Energy correlator and jet substructure experimental progress

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2025.10.12

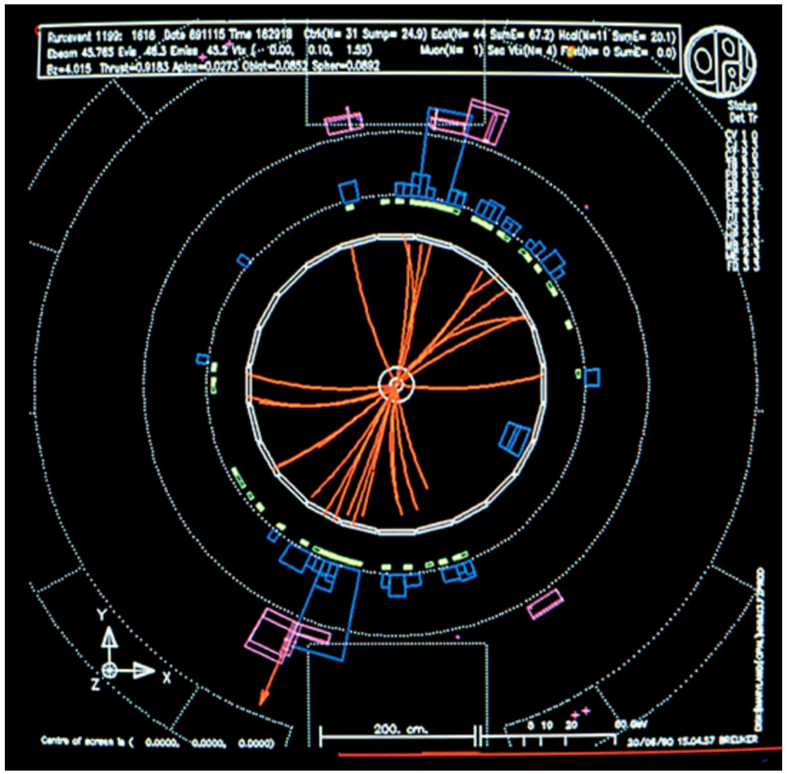
TeV物理前沿专题研讨会暨第31届LHC Mini-Workshop

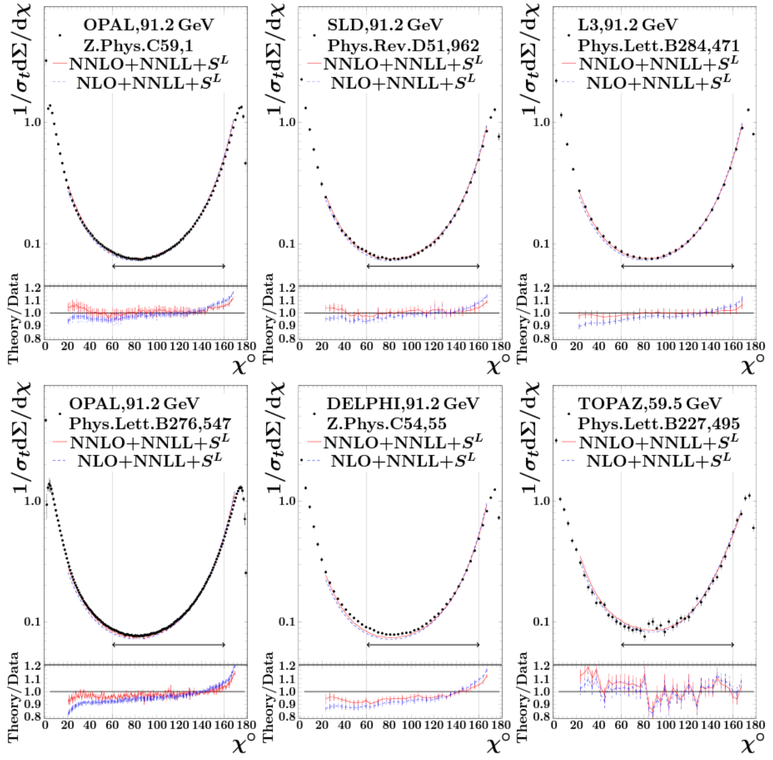
Measurement of energy-energy correlator: history at e^+e^-

EEC: event shape observable proposed for e^+e^- experiment in 1978 [PRL 41 (1978) 1585]

$$\frac{1}{\sigma_t}\frac{\mathrm{d}\Sigma(\chi)}{\mathrm{d}\cos\chi} \equiv \frac{1}{\sigma_t}\int \sum_{i,j} \frac{E_i E_j}{Q^2} \mathrm{d}\sigma_{e^+e^-\to ij+X} \delta(\cos\chi - \cos\theta_{ij}) \,,$$

All particles Energy weight Azimuthal distance





Widely measured at e^+e^-

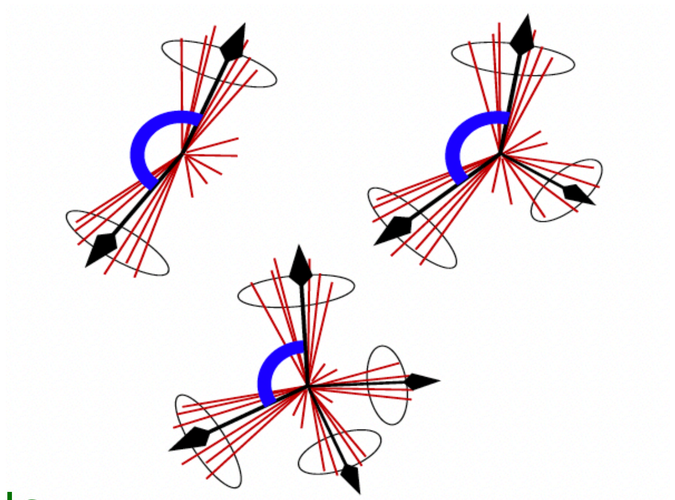
Extract α_S at NNLO+NNLL
~ 2% precision
[arXiv:1804.09146].

Energy-energy correlator at LHC

Adaptions for hadron collider

Transverse EEC (TEEC)
***PLB* 141 (1984) 447**

Angular correlation between jets in an event



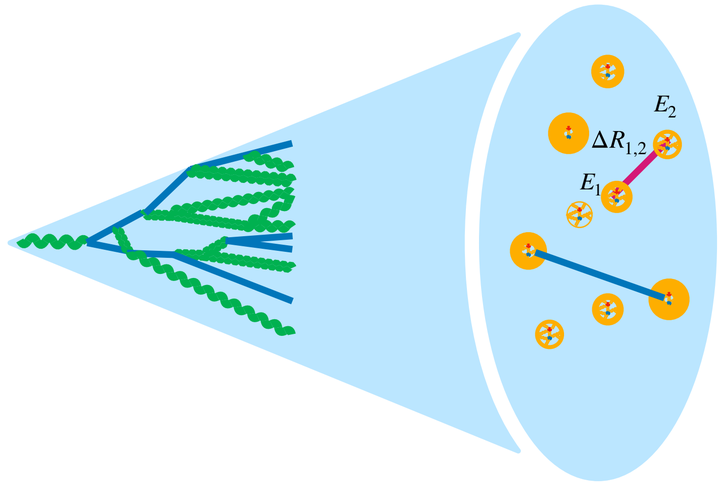
All jets

$$\frac{1}{N}\sum_{A=1}^{N}\sum_{i,j}\frac{E_{\mathrm{T}i}^{A}E_{\mathrm{T}j}^{A}}{\left(\sum_k E_{\mathrm{T}k}^{A}\right)^2}\delta(\cos\phi-\cos\varphi_{ij}),$$

Transverse energy weight

EEC inside jets
Chen, Moult, Zhang, and Zhu, *arXiv:2004.11381*

Angular correlation between particles in a jet



All particles inside a jet

$$\sum_{i,j}^{n}\int d\sigma\,\frac{E_iE_j}{E^2}\delta(x_L-\Delta R_{i,j}),$$

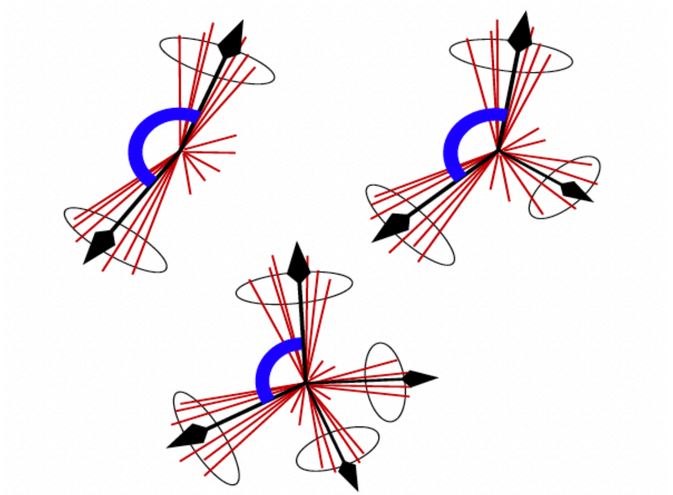
ΔR

Energy-energy correlator at LHC

Adaptions for hadron collider

Transverse EEC (TEEC)
***PLB* 141 (1984) 447**

Angular correlation between jets in an event

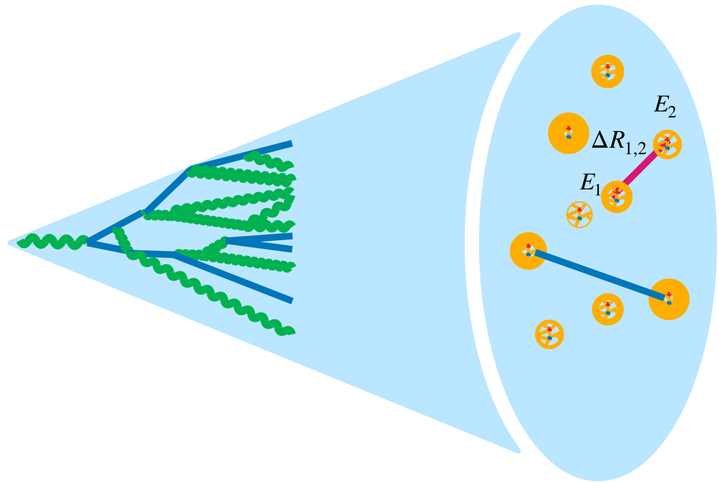


Energy scale Q ~ **O (TeV)**

Fixed order QCD dominant
NNLO pQCD available [JHEP 03 (2023) 129]

EEC inside jets
Chen, Moult, Zhang, and Zhu, *arXiv:2004.11381*

Angular correlation between particles in a jet



Energy scale Q ~ pT * ΔR ~ **O (10 GeV)**

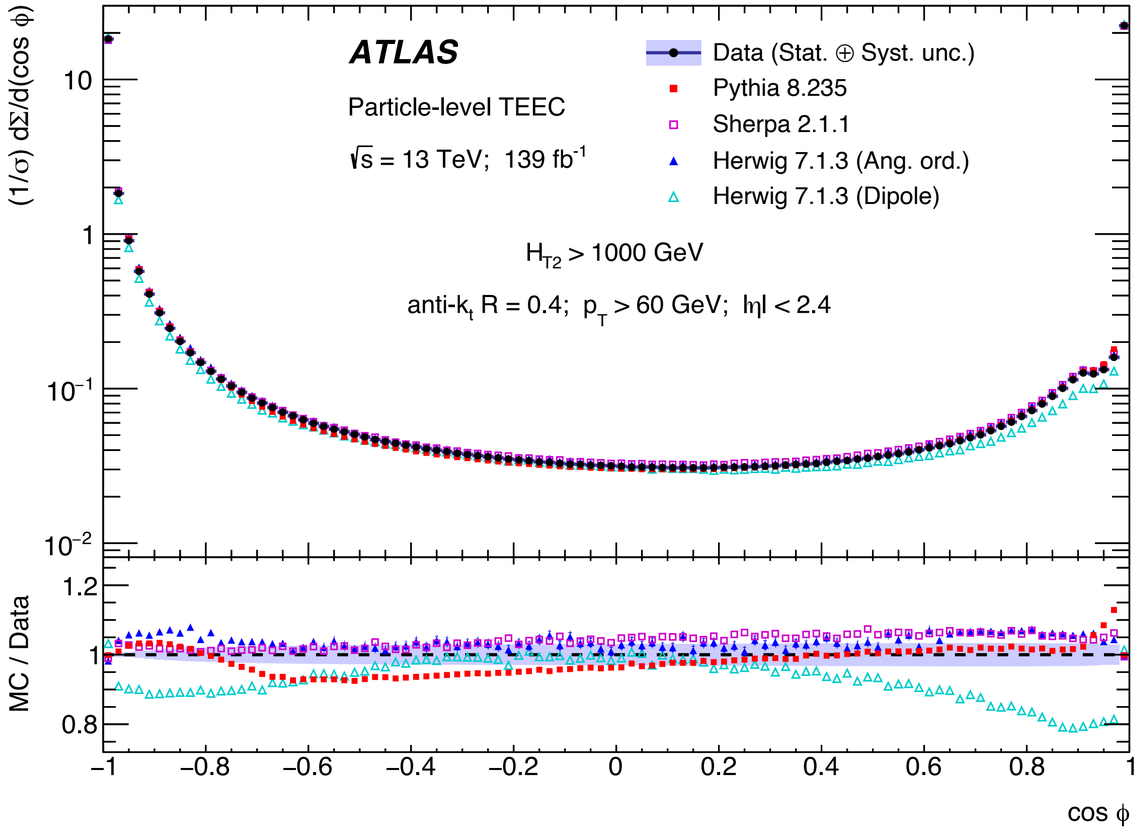
Collinear QCD dominant
NLO+NNLL$_{approx}$, arXiv:2307.07510

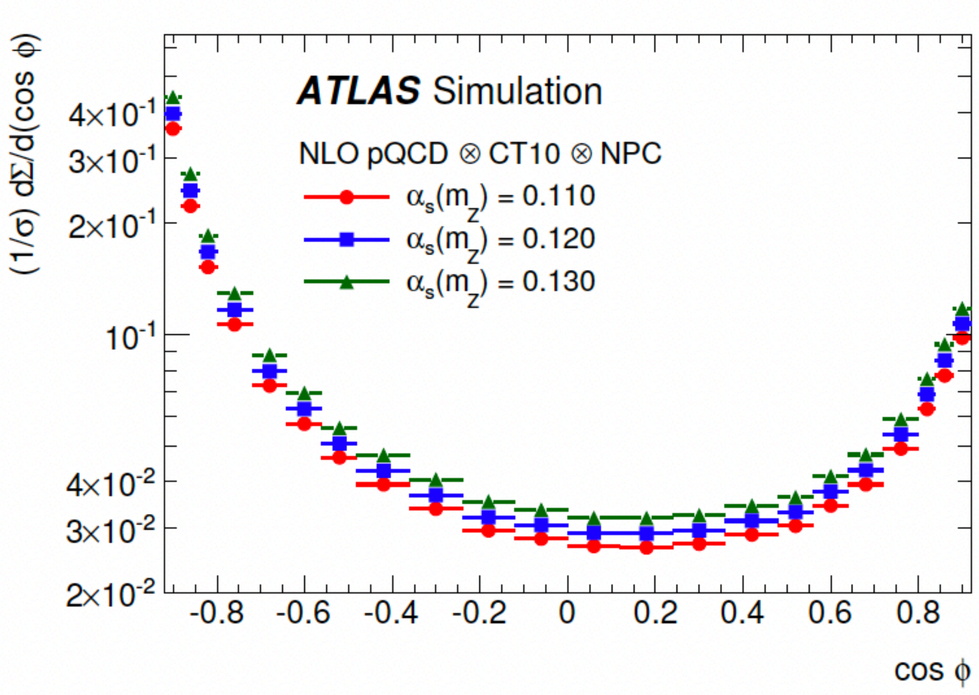
Measurement of TEEC

ATLAS, JHEP 07 (2023) 85

Anti-kt jets, R = 0.4
HT= pT1+pT2: [1, 3.5] TeV

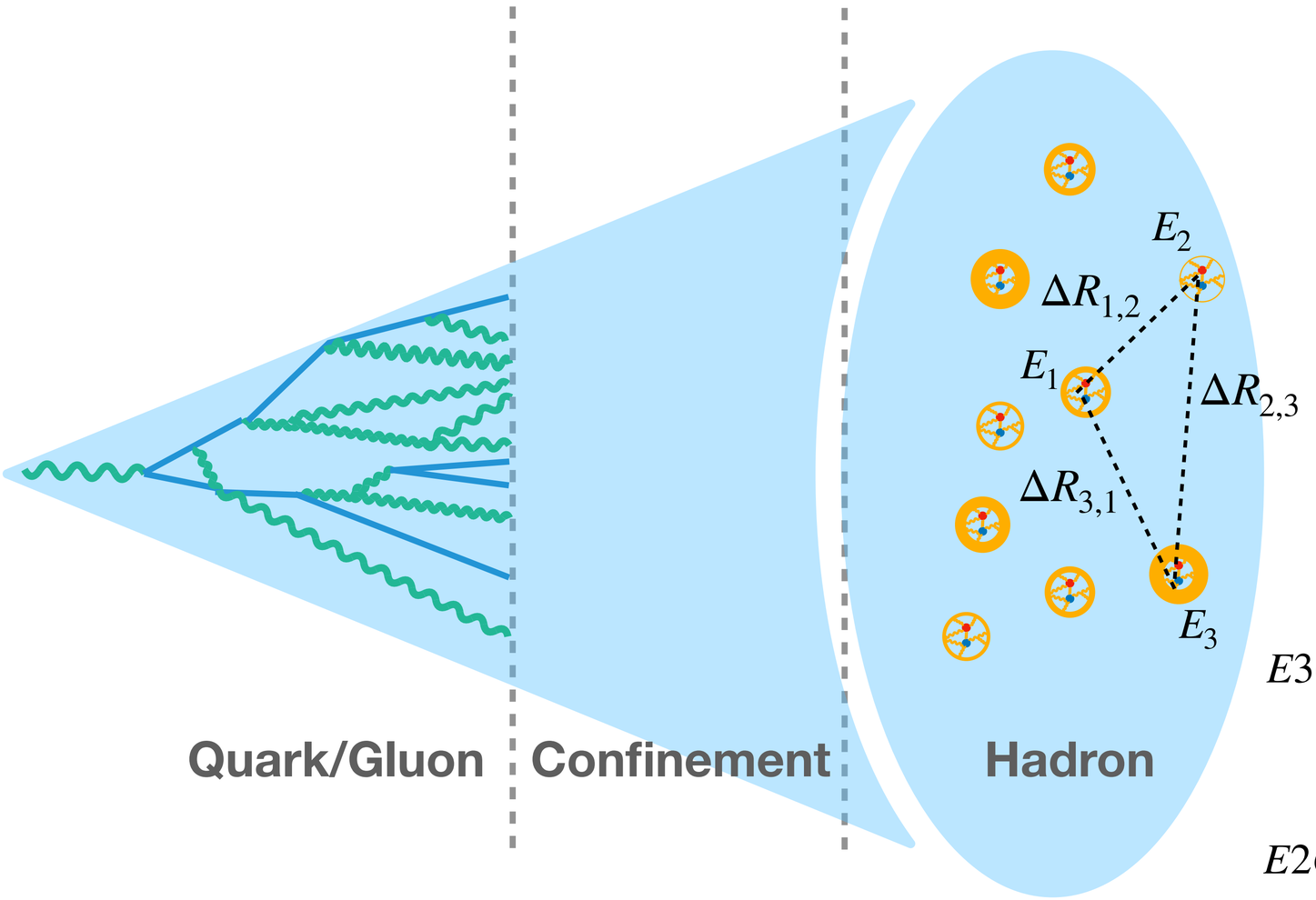
TEEC

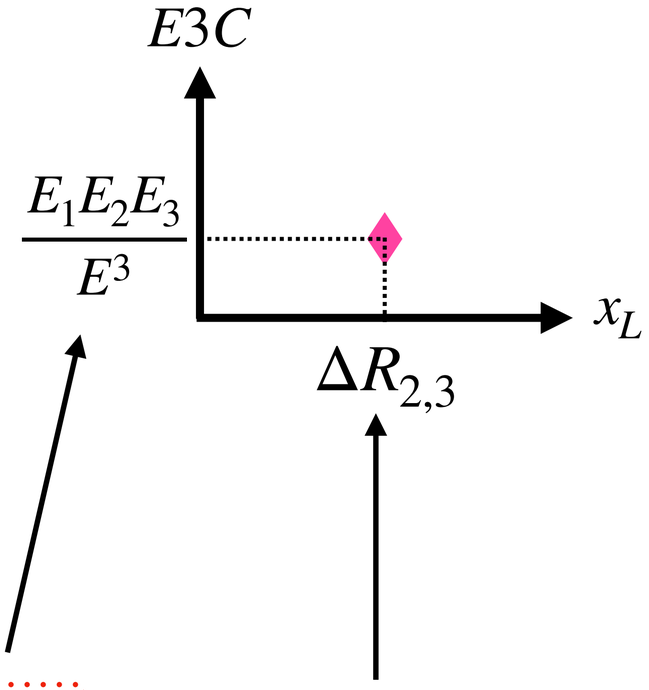




$$\alpha_s(m_Z) = 0.1175 \pm 0.0006\,(\text{exp.})^{+0.0034}_{-0.0017}\,(\text{theo.})$$

Energy correlators in jets: E2C & E3C





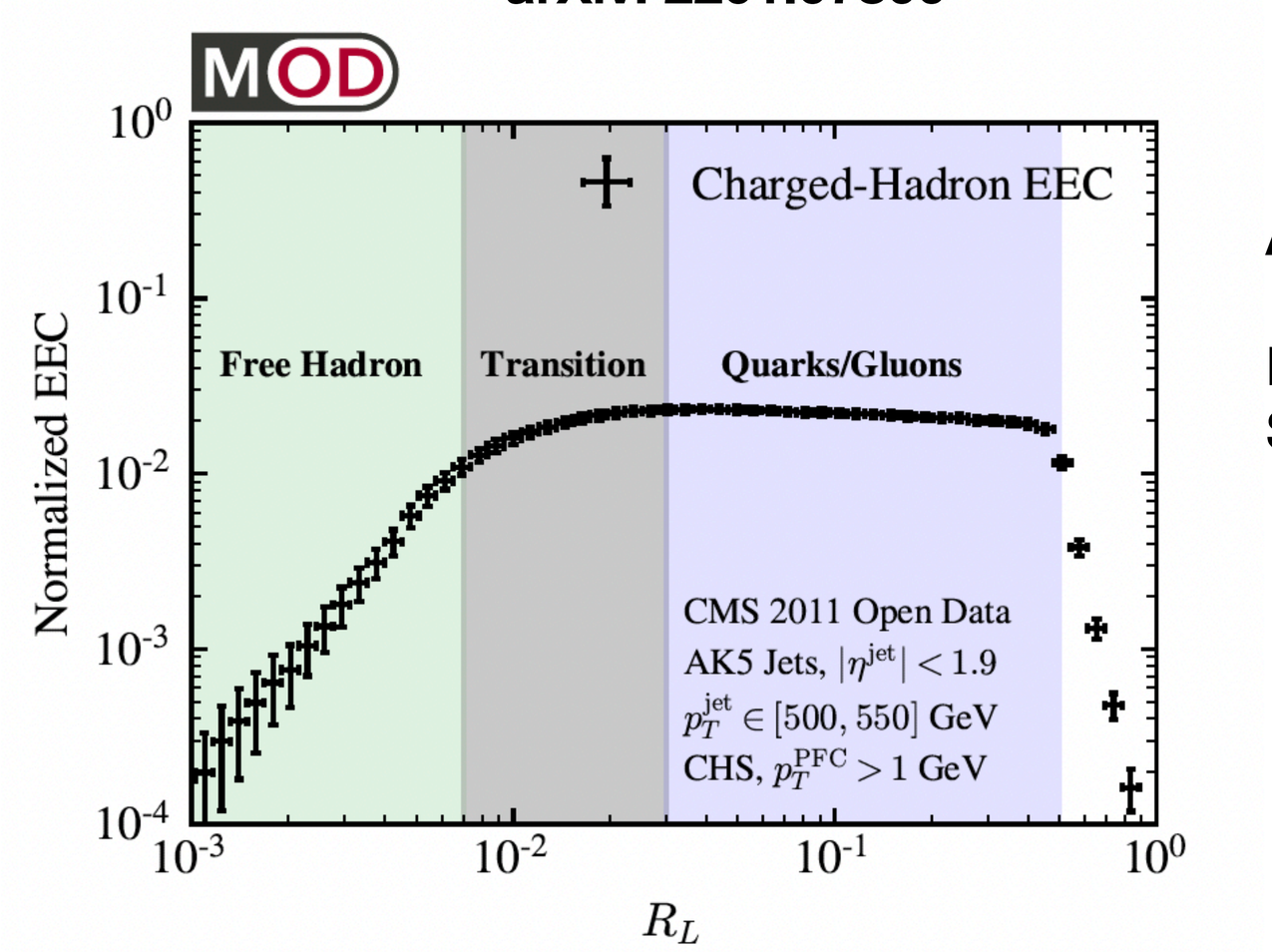
$$E3C = \frac{d\sigma^{[3]}}{dx_L} = \sum_{i,j,k}^{n} \int d\sigma \frac{E_i E_j E_k}{E^3} \delta(x_L - \max(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{j,k}))$$

$$E2C = \frac{d\sigma^{[2]}}{dx_L} = \sum_{i,j}^{n} \int d\sigma \frac{E_i E_j}{E^2} \delta(x_L - \Delta R_{i,j})$$

Jet substructure observable, sensitive to jet formation

EEC reconstructed from open data

arXiv: 2201.07800

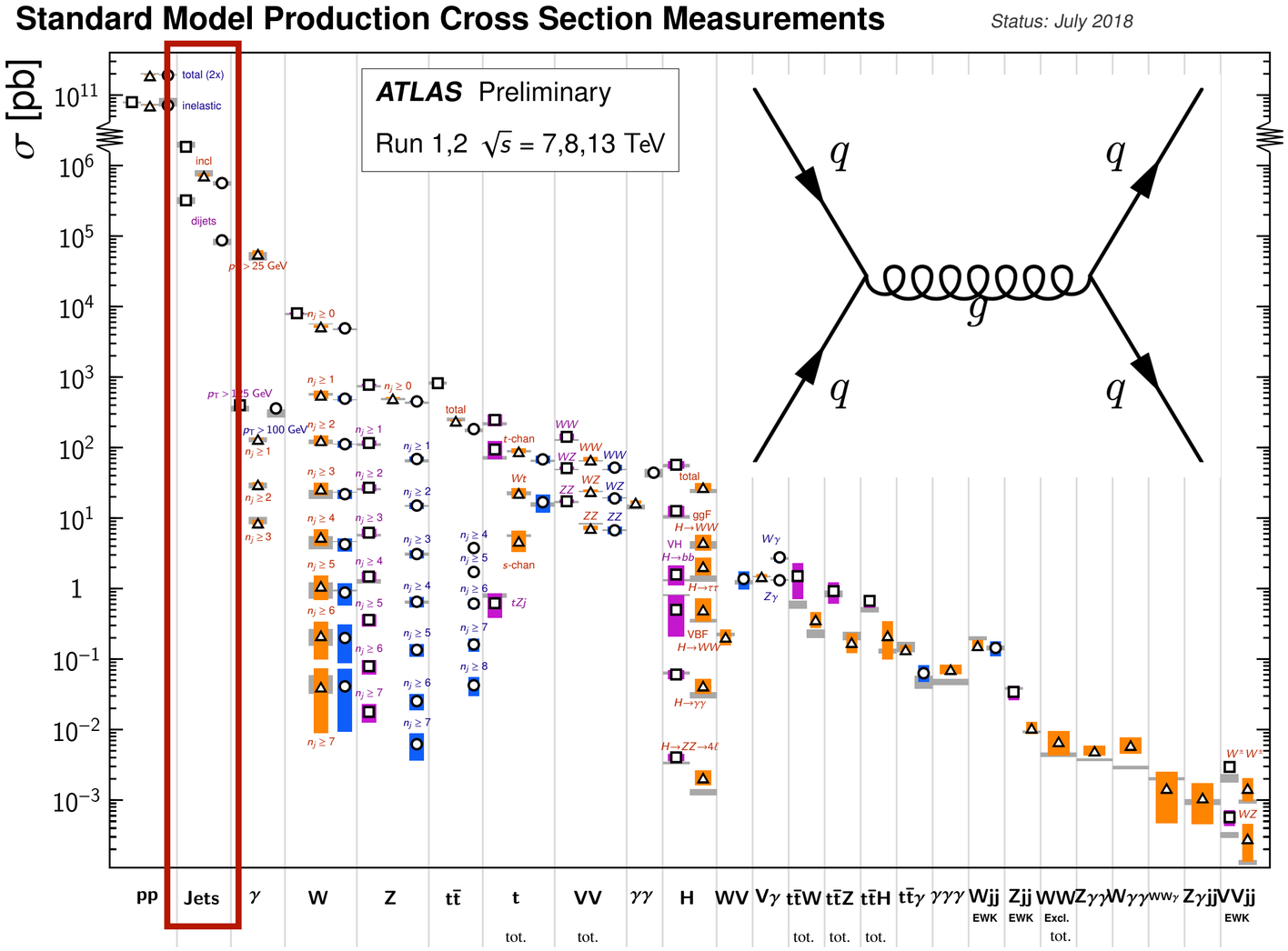


A few caveats!

Data only, detector effects not removed
Statistical correlation between bins

Measurement in nutshell

CMS, PRL 133 (2024), 071903



Dijet events in central region $|\eta| < 2.1$

- Large cross section

anti-kT with R = 0.4

Probe energy scale dependency

- 8 p_T^{jet} region in 97 ~ 1784 GeV

Neutral & charged & photon with p_T > 1 GeV

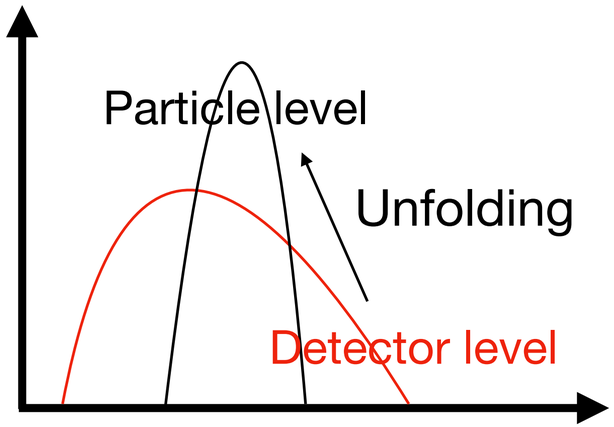
- All particles included

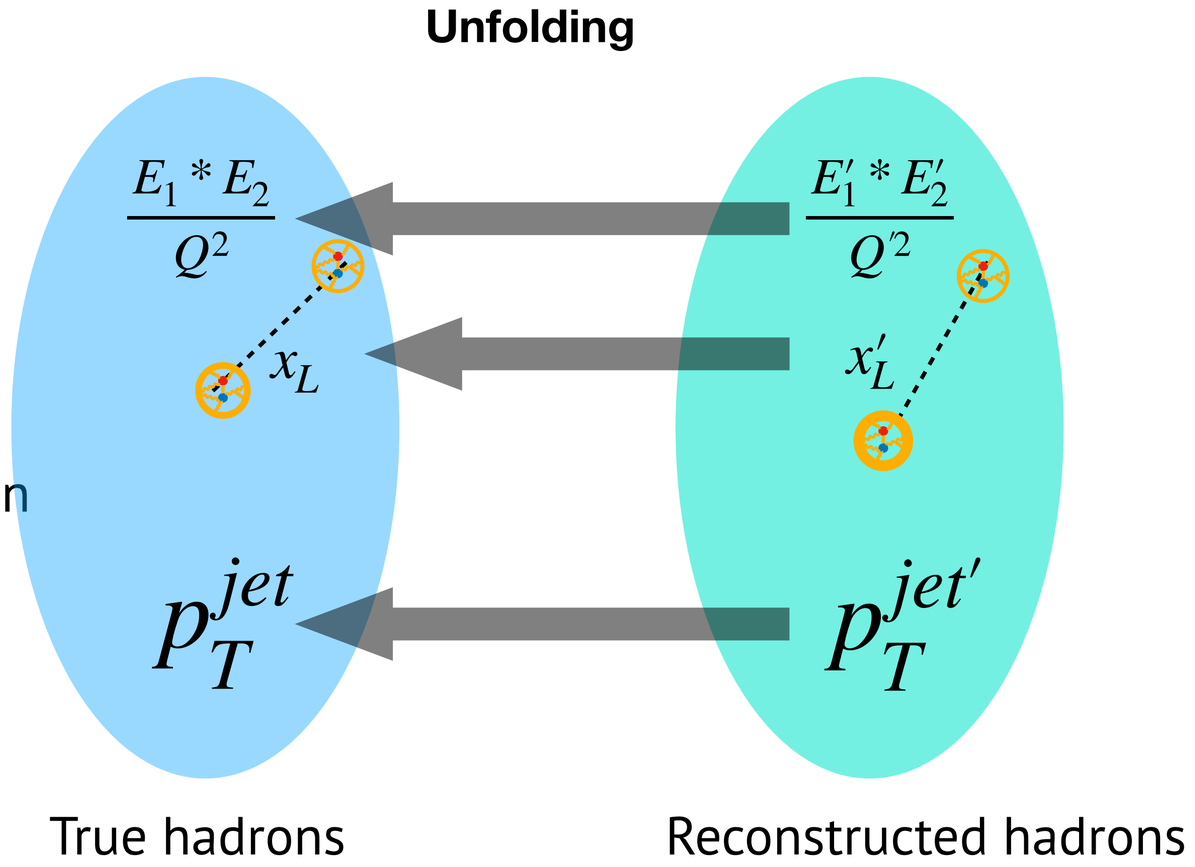
Extra experimental steps: unfolding

Unfolding: detector hadron -> true hadron

Unfold jet constituents:

- p_T^{jet}, x_L and energy weight, 3D unfolding
- $10 * 22 * 20 = 4400$ bins
- 4400x4400 migration matrix and regularization



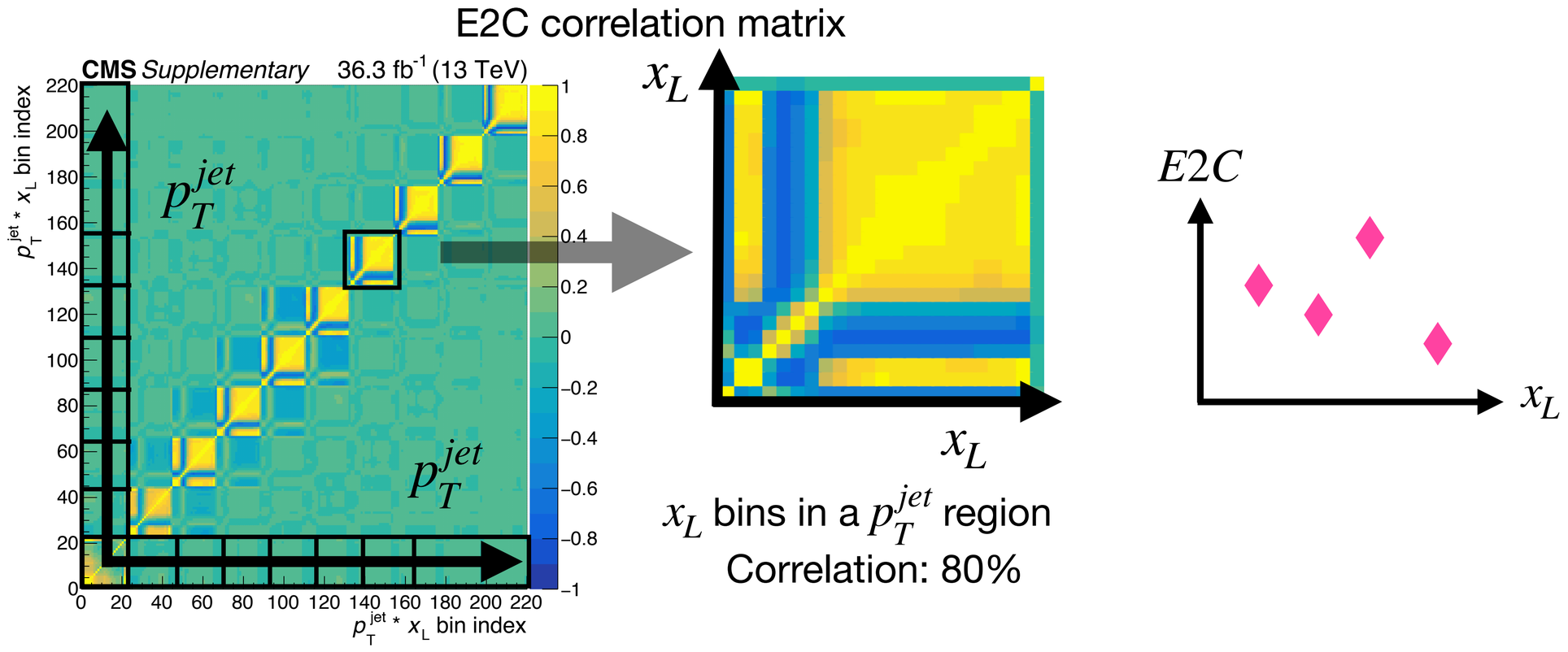


Extra experimental steps: statistical correlations

Multi entry distribution for every jet, statistical correlation important

Detector level => Unfolding => Normalization

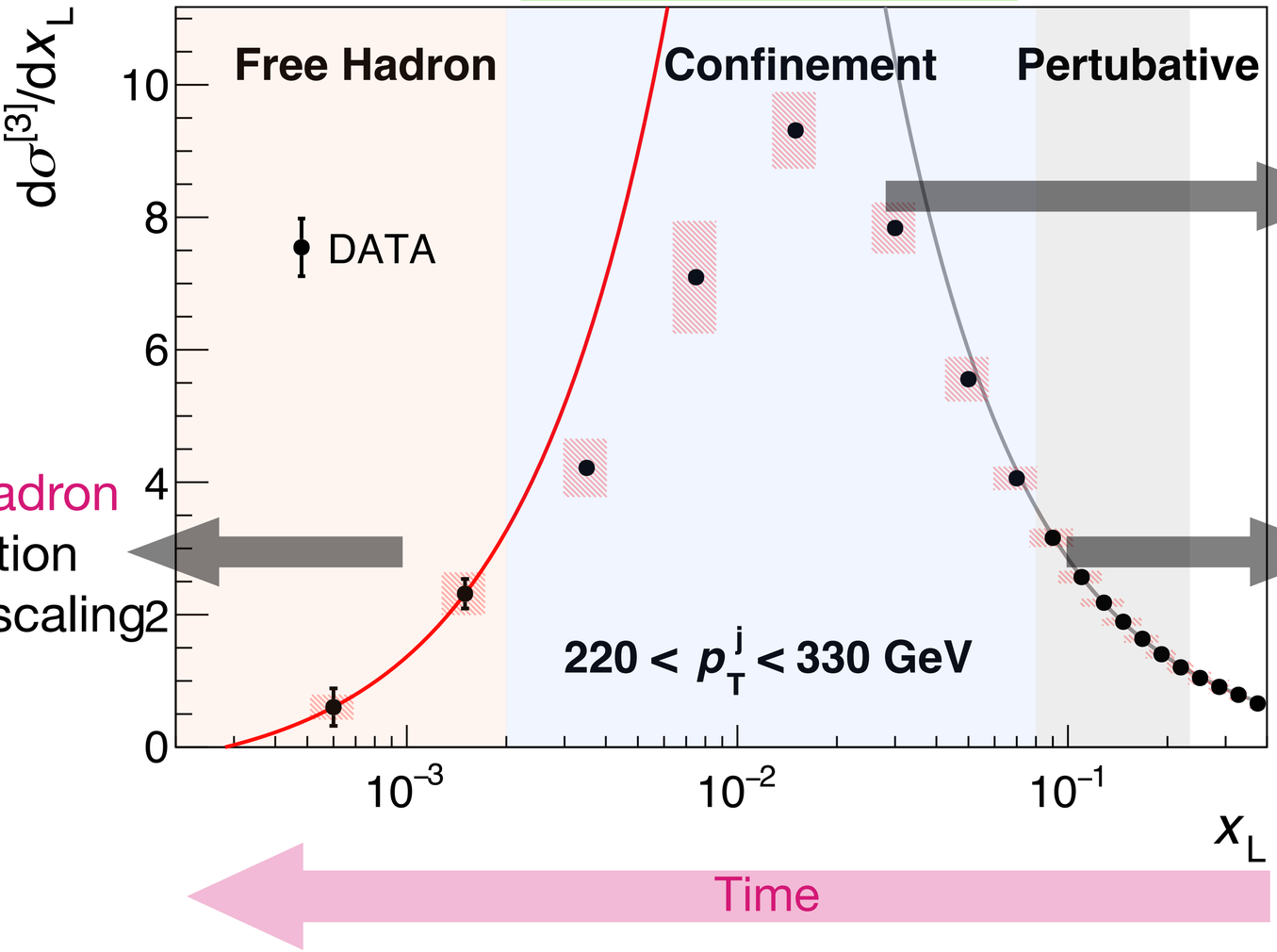
Independent statistics for E2C, E3C



E3C after unfolding

Using all neutral & charged hadrons > 1GeV in a jet

CMS, PRL 133 (2024), 071903

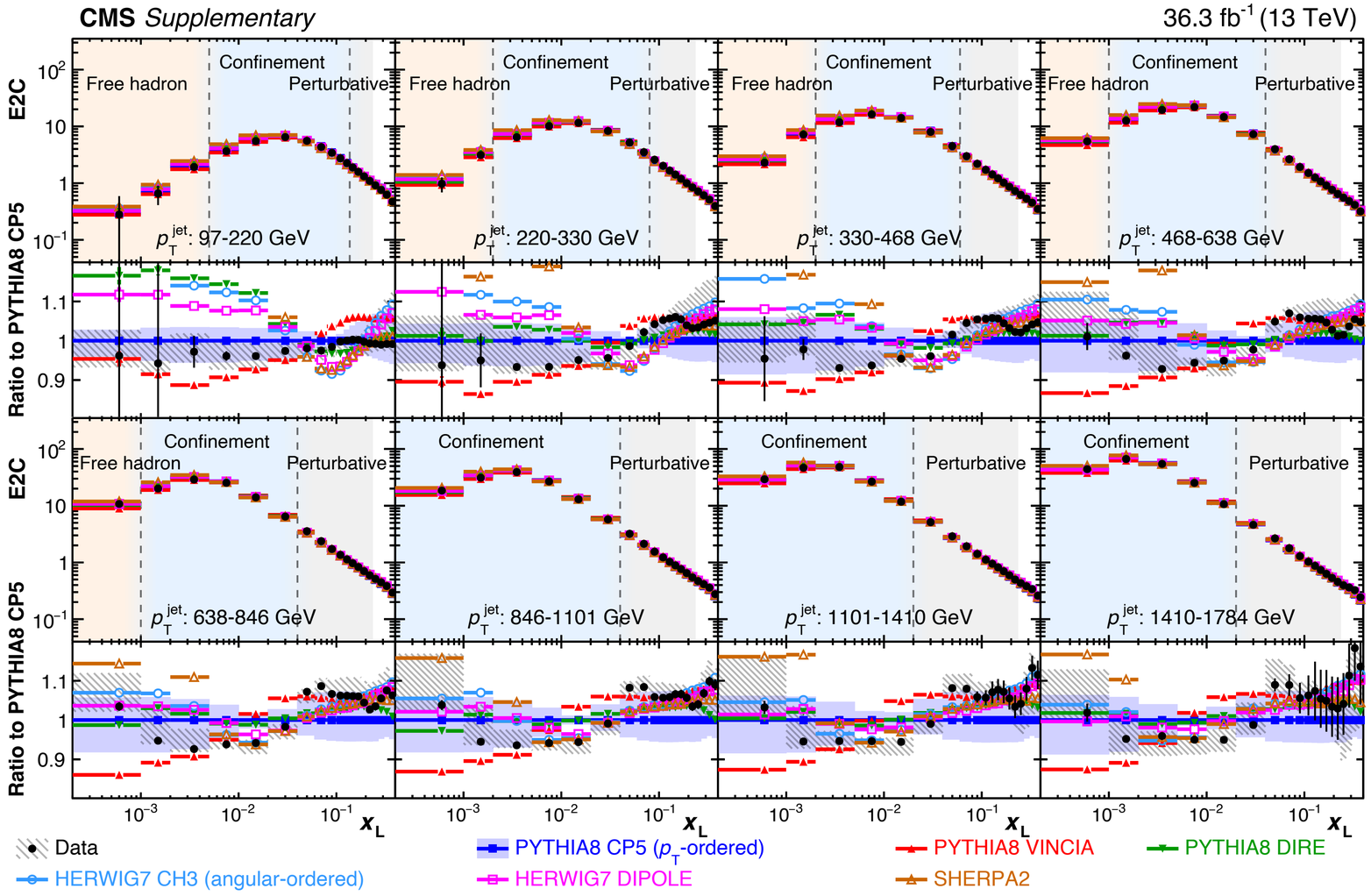


Phase transition
from parton to hadron

Non-interacting hadron
random distribution
integer power-law scaling

Interacting partons
non-integer scaling

Unfolded E2C vs MC



97 ~ 1784 GeV

Data vs various parton shower model, difference ~ 10%

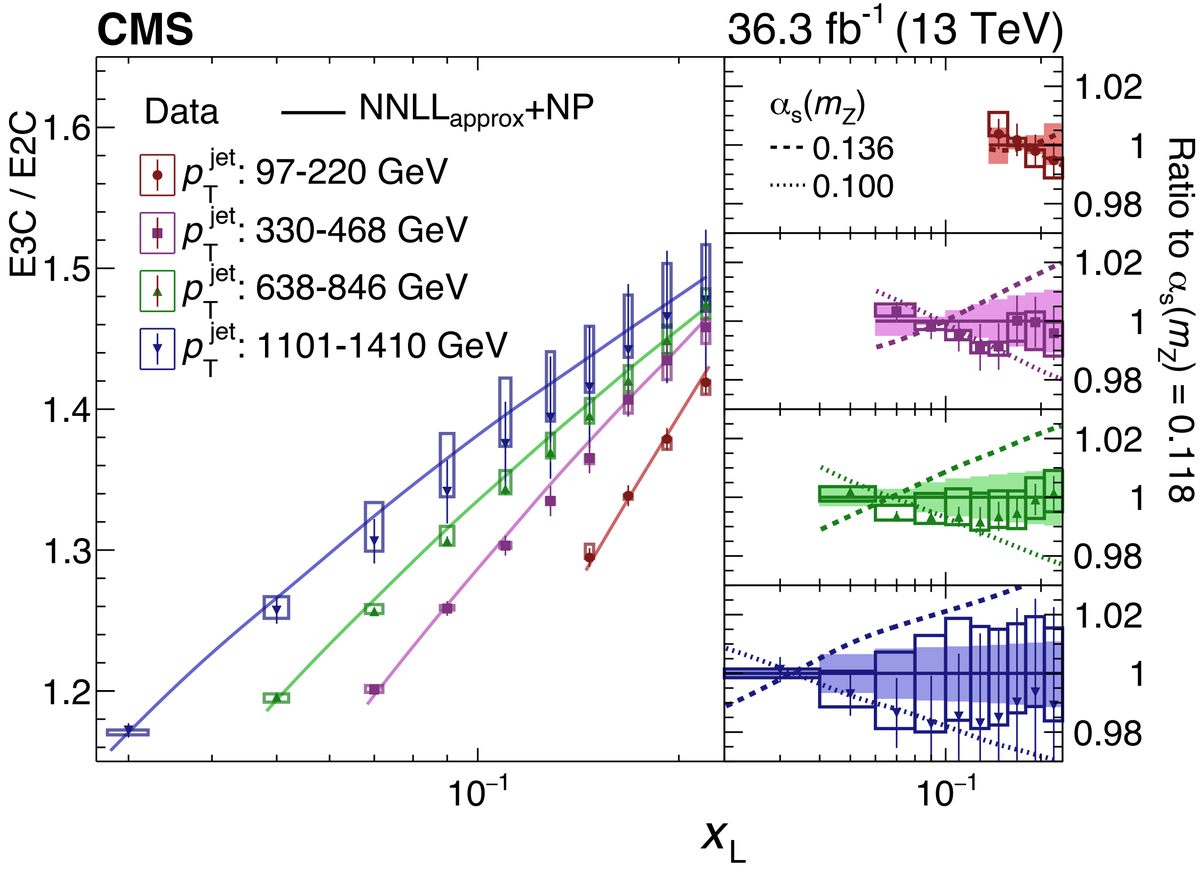
No model match data well in all p_t^{jet} region

: Data stat error

: Exp systematic

: Theo systematic

Perturbative region



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

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

major source

QCD scale of NNLLapprox

Neutral hadron energy scale

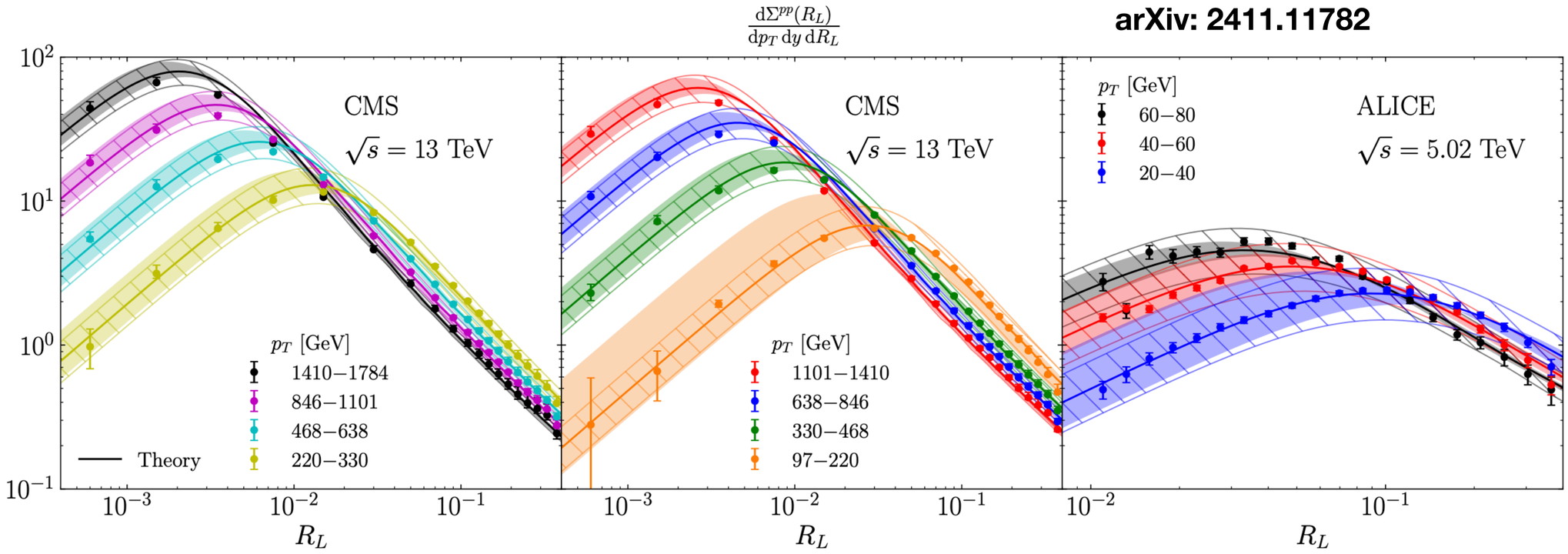
Uncertainty ~ 4%,
Q~ O(10) GeV, collinear regime
Most precise from jet substructure to date

NLO+NNLLapprox ,Chen, Gao, Li, Xu, Zhang, and Zhu, arXiv:2307.07510

Non-perturbative region

Theorists took our measurement and made a much nicer plot!
Now non-perturbative region also has predictions

Data used to extract fragmentation related parameter a0=3.8 GeV $j_{\mathrm{np}}(b) = \exp(-a_0 b)\,,$



Many EEC experimental measurements!

Boost workshop 2025

Probing QCD using N -point energy correlator measurements in charged-particle jets with ALICE

Barus and Holley 168, Brown University

Studying high-order QCD operators with resolved energy-energy correlators at the CMS experiment

Barus and Holley 168, Brown University

N-point Energy Correlators in heavy ion collisions - What can we learn? *Rithya Kunnav*

Barus and Holley 168, Brown University

Observable Optimization for Precision Theory: Machine Learning Energy Correlators *Arindam Bhattacharya*

Barus and Holley 168, Brown University 16:00 - 16:20

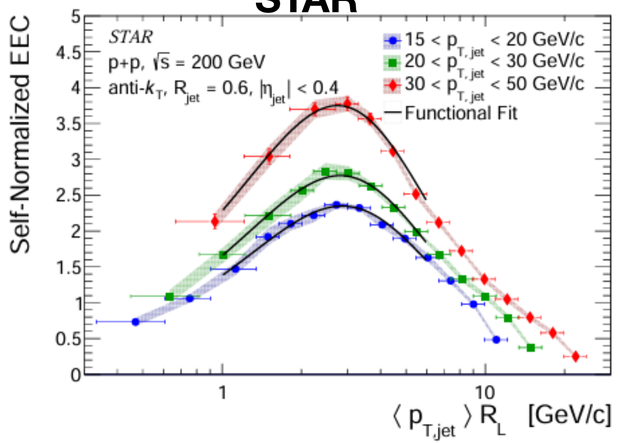
Precision measurement of the fully-corrected energy-energy correlator in the back-to-back limit using archived ALEPH

Yi Chen

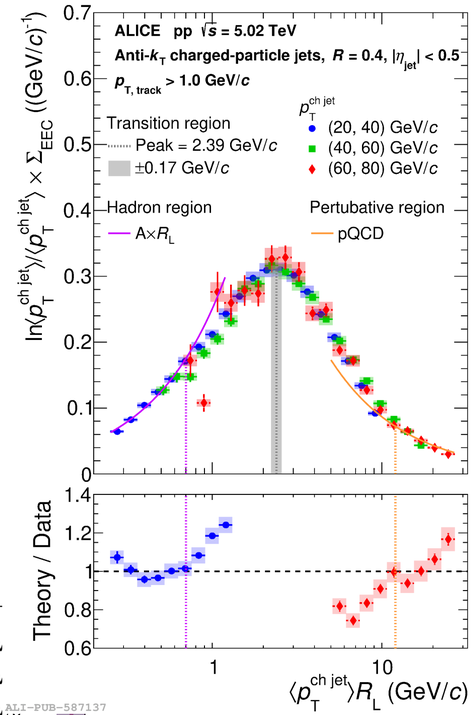
Measurement of Hadronic Event Shape, Energy-Energy Correlator, and Two-Particle Correlation with DELPHI Open Data

Jingyu Zhang

STAR



ALICE



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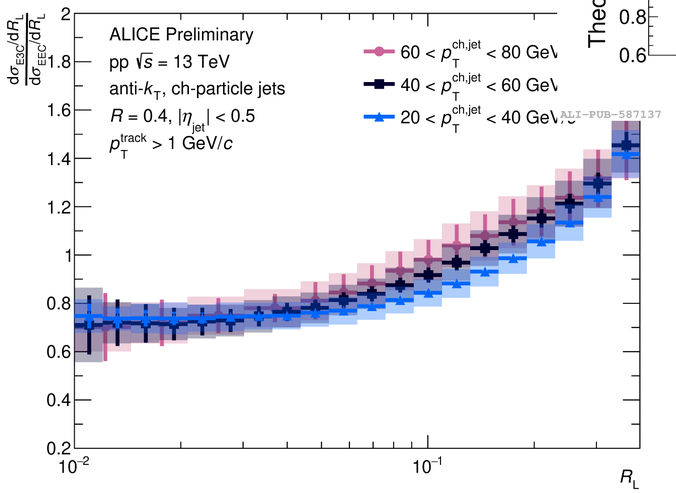
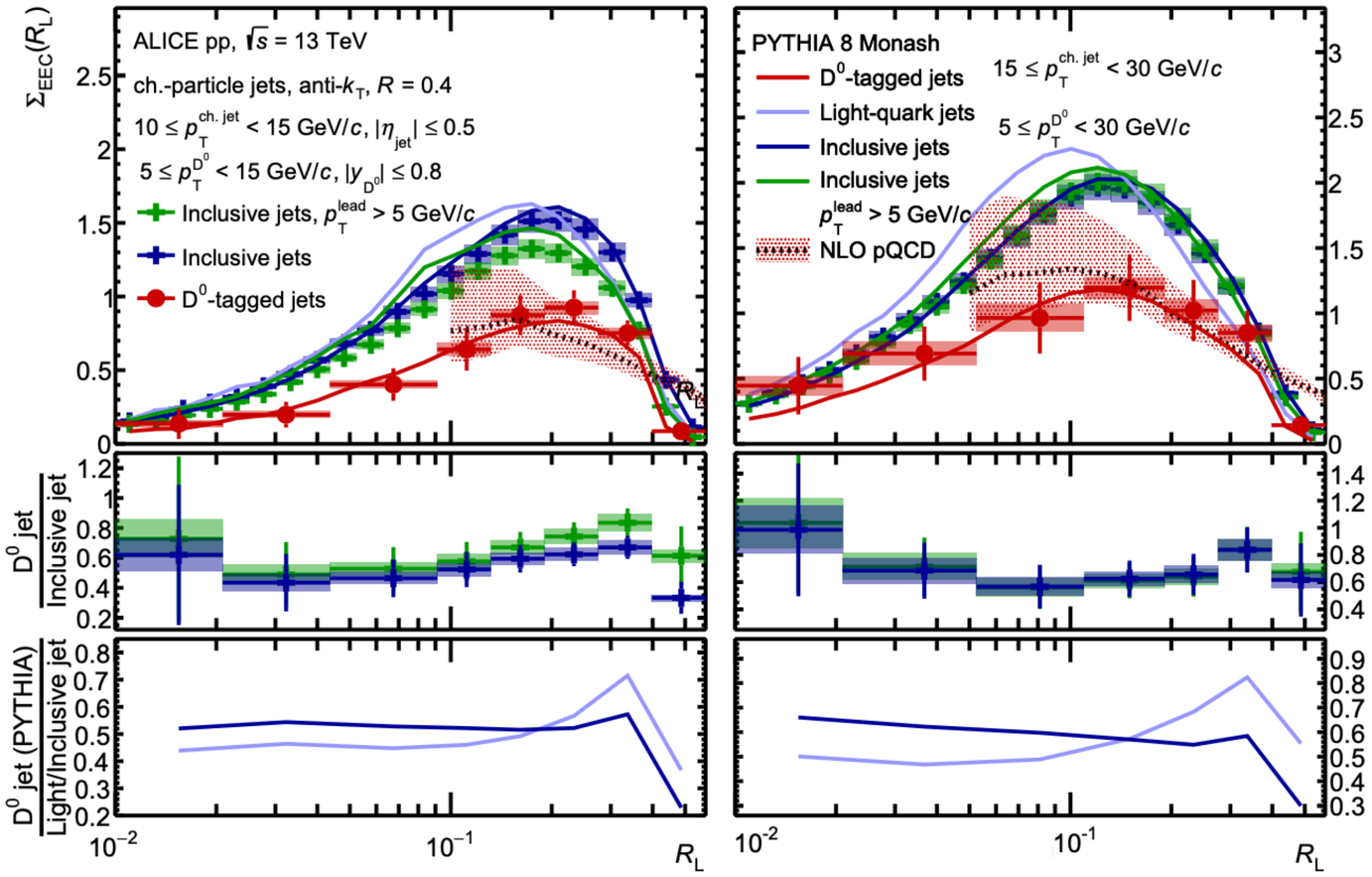


Also studies on jet quenching

Charm-tagged jet EEC

ALICE, arXiv:2504.03431

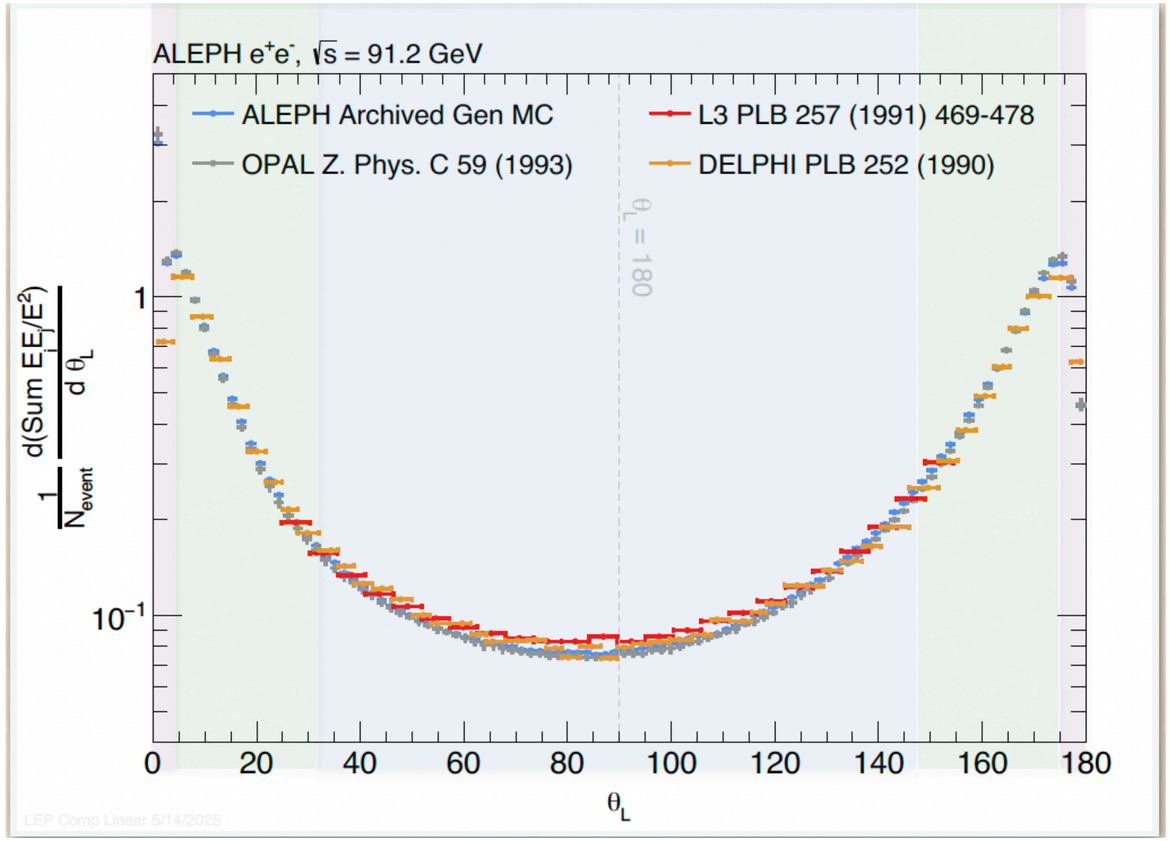


Dead cone effect, suppression of radiation from massive quarks

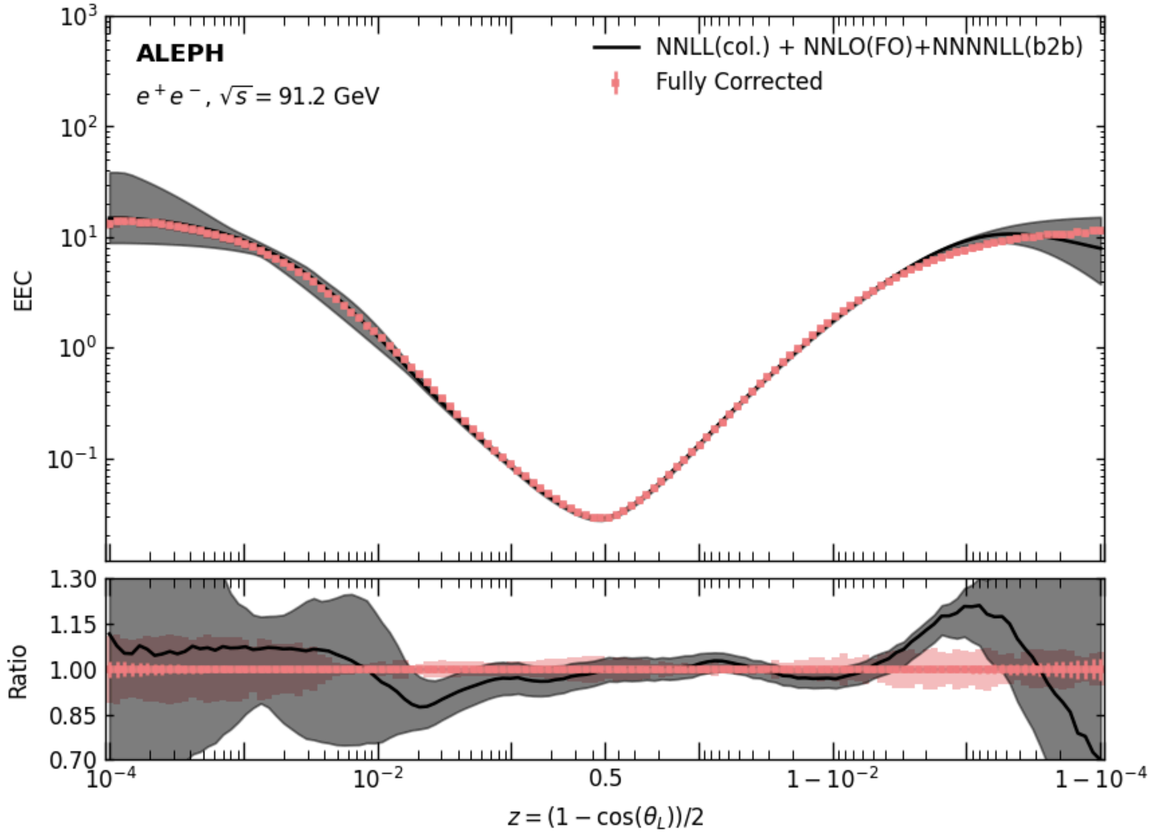
Interplay between hadronization, mass effects

Reanalysis EEC in e+e- data

Previous measurement
Very few bins in the collinear region



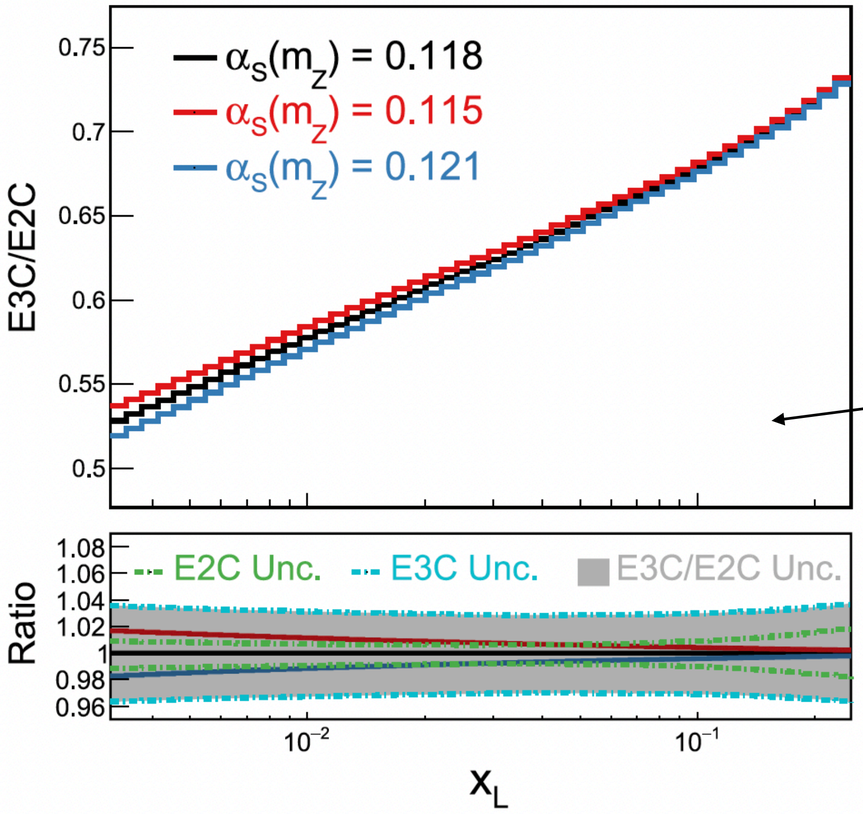
New measurement
Goes down to theta~10^{-2}



Reanalysis EEC in e+e- data

If E3C/E2C can be measured
1-2% uncertainty on α_S

arXiv:2406.10946



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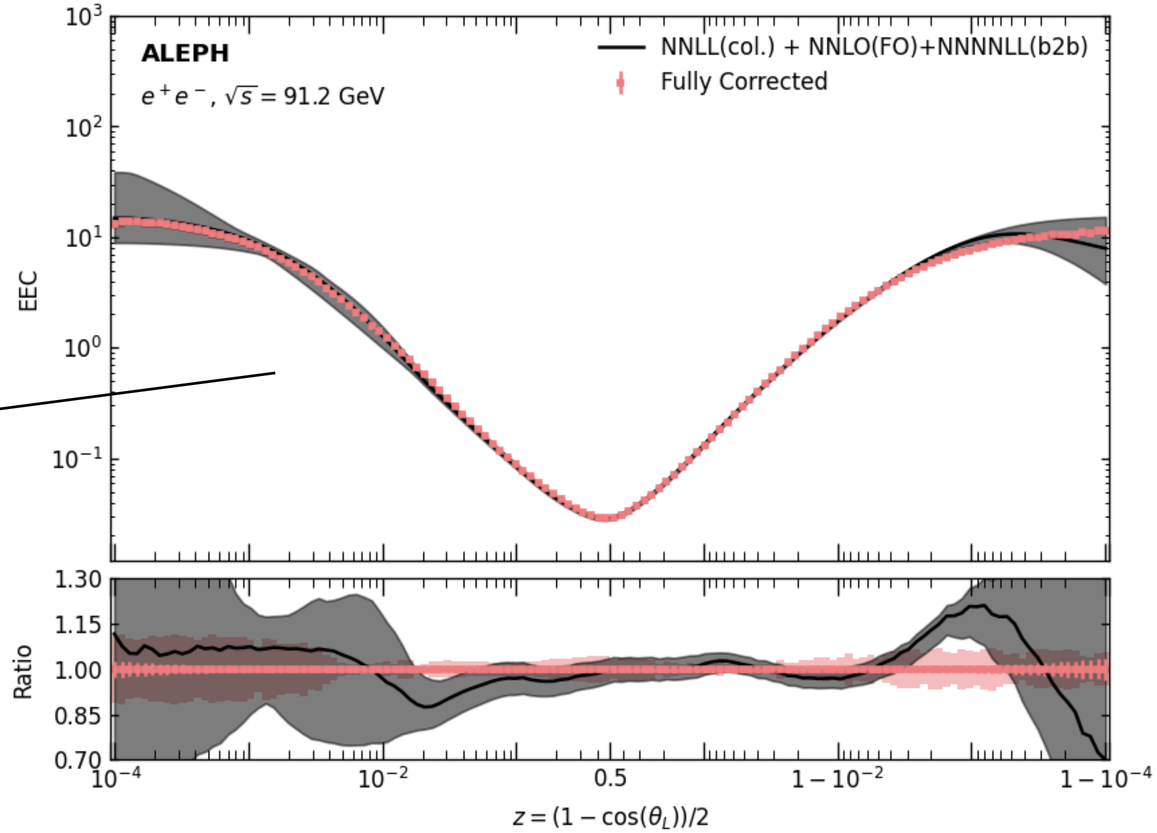


Other jet substructures

- A lot of developments in PS models towards NLL and NNLL models
  - Panscale, Deductor, ALARIC..
- A key to higher order PS model, spin correlation in the shower due to gluon spin-1 nature
- Current LL PS models:
  - Herwig fully implemented
  - Pythia ad-hoc modulation

PanScales

- ▷ Parton showers Beyond leading logarithmic accuracy [2002.11114]
- ▷ PanScales parton showers for hadron collisions: formulation and fixed-order studies [2205.02237]
- ▷ PanScales showers for hadron collisions: all-order validation [2207.0946
- ▷ Next-to-leading logarithmic PanScales showers for Deep Inelastic scatte and Vector Boson Fusion [2305.08645]
- ▷ Colour and logarithmic accuracy in final-state parton showers [2011.10
- ▷ Spin correlations in final-state parton showers and jet observables [2103
- ▷ Soft spin correlations in final-state parton showers [2111.01161]
- ▷ Introduction to the PanScales framework, version 0.1 [2312.13275]

Various combinations of M.vanBeekveld, M.Dasgupta, B.El Menoufi, S.Fe Ravasio, K.Hamilton, J.Helliwell, A.Karlberg, R.Medves, P.Monni, G.P.Sa L.Scyboz, A.Soto-Ontoso, G.Soyez, R.Verheyen

Deductor

- ▷ Summations of large logarithms by parton showers [2011.04773]
- ▷ Summations by parton showers of large logarithms in electron-positron annihilation [2011.04777]

Z.Nagy, D.Soper

Apollo

- ▷ A partitioned dipole-antenna shower with improved transverse recoil [24

C. Preuss

Alaric

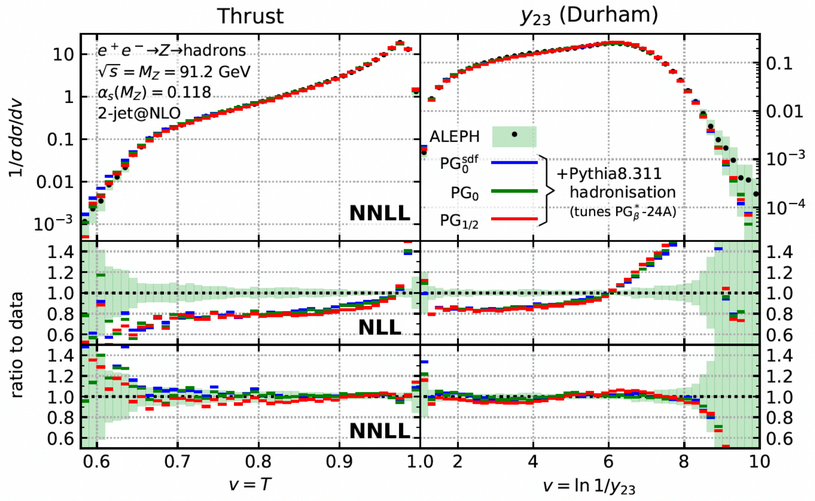
- ▷ A new approach to color-coherent parton evolution [2208.06057]
- ▷ New approach to QCD final-state evolution in processes with massive partons [2307.00728]
- ▷ alaric parton shower for hadron colliders [2404.14360]

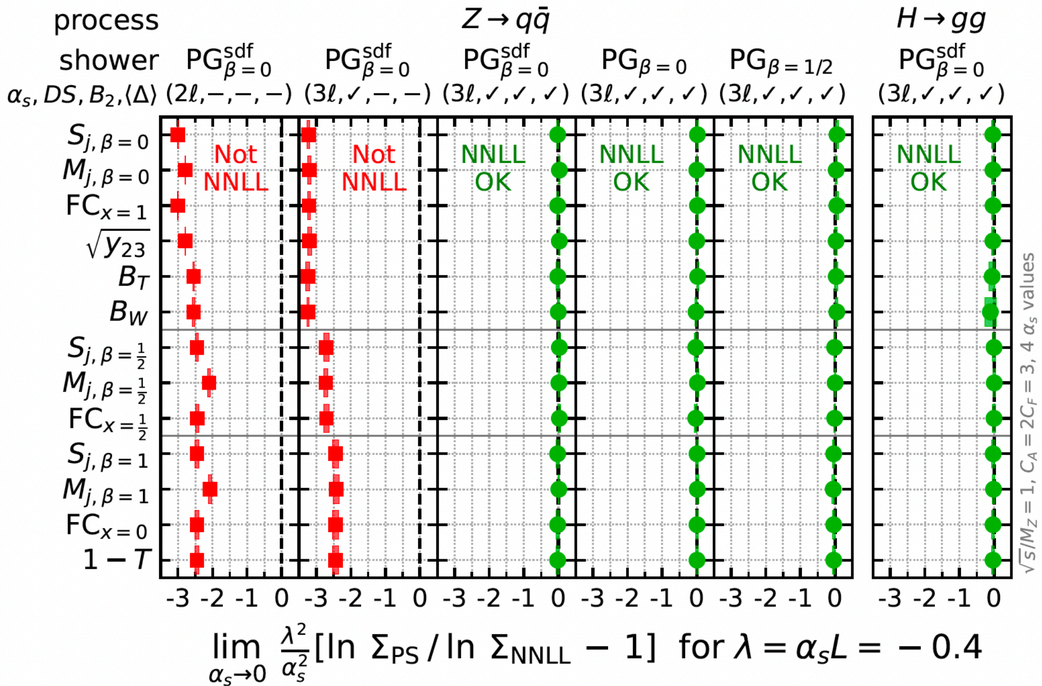
Combinations of B.Assi, F.Herren, S.Höche, F.Krauss, D.Reichelt, M.Schönherr

CVolver

- ▷ Parton branching at amplitude level [1905.08686]
- ▷ Building a consistent parton shower [2003.06400]
- ▷ Improvements on dipole shower colour [2011.15087]

J.Forshaw, J.Holguin, S.Platzer

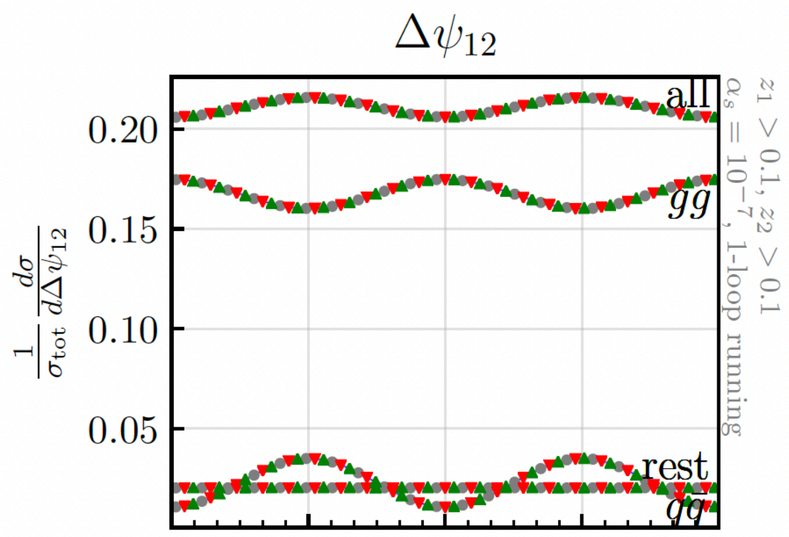


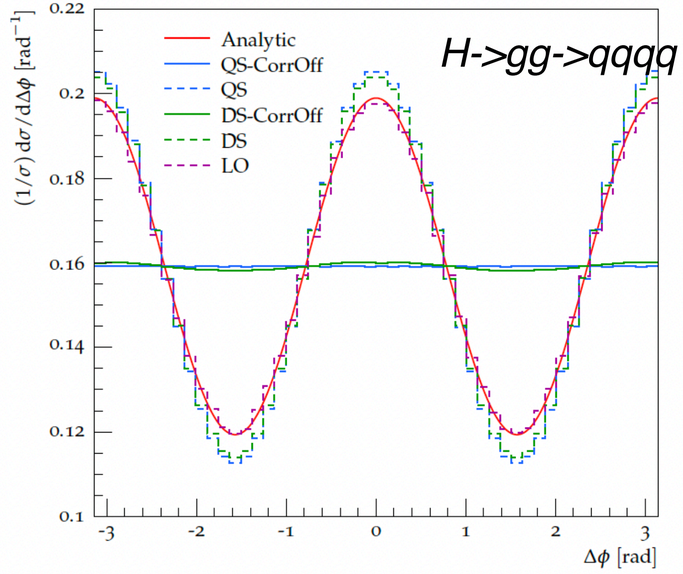


Spin correlation in PS

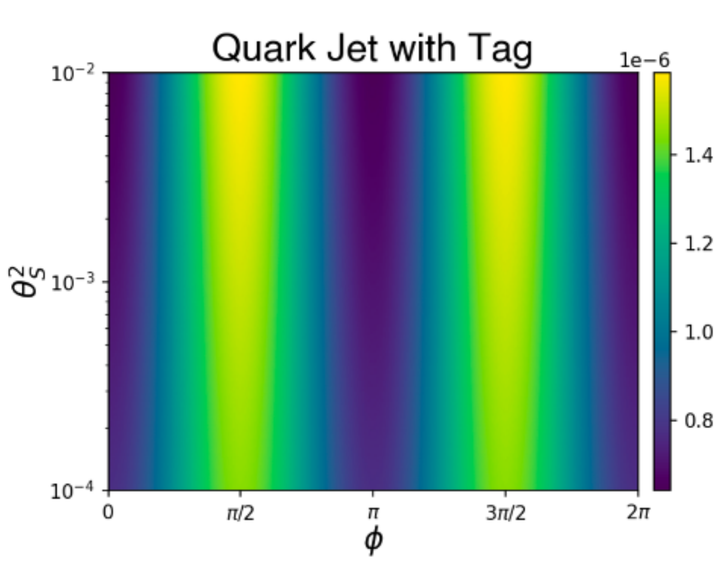
- Can be seen in
  - gluon production & decay plane angles / EEC
- However
  - Cancellation of g->qq and g->gg, overall effect small
  - Not clear how non-perturbative effect plays a role
- Would be interesting to test in data
- An immediate application H→ gg→ qqqq search

arXiv:2103.16526, in Panscale





H->gg->qqqq spin correlation



Chen, Moult, Zhu
Phys. Rev. Lett. 126 (2021) 112003

Measurement of spin correlation in PS

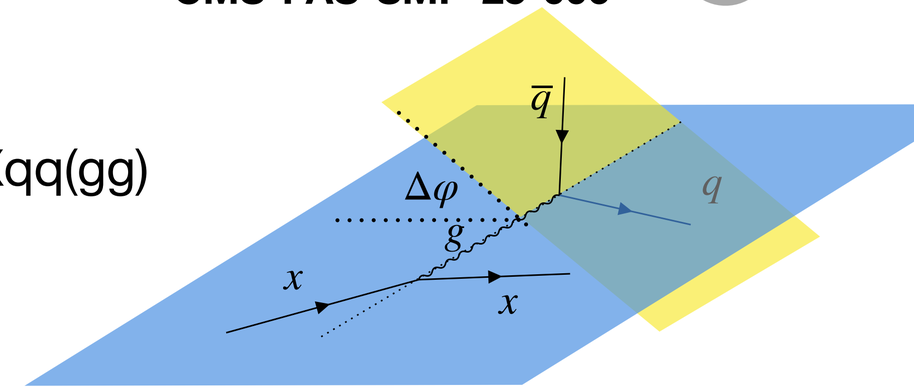
CMS-PAS-SMP-25-006

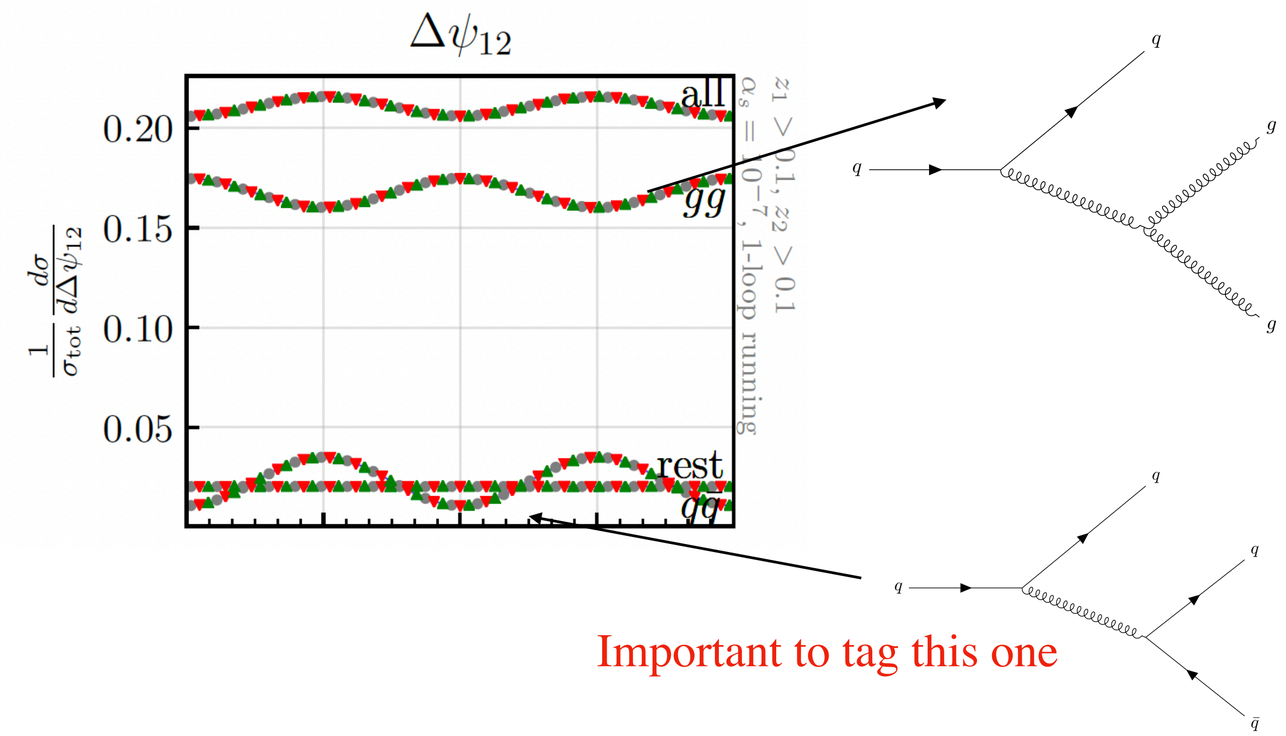
A measurement of spin-sensitive observable $\Delta\varphi$ inside jets

- Angle between gluon production and decay plane, X→ Xg → Xqq(gg)

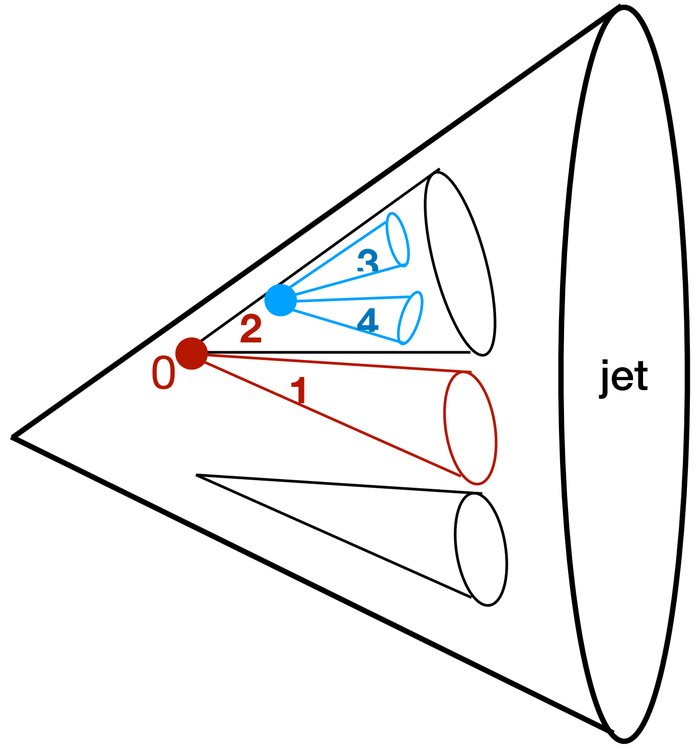
A few difficulties

- How to find PS splitting chain inside jet
- How to pick up only X→ Xg → Xqq



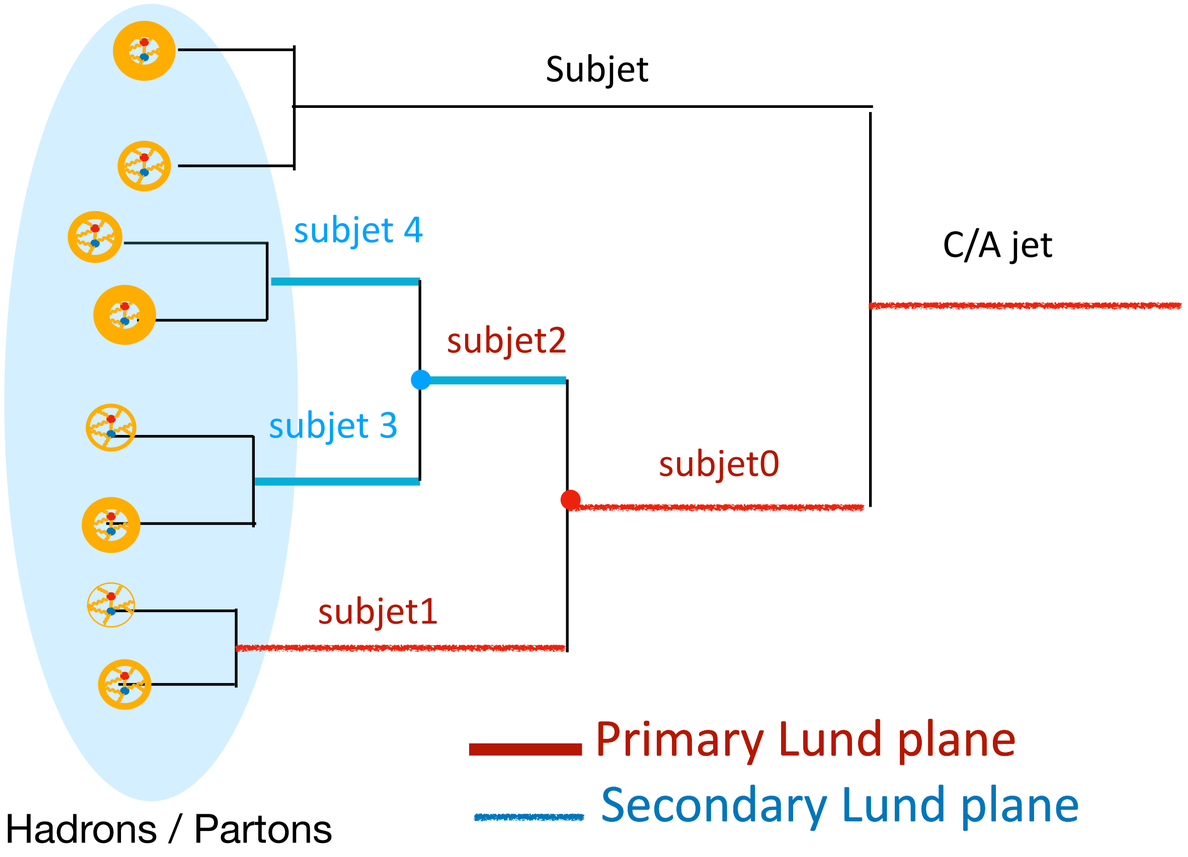


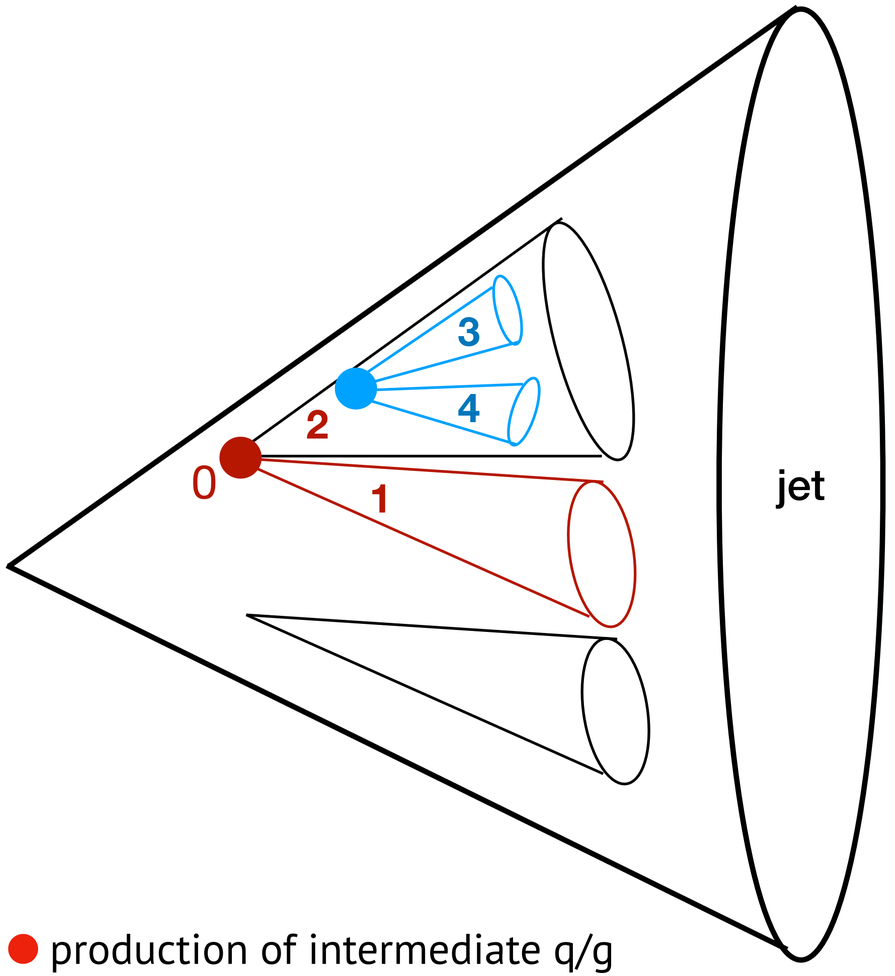
Important to tag this one



Analysis strategy

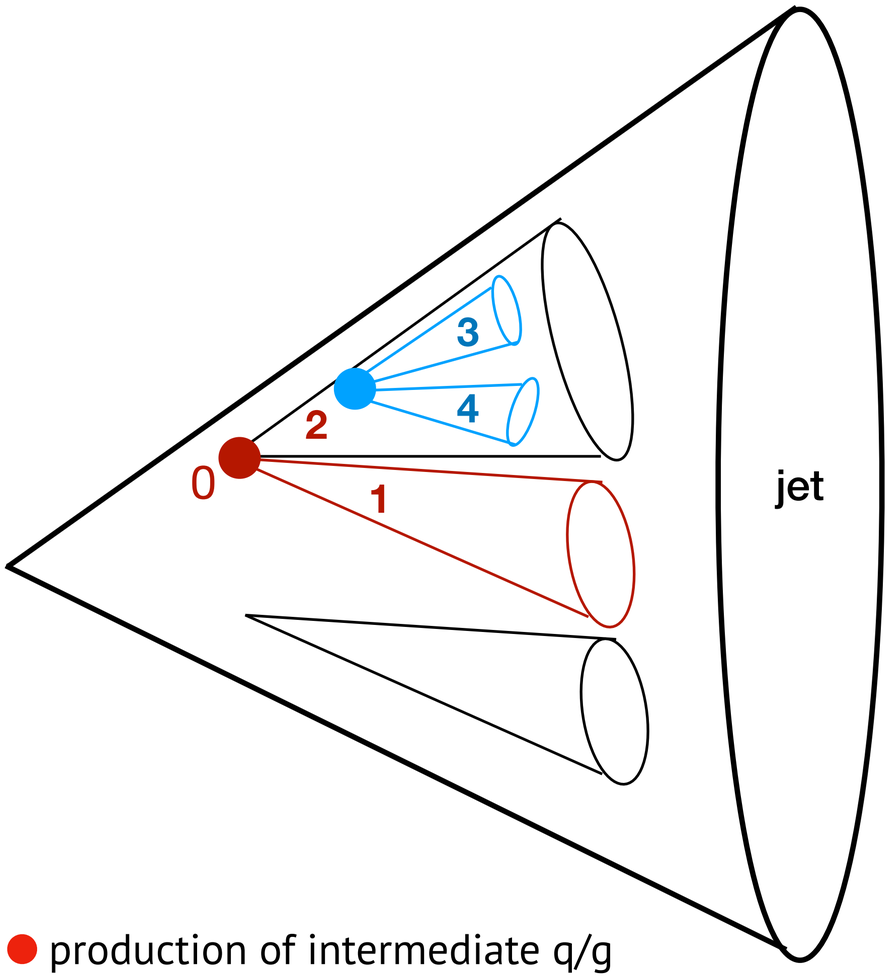
- Restore parton splitting in jets
  - C/A decluster





Analysis strategy

- In each jet, select subjets representing splitting of 0 -> 1, 2 (2->3,4)



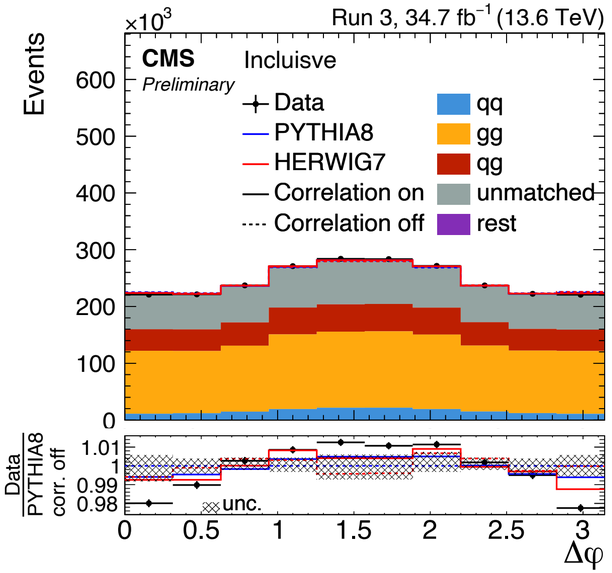
- production of intermediate q/g
- decay of intermediate q/g

- 0->1,2, max k_T in primary lund plane
- 2->3,4, max k_T in secondary lund plane

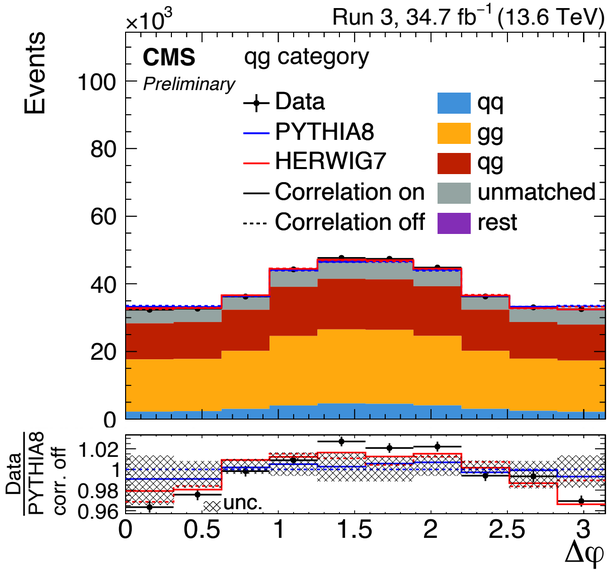
arXiv:2111.01161

  - need flavor tagging on subjet 3&4
    - g->qq; g->gg; q->qg;
  - True flavor learnt from matching to parton subjets
  - Parton subjets flavor
    - IFN algorithm: infrared and collinear safe definition
  - Machine learning and categorization

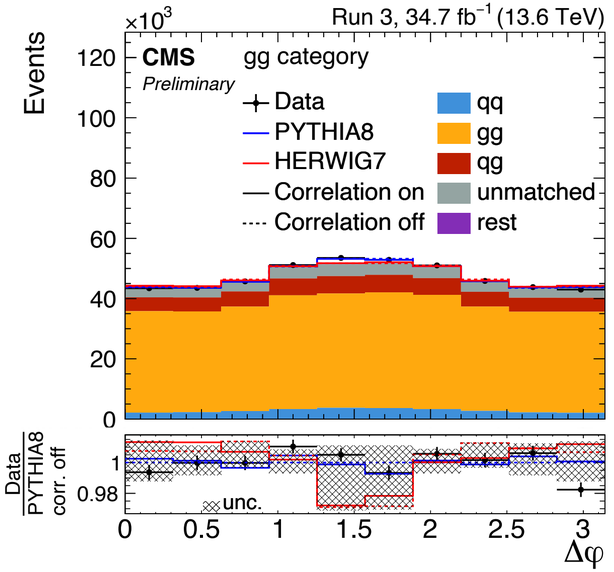
Spin effect in other categories



Inclusive



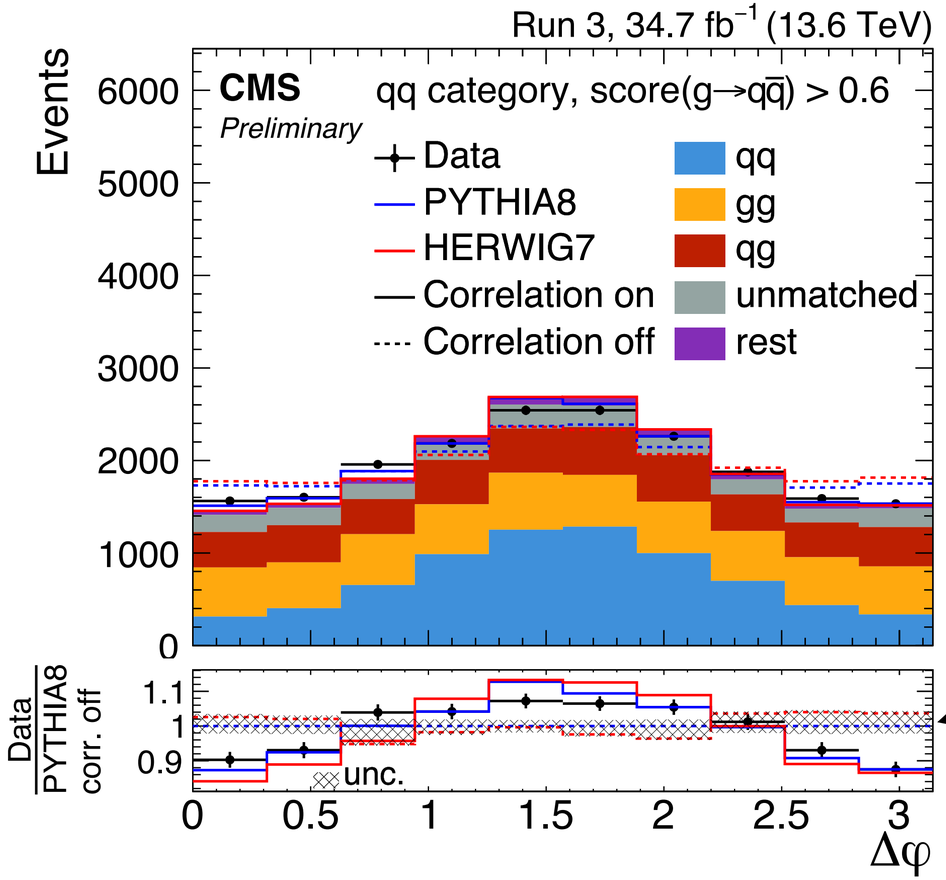
$q \rightarrow qg$ category



$g \rightarrow gg$ category

- Inclusive spin effect is 0.5% level, also tiny in non-qq categories
- Difference between Pythia and Herwig is small, most dominant in g->gg
- Data agrees better with Herwig in unmatched and qg, and Pythia in gg category

Spin effects in qq category



qq category

$\text{score}_{g\to q\bar{q}} > 0.6$

Data favors the correlation-on model, but still visible difference

- 6.8 σ from correlation-off, 1.9 σ from correlation-on
- Observation of spin correlation effect in PS

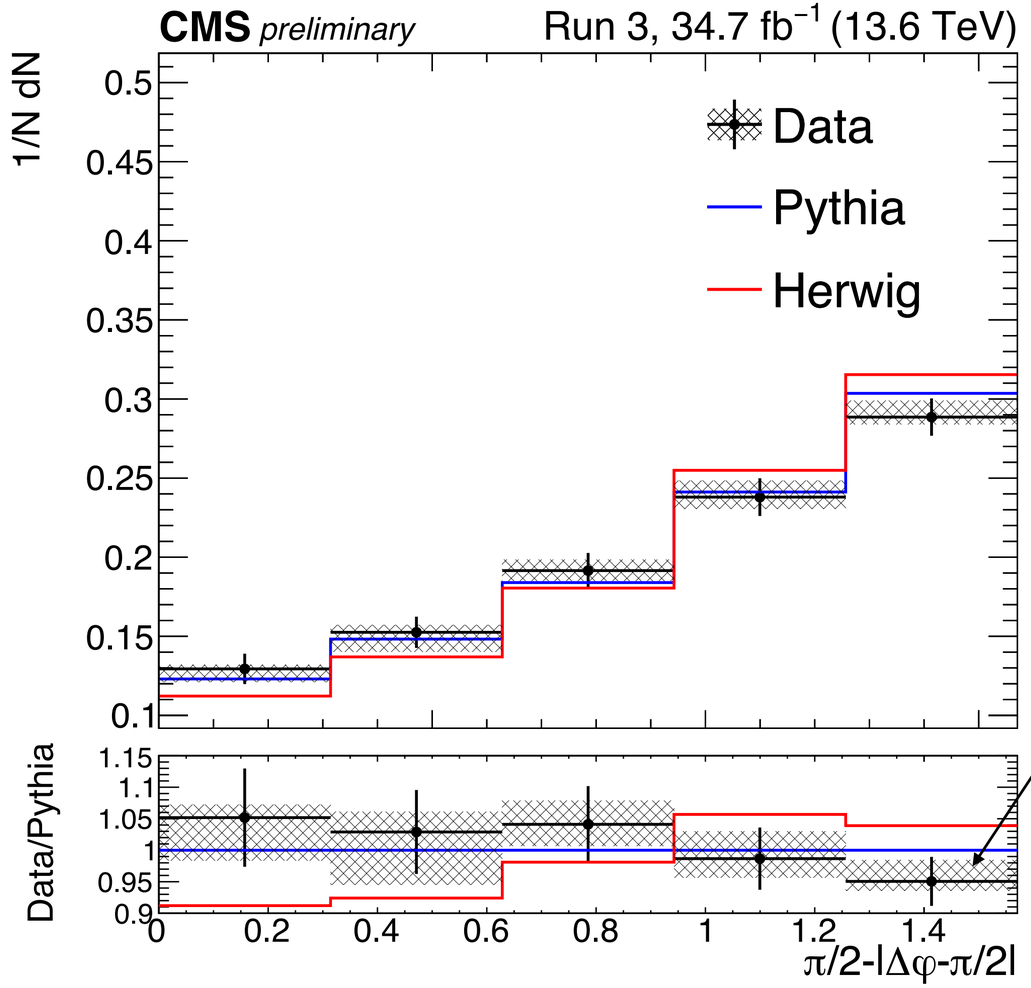
- Leading uncertainties
  - FSR
  - MC stat
  - Pileup

Summary

- Interesting program in jet substructure
- A lot of ongoing developments from both theory and experiment side
- LHC a great avenue for QCD studies!

Backup

Unfolding



- Reco (gen) phase space:
  - score (g->qq) >0.6
  - jet pT > 700 (600) GeV
  - subjet2 pT> 130 (120) GeV
  - all particles pT >1 GeV
- Since $\Delta\varphi$ should be symmetric around π/2, we unfold $\pi/2 - |\Delta\varphi - \pi/2|$
- Leading uncertainties
  - modeling uncertainty (1-7%)

    Different unfolding results from PYTHIA and HERWIG.
  - tracking efficiency (1–3%)
- Data agrees better with PYTHIA