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Kaon parton distributions:
Higgs modulation of emergent mass

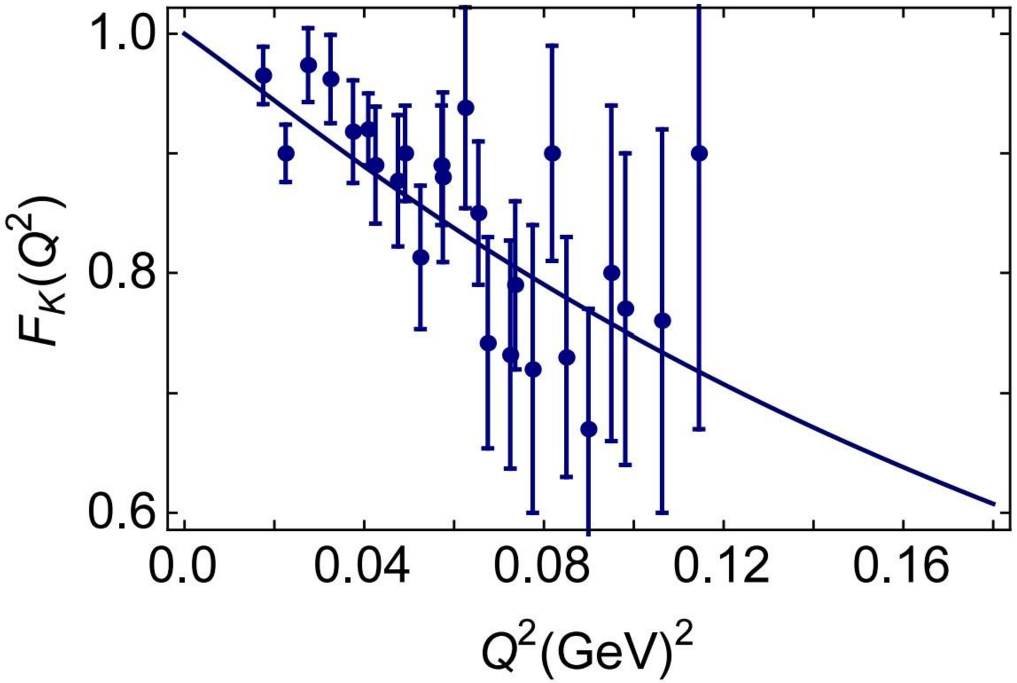
Perceiving the Emergence
of Hadron Mass through
AMBER@CERN

6 - 7 August 2020
CERN, Geneve - Switzerland

Kaon

- Kaon was discovered in 1947
- Today, 70 years later (!!), little is known about kaon structure.
- Regarding the pion, Nature's closest approximation to a Nambu-Goldstone (NG) mode, position is a bit better
- Unsatisfactory for many reasons, primarily:
    - Standard Model has two sources of mass.
        - Explicit – generated by couplings to Higgs-boson
        - Emergent – dynamical consequence of strong interactions
            - Responsible for the $m_N \sim 1$ GeV mass-scale that characterises nuclei
            - Origin of more than 98% of visible mass.
- Emergent hadronic mass (EHM) is dominant for all nuclear physics systems
- But Higgs mechanism introduces modulations … crucial to the evolution of the Universe, *e.g*. CP-violation, discovered in neutral kaon decays

Even the radius is uncertain



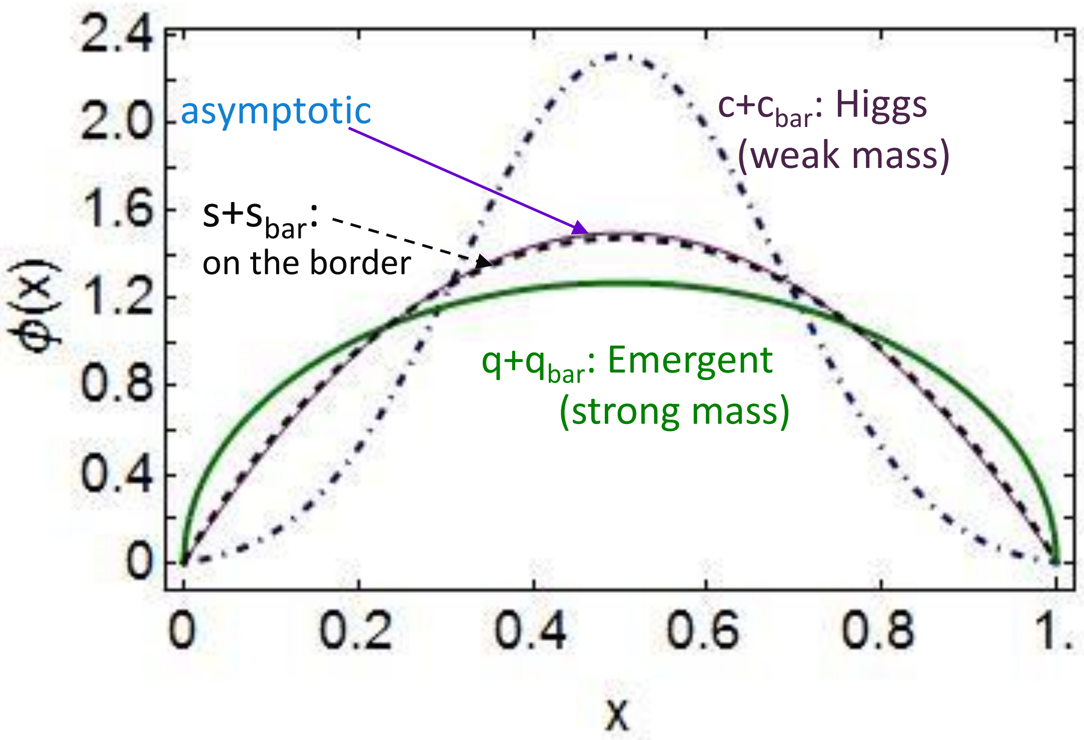
Kaon

- Knowledge of kaon structure is crucial because it provides a window onto interference between Higgs boson effects & EHM
- E.g. within quantum chromodynamics (QCD), π and K mesons are identical without a Higgs mechanism
  - π & K are NG modes whose common properties are determined by EHM.
- Switch on Higgs couplings:
  - Lagrangian mass of the s-quark becomes ≈ 27-times greater than the mean u, d quark mass;
  - Yet, ratio of K and π decay constants changes by only 20%: $\frac{f_K}{f_\pi} \approx 1.2$
  - $SU_f(3)$ breaking in ultraviolet = 3000%
  - $SU_f(3)$ breaking in infrared = 20%
  - Effect on structure functions?

Parton distribution amplitudes of S-wave heavy-quarkonia
Minghui Ding, Fei Gao, Lei Chang, Yu-Xin Liu and Craig D. Roberts
arXiv:1511.04943 [nucl-th], Phys. Lett. B **753** (2016) pp. 330-335

Emergent Mass *vs.* Higgs Mechanism

- When does Higgs mechanism begin to influence mass generation?
- limit $m_{\text{quark}} \to \infty$
  $\varphi(x) \to \delta(x-½)$
- limit $m_{\text{quark}} \to 0$
  $\varphi(x) \sim (8/\pi)\,[x(1-x)]^{½}$
- Transition boundary lies just above m_{strange}
- *Hence … Comparisons between distributions of truly light quarks and those describing strange quarks are ideally suited to exposing measurable signals of emergent mass in counterpoint to Higgs-driven effects*

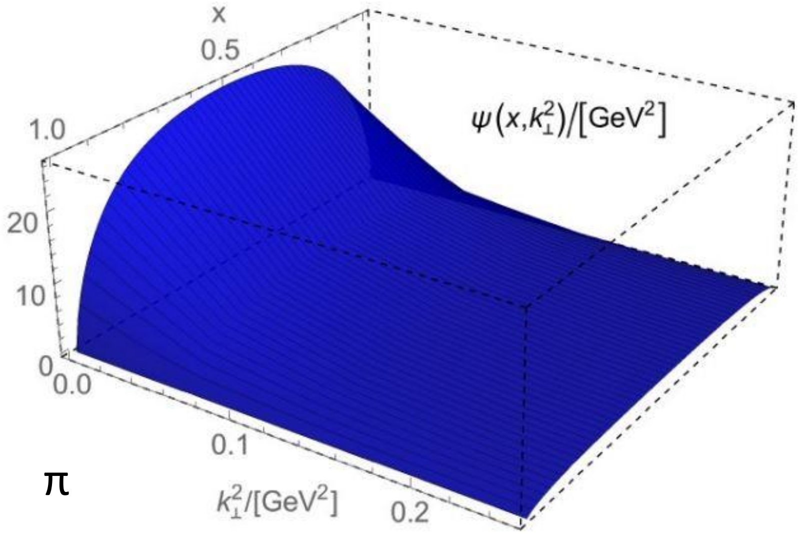


Light Front Wave Function

- In many respects, a hadron’s LFWF is the key.
- LFWF correlates all observables
- EHM is expressed in every hadron LFWF
- The “trick” is to find a way to compute the LFWF

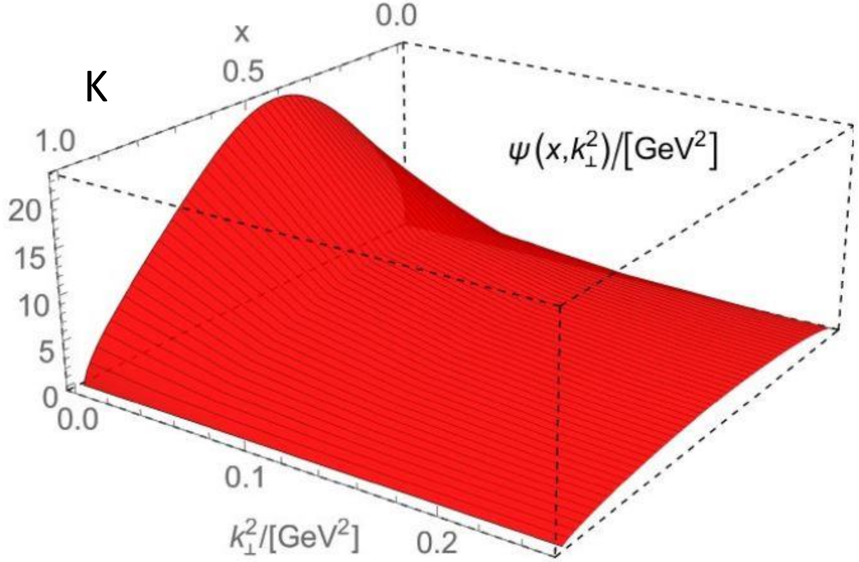
- Experiments sensitive to differences in LFWFs are sensitive to EHM

- Excellent examples are π & K DAs and DFs
  - Two sides of the same coin
  - Accessible via different processes
  - Independent measurements of the same thing
  - Great check on consistency



π

K



PDAs & PDFs

- Relationship between leading-twist PDAs and valence-quark PDFs, expressed via a meson's light-front wave function (LFWF):

$$\varphi(x) \sim \int d^2k_\perp \psi(x, k_\perp^2)\,,$$

$$q(x) \sim \int d^2k_\perp |\psi(x, k_\perp^2)|^2$$

- Given that factorization of LFWF is a good approximation for integrated quantities, then at the hadronic scale, ζ_H:

$$q_{\pi,K}(x;\zeta_H) \propto \varphi^q_{\pi,K}(x;\zeta_H)^2$$

Proportionality constant is fixed by baryon number conservation

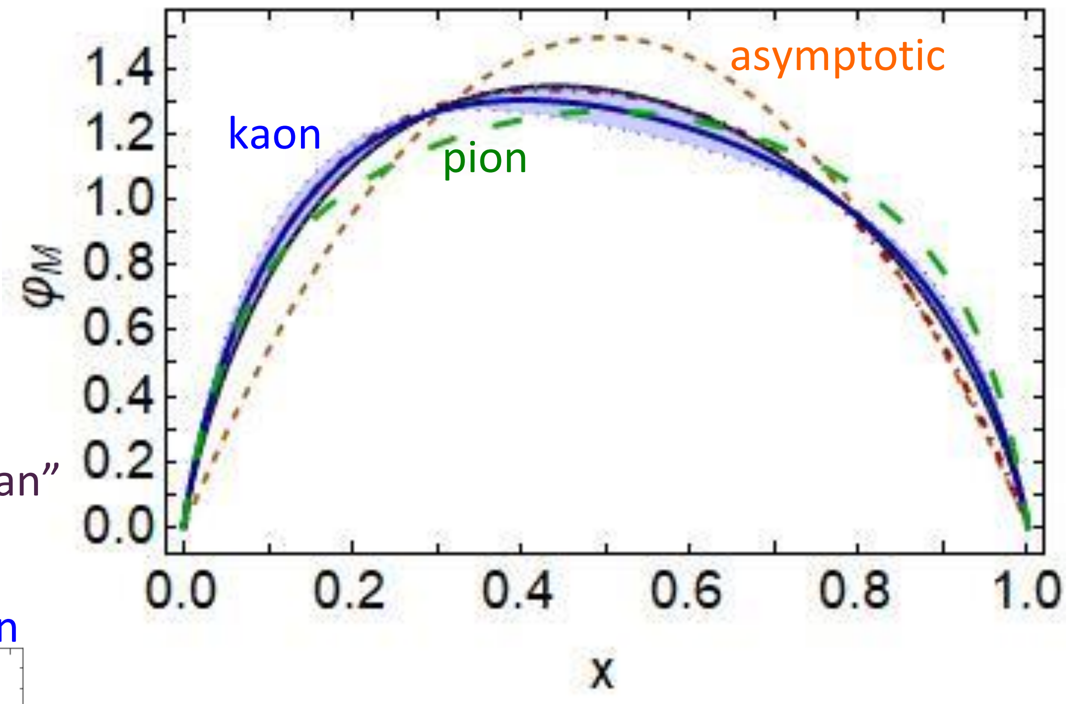
- Owing to parton splitting effects, this identity is not valid on $\zeta > \zeta_H$.

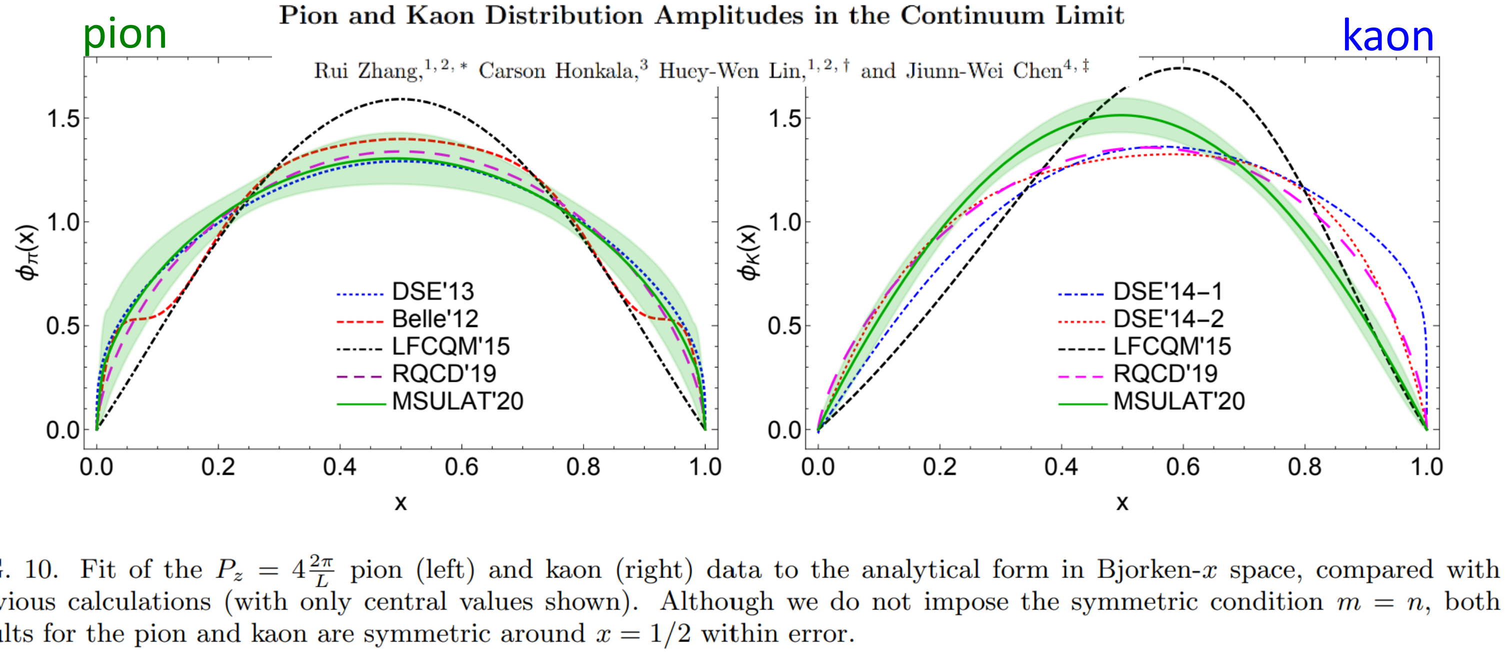
(Think about DGLAP and ERBL regions for a GPD.)

- Nevertheless, evolution equations are known; so the connection is not lost, it just metamorphoses.

Meson leading-twist DAs

- Continuum results exist & lQCD results arriving
- Common feature = broadening
- Origin = EHM
- NO differences between π & K if EHM is all there is
  - Differences arise from Higgs-modulation of EHM mechanism
  - "Contrasting π & K properties reveals Higgs wave on EHM ocean"





Pion and Kaon Distribution Amplitudes in the Continuum Limit

Rui Zhang,[1,2,*] Carson Honkala,[3] Huey-Wen Lin,[1,2,†] and Jiunn-Wei Chen[4,‡]

FIG. 10. Fit of the $P_z = 4\frac{2\pi}{L}$ pion (left) and kaon (right) data to the analytical form in Bjorken-x space, compared with previous calculations (with only central values shown). Although we do not impose the symmetric condition $m = n$, both results for the pion and kaon are symmetric around $x = 1/2$ within error.

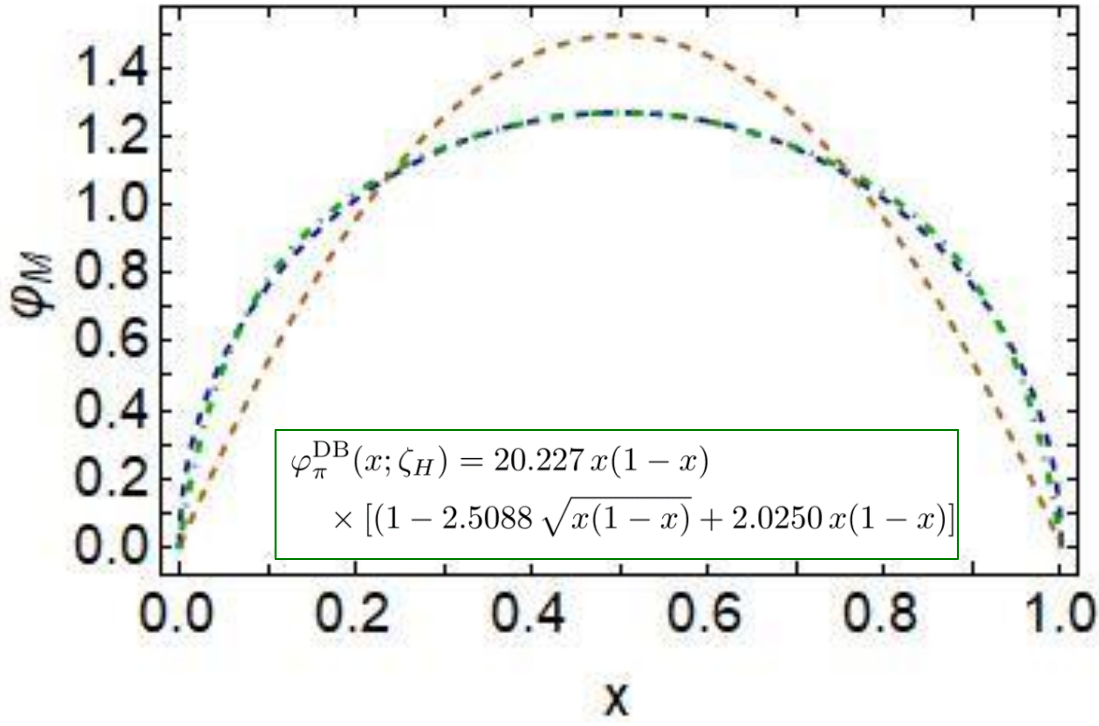
- Kaon DA vs pion DA
  - almost as broad
  - peak shifted to x=0.40(5)
  - $\langle \xi^2 \rangle = 0.24(1)$, $\langle \xi \rangle = 0.035(5)$
- ERBL evolution logarithmic
- Broadening & skewing persist to *very* large resolving scales – beyond LHC

Meson leading-twist DAs and valence-quark DFs

- Broadening need not and should not disturb the DA's endpoint behaviour

  QCD: $\varphi(x) = x\,(1-x) f(x), f(x \simeq 0) = constant_1, f(x \simeq 1) = constant_2$
- Many models that express EHM-induced broadening violate this constraint
- Typically not a problem, unless endpoint behaviour is taken too seriously
- Example AdS/QCD: $\varphi(x) = \frac{8}{\pi}\sqrt{x(1-x)}$
- Practically identical to the continuum prediction that preserves QCD constraint:

  blue dashed *vs* green dot-dashed
  - However, AdS/QCD practitioners use DA to argue for $x \simeq 1 \Rightarrow q^\pi(x;\zeta_{\rm H}) \propto (1-x)^1$
  - Endpoint behaviour taken "too seriously"


$$\varphi_\pi^{\rm DB}(x;\zeta_H) = 20.227\,x(1-x) \times [(1 - 2.5088\,\sqrt{x(1-x)} + 2.0250\,x(1-x)]$$

Pion DA & form factor

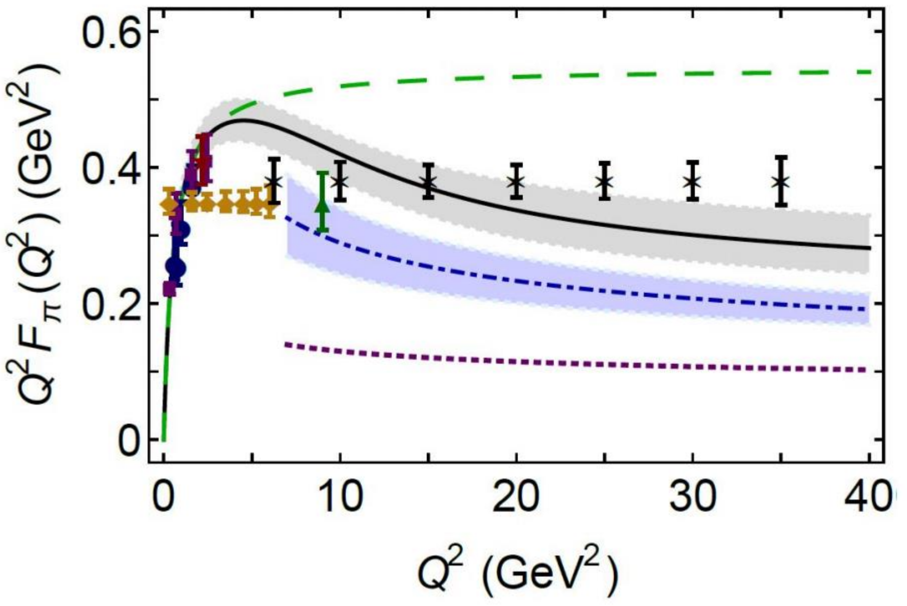
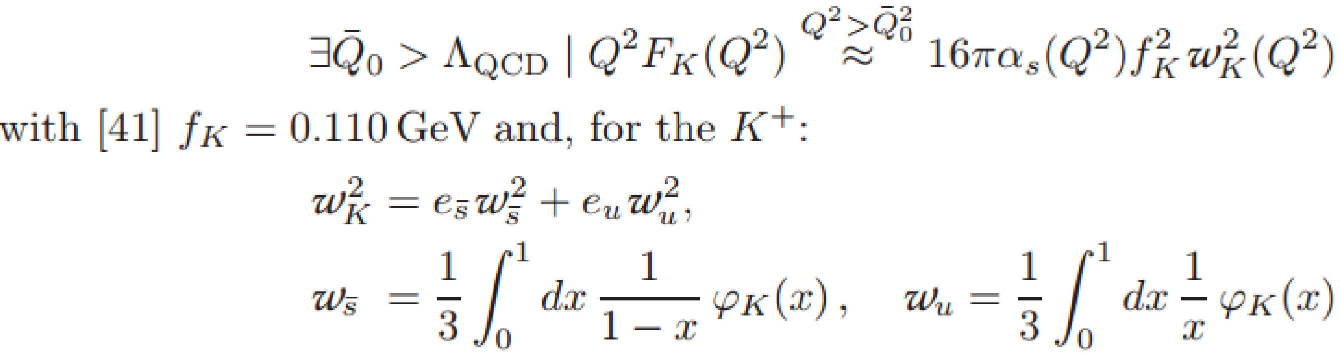


FIG. 9: Projected EIC pion form factor data as extracted from a combination of electron-proton and electron-deuteron scattering, each with an integrated luminosity of 20 fb^{-1} – black stars with error bars. Also shown are projected JLab 12-GeV data from a Rosenbluth-separation technique – orange diamonds and green triangle. The long-dashed green curve is a monopole form factor whose scale is determined by the pion radius. The black solid curve is the QCD-theory prediction bridging large and short distance scales, with estimated uncertainty [41]. The dot-dashed blue and dotted purple curves represent the short-distance views [79–81], comparing the result obtained using a modern DCSB-hardened PDA and the asymptotic profile, respectively.

- QCD is not found in scaling

  … QCD is found in scaling violations
- Continuum predictions
  - Match existing data
  - Suggest that JLab 12 could potentially be first to reveal scaling violations in a hard-scattering process = see QCD in a hard-scattering process
- Simulations indicate that EIC and EicC are certainly capable of doing so.
- Normalisation of the form-factor curve is a measure of the level of DA broadening; hence, size of EHM

Kaon Form Factor



$$\exists \bar{Q}_0 > \Lambda_{\rm QCD} \mid Q^2 F_K(Q^2) \overset{Q^2>\bar{Q}_0^2}{\approx} 16\pi\alpha_s(Q^2) f_K^2 w_K^2(Q^2)$$

with [41] $f_K = 0.110\,{\rm GeV}$ and, for the K^+:

$$w_K^2 = e_{\bar{s}} w_{\bar{s}}^2 + e_u w_u^2 ,$$

$$w_{\bar{s}} = \frac{1}{3}\int_0^1 dx\, \frac{1}{1-x}\,\varphi_K(x)\,, \quad w_u = \frac{1}{3}\int_0^1 dx\, \frac{1}{x}\,\varphi_K(x)$$

- QCD … “ultraviolet” behaviour of the kaon form factor is “simple”
  - Power law = 2
  - Anomalous dimension ⇒ additional ${}^{1}/_{\ln Q^2}$ suppression
- At any experimentally accessible scale, normalisation is set by two EHM scales
  - f_K & $\omega_u(x) = \omega_{\bar{s}}(1-x)$
- At any experimentally accessible scale, ratio of kaon to pion form factors measures Higgs modulation of EHM
- $\dfrac{F_{\bar{s}}^K(Q^2)}{F_u^K(Q^2)}$ measures ratio of strange and normal matter distributions inside kaon
- $\dfrac{f_K^2}{f_\pi^2} = 1.4$ … $\dfrac{\omega_K^2}{\omega_\pi^2} \approx 1.0$ because even though K DA is skewed, the broadening is similar

… So if EHM is dominant, then the ratio of form factors should not exceed ≈ 1.4

*Exposing strangeness: projections for kaon electromagnetic form factors, Fei Gao et al., arXiv:1703.04875 [nucl-th], Phys. Rev. D **96** (2017) 034024*

Kaon form factor - flavour separation

$$\exists \bar{Q}_0 > \Lambda_{\rm QCD} \mid Q^2 F_K(Q^2) \overset{Q^2 \geq \bar{Q}_0^2}{\approx} 16\pi\alpha_s(Q^2) f_K^2 w_K^2(Q^2)$$

with [41] $f_K = 0.110\,\text{GeV}$ and, for the K^+:

$$w_K^2 = e_{\bar{s}} w_{\bar{s}}^2 + e_u w_u^2,$$

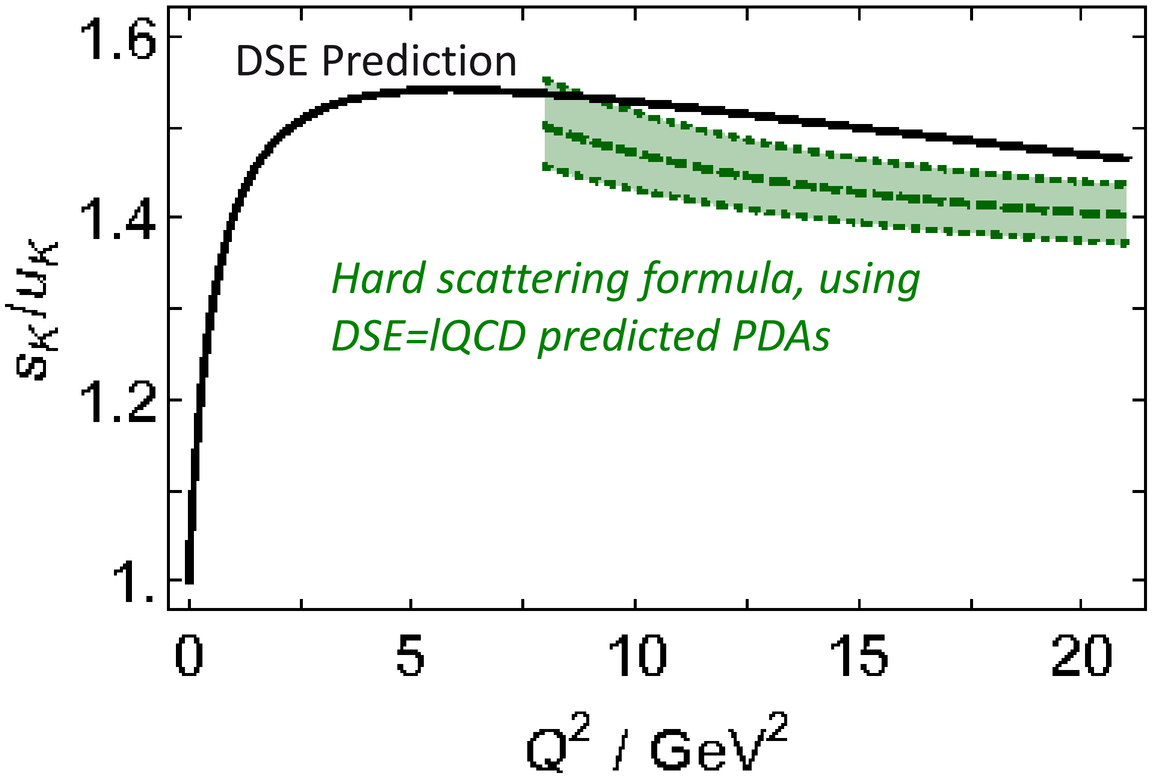
$$w_{\bar{s}} = \frac{1}{3}\int_0^1 dx\, \frac{1}{1-x}\varphi_K(x)\,, \quad w_u = \frac{1}{3}\int_0^1 dx\, \frac{1}{x}\varphi_K(x)$$

$$[\, \bar{s}\, \gamma\, s\, u_{\rm spectator} \,/\, \bar{u}\, \gamma\, u\, s_{\rm spectator}\,]^2 \leq 1.5$$

- Current conservation: $F_{uss}(0) = F_{uus}(0)$
- Under evolution:

  $\varphi_K \rightarrow 6\, x\, (1-x) \Rightarrow \omega_{\bar{s}} \rightarrow \omega_u \Rightarrow$ Ratio $\rightarrow 1$
- Agreement between direct calculation and hard-scattering formula, using consistent PDA
- Ratio never exceeds 1.5 and

  Logarithmic approach to unity
- Typical signal of EHM-dominance in flavour-symmetry breaking, taming the large Higgs-produced current-quark mass difference:
  - *ms ~ 30 mu* $\Rightarrow M_s(0) \sim 1.25\, M_u(0)$
  - scale difference does finally become irrelevant under evolution, but only at *very* large scales

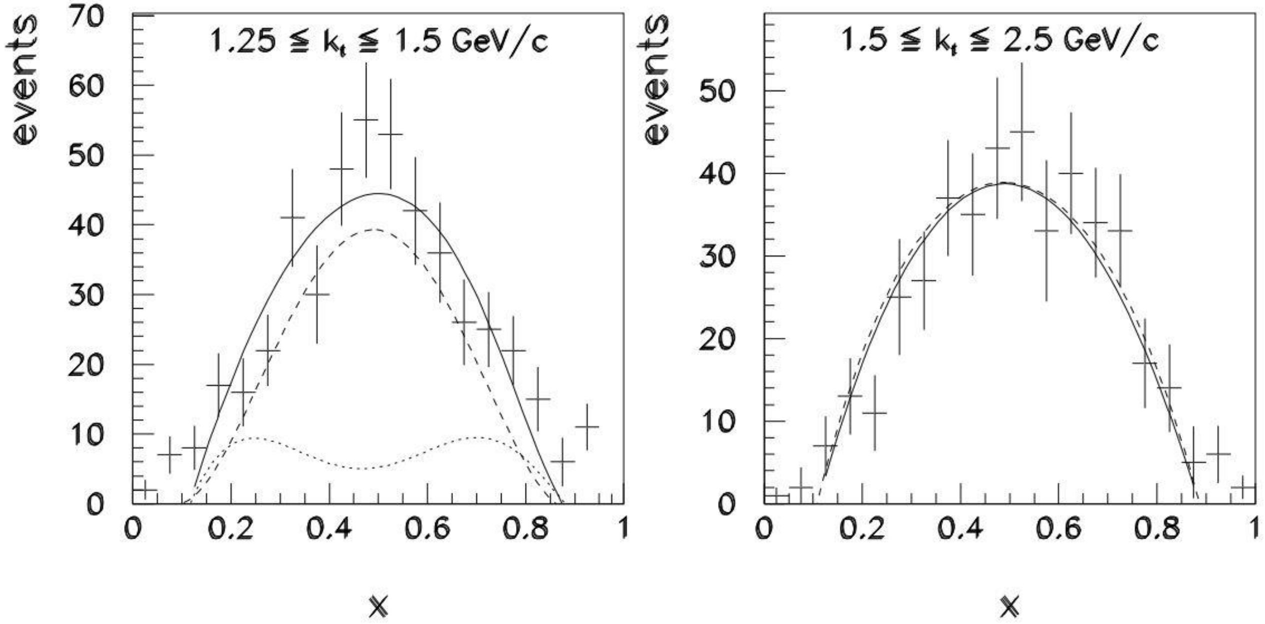


Hard scattering formula, using DSE=lQCD predicted PDAs

Controversy over PDAs

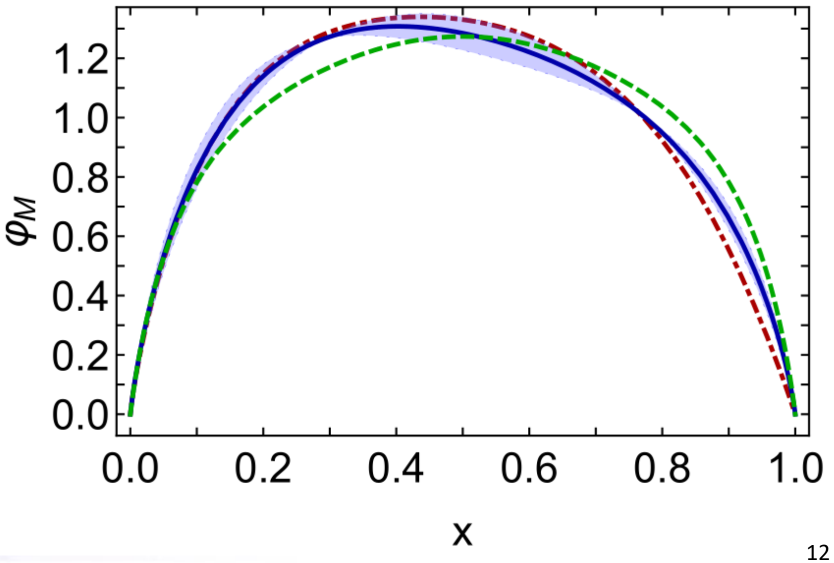
- E791 Collaboration, E. Aitala *et al.*, Phys. Rev. Lett. 86, 4768 (2001).
  - Claim: $\varphi_\pi(x)$ is well represented by the asymptotic profile for $\zeta^2 > 10\ \text{GeV}^2$
- Modern continuum predictions and analyses of lQCD
  - PDAs are broadened at $\zeta^2=4\ \text{GeV}^2$
  - Evolution is logarithmic ⇒ if φ not asymptotic at $\zeta^2=4\ \text{GeV}^2$, then φ not asymptotic at $\zeta^2=10\ \text{GeV}^2$
- Theory indicates that E791 conclusion cannot be correct
  - The E791 images cannot represent the same pion property
  - Not credible to assert that $\varphi_\pi(x)$ is well represented by the asymptotic distribution for $\zeta^2 > 10\ \text{GeV}^2$

Left: Nonpertubative (broadening) important
Right: Asymptotic profile sufficient



- Hard exclusive processes only sensitive to low-order PDA moments.
- Diffractive processes much better because sensitive to x-dependence?

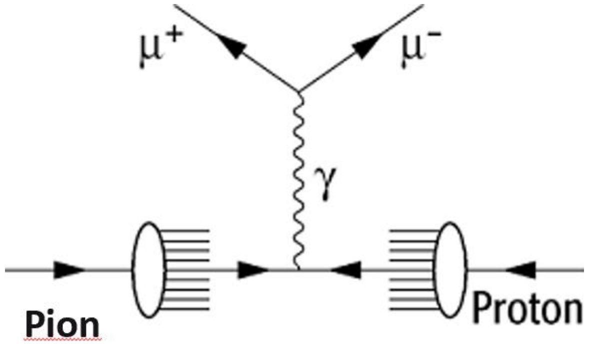
  (check this claim)



QCD prediction of *meson* valence-quark distributions

- Owing to absence of stable NG mode targets, π & K valence-quark distribution functions have hitherto been measured via the Drell-Yan process:

$$\pi\, p \to \mu^+ \mu^- X$$



- Consider a theory in which quarks scatter via a vector-boson exchange interaction whose $k^2 >> m_G^2$ behaviour is $(1/k^2)^\beta$
- Then at a resolving scale ζ_H … $u_\pi(x;\zeta_H) \sim (1-x)^{2\beta}$

  Namely, the large-x behaviour of the quark distribution function is a direct measure of the momentum-dependence of the underlying interaction.
- In QCD, β=1 and hence

QCD: $Q > \zeta_H \Rightarrow 2 \to 2+\gamma,\ \gamma > 0$

$${}^{QCD}u_\pi(x;\zeta_H) \sim (1-x)^2$$

Controversy over pion valence DF

- ➢ Vector boson Interaction $(\frac{m_g^2}{k^2})^\nu, \nu = 0$
  - – Contact interaction … translationally invariant regularisation … algebraic proof
  - – $\varphi_\pi(x;m_g) = [x(1-x)]^0 =$ constant & $q_\pi(x;m_g) \propto [x(1-x)]^{2\times 0} =$ constant
- ➢ Vector boson Interaction $(\frac{m_g^2}{k^2})^\nu, \nu > 1$
  - ✓ Such theories are super-renormalizable … no anomalous dimensions … pure scaling behaviour in UV
  - ✓ Hadronic scale is set by m_g, which is on the order of the mass of the "proton"
- ✓ Chiral limit – algebraic proof, confirmed by numerical studies: gap equation ⇒ $B(k^2) \propto [\frac{-\langle \bar{q}q\rangle}{k^2}]^\nu$
- ✓ Goldberger-Treiman relation: $f_\pi^0 E_\pi(k;P=0) = B(k^2) \propto [\frac{-\langle \bar{q}q\rangle}{k^2}]^\nu$
- ➢ Algebraic proof, confirmed by numerical studies:
  - – $\varphi_\pi(x;m_g) \propto [x(1-x)]^\nu$ & $q_\pi(x;m_g) \propto [x(1-x)]^{2\nu}$
- ➢ ν = 1 + ε, power on PDF = 2 + 2 ε
- ➢ QCD: ε → 0⁺, regularisation & renormalisation … power on PDF = 2 + $\frac{3}{2}\ln\frac{\langle x\, q(x;\zeta_H)\rangle}{\langle x\, q(x;\zeta>\zeta_H)\rangle} > 2$ because the active anomalous dimension is positive. (Recall elastic form factor: damping factor 2 -> 2 + positive no.)

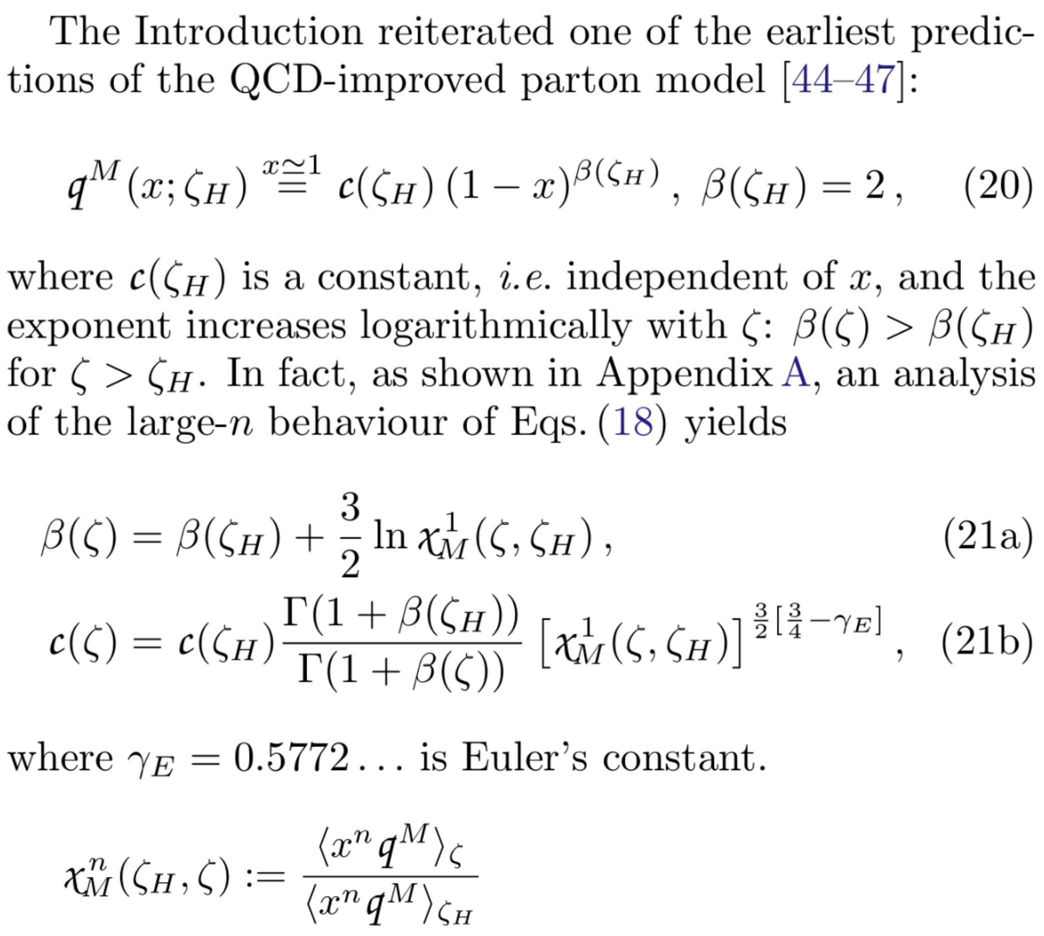
ν =0, and any number (infinitesimally) greater than 1 … power on PDF is plainly determined by power-law behaviour of interaction

QCD prediction of *meson* valence-quark distributions

- **Fact 1**: After 40 years, no flaw has been found in the proof that $x \simeq 1 \Rightarrow q^{\pi}(x;\zeta_{\mathrm{H}}) \propto (1-x)^2$
- **Fact 2**: Power law fixed by asymptotic behaviour of bound-state wave function
- **Fact 3**: Gluon corrections do NOT change power laws.

  They only modify anomalous dimensions.

  Again, proof is 40 years old and no flaw has been found. Rather, it has been confirmed in numerous continuum calculations.
- Exact statement – in textbooks, but often overlooked:
  - *β(ζ) increases logarithmically with inverse of valence-quark momentum fraction*
  - Coefficient decreases also, but at a different rate



The Introduction reiterated one of the earliest predictions of the QCD-improved parton model [44–47]:

$$q^M(x;\zeta_H) \overset{x\simeq 1}{=} c(\zeta_H)\,(1-x)^{\beta(\zeta_H)}\,,\quad \beta(\zeta_H)=2\,, \qquad (20)$$

where $c(\zeta_H)$ is a constant, *i.e.* independent of x, and the exponent increases logarithmically with ζ: $\beta(\zeta) > \beta(\zeta_H)$ for $\zeta > \zeta_H$. In fact, as shown in Appendix A, an analysis of the large-n behaviour of Eqs. (18) yields

$$\beta(\zeta) = \beta(\zeta_H) + \frac{3}{2}\ln \chi^1_M(\zeta,\zeta_H)\,, \qquad (21a)$$

$$c(\zeta) = c(\zeta_H)\frac{\Gamma(1+\beta(\zeta_H))}{\Gamma(1+\beta(\zeta))}\left[\chi^1_M(\zeta,\zeta_H)\right]^{\frac{3}{2}[\frac{3}{4}-\gamma_E]}\,, \qquad (21b)$$

where $\gamma_E = 0.5772\ldots$ is Euler's constant.

$$\chi^n_M(\zeta_H,\zeta) := \frac{\langle x^n q^M\rangle_\zeta}{\langle x^n q^M\rangle_{\zeta_H}}$$

Controversy over pion valence DF

- Parton model prediction for the valence-quark DF of a spin-zero meson:

$$x \simeq 1 \Rightarrow q^{\pi}(x;\zeta_{\mathrm{H}}) \propto (1-x)^2$$

- The hadronic scale is not empirically accessible in Drell-Yan or DIS processes.
  (Matter of conditions necessary for data to be interpreted in terms of distribution functions.)

- For such processes, QCD-improvement of parton model leads to the following statement:

  At any scale for which experiment can be interpreted in terms of parton distributions, then

$$x \simeq 1 \Rightarrow q^{\pi}(x;\zeta) \propto (1-x)^{\beta=2+\gamma}, \gamma > 0$$

- Simple restatement of the following:
  - The parton model gives us scaling and scaling laws.
  - QCD's gluon corrections give us scaling violations
  - Scaling violations do NOT alter the integer-number that characterises scaling powers [L&B-1980 Lepage:1980fj]
  - Certainly don’t reduce 2 → 1 (or 3 → 2 for nucleon valence) – scaling violations increase power logarithmically

Controversy over pion valence DF

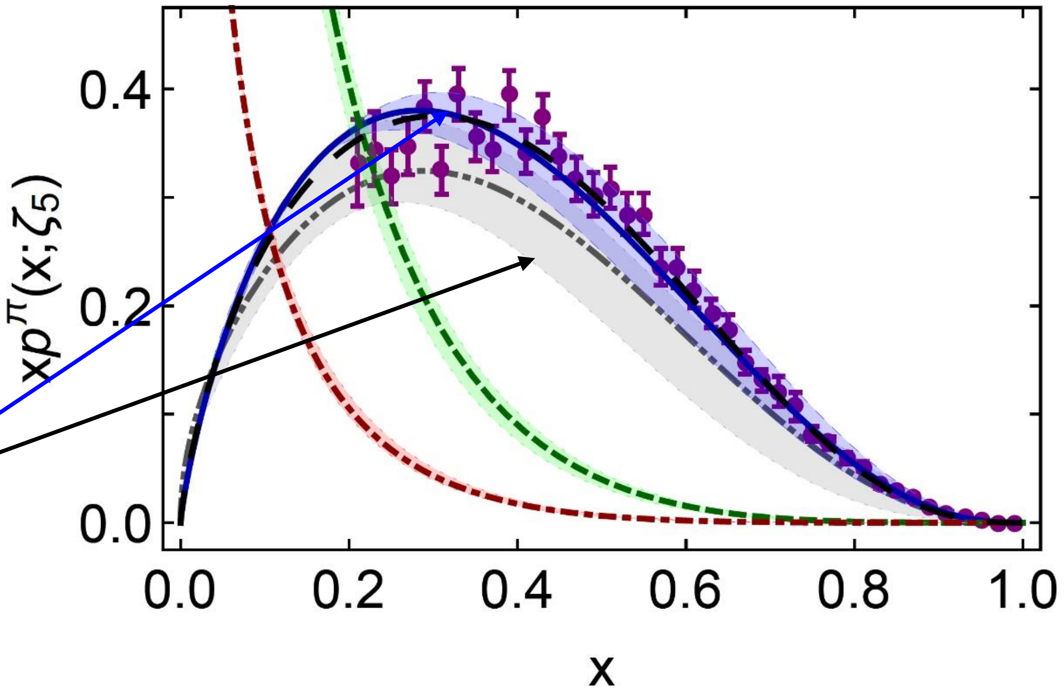
- Consequence
  - Any analysis of DY or DIS (or similar) experiment which returns a value of $\beta < 2$ conflicts with QCD.
- Observation
  - All existing internally-consistent calculations preserve connection between large-k^2 behaviour of interaction and large-x behaviour of DF.
    - $J=0$ … $(1/k^2)^n \Leftrightarrow (1-x)^{2n}$
- No existing calculation with n=1 produces anything other than $(1-x)^2$
- Internally-consistent calculation that preserve RG properties of QCD,

  then $2 \to 2+\gamma$, $\gamma>0$, at any factorisation-valid scale
- Controversy:
  - Ignore threshold resummation – typical of all modern phenomenology, despite Aicher *et al*., then data analysis yields $(1-x)^{\mathbf{1}+\gamma}$
  - Include threshold resummation, then data analysis yields $(1-x)^{\mathbf{2}+\gamma}$

π valence-quark distributions
20 Years of Evolution → 2019

- Novel lattice-QCD algorithms beginning to yield results for pointwise behaviour of $u^{\pi}(x;\zeta)$
- Developments in continuum-QCD have enabled 1st parameter-free predictions of valence, glue and sea distributions within the pion
  - Reveal that $u^{\pi}(x;\zeta)$is hardened by emergent mass
- Agreement between new continuum prediction for $u^{\pi}(x;\zeta)$ [Ding:2019lwe] and recent lattice-QCD result [Sufian:2019bol]
- Real strides being made toward understanding pion structure.
- Standard Model prediction is stronger than ever before

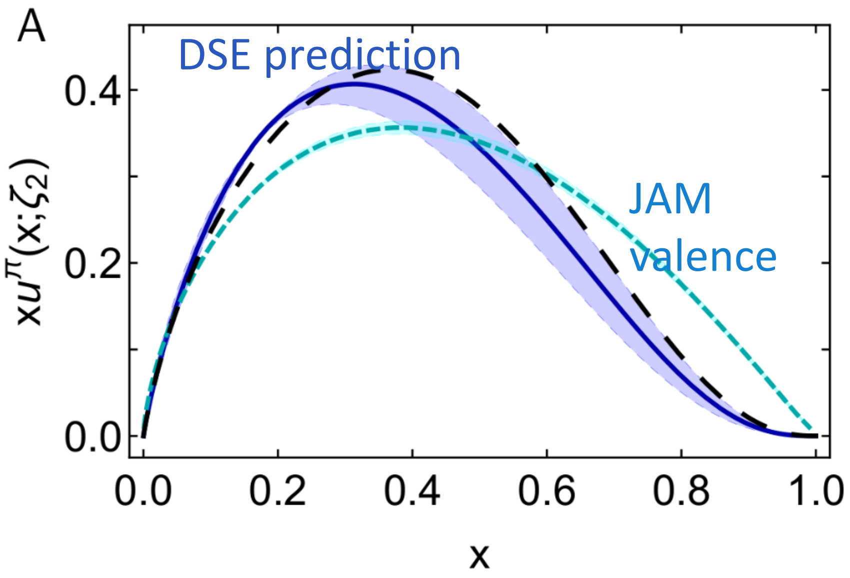
$\beta^{\mathrm{contm}}(\zeta_5) = 2.66(12)$
$\beta^{\mathrm{lattice}}(\zeta_5) = 2.45(58)$

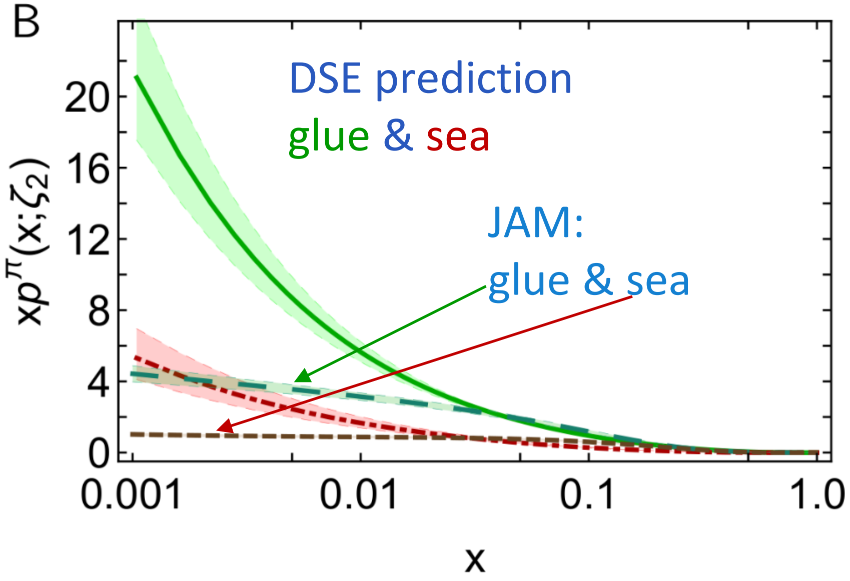


- *Now – after 30 years – new era dawning in which the ultimate experimental checks can be made*

π valence-quark distributions Comparison with JAM fits

- Valence:
  - momentum fraction similar
  - JAM profile much harder & inconsistent with QCD prediction
- Glue:
  - Pointwise agreement on x ≥ 0.05, but marked disagreement on <u>important</u> complementary domain
  - Both continuum prediction and JAM fit are very different from early phenomenology
  - Should be tested in new experiments that are directly sensitive to the pion's gluon content.
  - Perhaps, prompt photon & J/Ψ production
- Sea:
  - Prediction and fit disagree on entire x-domain
  - If pion's gluon content is considered uncertain, then fair to describe sea-quark distribution as empirically unknown
  - Motivation for the collection and analysis of DY data with $\pi^{\pm}$ beams on isoscalar targets



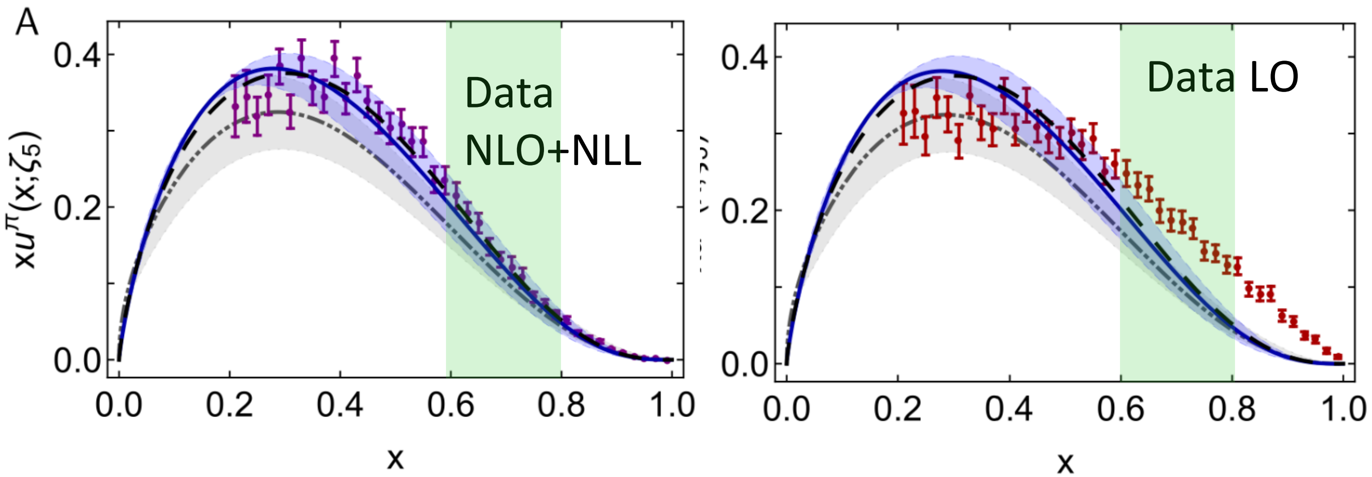


Where is “2” to be seen?

- Use DSE DF … prediction … NOT fit to data
  - Within uncertainty, brackets DF points obtained in NLO+NLL analysis
    - Central curve: $\chi^2/\mathrm{dof} = 1.66$
  - By same measure, inconsistent with LO E615
    - Central curve: $\chi^2/\mathrm{dof} = 19.4$ – order of magnitude larger
- Valence domain begins after peak, at which point 2 x V(x) > x (S(x)+G(x))
- Power discriminating function – local (x-dependent) exponent:

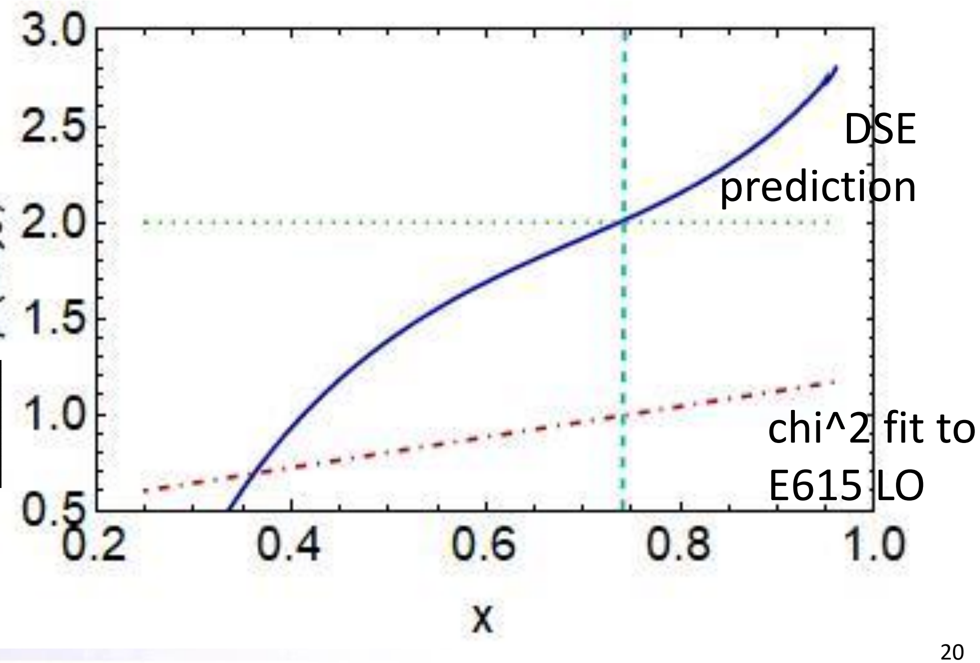
$$\beta(x) = -\frac{1-x}{q_V^\pi(x)}\frac{dq_V^\pi(x)}{dx}$$

  - “Active” power greater > 2 on x > 0.75



Precise data & sound extraction on 0.6 < x < 0.8 sufficient to test QCD prediction: 2 ≠ 1

Effective $\beta(x)$



This is not the end, this is not even the beginning of the end, this is just perhaps the end of the beginning.

Kaon parton distributions: revealing Higgs modulation of emergent mass, Zhu-Fang Cui, Minghui Ding, Fei Gao, Khépani Raya, Daniele Binosi, Lei Chang, Craig D. Roberts, Jose Rodríguez-Quintero and Sebastian M. Schmidt, NJU-INP 019/20, arXiv:2006.14075 [hep-ph]

Kaon Distribution Functions

- ✓ Improved & extended approach used for pion DFs
- ✓ Unified distribution amplitudes and functions for pion and kaon
  - – connect with pion and kaon form factors
- ✓ Kaon DA and DF at ζ_H are hardened much like those of the pion

Blue = kaon
Green = pion

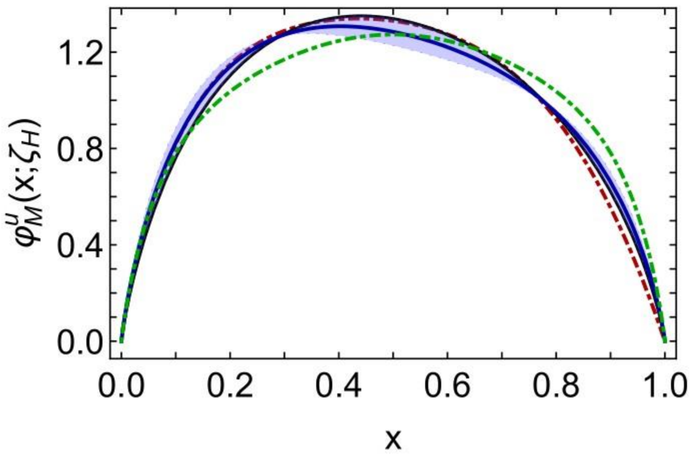


Fig. 7 Kaon DA, $\varphi_K^u(x;\zeta_H)$, described by Eq. (45) and the "middle" coefficients in Table 3 – solid blue curve. The associated band marks the domain bounded by the "upper" and "lower" coefficients in Table 3. Result obtained using the DB kernel in Ref. [74] – dot-dashed red curve. Pion DA in Eq. (28) – dashed green curve.

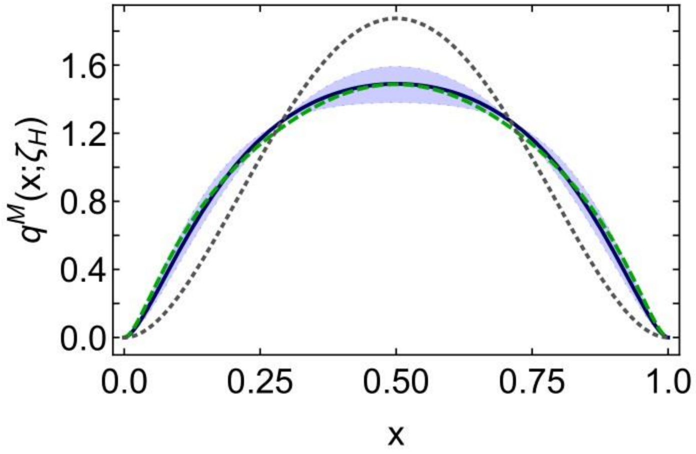


Fig. 8 A comparison between kaon and pion valence-quark DFs. Solid blue curve: $\frac{1}{2}[u^K(x;\zeta_H)+\bar{s}^K(x;\zeta_H)]$ calculated from Eq. (47). The associated band marks the domain bounded by the kaon DFs produced using Eqs. (12), (45) and the "upper" and "lower" rows in Table 3. Dashed green curve: $u^\pi(x;\zeta_H)$ in Eq. (29). Dotted grey curve: scale free form, $q^{\rm sf}(x;\zeta_H)=30x^2(1-x)^2$.

Kaon Distribution Functions

- Evolution $\zeta_H \rightarrow \zeta_5$ = 5.2 GeV using QCD's PI effective charge to integrate DGLAP equations
- Mass-independent splitting
  - $\langle 2\, x\, u_\pi(x;\zeta_5)\rangle = 0.41(4) = \langle x\, \bar{s}_K(x;\zeta_5) + x\, u_K(x;\zeta_5)\rangle$

One lQCD calculation (2003.14128 [hep-lat]):

- Fractions systematically larger than continuum predictions, especially for $\bar{s}$:
  - u – 0.6(4.8)%, 21(6)%, 40(4)%;
  - $\bar{s}$ – 24(7)%, 53(13)%, 84(16)%
- lQCD *vs*. with DSE predictions, lQCD DFs = *much* harder.
- lQCD DFs inconsistent with QCD prediction

  … $(1 - x)^\beta$, β = 1.13(16)

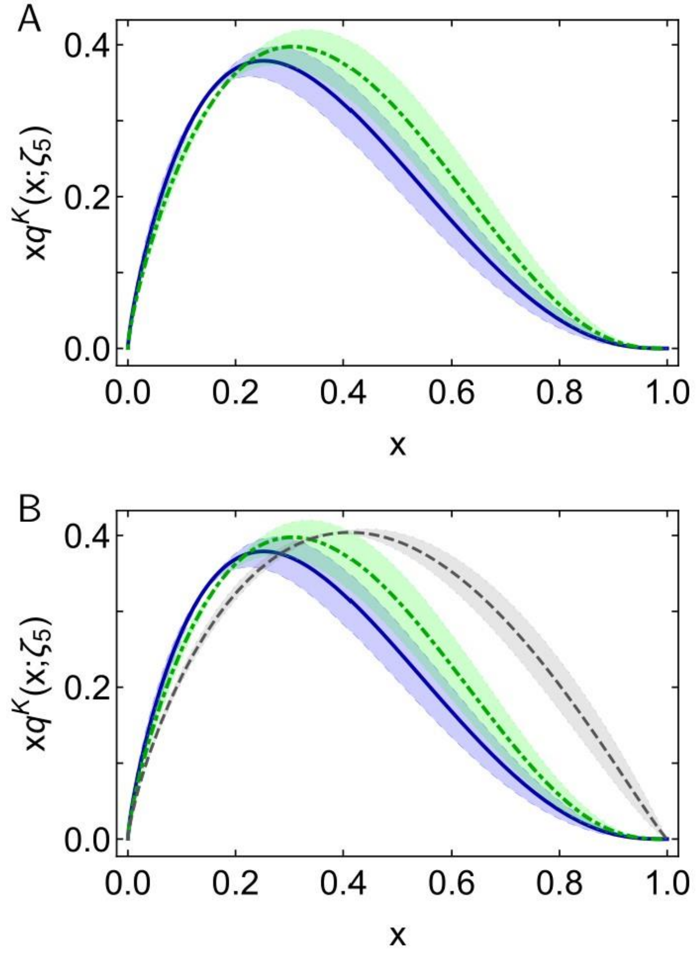


Fig. 11 *Upper panel–A*. Solid blue curve – kaon's valence *u*-quark distribution, defined at ζ_H by Eq. (47), evolved $\zeta_H \rightarrow \zeta_5$ using the procedure explained in Sec. 4.1. Dot-dashed green curve – analogous result for the kaon's valence $\bar{s}$ distribution. *Lower panel–B*. Dashed grey curve within grey bands – kaon $\bar{s}$ valence-quark distribution obtained in a recent lQCD study [120]; otherwise, as in *A*. (In both panels, the bands bracketing our central DF curves reflect the uncertainty in $\hat{\alpha}(0)$, Fig. 1.)

Kaon Distribution Functions: $^{u_K(x)}/_{u_\pi(x)}$

- Uncertainty in continuum predictions for DFs cancels in ratio
- First lQCD results for ratio also drawn
- Relative difference between the central lQCD result and DSE prediction is ≈ 5% … despite fact that individual lQCD DFs are very different from continuum results
- Long known fact, *i.e.* $^{u_K(x)}/_{u_\pi(x)}$ is very forgiving of even large differences between the individual DFs used to produce the ratio
- More precise data crucial if ratio is to be used effectively to inform and test the modern understanding of SM NG modes
- Results for $u_\pi(x;\zeta_5)$, $u_K(x;\zeta_5)$ separately have greater discriminating power.

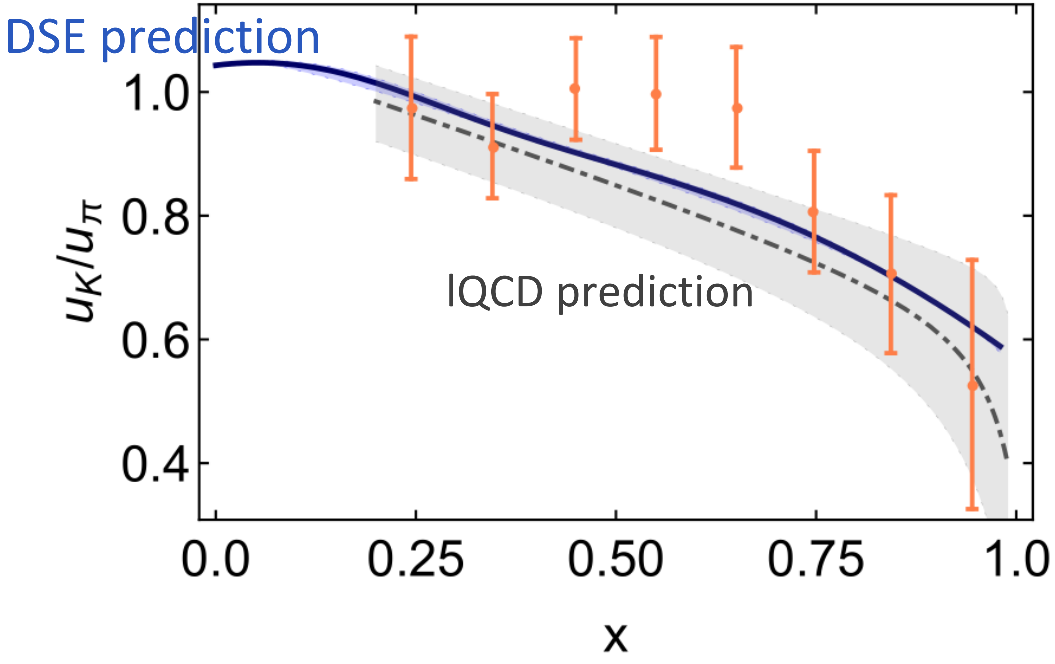


FIG. 12. $u^K(x;\zeta_5)/u^\pi(x;\zeta_5)$. Solid blue curve – result obtained for the ratio after $\zeta_H \to \zeta_5$ evolution of Eq. (28) [π] and Eq. (45), Table III–middle [K]. The lighter-blue band bracketing this curve reveals the effect of $\zeta_H \to \zeta_H(1.0 \pm 0.1)$: it is negligible. Dot-dashed grey curve within grey band – lQCD result [116]. Data (orange) from Ref. [115].

Kaon Distribution Functions

- With unique hadronic scale and mass-independent splitting, glue and sea distributions in the kaon must be practically identical to those in the pion
- Mass-dependent splitting functions

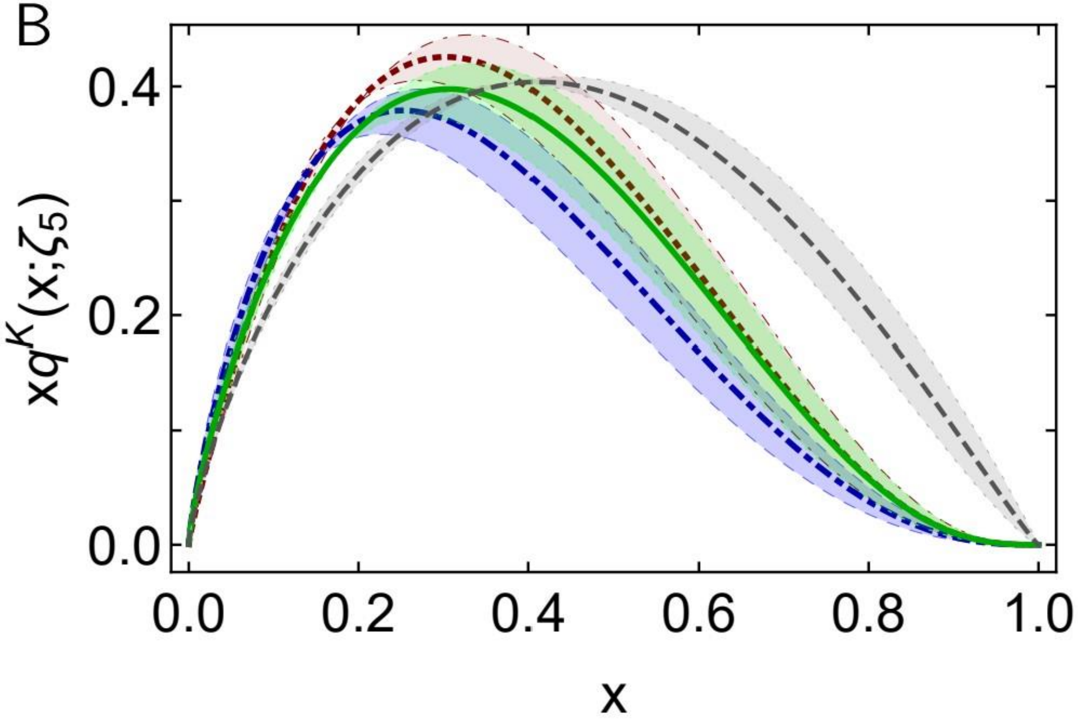
$$\begin{pmatrix} P_{q\leftarrow q} & P_{q\leftarrow g} \\ P_{g\leftarrow q} & P_{g\leftarrow g} \end{pmatrix}$$

- Identify quark flavours and modify s-quark splitting so that:
  - Reduce number of gluons emitted by $\bar{s}$ quarks because they’re heavier
  - Reduce number of $\bar{s}s$ pairs produced by gluons, again because they’re heavier

Kaon Distribution Functions

$(\mathbf{B})$	$\langle x q^K \rangle$	$\langle x^2 q^K \rangle$	$\langle x^3 q^K \rangle$
u	0.19(2)	0.067(09)	0.030(05)
$\bar{s}_{\cancel{m}}$	0.22(2)	0.081(11)	0.038(07)
$\bar{s}_m$	0.23(2)	0.085(11)	0.040(07)
$u + \bar{s}_m$	0.42(3)	0.152(20)	0.070(12)

- Mass-dependent splitting
  - Red curve cf. green curve
  - $\bar{s}$ momentum fractions increased by 4.8(8)%
- Large-*x* exponent unchanged for both u and $\bar{s}$
  - $\beta = 2.73(7)$



Glue and Sea in Kaon

- Kaon's glue and sea distributions differ from those of the pion only on the valence region x > 0.2.
- Hindsight, unsurprising:
  - ✓ mass-dependent splitting functions act primarily to modify valence DF of the heavier quark;
  - ✓ valence DFs are negligible at low-x, where glue and sea distributions are large, and vice versa;
  - ✓ hence the biggest impact of a change in the valence DFs must lie at large-*x*.
- Curious: each of the predicted ratios is pointwise similar to the measured value of $\boldsymbol{u_K(x)}/\boldsymbol{u_\pi(x)}$

	valence quark	valence antiquark	glue	sea
Kaon	0.19(2)	0.23(2)	0.44(2)	0.14(2)
Pion	0.20(2)	0.20(2)	0.45(1)	0.15(2)

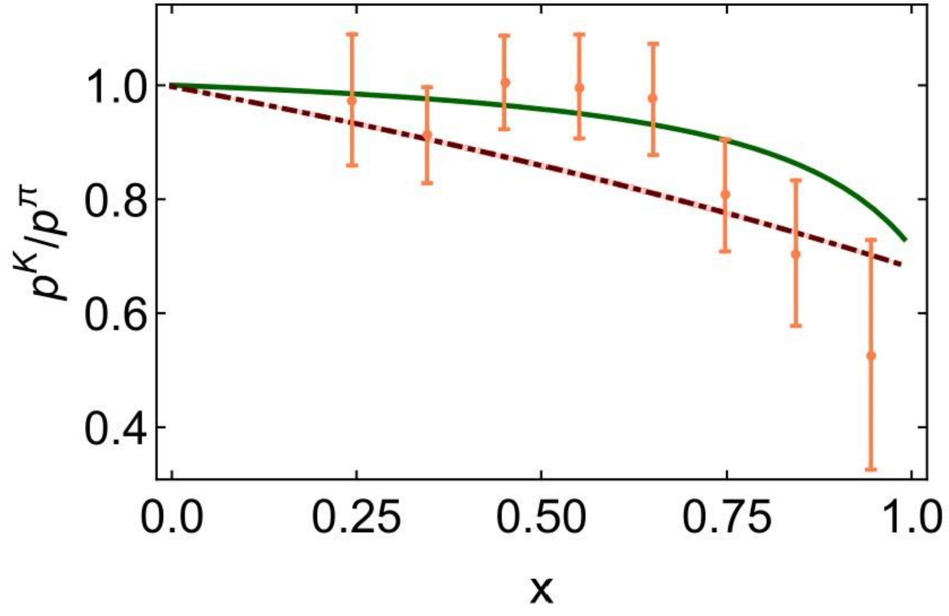


Fig. 14 Prediction for $g^K(x;\zeta_5)/g^\pi(x;\zeta_5)$ – solid green curve within green shading; and for $\mathcal{S}^K(x;\zeta_5)/\mathcal{S}^\pi(x;\zeta_5)$ – dot-dashed red curve within red shading. (The uncertainty introduced by that in the $k^2 = 0$ value of the PI charge, Fig. 1, is indicated by the shaded band bracketing each curve. In both cases here, that band is no thicker than the width of the central line.) Data on $u^K(x;\zeta_5)/u^\pi(x;\zeta_5)$ (orange) from Ref. [119] are included to guide comparisons.

Status: pion and kaon structure functions

Pion

- Pointwise behaviour of pion’s valence-quark distribution function: agreement between predictions from lQCD and symmetry-preserving QCD-consistent continuum analyses
- Amongst existing phenomenological studies of pion structure functions, only one employs a next-to-leading-order analysis that includes threshold resummation. This study is unique in producing a valence-quark DF that is consistent with large-*x* QCD and matches continuum and lattice prediction
- General disagreement between phenomenological results and theory predictions for the pion’s valence-quark DF feeds into uncertainty about pion’s glue and sea distributions
- Resolution of these conflicts must await
  - Improved phenomenological analyses that include threshold resummation
  - New data that constrains the pion’s glue and sea distributions.

Status: pion and kaon structure functions

Kaon

- Very little empirical information available on K DFs ⇒ no recent phenom. inferences.
  - Valence-quark distributions: results from models and a single, recent lQCD study
  - Kaon's glue and sea distributions: no results
- Hence, symmetry-preserving continuum QCD predictions sketched here for entire array of kaon DFs currently stand alone.
- One piece of available experimental information: $\boldsymbol{u_K(x)}/\boldsymbol{u_\pi(x)}$
  - Continuum prediction for ratio is consistent with the data.
  - But, given the large errors, this ratio is very forgiving of even large differences between various calculations of the individual DFs used to produce the ratio.
    - Modern, precise data is critical if this ratio is to be used as a path to understanding the Standard Model's Nambu-Goldstone modes;
    - Results for $u_\pi(x;\zeta_5)$, $u_K(x;\zeta_5)$ separately would be better.

Status: pion and kaon structure functions

Kaon

- Glue and Sea – Predictions:
  - DFs very similar to those in the pion
  - Detailed comparison requires the use of mass-dependent splitting functions.
  - Development underway … Preliminary conclusions:
    1. Light-front momentum fraction carried by s-quarks in the kaon increases by ~ 10%;
    2. Compensated by a commensurate decrease in fractions carried by glue (−1%) and sea (−2%).

NEEDS: pion and kaon structure functions

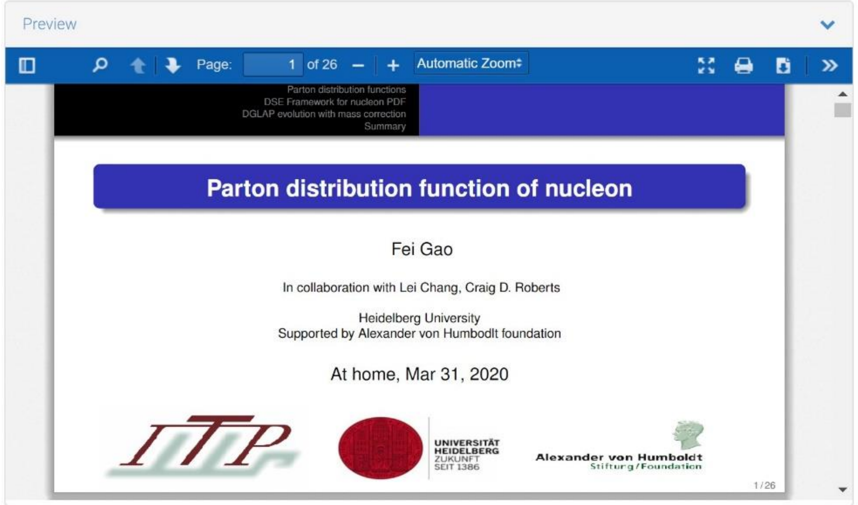
- Standard Model’s (pseudo-) Nambu-Goldstone modes – pions and kaons – are basic to the formation of everything from nucleons, to nuclei, and on to neutron stars.
- Hence, new-era experiments capable of discriminating between the results from models, phenomenology and QCD-connected predictions should have high priority.
- Phenomenological methods needed to proceed from data to DFs must match modern experiments in precision.
- Theory: continuum and lattice analyses of the pion’s valence-quark DF are converging on the same form, confirming the longstanding QCD expectation
  - But, lattice results for the pion’s glue and sea distributions would be very valuable.
- Even more true for the kaon.
  - Only one extant lattice study of kaon DFs
  - Addressing solely valence distributions
  - Disagreeing in many respects with continuum predictions
  - Conflict with large-x QCD

  ⇒ Many opportunities are available.

Nucleon Distribution Functions

- EHM ⇒ proton wave function contains nonpointlike, fully-interacting diquark correlations and significant quark-diquark orbital angular momentum
- These features are expressed in the proton's DFs, *e.g*. in the large-x behaviour of F_2^n/F_2^p
- F_2^n/F_2^p is a surrogate for d_V/u_V
- MARATHON experiment was proposed at JLab … DIS off mirror nuclei ^{3}H and ^{3}He to determine F_2^n/F_2^p on valence-quark domain
- MARATHON experiment is complete.
  - Preliminary results were released in 2019
  - Quantitatively consistent with new reanalyses of existing data on a wide variety of nuclei
  - This agreement increases confidence in the preliminary MARATHON analysis.

Presentation from 2020 AMBER@CERN Workshop



Parton distribution functions
DSE Framework for nucleon PDF
DGLAP evolution with mass correction
Summary

Parton distribution function of nucleon

Fei Gao

In collaboration with Lei Chang, Craig D. Roberts

Heidelberg University
Supported by Alexander von Humbodlt foundation

At home, Mar 31, 2020

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1/26

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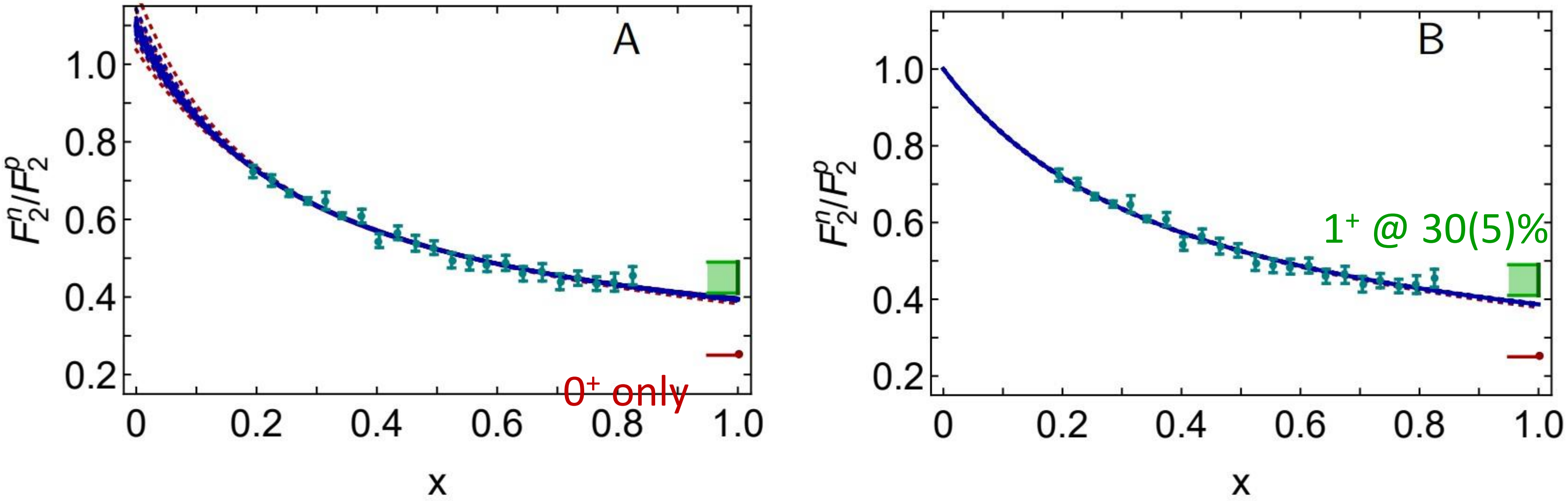
Segarra et al., Phys.Rev.Lett. 124 (2020) 9, 092002 • e-Print: 1908.02223 [nucl-th]

MARATHON

- Padé-fits according to Jackknife analysis of data
- A … consistent with sea-quarks saturating ratio on $x \simeq 0$
- B … repeat analysis assuming this true
- In both cases, MARATHON data confirm CSM prediction that axial-vector diquarks contribute 30(5)% of proton's normalisation
- No model of the nucleon is physical unless it contains material axial-vector diquark component



0^+ only

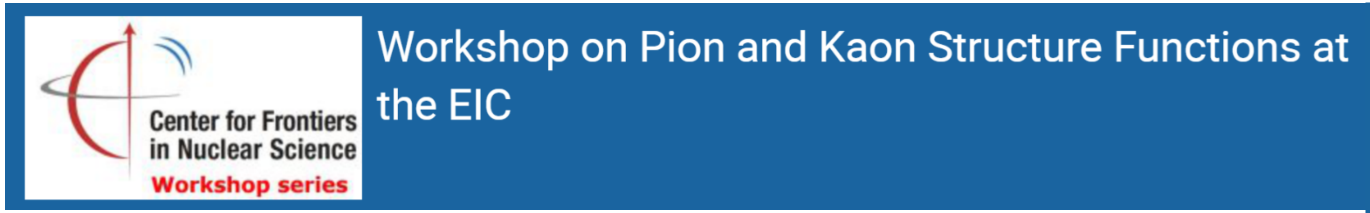
1^+ @ 30(5)%

Fig. 8 Preliminary data from the MARATHON experiment (teal). *Left panel* – *A*. Dotted red and blue curves: array of [1, 1] Padé fits obtained from a jackknife analysis of the data. Extrapolated, these curves yield $F_2^n/F_2^p|_{x=0} = 1.10(3)$, consistent with dominance of sea- over valence-quarks on $x \simeq 0$; and $F_2^n/F_2^p|_{x=1} = 0.395(3)$. *Right panel* – *B*. Array of [1, 1] Padé fits obtained from a jackknife analysis of the data constrained by the assumption of sea-quark dominance, *i.e.* enforcing $F_2^n/F_2^p|_{x=0} = 1$. Extrapolated, these curves yield $F_2^n/F_2^p|_{x=1} = 0.387(2)$. Theory predictions in both panels: (*i*) red line and circle at $x = 1$, the value $\frac{1}{4}$, which is obtained if the proton's valence structure is simply u-quark + isoscalar-scalar [ud]-diquark; and (*ii*) green band, range of values obtained when axial-vector diquark correlations contribute 25-35% of the proton's normalization. Evidently, current indications are that the MARATHON data and the reanalysis in Ref. [159] lean heavily in favour of scenario (*ii*).

lean heavily in favour of scenario (*ii*).

The MARATHON data are a crucial step forward in understanding hadron structure. They could have a far-reaching impact on developing a solution to the puzzle of EHM. This is strong motivation for the development of new experiments aimed at extracting F_2^n/F_2^p on the valence-quark domain.

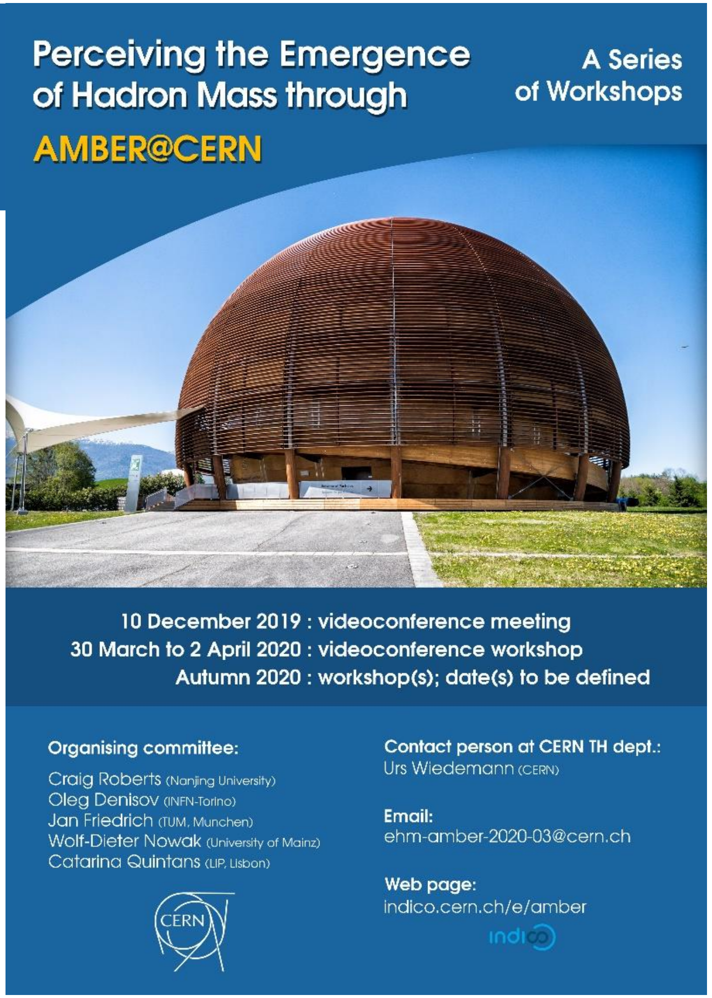
Future



Center for Frontiers in Nuclear Science
Workshop series

Workshop on Pion and Kaon Structure Functions at the EIC

- Challenge: Explain the Origin & Distribution of the Bulk of Visible Mass
- *Progress* and *Insights* being delivered by amalgam of
  - Experiment … Phenomenology …Theory
- Continued exploitation of synergies essential
  to capitalise on new opportunities provided by existing & planned facilities
- This Discussion … join theorists from high-energy nuclear & particle physics in dialogue with the experimentalists … address the Emergence of Hadron Mass



Perceiving the Emergence of Hadron Mass through
AMBER@CERN

A Series of Workshops

10 December 2019 : videoconference meeting
30 March to 2 April 2020 : videoconference workshop
Autumn 2020 : workshop(s); date(s) to be defined

Organising committee:
Craig Roberts (Nanjing University)
Oleg Denisov (INFN-Torino)
Jan Friedrich (TUM, Munchen)
Wolf-Dieter Nowak (University of Mainz)
Catarina Quintans (LIP, Lisbon)

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- Consolidate & expand collaboration between experimentalists proposing new measurements, phenomenologists doing global data analyses, & hadron-structure theorists.

Future

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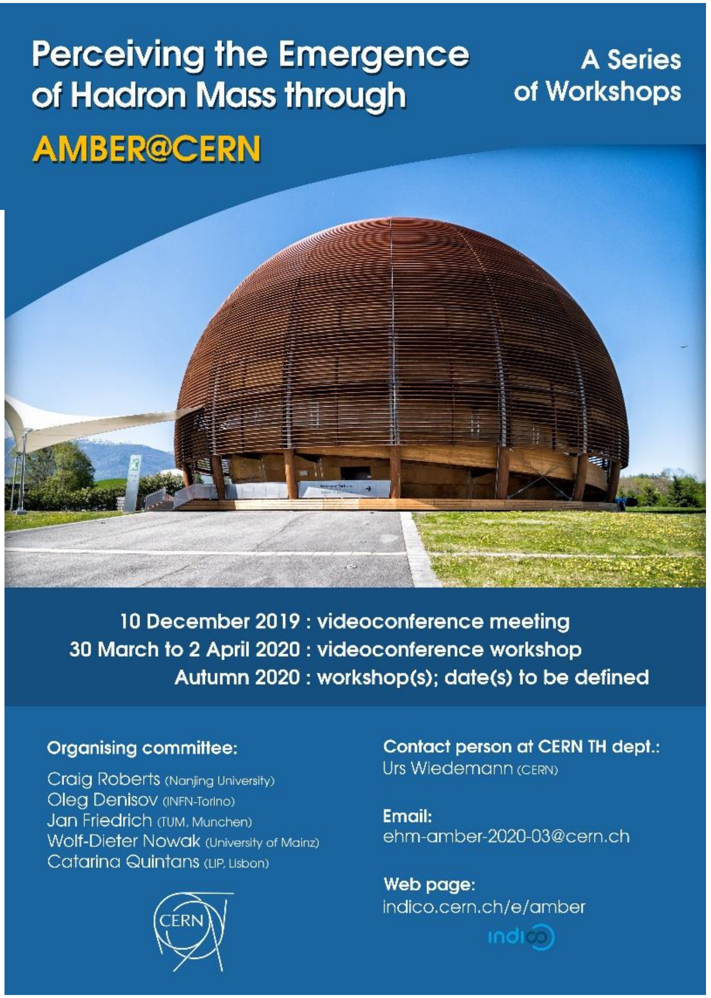
- Challenge: Explain the Origin & Distribution of the Bulk of Visible Mass
- *Progress* and *Insights* being delivered by amalgam of
  - Experiment … Phenomenology …Theory
- Next Steps …
  - Ongoing efforts/meetings toward
    - Significant new element → the EIC UG Physics and Detector Handbook
    - Developing contributions as part of Yellow Report Initiative.
  - Discussions to explore EicC reach into pion and kaon structure
  - 2020 Oct. … 1-week workshop *Exploring QCD with Tagged Processes* – Université Paris-Saclay
  - 2020 Autumn … Hopefully, a face-to-face meeting at CERN in Autumn
  - 2020 November … IWHSS Trieste
  - 2021 March … NJU INP Workshop on EHM Physics
  - 2021 April … ECT* Trento



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Thank you