

- A new framework on global analysis of fragmentation functions
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	- based on 2305.14620 with ChongYang Liu, XiaoMin Shen, Bin Zhou and 2401.02781 with ChongYang Liu, XiaoMin Shen, HongXi Xing, YuXiang Zhao
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✦ 1. Introductions

✦ 2. Fragmentation functions and QCD factorization

✦ 4. Outlook and Summary

✦ 3. A new global analysis on FFs to light charged hadrons

Outline

✦ Quantum Chromodynamics is a beautiful theory with enormous success, rich phenomena and powerful predictions; yet still more to come after 50 years with future facilities and developments of lattice energy weights. These observables can be expressed as correlations of energy flows of energy flows of energy f neory with enormous success, rich phenomena and power orders, making precise experimental measurements valuable inputs for testing fundamental the years with future facilities and developments of fatti

*E*2*C* = $\frac{1}{2}$ \overline{a} *n* Â $\overline{}$ *ds EiEj* E ² *d*² *d*₂ running coupling constant three-point energy correlator inside jet

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

\n
$$
\sum_{i,j,k}^{m} \sum_{i=1}^{n} \frac{12}{12}
$$
\nFree hadron\n\n
$$
= \sum_{i,j,k}^{m} \frac{12}{12} \text{Free hadron}\n\text{Confinement}\n\text{Pertrivative}\n\frac{12}{12} \text{Total}
$$
\n
$$
8 = \sum_{i,j,k}^{m} \frac{12}{12} \text{Total}
$$
\n
$$
10^{-3} = \frac{12}{12} \text{Total}
$$
\n
$$
10^{-2} = \frac{12}{12} \text{Total}
$$

 $T_{\rm eff}$ is the error bars for the correlated data distribution account for the input data distribution $T_{\rm eff}$ Experimental uncertainties are presented by error bands around data. Three distinct regions scaling violation in the parton of **intervalse control process described by the Dokshitzer-Gribov-Lipatov-Lipatov-Lipatov-Lipatov-Lipatov-Lipatov-Lipatov-Lipatov-Lipatov-Lipatov-Lipatov-Lipatov-Lipatov-Lipatov-Lipatov-Lipa** Altarelli-Parisi (DGLAP) evolution equation [52, 53], and is a function of *aS*(*Q*), where Q rep-

QCD at its 50 years scale variations. From the CMS Collaboration we quote for the inclusive jet production at Ô*s* = 7 and 8 Tev, and for digital production at Tev the values that have been derived in a simulation of the value of fit with the PDFs and marked with "*" in the figure. The last point of the inclusive jet sub-field

simulations partially includes data used already for the other data points, *e.g.* the CMS result at 7 TeV. **The multimest are based on 3-jet cross sections of a section of 3-jet c**ross sections and 3-jet contains to 2-jet radictions unt still more to come after predictions, yet still filore to come and

the associated analyses provide valuable new values α *–s* at energy scale of α at α at α at α at α now extending up to all α .

degree of QCD perturbation theory used in the extraction of *–^s* is indicated in brackets (NLO: next-to-leading order; NNLO 2022]

✦ QCD predictions to observables rely on both perturbative calculations describing interactions of highenergy quarks and gluons, as well as non-perturbative inputs and hadronization corrections since only $\ddot{}$ nteraci actions of high-
..

color-neutral hadrons appearing in both the initial and final states

inclusive cross sections at pp collisions

Standard Model Total Production Cross Section Measurements

Observables at colliders

5

Jet charge and flavor-tagging \mathbf{r} construction the jet charge \mathbf{r}

There is no unique way to define the jet charge. The most naïve construction is to add up the charge of α fragmentation functions or from models implemented in MC generators

 \mathbf{F} , plot of the ROC curve for up versus down \mathbf{F} u/d quark separation **[2103.09649]**

◆ Jet charge is a typical observable requiring knowledge on transition of parton to hadrons, especially the distribution of electric charges to hadrons; can be calculated in QCD from first principle based on

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✦ In its simplest form, fragmentation functions (FFs) describe number density of the identified hadron wrt the fraction of momentum of the initial parton it carries, as measured in single inclusive hadron production, e.g., from single-inclusive annihilation (SIA), semi-inclusive DIS (SIDIS), pp collisions FFS) descripe numper density of the identified nadron wrt
Carries as measured in single inclusive hadron productiv

Single inclusive hadron production

full description of final state hadrons single inclusive hadron production/observable $\frac{1}{2}$ $\$

$$
\frac{1}{\sigma_{\text{tot}}} \frac{d\sigma^{e^+e^- \to hX}}{dz} = F^h(z, Q^2), \quad z = \frac{2E_h}{\sqrt{s}}
$$

• $\frac{1}{2}$ single-include-independent production of unpolarized collinear FFs che acimiento anpotanze d exp. definition of unpolarized collinear FFs 2 *CON E E F***h** E *E F* exp. definition of unpolarized collinear FFs

other forms: polarized FFs, TMD FFs, di-hadron FFs \mathbf{r} separate uses \mathbf{r} is a degrigated \mathbf{r} , \mathbf{r} \mathbf{r} \mathbf{r} \mathbf{r} \mathbf{r} *•* single-inclusive hadron production in proton-proton collisions, *p* + *p* ! *h* + *X*. Related processes like proton-antiproton (*pp*¯) collisions have been studied as well. *F^h* = $\frac{1}{2}$ a. Underlying Event is the structure of the functions of the potatized in the two structure functions **4.**

rely on model and PS at the lowest order

QCD collinear factorization *•* A contribution is to a flavor dependence of ϵ

↑ QUD collinear factorization ensures universal separation o where ˆ*ij* is the partonic cross section to produce partons *i* and *j*, which at LO will be a *qq*¯ pair. in nigh energy scallenings involving initial/initial state nation 3.1 Observation integrated France F
2.1 Observation of the process of

> **[Collins, Soper, Sterman]** which is basical with identical with the form of the form of the evolution equation equation equations for \mathbf{C} mind that the matrix for the time-like splitting functions in (93) is *Pji*, as opposed to *Pij* in the case of ρ *per, Sterman]*

$$
\frac{1}{\sigma_{\text{tot}}} \frac{d\sigma^{e^+e^- \to hX}}{dz} = \frac{1}{\sum_q e_q^2} \left(2F_1^h(z, Q^2) + F_L^h(z, Q^2) \right)
$$

$$
2F_1^h(z,Q^2) = \sum_q e_q^2 \bigg(D_1^{h/q}(z,Q^2) + \frac{\alpha_s(Q^2)}{2\pi} \Big(C_1^q \otimes D_1^{h/q} + C_1^g \otimes D_1^{h/g}\Big)(z,Q^2)\bigg)
$$

$$
\frac{d^3\sigma^{\ell p \to \ell h X}}{dx\,dy\,dz} = \frac{2\pi\alpha_{\text{em}}^2}{Q^2} \left(\frac{1 + (1 - y)^2}{y} 2F_1^h(x, z, Q^2) + \frac{2(1 - y)}{y} F_L^h(x, z, Q^2) \right)
$$

$$
2F_1^h(x, z, Q^2) = \sum_q e_q^2 \bigg(f_1^{q/p} D_1^{h/q} + \frac{\alpha_s(Q^2)}{2\pi} \bigg(f_1^{q/p} \otimes C_1^{qq} \otimes D_1^{h/q} + f_1^{q/p} \otimes C_1^{qq} \otimes D_1^{h/q} \bigg) + f_1^{q/p} \otimes C_1^{qq} \otimes D_1^{h/q} \otimes D_1^{h/q} \bigg) \bigg],
$$

← QCD collinear factorization ensures universal separation of long-distance and short-distance contributions in high energy scatterings involving initial/final state hadrons, and enables predictions on cross sections anaration of long distance and short distance contributions Eparation of fong abiance and short distance continuations state hadrons, and enables predictions on cross sections

- ❖ FFs/PDFs, reveal inner structure of hadrons; nonperturbative (NP) origin, universal, e.g. DIS vs. pp collisions; fitted from data S_{S} and universality of TMD Final works confirmed the universality of TMD Final works \mathcal{L} it was shown, \mathcal{L} it was shown in Refs. In \bullet **→** \bullet **FFS/PUFS, reveal inner structure of nadrons; non**phenomenology, in particular for the Collins function, is compatible with universality.
- [◆] runnings of FFs/PDFs with μ _D/ μ _f are governed by the DGLAP equation 2.7 Evolution \mathbf{r} hadrons this function gets multiplied by 2 if one sums over the hadron spins. The FF *Gh/q* density of longitudinally polarized hadrons in a longitudinally polarized quark, whereas *Hh/q*

, (100)

 σ $\mathbf{e}(Q^2)$ and $\mathbf{e}(Q^2)$ is governed by $\mathbf{e}(Q^2)$ evolutions. Here $\mathbf{e}(Q^2)$ evolutions. Here $\mathbf{e}(Q^2)$ experience to the physical interpretation of the physical interpretation of the physical interpretation obtains the operator definition for *Dh/q* ¹ (*z*), unpolarized collinear FFs, operator definition

◆

$$
D_1^{h/q}(z) = \frac{z}{4} \sum_{K} \int \frac{d\xi^+}{2\pi} e^{ik^-\xi^+} \text{Tr} \left[\langle 0 | \mathcal{W}(\infty^+, \xi^+) \psi_q(\xi^+, 0^-, \vec{0}_T) | P_h, S_h; X \rangle \right. \\ \times \langle P_h, S_h; X | \bar{\psi}_q(0^+, 0^-, \vec{0}_T) \mathcal{W}(0^+, \infty^+) | 0 \rangle \gamma^- \right].
$$

$$
\frac{d}{d\ln\mu^2}D_1^{h/i}(z,\mu^2) = \frac{\alpha_s(\mu^2)}{2\pi}\sum_j \int_z^1 \frac{du}{u}\,P_{ji}(u,\alpha_s(\mu^2))\,D_1^{h/j}\left(\frac{z}{u},\mu^2\right)
$$

FMNLO (fragmentation at NLO in QCD) events in *pp* collisions (p*s* = 13 TeV) consisting of two or more jets. Jets are clustered with anti-*k^T* algorithm with *R* = 0*.*4 and are required to have *pT,j >* 60 GeV and *|*⌘*^j | <* 2.1. The two leading jets are required to satisfy a balance condition *pT,j*1*/pT,j*² *<* 1.5, where *pT,j*1(2)

- accurate to NLO in QCD
	- ❖ automation of fragmentation calculations from arbitrary hard processes at NLO, within SM and BSMs via MG5_aMC@NLO
	- ❖ fast convolution algorithms of partonic cross sections with FFs without repeating the time consuming MC integrations
	- ❖ future goal/generalizations: transverse observables, NNLO corrections

QCD inclusive dijets at LHC
Z-boson tagged jet

2023.05: FMNLOv1.0 first release of FMNLO interfaced with MG5 aMC@NLO.

 \rightarrow FMNLO is a new program for automated and fast calculations of fragmentation cross sections of arbitrary processes. It is based on a hybrid scheme of phase-space slicing method and local subtraction method, (forward or central) in Ref. [57]. The charged tracks are required to have *pT,h >* 0*.*5 GeV and *|*⌘*h| <* 2.5. The results are presented in a di↵erential cross section of 1*/NjdNtrk/d*⇣ with *trk,Z >* 7⇡*/*8 in Ref. [56]. The charged tracks are required to have *pT,h >* 1 GeV and *|*⌘*h| <* ing method and local subtraction method, with p

h MG5 aMC@NL0. **https://fmnlo.sjtu.edu.cn/~fmnlo/ [JG+, 2305.14620]**

[JG+, 2305.14620]

Global data and phenomenological analysis stattering of particulations and the long-distance distance distance distance distance distance distance distance d

phenomenological FFs from global analysis at NLO/NNLO in QCD $\mathcal F$ and $\mathcal F$ are not functions are not functions by constraints by

5 *19. Fragmentation Functions in e*+*e*≠*, ep, and pp Collisions* single incl. production $\tilde{\sigma}_{\text{f}}^{\text{f0}}$ inidentified P_{T}^{f} substantion to $\tilde{\sigma}_{\text{f}}^{\text{f0}}$ intercharged hadrons (SIA & SIDIS) α_{10} & SIDIS) charged hadrons (LHCb) \overline{R} experiments. In Monte Carlo (MC) generations. In Monte Carlo Carlo (MC) generators, phenomenology and models. In Monte Carlo (MC) generators, phenomenology and models. In Monte Carlo Carlo (MC) generators, phenome t^{α} unidentified to death defined to t are used to t and t are t and t are t and t s s and s $\frac{10}{10}$ $\overline{}$ $\frac{10}{100}$ inidentified $p_T^{\text{jet}} < 30 \text{ GeV}$ let framentation to $\frac{100}{100}$ 0 and 0 and 10 $\overline{}$ 10^2 O h t $50 < p_{\rm T}^{\rm jet} < 100 \text{ GeV}$

> ^{π^{\pm}} exact NNLO₁CO
^{ata} 10^{-1} **i** \cdot (10⁻¹) $exact NNLO₁ coefficient functions not$ 10^{-1} 10 $\mathcal{H}^{\text{\tiny H}}$ K^{\pm} *z*

dorfferent depestor well as theory treatments, not converge as well as the case of PDF fits *z* 40^{-2} objittere *z* [−]² 10 [−]¹ 10 Ratio $R\ddot$ 0 0.05 0.1 $\mathbb{M}\oplus$ 0.2 0.25 $0\overline{\mathcal{S}}$ 9.5 to 9.01 8.01 K^{\pm}/π^{\pm} *z z*

 10^{-2} 10⁻¹

$$
z = \frac{\mathbf{p}_{\text{had}} \cdot \mathbf{p}_{\text{jet}}}{|\mathbf{p}_{\text{jet}}|^2}, \quad F(z) = \frac{1}{N_{Z+\text{jet}}} \frac{dN_{\text{had}}(z)}{dz}
$$

← Measurements are available from colliders SLAC, LEP, HERA, RHIC, LHC and fixed-target HERMES, COMPASS experiments for various charged hadrons as well neutral hadrons; several major groups provide part in the scattering process. Hence, hence p is described by the scattering particles is described by the scattering by p nts for various charged hadrons as well heutral hadrons; several

> $A K \omega$ $H \times N$ S, DSS, NNFF etc. $\frac{10}{\pi^2}$ **30** $\frac{10}{\pi^2}$ **30** $\frac{10}{\pi^2}$ **30** $\frac{10}{\pi^2}$ $\widehat{\mathbf{w}}$ $\mathbb{E}_{10^2}^{\mathbb{F}}$ and $\mathbb{E}_{10^2}^{\mathbb{F}}$ and $\mathbb{E}_{10^2}^{\mathbb{F}}$ and $\mathbb{E}_{10^2}^{\mathbb{F}}$

global analysis

z

z **[2208.11691] [1607.02521 for a review]**

z

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parametrization of FFs to charged pion/kaon/ proton at initial scale (Q=5 GeV): and analysis of \mathbb{F}_{p} requires a parametrization for \mathbb{F}_{p} requires a parametrization for \mathbb{F}_{p} arametrization of FFs to charged pion/Raon/ patrization of FEs to charged nion/ alion of **the conduct of product**

A new global analysis of FFs global analysis, including data from SIA, SIDIS and *pp* ew global analysis of FFS tation measurements in a global analysis for light charged σ

✦

hadrons. The comprehensive analysis provides a state-ofartshing a new framework on global and *Theoretical setup and data characteristics.–* The global

termination of FFs of Γ Fs of various charged hadrons from a state of various charged hadrons from a state o

- ❖ a joint determination of FFs to charged pion, kaon and proton at NLO in QCD (63 parameters) including estimation of uncertainties with Hessian sets of the various nominal scales is minimal scales in the various σ as well a include the theoretical uncertainties. The term of the term a joint determines pp_p collisions, we incorporate measurements of the measureme uncertamined virul reduction from from from $\frac{1}{2}$ \mathbf{i}
- ❖ apply a strong selection criteria on the **Extra Externation is a** *Z* isolated photon is a *z* boson recoiled photon processes to **Example 12** ensure validity of LT factorization and perturbative calculations (z>0.01 and Eh/ $p_{T,h}>4$ GeV) tation is the installation inside \mathbf{z} and \mathbf{z} \bullet apply a strong selection criteria $\overline{}$ $t = \frac{1}{\sqrt{2}}$ ensure
- **The Adrian** including theory uncertainties (residual **interest into the covariance matrix** scale variations) into the covariance matrix ton, while the residual contribution from our contribution from our contribution from our contribution from ou
The residual contribution from our contribution from our contribution from our contribution from our contribut , *K[±]* and *p/p*¯ production from fragmentation inside *z* (*z*) share α
- ❖ use fast interpolation techniques for relations of cross sections which largely increase efficiency of the global fit \therefore \therefore ally verse hadron production commique. or of di↵erent collision energies are considered to mini-

to be fully correlated among points in each subset of the

⇡*[±]*

mize the impact of normalization uncertainties. In the

well as from OPAL, as from OPAL, ALEPHI, and SLD at the OPAL, and SLD at the OPAL, and SLD at the OPAL, and SL

$$
zD_i^h(z,Q_0) = z^{\alpha_i^h} (1-z)^{\beta_i^h} \exp\left(\sum_{n=0}^m a_{i,n}^h(\sqrt{z})^n\right)
$$

Z-pole [40, 41]. These measurements encompass the pro-

^s (*z,Q*0) and *D*⇡⁺

\blacksquare \mathbf{r} \mathbf{r} \mathbf{r} \mathbf{r} , \mathbf{r} as \mathbf{r} , as \mathbf{r} **[JG+, 2401.02781 and work in preparation]**

TABLE VI: Similar to Tab. V, but for the parton-to-*K*⁺ FFs. There are 20 d.o.f. in total.

time-like splitting kernels to maintain consistency with the constant of the constant of the constant of the c

^s (*z,Q*0) and *D*⇡⁺

zD^h

 \rightarrow Establishing a new framework on global analysis of fragmentation functions to identified charged hadrons, including charged pion, kaon and proton, using most recent data from SIA, SIDIS, and pp collisions data. These uncertainties are estimated by the half width \mathbf{I} s <mark>of</mark> inagmentation functions to identified *n*_p *m*_p term of *z f*_{*F*} *f*_{*F*} *n*_{*R*} *f*_{*F*} *<i>n*_{*R*} *n*_{*R*} *<i>n***_{***R***}** *n***_{***F***}** *and p_l**<i>n***_{***F***}** *n*_{*F*} *and pl*_{*n*} *and pl*_{*n*} *and pl*_{*n*} *and pl*_{*n*} *and pl*_{*n*} *and pl*_{*n*} *and µD/µD,*⁰ = *{*1*/*2*,* 1*,* 2*}*. The impact of di↵erent choices $\frac{1}{2}$

multiplied by the jet cone size for fragmentation inside σ fragmentation inside σ

the jet \mathcal{Z} are included in the jet \mathcal{Z} are included in the included

covariance matrix of 2 calculations, and 2 calculations, and are assumed are assumed are assumed assumed assum
The assumed are assumed as a calculations, and are assumed as a calculations, and are assumed as a calculation

n=0

S_{ol} *n* A_{ion} of A_{ol} A_{on} Selection of data

productions, due to the development of FMNLO ALICE[2] 5.02 120(*pp*) [2*,* 20] GeV ⇡*, K, p K/*⇡*, p/*⇡ 34 ◆ For the first time the jet fragmentation data from LHC have be *stare instants are jet nagmentation state nome Eric nare* se TABLE I: Selected inclusive hadron prodcution data sets on hadron (ion) colliders used in the fit, together with the productions, que to the development of Fivincular hadrons, the observable used in the fit α

✦ For the first time the jet fragmentation data from LHC have been incorporated into the global analysis of FFs to light charged hadrons, including from processes of incl. jet, dijet, Z or photon tagged jet

$\mathsf{L}\mathsf{L}\mathsf{C}$ moscurements for hadron inside jot shown here, such as ⇢⁰. For ALICE 2.76TeV and 5TeV, we only use *pT ,h >* 2 GeV data. The STAR Au-Au data and measurements (jet fragmentation) luminosity, so only number of events are shown here, The STAR ¯*p/p* data set is not used in the fit. LHC measurements for hadron inside jet

of data points after data selection. The luminosity of ALICE13 depends on particle species. ⇡*, K, p* denote

- cuts, identified hadrons, final states, anti-*k^T* jet radius *R^j* , cuts on jets or/and hadrons, the observable, and the ◆ LHC measurements on hadron inside jet provide essential inputs $\frac{1}{2}$ back-to-back matrix with with with residence to the *leading in* the *Linematic coverage* hath in though no separation with which reconstructed the definition of α , *i*, *position of the definition of a p* energy scale Q and in momentum fraction z for u/d/g flavor separation with wide kinematic coverages, both in
- \bullet In dijets or inclusive jets production, low p_T and central (high p_T tagged jets are more likely from u/d quarks and forward) jets are mostly initiated by g(u-quark); Z or photon

kinematic/flavor coverage (LO) for ATLAS jet fragmentation

Selection of data

✦ Other data include ratios of inclusive production rates of different hadrons measured in pp collisions, single incl. hadron production from SIA (w/wo heavy-flavor tagging) mostly at Z-pole, and incl. hadron

incl. hadron production at RHIC and LHC (pp) $\frac{1}{2}$ \blacksquare and a production at Krit and Lric (pp)

production in SIDIS from HERA and COMPASS, for identified or unidentified charged hadrons H1[13] ³¹⁸ 44 pb¹ *^Q*² ²[175,20000] GeV² *^h[±] ^D* ⌘ ¹ *dnh[±]*

c.m. energy, number of events, cuts, the identified hadrons, the identified hadrons, the fit, and the number of the number of the number of the fit, and the number of the fit, and the number of the fit, and the number of t incl. hadron production at Z-pole (SIA) incl. hadron production at HE (considering the small ^p*^s* and *^Eh*), we include data on the cross section ratio of *p/p*¯ instead of the absolute cross

incl. hadron production at HERA and COMPASS (SIDIS)

determination of Hessian uncertainties Fig. 110 and the momentum fraction of the model subsets of the model subsets of the model subsets of the model o

overall agreement: χ2 breakdown to sub-groups for the best-fit lower limit of *z* of the subset and the width of each colored overali agreement: **x**² breakdown to

 \mathcal{L}

 $\frac{1}{2}$ and $\frac{1}{2}$ is the global data sets (1370 points in total) are found, χ^2/N well below 1; individual agreements to the 138 sub-datasets are also tested, motivating usage of a tolerance $\Delta \chi^2 \sim 2$ in It is important to assess the agreement for each of the usage of a tolerance $\Delta X^2 \sim Z$ in

◆ We arrive at a best-fit of the charged pion, kaon and proton FFs together with 126 Hessian error FFs, two for each of the eigenvector direction; FFs are generally well constrained in the region with z~0.1-07

FFs to light charged hadrons

- ❖ our results show an uncertainty of 3%, 4% and 8% for FFs of gluon to pion at z=0.05, 0.1 and 0.3, respectively
- ❖ similarly an uncertainty of 4%, 4% and 7% for FFs of u-quark to pion, kaon and proton at $z=0.3$, respectively
- ❖ FFs of heavy-quarks are well constrained for z between 0.1~0.5 due to the tagged SIA events at Z-pole measurements
- ❖ a preference for larger FFs of s quark to pion possibly due to decays of short-lived strange hadrons
- ❖ high precision of gluon FFs is mostly due to the data of jet fragmentation from the LHC

✦ Our new extractions on FFs are compared to previous determinations from other groups (DSS and NNFF) for the charge-summed pion, kaon and proton; large discrepancies are found and will need further

clarifications

FFs to light charged hadrons

- ❖ We find general agreement between ours and DSS for FFs of u and d quarks to pion, and of s quark to kaon
- ❖ however, large discrepancies are found for FFs to protons and for FFs of gluon to all three charged hadrons
- ❖ NNFFs show larger uncertainties in general and can even become negative in some kinematic regions
- ❖ future works involving coordinations from different groups will be needed for clarifications on discrepancies

FFs (charge-summed) vs. momentum fraction

✦ FFs have the interpretation of number densities of hadrons and satisfy various fundamental sum rules as derived from first principle, including momentum sum rule, charge sum rule, etc.; momentum sum rules

are tested with the extracted FFs and find consistency

Test of sum rules

momentum sum rule:
$$
\sum_{h} \int_{0}^{1} dz z D_{i}^{h}(z, Q) = 1
$$
with finite cutoff: $\langle z \rangle_{i}^{h} = \int_{z_{min}}^{1} dz z D_{i}^{h}(z, Q)$

arried by individual/all light $\frac{1}{2}$ P d hadrons at $Q=5$ GeV 1.25 *d* and *s* quarks, carried by various charged hadrons (⇡*[±] p* and *p* and *p* and *p* and *p* and *u* and using the central values and uncharged hadrons at Q=5 GeV momentum carried by individual/all light

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✦ Future run of Circular Electron Positron Collider (CEPC) will collect high-quality and diverse data on

hadron production, sufficiently for precision determination of fragmentation functions alone

Opportunities with CEPC

CEPC operation plans **[a projection study on FFs from CEPC data alone is in preparation]**

- ❖ producing qqbar samples at various energies with high statistics, important for u/d separation
- ❖ separated into bins of different polar angles for additional flavor and charge separation
- ❖ heavy-quark enriched samples and gluon samples from Higgs hadronic decays
- ❖ further quark flavor and charge separation from W-boson production with hadronic decays

Nuclear physics: hadron suppression and \mathbb{N} **1. Interpretera**

are thus important for studying properties of Q_{\square} matter, especially jet transportation effects $\frac{1}{2}$ as important for studying properties of GOT matter, especially

\mathcal{L} medium (QGP) induced radiations incl. hadron potential system of a deconfined system of a deconfined system of a mediations of a mediation of a med

✦

$$
\tilde{D}_{h/d}(z_d, \mu^2, \Delta E_d) = (1 - e^{-\langle N_g^d \rangle}) \left[\frac{z_d'}{z_d} D_{h/d}(z_d', \mu^2) + \langle N_g^d \rangle \frac{z_g'}{z_d} D_{h/g}(z_g', \mu^2) \right] + e^{-\langle N_g^d \rangle} D_{h/d}(z_d, \mu^2)
$$
\n(13)

T*Ez* is the momentum fraction of a set of a se **[2208.14419] Figure 1:** Left: Examples of the sensitivity of various perturbative probes to quark-gluon matter properties in A-A collisions [4]. Right: "Jet quenching" event displays in central Pb-Pb collisions at the LHC: monojet-

uncertainties are shown as error bars around the data points. The data points in the total normalization uncertainty (pp and p and PbPb) is indicated in each panel by the vertical scale of the box centered at *p*^T = 1 GeV*/c* and *R*AA = 1. incl. hadron production: Pb-Pb vs pp collisions

is the 1910.07678] fluid ˆ*^q* = ˆ*q*(*T*)*p^µ·uµ/p*⁰ depends both on the fluid velocity pp cross section, defined as *^T*AA ⁼ ^h*N*colli/*s*pp

modifications to FFs as functions of jet

R

Summary

✦ FMNLO a new program for automated and fast calculations of fragmentation processes at NLO in QCD is now publicly available, which is desirable for global analysis of FFs providing much improved efficiency

✦ We perform a new global analysis of FFs to identified charged hadrons, including charged pion, kaon and proton, at NLO in QCD, using most recent data from SIA, SIDIS, and pp collisions; constraints on gluon

✦ Fragmentation functions (FFs) are essential non-perturbative inputs for precision calculations of hadron

- production cross sections in high energy scattering from first principle of QCD
- and capability for arbitrary hard processes
- FFs are much improved and large discrepancies are found wrt. previous determinations
- hadrons and medium modified FFs, projections for future e+e- colliders, etc.

✦ Ongoing developments include extensions to higher orders in QCD (NNLO), studies of FFs to neutral

Summary

✦ FMNLO a new program for automated and fast calculations of fragmentation processes at NLO in QCD is now publicly available, which is desirable for global analysis of FFs providing much improved efficiency

- production cross sections in high energy scattering from first principle of QCD
- and capability for arbitrary hard processes
- FFs are much improved and large discrepancies are found wrt. previous determinations
- hadrons and medium modified FFs, projections for future e+e- colliders, etc.

✦ We perform a new global analysis of FFs to identified charged hadrons, including charged pion, kaon and proton, at NLO in QCD, using most recent data from SIA, SIDIS, and pp collisions; constraints on gluon

Thank you for your attention!

✦ Fragmentation functions (FFs) are essential non-perturbative inputs for precision calculations of hadron

✦ Ongoing developments include extensions to higher orders in QCD (NNLO), studies of FFs to neutral