QCD and jet physics

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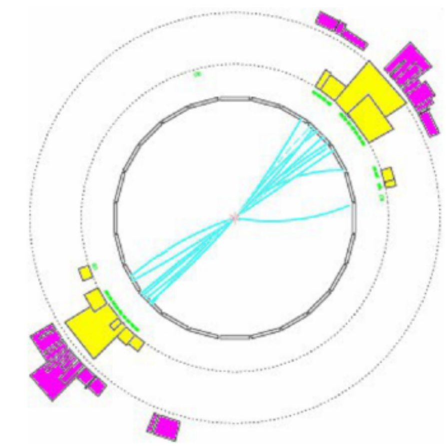
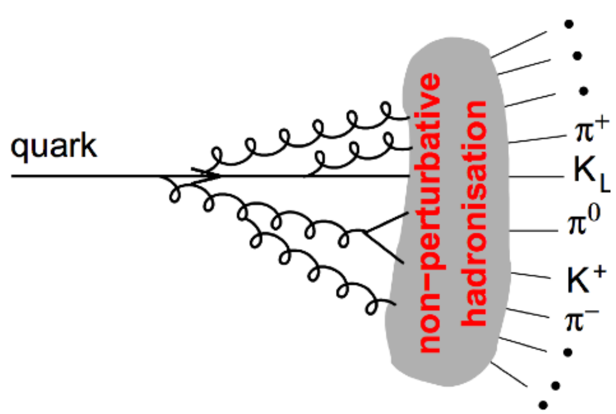
QCD and jets

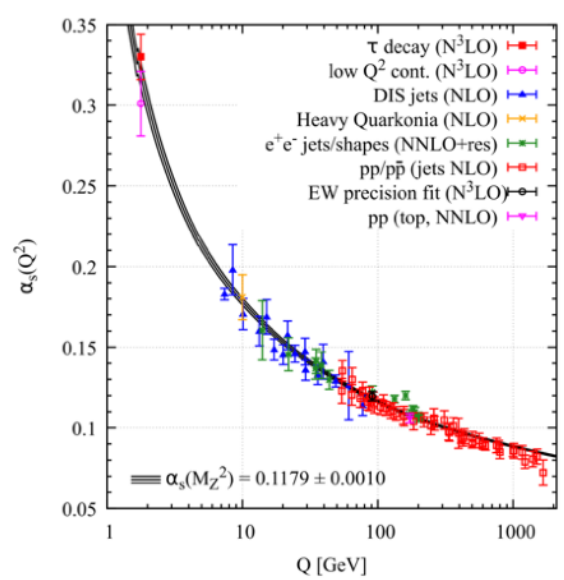
QCD: non-abelian Yang-Mills theory



$$\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_q \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu}$$

Parton (quark or gluon) fragmentation and hadronization





Jets are emergent property of QCD

- **Soft-collinear singularity**
- **Asymptotic freedom**
- **Color string breaks**

Dynamics of jets formation: from short to long distance in quantum field theory

$$J\,(\text{ scale }\mu_2) \sim J\,(\text{scale}\,\mu_1)\exp\left[\int_{\mu_1}^{\mu_2}\frac{d\mu'}{\mu'}\int dx P\left(x,\alpha_s\left(\mu'\right)\right)\right]$$

Jets at the LHC

Jets are produced copiously at the LHC

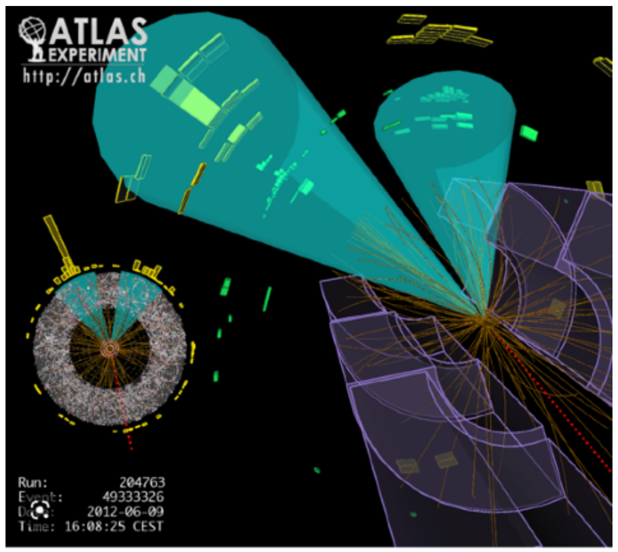
Not jets (QED jets?): $e \quad \mu \quad \gamma$

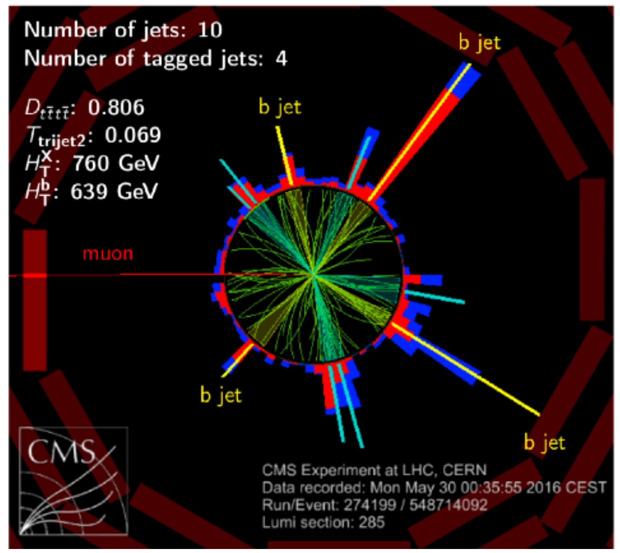
Tau jets: τ

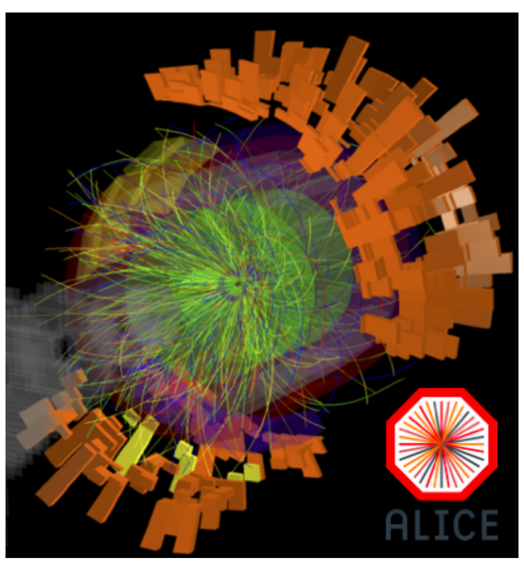
Light Jets: $u\ d\ s\ g$

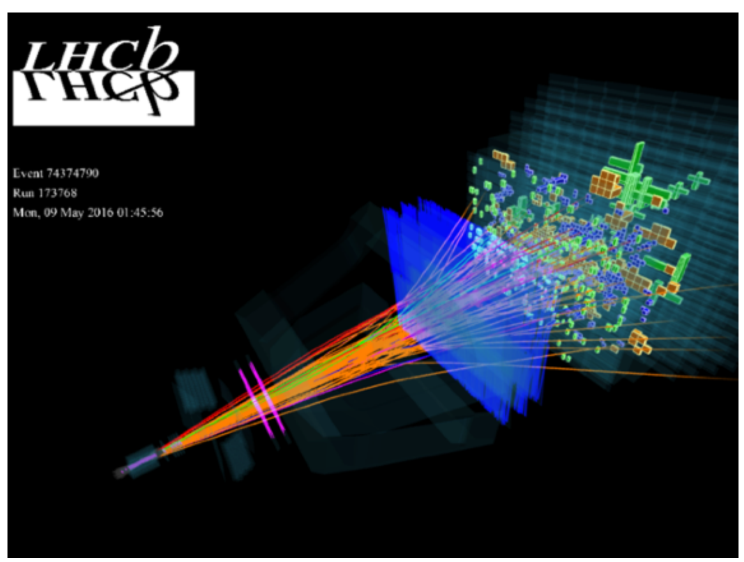
Heavy Jets: $c\ b$

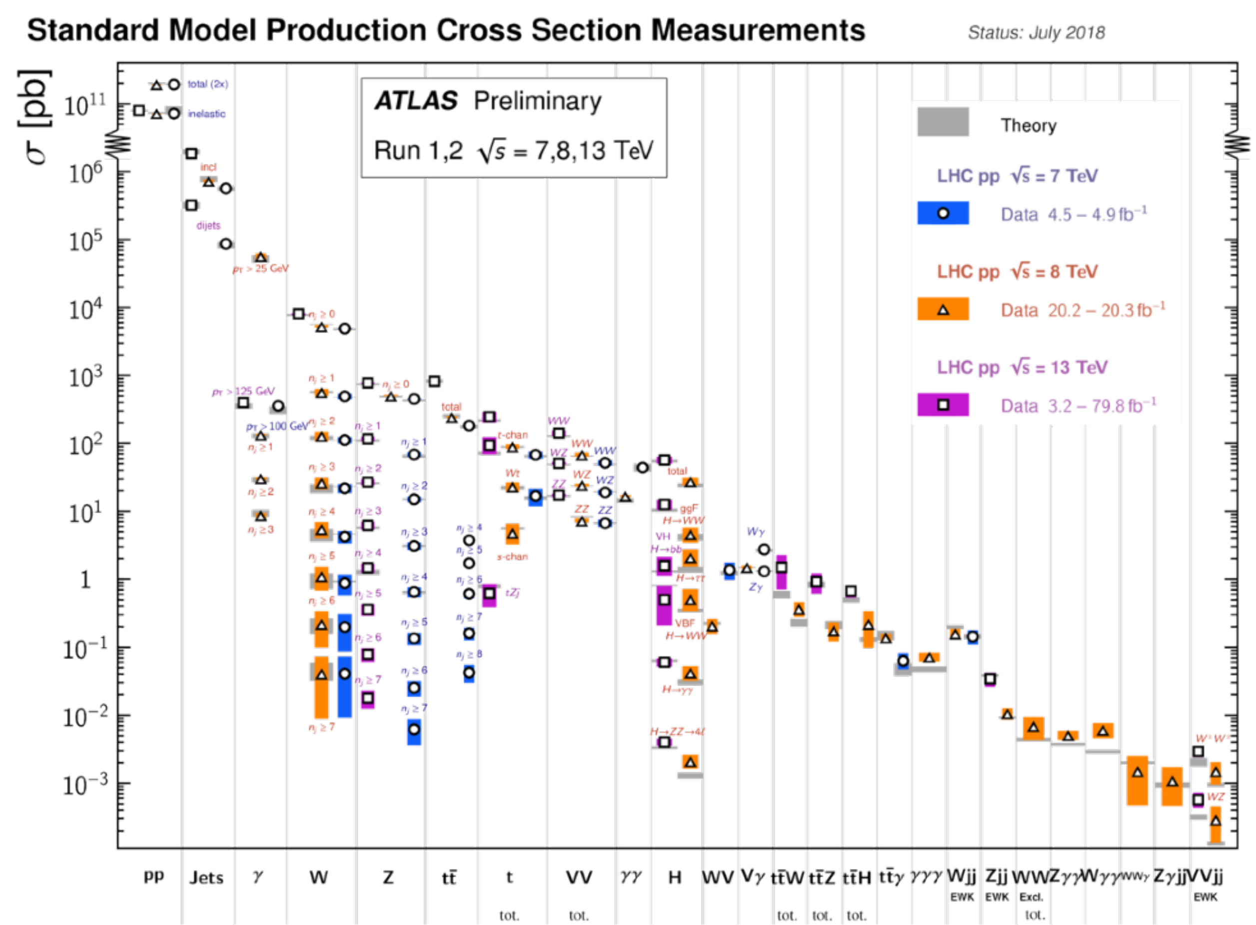
Fat Jets: $W\ Z\ H\ t$







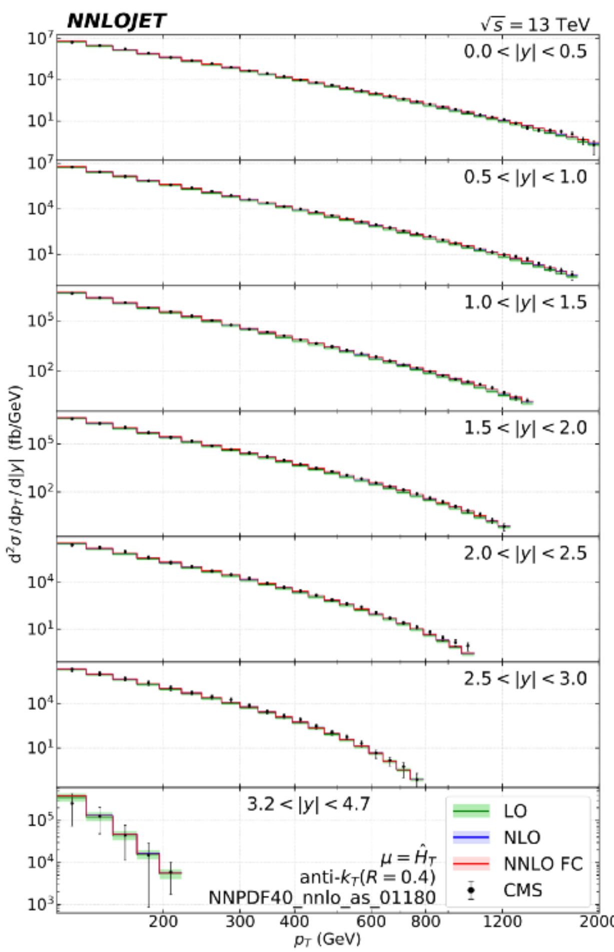


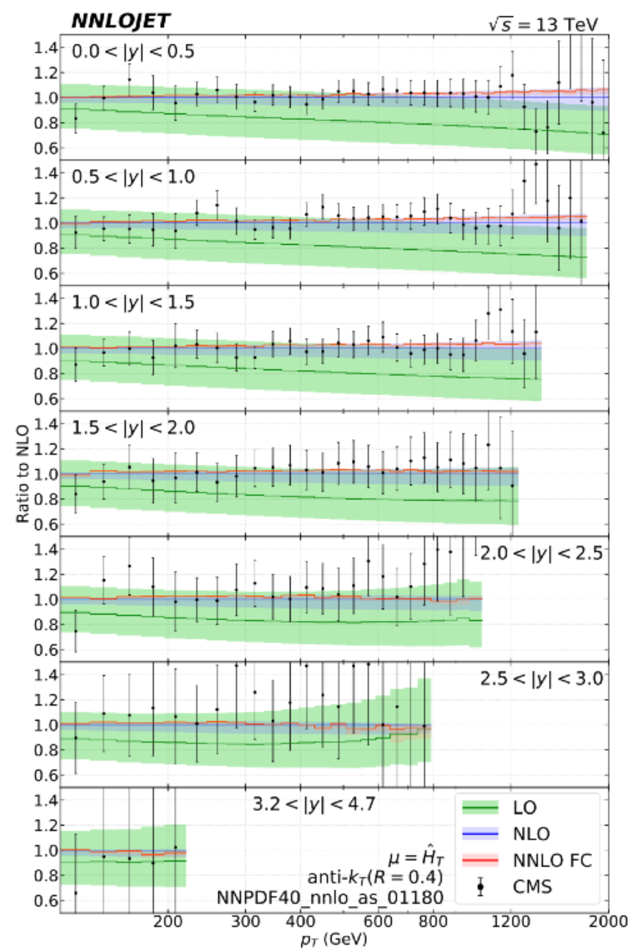


Jets cross section @ LHC: NNLO QCD in full color

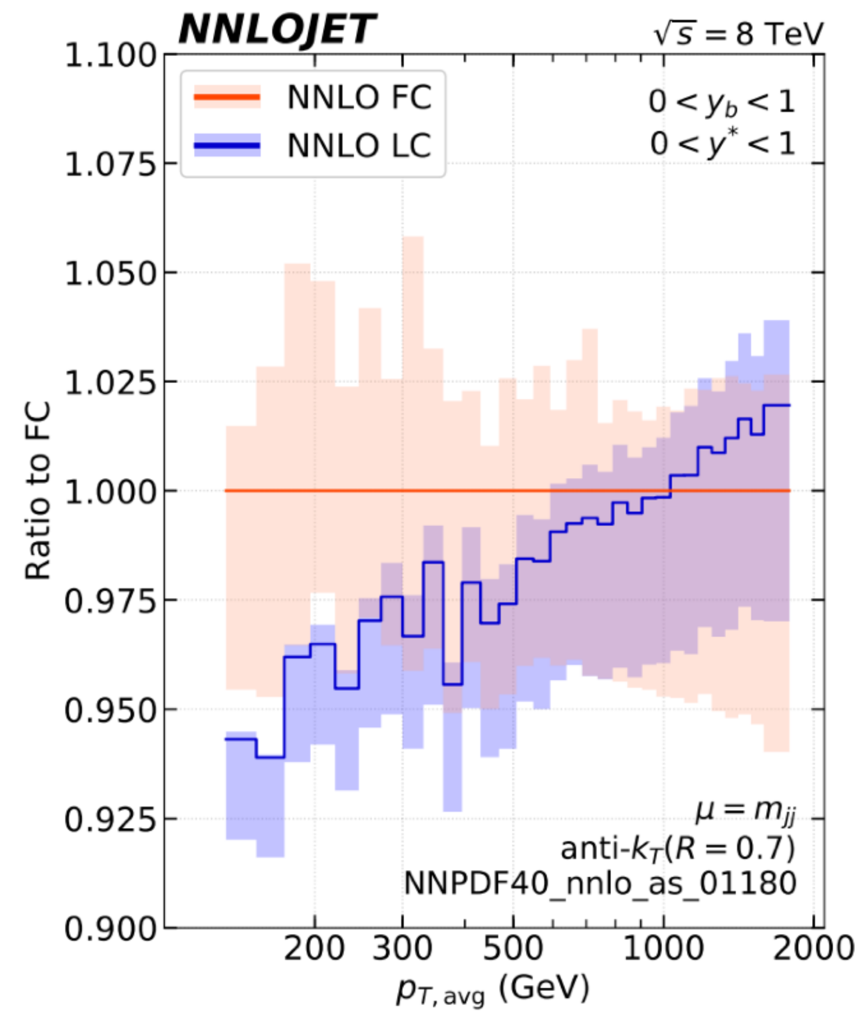
(Chen, Gehrmann, Glover, Huss, Mo ’22)

$$p + p \to j + X$$



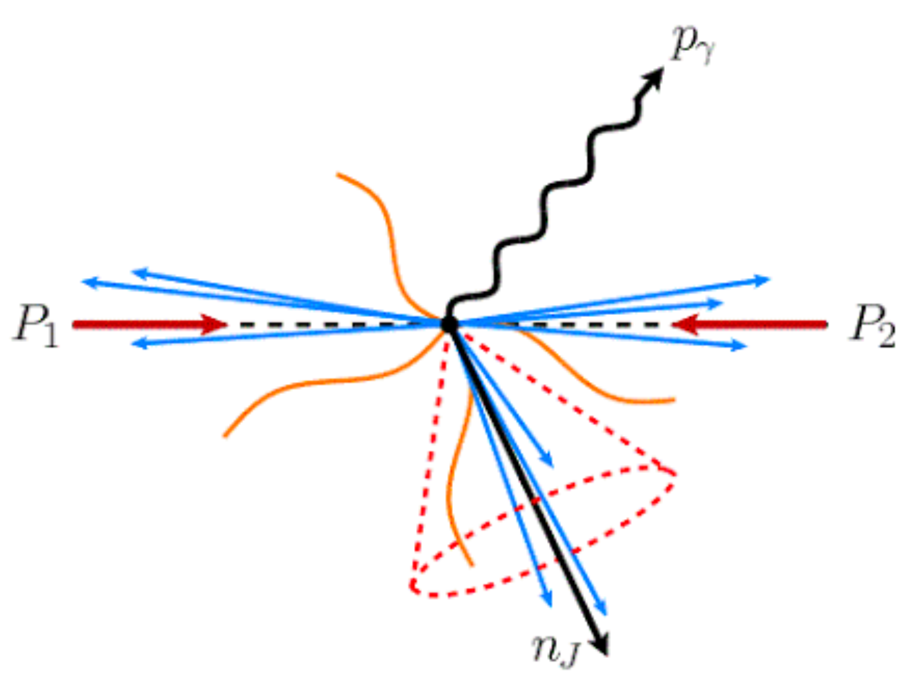


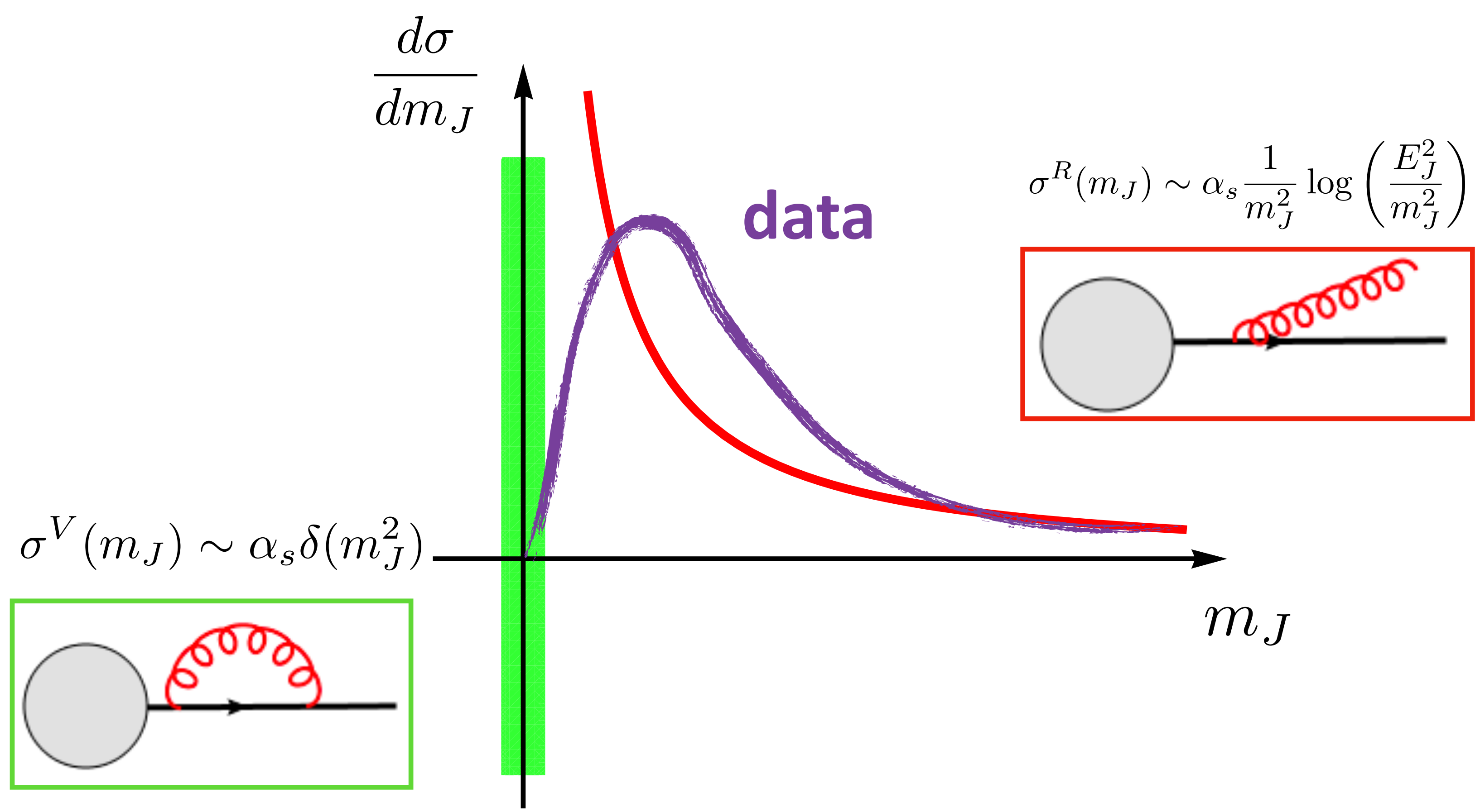
$$p + p \to j + j + X \qquad d^3\sigma/dp_T dy_* dy_b$$



- A new calculation of the NNLO corrections to jet production observables with full-color information
- The subleading color contributions play a potentially sizable role in the description of the triply differential distributions

Jet evolution from perturbative QCD: Jet Mass





$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_J} = \frac{\mathrm{d}}{\mathrm{d}m_J}\left[\sigma_0 \exp\left(-\frac{\alpha_s C_F}{2\pi} L^2\right)\right]$$

- **Fixed order in** α_s **fails if** $L \gg 1$
- **Accounts for all terms** $\sim \alpha_s^n L^{2n}$

$$L = \log(E_J^2/m_J^2)$$

- **All order results generally exponentiate**

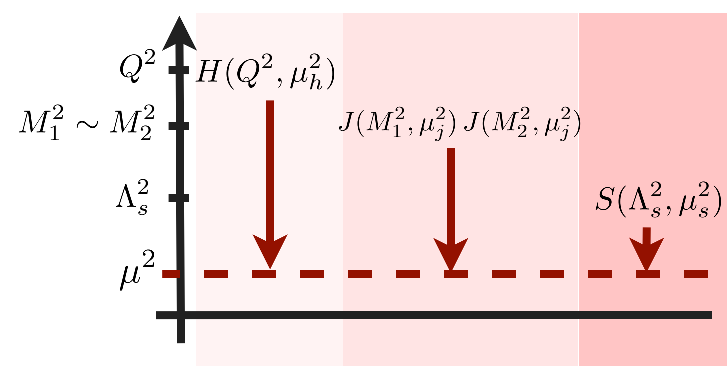
$$\sigma \sim \sigma_0 \exp(\alpha_s L^2 + \alpha_s L + \alpha_s^2 L + \dots)$$

Two general approaches to evolution

- **Top down: all-order factorization theorems e.g. Soft-Collinear Effective Theory, . . .**
  - **All-order structure manifest**

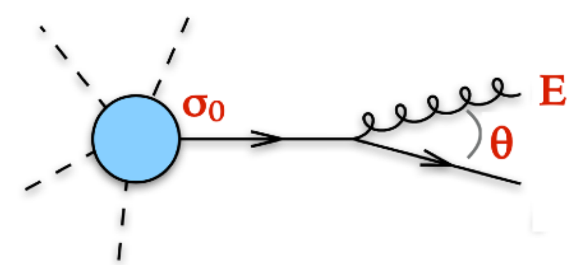
$$\mu \frac{d}{d\mu} \log \sigma_{\mathrm{phys}}(Q, M_1, M_2) = 0$$

$$\sigma(Q, M_1, M_2) = H(Q^2, \mu) \cdot J(M_1^2, \mu) \otimes J(M_2^2, \mu) \otimes S(M_1^2 M_2^2/Q^2, \mu)$$



- **Bottom up: corrections to coherent branching. e.g. parton shower, . . .**
  - **Simplifications at a given accuracy Lends itself to automation and Monte Carlo implementation**

Probability of emitting gluon: $P_g \simeq \frac{2\alpha_s C_F}{\pi} \int_{Q_0}^{Q} \frac{dE}{E} \int_{\frac{Q_0}{E}}^{1} \frac{d\theta}{\theta}$



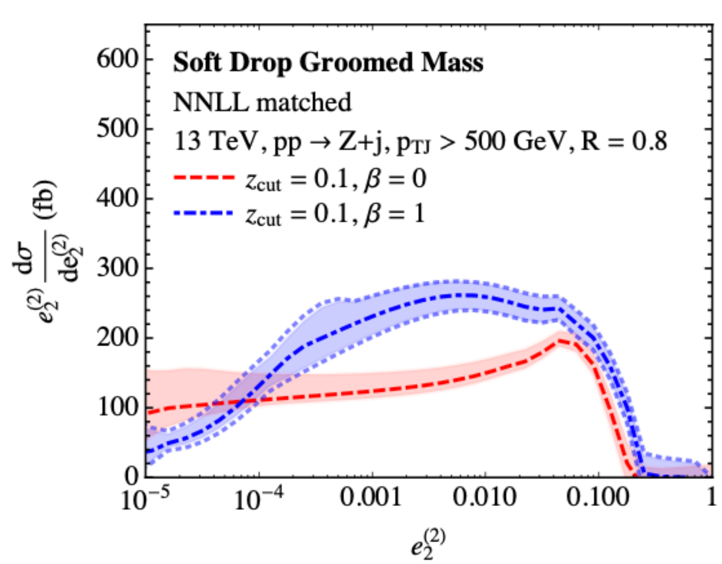
Use a random number (r) to sample pT distribution

$$r = \exp\left[-\frac{2\alpha_s C_F}{\pi} \ln^2 \frac{p_{T,\max}^2}{p_T^2}\right]$$

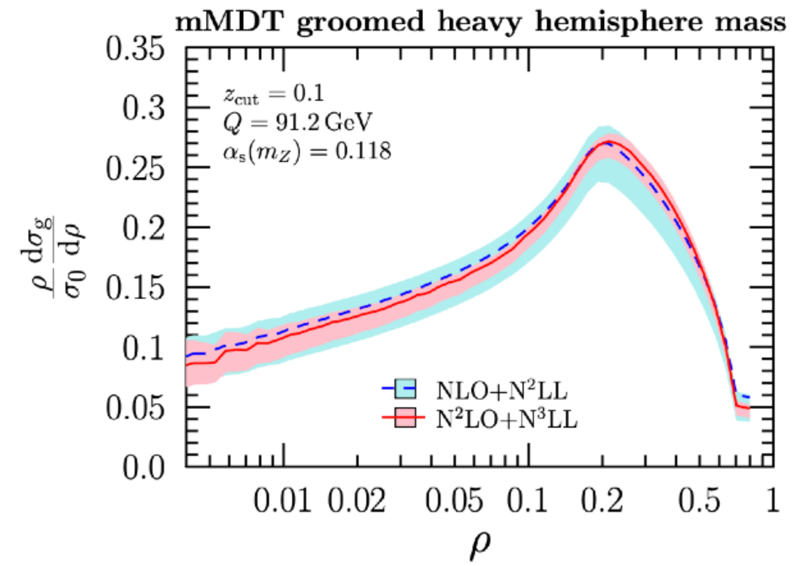
IHEP	ID	IDPDG	IST	MO1	MO2	DA1	DA2	P-X	P-Y	P-Z	ENERGY	MASS
9	UQRK	94	141	4	6	11	16	2.64	-9.83	592.2	590.2	-49.07
10	CONE	0	100	4	5	0	0	-0.27	0.96	0.1	1.0	0.00
11	GLUON	21	2	9	12	32	33	-1.02	3.59	5.6	6.7	0.75-
12	GLUON	21	2	9	13	34	35	0.25	1.46	3.6	4.0	0.75-
13	GLUON	21	2	9	14	36	37	-0.87	1.62	4.7	5.1	0.75-
14	GLUON	21	2	9	15	38	39	-0.81	4.17	3611.7	3611.7	0.75-
15	GLUON	21	2	9	16	40	41	-0.19	-1.01	1727.7	1727.7	0.75-
16	UD	2101	2	9	25	42	41	0.00	0.00	1054.6	1054.6	0.32-
17	GLUON	94	142	5	6	19	21	-2.23	0.44	-233.5	232.8	-18.36
18	CONE	0	100	5	8	0	0	0.77	0.64	0.2	1.0	0.00
19	GLUON	21	2	17	20	43	44	1.60	0.58	-2.1	2.8	0.75
20	UD	2101	2	17	21	45	44	0.00	0.00	-2687.6	2687.6	0.32
21	UQRK	2	2	17	32	46	45	0.63	-1.02	-4076.9	4076.9	0.32

Grommed jet mass at high precision

Soft Drop: clean up a jet by removing soft radiation



Frye, Larkoski, Schwartz, Yan ’16

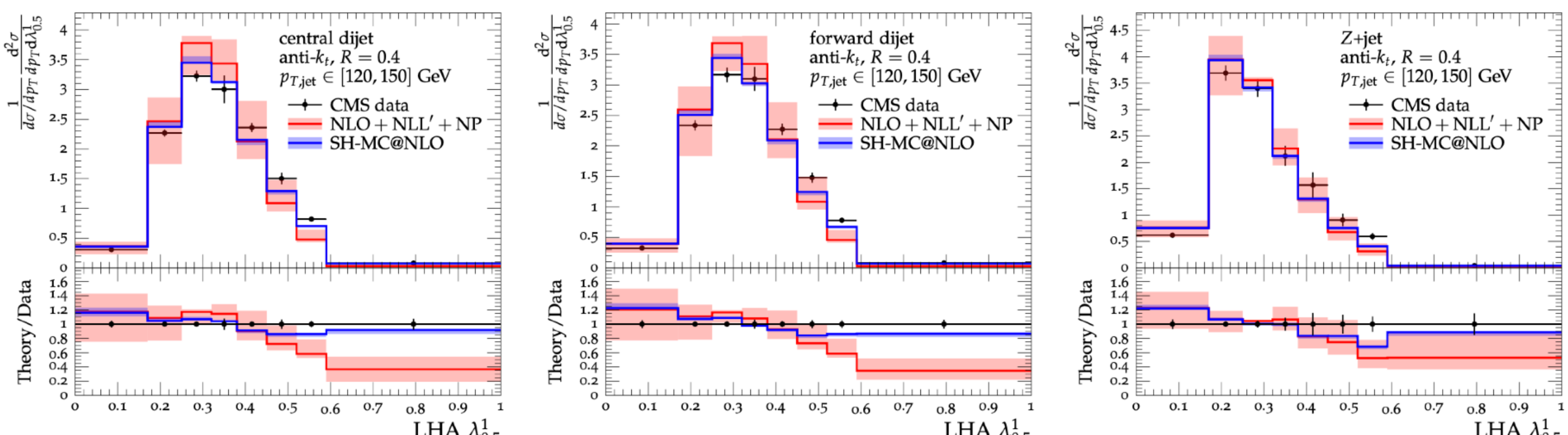


Kardos, Larkoski, Trócsányi ‘20

Non-perturbative corrections:

$$\left.\frac{d\sigma}{dm}\right|_{\rm NP} = \left.\frac{d\sigma}{dm}\right|_{\rm pert}\left(1 + f\left(z_{\rm cut},\beta\right)\frac{p_t\Lambda_{\rm NP}}{m^2}\left(\frac{m}{p_t}\right)^{\frac{2}{2+\beta}}\right)$$

Marzani, Schunk, Soyez ‘18
Hoang, Pathak, Mantry, Stewart ‘19
Pathak, Vaida, Stewart, Zoppi ’20



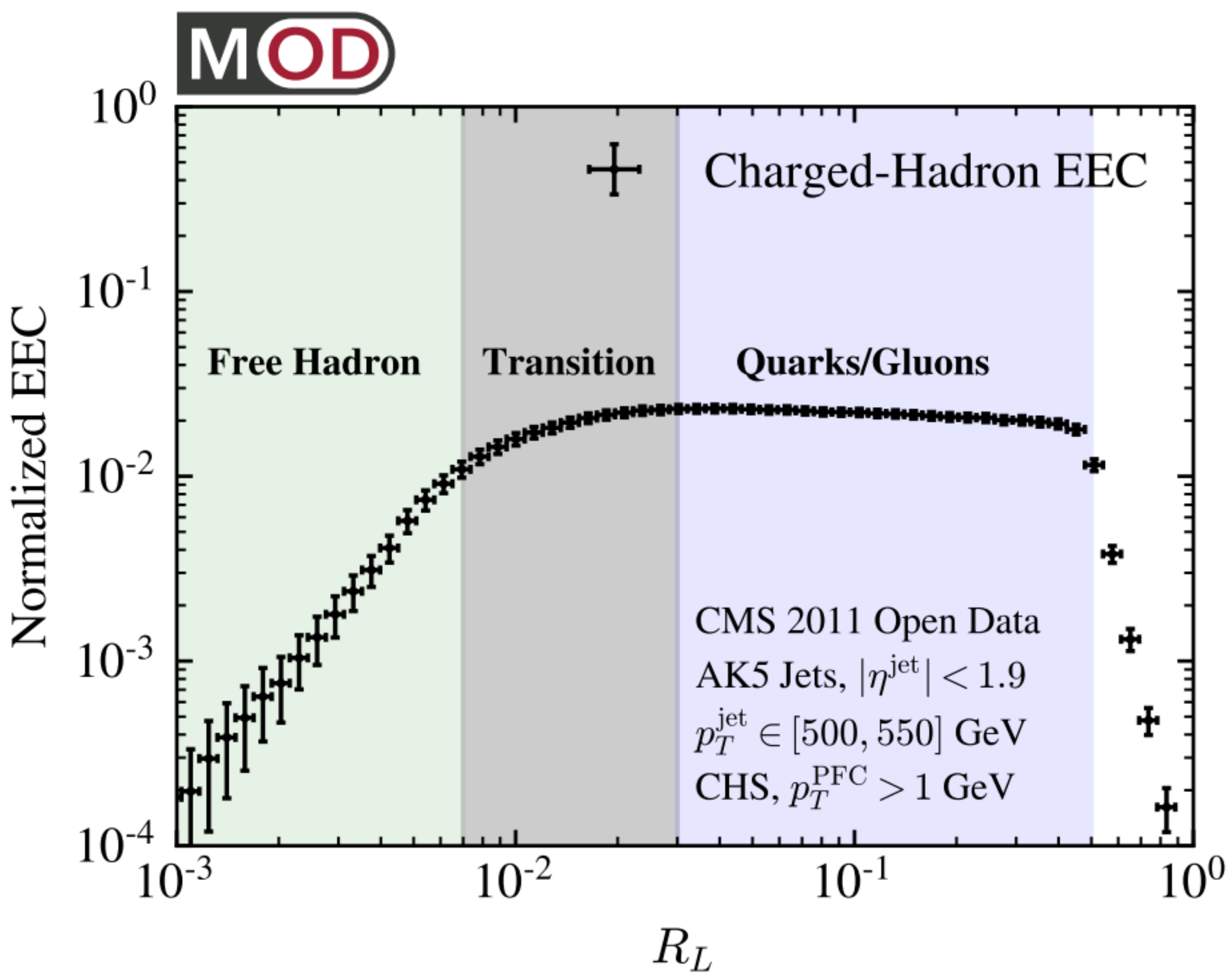
CMS ‘21

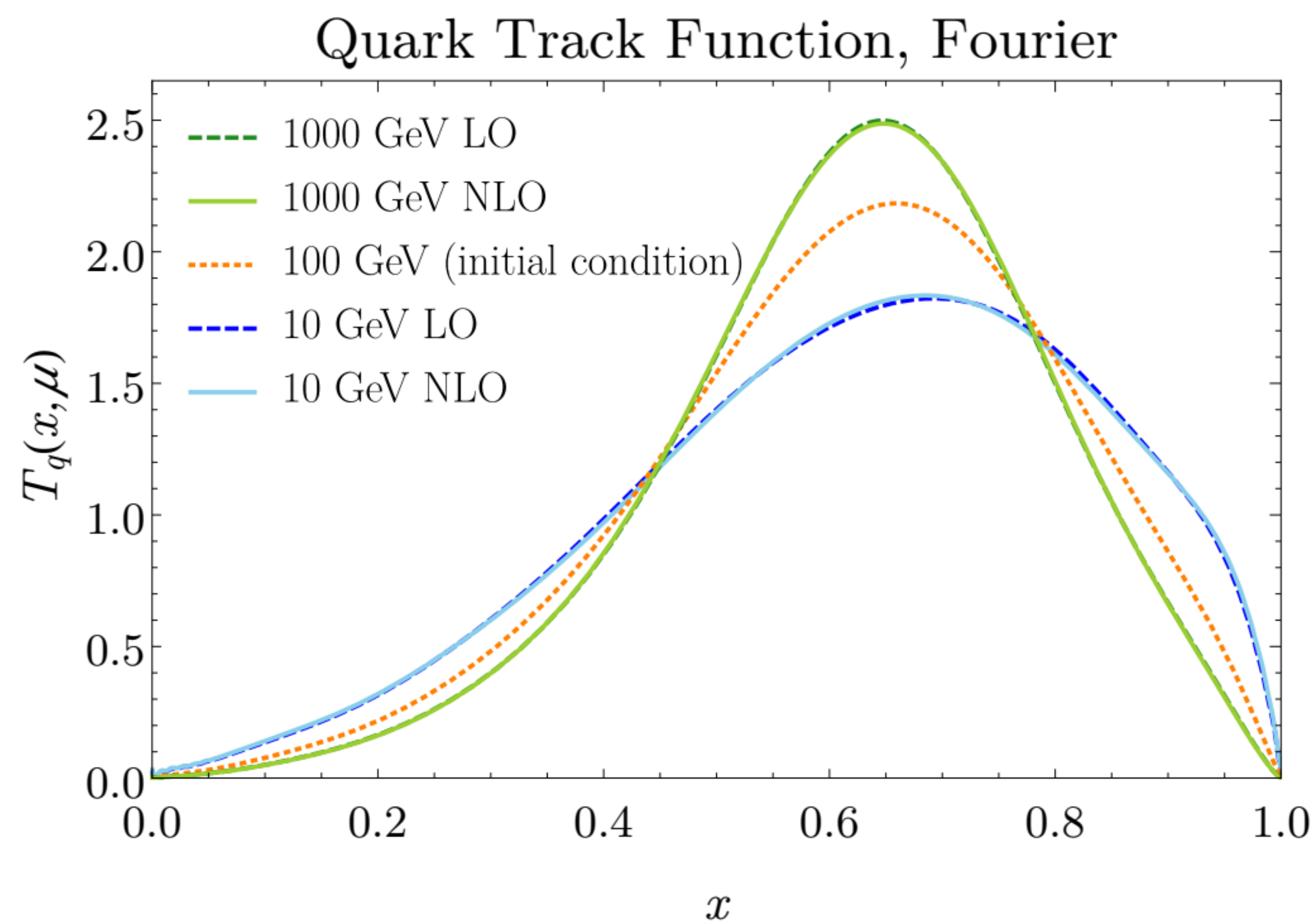
$$\lambda^\kappa_\beta = \sum_{i\in \rm jet} z_i^\kappa \left(\frac{\Delta R_i}{R}\right)^\beta$$

Jet substructure with energy correlators and track functions

$$\frac{1}{\sigma}\frac{d\Sigma_{\mathrm{EEC}}(\chi)}{d\cos\chi} = \frac{1}{\Delta\chi N_{\mathrm{events}}}\sum_{N_{\mathrm{events}}}\sum_{ij}\frac{E_iE_j}{E^2}$$

$$T_q(x) = \int \mathrm{d}y^+\mathrm{d}^{d-2}y_\perp e^{\mathrm{i}k^-y^+/2}\sum_X \delta\left(x - \frac{P_R^-}{k^-}\right)\frac{1}{2N_c}\mathrm{tr}\left[\frac{\gamma^-}{2}\langle 0|\psi(y^+,0,y_\perp)|X\rangle\langle X|\bar{\psi}(0)|0\rangle\right]$$





Distinct scaling behaviors associated with asymptotically free partons and hadrons

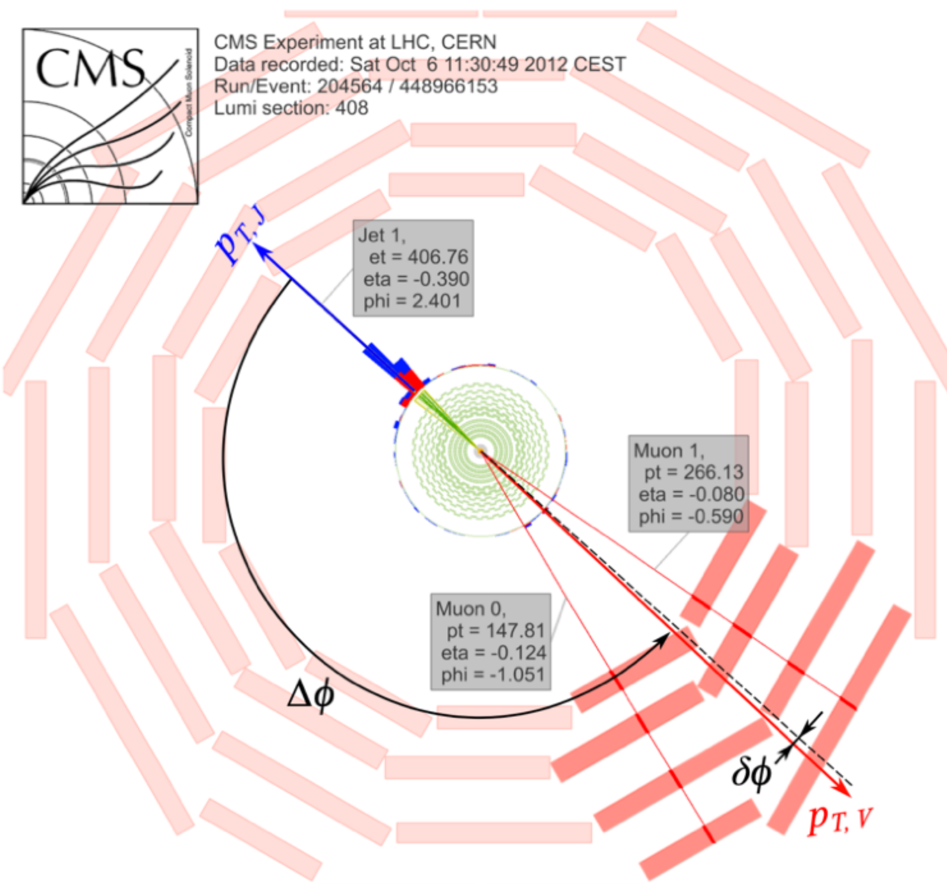
First NLO evolution of the track functions

Komiske, Moult, Thaler, Zhu ‘22

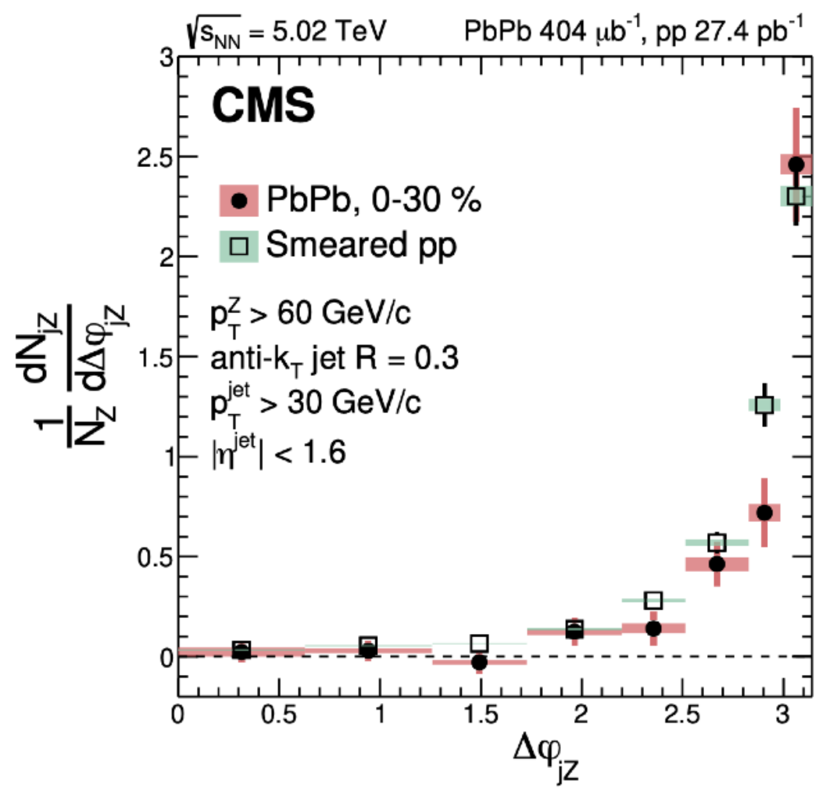
Chen, Jaarsma, Li, Moult, Waalewijn, Zhu ‘22

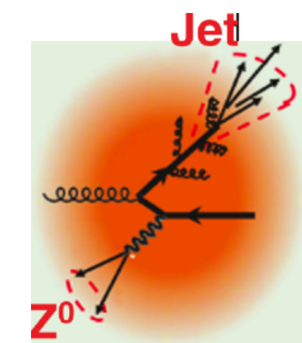
Azimuthal decorrelation of QCD jets

$$\Delta\phi \equiv |\phi_V - \phi_J| \ (\delta\phi \equiv \pi - \Delta\phi)$$



- **TMD evolution; 3D imaging of nucleon**
- **Validity of TMD factorization**
- **Properties of QCD matter measured as deviation from pp collisions**



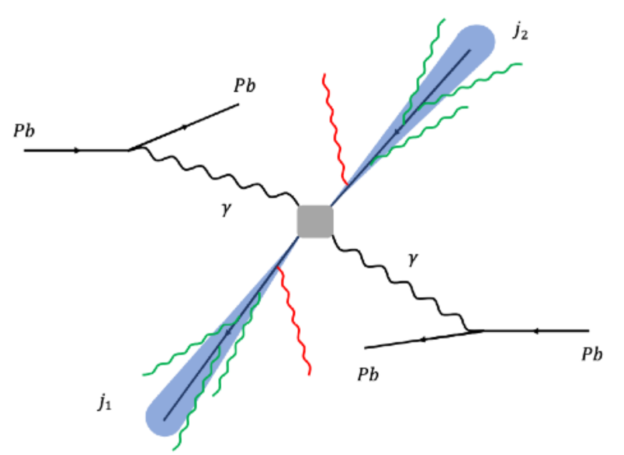


See Yaxian Mao and Yifeng Sun's talk

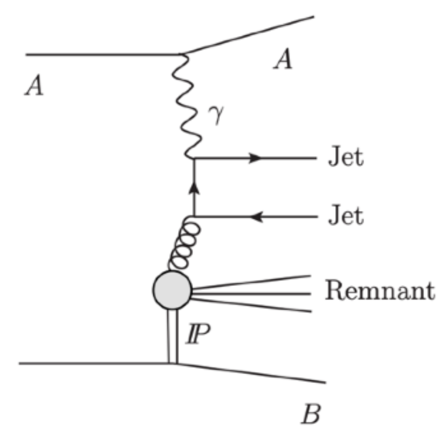
- **NLL ln$\delta\phi$ resummation**
  - **ep dijet** (Banfi, Dasgupta & Delenda '08) **dijet** (Sun, Yuan & Yuan '14 & '15) **jet + V** (Sun, Yuan & Yuan '18; Chen, Qin, Wang, Wei, Xiao, Zhang '18;Buffing, Kang, Lee & Liu '18, Chien, DYS, Wu '19) **lepton + jet** (Liu, Yuan & Felix '19) **jet + top** (Cao, Sun, Yan, Yuan & Yuan '18 & '19)

Azimuthal decorrelation of QCD jets in ultra-peripheral collisions

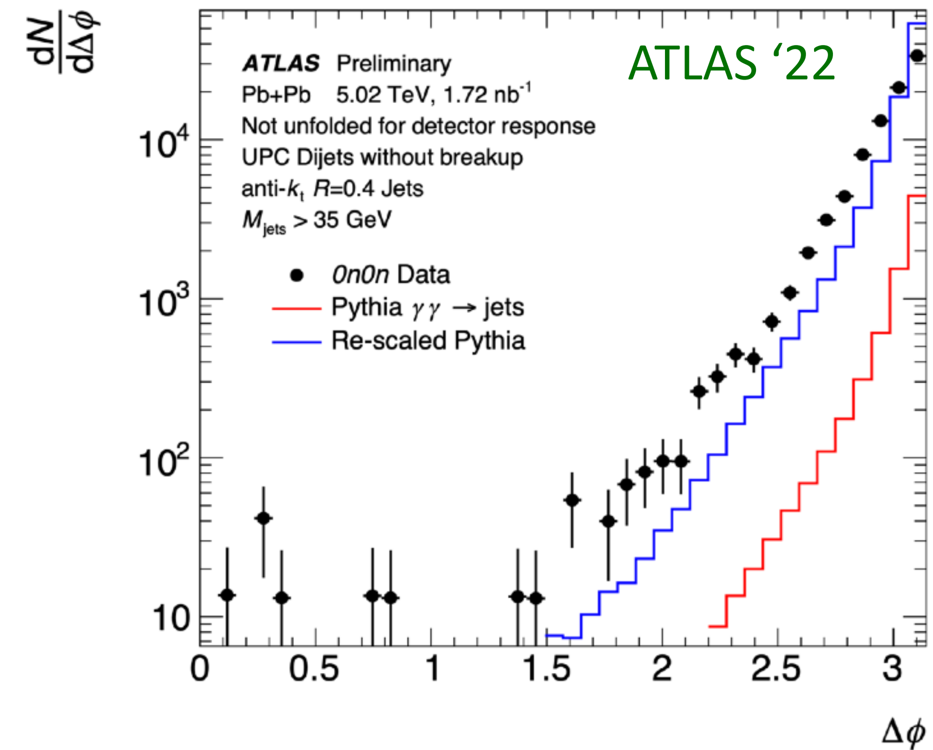
Dijet Production with no Nuclear Breakup



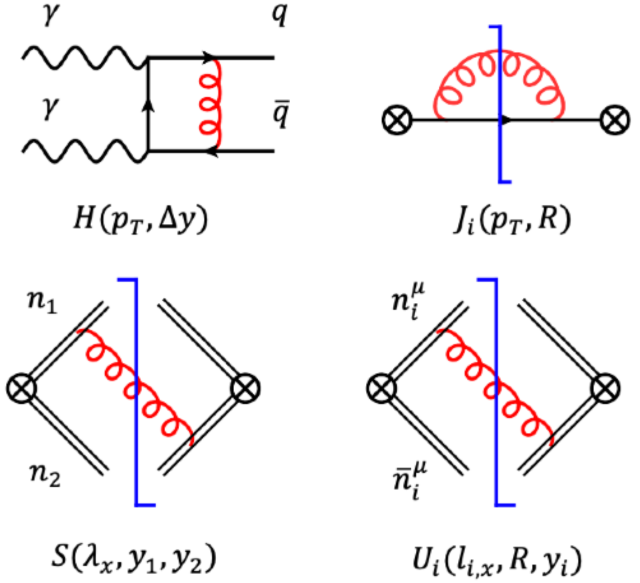
Photon-photon fusion

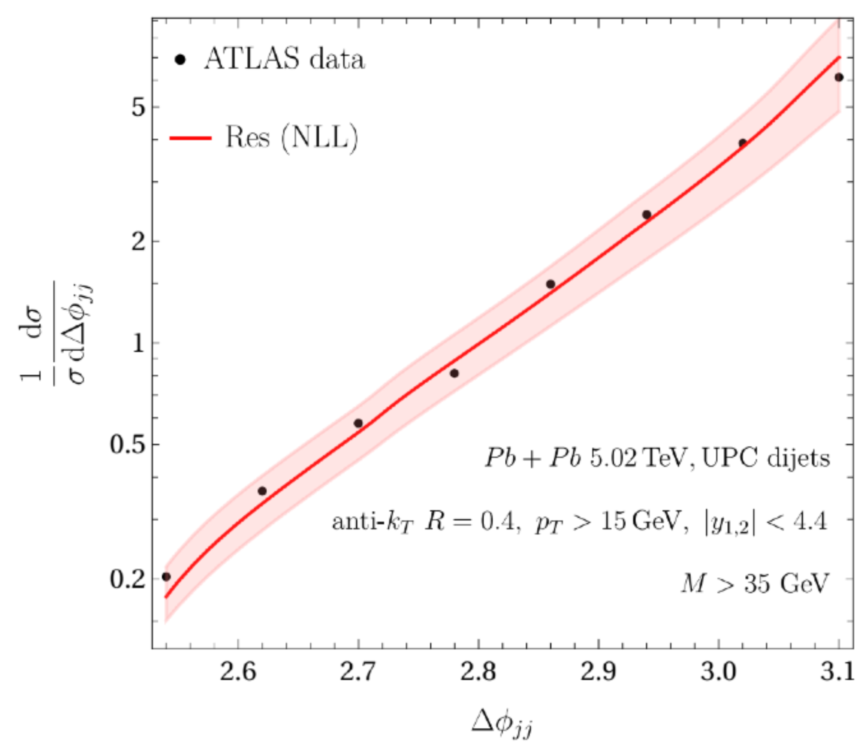


diffractive photo-production



(Zhang, Dai, DYS, '22)



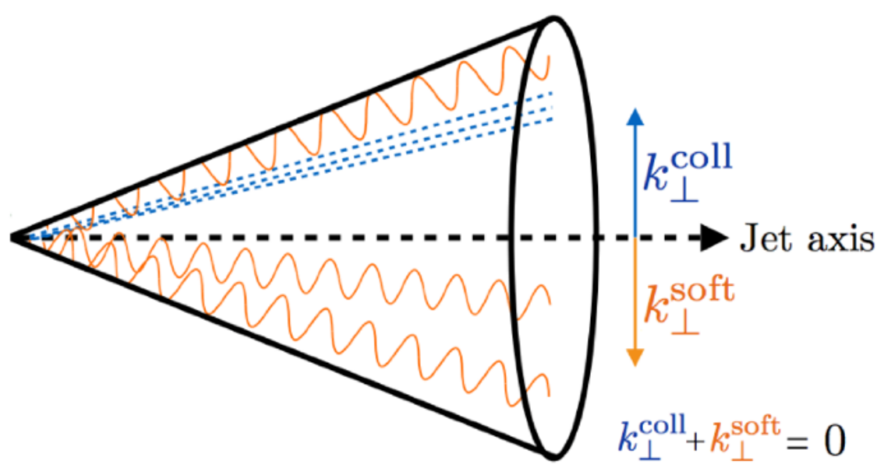


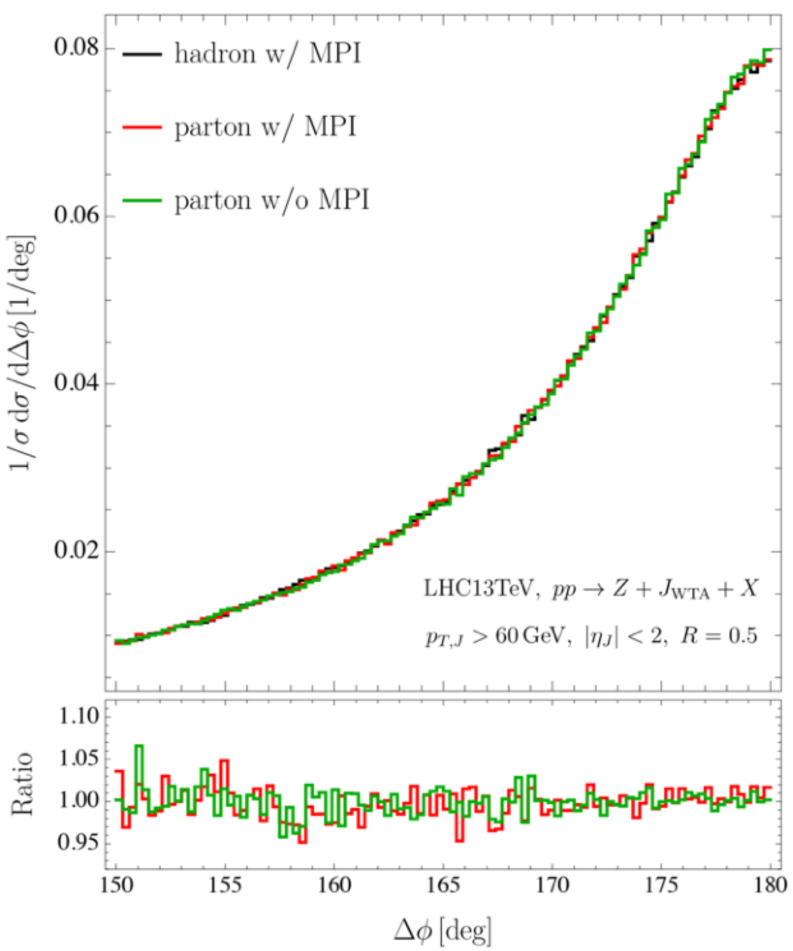
- Equivalent photon approximation + Soft-Collinear Effective Theory
- a good agreement with the ATLAS data in the nearly back-to-back region
- photo-productions may enhance the dijet production rate, but should barely change the shape

Recoil-free azimuthal angle at high precision

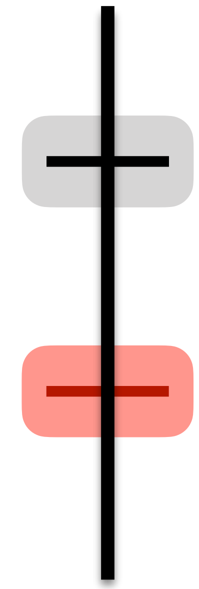
(Chien, Rahn, DYS, Waalewijn & Wu '22 + Schrignder '21)

anti-k_T + recoil-free recombination scheme





Standard TMD factorization (CSS, JMY, SCET2 …)



$p_h \sim Q(1,1,1)$

$p_n \sim (p_x^2/Q, Q, p_x)_{n\bar{n}}$

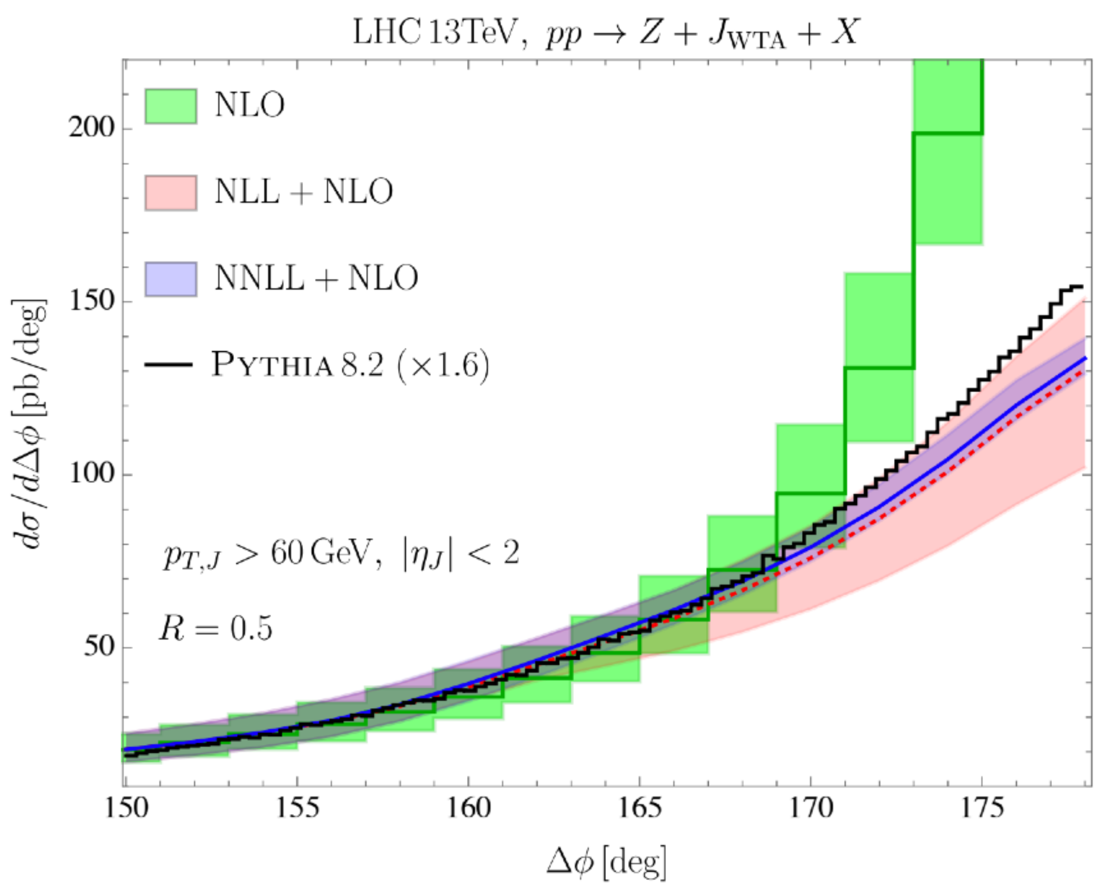
$p_s \sim (p_x, p_x, p_x)$

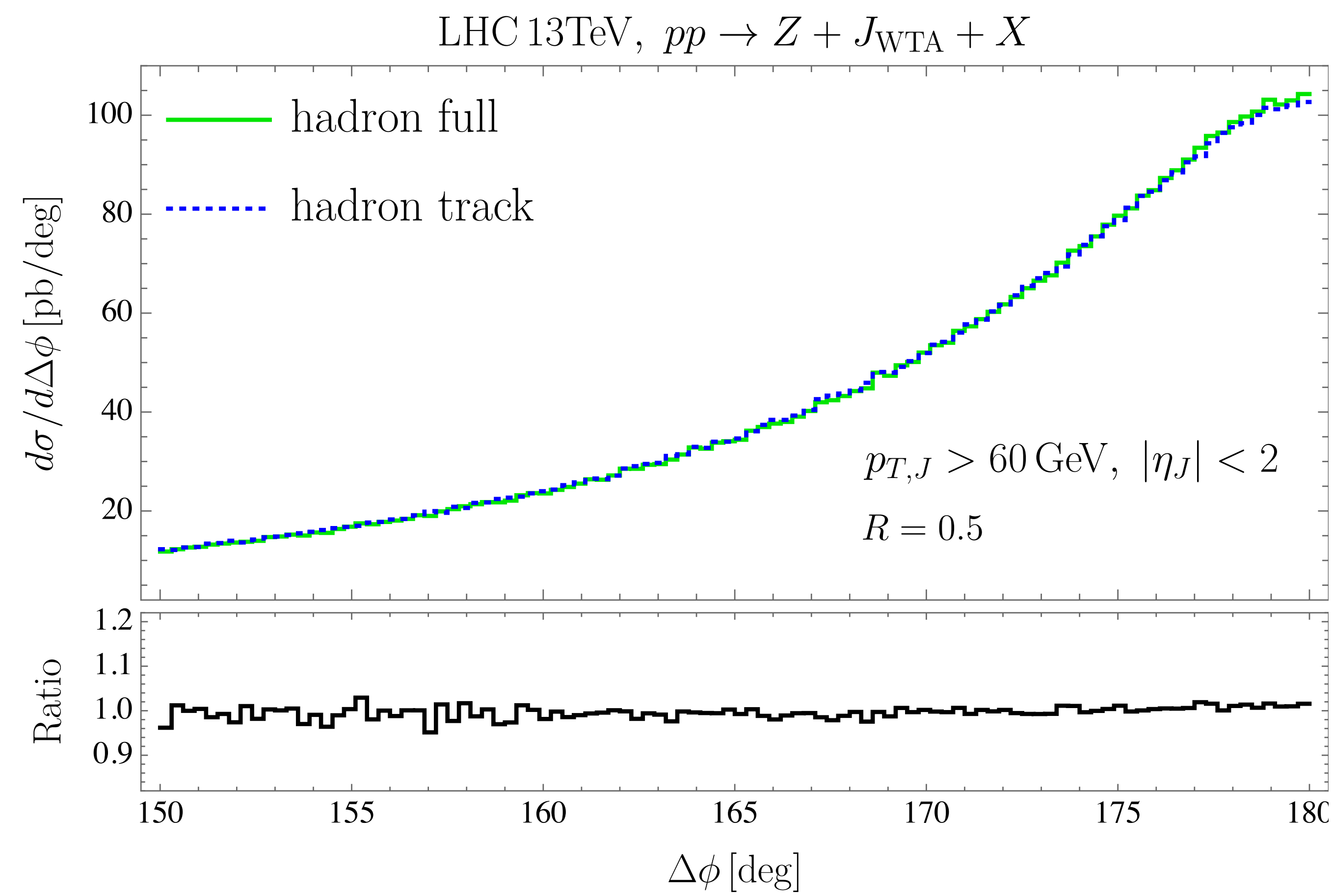
(also see Gao,Li,Moult,Zhu '19)

$$\frac{d\sigma}{dp_{x,V}\, dp_{T,J}\, dy_V\, d\eta_J} = \int \frac{db_x}{2\pi}\, e^{ip_{x,V} b_x} \sum_{i,j,k} B_i(x_a, b_x) B_j(x_b, b_x) S_{ijk}(b_x, \eta_J) H_{ij\to Vk}(p_{T,V}, y_V - \eta_J) J_k(b_x)$$

- **Effects of soft radiation in jet algorithm are suppressed**
- **the shape of the Δϕ distribution is remarkably insensitive to hadronization and MPI**
- **dominated by perturbative contributions**

Numerical results



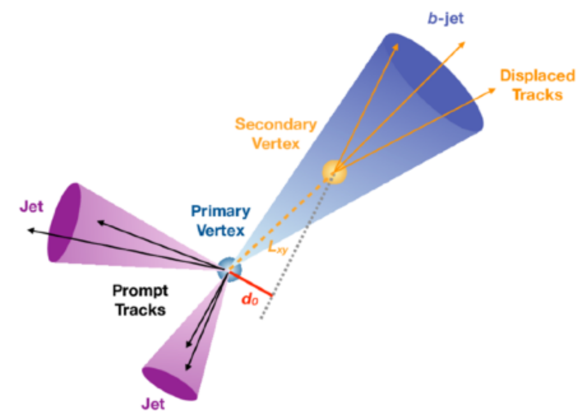


- **N²LL resummation including full jet dynamics**
- **serves as a baseline for pinning down the inner workings of QCD matter using hard probes**
- **the superior angular resolution can be achieved by using the tracking systems at the LHC**

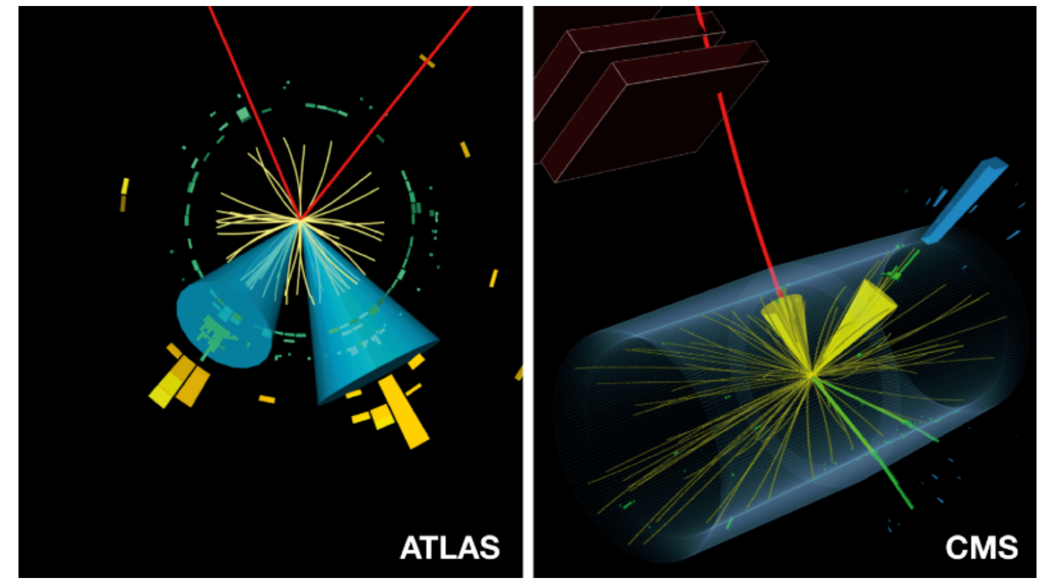
Heavy flavor jets

Jets containing heavy quark are important to the LHC

- **Higgs physics**
- **Top physics**
- **PDFs**
- **m_b m_c in the evolution**
- **Fragmentations**
- **....**

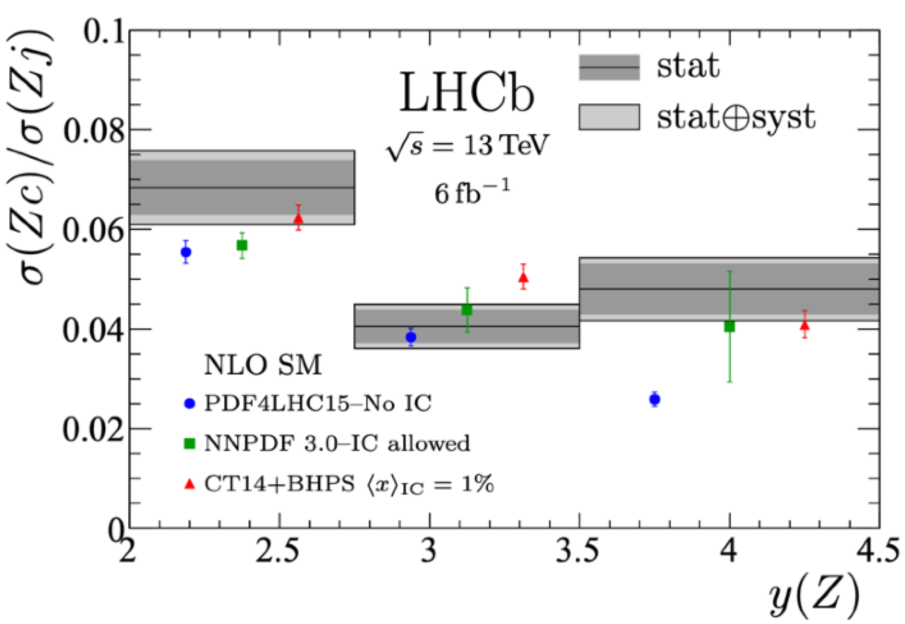


Charm Yukawa couplings



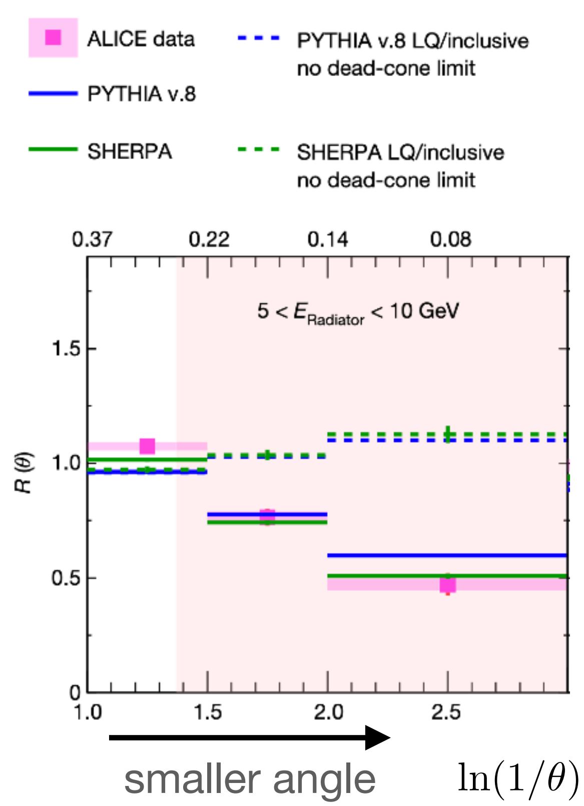
See Meng Xiao's talk

Intrinsic charm in the proton



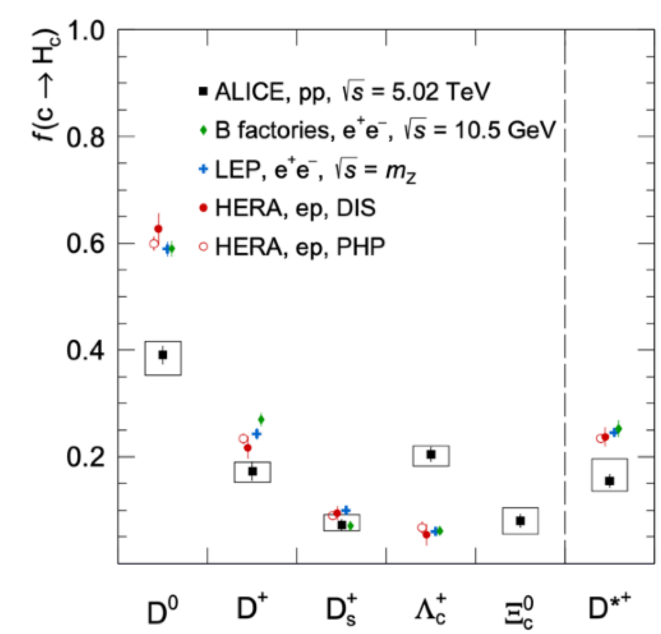
See Hang Yin & Zhao Li's talk

Dead cone effect



See Yaxian Mao's talk

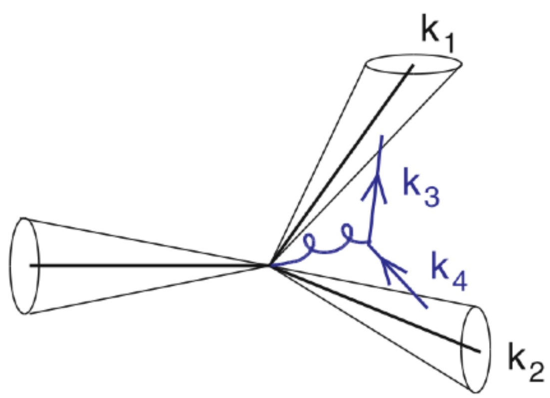
Charm fragmentation



See Zebo Tang's talk

Heavy flavor jets in QCD theory

anti-k_T jets counting the flavor is not IR safe



- A large-angle soft gluon splitting to a large-angle soft quark pair can affect jet flavor
- One solution: recombine the soft quark pair

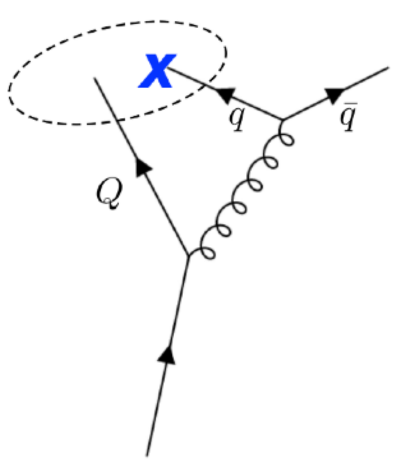
$$d_{ij}^{(F)} = (\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2) \times \begin{cases} \max(k_{ti}^2, k_{tj}^2)\,, & \text{softer of } i,j \text{ is flavoured,} \\ \min(k_{ti}^2, k_{tj}^2)\,, & \text{softer of } i,j \text{ is flavourless,} \end{cases}$$

Banfi, Salam, Zanderighi '20

New ideas:

Soft drop

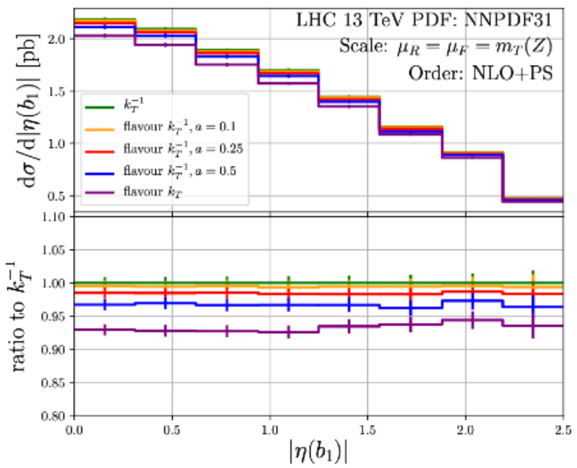
remove soft quarks



Caletti, Larkoski, Marzani, Reichelt '22

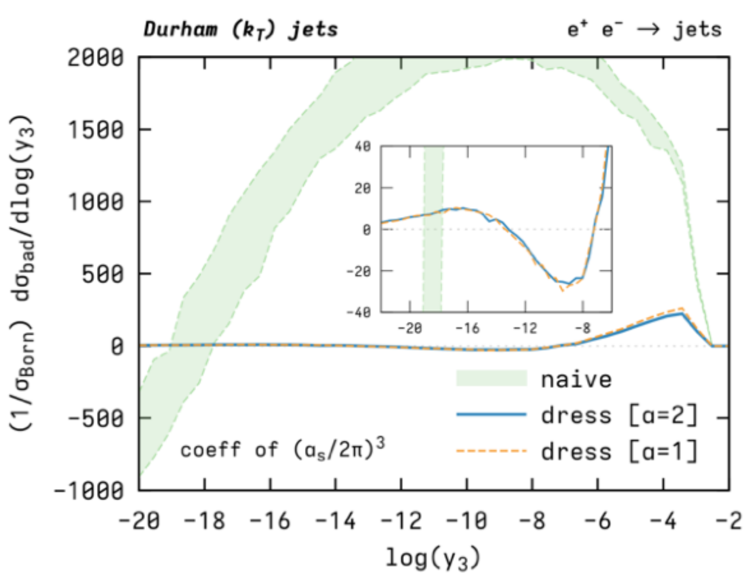
Flavor anti-k_T

$$d_{ij}^{(F)} \equiv d_{ij} \times \begin{cases} \mathcal{S}_{ij}\,, & \text{if both } i \text{ and } j \text{ have non-zero flavour of opposite sign,} \\ 1\,, & \text{otherwise.} \end{cases}$$



Czakon, Mitov, Poncelet '22

Flavor dressing jets



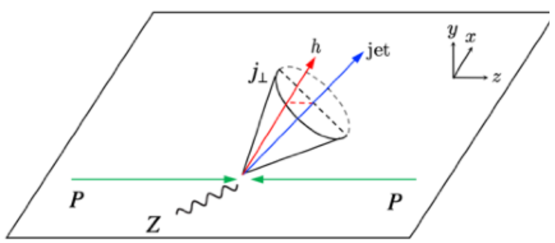
Gauld, Huss, Stagnitto '22

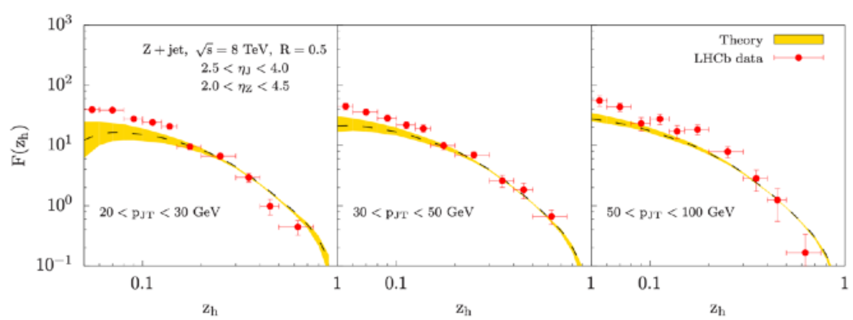
Jet fragmentation function: hadron inside jets

E.g. Hadrons produced inside Z-tagged jets in proton-proton collisions

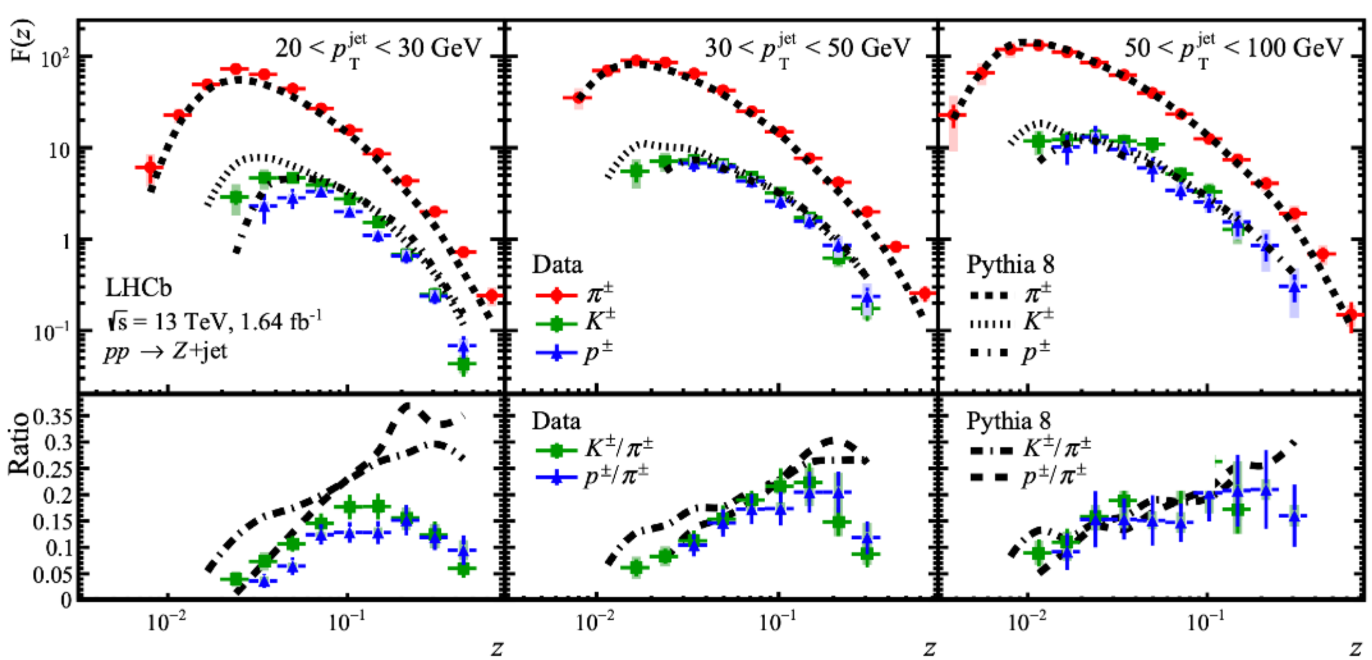
$$p(p_A) + p(p_B) \to Z(\eta_Z, \boldsymbol{p}_{ZT}) + \mathrm{jet}(\eta_J,\ \boldsymbol{p}_{JT}, R)\ h(z_h, \boldsymbol{j}_\perp) + X$$

Kang, Lee, Terry, Xing '19





LHCb '22

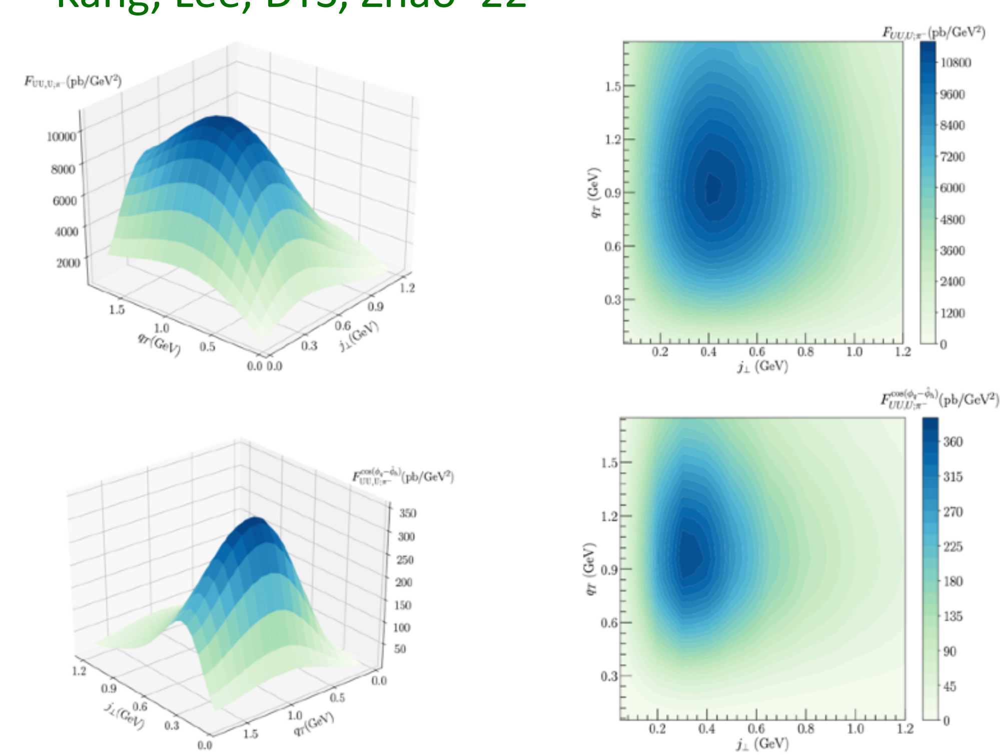


Polarized hadron inside a jet

H \ q	U	L	T
U	$\mathcal{D}_1^{h/q}$		$\mathcal{H}_1^{\perp h/q}$
L		$\mathcal{G}_{1L}^{h/q}$	$\mathcal{H}_{1L}^{h/q}$
T	$\mathcal{D}_{1T}^{\perp h/q}$	$\mathcal{G}_{1T}^{h/q}$	$\mathcal{H}_1^{h/q}$, $\mathcal{H}_{1T}^{\perp h/q}$

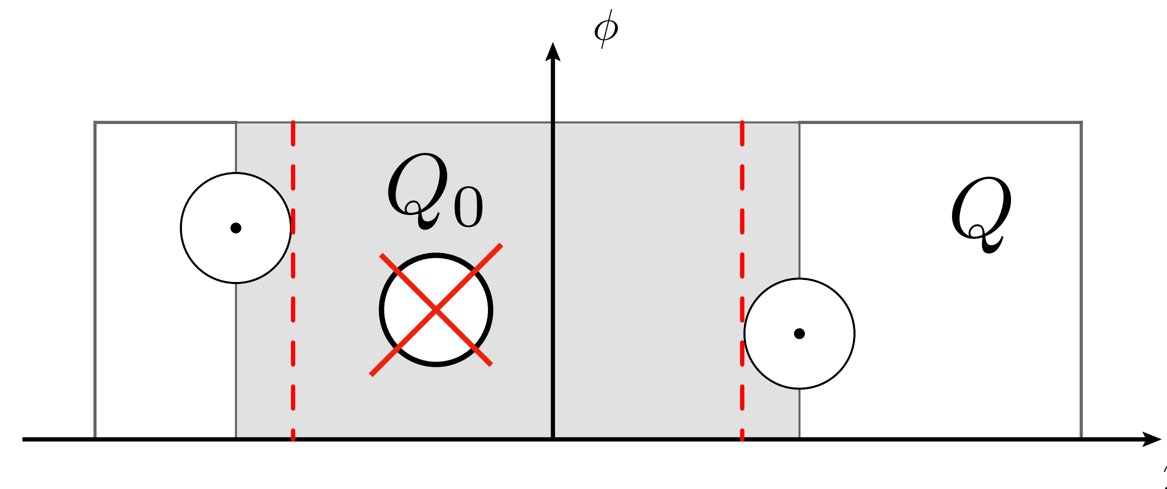
$$\Delta_{\mathrm{jet}}^{h/q}(z_h, \boldsymbol{j}_\perp, S_h) = \frac{1}{2}\Big\{ \Big(\mathcal{D}_1 - \frac{\epsilon_T^{ij} j_\perp^i S_{h\perp}^j}{z_h M_h}\mathcal{D}_{1T}^\perp\Big) \not{n}_J + \Big(\lambda_h \mathcal{G}_{1L} - \frac{\boldsymbol{j}_\perp \cdot \boldsymbol{S}_{h\perp}}{z_h M_h}\mathcal{G}_{1T}\Big)\gamma_5 \not{n}_J$$
$$- i\sigma^{i\mu} n_{J,\mu}\Big(\mathcal{H}_1 S_{h\perp}^i \gamma_5 - i\mathcal{H}_1^\perp \frac{j_\perp^i}{z_h M_h} - \mathcal{H}_{1L}^\perp \frac{\lambda_h j_\perp^i}{z_h M_h}\gamma_5$$
$$+ \mathcal{H}_{1T}^\perp \frac{\boldsymbol{j}_\perp \cdot \boldsymbol{S}_{h\perp} j_\perp^i - \frac{1}{2} j_\perp^2 S_{h\perp}^i}{z_h^2 M_h^2}\gamma_5\Big)\Big\},$$

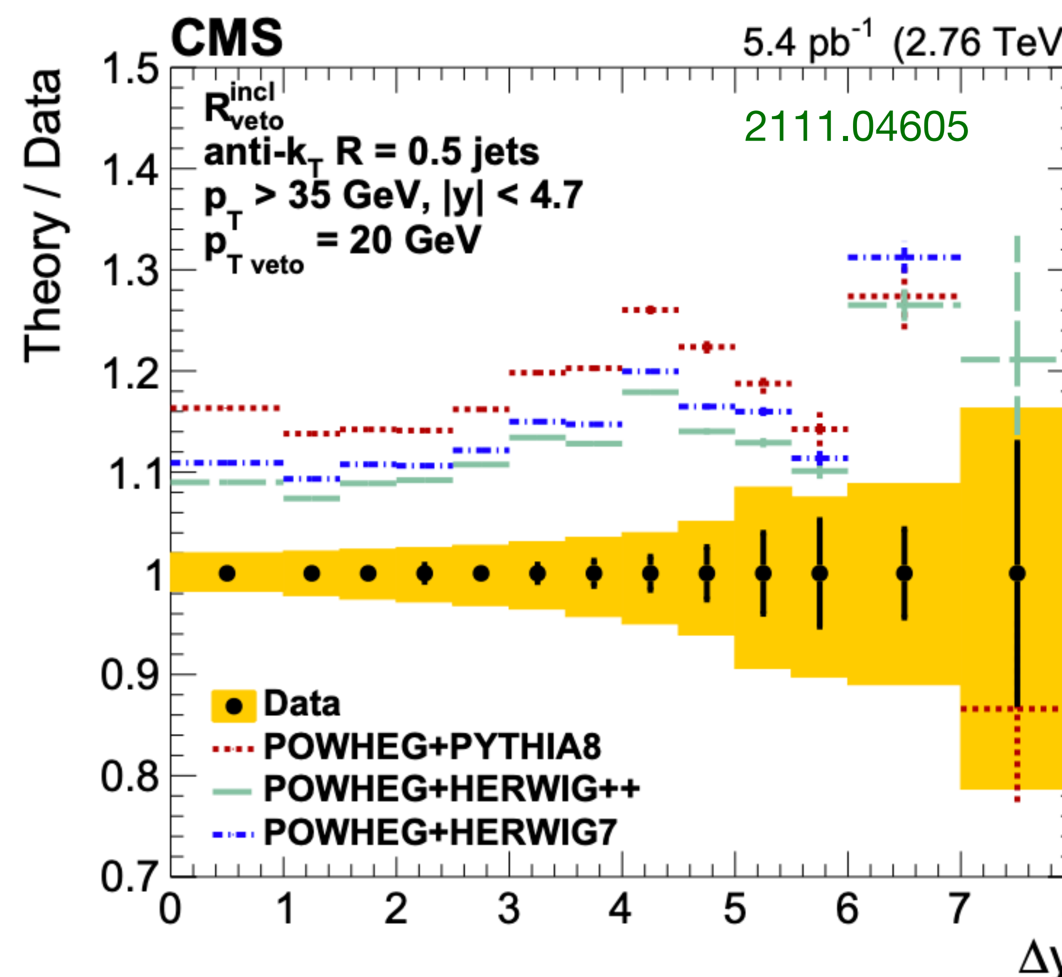
Kang, Lee, DYS, Zhao '22



Jets: push the boundaries of quantum field theory

- **Gap fraction originally suggested on the basis of color flow considerations in QCD** Bjorken ’93
- Forshaw, Kyrieleis, Seymour ’06 **have analyzed the effect of Glauber phases in the exclusive jet cross section directly in pQCD**
  - **Collinear logarithms starting at 4 loops: Super-leading logs**
- **Even 15 years after this effect was discovered, leading order resummation is unknown, process dependence is unknown, …**
  - **At forth order there are 1,746,272 diagrams !!!**
- **We apply renormalization-group approach and obtain the all-order results of leading SLLs**
  Becher, Neubert, DYS ’21 PRL





All-order results of leading Super-Leading Logs

(Becher, Neubert, DYS '21 PRL + '22 in progress)

All-order structure: Kampe de Feriet function (a two-variable generalization of the generalized hypergeometric series, the general sextic equation can be solved in terms of it)

$$\Sigma(v,w) = \sum_{m=0}^{\infty}\sum_{r=0}^{\infty} \frac{(1)_{m+r}(1)_m\left(\frac{1}{2}\right)_r}{(2)_{m+r}\left(\frac{5}{2}\right)_{m+r}} \frac{(-w)^m(-vw)^r}{m!\,r!}$$

$$= {}^{1+1}F_{2+0}\left(\begin{matrix}1:1,\frac{1}{2};\\ 2,\frac{5}{2}: \quad ;\end{matrix}, -w, -vw\right)$$

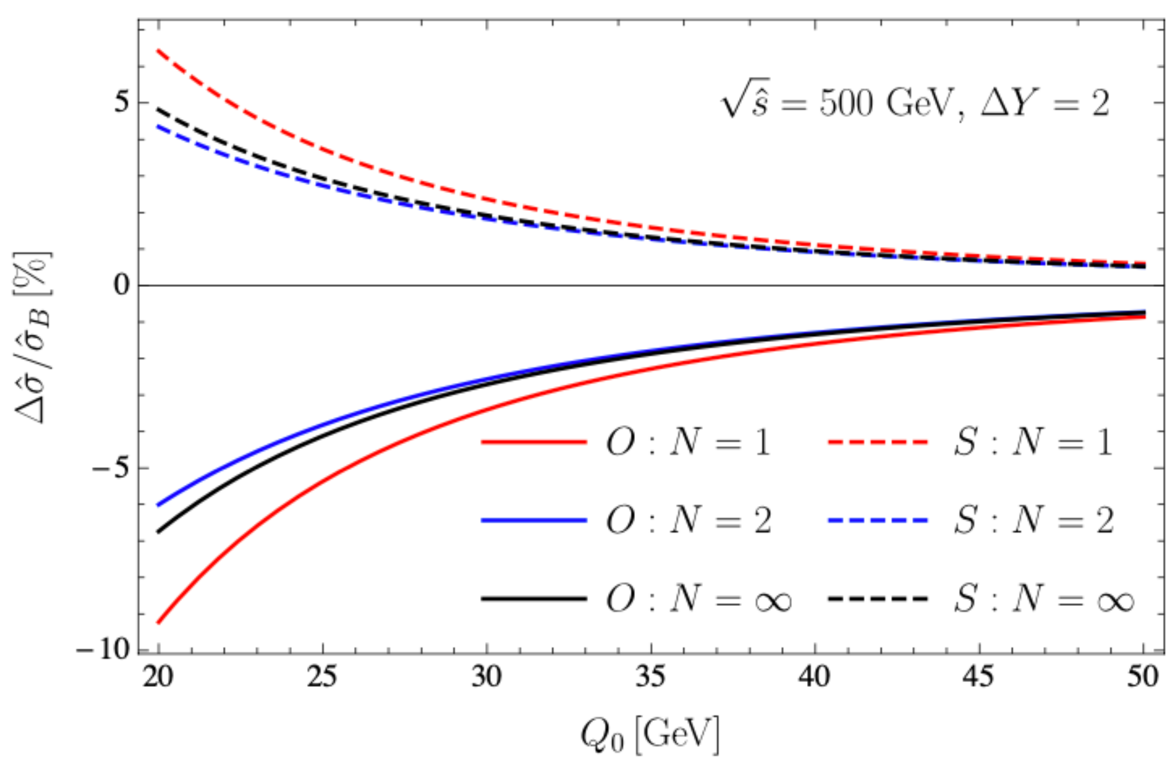
$$w = \frac{N_c\alpha_s(\bar{\mu})}{\pi}\ln^2\left(\frac{\mu_h}{\mu_s}\right)$$

Sudakov suppression of the superleading logarithms is weaker than the one present for global observables

Global logs ⟶ $e^{-\omega}$

Superleading logs $\xrightarrow{\omega\to\infty}$ $\frac{1}{\omega}$

Numerical results



Red: Four loop **Blue: Five loop** **Black: all order**

Summary

- **Jets and jet substructures**
  - **display QCD over a wide range of energy scales, from colliding energy to the hadronization energy.**
  - **contain important signatures of exotic physics, such as Higgs and top quarks**
  - **boost the searcher for new physics**
  - **push the boundaries of QFT**
- **Other interesting topics not be covered: machine learning; jet probe in QGP ……**

Thank you