EEC plateau height as a precision probe of α_s

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also based on [2507.15923] with Cyuan-Han Chang, Xiaohui Liu, David Simmons-Duffin, Feng Yuan, Hua Xing Zhu

The XXIII Annual Workshop on Soft-Collinear Effective Theory

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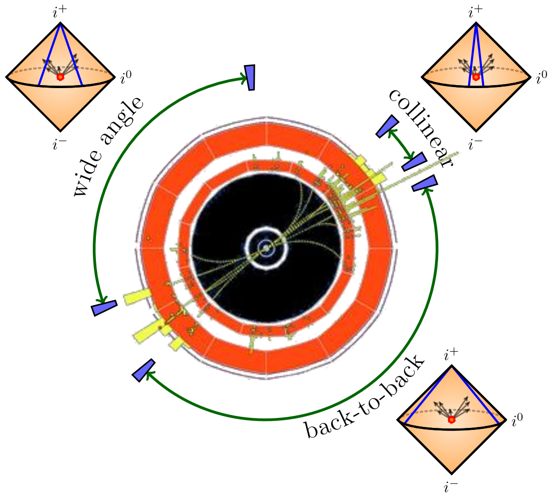
Outline

- Motivation
- Two-step Factorization
- Comparison with Data
- α_s Extraction
- Summary

Motivation

EEC as IR-safe probe

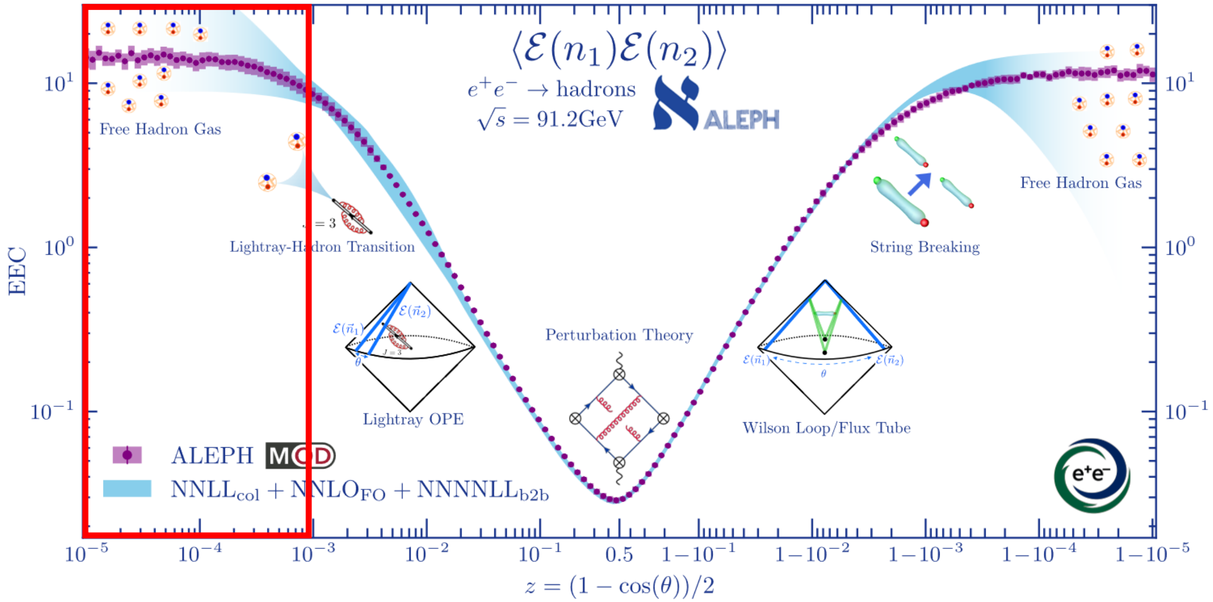
$$\frac{d\Sigma}{d\zeta} = \sum_{i,j} \int d\sigma \frac{E_i E_j}{Q^2} \delta\left(\zeta - \frac{1 - \cos\theta_{ij}}{2}\right)$$



[2511.00149]

Enable precision extractions of QCD parameters

[Jaarsma, Li, Moult, Waalewijn, Zhu, 2512.11950]



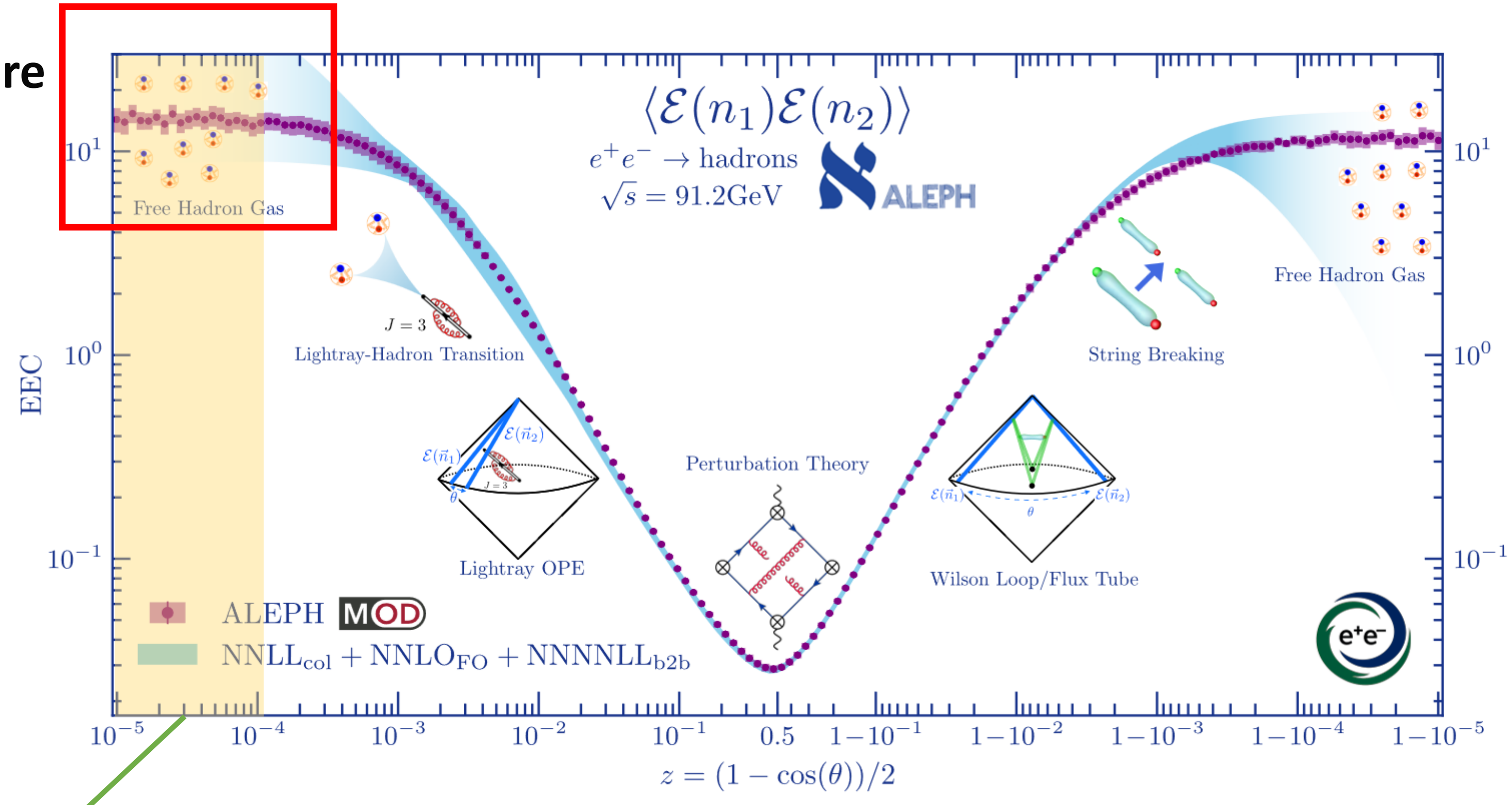
Collinear Limit

[2511.00149]

Reanalysis of Archived LEP Data

Striking New Feature

EEC plateau



$\sqrt{z}Q \ll \Lambda_{\mathrm{QCD}}$

Virtuality evolution

$\sqrt{z}Q \quad \Lambda_{\mathrm{QCD}} \quad Q$

EEC Measurement @LHC

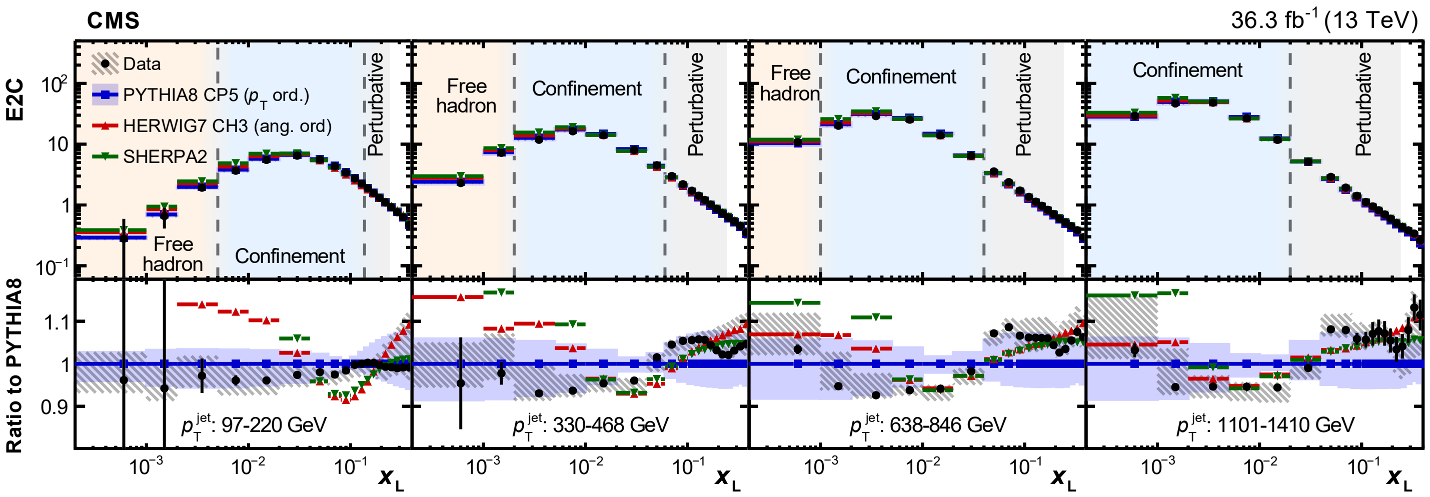
E3C/E2C Slope

[Chen, Gao, Li, Xu, Zhang, Zhu, 2307.07510]

Most precise α_s measurement @ Jet substructure

$\alpha_S(m_Z)$ is $0.1229^{+0.0014}_{-0.0012}(\text{stat})^{+0.0030}_{-0.0033}(\text{theo})^{+0.0023}_{-0.0036}(\text{exp})$

CMS [2402.13864]



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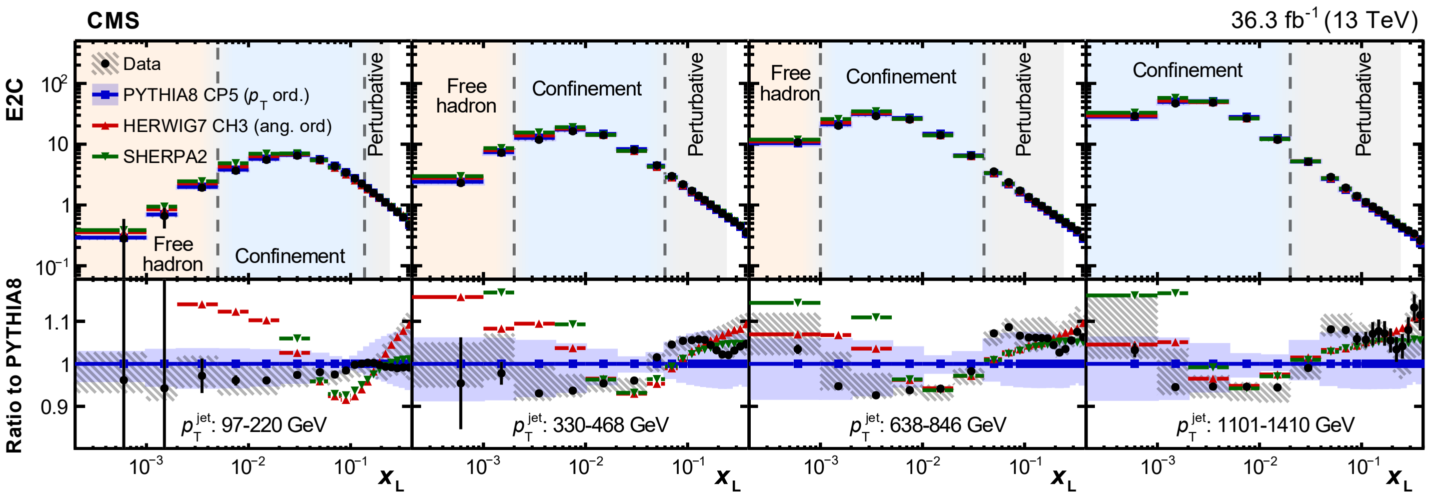
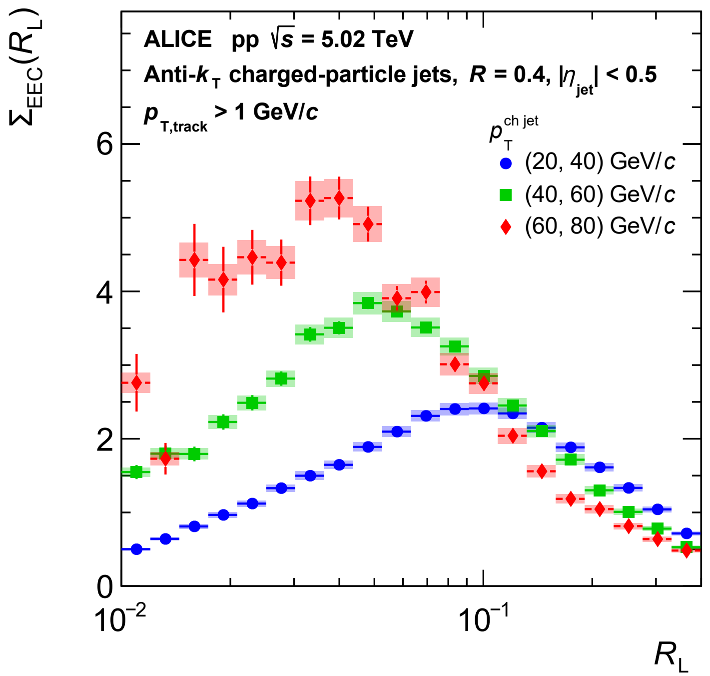




[2409.12687]

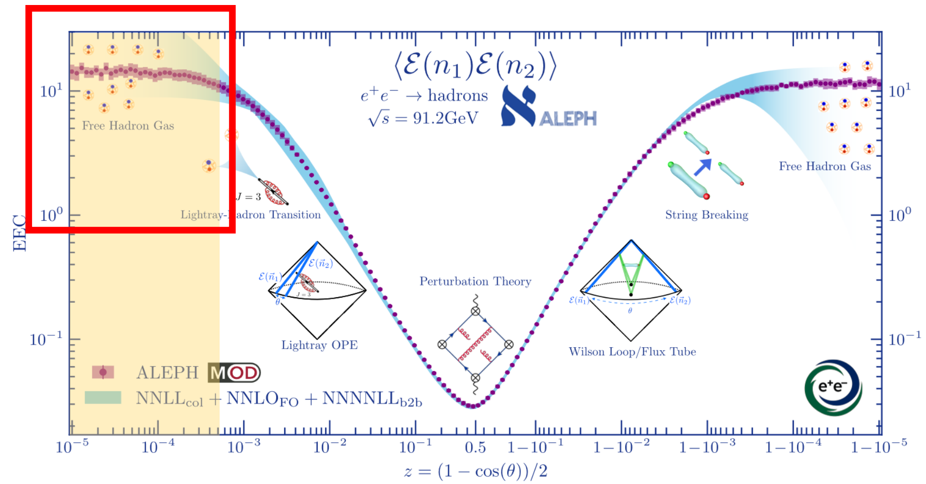
Track-based EEC @ALICE

Dramatically higher angular resolution @ $\sqrt{z}Q \ll \Lambda_{QCD}$

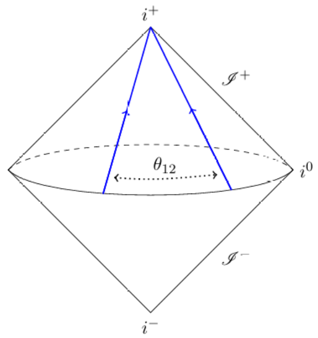
Two equivalent approaches :

Collinear Limit

EEC plateau



Light-ray operator product expansion



[Hofman, Maldacena, 0803.1467; Kologlu, Kravchuk, Simmons-Duffin, Zhiboedov, 1905.01311; HC, Moult, Zhu, 2020; …]

Dihadron fragmentation function

[Lee, Stewart, 2507.11495; Kang, Metz, Pitonyak, Zhang, 2507.17444; Herrmann, Kang, Penttala, Zhang, 2507.17704; Guo, Yuan, Zhao, 2507.15820]

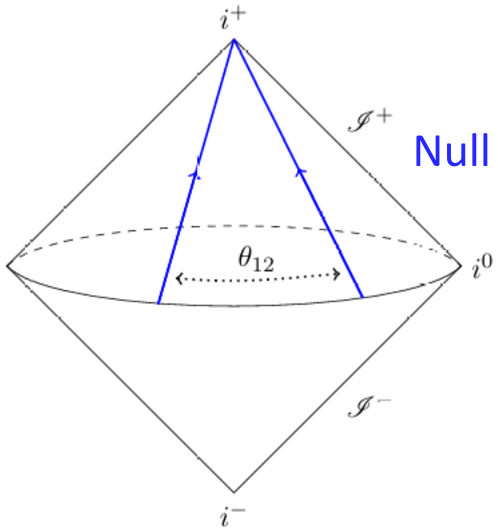
Light-ray operator

Light transform $\lim_{r\to\infty} r^2 \int_0^\infty dt$

Light-ray operator

Local operator

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



	Local operator	Light-ray operator
dimension	Δ	$-\Delta_L = J - 1$
spin	J	$J_L = 1 - \Delta$
twist	$\tau = \Delta - J = -\Delta_L - J_L$	

$T_{\mu\nu}$	$\mathcal{E}(\vec{n})$	$\mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)$
$\Delta = 4$	$\Delta_L = 1$	$\Delta_L = 2$
$J = 2$	$J_L = -3$	$J_L = -6$

Two-step Factorization

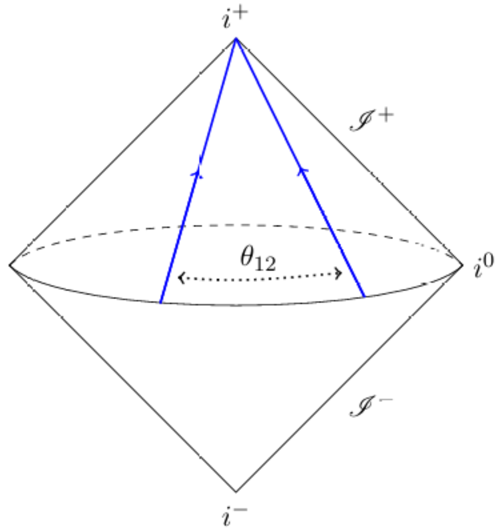
1. physical detector -----> composite hadronic operator

EEC plateau region $\sqrt{z}Q \ll \Lambda_{\mathrm{QCD}}$

$$\underline{\mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)} \sim z^0 \boxed{\mathbb{O}^H_{-6,k}} + z^1 \mathbb{O}^H_{-8,k} + \ldots$$

$J_L = -6$

leading contribution with $J_L = -6$



Two-step Factorization

2. hadronic operator -----> DGLAP operator

hadronic operator $J_L = -6$

↓ operator matching

Light-ray spin conservation

DGLAP operator $J_L = -6$

Twist-2 operator —Light transform→ DGLAP operator

DGLAP operator

$$J = -\Delta + 1 = (\underbrace{-\tau}_{\text{Twist-2}} + J_L) + 1 = -1 + J_L = 5$$

Obey J=5 DGLAP Evolution

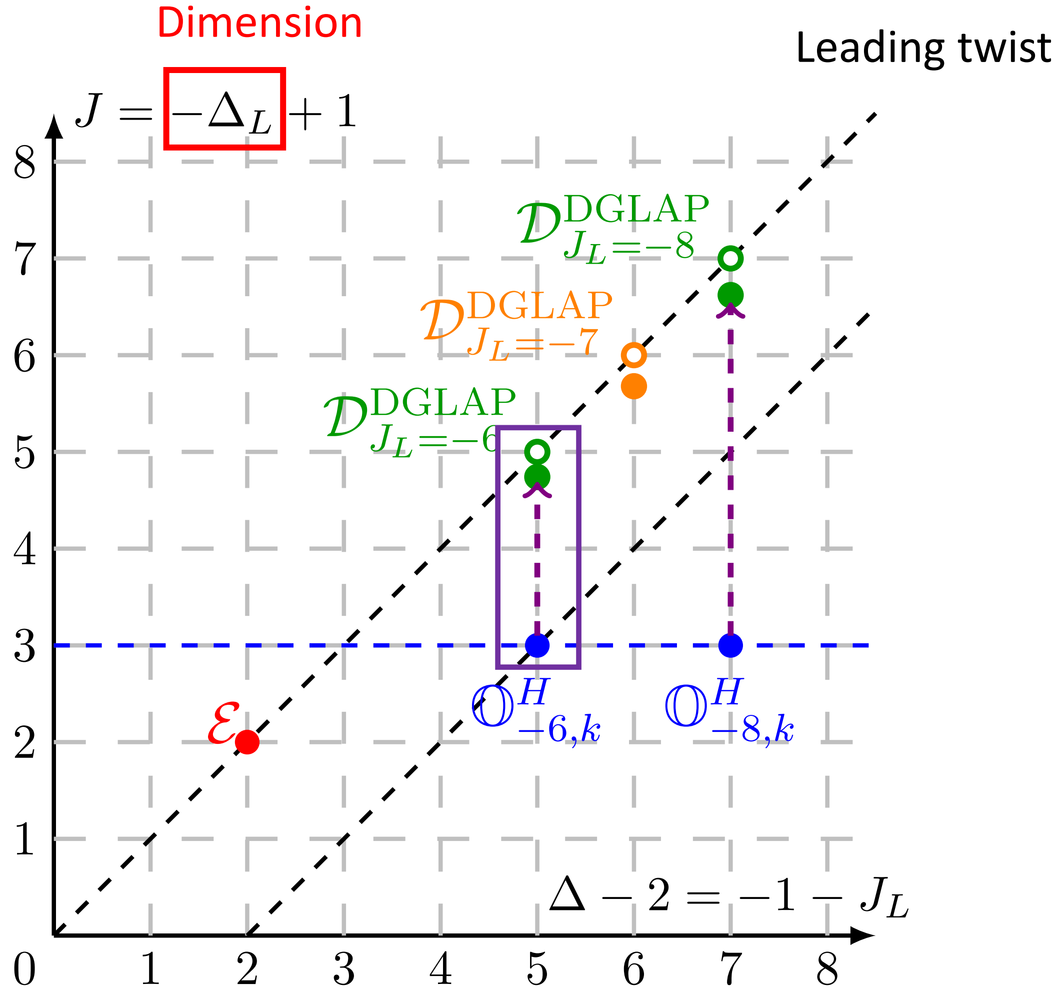
Two-step Factorization

2. hadron detector -> DGLAP operator

DGLAP operator dimension 4

Matching

hadronic operator dimension 2



Two-step Factorization

2. hadron detector -> DGLAP operator

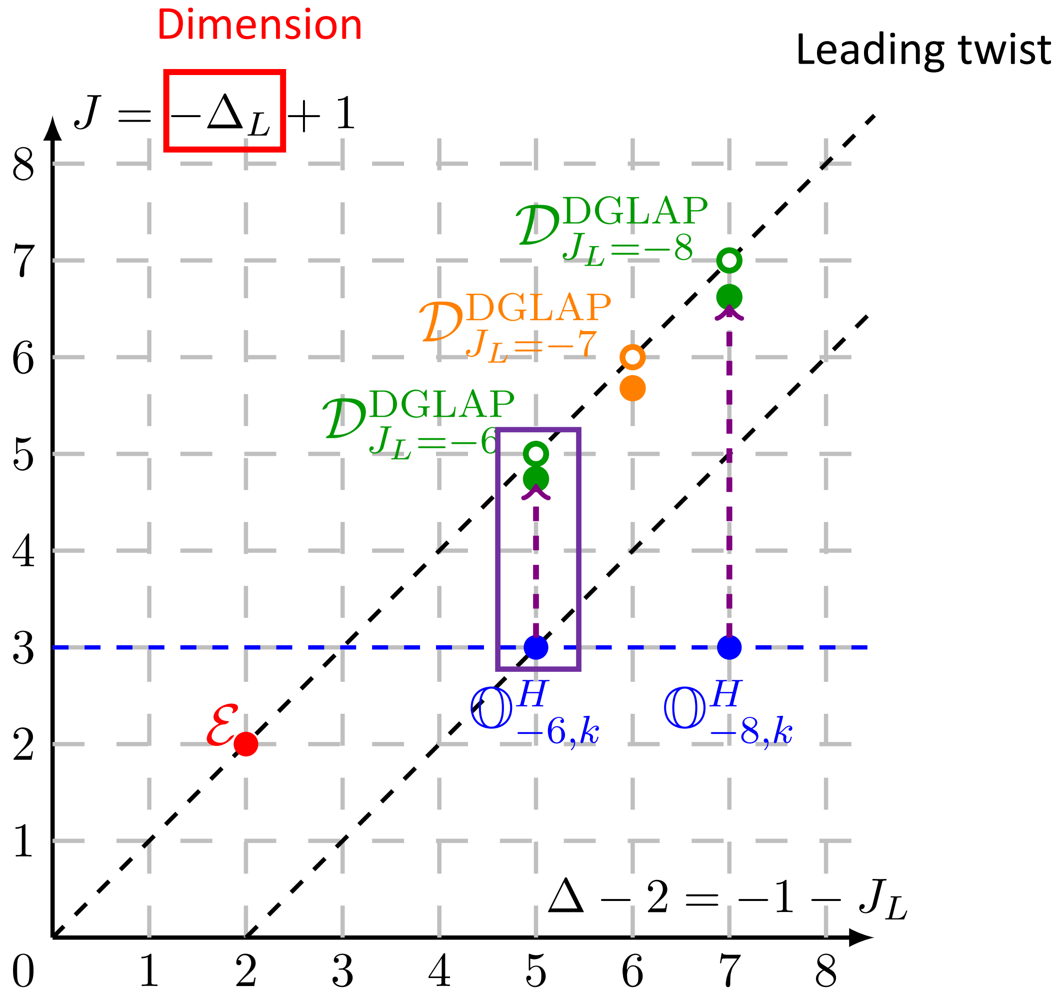
Classical Scaling $\frac{Q^2}{\Lambda_{\mathrm{QCD}}^2}$

DGLAP operator dimension 4

Matching

hadronic operator dimension 2

Matching coefficients scale as $\frac{1}{\Lambda_{\mathrm{QCD}}^2}$



Perturbative Accuracy

Perturbative Evolution: 3-loop time-like DGLAP evolution, 4-loop in progress

[He, Xing, Yang, Zhu, 2025]

[Magerya, Fekésházy, 2503.19837;
Falcioni, Herzog, Moch, Vogt, 2307.04158]

e^+e^- annihilation: $\mathrm{N^3LO_{QCD}}$ hard function

[He, Xing, Yang, Zhu, 2503.20441]

pp collision NNLO hard function

[Czakon, Generet, Mitov, Poncelet 2025; NNLOJET from Gehrmann's group, 2025]

ep collision @EIC: $\mathrm{N^3LO_{QCD}}$ hard function

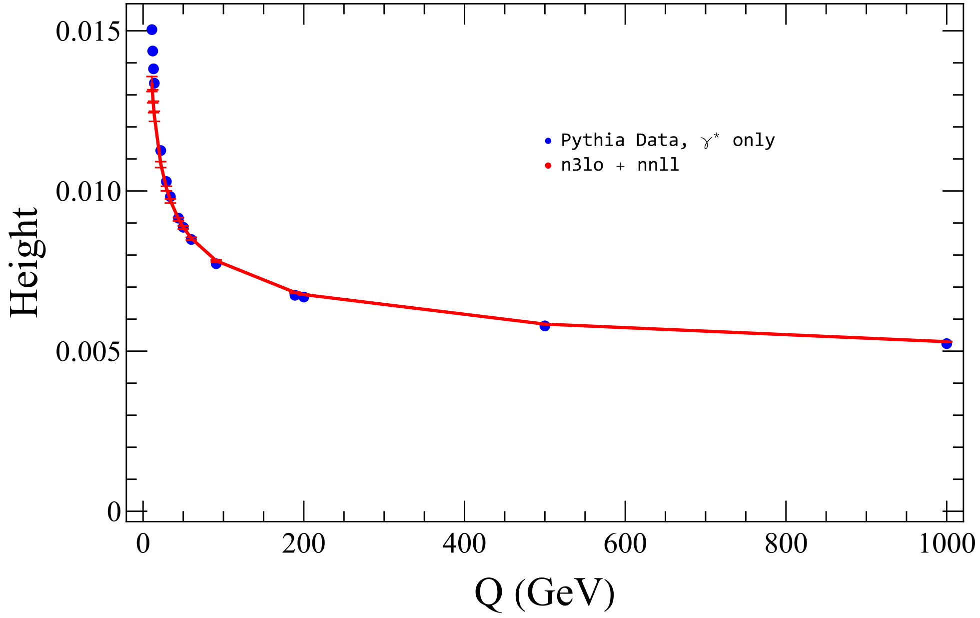
[Moch, Vermaseren, Vogt 2004]

Comparison with Pythia Simulation

$$\mathcal{H}(Q) = \sum_{i=q,g} \sigma_i^{(5)}(Q,\mu) C_i(\mu)$$

$$\mathbf{N3LO + NNLL}$$

$$\sigma_i^{(5)} = \int x^4 \hat{\sigma}(x) dx$$



Fix $\alpha_s(M_Z)$ and Fit the C at 50 GeV

J=5 DGLAP Evolution

$$\frac{dC_i(\mu)}{d\ln\mu^2} = -\hat{\gamma}_{T,ij}\, C_j(\mu) \qquad \gamma_{T,ij} = -\int_0^1 dx\, x^4\, \hat{P}_{ij}(x)$$

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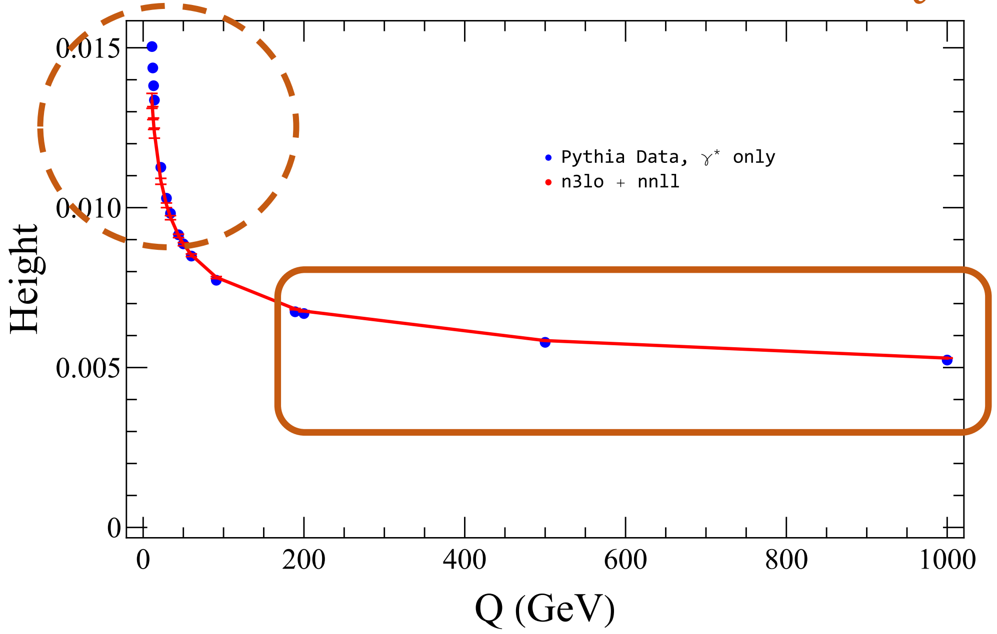
need power correction as $\frac{1}{Q^2}$



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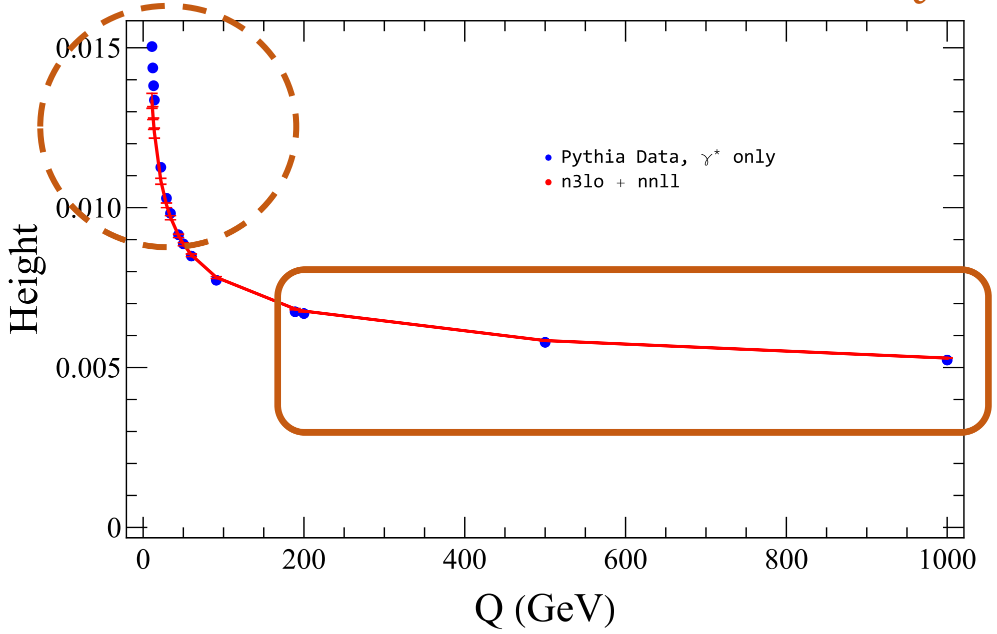
Comparison with Pythia Simulation

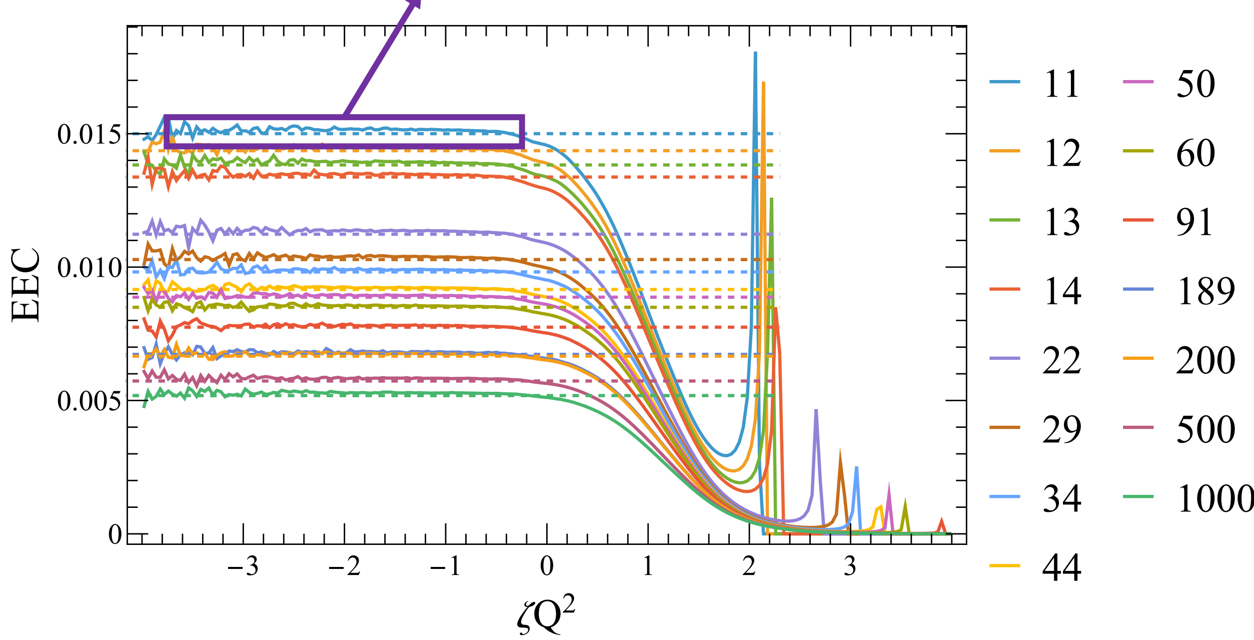
$$\mathcal{H}(Q) = \sum_{i=q,g} \sigma_i^{(5)}(Q,\mu) C_i(\mu) + \frac{\Omega}{Q^2}$$

Twist-4 power correction

need power correction as $\frac{1}{Q^2}$



Good agreement @11 GeV



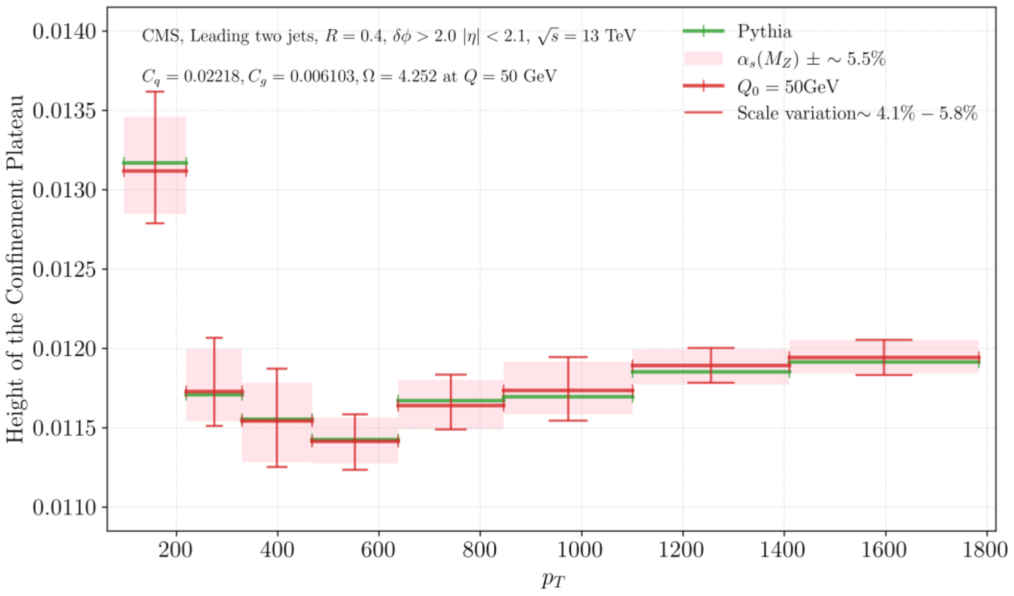
Comparison with Pythia Simulation

Pythia simulations performed with the same kinematic setup as CMS and ALICE

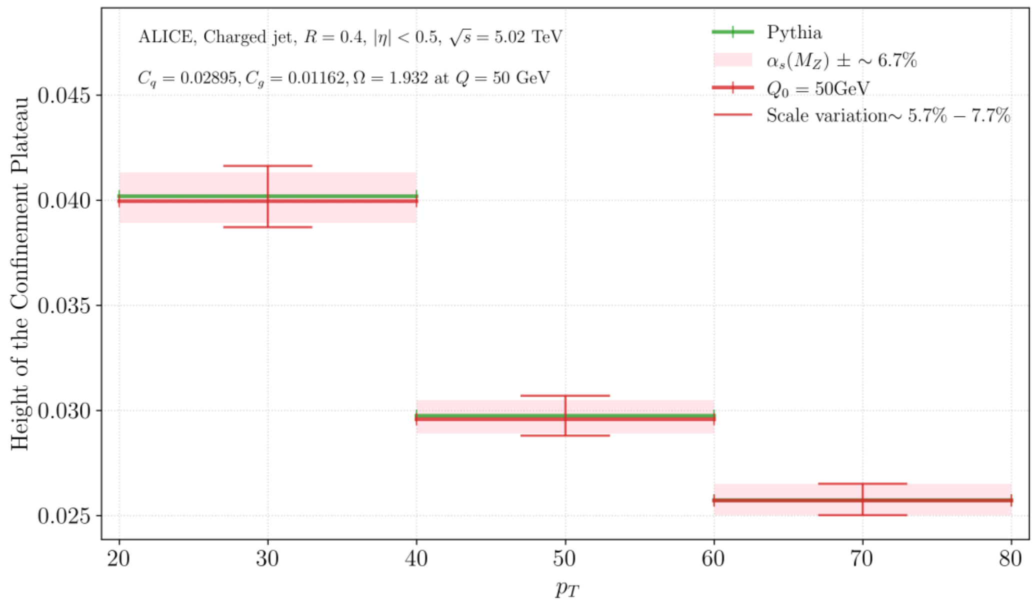
$\alpha_s(M_z)$ (around 0.118) varied to cover the **scale variation uncertainty band**

NLO + NNLL [FMNLO & MadGraph; Liu, Shen, Zhou, Gao, 2305.14620]

Full-hadron dijet



Charged jet



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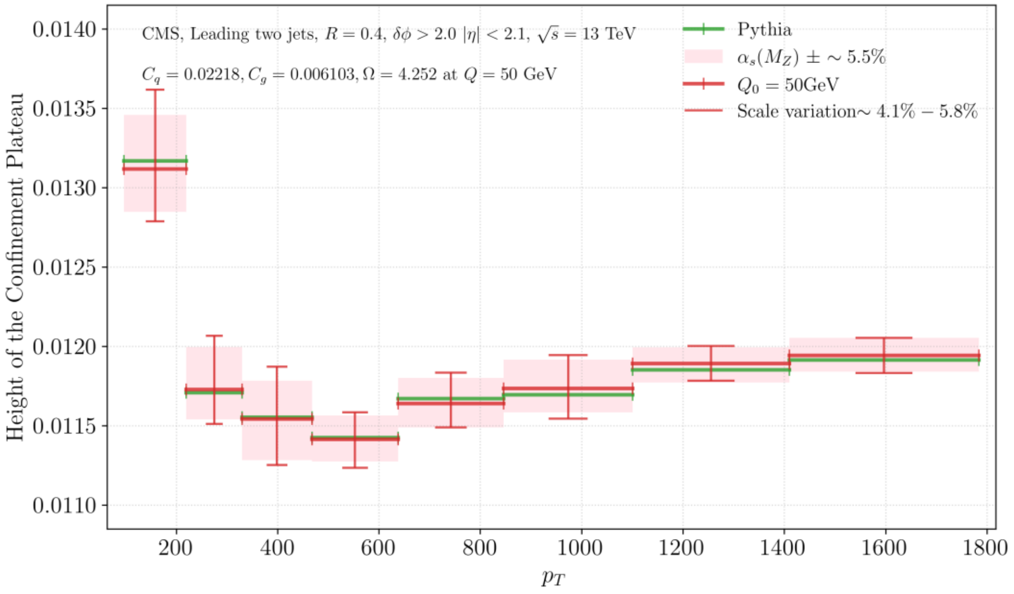


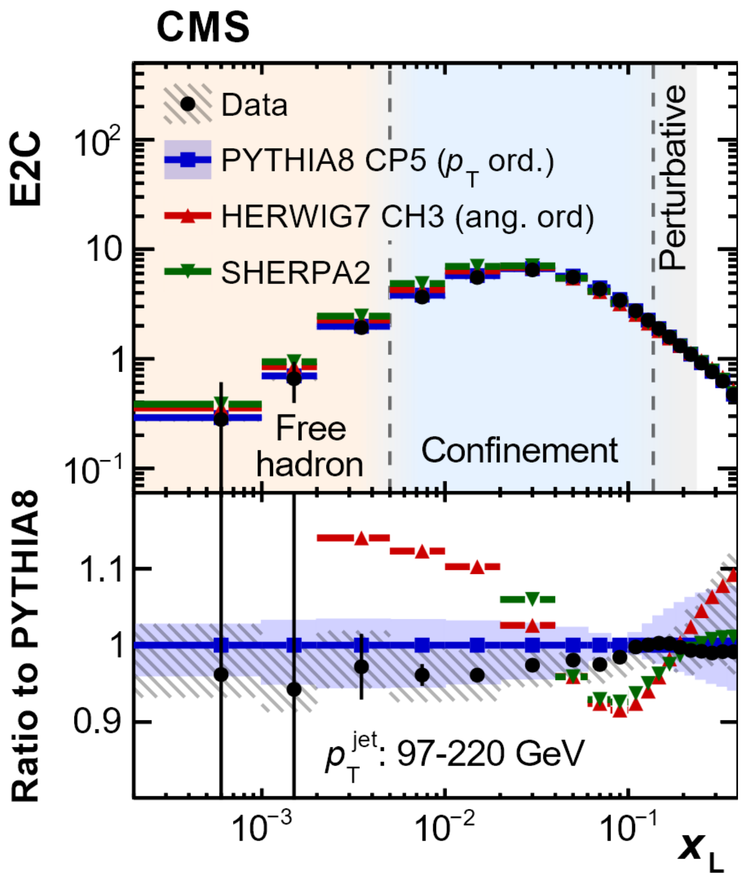
e^+e^- annihilation:

$C_q = 0.02493 \quad C_g = 0.006902$

pp collision

$C_q = 0.02218 \quad C_g = 0.006103$

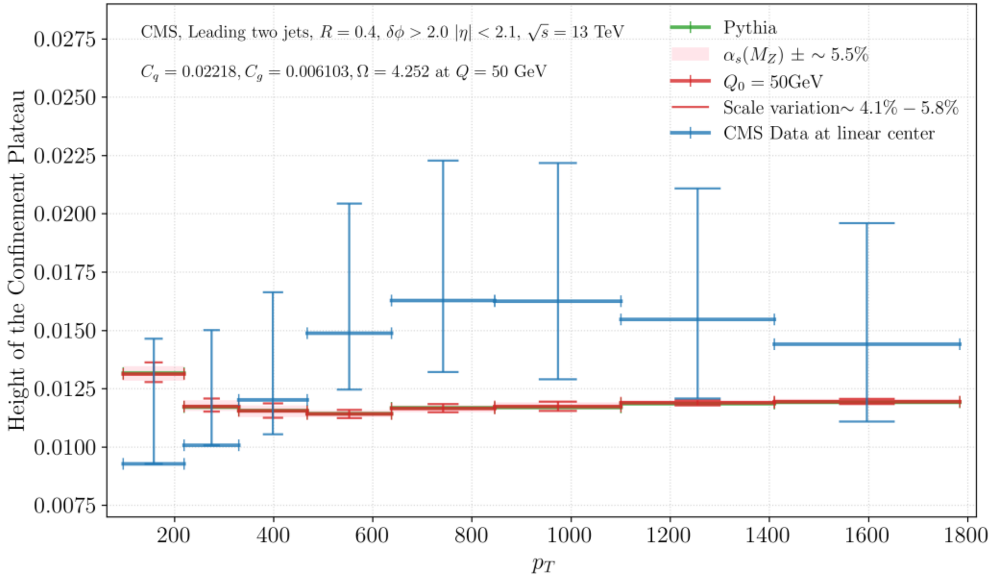
Comparison with Measurements @LHC



[2402.13864]

Strip off Classical Scaling

$$R_L \Rightarrow p_T^2 R_L^2$$



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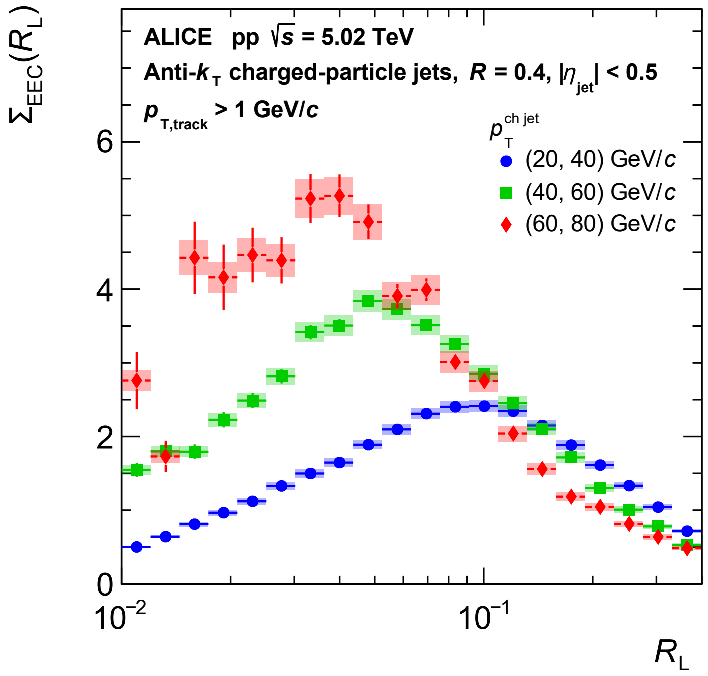

[2409.12687]

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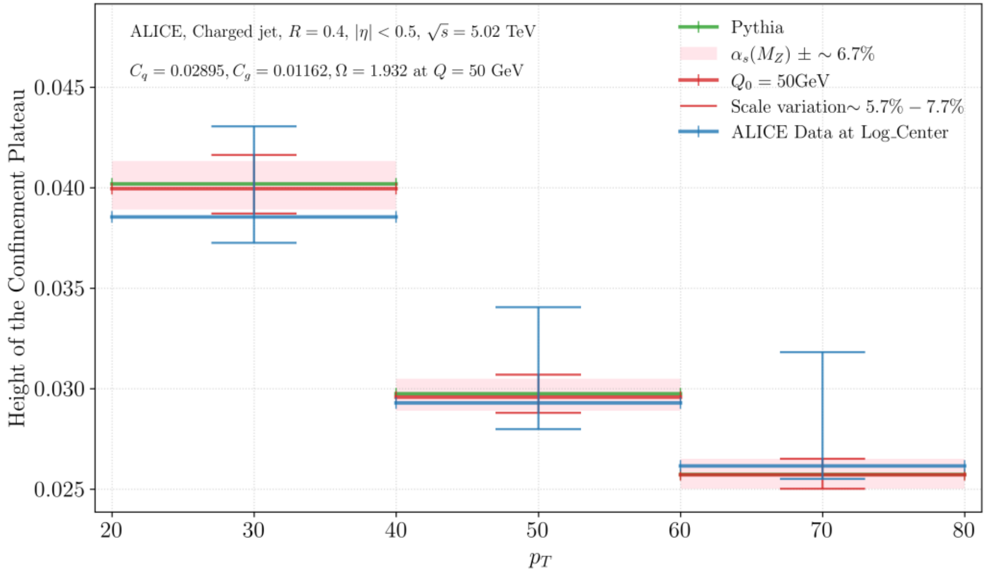
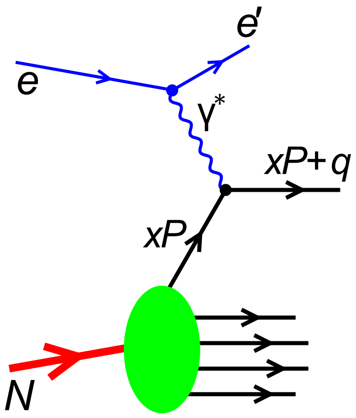
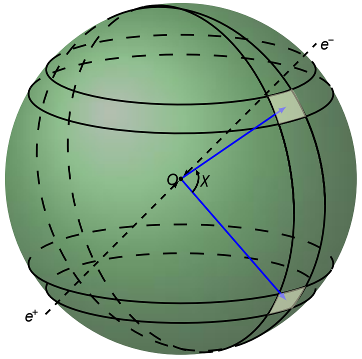


Finite p_T and R_L bins → Solution → Higher angular resolution



α_s Extraction



PDF vs EEC plateau

Non-perturbative Input + Perturbative Evolution

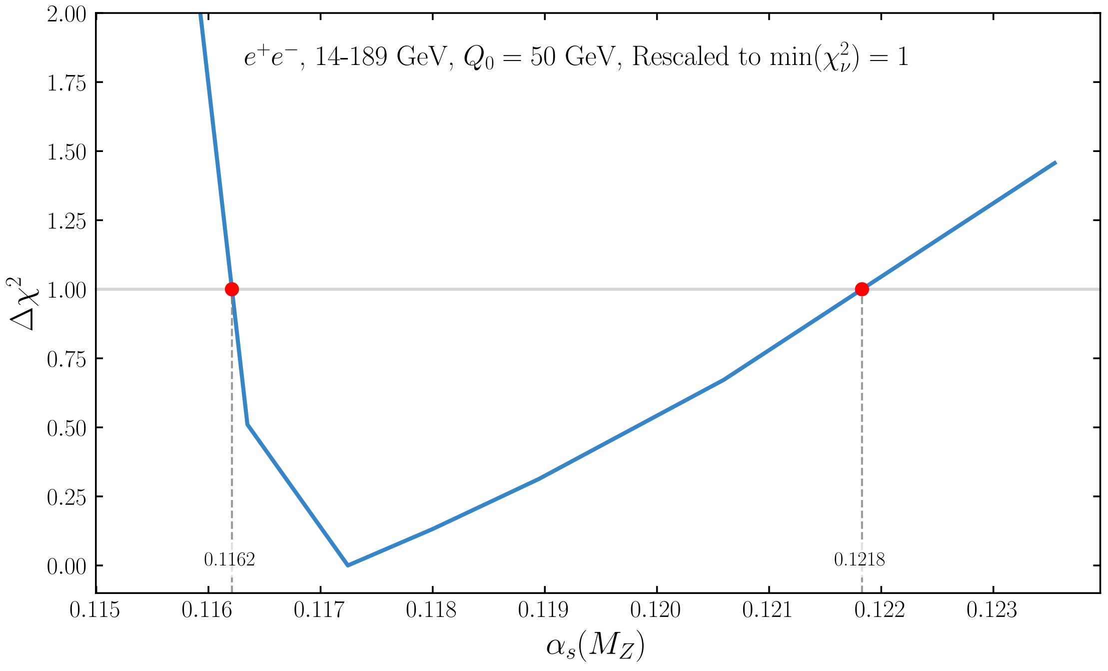
	PDF	EEC plateau
Perturbative	$\hat{\sigma}$	$\sigma_i^{(5)} = \int x^4 \hat{\sigma}(x) dx$
Initial input	$f_i(x, \sim 1\mathrm{GeV})$	$C_i(\mu_0)$
Evolution	Space-like DGLAP	J = 5 Time-like DGLAP
α_s determination	**Global χ^2 Fit**	**Global χ^2 Fit**
	State-of-the-art	

α_s Sensitivity

$$\chi^2(\boldsymbol{\theta}) = \sum_{i=1}^{N} \frac{\left[y_{i,\text{sim}} - y_{i,\text{theo}}(\boldsymbol{\theta})\right]^2}{\sigma^2_{\text{stat},i}}$$

Statistical error in height extraction

Three-Parameter $\{\boldsymbol{C_q}, \boldsymbol{Cg}, \boldsymbol{\Omega}\}$ and $\alpha_s(M_Z)$ Fit Minimizing Global χ^2



Rescale :

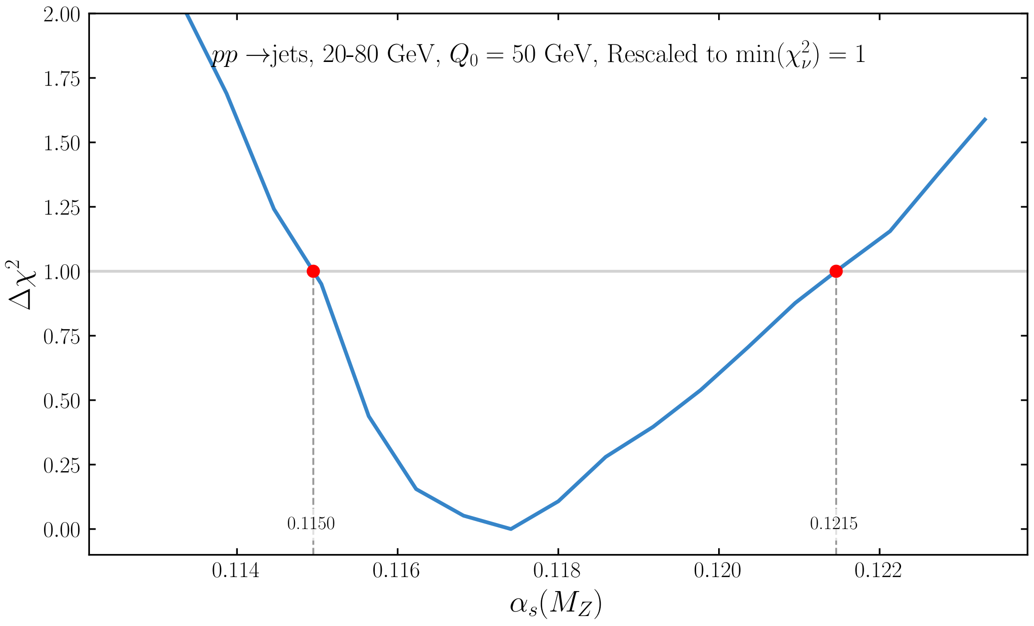
$$\sigma_{\text{stat,i}} \rightarrow \lambda\sigma_{\text{stat,i}} \Rightarrow \min(\chi^2_\nu) = 1$$

Avoid unrealistically tight constraints as statistics increase

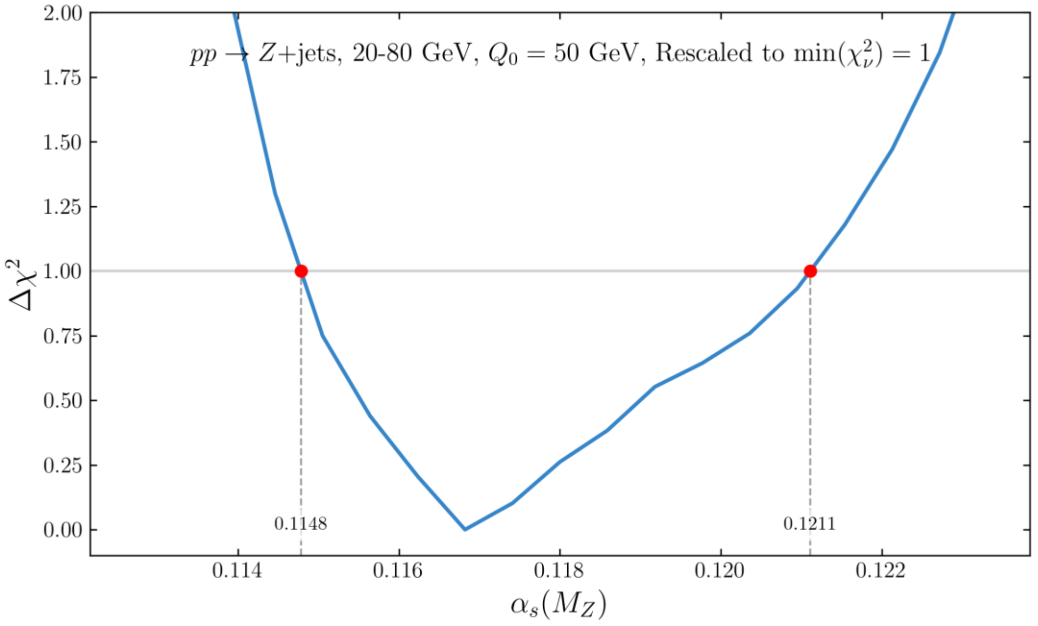
α_s Sensitivity

For pp collision, p_T range [20-80]GeV and reference scale is 50 GeV

$pp \to$ jets



$pp \to$ Z+jets



Preliminary Study On Pythia stimulation yield a precision of $\sim$ 5% for the $\alpha_s(M_Z)$

Summary

- [x] EEC plateau height for high theoretical precision

  e^+e^-: N3LO+NNLL　　　pp: NLO+NNLL

- [x] Preliminary study with Pythia data demonstrate feasibility of α_s extraction

- [ ] Theoretical precision improved to currently feasible levels, with results extended to ep collisions for future EIC experiments

- [ ] Needs experimentalist to get higher precision results (experiment setup, statistics analysis,…)

Thanks

Extra Slides

FMNLO Modification

The relation between hadronic moment and the partonic short-distance weight follows from:

[Liu, Shen, Zhou, Gao; 2305.14620]

$$\frac{d\sigma}{dx} = \sum_i \int_x^1 \frac{dz}{z} \hat{\sigma}_i(z) D_i\left(\frac{x}{z}\right) \xrightarrow{z\, D_i(z)=1} \sum_i \frac{1}{x} \int_x^1 dz\, \hat{\sigma}_i(z)$$

$$\int_0^1 x^4 \frac{d\sigma}{dx}\, dx = \sum_i \int_0^1 dz\, \hat{\sigma}_i(z) \int_0^z \xi^3\, d\xi = \frac{1}{4} \sum_i \sigma_{J,i}^{(5)}$$

NNLL resummation @DGLAP

Evolution of non-perturbative parameters C_i is governed by DGLAP with $N = 5$ moment

$$\frac{dC_i(\mu)}{d\ln\mu^2} = -\hat{\gamma}_{T,ij}\, C_j(\mu)$$

Using the U-matrix approach

Up to 3-loop: $\gamma_{T,ij} = -\int_0^1 dx\, x^4\, \hat{P}_{ij}(x)$

$$C(a_s) = U(N, a_s)\, L(N, a_s, a_0)\, U^{-1}(N, a_0)\, C(a_0)$$

[Vogt; hep-ph/0408244]