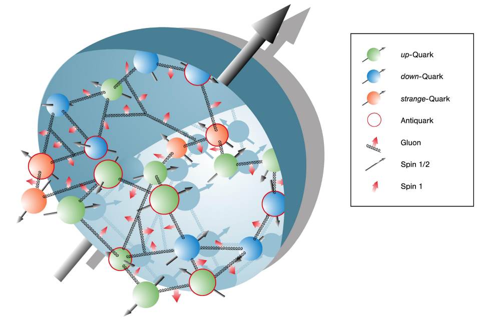
Multiplicities and phenomenology

Transversity 2014, Chia (Cagliari)



Andrea Signori

In collaboration with:

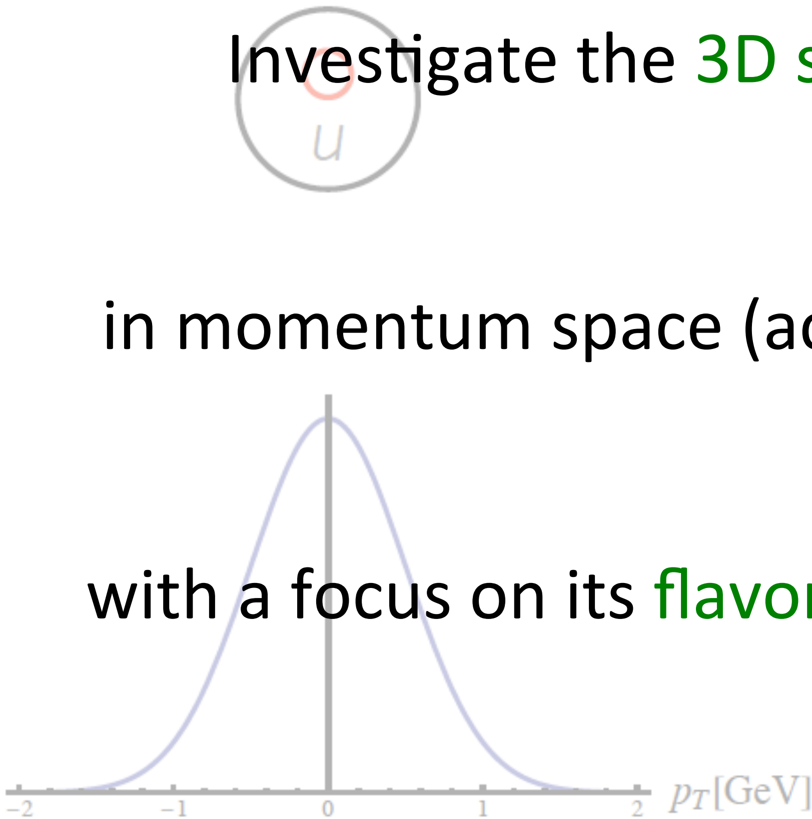
A. Bacchetta
M. Echevarria
M. Radici
G. Schnell

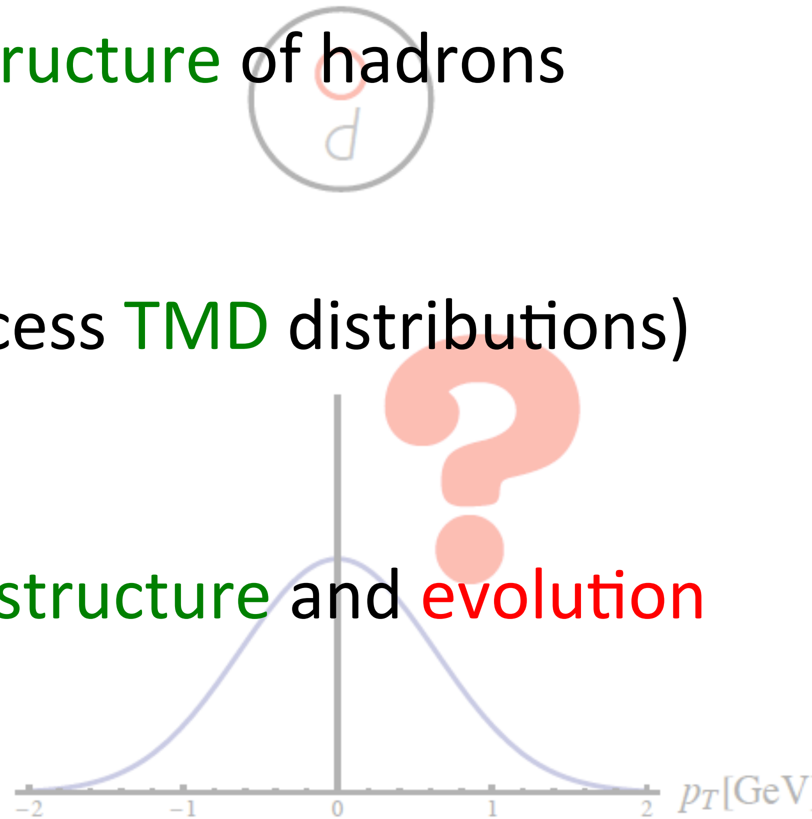
Goals

Investigate the 3D structure of hadrons

in momentum space (access TMD distributions)

with a focus on its flavor structure and evolution





The to-do list

- SIDIS fit with no evolution at all (Hermes) [***done***]
- Get hints on the non-perturbative parameters involved in evolution from e+e- annihilations, compatible with the previous fit [***in progress***]
- SIDIS fit with QCD evolution (Hermes + Compass)
- Global SIDIS + DY + e+e- fits

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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]

TODAY:

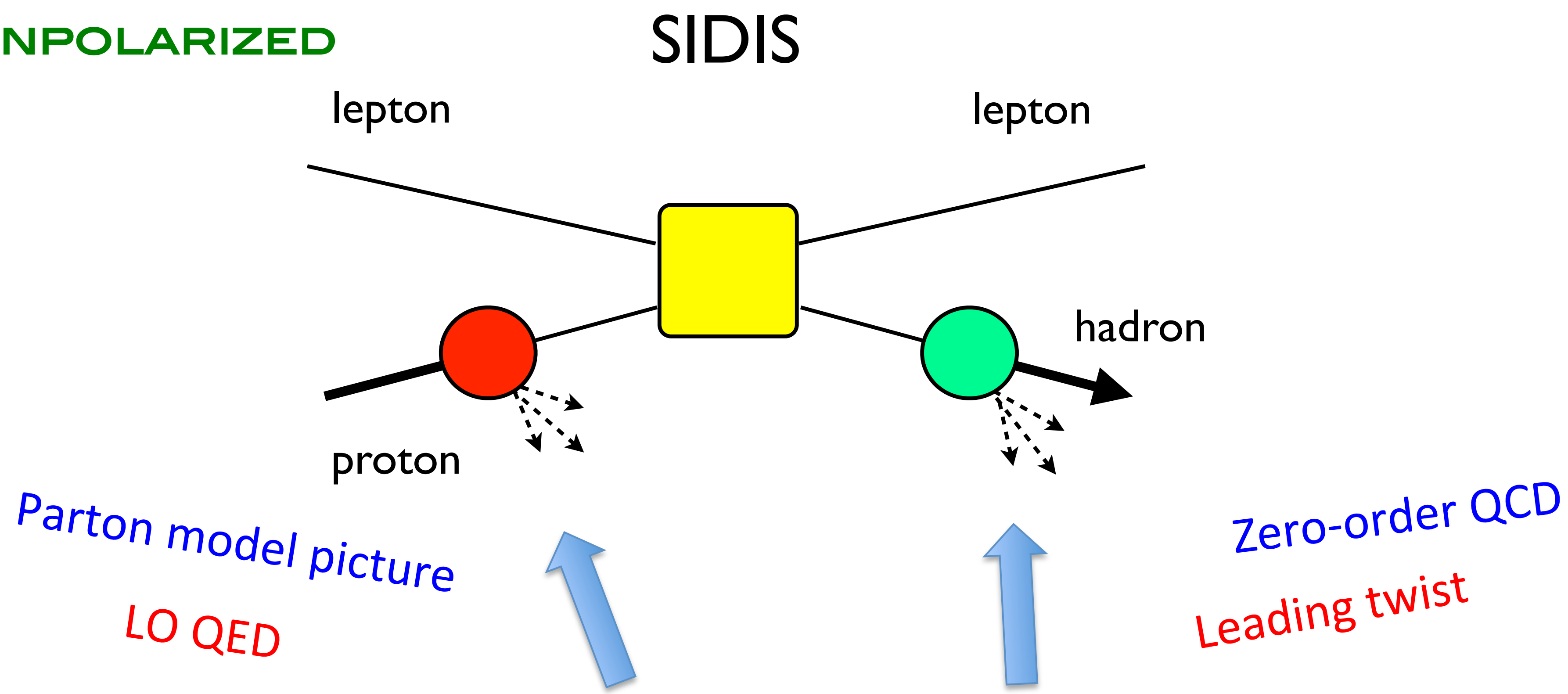
1) SIDIS multiplicities
2) e+e- multiplicities

SIDIS

multiplicities

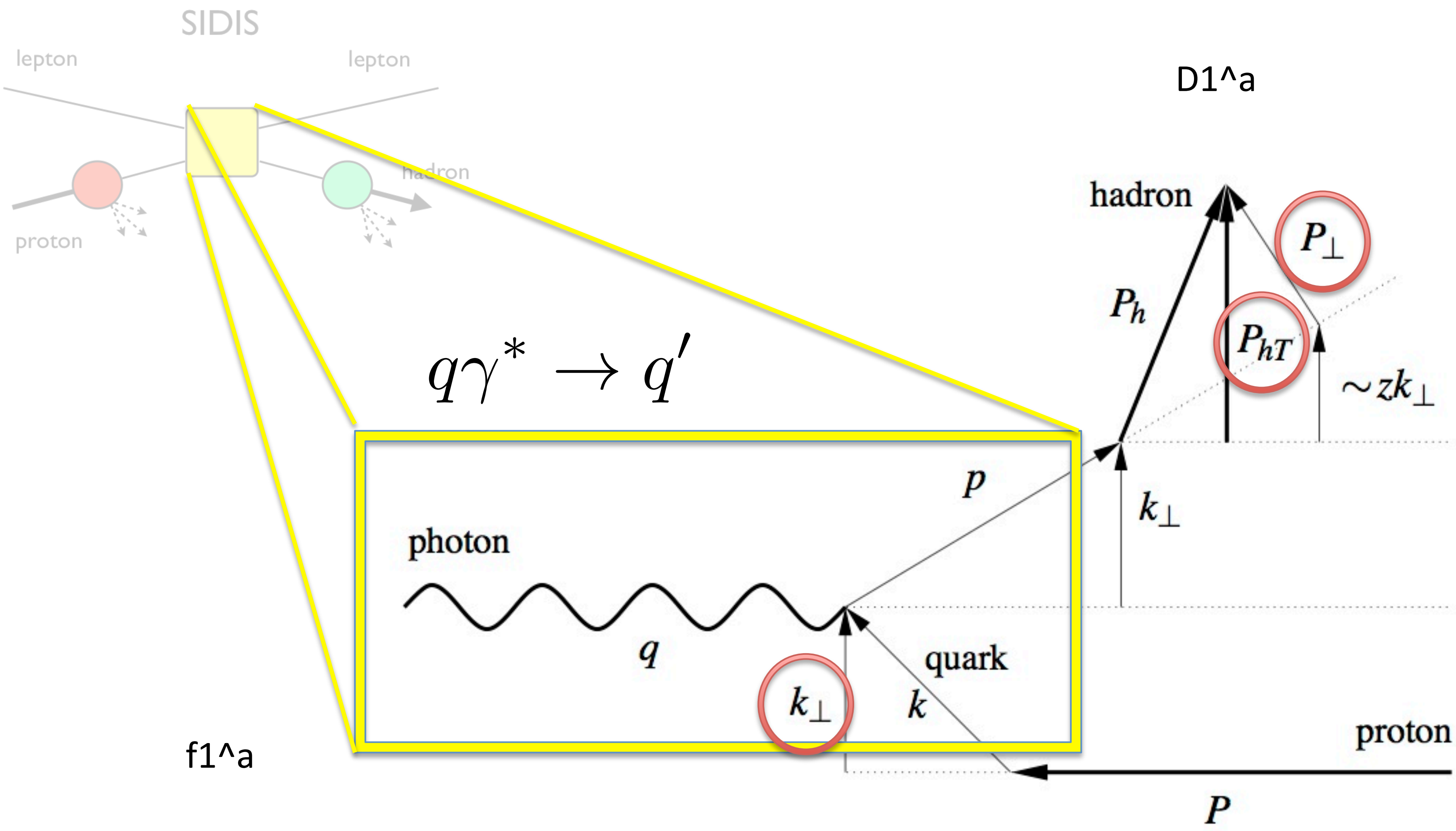
TMDs in SIDIS

Unpolarized



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

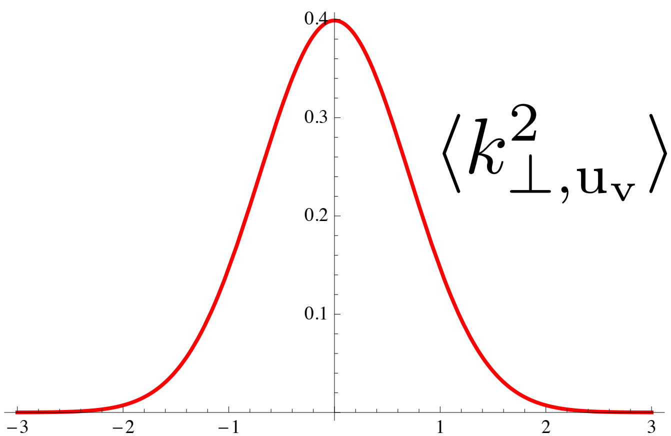
Which transverse momenta ?



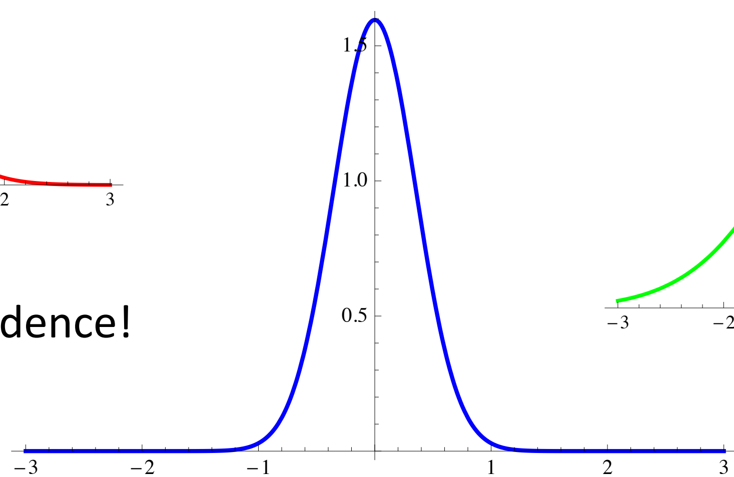
Flavor dependent Gaussians

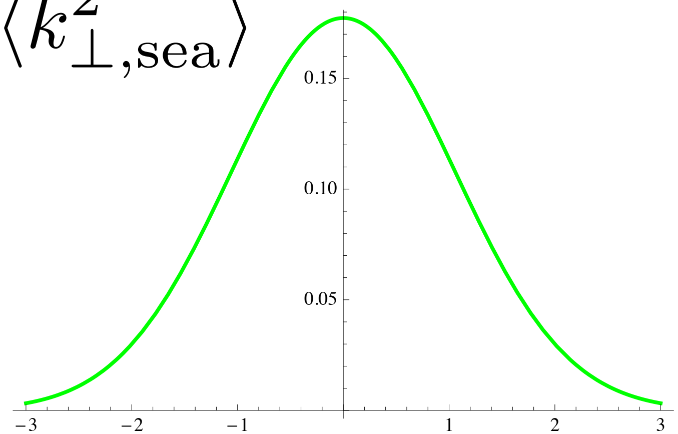
Different Gaussian parametrizations of TMD parts

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



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



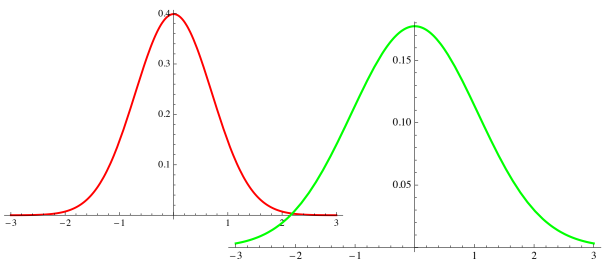


Simplified flavor dependence!

Flavor dependent Gaussians

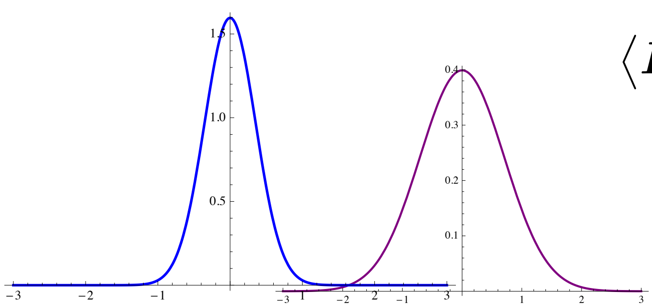
Different Gaussian parametrization of TMD parts

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



4 different combinations out of

u, d, s ⟺ $\pi^\pm,\ K^\pm$



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

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

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

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

Kinematic dependence

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

→ Flavor independent Kinematic dependence

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

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

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

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]

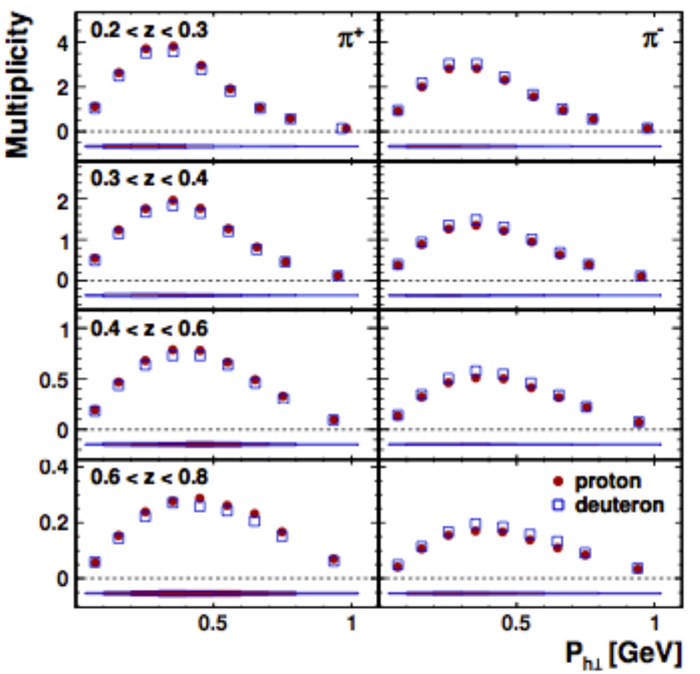
Parameters for TMD FFs							
	$\langle \hat{\boldsymbol{P}}^2_{\perp,\mathrm{fav}} \rangle$ [GeV^2]	$\langle \hat{\boldsymbol{P}}^2_{\perp,\mathrm{unf}} \rangle$ [GeV^2]	$\langle \hat{\boldsymbol{P}}^2_{\perp,sK} \rangle$ [GeV^2] (random)	$\langle \hat{\boldsymbol{P}}^2_{\perp,uK} \rangle$ [GeV^2]	β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

7 parameters

interval [0.125,0.250]

Fitting procedure

hermes



$\times$ 200

Monte Carlo fit

Distributions of best-values

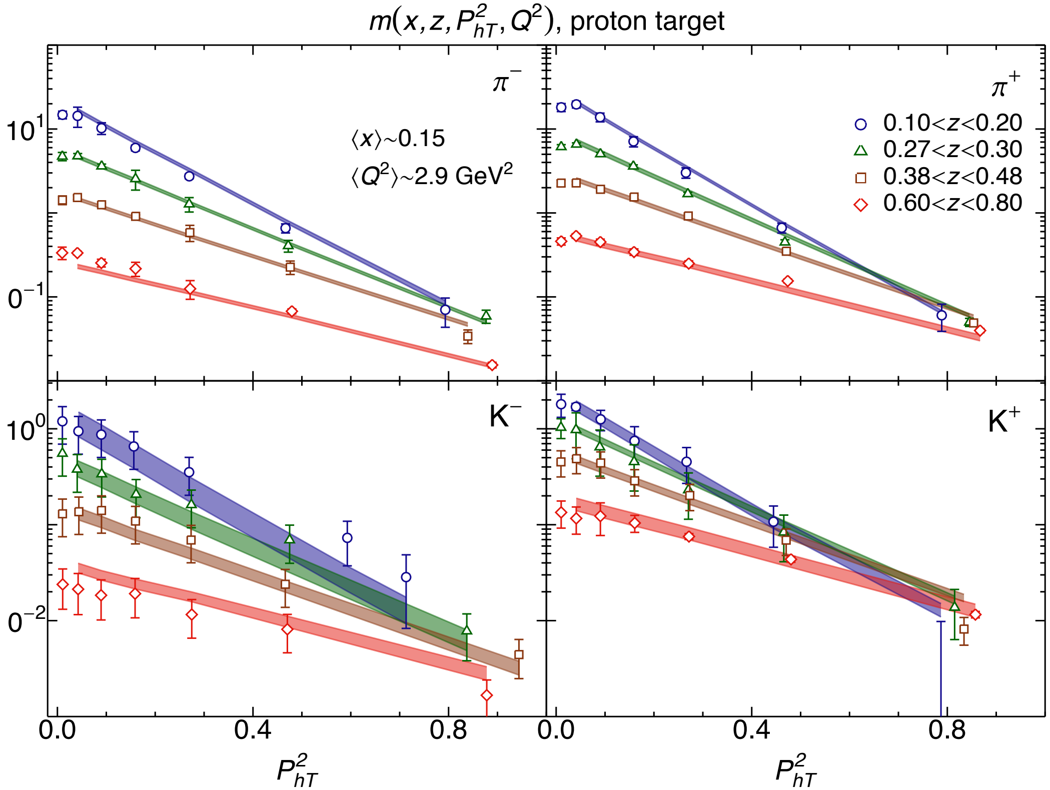
Fitting procedure

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

π^+
2.64 ± 0.21
2.89 ± 0.23

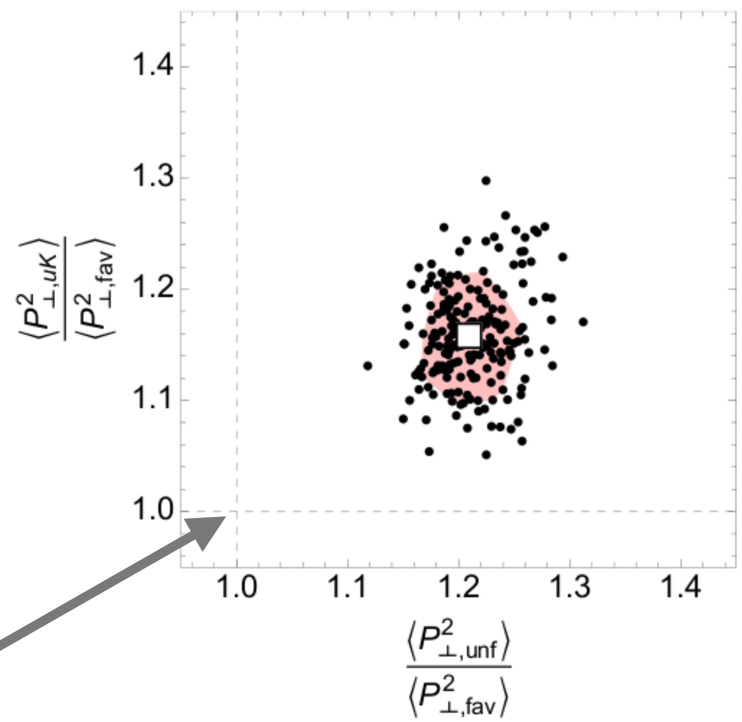


K^-
0.78 ± 0.15
0.87 ± 0.16

K^+
0.46 ± 0.07
0.43 ± 0.07

TMD FFs – full analysis

q→π favored width
<
q→K favored width



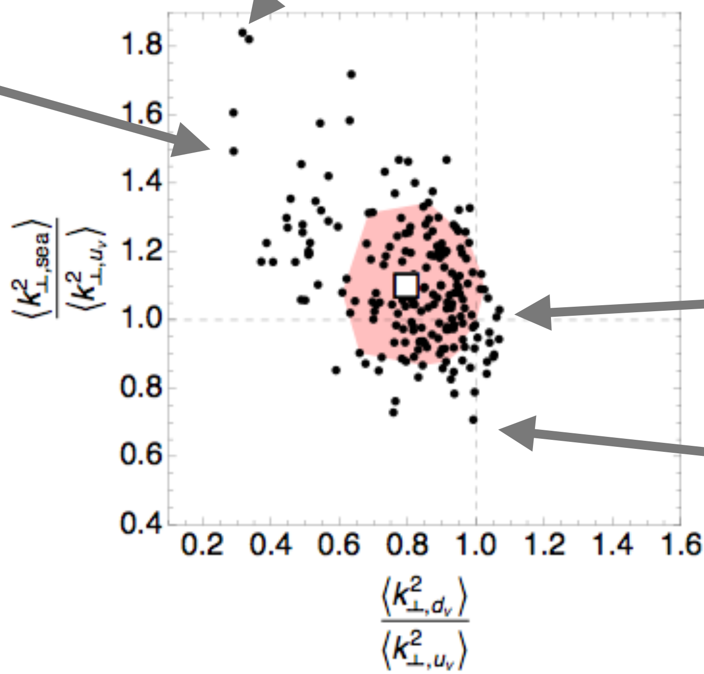
point of
no flavor dep.

q→π favored width < unfavored

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

QCD evolution

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

Collins (2011)
EIS (2012-2013)

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

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

Intrinsic (large b) transverse momenta

Collinear OPE for small b_T

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

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

Soft evolution

Perturbative transverse momenta and evolution (resummed logs)

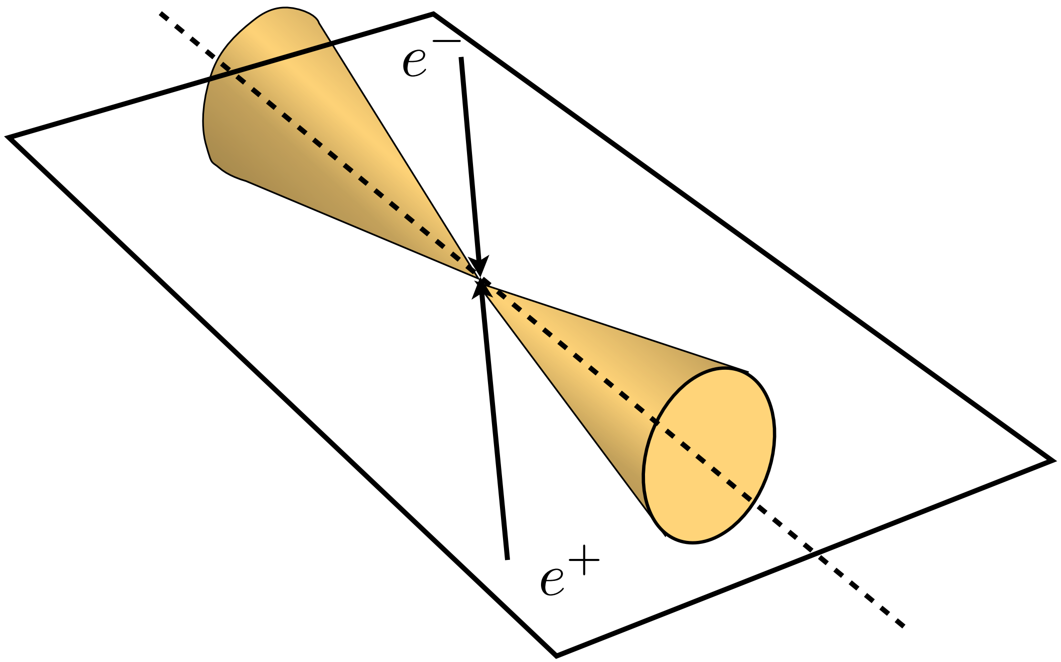
$$\exp\left\{\int_{Q_0}^{Q_f} \frac{d\mu}{\mu}\, \gamma_{FF}\left[\ln\frac{Q_f^2}{\mu^2}, \alpha_S(\mu)\right]\right\}\left[\frac{Q_f}{Q_0}\right]^{-D(b^*,Q_0)+NP}$$

e^+e^- multiplicities

double goal:

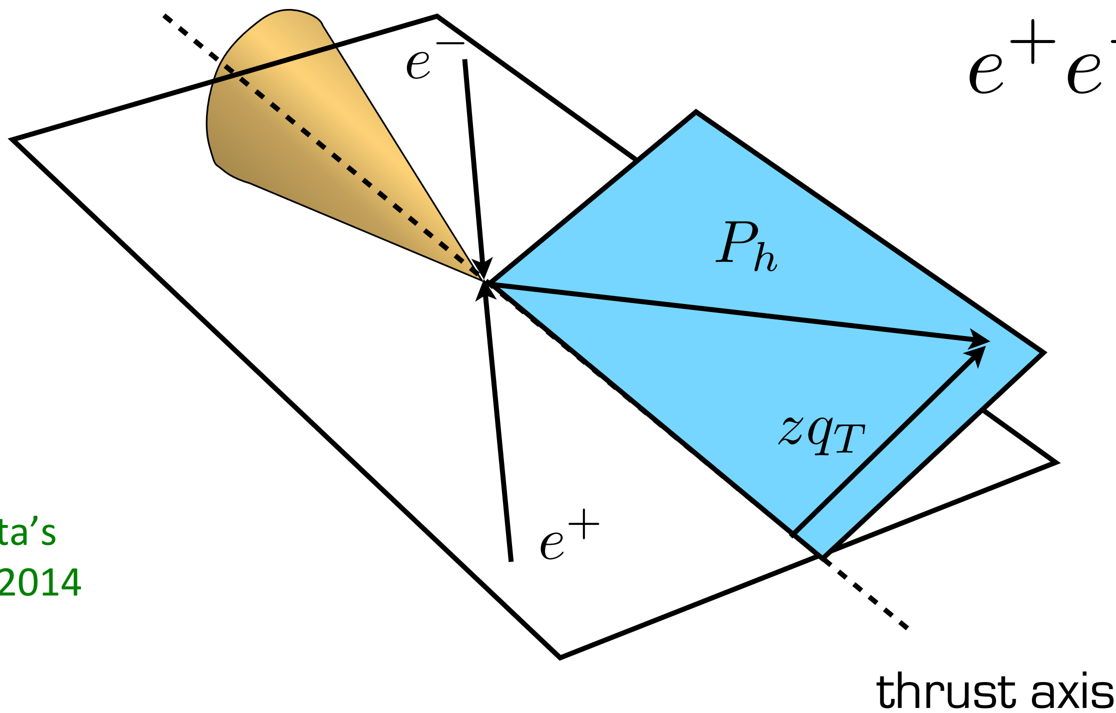
- pin down flavor dependence in TMD FFs
- get info on the non-perturbative evolution

Hadron production



$$e^+e^- \to \text{jets}$$

One hadron

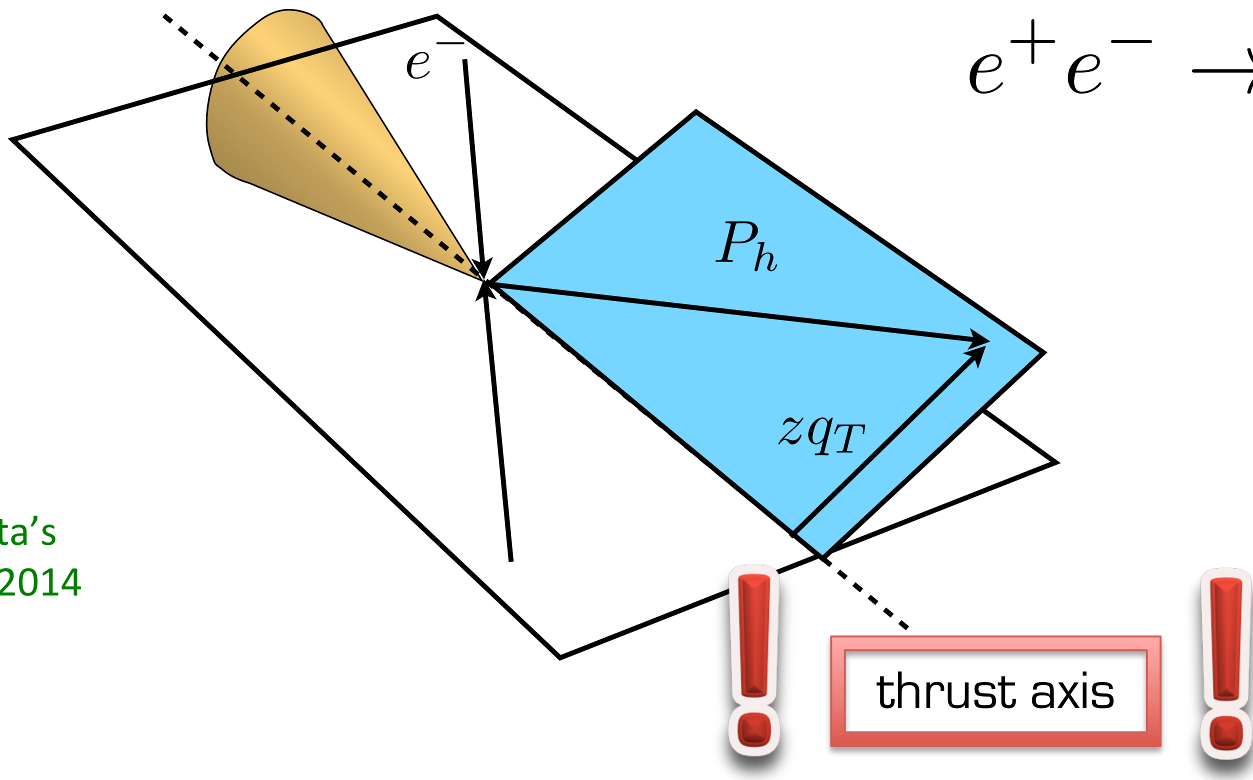


$$e^+e^- \to hX$$

See A. Bacchetta's talk in QCD Evo 2014

$$\frac{d\sigma}{dz\,dq_T^2\,dy} = \frac{6\pi\alpha^2}{Q^2} A(y)\; z^2\; \mathcal{H}(Q/\mu) \sum_q e_q^2 \int_0^\infty db_T\; b_T\; J_0(q_T b_T)\; D_1^{q\to h}(z, b_T, \mu) \;+\; Y(q_T^2, Q^2)$$

One hadron



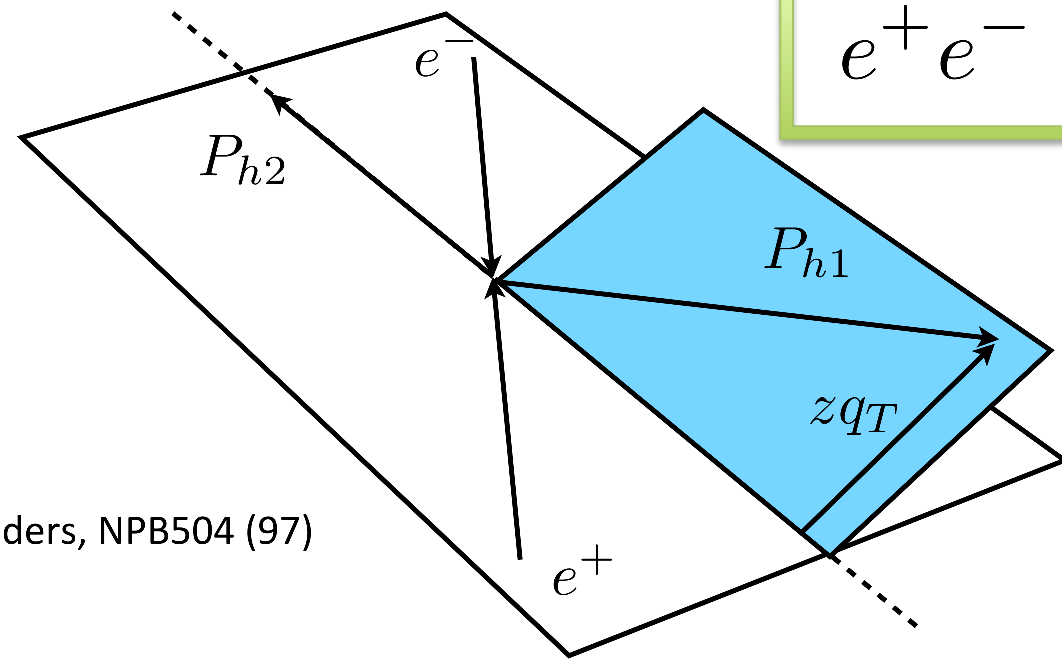
$e^+e^- \to hX$

See A. Bacchetta's talk in QCD Evo 2014

$$\frac{d\sigma}{dz\,dq_T^2\,dy} = \frac{6\pi\alpha^2}{Q^2} A(y)\; z^2\; \mathcal{H}(Q/\mu) \sum_q e_q^2 \int_0^\infty db_T\; b_T\; J_0(q_T b_T)\; D_1^{q\to h}(z, b_T, \mu) \;+\; Y(q_T^2, Q^2)$$

Two hadrons

$$e^+e^- \to h_1 h_2 X$$



Boer, Jakob, Mulders, NPB504 (97)

$$\frac{d\sigma}{dz_1 dz_2 dq_T^2 dy} = \frac{6\pi\alpha^2}{Q^2} A(y)\ z_1^2 z_2^2\ \mathcal{H}(Q/\mu) \sum_q e_q^2 \int_0^\infty db_T b_T\ J_0(q_T b_T) \times$$

$$\left[\underline{D_1^{q\to h_1}(z_1, b_T, \mu) D_1^{\bar{q}\to h_2}(z_2, b_T, \mu) + (q \to \bar{q})} \right] + Y(q_T^2, Q^2)$$

e^+e^- multiplicities

$$\{e^+e^- \to h_1 h_2 X\} \;/\; \{e^+e^- \to h_1 X\}$$

TMD collinear

$$M(h_1, h_2) = \frac{\dfrac{d\sigma^{2h}}{dz_1\, dz_2\, dy\, dq_T^2}}{\dfrac{d\sigma^{1h}}{dz_1\, dy}}$$

The same structure as in the SIDIS case

NB The experimental transverse momentum is

$$P_{1\perp} = -z_1 q_T$$

Evolved TMD FFs

Intrinsic b_T part

OPE of the perturbative part on the collinear distribution

Gaussians from Hermes!

$$D_1^{a\to h}(z, b_T, Q^2, \mu^2) = \sum_i \left[C_{a/i} \otimes D_{i/h}\right](z, b^*, \mu_b^2, \mu_b)\ \mathcal{F}_{FF}^{NP}(z, b_T) \times$$

$$\exp\left[\int_{\mu_b}^{\mu} \frac{ds}{s} \gamma_{FF}\left(\ln\frac{Q^2}{s^2}, \alpha_S(s)\right)\right] \times$$

$$\exp\left[-\ln\frac{Q^2}{\mu_b^2}\left(D(b^*, \mu_b) + \frac{g_2}{4} b_T^2\right)\right]$$

Perturbative evolution

Soft evolution

$$b_* \equiv \frac{b_T}{\sqrt{1 + b_T^2/b_{\max}^2}}$$

b-star prescription

Collins (2011)
EIS (2012-2013)

Input from the Hermes fit

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

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

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

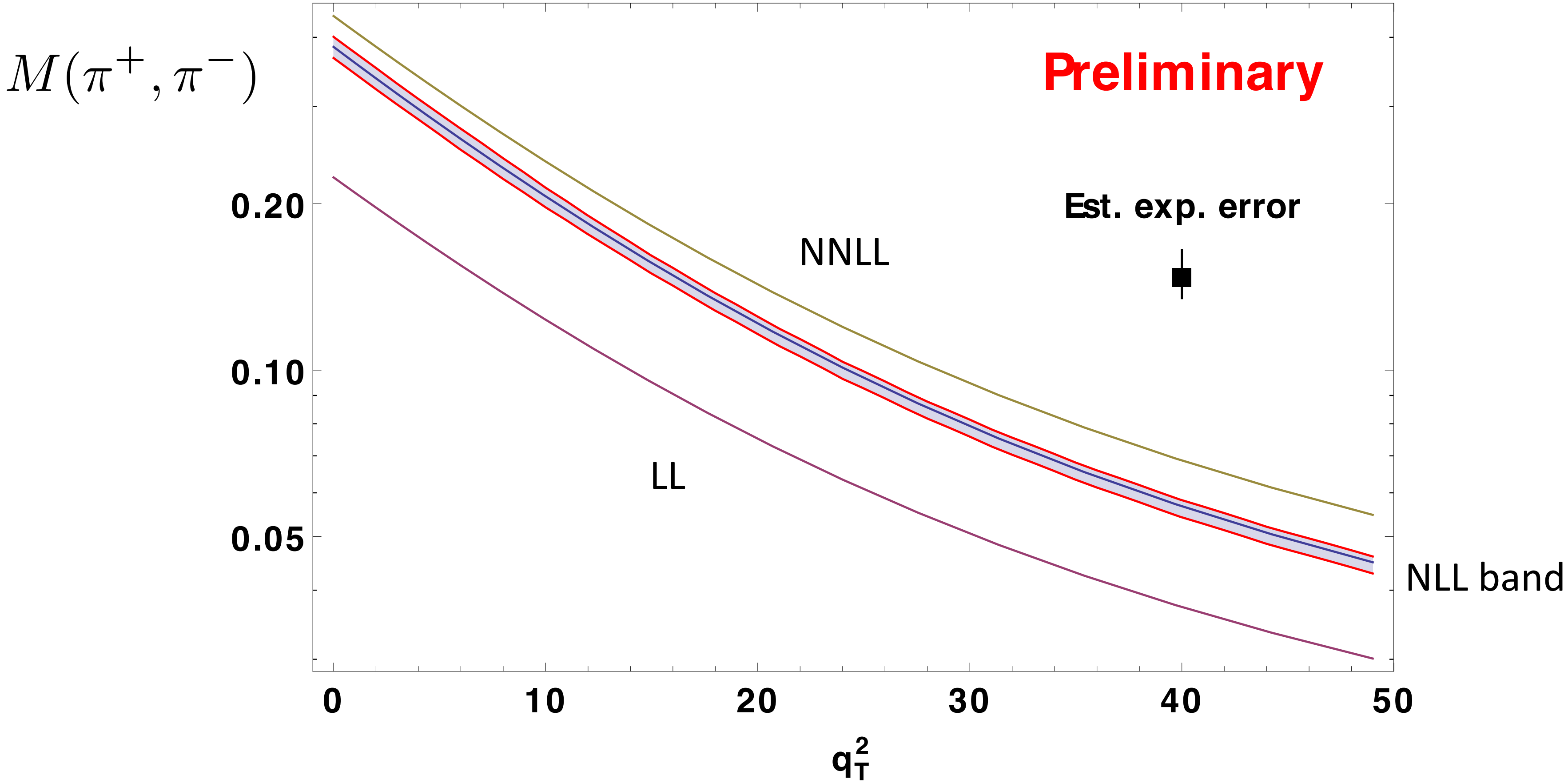
$$\langle \boldsymbol{P}^2_{\perp,\text{all others}} \rangle \equiv \langle \boldsymbol{P}^2_{\perp,\text{unf}} \rangle\,.$$

200 VALUES

Kinematic dependence

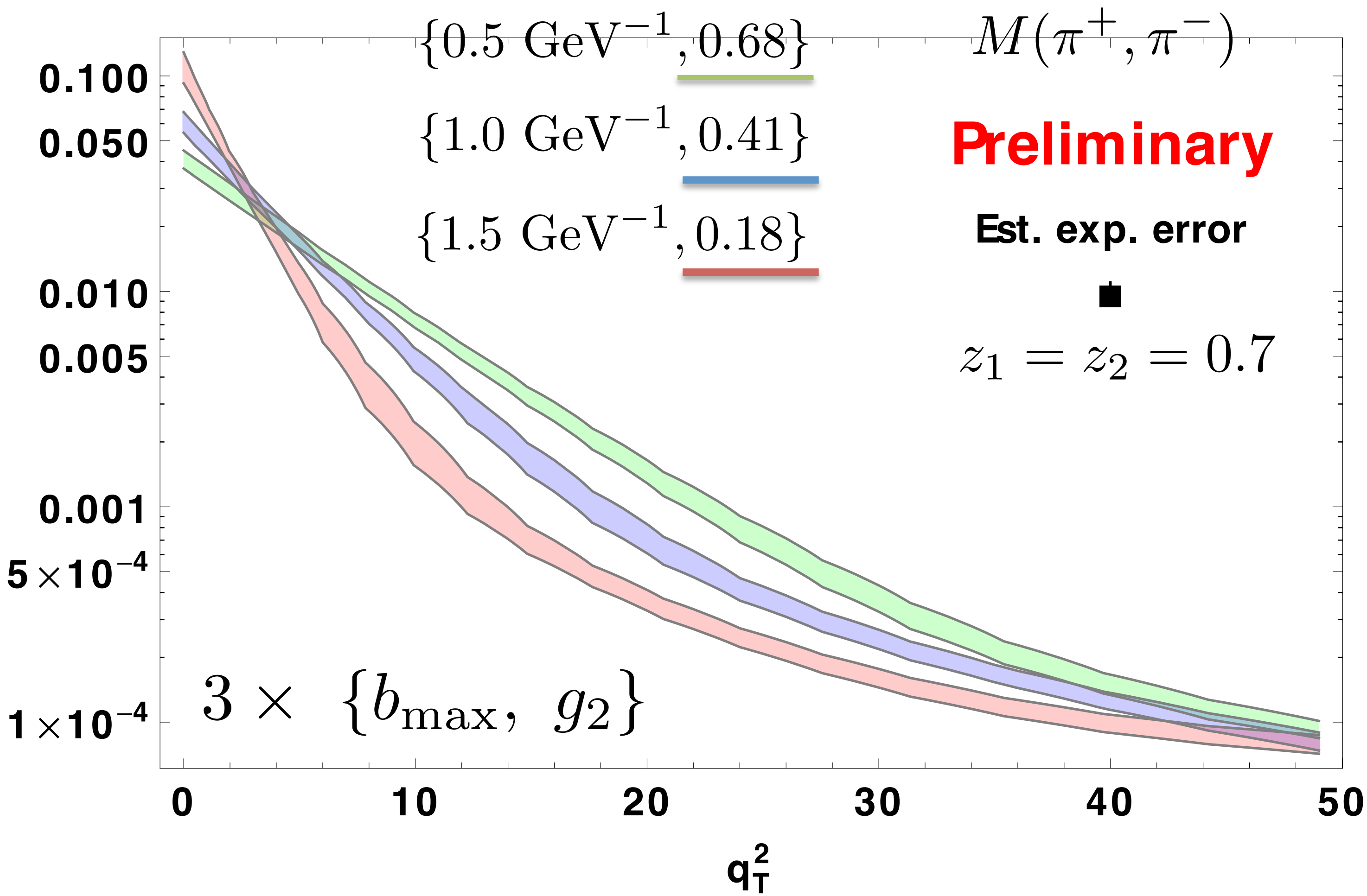
$$\langle \boldsymbol{P}^2_{\perp,\,q\to h} \rangle(z) = \langle \widehat{\boldsymbol{P}^2_{\perp,\,q\to h}} \rangle \,\frac{(z^\beta+\delta)\,(1-z)^\gamma}{(\hat{z}^\beta+\delta)\,(1-\hat{z})^\gamma}$$

Effects of theoretical accuracy

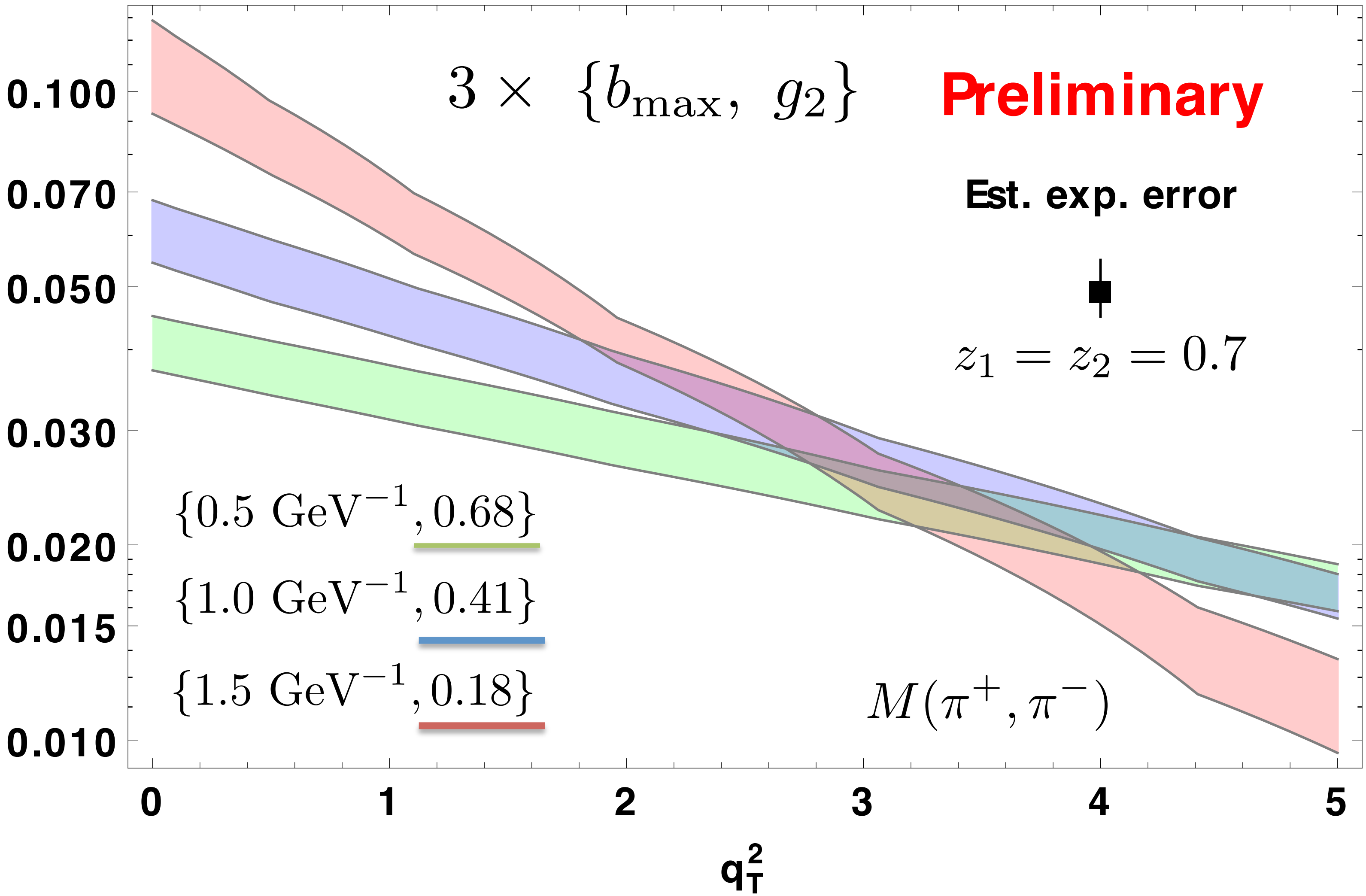


$$z_1 = z_2 = 0.2$$

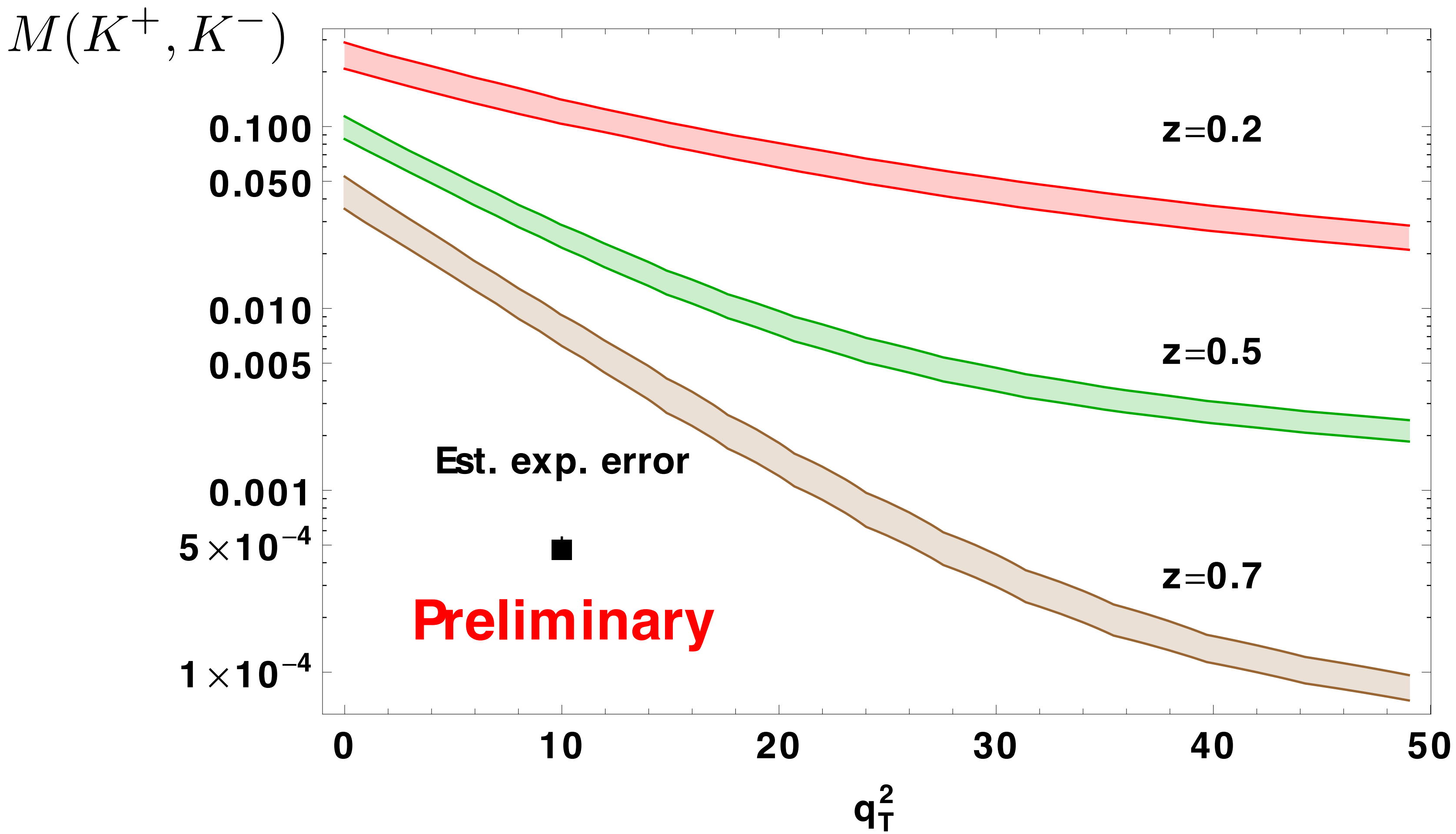
Sensitivity to evolution parameters



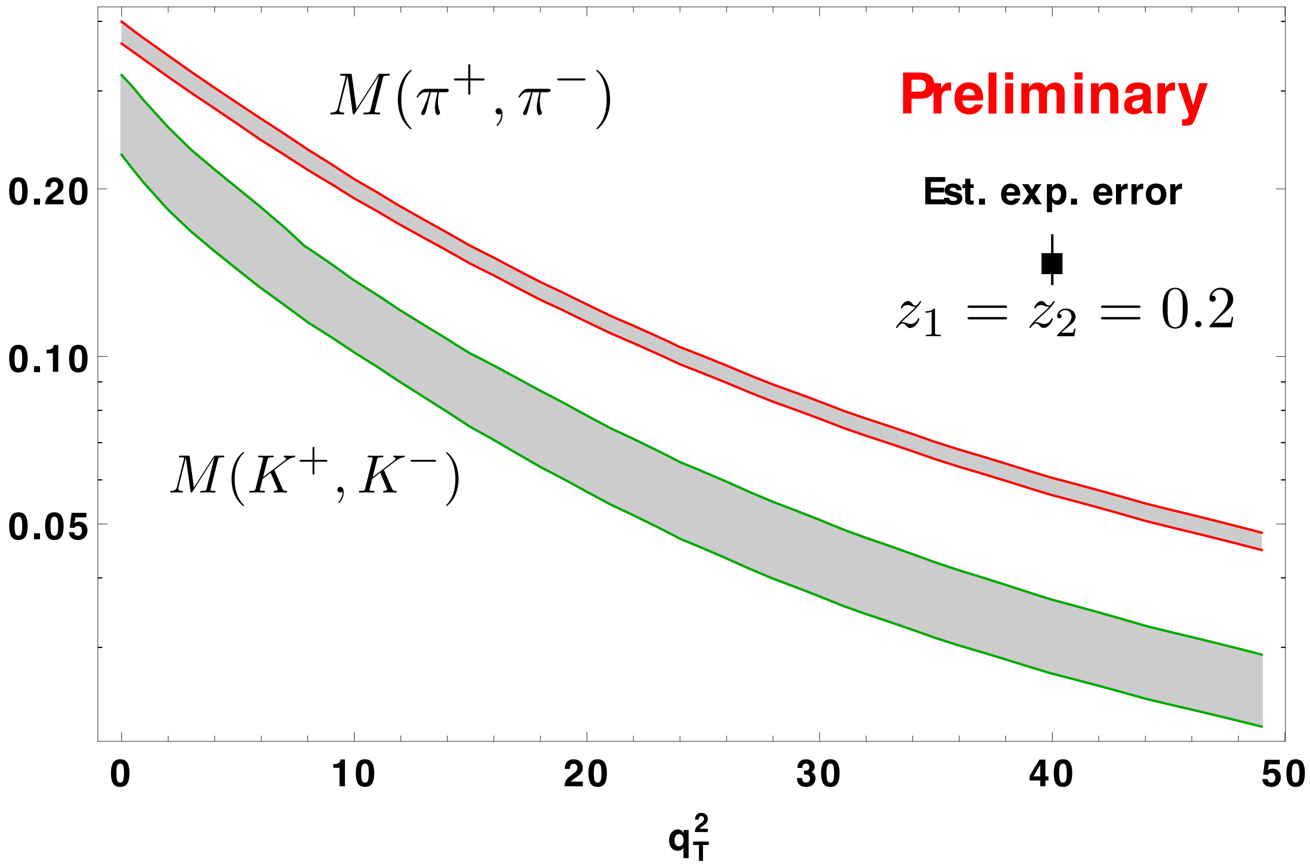
Sensitivity to evolution parameters



Intrinsic parameters: z-dependence



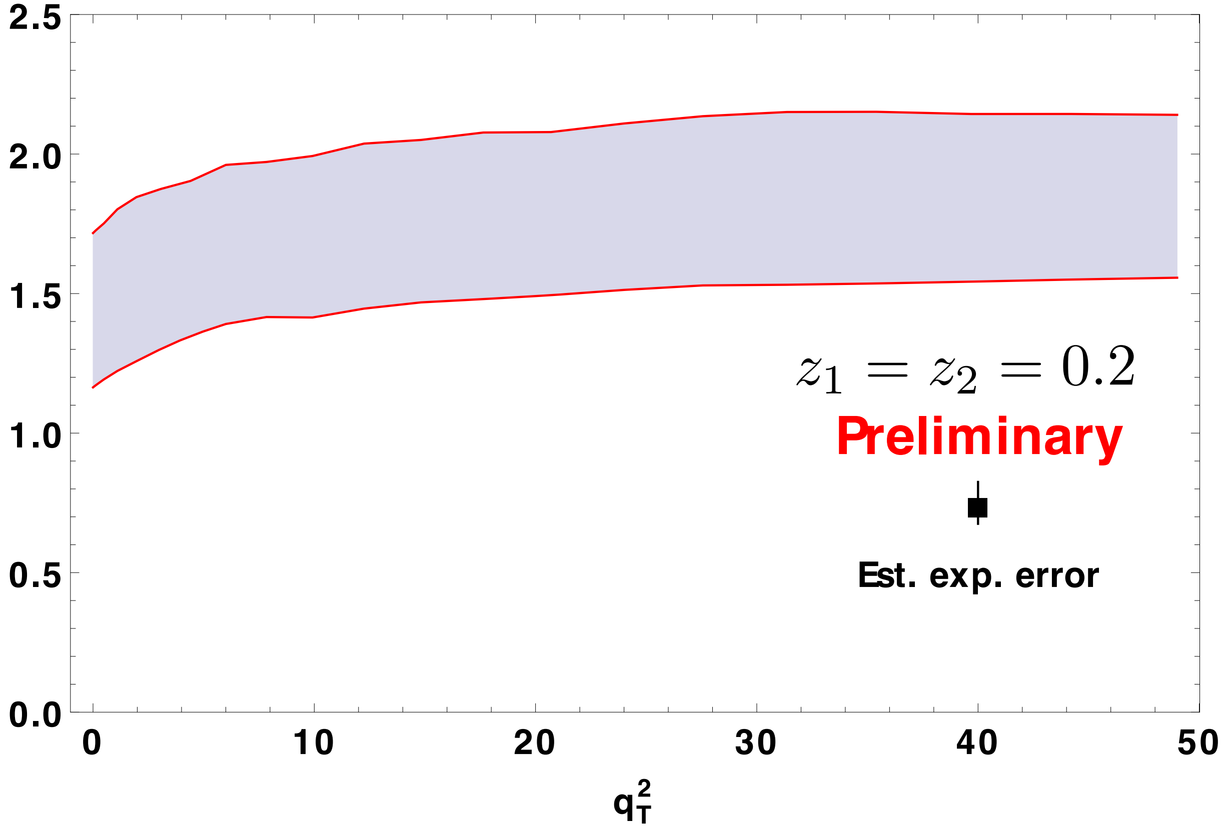
Intrinsic parameters: flavor



$$\{b_{\max} = 1.5 \ \mathrm{GeV}^{-1}, g_2 = 0.18\}$$

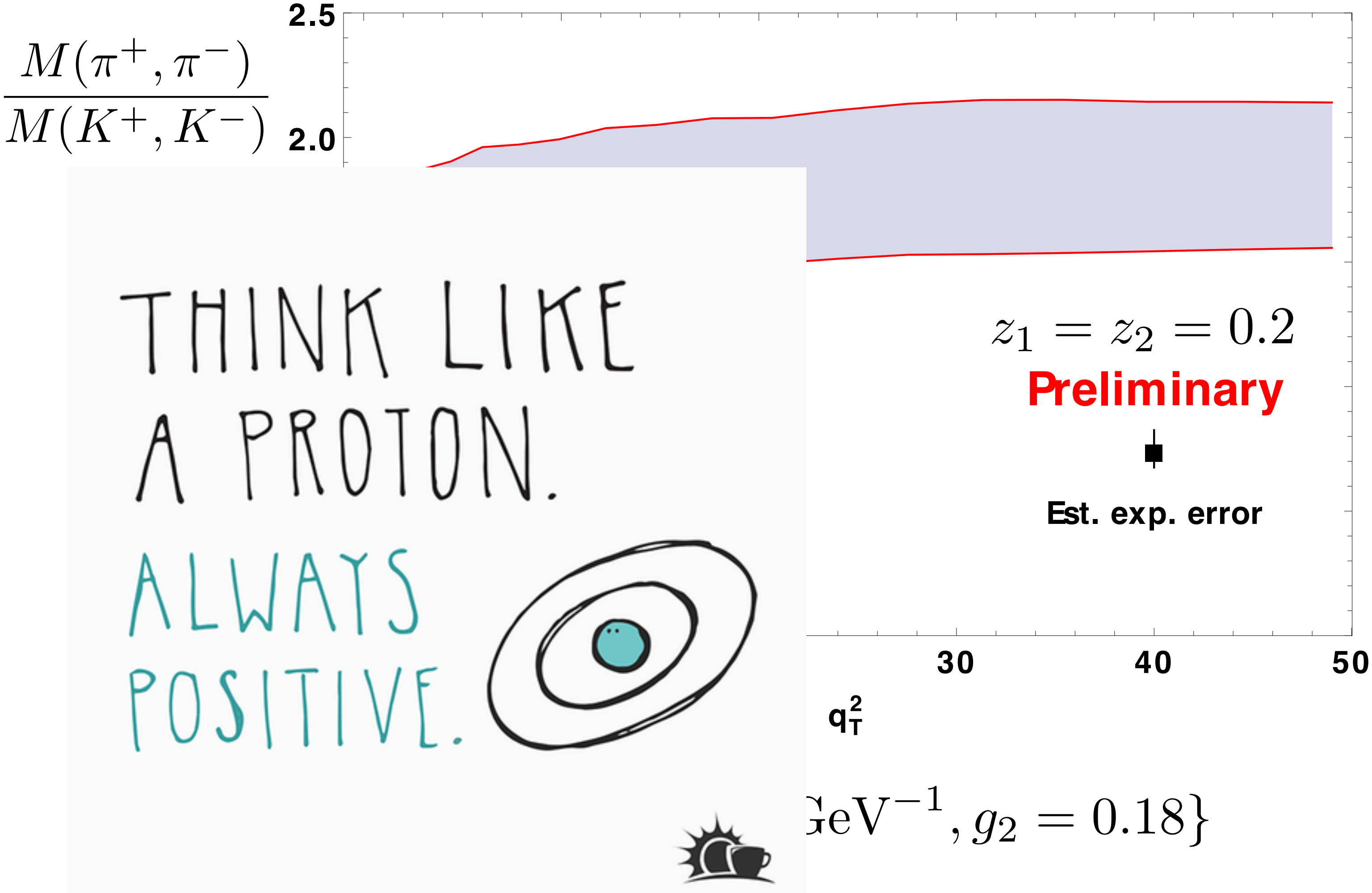
Intrinsic parameters: flavor

$$\frac{M(\pi^+, \pi^-)}{M(K^+, K^-)}$$



$$\{b_{\max} = 1.5\ \text{GeV}^{-1}, g_2 = 0.18\}$$

Intrinsic parameters: flavor



$\text{GeV}^{-1}, g_2 = 0.18\}$

Conclusions

SIDIS multiplicities

There is a lot of room for flavor dependence :

- clear indication in TMD FFs that
  "$q \rightarrow \pi$ favored" width < "unfavored" & "$q \rightarrow K$ favored"
- TMD PDFs: hints that d_v width < u_v width < sea width
- flavor-independent fit is not ruled out
- anticorrelation: many intrinsic $\{\mathbf{k}_\perp, \mathbf{P}_\perp\}$ give same $\mathbf{P}_{hT}$

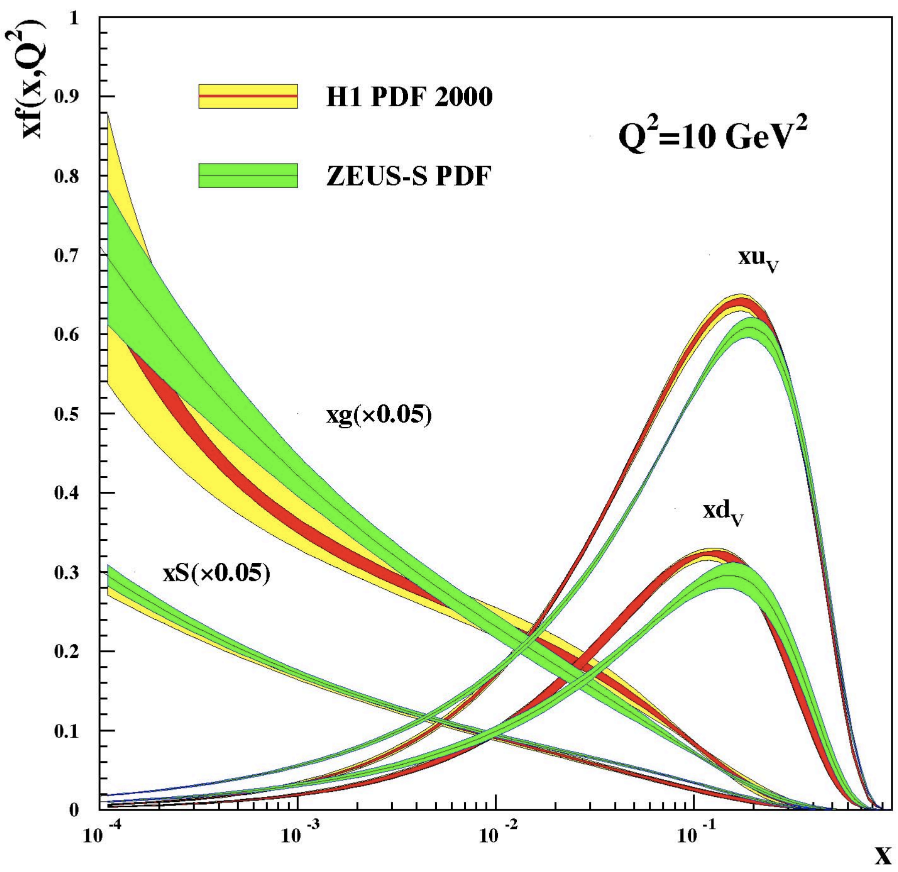
Conclusions

<u>*e+e- multiplicities*</u>

- Electron-positron data at 100 GeV^2 can be extremely valuable to **pin down evolution parameters**
- They are useful to **constrain flavor dependence** of the TMD fragmentation functions
- They are needed to determine the **nonperturbative parameters** of TMD fragmentation functions
- Indirectly, the knowledge of TMD fragmentation functions will help constraining TMD distribution functions

Backup slides

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

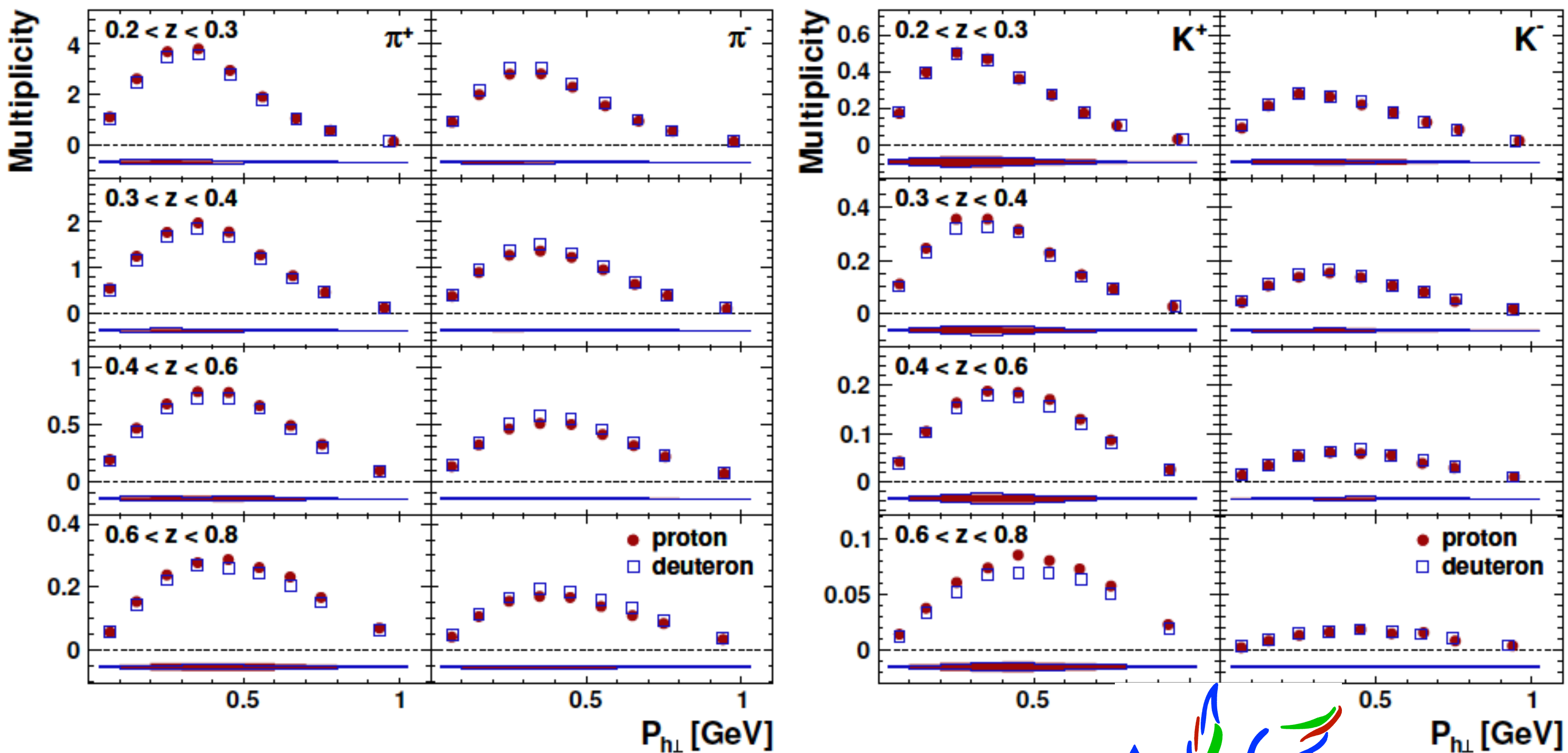
- ✓ Lattice QCD calculations
  Musch *et al.*, PRD **83** (11) 094507
  […]

- ✓ 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.



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)
- $0.1 < z < 0.8$
- $P_{hT}^2 < Q^2/3$

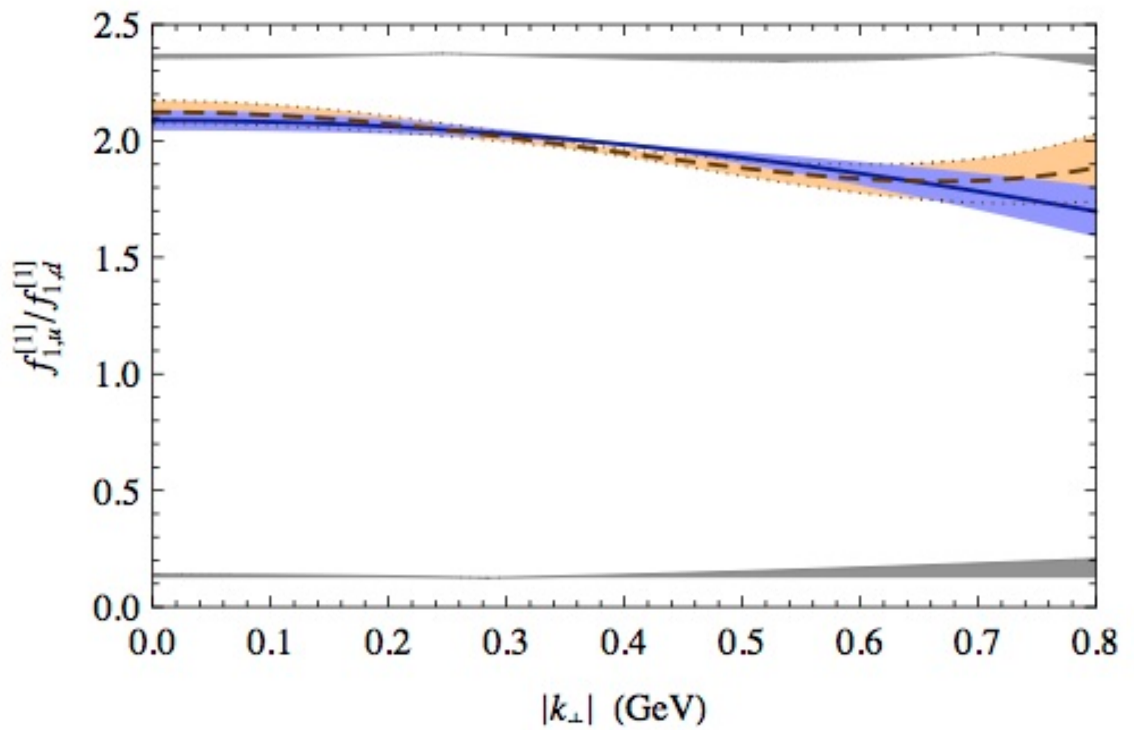
1538 analyzed points

limited Q^2 range $\Rightarrow$ safely neglect evolution <u>everywhere</u>

Flavor in transverse space

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

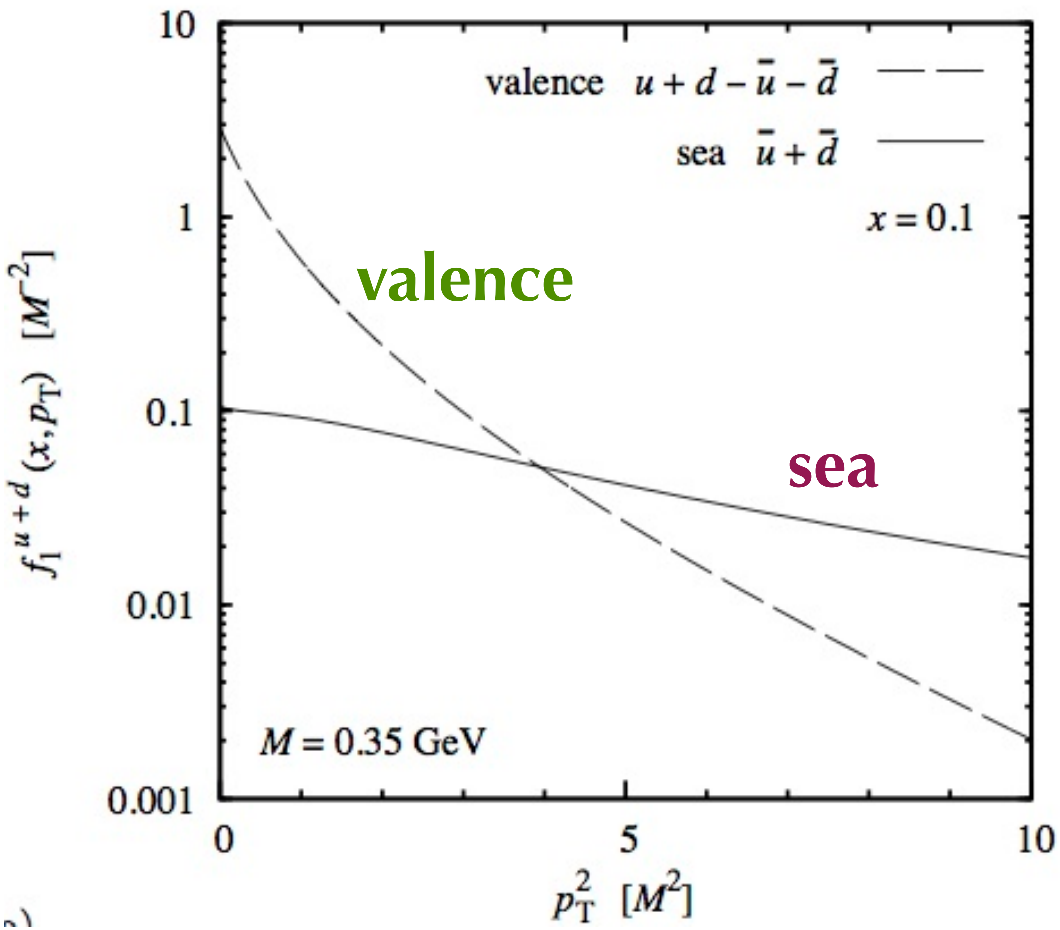
Less up at larger transverse momentum..!



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

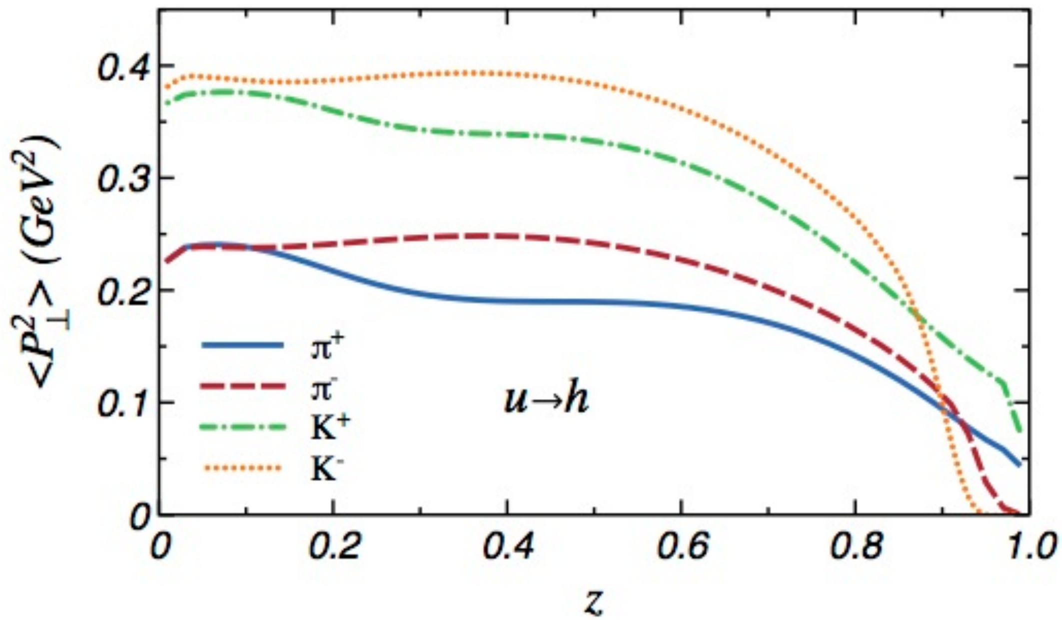
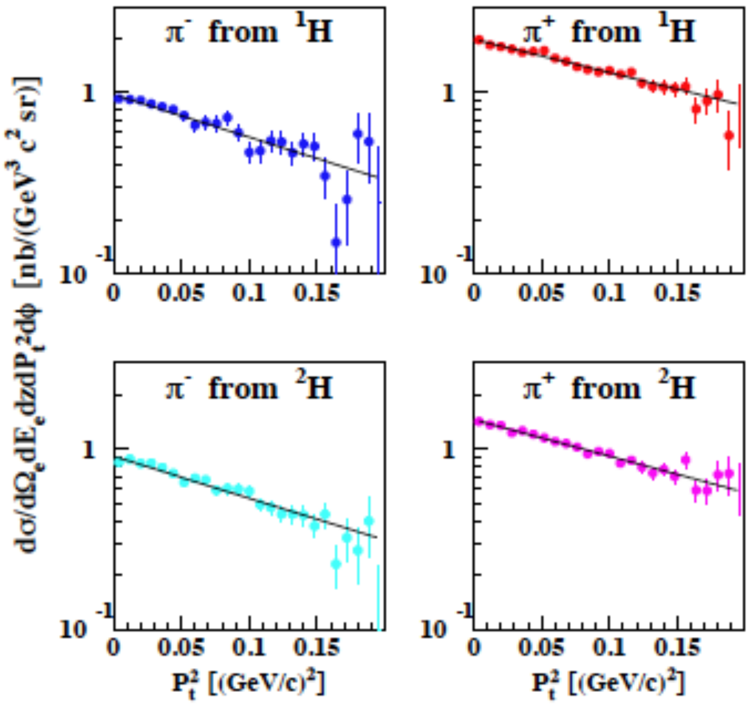


FIG. 14. The averaged transverse momentum of π and K mesons emitted by a u quark.

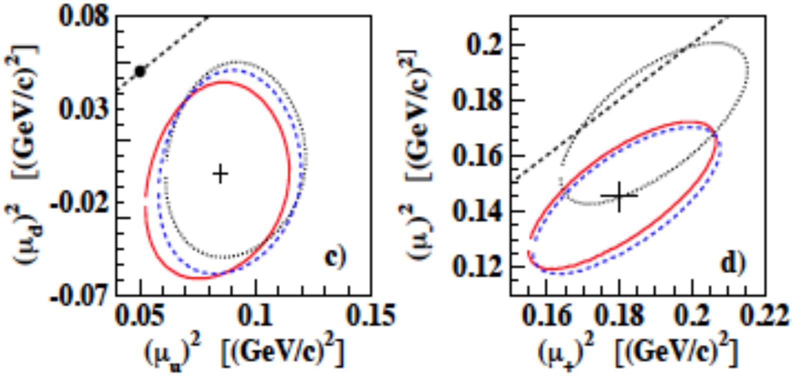
Matevosyan *et al*., P. R. D**85** (12) 014021

Flavor in transverse space



no kaons, no sea,

no *x-z* dependence



up is wider than down

Jefferson Lab

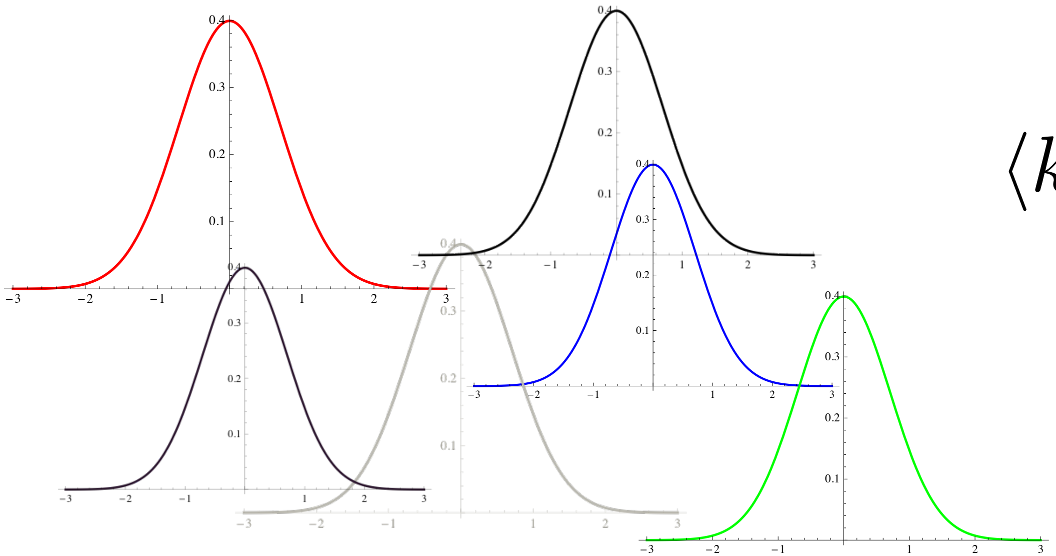
favored wider than unfavored

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!

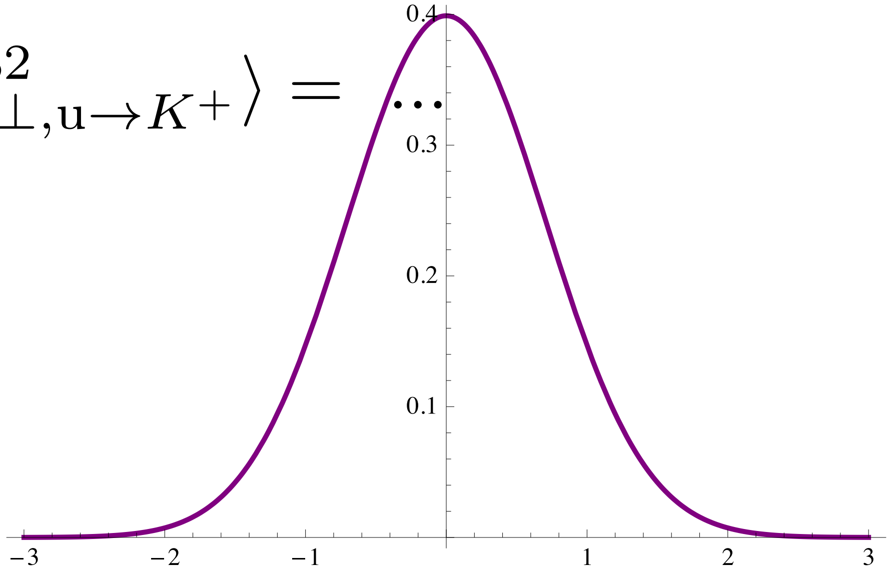
Flavor independent Gaussianity

Gaussian parametrization of TMD parts

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

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

The same variance
for all the fragmentation
processes



TMD PDFs – full analysis

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

Parameters for TMD PDFs				
	Default	$Q^2 > 1.6$ 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

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

Parameters for TMD FFs				
	Default	$Q^2 > 1.6$ GeV^2	Pions only	Flavor-indep.
$\langle \hat{\boldsymbol{P}}^2_{\perp,\text{fav}} \rangle$ [GeV^2]	0.15 ± 0.04	0.15 ± 0.04	0.16 ± 0.03	0.18 ± 0.03
$\langle \hat{\boldsymbol{P}}^2_{\perp,\text{unf}} \rangle$ [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

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

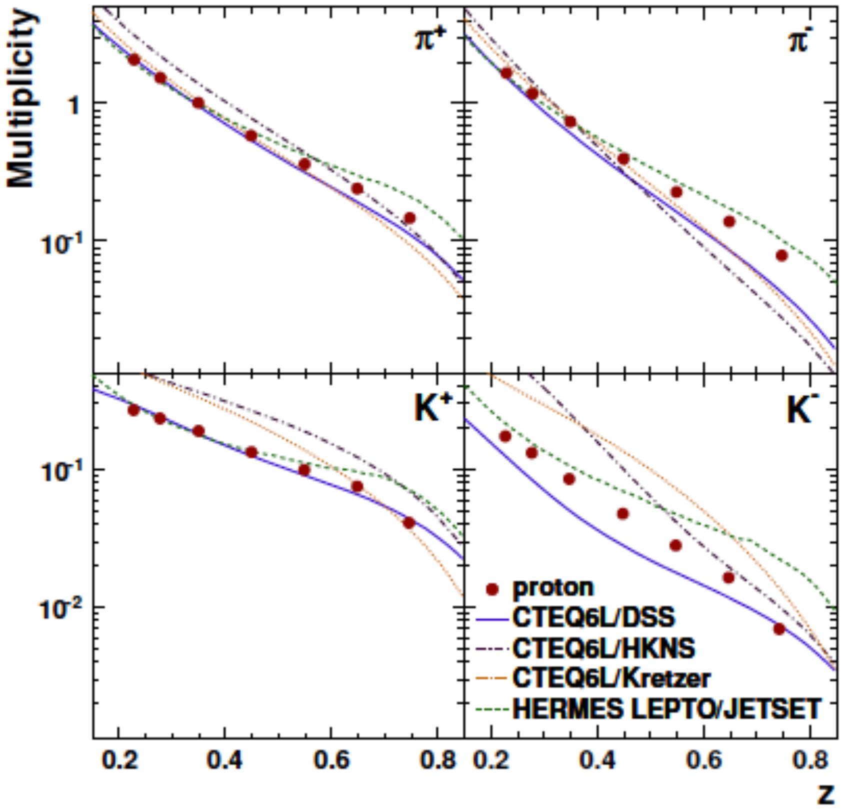


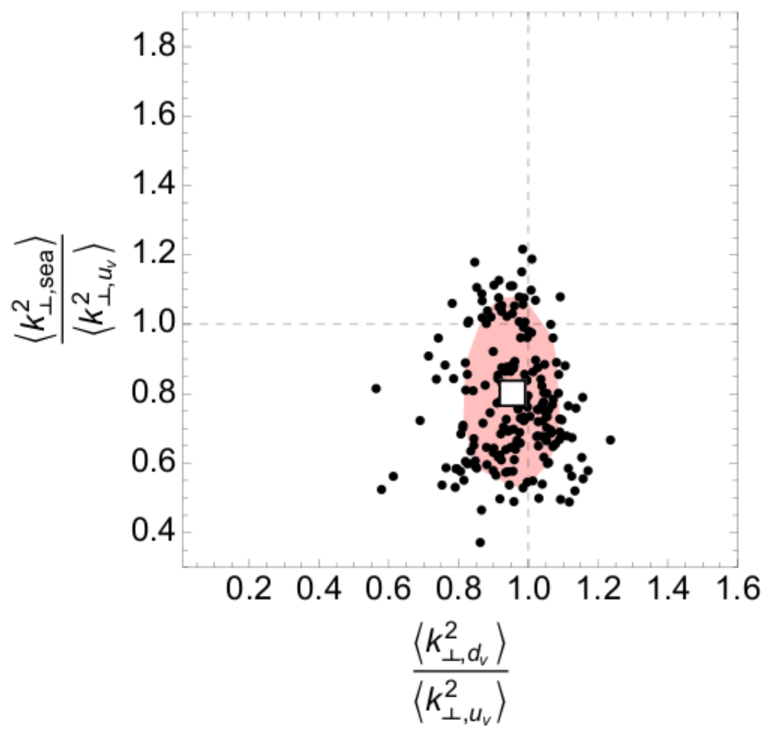
Table 2. Values of χ^2/d.o.f. obtained from the comparison of the HERMES multiplicities $m_N^h(x, z, Q^2)$ with the theoretical prediction using the MSTW08LO collinear PDFs [8] and the DSS LO collinear FFs [48]. In all cases, the range $0.1 \le z \le 0.8$ was included.

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

TMD lib & plotter

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

NIKHEF
PHYSICS AT THE TERA SCALE Helmholtz Alliance
DESY

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 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.

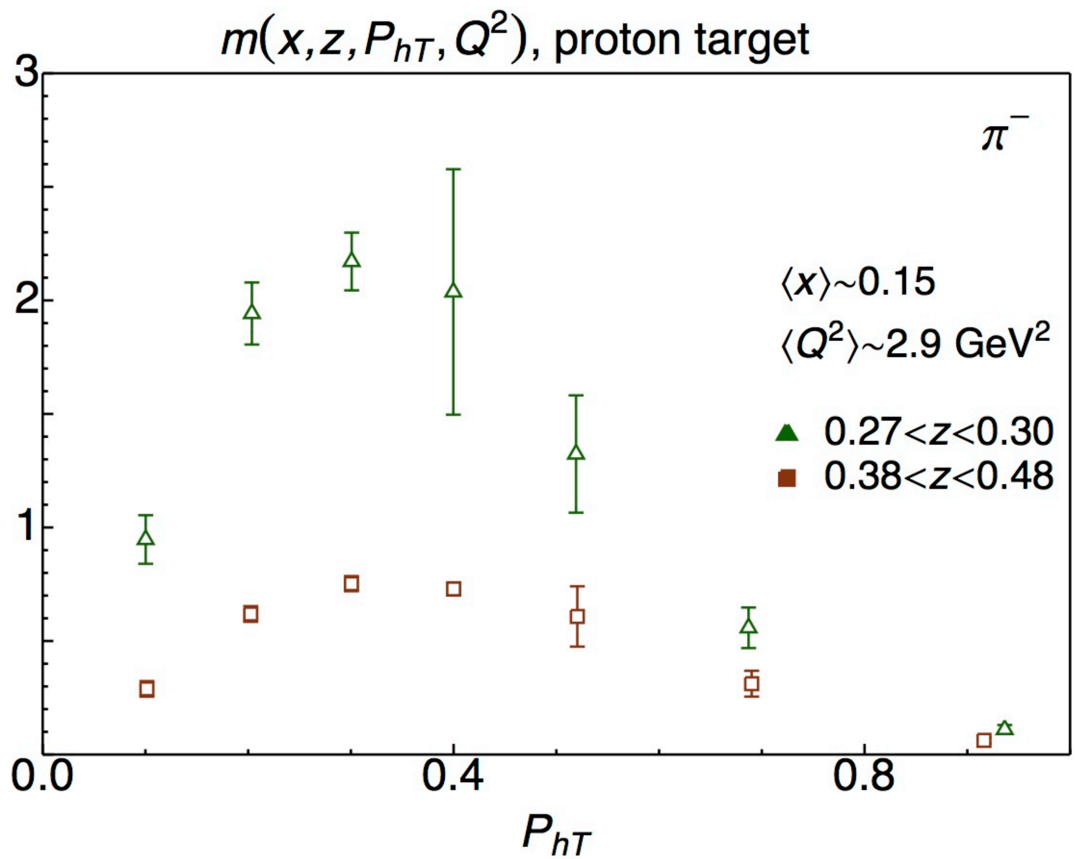
Coming soon !

High Energy Physics | TMD Plotter

HELMHOLTZ GEMEINSCHAFT

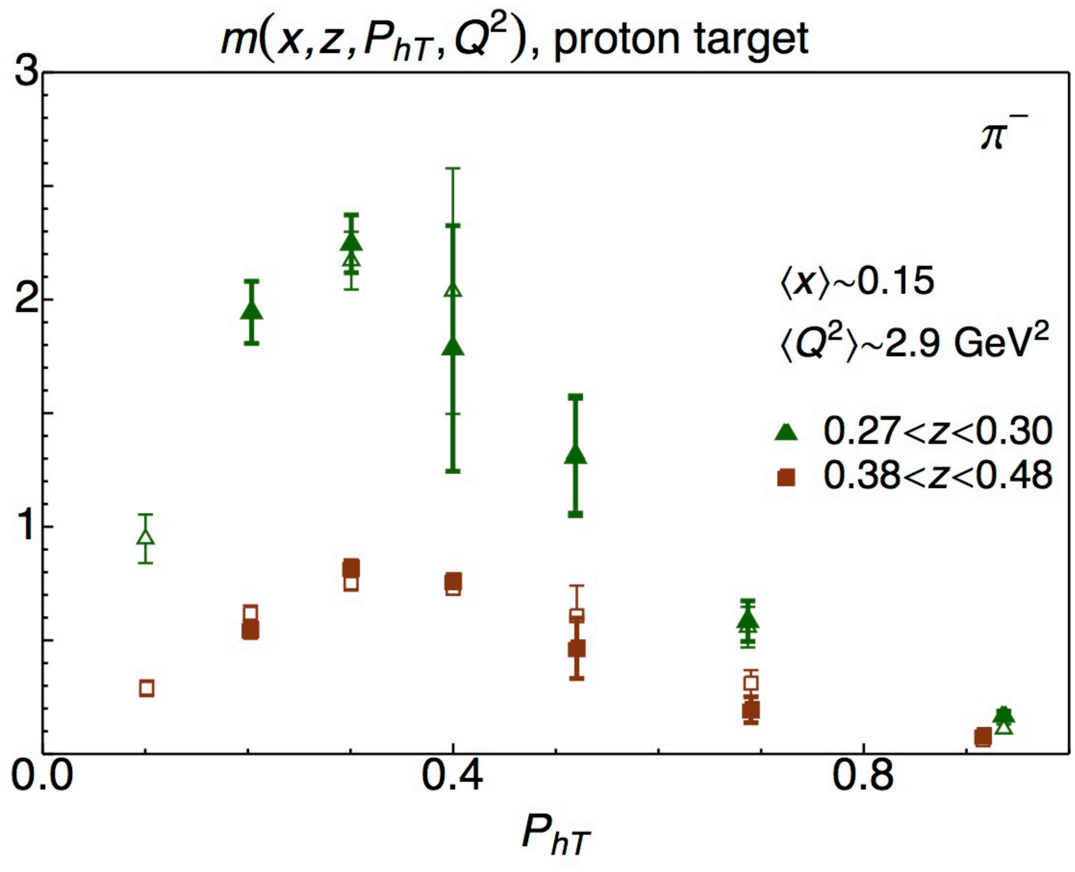
Home | TMD Plotter | Publications | HEP Links

Fitting procedure



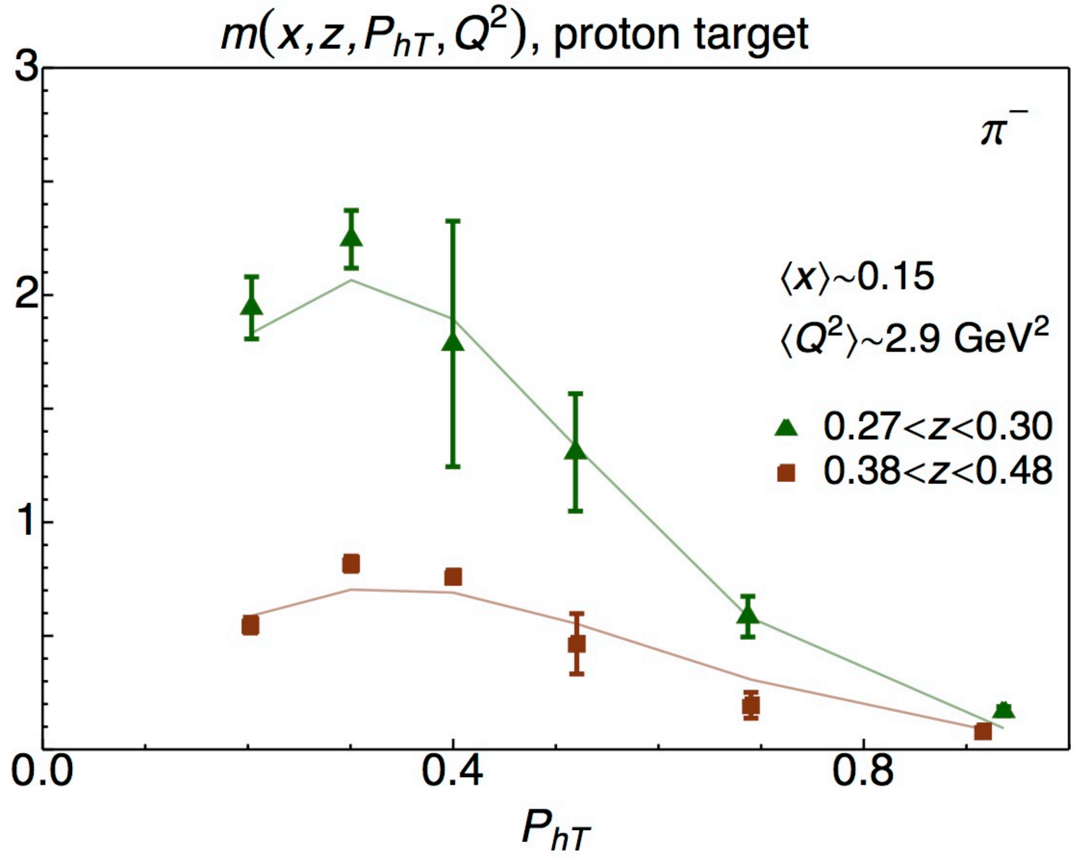
Sample of original data

Fitting procedure



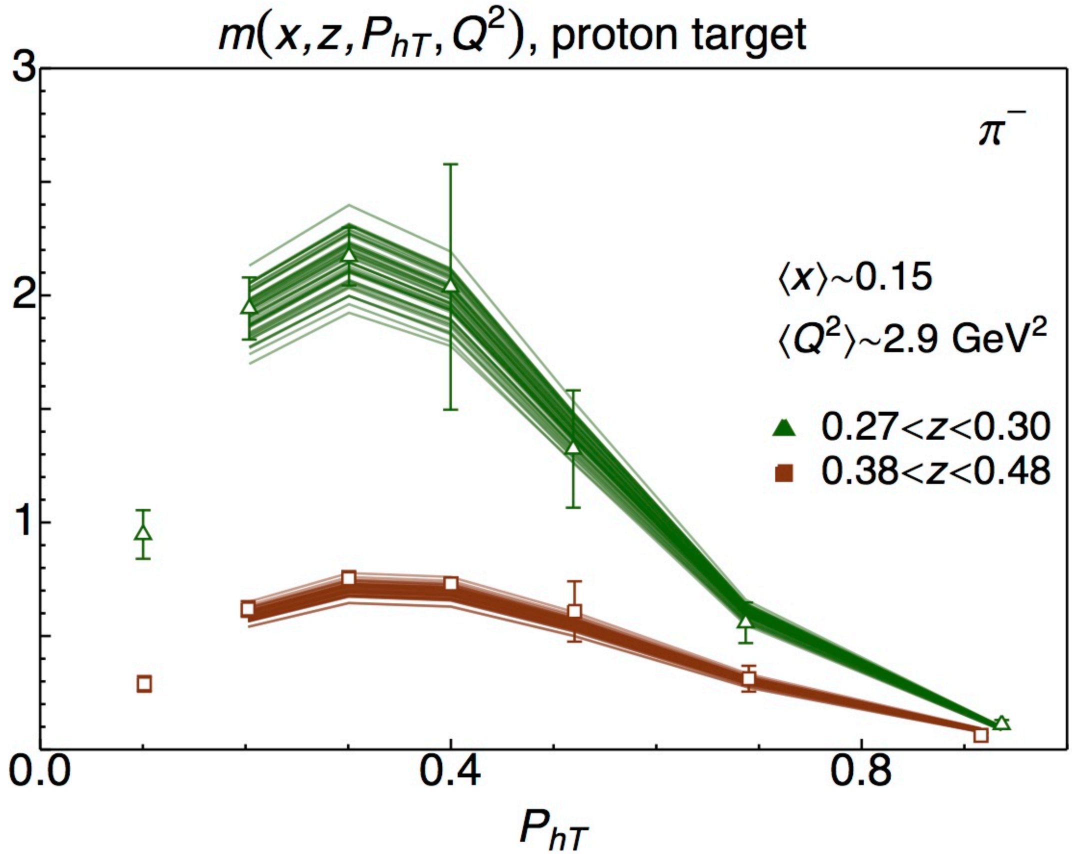
Replica of the original data with Gaussian noise

Fitting procedure



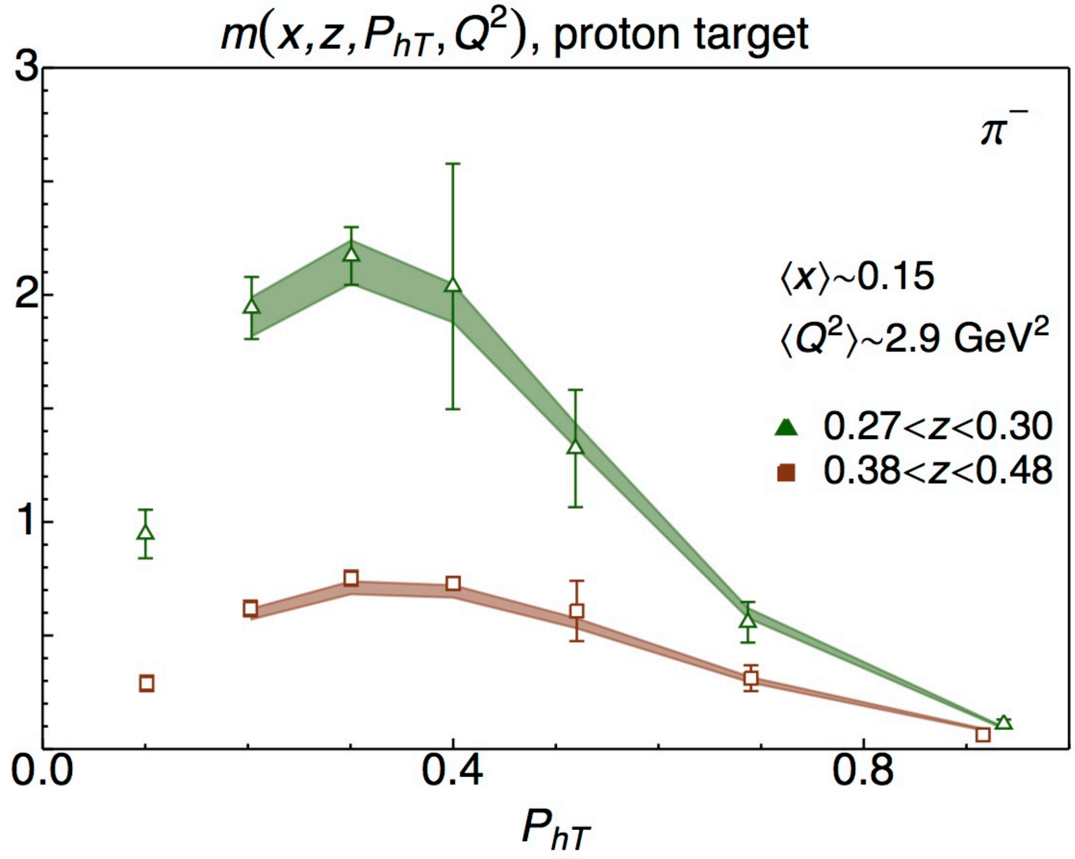
We fit the replicated data…

Fitting procedure



… repeating the fit over the 200 replicas

Fitting procedure



Plot of the 68% CL bands