UNIVERSITY OF SCIENCE AND TECHNOLOGY OF MAZANDARAN

Institute for Research in Fundamental Sciences

Transverse momentum dependent of charged pion, kaon, and proton/antiproton fragmentation functions from $e^+ e^-$ annihilation process

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In collaboration with

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Based on:

arXiv:1907.12294 [hep-ph], Phys Rev D 100 (2019) 094033

ICHEP2020, 28 July 2020 to 6 August 2020, Prague, Czechia

Outline

- Hadronization
- ➢ Single inclusive electron-positron annihilation (SIA)
- ➢ Semi inclusive deep inelastic scattering (SIDIS)
- ➢ Single inclusive hadron collisions

- ➢ Transverse momentum dependent (TMD) PDFs and TMD FFs

- ➢ Methodology (Belle data set, factorization and fitting methodology, kinematical cuts, …)

- ➢ Results

Hadronization

- Hadronization process turns partons produced in hard-scattering reactions into the physical, colorless, non- perturbative hadronic bound states detected in experiments.

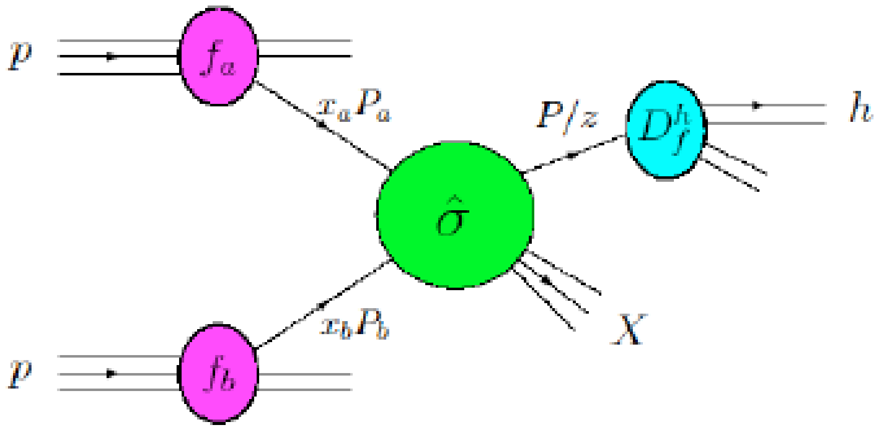
- Processes with an observed hadron in the final state can be described in terms of perturbative hard-scattering cross sections and certain non-perturbative but universal functions:

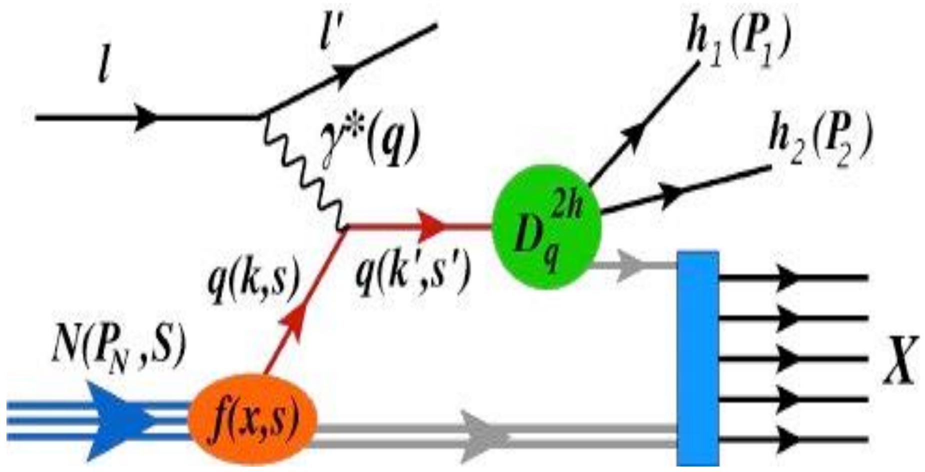
❖ Parton distribution functions (PDFs), accounting for the partonic structure of the hadrons in the initial state just before the interaction.

❖ Fragmentation Functions (FFs), encoding the details of the subsequent hadronization process .

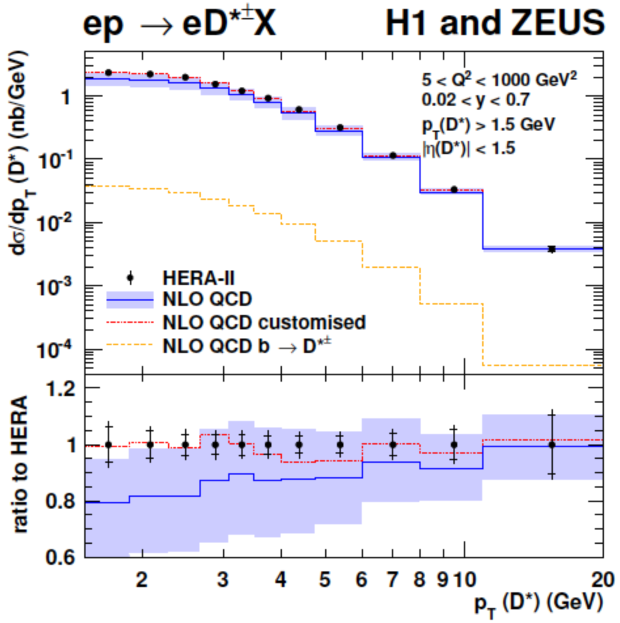
Fragmentation Functions (FFs)

- FFs are essential ingredients of theoretical predictions for the present and future hadron colliders such as LHC and LHeC, FCC [arXiv:2004.04213].
- FFs are basic ingredient for the calculation of the production of high transverse-momentum particles at collider energies within perturbative QCD, [J. High Energy Phys.06 (2019) 51].





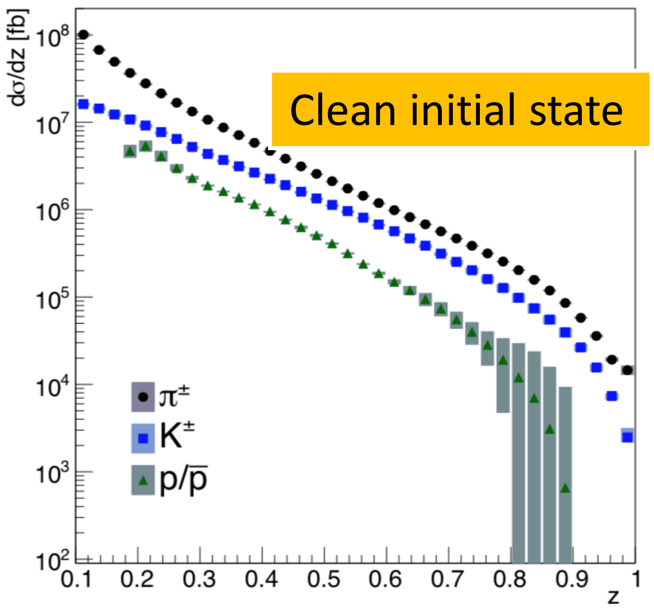
- Precise determination of Fragmentation Functions (FFs) including their experimental uncertainties had become active topics for many hard Processes.



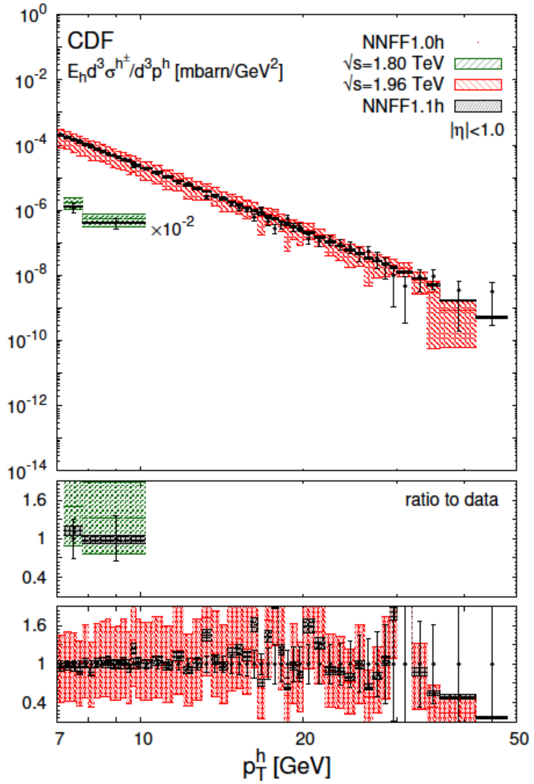
[JHEP 1509 (2015) 149]

$$\sigma^h(x, z, Q^2, P_{h\perp}) \propto \sum_q e_q^2 q(x, p_t, Q^2) D^h_{1,q}(z, k_t, Q^2)$$

$$\sigma^h(z, Q^2, k_t) \propto \sum_q e_q^2 \left(D^h_{1,q}(z, k_t, Q^2) + D^h_{1,\bar{q}}(z, k_t, Q^2)\right)$$



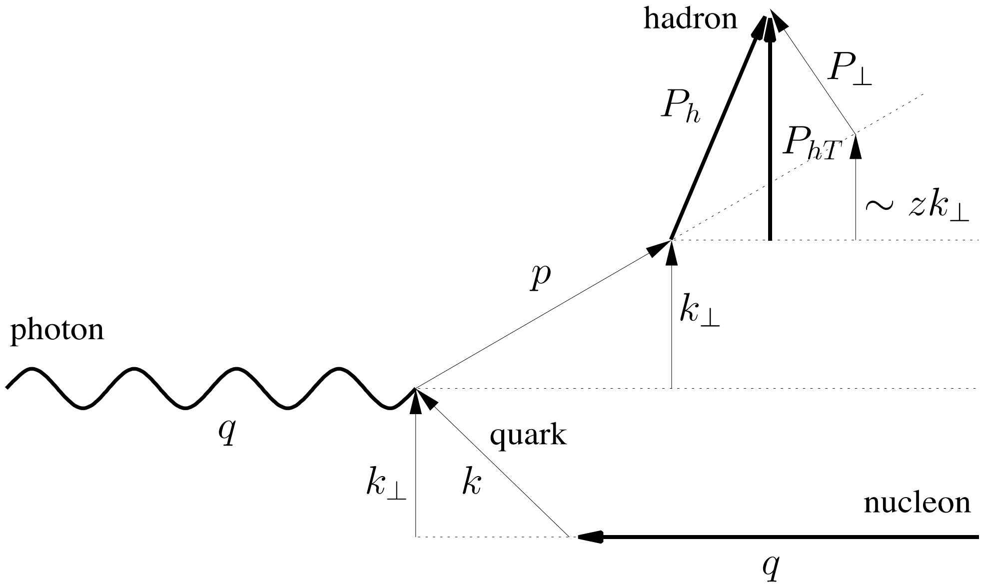
[arXiv:2001.10194v2]



[Phys Rev D 82 (2010) 119903]

$$\sigma^h(P_T) \propto \int_{x_1, x_2, z} \sum_{a, a' \in q, g} f_a(x_1) \otimes f_{a'}(x_2) \otimes \sigma_{aa'} \otimes D^h_{1,q}(z)$$

Transverse Momentum Dependent (TMD) PDFs and TMD FFs



$f_1^a(x, \boldsymbol{k}_\perp^2; Q^2)$ is the TMD PDFs of unpolarized partons with flavor a in an unpolarized proton, carrying longitudinal momentum fraction x and transverse momentum $k_\perp$

$D_1^{a\to h}(z, \boldsymbol{P}_\perp^2; Q^2)$ is the TMD FFs describing the fragmentation of an unpolarized parton with flavor a into an unpolarized hadron h carrying longitudinal momentum fraction z and transverse momentum $P_\perp$

Workshop on Novel Probes of the Nucleon Structure in SIDIS, e+e- and pp (FF2019)

chaired by Anselm Vossen (Duke University), Harut Avagyan (Jefferson Lab)

from Thursday, 14 March 2019 at **08:00** to Saturday, 16 March 2019 at **18:00** (US/Eastern)
at **Bostock Library (127)**

Go to day

Thursday, 14 March 2019

08:30 - 09:00 Registration

09:00 - 09:10 Welcome *10'* (127 Bostock Library)
Speaker: Dr. Anselm Vossen (Duke University)
Material: **Slides**

09:10 - 09:50 Recent Belle Results *40'*
Speaker: Dr. Ralf Seidl (RIKEN)
Material: **Slides**

09:50 - 10:30 Recent SIDIS results *40'*
Speaker: Dr. Gunar Schnell (University of the Basque Country UPV/EHU)
Material: **Slides**

10:30 - 11:00 Coffee!

11:00 - 11:40 News from NNPDF *40'*
Speaker: Dr. Emanuele Nocera (NIKHEF)
Material: **Slides**

11:40 - 12:20 Challenges and recent progress in SIDIS *40'*
Speaker: Nobuo Sato (ODU)
Material: **Slides**

12:20 - 12:50 Simultaneous analysis of unpolarized PDFs and fragmentation functions from JAM *30'*

PHYSICAL REVIEW D **99,** 112006 (2019)

Transverse momentum dependent production cross sections of charged pions, kaons and protons produced in inclusive e^+e^- annihilation at $\sqrt{s} = 10.58$ GeV

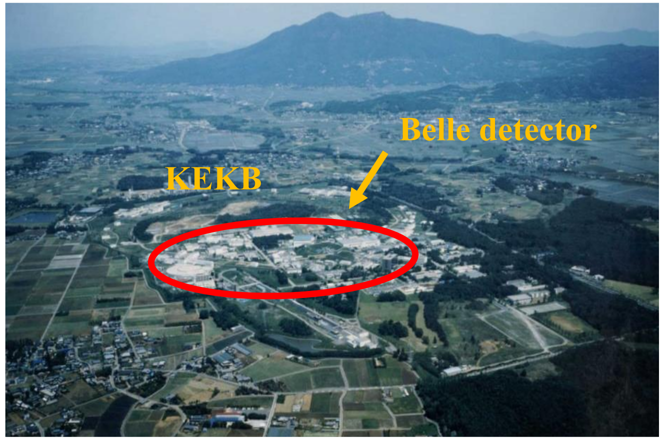
(Belle Collaboration)

(Received 5 February 2019; published 14 June 2019)

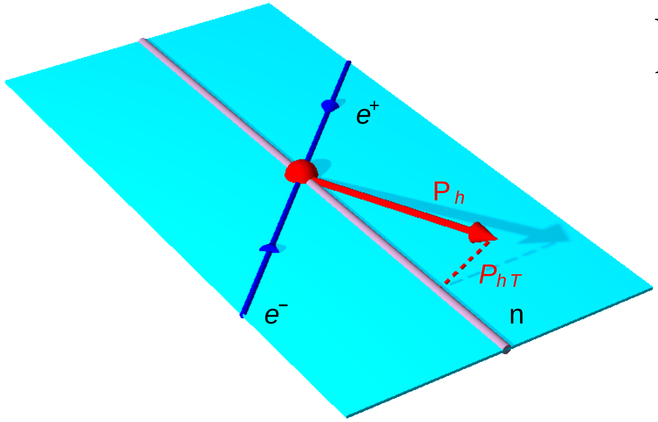
We report measurements of the production cross sections of charged pions, kaons, and protons as a function of fractional energy, the event-shape variable called thrust, and the transverse momentum with respect to the thrust axis. These measurements access the transverse momenta created in the fragmentation process, which are of critical importance to the understanding of any transverse-momentum-dependent distribution and fragmentation functions. The low transverse-momentum part of the cross sections can be well described by Gaussians in transverse momentum as is generally assumed but the fractional-energy dependence is nontrivial and different hadron types have varying Gaussian widths. The width of these Gaussians decreases with thrust and shows an initially rising, then decreasing fractional-energy dependence. The widths for pions and kaons are comparable within uncertainties, while those for protons are significantly narrower. These single-hadron cross sections and Gaussian widths are obtained from a 558 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider.

TMD Production Cross section by Belle Collaboration

This single-hadron cross-section measurement is based on a data sample of 558 fb^{-1} collected with the Belle detector at the KEKB asymmetric-energy e^+e^- (3.5 GeV on 8 GeV) collider.



$$d^3\sigma(e^+e^- \to hX)/dz dP_{hT} dT$$



Experimentally, the transverse momentum of the hadron is calculated relative to the thrust axis $\hat{n}$ which maximizes the event-shape variable thrust T

$$T \overset{\max}{=} \frac{\sum_h |\mathbf{P}_h^{\mathrm{CMS}} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\mathrm{CMS}}|}$$

$$\sqrt{s} = 10.58 \ \mathrm{GeV}$$

As the thrust variable describes how collimated all particles in an event are, the results are presented in bins of this value.

Binning

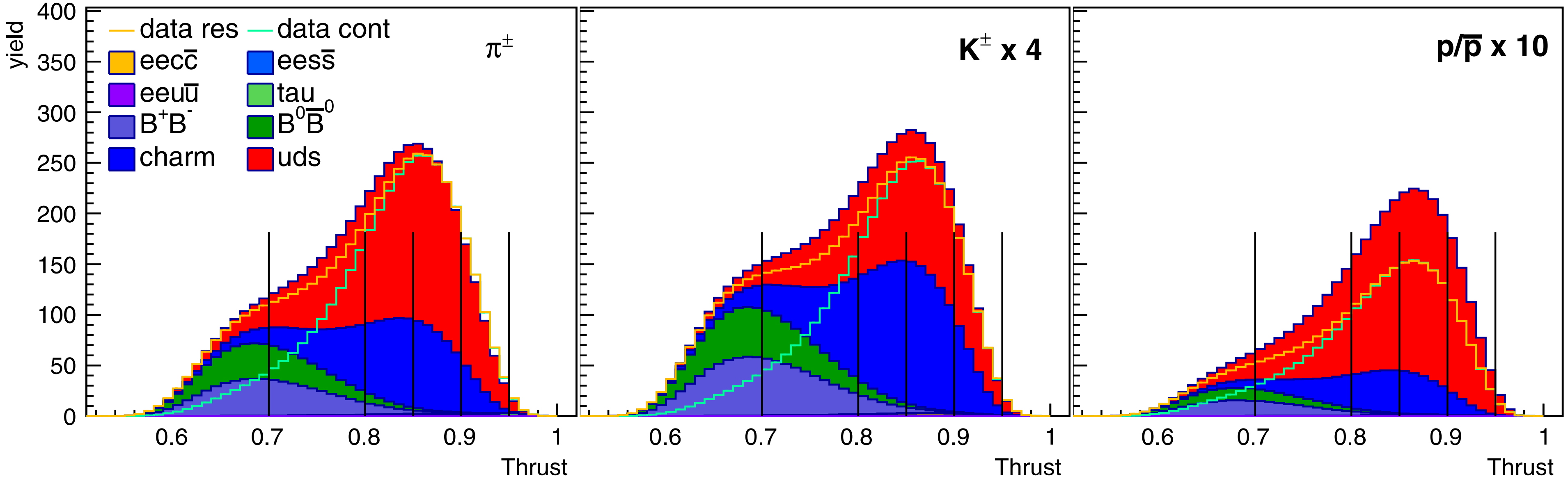
$$d^3\sigma(e^+e^- \to hX)/dzdP_{hT}dT$$

For the hadron cross section, a (z, P_{hT}) binning of 18 equidistant z bins from 0.1 to 1.0 and 20 equidistant P_{hT} bins from 0 to 2.5 GeV/c is chosen. The thrust values are separated into six bins with boundaries at 0.5, 0.7, 0.8, 0.85, 0.9, 0.95, and 1.0

#Final	weak de	cays	subtract	ed cross	secti	ons
d2sigma	/ dz dkt	in	microb/GeV	for the		pi+- data.
#thrus	t range	#zbin	range	#kbin	range	xsec[fb/G
0.5	0.7	0.1	0.15	0	0.125	1.46E+06
0.5	0.7	0.1	0.15	0.125	0.25	4.50E+06
0.5	0.7	0.1	0.15	0.25	0.375	7.43E+06
0.5	0.7	0.1	0.15	0.375	0.5	1.26E+07
0.5	0.7	0.1	0.15	0.5	0.625	1.17E+07
0.5	0.7	0.1	0.15	0.625	0.75	3.09E+06
0.5	0.7	0.1	0.15	0.75	0.875	6.92E+04
0.5	0.7	0.15	0.2	0	0.125	3.40E+05
0.5	0.7	0.15	0.2	0.125	0.25	9.76E+05
0.5	0.7	0.15	0.2	0.25	0.375	1.53E+06
0.5	0.7	0.15	0.2	0.375	0.5	1.94E+06
0.5	0.7	0.15	0.2	0.5	0.625	2.22E+06
0.5	0.7	0.15	0.2	0.625	0.75	2.54E+06
0.5	0.7	0.15	0.2	0.75	0.875	2.09E+06
0.5	0.7	0.15	0.2	0.875	1	5.22E+05
0.5	0.7	0.15	0.2	1	1.125	2.21E+04
0.5	0.7	0.2	0.25	0	0.125	1.08E+05
0.5	0.7	0.2	0.25	0.125	0.25	3.16E+05
0.5	0.7	0.2	0.25	0.25	0.375	4.63E+05
0.5	0.7	0.2	0.25	0.375	0.5	5.47E+05
0.5	0.7	0.2	0.25	0.5	0.625	5.72E+05
0.5	0.7	0.2	0.25	0.625	0.75	5.27E+05
0.5	0.7	0.2	0.25	0.75	0.875	4.20E+05
0.5	0.7	0.2	0.25	0.875	1	3.78E+05
0.5	0.7	0.2	0.25	1	1.125	2.93E+05

Binning and cross-section extraction

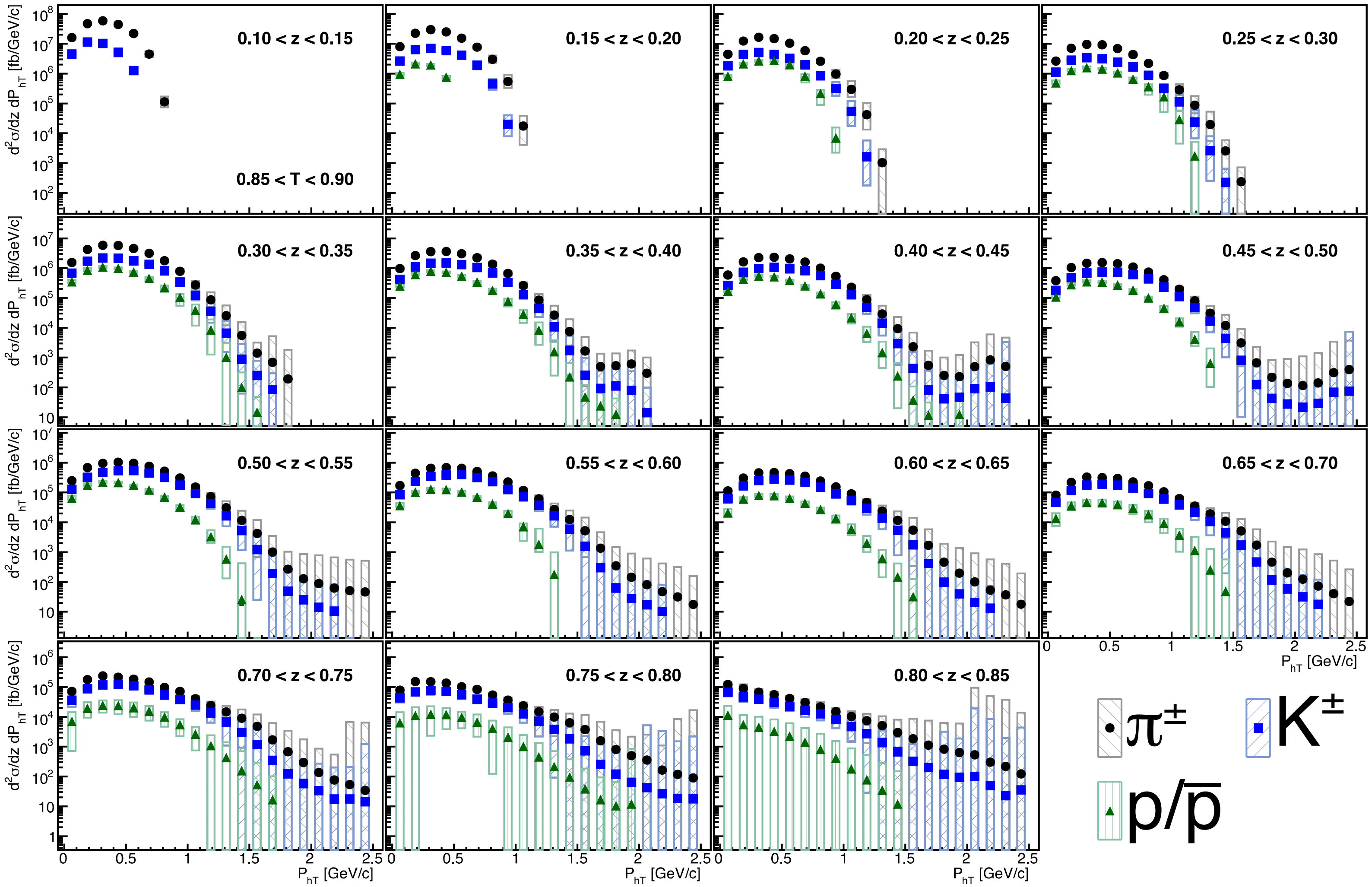
The goal of this analysis is to extract hadron cross sections from *uds* and *charm* pair events.



The distributions of thrust for the selected hadron samples are displayed in above plots, where the different processes are depicted. It can be seen that *uds* and *charm* events peak at high thrust values, which is why in the following most corrections and results are displayed in the $0.85 < T < 0.9$ thrust bin.

TMD Production Cross section by Belle Collaboration

First direct transverse-momentum-dependent single-hadron production cross sections e+ e- collisions at Q =10.58 GeV for pions, kaons, and protons.



Factorization of TMD FFs

Factorization of TMD for e+ e- → hX process, one observed hadron at the final state

$$\frac{d\sigma^h}{dzdP_{hT}} = 2\pi P_{hT}\frac{4\pi\alpha^2}{3s}\sum_q e_q{}^2 \mathcal{N} D_{h/f}(z, P_{hT}, Q^2)$$

$$= 2\pi P_{hT}\sigma_{\text{tot}}\sum_q \mathcal{N} D_{h/f}(z, Q^2) h^h(P_{hT}),$$

$$\sigma_{\text{tot}} = \sum_q e_q{}^2 \frac{4\pi\alpha^2}{3s}.$$

TMD fragmentation function two terms:

- ❑ First term is the unpolarized collinear FFs: [$D_{h/f}(z,Q^2)$]
- ❑ Second term corresponds to the TMD dependent: [$h^h(P_{hT})$]

not dependent on the scale of energy and also the flavor

$$D_{h/f}(z, P_{hT}, Q^2) = D_{h/f}(z, Q^2)h^h(P_{hT}).$$

FFs by NNFF1.0 Collaboration: Eur Phys J C 77 (2017) 516

NNFF1.0 (FFs)

$\boxed{D_i^H(z, Q_0)}$ $\boxed{i = u^+, d^+, s^+, c^+, b^+, g.}$

$\boxed{Q_0 = 5 \text{ GeV.}}$ $\boxed{q^+ = q + \bar{q}}$

		DHESS	HKNS	JAM	NNFF
DATA	SIA	☑	☑	☑	☑
	SIDIS	☑	☒	☒	☒
	PP	☑	☒	☒	☑
METH.	statistical treatment	Iterative Hessian 68% - 90%	Hessian $\Delta\chi^2 = 15.94$	Monte Carlo	Monte Carlo
	parametrisation	standard	standard	standard	neural network
THEORY	pert. order	(N)NLO	NLO	NLO	LO, NLO, NNLO
	HF scheme	ZM(GM)-VFN	ZM-VFN	ZM-VFN	ZM-VFN
	hadron species	$\pi^\pm$, $K^\pm$, $p/\bar{p}$, $h^\pm$	$\pi^\pm$, $K^\pm$, $p/\bar{p}$	$\pi^\pm$, $K^\pm$	$\pi^\pm$, $K^\pm$, $p/\bar{p}$
	latest update	PRD 91 (2015) 014035 PRD 95 (2017) 094019	PTEP 2016 (2016) 113B04	PRD 94 (2016) 114004	EPJ C77 (2017) 516

Fitting Methodology

Commonly parameterizations for the TMD FFs in SIDIS, Drell-Yan and SIA processes, Gaussian form at low $p_\perp$

$$D_{h/f}(z, P_{hT}, Q^2) = D_{h/f}(z, Q^2)\,\frac{e^{-P_{hT}{}^2/\langle P_{hT}{}^2\rangle}}{\pi\langle P_{hT}{}^2\rangle}$$

Physics Letters B 772 (2017) 78-86

JHEP 04 (2014) 005

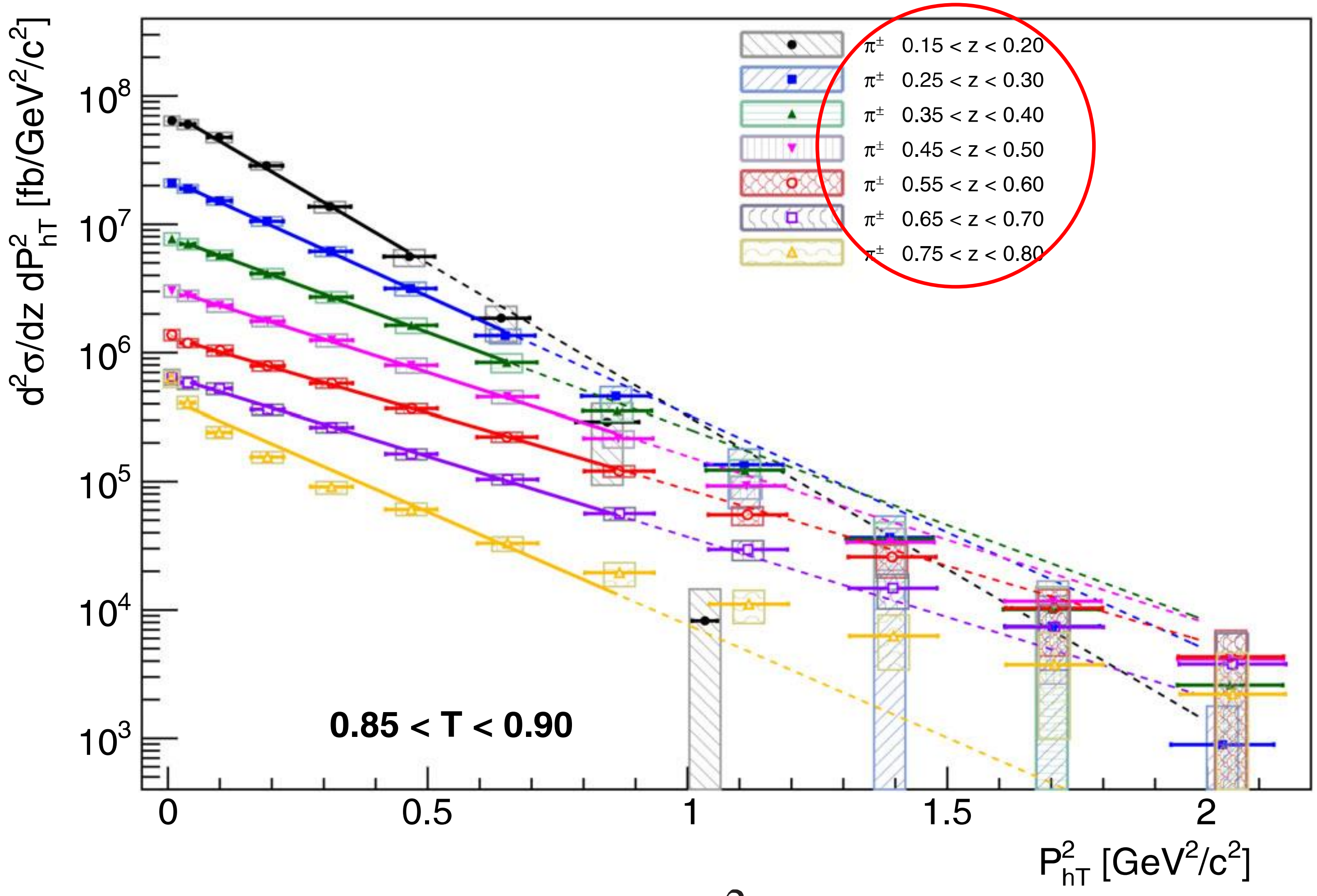
$$\langle P_{hT}^2\rangle = \alpha + z^{\beta}(1-z)^{\gamma} \qquad Q_0 = 5\ \text{GeV}.$$

$$\chi_n^2(p) = \sum_{i=1}^{N_n^{\text{data}}}\left(\frac{\mathcal{E}_i - \mathcal{T}_i(p)}{\Delta(\mathcal{E}_i)}\right)^2$$

Minimization has been done by the CERN program library MINUIT

[Comput. Phys. Commun. 10, 343 (1975)]

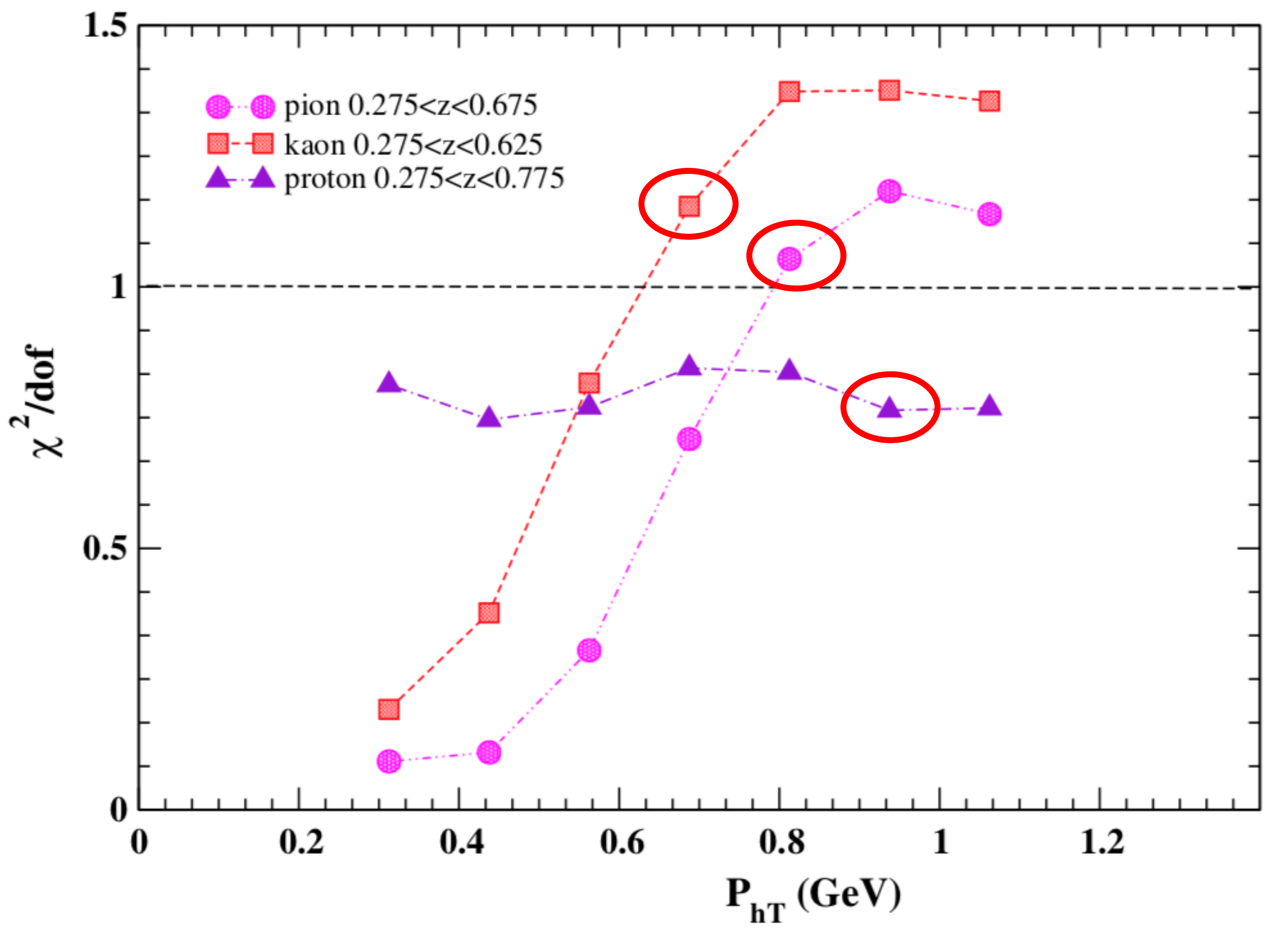
Kinematical cuts



χ^2 scans.

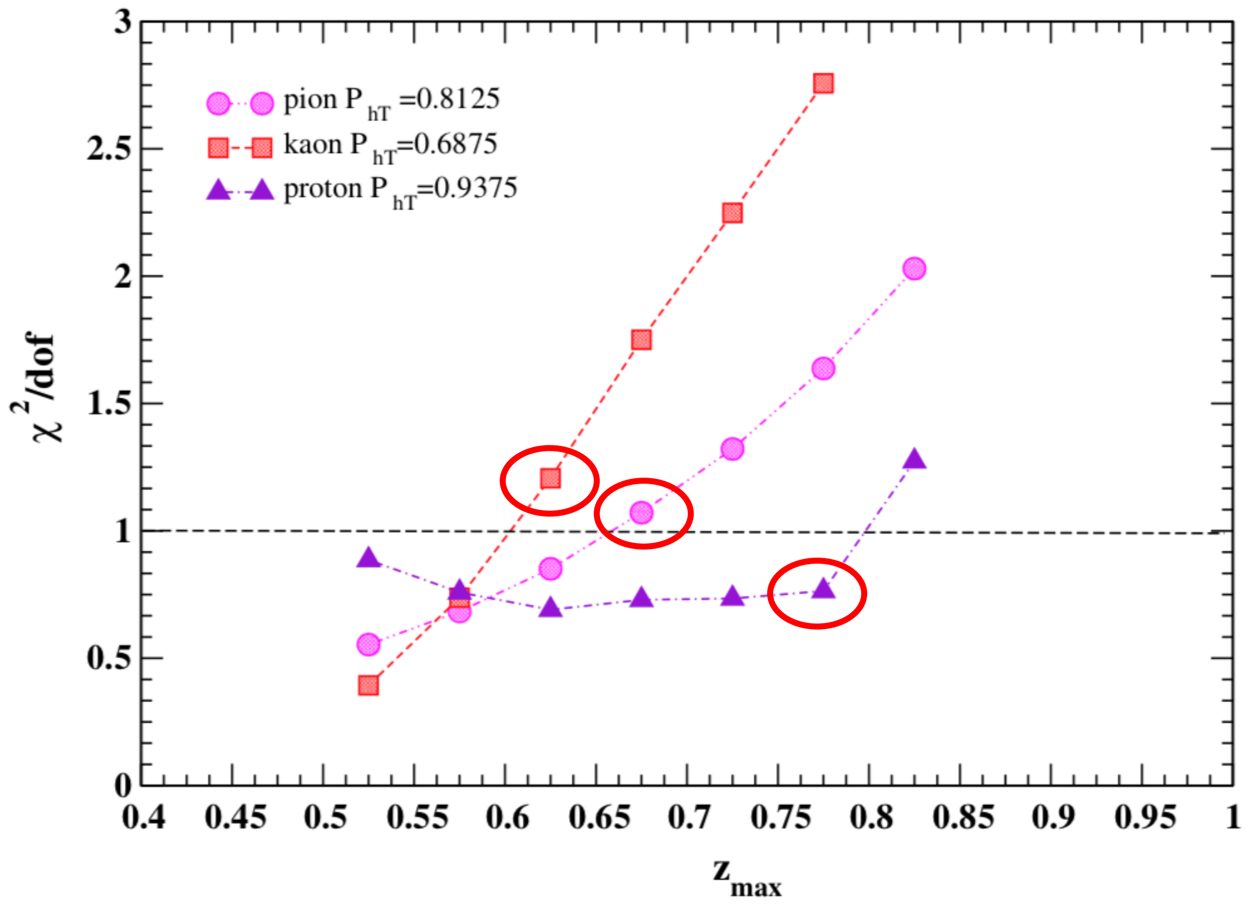
X^2 Scanning

TMD FFs fits for each different $P_{hT} < P_{hT}^{max}$ cut



Dependence on z parameter:

Sensitivity of χ^2 to the particular value of z_{max}
Exclude the datasets with $z > z_{max}$ from the analysis.



Results

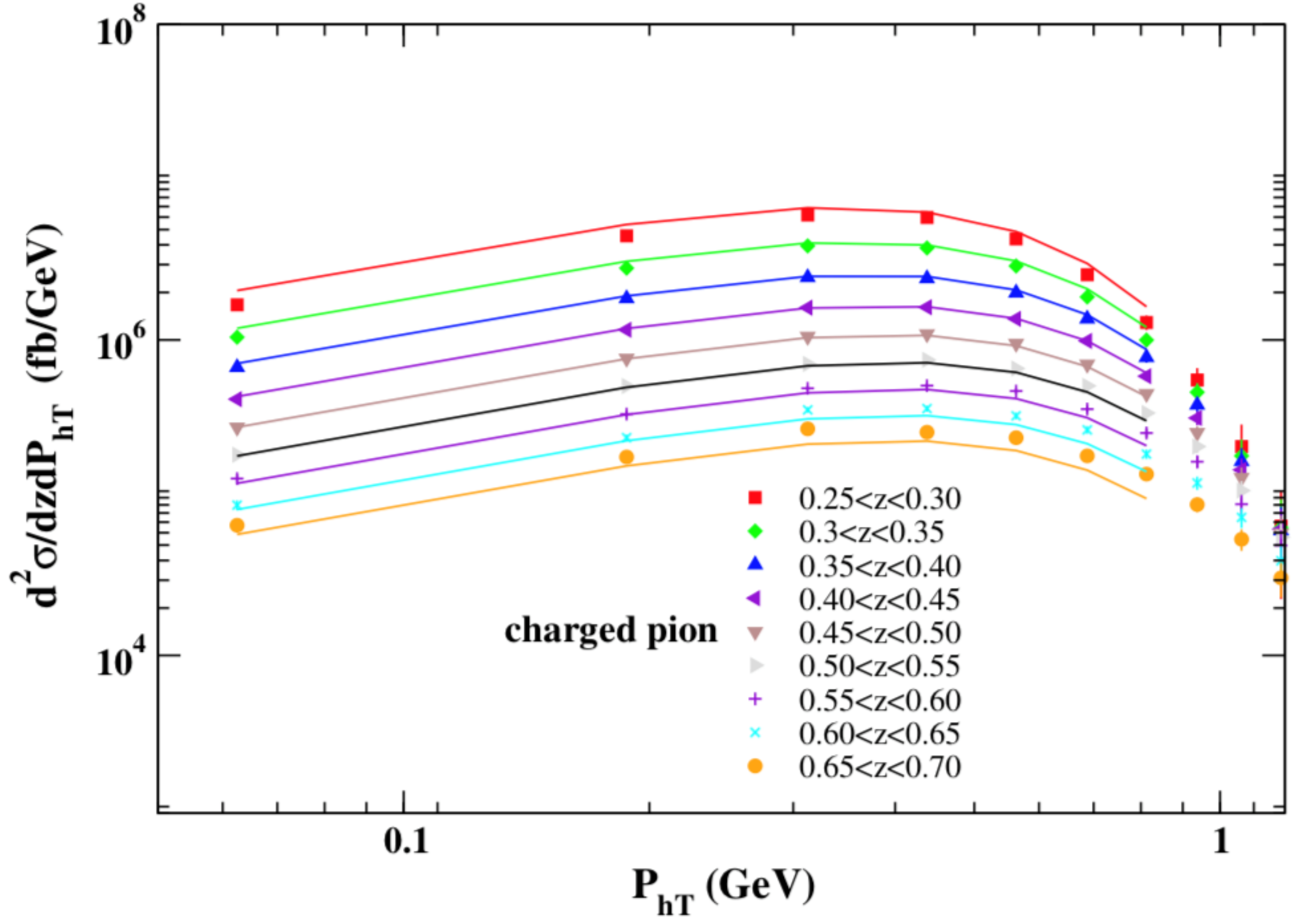
TABLE I. The input datasets included in the three individual analyses for $\pi^{\pm}$, $K^{\pm}$, and $p/\bar{p}$. For each hadron, we indicate the kinematical cuts of z and P_{hT}, number of data points in the fits, and the χ^2/d.o.f. values for each dataset.

Hadron	z cut	P_{hT} cut	Data points	χ^2/d.o.f.
$\pi^{\pm}$	[0.275–0.675]	[0–0.9]	63	1.053
$K^{\pm}$	[0.275–0.625]	[0–0.8]	48	1.154
$p/\bar{p}$	[0.275–0.775]	[0–1]	88	0.755

TABLE II. The best-fit parameters for the `SK19 TMD FFs` into $\pi^{\pm}$, $k^{\pm}$, and $p/\bar{p}$. The values labeled by (*) have been fixed. The details of the determination of best fit values are described in the text.

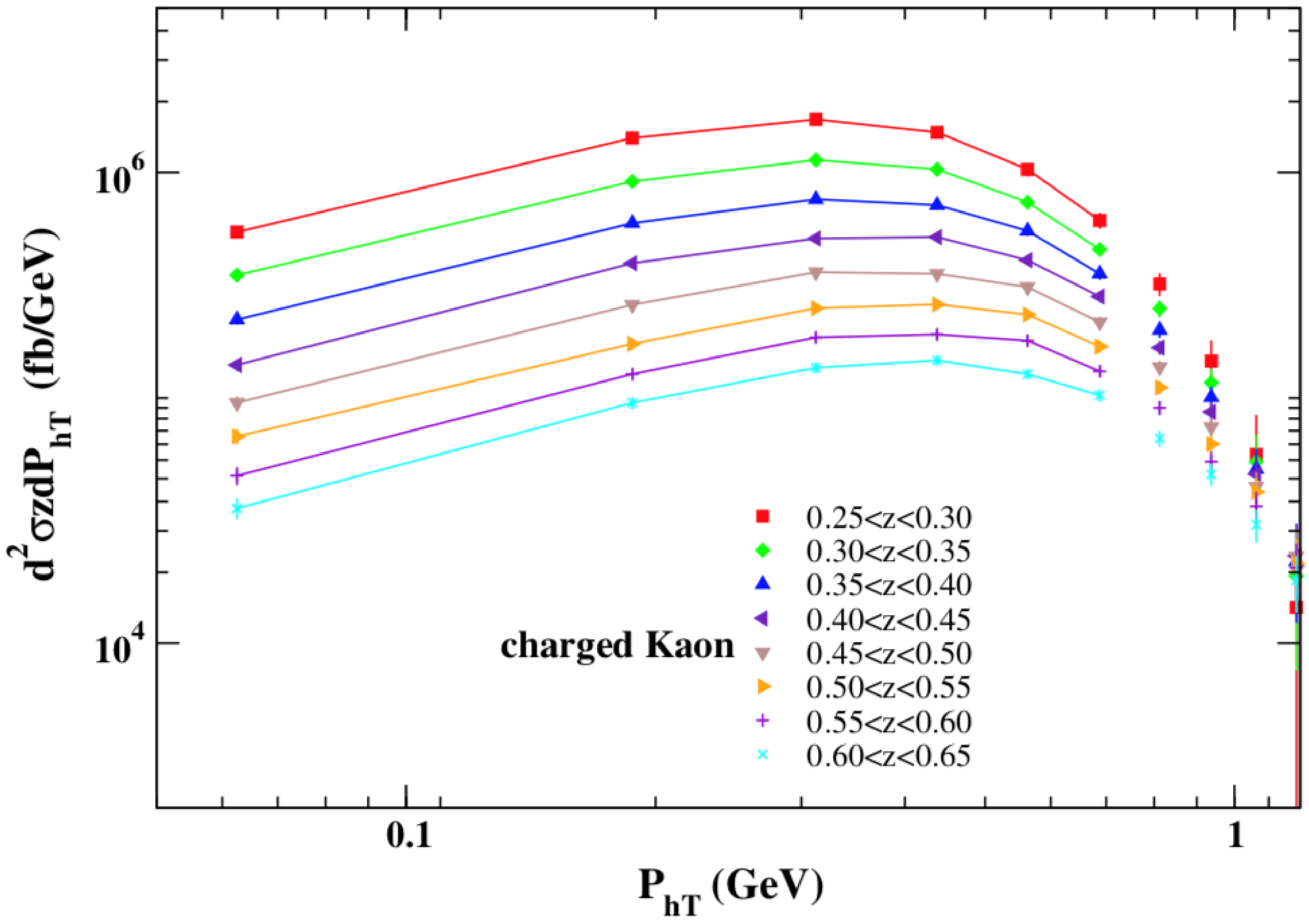
Parameters	$\pi^{\pm}$	$K^{\pm}$	$p/\bar{p}$
α	0.105	0.002	0.240
β	1.413	1.077	4.648
γ	0.854	0.739	1.153
$\mathcal{N}$	0.290*	0.166*	0.335*

Pion Results

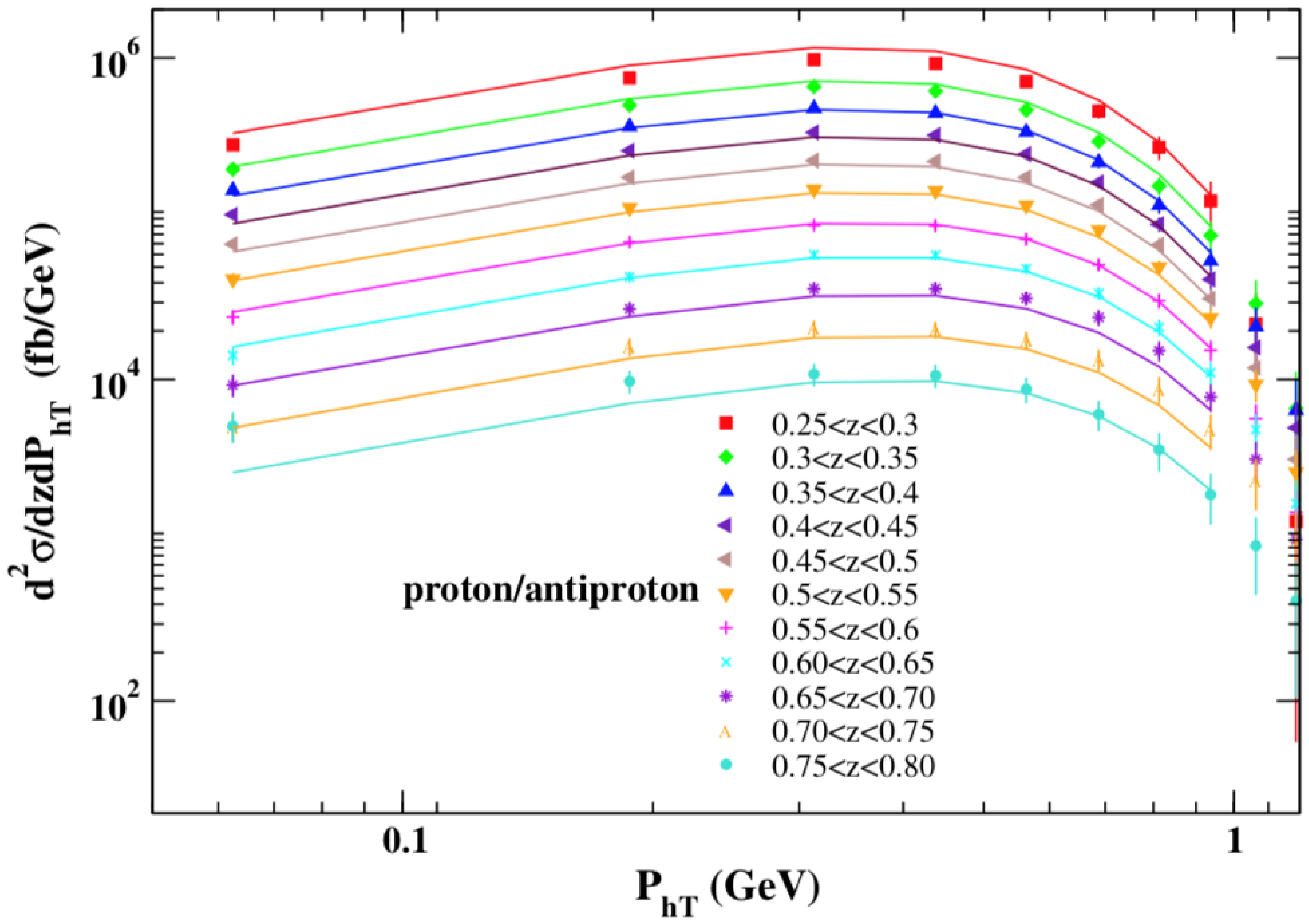


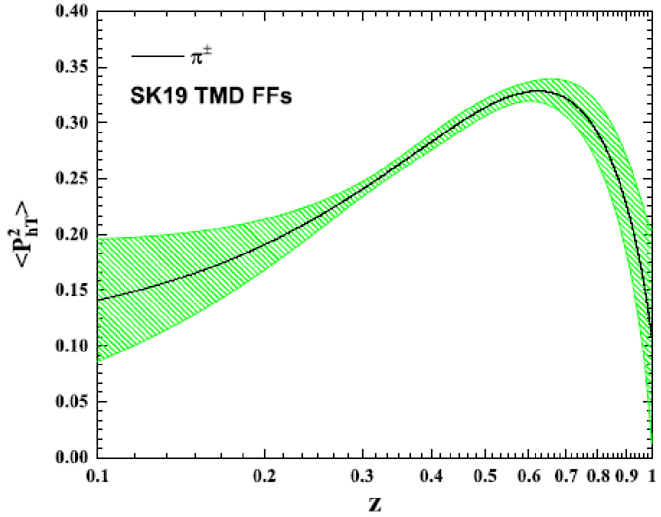
Comparisons between the differential cross sections measurements from Belle Collaboration for pion and our theory predictions as a function of P_{hT} for different z bins.

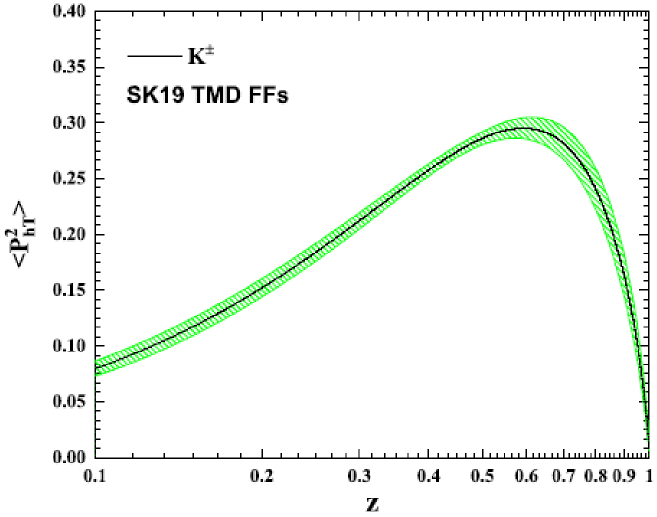
Kaon Results



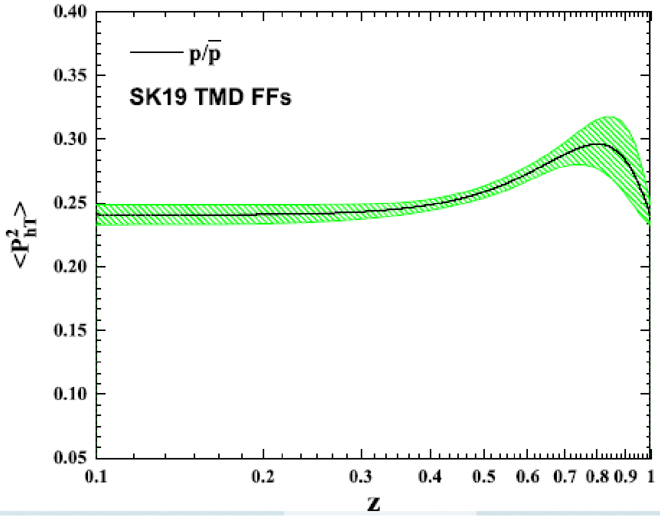
Proton Results





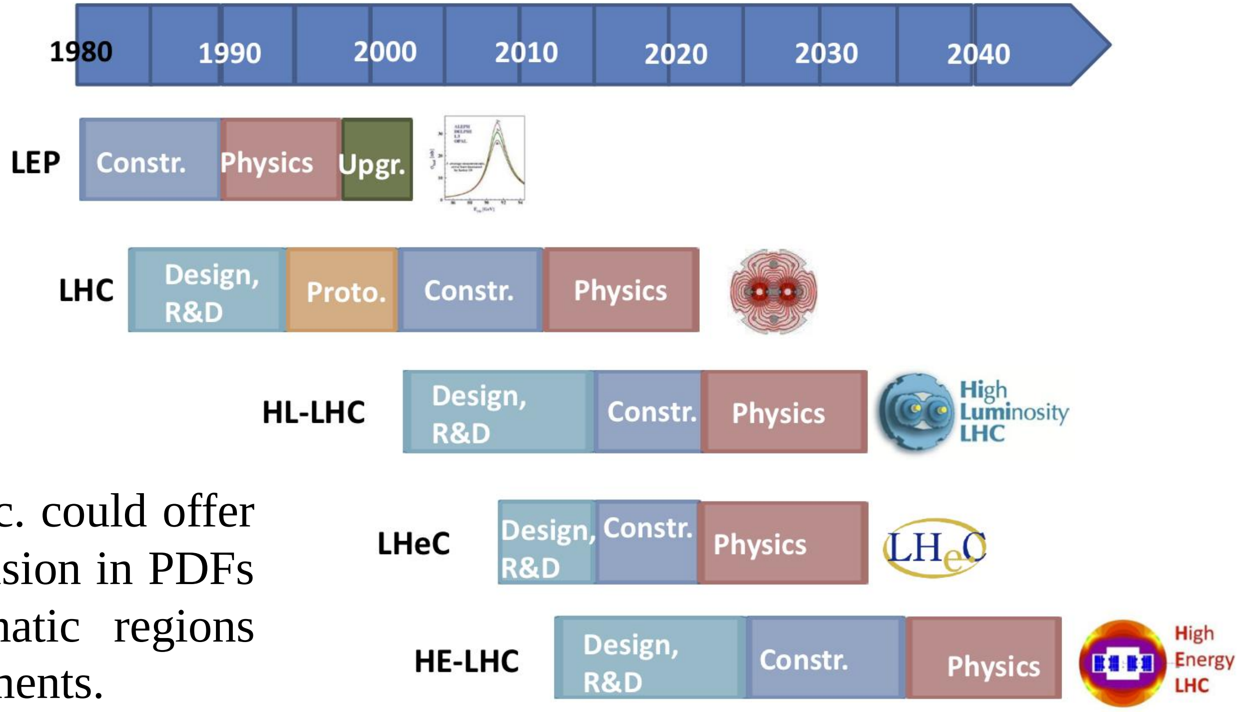


$$\langle P^2_{hT} \rangle = \alpha + z^{\beta}(1-z)^{\gamma}$$

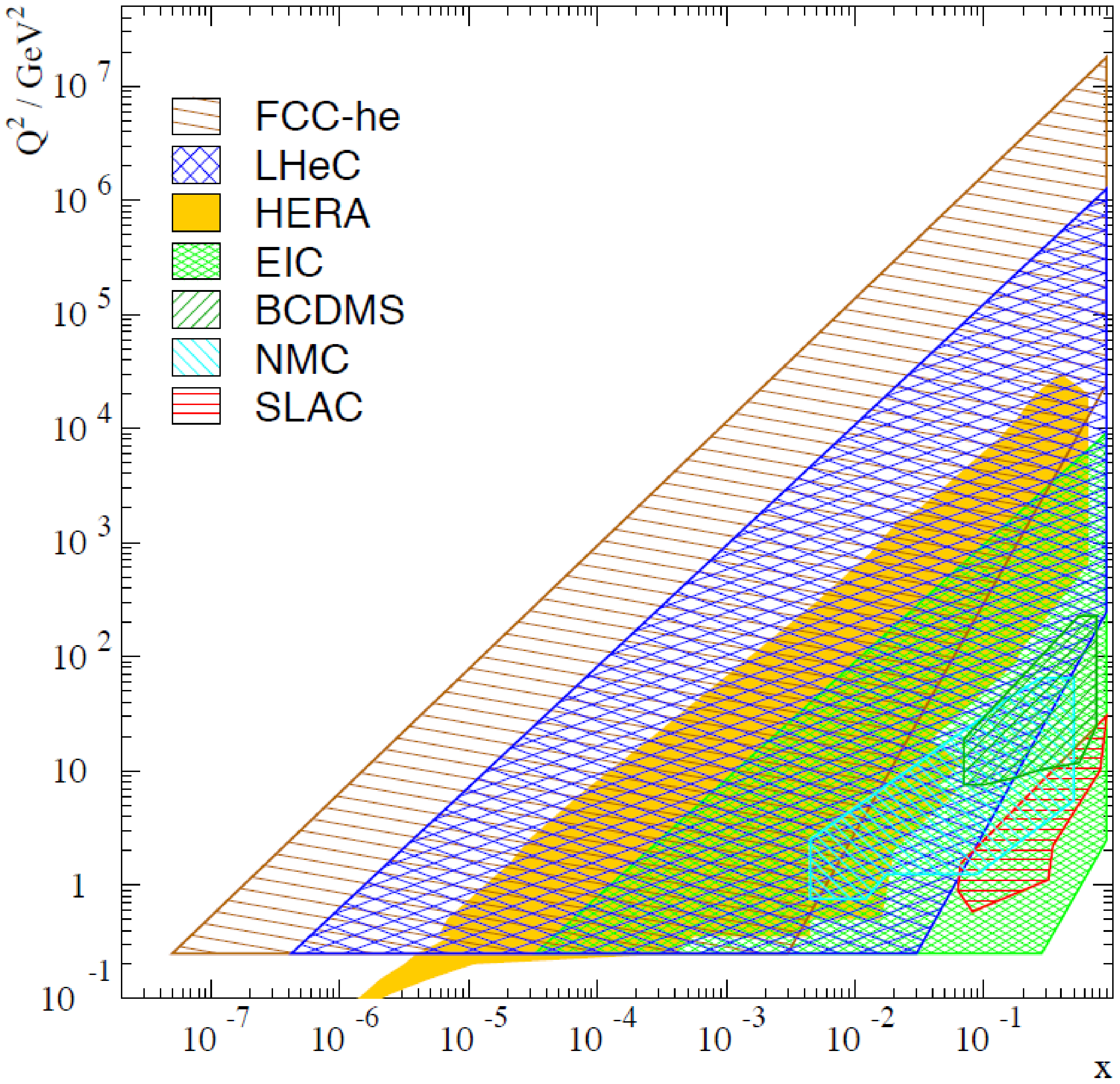


The distributions for $< p^2_{hT} >$ as a function of z. The plots shown are for the charged pion, kaon, and proton/antiproton FFs, respectively. The error bars correspond to the 1-σ uncertainty at 68% CL.

Future high-energy colliders



- ✓ Future colliders, such as LHeC, EIC, FCC, etc. could offer unique possibilities to reach the ultimate precision in PDFs and FFs determinations by probing kinematic regions which are far from the reach of current experiments.



CERN-ACC-Note-2020-0002
Geneva, June 18, 2020

To appear in:
Journal of Physics G

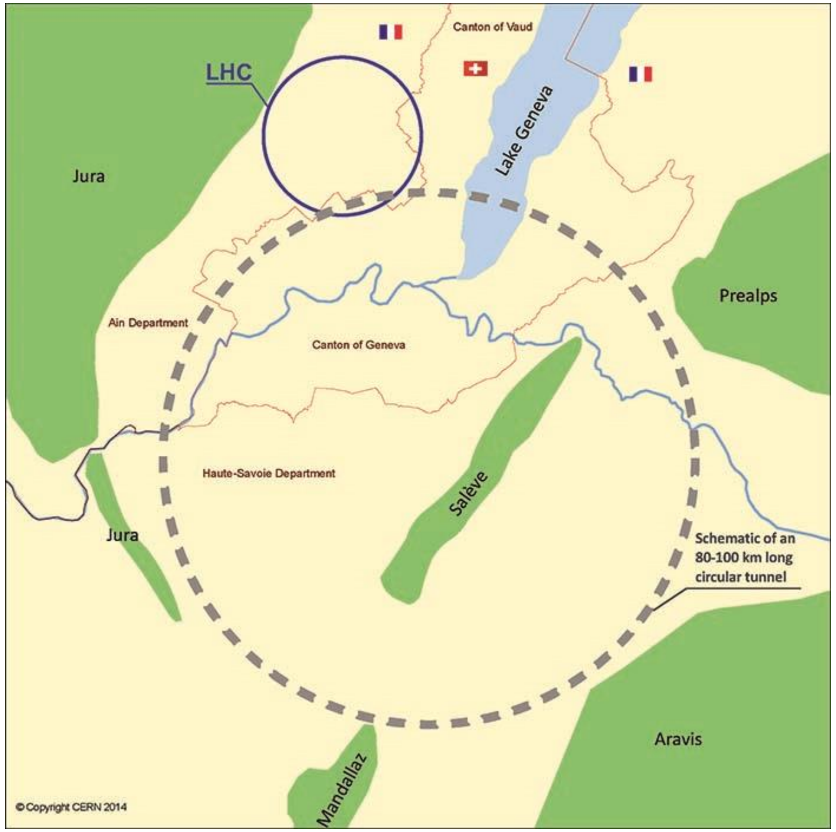
Coverage of the kinematic plane in deep inelastic lepton-proton scattering by some initial fixed target experiments, with electrons (SLAC) and muons (NMS, BCDMS), and by the ep colliders: the EIC (green), HERA (yellow), the LHeC (blue) and the FCC-eh (brown).

Future Circular Collider (FCC)

- The goal of the FCC is to greatly push the energy and intensity frontiers of particle colliders, with the aim of reaching collision energies of 100 TeV, in the search for new physics.
- The FCC Study, hosted by CERN, is an international collaboration of more than 150 universities, research institutes and industrial partners from all over the world.

The phenomenology of PDFs at such extreme energies is very rich: such as top quark PDFs and ... lots of fun!!!

Growing consensus that the next big machine more suitable to explore the energy frontier should be a 100 TeV hadron collider, possibly with also e^+e^-, ep and pp operation modes.



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Summary and Conclusion

- ✓ Recently, Belle Collaboration at KEKB has published the first measurements on $e^+e^- \rightarrow hX$ differential cross sections in both z and P_{hT} space for charged pion, kaon, and proton/antiproton. Previously, there was no dataset on the transverse momentum dependence of the cross sections or multiplicities for extraction of the unpolarized TMD FFs for the identified light hadrons.

- ✓ These datasets are the only available observables in SIA process which we used, for the first time, to determine the unpolarized TMD FFs for pion, kaon, and proton/antiproton from QCD fits. These new measurements could provide enough constrains on the energy fraction z of the fragmentation process.

- ✓ This analysis is restricted to the electron-positron annihilation processes, and hence, another possible area of future research would be to investigate the effect of another source of information on the TMD FFs which mainly come from the SIDIS processes. In terms of future work, it would be interesting to repeat the analysis described here considering the mentioned improvements.

It is my honor to thank: The organizers of ICHEP2020 conference, and your attentions!