FF 2018

Workshop on Fragmentation Functions

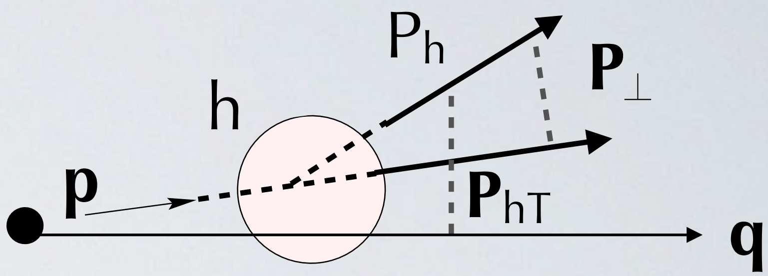
19-22 Febr. 2018, Stresa (Italy)

Marco Radici
INFN - Pavia

INFN Istituto Nazionale di Fisica Nucleare
3DSPIN MAPPING THE PROTON IN 3D
erc European Research Council

Theory open issues

TMD FF map



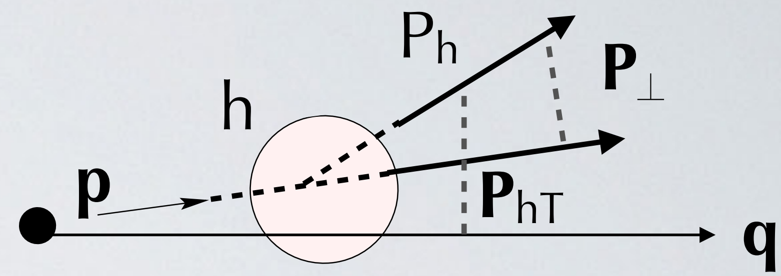
leading twist

$S_h \leq 1/2$

Hadron Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	D_1 ***Unpolarized***		$H_1^\perp$ - ***Collins***
L		G_{1L} -	$H_{1L}^\perp$ -
T	$D_{1T}^\perp$ -	G_{1T} -	H_1 - $H_{1T}^\perp$ -

TMD FF map

leading twist
$S_h \leq 1/2$



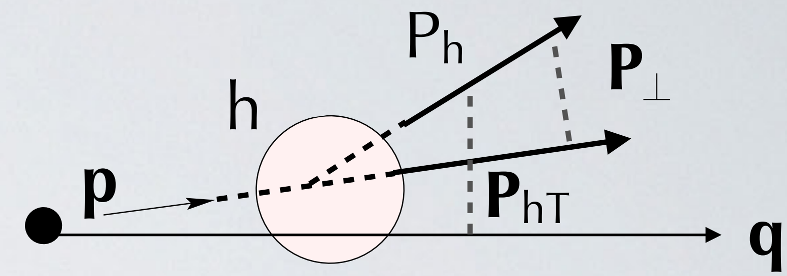
$S_h = 0$

Hadron Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	D_1 **Unpolarized**		$H_1^\perp$ **Collins**
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	H_1, $H_{1T}^\perp$

most of the time, detection of final unpolarized mesons (π, K..)
⇒ use only first row of table

TMD FF map

leading twist
$S_h \leq 1/2$



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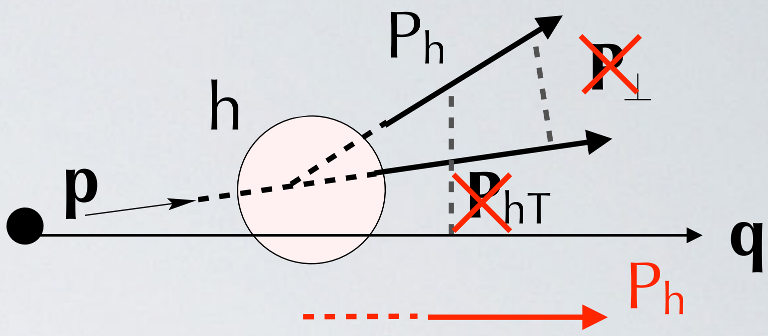
	T	$D_{1T}^\perp$ -	G_{1T} -	H_1 - $H_{1T}^\perp$ -

data on $\Lambda^\uparrow$ production from BELLE / COMPASS (and CERN- NA48/OPAL/ATLAS
HERA-B
old FermiLab)

collinear FF map

leading twist
$S_h \leq 1/2$



Hadron Polarization		Quark polarization		
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	U	D_1 ***Unpolarized***		$H_1^\perp$ - ***Collins***
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collinear FF map

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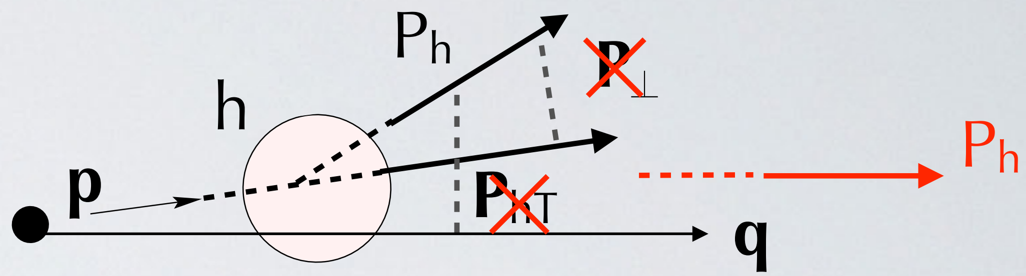

“standard”

NLO analysis of e^+e^- data for $\pi^\pm, K^\pm$ $0.1 \lesssim z \lesssim 0.9$ Ex: JAMFF

collinear FF map

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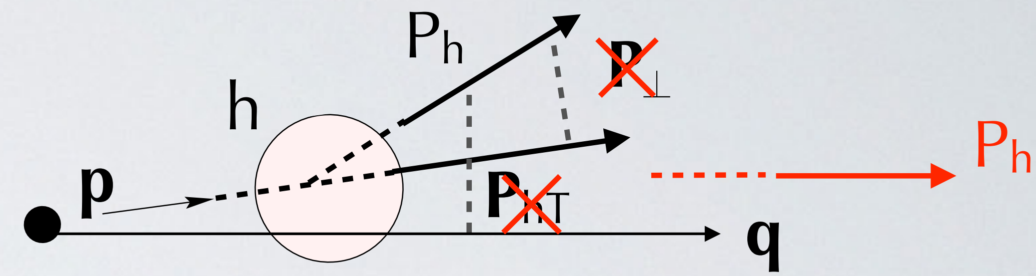
U	D_1 Unpolarized		$H_1^{\perp}$ Collins
L		G_{1L}	$H_{1L}^{\perp}$
T	$D_{1T}^{\perp}$	G_{1T}	H_1, $H_{1T}^{\perp}$



“standard”

NLO analysis of e^+e^- data for $\pi^\pm, K^\pm$ $0.1 \lesssim z \lesssim 0.9$ Ex: JAMFF

NNLO 1st: ASR15 (only $\pi^\pm$, no error)
then NNFF1.0 (“standard” data + $\overset{(-)}{p}$)

collinear FF map

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
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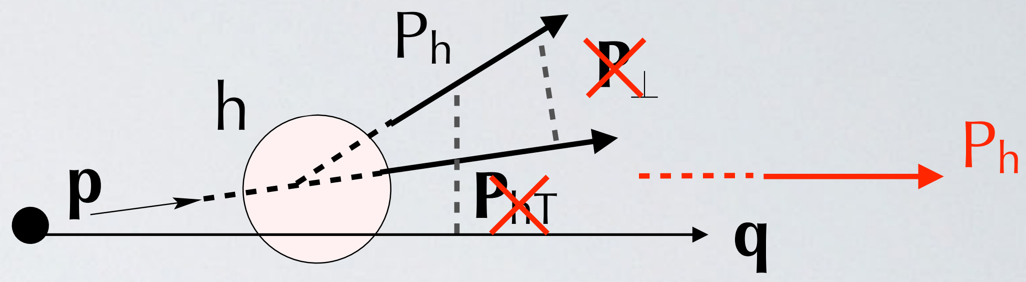
	L		G_{1L}	$H_{1L}^{\perp}$
	T	$D_{1T}^{\perp}$	G_{1T}	H_1 $H_{1T}^{\perp}$



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NNLO+NNLL AKSR17 (only $\pi^\pm$, no error, small z)

collinear FF map

		Quark polarization		
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Hadron Polarization	U	D_1 *Unpolarized*		$H_1^\perp$ Collins
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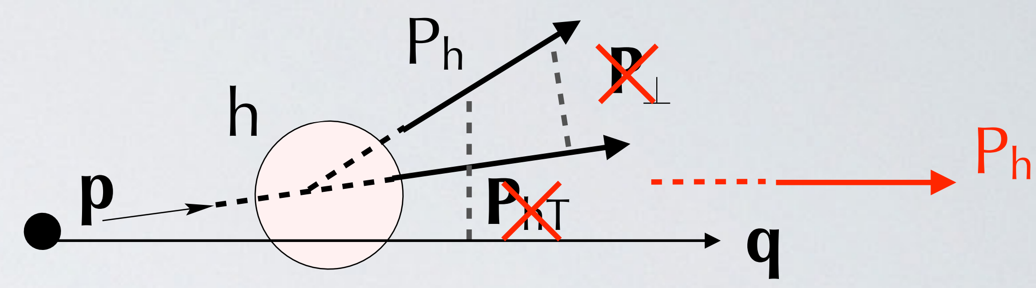


"standard"

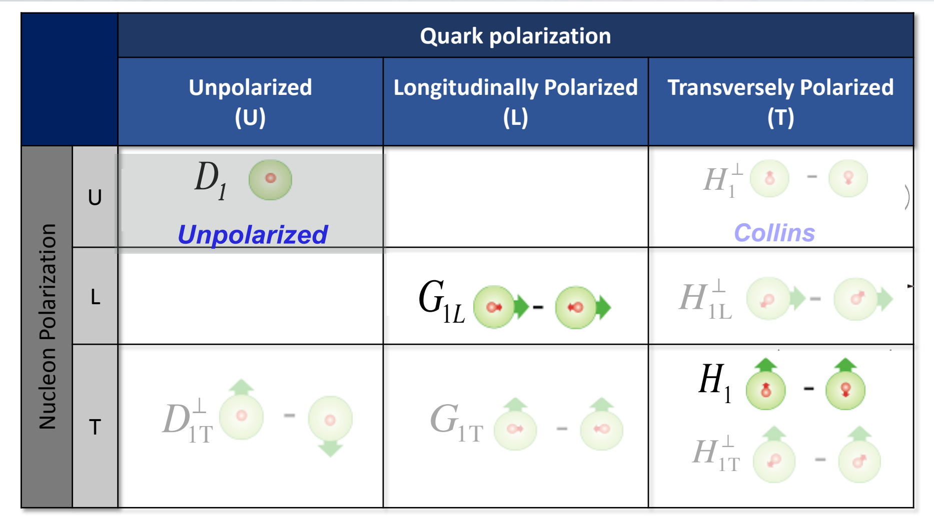
NLO analysis of e^+e^- data for $\pi^\pm, K^\pm$ $\quad 0.1 \lesssim z \lesssim 0.9$ $\quad$ Ex: JAMFF

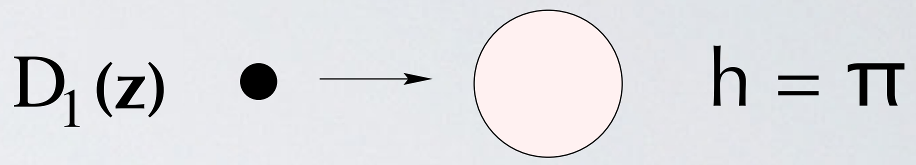
NNLO 1st: ASR15 (only $\pi^\pm$, no error)
then NNFF1.0 ("standard" data + $\overset{(-)}{p}$)

NNLO+NNLL AKSR17 (only $\pi^\pm$, no error, small z)

global fit DSS 2015 ($\pi^\pm$) + DSS 2017 ($K^\pm$) : e^+e^-, SIDIS, p-p data

collinear π FF at NLO: DSS 2015





De Florian, Sassot, Epele, Hernandez-Pinto, Stratmann, P.R. D ***91*** *(15) 014035*

DSS 2007 → major update DSS 2015 (only for q→π)

first time use of LHC data →

- more/better data for e^+e^- (BELLE, BaBar)
- SIDIS (Hermes, COMPASS)
- p-p data (STAR), also on π^- / π^+
- LHC (ALICE)
- new error analysis

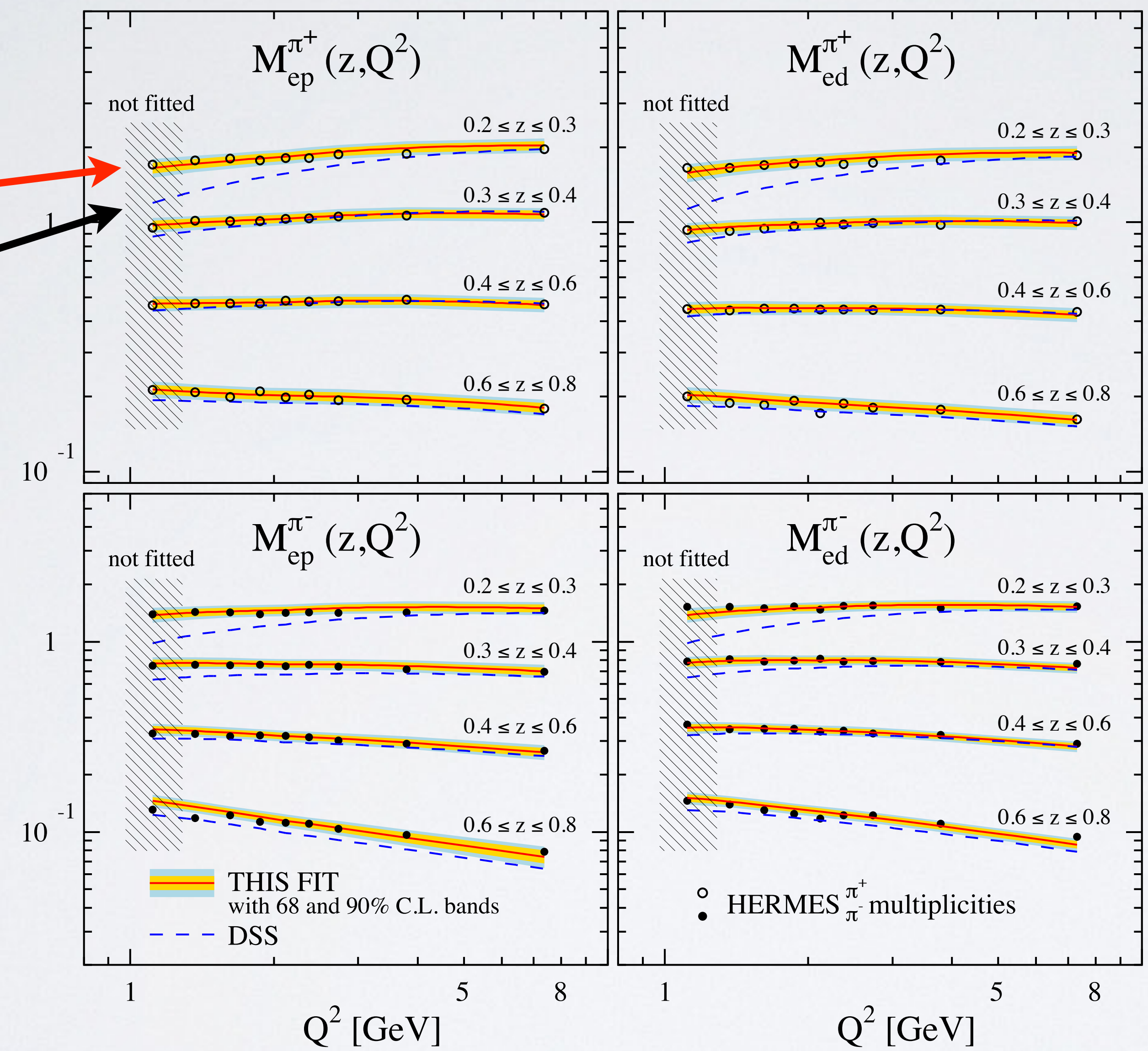
  Iterative Hessian (IH) + ||N|| χ^2-penalty
- 973 data points, 28 parameters [$0.05 \lesssim z$]
- **global χ^2/dof ~ 2.2 → 1.2**

collinear π FF at NLO: DSS 2015

Hermes multiplicities

DSS 2015

DSS 2007



(MSTW +)

DSS 2007 → **DSS 2015**

HERMES data χ^2

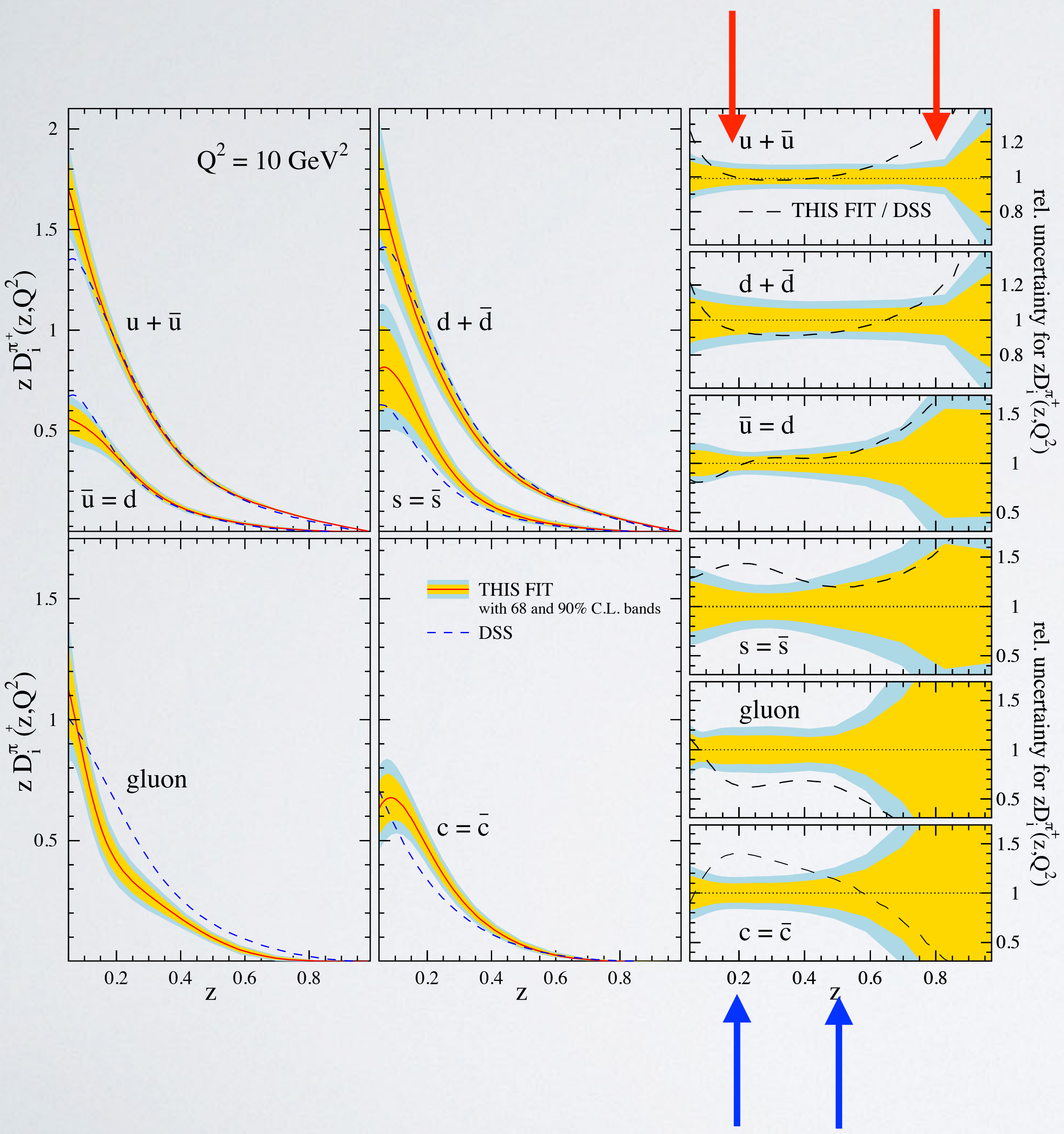
2.86 → **1.37**

talk Kunne

*De Florian, Sassot, Epele, Hernandez-Pinto, Stratmann, P.R. D**91** (15) 014035*

collinear π FF at NLO: DSS 2015

*De Florian, Sassot, Epele, Hernandez-Pinto, Stratmann, P.R. D**91** (15) 014035*



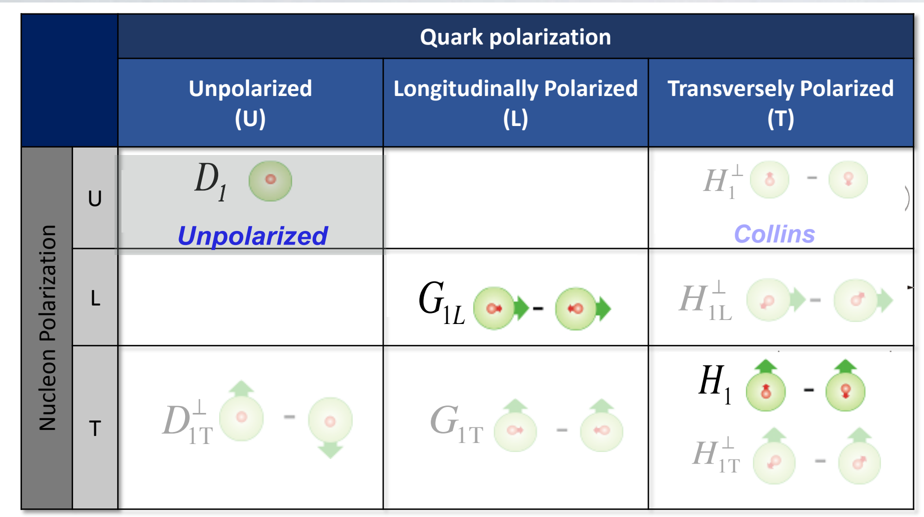
caveat

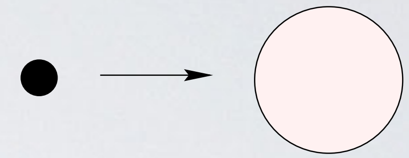
- major improvement only for total up & down channels: rel. uncertainty ≲10% for 0.2< z< 0.8

- Compass data for SIDIS multiplicities for deuteron target only

- for other channels, improvement upon DSS 2007 only for 0.2< z< 0.5

collinear K FF at NLO: DSS 2017



$D_1(z)$  h = K

De Florian, Epele, Hernandez-Pinto, Sassot, Stratmann, P.R. D95 (17) 094019

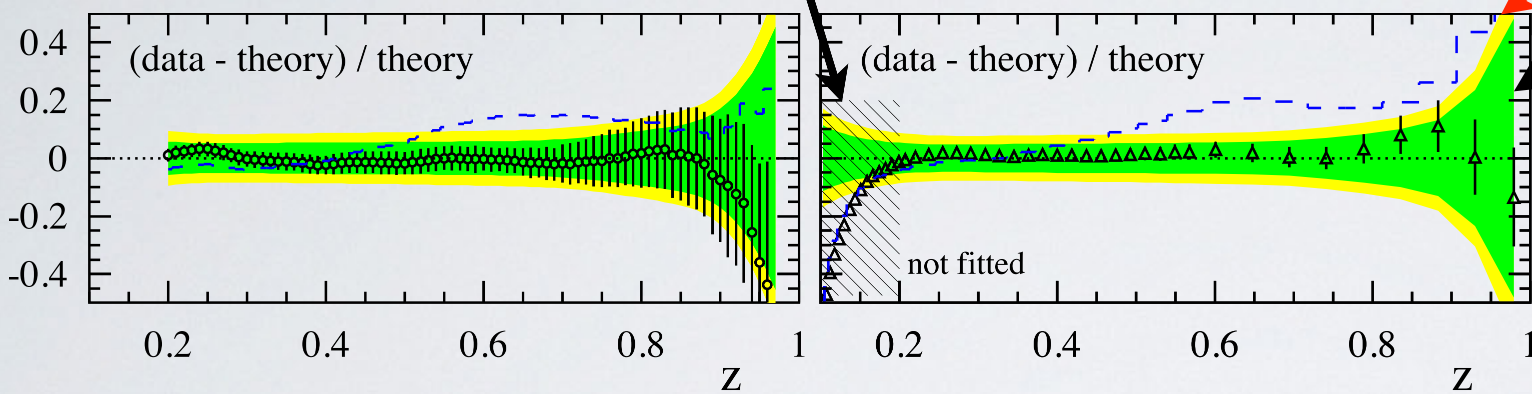
DSS 2007 → major update DSS 2017 for q→K

talks → Schnell, Stolarski, Drachenberg

- newer precise data for e^+e^- (BELLE, BaBar)
- final (Hermes) and new (COMPASS) SIDIS data
- new p-p data (STAR), also on K^+ / K^-
- LHC data (ALICE) on K / π
- same error analysis as for π FF
- 1194 data points, 20 parameters [$0.1 \lesssim z$]
- **global χ^2/dof ~ 1.83 → 1.08**

collinear K FF at NLO: DSS 2017

caveat!



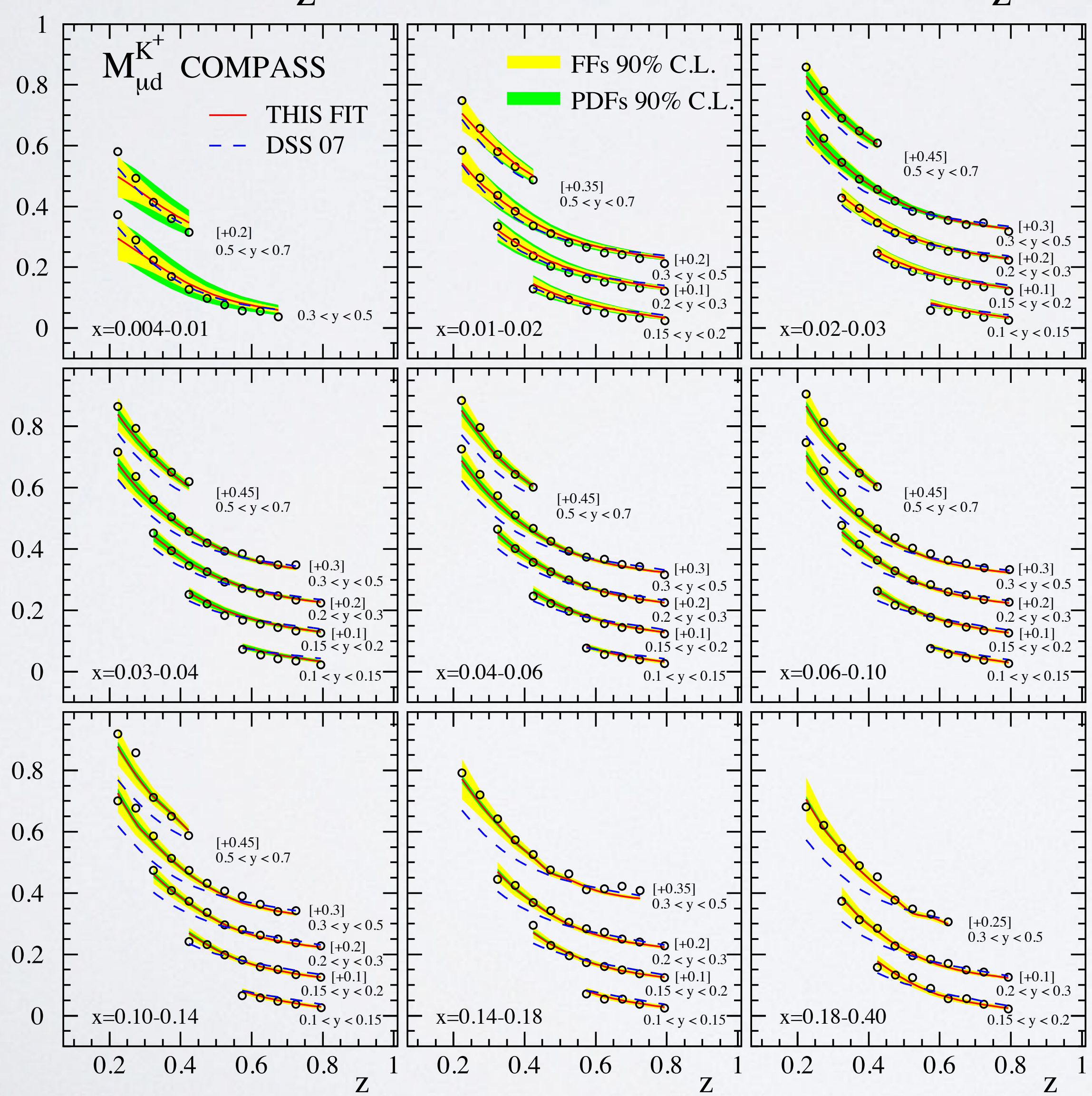
DSS 2017

DSS 2007

new precise data

→ stronger constraint on Σ and valence $u+\bar{u}$ and $s+\bar{s}$

multiplicities



DSS 2007 → **DSS 2017**

(+ MMHT14)

global χ^2

1.83 → **1.08**

(z,Q^2) and (z,x) projections

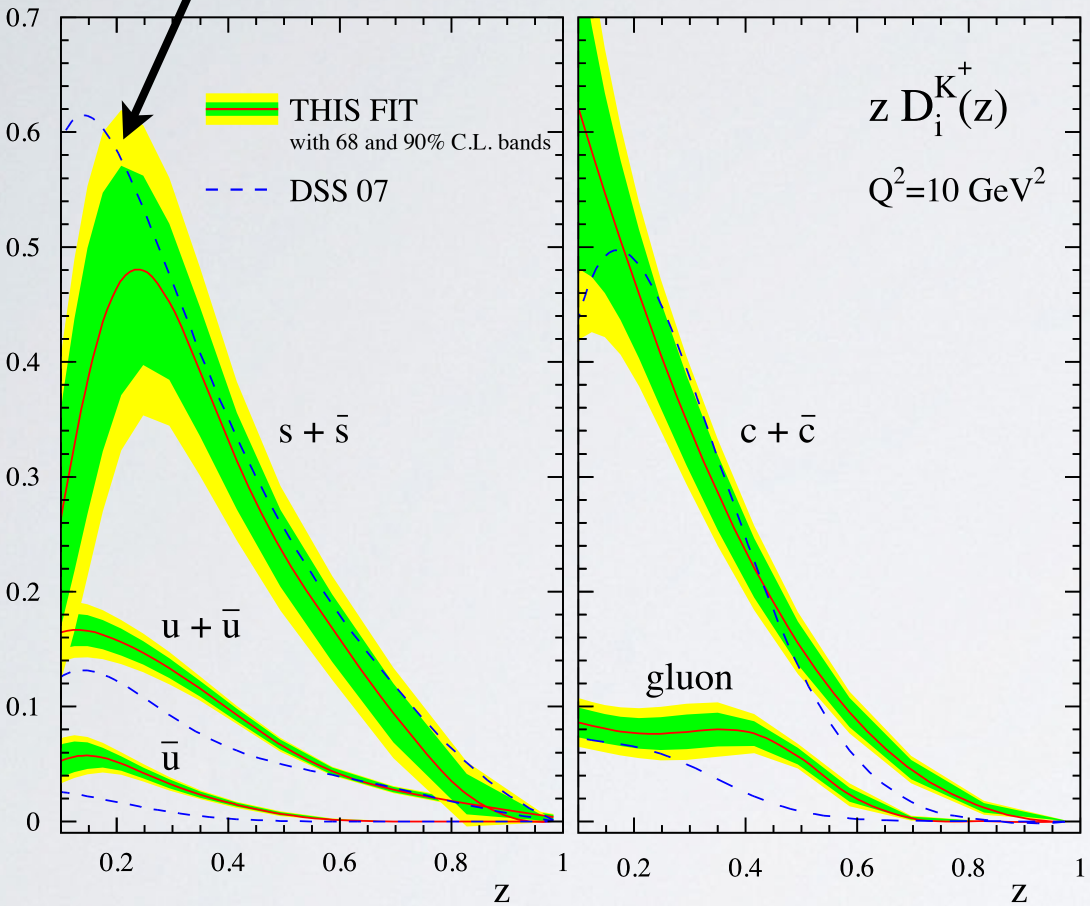
→ better flavor separation

*De Florian et al., P.R. D**95** (17) 094019*

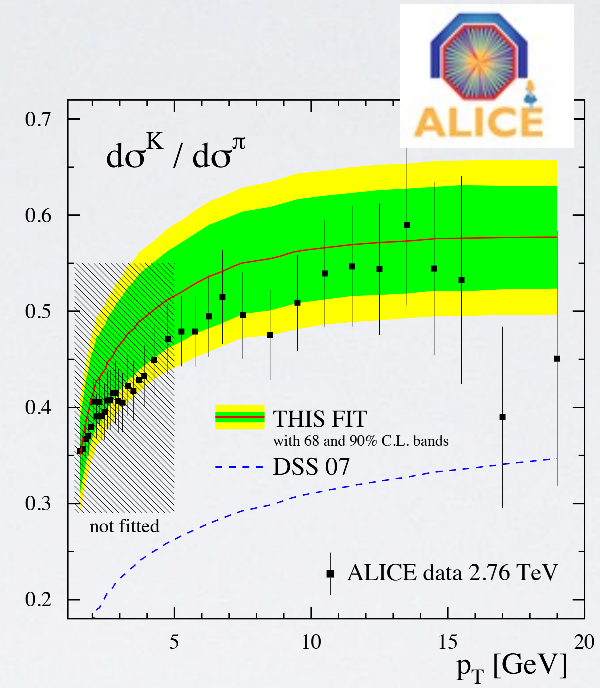
collinear K FF at NLO: DSS 2017

*De Florian, Epele, Hernandez-Pinto, Sassot, Stratmann, P.R. D***95** *(17) 094019*

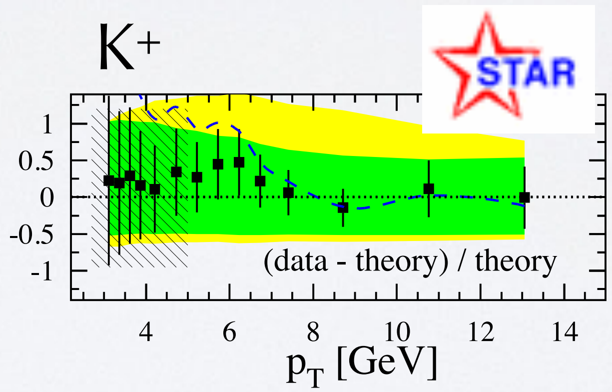
important for s(x) extraction



caveat



- good global fit including p-p data only if $p_T > 5$ GeV

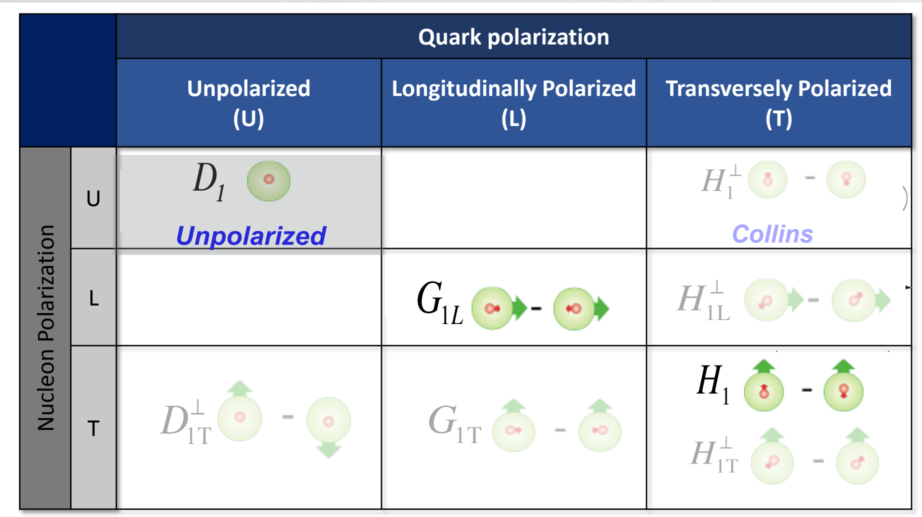


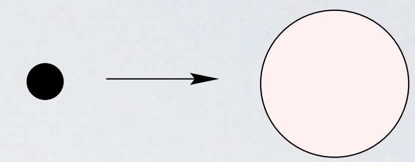
- DSS 2007 within errors → is gluon constrained from p-p data?

- best fit with flavor symmetric unfavored channels; SIDIS data not enough sensitive

- problem with z < 0.2 in BaBar data

collinear FF at NLO: JAMFF



$D_1(z)$  $h = \pi, K$

*Sato, Ethier, Melnitchouk, Hirai, Kumano, Accardi, P.R. D**94** (16) 114004*

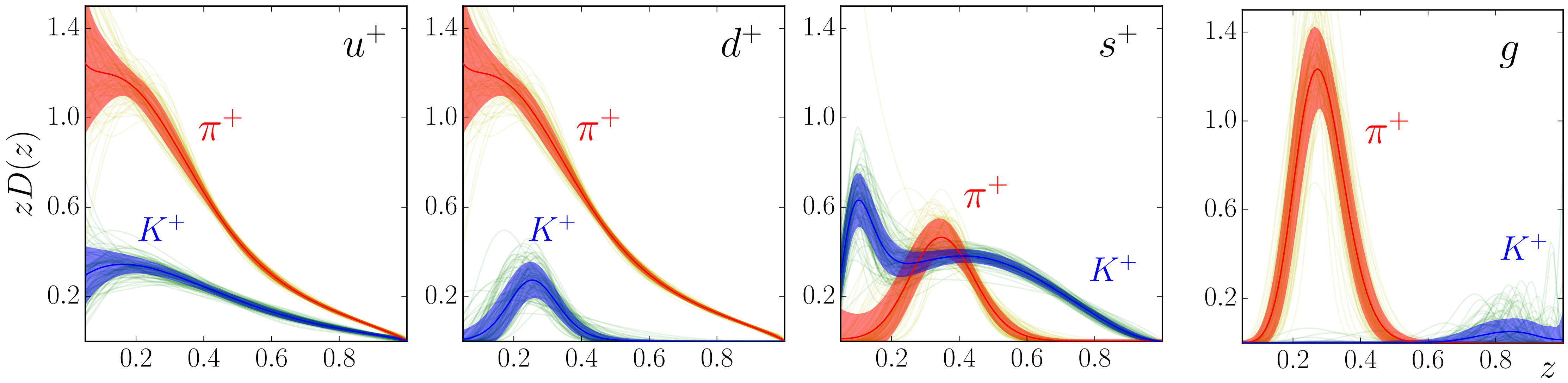
new fit from JAM collaboration: JAMFF (for $q \to h=\pi, K$)

- only e^+e^- data from SLAC + LEP + KEK + DESY
- 459 data for π, 391 for K [$0.05 \lesssim z \lesssim 0.95$]
- 18 parameters for π, 24 for K
- Iterative Monte Carlo methodology ← new method
- **global χ^2/dof ~ 1.31 (π) , 1.01 (K)**

collinear FF at NLO: JAMFF

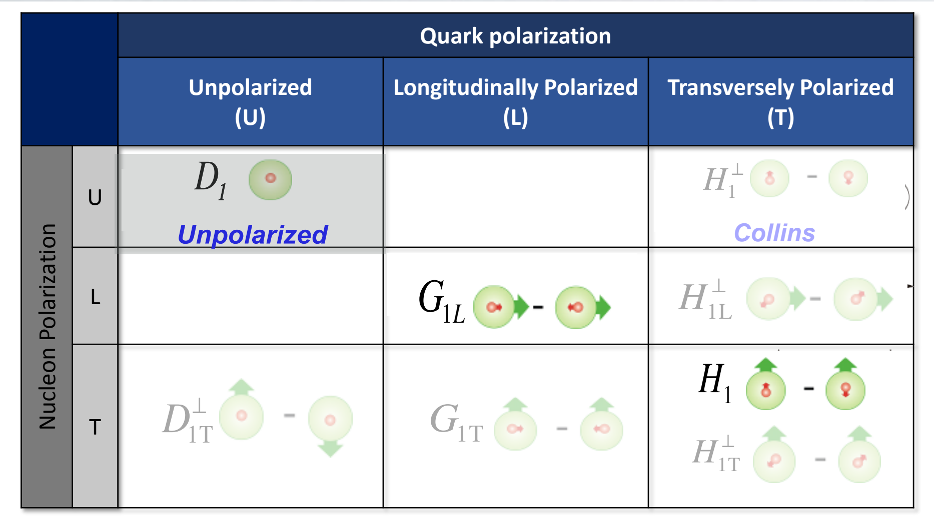
$$q^+ = q + \bar{q}$$

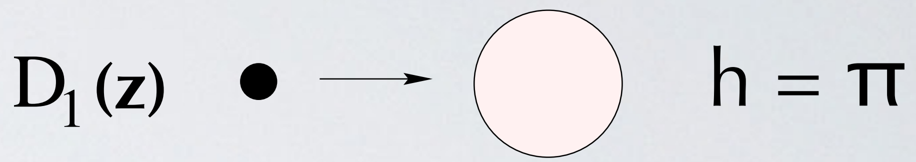
$Q^2 = 1 \text{ GeV}^2$



*Sato, Ethier, Melnitchouk, Hirai, Kumano, Accardi, P.R. D**94** (16) 114004*

collinear π FF at NNLO: ASR15



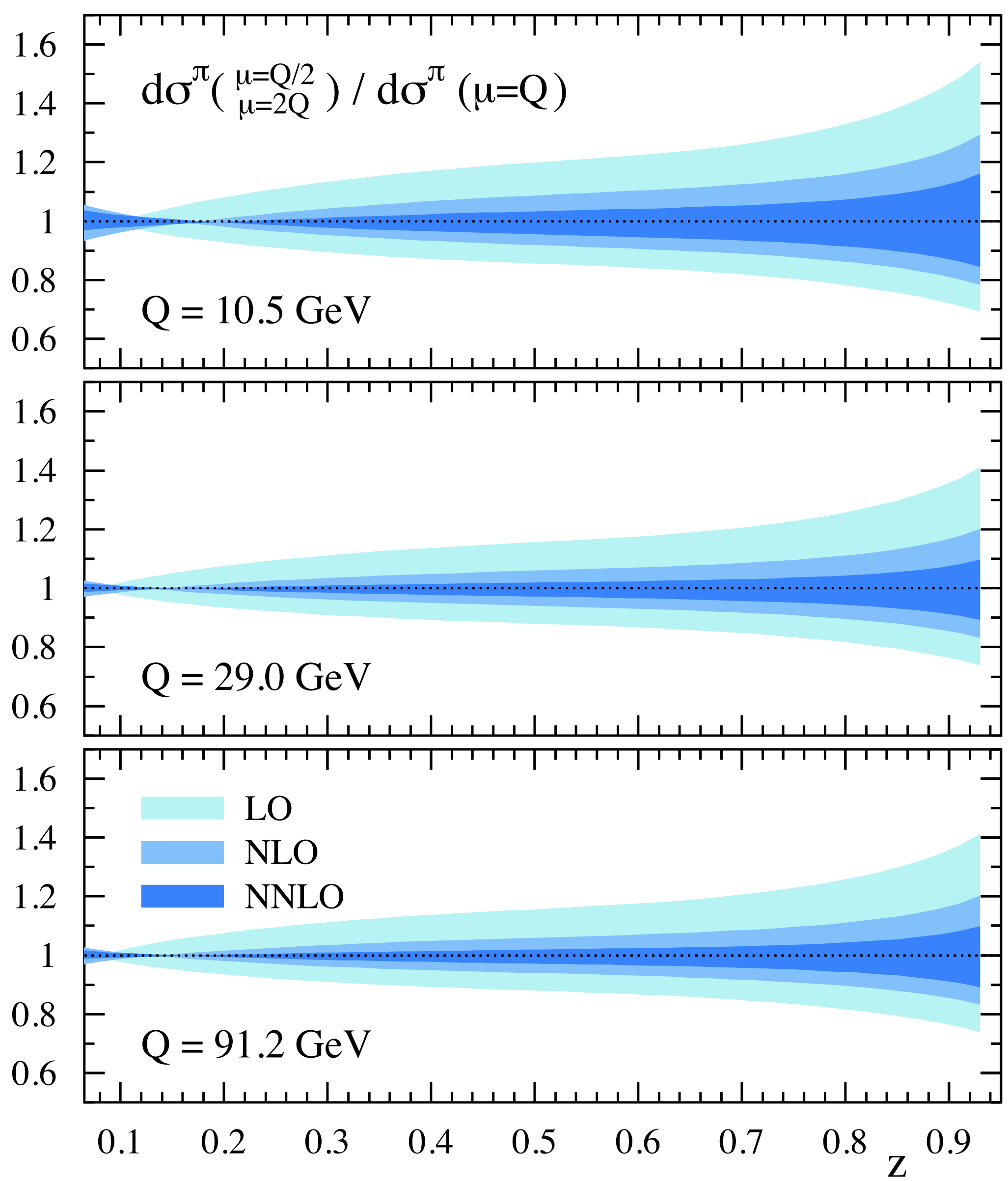


Anderle, Stratmann, Ringer, P.R. D92 (15) 114017

first extraction at NNLO: ASR15 (q→ h=π only)

- only $e^+ e^-$ data from reduced set of SLAC + LEP + KEK + DESY
- 288 data points [$0.075 \lesssim z \lesssim 0.95$]
- 16 parameters
- **global χ^2/dof : LO=0.89**
  NLO=0.70
  NNLO=0.64

collinear π FF at NNLO: ASR15



scale uncertainty

$$\frac{\{\, d\sigma[Q/2]\,,\ d\sigma[Q]\,,\ d\sigma[2Q]\,\}}{d\sigma[Q]}$$

NNLO NLO LO

benefits of NNLO

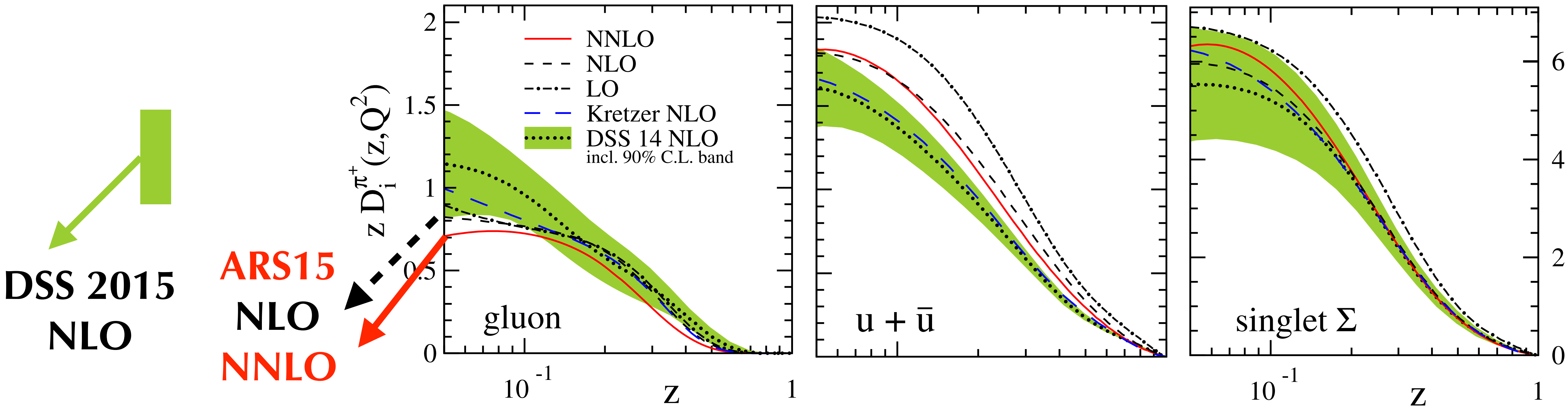
- smaller scale uncertainty
- more flat K factor → 1

Anderle, Ringer, Stratmann, P.R. D92 (15) 114017

collinear π FF at NNLO: ASR15

Anderle, Ringer, Stratmann,
P.R. D92 (15) 114017

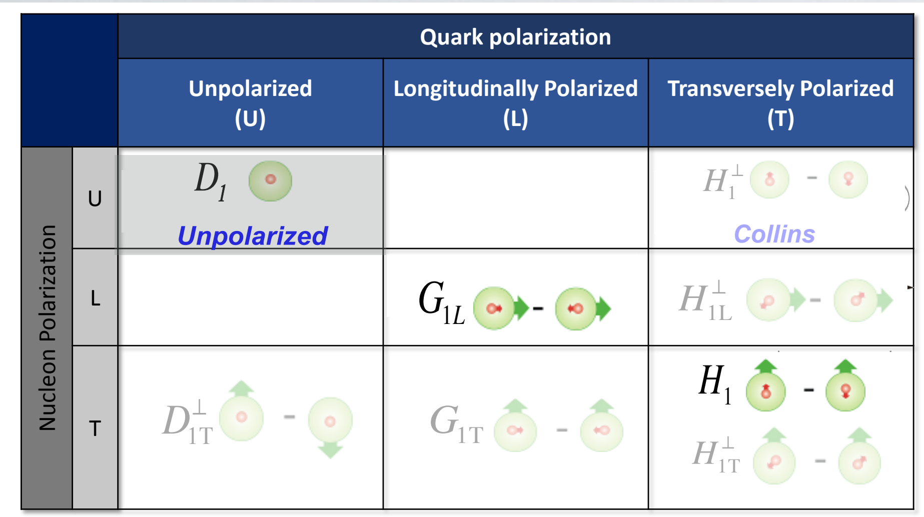
$Q^2 = 10\ \text{GeV}^2$

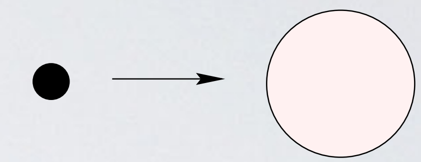


caveat

- smaller data set w.r.t. “standard”
- no statistical error analysis
- NLO for some channels is incompatible with previous DSS 2015

collinear FF at NNLO: NNFF1.0



$D_1(z)$  $h = \pi, K, \overset{(-)}{p}$

*Bertone, Carrazza, Hartland, Nocera, Rojo, E.P.J. C**77** (17) 516*

new fit from NNPDF collaboration: NNFF1.0 (for $q \to h = \pi, K$)

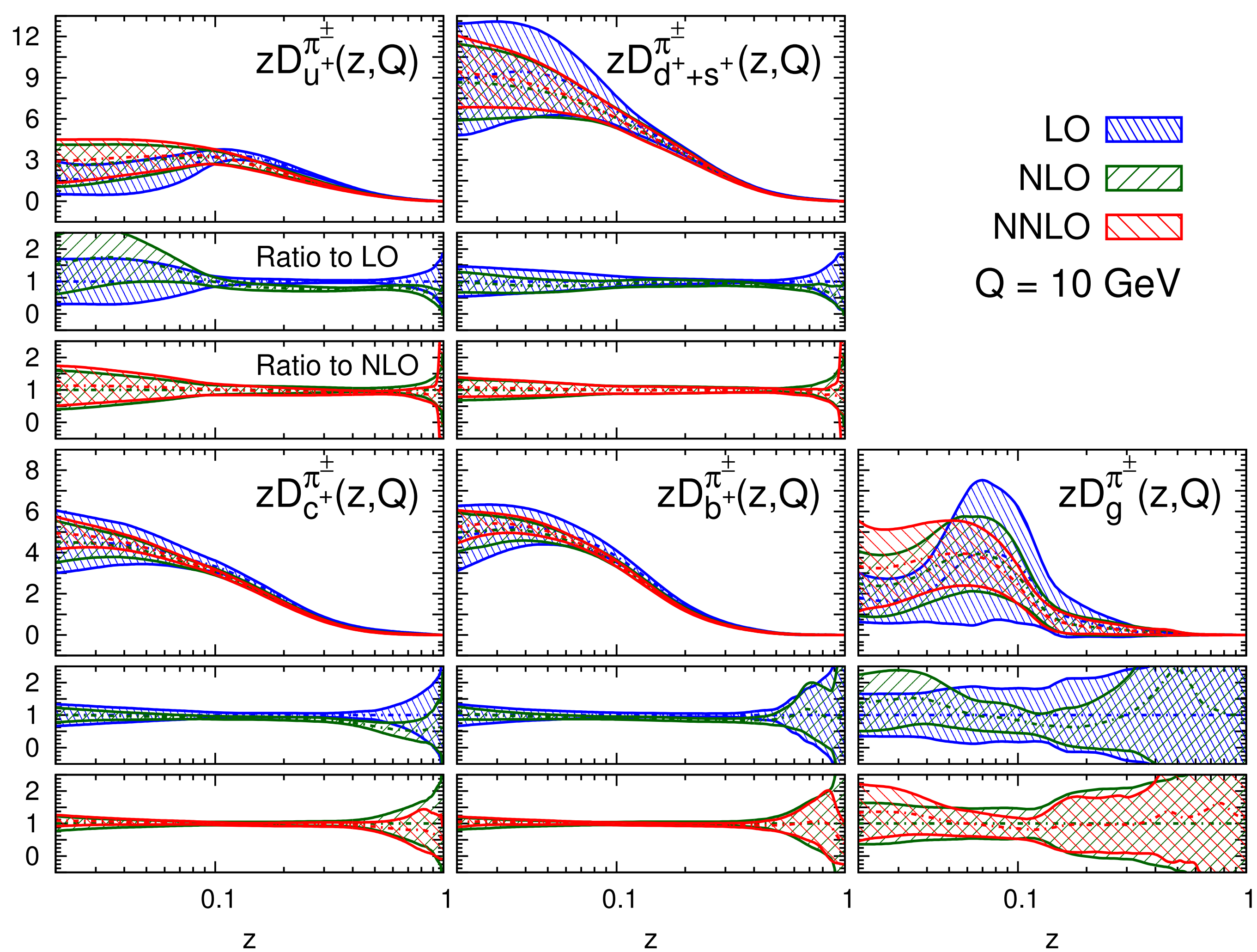
- only e^+e^- data from SLAC + LEP + KEK + DESY
- 1173 data points [$0.02 / 0.075 \lesssim z \lesssim 0.9$]
- same NN method as for NNPDFx.x
- 185 parameters for a 4-layers NN with 2-5-3-1 nodes

more details → talk Bertone

collinear FF at NNLO: NNFF1.0

tension between
BaBar & BELLE (large z)

LO → NLO → NNLO stability



Exp.	$\chi^2/N_{\rm dat}$ $(h=\pi^\pm)$ LO	NLO	NNLO	$\chi^2/N_{\rm dat}$ $(h=K^\pm)$ LO	NLO	NNLO	$\chi^2/N_{\rm dat}$ $(h=p/\bar{p})$ LO	NLO	NNLO
BELLE	0.60	0.11	0.09	0.21	0.32	0.33	0.10	0.31	0.50
BABAR	1.91	1.77	0.78	2.86	1.11	0.95	4.74	3.75	3.25
TASSO12	0.70	0.85	0.87	1.10	1.03	1.02	0.69	0.70	0.72
TASSO14	1.55	1.67	1.70	2.17	2.13	2.07	1.32	1.25	1.22
TASSO22	1.64	1.91	1.91	2.14	2.77	2.62	0.98	0.92	0.93
TPC (incl.)	0.46	0.65	0.85	0.94	1.09	1.01	1.04	1.10	1.08
TPC (*uds* tag)	0.78	0.55	0.49	—	—	—	—	—	—
TPC (*c* tag)	0.55	0.53	0.52	—	—	—	—	—	—
TPC (*b* tag)	1.44	1.43	1.43	—	—	—	—	—	—
TASSO30	—	—	—	—	—	—	0.25	0.19	0.18
TASSO34	1.16	0.98	1.00	0.27	0.44	0.36	0.82	0.81	0.78
TASSO44	2.01	2.24	2.34	—	—	—	—	—	—
TOPAZ	1.04	0.82	0.80	0.61	1.19	0.99	0.79	1.21	1.19
ALEPH	1.68	0.90	0.78	0.47	0.55	0.56	1.36	1.43	1.28
DELPHI (incl.)	1.44	1.79	1.86	0.28	0.33	0.34	0.48	0.49	0.49
DELPHI (*uds* tag)	1.30	1.48	1.54	1.38	1.49	1.32	0.47	0.46	0.45
DELPHI (*b* tag)	1.21	0.99	0.95	0.58	0.49	0.52	0.89	0.89	0.91
OPAL	2.29	1.88	1.84	1.67	1.57	1.66	—	—	—
SLD (incl.)	2.33	1.14	0.83	0.86	0.62	0.57	0.66	0.65	0.64
SLD (*uds* tag)	0.95	0.65	0.52	1.31	1.02	0.93	0.77	0.76	0.78
SLD (*c* tag)	3.33	1.33	1.06	0.92	0.47	0.38	1.22	1.22	1.21
SLD (*b* tag)	0.45	0.38	0.36	0.59	0.67	0.62	1.12	1.29	1.33
Total dataset	**1.44**	**1.02**	**0.87**	**1.02**	**0.78**	**0.73**	**1.31**	**1.23**	**1.17**

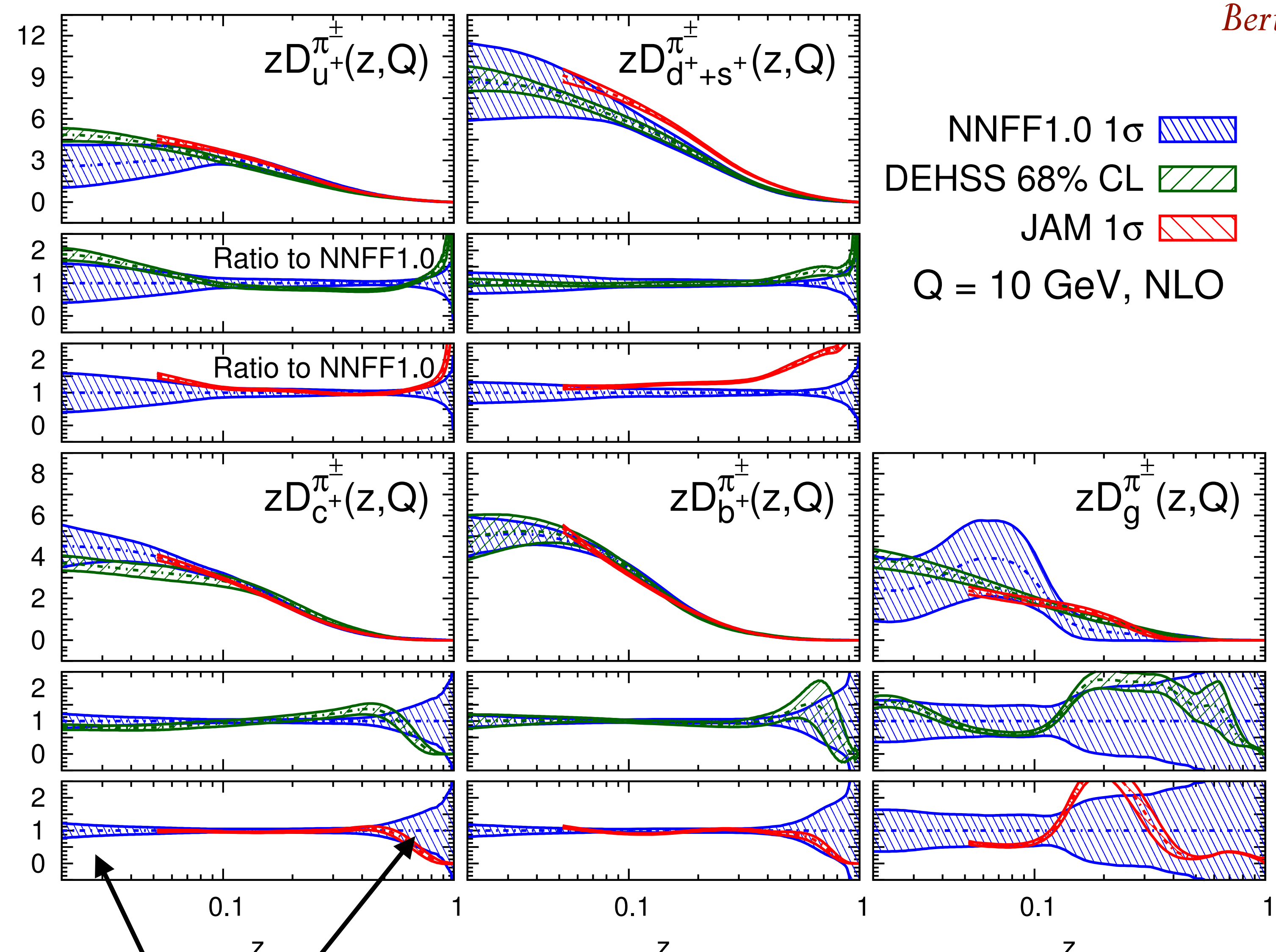
very good overall χ^2

*Bertone, Carrazza, Hartland, Nocera, Rojo, E.P.J. C***77** *(17) 516*

comparison at NLO: NNFF1.0 - JAMFF - DSS

*Bertone, Carrazza, Hartland, Nocera, Rojo, E.P.J. C***77** *(17) 516*

NNPDF



larger NN uncertainty
where less or no data

differences due to
different z cuts
(target mass corrections at low z!)

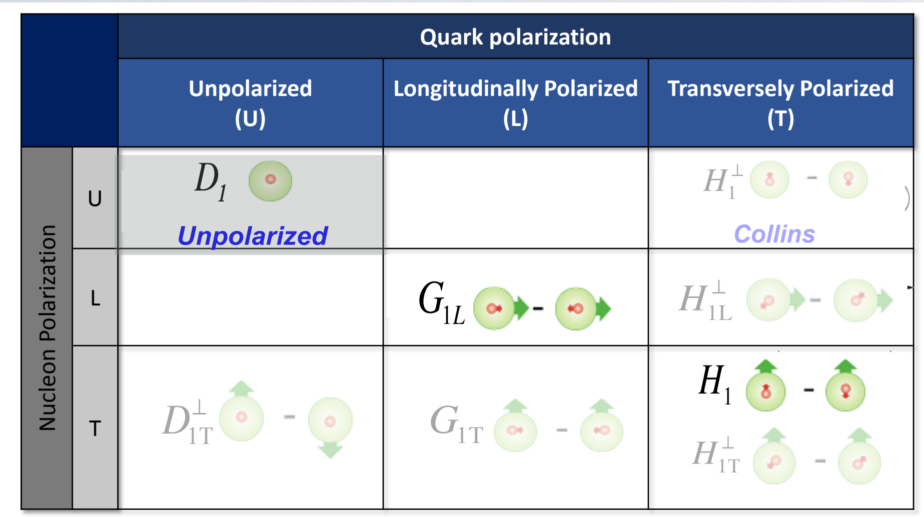
in fact, similar cuts give
similar results
(particularly for gluon)

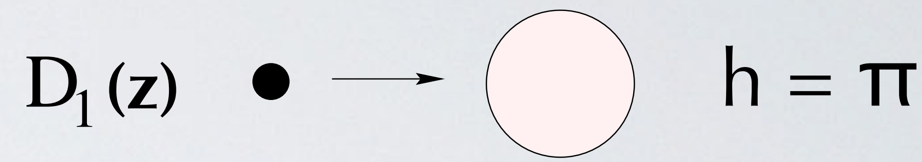
→ talk Bertone

expect larger uncertainty
on D^g (NLO only) than D^q

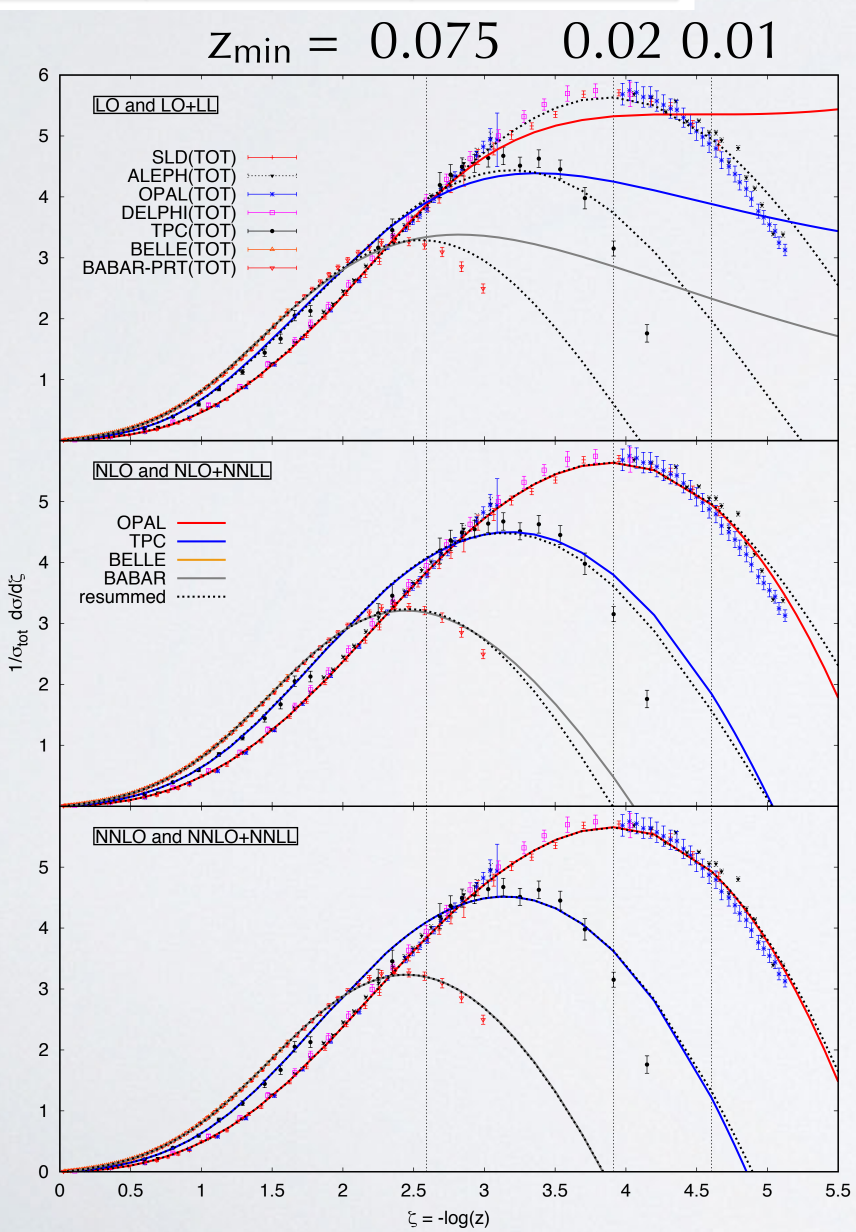
- visible in NNF1.0
- not visible in DSS15 (bound from p-p data?)
- not visible in JAMFF (rigid functional form?)

collinear π FF at NNLO+NNLL: AKSR17





first extraction with resummation at NNLO + NNLL : AKSR17 (q→ h=π and small z only)

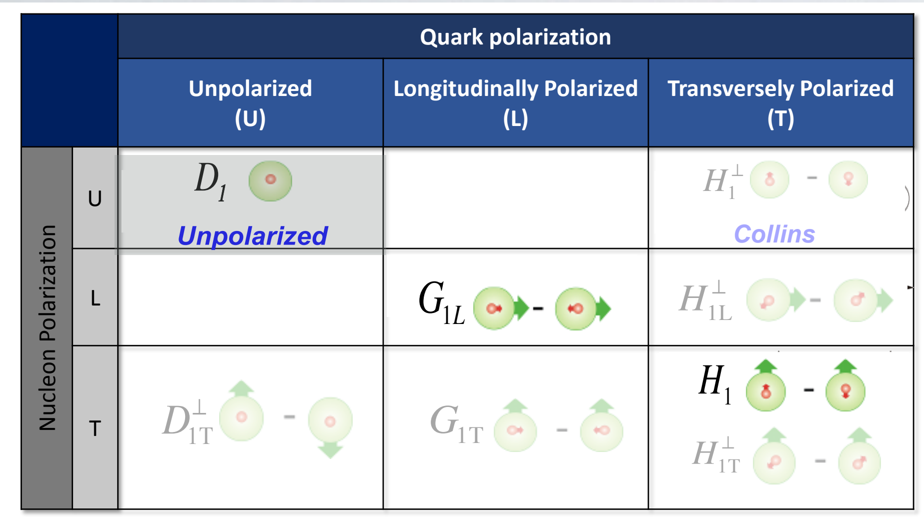


- only $e^+ e^-$ data from SLAC + LEP + KEK + DESY
- 436 data points, 19 parameters

accuracy	χ^2	norm shift	χ^2/dof
LO	1260.78	29.02	2.89
NLO	354.10	10.93	0.81
NNLO	330.08	8.87	0.76
LO+LL	405.54	9.83	0.93
NLO+NNLL	352.28	11.27	0.81
NNLO+NNLL	329.96	8.77	0.76

Anderle, Kaufmann, Stratmann, Ringer, P.R. D95 (17) 054003

collinear D* FF at NLO

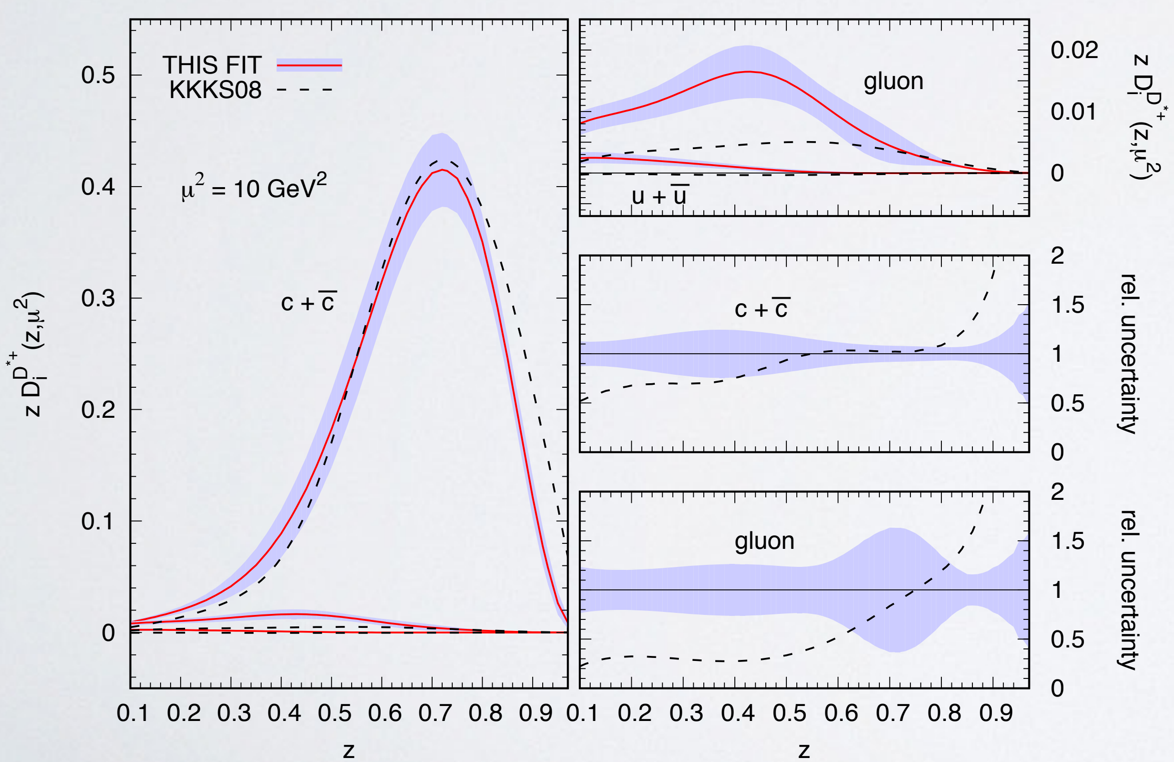


talk Scimemi

$D_1(z)$ • ⟶ ○ $h = D^*$

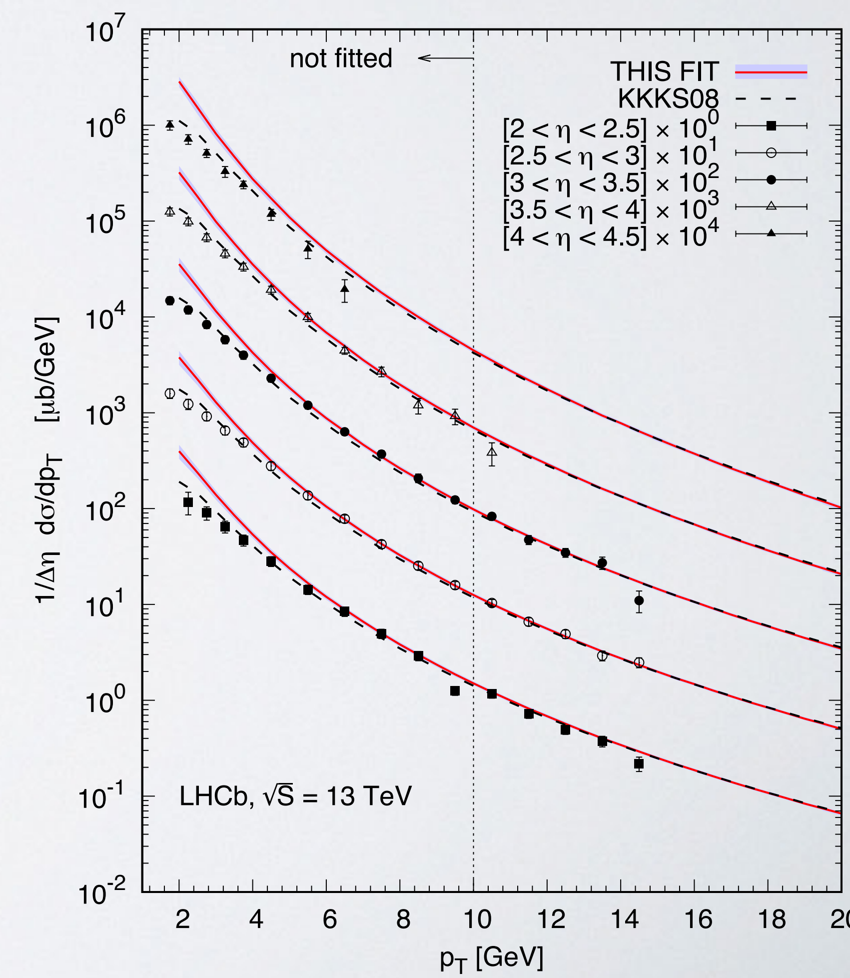
NLO analysis (q→ h=D* only)

- LEP e+e− data
- ATLAS, ALICE, CDF, LHCb p-p→D* X
- ATLAS p-p→(jet D*) X
- 96 data points, 9 parameters
- **global χ^2/dof ~ 1.18**



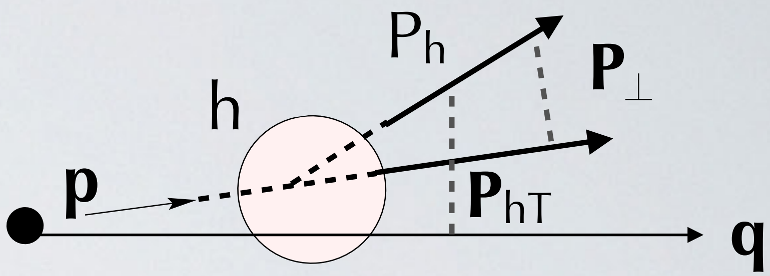
z dependence

p_T



*Anderle, Kaufmann, Stratmann, Ringer, Vitev, P.R. D**96** (17) 034028*

unpolarized TMD FF

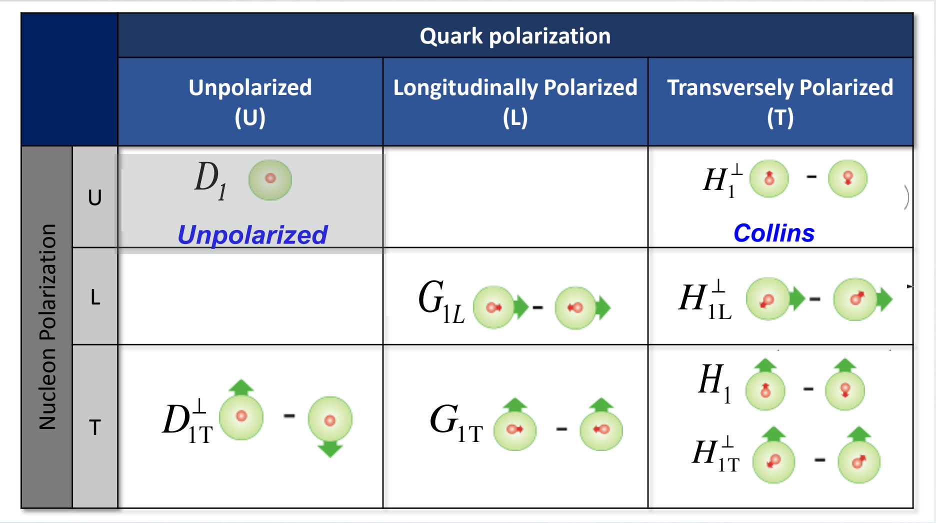


$S_h = 0$

Hadron Polarization		Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
	U	D_1 *Unpolarized*		$H_1^\perp$ - **Collins**
	L		G_{1L} -	$H_{1L}^\perp$ -
	T	$D_{1T}^\perp$ -	G_{1T} -	H_1 - $H_{1T}^\perp$ -

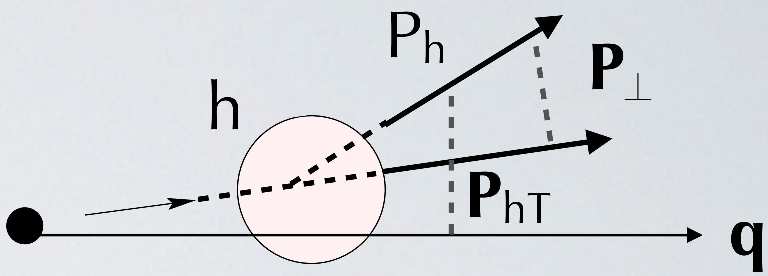
What do we know about the $\mathbf{P}_{hT}$ dependence of D_1 ?

unpolarized TMD FF



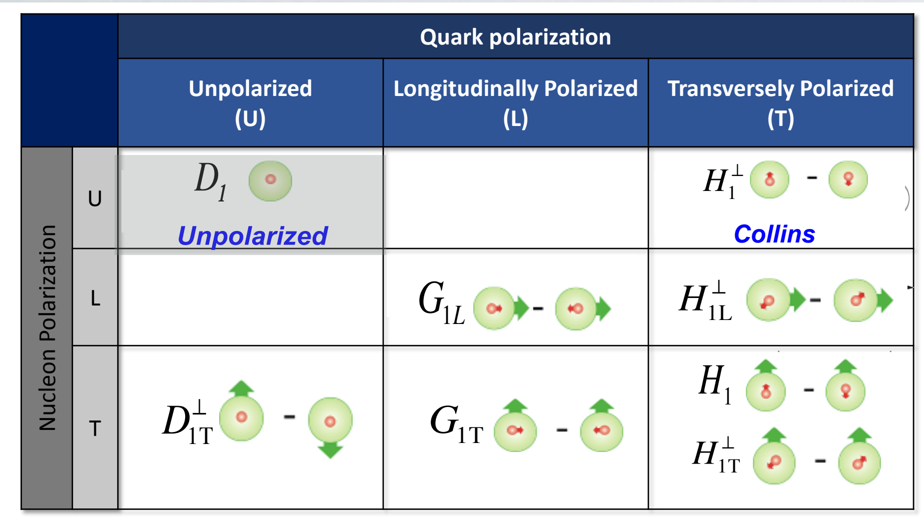
Nucleon Polarization		Quark polarization: Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
	U	D_1 Unpolarized		$H_1^\perp$ Collins
	L		G_{1L}	$H_{1L}^\perp$
	T	$D_{1T}^\perp$	G_{1T}	H_1, $H_{1T}^\perp$

D_1 (z, $\mathbf{P}_{hT}$)



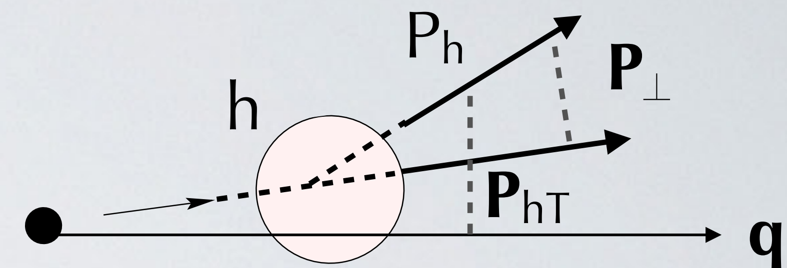
1. Does the $\mathbf{P}_{hT}$ dependence change with **flavor ?**
2. Does the $\mathbf{P}_{hT}$ dependence change with **z ?**
3. Does the $\mathbf{P}_{hT}$ dependence change with **energy $\sqrt{s}$?**
4. Does the $\mathbf{P}_{hT}$ dependence change with **scale Q^2 ?**

unpolarized TMD FF



Nucleon Polarization	Quark polarization: Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	D_1 Unpolarized		$H_1^{\perp}$ Collins
L		G_{1L}	$H_{1L}^{\perp}$
T	$D_{1T}^{\perp}$	G_{1T}	H_1, $H_{1T}^{\perp}$

$D_1\ (z,\ \mathbf{P}_{hT})$



data

fits

SIDIS

hermes

COMPASS

multiplicities

PV2013, TO2014 (EIKV14), PV2016

e^+e^-

TASSO (DESY)
MARKII (SLAC)

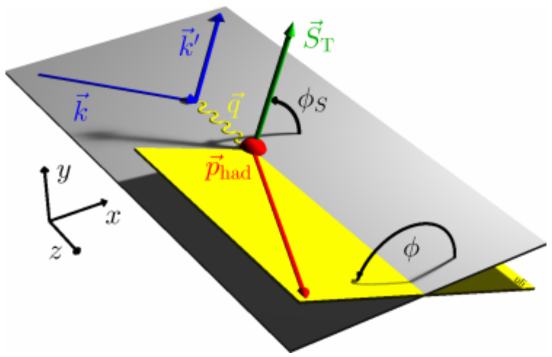
cross section

TO2017

PLUTO (DESY)

$\langle P_{hT}^2 \rangle$

D_1 from unintegrated SIDIS multiplicities

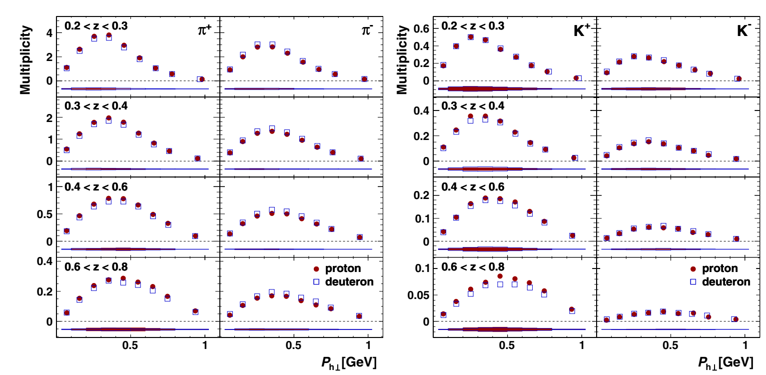


$$M_N^h = \frac{d\sigma_N^h / dx\, dz\, d\boldsymbol{P}_{hT}^2\, dQ^2}{d\sigma_{\rm DIS}/dx\, dQ^2} \approx \frac{\sum_q e_q^2\, [f_1^q \otimes D_1^q]\,(x,z,\boldsymbol{P}_{hT}^2; Q^2)}{\sum_q e_q^2\, f_1^q(x;Q^2)}$$

$$\boldsymbol{P}_{hT}^2 / z \ll Q^2$$

hermes

- target: proton, deuteron
- final state: π^+, π^-, K^+, K^-
- 2688 points



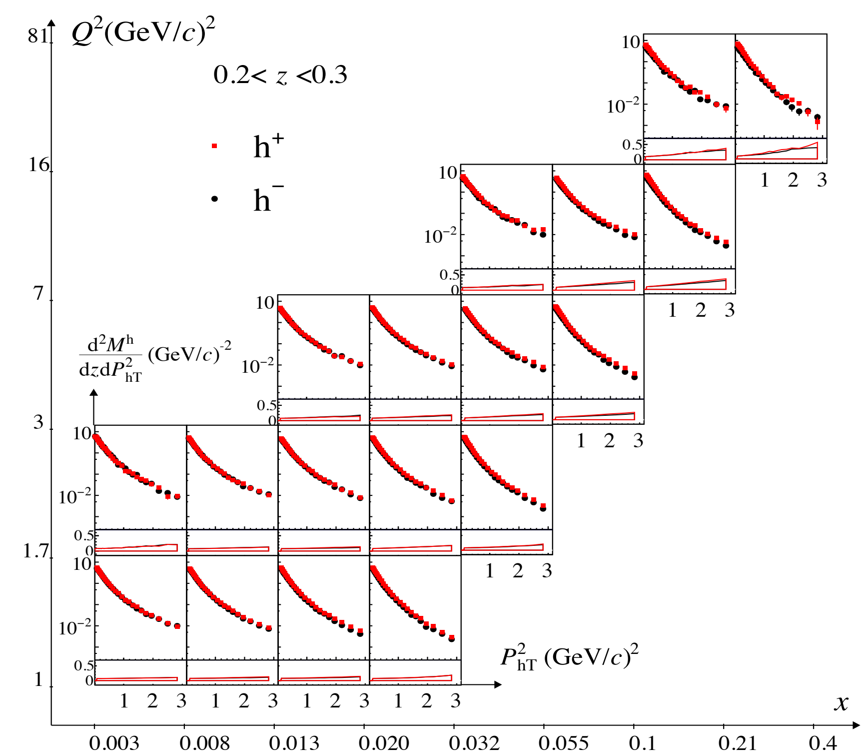
Airapetian et al.,
*P.R. D**87** (13) 074029*

COMPASS

about 5000 data points

- target: deuteron
- final state:
  - h^+, h^- (run 2004)
  - π^+,π^-,K^+,K^- (run 2006)

Aghasyan et al.,
*P.R. D**97** (18) 032006*



talk Bressan

D_1 from unintegrated SIDIS multiplicities

available fits

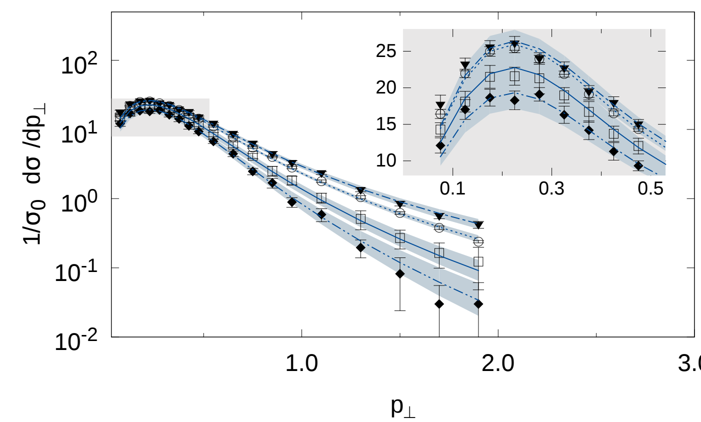
	Framework	Hermes	Compass	# points
Pavia 2013 *Bacchetta et al.,* *JHEP* ***1311*** *(13) 194*	Gaussian $\langle \mathbf{p}_T^2 \rangle_q (z)$ 7 parameters no evolution	✔	✘	1538
Torino 2014 *Anselmino et al.,* *JHEP* ***1404*** *(14) 005*	Gaussian $\langle \mathbf{p}_T^2 \rangle$ (1 parameter) only collinear DGLAP evolution $N_y = A + By$ $(y = Q^2/xs)$ **(C)**	✔ separately	✔ separately	576 (H) 6284 **(C)**
	↓ Framework of TMD evolution ↓			
EIKV 2014 *Echevarria et al.,* *P.R.D****89*** *(14) 074013*	TMD framework, NLL level not a real fit	1 bin (x, Q^2)		(?)
Pavia 2016 **Bacchetta et al.,** **JHEP *1706* (17) 081**	TMD framework, NLL level **first global fit** **(includes DY and Z^0)**	✔	✔	8156

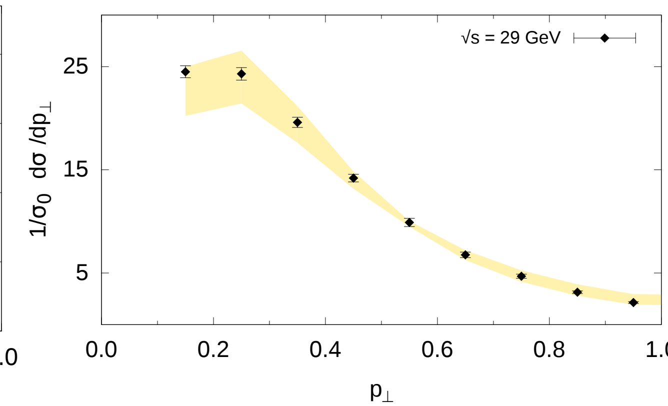
→ talk Signori

D_1 from old e^+e^- data

available fits	Framework	# points	TASSO	MARKII PLUTO
	↓ Framework of TMD evolution ↓			
Torino 2017 *Boglione et al., P.L.* ***B772*** *(17) 78*	LO + LL analysis 1) Gaussian with $\langle \mathbf{p}_T^2 \rangle = a + b\, z^2 \log(Q/Q_0)$ 2) Power law with $\alpha = \alpha_0 + \alpha_1 \log(Q/Q_0)$ peak & normalization fitted	76	✔	✘

- fit of TASSO,
  cross-check on MARKII (+ PLUTO)
- hints of p_T-broadening with Q
- power law good, Gaussian bad





caveat

- z integrated, $\langle z \rangle \lesssim 0.1$ $p_T/\langle z \rangle \sim Q$ [14-44 GeV] TMD factor. broken?
- need to extend to $p_T \lesssim 3$ GeV to reproduce $\langle p_T^2 \rangle$
- equivalent fit with Hp ≠ TMD factorization

What do we know about $D_1 (z, P_{hT})$?

1. does $\mathbf{P}_{hT}$ dependence change with flavor ?

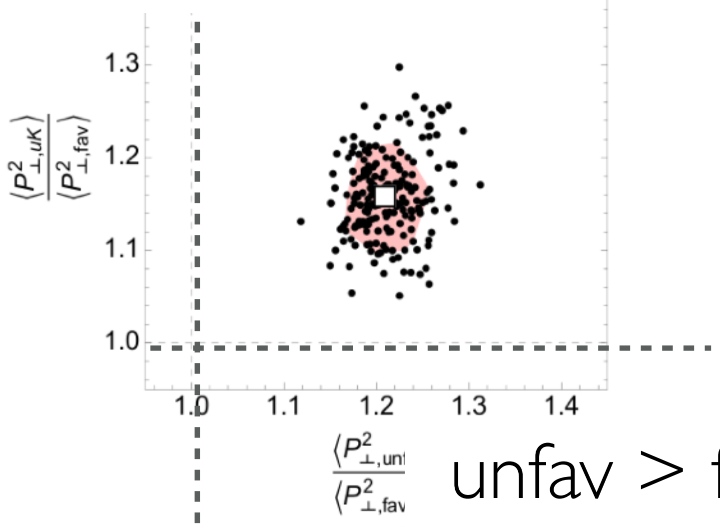
What do we know about $D_1(z, P_{hT})$?

1. does P_{hT} dependence change with flavor ?

Pavia 2013

(Hermes)

K fav > π fav



unfav > fav

χ^2/dof = **1.63**

Torino 2014

(Hermes)

flavor indep. → χ^2/dof = **1.69**

unfav > fav → χ^2/dof = **1.60**

Pavia 2016

(global)

flavor indep.

global χ^2/dof ~ **1.55**

(flavor dep. in progress)

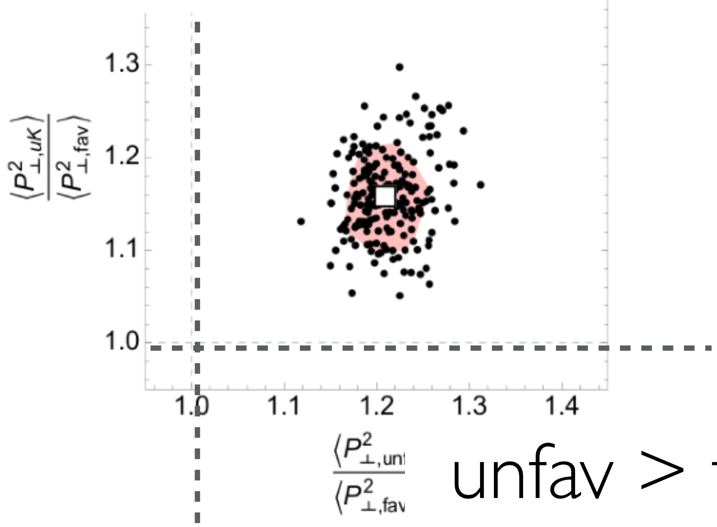
What do we know about $D_1(z, P_{hT})$?

I. does P_{hT} dependence change with flavor ?

Pavia 2013

(Hermes)

K fav > π fav



unfav > fav

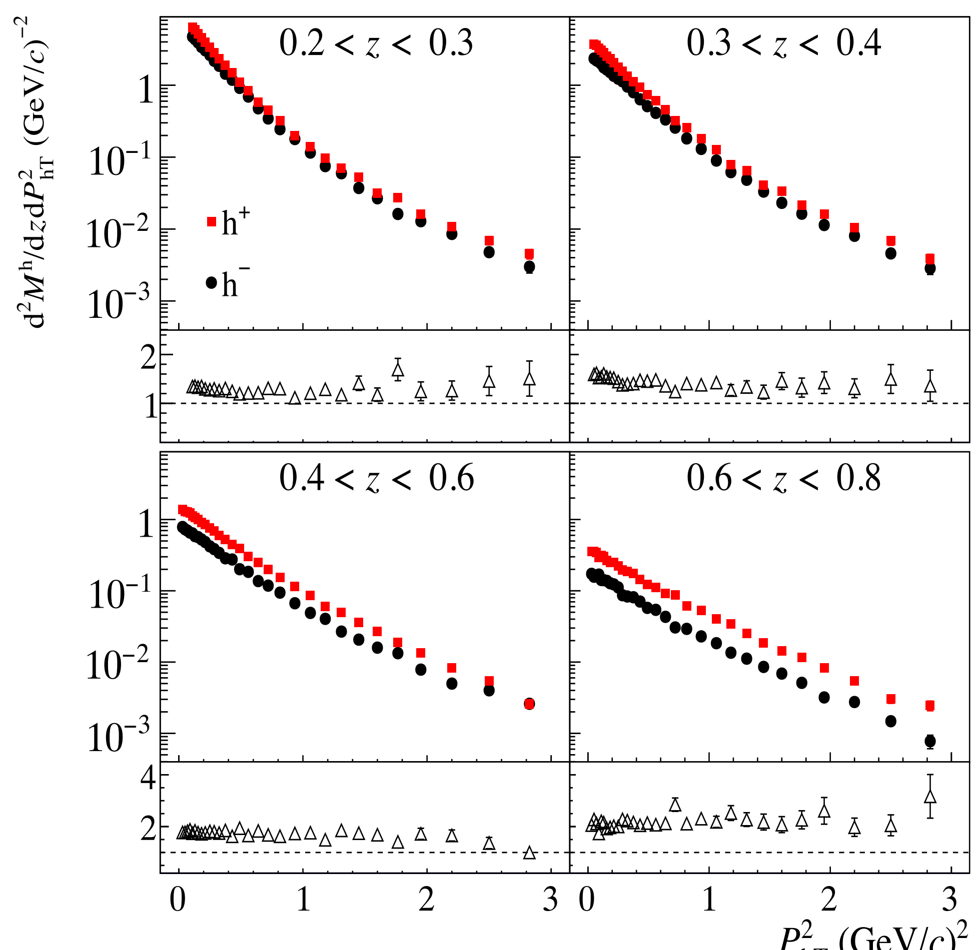
χ^2/dof = **1.63**

Torino 2014

(Hermes)

flavor indep. → χ^2/dof = **1.69**

unfav > fav → χ^2/dof = **1.60**



Aghasyan et al.,
*P.R. D**97** (18) 032006*

Pavia 2016

(global)

flavor indep.

global χ^2/dof~ **1.55**

(flavor dep. in progress)

Answer :
visible at large z

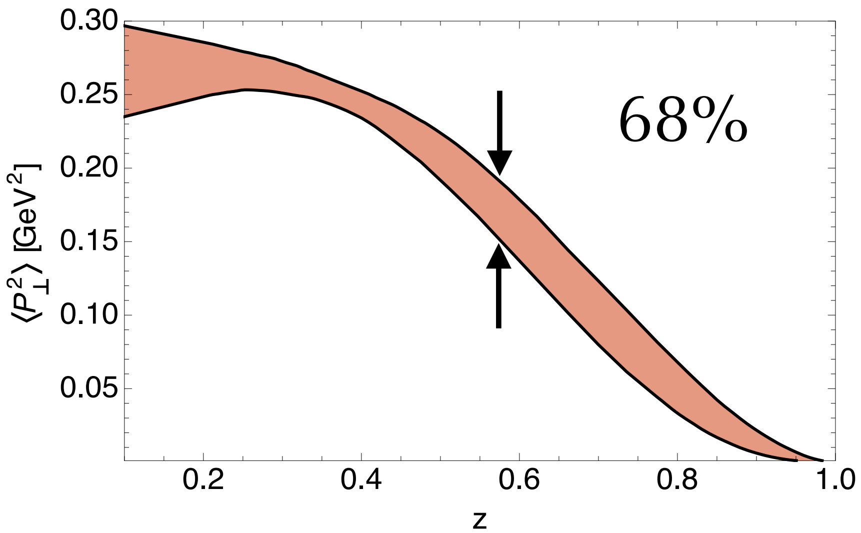
What do we know about D_1 (z, P_{hT}) ?

2. does $\mathbf{P}_{hT}$ dependence change with z ?

What do we know about $D_1(z, P_{hT})$?

2. does P_{hT} dependence change with z ?

Bacchetta et al., JHEP ***1706*** *(17) 081*



Pavia 2016

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

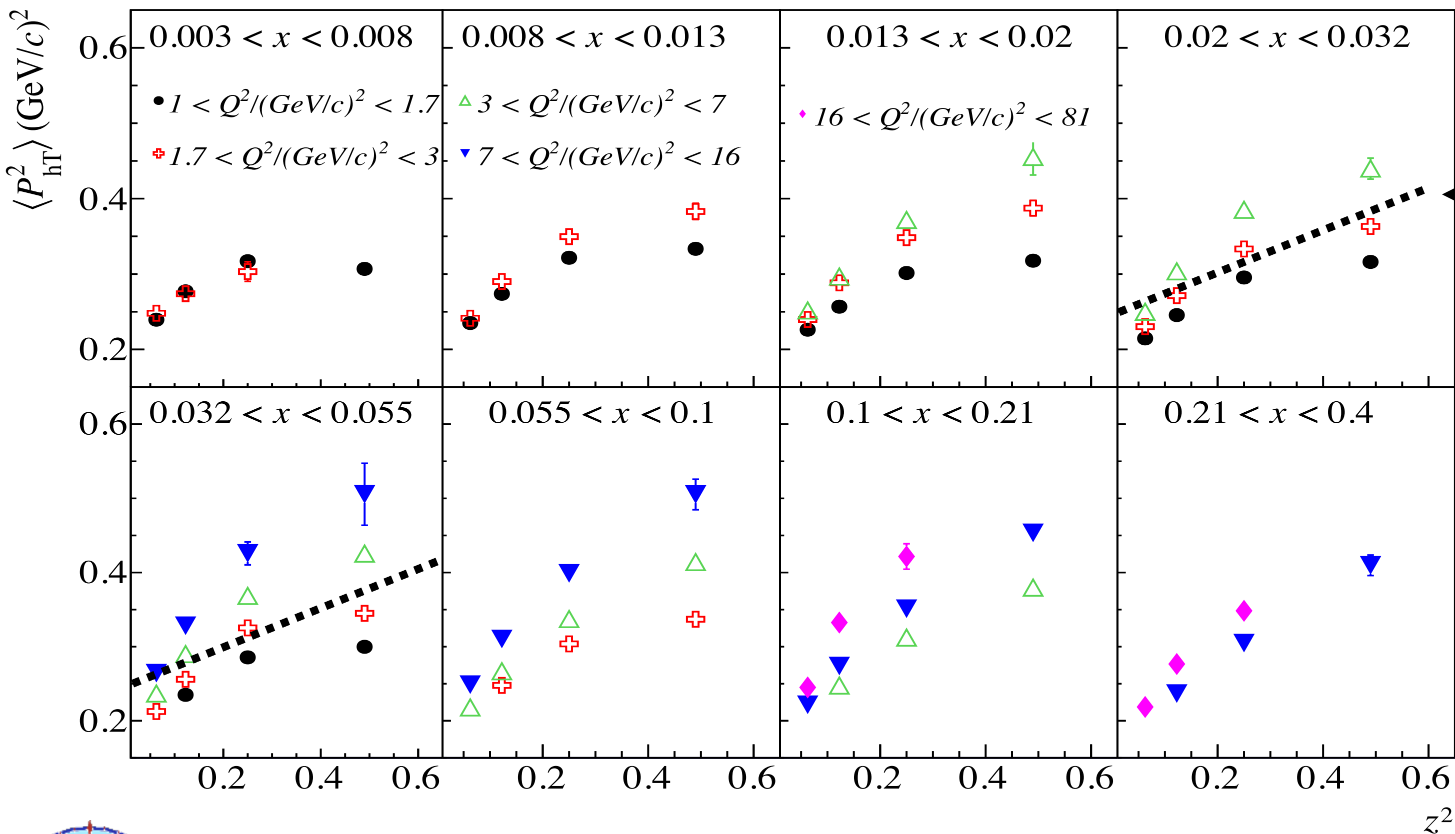
$\beta = 2.68 \pm 0.08$

$\delta = 3.36 \pm 0.12$ $\quad \hat{z} = 0.5$

$\gamma = 0.04 \pm 0.004$

What do we know about $D_1(z, P_{hT})$?

2. does P_{hT} dependence change with z ?



COMPASS

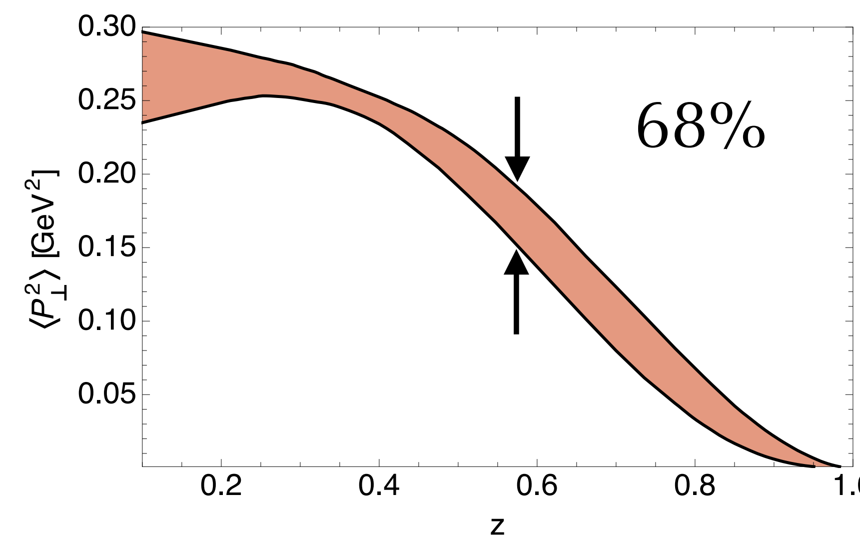
*Aghasyan et al., P.R. D**97** (18) 032006*

detected hadron | fragm. parton | initial parton

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

Gaussian 0.25 0.28

*Bacchetta et al., JHEP **1706** (17) 081*



Pavia 2016

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

$\beta = 2.68 \pm 0.08$

$\delta = 3.36 \pm 0.12$ $\hat{z} = 0.5$

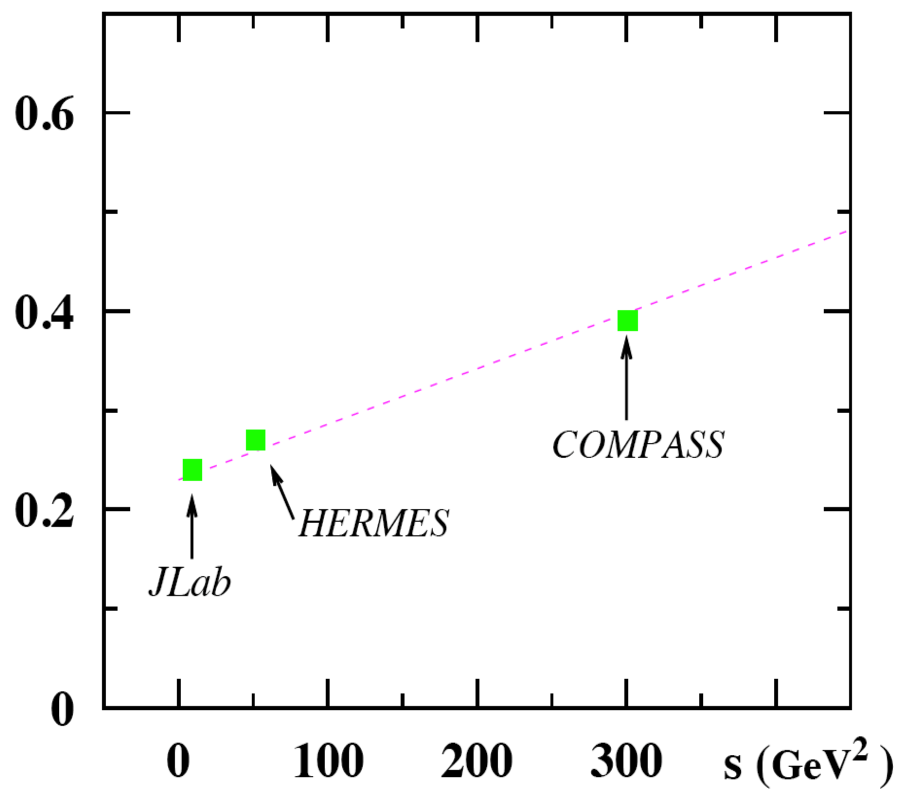
$\gamma = 0.04 \pm 0.004$

Answer:
nonlinear z^2 dependence at large z (small x, Q^2)

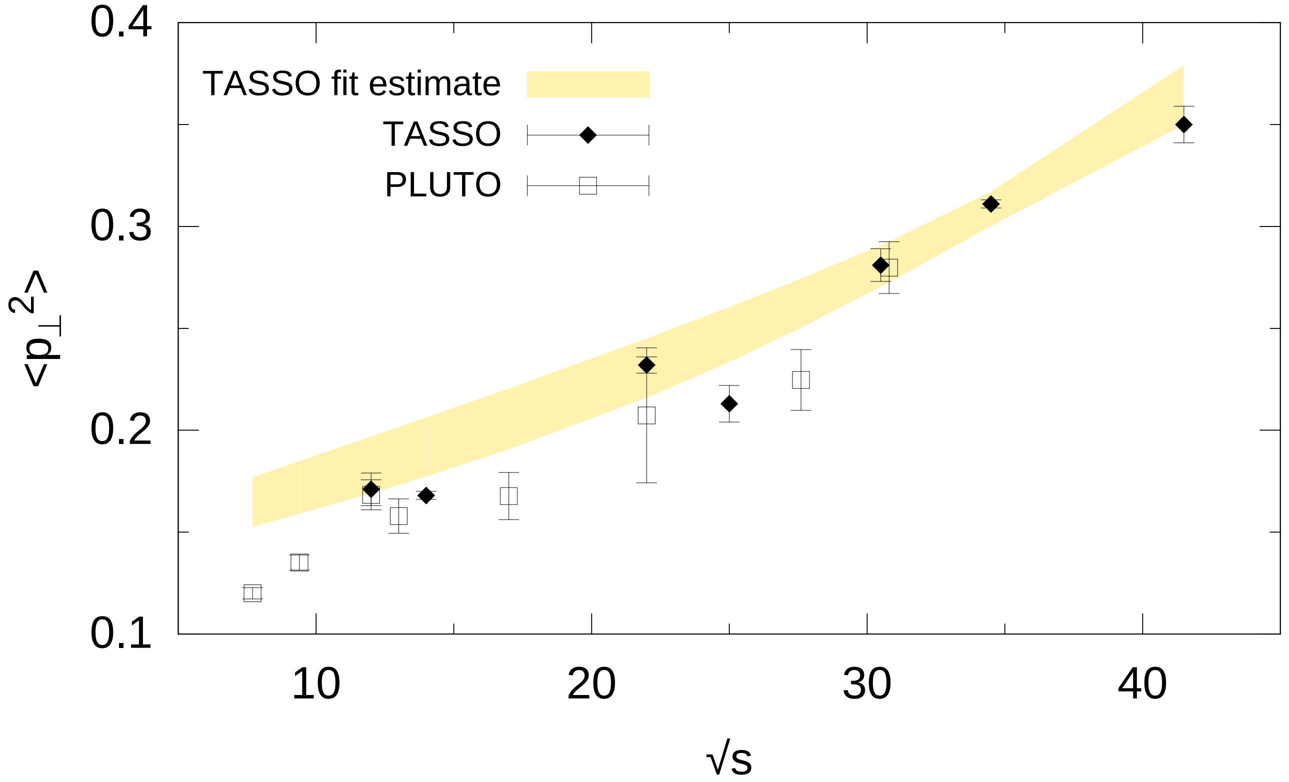
What do we know about $D_1(z, P_{hT})$?

3. does P_{hT} dependence change with energy $\sqrt{s}$?

$\langle p_T^2 \rangle$ of Gaussian



*Schweitzer, Teckentrup, Metz, P.R. D**81** (10) 094019*



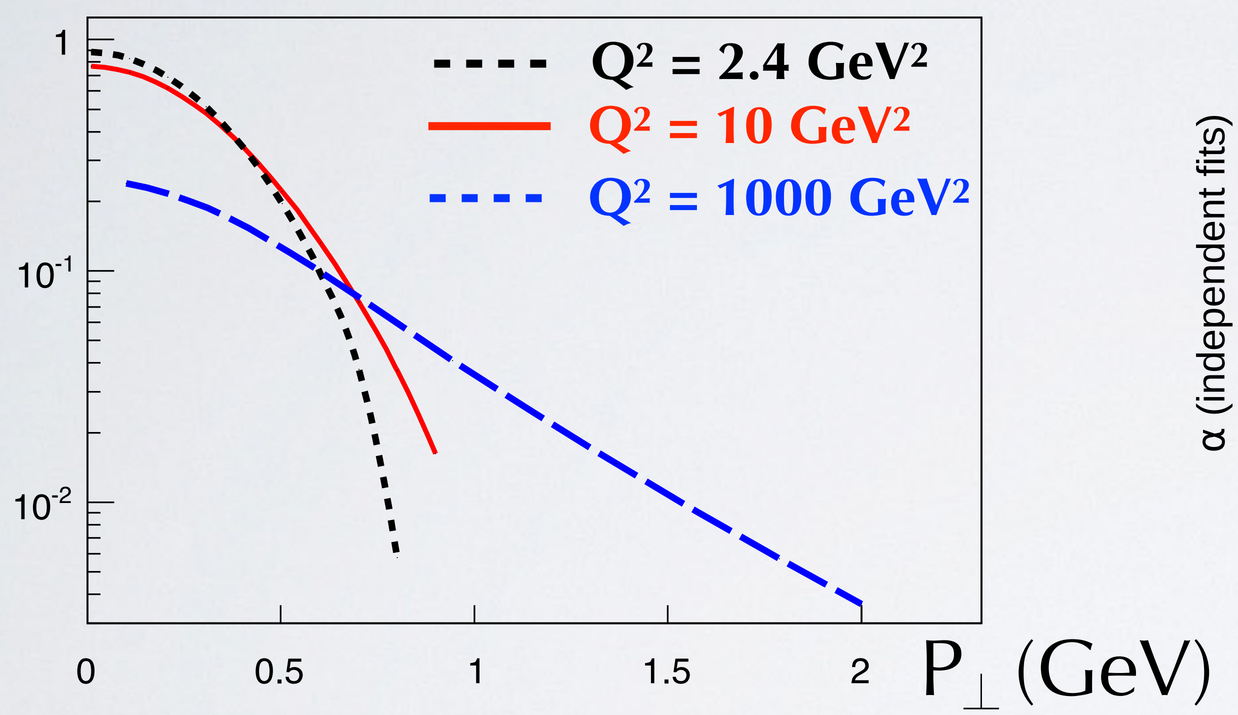
*Boglione, Gonzalez, Taghavi, P.L. **B772** (17) 78*

**Answer: it is likely,
but need better e^+e^- data**

What do we know about $D_1(z, P_{hT})$?

4. does P_{hT} dependence change with scale Q^2 ?

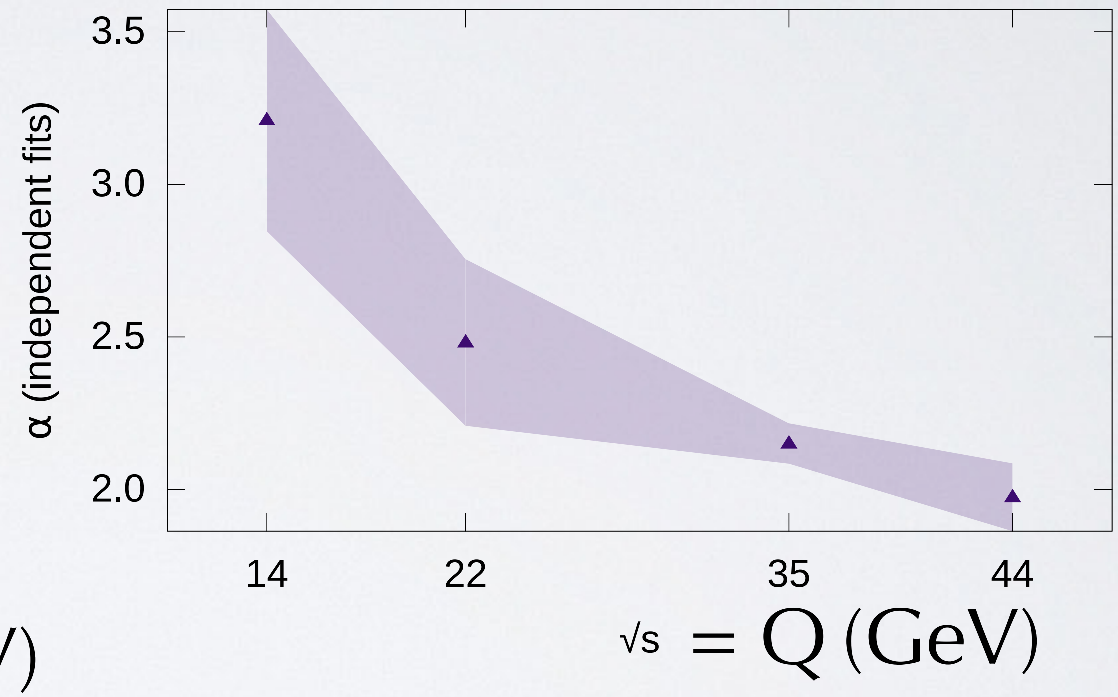
$D_1^{u\to\pi+}$



*Kang, Prokudin, Sun, Yuan, P.R. D**93** (16) 014009*

$$\alpha = \alpha_0 + \alpha_1 \log \frac{Q}{Q_0}$$

$$\text{power law} \sim \frac{1}{(p_T^2 + p_{T0}^2)^\alpha}$$



*Boglione, Gonzalez, Taghavi, P.L. **B772** (17) 78*

strong dependence predicted

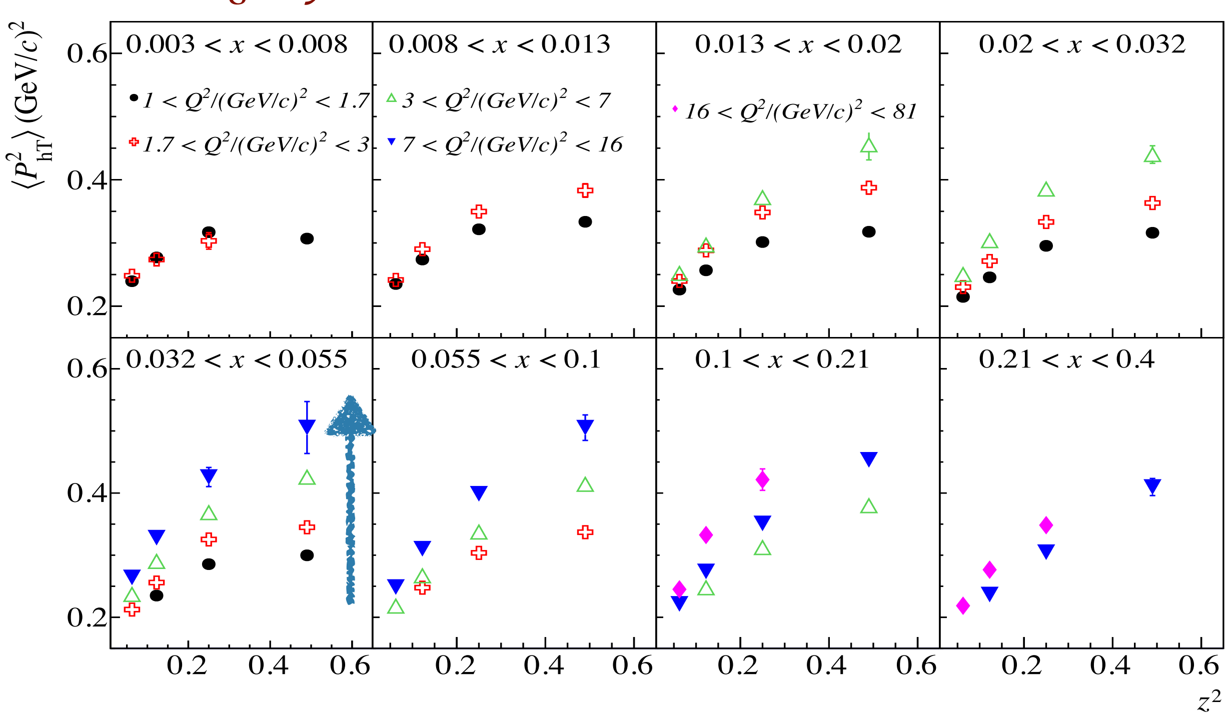
log-like behavior observed (so far..)

What do we know about $D_1(z, P_{hT})$?

4. does P_{hT} dependence change with scale Q^2 ?

COMPASS D(e,e′ h+)

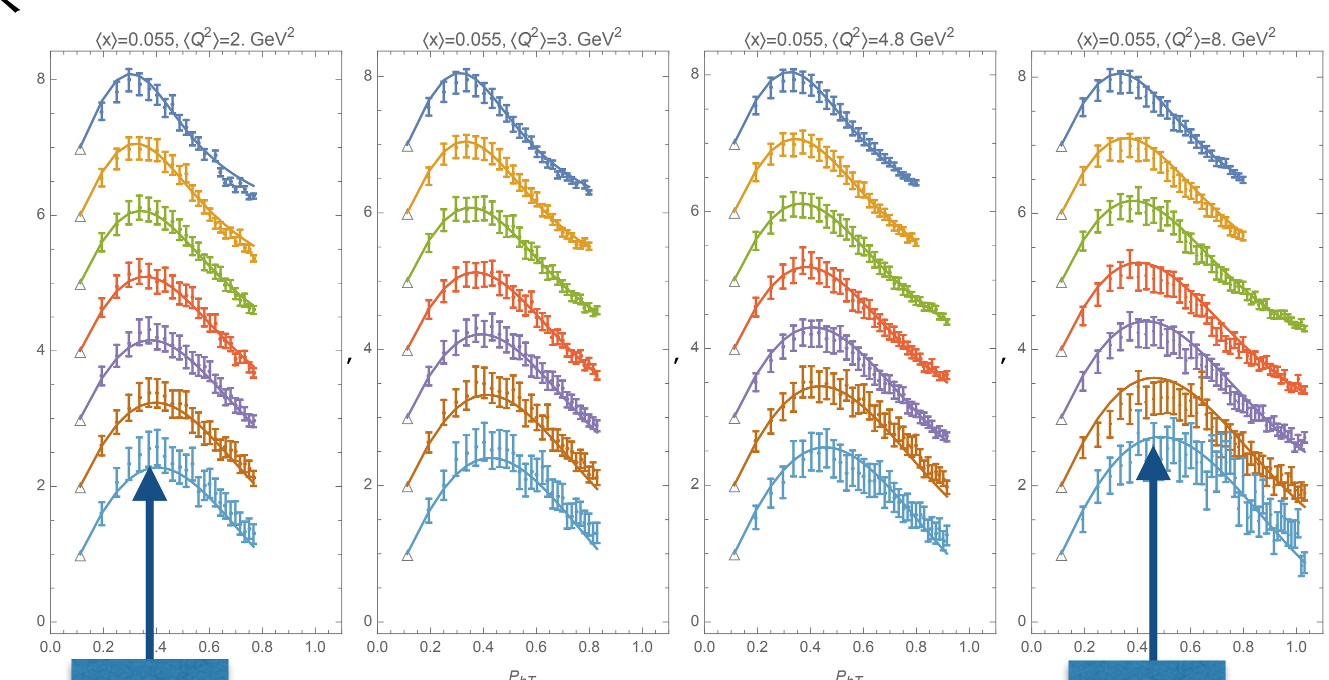
Aghasyan et al., P.R. D ***97*** *(18) 032006*



Bacchetta et al.,
JHEP ***1706*** *(17) 081*

Pavia 2016

$<Q^2> = 2 \rightarrow \ \dots \ \rightarrow 8$ GeV^2



0.35

0.45

$<x> = 0.055$

χ^2/dof =1.49

P_{hT} (GeV)

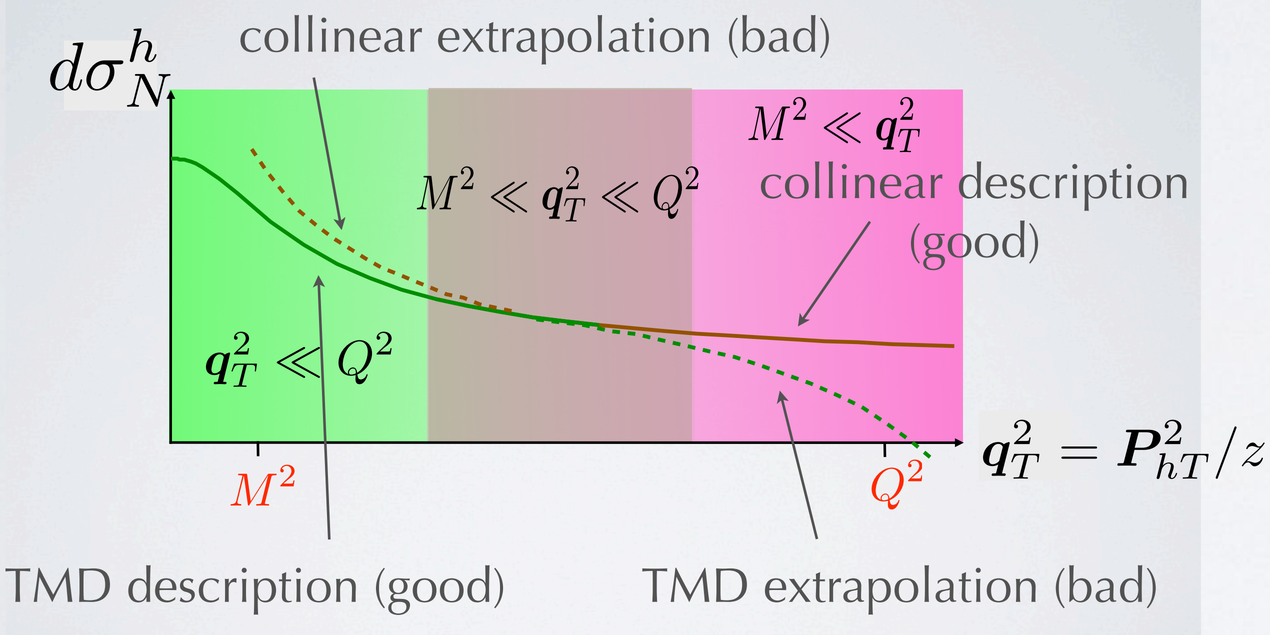
at SIDIS scales, very moderately

The matching problem in SIDIS

SIDIS unpolarized cross section

$$\frac{d\sigma_N^h}{dx\,dz\,d\boldsymbol{P}_{hT}^2\,dQ^2} \approx \sum_q e_q^2\,[f_1^q \otimes D_1^q]\,\mathcal{H}_q(Q^2) + Y(Q^2,\boldsymbol{q}_T^2) + \mathcal{O}(M^2/Q^2)$$

$$\boldsymbol{q}_T^2 = \boldsymbol{P}_{hT}^2/z$$



need to match collinear (fixed-order) description such that

$$\int_0^\infty d\boldsymbol{P}_{hT}^2\,\frac{d\sigma_N^h}{dx\,dz\,d\boldsymbol{P}_{hT}^2\,dQ^2} = \frac{d\sigma_N^h}{dx\,dz\,dQ^2}$$

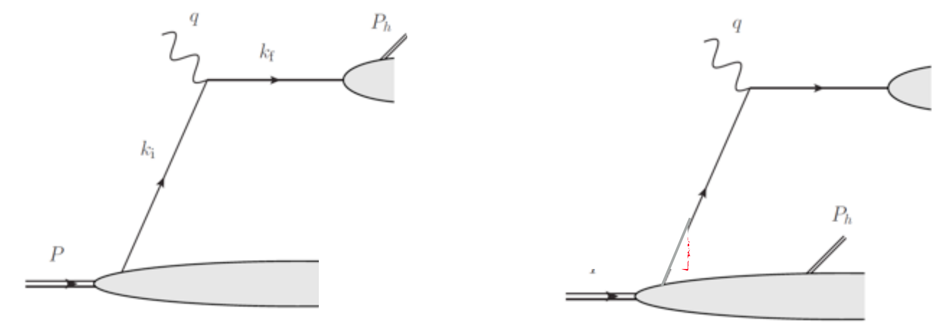
various prescriptions

*Collins, Gamberg, Prokudin, Rogers, Sato, Wang, P.R. D**94** (16) 034014*

Echevarria, Kasemets, Lansberg, Pisano, Signori, arXiv:1801.01480

The factorization problem in SIDIS

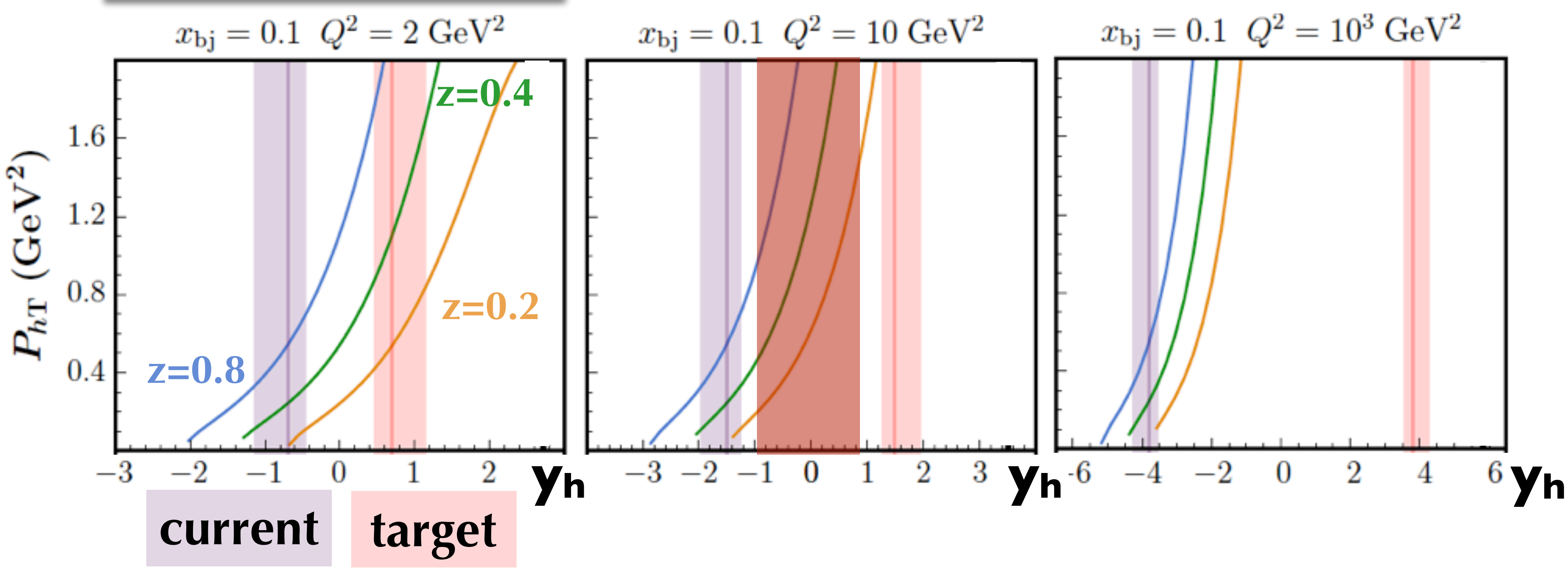
factorization th.'s for (current) fragmentation and (target) fracture functions assume that current and target regions are well separated in rapidity $y_h = \frac{1}{2} \log \frac{P_h^+}{P_h^-}$



at hermes COMPASS it's true for few $\mathbf{P_{hT}}$

at JLab12 still Y term is relevant

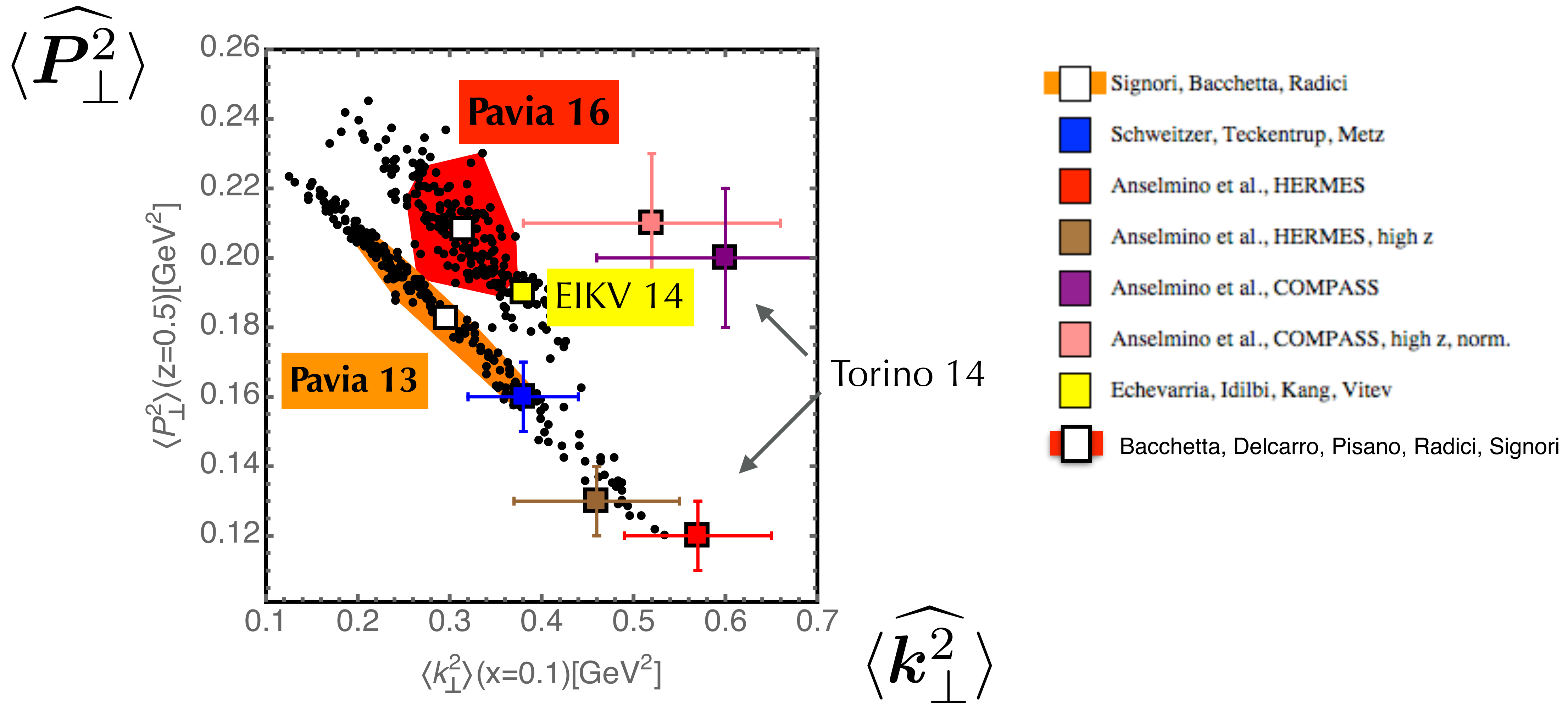
at EIC it's ok



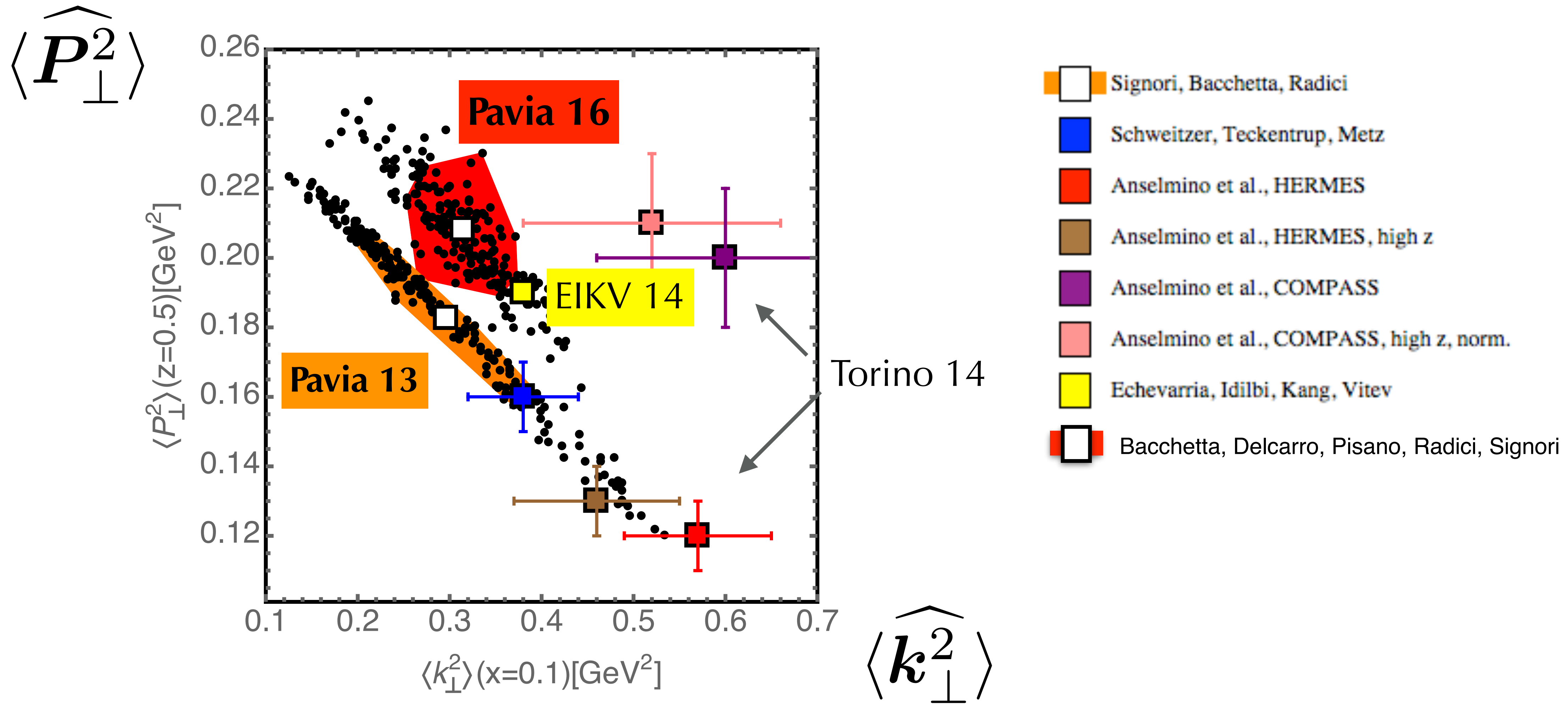
Boglione, Collins, Gamberg, Gonzalez, Rogers, Sato, *P.L.* ***B766*** *(17) 245*

talk Gonzalez

The anticorrelation problem in SIDIS



The anticorrelation problem in SIDIS

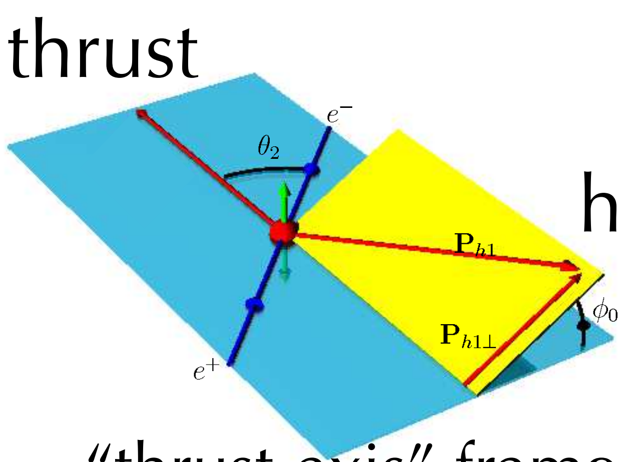


need independent determination of <P_{hT}^2>

→ extract $D_1(z,P_{hT})$ from large set of e^+e^- data

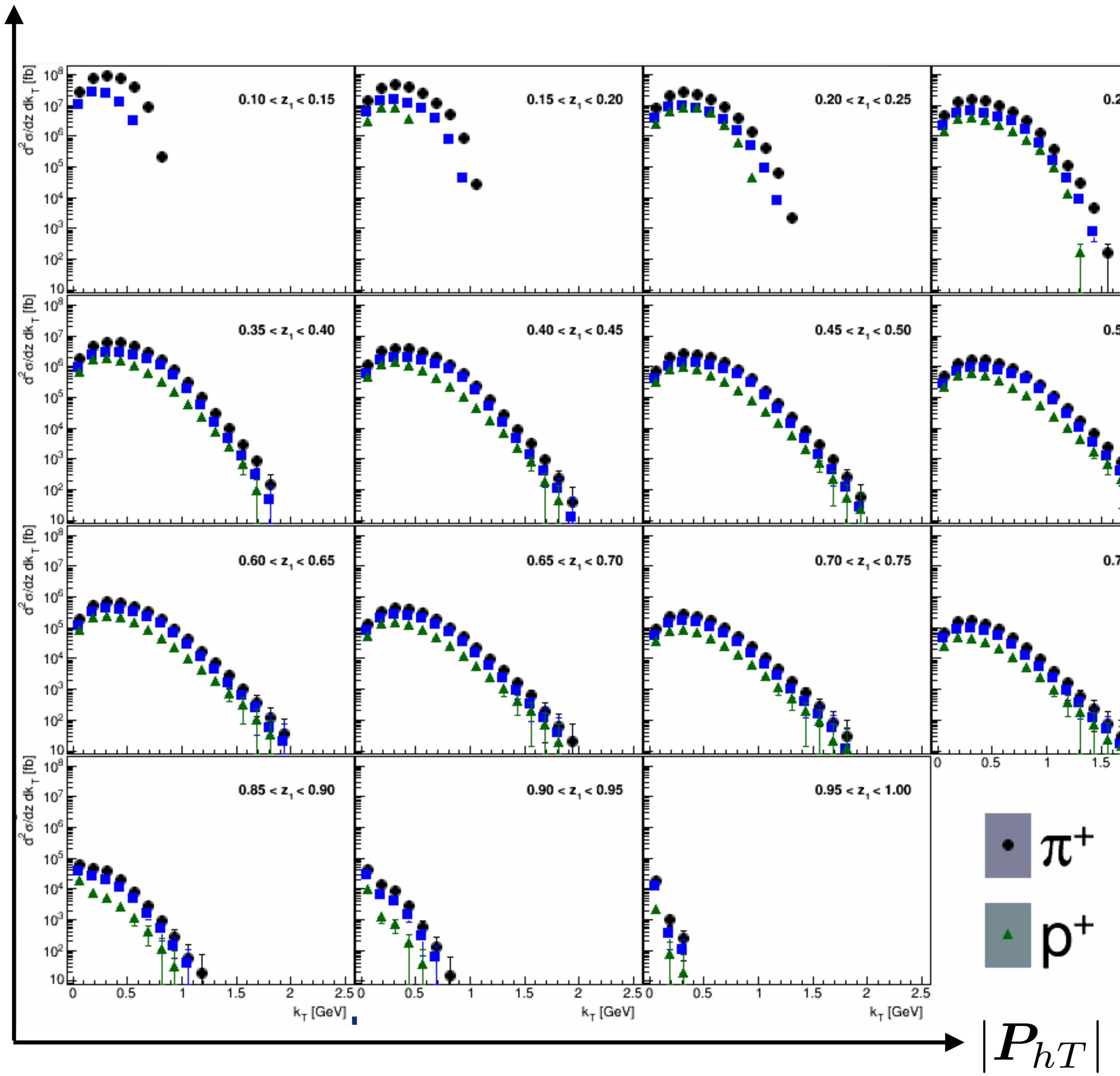
e^+e^- cross section

$e^+ e^- \to h X$



"thrust-axis" frame

$$\frac{d\sigma}{dz\, d\boldsymbol{P}_{hT}}$$



Monte Carlo simulation

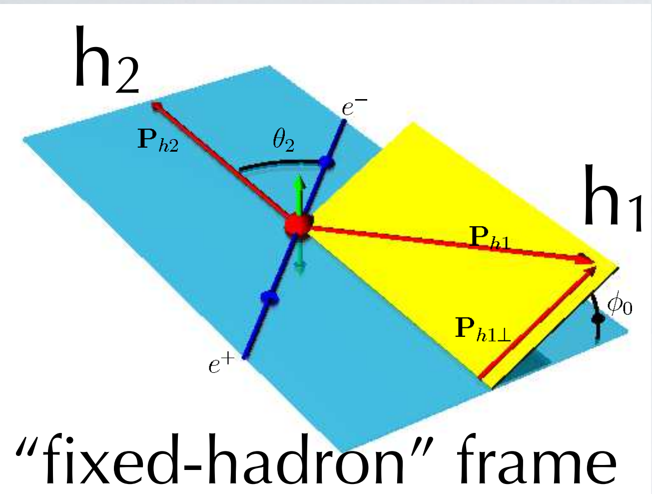
R. Seidl, talk at SPIN2016

preliminary Belle data

→ talk Seidl

e^+e^- unintegrated multiplicity

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

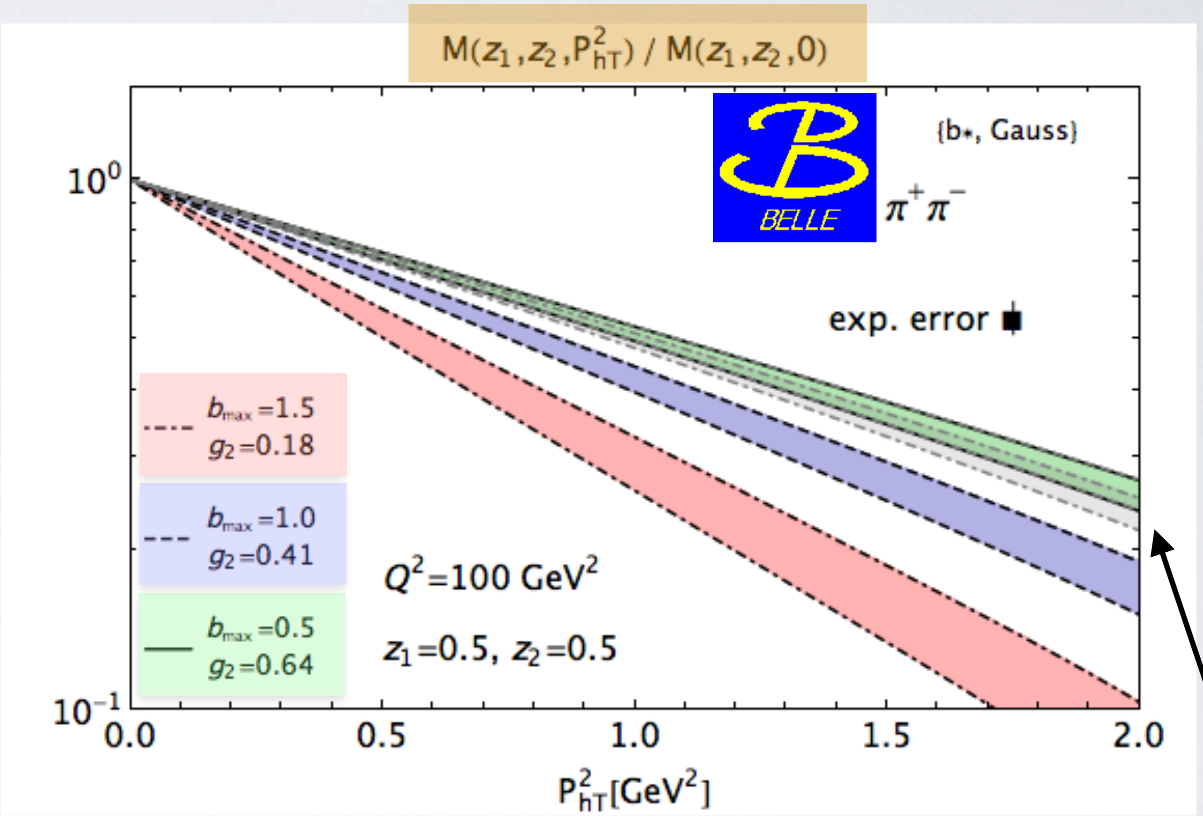


$$M = \frac{d\sigma^{h_1 h_2}/dz_1\, dz_2\, d\boldsymbol{P}^2_{h_1 T}\, dy}{d\sigma_{\rm incl}/dz_2\, dy} \approx \frac{\sum_q e_q^2\, [D_1^q \otimes D_1^{\bar q}](z_1, z_2, \boldsymbol{P}^2_{h_1 T}; Q^2)}{\sum_q e_q^2 D_1^q(z_2; Q^2)}$$

$$\frac{\boldsymbol{P}^2_{h_1 T}}{z_1} \ll Q^2$$

$$D_1^q(z, \boldsymbol{b}_T; Q^2) = R(Q^2, \mu_b^2(b_T, b_{\rm max}))\, e^{-\frac{1}{2} g_2 b_T^2 \log \frac{Q}{Q_0}}\, D_1^q(z, \boldsymbol{b}_T; \mu_b)$$

parameters of nonperturbative evolution

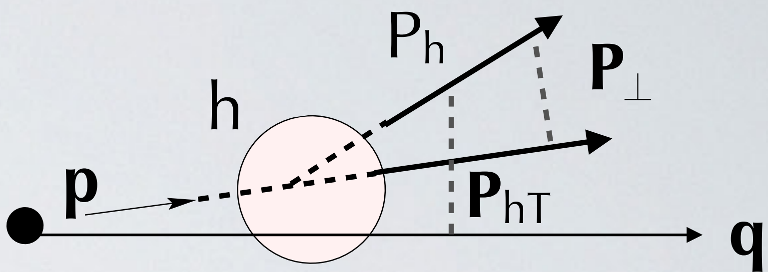


Bacchetta et al., JHEP ***1511*** *(15) 076*

sensitivity to C_1 in $\mu_b = C_1 / b_T$: $C_1/2 < C_1 < 2\, C_1$

a 7% error at BELLE scale can constrain nonperturbative parameters $\{b_{max}, g_2\}$

TMD FF map



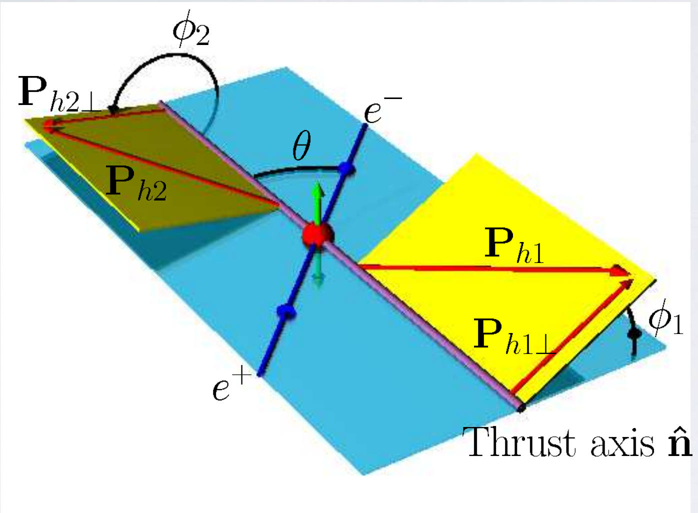
$S_h = 0$

Hadron Polarization		Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
	U	D_1 ***Unpolarized***		$H_1^\perp$ - ***Collins***
	L		G_{1L} -	$H_{1L}^\perp$ -
	T	$D_{1T}^\perp$ -	G_{1T} -	H_1 - $H_{1T}^\perp$ -

What do we know about the Collins function ?

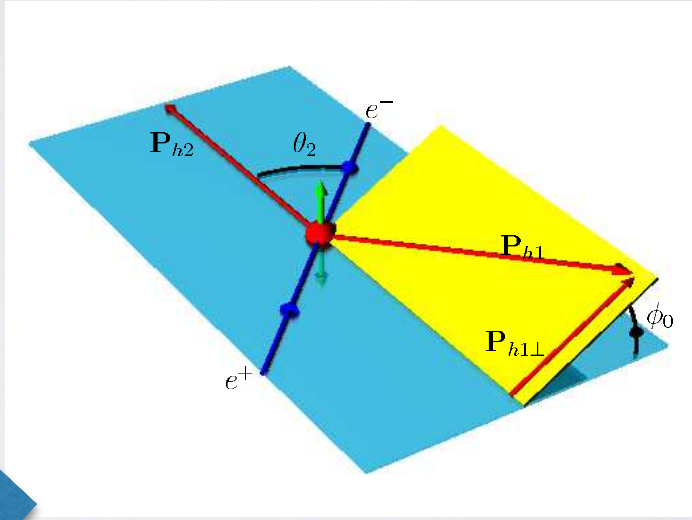
e^+e^- Collins effect

“thrust axis” frame : A_{12}



not obvious QCD generalization of TMD factorization formula because of thrust axis definition

“fixed hadron” frame : A_0



$$A_0^{e^+e^-} \sim \frac{\sin^2\theta}{1+\cos^2\theta}\cos 2\phi_0 \frac{\sum_q e_q^2 \left[H_{1,q}^{\perp}(z_1,\boldsymbol{p}_{1T}^2)\otimes H_{1,\bar{q}}^{\perp}(z_2,\boldsymbol{p}_{2T}^2)\right](z_1,z_2,\boldsymbol{P}_{1\perp}^2)}{\sum_q e_q^2 \left[D_1^q(z_1,\boldsymbol{p}_{1T}^2)\otimes D_1^{\bar{q}}(z_2,\boldsymbol{p}_{2T}^2)\right](z_1,z_2,\boldsymbol{P}_{1\perp}^2)}$$

$$\ldots\otimes\ldots\to\int d\boldsymbol{p}_{1T}\,d\boldsymbol{p}_{2T}\,\delta\left(\boldsymbol{p}_{1T}+\boldsymbol{p}_{2T}+\frac{\boldsymbol{P}_{1\perp}}{z_1}\right)\ldots$$

$$R_{\rm exp}\equiv\frac{d\sigma}{d\sigma_0}$$

Unlike | Like

Unlike-sign / Like-sign

$$\frac{R^U_{\rm exp}}{R^L_{\rm exp}}\approx 1+A_0^{e^+e^-}\left(\frac{\pi^+\pi^-+\pi^-\pi^+}{\pi^+\pi^-+\pi^-\pi^+}\right)-A_0^{e^+e^-}\left(\frac{\pi^+\pi^++\pi^-\pi^-}{\pi^+\pi^++\pi^-\pi^-}\right)$$

Unlike-sign / Charged

$$\frac{R^U_{\rm exp}}{R^C_{\rm exp}}\approx 1+A_0^{e^+e^-}\left(\frac{\pi^+\pi^-+\pi^-\pi^+}{\pi^+\pi^-+\pi^-\pi^+}\right)-A_0^{e^+e^-}\left(\frac{\text{all}\quad\pi\pi}{\text{all}\quad\pi\pi}\right)$$

to kill false asymmetries

Data for e^+e^- Collins effect

Abe et al., P.R.L. ***96*** *(06) 232002*
Seidl et al., P.R. D78 (08) 032011
D86 (12) 039905(E)

$A_{12}^{U/L/C}(z_1, z_2)$

$A_0^{U/L/C}(z_1, z_2)$

$s = Q^2 = 112\ \text{GeV}^2$

→ talk Seidl

Lees et al., P.R. D90 (14) 052003

$A_{12}^{U/L/C}(z_1, z_2, P_{1T}, P_{2T})$

$A_0^{U/L/C}(z_1, z_2, P_{1T})$

Lees et al., P.R. D92 (15) 111101

$A_{12}^{U/L/C}(z_1, z_2)$

$A_0^{U/L/C}(z_1, z_2)$

KK and Kπ pairs

$s = Q^2 = 112\ \text{GeV}^2$

Ablikim et al., P.R.L. ***116*** *(16) 042001*

$A_0^{U/L/C}(z_1, z_2, P_{1T})$

$s = Q^2 = 13\ \text{GeV}^2$

→ talk Anulli

Data for e^+e^- Collins effect

Abe et al., P.R.L. ***96*** *(06) 232002*
*Seidl et al., P.R. D**78** (08) 032011*
*D**86** (12) 039905(E)*

$A_{12}^{\,U/L/C}(z_1, z_2)$

$A_0^{\,U/L/C}(z_1, z_2)$

$s = Q^2 = 112$ GeV^2

talk Seidl

*Lees et al., P.R. D**90** (14) 052003*

$A_{12}^{\,U/L/C}(z_1, z_2, P_{1T}, P_{2T})$

$A_0^{\,U/L/C}(z_1, z_2, P_{1T})$

*Lees et al., P.R. D**92** (15) 111101*

$A_{12}^{\,U/L/C}(z_1, z_2)$

$A_0^{\,U/L/C}(z_1, z_2)$

KK and Kπ pairs

$s = Q^2 = 112$ GeV^2

Ablikim et al., P.R.L. ***116*** *(16) 042001*

$A_0^{\,U/L/C}(z_1, z_2, P_{1T})$

$s = Q^2 = 13$ GeV^2

phase transition :
direct access to transverse dynamics
and to its chiral-odd QCD evolution

talk Anulli

e^+e^- Collins effect

available fits

both perform global fits (SIDIS + e^+e^-) with χ^2/dof in [0.85 - 1.2]

	Framework	Belle	BaBar $A_0(z_1,z_2,P_{1T})$ U / L / C	# points	BaBar A_{12} U / L / C	BESIII $A_0(z_1,z_2,P_{1T})$ U / L / C
Torino 2015 *Anselmino et al., P.R.D**92** (15) 114023*	Gaussian, fixed width various params. for fav (z) unfav (z) = $N_{unf}\, D_1(z)$ **only chiral-odd collinear DGLAP evolution** 5 parameters	✔	✔	122	**predicted**	**predicted**
KPSY 2015 *Kang et al., P.R.D**93** (16) 014009*	**TMD evolution in CSS scheme** at NLO + NLL level * $\hat{H}^{(3)}(z) \propto D_1(z)$ fav (z) ≠ unfav (z) only homogeneous evo eqs. 7 parameters	✔	✔	122	✘	**predicted**

$$* \quad H_1^{\perp\, q}(z, \boldsymbol{b}_T; Q^2) = \sum_i \left(\delta C_{q/i} \otimes \hat{H}^{(3)\, i}\right)(z, b_*; \mu_b)\, e^{S(b_*,\mu_b;Q)}\, e^{S_{\rm NP}(b_T;Q)}\, H^q_{\rm NP}(z, \boldsymbol{b}_T; Q_0^2)$$

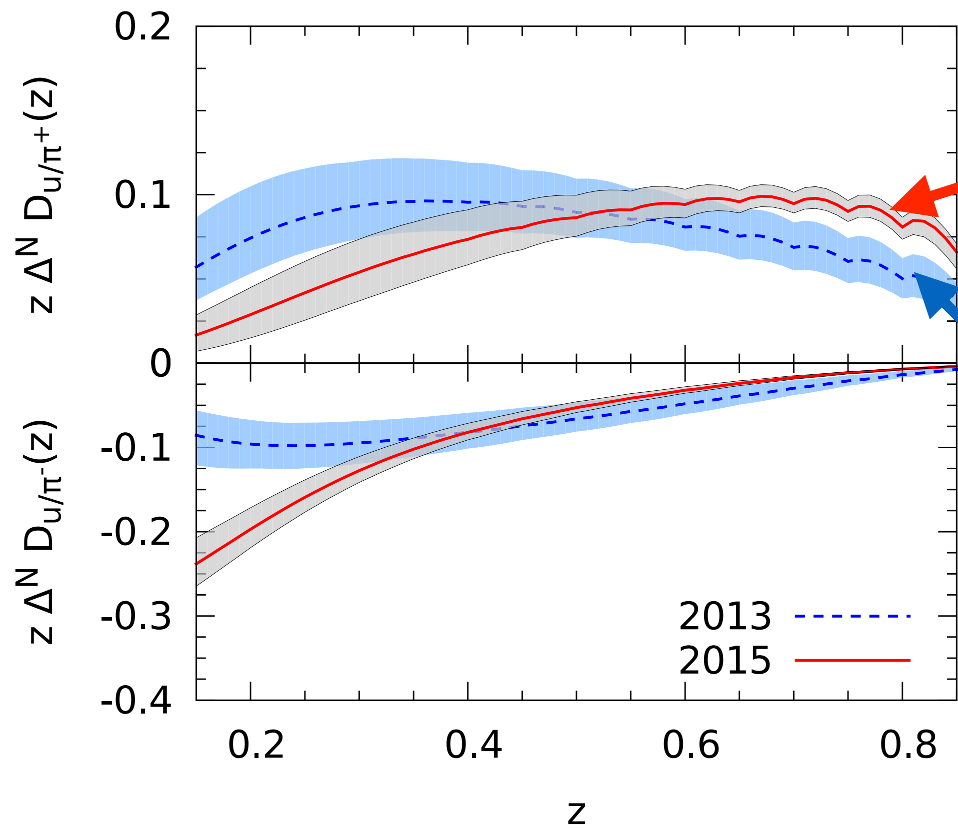
Moments of Collins function : z dep.

favored

$$\Delta^N D_{h/q}(z) = 4\, H_1^{\perp (1/2) q\to h}(z)$$

$$H_1^{\perp (n)}(z) = \int d\boldsymbol{P}_\perp \, \frac{1}{2} \left(\frac{\boldsymbol{P}_\perp^2}{z^2 m_h^2} \right)^n H_1^\perp(z, \boldsymbol{P}_\perp^2)$$

unfavored



*Anselmino et al., P.R. D**92** (15) 114023*

*Anselmino et al., P.R. D**87** (13) 094019*

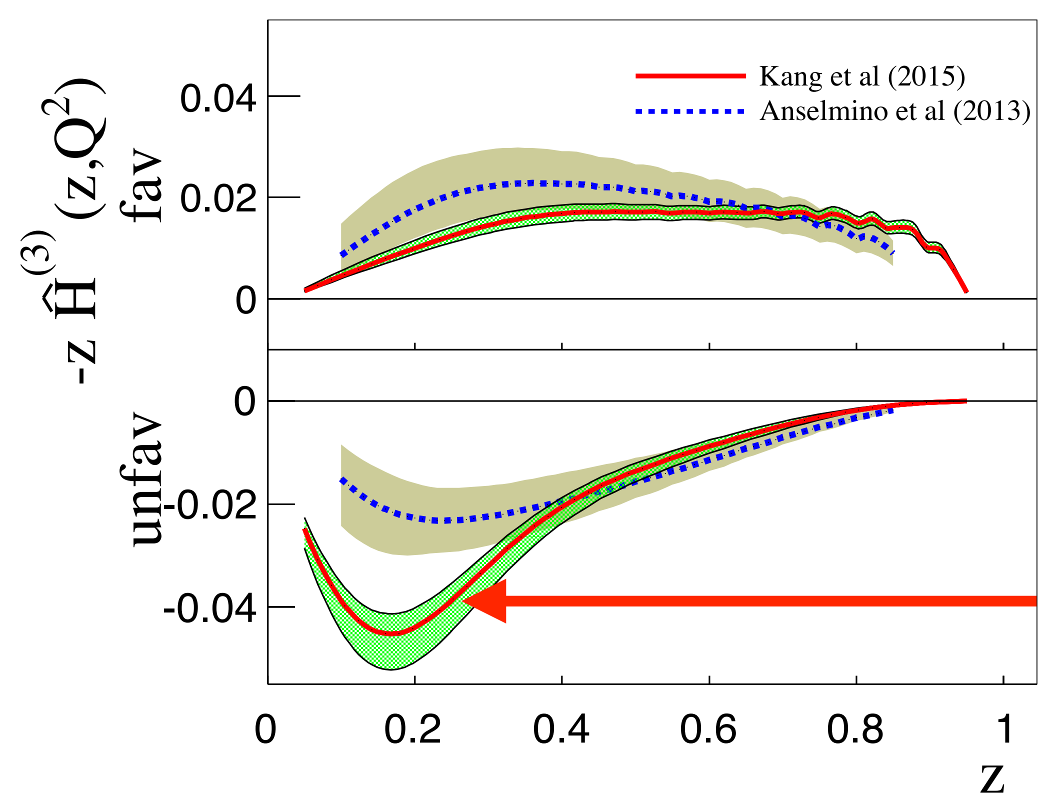
Torino 2013

Torino 2015

$$\hat{H}^{(3)}(z) = -2zM_h\, H_1^{\perp\,(1)}(z)$$

- similar results
- both very good χ^2/dof

→ R^U/R^L or R^U/R^C not very sensitive to TMD evolution



Torino 2013

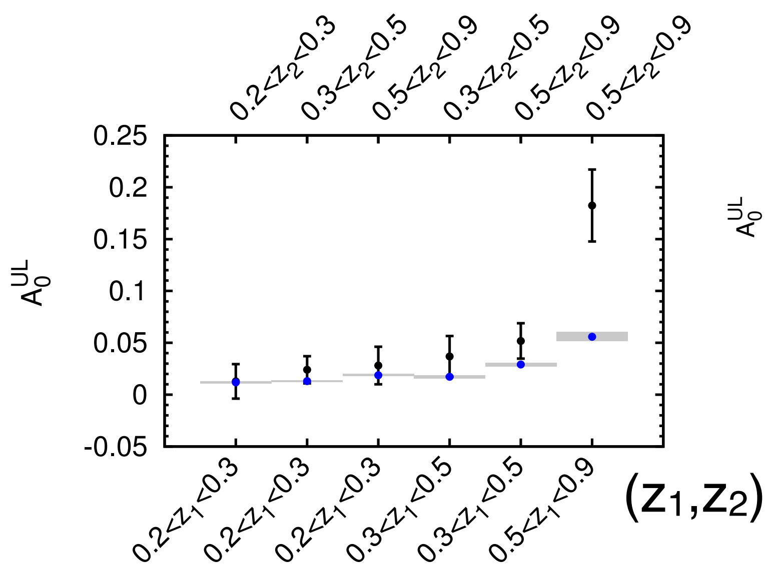
KPSY 2015

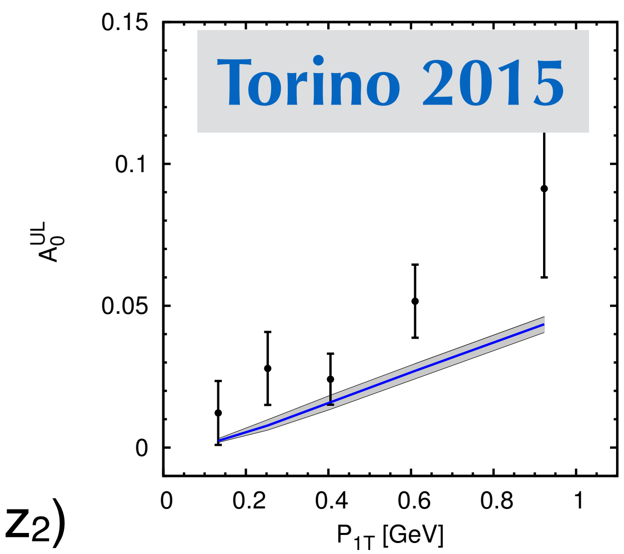
*Kang et al., P.R. D**93** (16) 014009*

Predicting the BESIII asymmetry

A_0^{UL}

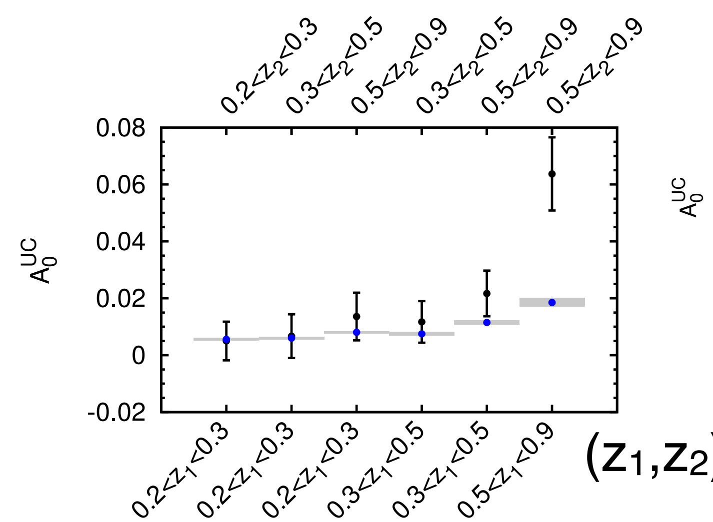
$$A_0^{e^+e^-}\left(\frac{\pi^+\pi^- + \pi^-\pi^+}{\pi^+\pi^- + \pi^-\pi^+}\right) - A_0^{e^+e^-}\left(\frac{\pi^+\pi^+ + \pi^-\pi^-}{\pi^+\pi^+ + \pi^-\pi^-}\right)$$

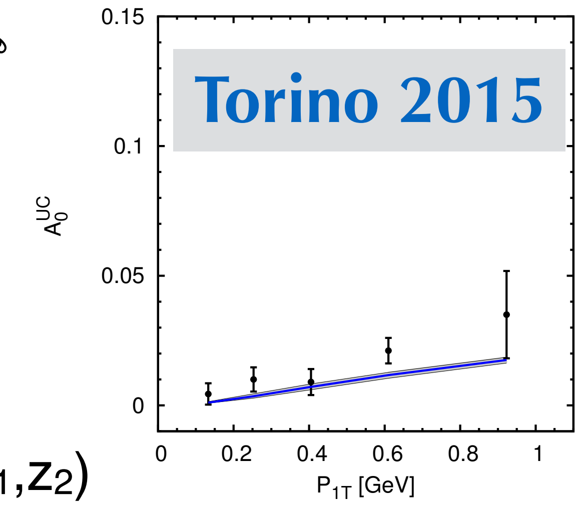




A_0^{UC}

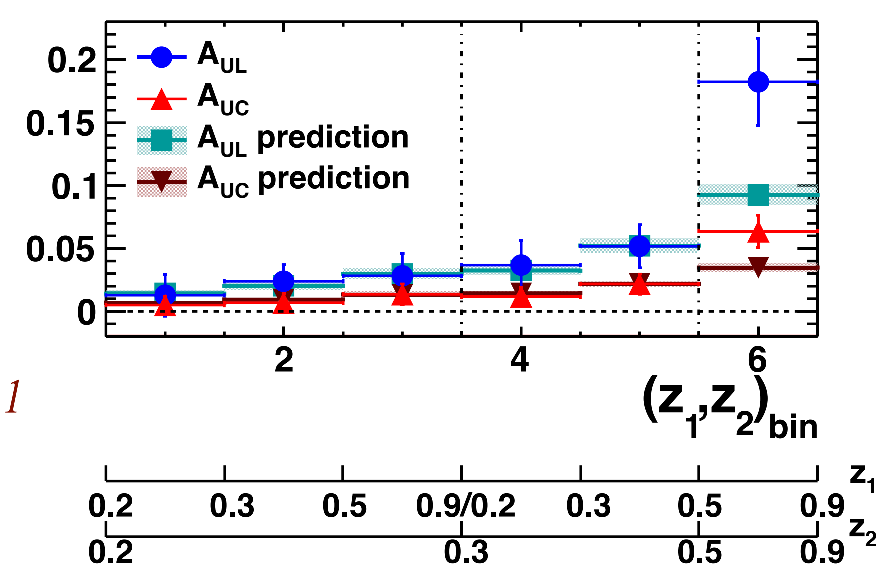
$$A_0^{e^+e^-}\left(\frac{\pi^+\pi^- + \pi^-\pi^+}{\pi^+\pi^- + \pi^-\pi^+}\right) - A_0^{e^+e^-}\left(\frac{\text{all } \pi\pi}{\text{all } \pi\pi}\right)$$

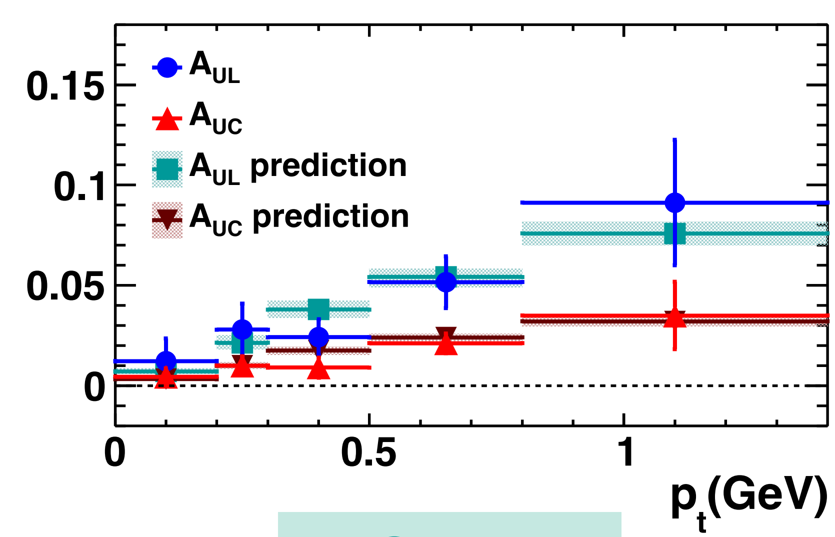




*Anselmino et al., P.R. D**92** (15) 114023*

Ablikim et al.,
*P.R.L. **116** (16) 042001*

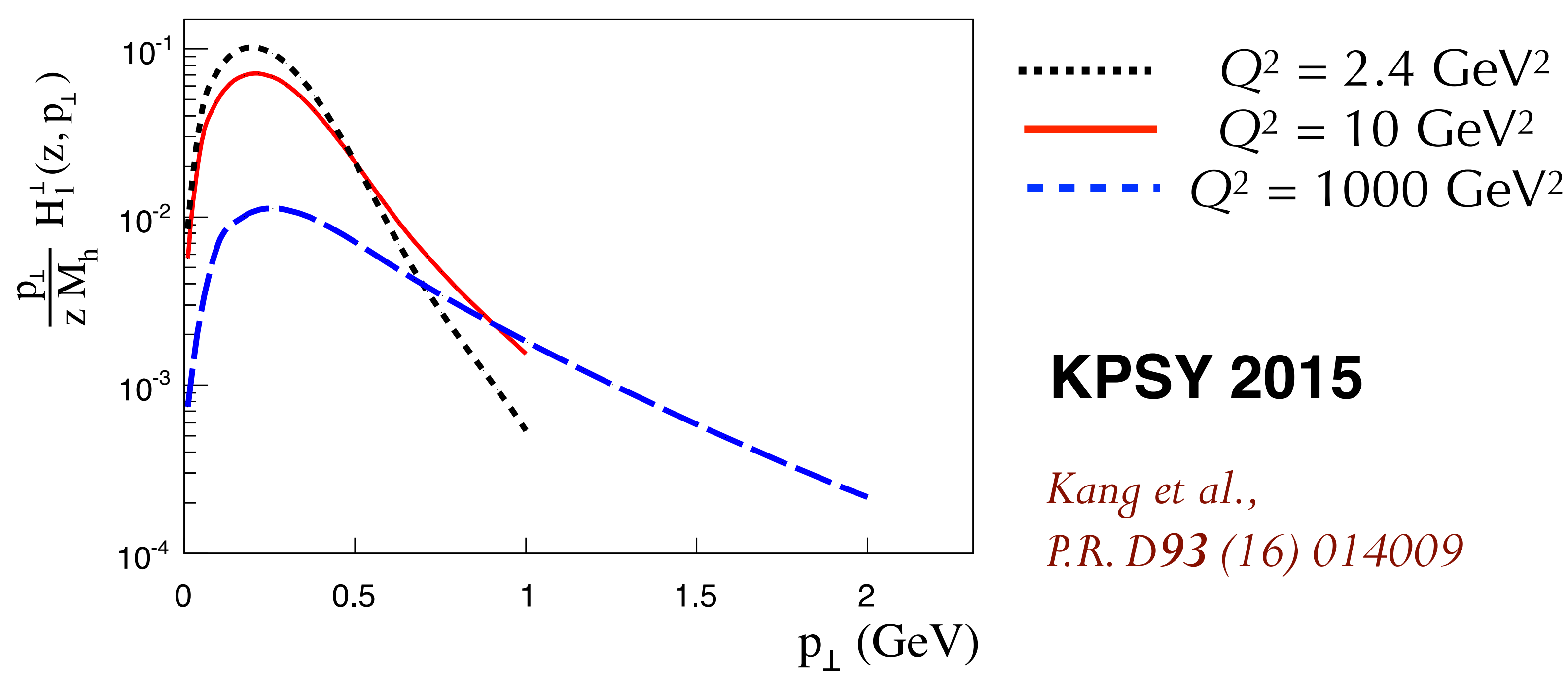




predictions = A_0^{UL} **KPSY 2015**, A_0^{UC} **KPSY 2015**

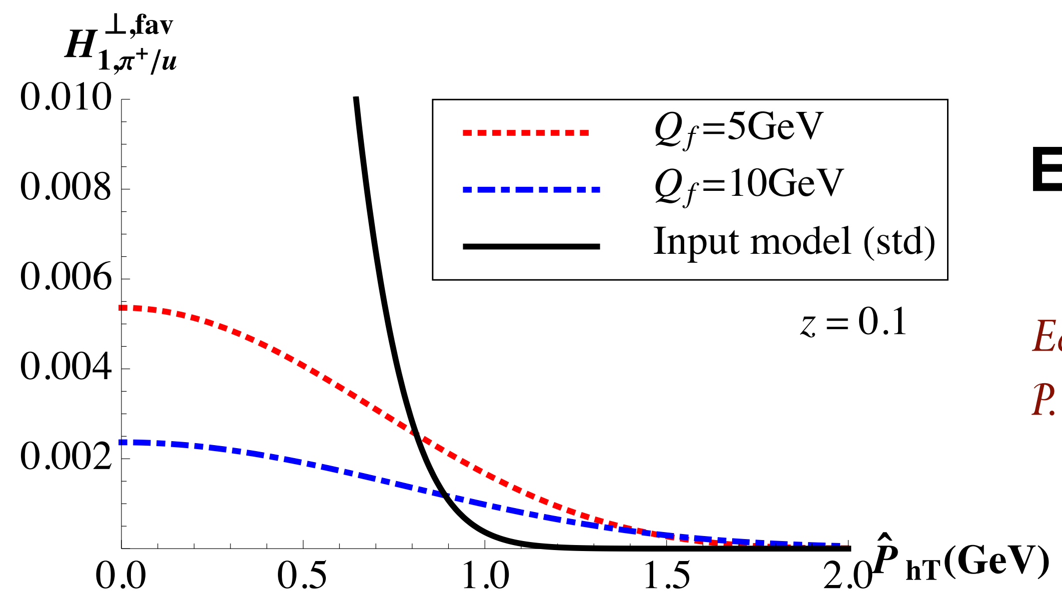
TMD evolution on Collins funct.

different broadening in the early range Q_0^2 — 10÷20 GeV^2



KPSY 2015

*Kang et al., P.R. D***93** *(16) 014009*



EIS 2014

*Echevarria, Idilbi, Scimemi, P.R. D***90** *(14) 014003*

Collins funct. for Kaons

64 data: $A_0^{U/L/C}$ for π K and KK pairs

*Lees et al., P.R. D***92** *(15) 111101*

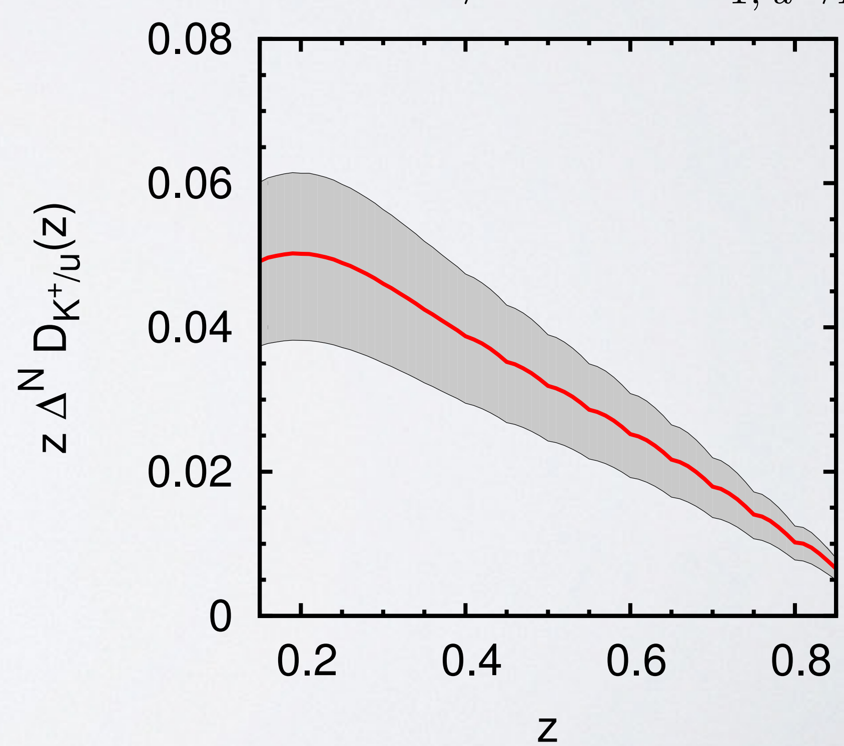
Torino 2016

- same p_T dependence as for π (Gaussian with fixed parameter)
- z dependence as $D_1^{q\to K}(z)$
- only non-chiral-odd DGLAP evolution of z-dependence
- 2 parameters: normalization for favored u and unfavored
- global χ^2/dof = 0.89

- favored $u\to K^+$ determined and positive
- favored $s\to K^-$ undetermined (also in sign)
- unfavored undetermined

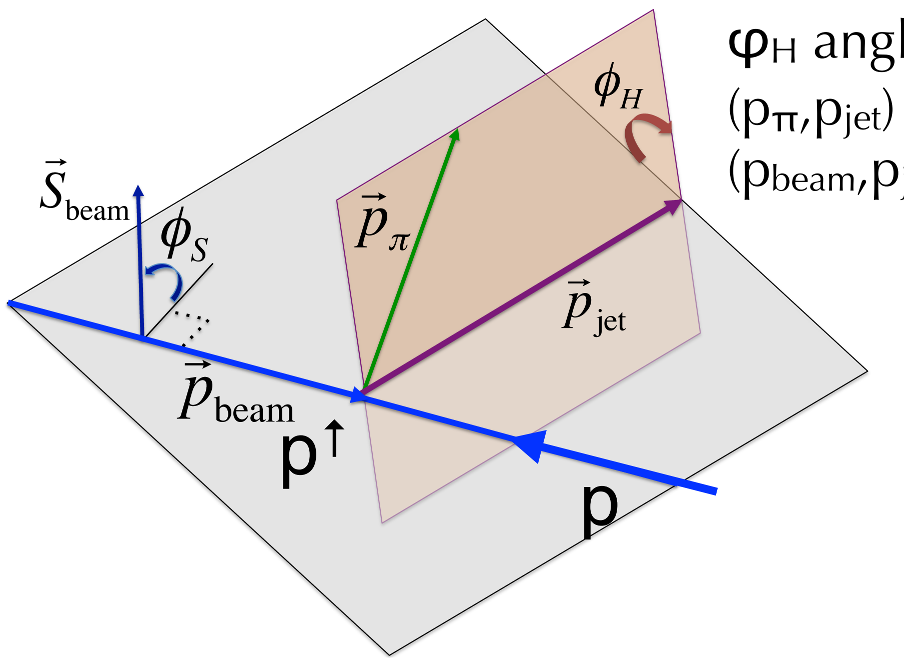
because of too few data

$$\Delta^N D_{K^+/u}(z) \equiv 4\, H_{1,\,u\to K^+}^{\perp\,(1/2)}(z)$$



*Anselmino et al., P.R.D***93** *(16) 034025*

Collins effect for hadron-in-jet

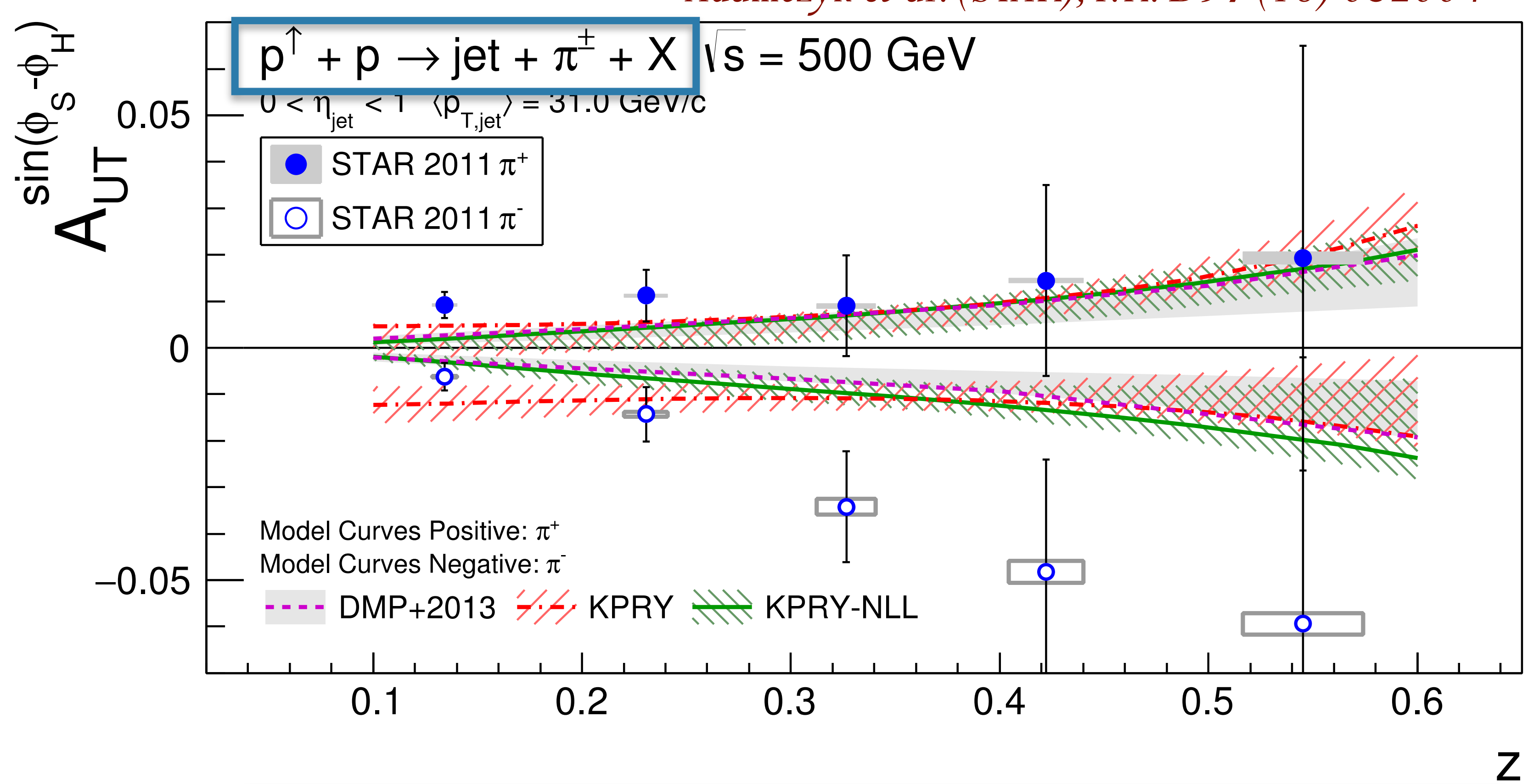


φH angle of (p_π,p_{jet}) plane and (p_{beam},p_{jet}) plane

- collinear collision, TMD only in fragmentation
- assuming factorization at large P_{jetT}

$$A_{UT}^{\sin(\phi_S-\phi_H)} \propto \frac{h_1^q \otimes f_1^{\bar{q}} \otimes H_1^{\perp q}}{f_1^q \otimes f_1^{\bar{q}} \otimes D_1^q}$$

*Adamczyk et al. (STAR), P.R. D**97** (18) 032004*



PDF & TMDFF from SIDIS + e⁺e⁻ analysis

DMP+2013 (no evolution)

*Anselmino et al., P.R. D**87** (13) 094019*
*D'Alesio et al., P.L. **B773** (17) 300*

KPRY (no evolution)

KPRY-NLL (TMD evolution)

*Kang et al., P.L. **B774** (17) 635*

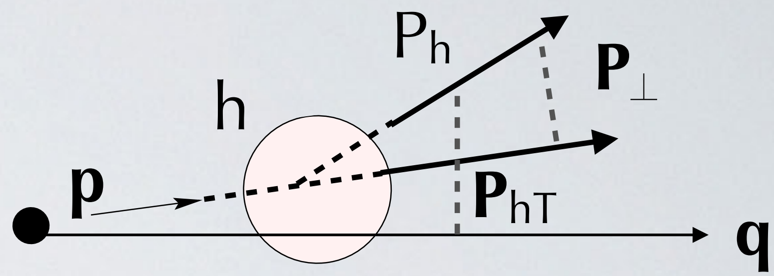
→ talks Pisano, Scimemi Drachenberg

is Collins function for quark universal ?

gluon signature: $A_{UT}^{\sin(\phi_S-2\phi_H)}$

TMD FF map

leading twist
$S_h \leq 1/2$

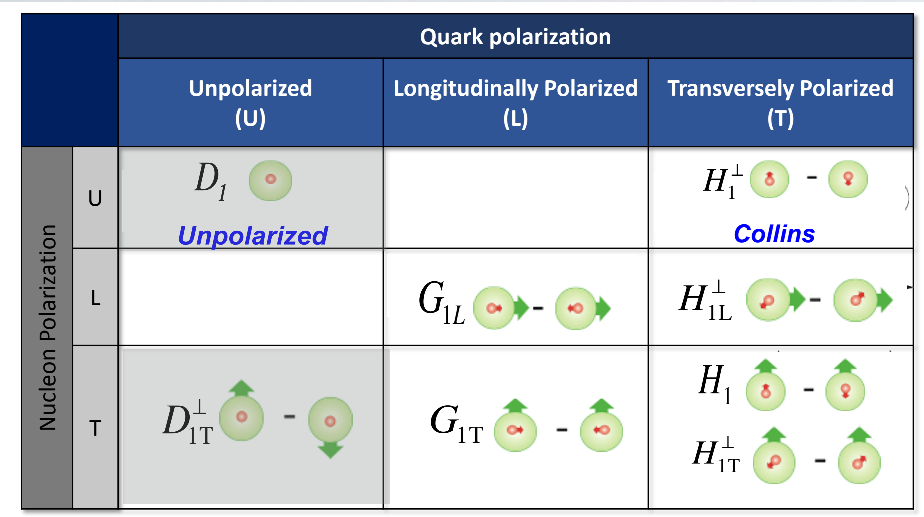


$S_h = 1/2$

Hadron Polarization		Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
	U	D_1 *Unpolarized*		$H_1^\perp$ **Collins**
	L		G_{1L}	$H_{1L}^\perp$
	T	$D_{1T}^\perp$	G_{1T}	H_1 $H_{1T}^\perp$

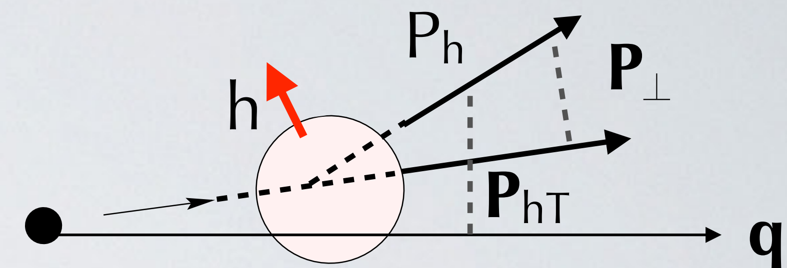
data on $\Lambda^\uparrow$ production from BELLE / COMPASS (and CERN- NA48/OPAL/ATLAS
HERA-B
old FermiLab)

Access to $D_{1T}^{\perp}$



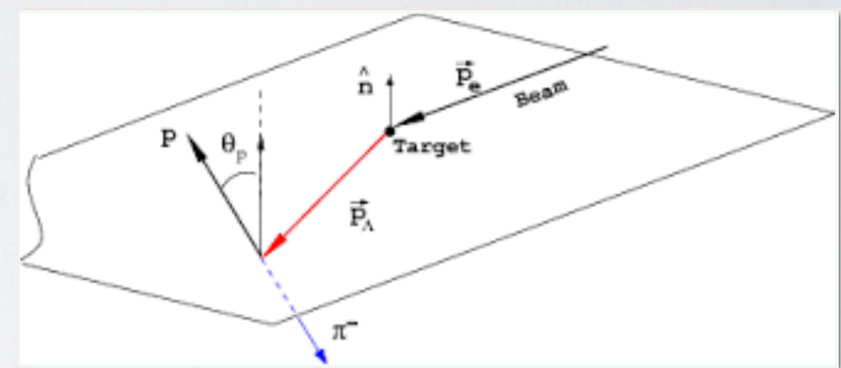
		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	D_1 Unpolarized		$H_1^{\perp}$ - Collins
	L		G_{1L} -	$H_{1L}^{\perp}$ -
	T	$D_{1T}^{\perp}$ -	G_{1T} -	H_1 - $H_{1T}^{\perp}$ -

$D_{1T}^{\perp}(z, \mathbf{P}_{hT})$



encodes "spontaneous" polarization of h

$$\frac{1}{N}\frac{dN}{d\cos\theta_p} = 1 + \alpha\, P\, \cos\theta_p$$



assuming TMD factorization,
p-Be and p-p data from FermiLab
can be interpreted as

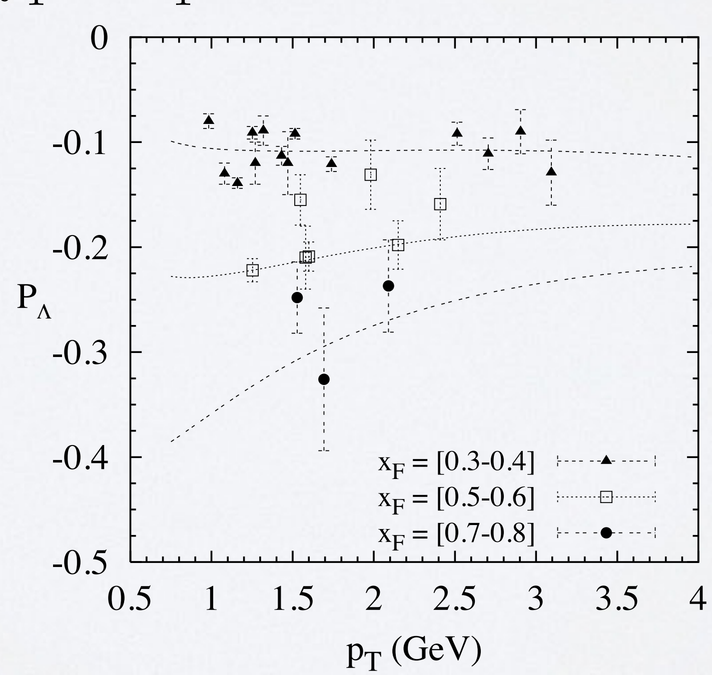
$$P_\Lambda \propto \frac{f_1^q \otimes f_1^{\bar{q}} \otimes D_{1T}^{\perp q}}{f_1^q \otimes f_1^{\bar{q}} \otimes D_1^q}$$

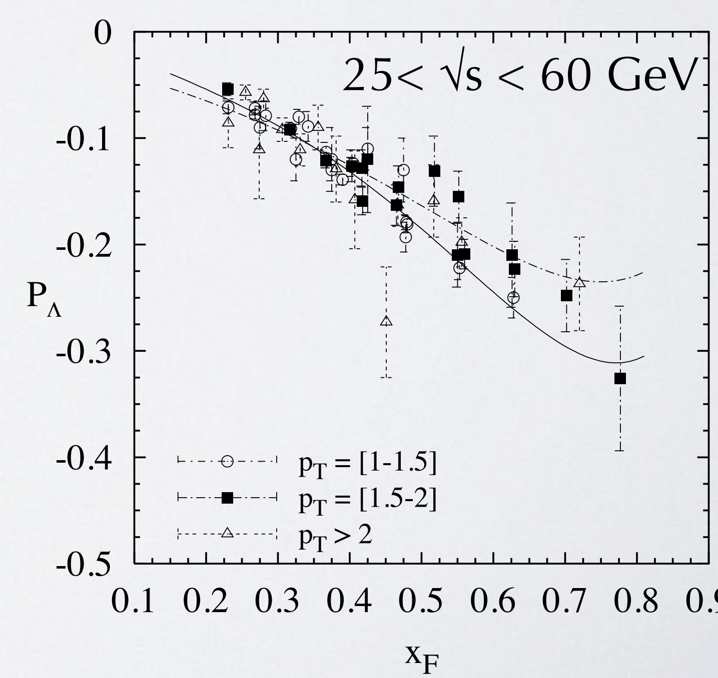
*Anselmino, Boer, D'Alesio, Murgia, P.R. D**63** (01) 054029*

caveat

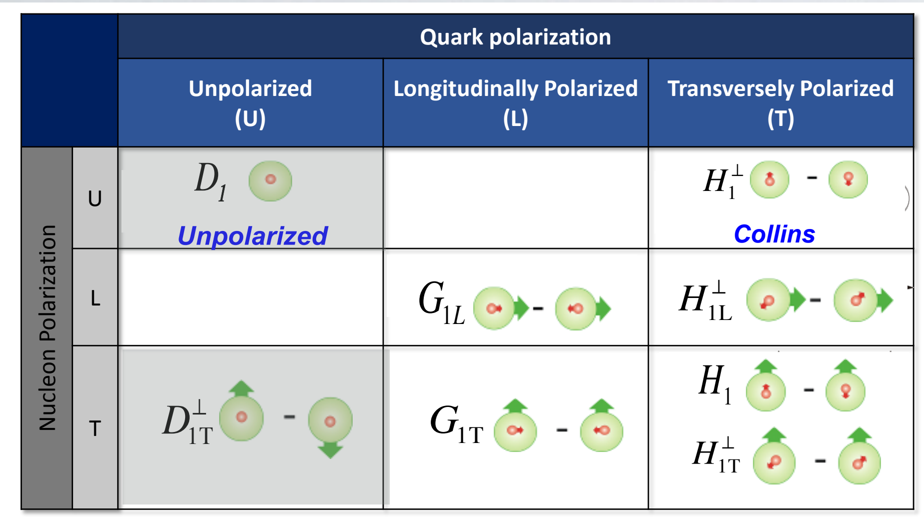
$d\sigma_0$ turns out too small w.r.t. data
factorization broken?

→ talk Boer

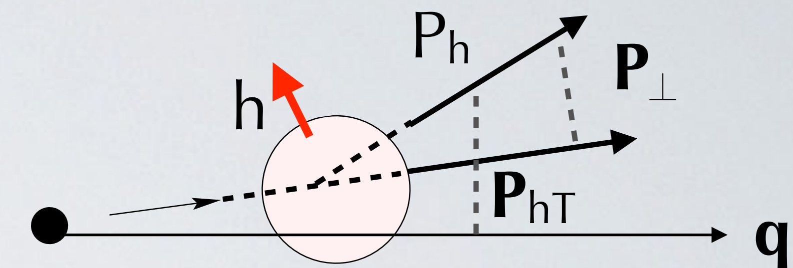




Λ polarization data



$D_{1T}^\perp$ (z, $\mathbf{P}_{hT}$)



encodes "spontaneous" polarization of h

extraction of $D_{1T}^\perp$ never attempted from e^+e^- so far

new data from Belle on $e^+e^- \to \Lambda^\uparrow(\bar{\Lambda}^\uparrow) + X$
$e^+e^- \to \Lambda^\uparrow(\bar{\Lambda}^\uparrow) + \pi(K) + X$
with full (z_Λ, $P_{\Lambda T}$) dependence

BELLE

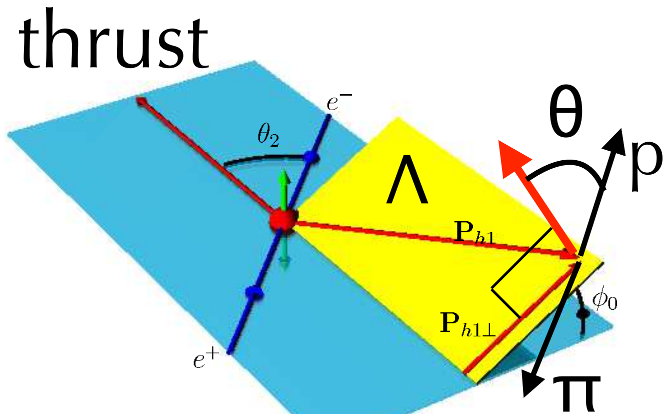
Abdesselam et al. (BELLE), arXiv:1611.06448

ongoing attempt to interpret data in
collinear factorization up to twist-3 and NLO:
$P_\Lambda \leftrightarrow D_T(z)$ "intrinsic twist-3"

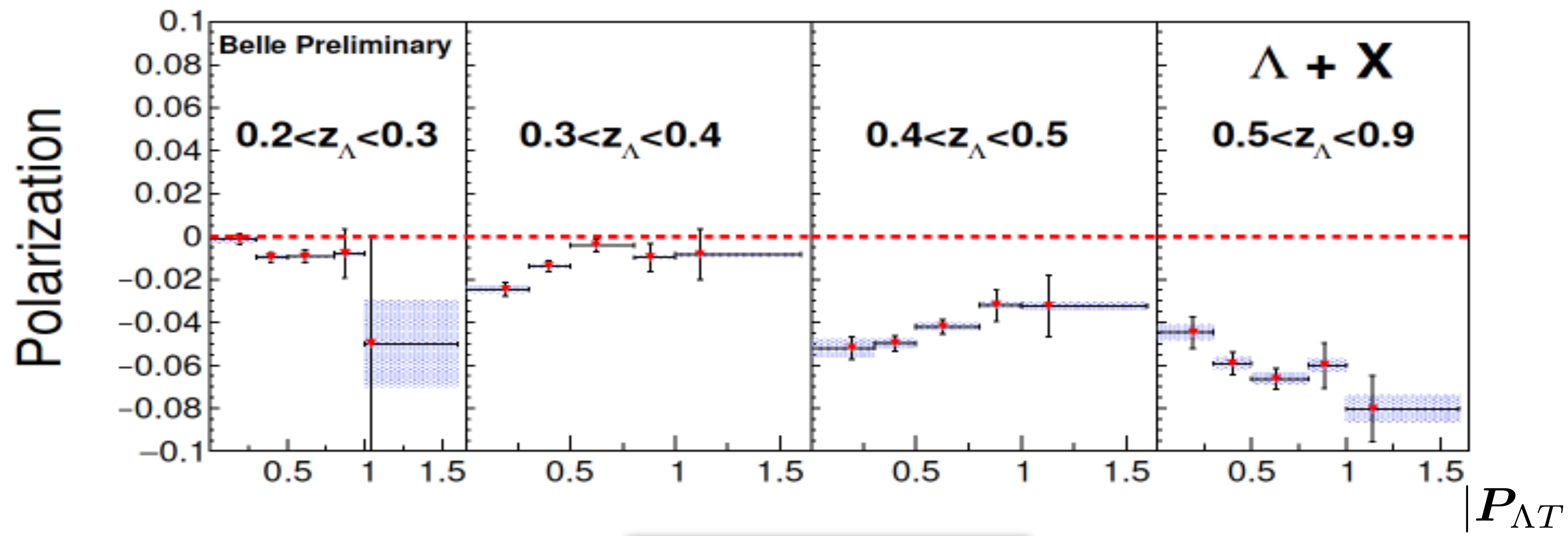
Schlegel, Transversity 2017

Λ polarization data

$e^+ e^- \to \Lambda^\uparrow + X$

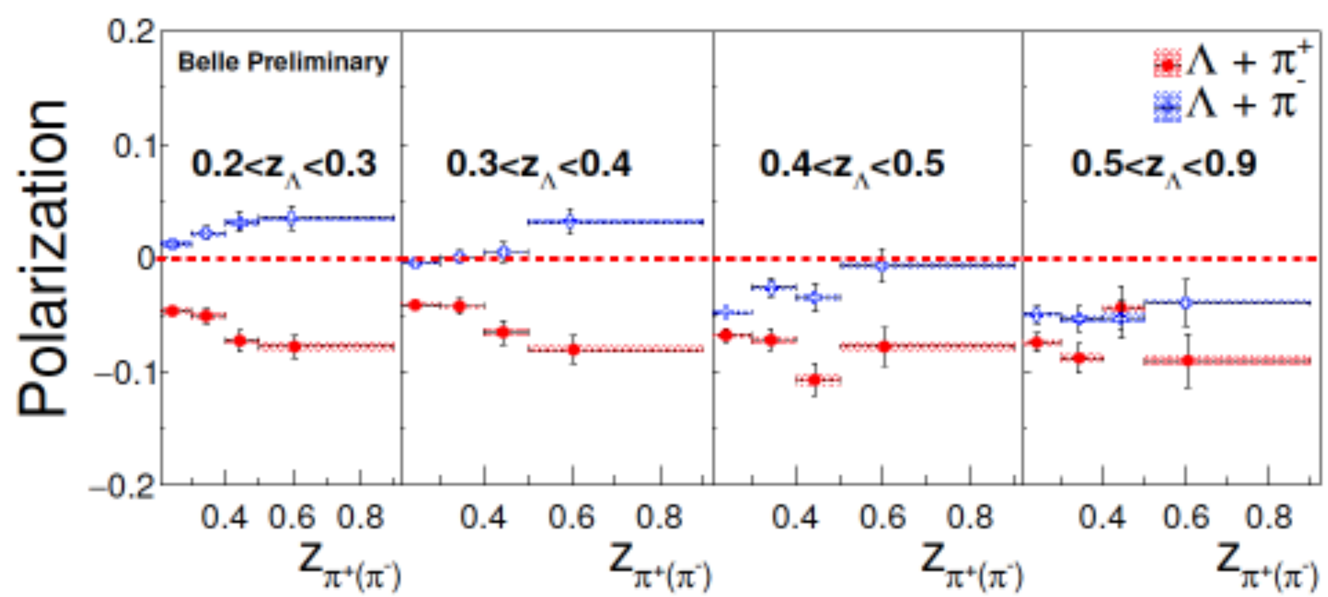


"thrust-axis" frame

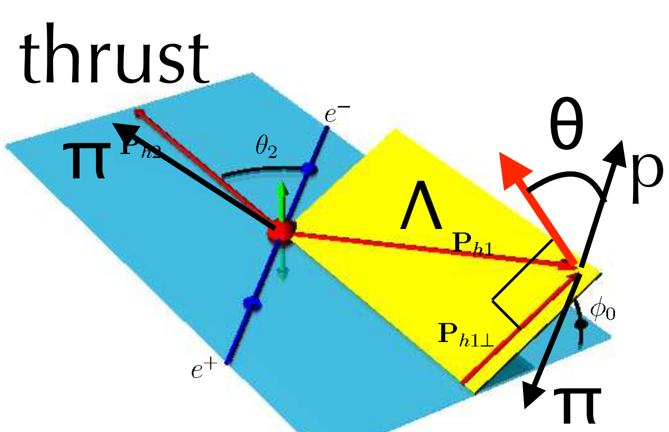


rising |P| | decreasing |P| | rising |P|

Abdesselam et al. (BELLE), arXiv:1611.06448



at large z_Λ polarization changes sign



"thrust-axis" frame

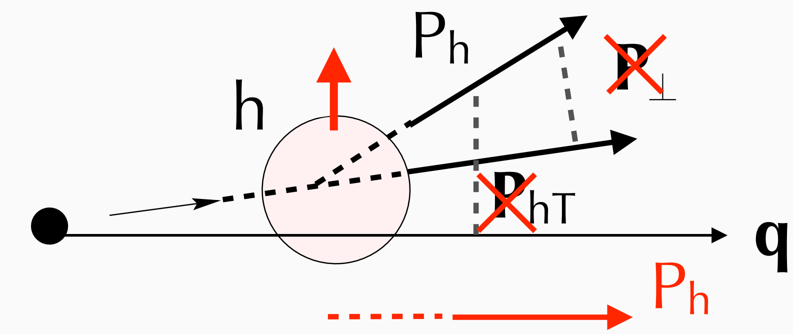
→ talk Seidl?

SIDIS Λ polarization data

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	D_1 *Unpolarized*		$H_1^{\perp}$ - *Collins*
	L		G_{1L} -	$H_{1L}^{\perp}$ -
	T	$D_{1T}^{\perp}$ -	G_{1T} -	H_1 - $H_{1T}^{\perp}$ -

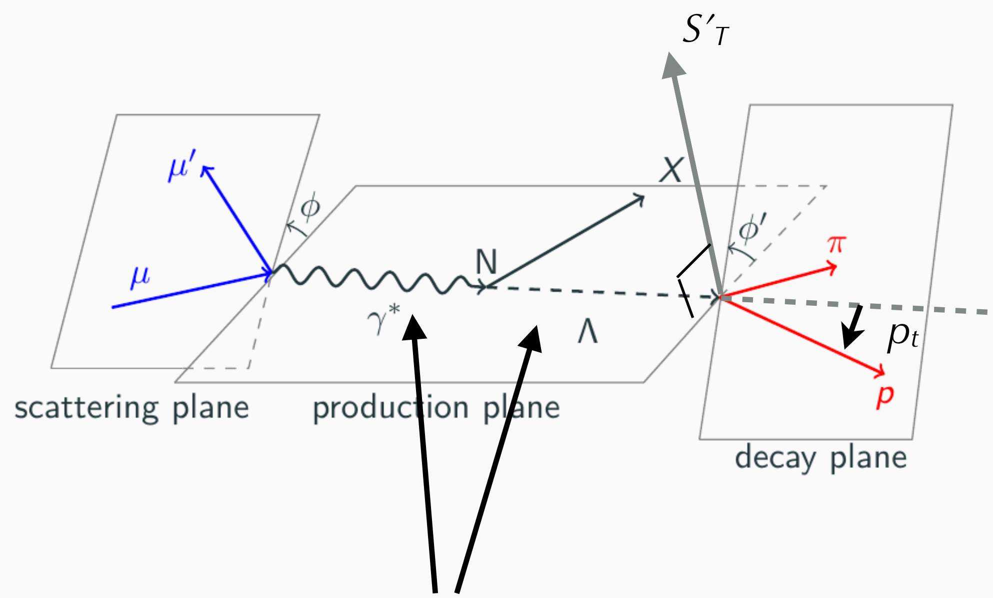
H_1 (z)

Λ "transversity"

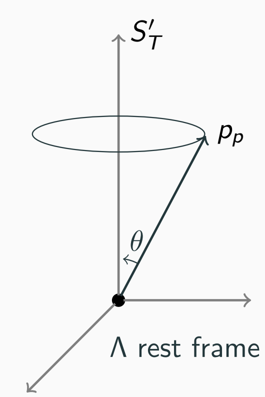


new data from COMPASS on $l\, p^{\uparrow} \rightarrow \Lambda^{\uparrow} + X$

Moretti, Transversity 2017

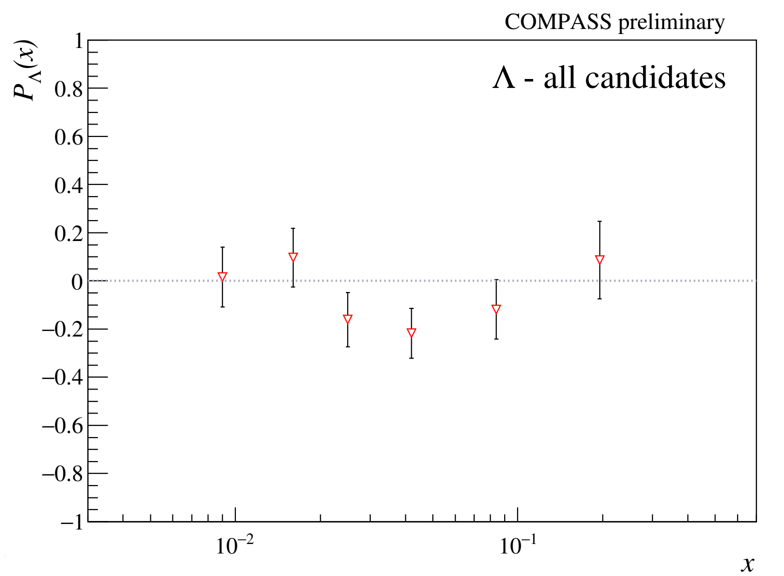


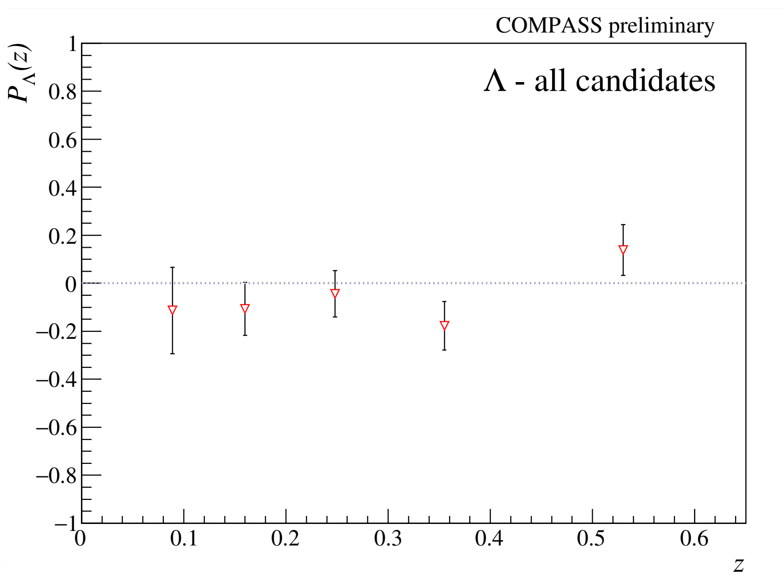
collinear kinematics

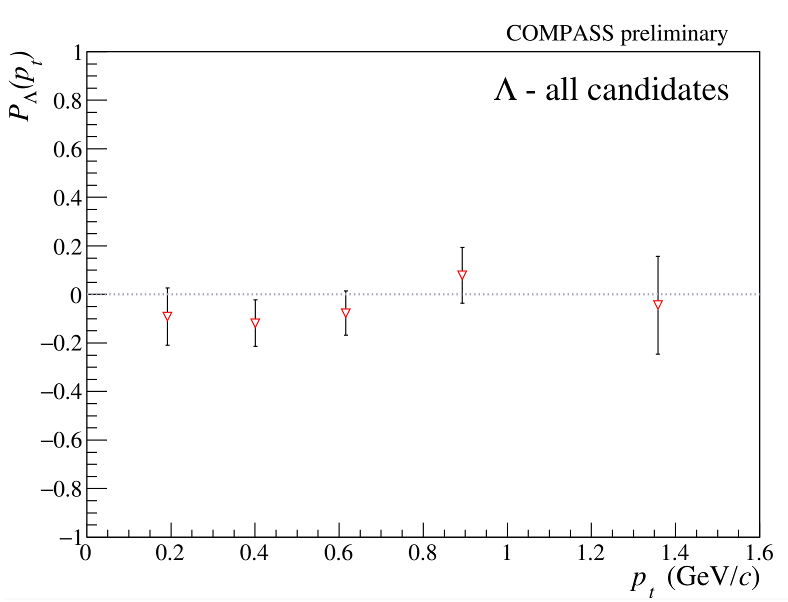


$$P_\Lambda \propto \frac{h_1^q\ H_1^q}{f_1^q\ D_1^q}$$

SIDIS Λ polarization data







Moretti, Transversity 2017

$P_\Lambda(x,z,p_t) \sim 0$ also for $\bar{\Lambda}$

2 Hp.'s based on isospin symmetry and

$$h_1^{\bar{q}} \approx FF^{\bar{q}} \approx 0\,, \quad FF^s = c\, FF^u$$

1) $h_1^s \approx 0$ ("valence Hp.") then $\dfrac{\int dz\, H_1^{u\to\Lambda}(z)}{\int dz\, D_1^{u\to\Lambda}(z)} \approx 0$

2) P_Λ only from *s* $\quad H_1^{u\to\Lambda} \approx H_1^{d\to\Lambda} \approx 0$, $\; H_1^{s\to\Lambda} = D_1^{s\to\Lambda}$ then