Experimental overview of QCD at LHC

肖朦，浙江大学

2024.12.14
Mini-workshop on the frontier of LHC, 福州

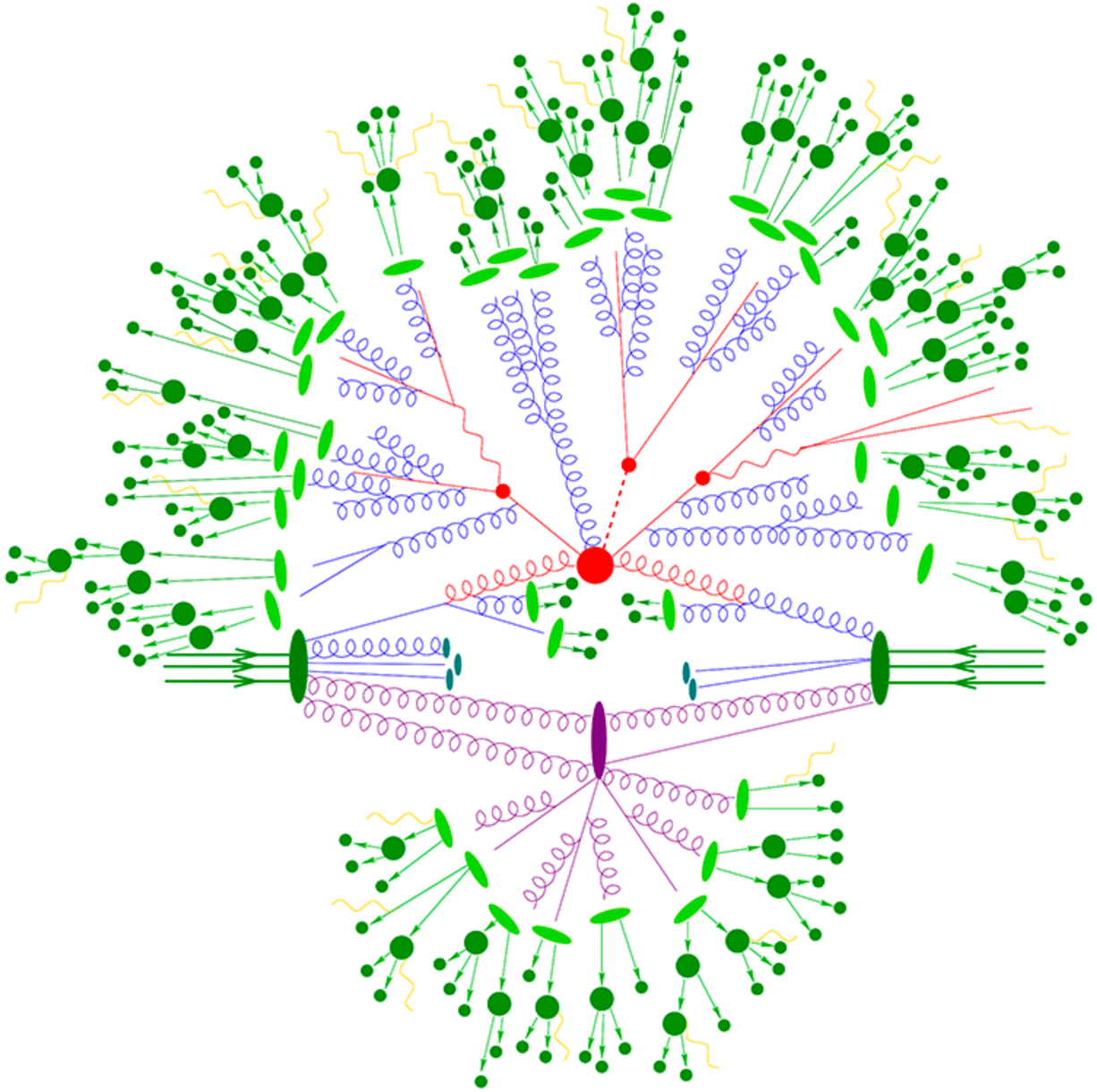
Hadron Collision

Hard Scattering
Perturbative QCD

Parton Shower
Resummation

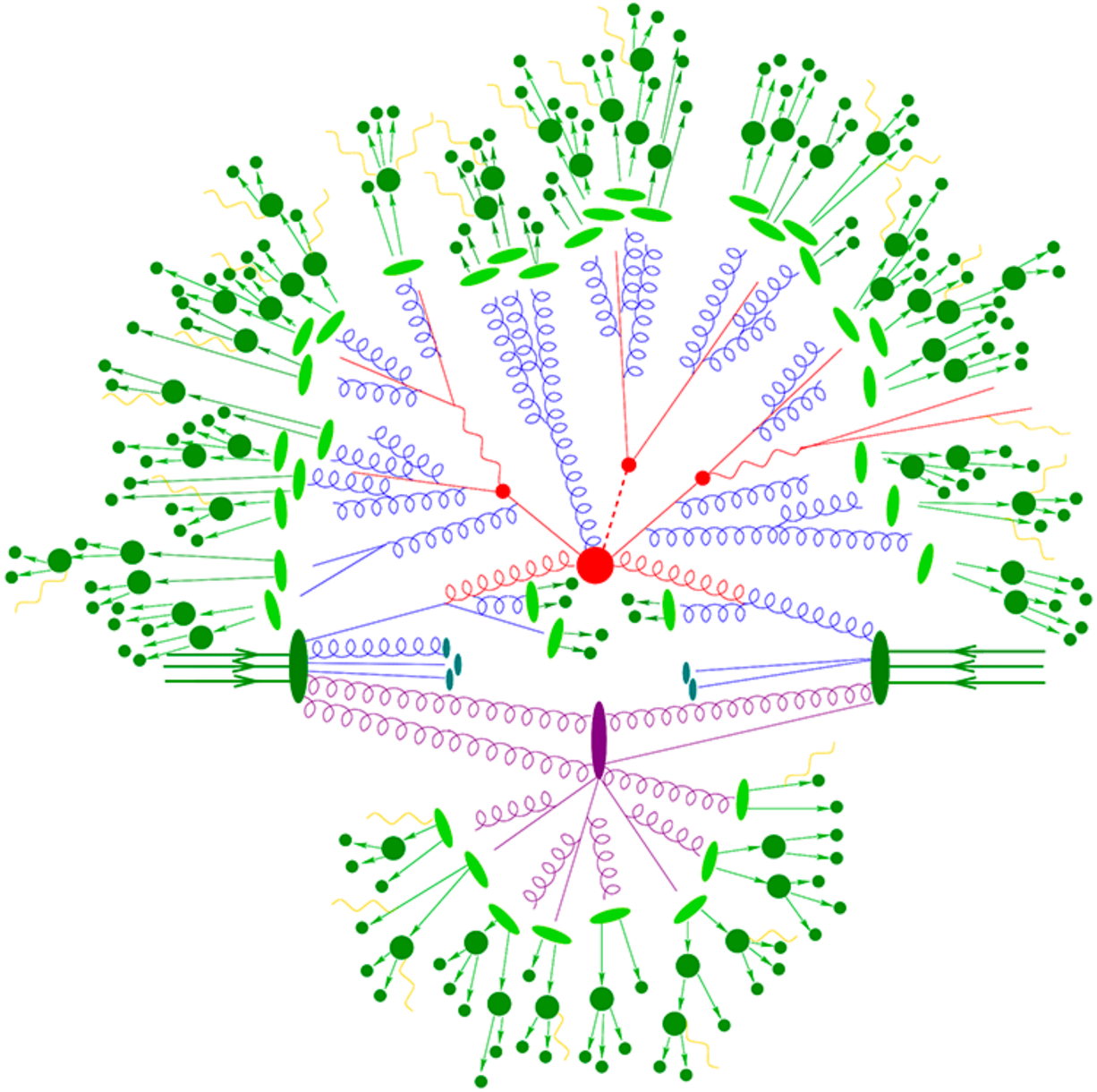
Hadronization
Non-perturbative, PDF

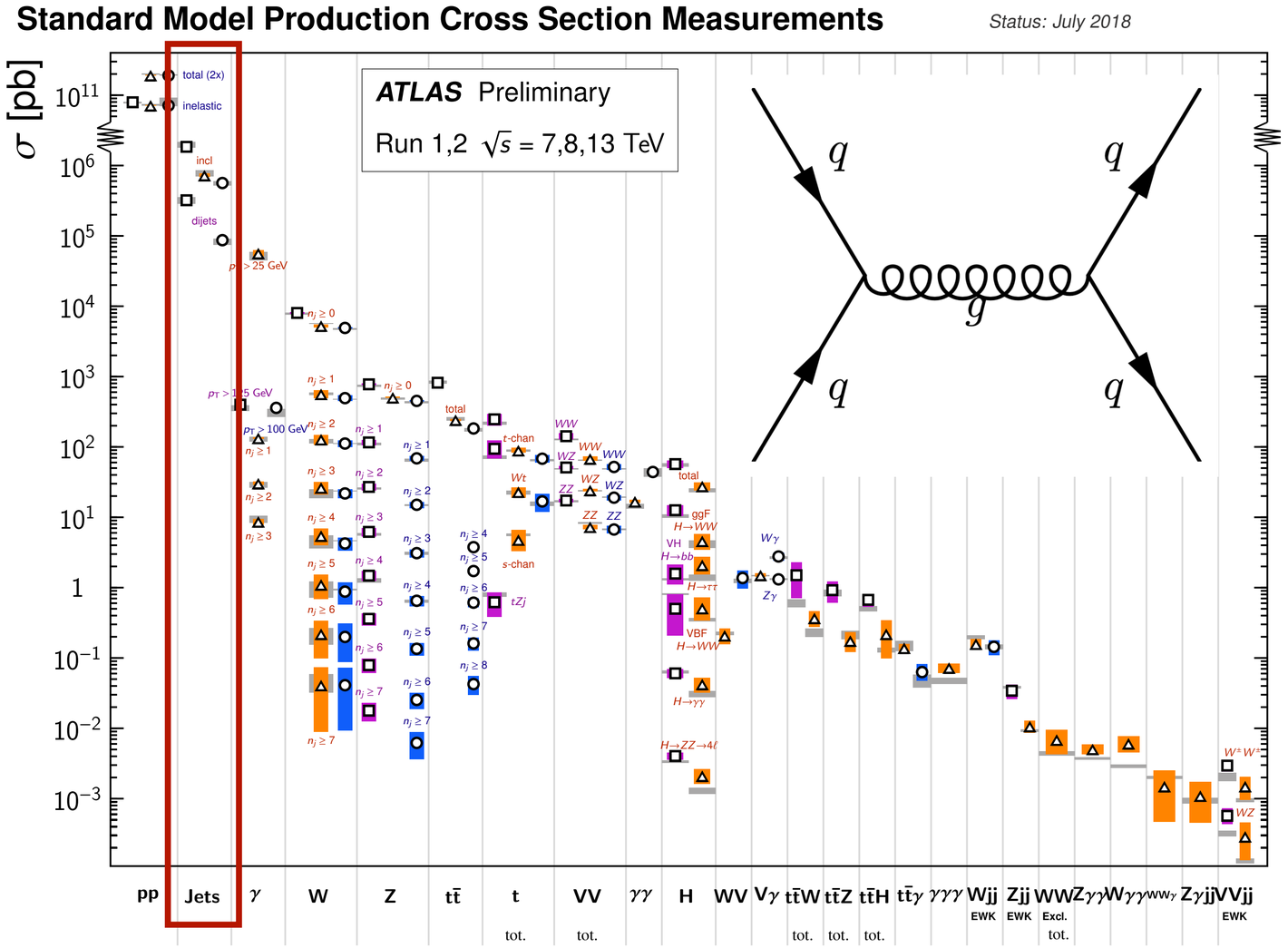
MPI
Tunes



Hard Scattering

Perturbative QCD

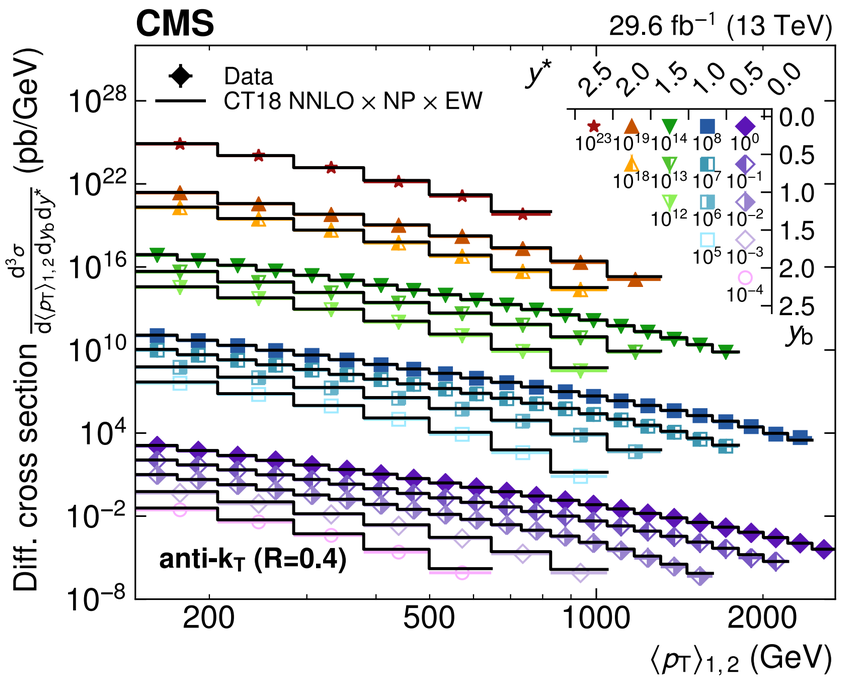


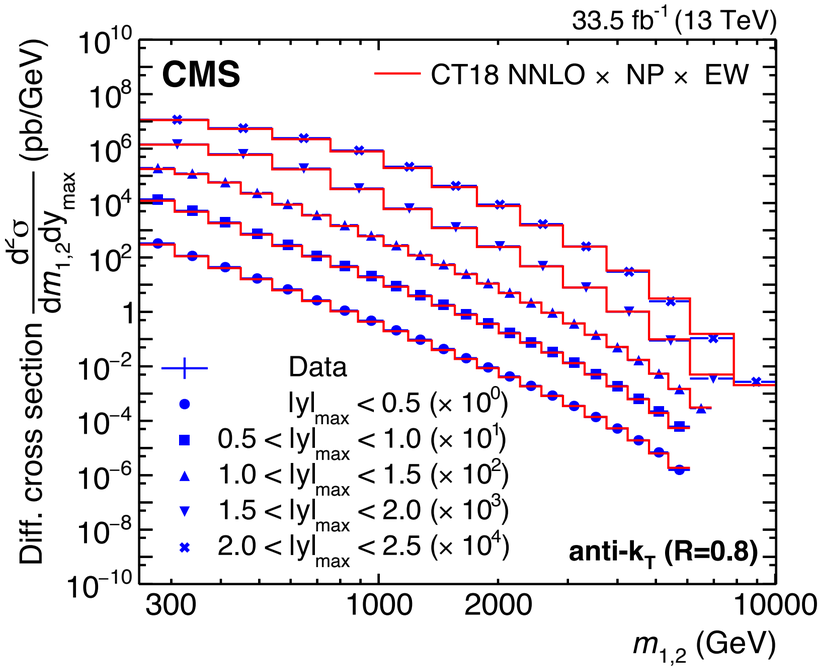

Standard Model Production Cross Section Measurements
Status: July 2018
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
σ [pb]
total (2x)
inelastic
incl
dijets
pp
Jets
γ
W
Z
tt̄
t
VV
γγ
H
WV
Vγ
tt̄W
tt̄Z
tt̄H
tt̄γ
γγγ
Wjj EWK
Zjj EWK
WW Excl.
Zγγ
Wγγ
WWγ
Zγjj
VVjj EWK
tot.
q
g

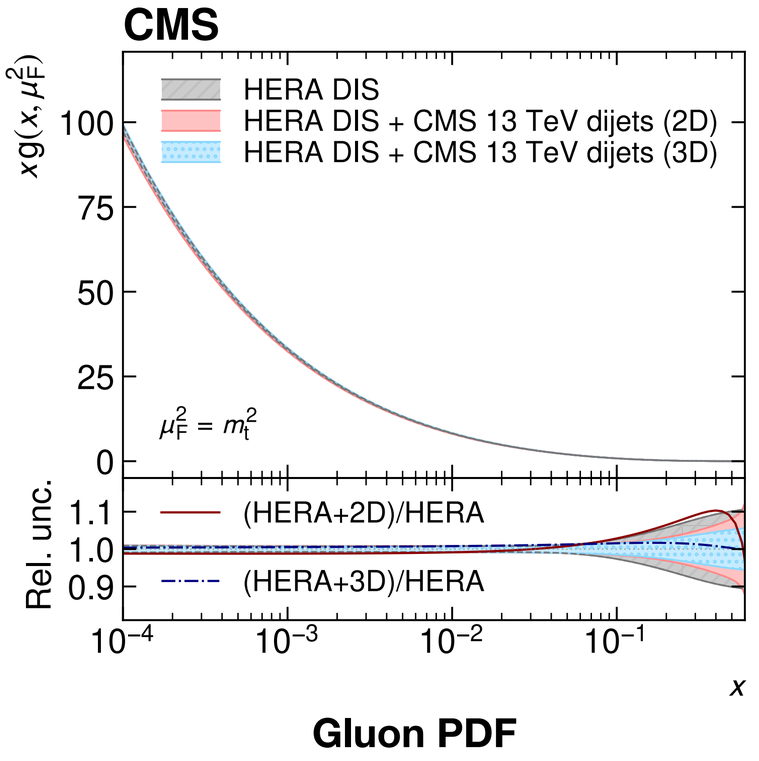
Dijet measurement

CMS,arXiv: 2312.16669

- Dijet double differential cross section compared to NNLO pQCD calculation
- Probe very high Q
- Extract α_S and PDF $\alpha_S(m_Z) = 0.1179 \pm 0.0019$, 1% NNLO uncertainty

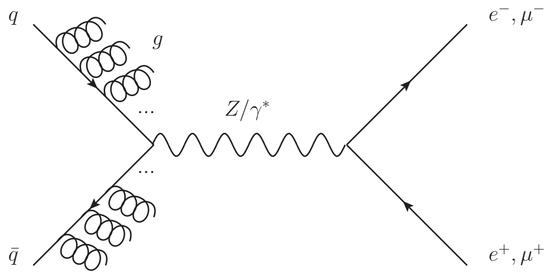






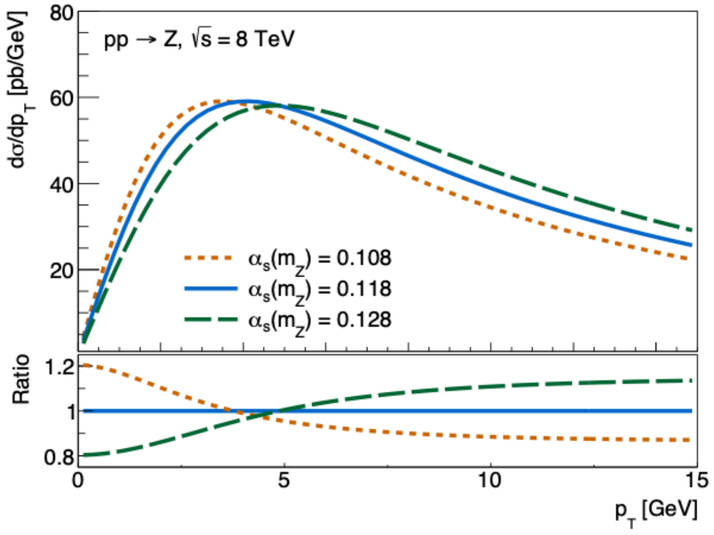
Gluon PDF

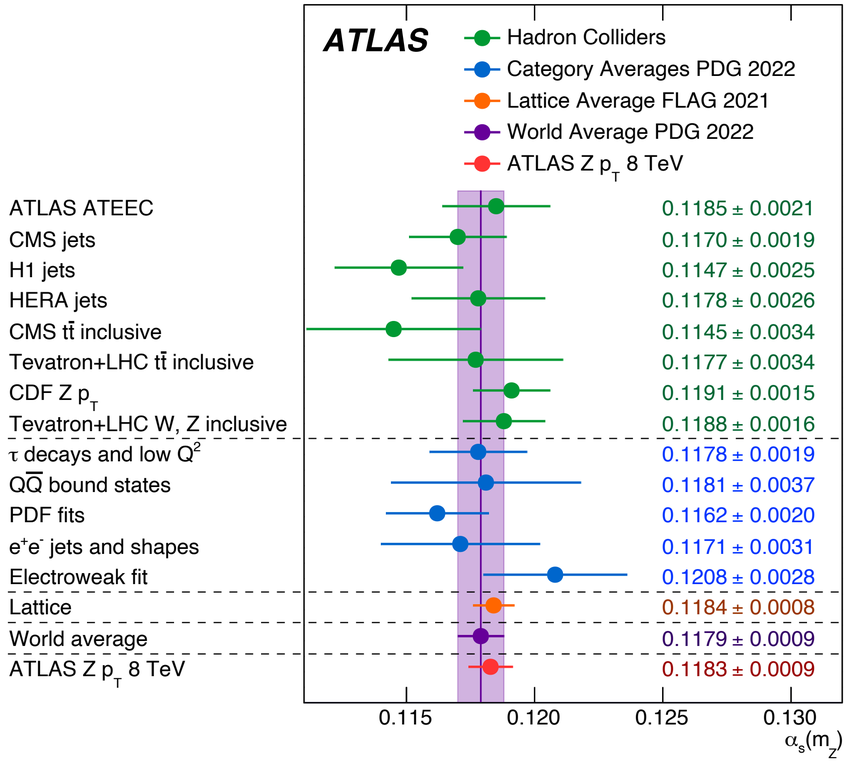
Z+jet measurement

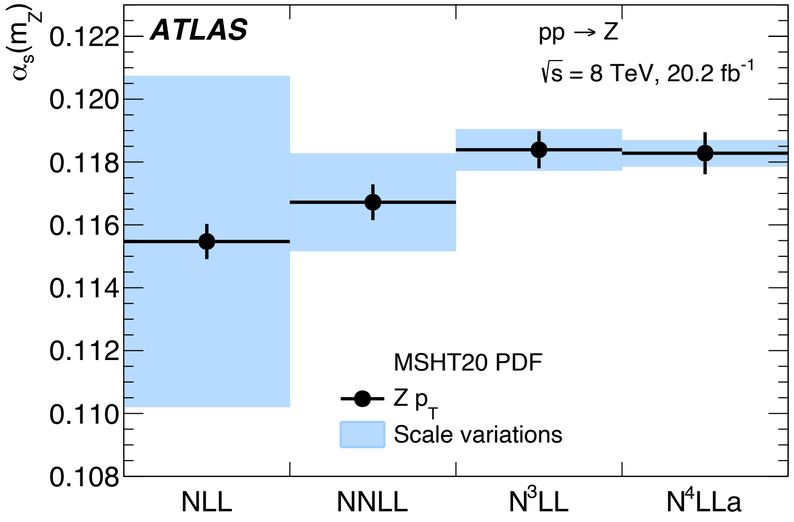


ATLAS, arXiv:2309.12986

- Using $p_T Z$ (ISR recoil) to extract α_S
- N³LO + N⁴LLa prediction, $\alpha_S(m_Z) = 0.1183 \pm 0.0009$







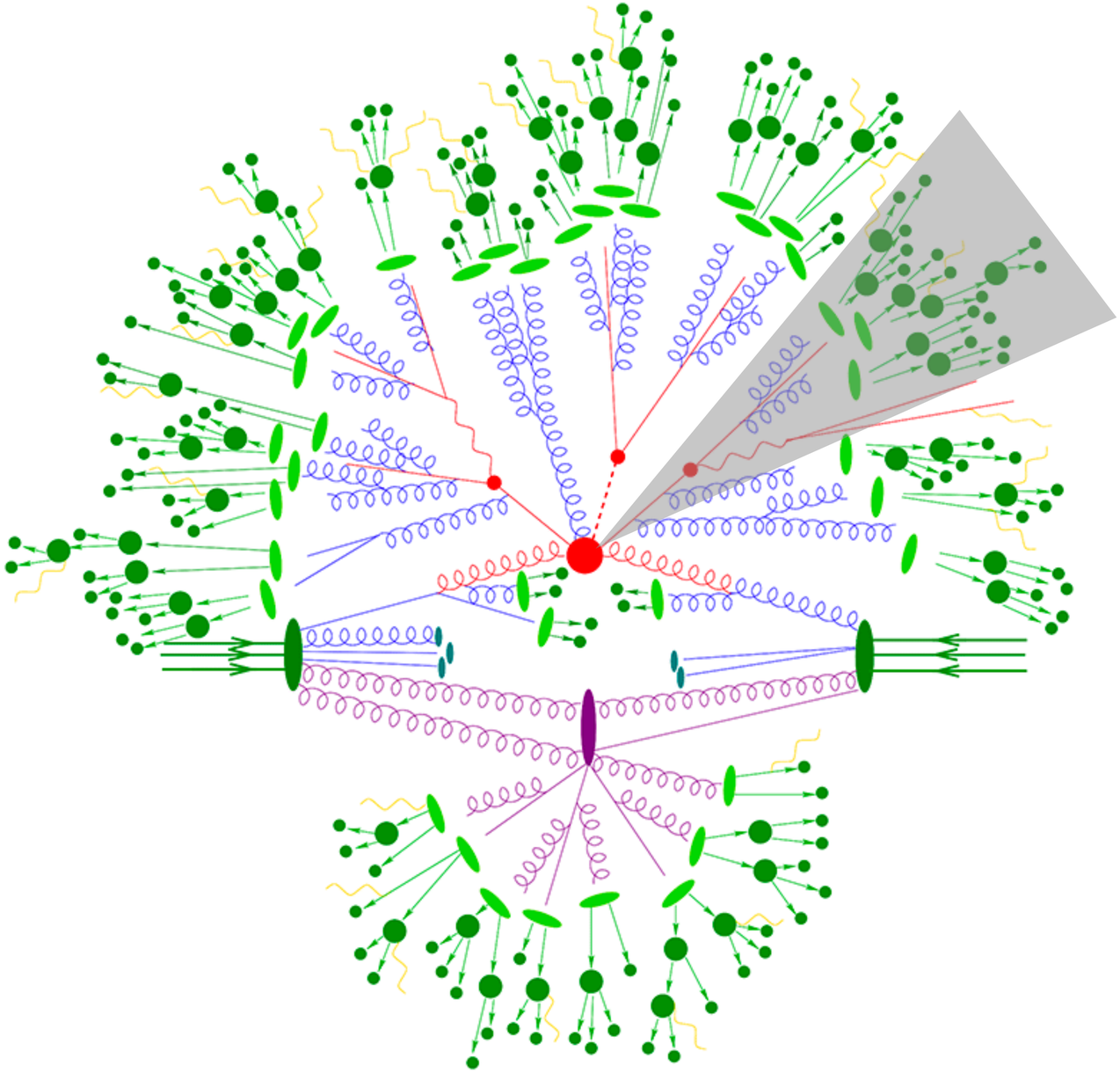
Hadron Collision

Parton Shower

Resummation

Hadronization

Non-perturbative, PDF



Hadron Collision

Jet substructure

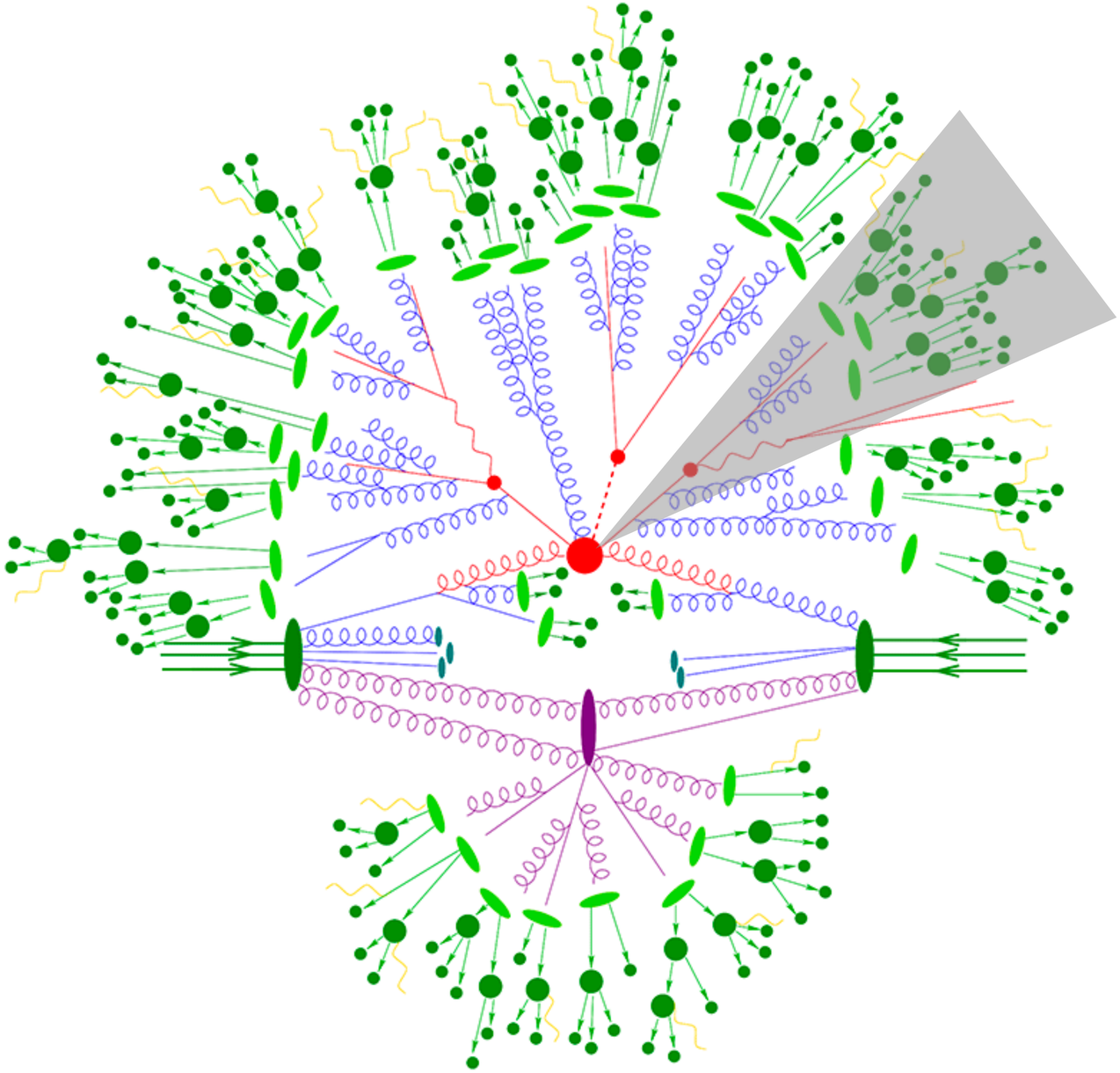
- **MC simulation**
- **Theoretical calculation**

Parton Shower

Resummation

Hadronization

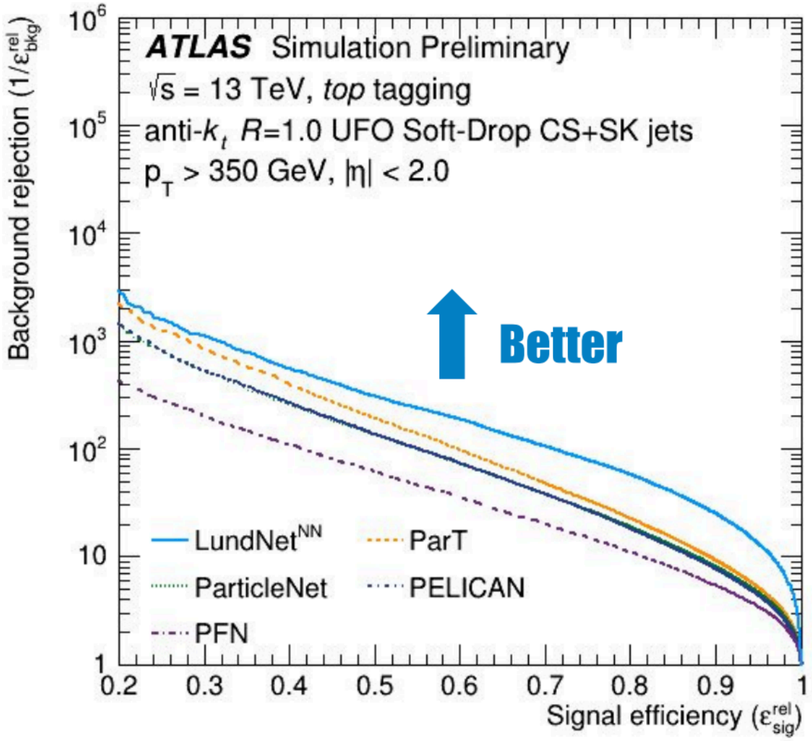
Non-perturbative, PDF

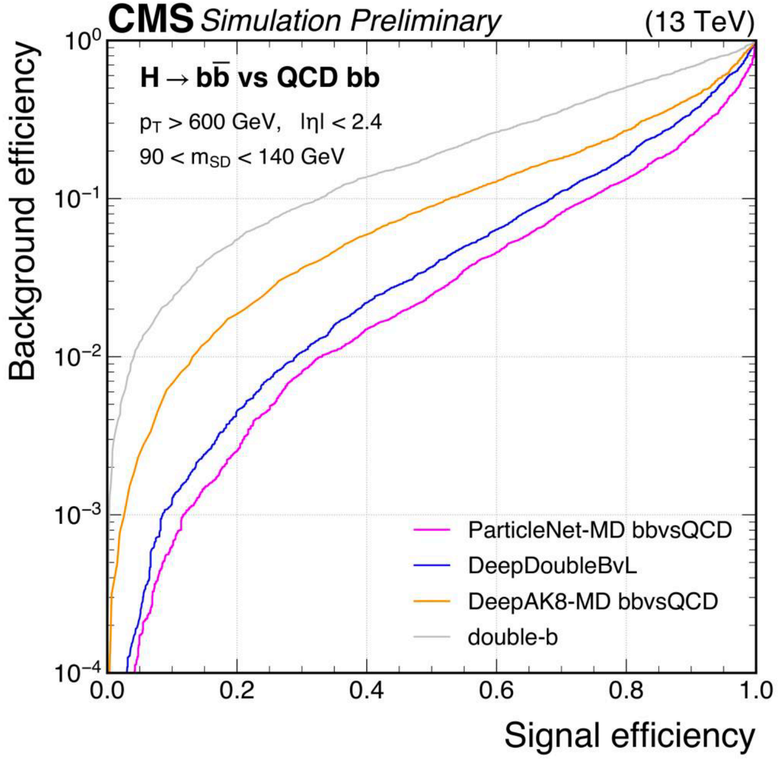


Jet substructure in searches

ATL-PHYS-PUB-2023-017
CMS-PAS-BTV-22-001

- Identification of boosted jets types
  - Benefit greatly from developments in machine learning techniques

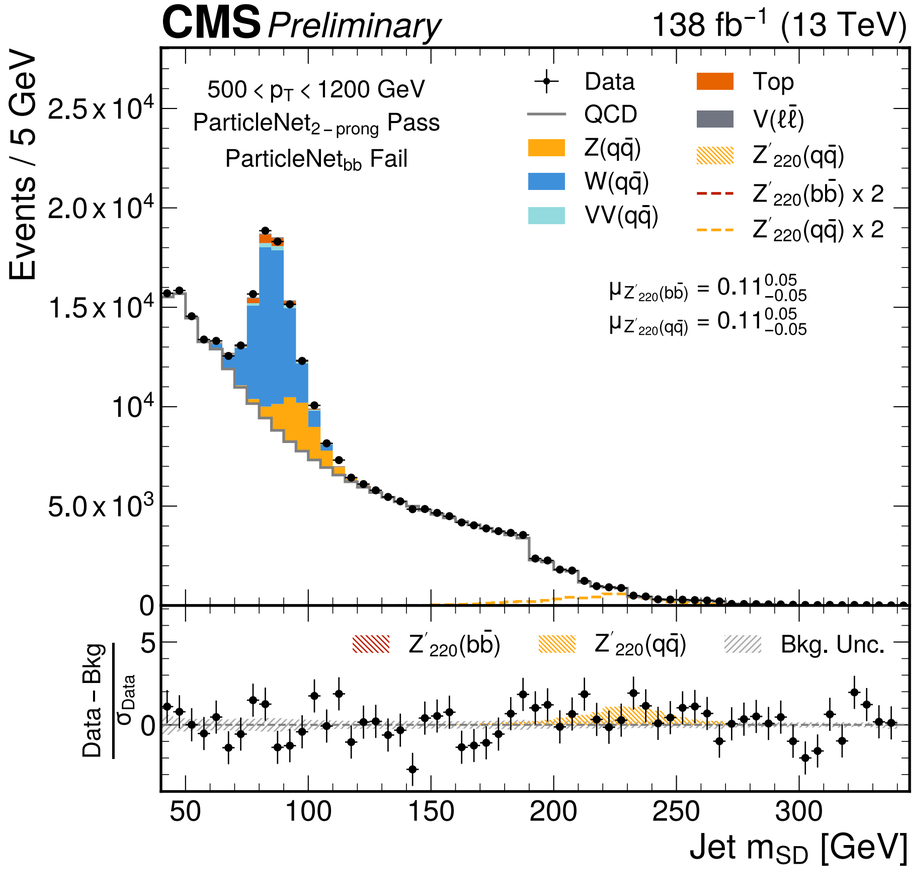


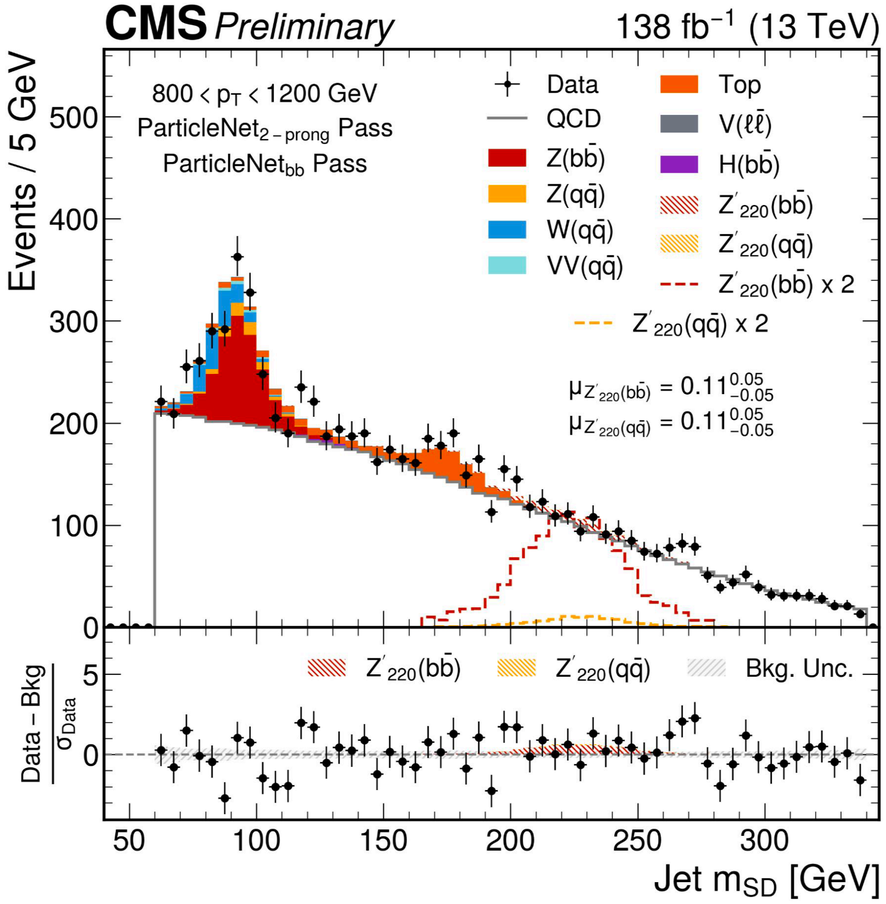


Jet substructure in searches

CMS-PAS-EXO-24-007

- Identification of boosted jets types
  - Benefit greatly from developments in machine learning techniques
  - rely on jet substructure inputs, PS model crucial





Understanding and improving PS

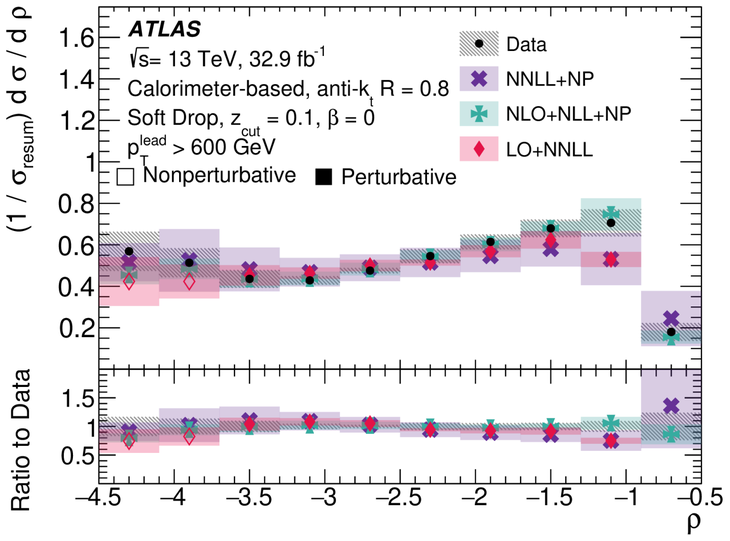
- Traditional jet substructure observables: event shapes, soft-drop mass

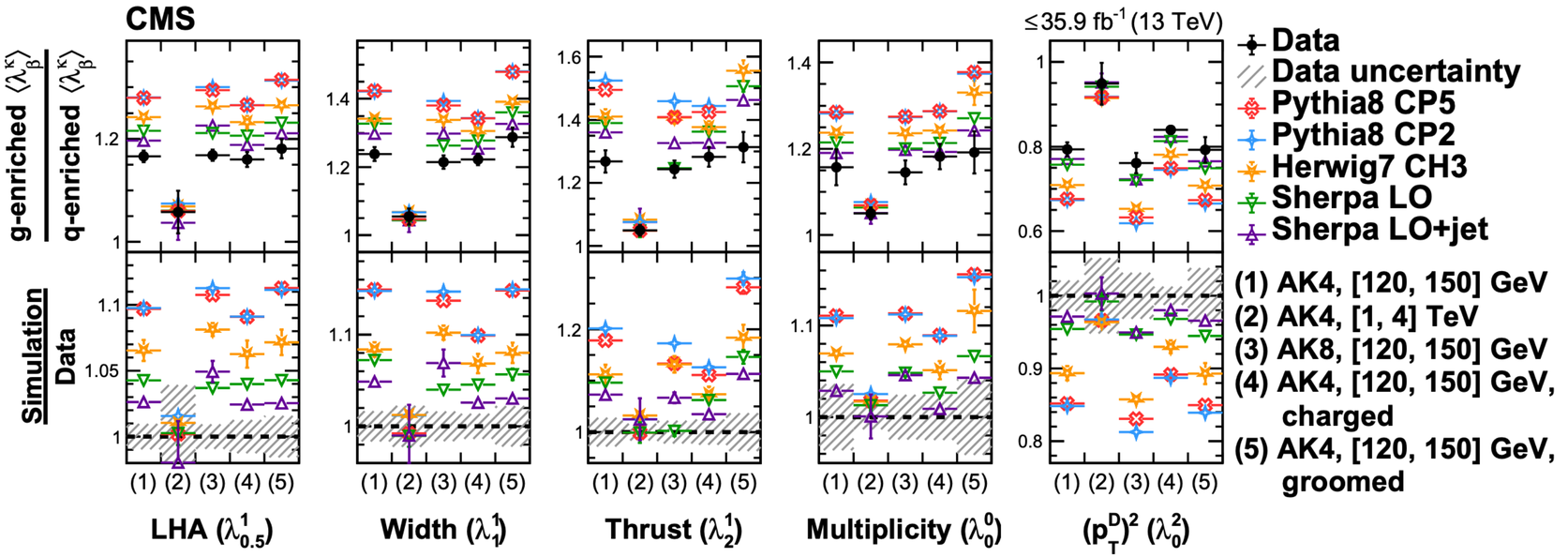
Recent CMS jet substructure measurements

Reference, $\sqrt{s}$	Final state	Jets flavours, p_T (GeV)	Observables
1808.0734 13 TeV pp	$t\bar{t}$	q/g-jets (AK4), p_T>30 g-jets (AK4), p_T>30 b-jets (AK4), p_T>30	Jet substructure and softdrop observables
1809.08602 5.02 TeV pp/PbPb	jets	q/g-jets (AK3), p_T>30	Jet shapes
1911.038 13 TeV pp	$t\bar{t}$	top-jets (XC12), p_T>400	XCone-groomed jet mass
2004.00602 5.02 TeV pp/PbPb	jets	q/g-jets (AK4), p_T>120	Jet charge
2101.0472 5.02 TeV pp/PbPb	dijets	q/g-jets (AK4), p_T>50	Jet shapes
2109.0334 13 TeV pp	dijets Z+jets	q/g-jets (AK4), p_T>30 q-jets (AK4), p_T>30	Generalised angularities
2210.08547 5.02 TeV pp/PbPb	jets	q/g-jets, b-jets (AK4), p_T>120	Jet shapes
2211.01456 13 TeV pp	$t\bar{t}$	top-jets (XC12), p_T>400	XCone-groomed jet mass
2312.16343 13 TeV pp	dijets	q/g-jets (AK4, AK8), p_T>700	Lund plane
2312.17103 13 TeV pp	Jets	q/g-jets (AK4), p_T>550	2D angular correlations
2402.13864 13 TeV pp	dijets	q/g-jets (AK4), 97<p_T<1784	Energy correlators
2405.02737 5.02 TeV pp/PbPb	γ+jet	q/g-jets (AK2), p_T>40	Groomed jet radius, girth

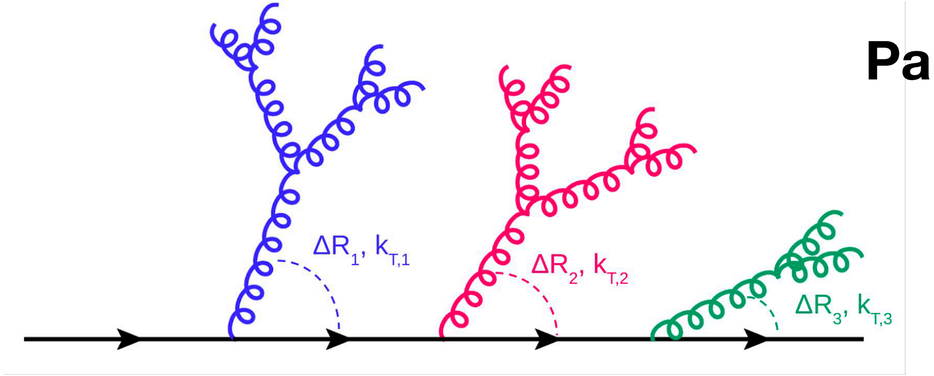
Understanding and improving PS

- Traditional jet substructure observables: event shapes, soft-drop mass

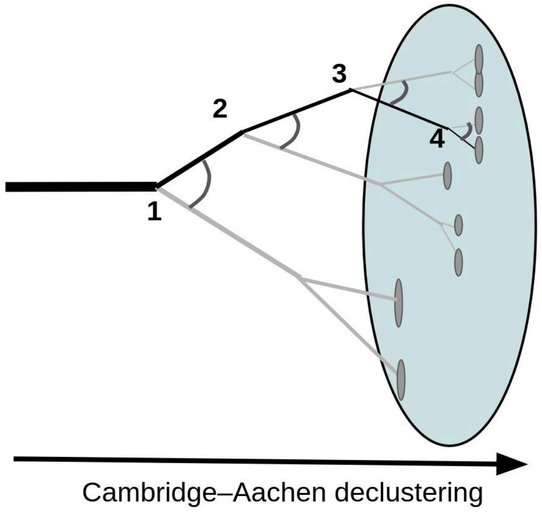


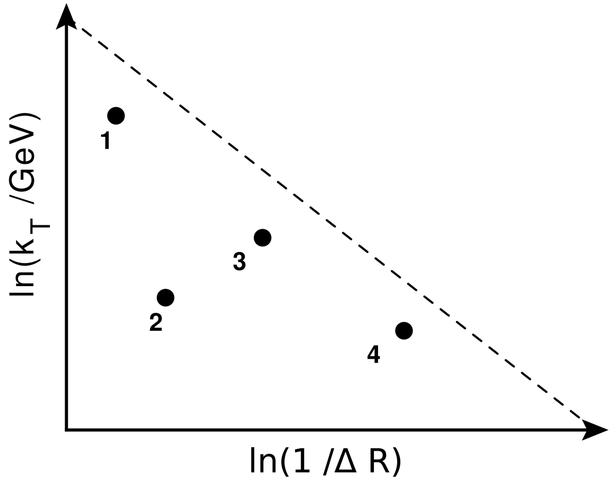


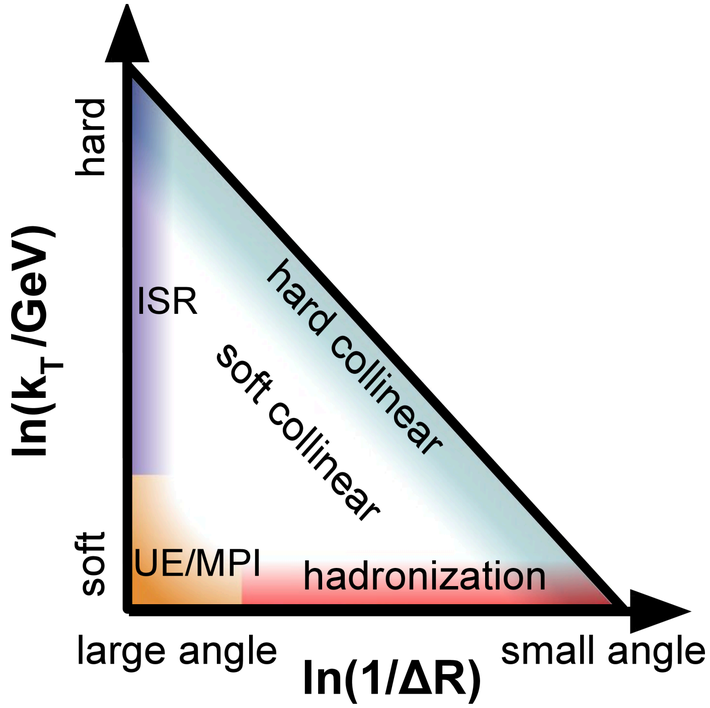
Getting more fundamental: restore jet formation chain



Parton shower







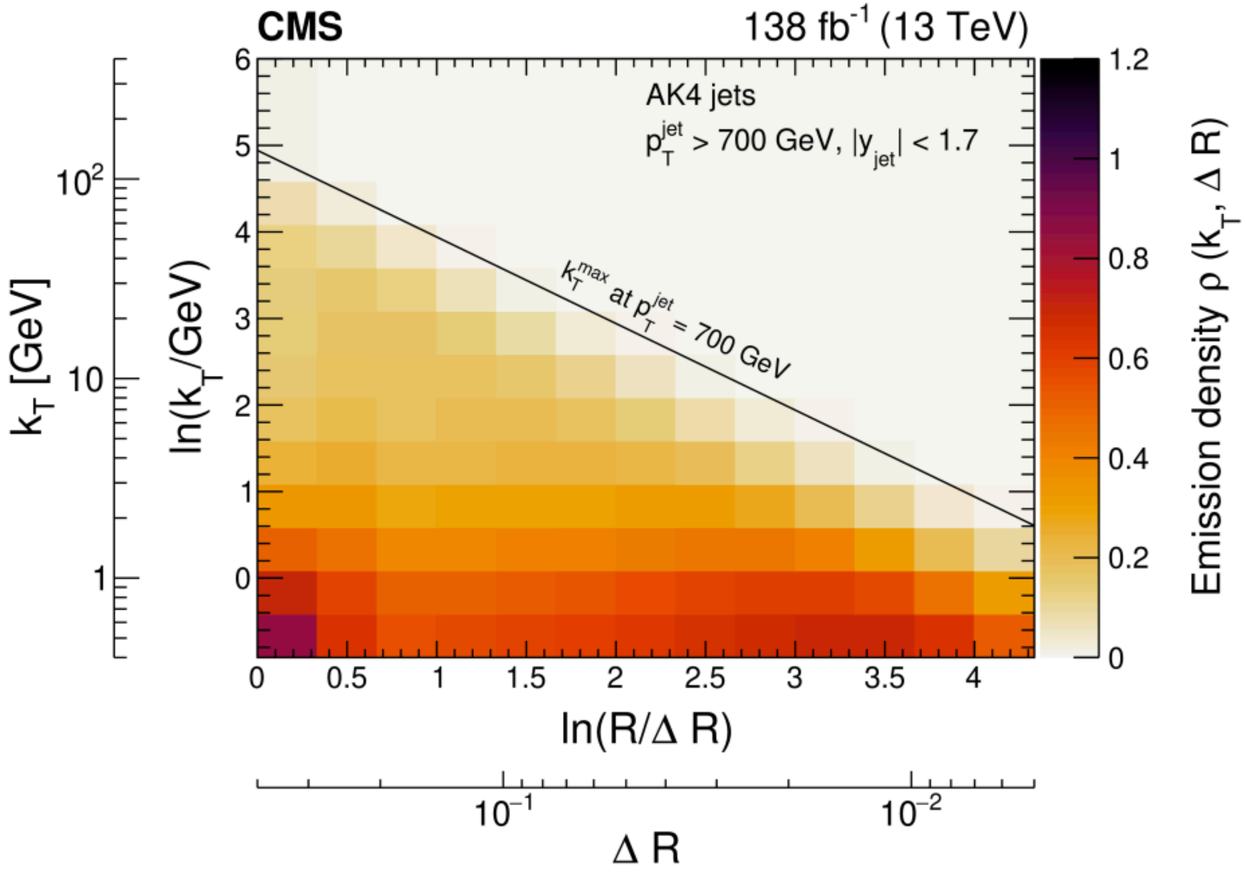
Decluster jets to mimic shower chain

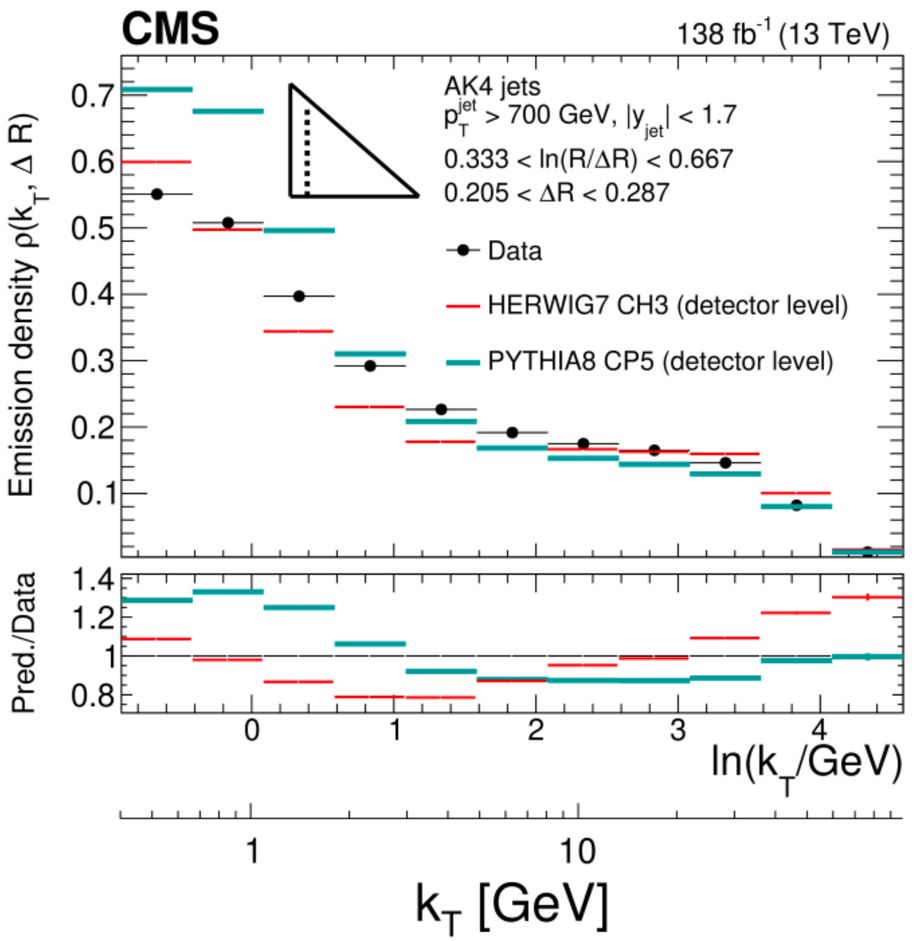
Record ΔR and kT of each splitting

Lund Plane

Lund Plane measurements

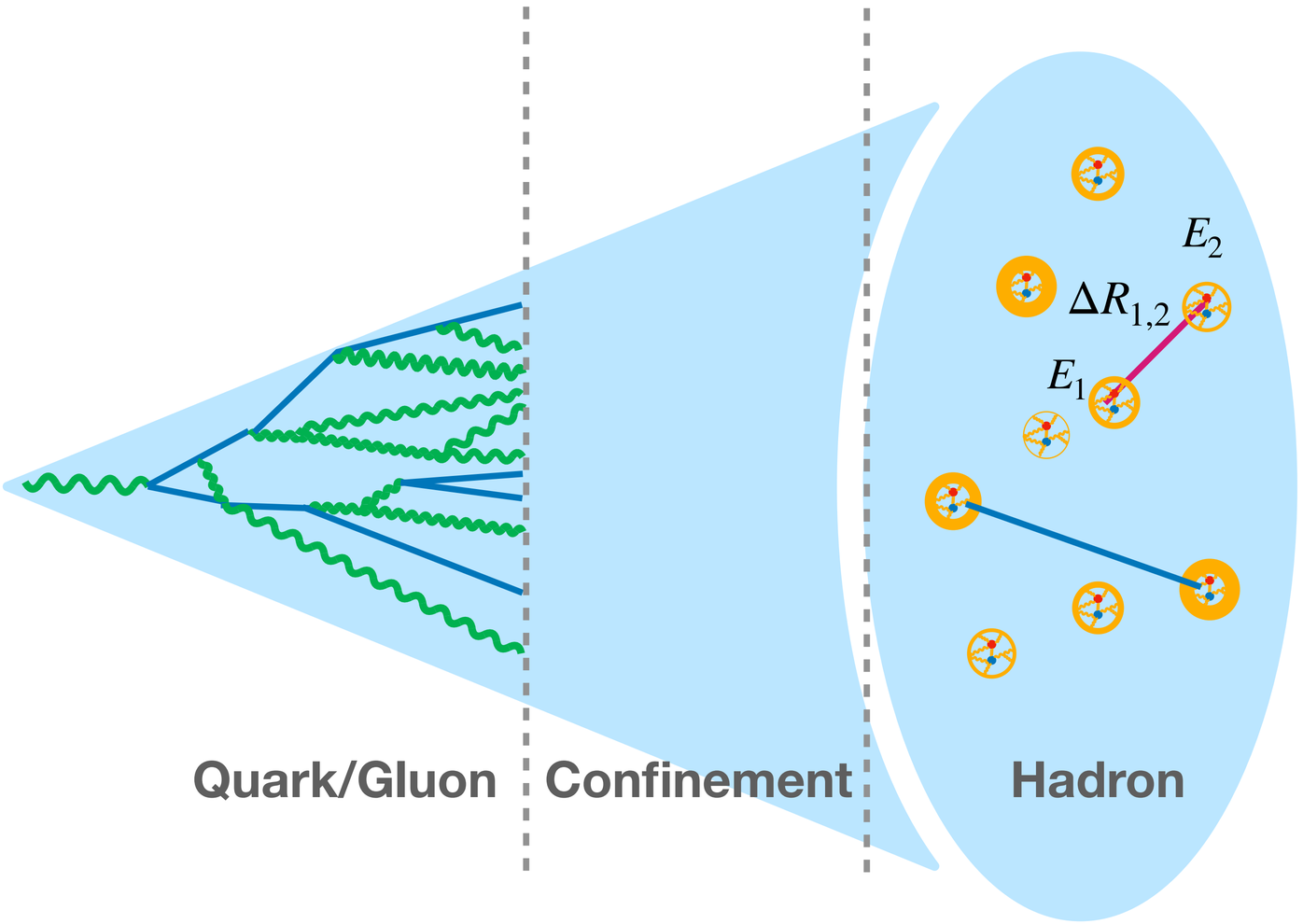
ALICE: arXiv:2111.00020
CMS: arXiv:2312.16343
ATLAS: Phys. Rev. Lett 124 (2020) 02
ATLAS: arXiv:2407.10879 (W/top jets)

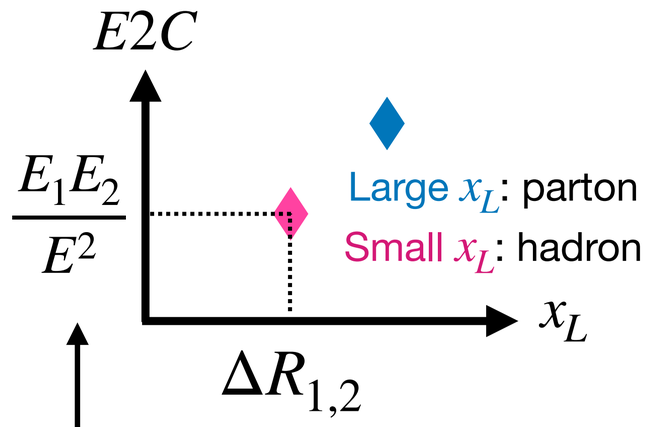




Data/MC differences already been used to calibrate jet substructure at CMS

A new way to probe jet formation: energy-energy correlators





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

Chen, Moult, Zhang, and Zhu, *arXiv:2004.11381*

Lee, Meçaj, and Moult, *arXiv:2205.03414*

Chen, Gao, Li, Xu, Zhang, and Zhu, *arXiv:2307.07510*

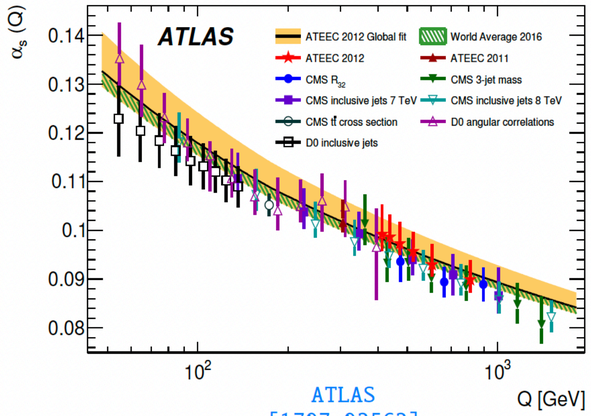
EEC: success story

The EEC: What makes it special?

The EEC addresses several important goals of QCD phenomenology, including:

$$\left\langle \sum_{\substack{\text{pairs } (i,j):\\ \theta_{ij}=\theta}} E_i\, E_j \right\rangle$$

- Measurements of α_s;



ATLAS
[1707.02562]

ATLAS:[1508.01579]
[1707.02562]

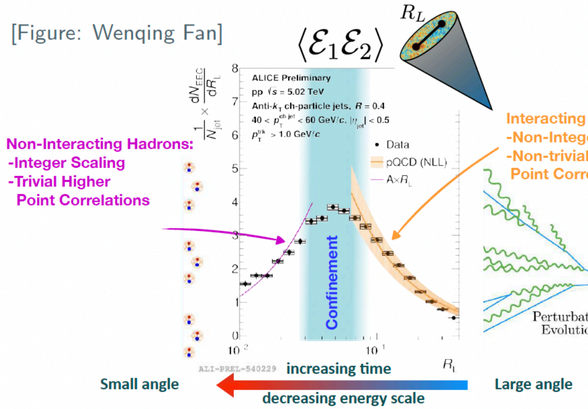
[CMS PAS SMP-22-015]

HERA:[2008.00271]

LEP+:[1804.09146]

Samuel Alipour-fard

[Figure: Wenqing Fan]



Non-Interacting Hadrons:
-Integer Scaling
-Trivial Higher Point Correlations

Interacting Partons:
-Non-Integer Scaling
-Non-trivial Higher Point Correlations

Perturbative Evolution

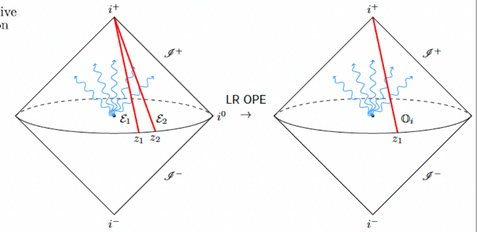
Small angle — Large angle

- Evolution of the jet goes from right to left
  - Distinct scaling regimes corresponding to partonic and hadronic physics
  - Transitions image the physical scales of QCD

Mark Gonzalez

Correlation function of detectors ⇒ jet substructure observable

A clear link between theory and experiment!



Perturbative scaling predicted by the light-ray OPE

⇒ **Universal scaling behavior!**

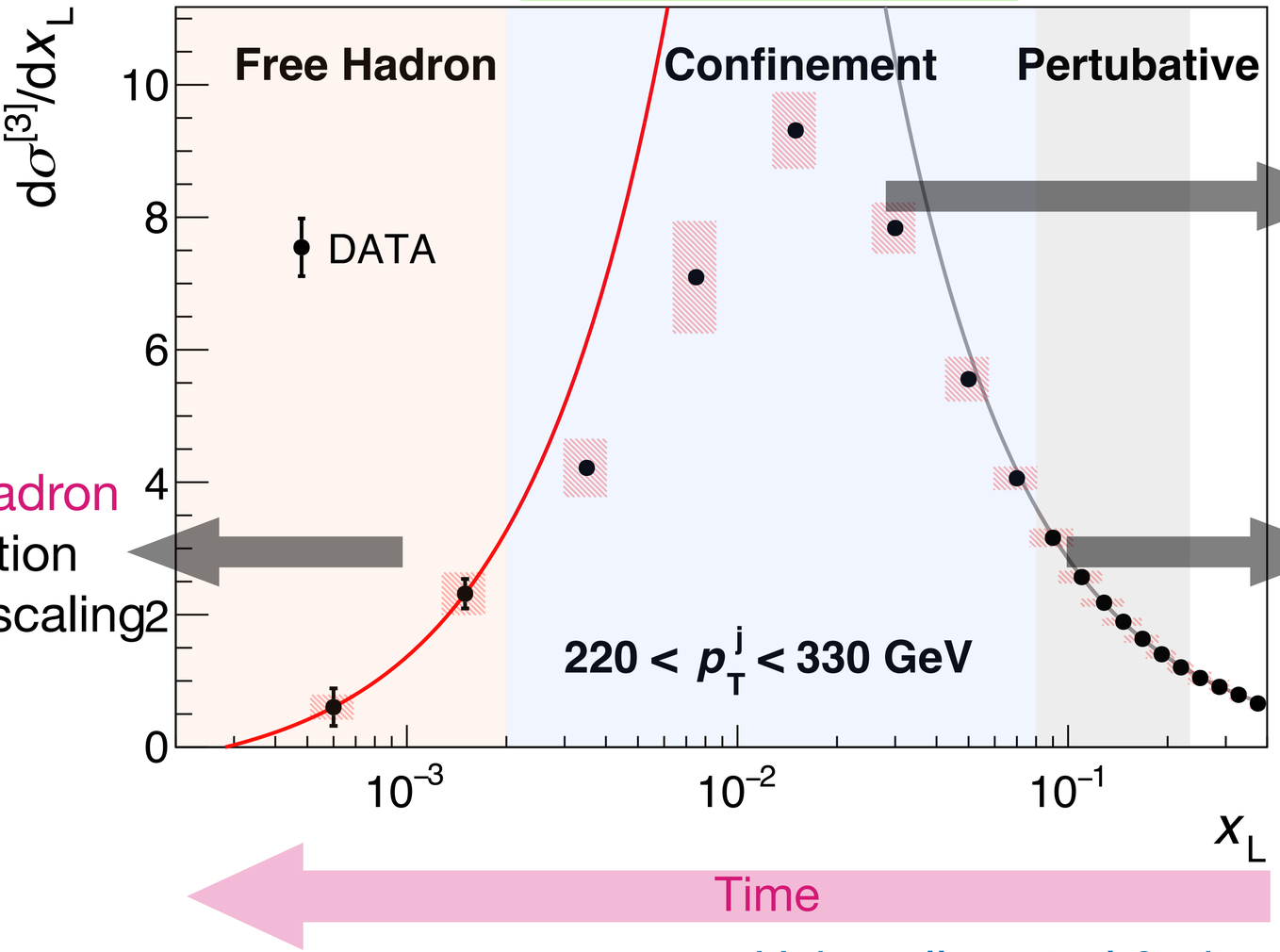
$$\mathcal{E}(\hat{n}_1)\mathcal{E}_2(\hat{n}_2) \sim \sum_i \theta^{\tau_i - 4} \mathbb{O}_i^+(\hat{n}_1)$$

What else can we do?

Melissa van Beekveld

EEC and E3C measurements

CMS, PRL 133 (2024), 071903



Phase transition
from parton to hadron

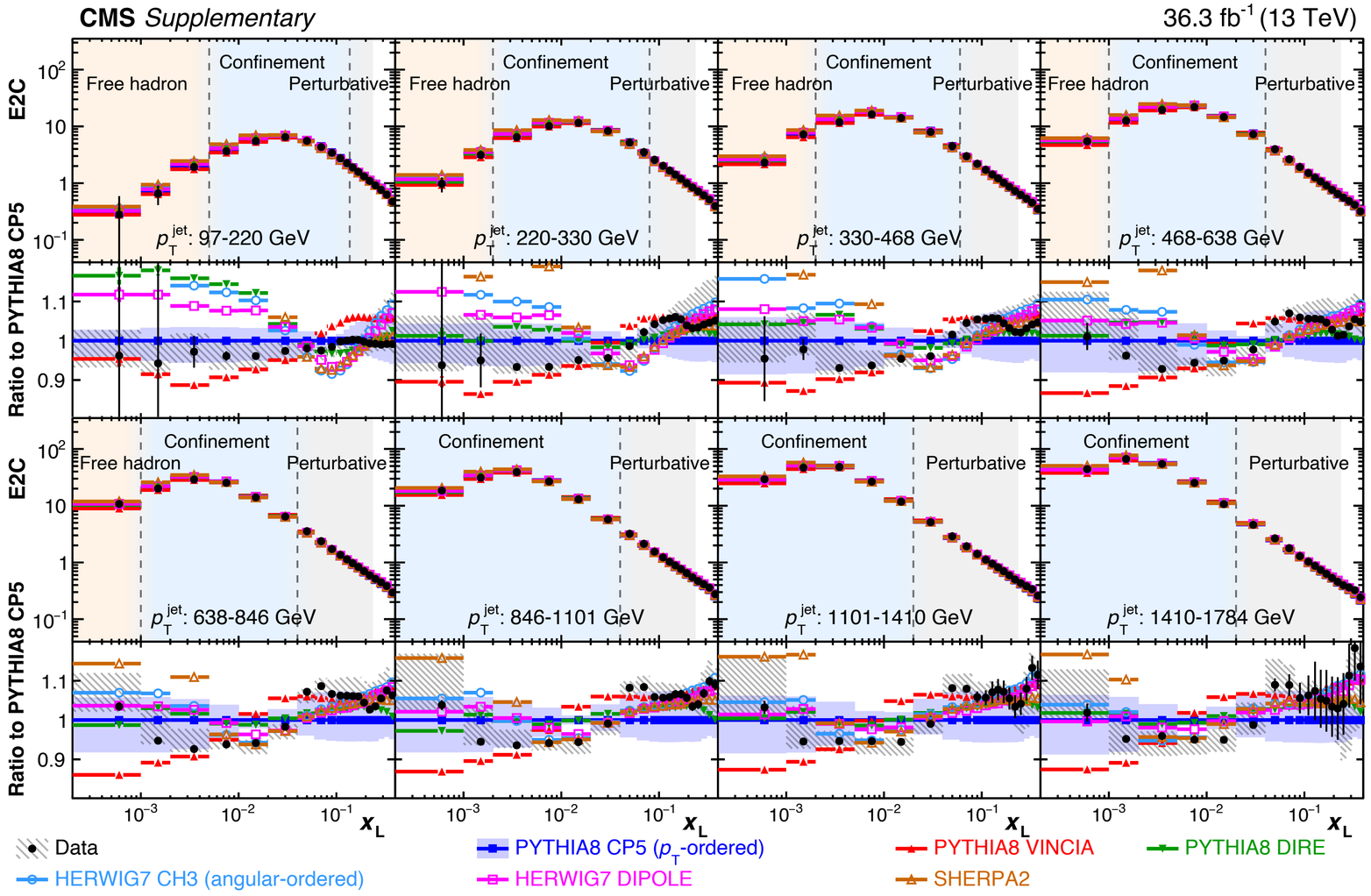
Non-interacting hadron
random distribution
integer power-law scaling

Interacting partons
non-integer scaling

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

EEC vs PS models

CMS, PRL 133 (2024), 071903



97 ~ 1784 GeV

Data vs various parton shower model, difference ~ 10%

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

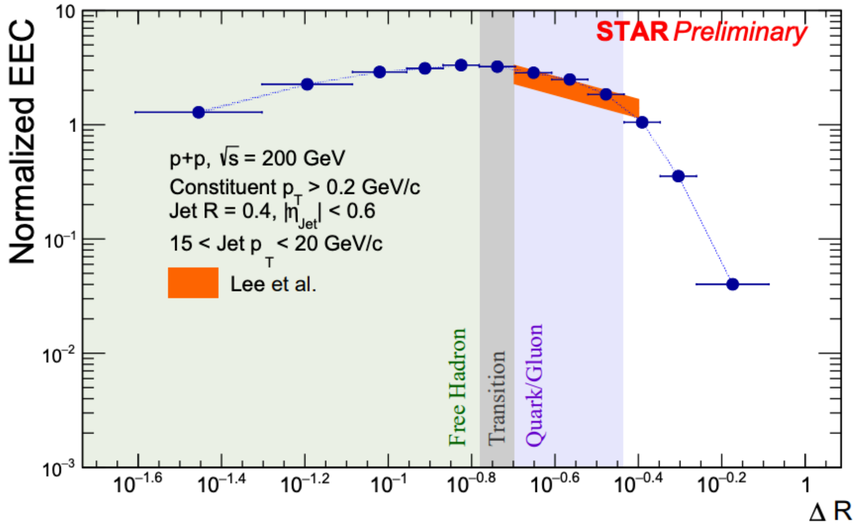
: Data stat error

: Exp systematic

: Theo systematic

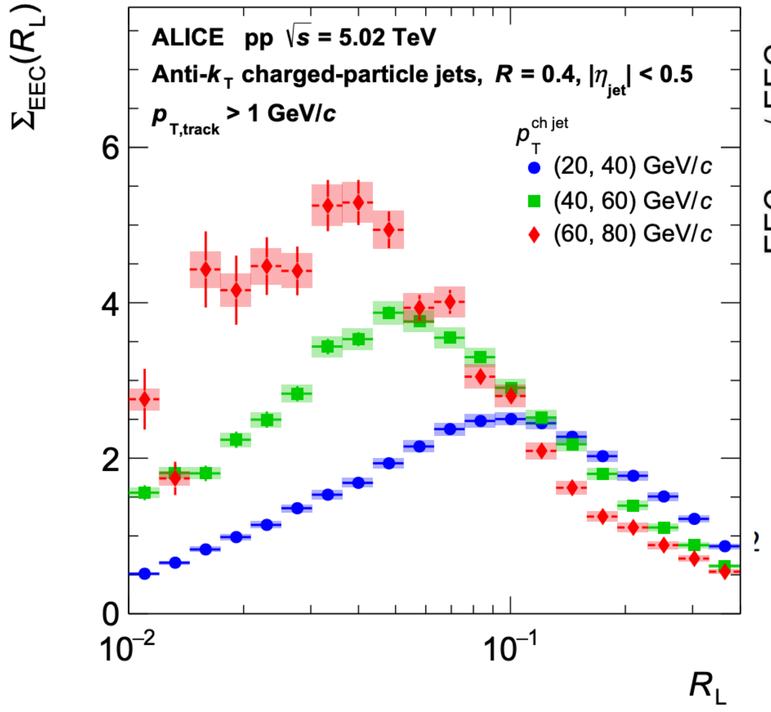
Many EEC measurements ongoing

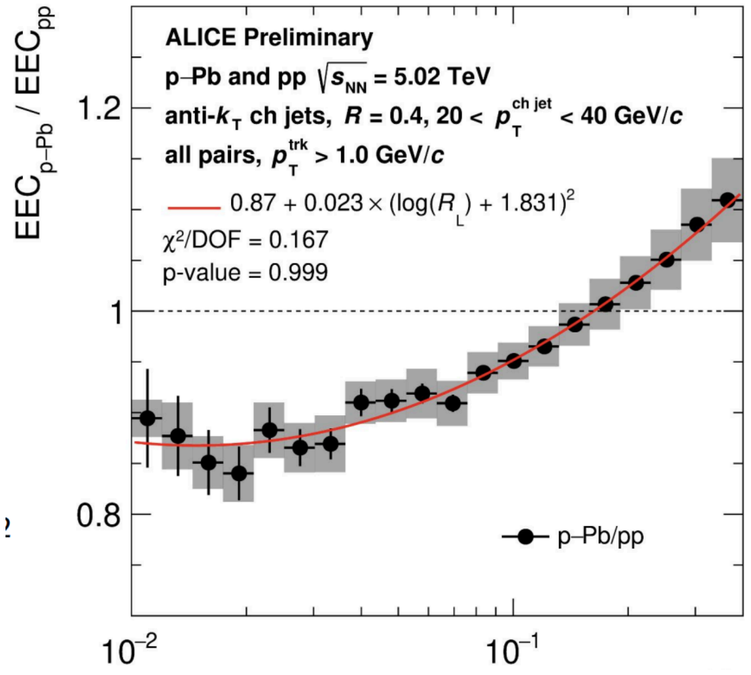
STAR: PoS HP2023 (2024) 175



ALICE pp and pPb

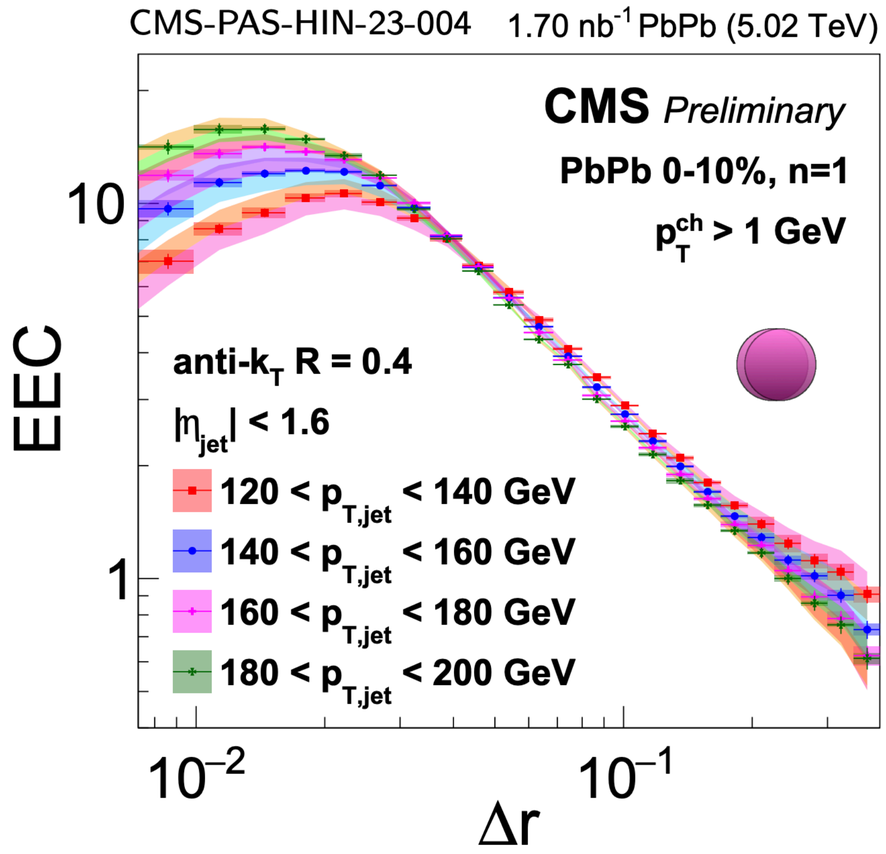
arXiv:2409.12687

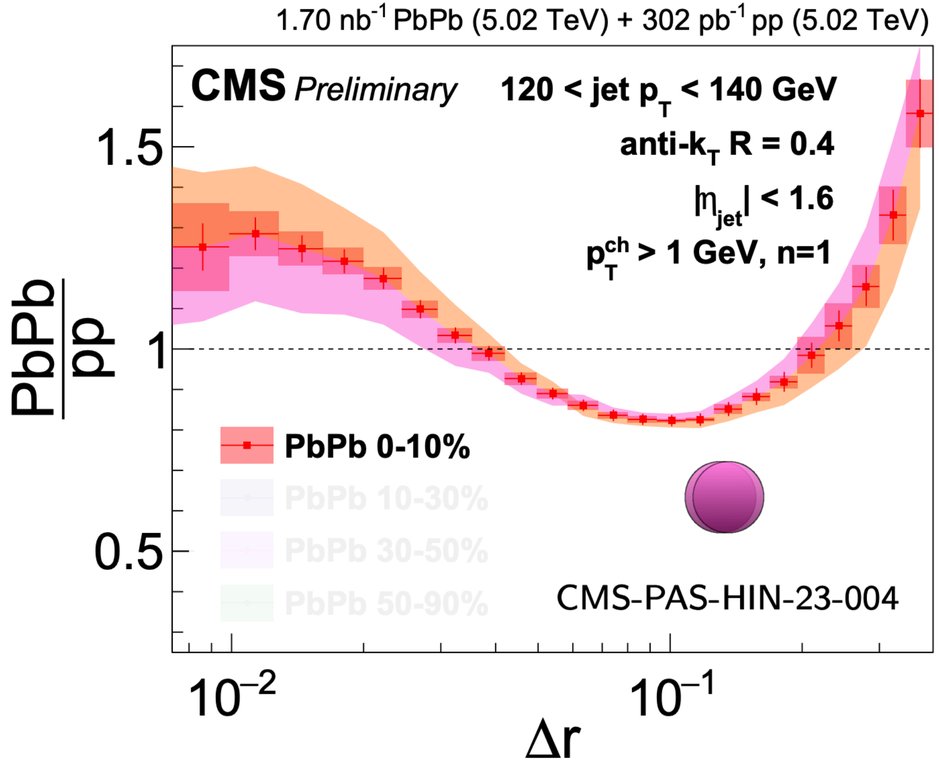




Many EEC measurements ongoing

CMS PbPb, CMS-PAS-HIN-23-004





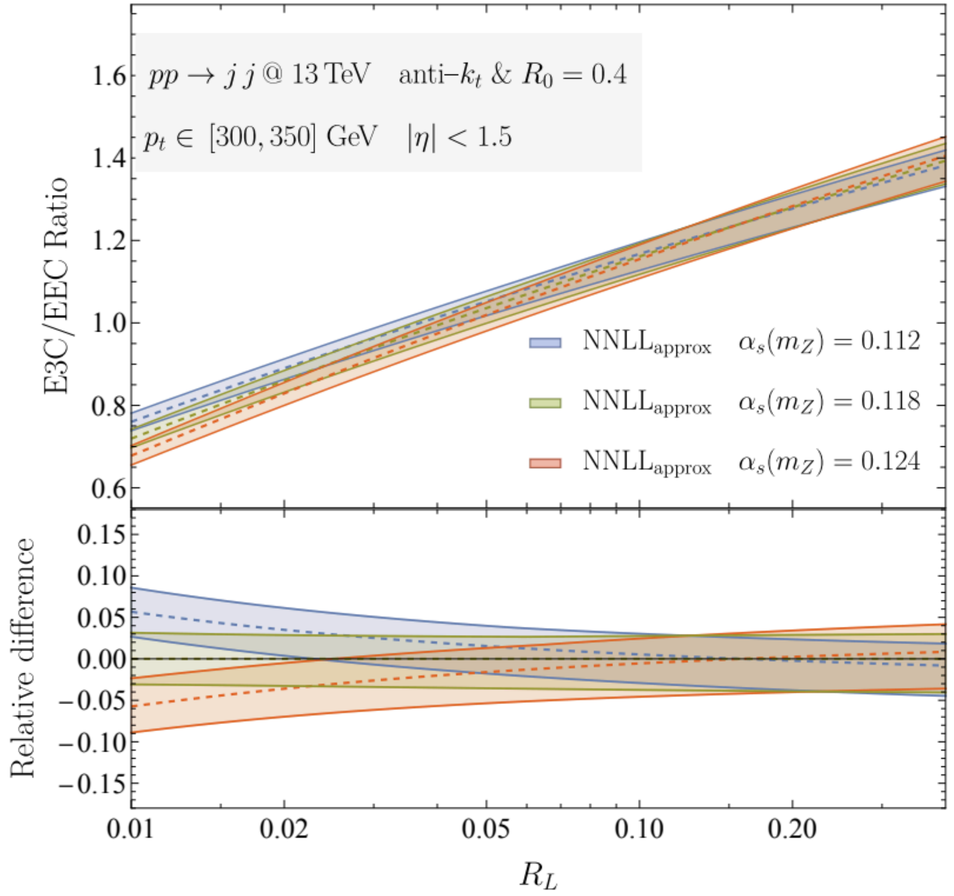
E3C/E2C: a new way to extract α_S

At LL, E3C/E2C is a linear function of α_s

$$\propto \alpha_S(Q)\ln x_L + O(\alpha_s^2)$$

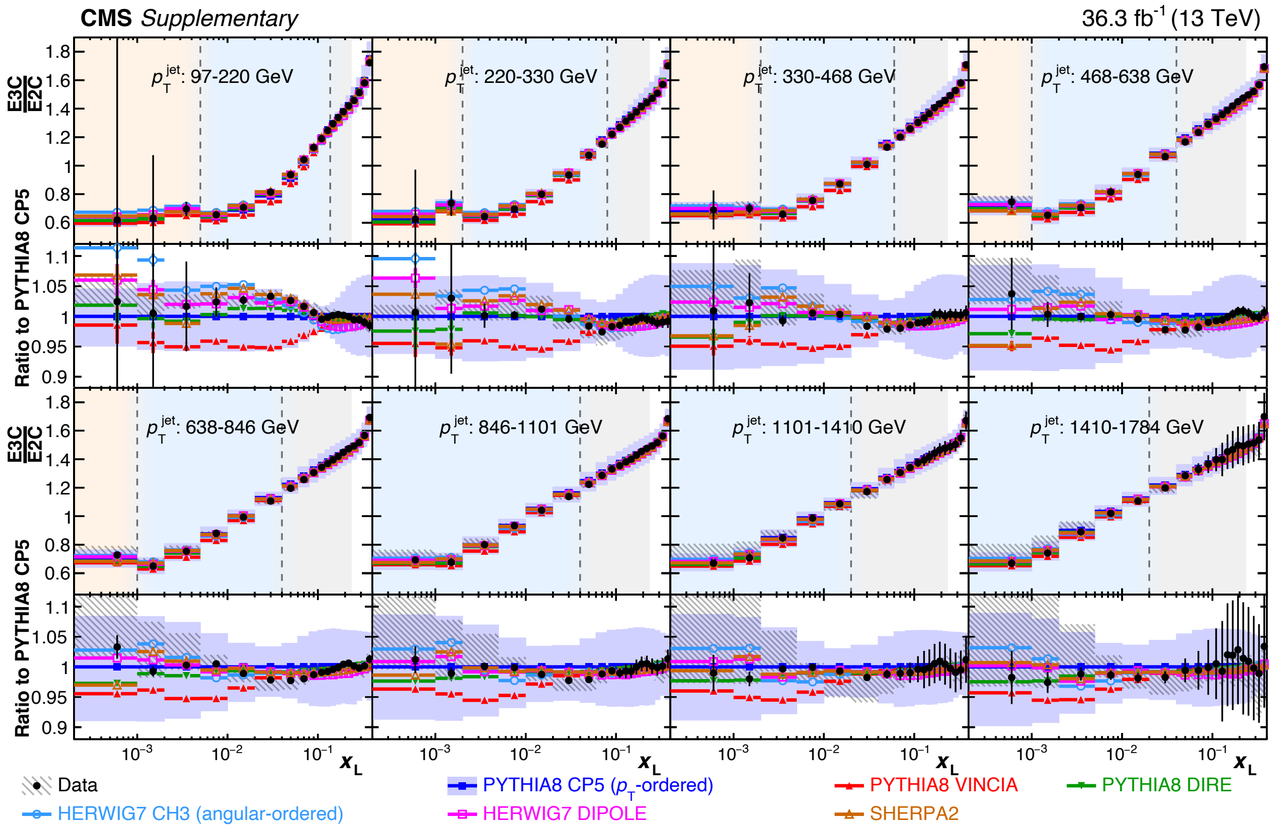
Ci factors enter E3C and E2C and partially cancel

Chen, Gao, Li, Xu, Zhang, Zhu,
arXiv:2307.07510

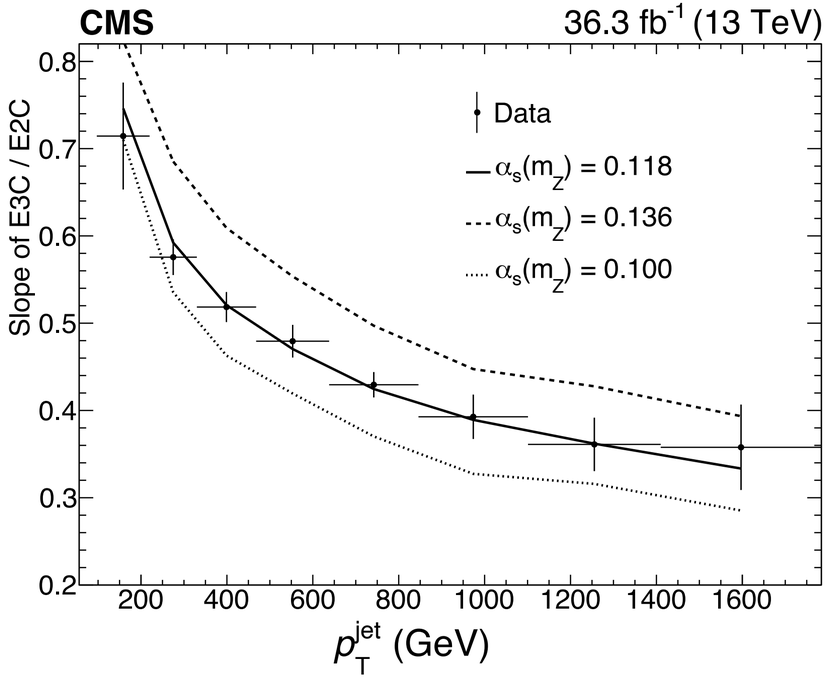


$\alpha_S(M_Z) \uparrow$ Slope $\uparrow$

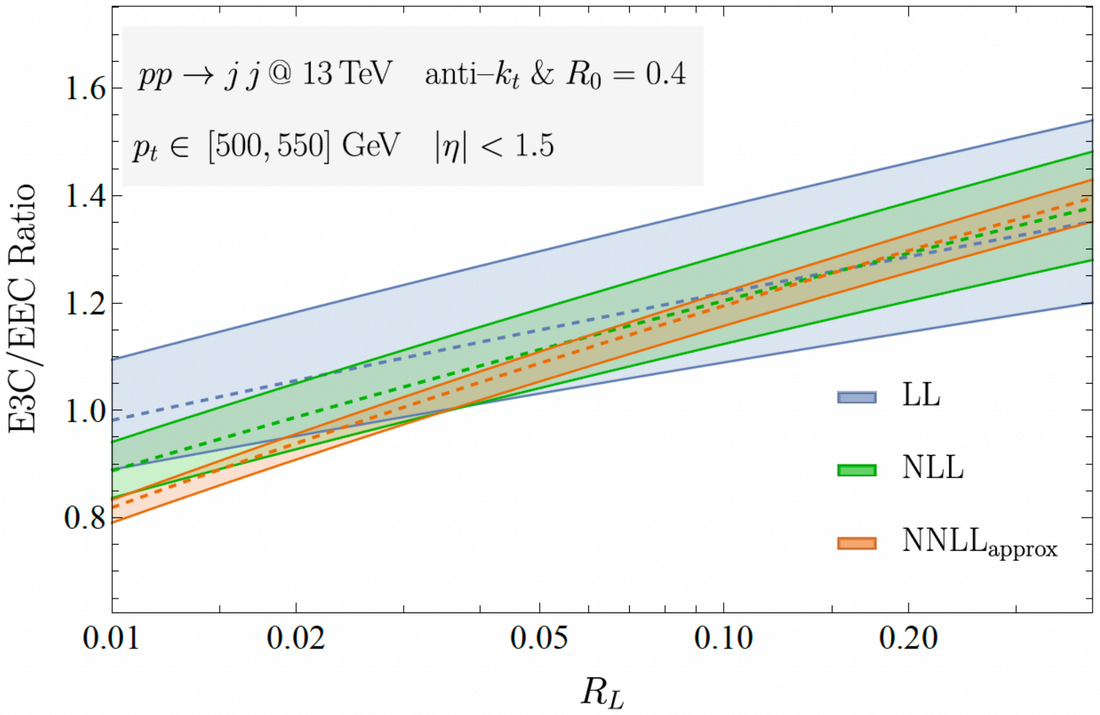
E3C/E2C at different energy scales



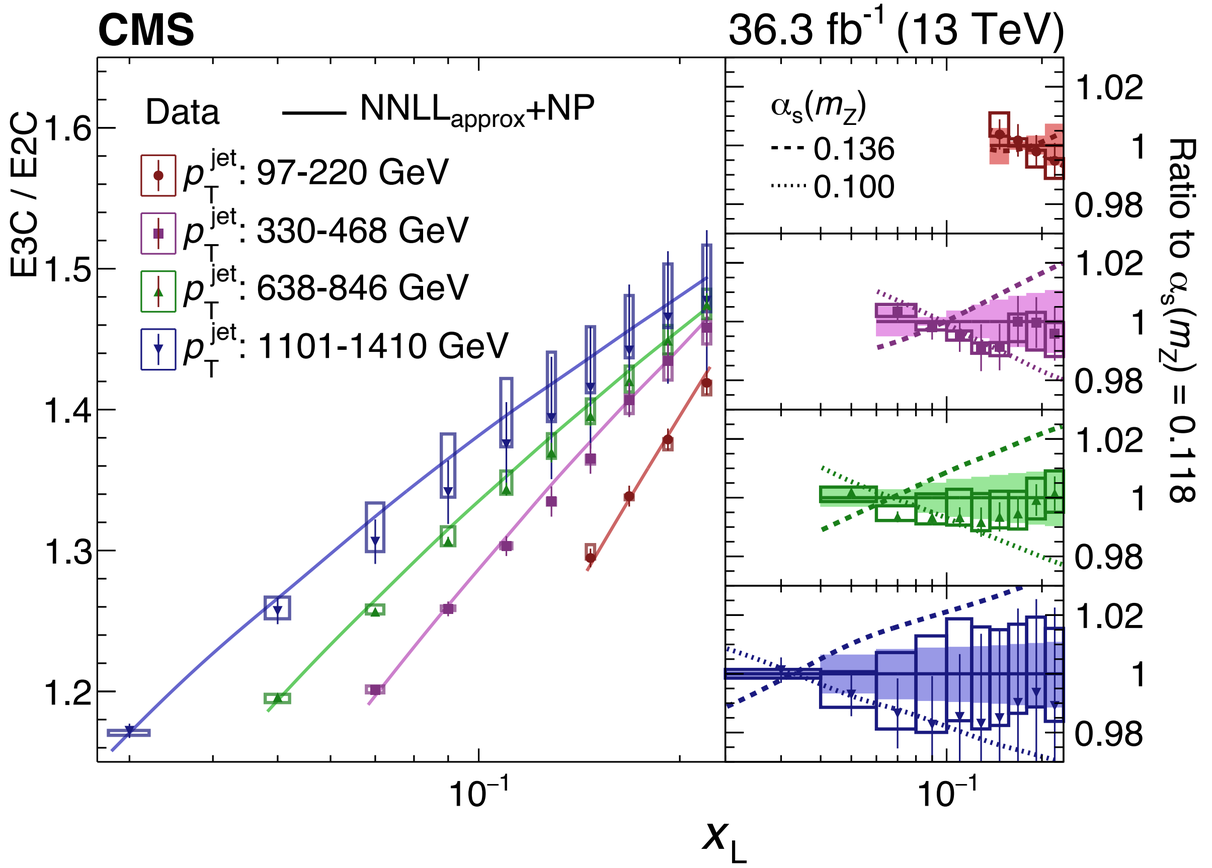
Asymptotic freedom!



E3C/E2C vs NNLL$_{approx}$



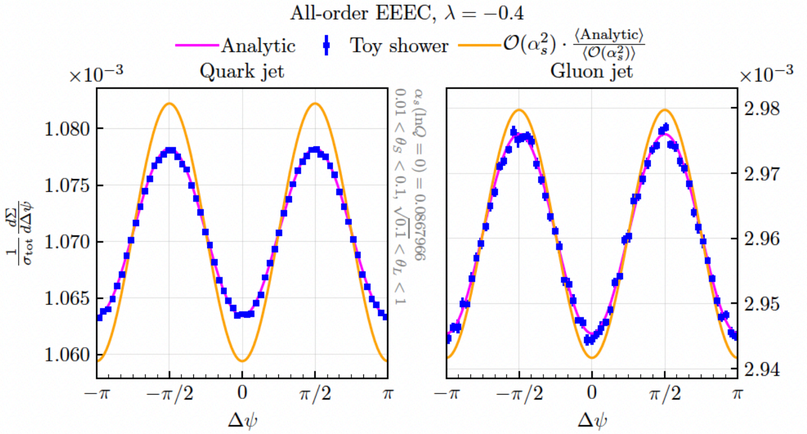
Data agrees with NNLL$_{approx}$ within uncertainty



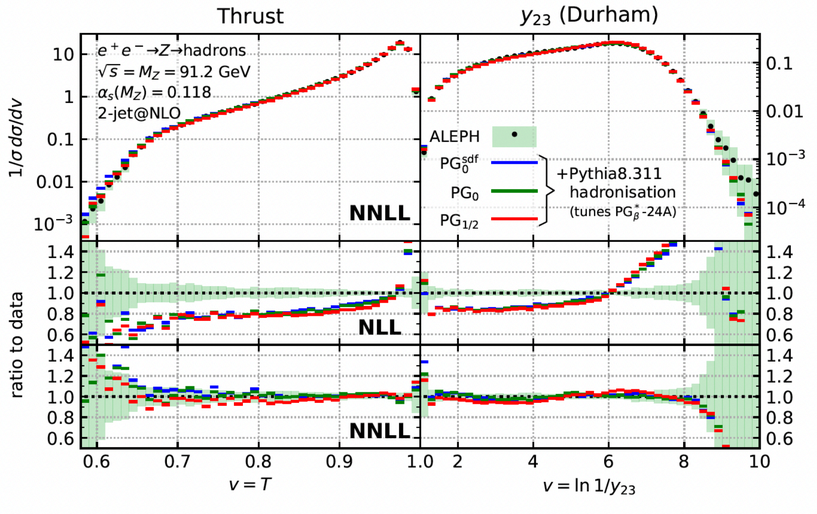
$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$
$$= 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$$

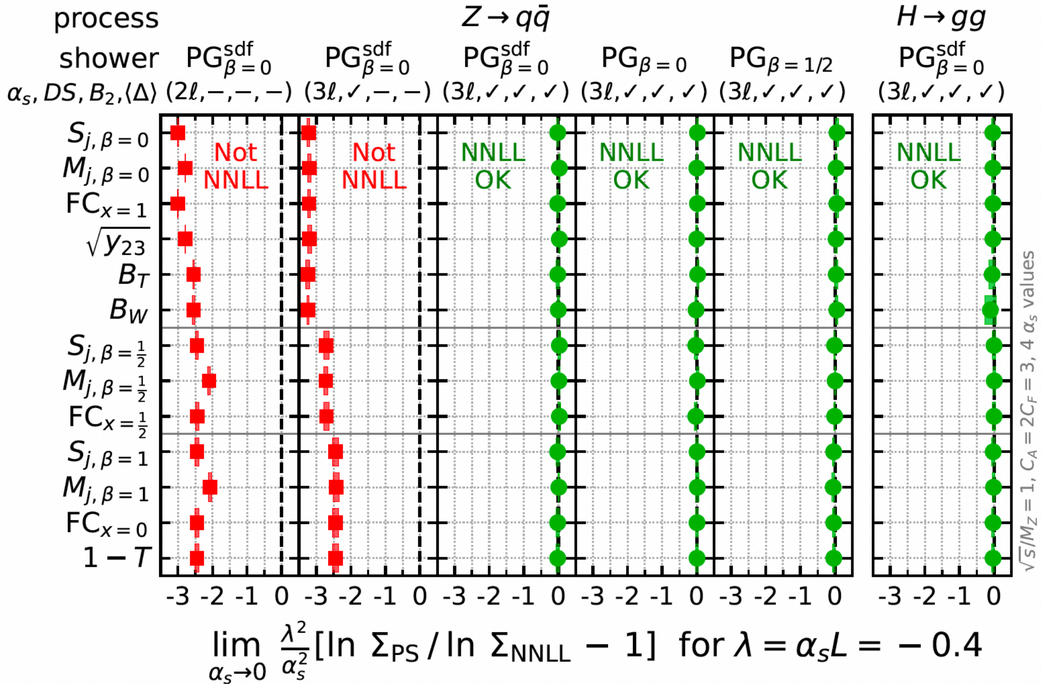
Uncertainty ~ 4%, Q~ O(10) GeV, collinear regime
Most precise from jet substructure to date

What could be done in the future?



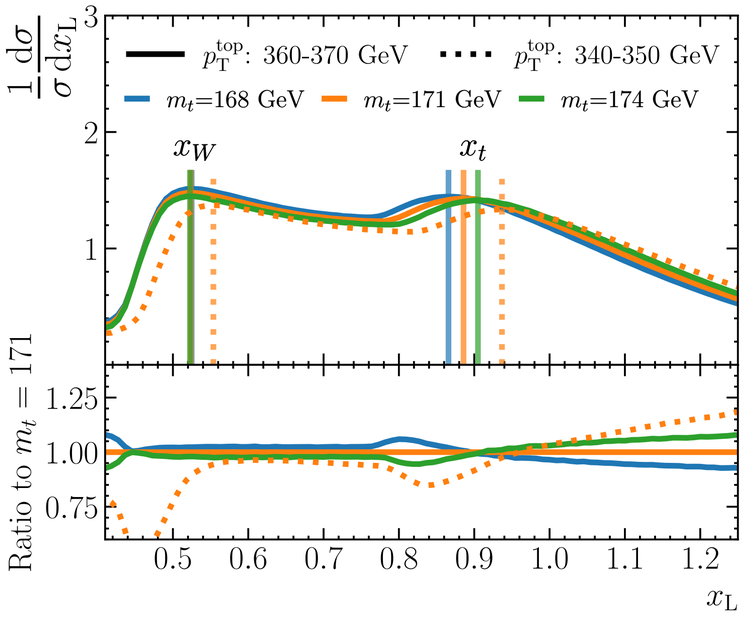
- A lot of developments in PS models
  - Spin correlation in PS
  - Towards NLL and NNLL models, Panscale, Deductor, ALARIC..
- Interesting to be tested experimentally



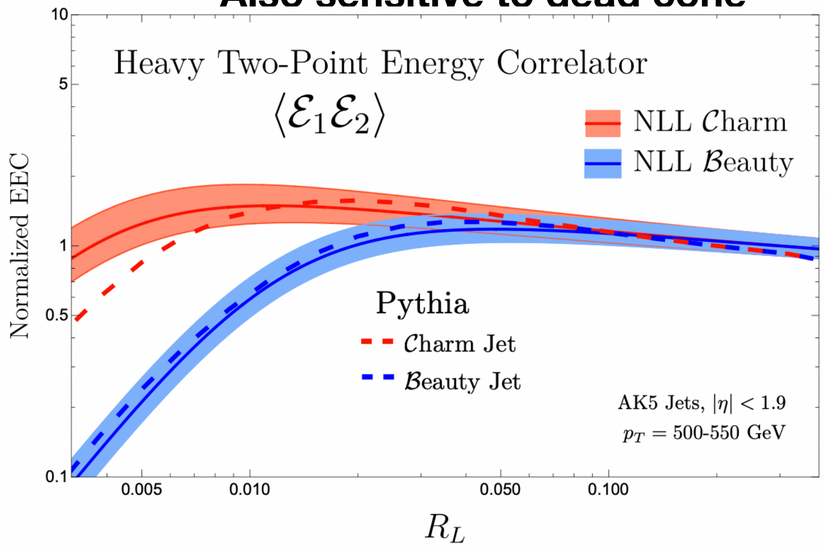


What could be done in the future?

- New ideas of using EEC to probe variety of physics
  - Heavy flavor
  - Confinement
  - Top and W mass measurements

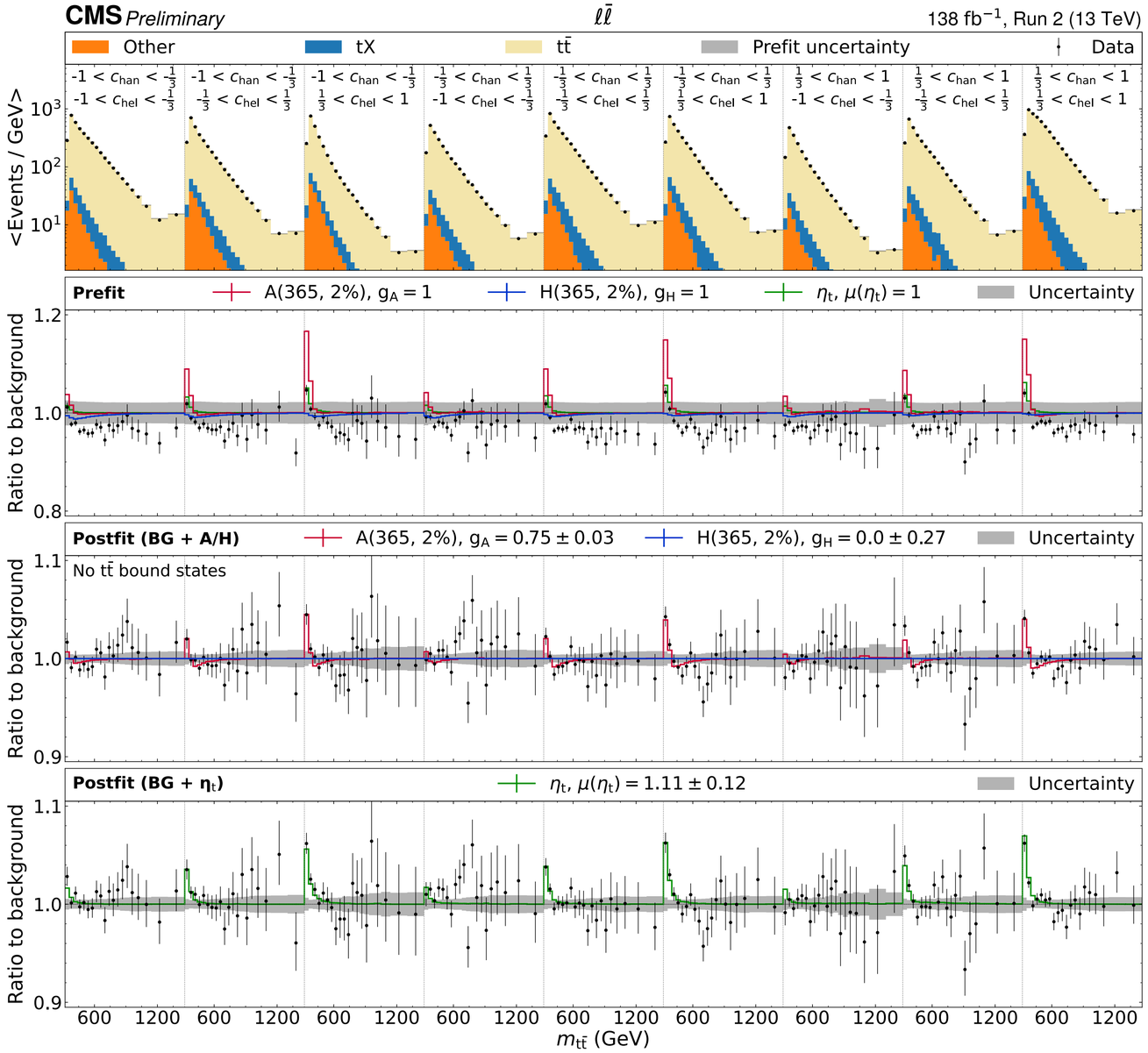


Also sensitive to dead cone



Toponium

CMS-PAS-HIG-22-013



A ttbar bound state with a cross section of 7.1 pb an uncertainty of 11%