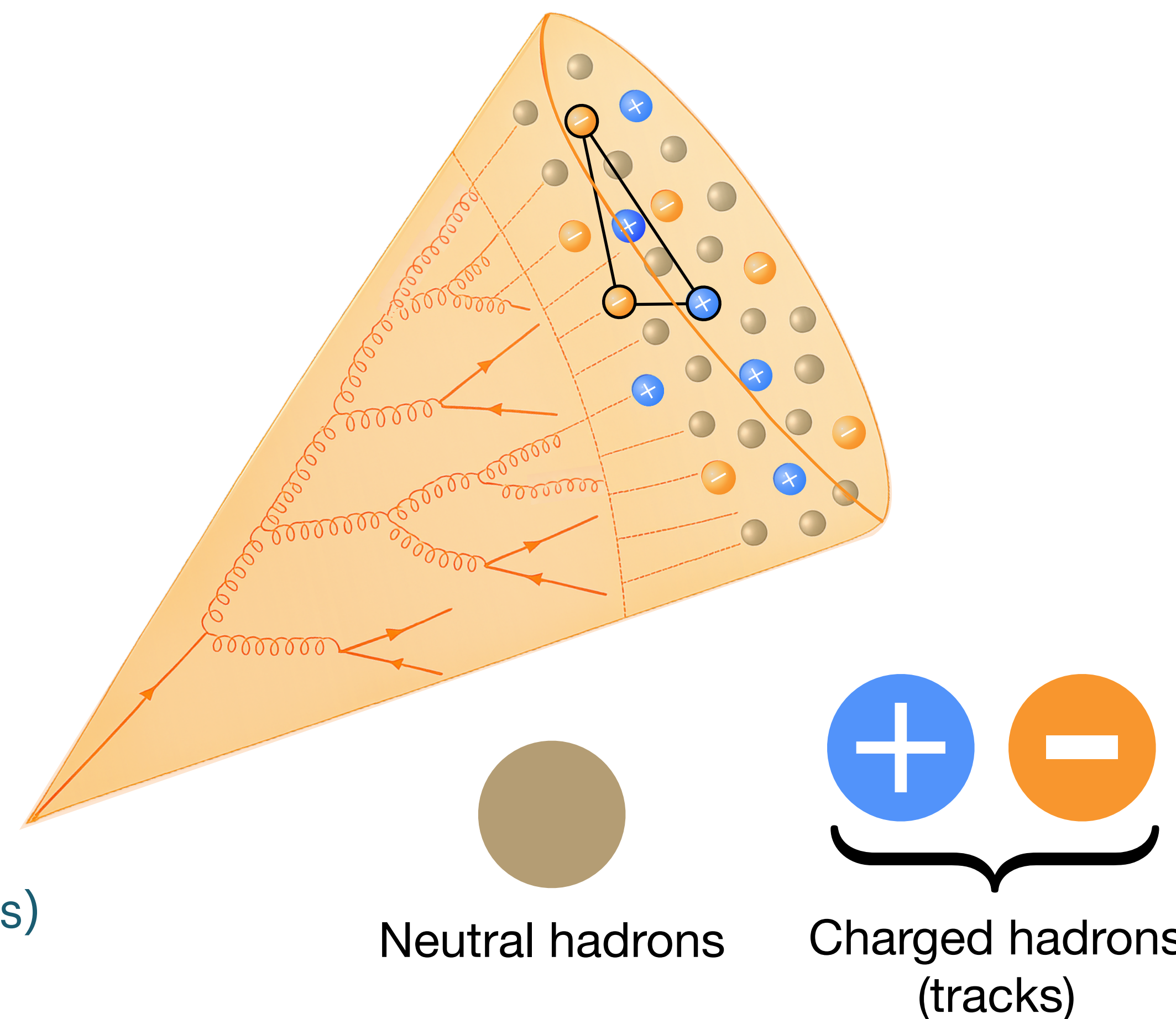
MEASURING ON TRACKS

4 NP measurements

Track EEC in e^+e^-



Track EEC in Jets

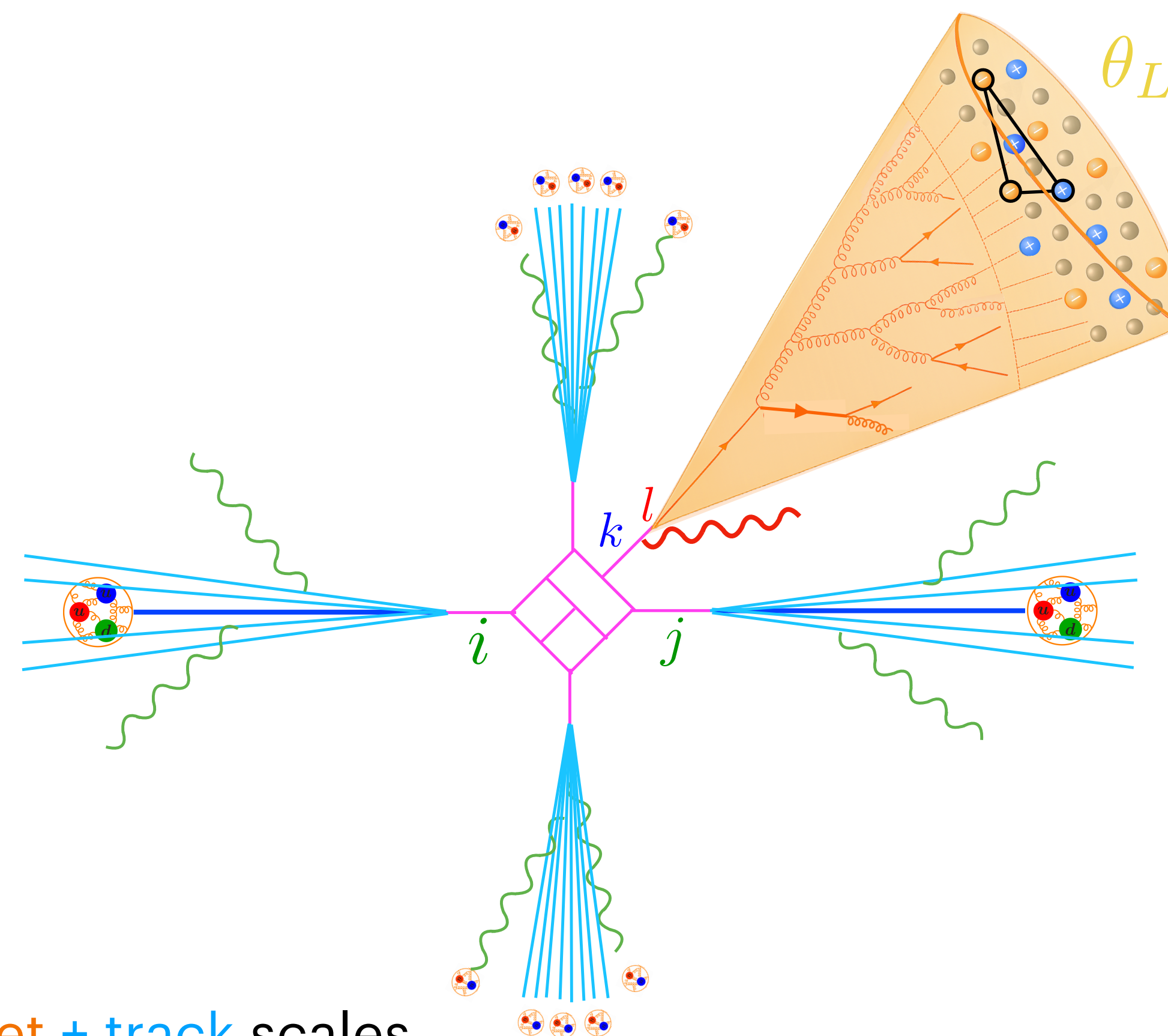
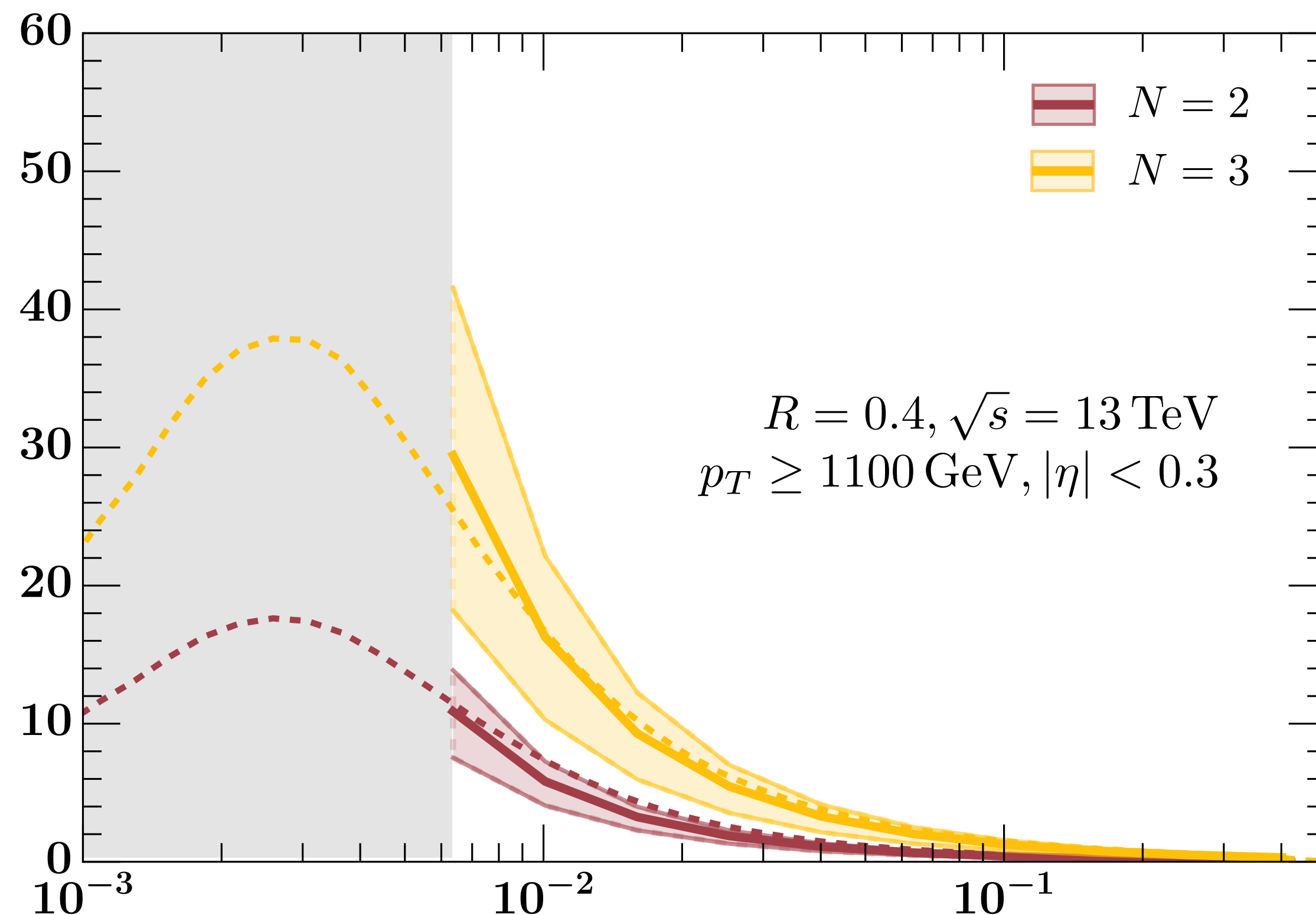


Experimental measurements on **tracks** (charged hadrons) provide more **precise angular resolutions!**

PUTTING JET SUBSTRUCTURE ON TRACK(S)

$$10^{\frac{N-2}{2}} \times \langle \Psi | \mathcal{E}_{\text{tr}}(\vec{n}_1) \cdots \mathcal{E}_{\text{tr}}(\vec{n}_N) | \Psi \rangle$$

1+2+3+4 Hard \otimes Jet \otimes Substructure \otimes Track



KL, Li, Moult, Waalewijn '26

See also Jaarsma, Li, Moult, Waalewijn, Zhu '25

Combining the functions of the **hard + jet + projected ENC jet + track** scales, we can study **projected track energy correlators** at the LHC!

QCD FACTORIZATION FRAMEWORK OF JET SUBSTRUCTURE

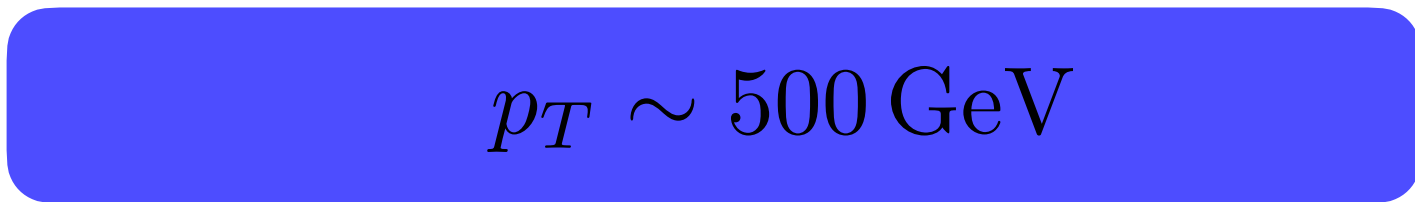
$$\frac{d\sigma}{dp_T d\eta d\theta_L} = \sum_{i,j,k,l} f_{i/P} \otimes f_{j/P} \otimes H_{ij}^k \otimes \mathcal{J}_{kl} \otimes [J_l \otimes T] + \text{fixed order}$$

PDFs
Parton Hard Scattering
Jet Production
Substructure Measurement
FFs

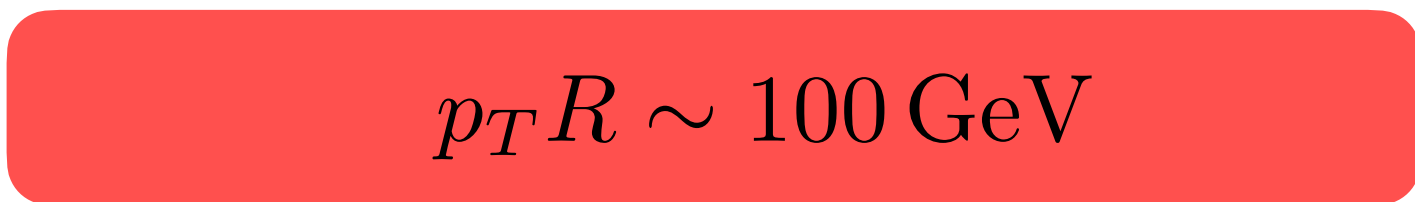
KL, Moul, Zhang '24

Energy scales

Hard Scale



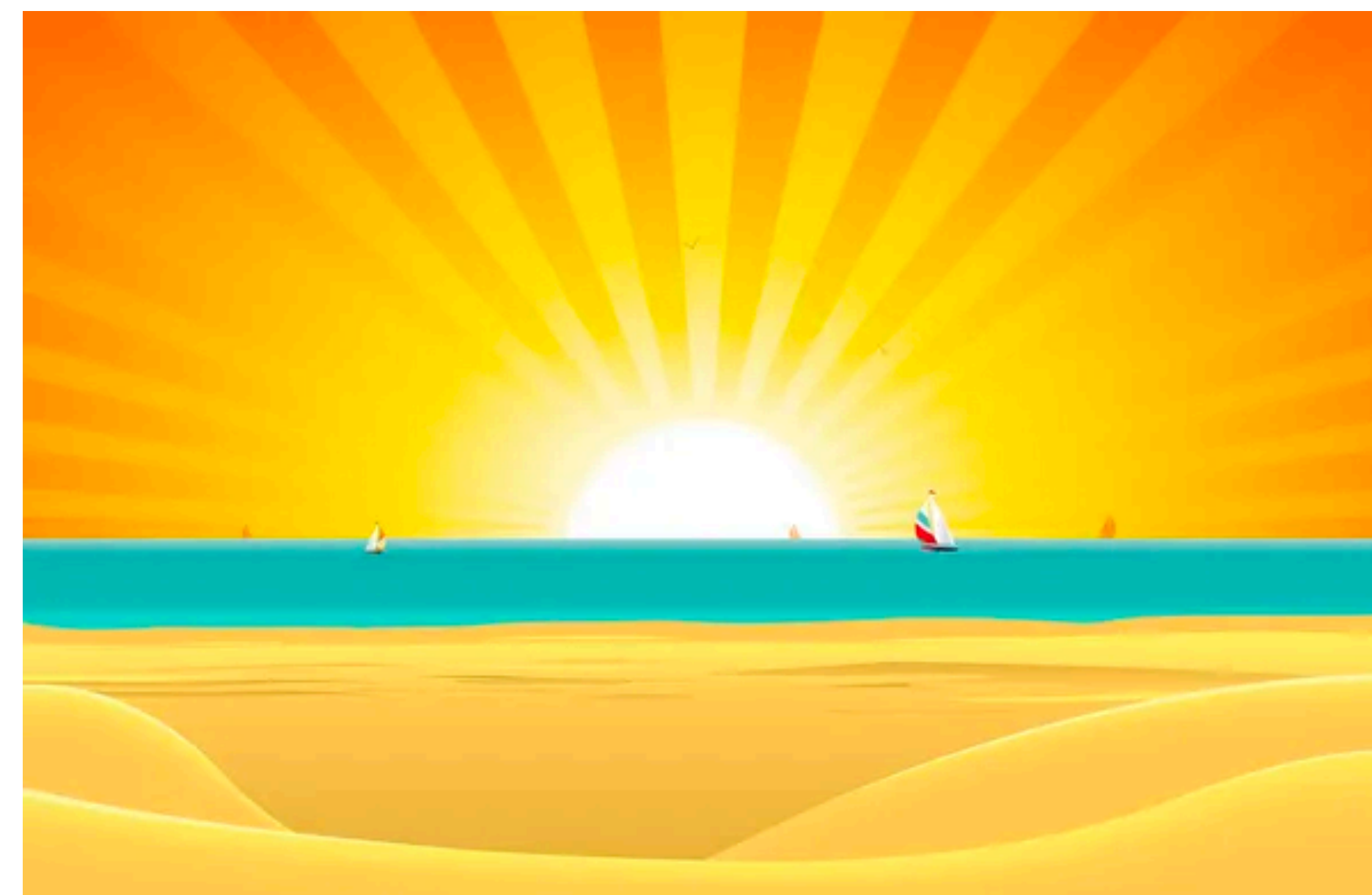
Jet Scale



Substructure Scale



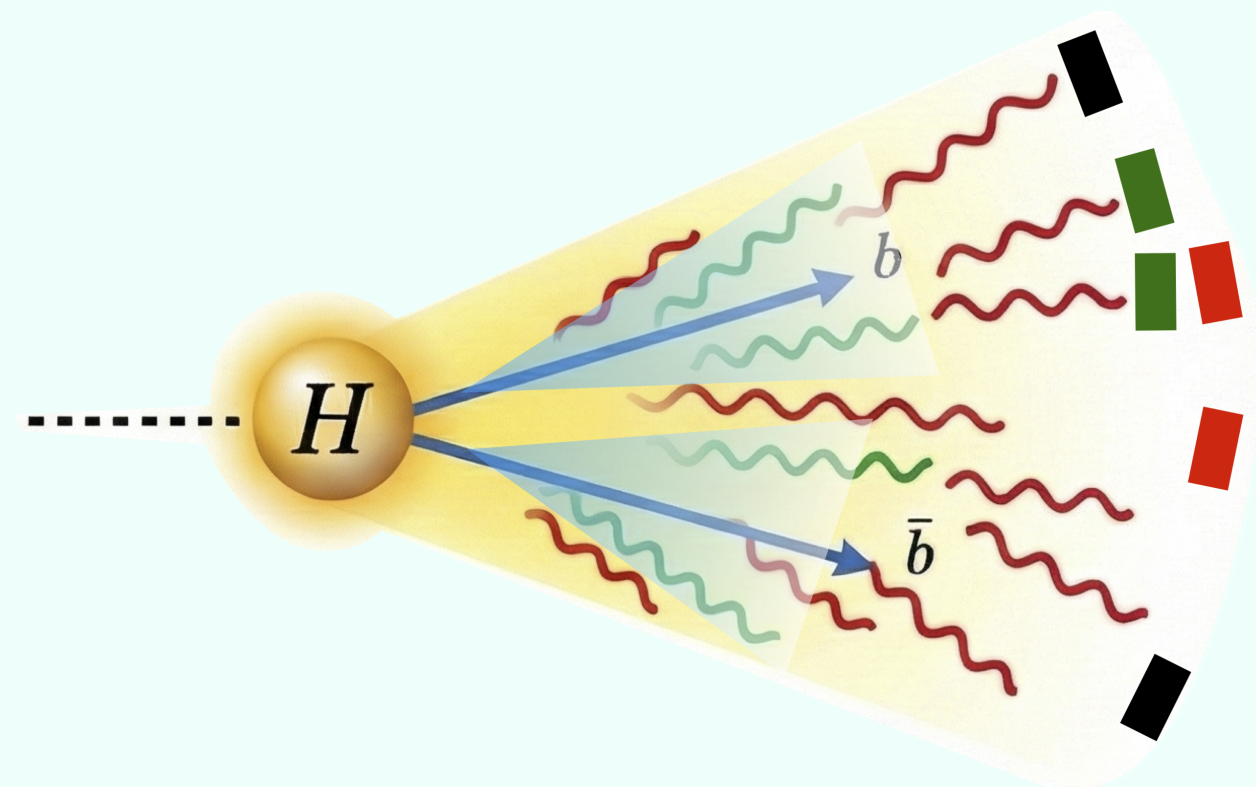
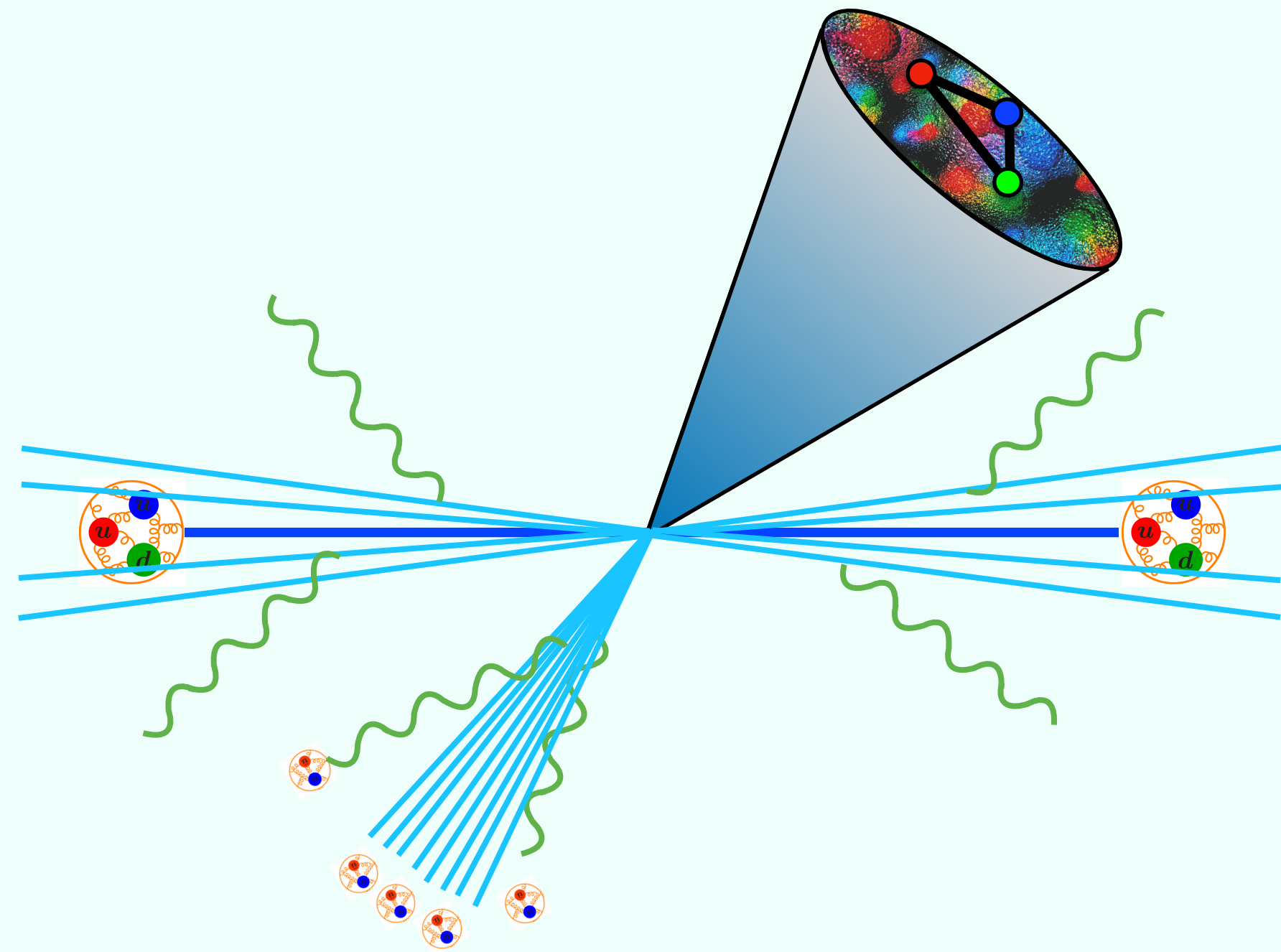
Nonperturbative Scale



Precision jet substructure near the horizon!

Stay tuned!

Outline.



- 1. Hard Scale
- 2. Jet Scale
- 1+2**
- 3. Substructure Scale
- 1+2+3**
- 4. Nonperturbative Scale
- 1+2+3+4**

Energy scales

$p_T \sim 500 \text{ GeV}$

$p_T R \sim 100 \text{ GeV}$

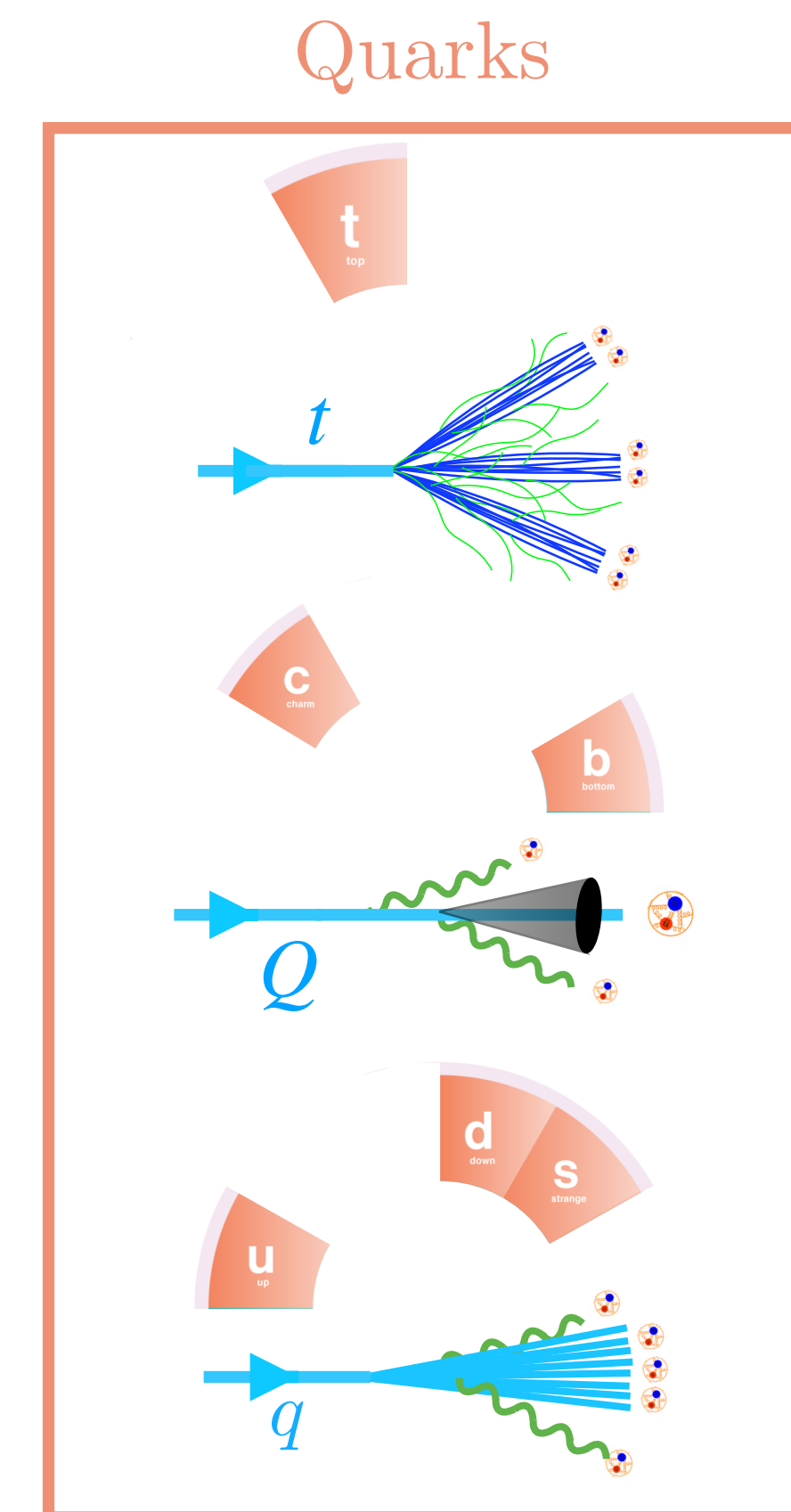
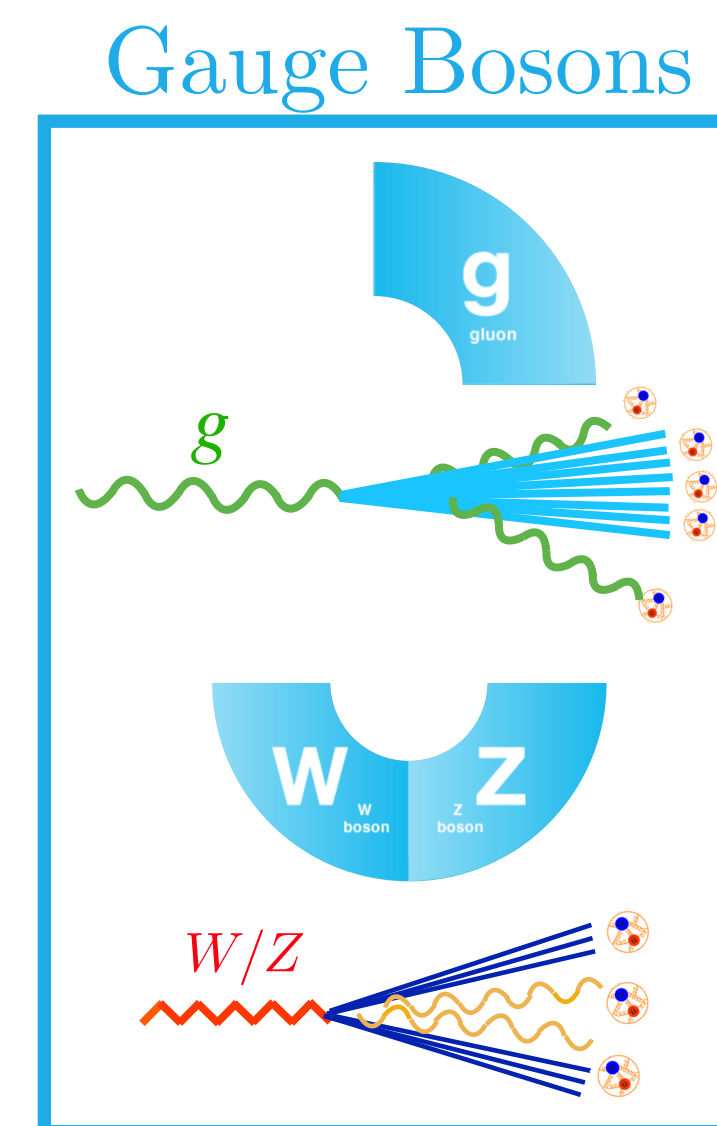
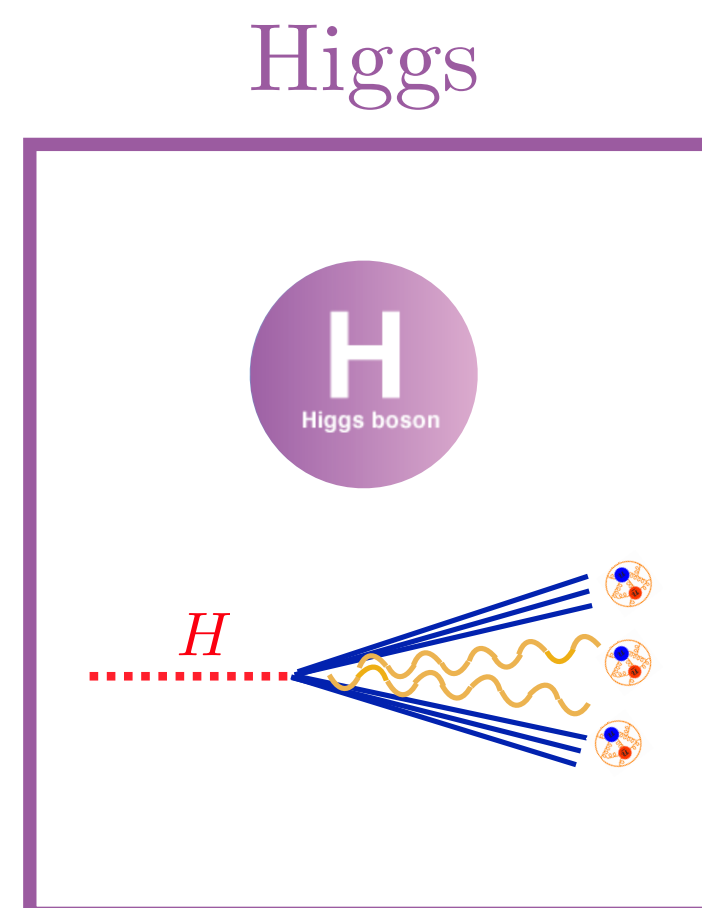
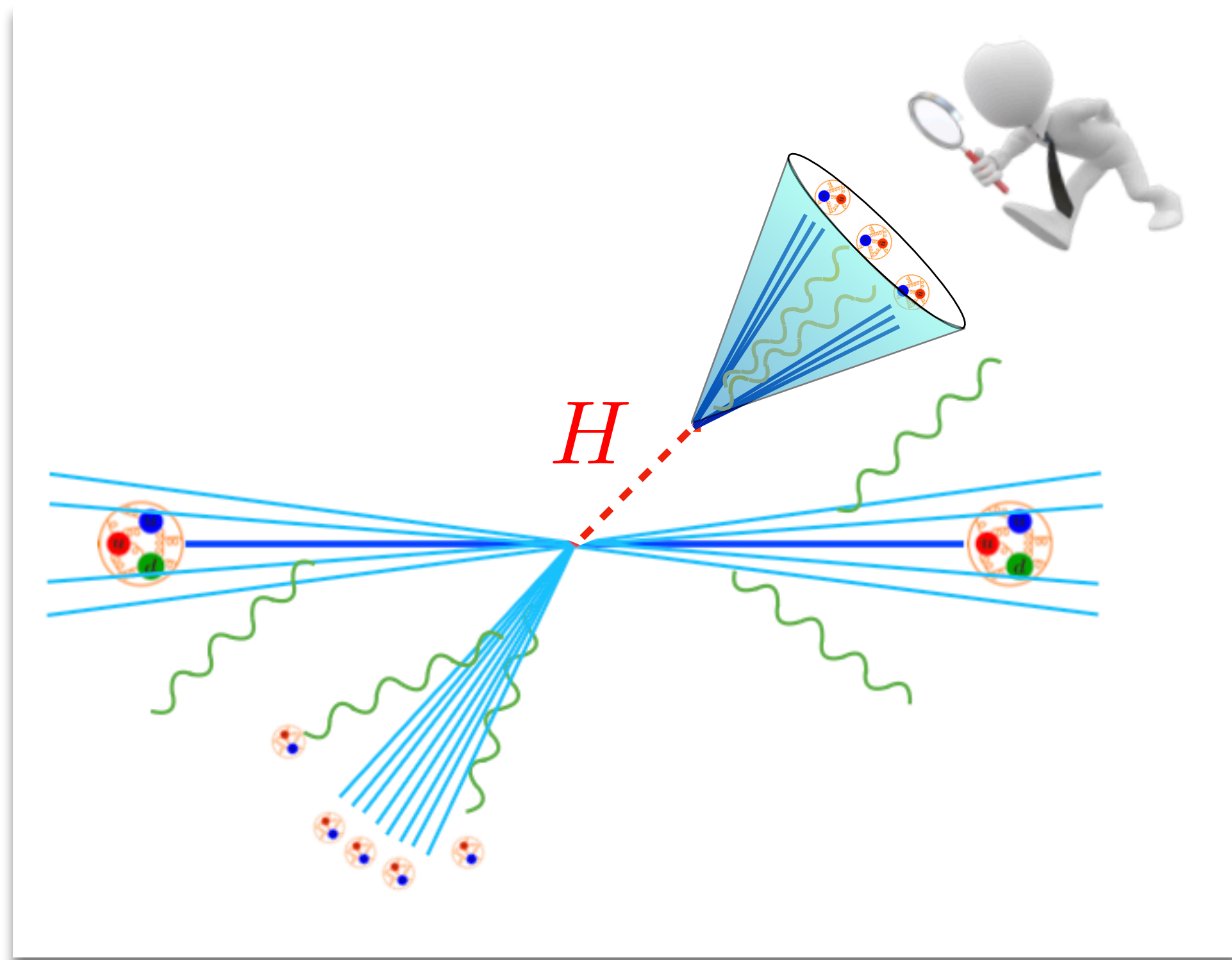
$p_T \theta \sim 30 \text{ GeV}$

$\Lambda_{\text{QCD}} \sim 1 \text{ GeV}$

5. Electroweak Jets and New Physics

STANDARD MODEL OF 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**.



HIGGS AT REST

Gao, KL, Zhang '26

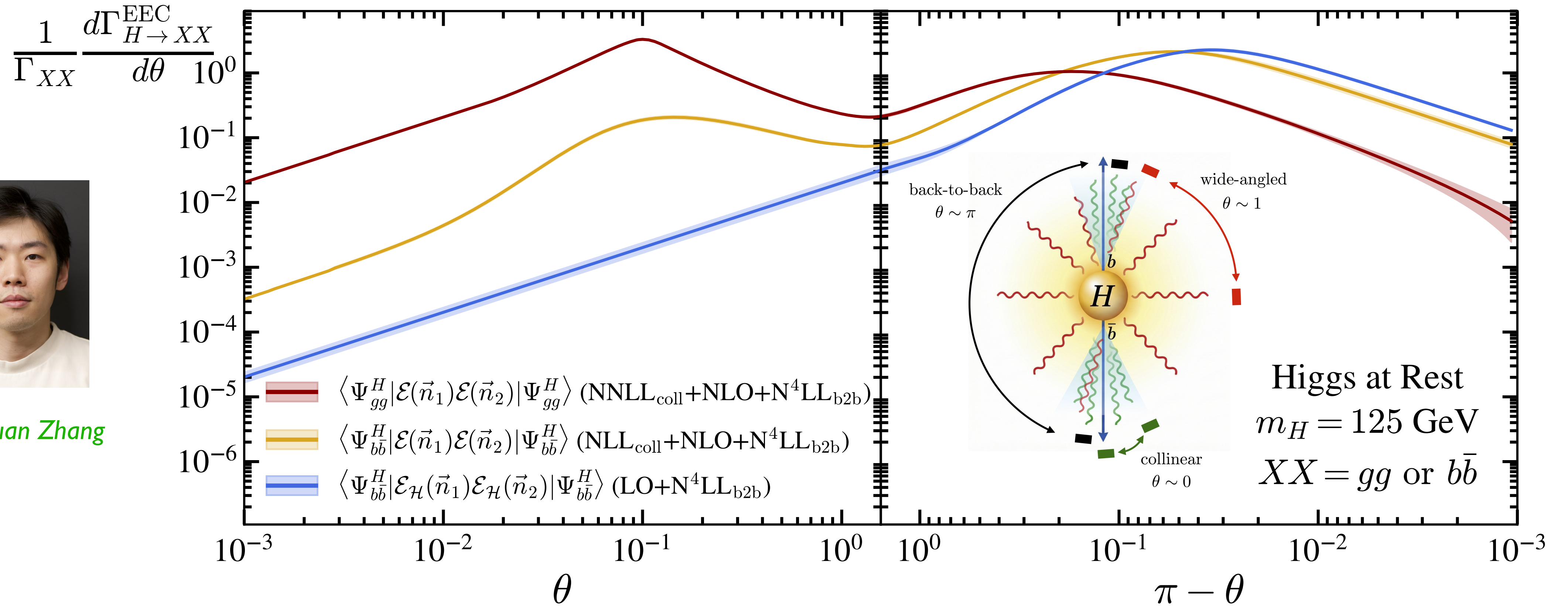
See also Holguin, Moul, Pathak, Procura, Sule '26



Anjie Gao



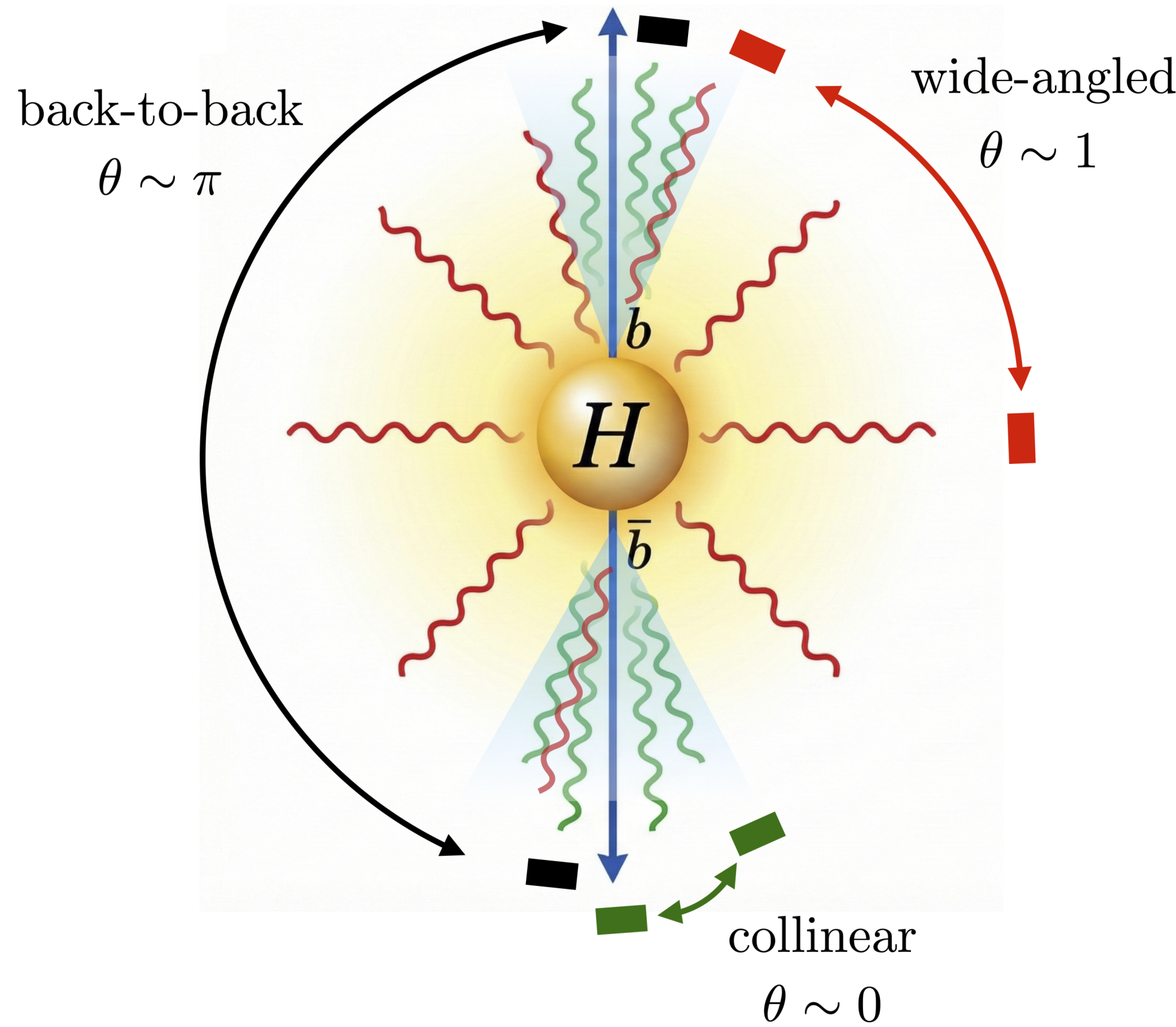
Xiaoyuan Zhang



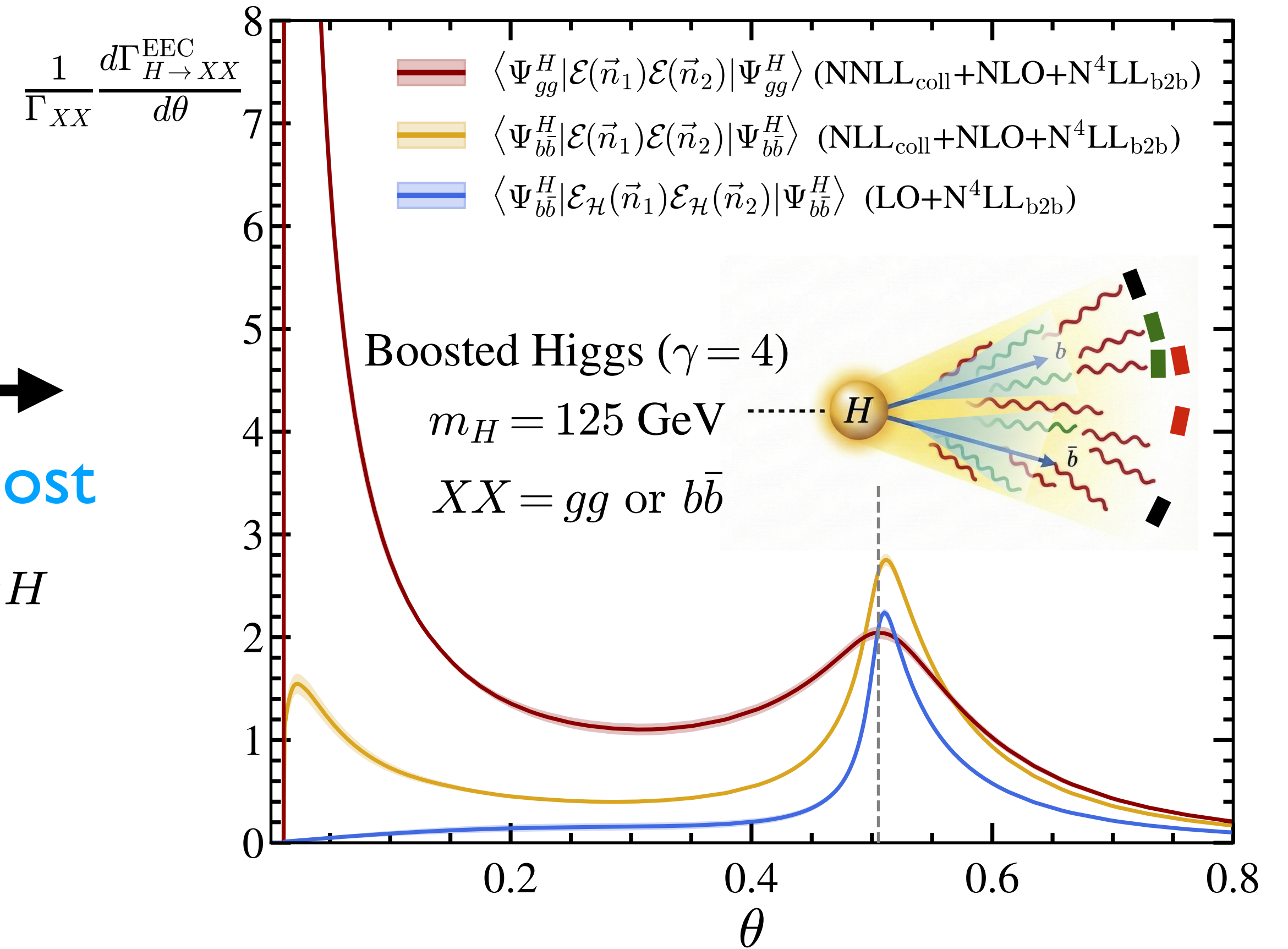
Energy correlators for Higgs decays into various channels, computed with remarkable accuracy!

Similar calculations for other color-singlet resonances

BOOSTED HIGGS JETS

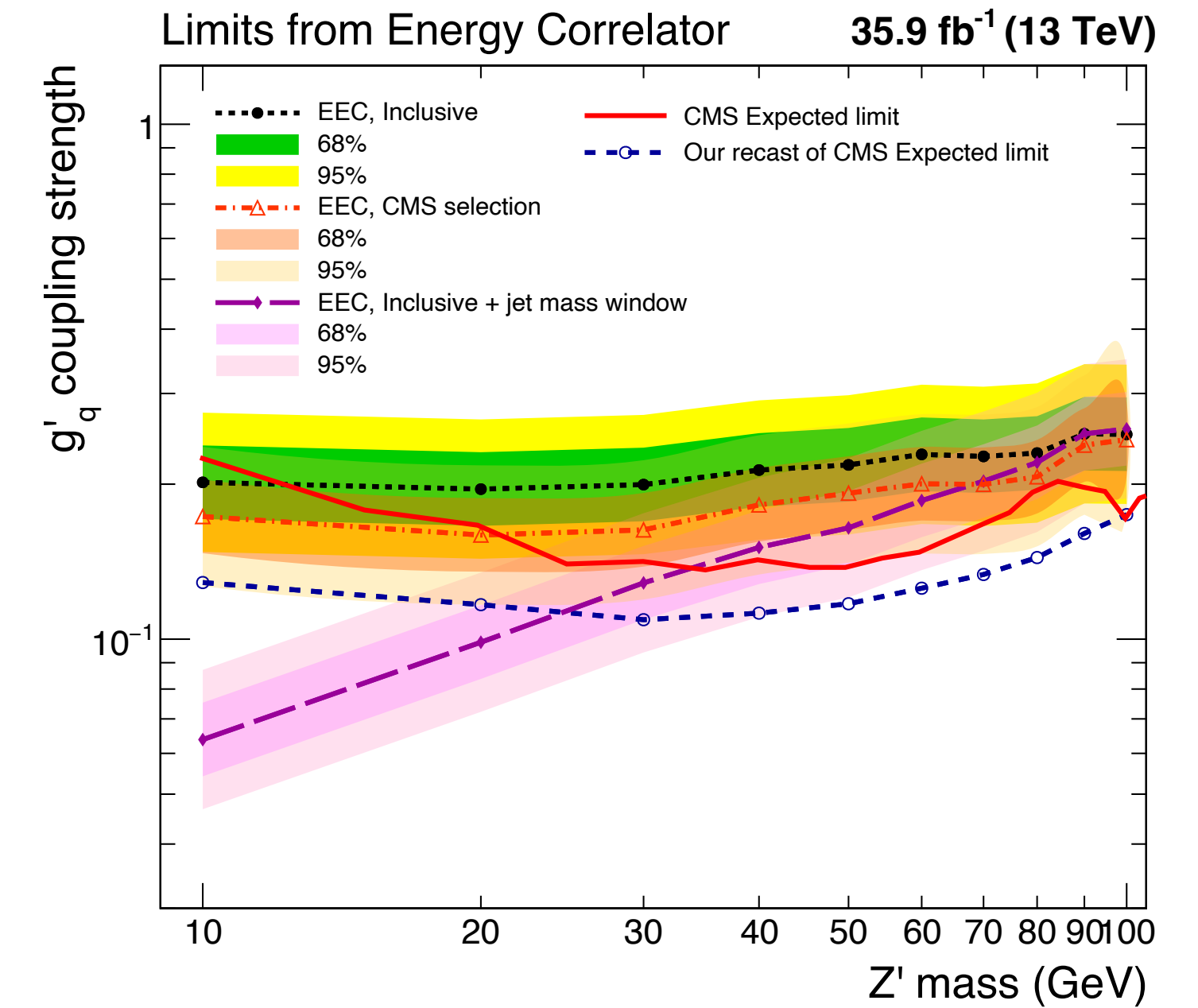
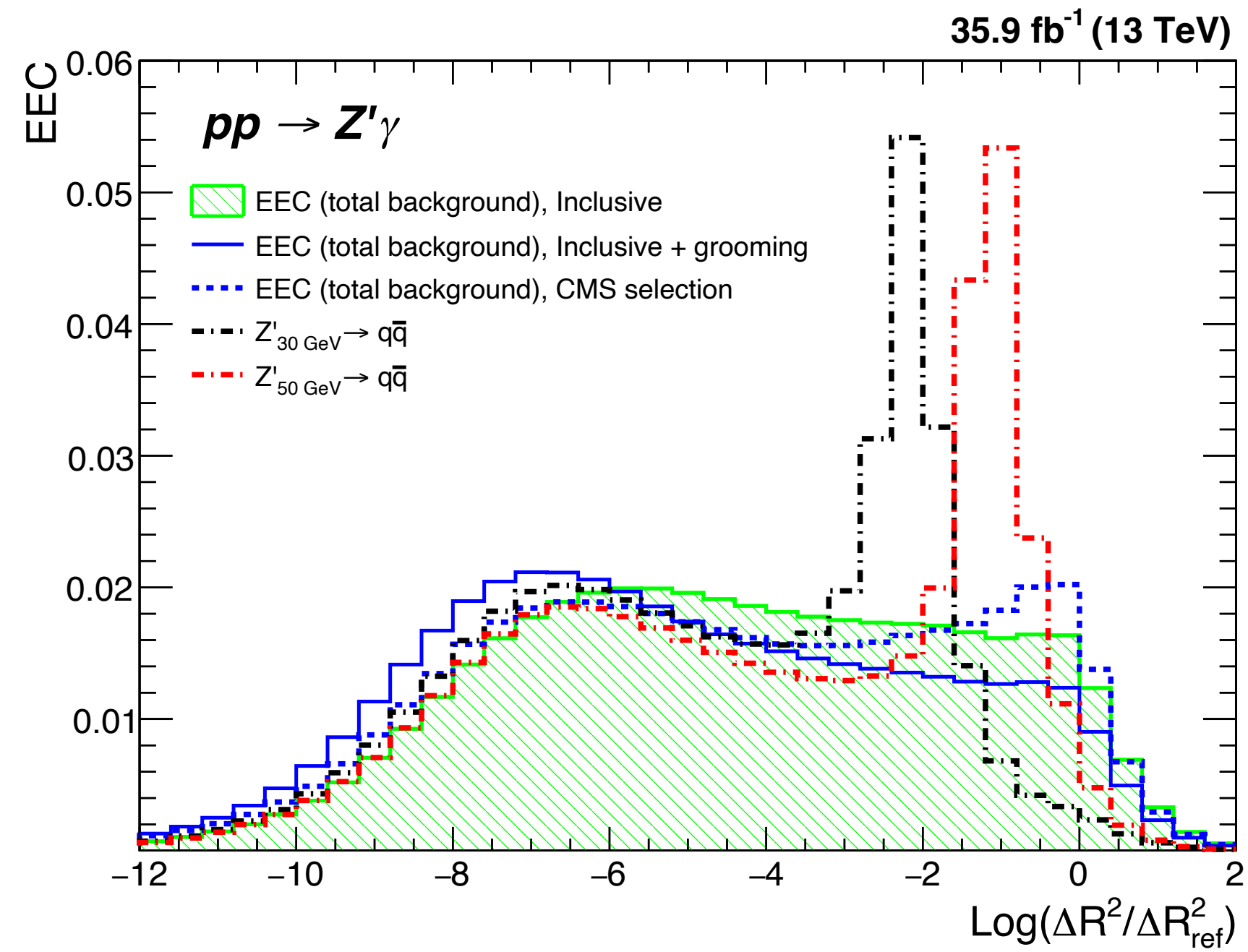
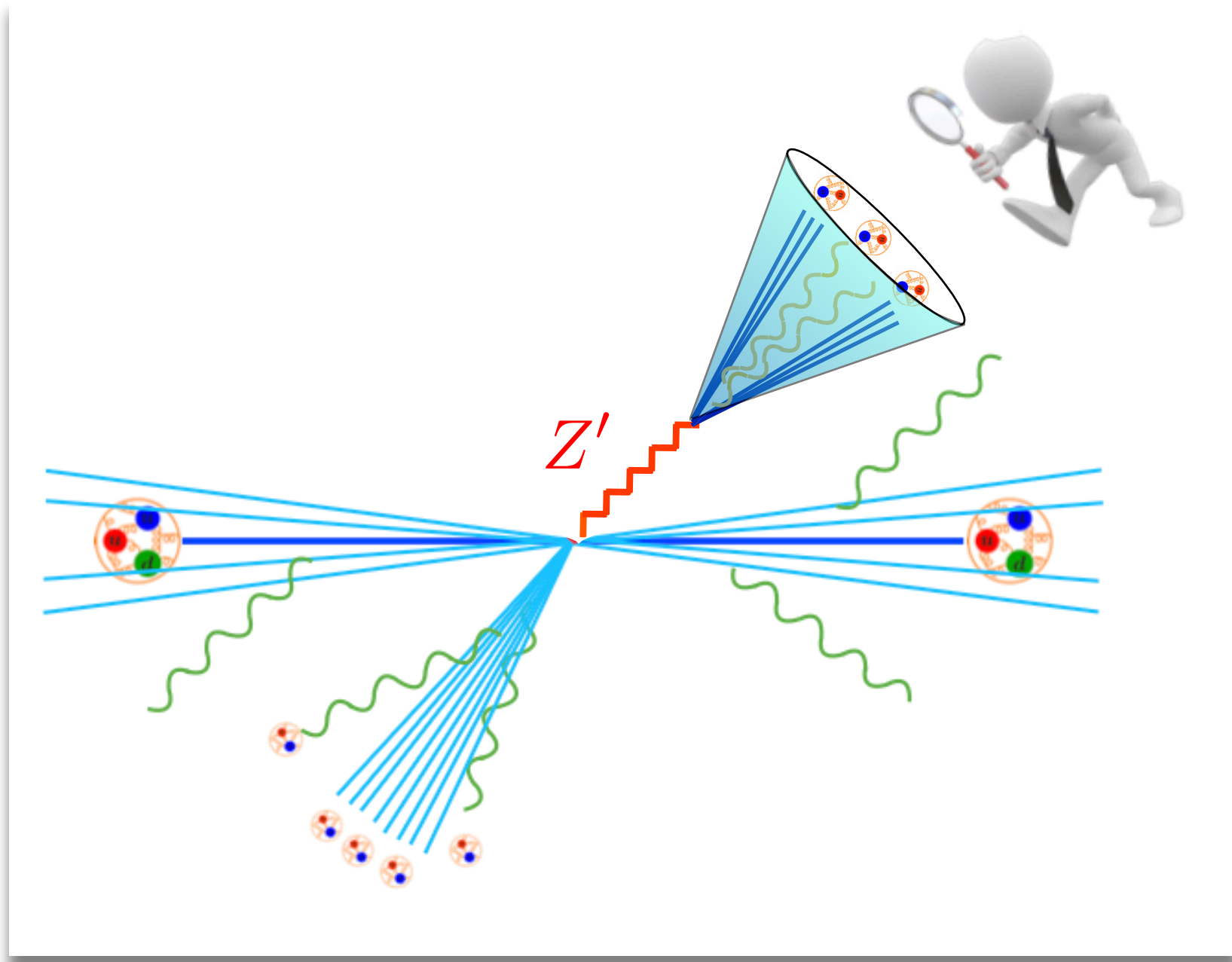


Large Boost
 $E \gg m_H$



The precision EEC calculations of Higgs decay can also be boosted to the LHC kinematics

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

Conclusion.

