Phenomenology of unpolarized TMDs from SIDIS data

Andrea Signori

XXIII. Workshop on DIS and related subjects
Warsaw – 30 April 2014

Our recent work

PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: *October 7, 2013*
ACCEPTED: *November 11, 2013*
PUBLISHED: *November 27, 2013*

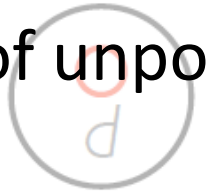
Investigations into the flavor dependence of partonic transverse momentum

Andrea Signori,[a,b] Alessandro Bacchetta,[c,d] Marco Radici[c] and Gunar Schnell[e,f]

DOI: 10.1007 / JHEP 11(2013)194

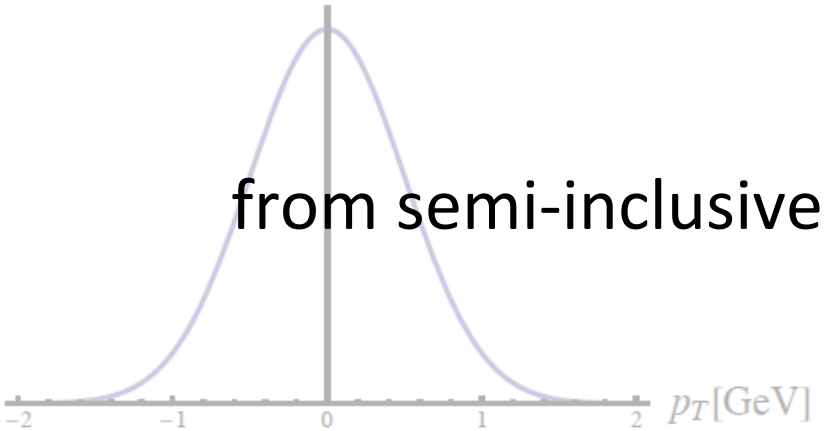
A new goal

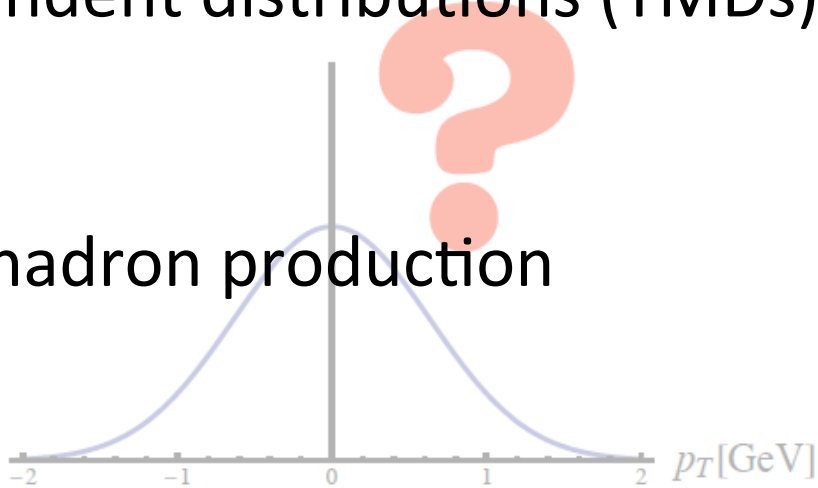
Access the flavor dependence of unpolarized

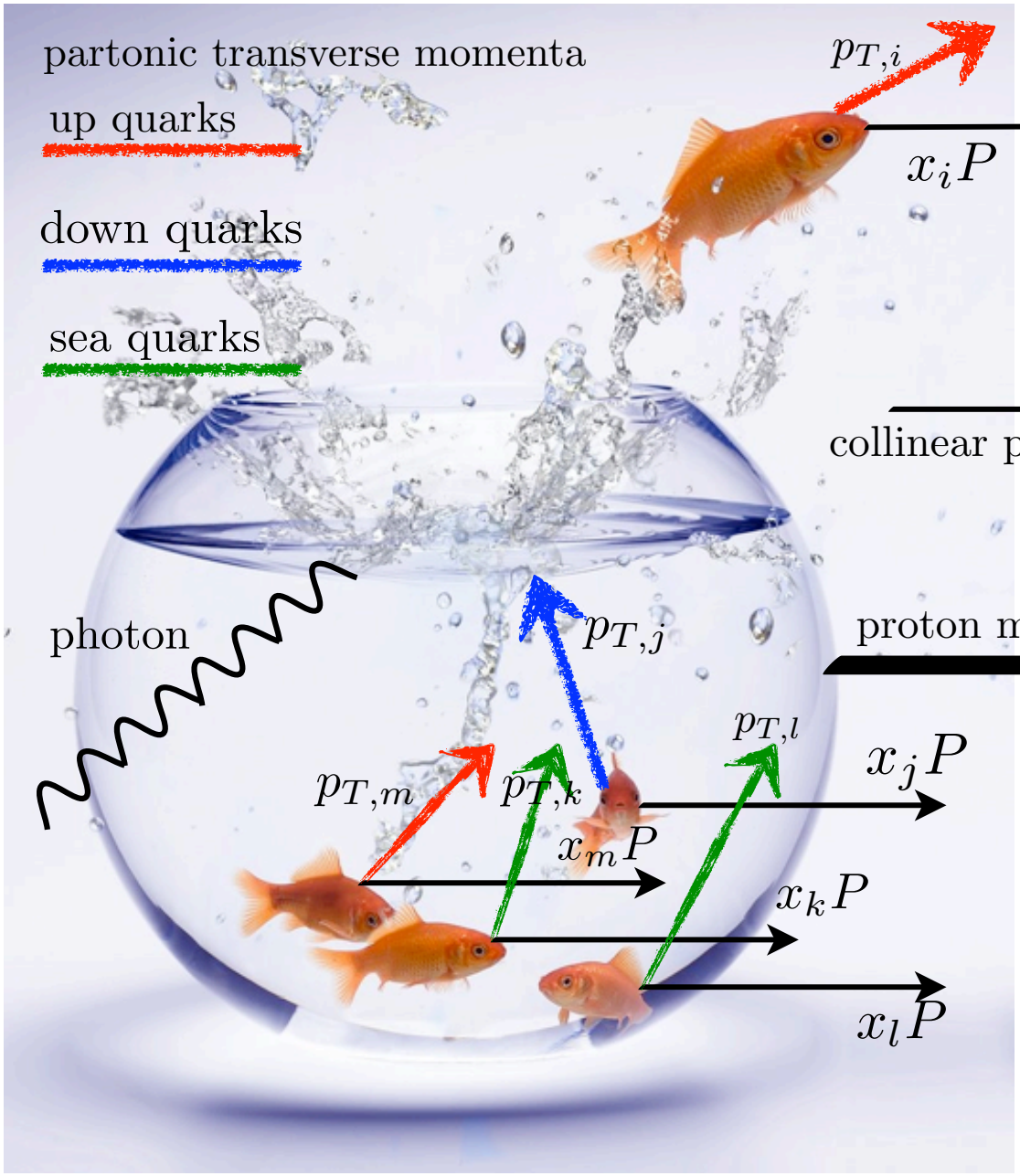


transverse-momentum-dependent distributions (TMDs)

from semi-inclusive hadron production



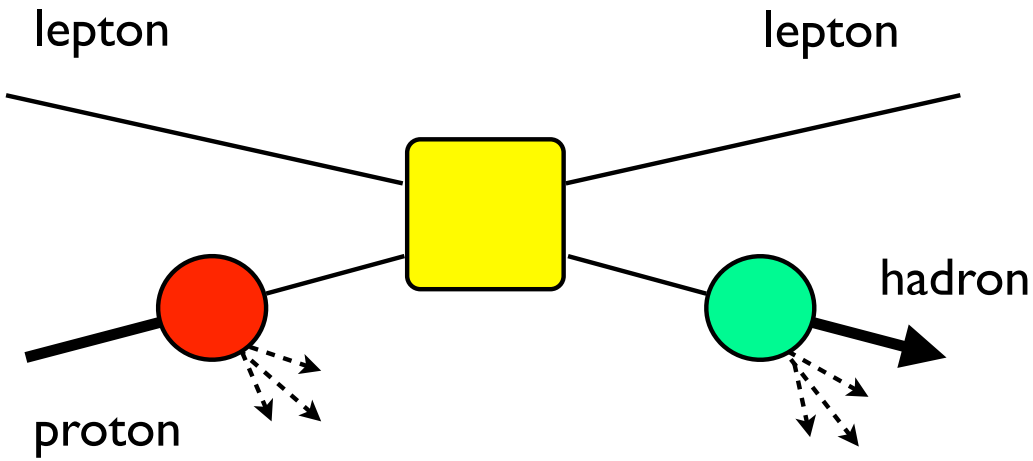



partonic transverse momenta
up quarks
down quarks
sea quarks
$p_{T,i}$
$x_i P$
$D_1^a(z, P_\perp^2, Q^2)$
collinear partonic momenta
P
proton momentum
photon
$p_{T,j}$
$p_{T,l}$
$x_j P$
$p_{T,m}$
$p_{T,k}$
$x_m P$
$x_k P$
$x_l P$
$f_1^a(x, k_\perp^2, Q^2)$

TMDs in SIDIS

Unpolarized

SIDIS



Parton model picture

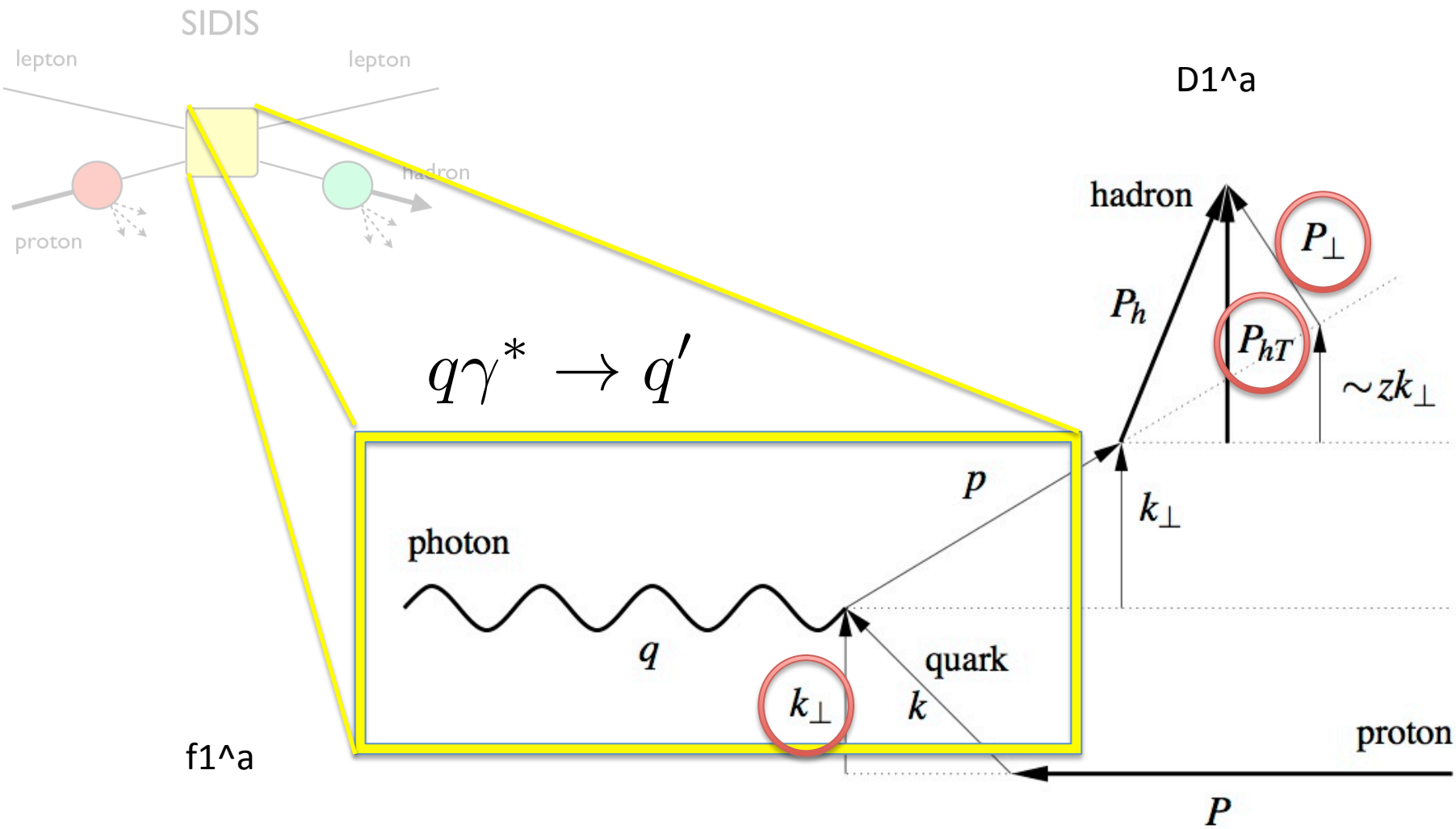
LO QED

Zero-order QCD

Leading twist

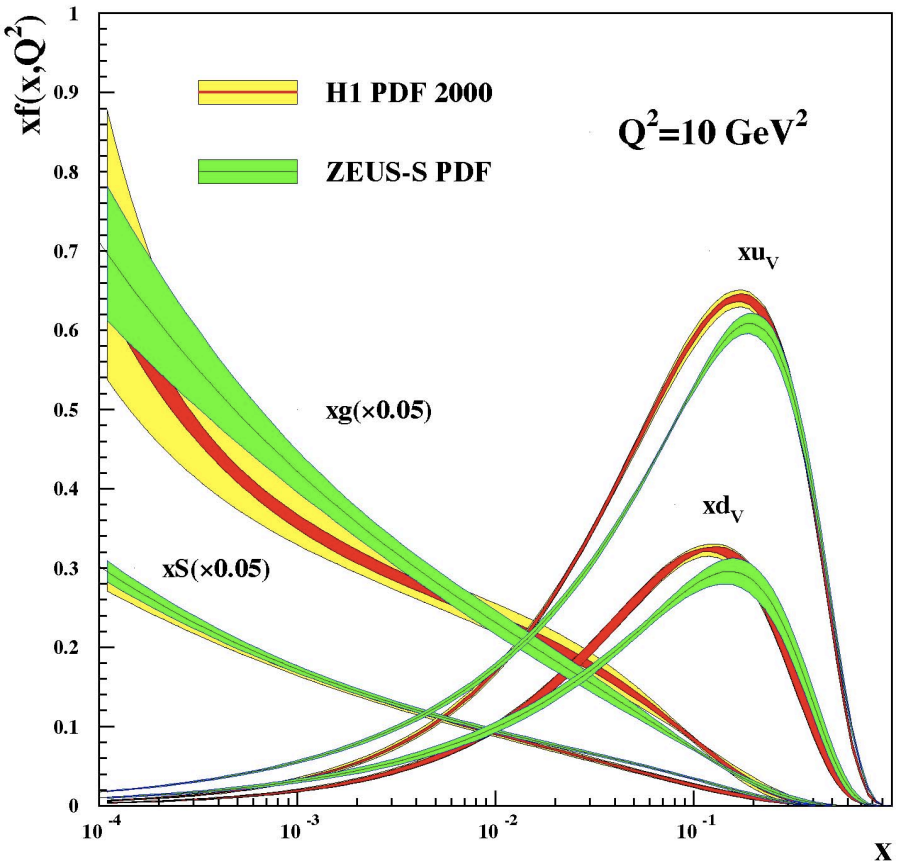
$$\sigma(P_{hT}^2) \sim \sum_a f_1^a(x, k_\perp^2) \otimes D_1^{a\to h}(z, P_\perp^2)$$

Which transverse momenta ?



Motivations

Flavor in transverse space



Since the flavor dependence
In the collinear case is strong …

… WHY NOT
LOOKING FOR IT IN

$K_\perp$ DEPENDENCE

OF TMDs ?

Flavor in transverse space

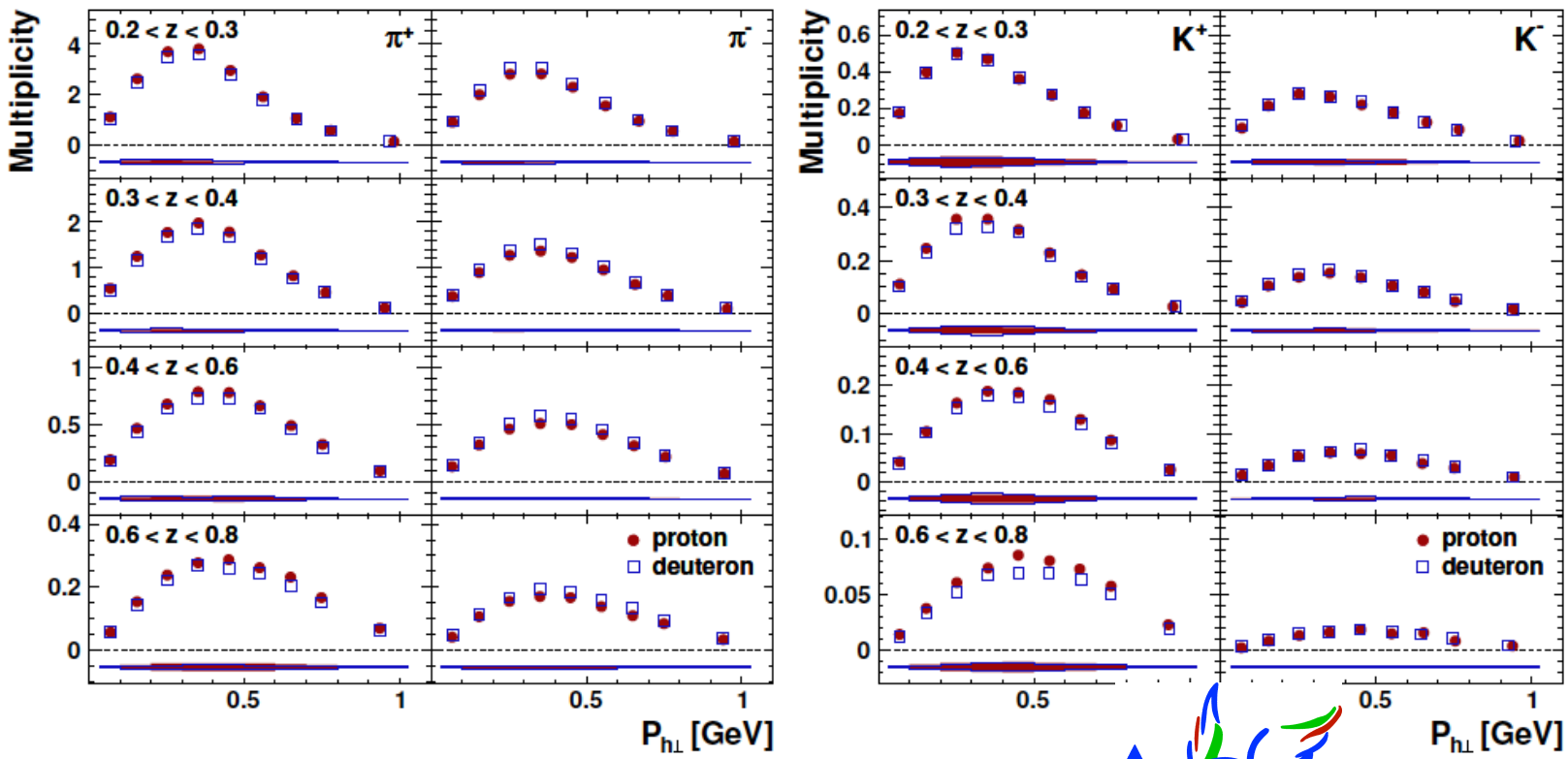
- ✓ Lattice QCD calculations
  Musch *et al.*, PRD **83** (11) 094507
  […]

- ✓ Model calculations
  Chiral quark soliton model [Scweitzer *et al.,* JHEP 1301 (913) 163]
  Diquark spectator model [Bacchetta *et al.,* PRD **78** (08) 074010]
  Statistical approach [Bourrely *et al.,* PRD **83** (11) 074008]
  NJL-jet model [Matevosyan *et al.*, PRD **85** (12) 014021]
  […]

- ✓ Previous fits
  JLab Hall C [Asaturyan *et al.*, (E00-108), PRC **85** (12) 015202]

Flavor in transverse space

With flavor dependence we can account ***theoretically*** for different cross sections for different target/final state hadron combinations.



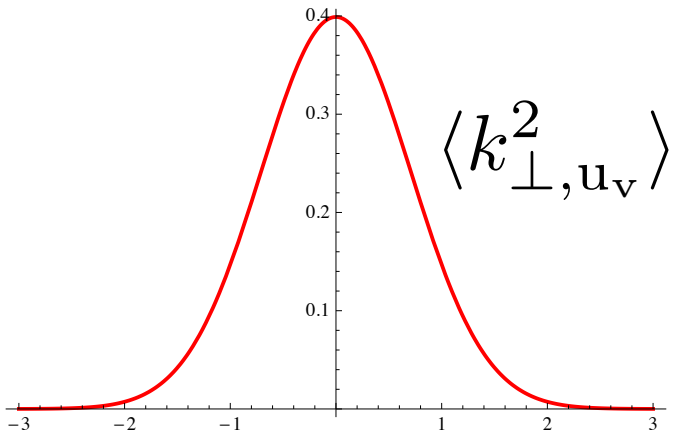
Flavor dependent

Gaussian TMDs

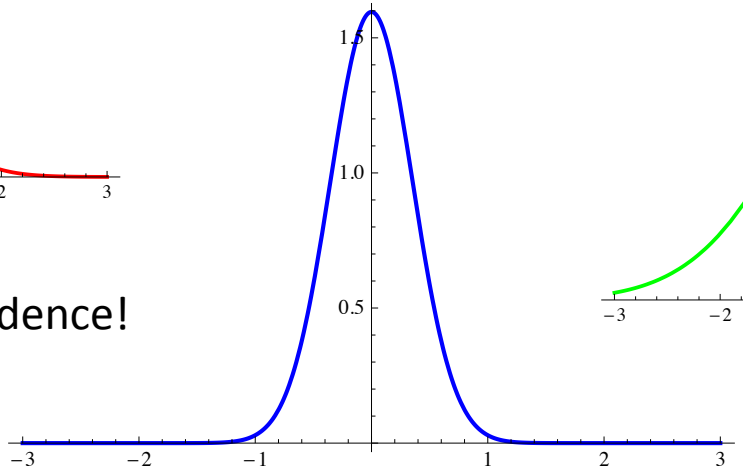
Flavor dependent Gaussians

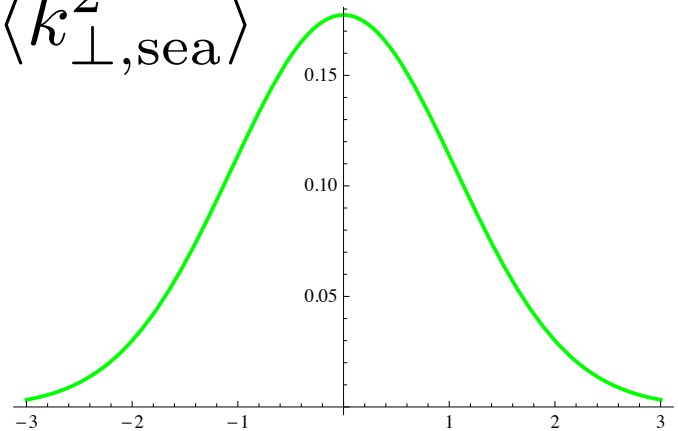
Different Gaussian parametrizations of TMD parts

$$f_1^a(x, k_\perp^2) = f_1^a(x) \boxed{\frac{1}{\pi \langle k_{\perp,a}^2 \rangle} \exp\left\{ -\frac{k_\perp^2}{\langle k_{\perp,a}^2 \rangle} \right\}}$$



$$\langle k_{\perp,\mathrm{u_v}}^2 \rangle \neq \langle k_{\perp,\mathrm{d_v}}^2 \rangle \neq \langle k_{\perp,\mathrm{sea}}^2 \rangle$$



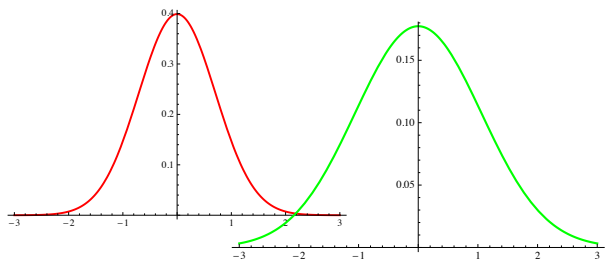


Simplified flavor dependence!

Flavor dependent Gaussians

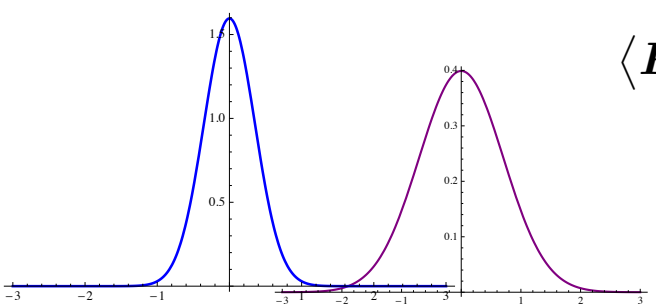
Different Gaussian parametrization of TMD parts

$$D_1^{a\to h}(z, P_\perp) = D_1^{a\to h}(z)\boxed{\frac{1}{\pi\langle P^2_{\perp,a\to h}\rangle}\exp\left\{-\frac{P_\perp^2}{\langle P^2_{\perp,a\to h}\rangle}\right\}}$$



4 different combinations out of

$$\mathrm{u,\ d,\ s} \Longleftrightarrow \pi^\pm,\ K^\pm$$



$$\langle \boldsymbol{P}^2_{\perp,u\to\pi^+}\rangle = \langle \boldsymbol{P}^2_{\perp,\bar{d}\to\pi^+}\rangle = \langle \boldsymbol{P}^2_{\perp,\bar{u}\to\pi^-}\rangle = \langle \boldsymbol{P}^2_{\perp,d\to\pi^-}\rangle \equiv \langle \boldsymbol{P}^2_{\perp,\mathrm{fav}}\rangle\,,$$

$$\langle \boldsymbol{P}^2_{\perp,u\to K^+}\rangle = \langle \boldsymbol{P}^2_{\perp,\bar{u}\to K^-}\rangle \equiv \langle \boldsymbol{P}^2_{\perp,uK}\rangle\,,$$

$$\langle \boldsymbol{P}^2_{\perp,\bar{s}\to K^+}\rangle = \langle \boldsymbol{P}^2_{\perp,s\to K^-}\rangle \equiv \langle \boldsymbol{P}^2_{\perp,sK}\rangle\,,$$

$$\langle \boldsymbol{P}^2_{\perp,\mathrm{all\ others}}\rangle \equiv \langle \boldsymbol{P}^2_{\perp,\mathrm{unf}}\rangle\,.$$

Kinematic dependence

$$\langle \boldsymbol{k}^2_{\perp,\,q} \rangle(x) = \langle \widehat{\boldsymbol{k}^2_{\perp,\,q}} \rangle \, \frac{(1-x)^{\alpha}\, x^{\sigma}}{(1-\hat{x})^{\alpha}\, \hat{x}^{\sigma}}$$

Flavor independent
Kinematic dependence

$$\langle \widehat{\boldsymbol{k}^2_{\perp,\,q}} \rangle = \langle \boldsymbol{k}^2_{\perp,\,q} \rangle (\hat{x} = 0.1)$$

$$\langle \boldsymbol{P}^2_{\perp,\,q\to h} \rangle(z) = \langle \widehat{\boldsymbol{P}^2_{\perp,\,q\to h}} \rangle \, \frac{(z^{\beta}+\delta)\,(1-z)^{\gamma}}{(\hat{z}^{\beta}+\delta)\,(1-\hat{z})^{\gamma}}$$

$$\langle \widehat{\boldsymbol{P}^2_{\perp,\,q\to h}} \rangle = \langle \boldsymbol{P}^2_{\perp,\,q\to h} \rangle (\hat{z} = 0.5)$$

Flavor independent
Kinematic dependence

Flavor analysis

Parameters for TMD PDFs					
	$\langle \hat{\boldsymbol{k}}^2_{\perp,d_v} \rangle$ [GeV^2]	$\langle \hat{\boldsymbol{k}}^2_{\perp,u_v} \rangle$ [GeV^2]	$\langle \hat{\boldsymbol{k}}^2_{\perp,\mathrm{sea}} \rangle$ [GeV^2]	α (random)	σ (random)

5 parameters

interval [0,2] interval [-0.3,0.1]

Parameters for TMD FFs							
	$\langle \hat{\boldsymbol{P}}^2_{\perp,\mathrm{fav}} \rangle$ [GeV^2]	$\langle \hat{\boldsymbol{P}}^2_{\perp,\mathrm{unf}} \rangle$ [GeV^2]	$\langle \hat{\boldsymbol{P}}^2_{\perp,sK} \rangle$ [GeV^2] (random)	$\langle \hat{\boldsymbol{P}}^2_{\perp,uK} \rangle$ [GeV^2]	β	δ	γ

7 parameters

interval [0.125,0.250]

Analysis

of HERMES data

Hermes

$$e^{\pm} + \boxed{P/D} \rightarrow e^{\pm} + \underline{\{\pi^{\pm}/K^{\pm}\}} + X$$

6 bins in x,
8 bins in z,
7 bins in P_{hT},
2 targets, 4 final-state hadrons

2688 points

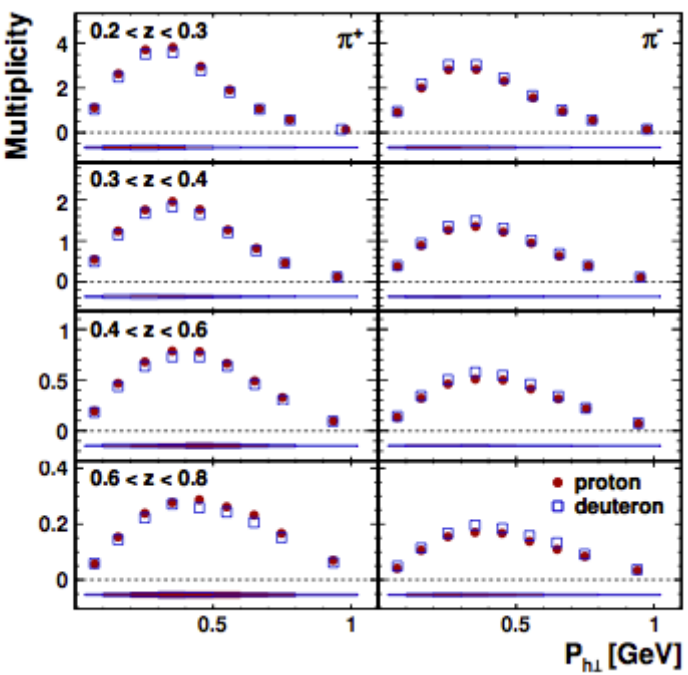
Our selection

- Remove the first bin x-Q^2 (Q^2>1.4 GeV^2)
- $0.1 < z < 0.8$
- $P_{hT}^2 < Q^2/3$

1538 analyzed points

limited Q^2 range ⇒ safely neglect evolution <u>everywhere</u>

Fitting procedure

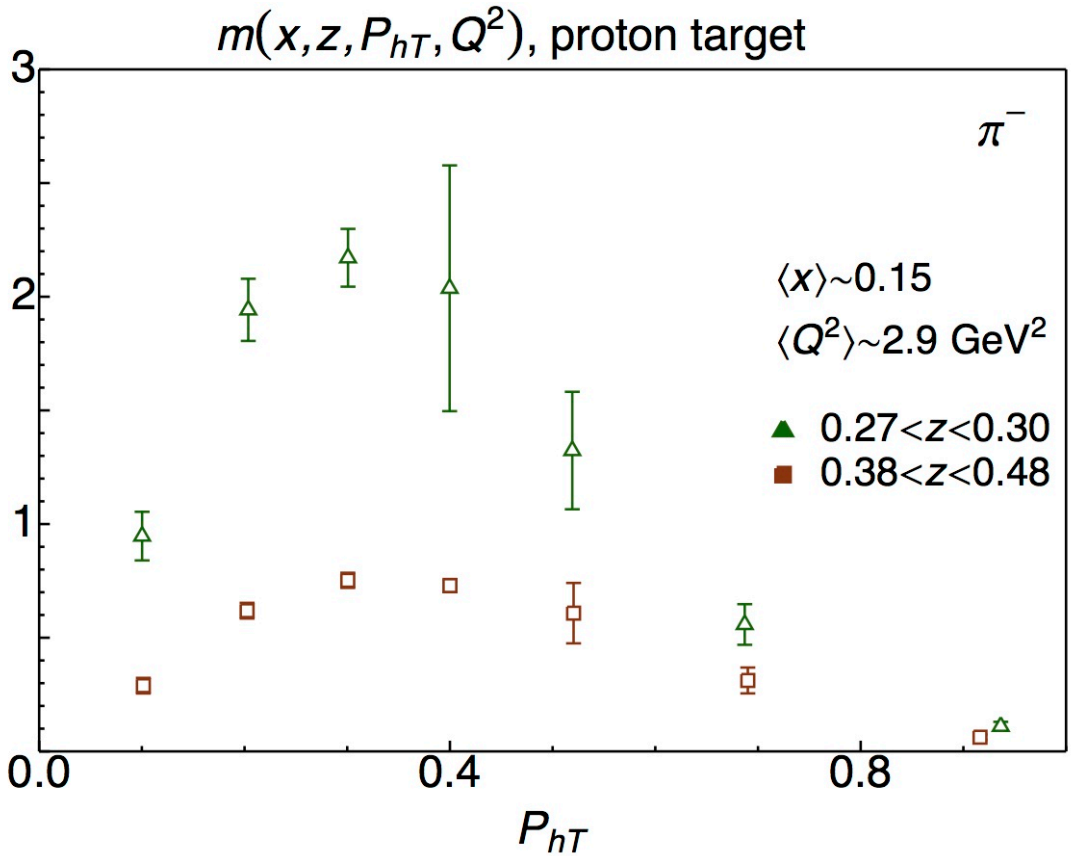


$\times$ 200

Monte Carlo fit

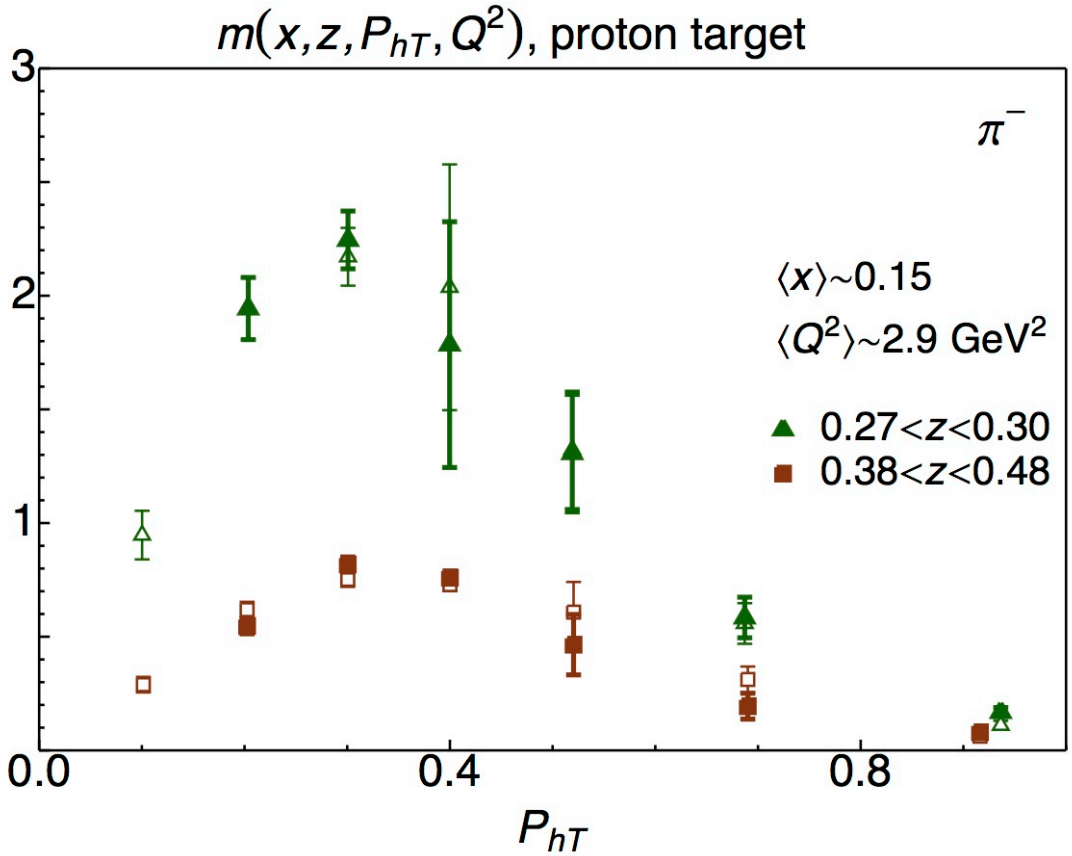
Distributions of best-values

Fitting procedure



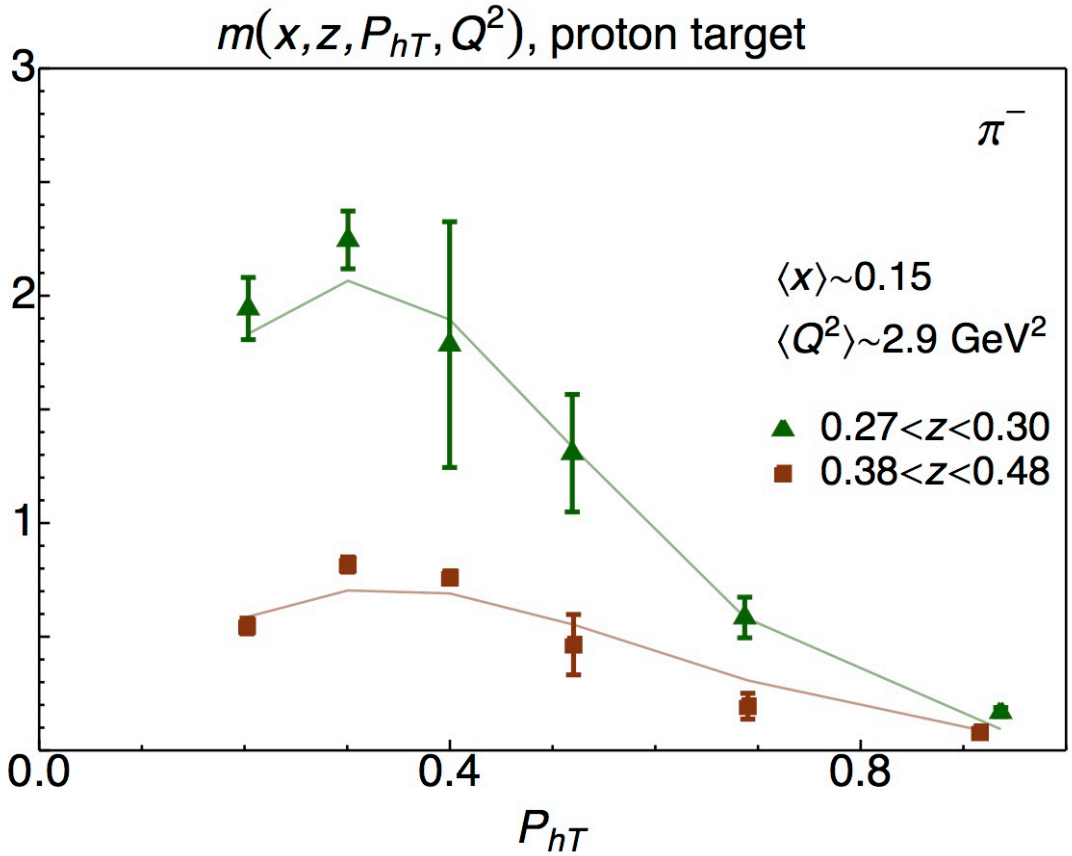
Sample of original data

Fitting procedure



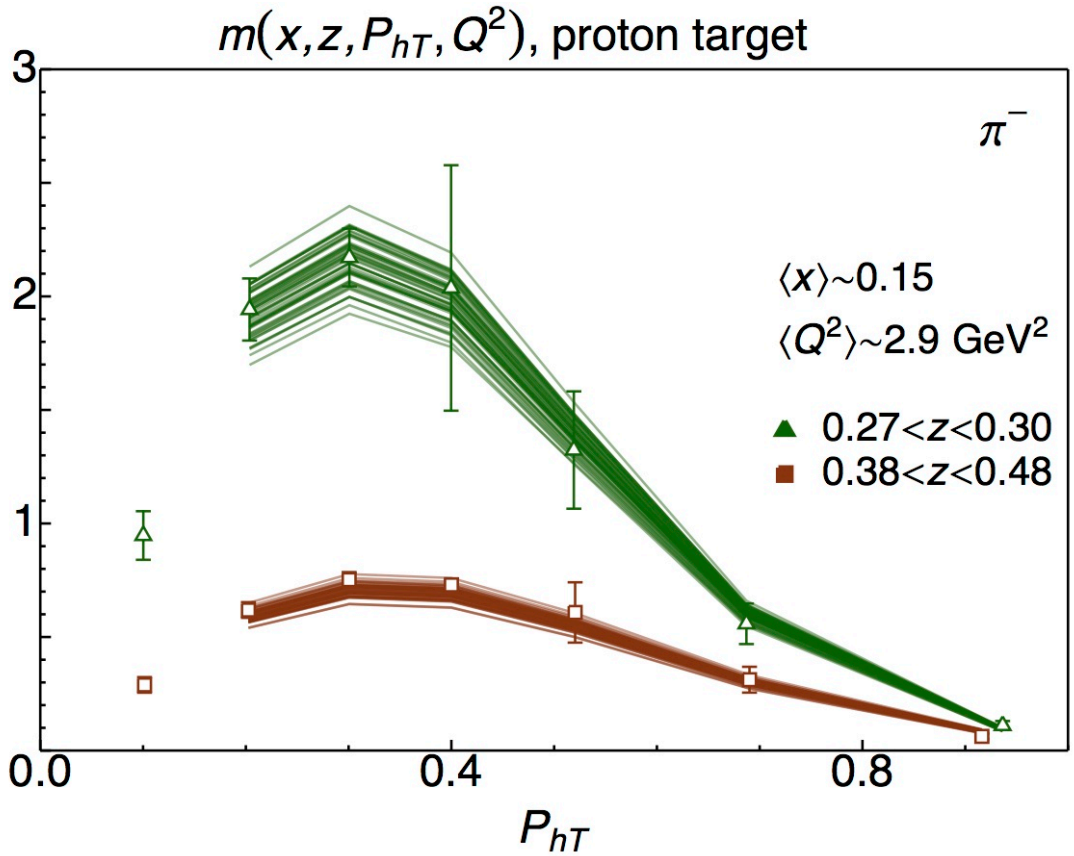
Replica of the original data with Gaussian noise

Fitting procedure



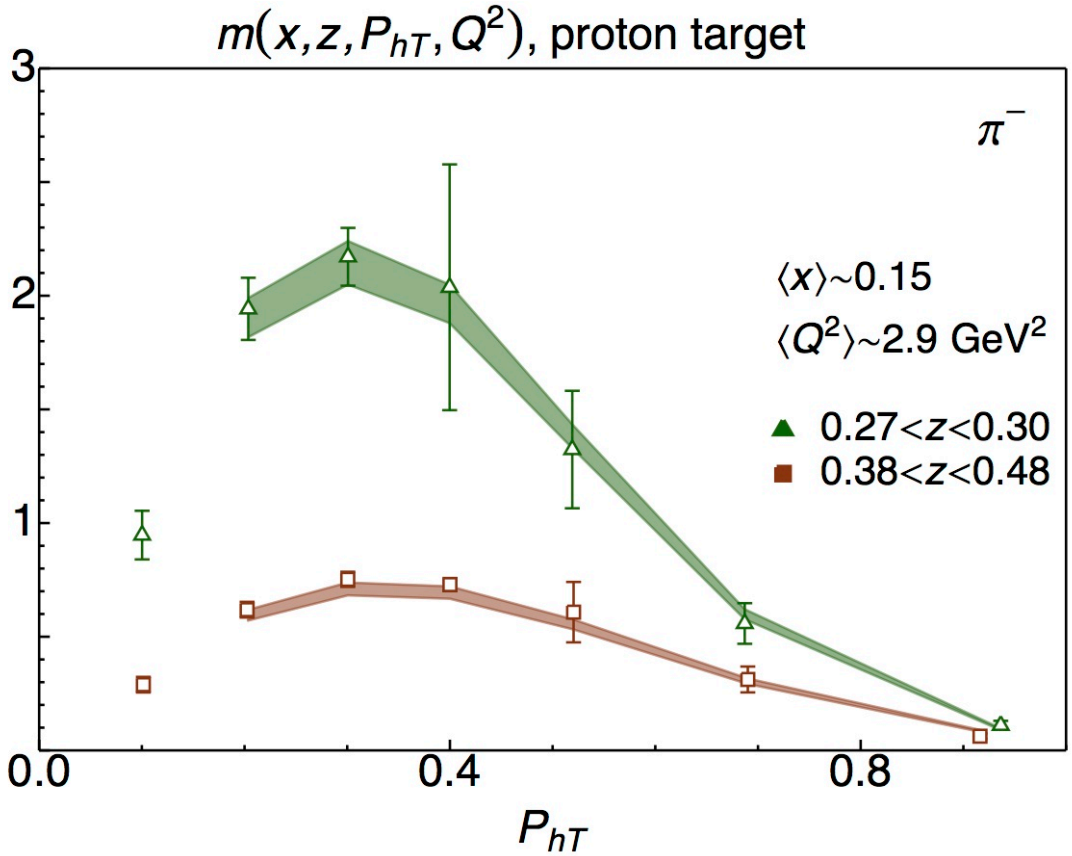
We fit the replicated data…

Fitting procedure



… repeating the fit over the 200 replicas

Fitting procedure



Plot of the 68% CL bands

Fitting procedure

proton target global χ^2 / d.o.f. = 1.63 ± 0.12

no flavor dep. 1.72 ± 0.11

π^-

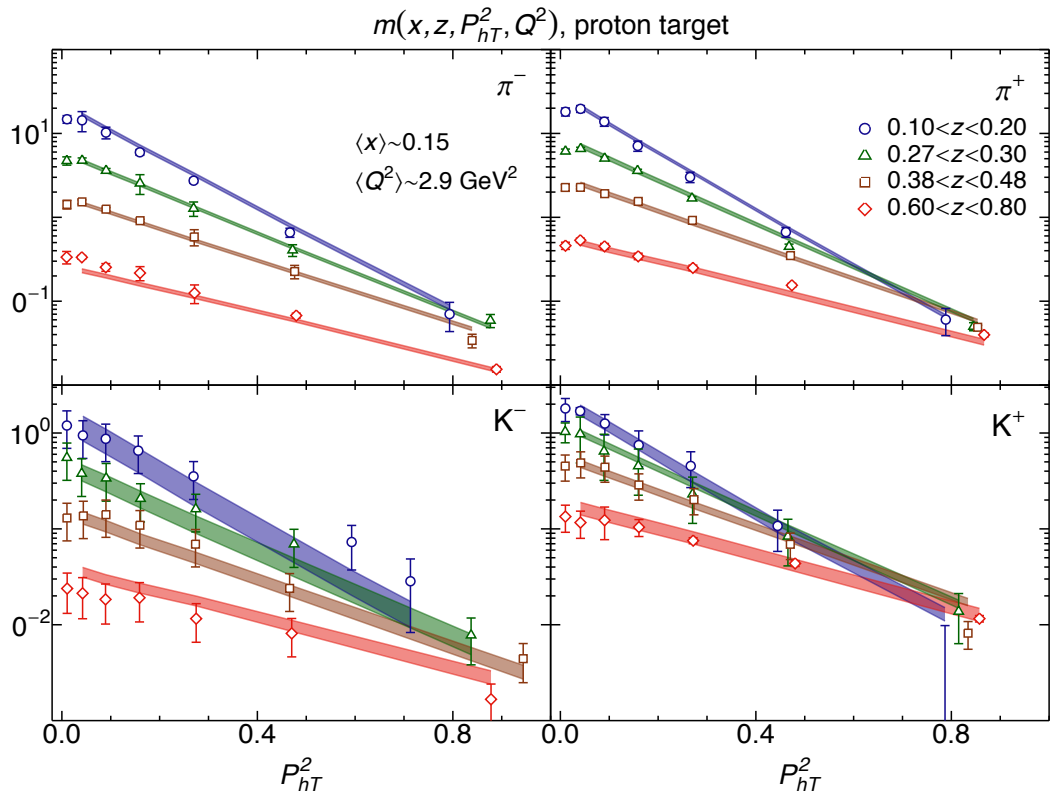
1.80 ± 0.27

1.83 ± 0.25

K^-

0.78 ± 0.15

0.87 ± 0.16



π^+

2.64 ± 0.21

2.89 ± 0.23

K^+

0.46 ± 0.07

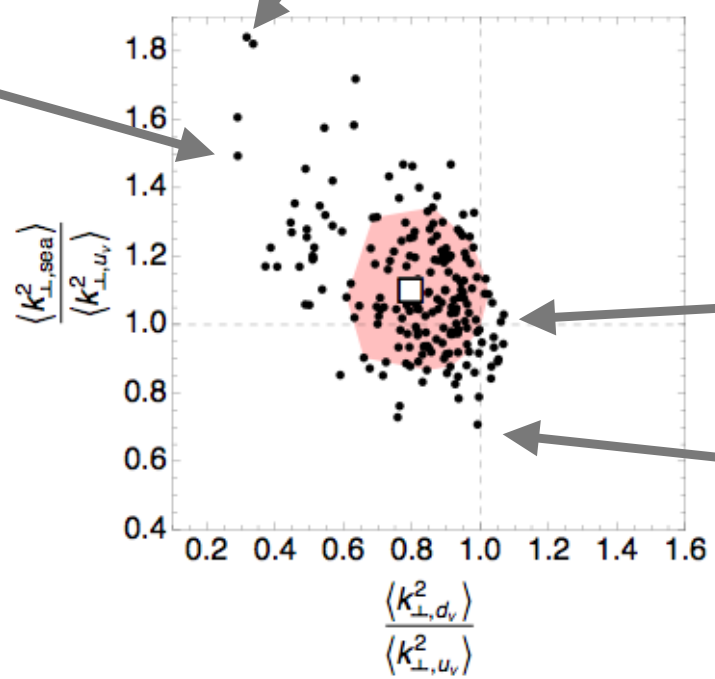
0.43 ± 0.07

TMD PDFs – full analysis

replica 149
χ^2/dof = 1.87

replica 73
χ^2/dof = 1.70

sea width
> (mostly)
u_v width



replica 130
χ^2/dof = 1.77

replica 186
χ^2/dof = 1.38

point of
no flavor dep.

d_v width < (mostly) u_v width

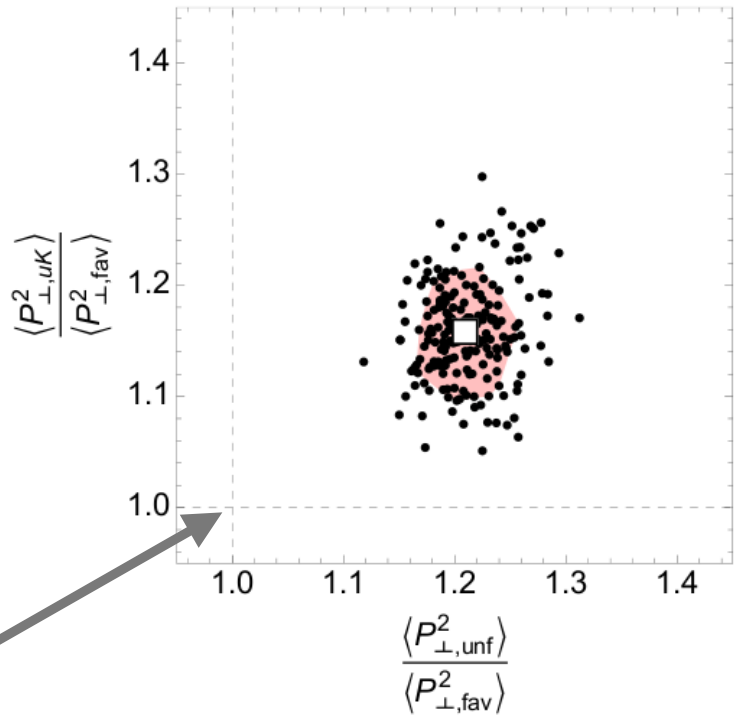
TMD PDFs – full analysis

68% confidence intervals of best-fit parameters for TMD PDFs in the different scenarios

Parameters for TMD PDFs				
	Default	$Q^2 > 1.6\ \mathrm{GeV}^2$	Pions only	Flavor-indep.
$\langle \hat{\boldsymbol{k}}^2_{\perp,d_v} \rangle$ [GeV^2]	0.30 ± 0.17	0.33 ± 0.19	0.34 ± 0.12	0.30 ± 0.10
$\langle \hat{\boldsymbol{k}}^2_{\perp,u_v} \rangle$ [GeV^2]	0.36 ± 0.14	0.37 ± 0.17	0.35 ± 0.12	0.30 ± 0.10
$\langle \hat{\boldsymbol{k}}^2_{\perp,\mathrm{sea}} \rangle$ [GeV^2]	0.41 ± 0.16	0.31 ± 0.18	0.29 ± 0.13	0.30 ± 0.10
α (random)	0.95 ± 0.72	0.93 ± 0.70	0.95 ± 0.68	1.03 ± 0.64
σ (random)	-0.10 ± 0.13	-0.10 ± 0.13	-0.09 ± 0.14	-0.12 ± 0.12

TMD FFs – full analysis

q→π favored width
<
q→K favored width



point of
no flavor dep.

q→π favored width < unfavored

TMD FFs – full analysis

68% confidence intervals of best-fit parameters for TMD FFs in the different scenarios

Parameters for TMD FFs				
	Default	$Q^2 > 1.6\ \mathrm{GeV}^2$	Pions only	Flavor-indep.
$\langle \hat{\boldsymbol{P}}^2_{\perp,\mathrm{fav}} \rangle$ [GeV^2]	0.15 ± 0.04	0.15 ± 0.04	0.16 ± 0.03	0.18 ± 0.03
$\langle \hat{\boldsymbol{P}}^2_{\perp,\mathrm{unf}} \rangle$ [GeV^2]	0.19 ± 0.04	0.19 ± 0.05	0.19 ± 0.04	0.18 ± 0.03
$\langle \hat{\boldsymbol{P}}^2_{\perp,sK} \rangle$ [GeV^2]	0.19 ± 0.04	0.19 ± 0.04	-	0.18 ± 0.03
$\langle \hat{\boldsymbol{P}}^2_{\perp,uK} \rangle$ [GeV^2]	0.18 ± 0.05	0.18 ± 0.05	-	0.18 ± 0.03
β	1.43 ± 0.43	1.59 ± 0.45	1.55 ± 0.27	1.30 ± 0.30
δ	1.29 ± 0.95	1.41 ± 1.06	1.20 ± 0.63	0.76 ± 0.40
γ	0.17 ± 0.09	0.16 ± 0.10	0.15 ± 0.05	0.22 ± 0.06

TMD lib & plotter

TMD lib :
a library of parametrizations of TMDs and uPDFs
on the same footing of LHAPDF

F. Hautmann, H. Jung
T. Rogers, P. Mulders, AS

TMD Project

Webpage maintained by: Ted Rogers, Andrea Signori

This is the development page for the TMD project. The purpose of this project is to organize a repository i theoretical and phenomenological studies of transverse-momentum-dependent parton distribution functions (PDFs) and fragmentation functions (TMD FFs). We provde access to parametrizations and fits of TMDs, with and without taking into account the perturbative QCD evolution.

Coming soon !

High Energy Physics | TMD Plotter

HELMHOLTZ GEMEINSCHAFT

Home | TMD Plotter | Publications | HEP Links

Extensions

[Amsterdam – Madrid – Pavia joint venture]

QCD evolution

Looking towards SIDIS + DY + l^+l^- global fits …

Collins (2011)
EIS (2012-2013)

$$\sigma \sim \int d^2\mathbf{b}\; e^{-i\mathbf{b}\cdot\mathbf{q}_T}\; \mathcal{H}\left[\frac{Q_f}{\mu}\right] \times$$

$$\left[C_{f/j} \otimes f_{j/N}\right](x, b_*, Q_0)\; \underline{\mathcal{F}^{NP}_{PDF}} \times$$

Intrinsic (large b) transverse momenta

Collinear OPE for small b_T

$$\left[C_{D/i} \otimes D_{i/h}\right](z, b_*, Q_0)\; \underline{\mathcal{F}^{NP}_{FF}} \times \quad (Q_0 \sim 1/b^*)$$

$$\exp\left\{\int_{Q_0}^{Q_f} \frac{d\mu}{\mu}\, \gamma_{PDF}\left[\ln\frac{Q_f^2}{\mu^2}, \alpha_S(\mu)\right]\right\}\left[\frac{Q_f}{Q_0}\right]^{-D(b^*,Q_0)+\underline{NP}} \times$$

Soft evolution

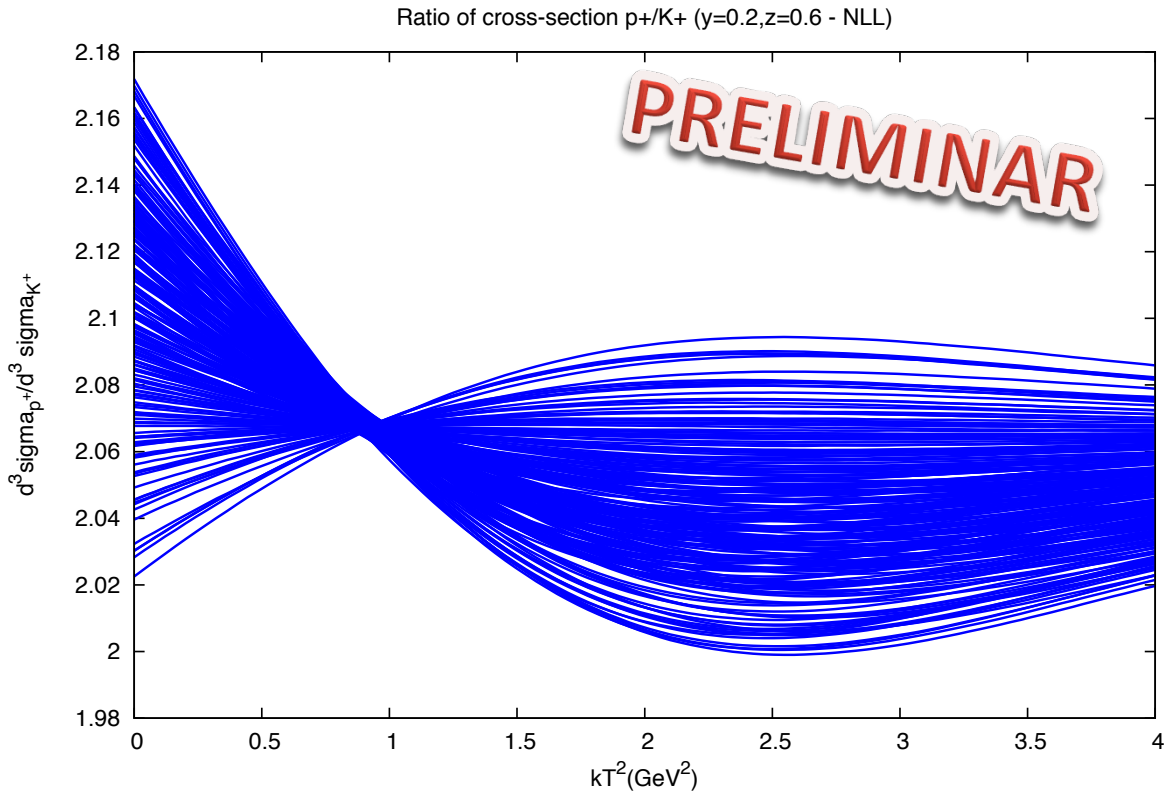
Perturbative transverse momenta and evolution (resummed logs)

$$\exp\left\{\int_{Q_0}^{Q_f} \frac{d\mu}{\mu}\, \gamma_{FF}\left[\ln\frac{Q_f^2}{\mu^2}, \alpha_S(\mu)\right]\right\}\left[\frac{Q_f}{Q_0}\right]^{-D(b^*,Q_0)+\underline{NP}}$$

e^+e^- multiplicities

$$e^+e^- \longrightarrow h \text{ jet } X$$

Pin down the most physical flavor dependent sets looking at the spectrum in transverse momentum of e^+e^- collisions



Bands built out of the 200 replicas for TMD FF D_1

Waiting for the experimental values of these ratios..!

Impact on HEP

Spin asymmetries – extractions of polarized TMDs

$$A_{\vec{e}\,\vec{N}}^{f(\phi_h,\,\phi_S)} \propto \frac{F_{\vec{e}\,\vec{N}}^{f(\phi_h,\,\phi_S)}}{F_{UU}} \propto \frac{\sum_q e_q^2 \;\; \mathrm{TMD\_PDF}^q \;\otimes_w\; \mathrm{TMD\_FF}^q}{\boxed{\sum_q e_q^2 \;\; f_1^q \otimes D_1^q}}$$

Monte Carlo generators dealing with intrinsic transverse momentum

Herwig++

gmc_trans
TMDgen

ResBos

Conclusions

There is a lot of room for flavor dependence :

- clear indication in TMD FFs that
  "$q \to \pi$ favored" width < "unfavored" & "$q \to K$ favored"

- TMD PDFs: hints that d_v width < u_v width < sea width

- if no K in final state: sea width < $d_v \sim u_v$ width

- flavor-independent fit performs worse but not ruled out

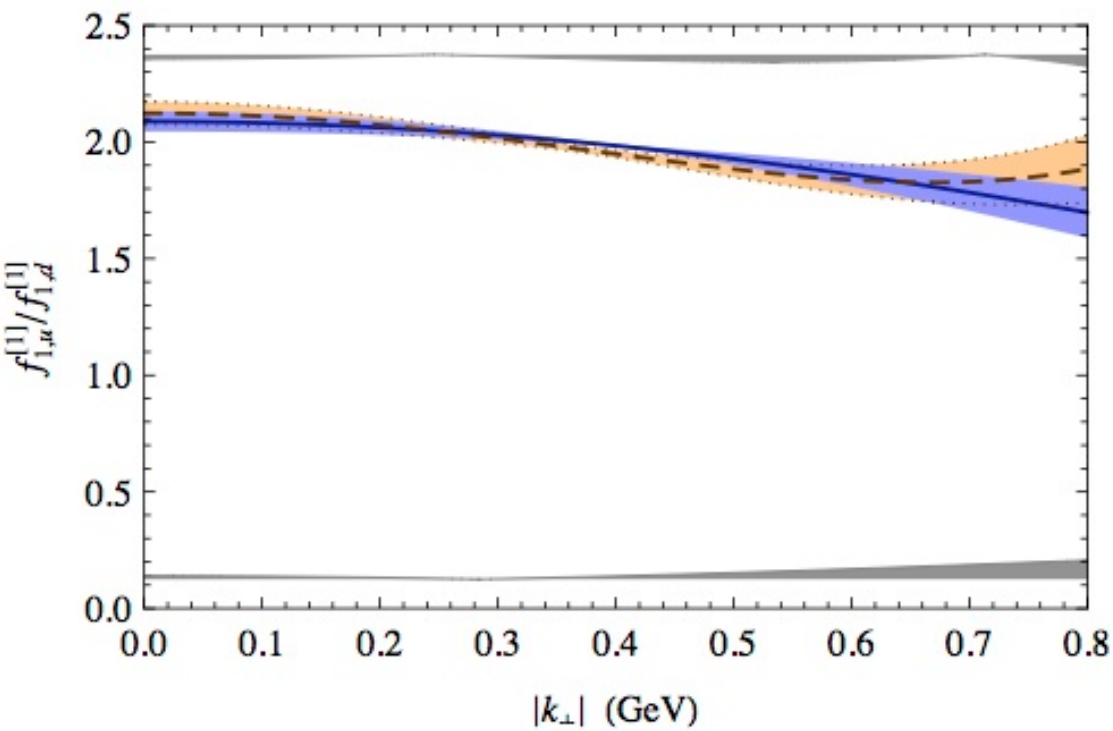
- anticorrelation: many intrinsic $\{\mathbf{k}_\perp, \mathbf{P}_\perp\}$ give same $\mathbf{P}_{hT}$

Backup slides

Flavor in transverse space

valence picture of proton, #u / #d = 2

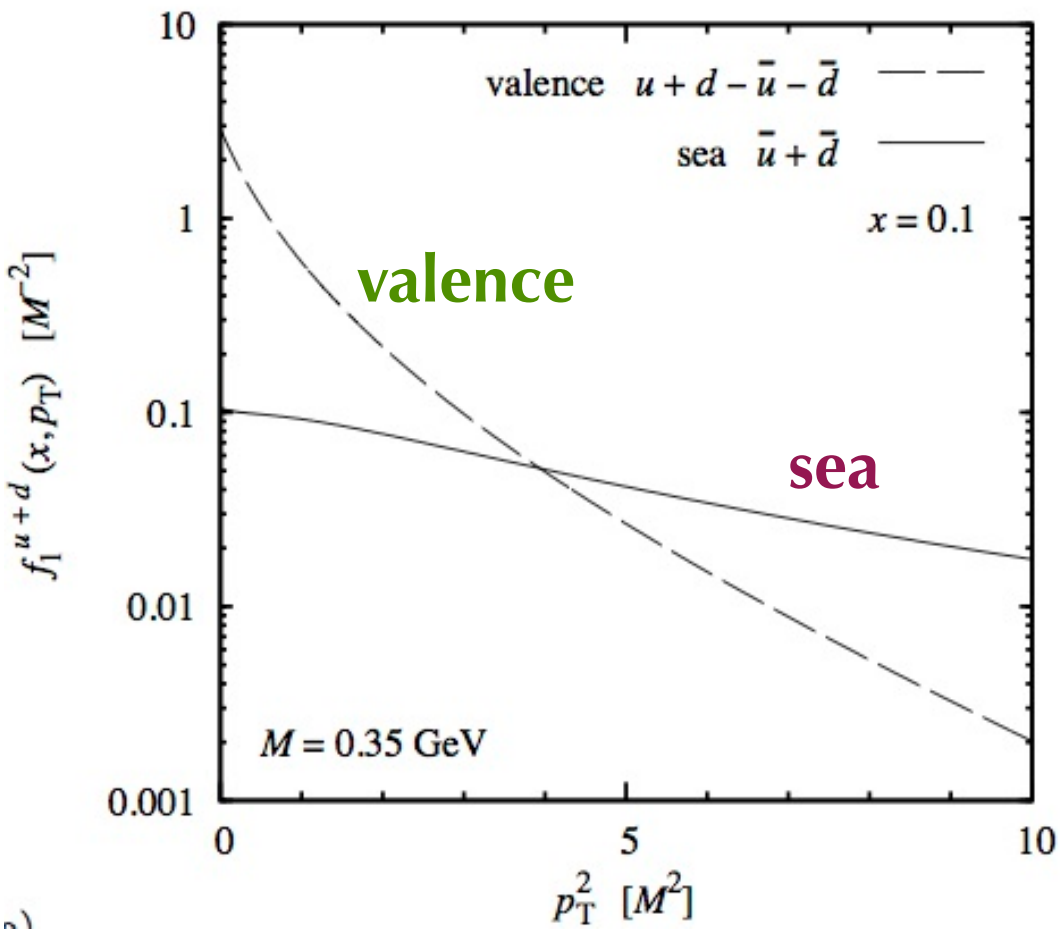
Less up at larger transverse momentum..!



Lattice QCD

Musch *et al.*, P.R. D**83** (11) 094507

Flavor in transverse space



Chiral quark soliton model
(Schweitzer, Strikman, Weiss)
JHEP 1301 (913) 163

And other models…

Diquark spectator
(Bacchetta, Courtoy, Radici – PRD 78 (08) 074010)

Statistical approach
(Bourrely, Buccella, Soffer - PRD 83 (11) 074008

Flavor in transverse space

TMD FFs - NJL-jet model

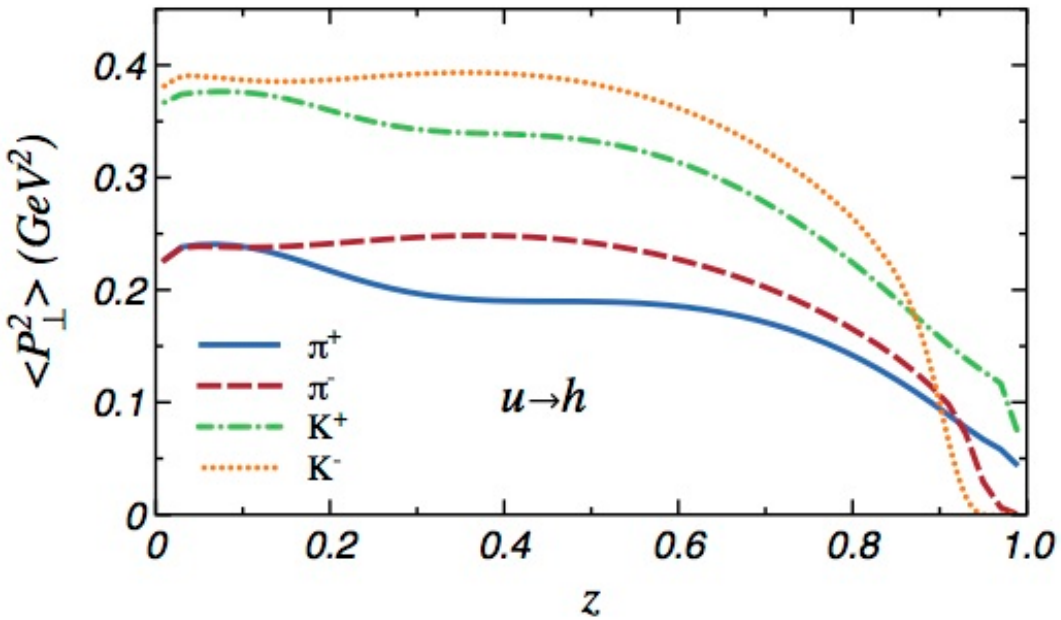
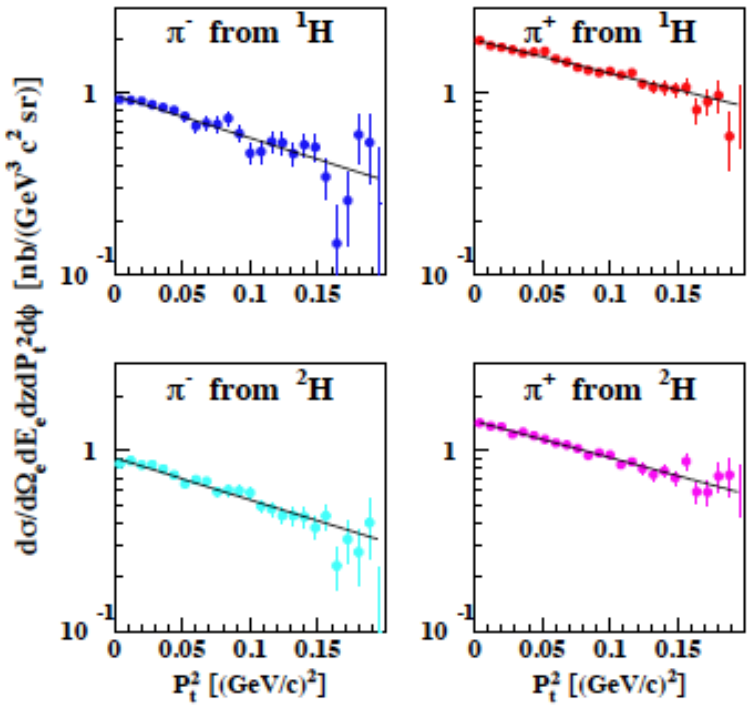


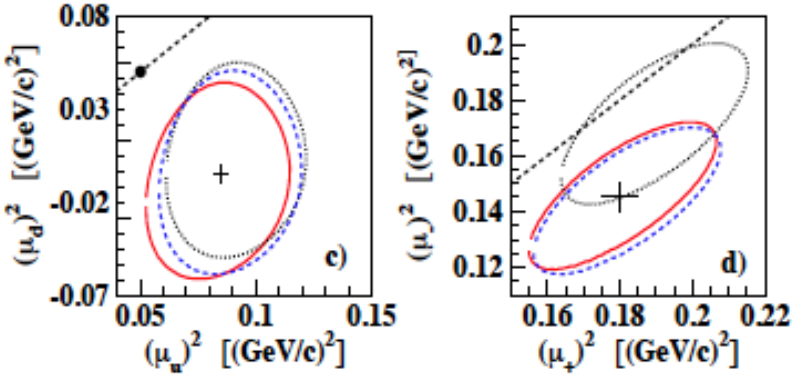
FIG. 14. The averaged transverse momentum of π and K mesons emitted by a u quark.

Matevosyan *et al.*, P. R. D**85** (12) 014021

Flavor in transverse space



no kaons, no sea,
no *x*-*z* dependence



up is wider than down

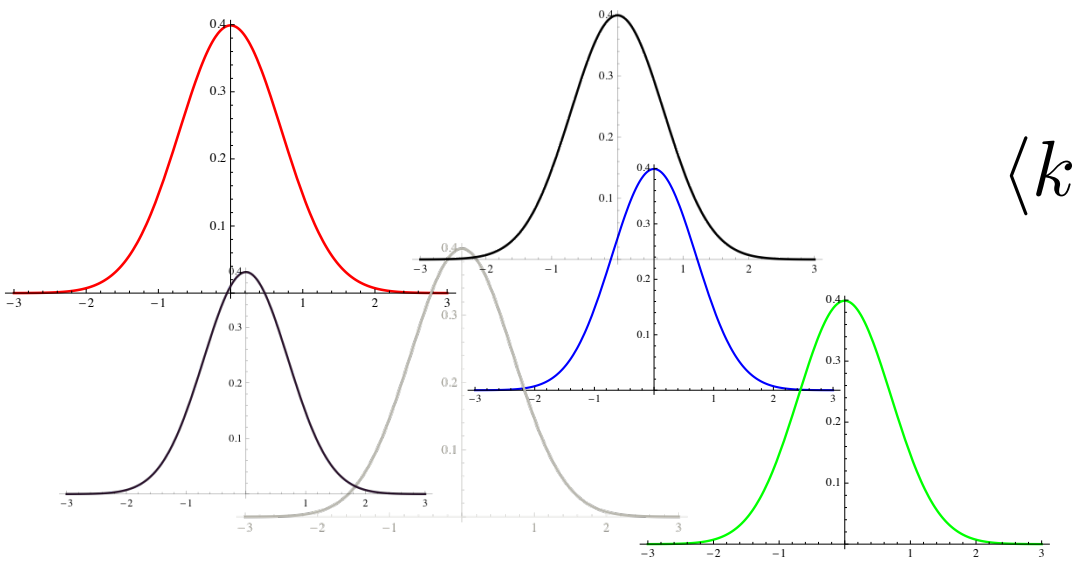
favored wider than unfavored

Asaturyan *et al*. (E00-108), P. R. C**85** (12) 015202

Flavor independent Gaussianity

Gaussian parametrization of TMD parts

$$f_1^a(x, k_\perp^2) = f_1^a(x) \boxed{\frac{1}{\pi \langle k_\perp^2 \rangle} \exp\left\{ -\frac{k_\perp^2}{\langle k_\perp^2 \rangle} \right\}}$$



$$\langle k_{\perp,\mathrm{u}}^2 \rangle = \langle k_{\perp,\mathrm{d}}^2 \rangle = \ldots$$

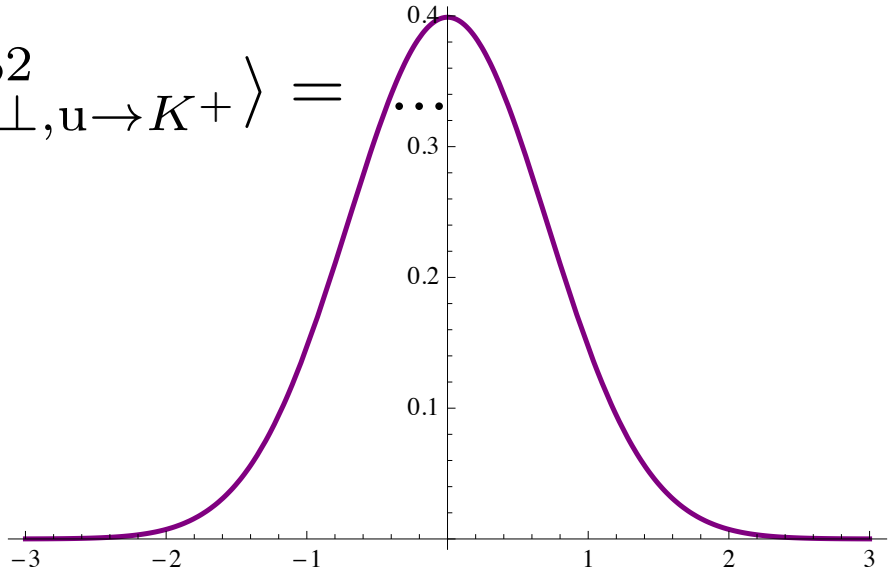
The same variance for all the flavors!

Flavor independent Gaussianity

Gaussian parametrization of TMD parts

$$D_1^{a\to h}(z, P_\perp^2) = D_1^{a\to h}(z) \boxed{\frac{1}{\pi\langle P_\perp^2\rangle} \exp\left\{-\frac{P_\perp^2}{\langle P_\perp^2\rangle}\right\}}$$

$$\langle P^2_{\perp,\mathrm{u}\to\pi^+}\rangle = \langle P^2_{\perp,\mathrm{u}\to\pi^-}\rangle = \langle P^2_{\perp,\mathrm{u}\to K^+}\rangle = \ldots$$



The same variance
for all the fragmentation
processes

Flavor analysis

$$\sigma(P_{hT}^2) \sim \sum_a f_1^a(x, k_\perp^2) \otimes D_1^{a\to h}(z, P_\perp^2)$$

Flavor dependent case

$$\sum_a \left[\frac{1}{\pi\langle k_{\perp,a}^2\rangle} \exp\left\{-\frac{k_\perp^2}{\langle k_{\perp,a}^2\rangle}\right\} \otimes \frac{1}{\pi\langle P_{\perp,a\to h}^2\rangle} \exp\left\{-\frac{P_\perp^2}{\langle P_{\perp,a\to h}^2\rangle}\right\}\right]$$

Simplified!

Sum of Gaussian functions!

Flavor analysis

$$\sigma(P_{hT}^2) \sim \sum_a f_1^a(x, k_\perp^2) \otimes D_1^{a\to h}(z, P_\perp^2)$$

Flavor dependent case

$$\sum_a \left[\frac{1}{\pi\langle k_{\perp,a}^2\rangle} \exp\left\{-\frac{k_\perp^2}{\langle k_{\perp,a}^2\rangle}\right\} \otimes \frac{1}{\pi\langle P_{\perp,a\to h}^2\rangle} \exp\left\{-\frac{P_\perp^2}{\langle P_{\perp,a\to h}^2\rangle}\right\}\right]$$

in the convolution, for each flavor we get a Gaussian with width

$$\langle \boldsymbol{P}_{hT,q}^2\rangle = z^2\langle \boldsymbol{k}_{\perp,q}^2\rangle + \langle \boldsymbol{P}_{\perp,q\to h}^2\rangle$$

Momenta are anticorrelated!

Results

'Tension' in the collinear case

	$Q^2 > 1.4\,\mathrm{GeV}^2$
global	2.86
$p \to K^-$	2.25
$p \to \pi^-$	3.39
$p \to \pi^+$	1.87
$p \to K^+$	0.89
$D \to K^-$	4.26
$D \to \pi^-$	5.05
$D \to \pi^+$	3.33
$D \to K^+$	1.80

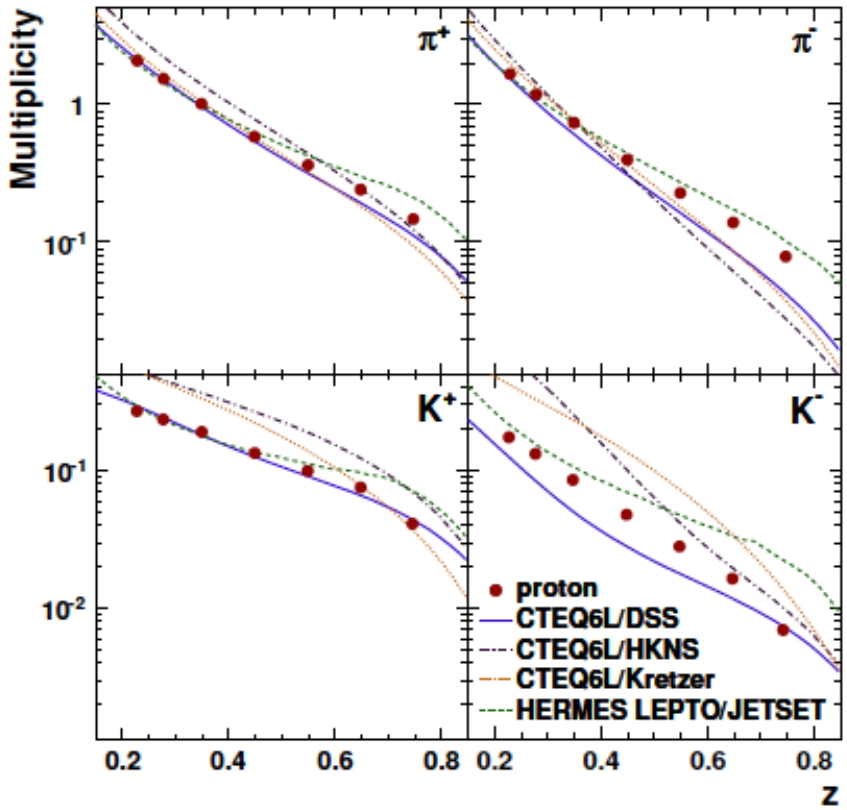
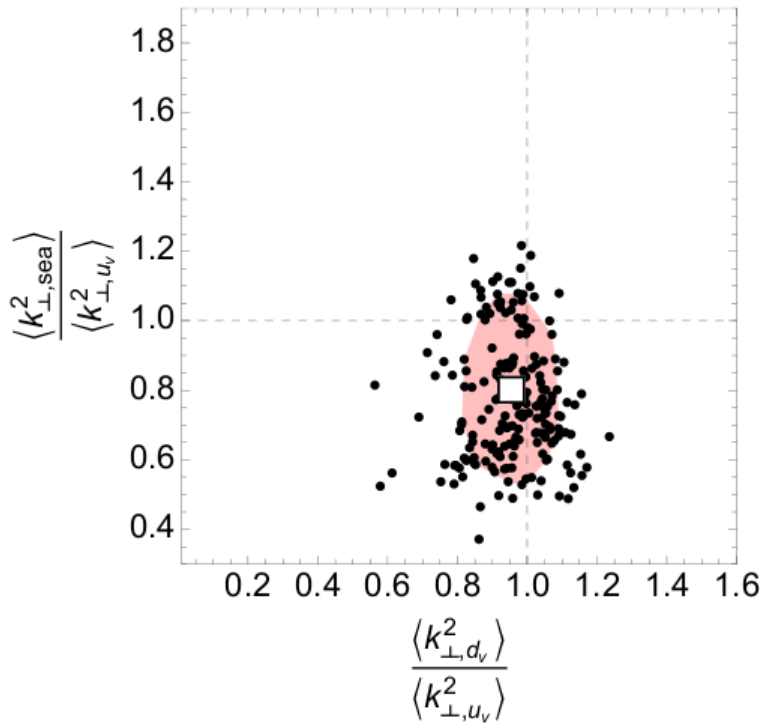


Table 2. Values of χ^2/d.o.f. obtained from the comparison of the HERMES multiplicities $m_N^h(x, z, Q^2)$ with the theoretical prediction using the MSTW08LO collinear PDFs [8] and the DSS LO collinear FFs [48]. In all cases, the range $0.1 \leq z \leq 0.8$ was included.

TMD PDFs – without Kaons

sea width
< (mostly)
u_v width



Strange quarks are relevant !

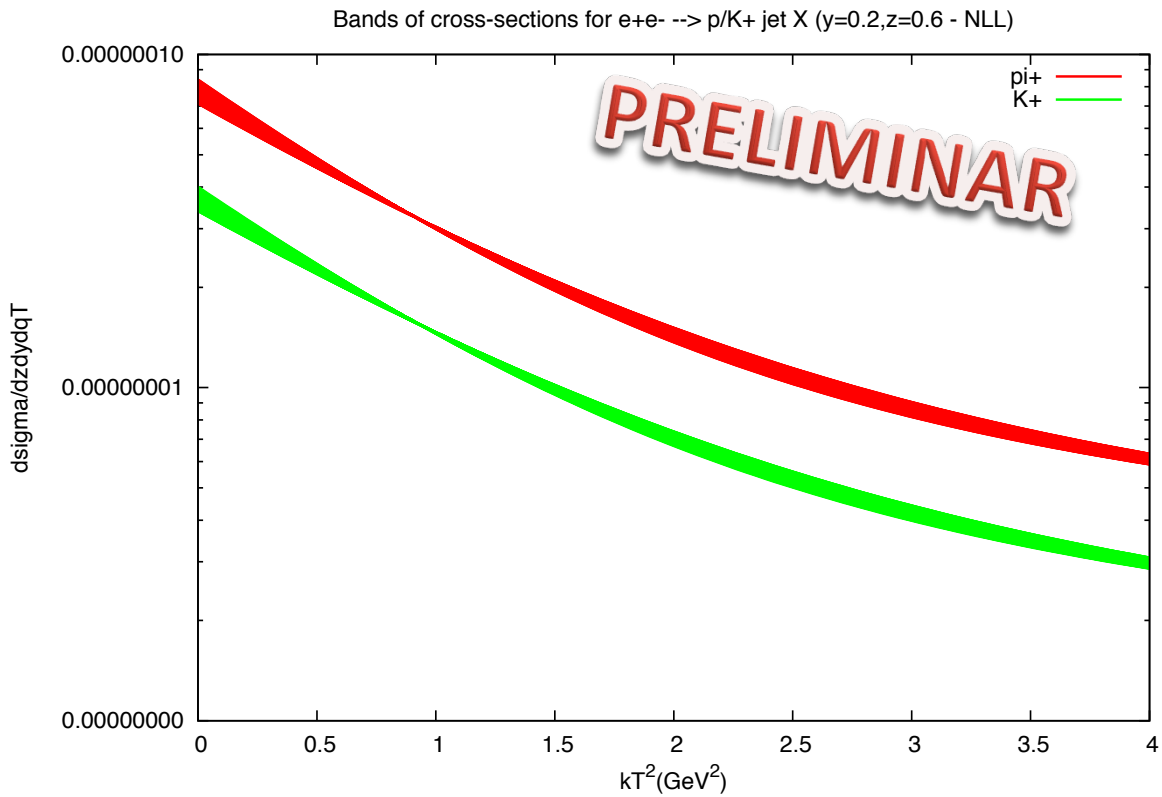
point of
no flavor dep.

d_v width ~ (mostly) u_v width

e^+e^- multiplicities

$$e^+e^- \longrightarrow h \text{ jet } X$$

Pin down the most physical flavor dependent sets looking at the spectrum in transverse momentum of e^+e^- collisions

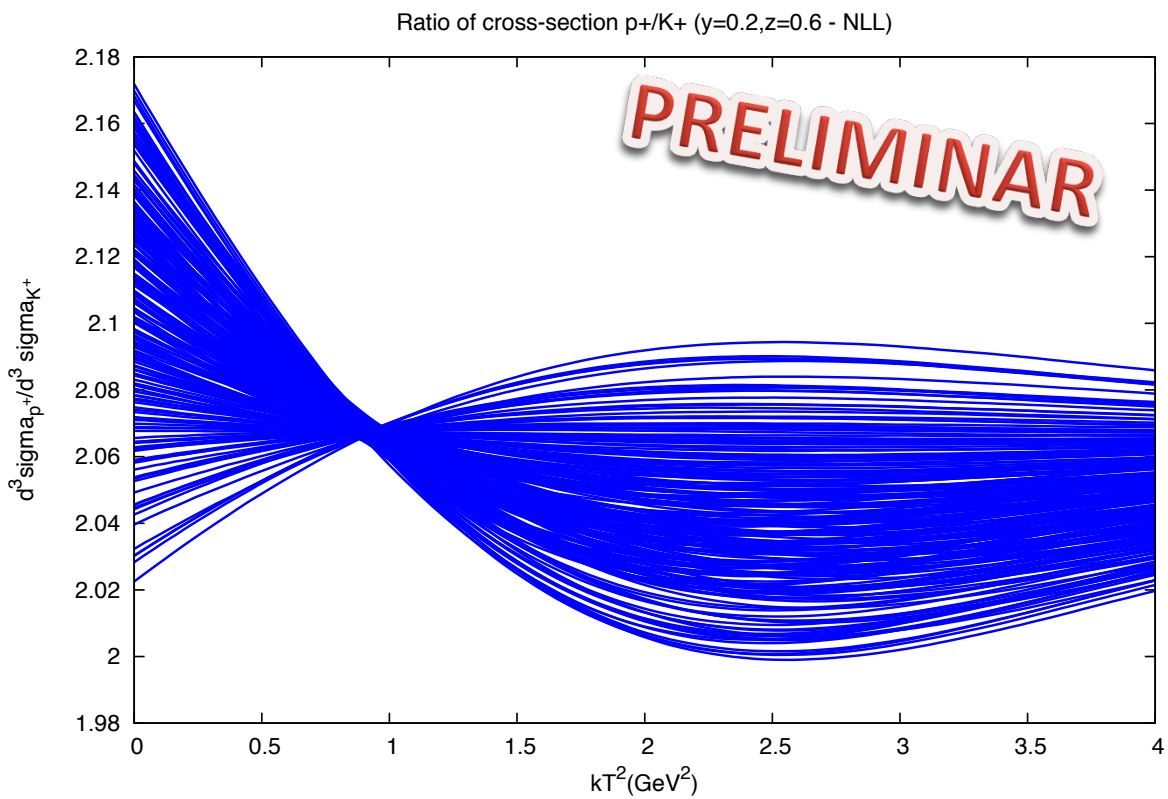


Bands built out of the 200 replicas for TMD FF D_1

e^+e^- multiplicities

$$e^+e^- \longrightarrow h \text{ jet } X$$

Pin down the most physical flavor dependent sets looking at the spectrum in transverse momentum of e^+e^- collisions



Bands built out of the 200 replicas for TMD FF D_1

Waiting for the experimental values of these ratios ..!