Summary of important theory issues

Alessandro Bacchetta

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UNIVERSITÀ DI PAVIA

The most crucial theme of the week

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- Bacchetta's function

Crucial themes

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- TMD extractions

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- Tensor charge

Crucial themes

- TMD extractions
- Tensor charge
- Orbital Angular Momentum

TMD extractions:
theory issues

TMD evolution: Fourier transform

$$f_1^a(x, k_\perp; \mu^2) = \frac{1}{2\pi} \int d^2 b_\perp e^{-ib_\perp \cdot k_\perp} \widetilde{f}_1^a(x, b_\perp; \mu^2)$$

Rogers, Aybat, PRD 83 (11)
Collins, "Foundations of Perturbative QCD" (11)

possible schemes, e.g.,
Collins, Soper, Sterman, NPB250 (85)
Laenen, Sterman, Vogelsang, PRL 84 (00)
Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)

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collinear PDF

pQCD

nonperturbative part of evolution

nonperturbative part of TMD

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$\mu_b = 2e^{-\gamma_E}/b_*$ $\qquad b_* \equiv \dfrac{b_T}{\sqrt{1 + b_T^2/b_{\rm max}^2}}$ $\qquad$ *Collins, Soper, Sterman, NPB250 (85)*

$\mu_b = 2e^{-\gamma_E}/b_*$ $\qquad b_* \equiv b_{\rm max}\left(1 - e^{-\frac{b_T^4}{b_{\rm max}^4}}\right)^{1/4}$ $\qquad$ *Bacchetta, Echevarria, Mulders, Radici, Signori arXiv:1508.00402*

$\mu_b = Q_0 + q_T$ $\qquad b_* = b_T$ $\qquad$ *D'Alesio, Echevarria, Melis, Scimemi arXiv:1407.3311*

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$$-g_2 \frac{b_T^2}{2}$$

Collins, Soper, Sterman, NPB250 (85)

$$-2\, g_2 \ln\left(1 + \frac{b_T^2}{4}\right)$$

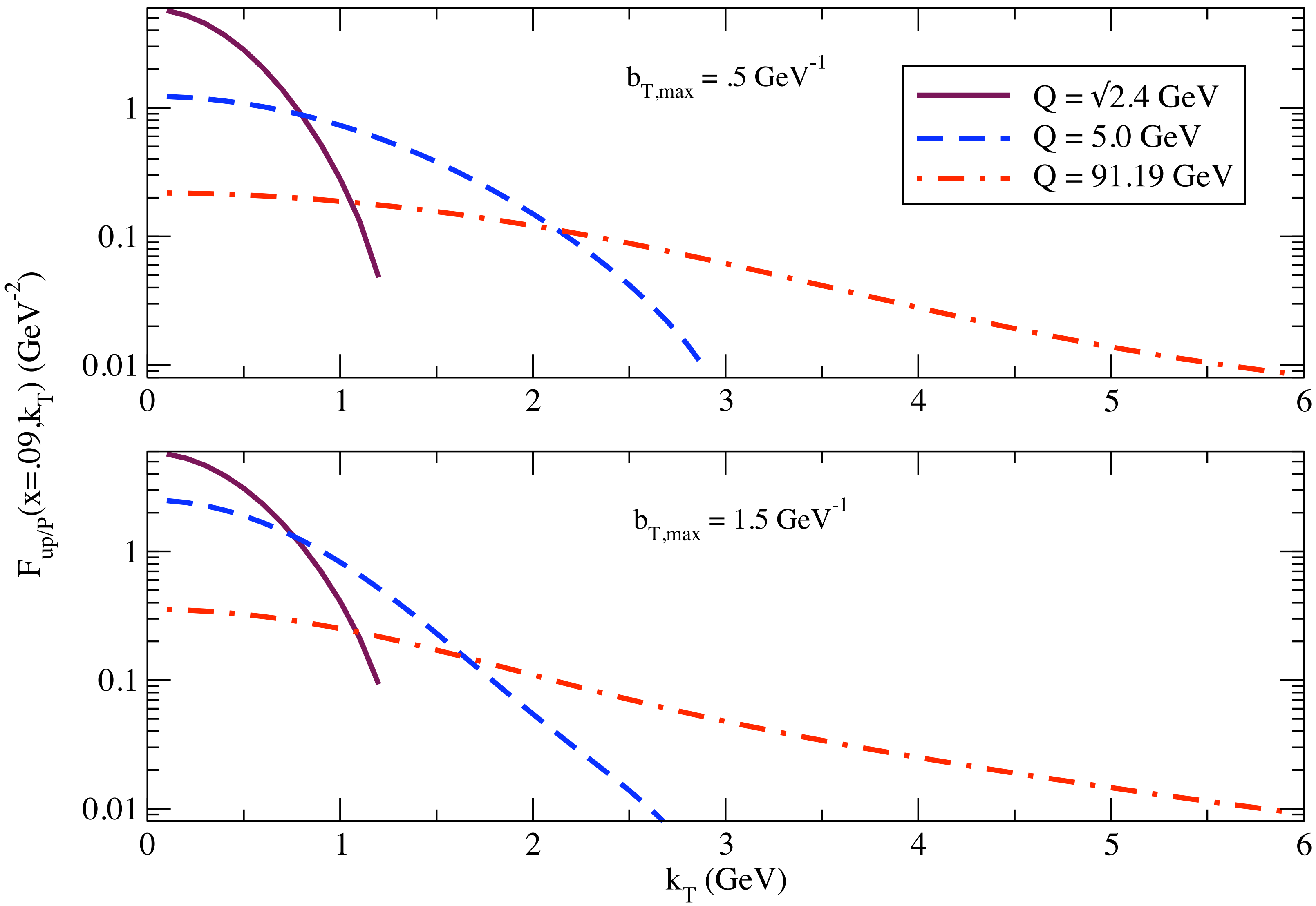
Aidala, Field, Gamberg, Rogers
arXiv:1401.2654

$$-g_0(b_{\rm max})\left(1 - \exp\left[-\frac{C_F \alpha_s(\mu_{b_*}) b_T^2}{\pi g_0(b_{\rm max}) b_{\rm max}^2}\right]\right)$$

Collins, Rogers
arXiv:1412.3820

TMD evolution: example

$$f_1(x,k_T;Q) = \frac{1}{2\pi}\int d^2b_T e^{-ik_T\cdot b_T}[C\otimes f_1](x,b_T)\, e^{-S'(b_T,Q)}\; e^{-S'_{\rm NP}(x,b_T,Q,\alpha_i)}$$



T. Rogers, M. Aybat, PRD83 (11)

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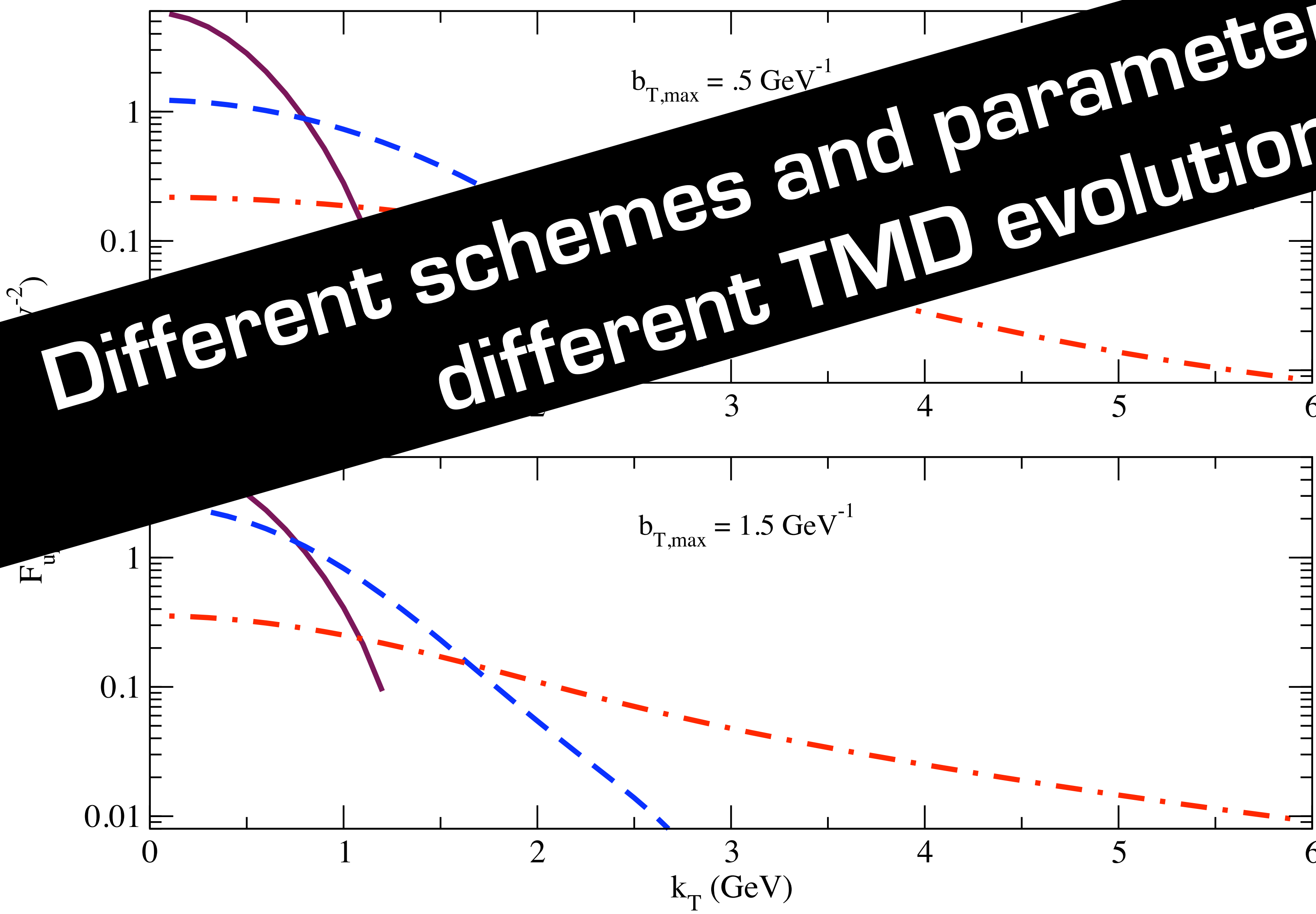


Different schemes and parameters lead to different TMD evolution

T. Rogers, M. Aybat, PRD83 (11)

Matching with fixed-order calculations

T. Rogers's talk

The W term
Good approximation
If
$q_{\mathrm{T}} \ll Q$

The Y term
Good approximation
If
$q_{\mathrm{T}} \gg m$

The Y term guarantees that the calculation at high P_{hT} agrees with perturbative calculation done with collinear factorization

Matching with fixed-order calculations

T. Rogers's talk

The W term

Good approximation

If

$q_{\mathrm{T}} \ll Q$

$$F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2) = x \sum_a \mathcal{H}_{UU,T}^a(Q^2;\mu^2) \int \frac{d\boldsymbol{b}_\perp^2}{4\pi} J_0(|\boldsymbol{b}_T||\boldsymbol{P}_{h\perp}|) \tilde{f}_1^a\big(x, z^2\boldsymbol{b}_\perp^2;\mu^2\big)\, \tilde{D}_1^{a\to h}\big(z, \boldsymbol{b}_\perp^2;\mu^2\big)$$
$$+ Y_{UU,T}\big(Q^2, \boldsymbol{P}_{hT}^2\big) + \mathcal{O}\big(M^2/Q^2\big)$$

The Y term

Good approximation

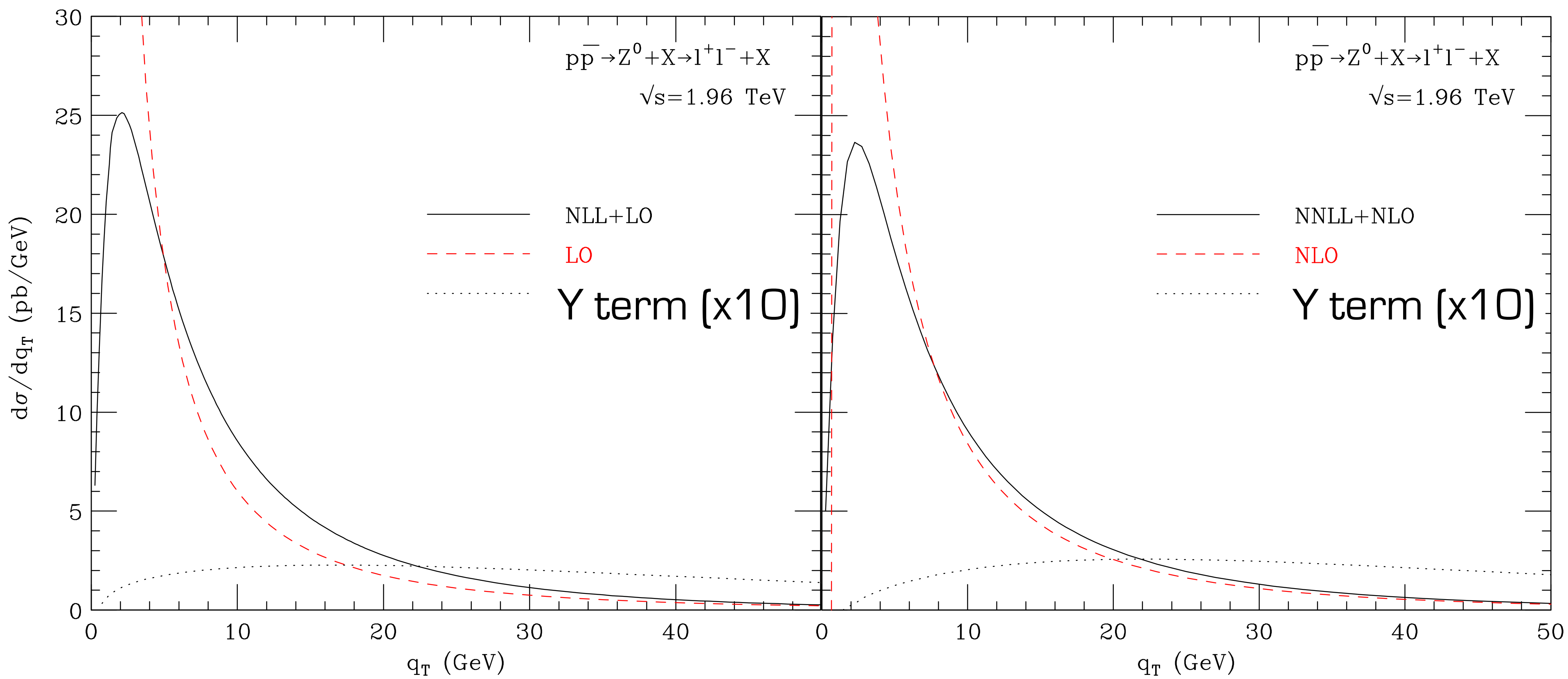
If

$q_{\mathrm{T}} \gg m$

The Y term guarantees that the calculation at high P_{hT} agrees with perturbative calculation done with collinear factorization

Matching with fixed-order calculations

G. Ferrera's talk

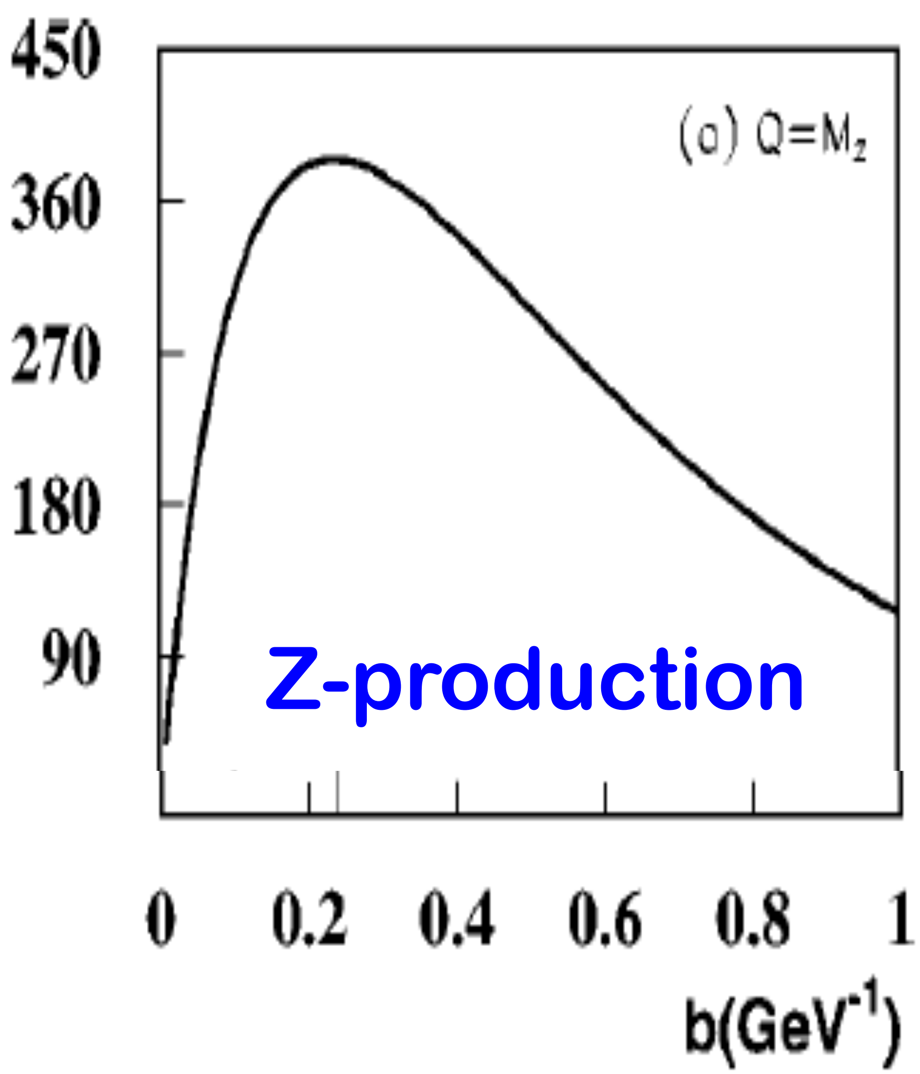


In these conditions, the matching works.
Almost the full range is dominated by resummation

$$\ln(Q^2b^2) \to \widetilde{L} \equiv \ln(Q^2b^2+1) \quad \Rightarrow \quad \exp\{\alpha_S^n \widetilde{L}^k\}|_{b=0} = 1 \;\Rightarrow\; \int_0^\infty dq_T^2 \left(\frac{d\hat{\sigma}}{dq_T^2}\right) = \hat{\sigma}^{(tot)}$$

In b_T space

J. Qiu's talk



$$\sqrt{s} = 1.8 \text{ TeV}$$

The cross section is dominated by the low-bT region

In b_T space

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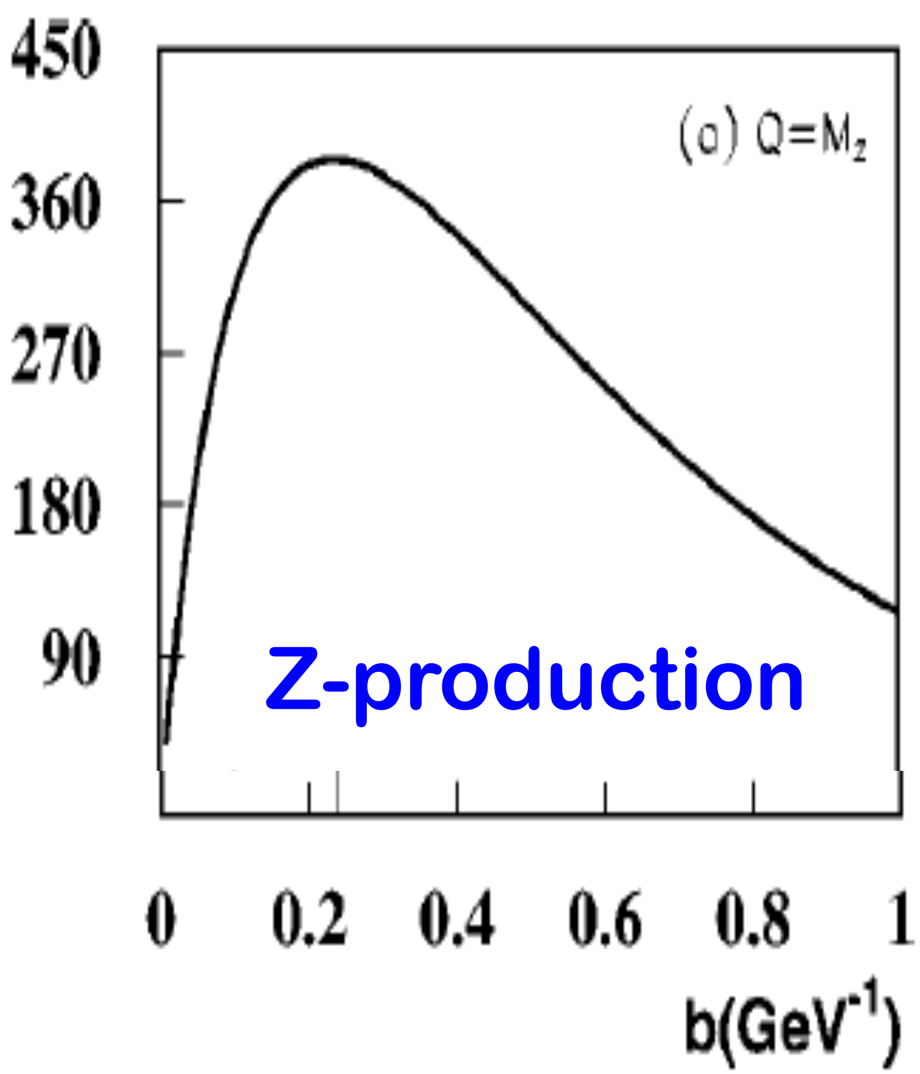

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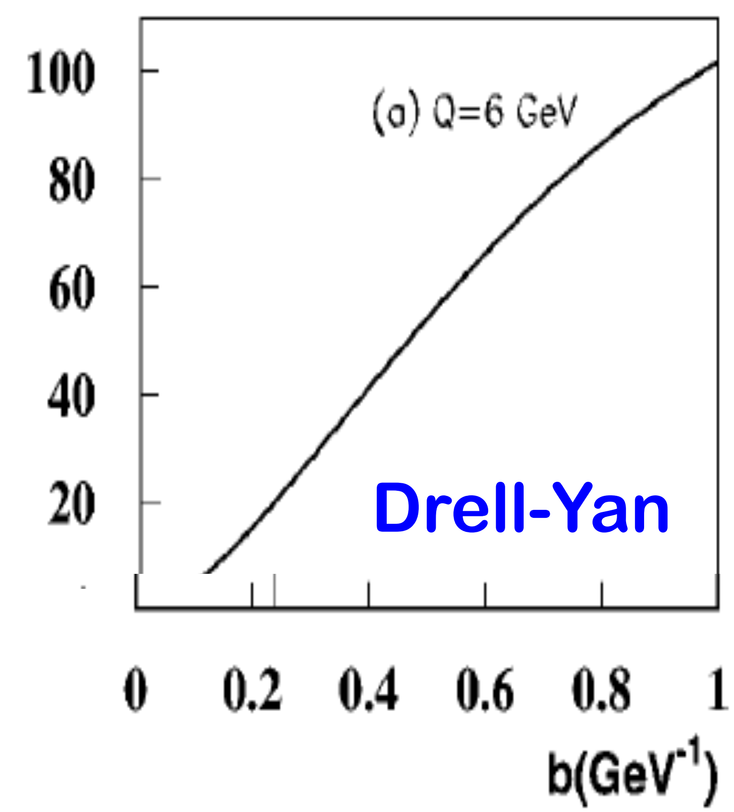


$$\sqrt{s} = 27.4\text{GeV}$$

The cross section is dominated by the low-bT region

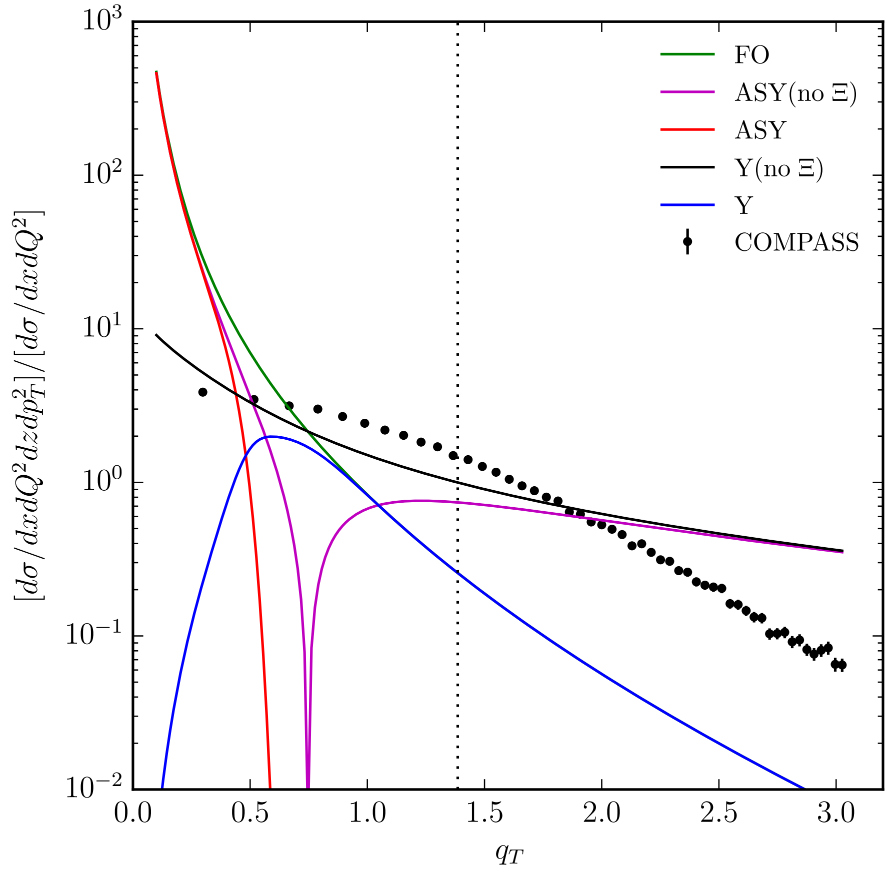
The situation is sharply different at lower energies

Matching with fixed-order calculations

N. Sato's talk

Issues with the standard recipe:

- FO is too small. The NLO calculation needed. (A. Daleo et al.)
- Y = FO − ASY is too big.
- Incomplete cancellation between W and ASY at large q_T $\rightarrow$new definition of $\mathbf{T}_{\mathrm{TMD}}^{\mathrm{New}}$ (T. Rogers talk)



$Q^2 = 1.92\mathrm{GeV}^2, x = 0.0318, z = 0.375$

One of the possible ways out

T. Rogers's talk

$$W_{\text{New}}(q_{\text{T}}, Q; \eta, C_5) = \Xi\left(\frac{q_{\text{T}}}{Q}, \eta\right) \int \frac{\mathrm{d}^2 \boldsymbol{b}_{\text{T}}}{(2\pi)^2} e^{i\boldsymbol{q}_{\text{T}}\cdot\boldsymbol{b}_{\text{T}}} \tilde{W}^{\text{OPE}}(b_*(b_c(b_{\text{T}})), Q) \tilde{W}_{\text{NP}}(b_c(b_{\text{T}}), Q)$$

– $$b_*(b_c(b_{\text{T}})) = \sqrt{\frac{b_{\text{T}}^2 + C_1^2/\mu_{\text{max}}^2}{1 + b_{\text{T}}^2/b_{\text{max}}^2 + C_1^2/(\mu_{\text{max}}^2 b_{\text{max}}^2)}}$$

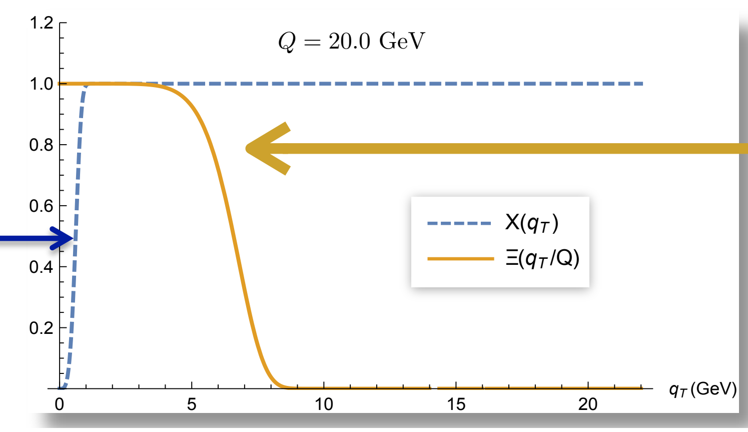
$$\boxed{\bar{\mu} \equiv \frac{C_1}{b_*(b_c(b_{\text{T}}))}}$$

Use in OPE

Y_{new} $$\Longrightarrow X(q_{\text{T}}/\lambda)\text{Approx. } 2\left[\ \Gamma(q_{\text{T}}, Q) - \overline{\text{Approx. } 1}\left[\ \Gamma(q_{\text{T}}, Q)\ \right]\ \right]$$

λ = hadronic mass scale (ResBos ≈ 0.5-1.5 GeV)

Blue Curve

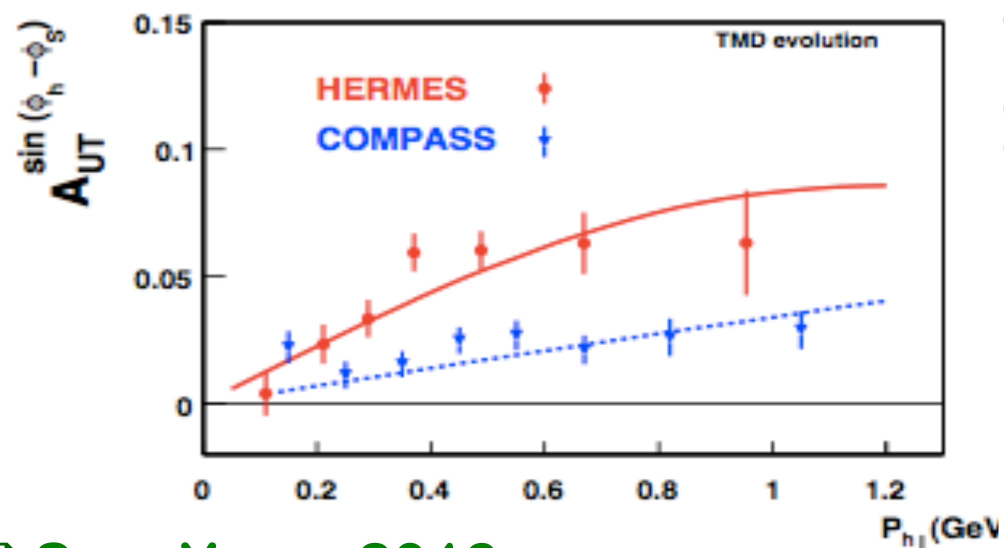


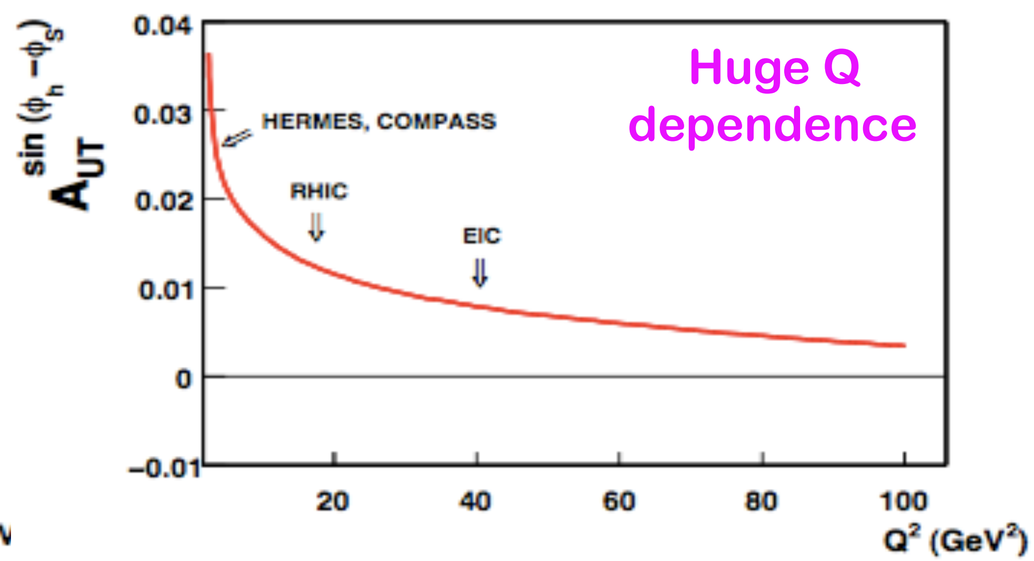
λ Corresponds to Q_T^{min} in CSS, 1985

Effect of evolution parameter choices

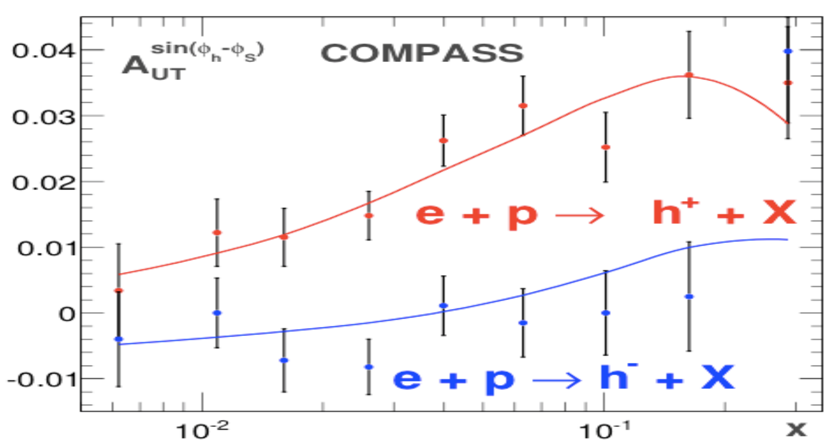
J. Qiu's talk

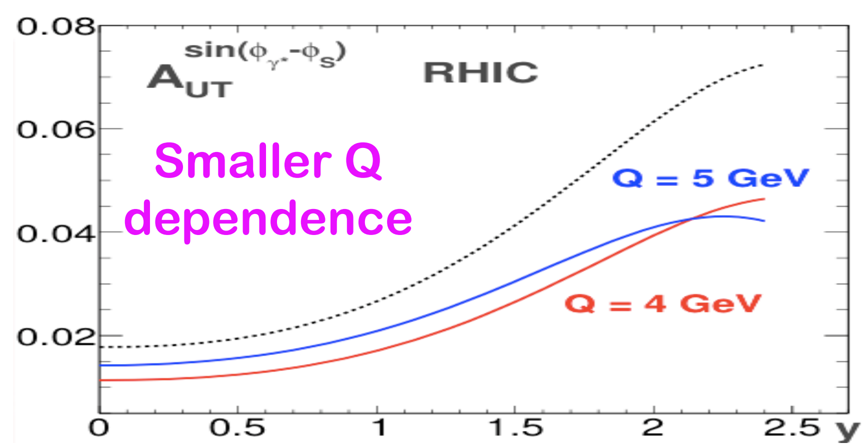
- **Aybat, Prokudin, Rogers, 2012:**





- **Sun, Yuan, 2013:**



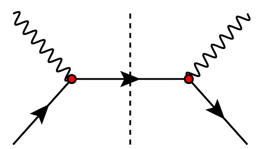
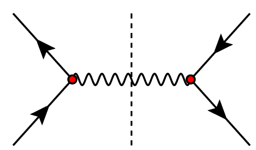
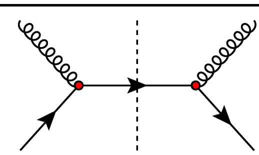
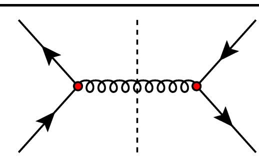


No disagreement on evolution equations!

Issues: Extrapolation to non-perturbative large b-region
Choice of the Q-dependent "form factor"

Intricacies of Wilson lines

P. Mulders's talk

	$f_{1T}^{\perp}$	$h_{1T}^{\perp(A)}$	$h_{1T}^{\perp(B1)}$	$h_{1T}^{\perp g(B2)}$
	1	1	1	0
	-1	1	1	0
	$-\frac{N_c^2+1}{N_c^2-1}$	1	1	$\frac{N_c^2}{N_c^2-1}$
	$\frac{N_c^2+1}{N_c^2-1}$	1	1	$\frac{N_c^2}{N_c^2-1}$

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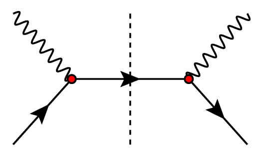
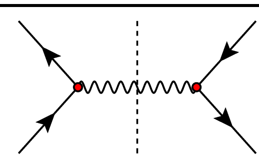
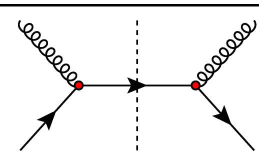
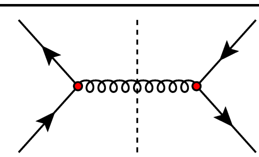
	1	1	1	0
	-1	1	1	0
	$-\frac{N_c^2+1}{N_c^2-1}$	1	1	$\frac{N_c^2}{N_c^2-1}$
	$\frac{N_c^2+1}{N_c^2-1}$	1	1	$\frac{N_c^2}{N_c^2-1}$

- There are in principle three different pretzelosity functions

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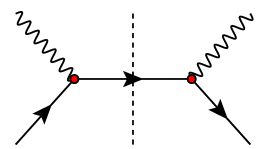
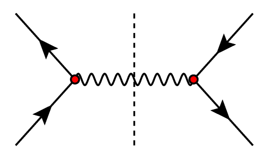
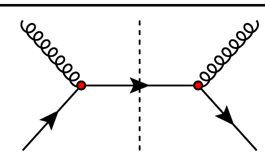
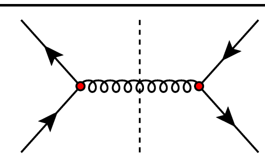
	1	1	1	0
	-1	1	1	0
	$-\frac{N_c^2+1}{N_c^2-1}$	1	1	$\frac{N_c^2}{N_c^2-1}$
	$\frac{N_c^2+1}{N_c^2-1}$	1	1	$\frac{N_c^2}{N_c^2-1}$

- There are in principle three different pretzelosity functions
- In DY and SIDIS only one combination is present

Intricacies of Wilson lines

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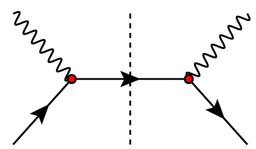
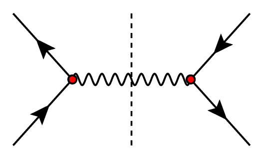
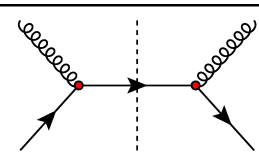
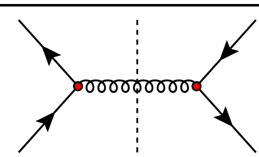
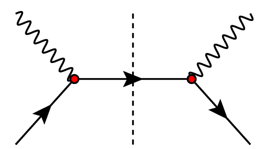
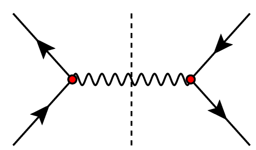
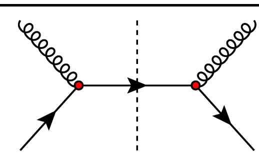
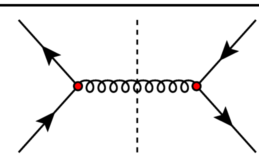
	1	1	1	0
	-1	1	1	0
	$-\frac{N_c^2+1}{N_c^2-1}$	1	1	$\frac{N_c^2}{N_c^2-1}$
	$\frac{N_c^2+1}{N_c^2-1}$	1	1	$\frac{N_c^2}{N_c^2-1}$

- There are in principle three different pretzelosity functions
- In DY and SIDIS only one combination is present
- In processes involving colors in the initial and final states, even T-even functions become process dependent...

Intricacies of Wilson lines

P. Mulders's talk

	$f_{1T}^{\perp}$	$h_{1T}^{\perp(A)}$	$h_{1T}^{\perp(B1)}$	$h_{1T}^{\perp g(B2)}$
	1	1	1	0
	-1	1	1	0
	$-\frac{N_c^2+1}{N_c^2-1}$	1	1	$\frac{N_c^2}{N_c^2-1}$
	$\frac{N_c^2+1}{N_c^2-1}$	1	1	$\frac{N_c^2}{N_c^2-1}$

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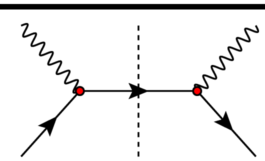
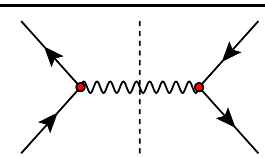
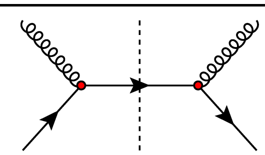
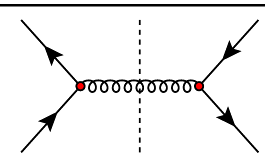
	1	1	1	0
	-1	1	1	0
	$-\frac{N_c^2+1}{N_c^2-1}$	1	1	$\frac{N_c^2}{N_c^2-1}$
	$\frac{N_c^2+1}{N_c^2-1}$	1	1	$\frac{N_c^2}{N_c^2-1}$

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- In DY and SIDIS only one combination is present
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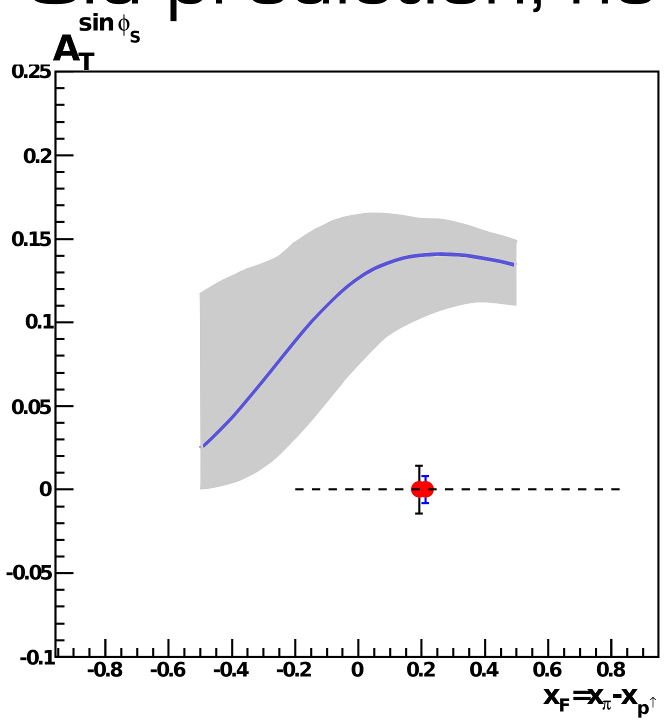
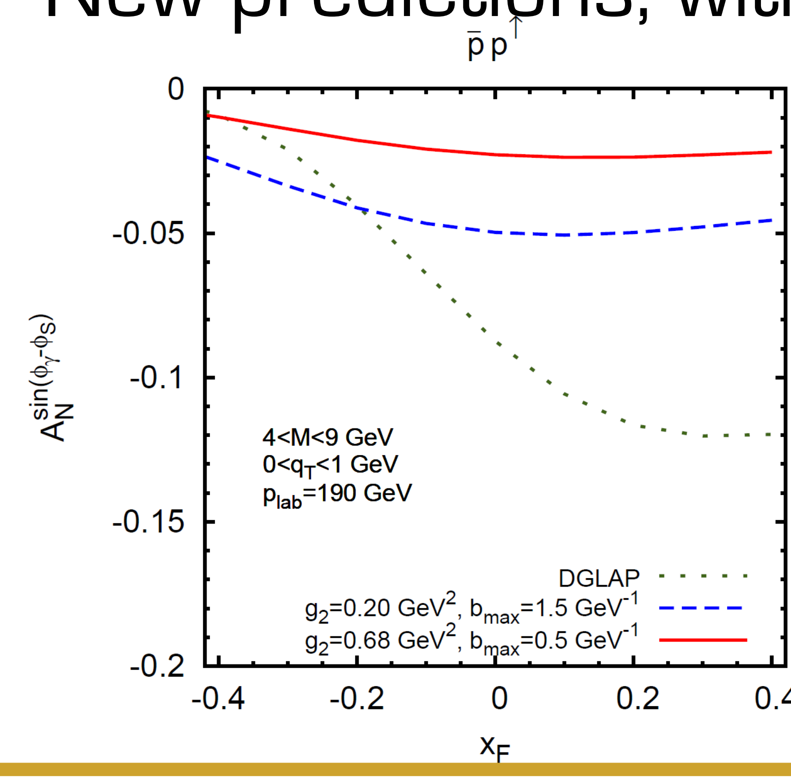
...but factorization is expected to fail anyway

Sign change of Sivers function

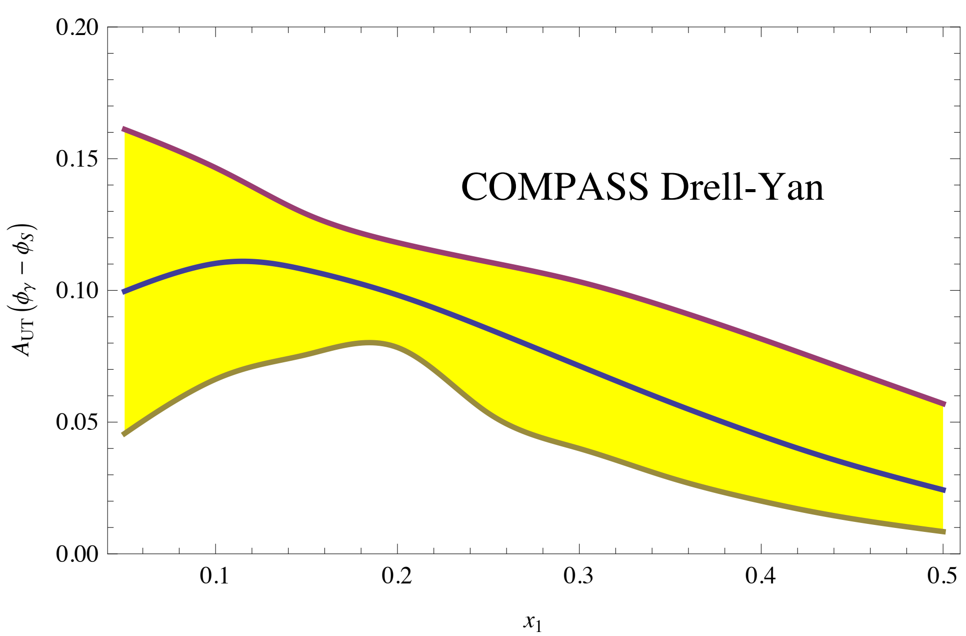
Old prediction, no evo



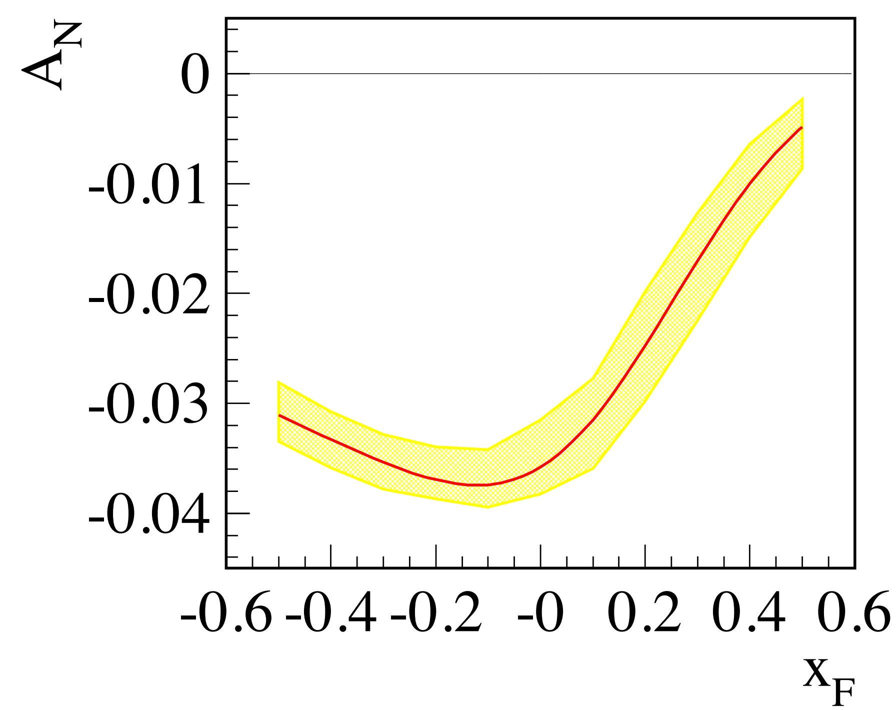
New predictions, with evo



Sun-Yuan, with evo



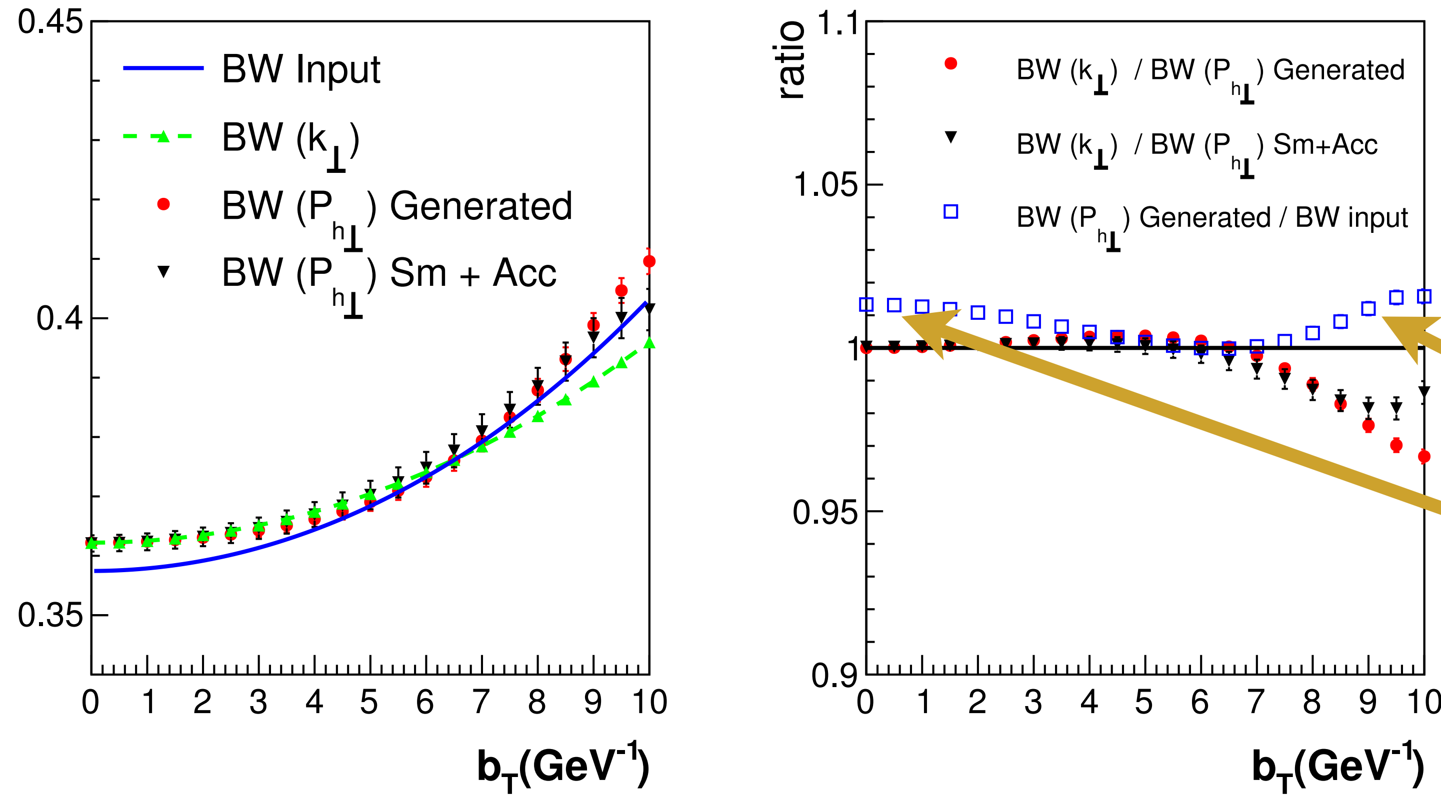
Echevarria et al., with evo



TMD extractions: phenomenology issues

Bessel weighting

L. Gamberg's talk

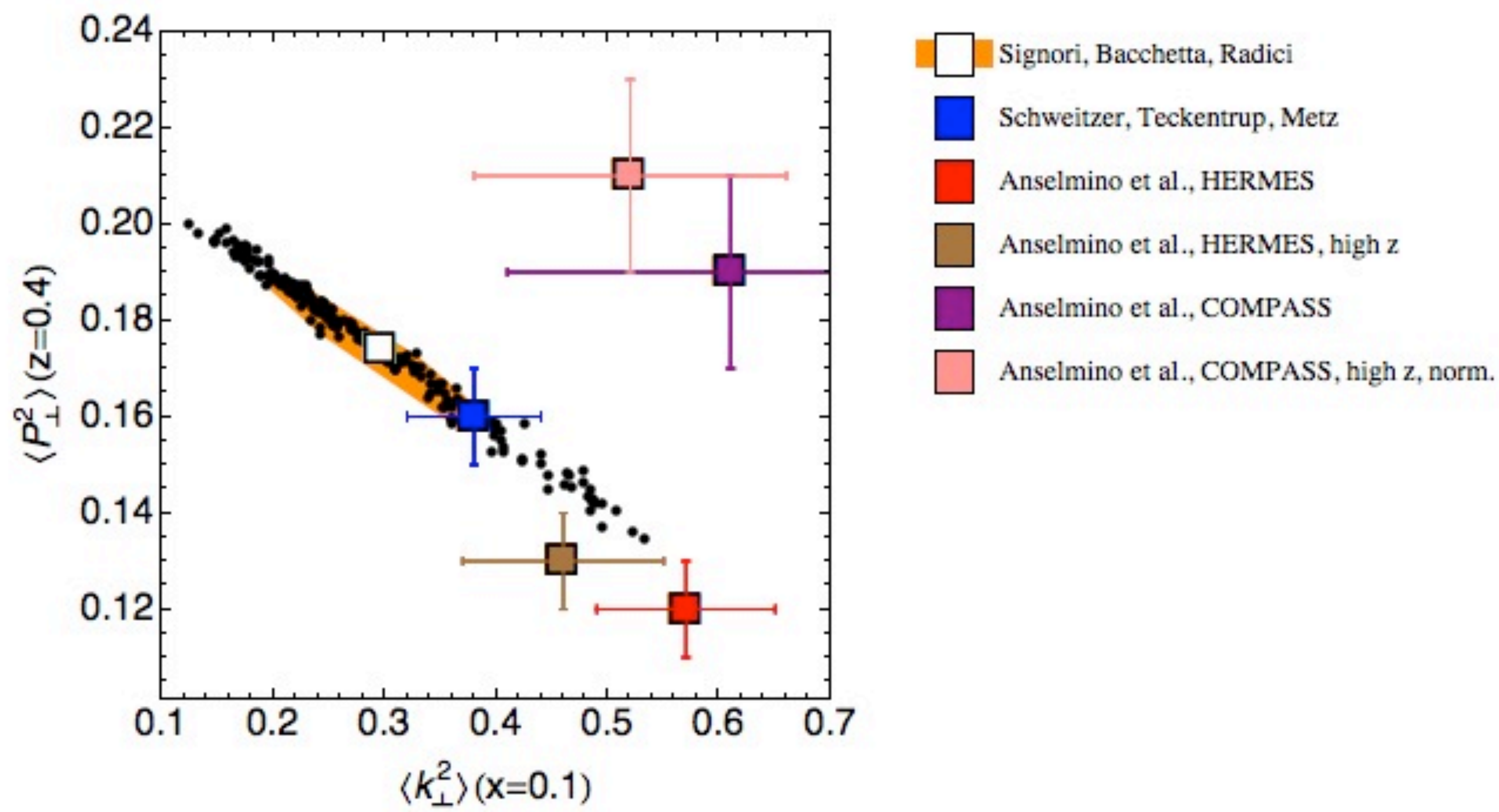


Deviations, but apparently small

Compare w/ the Monte Carlo generated distribution using Eq (full red points) labeled "BW(Ph⊥) Generated",

$$A_{LL}^{J_0(b_T P_{h\perp})}(b_T) = \frac{\sum_j^{N^+} J_0(b_T P_{h\perp j}^{[+]}) - \sum_j^{N^-} J_0(b_T P_{h\perp j}^{[-]})}{\sum_j^{N^+} J_0(b_T P_{h\perp j}^{[+]}) + \sum_j^{N^-} J_0(b_T P_{h\perp j}^{[-]})}$$

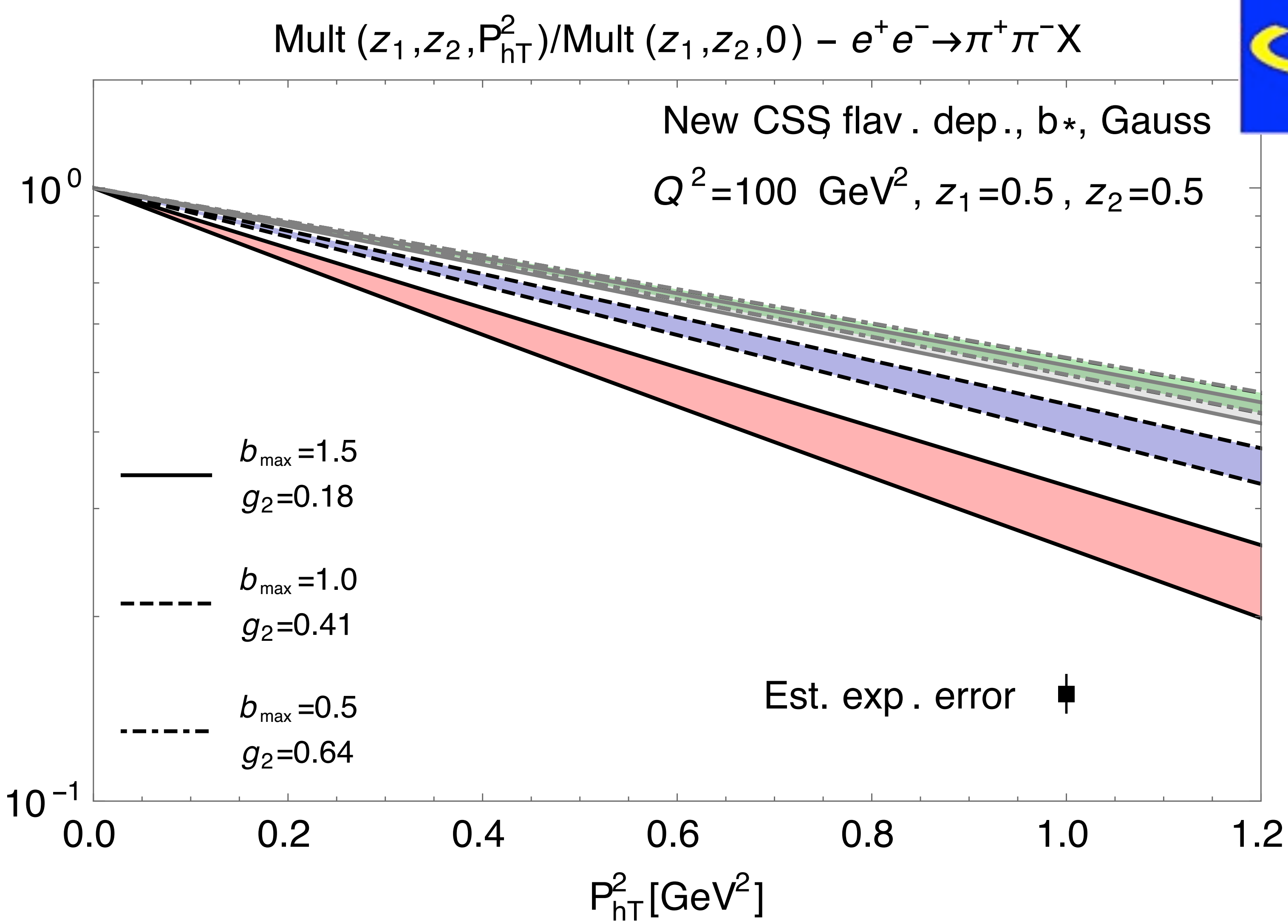
Comparison



Transverse momentum in FFs

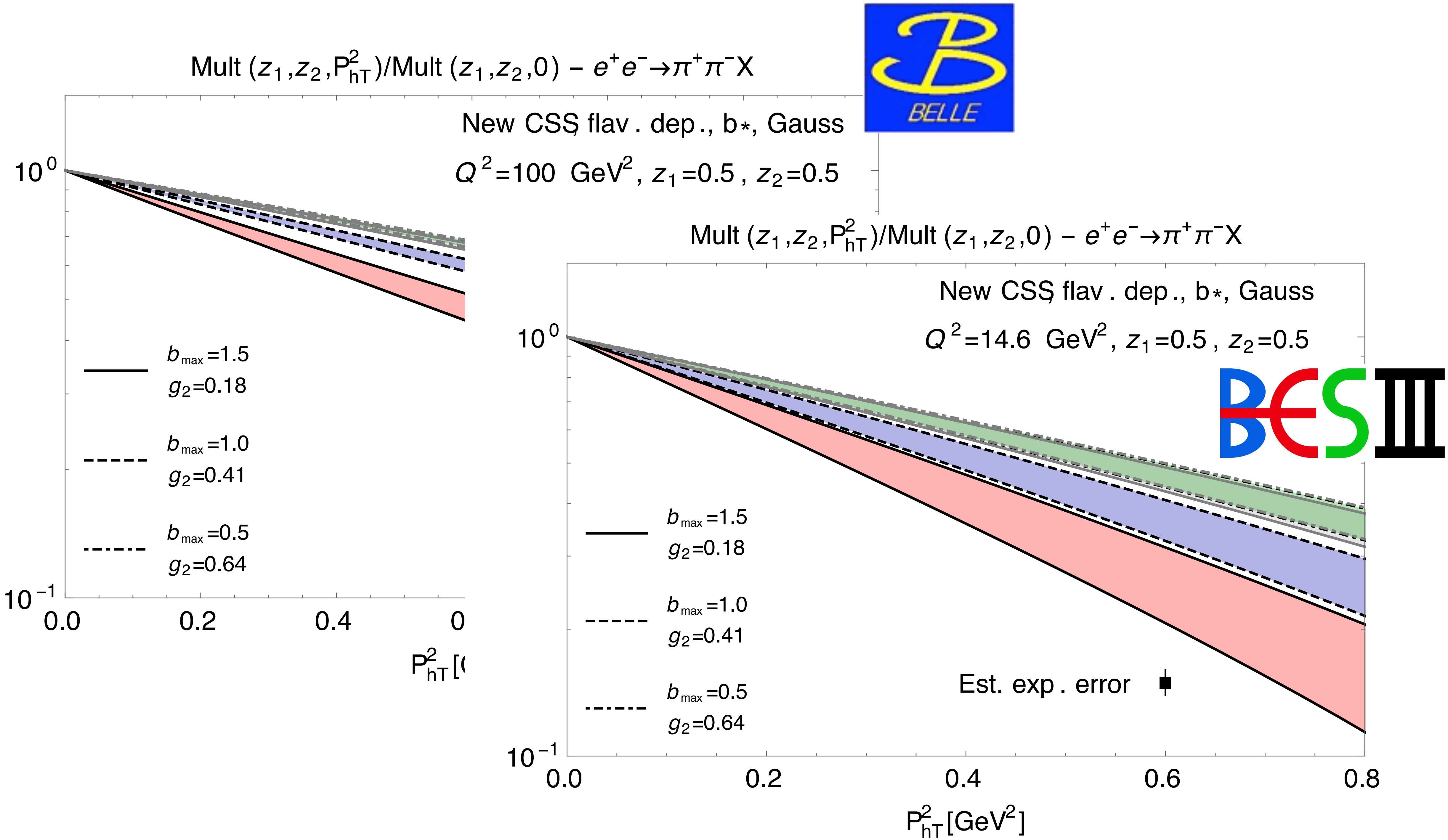
Transverse momentum in PDFs

Evolution of TMD fragmentation funct.



Bacchetta, Echevarria, Mulders, Radici, Signori, arXiv:1508.00402

Evolution of TMD fragmentation funct.



Bacchetta, Echevarria, Mulders, Radici, Signori, arXiv:1508.00402

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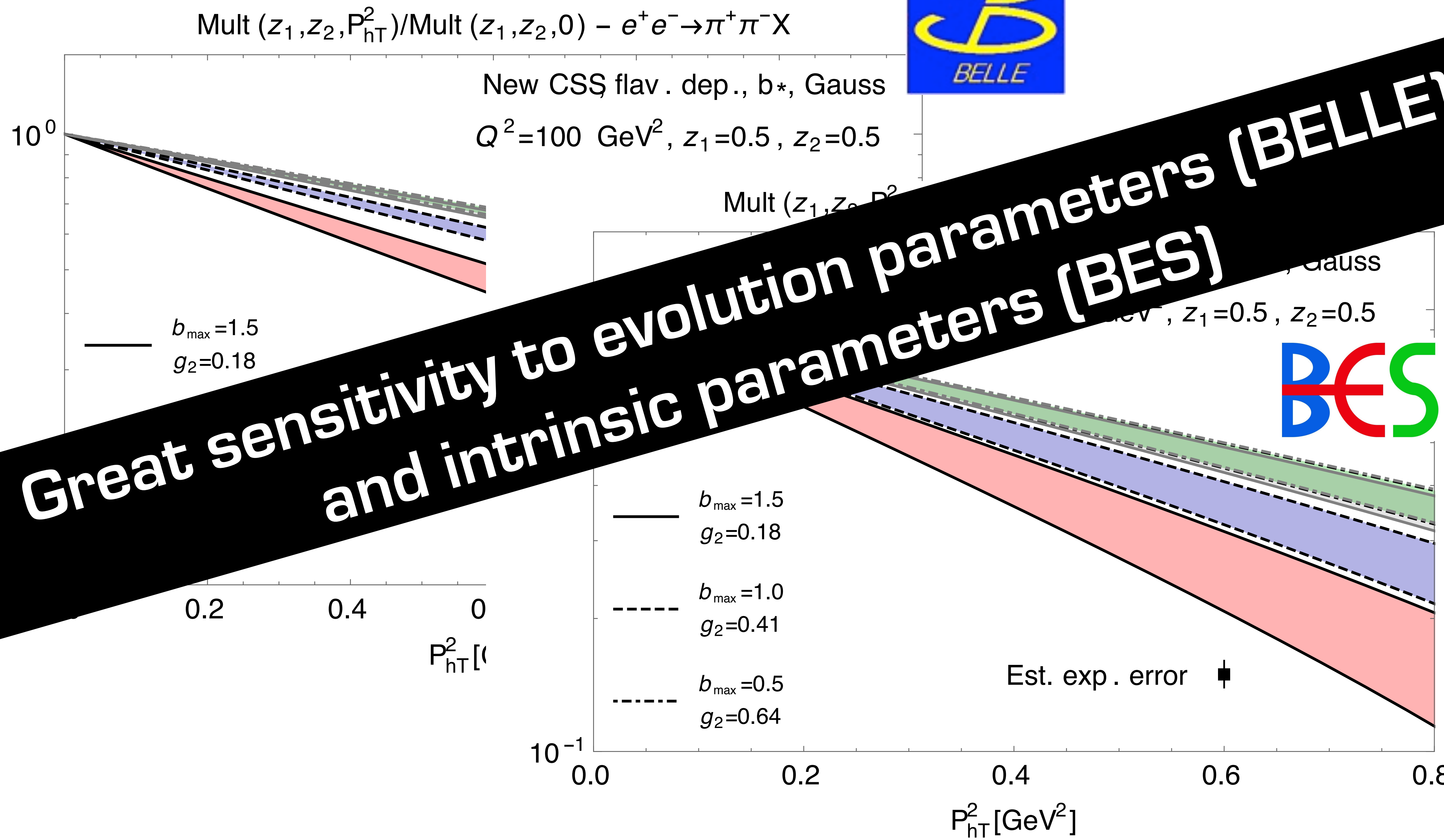
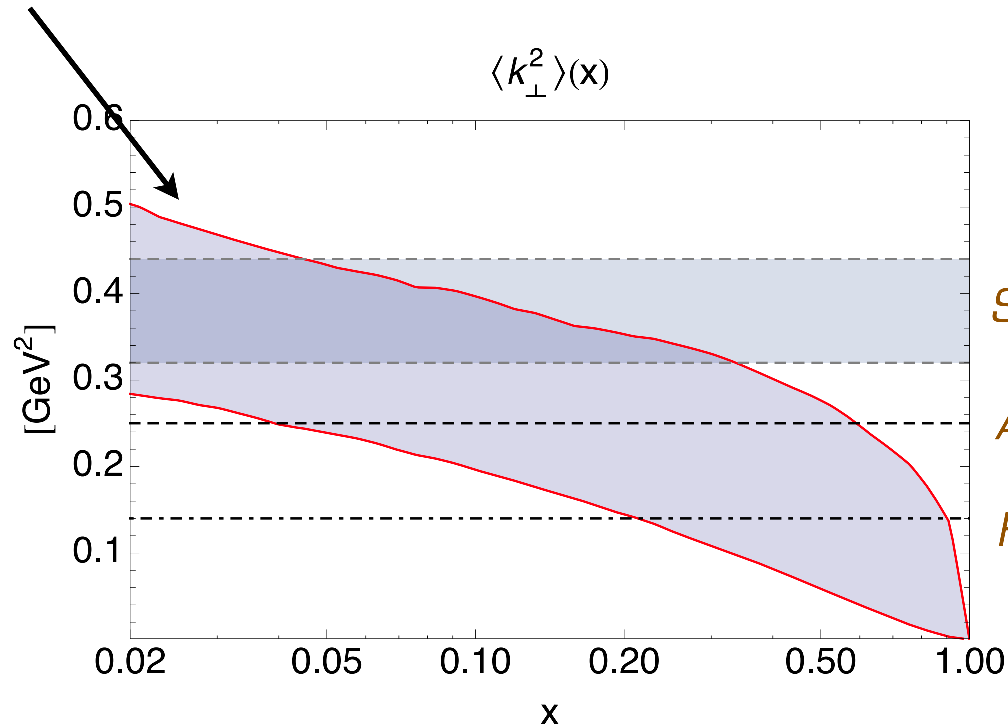


Great sensitivity to evolution parameters (BELLE) and intrinsic parameters (BES)

Bacchetta, Echevarria, Mulders, Radici, Signori, arXiv:1508.00402

x-behavior of TMDs

Signori, Bacchetta, Radici, Schnell JHEP 1311 (13)



Schweitzer, Teckentrup, Metz, PRD 81 (2010)

Anselmino et al., PRD 71 (2005)

HERMES gmc_trans

x-behavior of TMDs

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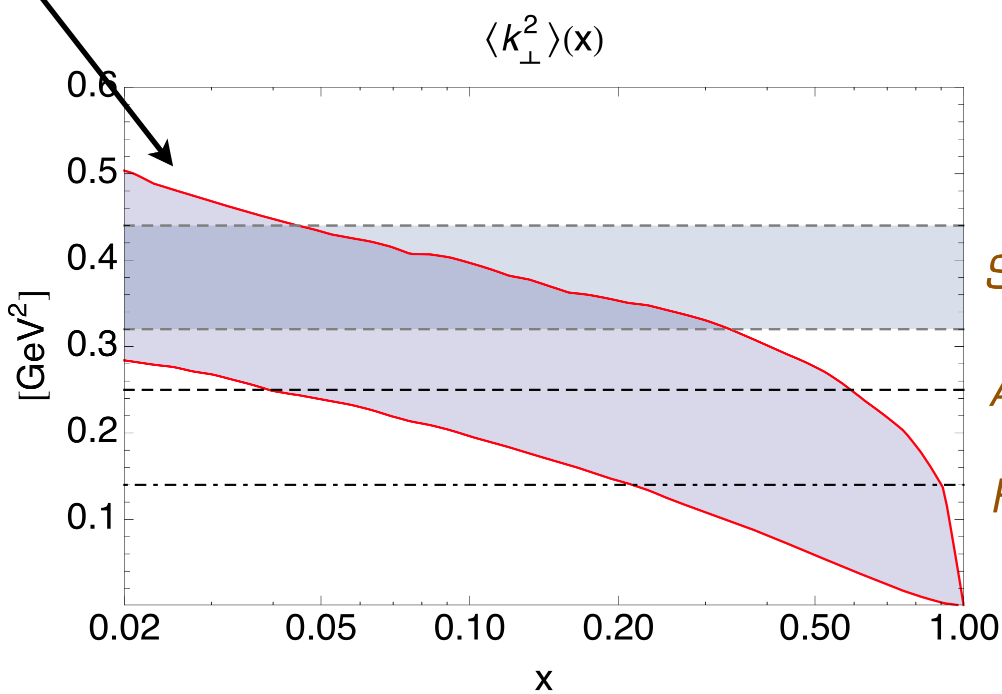

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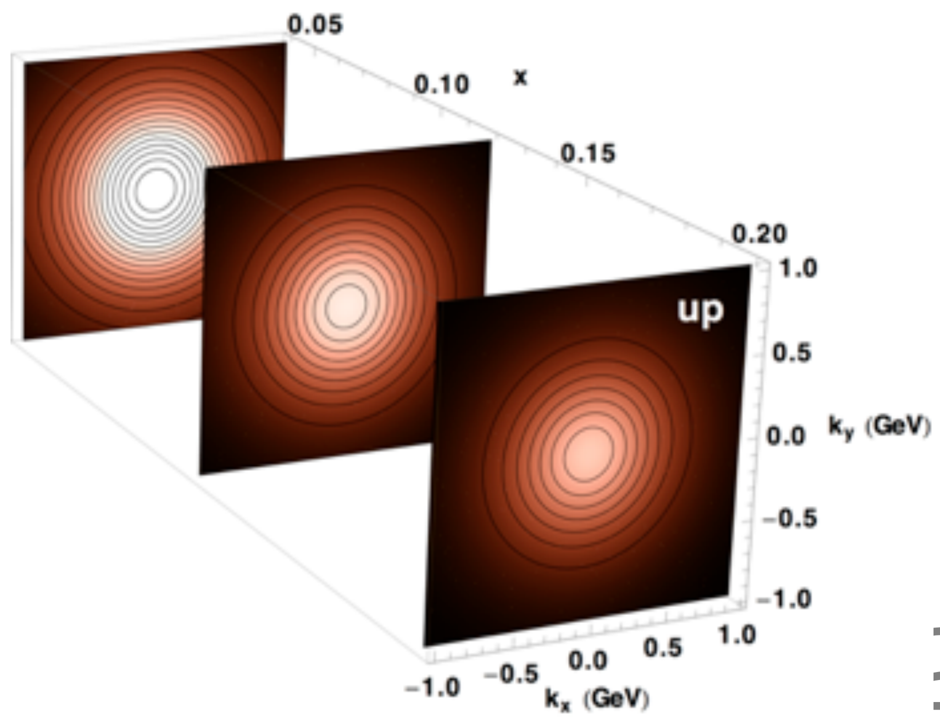
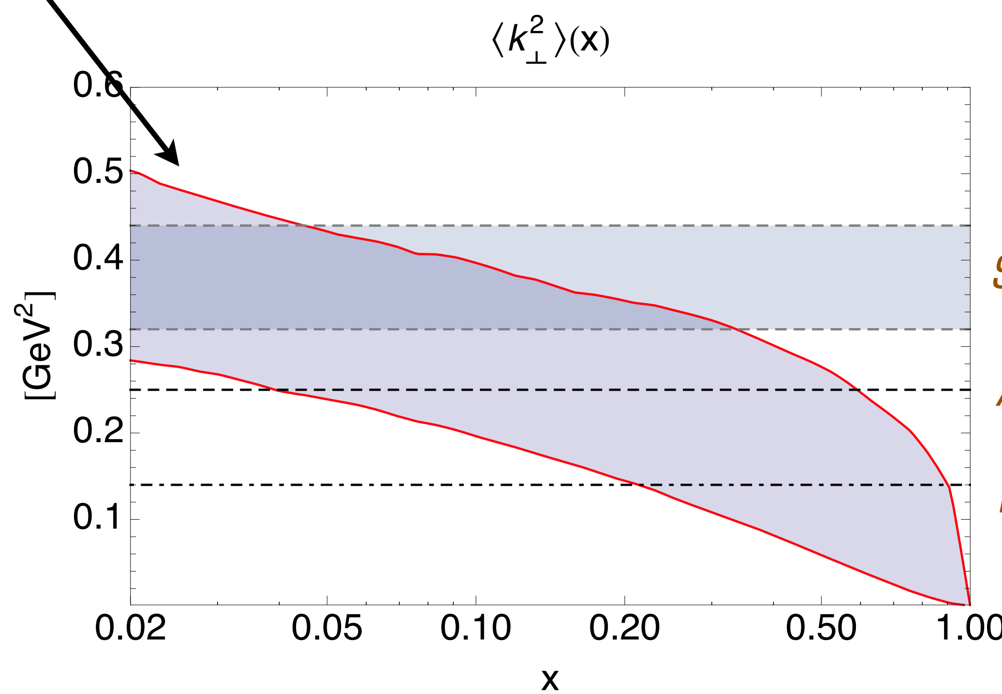


Still difficult to say, but possibly a widening at lower x

x-behavior of TMDs

Signori, Bacchetta, Radici, Schnell JHEP 1311 (13)



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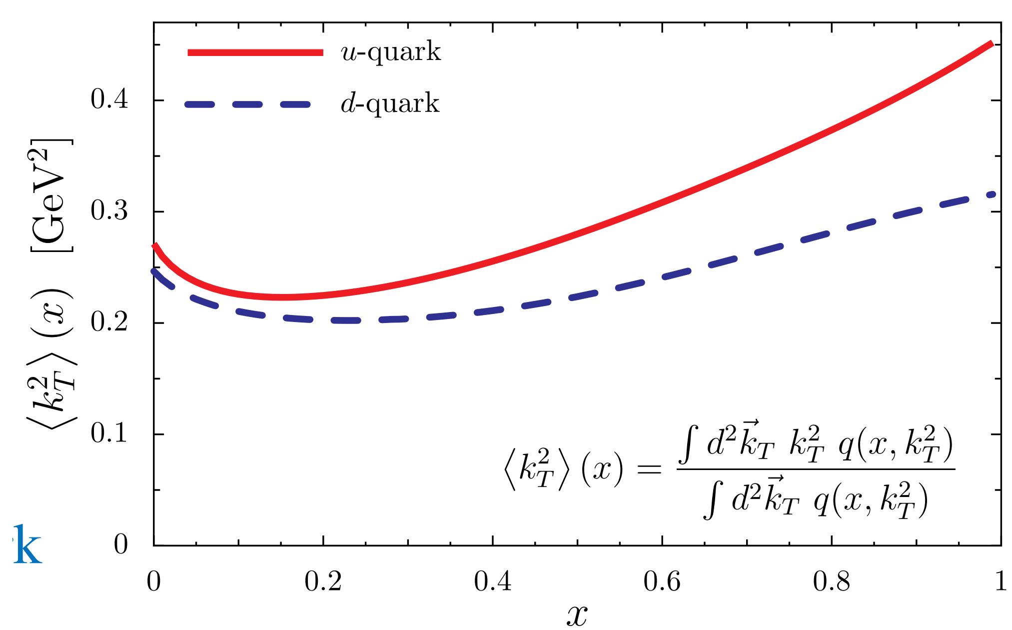


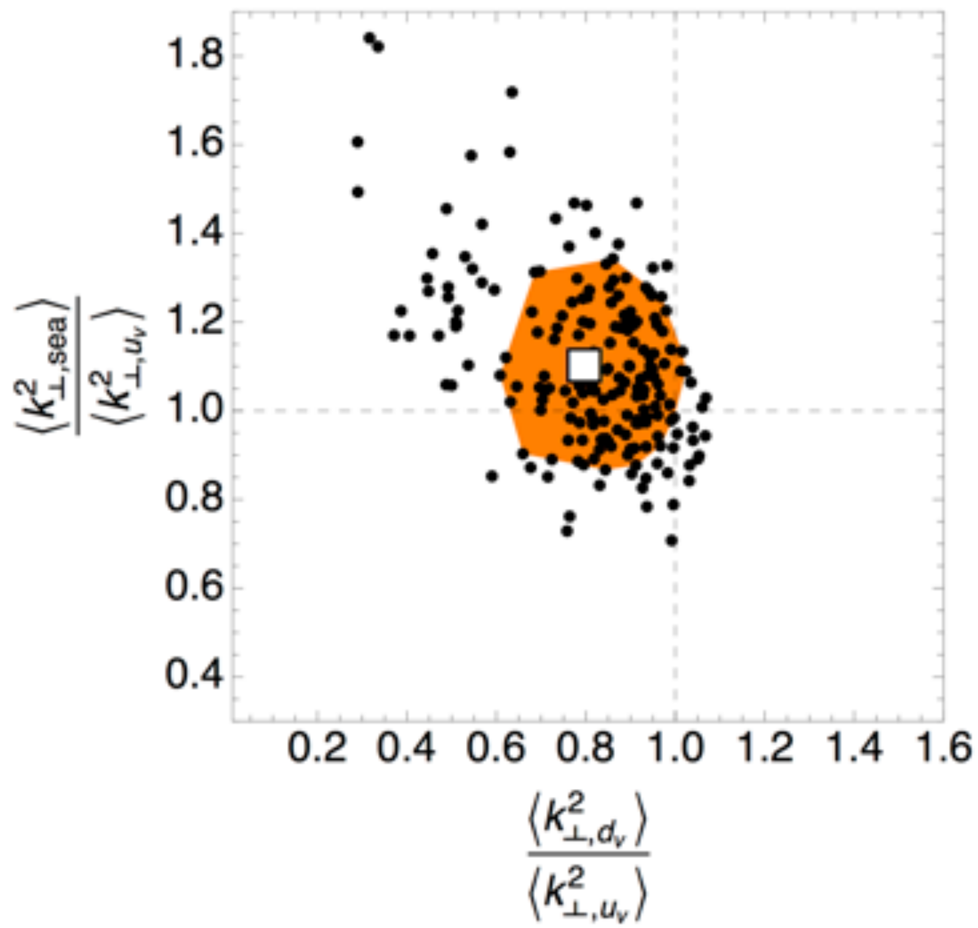
diquark model

I. Cloet's talk

Flavor structure of TMDs

Signori, Bacchetta, Radici, Schnell JHEP 1311 (13)

Ratio of width of sea /
width of up valence

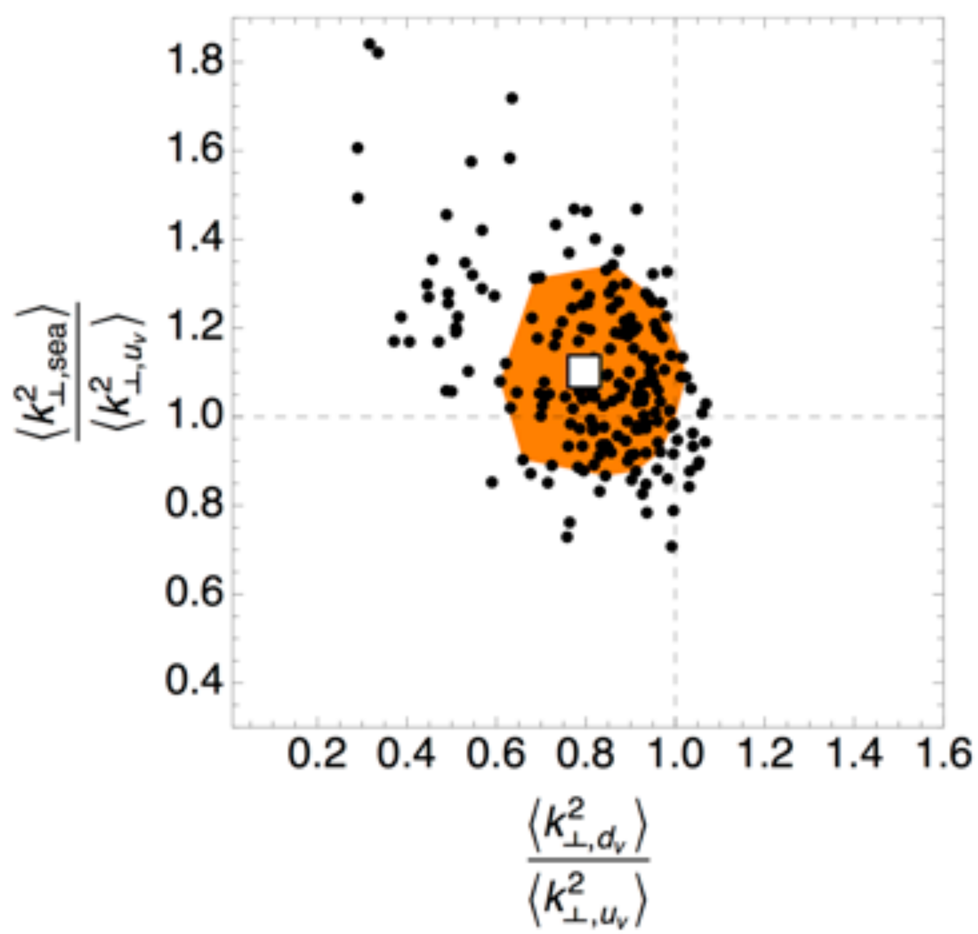


Ratio width of down valence/
width of up valence

Flavor structure of TMDs

Signori, Bacchetta, Radici, Schnell JHEP 1311 (13)

Ratio of width of sea / width of up valence



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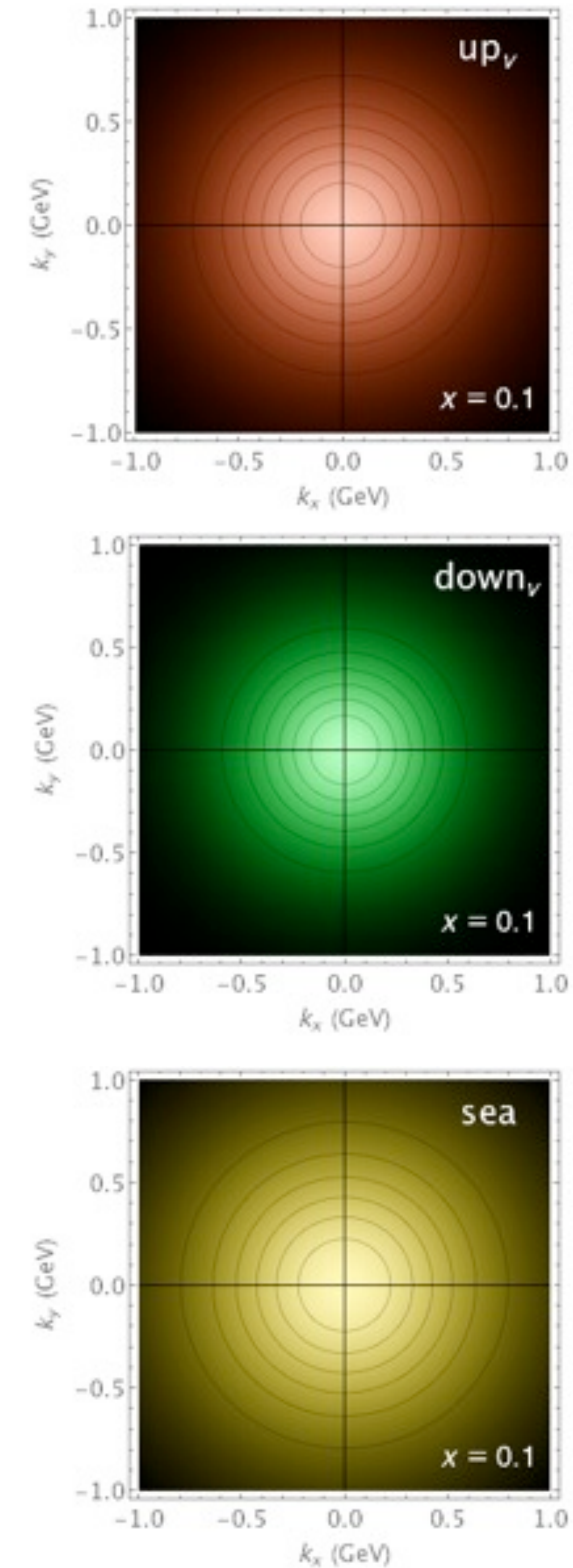

Flavor structure of TMDs

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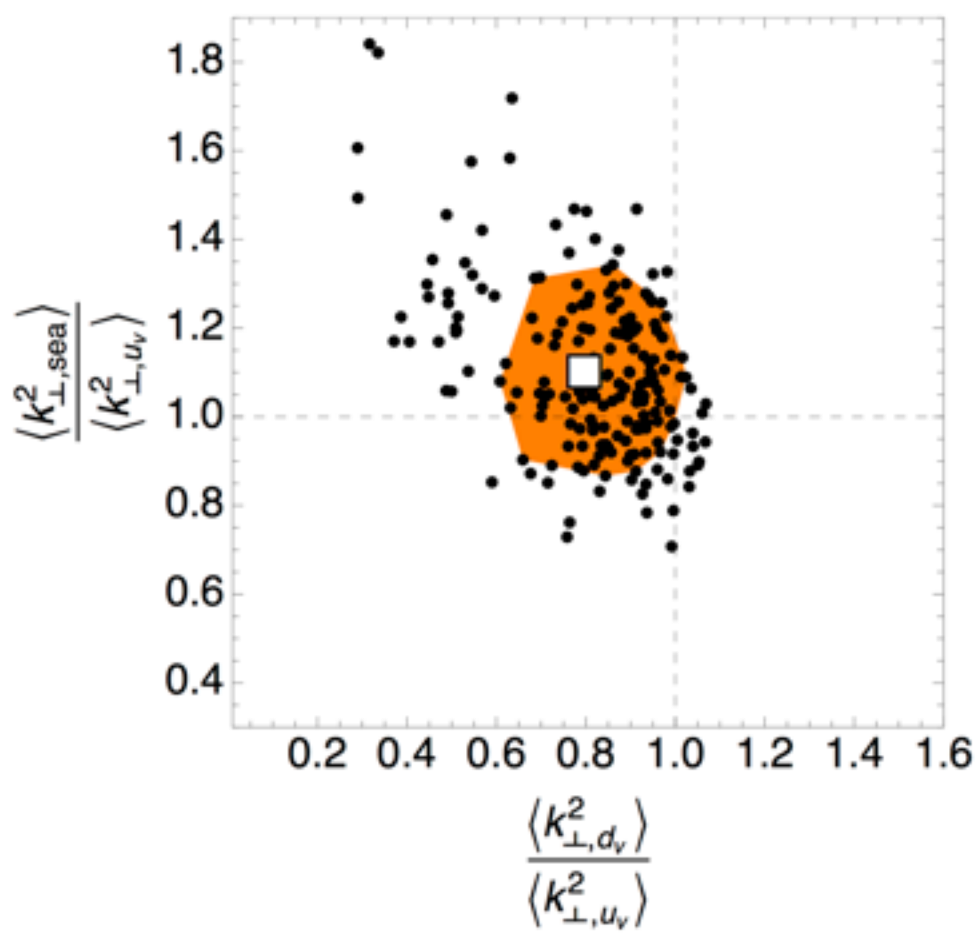

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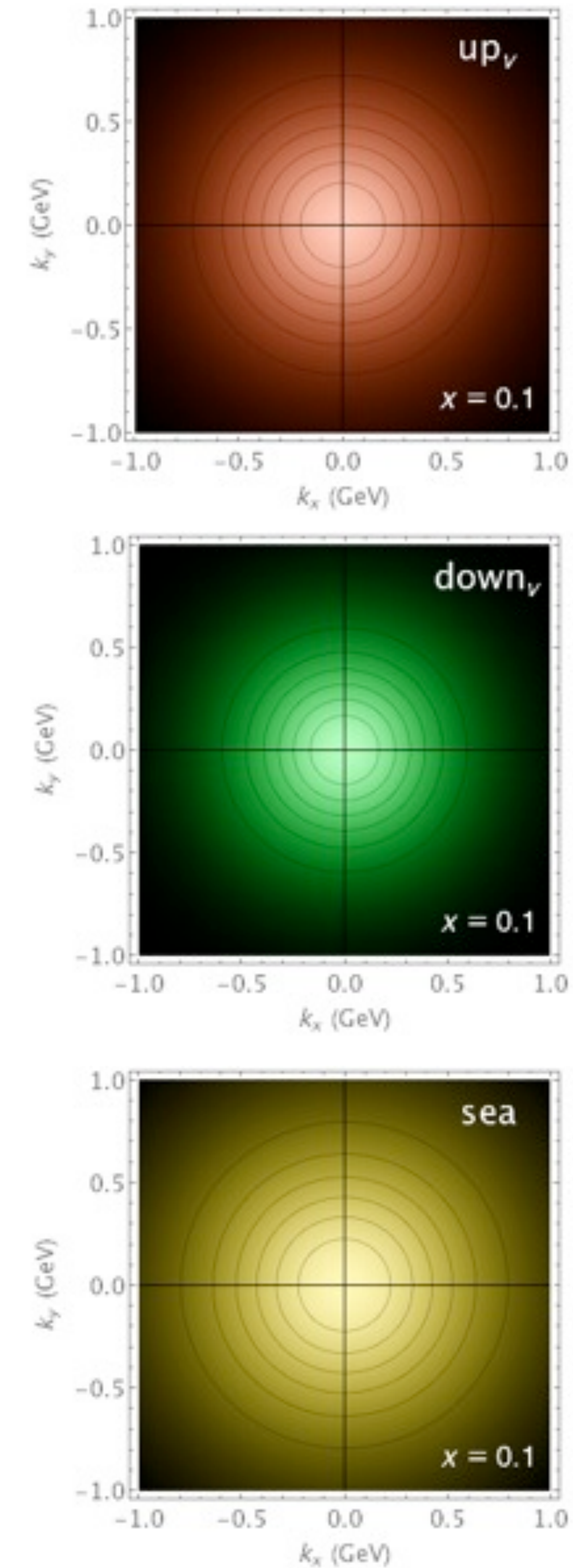
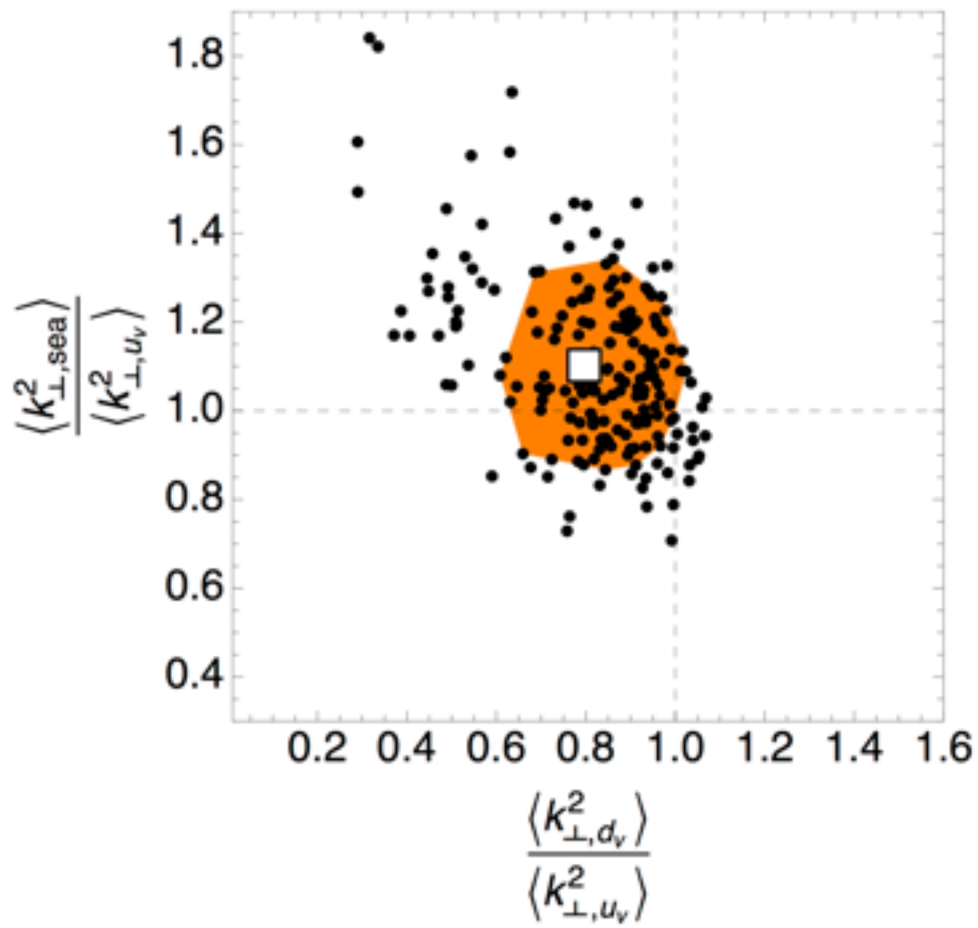


Indications that width of down < up < sea

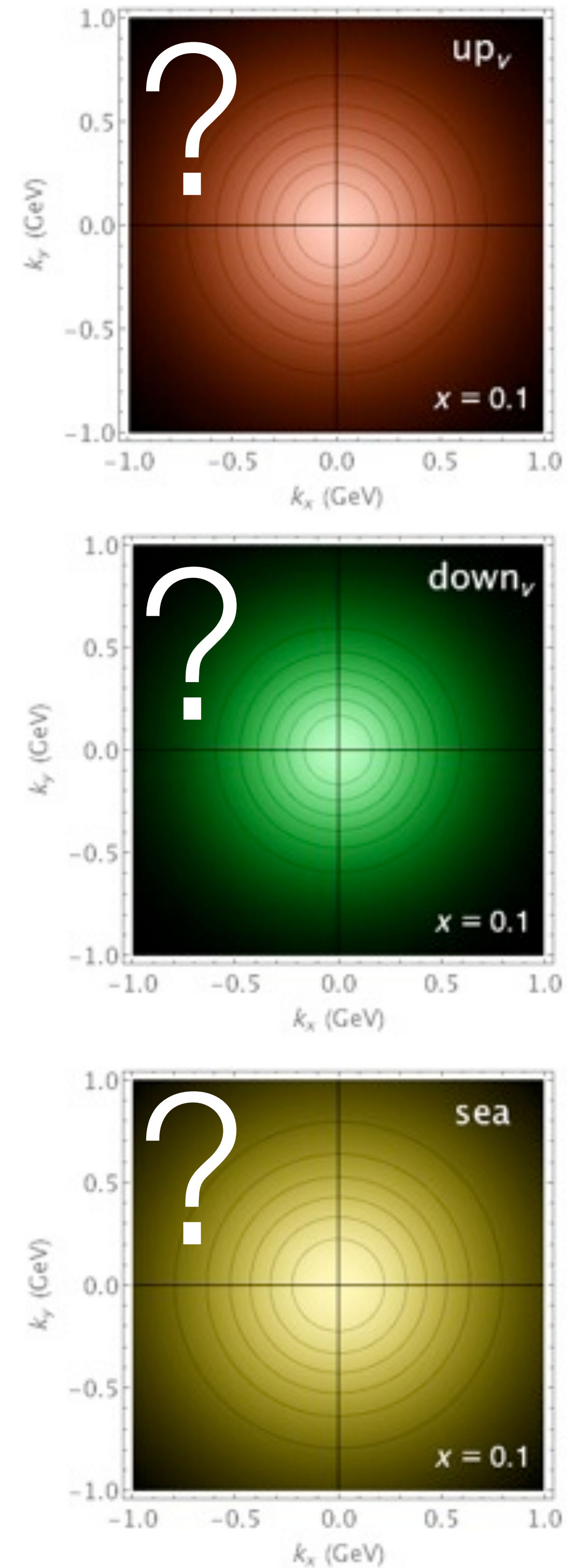
Flavor structure of TMDs

Signori, Bacchetta, Radici, Schnell JHEP 1311 (13)

Ratio of width of sea / width of up valence



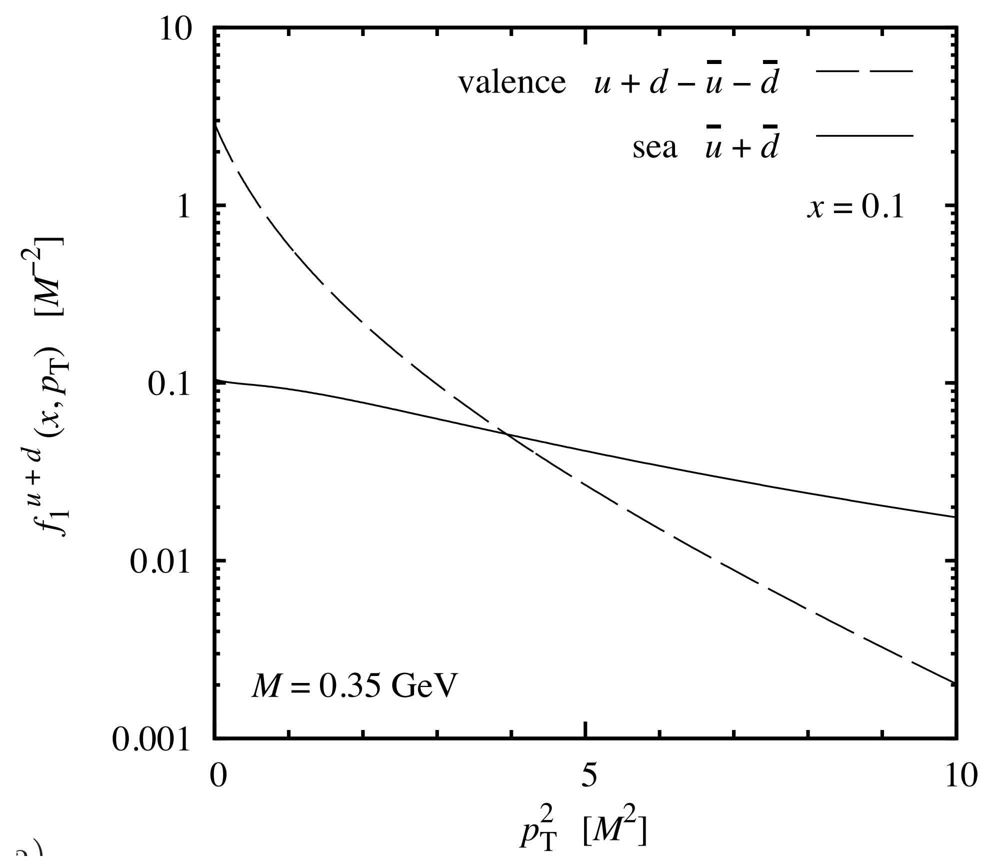
Ratio width of down valence/ width of up valence



Indications that width of down < up < sea

Chiral quark soliton model

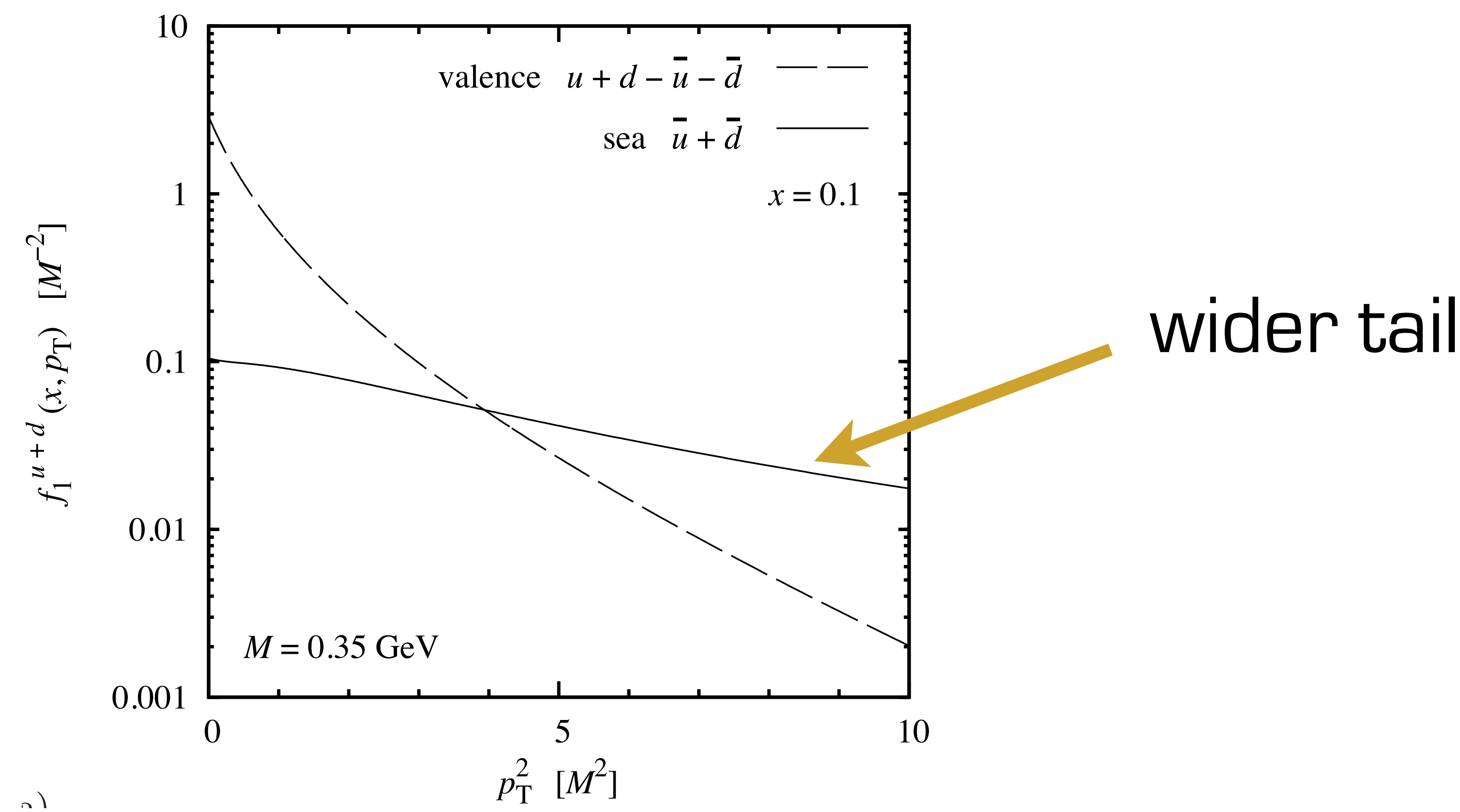
P. Schweitzer's talk



Schweitzer, Strikman, Weiss, JHEP 1301 (13)

Chiral quark soliton model

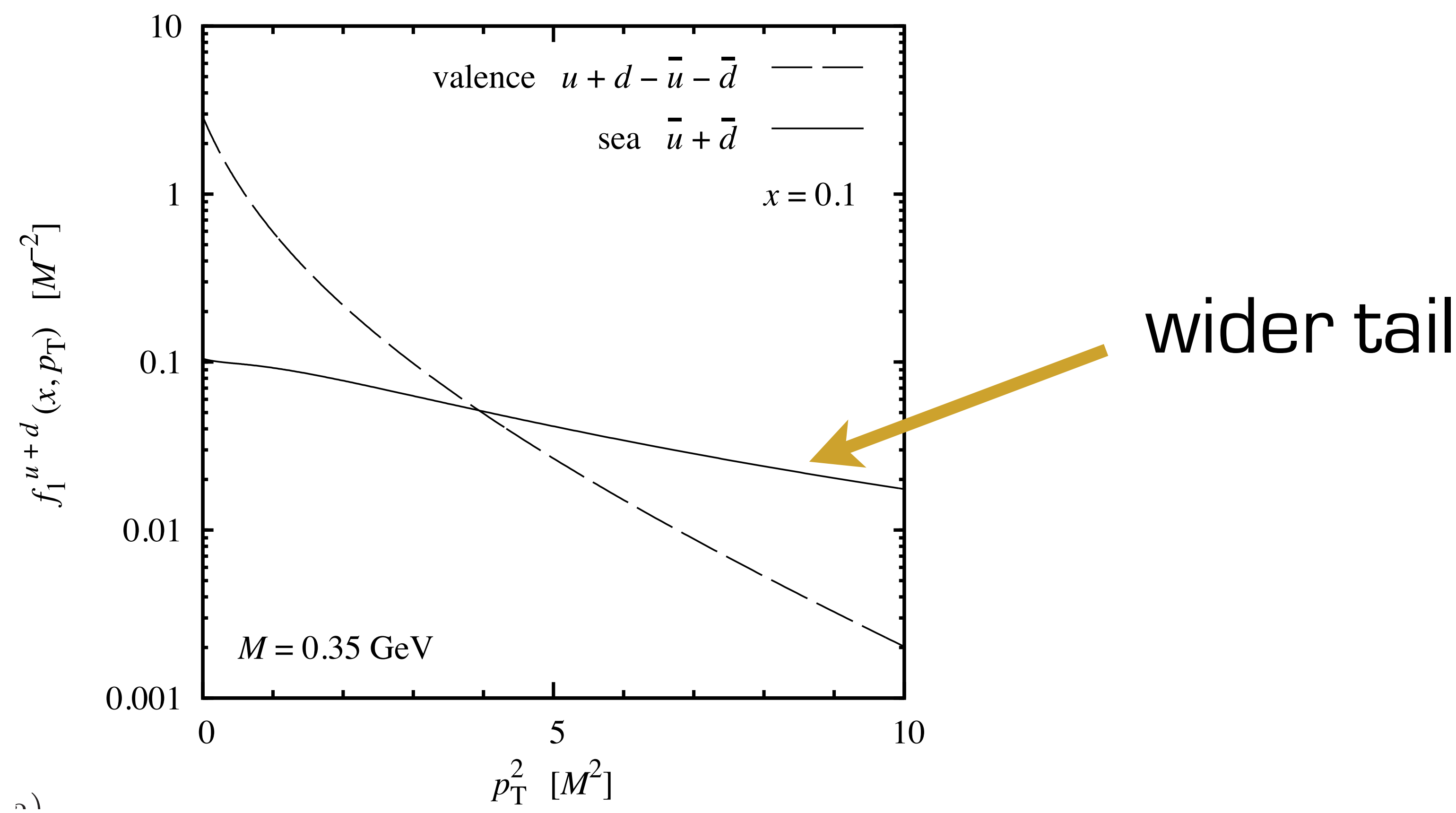
P. Schweitzer's talk



Schweitzer, Strikman, Weiss, JHEP 1301 (13)

Chiral quark soliton model

P. Schweitzer's talk



Schweitzer, Strikman, Weiss, JHEP 1301 (13)

In chiral quark-solition model,
sea quarks are expected to have a wider distribution

Chiral quark soliton model

P. Schweitzer's talk

- **valence quarks** $\equiv (u+d)-(\bar{u}+\bar{d})$

  $\langle p_T^2\rangle_{\rm val} \sim 0.15\mathrm{GeV}^2 \sim 1/R^2_{\rm hadron}$ ("bound state")

  no Gauss, but also no extreme disagreement

- **sea quarks** $\equiv \bar{q} \equiv (\bar{u}+\bar{d})$ **!**

  $p_T \sim 1/\rho$ power-like behavior

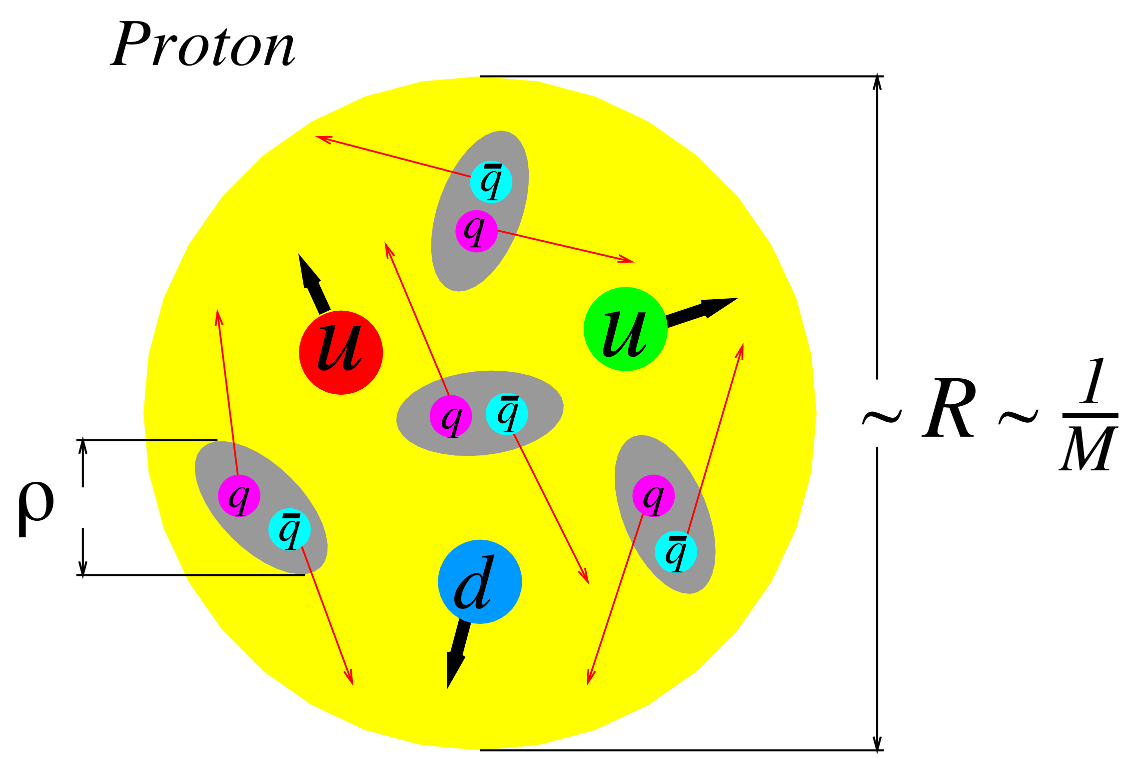
  quasi model-independent:

  $$f_1^{\bar{q}}(x,p_T) \approx f_1^{\bar{q}}(x)\,\frac{C_1\,M^2}{M^2+p_T^2}$$

  $$C_1 = \frac{2N_c}{(2\pi)^3 F_\pi^2} \quad \leftarrow \text{chiral dynamics!}$$

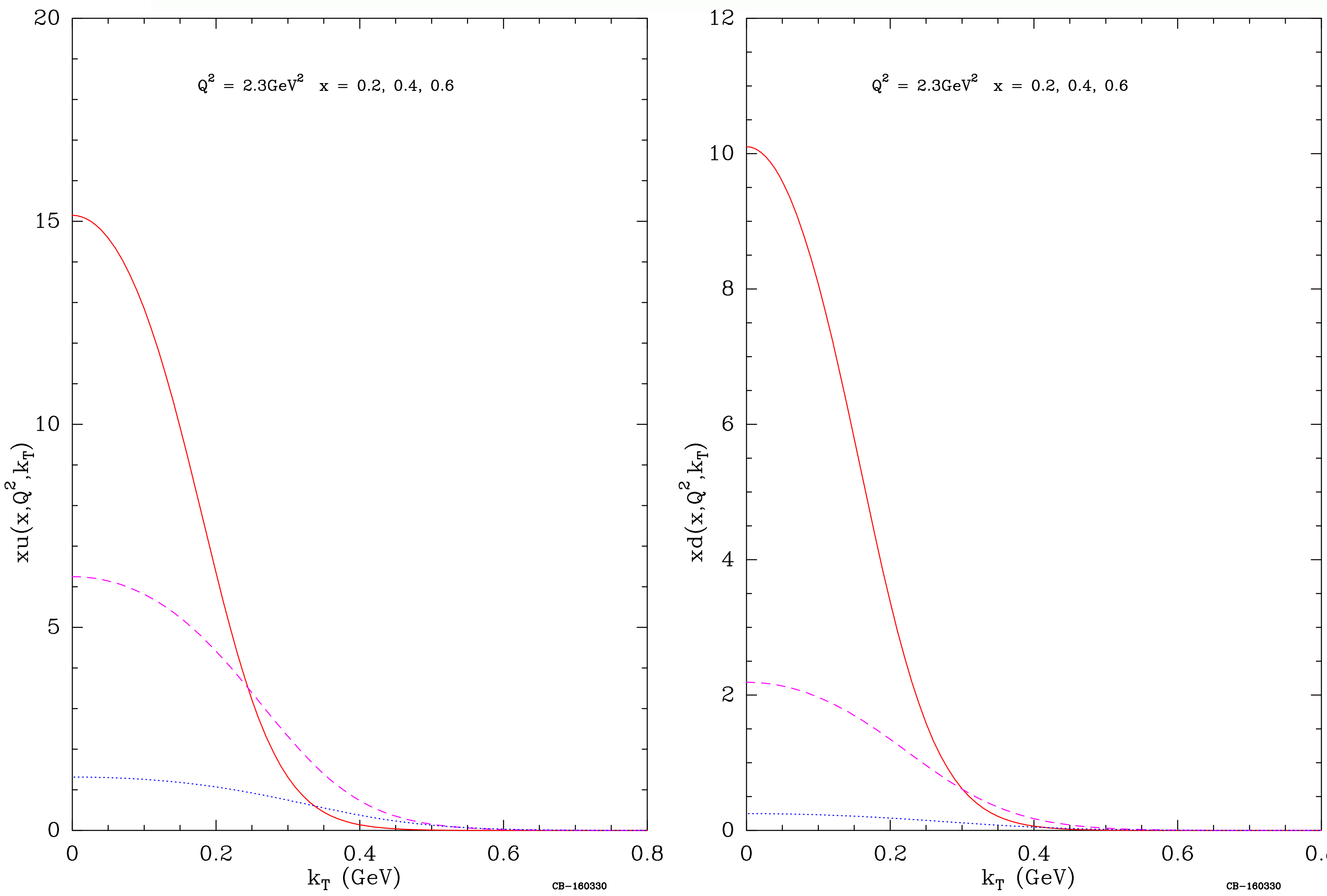
$$\langle p_T^2\rangle_{\rm val} \sim M^2$$

$$\langle p_T^2\rangle_{\rm sea} \sim \rho^{-2}$$



Statistical model

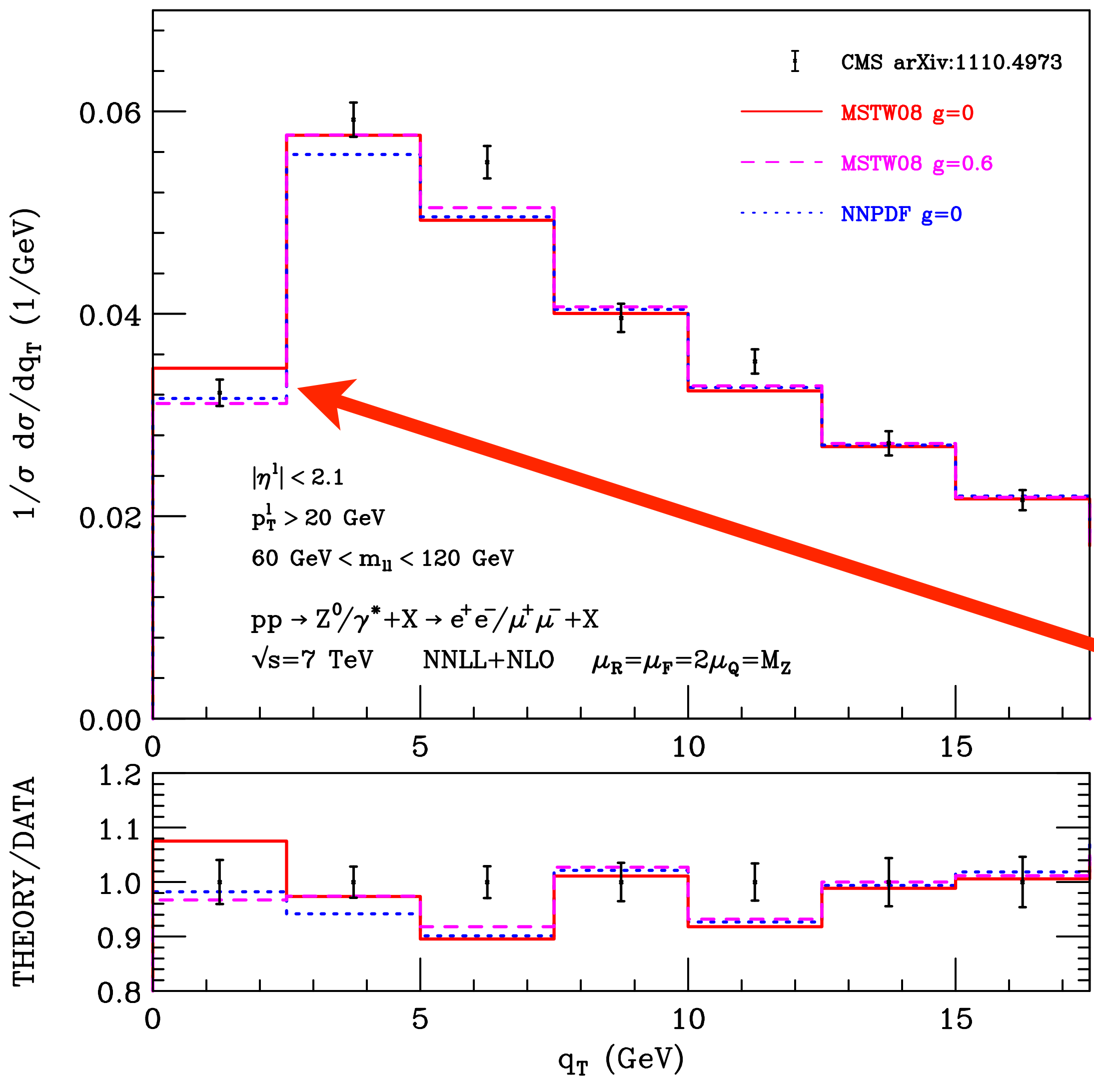
J. Soffer's talk



Down slightly narrower than up,
magenta (what x value?) larger than red
(different qualitative behavior for helicity TMD)

TMDs at LHC

Z transverse momentum

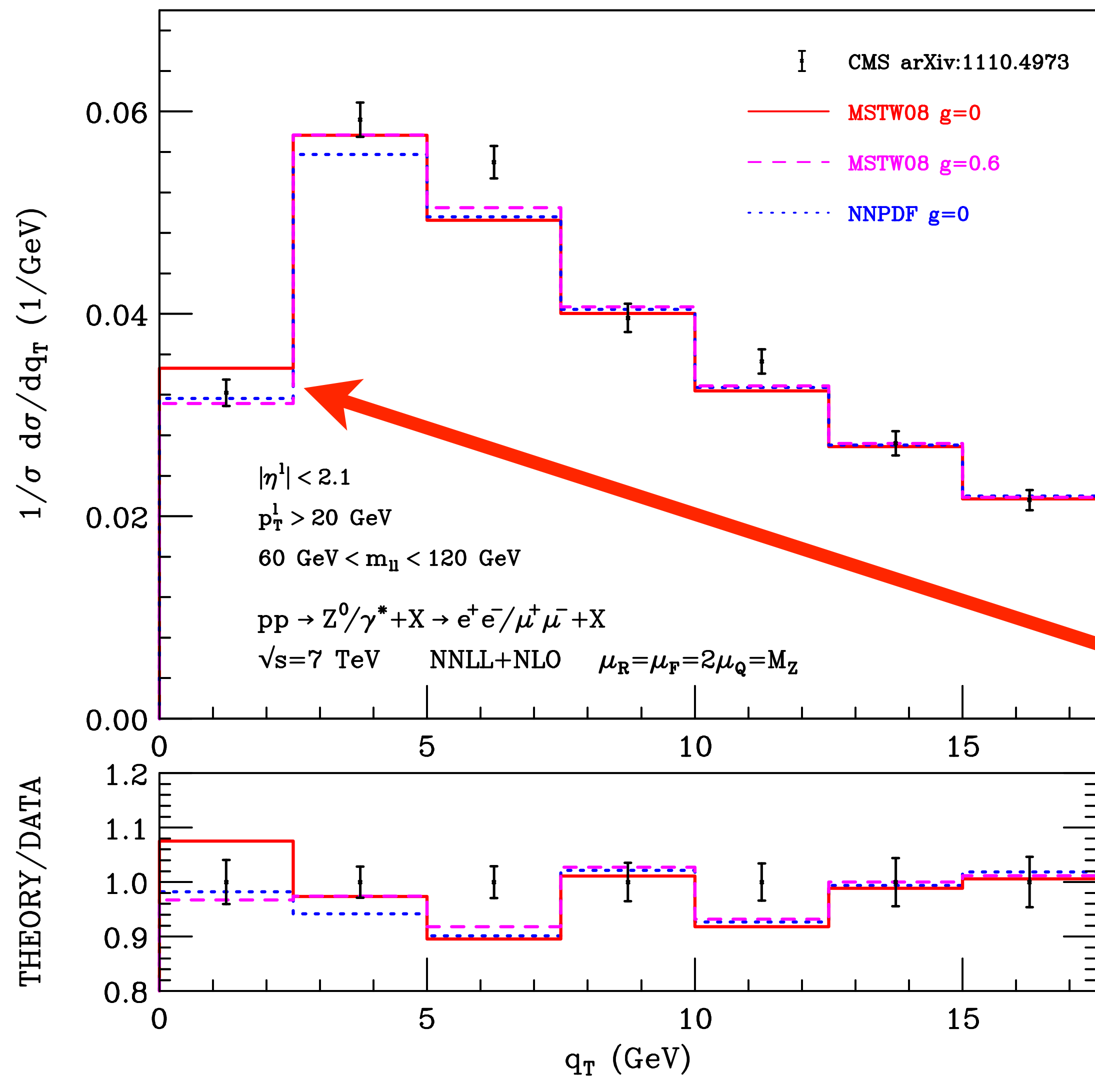


Intrinsic transverse momentum effects

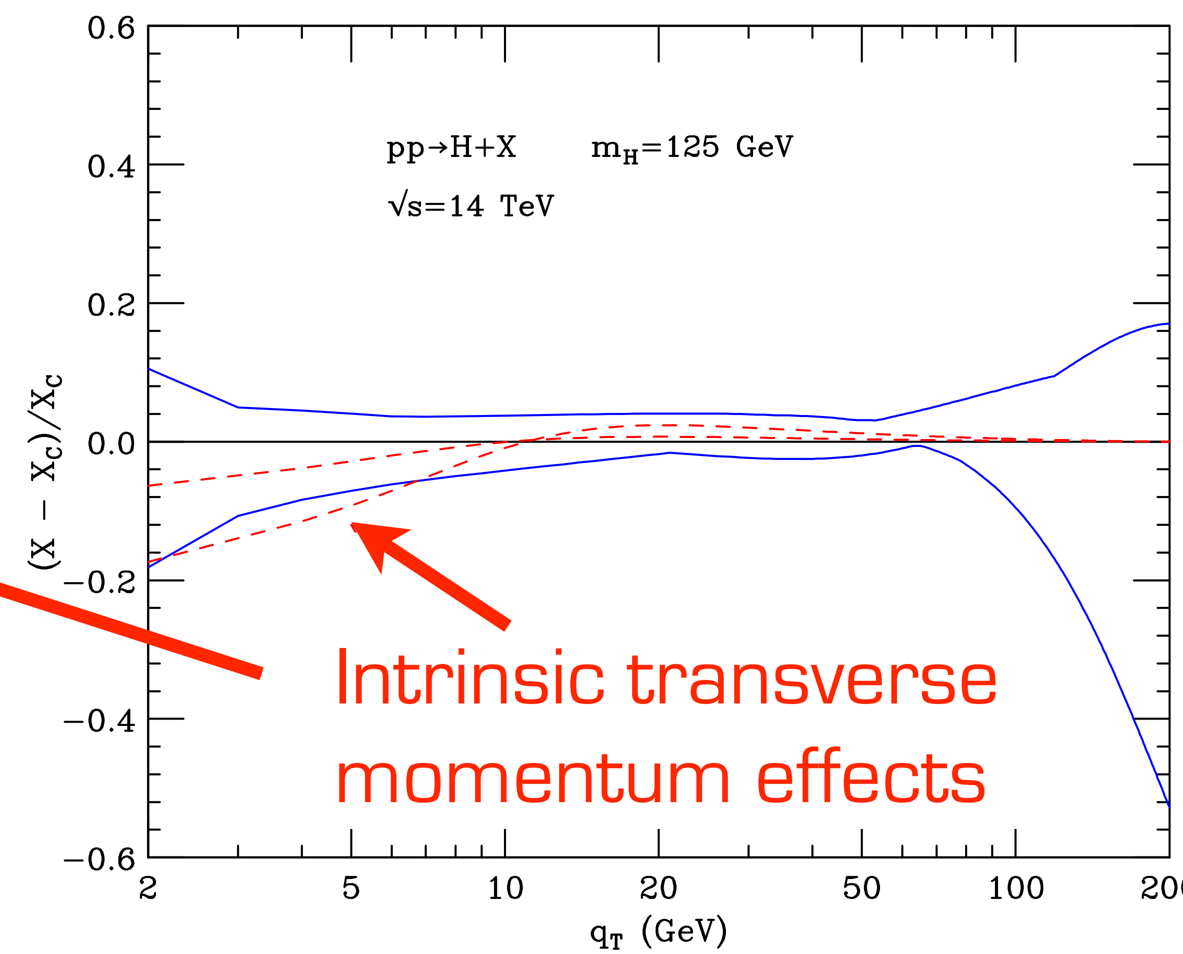
G. Ferrera, talk at REF 2014, Antwerp, https://indico.cern.ch/event/330428/

TMDs at LHC

Z transverse momentum



Higgs transverse momentum



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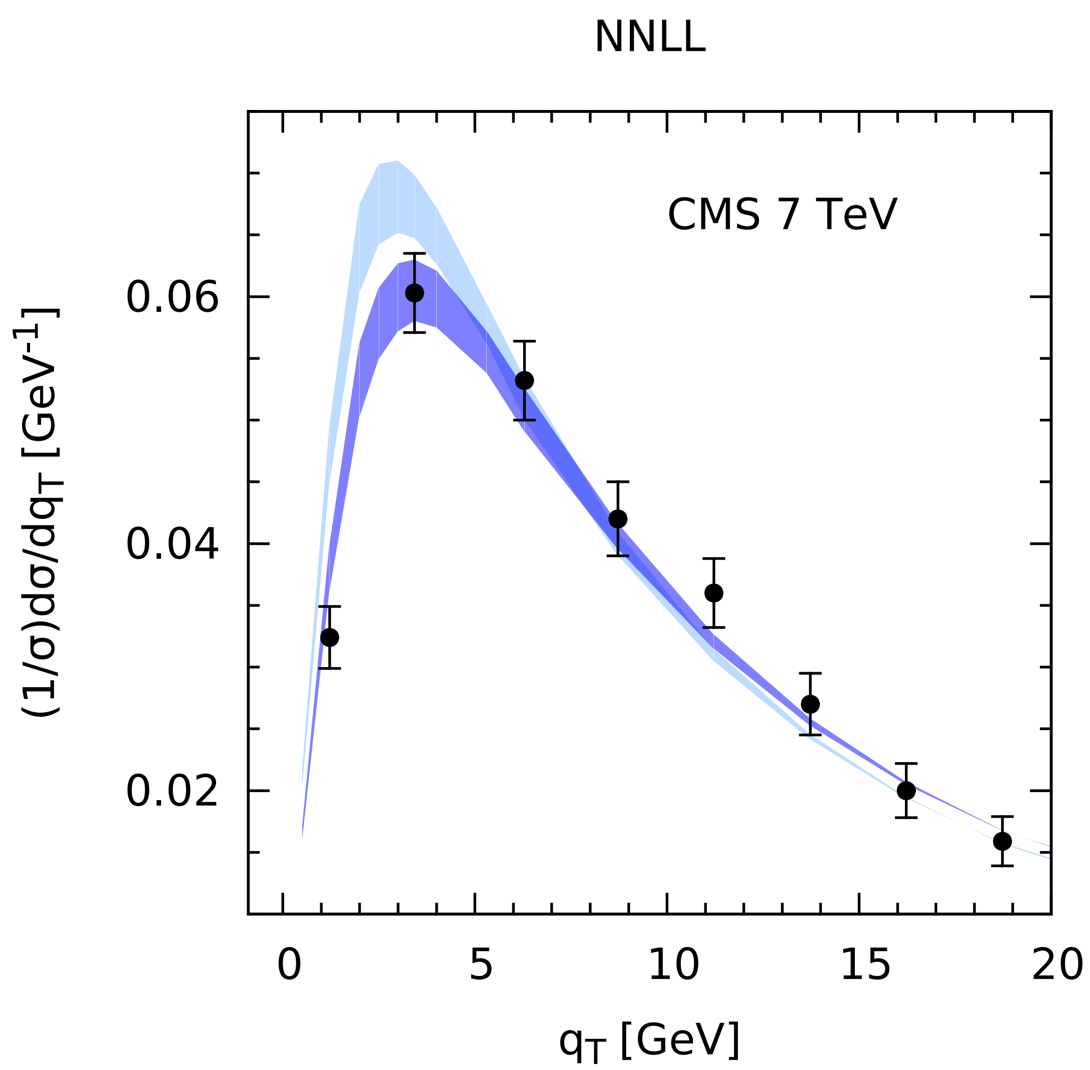
TMDs at LHC

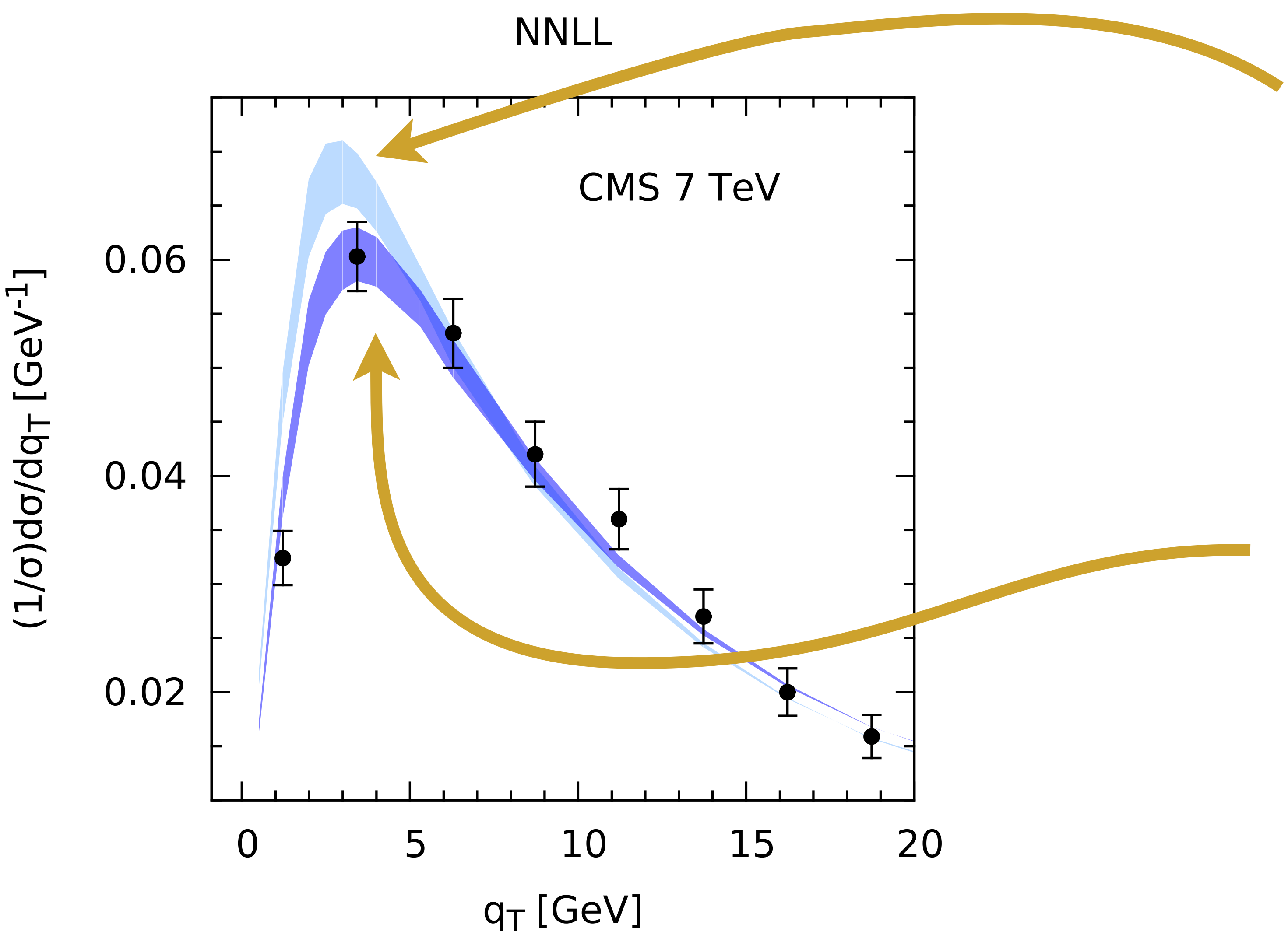
Z transverse momentum



D'Alesio, Echevarria, Melis, Scimemi, JHEP 1411 (14)

TMDs at LHC

Z transverse momentum



Perturbative transverse momentum only

With intrinsic transverse momentum

D'Alesio, Echevarria, Melis, Scimemi, JHEP 1411 (14)

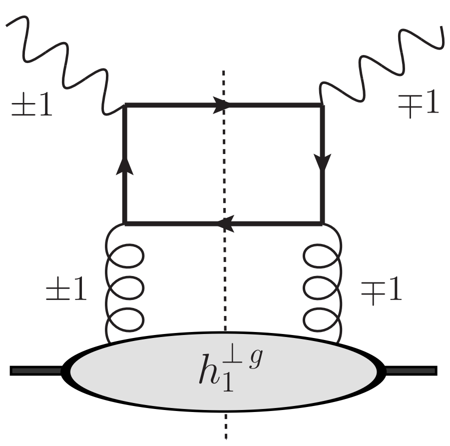
Gluon TMDs

C. Pisano's talk

Ideal process: $e(\ell) + p(P) \rightarrow e(\ell') + Q(K_1) + \bar{Q}(K_2) + X$

- the $Q\bar{Q}$ pair is almost back to back in the plane $\perp$ to q and P
- $q \equiv \ell - \ell'$: four-momentum of the exchanged virtual photon γ^*

Heavy quark pair production in DIS
Angular structure of the cross section



y_1 (y_2) rapidities of Q ($\bar{Q}$) in the $\gamma^* p$ cms; x_B, y: DIS variables

$\boldsymbol{q}_T \equiv \boldsymbol{K}_{1\perp} + \boldsymbol{K}_{2\perp} = |\boldsymbol{q}_T|(\cos\phi_T, \sin\phi_T)$
$\boldsymbol{K}_\perp \equiv (\boldsymbol{K}_{1\perp} - \boldsymbol{K}_{2\perp})/2 = |\boldsymbol{K}_\perp|(\cos\phi_\perp, \sin\phi_\perp)$

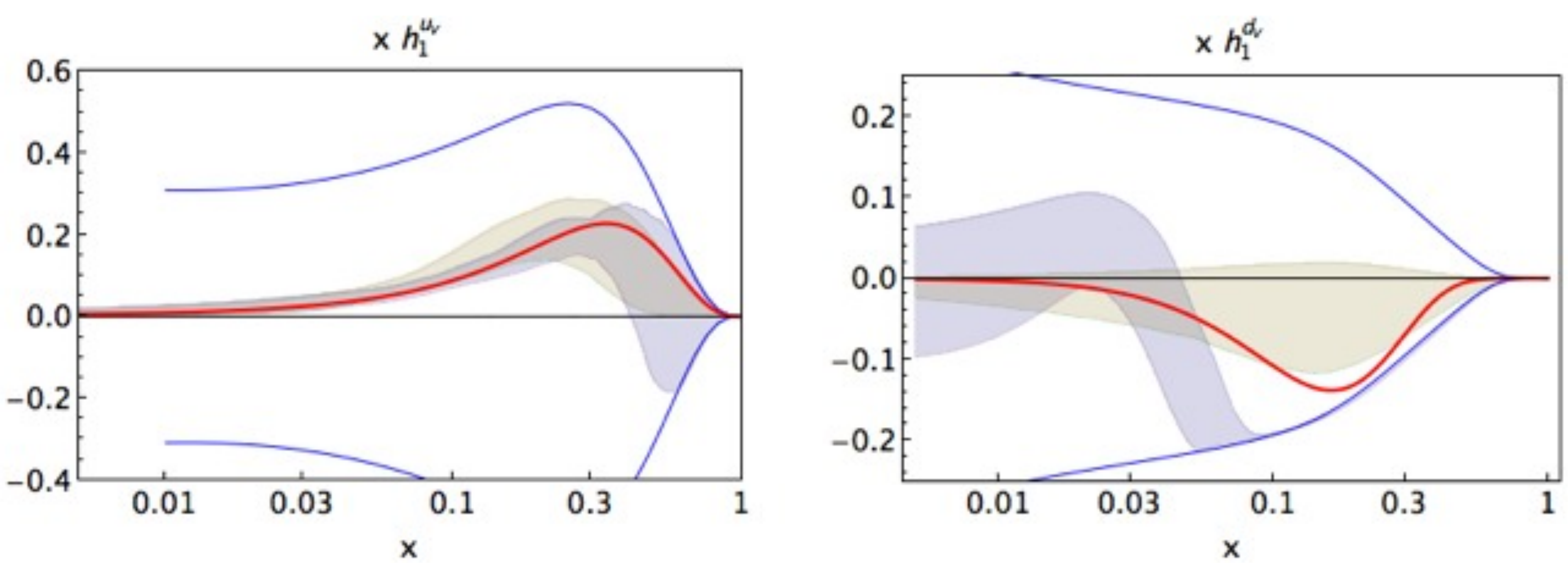
$$\frac{\mathrm{d}\sigma}{\mathrm{d}y_1\,\mathrm{d}y_2\,\mathrm{d}y\,\mathrm{d}x_B\,\mathrm{d}^2\boldsymbol{q}_T\,\mathrm{d}^2\boldsymbol{K}_\perp} \propto \left\{A_0 + A_1\cos\phi_\perp + A_2\cos 2\phi_\perp\right\} f_1^g$$

$$+\ \frac{\boldsymbol{q}_T^2}{M_p^2}\, h_1^{\perp\, g}\left\{B_0\cos 2(\phi_\perp - \phi_T) + B_1\cos(\phi_\perp - 2\phi_T) + B_1'\cos(3\phi_\perp - 2\phi_T) + B_2\cos 2\phi_T + B_2'\cos 2(2\phi_\perp - \phi_T)\right\}$$

$|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$

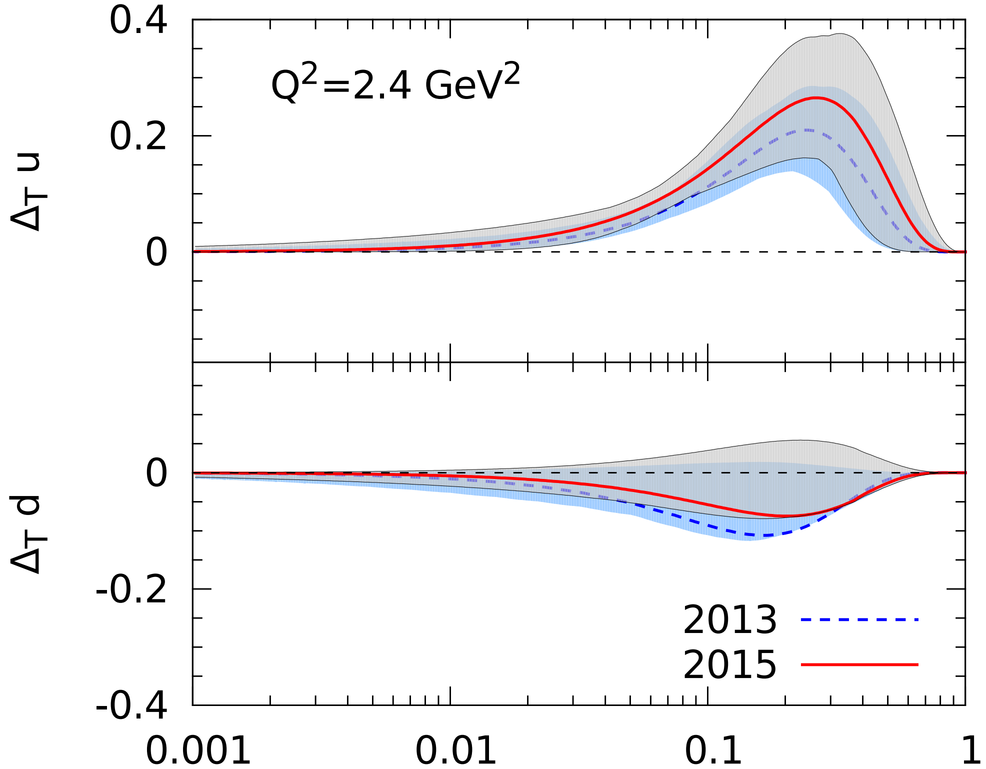
Transversity and tensor charge

Comparison of extractions

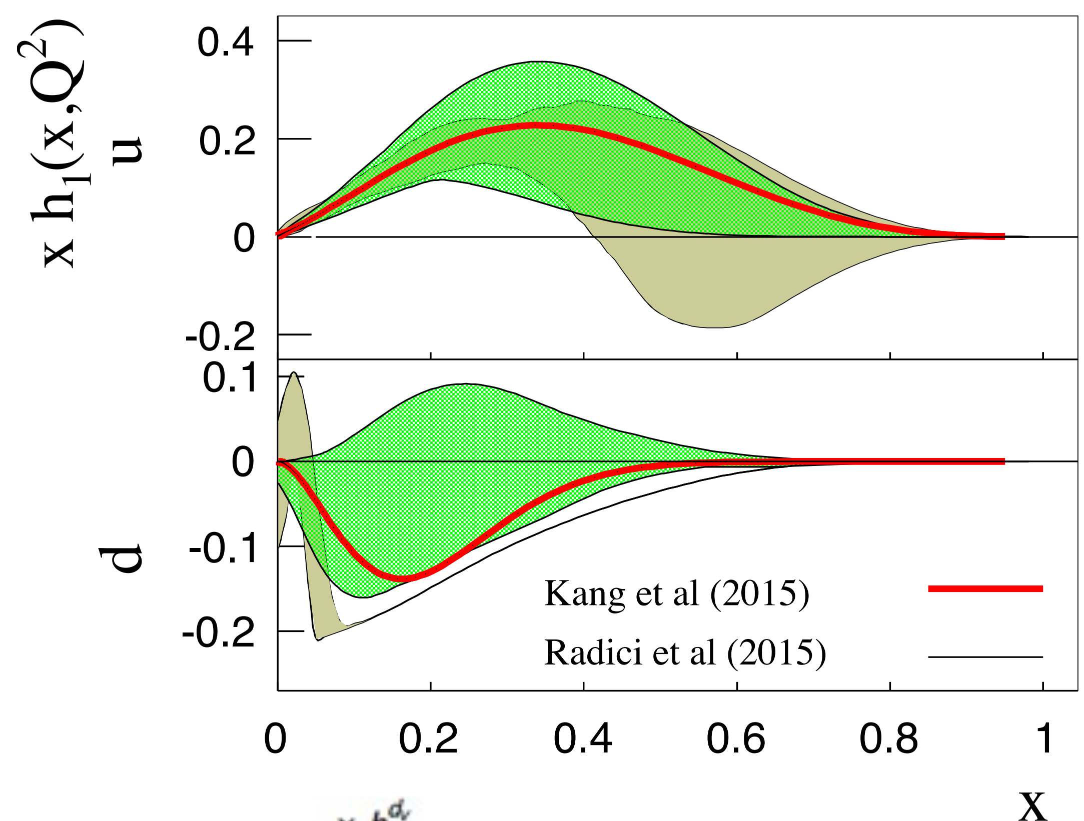


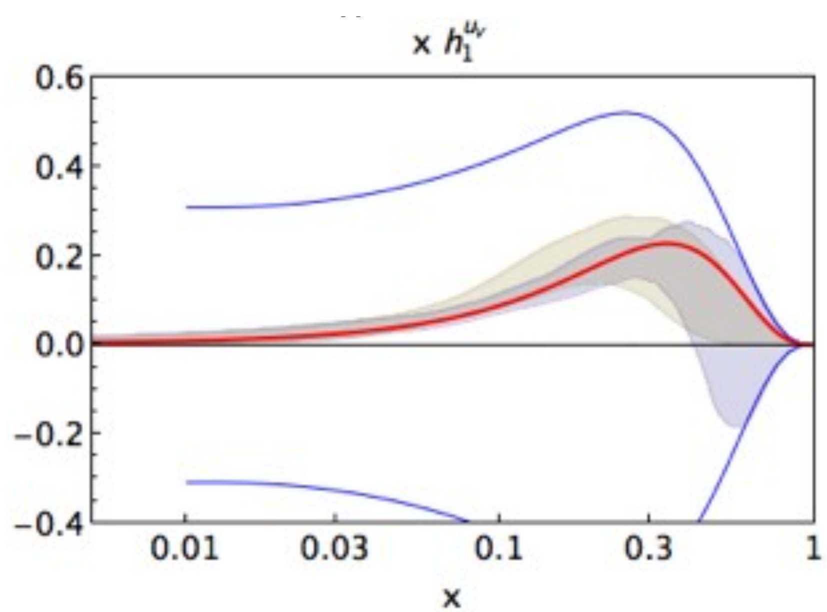
Comparison of extractions

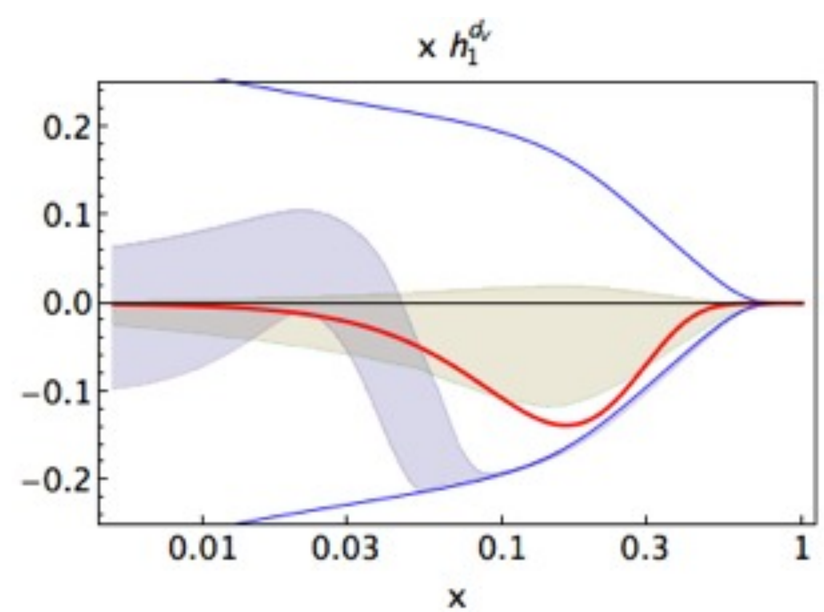
Torino 2013 & 2015



Radici et al & Kang et al. 2015

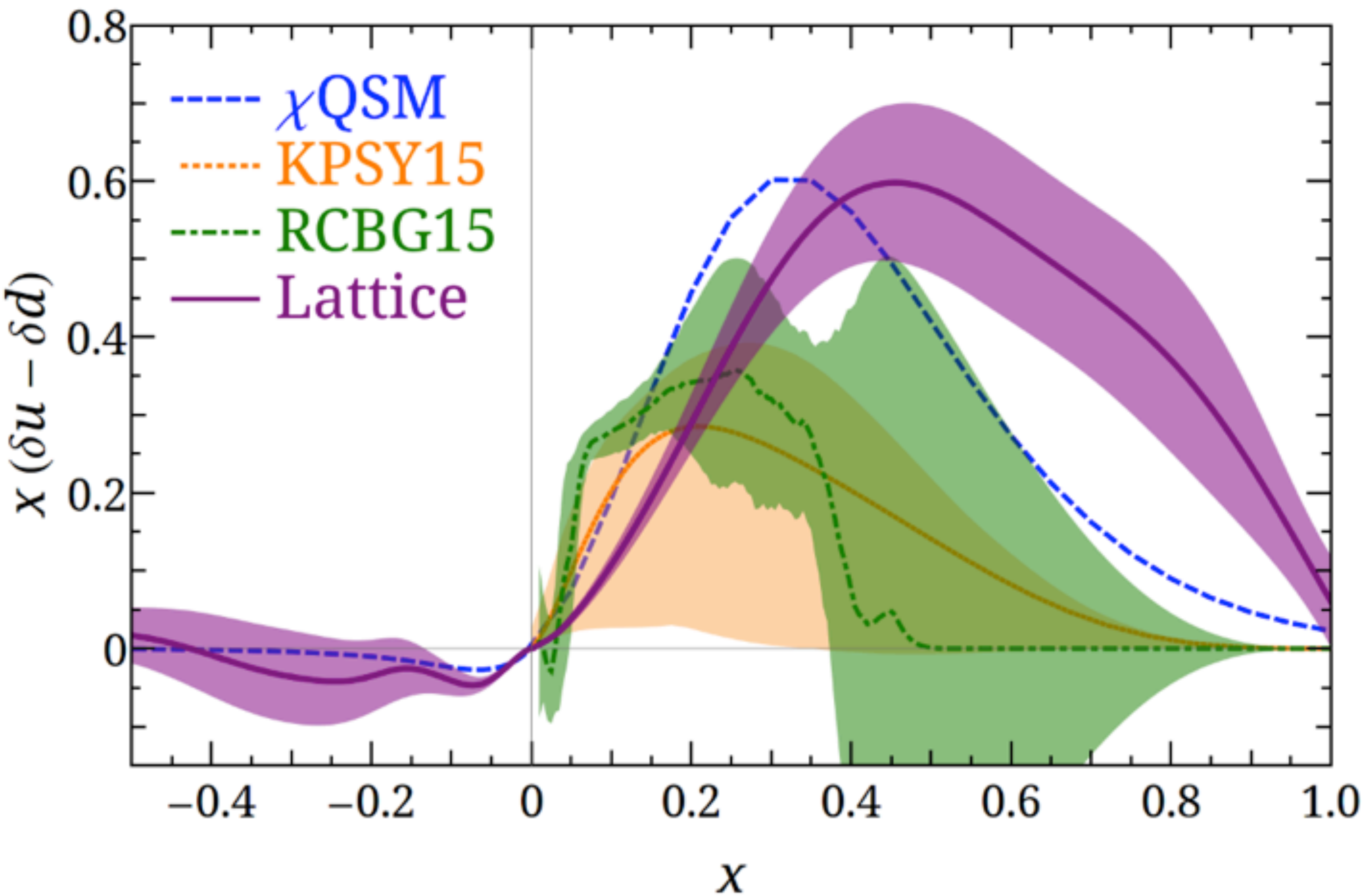






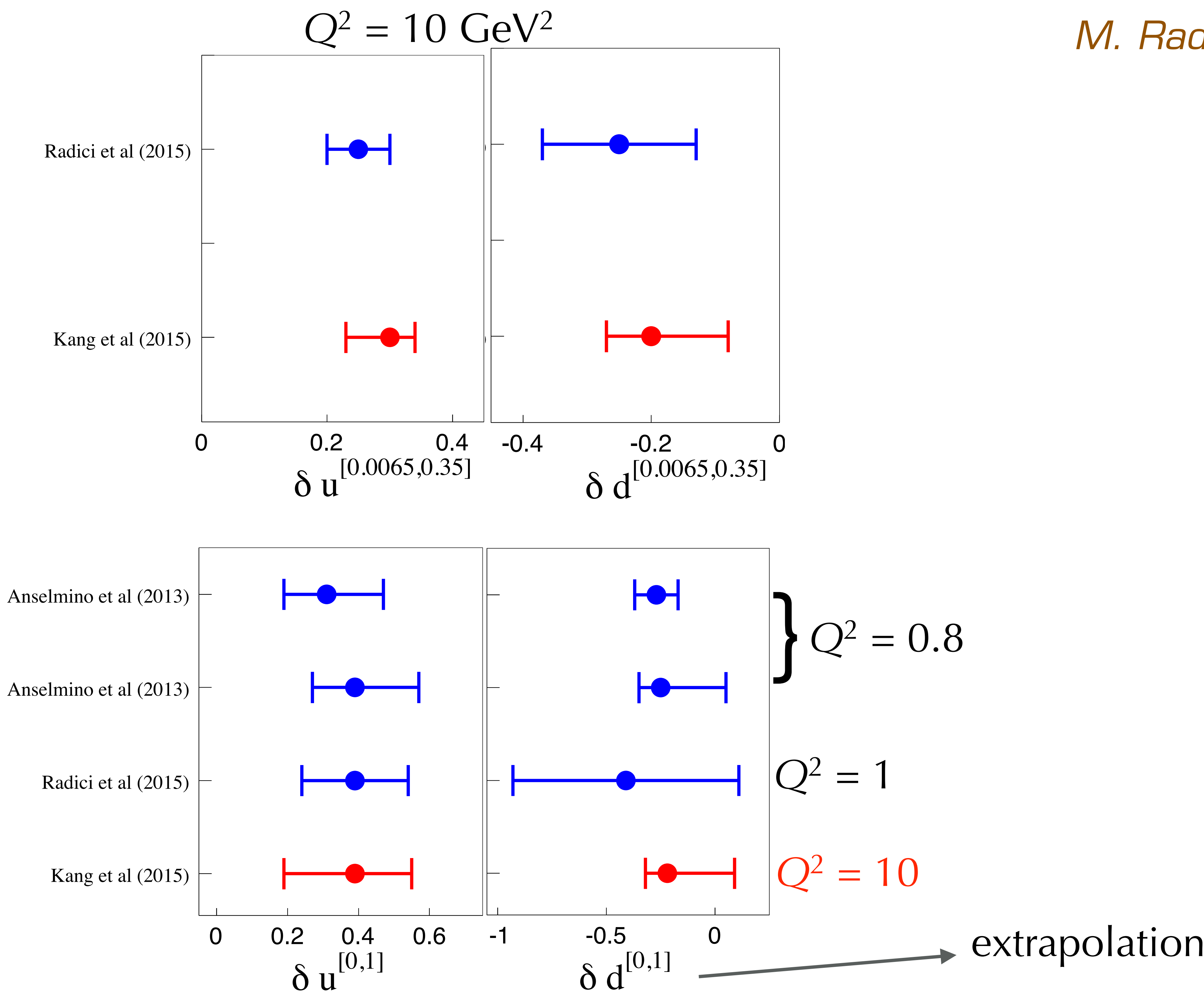
LaMET results

M. Radici's talk and X. Xiong's talk



Comparison between extractions

M. Radici's talk

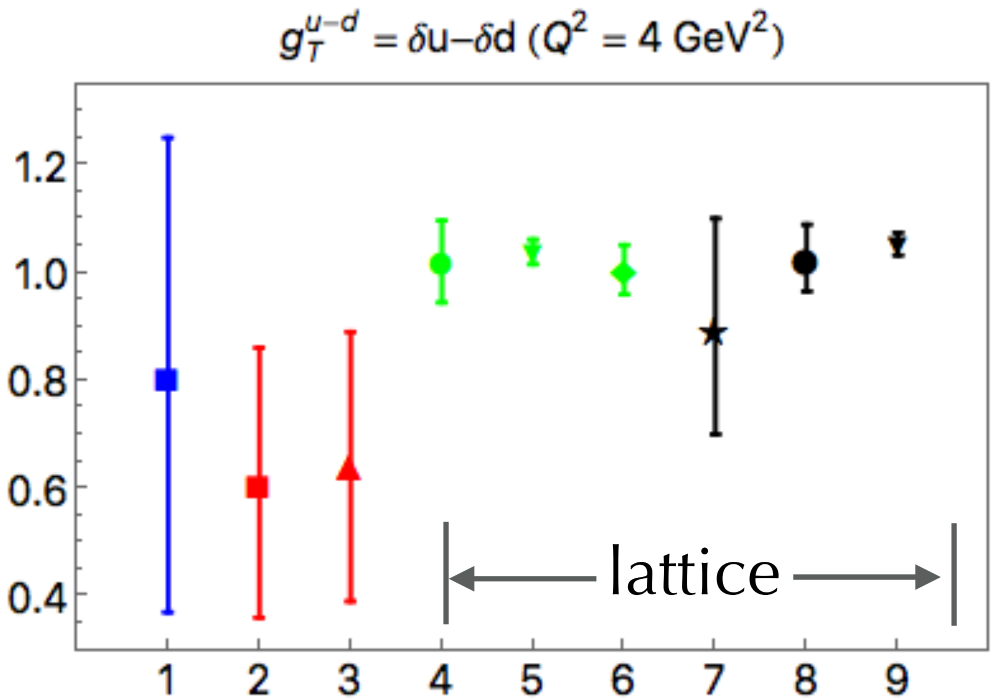


Friday, 15 April 16

Comparison to lattice

M. Radici's talk

1) Radici et al. 2015



2) Kang et al. 2015

$Q^2 = 10$

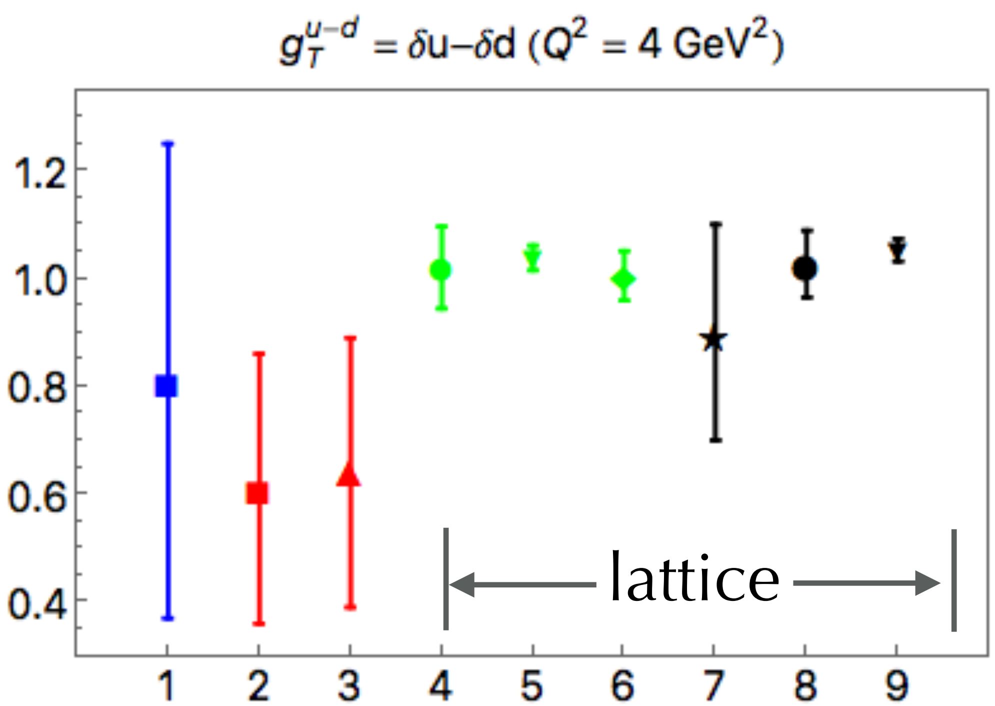
3) Anselmino et al. 2013

$Q^2 = 0.8$

Comparison to lattice

1) Radici et al. 2015

M. Radici's talk



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I. Cloet's talk

Comparison to lattice

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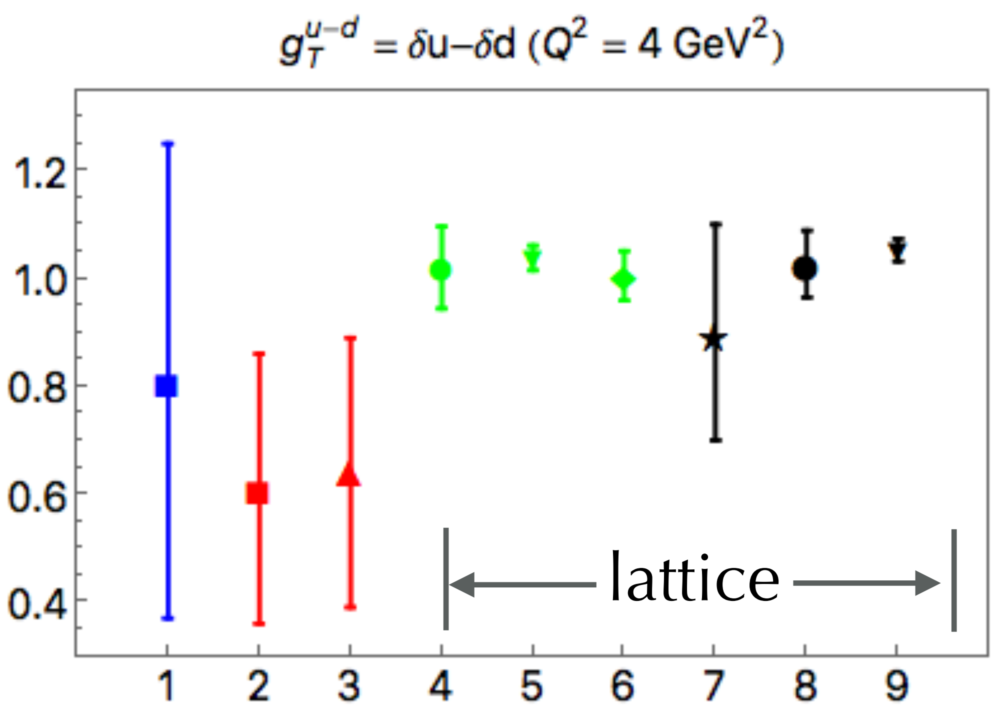

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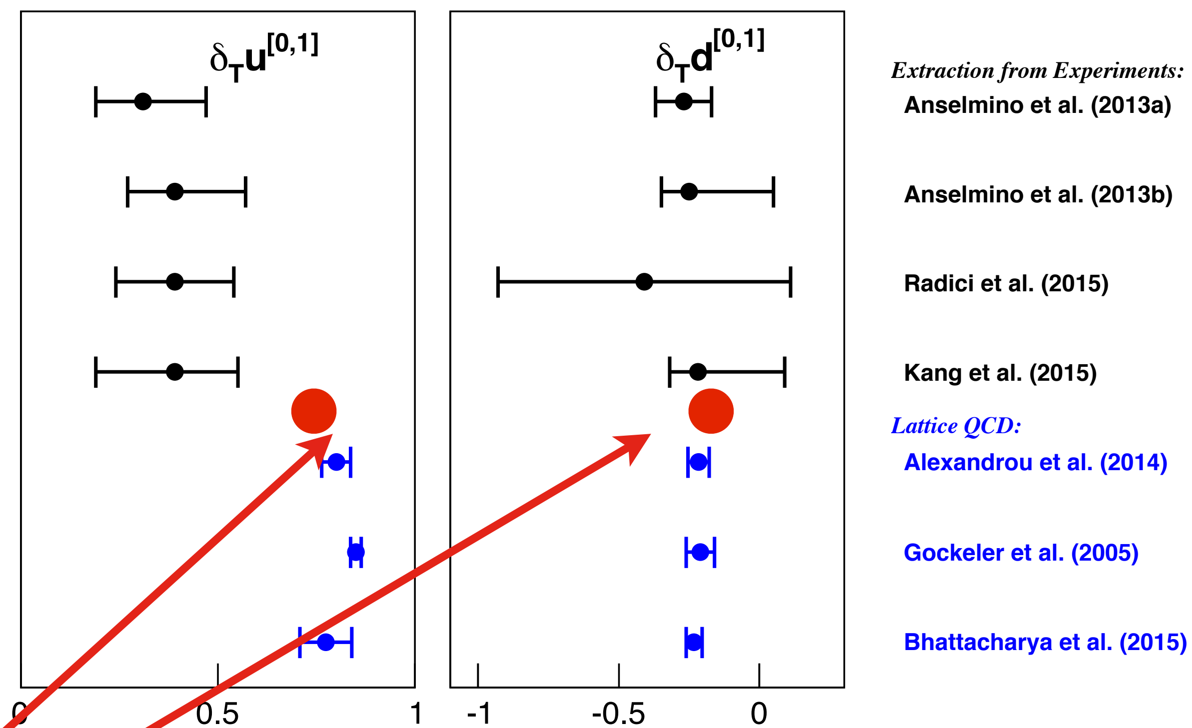

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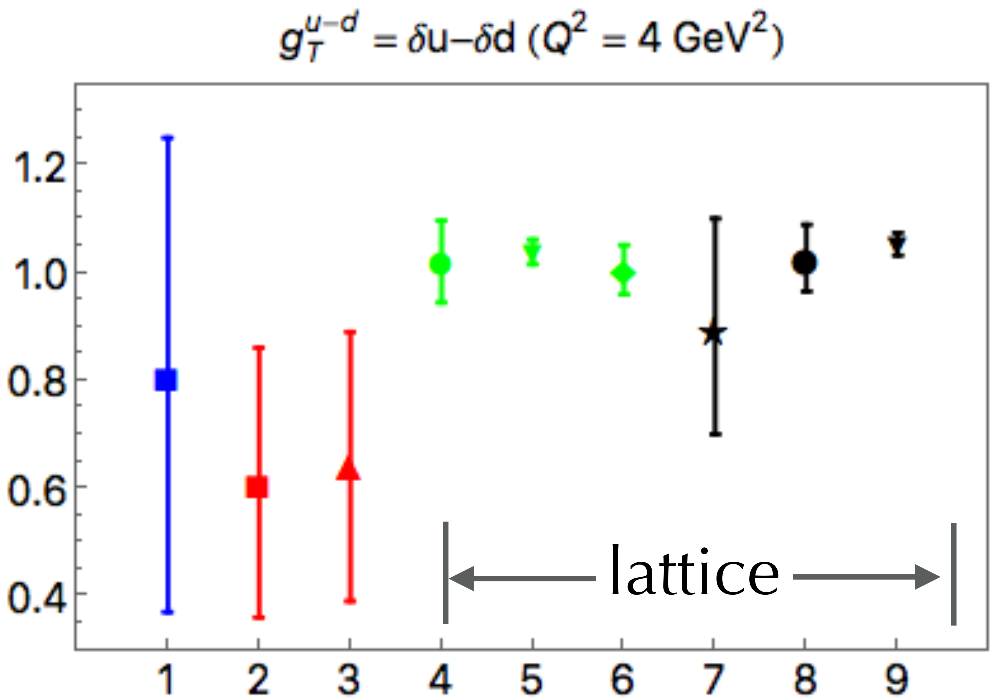

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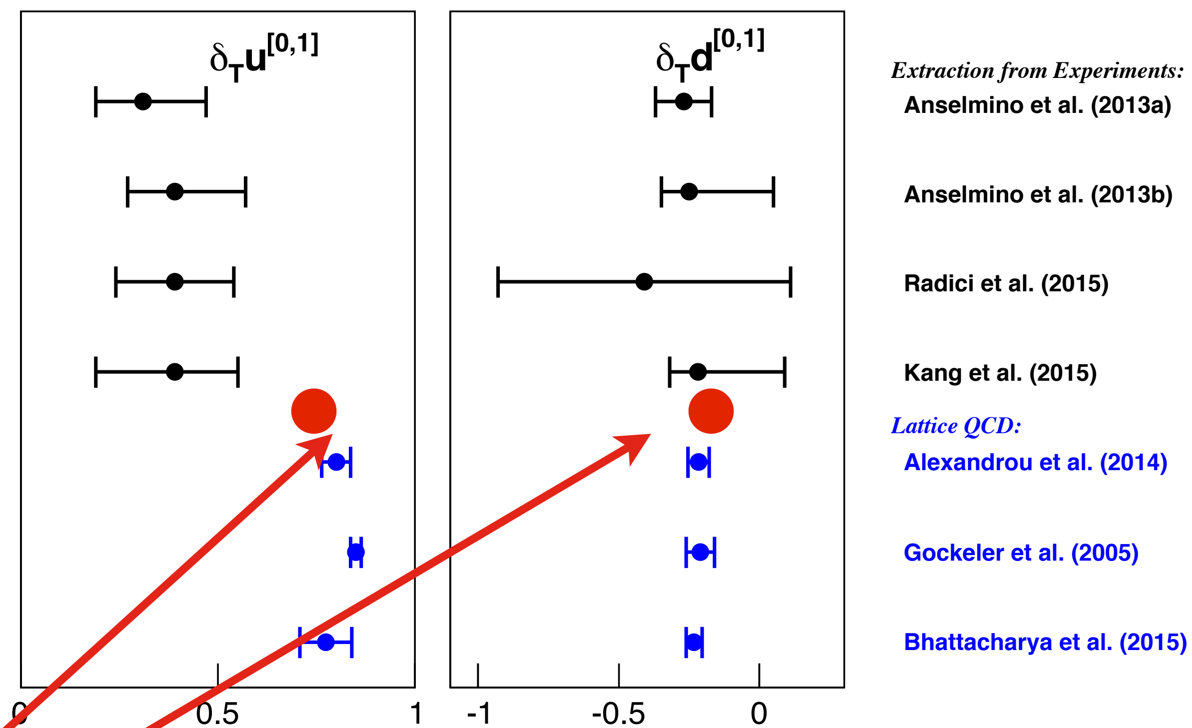

I. Cloet's talk

Gao et al., The Universe, vol. 3, n. 2, April 2015

Comparison to lattice

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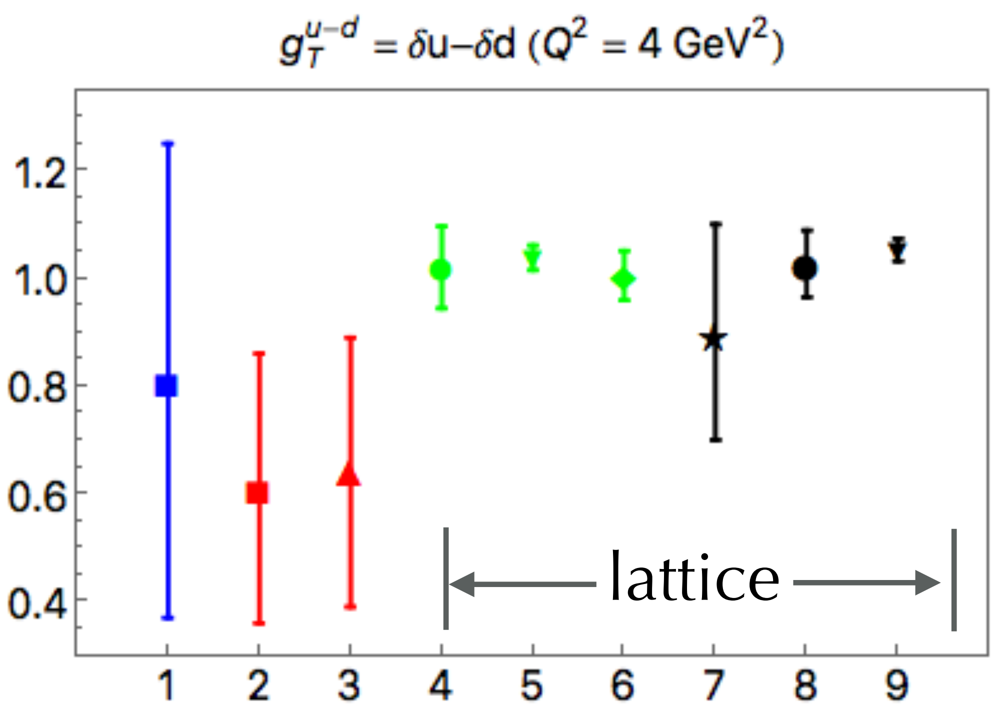

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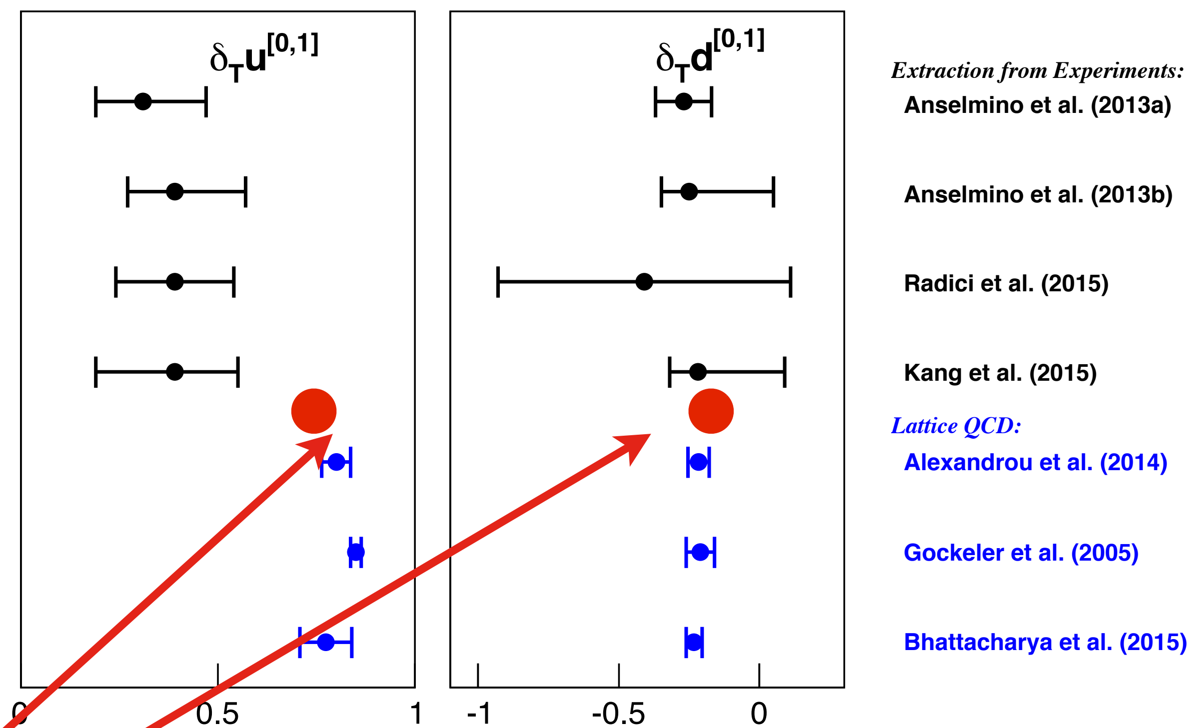


I. Cloet's talk

Gao et al., The Universe, vol. 3, n. 2, April 2015

P. Schweitzer's talk

$g_T^u = \int dx\, (h_1^u - h_1^{\bar{u}})(x)$ more positive with $h_1^{\bar{u}}(x) < 0$

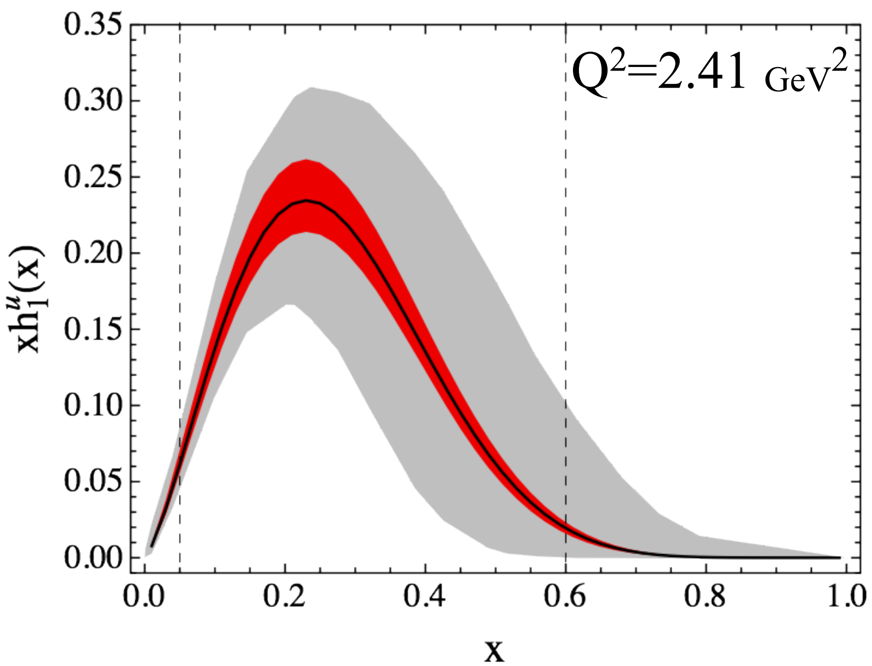
$g_T^d = \int dx\, (h_1^d - h_1^{\bar{d}})(x)$ more negative with $h_1^{\bar{d}}(x) > 0$

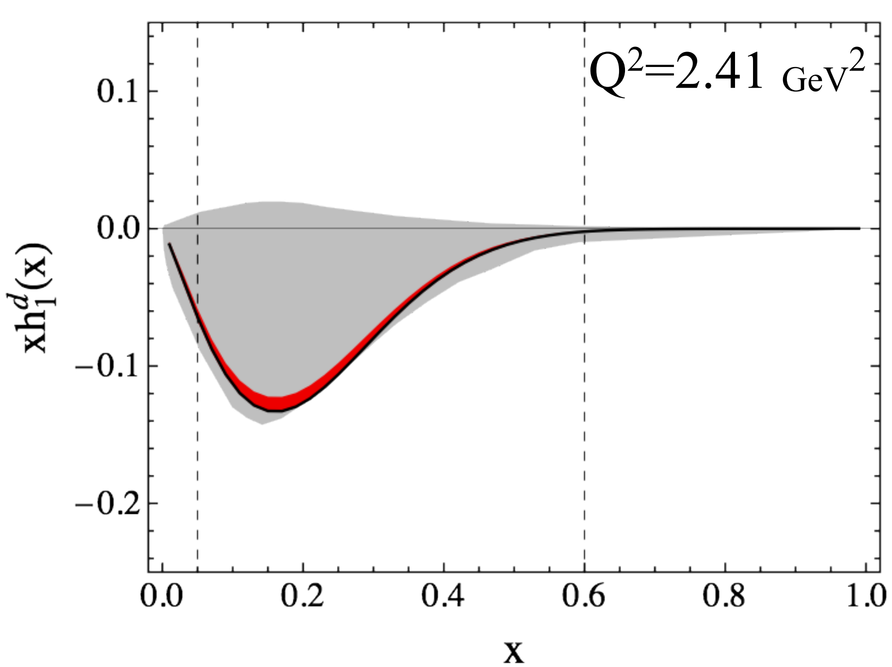
"valence result" for $\begin{cases} (g_T^u + g_T^d) & \text{okay} \\ (g_T^u - g_T^d) & \text{underestimated} \end{cases}$

$\rightarrow$ tensor "charge" extractions

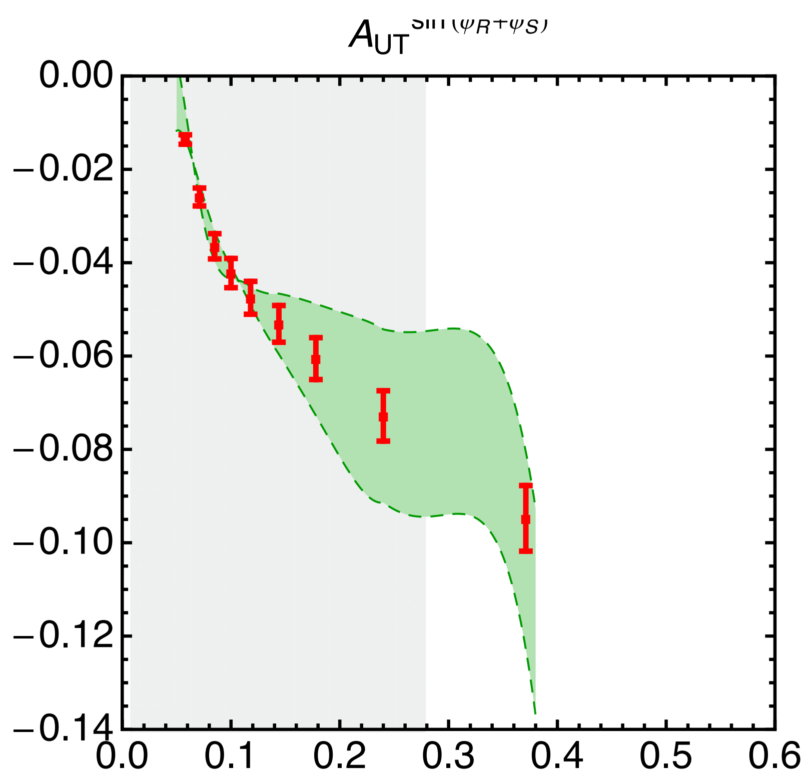
Impact of SOLID data

H. Gao's talk and SOLID proposals





Impact on transversity



Impact on dihadron asymmetry

Orbital angular momentum

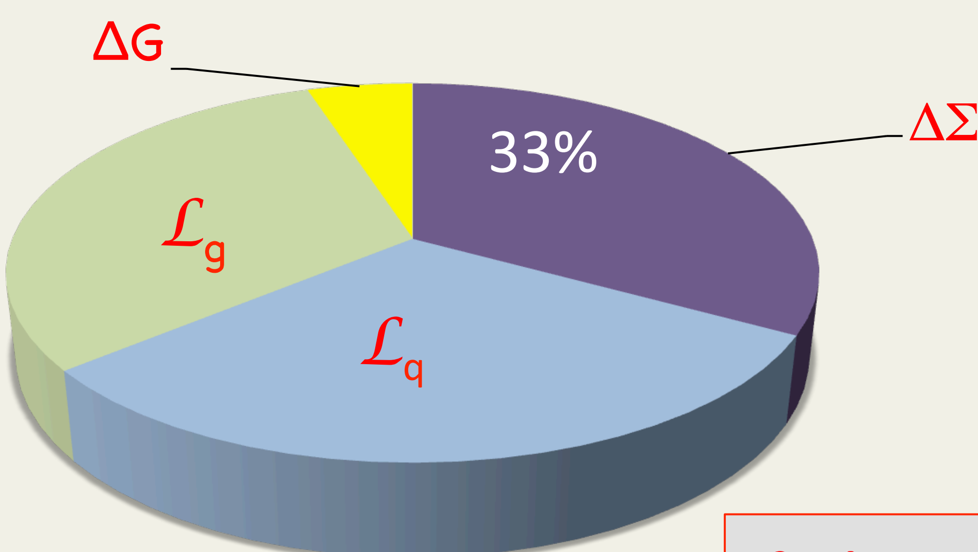
S. Liuti's talk

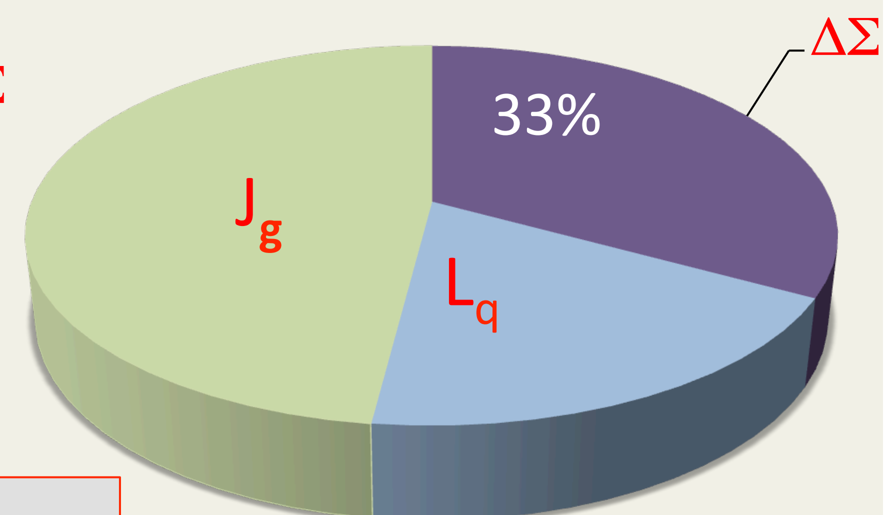
Jaffe Manohar

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \mathcal{L}_q + \Delta G + \mathcal{L}_g$$

Ji

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$





$\mathcal{L}_q \neq L_q$

$J_g \neq \mathcal{L}_g + \Delta G$

Orbital angular momentum

OAM: Correlation between parton's position and its motion – in an averaged (or probability) sense

- **Jaffe-Manohar's quark OAM density:**

$$\mathcal{L}_q^3 = \psi_q^\dagger \left[\vec{x} \times (-i\vec{\partial})\right]^3 \psi_q$$

- **Ji's quark OAM density:**

$$L_q^3 = \psi_q^\dagger \left[\vec{x} \times (-i\vec{D})\right]^3 \psi_q$$

- **Difference between them:**

Hatta, Yoshida, Burkardt, Meissner, Metz, Schlegel, …

✧ **generated by a "torque" of color Lorentz force**

$$\mathcal{L}_q^3 - L_q^3 \propto \int \frac{dy^- d^2 y_T}{(2\pi)^3} \langle P' | \overline{\psi}_q(0) \frac{\gamma^+}{2} \int_{y^-}^{\infty} dz^- \Phi(0, z^-)$$
$$\times \sum_{i,j=1,2} \underbrace{\left[\epsilon^{3ij} y_T^i F^{+j}(z^-)\right]}_{\text{"Chromodynamic torque"}} \Phi(z^-, y) \psi(y) | P \rangle_{y^+=0}$$

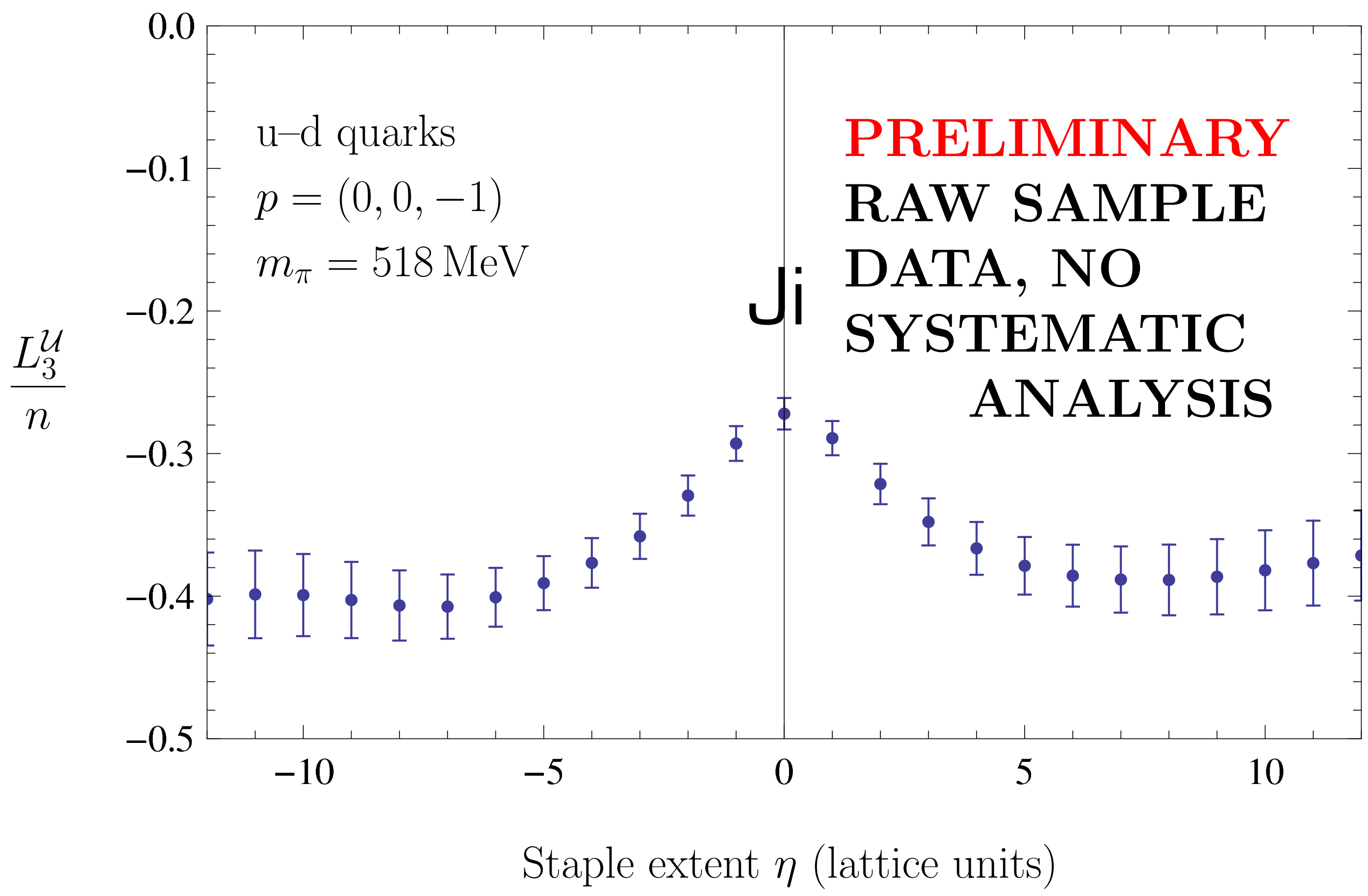
Similar color Lorentz force generates the single transverse-spin asymmetry (Qiu-Sterman function), and is also responsible for the twist-3 part of g_2

Lattice calculation

M. Engelhardt's talk

Quark orbital angular momentum in units of the number of valence quarks

$$\frac{L_3^{\mathcal{U}}}{n} = \frac{2\epsilon_{ij}\frac{\partial}{\partial b_{T,i}}\frac{\partial}{\partial \Delta_{T,j}} \langle P,S \mid \overline{\psi}(-b/2)\gamma^+\mathcal{U}[-b/2,b/2]\psi(b/2) \mid P',S\rangle\big|_{b^+=b^-=0\,,\ \Delta_T=0\,,\ b_T\to 0}}{\langle P,S \mid \overline{\psi}(-b/2)\gamma^+\mathcal{U}[-b/2,b/2]\psi(b/2) \mid P',S\rangle\big|_{b^+=b^-=0\,,\ \Delta_T=0\,,\ b_T\to 0}}$$



Jaffe-Manohar

Measuring Ji's OAM

S. Liuti's talk

$$F_{14}^{(1)} = -\int_x^1 dy\,(\tilde{E}_{2T} + H + E) \;\; \Rightarrow -L_q = \int_0^1 dx F_{14}^{(1)} = \int_0^1 dx x G_2$$

k_T moment of a GTMD

twist 3 GPD

Measuring Ji's OAM

S. Liuti's talk

$$F_{14}^{(1)} = -\int_x^1 dy\,(\tilde{E}_{2T} + H + E) \;\Rightarrow -L_q = \int_0^1 dx F_{14}^{(1)} = \int_0^1 dx x G_2$$

k_T moment of a GTMD

twist 3 GPD

$$d_2 = 2\int dx\, x^2 g_1(x) + 3\int dx\, x^2 g_2(x)$$
$$d_2 = 2\int dx\, x^2\,(H(x) + E(x)) + 3\int dx\, x^2 \tilde{E}_{2T}(x)$$

Measuring Ji's OAM

S. Liuti's talk

$$F_{14}^{(1)} = -\int_x^1 dy\,(\tilde{E}_{2T} + H + E) \;\Rightarrow -L_q = \int_0^1 dx F_{14}^{(1)} = \int_0^1 dx x G_2$$

k_T moment of a GTMD | twist 3 GPD

$$d_2 = 2\int dx\, x^2 g_1(x) + 3\int dx\, x^2 g_2(x)$$
$$d_2 = 2\int dx\, x^2\,(H(x) + E(x)) + 3\int dx\, x^2 \tilde{E}_{2T}(x)$$

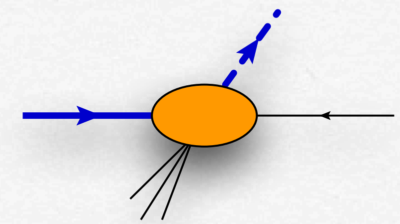
Twist 3 is a lot of fun!

More twist-3 stuff

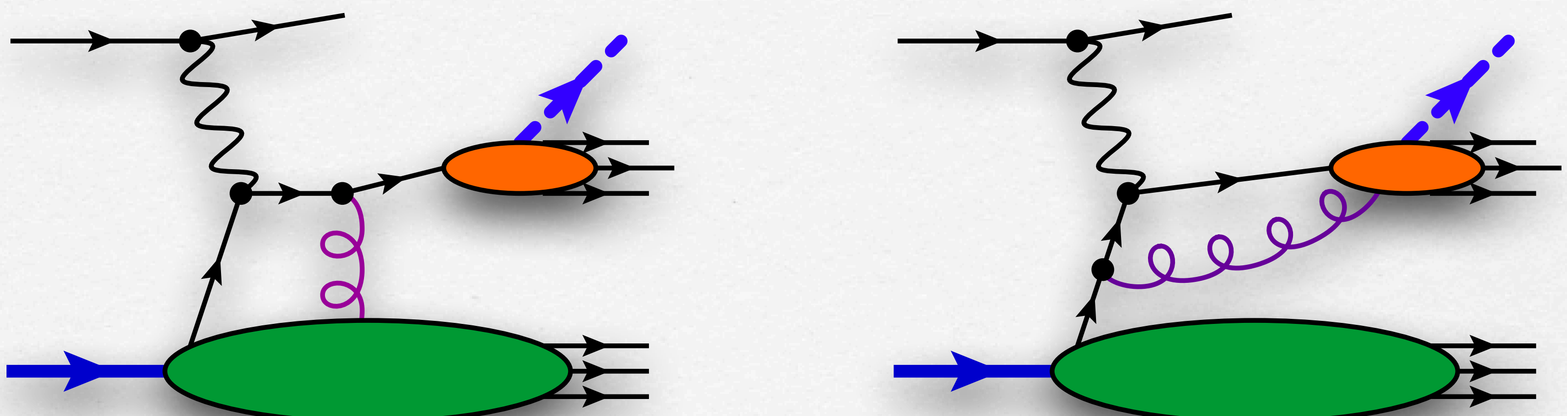
M. Schlegel's talk

Example: Single-Inclusive Hadron Production in e-p collisions [e(l) + N(P) → h(P_h) + X]

theoretically simple, measured at HERMES, JLab 6



Transverse single spin asymmetry A_{UT} (LO):

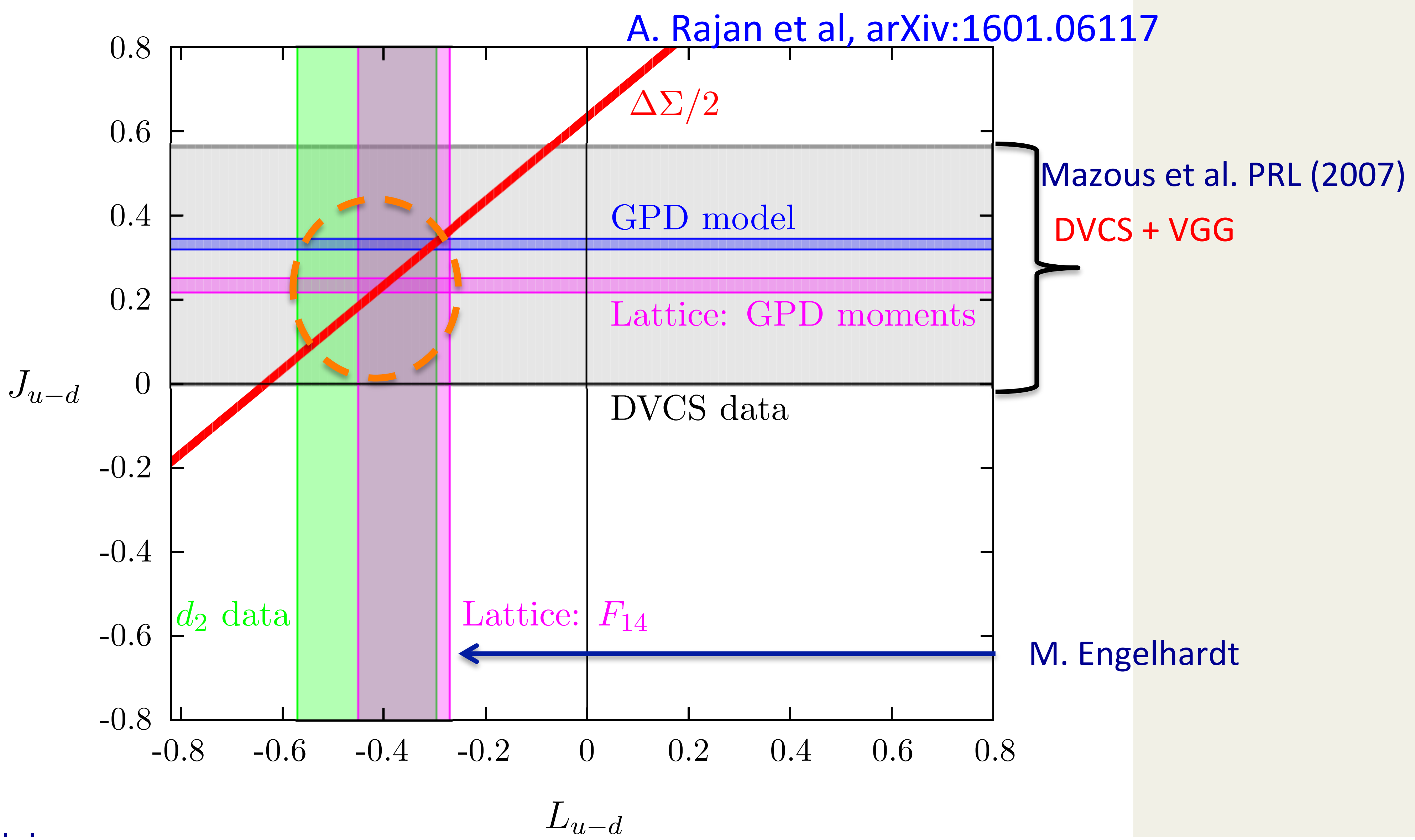


$$A_{UT} \sim \left[\left(1 - x\frac{\mathrm{d}}{\mathrm{d}x}\right) F_{FT}(x,x) \otimes D_1(z) \otimes \hat{\sigma}_1\right]$$
$$+ h_1(x) \otimes \left[H_1^{\perp(1)}(z) \otimes \hat{\sigma}_2 + \left(z\frac{\mathrm{d}}{\mathrm{d}z}\right) H_1^{\perp(1)}(z) \otimes \hat{\sigma}_3 + H(z) \otimes \hat{\sigma}_4 + \Im[\hat{H}_{FU}] \otimes \hat{\sigma}_5\right]$$

Partonic Coefficients differ in various frames (!?)

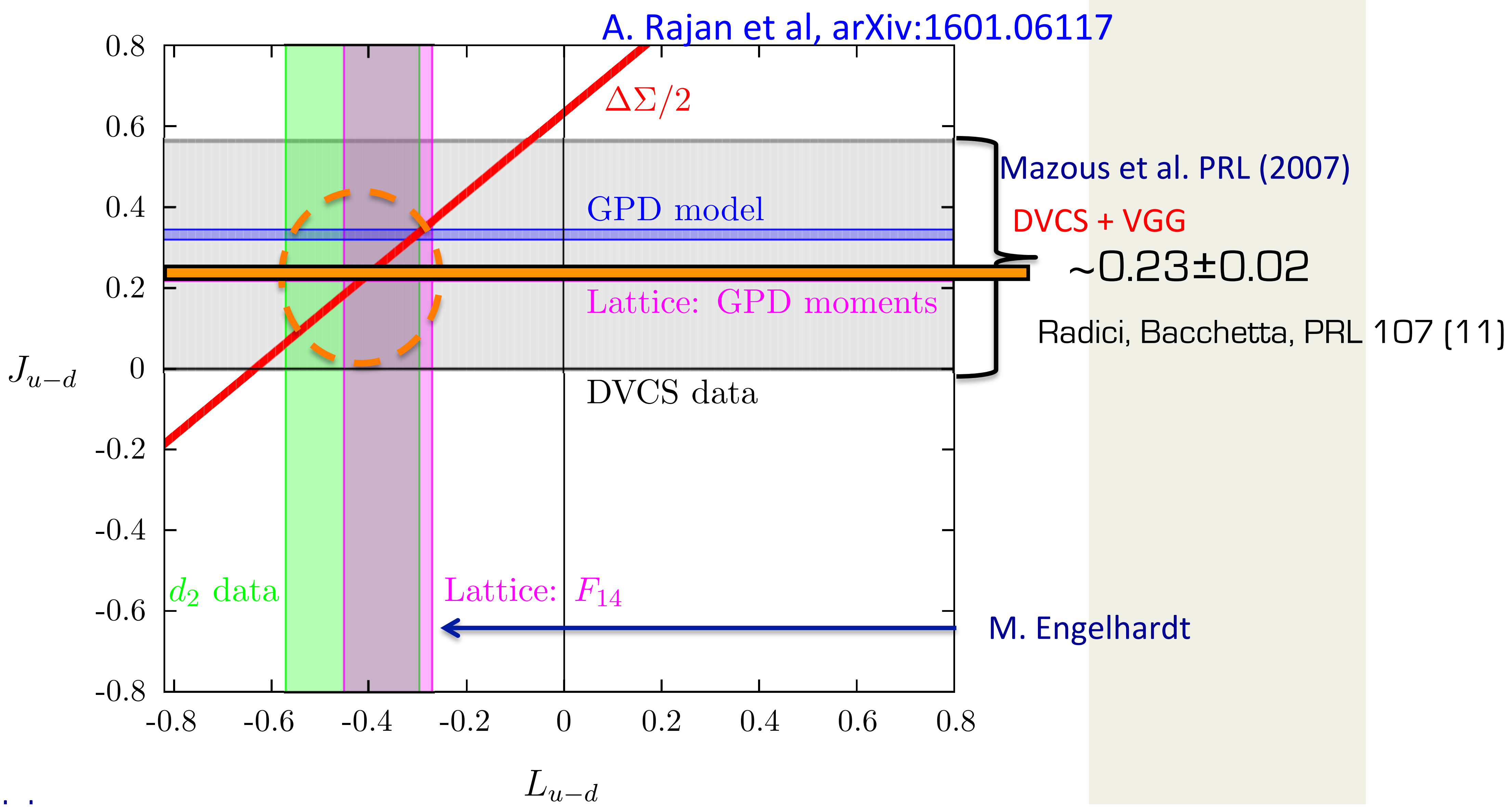
Constraints on angular momenta

S. Liuti's talk



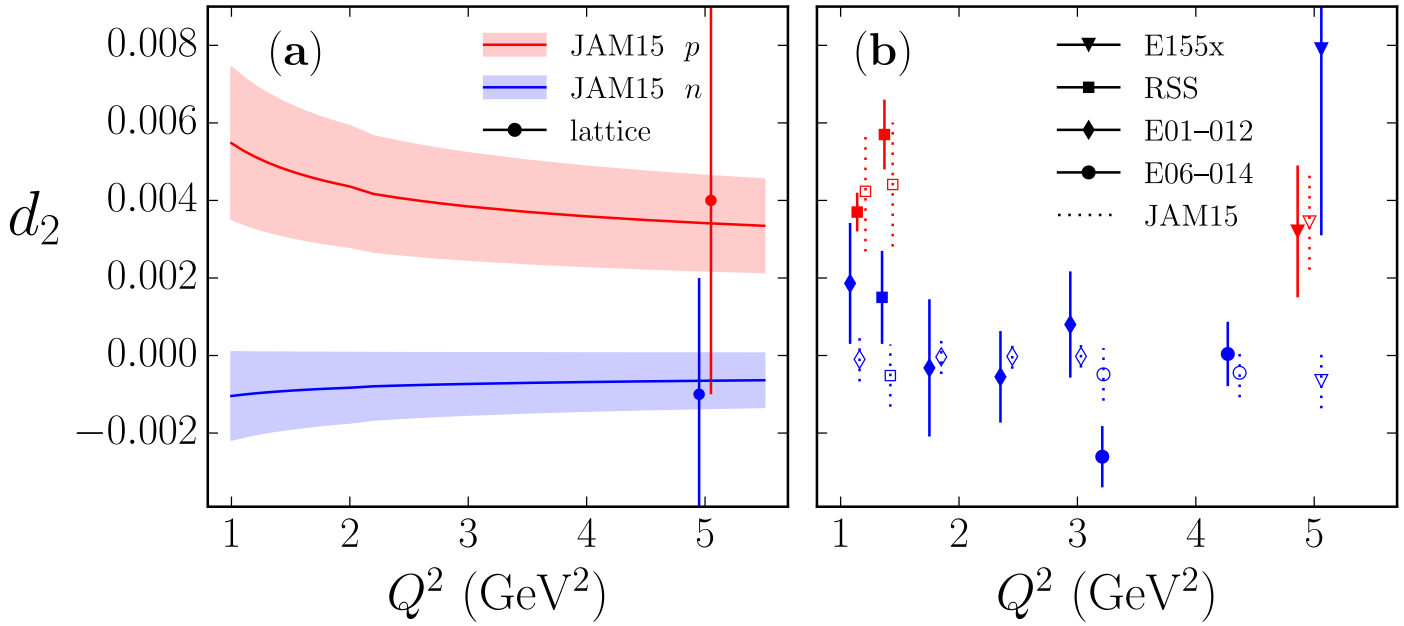
Constraints on angular momenta

S. Liuti's talk



g_2 measurements

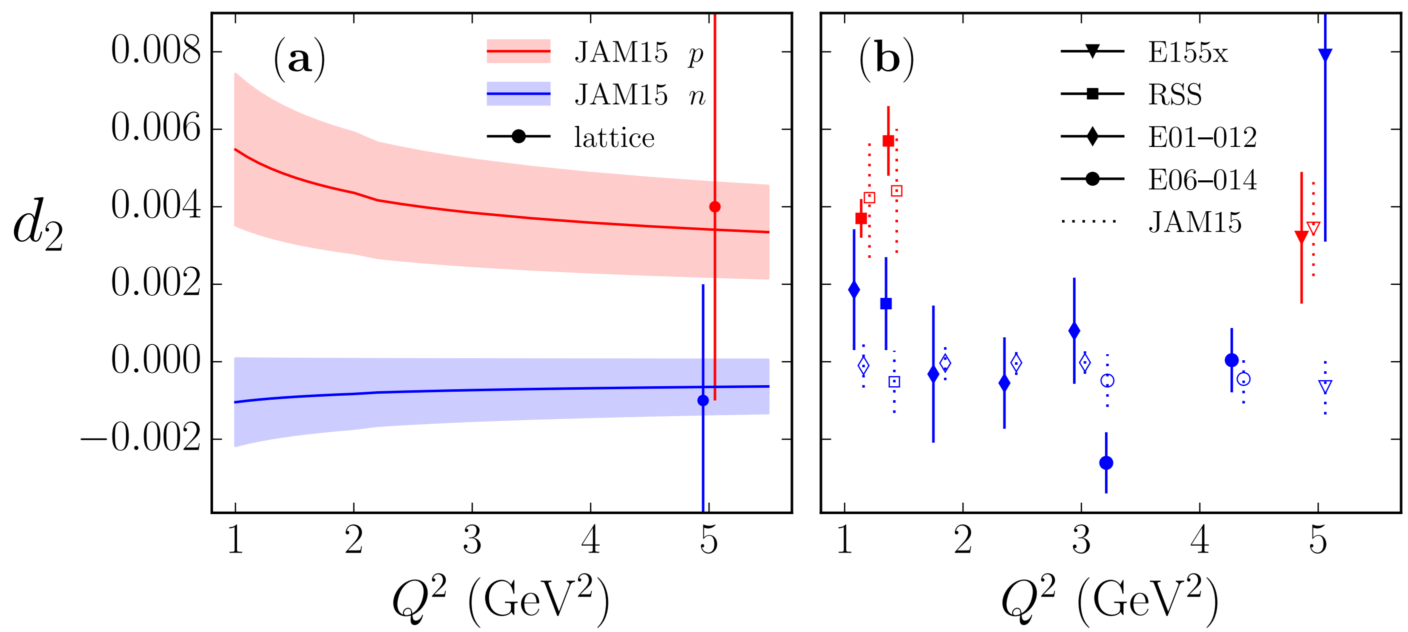
N. Sato's talk



- $d_2(Q^2) \equiv \int_0^1 dx x^2 \left[2g_1^{\mathrm{T3}}(x,Q^2) + 3g_2^{\mathrm{T3}}(x,Q^2)\right]$

g_2 measurements

N. Sato's talk



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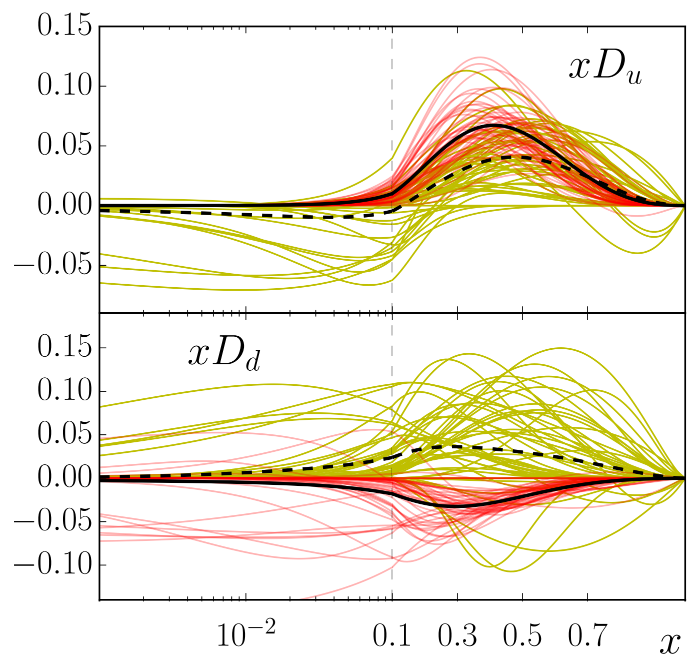
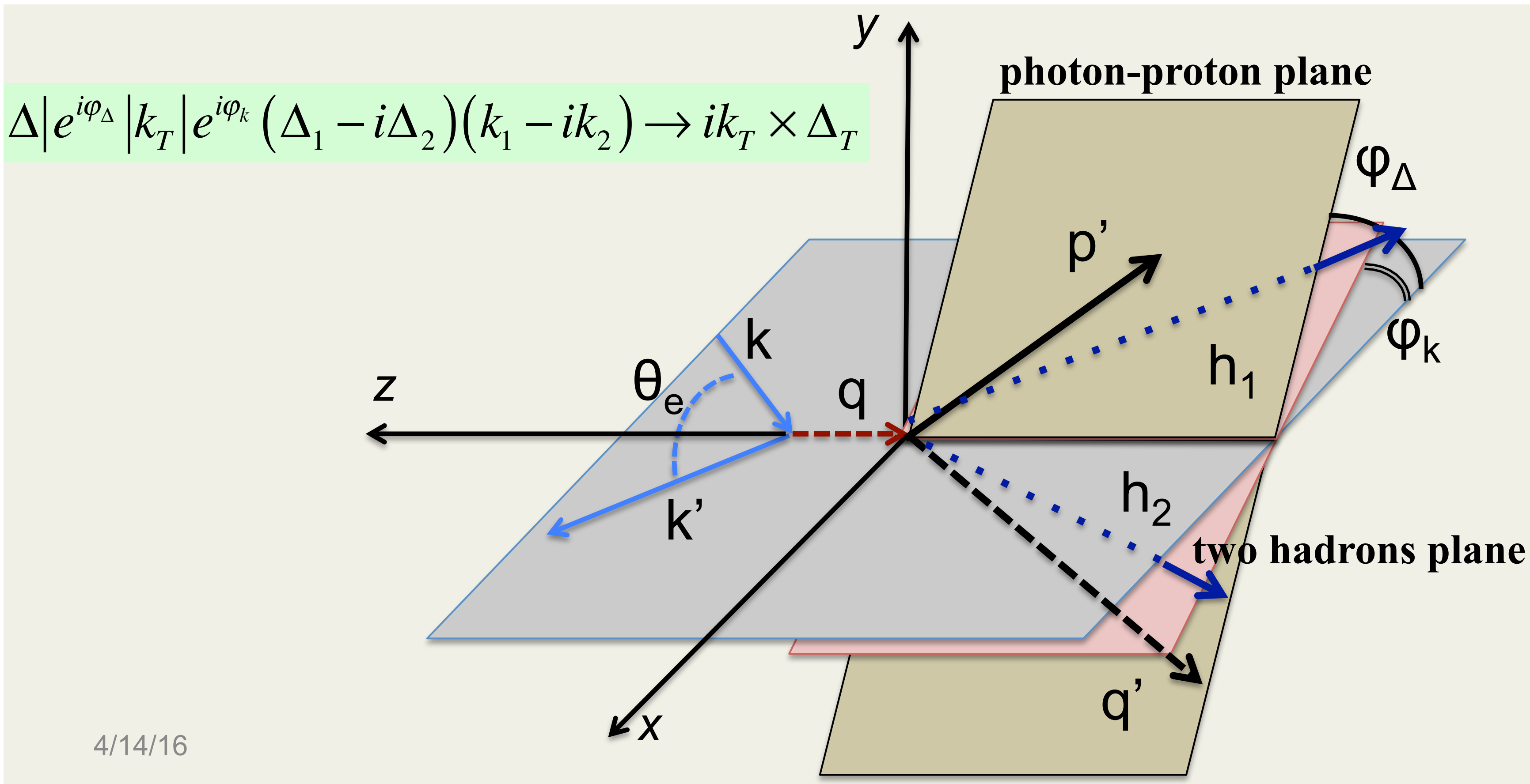


Impact of JLab data on JAM twist-3 determination

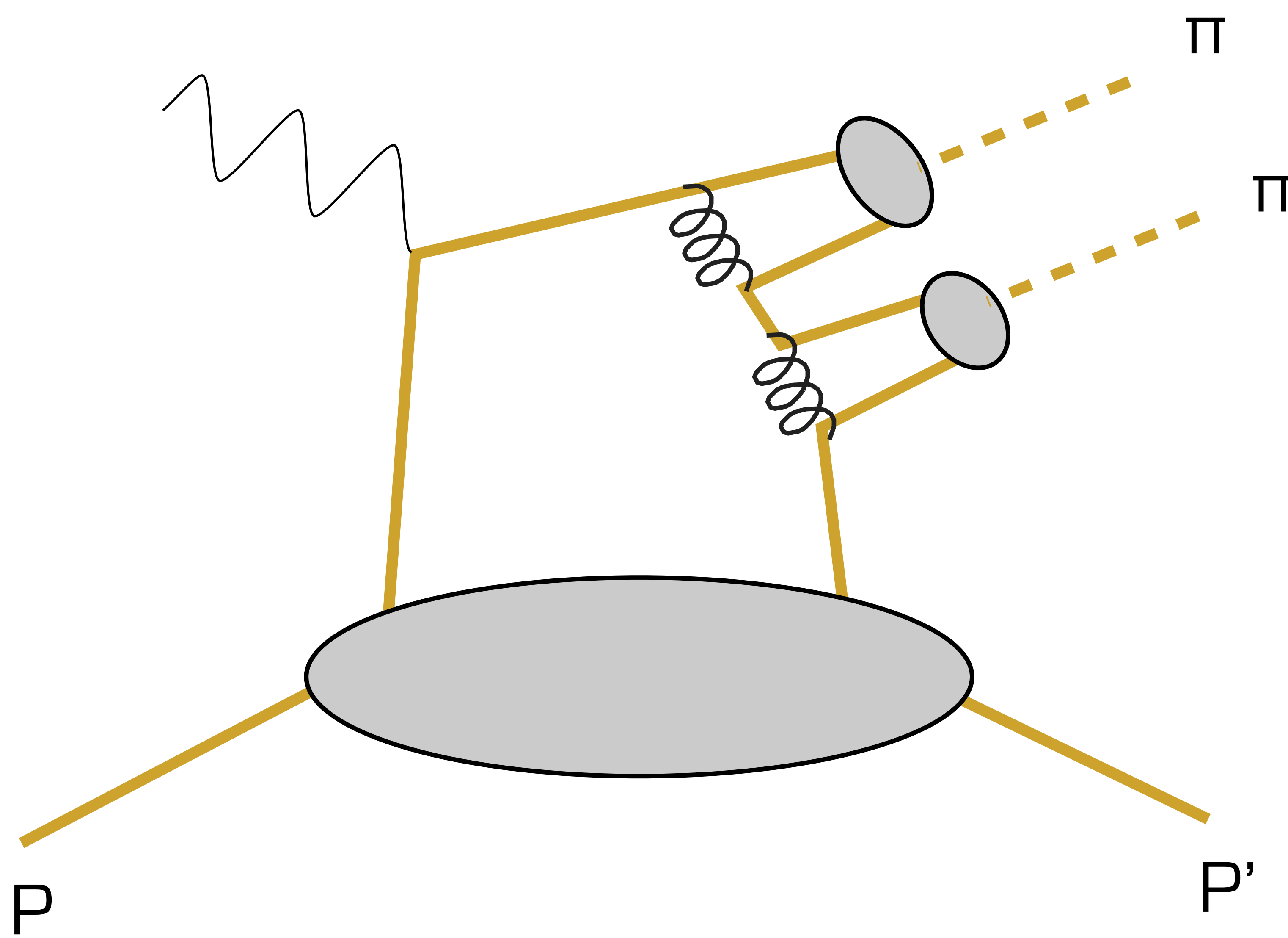
Two claims to observe GMTDs

S. Liuti's talk



Two claims to observe GMTDs

J. Qiu during discussion



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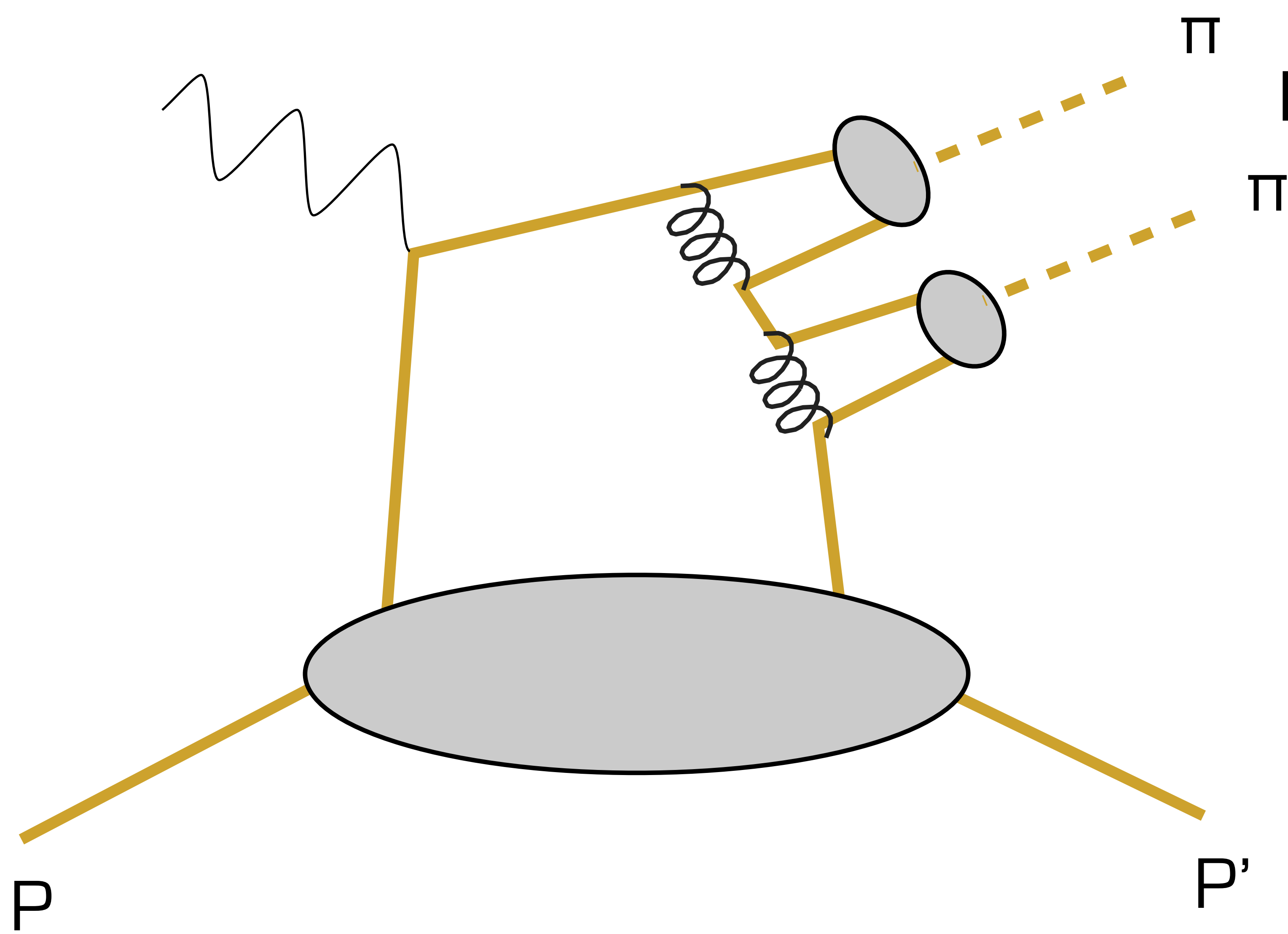


High invariant mass

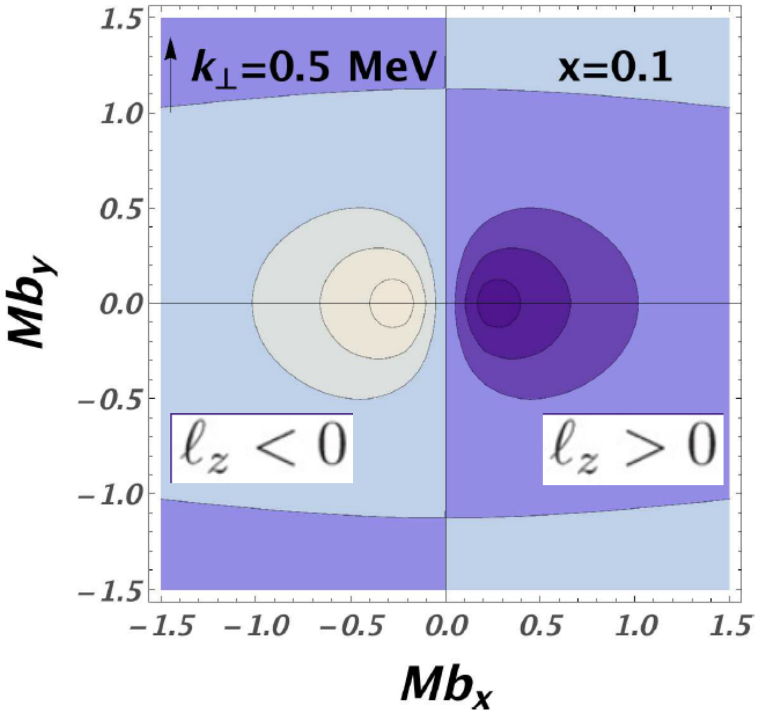
I am personally skeptical, but let's wait for a publication

Can QED be helpful?

L. Mantovani's talk

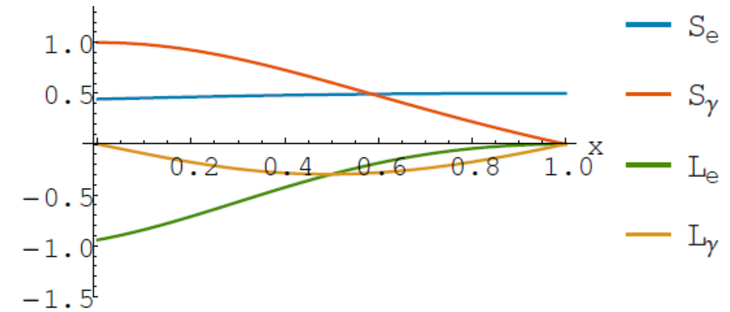
Unpol. electron in long. pol. dressed electron

$$\rho_{LU} := \frac{1}{2}\left[\rho^{[\gamma^+]}_{\uparrow\uparrow} - \rho^{[\gamma^+]}_{\downarrow\downarrow}\right] = -\frac{1}{M^2}\left(\mathbf{k}_\perp \times \frac{\partial}{\partial \mathbf{b}}\right)_z \mathrm{FT}\left[F_{1,4}\right]$$

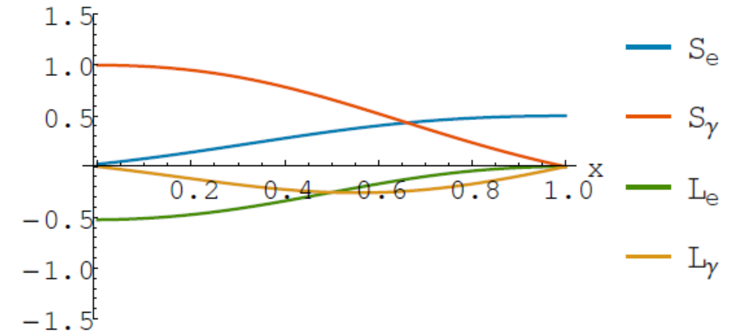


$$l_z = \int dx\, d^2\mathbf{b}_\perp d^2\mathbf{k}_\perp \left(\mathbf{b}_\perp \times \mathbf{k}_\perp\right)_z \rho_{UU} = 0$$

$b = 0.1/M$



$b = 10/M$



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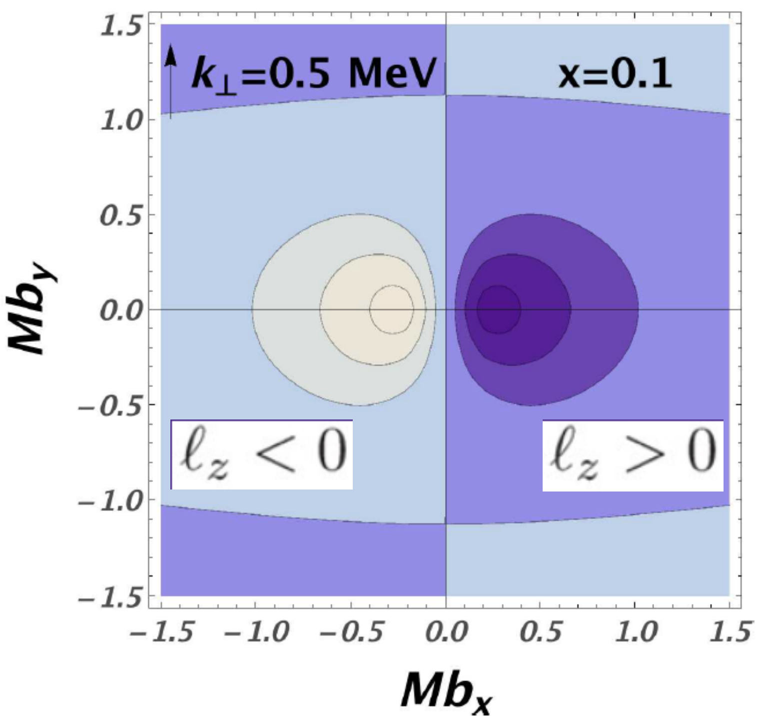

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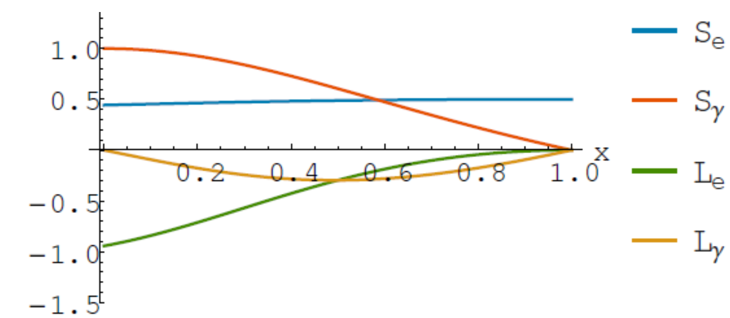

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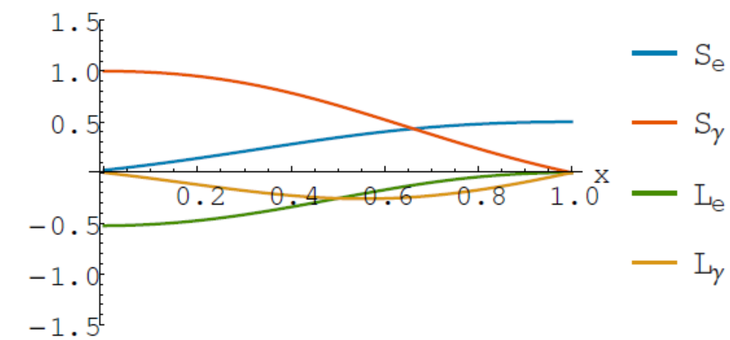

Wigner distribution and GTMDs can be computed in QED, but can we define a way to measure them?

Conclusions

Theory is in good shape, we are waiting for more data to challenge it