TMDS IN UNPOLARIZED DRELL-YAN

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Disclaimer

Disclaimer

- I am presenting mainly work done by others. In particular, Marc Schlegel, Zhun Lu and Stefano Melis among the workshop participants

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- I will repeat some things that have been said in the talks by Werner and Enzo

General formula

$$\frac{d\sigma}{d^4q\, d\Omega} \propto \frac{\alpha^2}{Q^2}\left[(1+\cos^2\theta)\, F_{UU}^{1} + (1-\cos^2\theta)\, F_{UU}^{2} + \sin 2\theta \cos\phi\, F_{UU}^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_{UU}^{\cos 2\phi}\right]$$

Boer, Vogelsang, PRD 74 (06)
Arnold, Metz, Schlegel, PRD 79 (09)

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“D-Y F_T”

Boer, Vogelsang, PRD 74 (06)
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General formula

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"D-Y F_T" "D-Y F_L"

Boer, Vogelsang, PRD 74 (06)
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General formula

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"D-Y F_T" "D-Y F_L" "Cahn"

Boer, Vogelsang, PRD 74 (06)
Arnold, Metz, Schlegel, PRD 79 (09)

General formula

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"D-Y F_T" "D-Y F_L" "Cahn" "Boer-Mulders"

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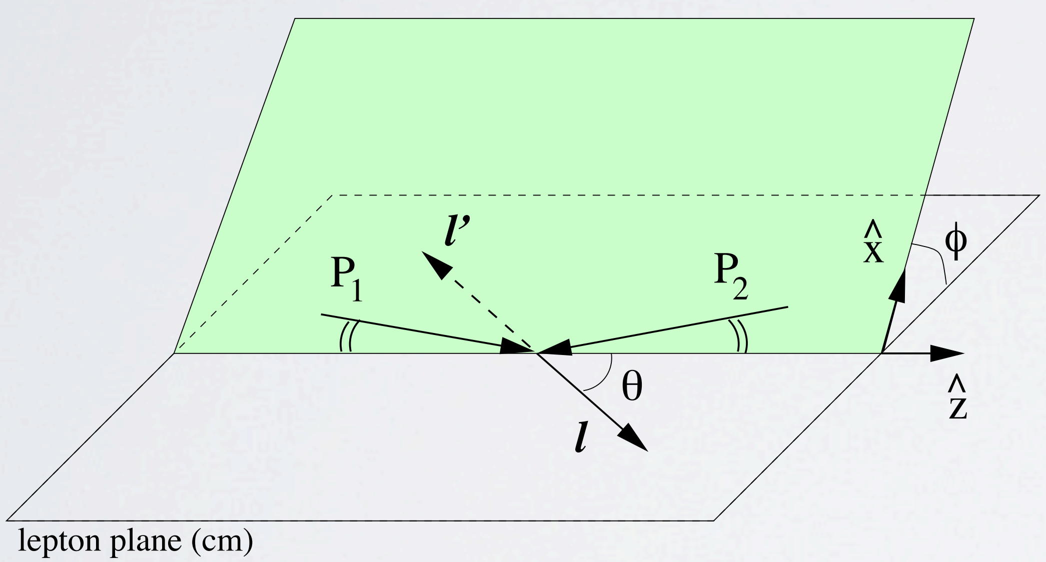
"D-Y F_T" "D-Y F_L" "Cahn" "Boer-Mulders"

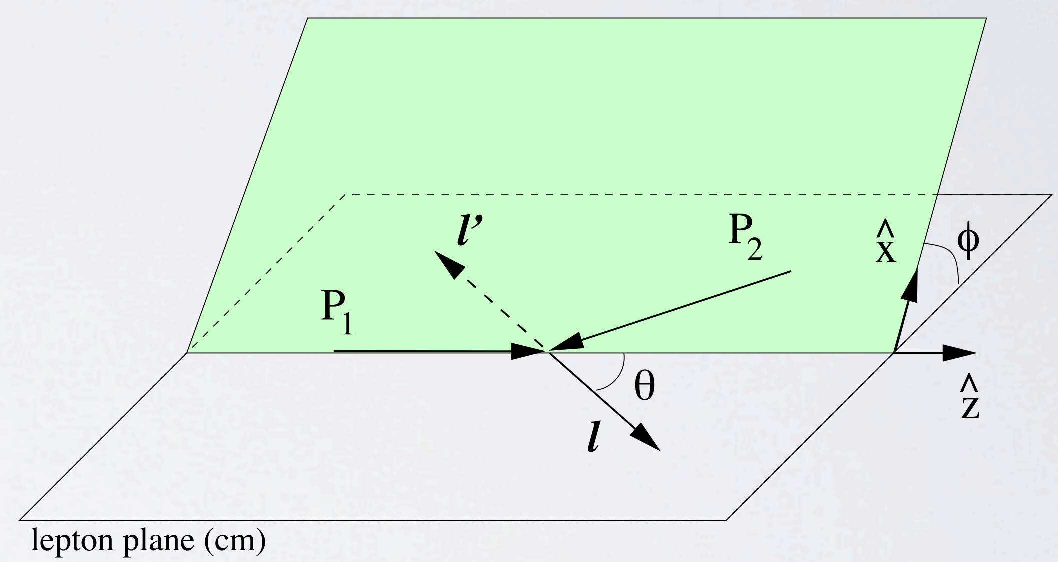
$$\lambda = \frac{F_{UU}^1 - F_{UU}^2}{F_{UU}^1 + F_{UU}^2}\,, \qquad \mu = \frac{F_{UU}^{\cos\phi}}{F_{UU}^1 + F_{UU}^2}\,, \qquad \nu = \frac{2\,F_{UU}^{\cos 2\phi}}{F_{UU}^1 + F_{UU}^2}$$

Boer, Vogelsang, PRD 74 (06)
Arnold, Metz, Schlegel, PRD 79 (09)

Different frames



Collins-Soper



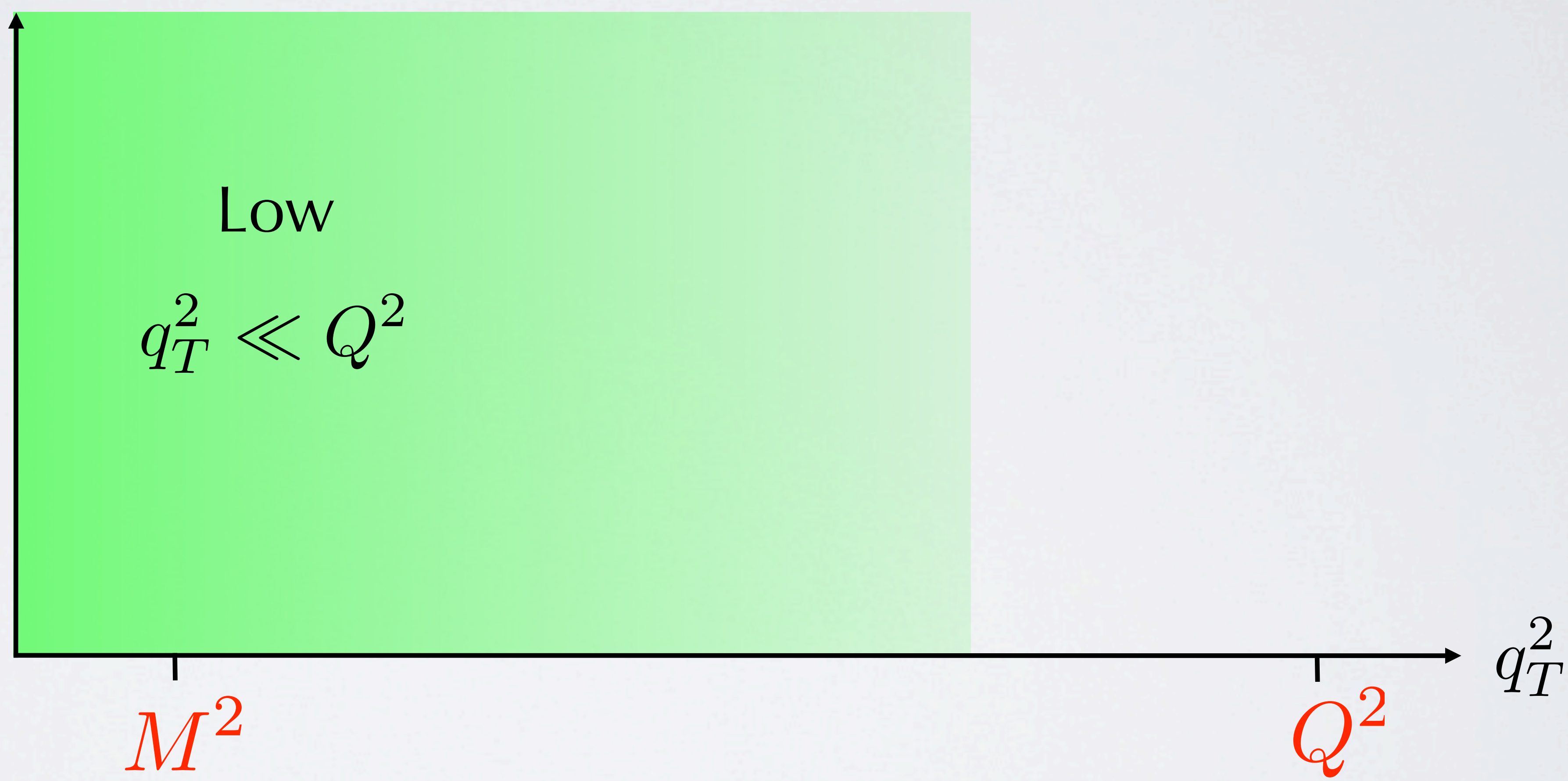
Gottfried-Jackson

Connecting the frames

$$\begin{pmatrix} F_{UU}^{1} \\ F_{UU}^{2} \\ F_{UU}^{\cos\phi} \\ F_{UU}^{\cos 2\phi} \end{pmatrix}_{\rm GJ} = \frac{1}{1+\rho^2} \begin{pmatrix} 1+\frac{1}{2}\rho^2 & \frac{1}{2}\rho^2 & -\rho & \frac{1}{2}\rho^2 \\ \rho^2 & 1 & 2\rho & -\rho^2 \\ \rho & -\rho & 1-\rho^2 & -\rho \\ \frac{1}{2}\rho^2 & -\frac{1}{2}\rho^2 & \rho & 1+\frac{1}{2}\rho^2 \end{pmatrix} \begin{pmatrix} F_{UU}^{1} \\ F_{UU}^{2} \\ F_{UU}^{\cos\phi} \\ F_{UU}^{\cos 2\phi} \end{pmatrix}_{\rm CS}$$

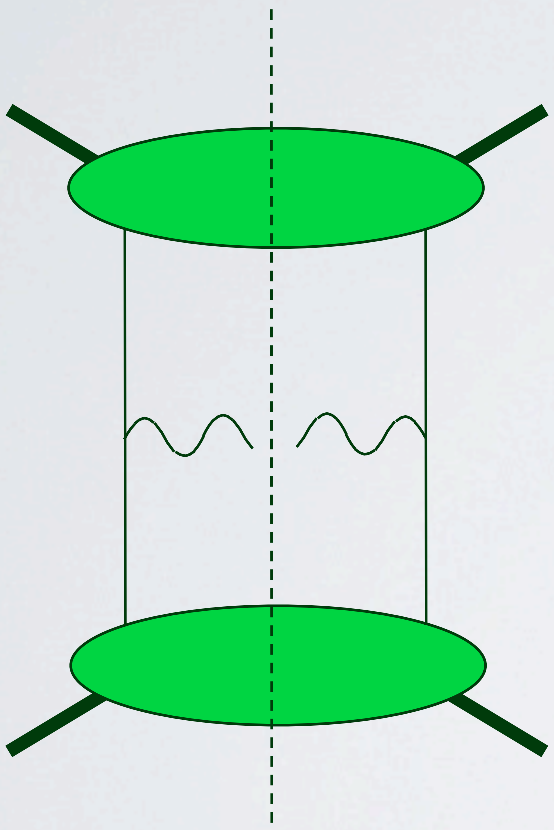
$$\rho \equiv \frac{q_T}{Q}$$

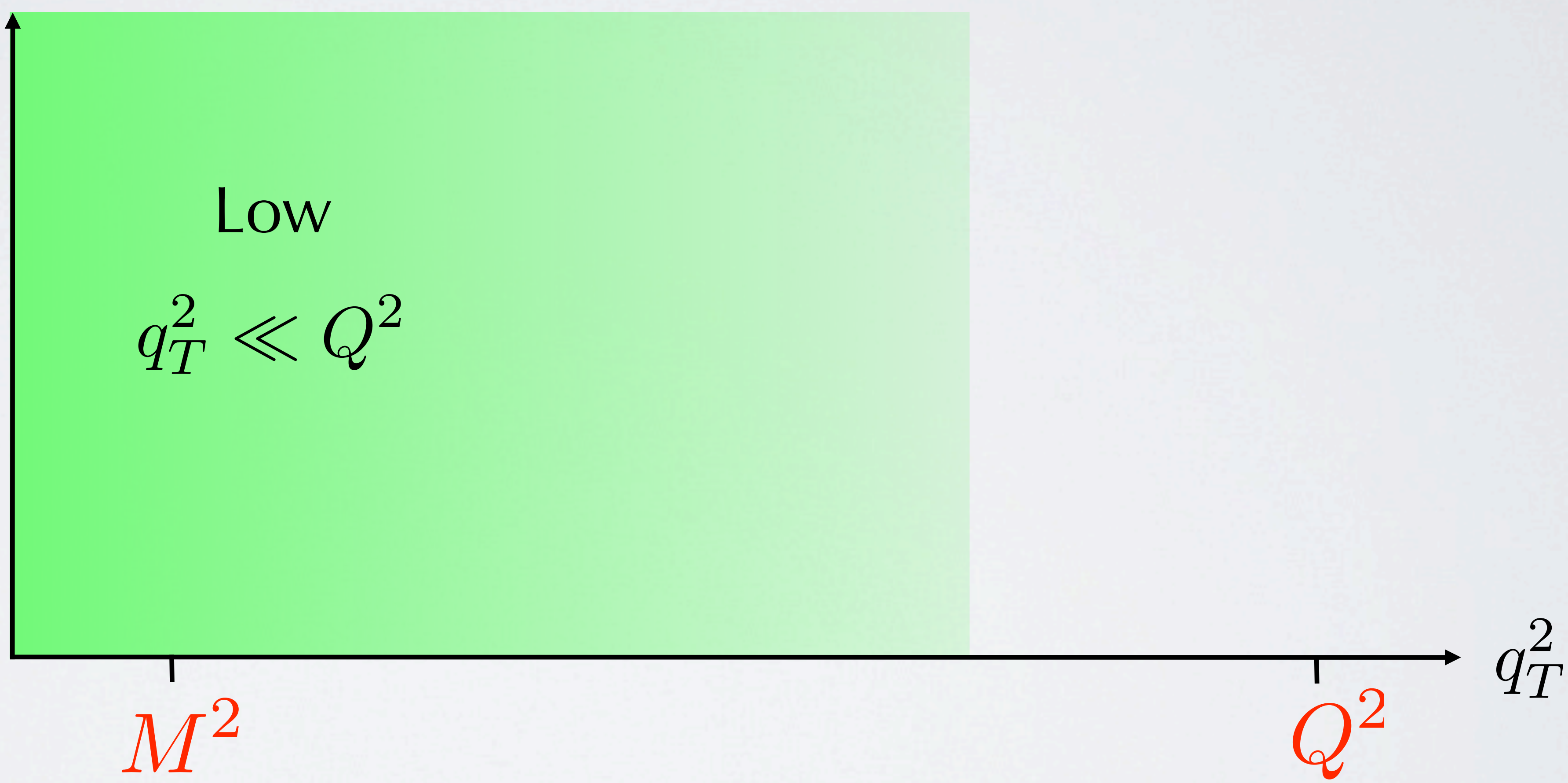
Low transverse momentum



see Werner's talk

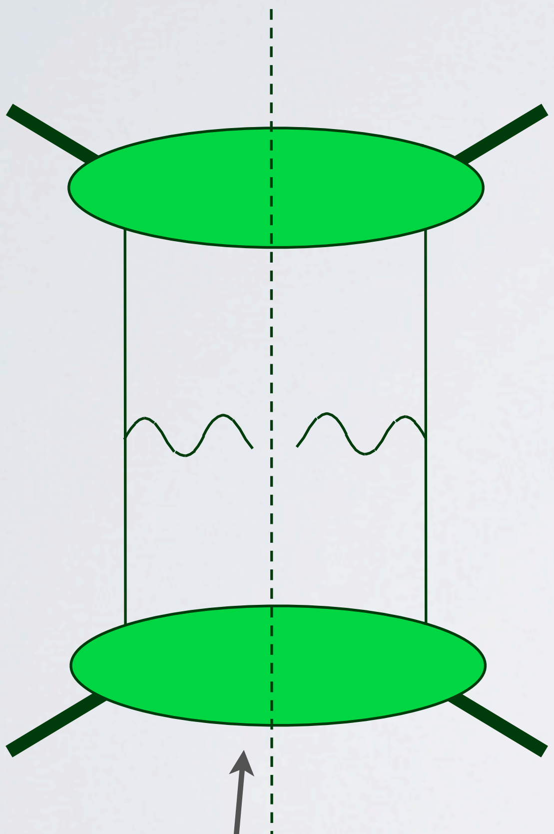
Low transverse momentum



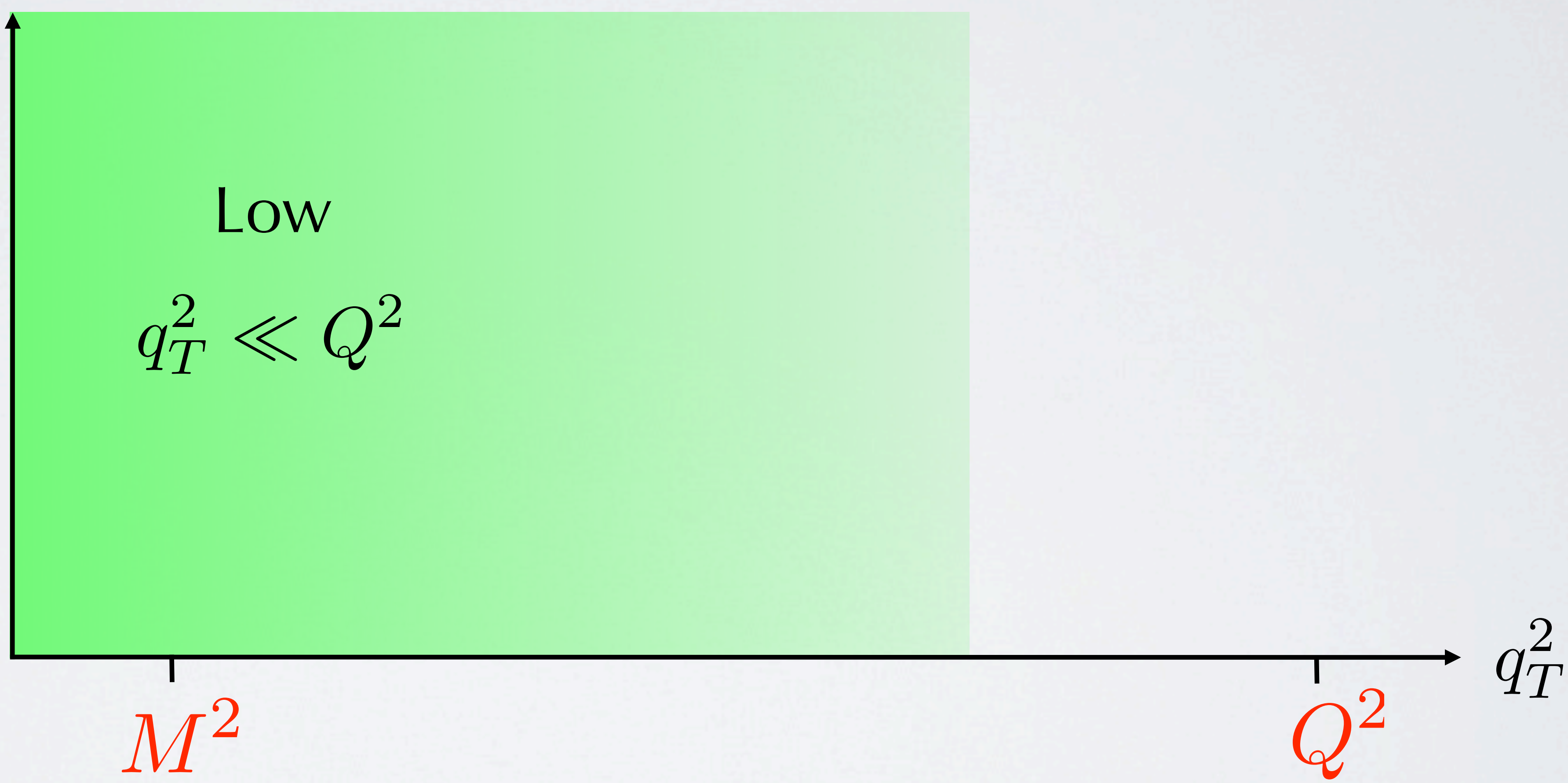


see Werner's talk

Low transverse momentum

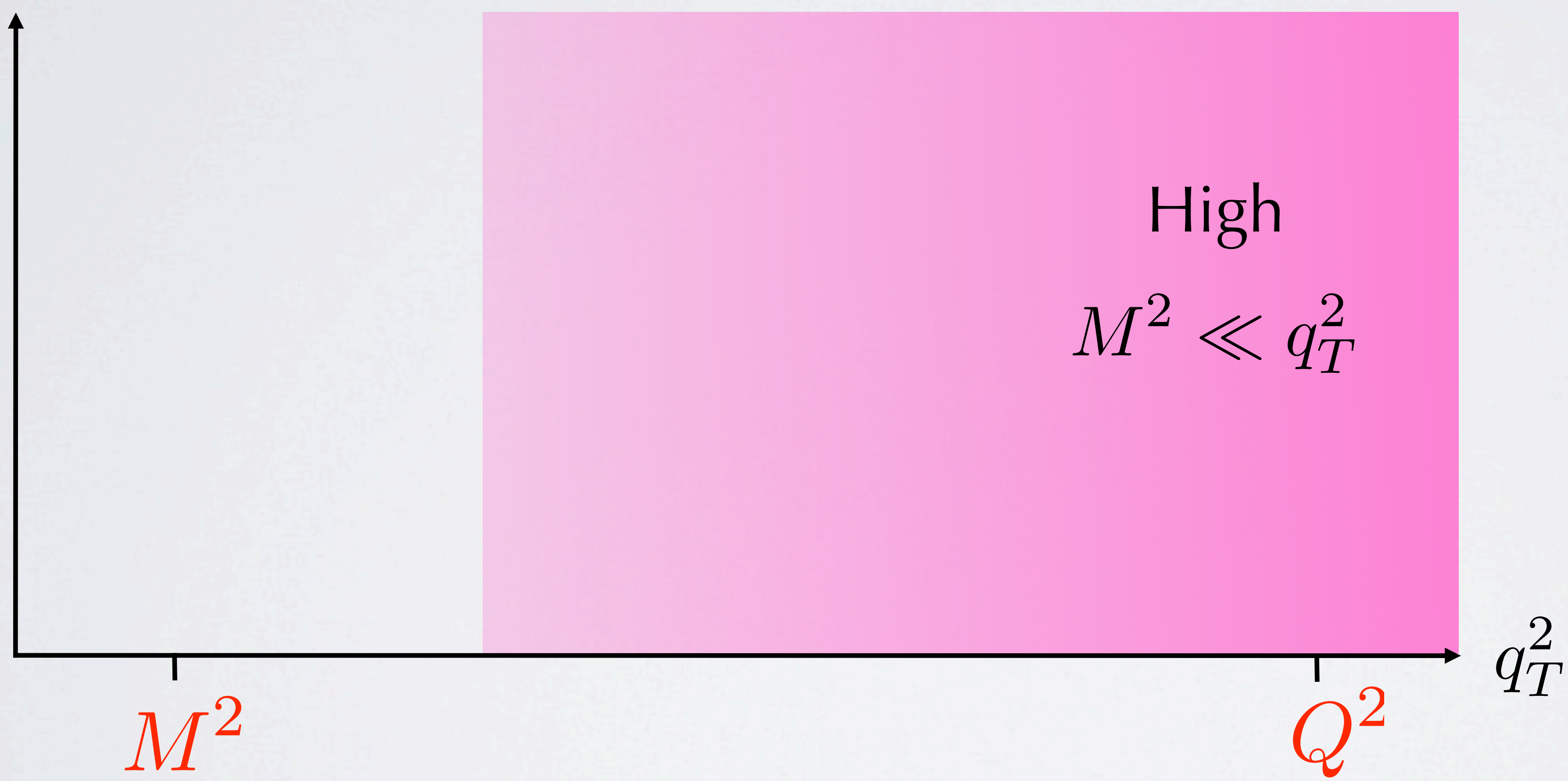


TMDs

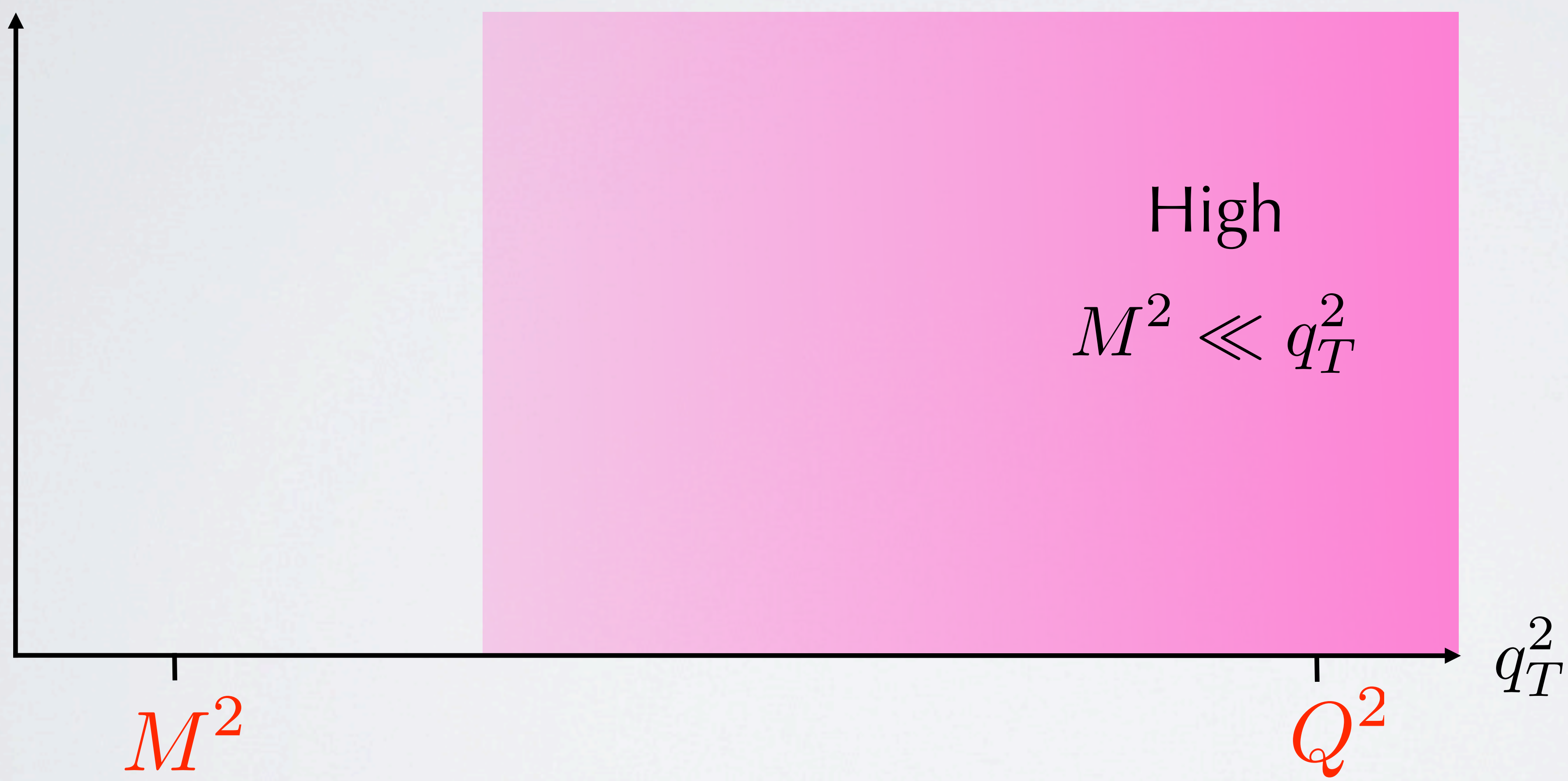


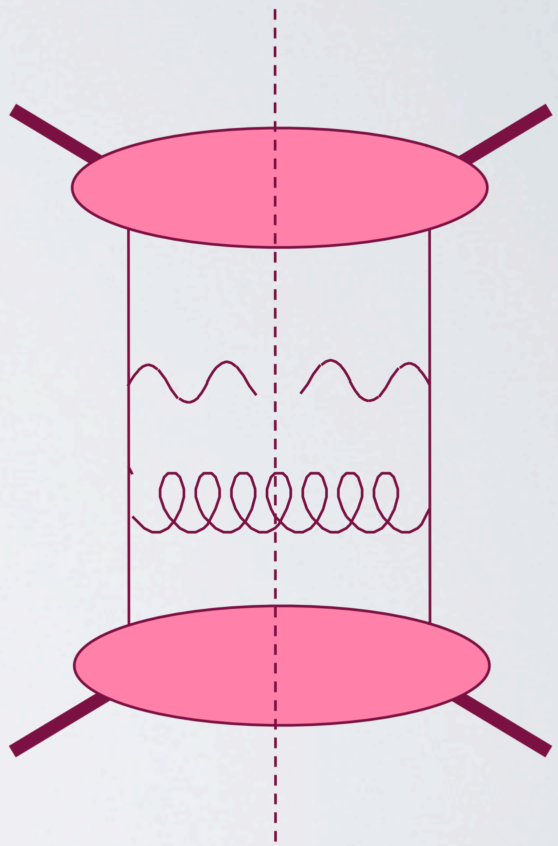
see Werner's talk

High transverse momentum

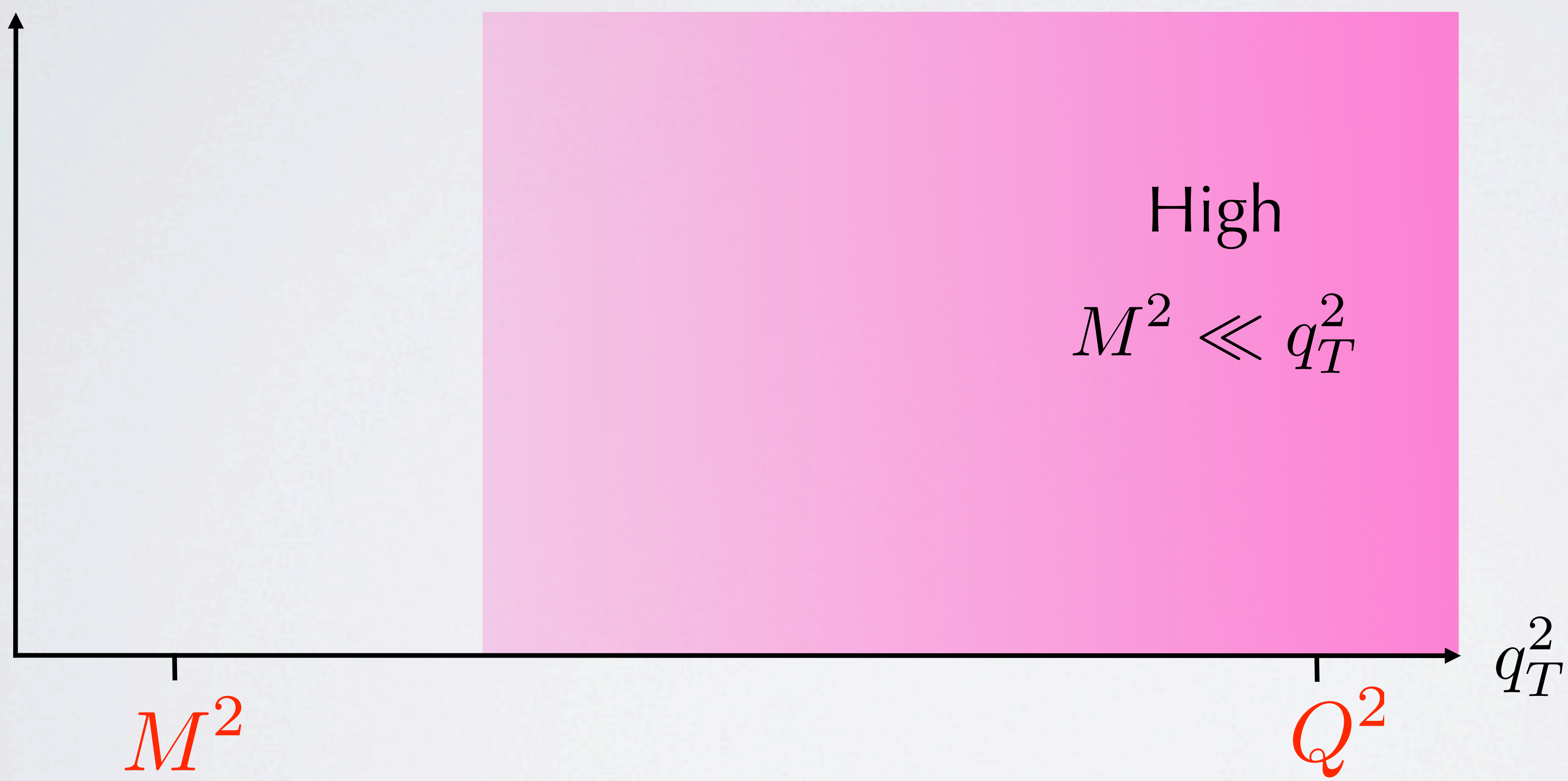


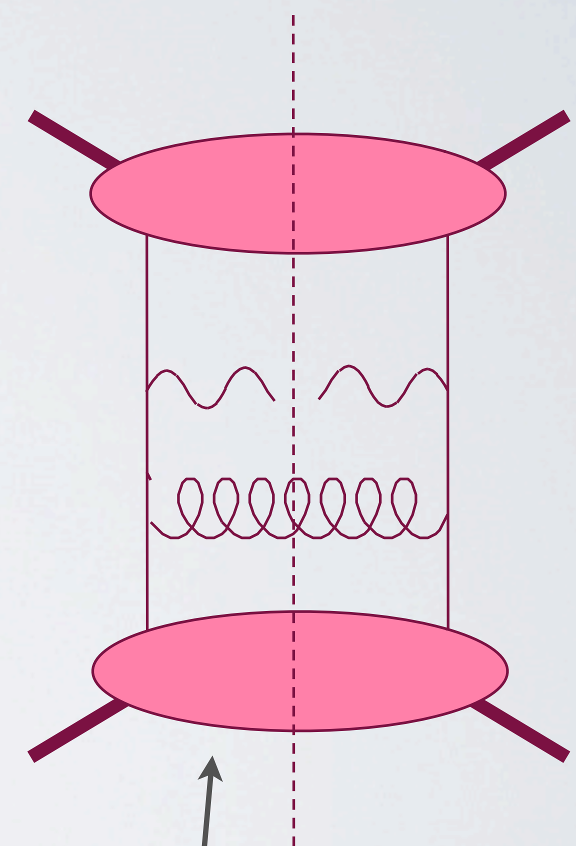
High transverse momentum





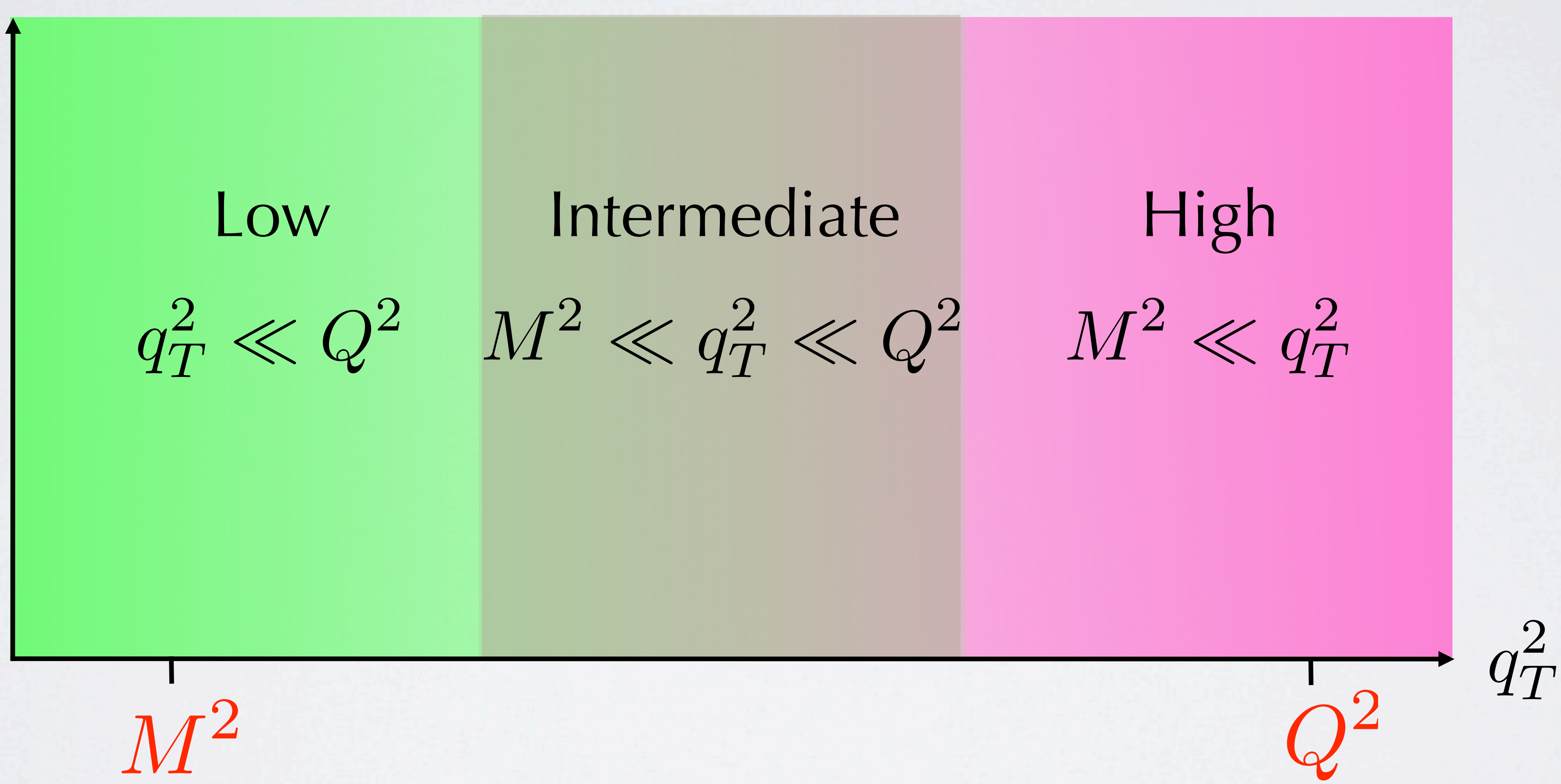
High transverse momentum





collinear PDFs

Matching?


Low
$q_T^2 \ll Q^2$
Intermediate
$M^2 \ll q_T^2 \ll Q^2$
High
$M^2 \ll q_T^2$
q_T^2
M^2
Q^2

Low transverse momentum

$$\frac{d\sigma}{d^4q\,d\Omega} \propto \frac{\alpha^2}{Q^2}\left[(1+\cos^2\theta)\,F_{UU}^{1} \qquad\qquad + \sin^2\theta\cos 2\phi\,F_{UU}^{\cos 2\phi}\right]$$

Low transverse momentum

$$\frac{d\sigma}{d^4q\, d\Omega} \propto \frac{\alpha^2}{Q^2}\Bigg[(1+\cos^2\theta)\, F_{UU}^1 \qquad\qquad + \sin^2\theta\cos 2\phi\, F_{UU}^{\cos 2\phi}\Bigg]$$

Twist 2 Twist 2

Low transverse momentum

$$\frac{d\sigma}{d^4q\, d\Omega} \propto \frac{\alpha^2}{Q^2}\left[(1+\cos^2\theta)\, F_{UU}^1 + (1-\cos^2\theta)\, F_{UU}^2 + \sin 2\theta \cos\phi\, F_{UU}^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_{UU}^{\cos 2\phi}\right]$$

Twist 2 Twist 4 Twist 3 Twist 2

High transverse momentum

$$\frac{d\sigma}{d^4q\,d\Omega} \propto \frac{\alpha^2}{Q^2}\left[(1+\cos^2\theta)\,F_{UU}^1 + (1-\cos^2\theta)\,F_{UU}^2 + \sin 2\theta\cos\phi\,F_{UU}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{UU}^{\cos 2\phi}\right]$$

High transverse momentum

$$\frac{d\sigma}{d^4q\,d\Omega} \propto \frac{\alpha^2}{Q^2}\left[(1+\cos^2\theta)\,F_{UU}^{1} + (1-\cos^2\theta)\,F_{UU}^{2} + \sin 2\theta\cos\phi\,F_{UU}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{UU}^{\cos 2\phi}\right]$$

All twist 2

Matching?

Low q_T

High q_T

$$F \sim \frac{M^2 q_T^2}{M^6 + q_T^6}$$

$$F \sim \frac{M^2}{q_T^4}$$

Matching?

Low q_T

High q_T

$$F \sim \frac{1}{M^2 + q_T^2}$$

$$F \sim \frac{M^2 q_T^2}{M^6 + q_T^6}$$

$$F \sim \frac{M^2}{q_T^4}$$

Matching?

Low q_T		High q_T
$F \sim \frac{1}{M^2}$	$F \sim \frac{1}{M^2 + q_T^2}$	
	$F \sim \frac{M^2 q_T^2}{M^6 + q_T^6}$	$F \sim \frac{M^2}{q_T^4}$

Matching?

	Low q_T		High q_T
Tw 2	$F \sim \frac{1}{M^2}$	$F \sim \frac{1}{M^2 + q_T^2}$	
		$F \sim \frac{M^2 q_T^2}{M^6 + q_T^6}$	$F \sim \frac{M^2}{q_T^4}$

Matching?

	Low q_T		High q_T
Tw 2	$F \sim \frac{1}{M^2}$	$F \sim \frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{q_T^2}$
		$F \sim \frac{M^2 q_T^2}{M^6 + q_T^6}$	$F \sim \frac{M^2}{q_T^4}$

Matching?

Low q_T		High q_T
Tw 2 $F \sim \frac{1}{M^2}$	$F \sim \frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{q_T^2}$ Tw 2
	$F \sim \frac{M^2 q_T^2}{M^6 + q_T^6}$	$F \sim \frac{M^2}{q_T^4}$

Matching?

Low q_T		High q_T
Tw 2 $F \sim \frac{1}{M^2}$	$F \sim \frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{q_T^2}$ Tw 2
	$F \sim \frac{q_T}{Q} \frac{1}{M^2 + q_T^2}$	
	$F \sim \frac{M^2 q_T^2}{M^6 + q_T^6}$	$F \sim \frac{M^2}{q_T^4}$

Matching?

Low q_T		High q_T

	Low q_T		High q_T	
Tw 2	$F \sim \frac{1}{M^2}$	$F \sim \frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{q_T^2}$	Tw 2
	$F \sim \frac{1}{Q}\frac{q_T}{M^2}$	$F \sim \frac{q_T}{Q}\frac{1}{M^2 + q_T^2}$		
		$F \sim \frac{M^2 q_T^2}{M^6 + q_T^6}$	$F \sim \frac{M^2}{q_T^4}$	

Matching?

	Low q_T		High q_T	
Tw 2	$F \sim \frac{1}{M^2}$	$F \sim \frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{q_T^2}$	Tw 2
Tw 3	$F \sim \frac{1}{Q}\frac{q_T}{M^2}$	$F \sim \frac{q_T}{Q}\frac{1}{M^2 + q_T^2}$		
		$F \sim \frac{M^2 q_T^2}{M^6 + q_T^6}$	$F \sim \frac{M^2}{q_T^4}$	

Matching?

	Low qT		High qT	
Tw 2	$F \sim \dfrac{1}{M^2}$	$F \sim \dfrac{1}{M^2 + q_T^2}$	$F \sim \dfrac{1}{q_T^2}$	Tw 2
Tw 3	$F \sim \dfrac{1}{Q}\dfrac{q_T}{M^2}$	$F \sim \dfrac{q_T}{Q}\dfrac{1}{M^2 + q_T^2}$	$F \sim \dfrac{1}{Q q_T}$	
		$F \sim \dfrac{M^2 q_T^2}{M^6 + q_T^6}$	$F \sim \dfrac{M^2}{q_T^4}$	

Matching?

	Low qT		High qT	
Tw 2	$F \sim \frac{1}{M^2}$	$F \sim \frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{q_T^2}$	Tw 2
Tw 3	$F \sim \frac{1}{Q} \frac{q_T}{M^2}$	$F \sim \frac{q_T}{Q} \frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{Q q_T}$	Tw 2
		$F \sim \frac{M^2 q_T^2}{M^6 + q_T^6}$	$F \sim \frac{M^2}{q_T^4}$	

Matching?

Low q_T		High q_T	
Tw 2 $\quad F \sim \frac{1}{M^2}$	$F \sim \frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{q_T^2}$	Tw 2
Tw 3 $\quad F \sim \frac{1}{Q}\frac{q_T}{M^2}$	$F \sim \frac{q_T}{Q}\frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{Q q_T}$	Tw 2
	$F \sim \frac{q_T^2}{Q^2}\frac{1}{M^2 + q_T^2}$		
	$F \sim \frac{M^2 q_T^2}{M^6 + q_T^6}$	$F \sim \frac{M^2}{q_T^4}$	

Matching?

	Low q_T		High q_T	
Tw 2	$F \sim \frac{1}{M^2}$	$F \sim \frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{q_T^2}$	Tw 2
Tw 3	$F \sim \frac{1}{Q} \frac{q_T}{M^2}$	$F \sim \frac{q_T}{Q} \frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{Q q_T}$	Tw 2
	$F \sim \frac{1}{Q^2} \frac{q_T^2}{M^2}$	$F \sim \frac{q_T^2}{Q^2} \frac{1}{M^2 + q_T^2}$		
		$F \sim \frac{M^2 q_T^2}{M^6 + q_T^6}$	$F \sim \frac{M^2}{q_T^4}$	

Matching?

	Low qT		High qT	
Tw 2	$F \sim \dfrac{1}{M^2}$	$F \sim \dfrac{1}{M^2 + q_T^2}$	$F \sim \dfrac{1}{q_T^2}$	Tw 2
Tw 3	$F \sim \dfrac{1}{Q}\dfrac{q_T}{M^2}$	$F \sim \dfrac{q_T}{Q}\dfrac{1}{M^2 + q_T^2}$	$F \sim \dfrac{1}{Q q_T}$	Tw 2
Tw 4	$F \sim \dfrac{1}{Q^2}\dfrac{q_T^2}{M^2}$	$F \sim \dfrac{q_T^2}{Q^2}\dfrac{1}{M^2 + q_T^2}$		
		$F \sim \dfrac{M^2 q_T^2}{M^6 + q_T^6}$	$F \sim \dfrac{M^2}{q_T^4}$	

Matching?

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Tw 4	$F \sim \frac{1}{Q^2} \frac{q_T^2}{M^2}$	$F \sim \frac{q_T^2}{Q^2} \frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{Q^2}$	
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Matching?

	Low q_T		High q_T	
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Tw 3	$F \sim \frac{1}{Q}\frac{q_T}{M^2}$	$F \sim \frac{q_T}{Q}\frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{Q q_T}$	Tw 2
Tw 4	$F \sim \frac{1}{Q^2}\frac{q_T^2}{M^2}$	$F \sim \frac{q_T^2}{Q^2}\frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{Q^2}$	Tw 2
		$F \sim \frac{M^2 q_T^2}{M^6 + q_T^6}$	$F \sim \frac{M^2}{q_T^4}$	

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Tw 3	$F \sim \frac{1}{Q}\frac{q_T}{M^2}$	$F \sim \frac{q_T}{Q}\frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{Q q_T}$	Tw 2
Tw 4	$F \sim \frac{1}{Q^2}\frac{q_T^2}{M^2}$	$F \sim \frac{q_T^2}{Q^2}\frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{Q^2}$	Tw 2
	$F \sim \frac{q_T^2}{M^4}$	$F \sim \frac{M^2 q_T^2}{M^6 + q_T^6}$	$F \sim \frac{M^2}{q_T^4}$	

Matching?

	Low q_T		High q_T	
Tw 2	$F \sim \frac{1}{M^2}$	$F \sim \frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{q_T^2}$	Tw 2
Tw 3	$F \sim \frac{1}{Q} \frac{q_T}{M^2}$	$F \sim \frac{q_T}{Q} \frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{Q q_T}$	Tw 2
Tw 4	$F \sim \frac{1}{Q^2} \frac{q_T^2}{M^2}$	$F \sim \frac{q_T^2}{Q^2} \frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{Q^2}$	Tw 2
Tw 2	$F \sim \frac{q_T^2}{M^4}$	$F \sim \frac{M^2 q_T^2}{M^6 + q_T^6}$	$F \sim \frac{M^2}{q_T^4}$	

Matching?

	Low q_T		High q_T	
Tw 2	$F \sim \frac{1}{M^2}$	$F \sim \frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{q_T^2}$	Tw 2
Tw 3	$F \sim \frac{1}{Q}\frac{q_T}{M^2}$	$F \sim \frac{q_T}{Q}\frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{Q q_T}$	Tw 2
Tw 4	$F \sim \frac{1}{Q^2}\frac{q_T^2}{M^2}$	$F \sim \frac{q_T^2}{Q^2}\frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{Q^2}$	Tw 2
Tw 2	$F \sim \frac{q_T^2}{M^4}$	$F \sim \frac{M^2 q_T^2}{M^6 + q_T^6}$	$F \sim \frac{M^2}{q_T^4}$	Tw 4

Tw 2 $F \sim \frac{q_T^2}{M^4}$ $F \sim \frac{M^2 q_T^4}{M^6 + q_T^6}$ $F \sim \frac{1}{q_T^4}$ Tw 4

1

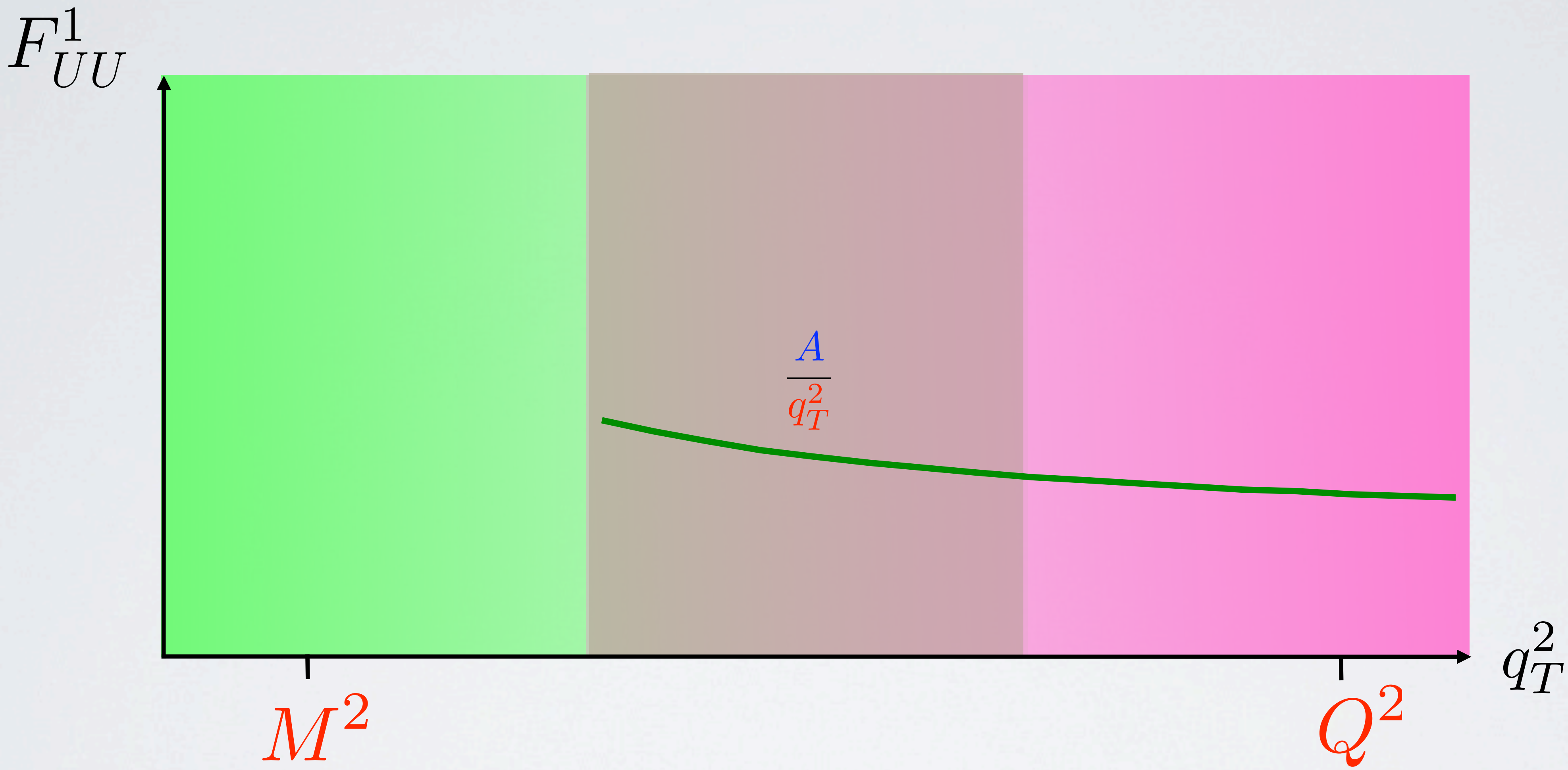
$$F_{UU}^{1}$$

Matching?

Low q_T		High q_T
Tw 2 $F \sim \frac{1}{M^2}$	$F \sim \frac{1}{M^2 + q_T^2}$	$F \sim \frac{1}{q_T^2}$ Tw 2

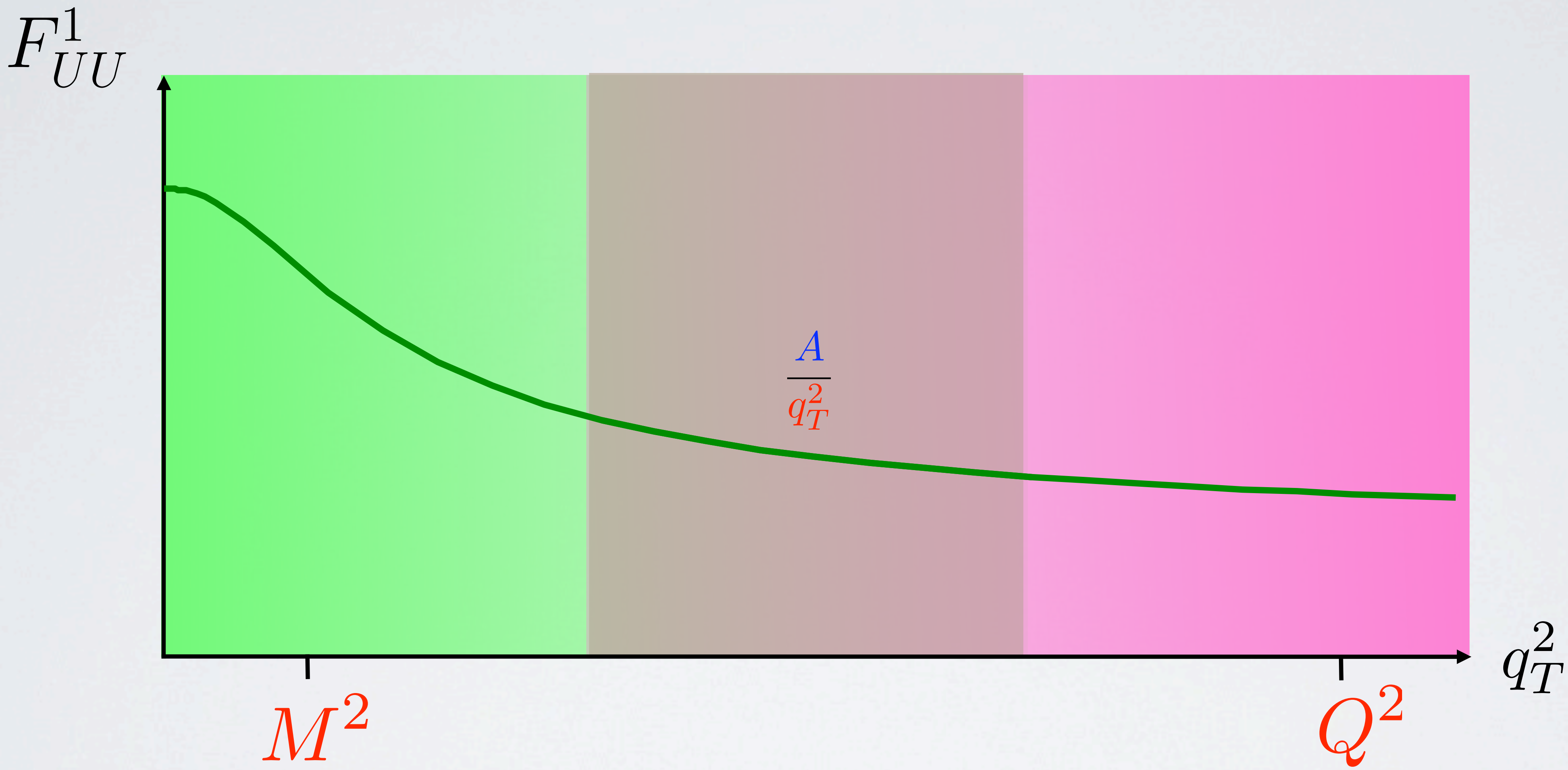
Yes

Matching behavior



Collins, Soper, Sterman, NPB250 (85)

Matching behavior



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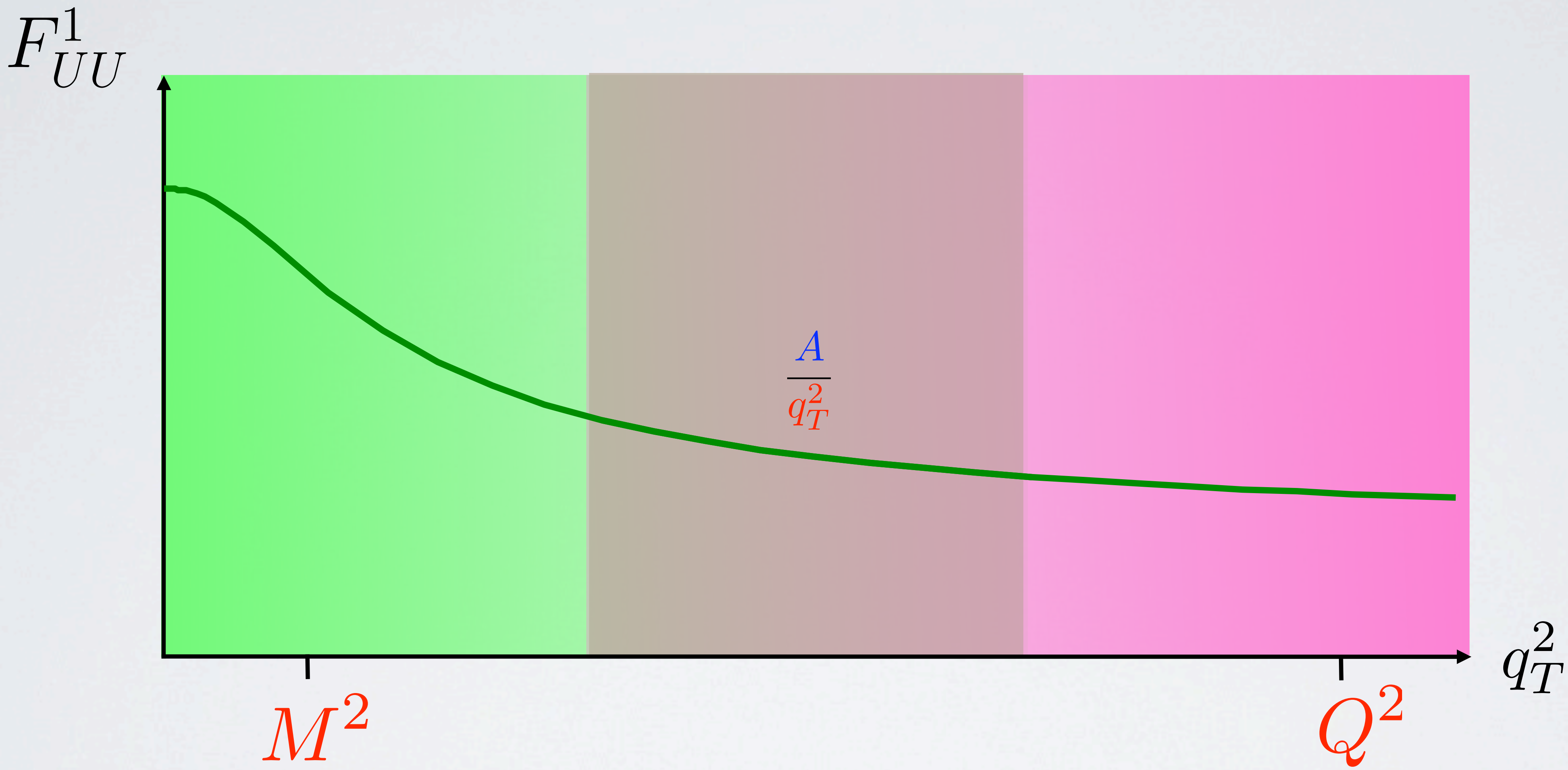
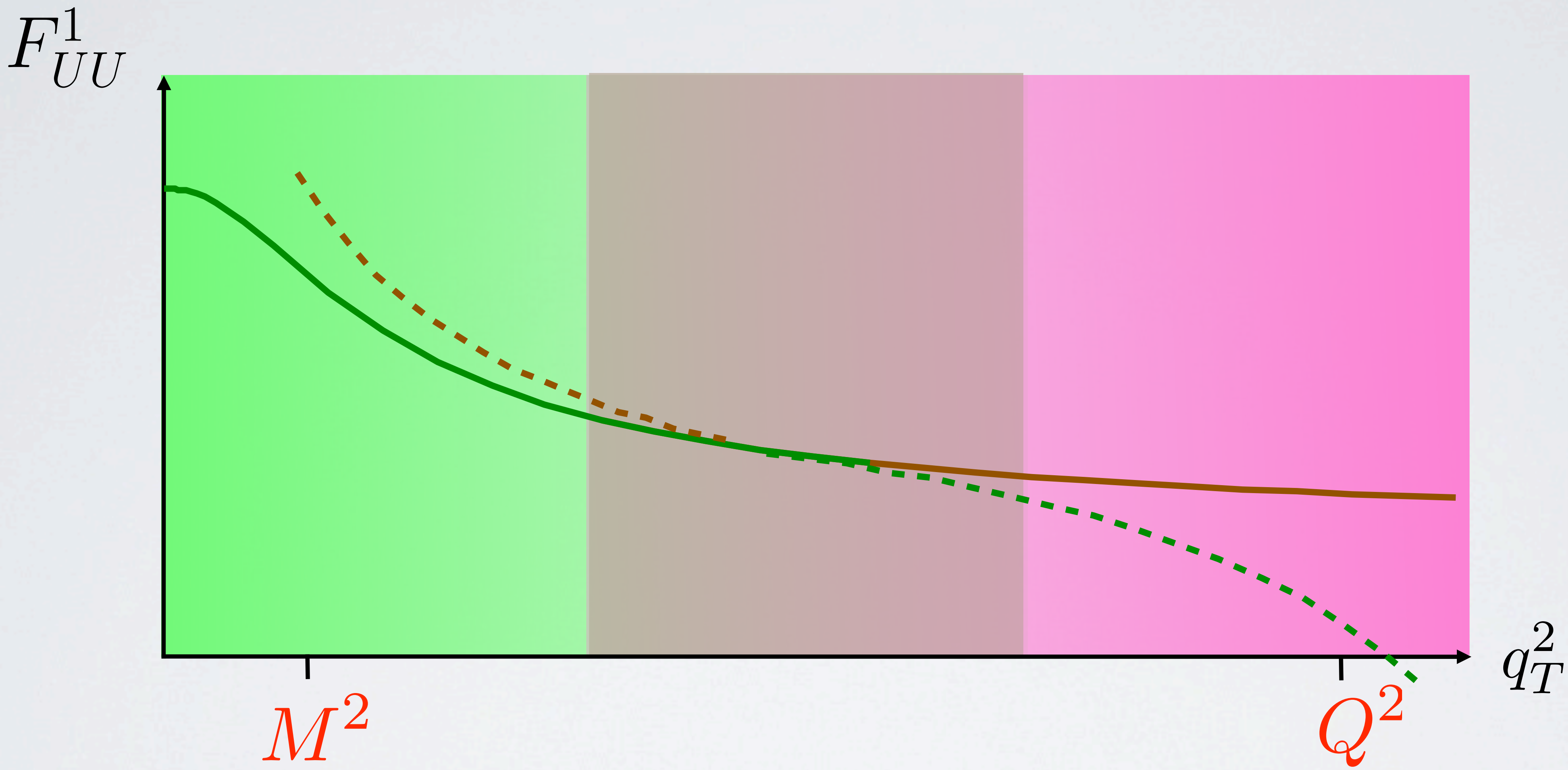


The leading high-q_T part is just the "tail" of the leading low-q_T part. It is in principle possible to write a single expression from low to high q_T.

Collins, Soper, Sterman, NPB250 (85)

Matching behavior



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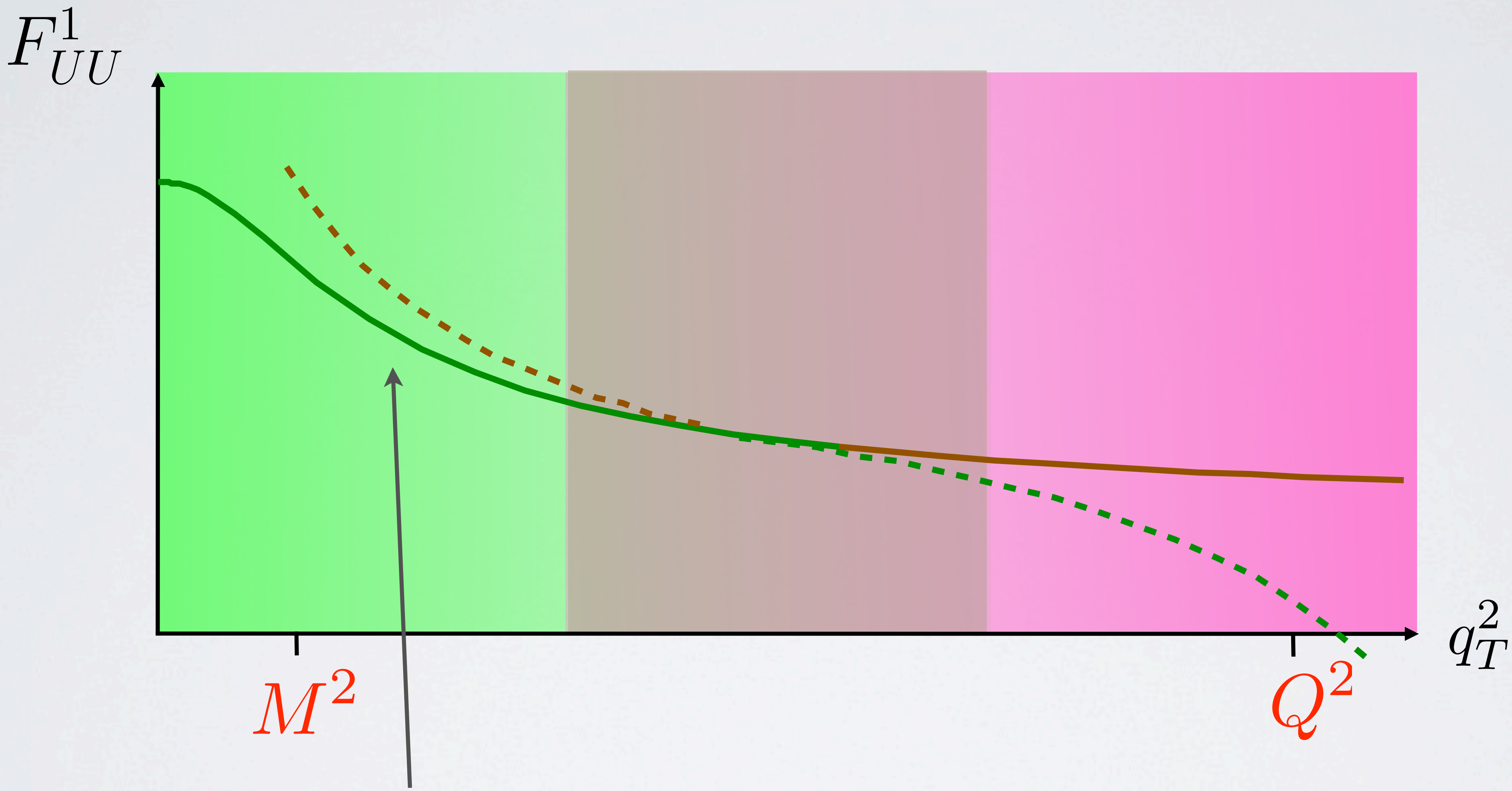
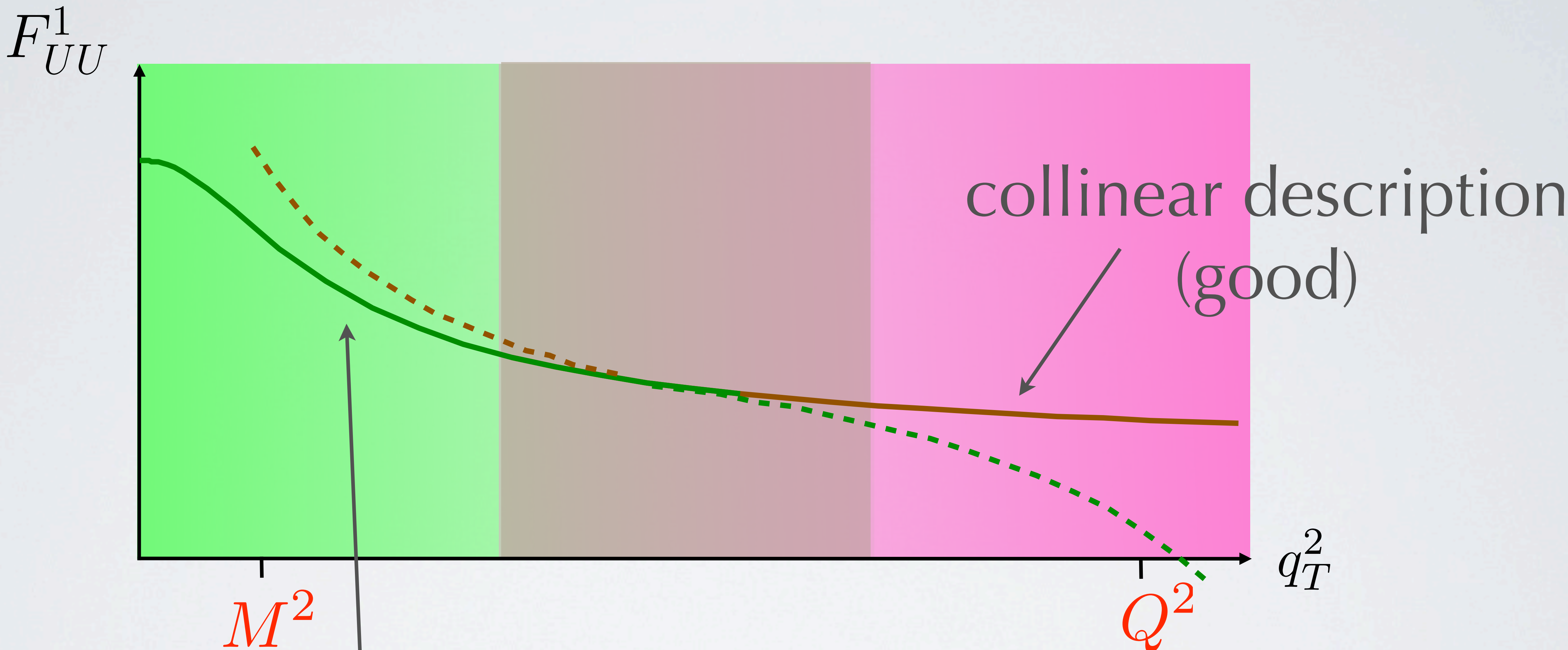


TMD description (good)

Collins, Soper, Sterman, NPB250 (85)

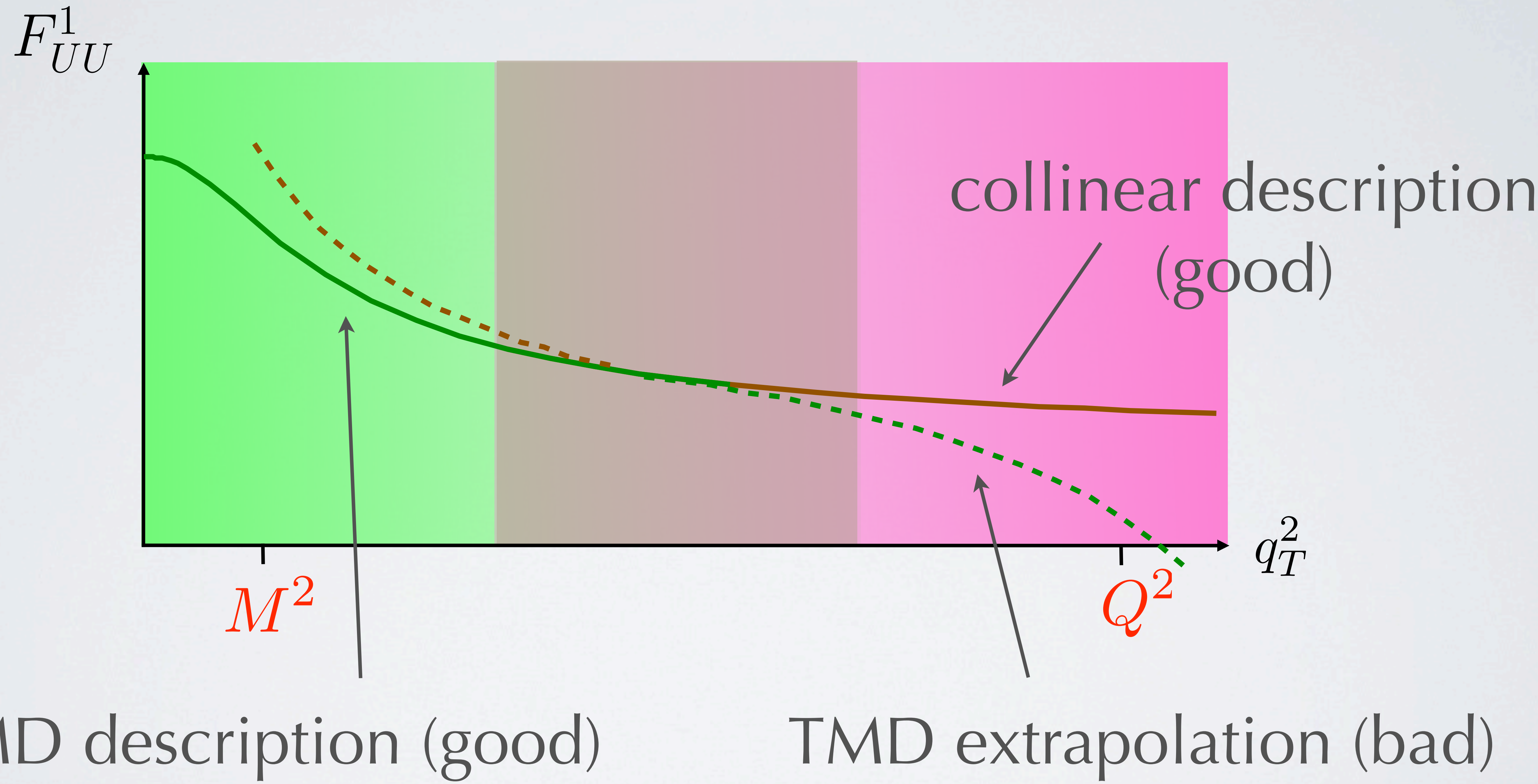
Matching behavior



TMD description (good)

Collins, Soper, Sterman, NPB250 (85)

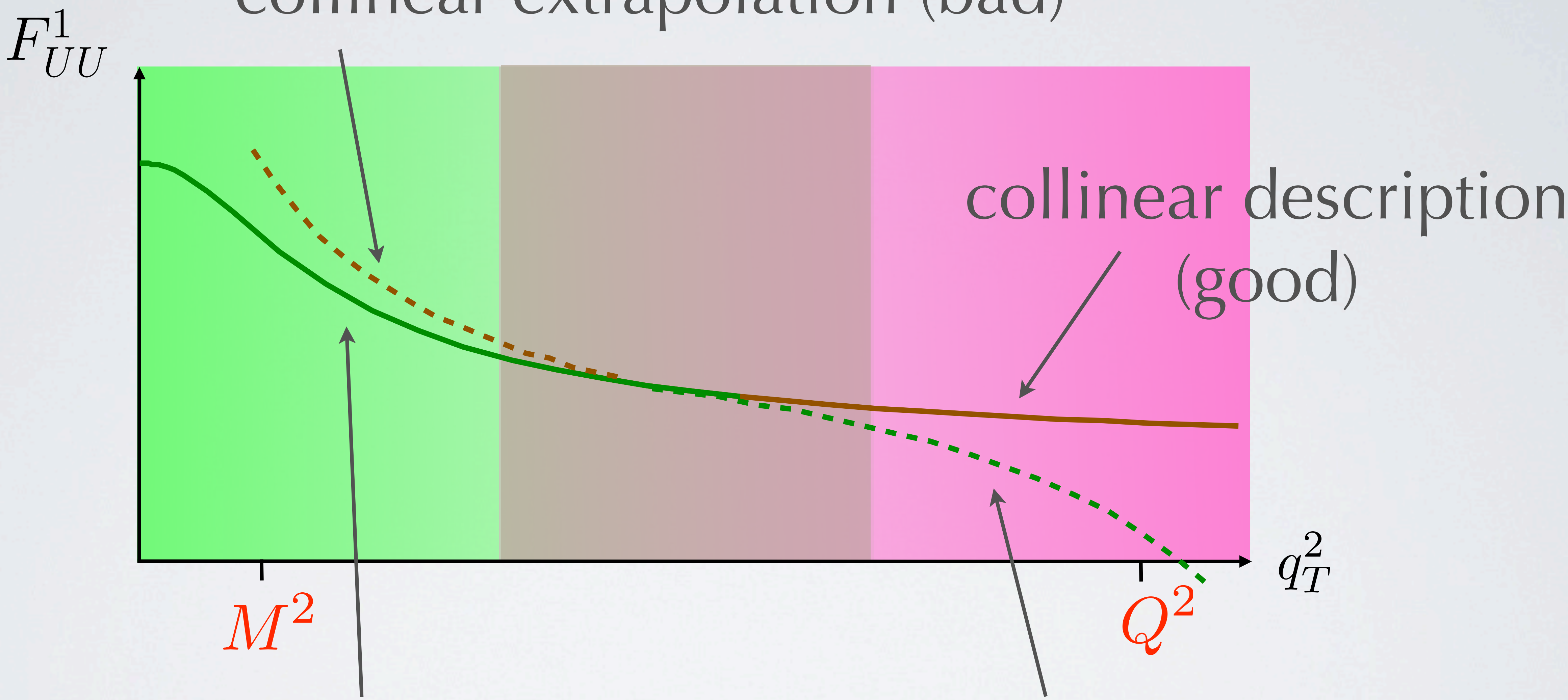
Matching behavior



Collins, Soper, Sterman, NPB250 (85)

Matching behavior

collinear extrapolation (bad)

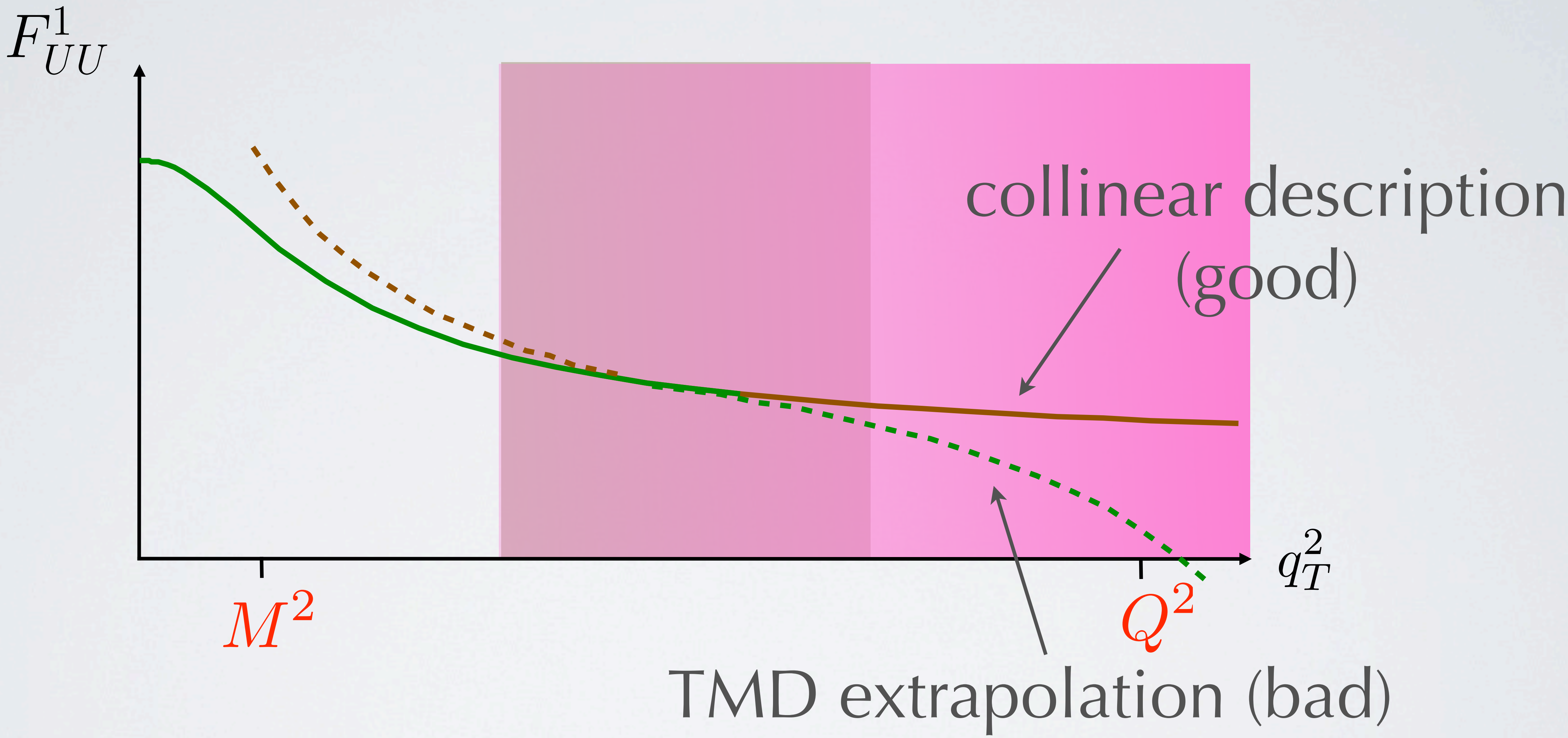


TMD description (good)

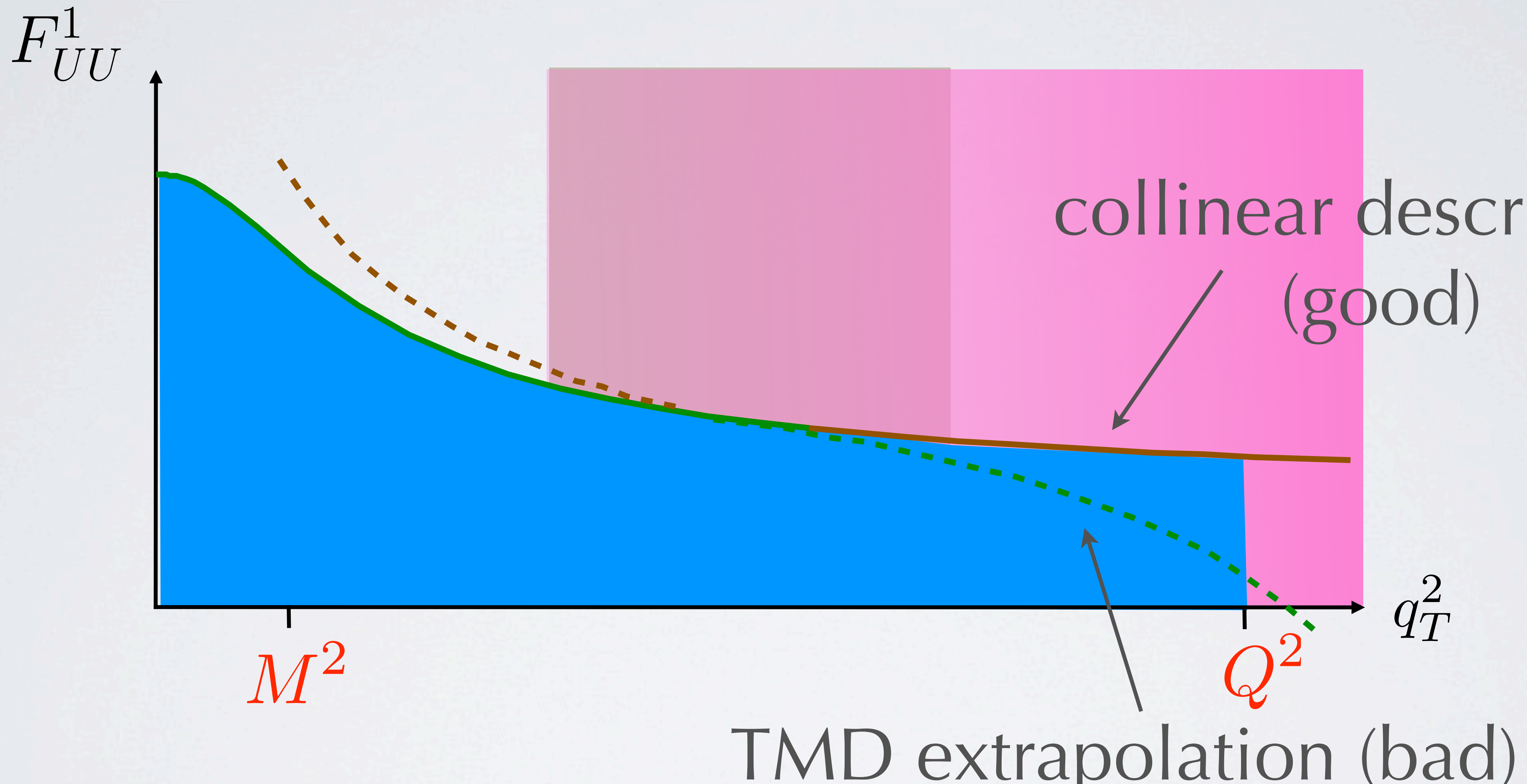
TMD extrapolation (bad)

Collins, Soper, Sterman, NPB250 (85)

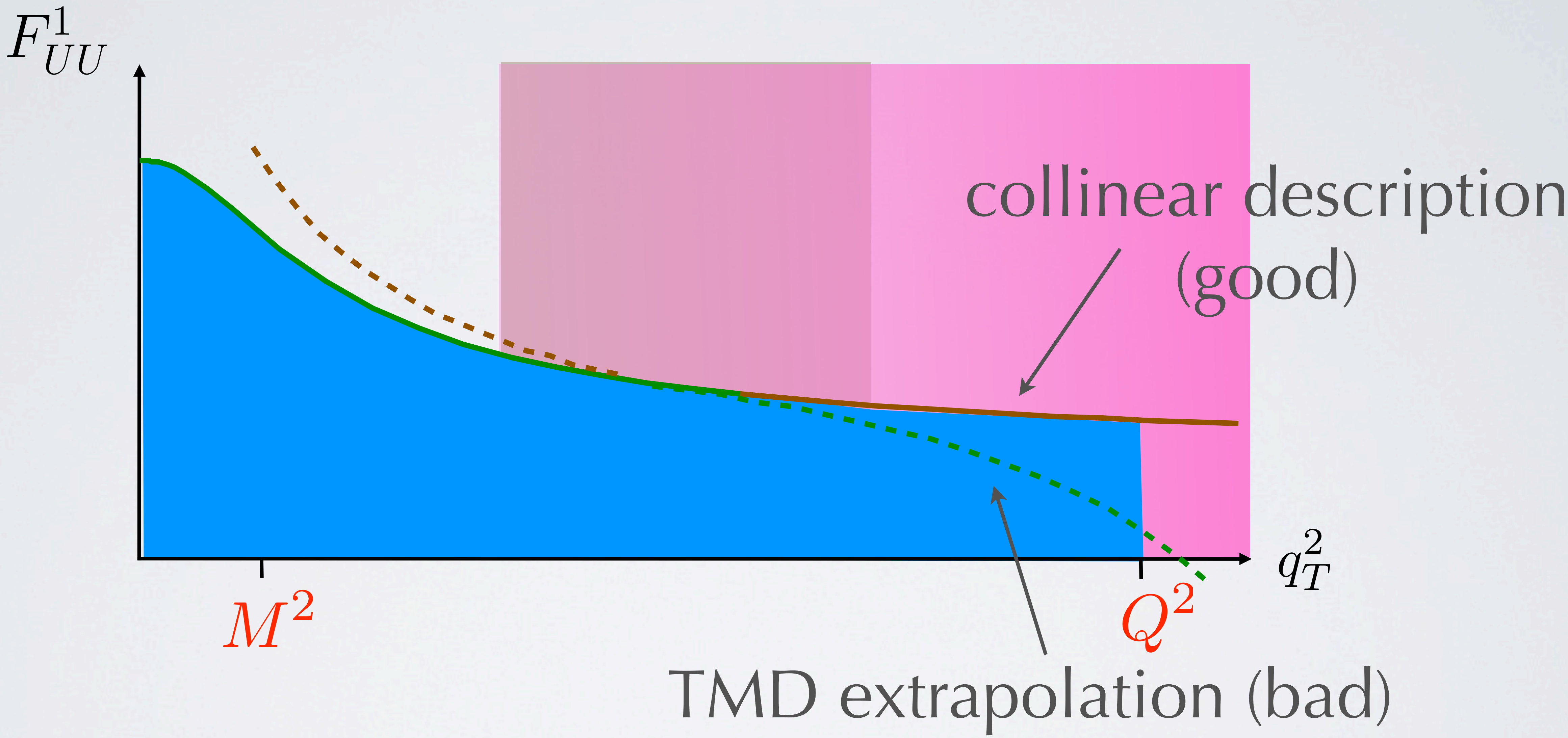
From TMD to collinear PDFs?



From TMD to collinear PDFs?

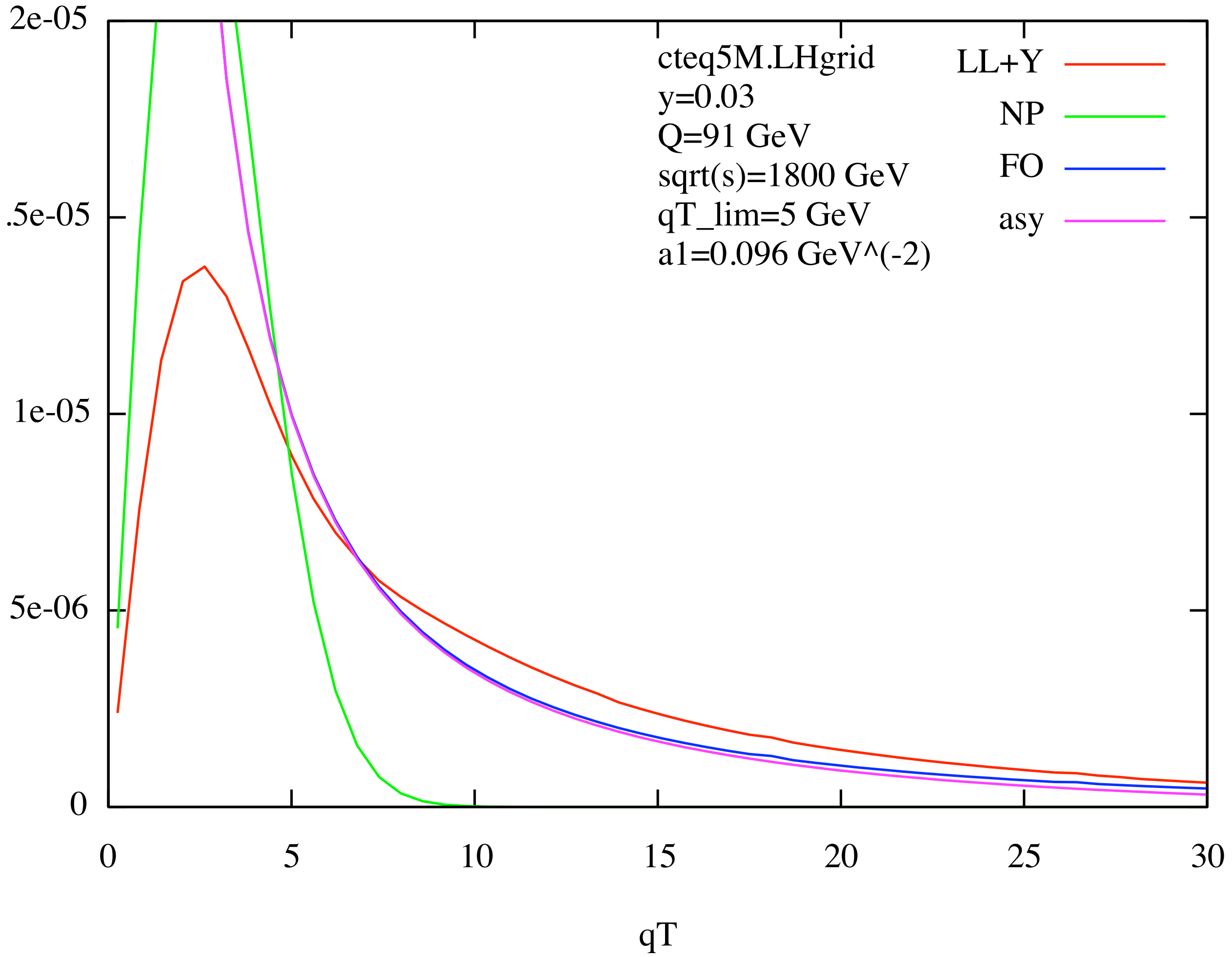


From TMD to collinear PDFs?



To obtain PDFs, you need to integrate into the high q_T region, where TMDs cannot be used.
You should NOT expect to recover PDFs from TMDs.

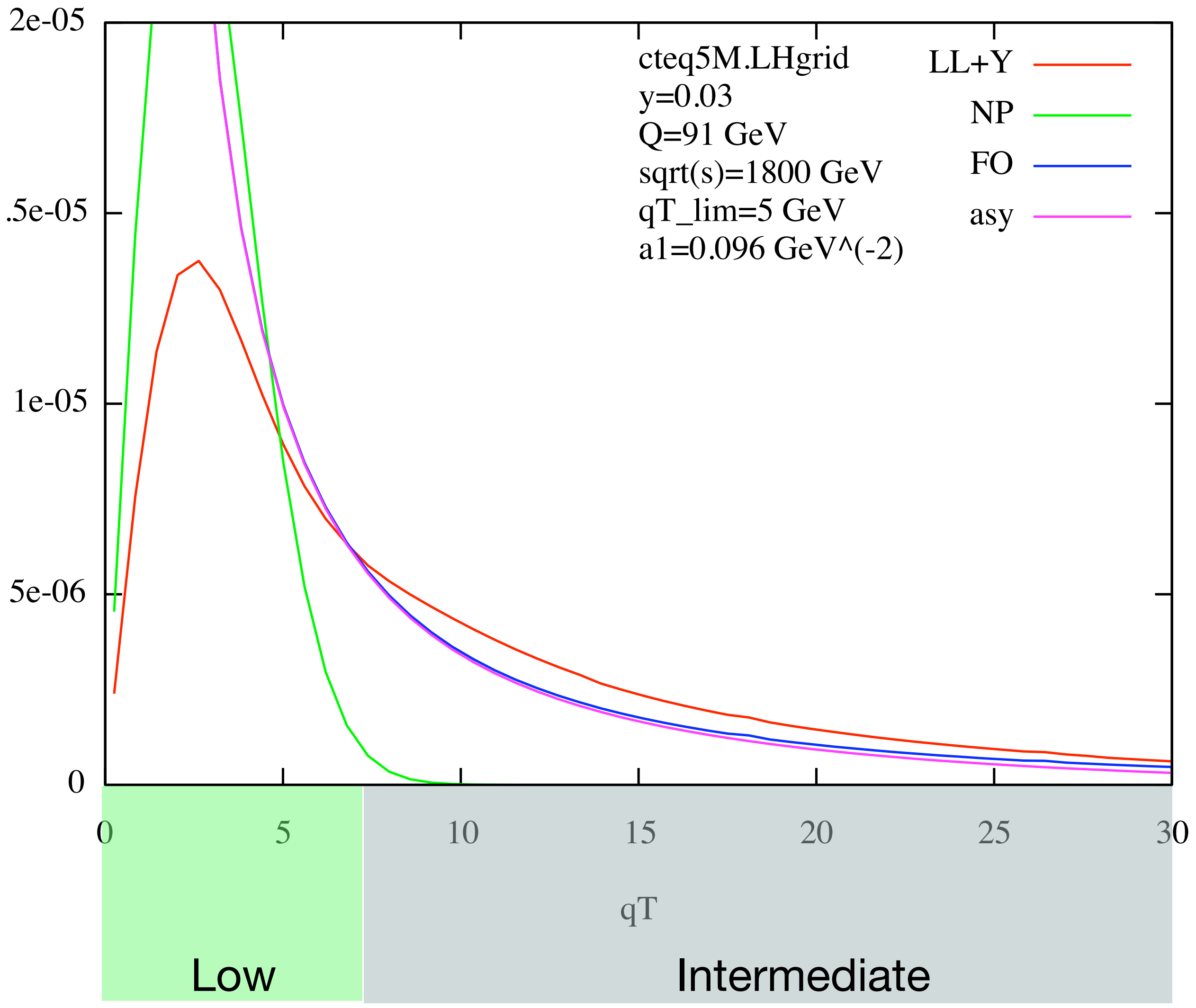
Low and high transverse momentum



Tevatron

see Werner's talk

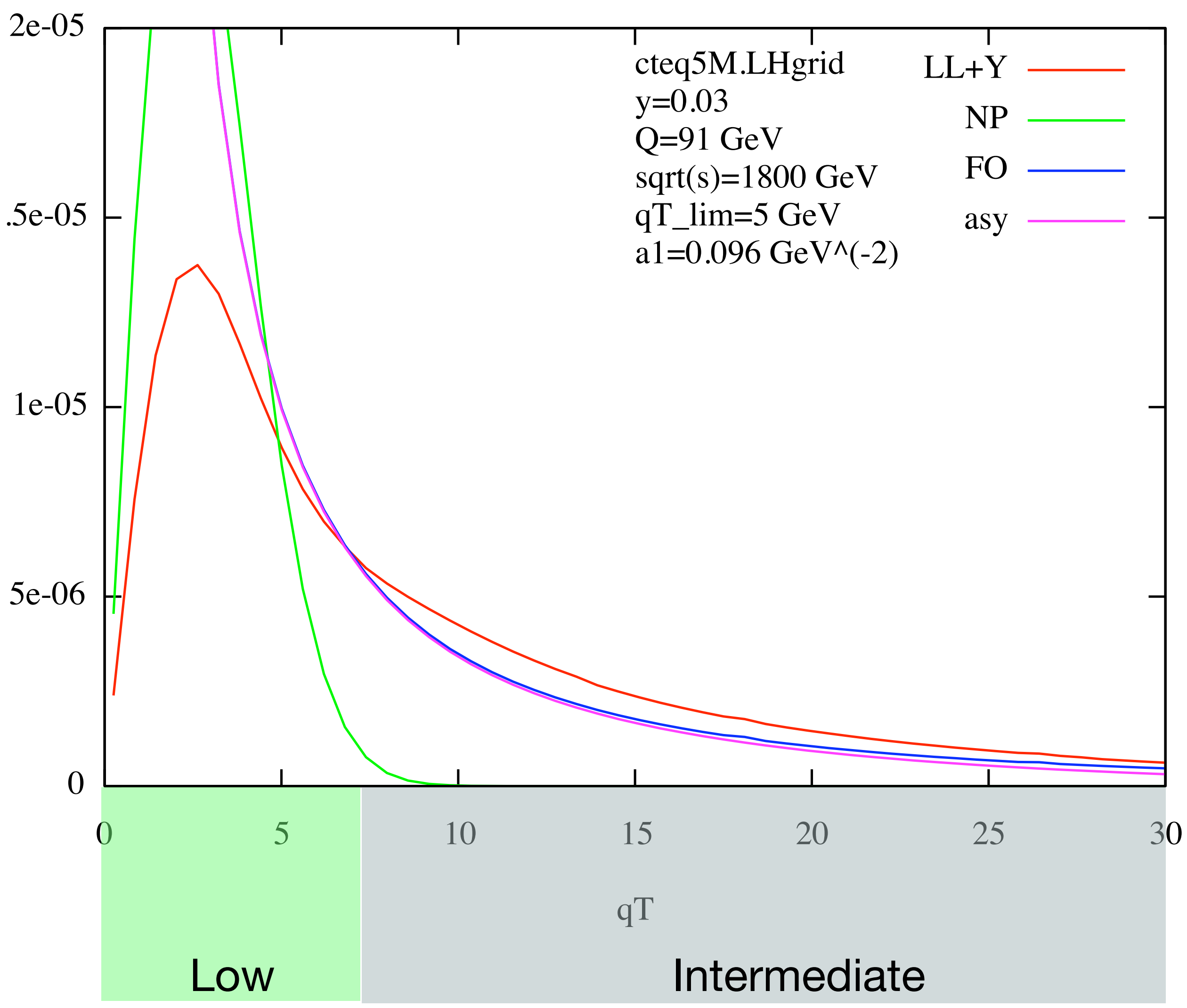
Low and high transverse momentum



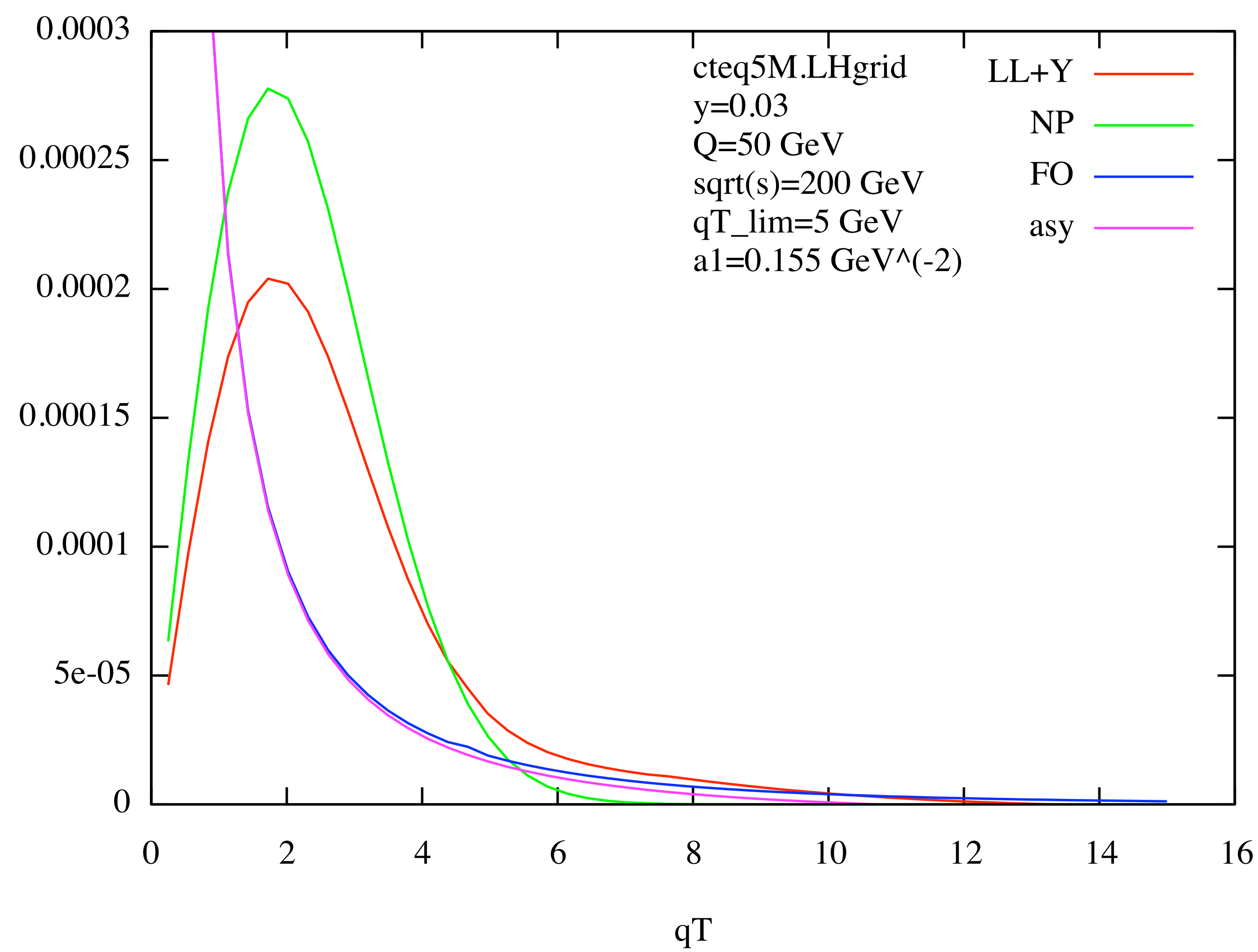
Tevatron

see Werner's talk

Low and high transverse momentum



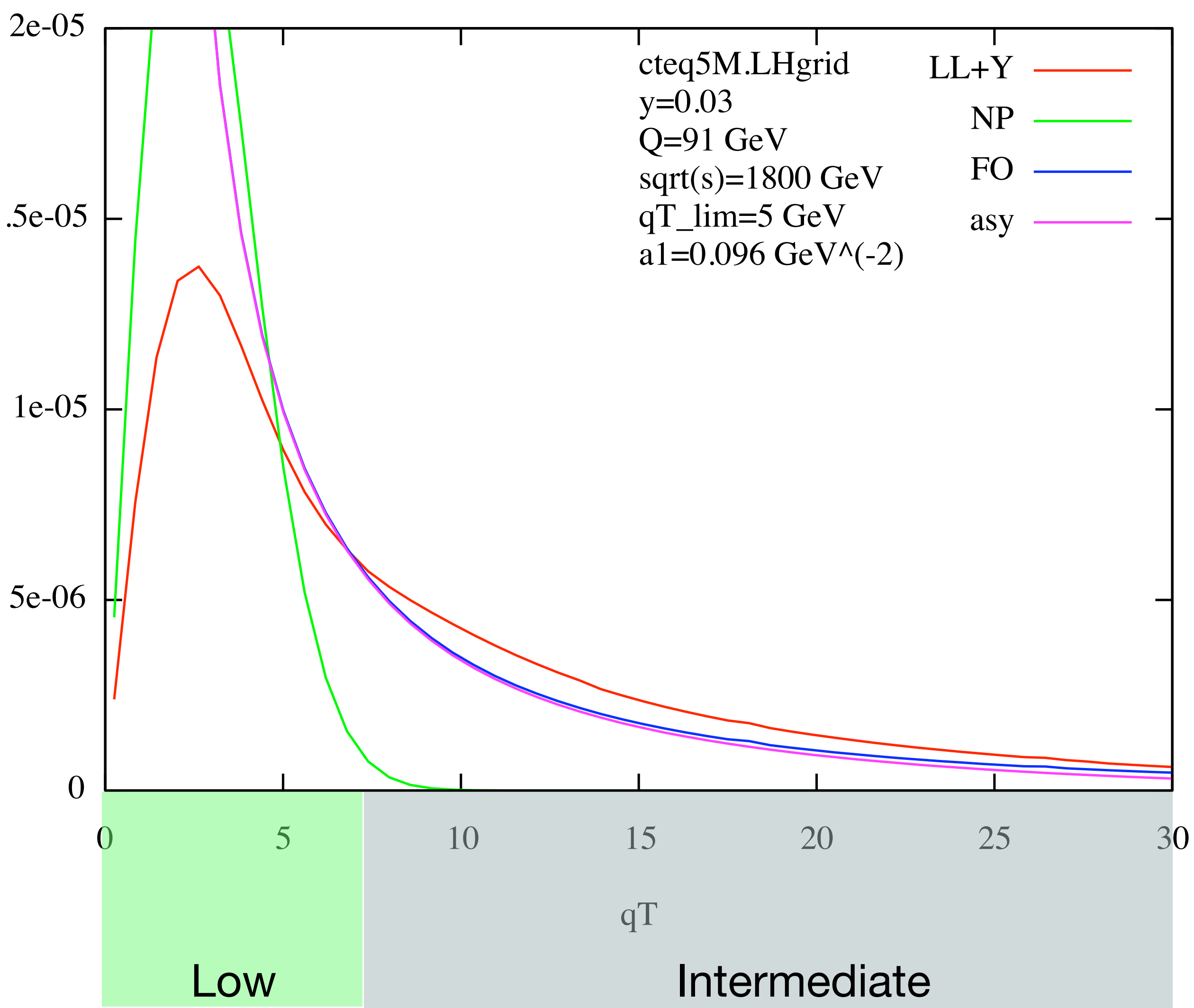
Tevatron



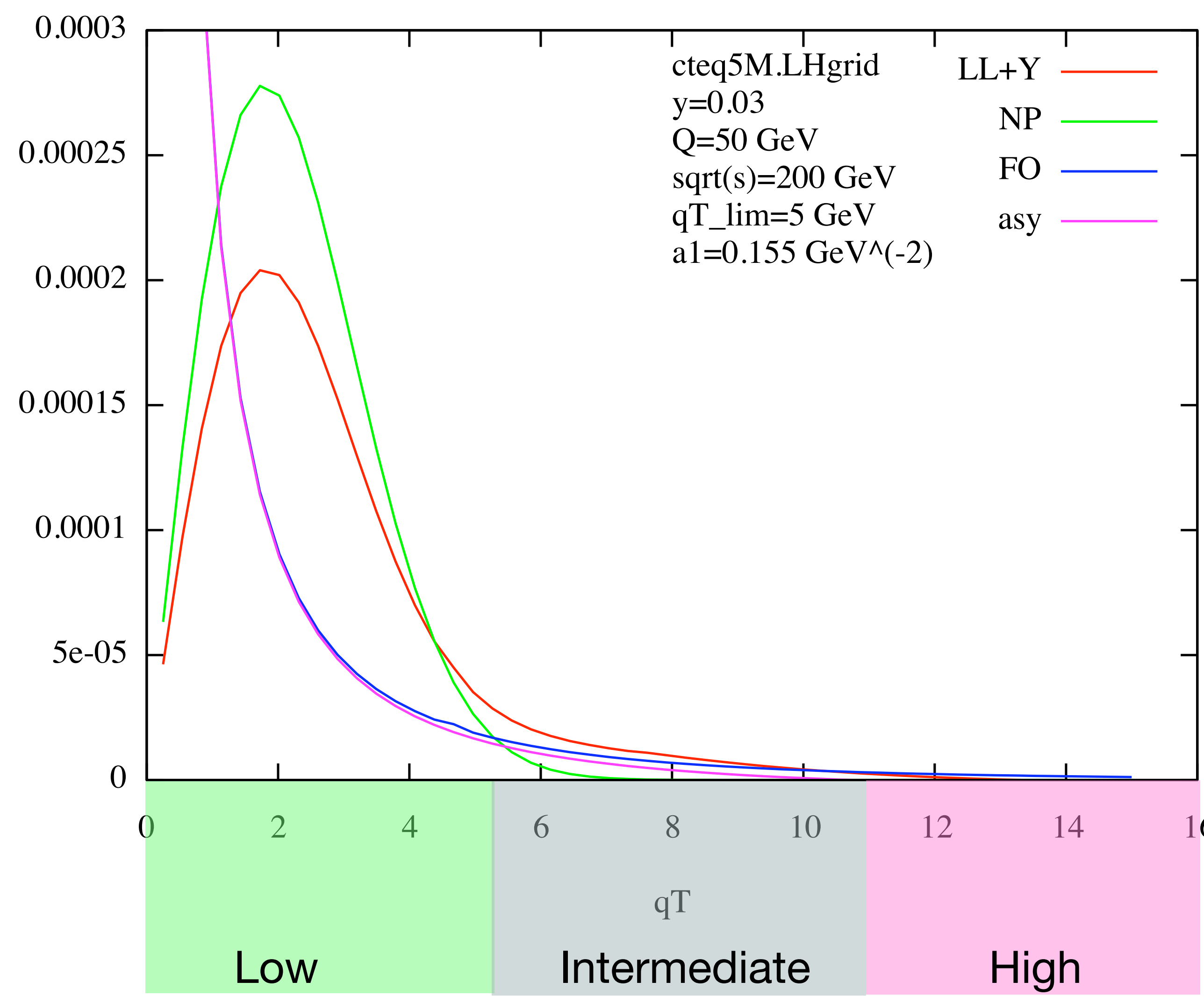
RHIC

see Werner's talk

Low and high transverse momentum



Tevatron



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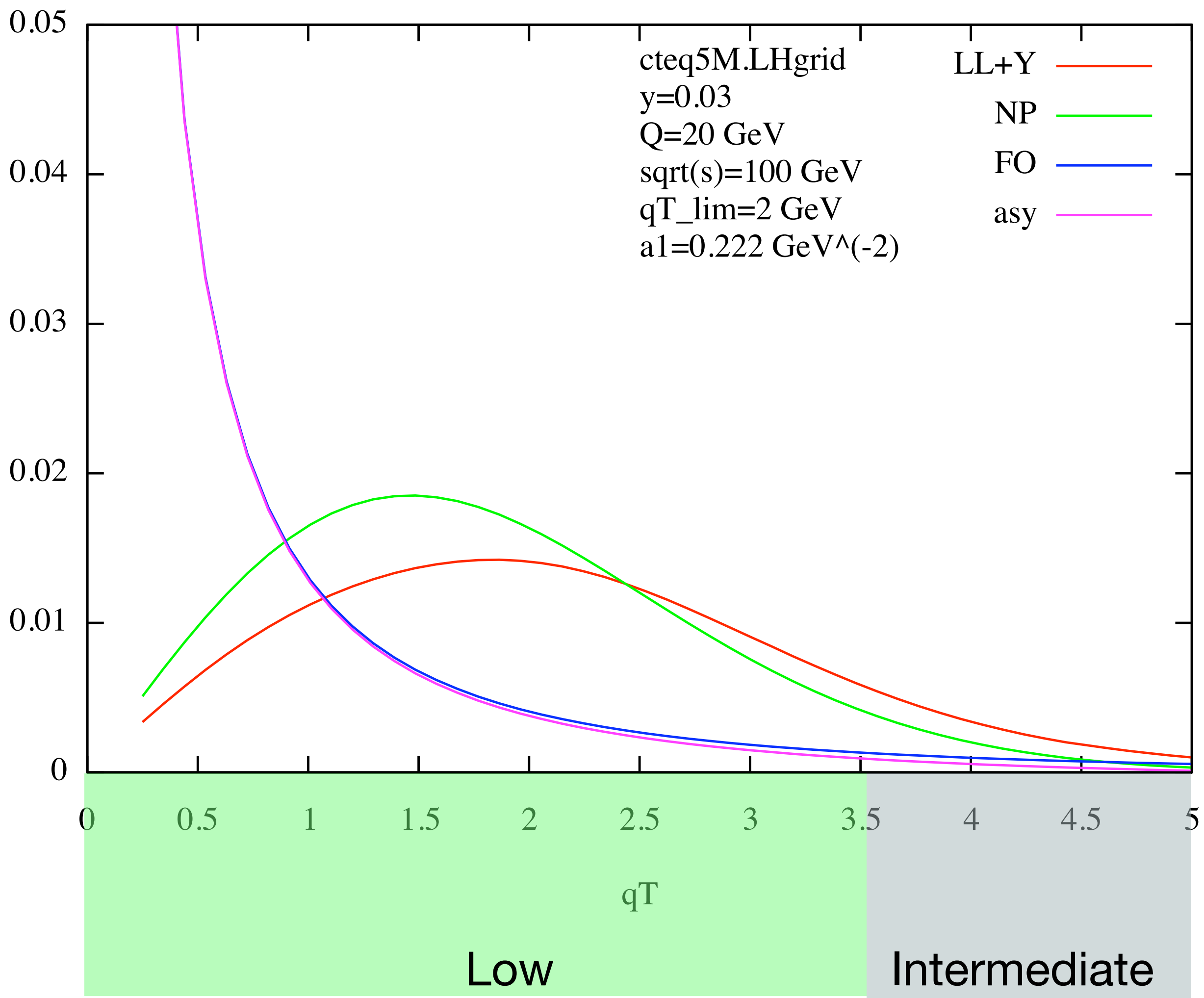
see Werner's talk

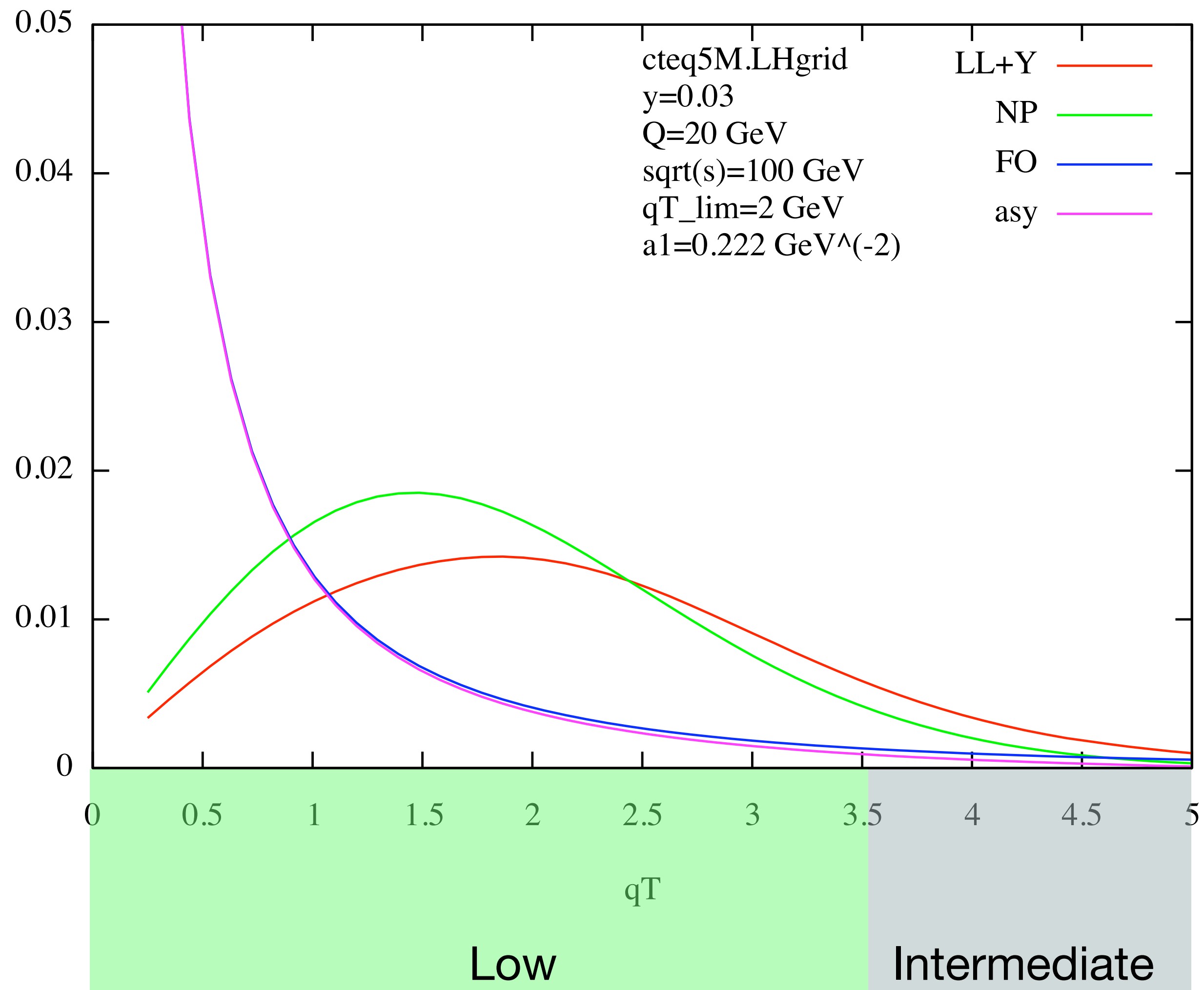
Low and high transverse momentum

Low and high transverse momentum

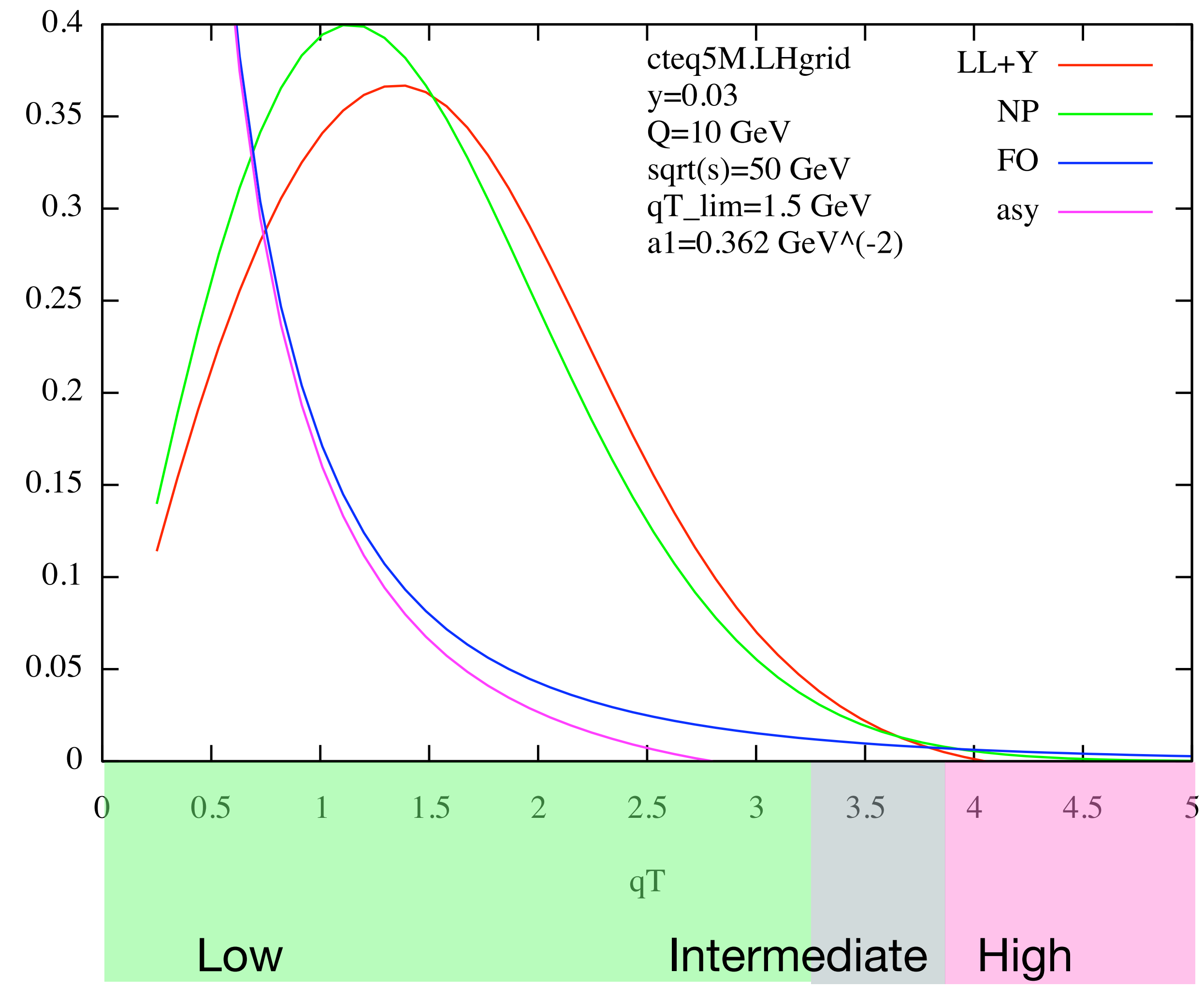


Medium energy

Low and high transverse momentum



Medium energy



Low energy

TMD part

$$F_{UU}^{1} = \mathcal{C}\left[f_1\, \bar{f}_1\right]$$

$$\sum_q e_q^2 \int d^2\vec{k}_{aT}\, d^2\vec{k}_{bT}\, \delta^{(2)}(\vec{q}_T - \vec{k}_{aT} - \vec{k}_{bT})\Big[f_1^q(x_a, \vec{k}_{aT}^2; Q)\, f_2^{\bar{q}}(x_b, \vec{k}_{bT}^2; Q) + (q \leftrightarrow \bar{q})\Big]$$

Unpol. TMD "state of the art"

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

T. Rogers, M. Aybat, arXiv:1101.5057
see also M. Garcia's talk

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collinear PDF

T. Rogers, M. Aybat, arXiv:1101.5057
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collinear PDF

pQCD

T. Rogers, M. Aybat, arXiv:1101.5057
see also M. Garcia’s talk

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collinear PDF

pQCD

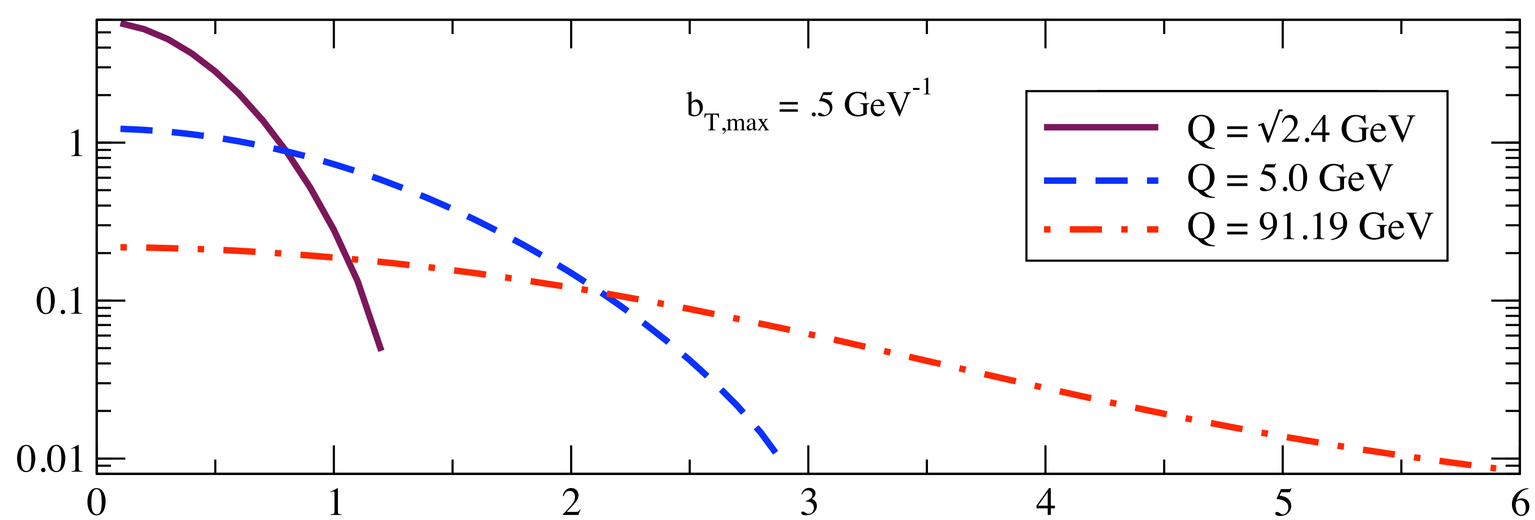
nonperturbative part of TMD

T. Rogers, M. Aybat, arXiv:1101.5057
see also M. Garcia's talk

Unpol. TMD “state of the art”

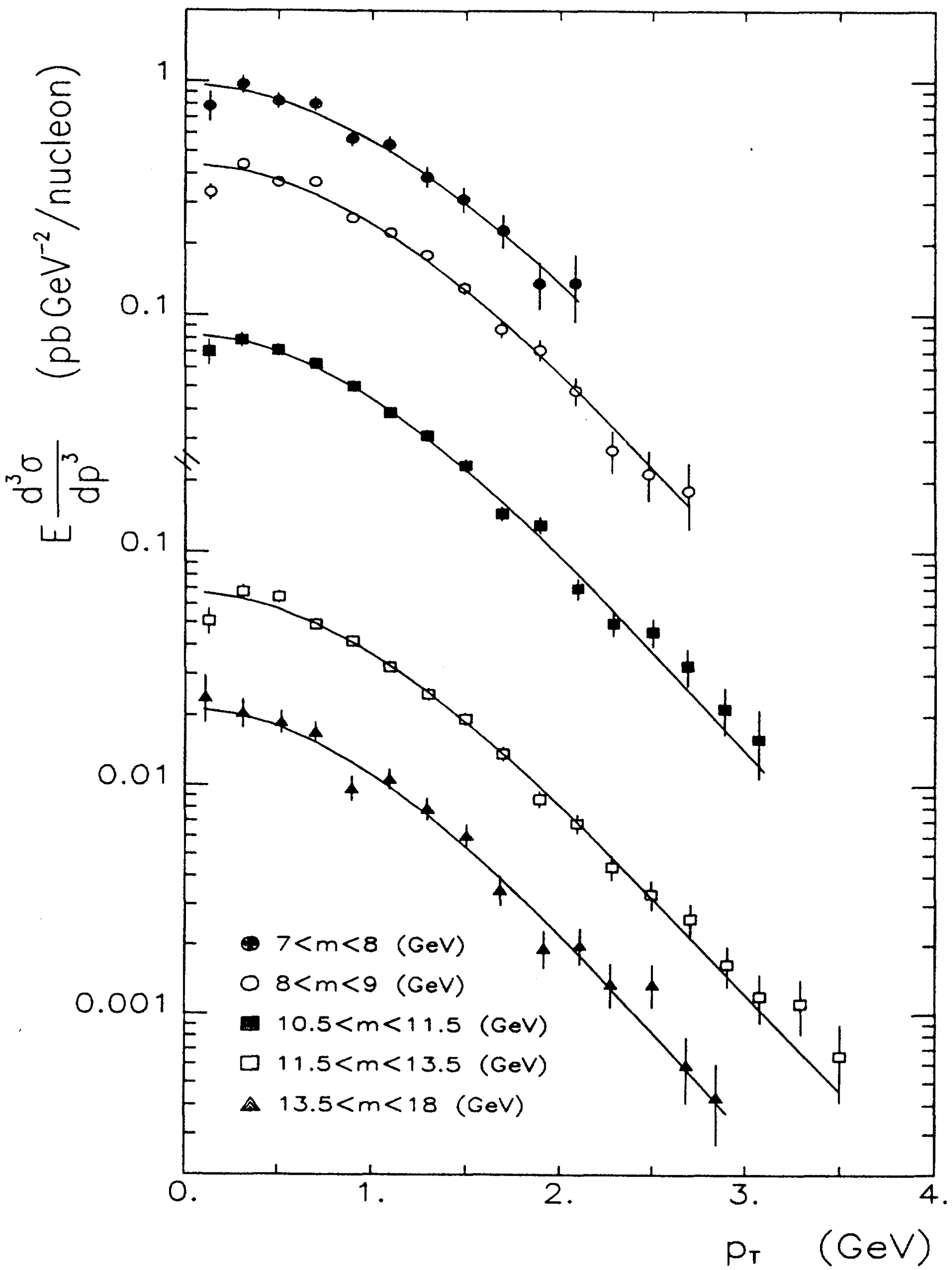
$$f_1(x, k_T; Q) = \frac{1}{2\pi} \int d^2 b_T e^{-ik_T \cdot b_T} [C \otimes f_1](x, b_T)\, e^{-S'(b_T, Q)}\, e^{-S'_{\rm NP}(x, b_T, Q, \alpha_i)}$$

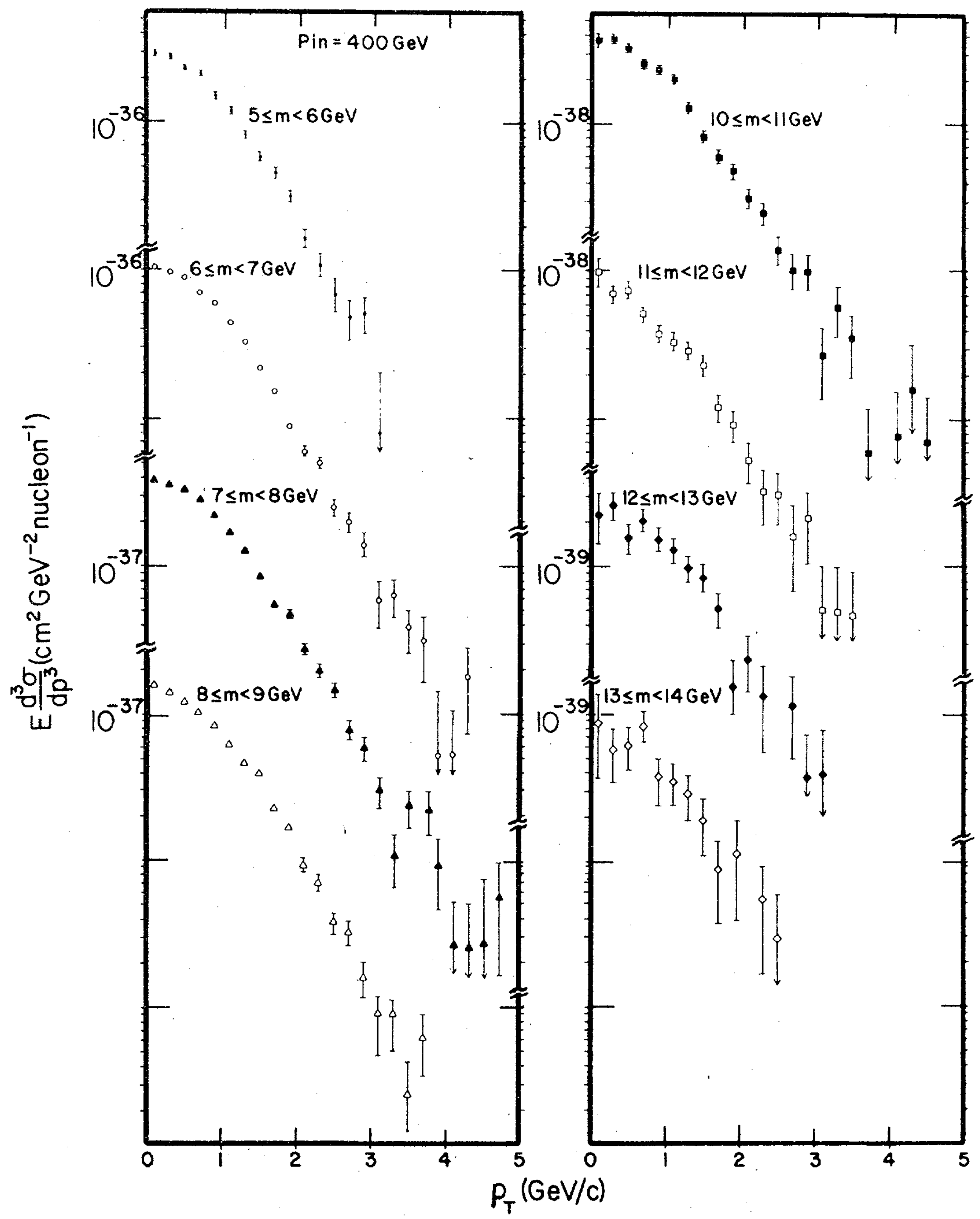
Up Quark TMD PDF, x = .09



T. Rogers, M. Aybat, arXiv:1101.5057
Landry, Brock, Nadolsky, Yuan, PRD67 (03)
P. Schweitzer, T. Teckentrup, A. Metz, PRD81(10)

Data and TMD extractions





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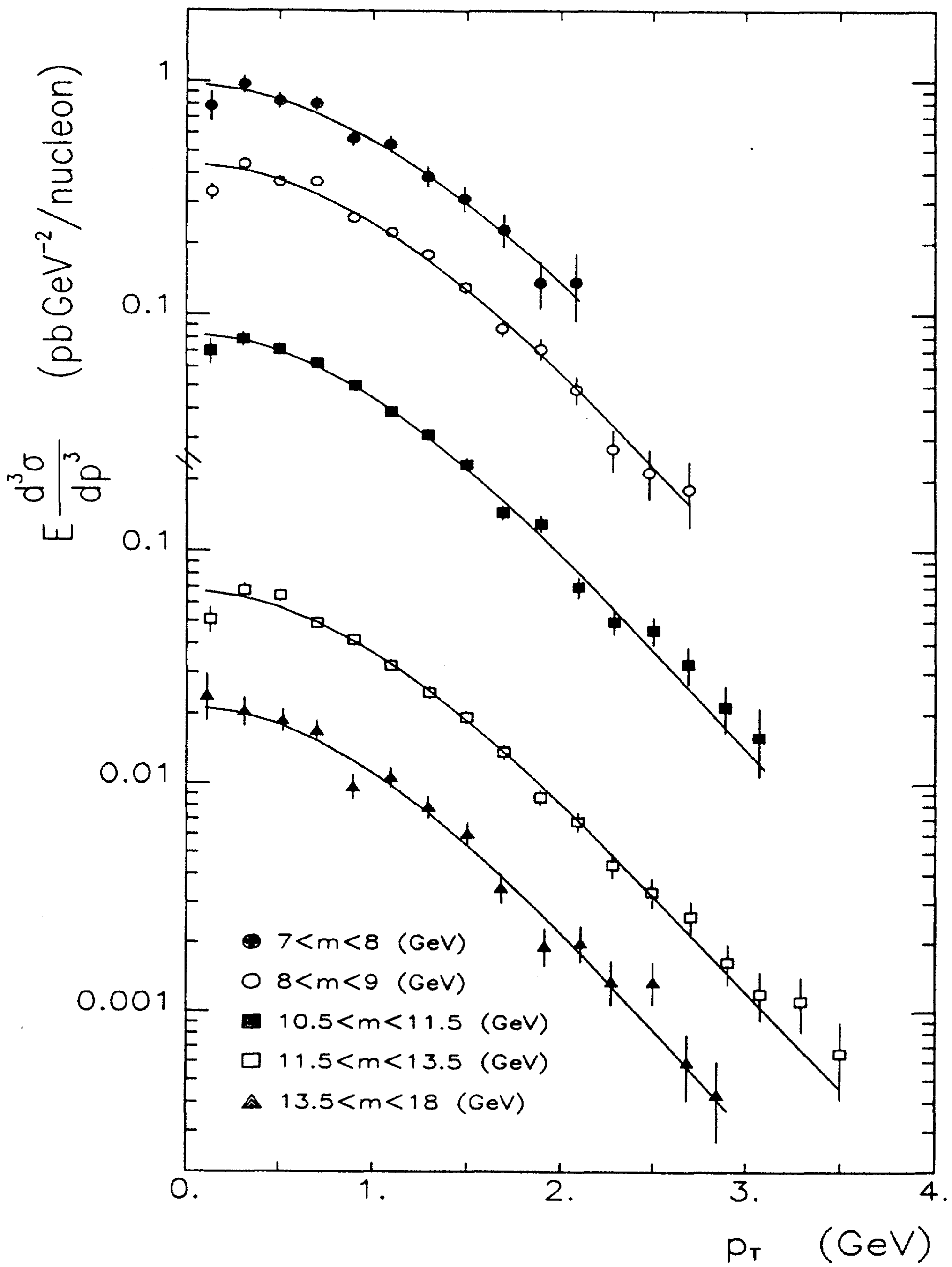
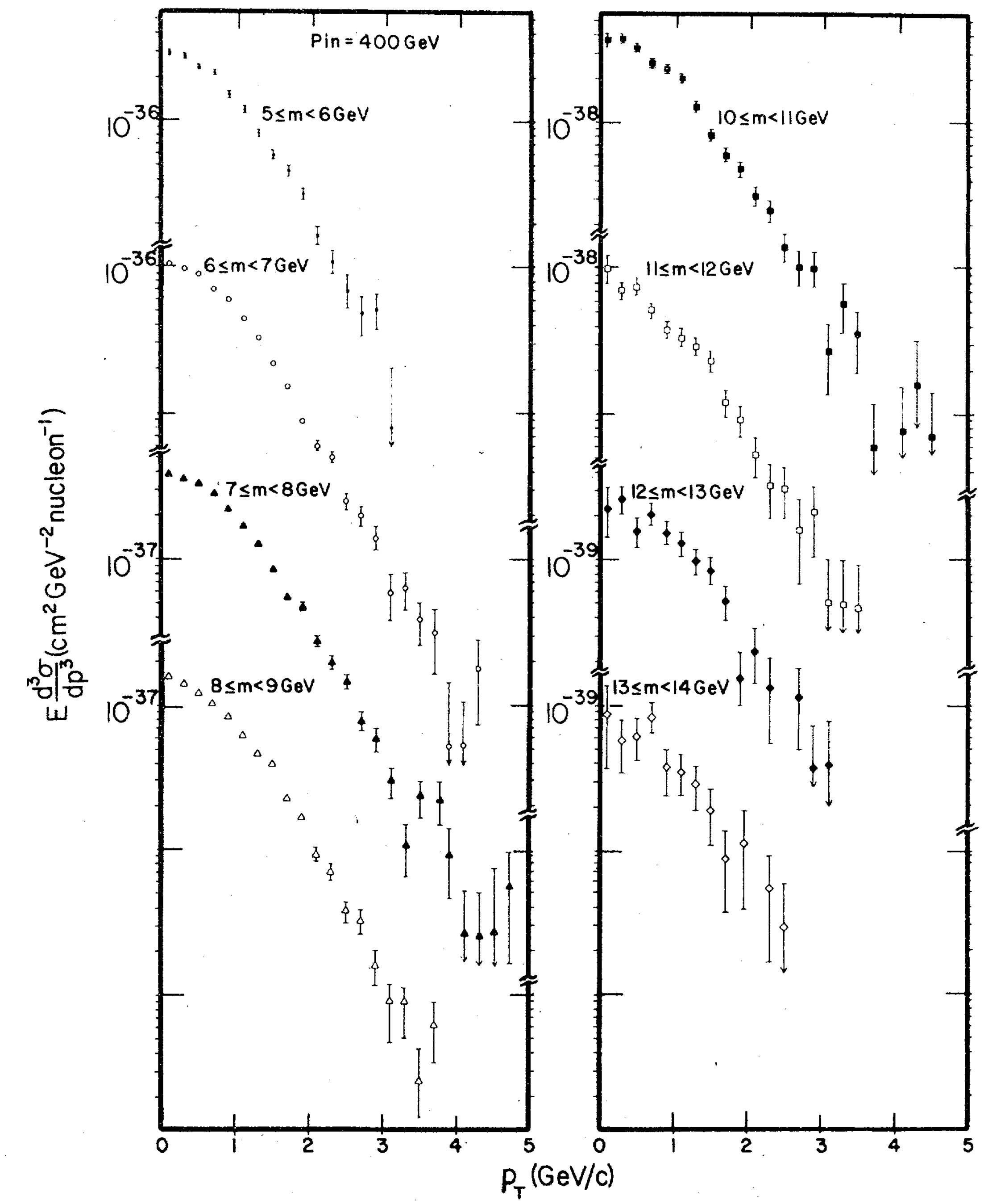
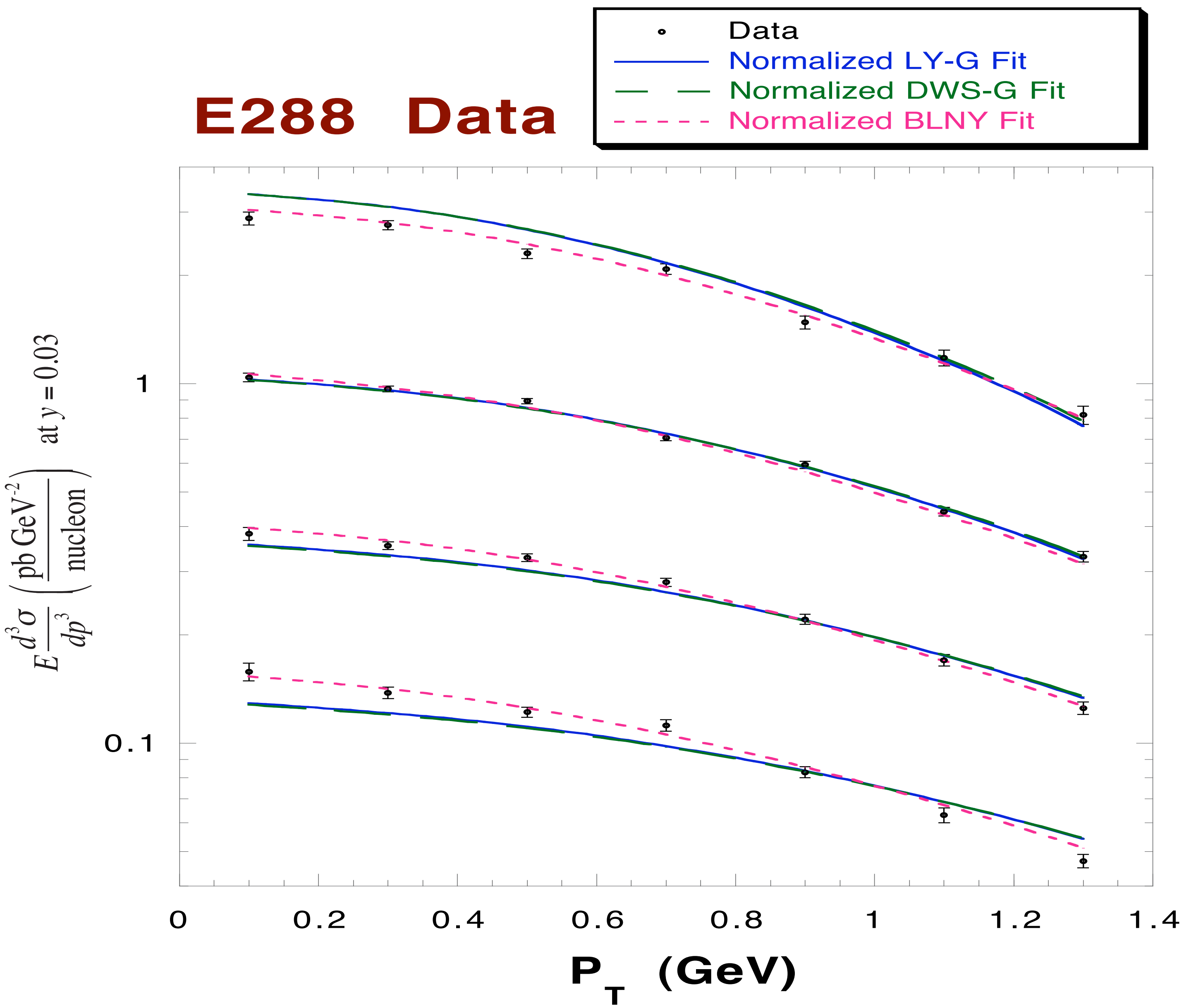


E605, Moreno et al. PRD43 (91)



E288, Ito et al., PRD23 (81)

BLNY fit


E288 Data
Data
Normalized LY-G Fit
Normalized DWS-G Fit
Normalized BLNY Fit
1
0.1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
P_T (GeV)
$E\frac{d^3\sigma}{dp^3}\left(\frac{\text{pb GeV}^{-2}}{\text{nucleon}}\right)$ at y = 0.03

BLNY fit

Landry, Brock, Nadolsky, Yuan, PRD67 (03)

Experiment	Reference	Reaction	$\sqrt{S}$ (GeV)	δN_{exp}
R209	[14]	$p+p \to \mu^+\mu^- + X$	62	10%
E605	[15]	$p+Cu \to \mu^+\mu^- + X$	38.8	15%
E288	[16]	$p+Cu \to \mu^+\mu^- + X$	27.4	25%
CDF-Z (Run-0)	[17]	$p+\bar{p} \to Z + X$	1800	–
DØ -Z (Run-1)	[18]	$p+\bar{p} \to Z + X$	1800	4.3%
CDF-Z (Run-1)	[19]	$p+\bar{p} \to Z + X$	1800	3.9%

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D-Y (including Z production) is the most important source of information for unpolarized TMDs

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Landry, Brock, Nadolsky, Yuan, PRD67 (03)

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COMPASS, E906, NICA

D-Y (including Z production) is the most important source of information for unpolarized TMDs

BLNY fit

Landry, Brock, Nadolsky, Yuan, PRD67 (03)

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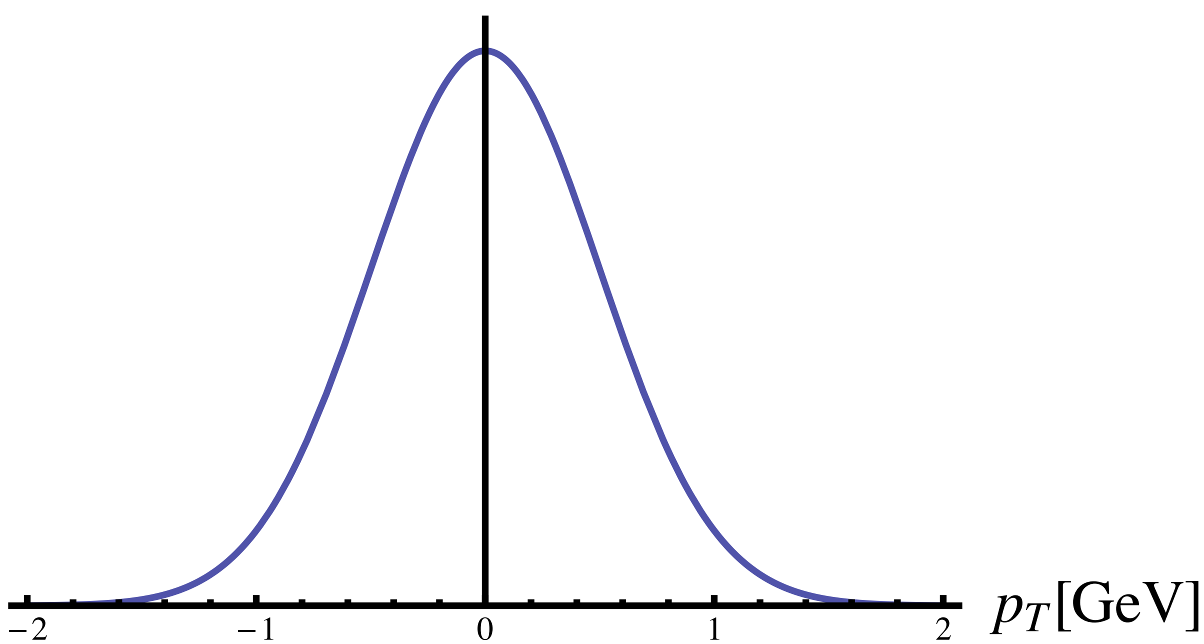
COMPASS, E906, NICA

RHIC

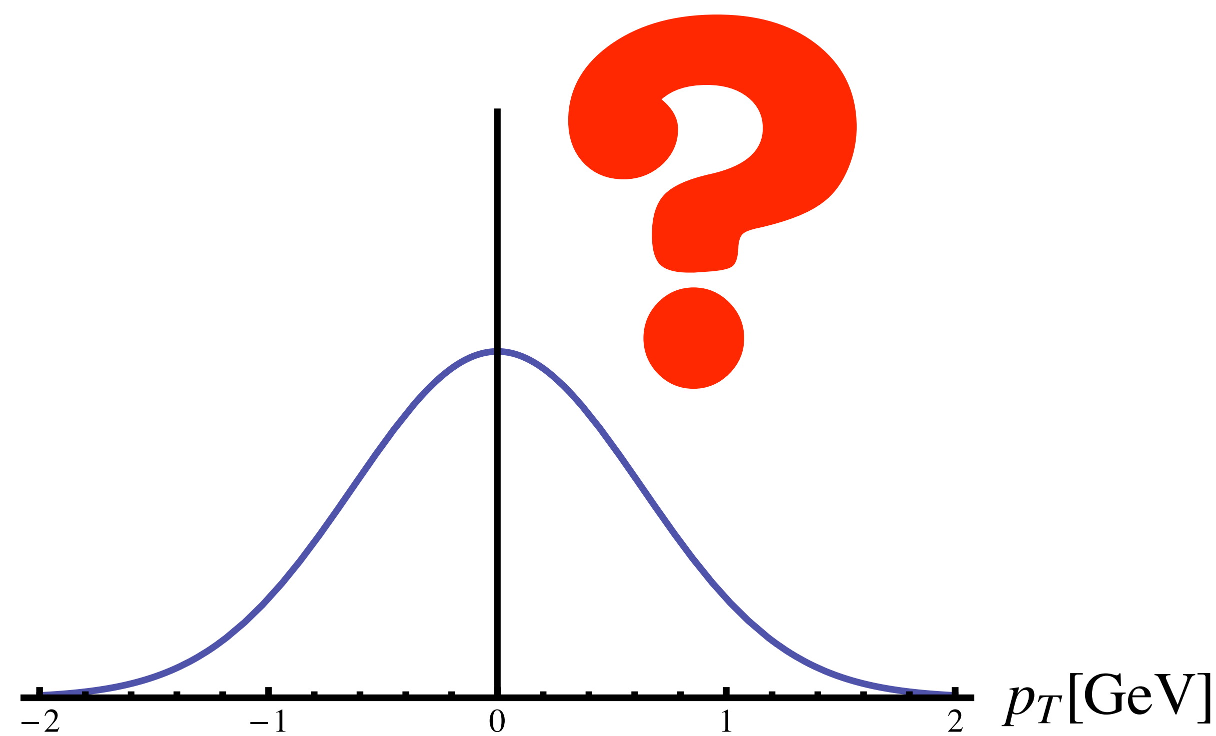
D-Y (including Z production) is the most important source of information for unpolarized TMDs

x dependence of TMDs

x=0.1

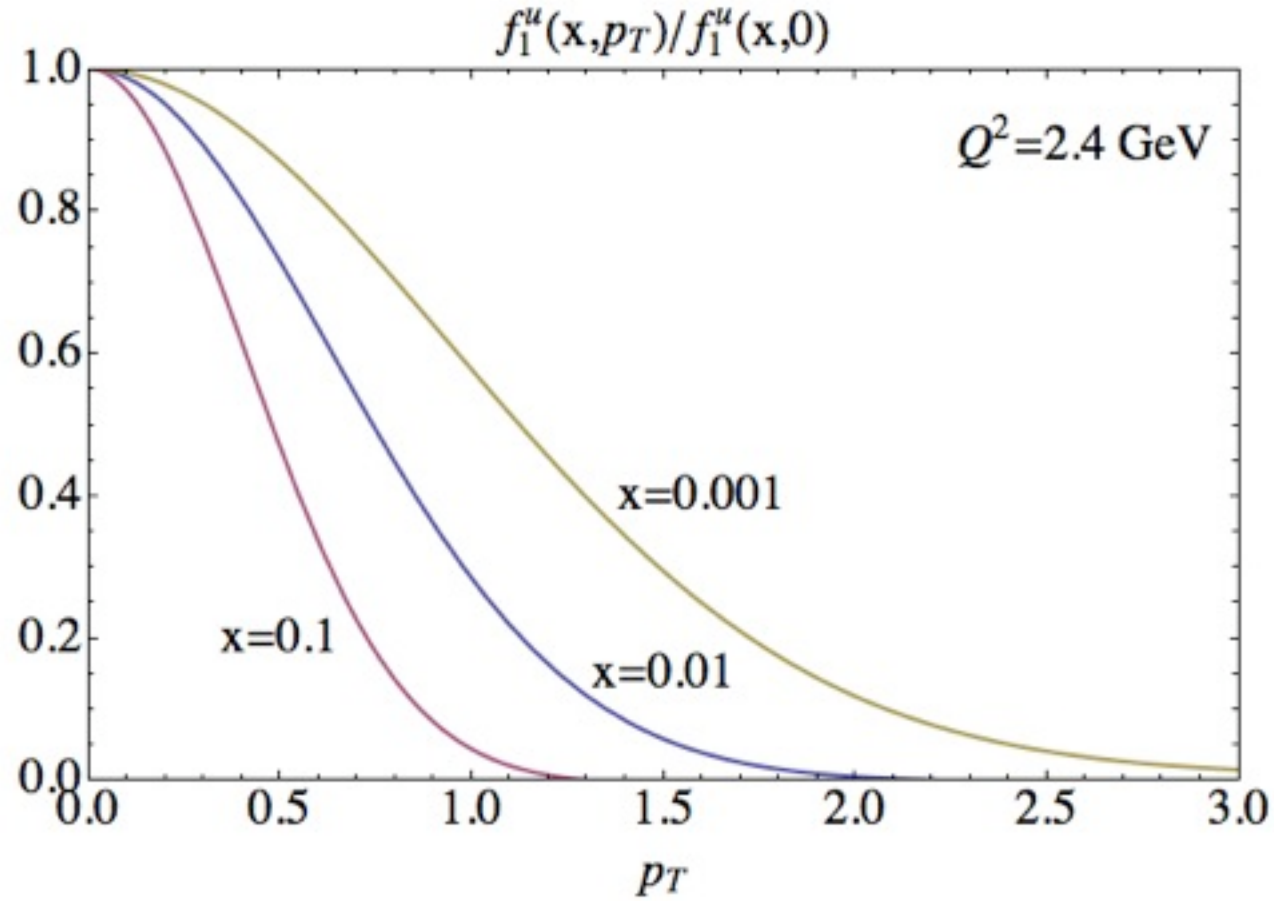


x=0.001



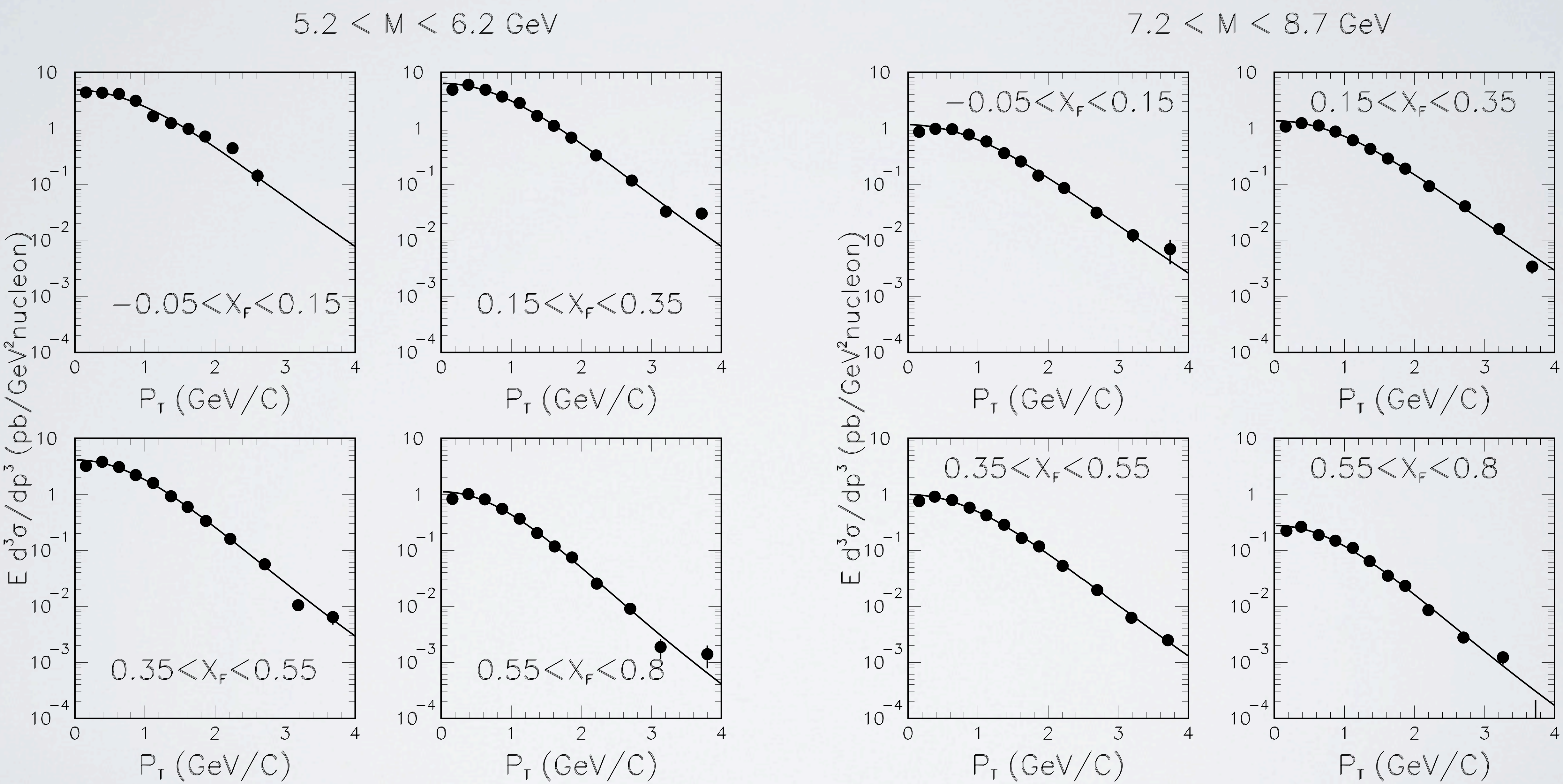
x dependence of TMDs

T. Rogers, M. Aybat, arXiv:1101.5057
Landry, Brock, Nadolsky, Yuan, PRD67 (03)
P. Schweitzer, T. Teckentrup, A. Metz, PRD81(10)



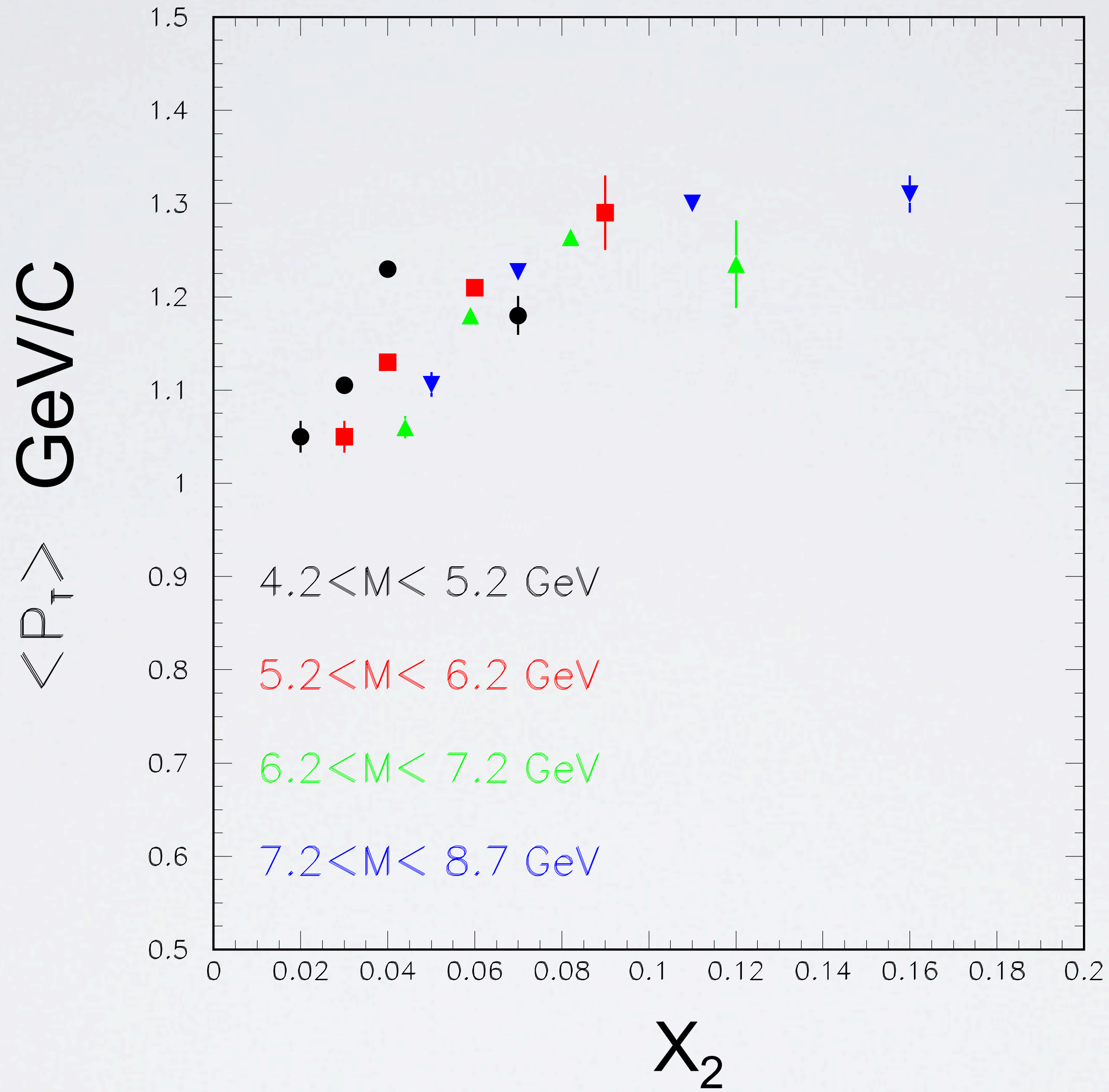
Widening driven by Tevatron data

Multidim. studies are needed



E866/NuSea preliminary,
talk by J.-C. Peng at DY@BNL workshop

New E866 data



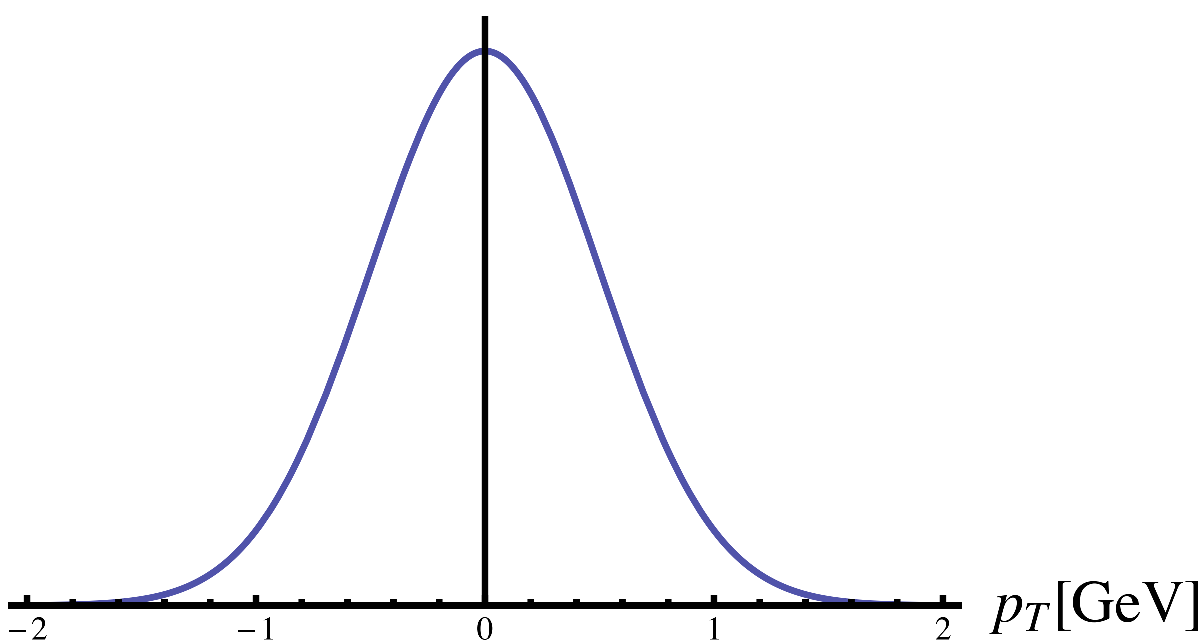
Behavior opposite to BLNY fit

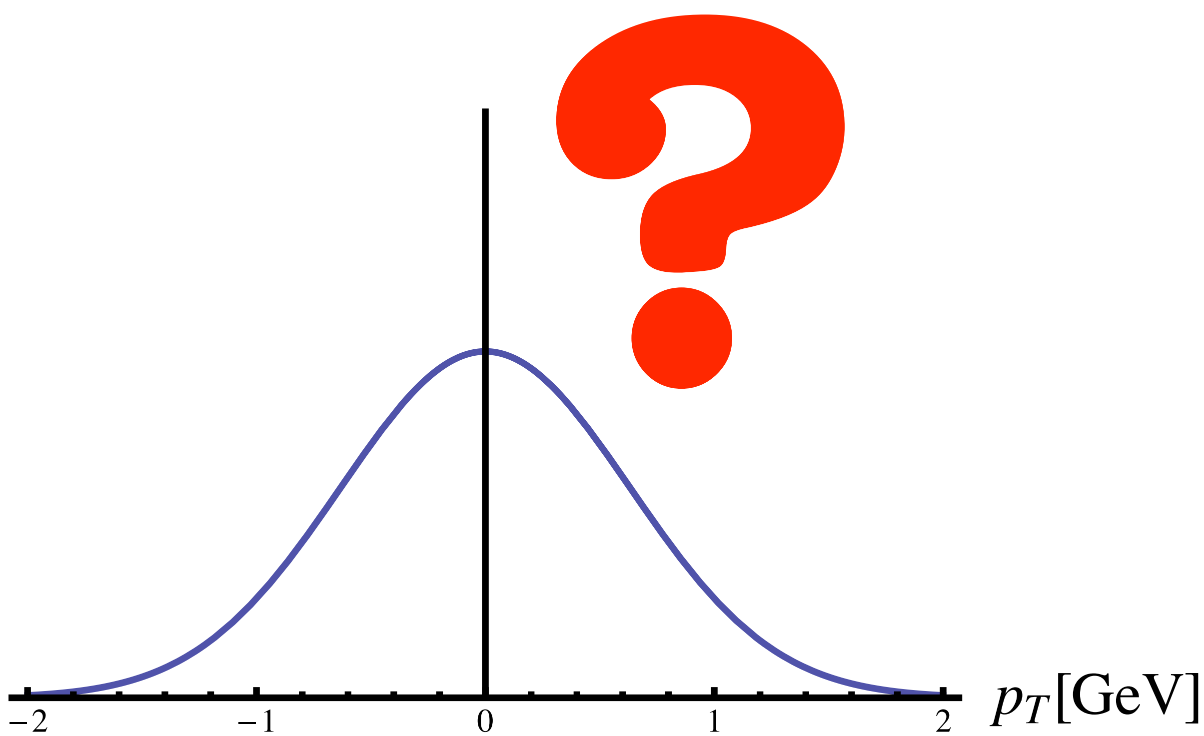
E866/NuSea preliminary,
talk by J.-C. Peng at DY@BNL workshop

Flavor-dependent TMDs

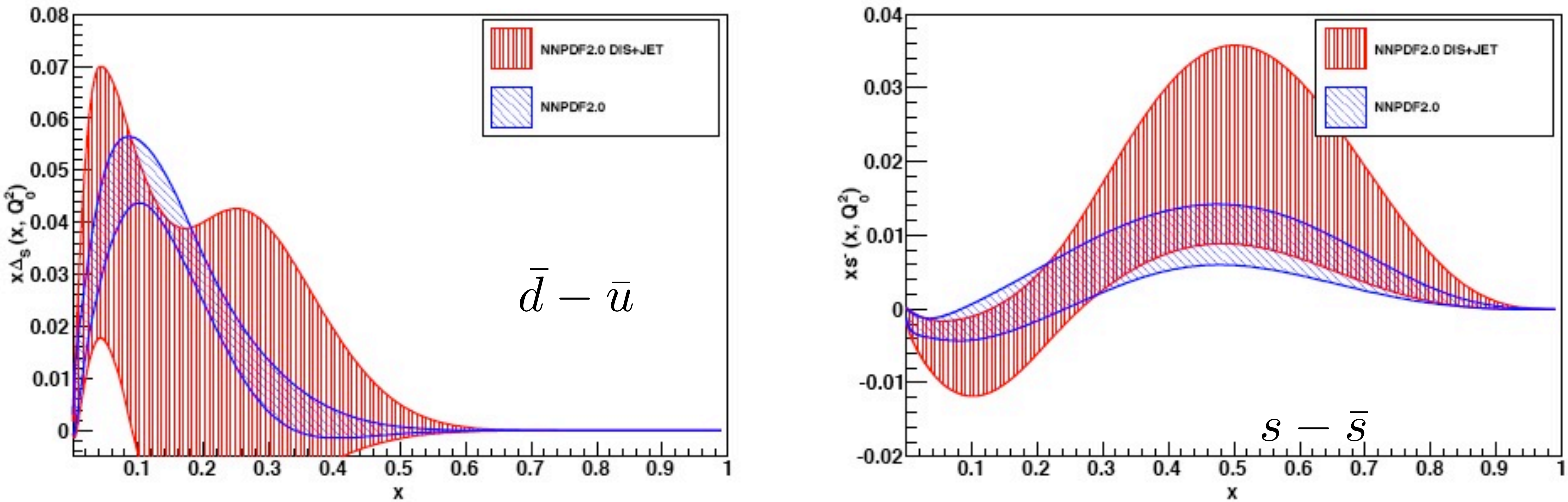
valence

sea





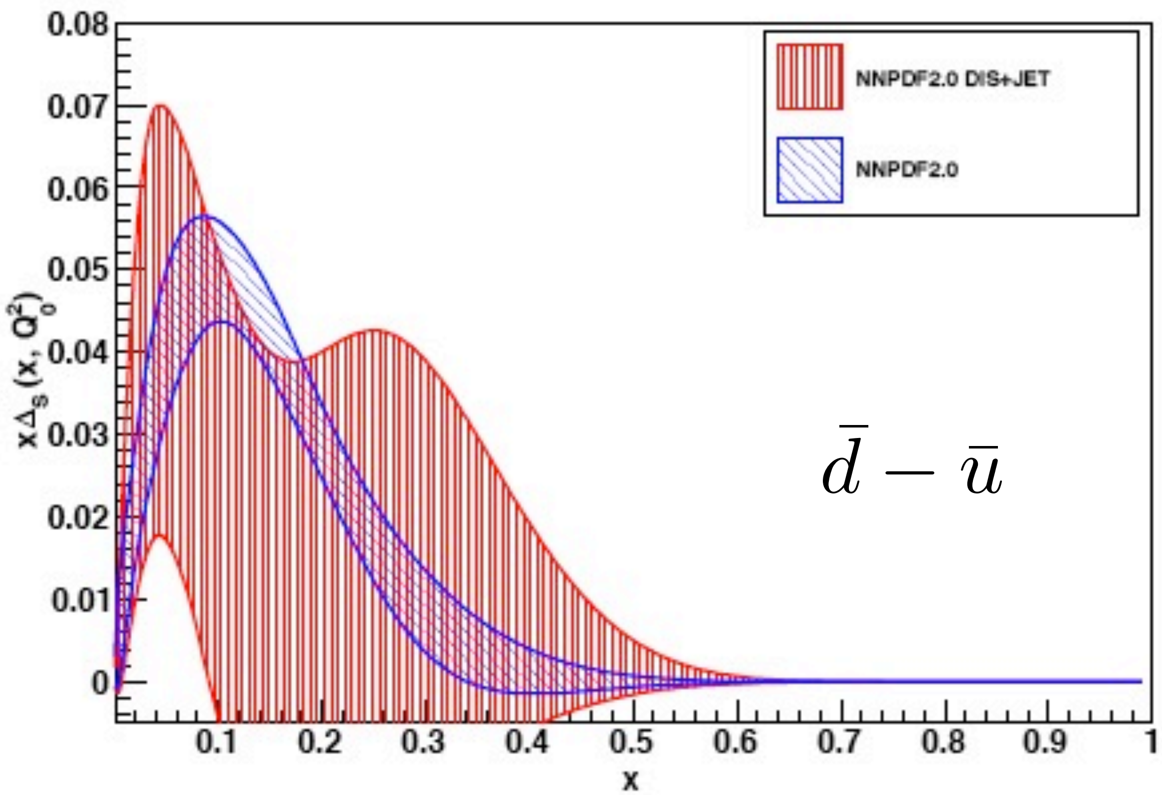
D-Y: impact on PDFs

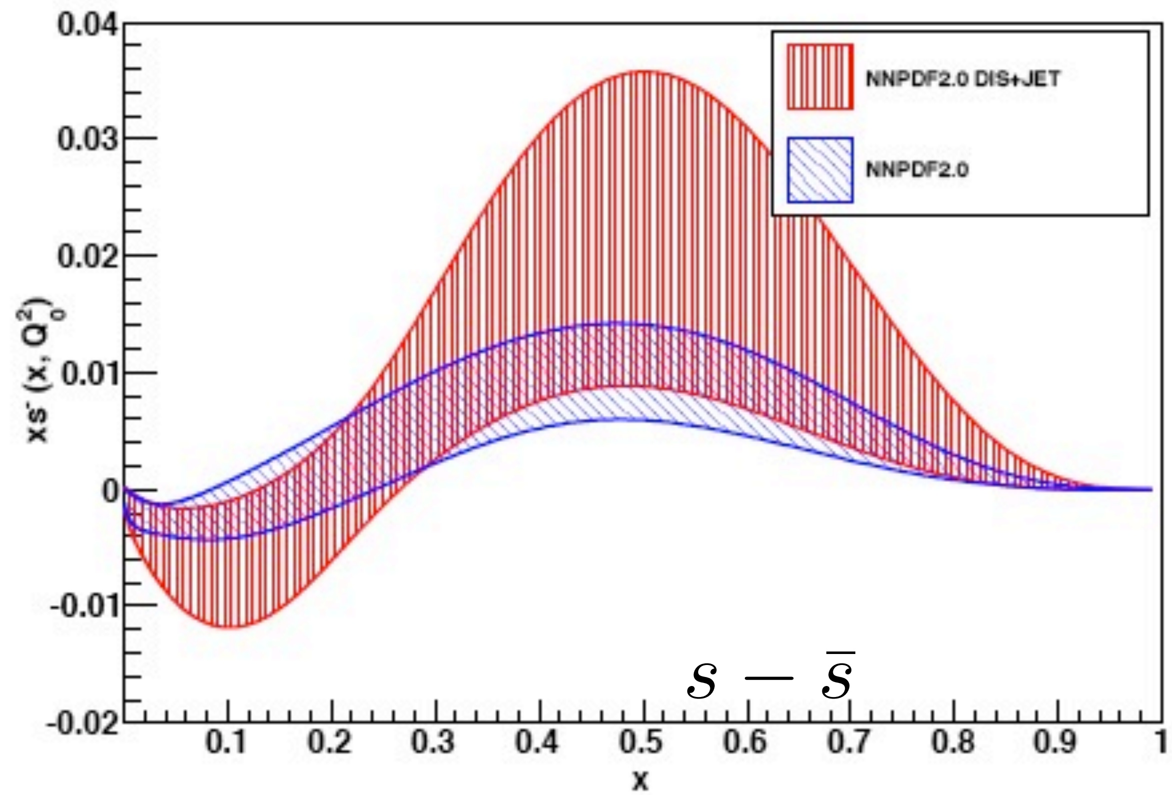


Blue: adding E605 and E866 data

We can expect similar impact on TMDs

D-Y: impact on PDFs





Blue: adding E605 and E866 data

We can expect similar impact on TMDs

NNPDF Coll., NPB838 (10), see E. Nocera's talk

Future perspectives

- COMPASS pion-nucleon may be useful to constrain pion unpolarized TMDs (will it be useful for the proton ones?)
- To study flavor dependence, it would be nice to have different beam/targets (e.g., antiprotons, deuterons)
- W production should be extremely useful for flavor studies

2

$$F_{UU}^{\cos\phi}$$

Matching?

Low q_T High q_T

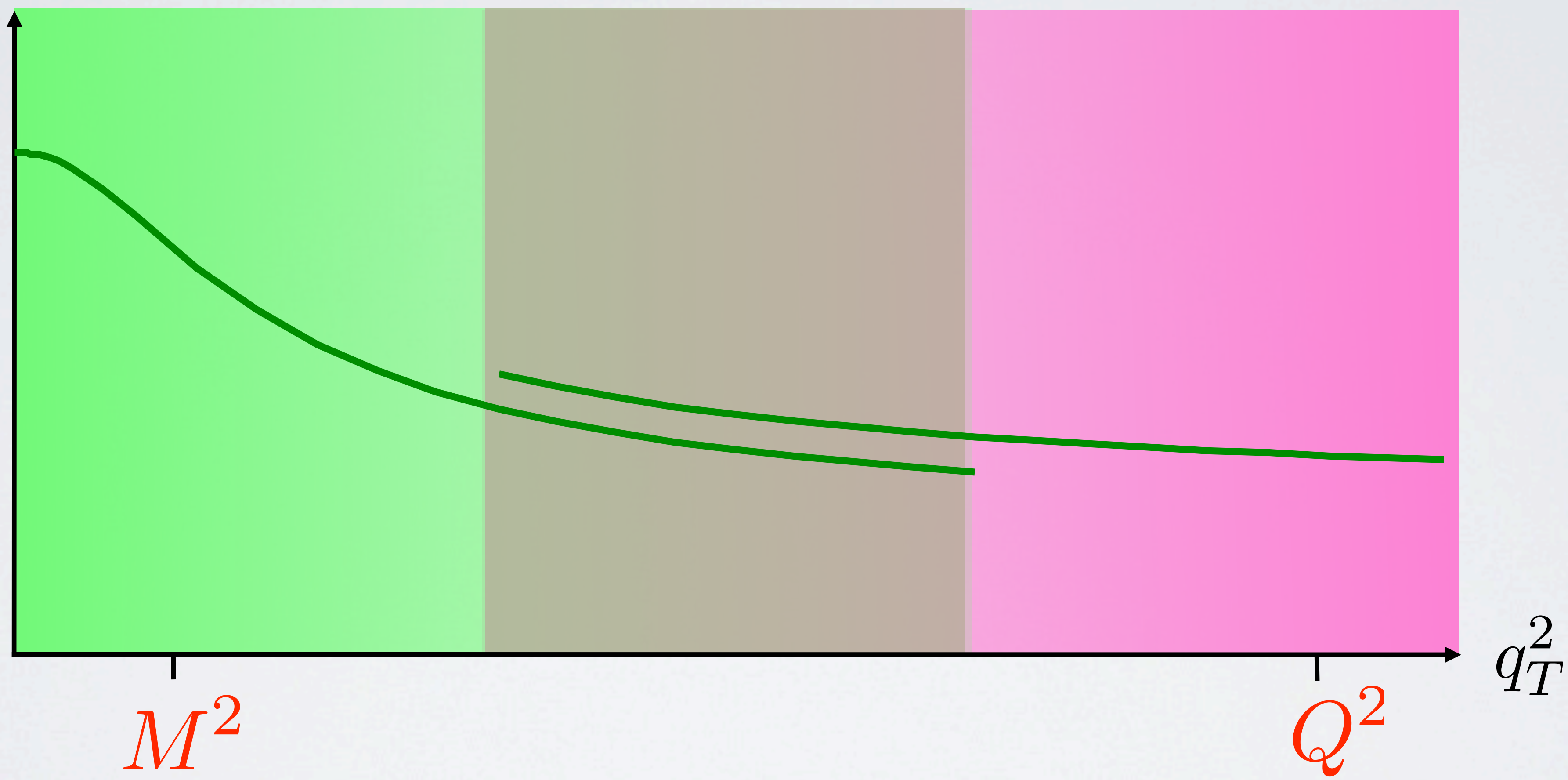
Tw 3 $F \sim \frac{1}{Q}\frac{q_T}{M^2}$ | $F \sim \frac{q_T}{Q}\frac{1}{M^2+q_T^2}$ | $F \sim \frac{1}{Qq_T}$ Tw 2

Yes, but not quite...

Unexpected mismatch

Bacchetta, Boer, Diehl, Mulders, JHEP08 (08)

Unexpected mismatch



Bacchetta, Boer, Diehl, Mulders, JHEP08 (08)

Unexpected mismatch

The TMD formalism at twist 3 is incomplete
(Is it possible to fix it?)

Bacchetta, Boer, Diehl, Mulders, JHEP08 (08)

Low transverse momentum

$$F_{UU,\mathrm{CS}}^{\cos\phi} = \frac{2M_1}{Q}\,\mathcal{C}\Big[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{2T}}{M_2}\Big(\frac{h+\tilde{h}}{2}\,\bar{h}_1^{\perp} - \frac{M_2}{M_1}f_1\frac{\bar{f}^{\perp}+\tilde{\bar{f}}^{\perp}}{2}\Big) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{1T}}{M_1}\Big(\frac{f^{\perp}+\tilde{f}^{\perp}}{2}\bar{f}_1 - \frac{M_2}{M_1}h_1^{\perp}\frac{\bar{h}+\tilde{\bar{h}}}{2}\Big)\Big]$$

Z. Lu and I. Schmidt, PRD84 (11)

Low transverse momentum

Pure twist 3

$$F_{UU,\mathrm{CS}}^{\cos\phi} = \frac{2M_1}{Q}\,\mathcal{C}\Big[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{2T}}{M_2}\Big(\frac{h+\tilde{h}}{2}\,\bar{h}_1^\perp - \frac{M_2}{M_1}f_1\frac{\bar{f}^\perp+\tilde{\bar{f}}^\perp}{2}\Big) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{1T}}{M_1}\Big(\frac{f^\perp+\tilde{f}^\perp}{2}\,\bar{f}_1 - \frac{M_2}{M_1}h_1^\perp\frac{\bar{h}+\tilde{\bar{h}}}{2}\Big)\Big]$$

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$$F_{UU,\mathrm{GJ}}^{\cos\phi_h} = \frac{2M_1}{Q}\,\mathcal{C}\Big[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{2T}}{M_2}\Big(h\,\bar{h}_1^{\perp} - \frac{M_2}{M_1}f_1\tilde{\bar{f}}^{\perp}\Big) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{1T}}{M_1}\Big(f^{\perp}\bar{f}_1 - \frac{M_2}{M_1}h_1^{\perp}\tilde{\bar{h}}\Big)\Big]$$

Z. Lu and I. Schmidt, PRD84 (11)

Low transverse momentum

Pure twist 3

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$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\Big[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\Big(x_B h\,H_1^{\perp} + \frac{M_h}{M}\,f_1\frac{\tilde{D}^{\perp}}{z}\Big) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\Big(x_B f^{\perp}D_1 + \frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{H}}{z}\Big)\Big]$$ SIDIS

Z. Lu and I. Schmidt, PRD84 (11)

From low to high q_T

$$F_{UU,\mathrm{GJ}}^{\cos\phi_h} = \frac{2M_1}{Q}\,\mathcal{C}\Big[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{2T}}{M_2}\Big(h\,\bar{h}_1^{\perp} - \frac{M_2}{M_1}f_1\tilde{\bar{f}}^{\perp}\Big) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{1T}}{M_1}\Big(f^{\perp}\bar{f}_1 - \frac{M_2}{M_1}h_1^{\perp}\tilde{\bar{h}}\Big)\Big]$$

Bacchetta, Boer, Diehl, Mulders, JHEP08 (08)

From low to high q_T

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$$x f_1 \sim \frac{1}{\boldsymbol{k}_T^2}\,\alpha_s\,\mathcal{F}\big[f_1\big]$$

$$x f^{\perp} \sim \frac{1}{\boldsymbol{k}_T^2}\,\alpha_s\,\mathcal{F}\big[f_1\big]$$

Bacchetta, Boer, Diehl, Mulders, JHEP08 (08)

From low to high q_T

$$F_{UU,\mathrm{GJ}}^{\cos\phi_h} = \frac{2M_1}{Q}\,\mathcal{C}\Big[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{2T}}{M_2}\Big(h\,\bar{h}_1^{\perp} - \frac{M_2}{M_1}f_1\tilde{\bar{f}}^{\perp}\Big) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{1T}}{M_1}\Big(f^{\perp}\bar{f}_1 - \frac{M_2}{M_1}h_1^{\perp}\tilde{\bar{h}}\Big)\Big]$$

$$x f_1 \sim \frac{1}{\boldsymbol{k}_T^2}\,\alpha_s\,\mathcal{F}\big[f_1\big] \qquad\qquad h_1^{\perp} \sim \frac{M^2}{\boldsymbol{k}_T^4}\,\alpha_s\,\mathcal{F}\big[h_1^{\perp(1)},\ldots\big]$$

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Bacchetta, Boer, Diehl, Mulders, JHEP08 (08)

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Bacchetta, Boer, Diehl, Mulders, JHEP08 (08)

SIDIS example

Low q_T

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\Big[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\Big(x_B h\, H_1^{\perp} + \frac{M_h}{M}\, f_1 \frac{\tilde{D}^{\perp}}{z}\Big) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\Big(x_B f^{\perp} D_1 + \frac{M_h}{M}\, h_1^{\perp}\frac{\tilde{H}}{z}\Big)\Big]$$

Intermediate q_T

Bacchetta, Boer, Diehl, Mulders, JHEP08 (08)

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Intermediate q_T

$$F_{UU}^{\cos\phi_h} = -\frac{1}{Qq_T}\,\frac{\alpha_s}{2\pi^2 z^2}\sum_a x e_a^2 \Big[f_1^a(x)\, D_1^a(z)\, L\Big(\frac{Q^2}{q_T^2}\Big) + f_1^a(x)\,\big(D_1^a \otimes P'_{qq} + D_1^a \otimes P'_{gq}\big)(z)$$

$$+ \big(P'_{qq} \otimes f_1^a + P'_{qg} \otimes f_1^g\big)(x)\, D_1^a(z) - 2C_F\, f_1^a(x)\, D_1^a(z)\Big]$$

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Does not match exactly!

Bacchetta, Boer, Diehl, Mulders, JHEP08 (08)

“Wandzura-Wilczek” approx

$$f^{\perp} = \frac{f_1}{x} + \tilde{f}^{\perp}$$

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Formally "fine," but probably is not realistic and misses nice physics of quark-gluon correlations

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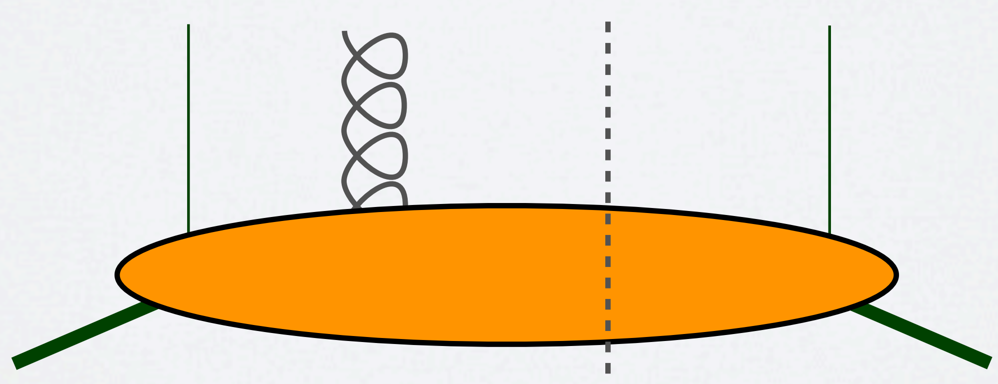

“Wandzura-Wilczek” approx

$$h = \frac{k_T^2}{M^2}\frac{h_1^{\perp}}{x} + \tilde{h}$$

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Formally wrong.
E.g., violates time-reversal condition:

$$\int d^2k_T \, h(x, k_T^2) = 0$$

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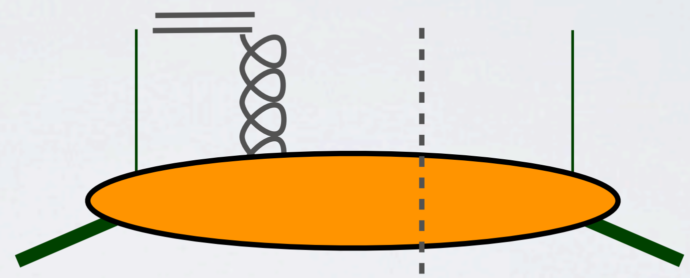

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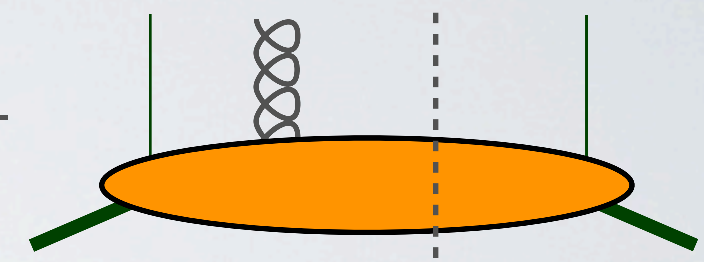

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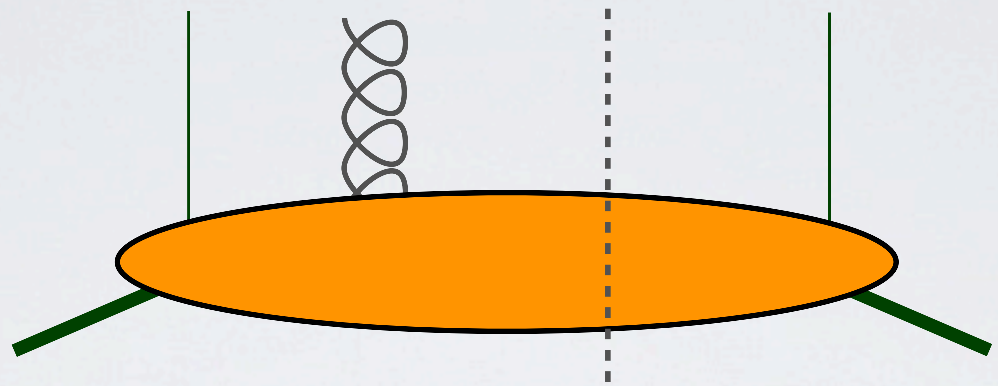
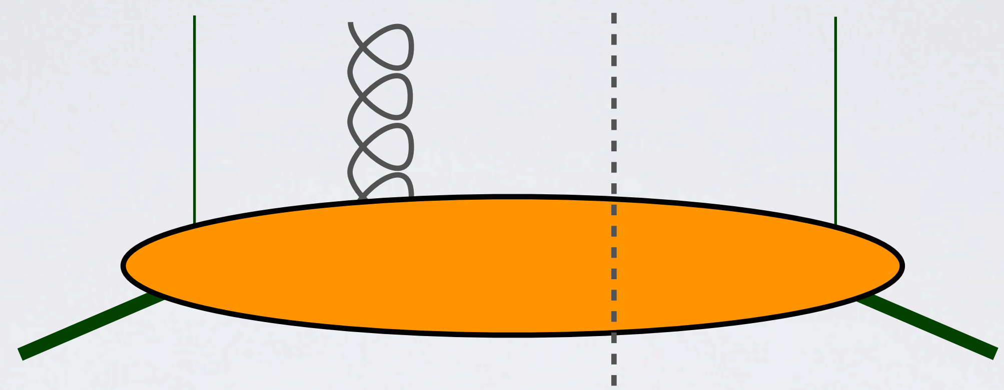
Formally “fine,” but probably is not realistic and misses nice physics of T-odd functions.

Quark-gluon correlations

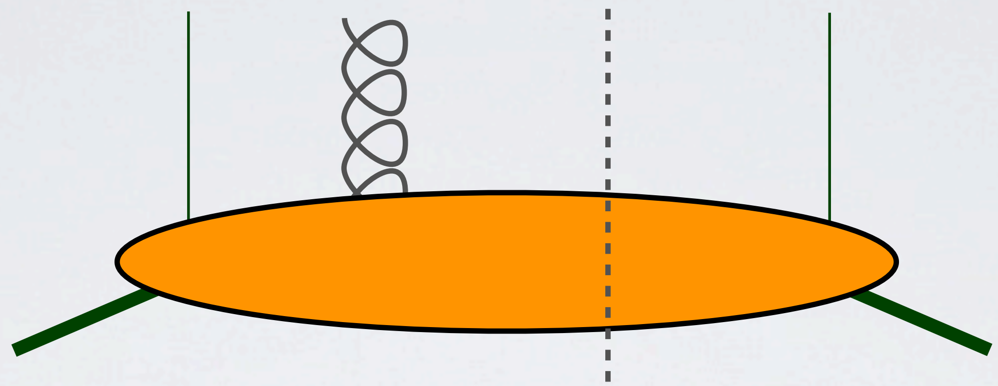


Quark-gluon correlations



- Describe physics effects of the presence of the gluons together with the quarks (quarks feeling the QCD interaction...)
  see, e.g., Burkardt arXiv:0810.3589

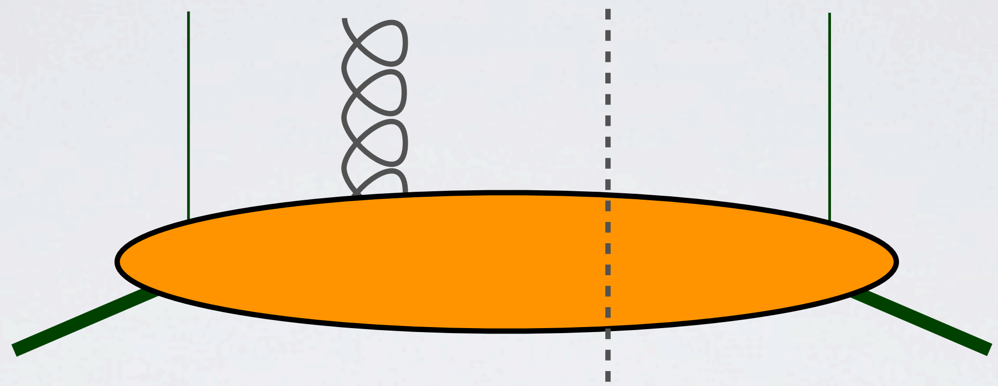
Quark-gluon correlations



- Describe physics effects of the presence of the gluons together with the quarks (quarks feeling the QCD interaction...)
  see, e.g., Burkardt arXiv:0810.3589

- Some models already exist
  see, e.g., Lu, Schmidt, arXiv:1202.0700

Quark-gluon correlations



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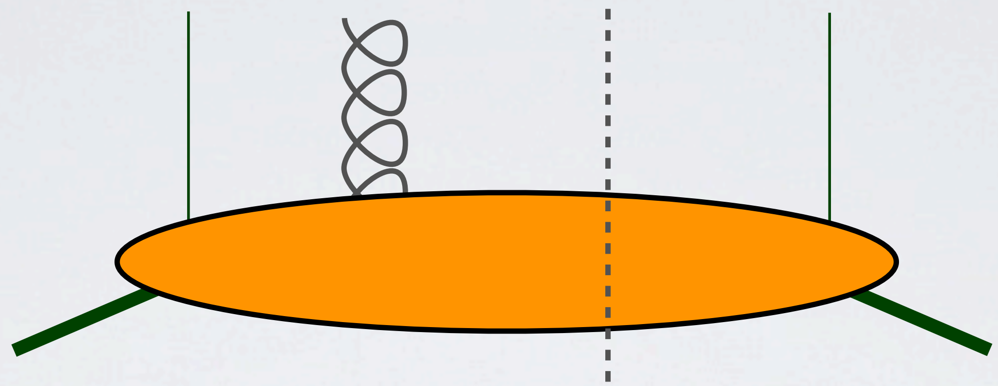

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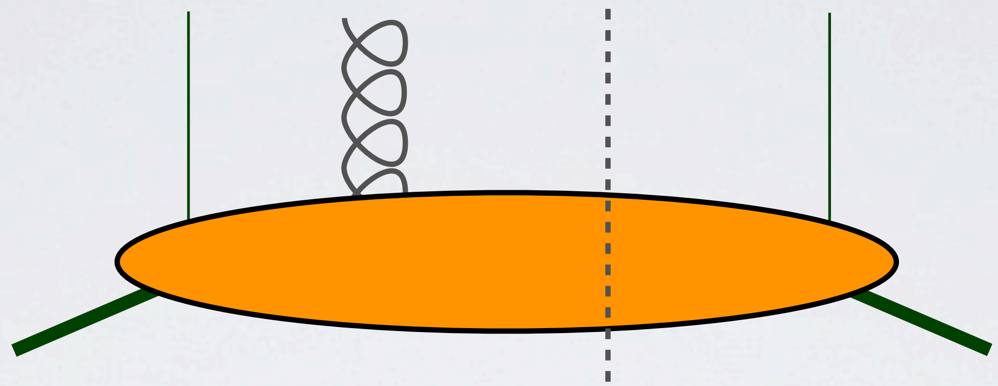
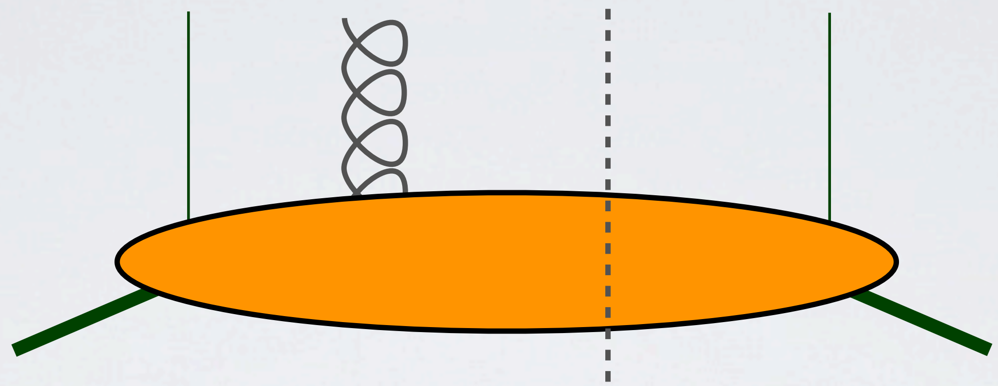


- Important for the high-transverse-momentum tails of TMDs
  see, e.g., Ji, Qiu, Vogelsang, Yuan, PLB638 (06)

Quark-gluon correlations



- Important for the high-transverse-momentum tails of TMDs
  see, e.g., Ji, Qiu, Vogelsang, Yuan, PLB638 (06)

- Intriguing properties from the theoretical point of view (e.g., evolution)
  see, e.g., Braun, Manashov, Pirnay, PRD80 (09)

3

$$F_{UU}^{\cos 2\phi}$$

Matching?

Low q_T		High q_T
Tw 4 $F \sim \frac{1}{Q^2}\frac{q_T^2}{M^2}$	$F \sim \frac{q_T^2}{Q^2}\frac{1}{M^2+q_T^2}$	$F \sim \frac{1}{Q^2}$ Tw 2

Matching?

Low q_T High q_T

Tw 4	$F \sim \frac{1}{Q^2}\frac{q_T^2}{M^2}$	$F \sim \frac{q_T^2}{Q^2}\frac{1}{M^2+q_T^2}$	$F \sim \frac{1}{Q^2}$ Tw 2

+

Matching?

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Tw 4 $F \sim \frac{1}{Q^2}\frac{q_T^2}{M^2}$	$F \sim \frac{q_T^2}{Q^2}\frac{1}{M^2+q_T^2}$	$F \sim \frac{1}{Q^2}$ Tw 2
	+
Tw 2 $F \sim \frac{q_T^2}{M^4}$	$F \sim \frac{M^2 q_T^4}{M^6+q_T^6}$	$F \sim \frac{1}{q_T^4}$ Tw 4

Matching?

Low q_T | High q_T

No

	Low q_T		High q_T	
Tw 4	$F \sim \frac{1}{Q^2}\frac{q_T^2}{M^2}$	$F \sim \frac{q_T^2}{Q^2}\frac{1}{M^2+q_T^2}$	$F \sim \frac{1}{Q^2}$	Tw 2
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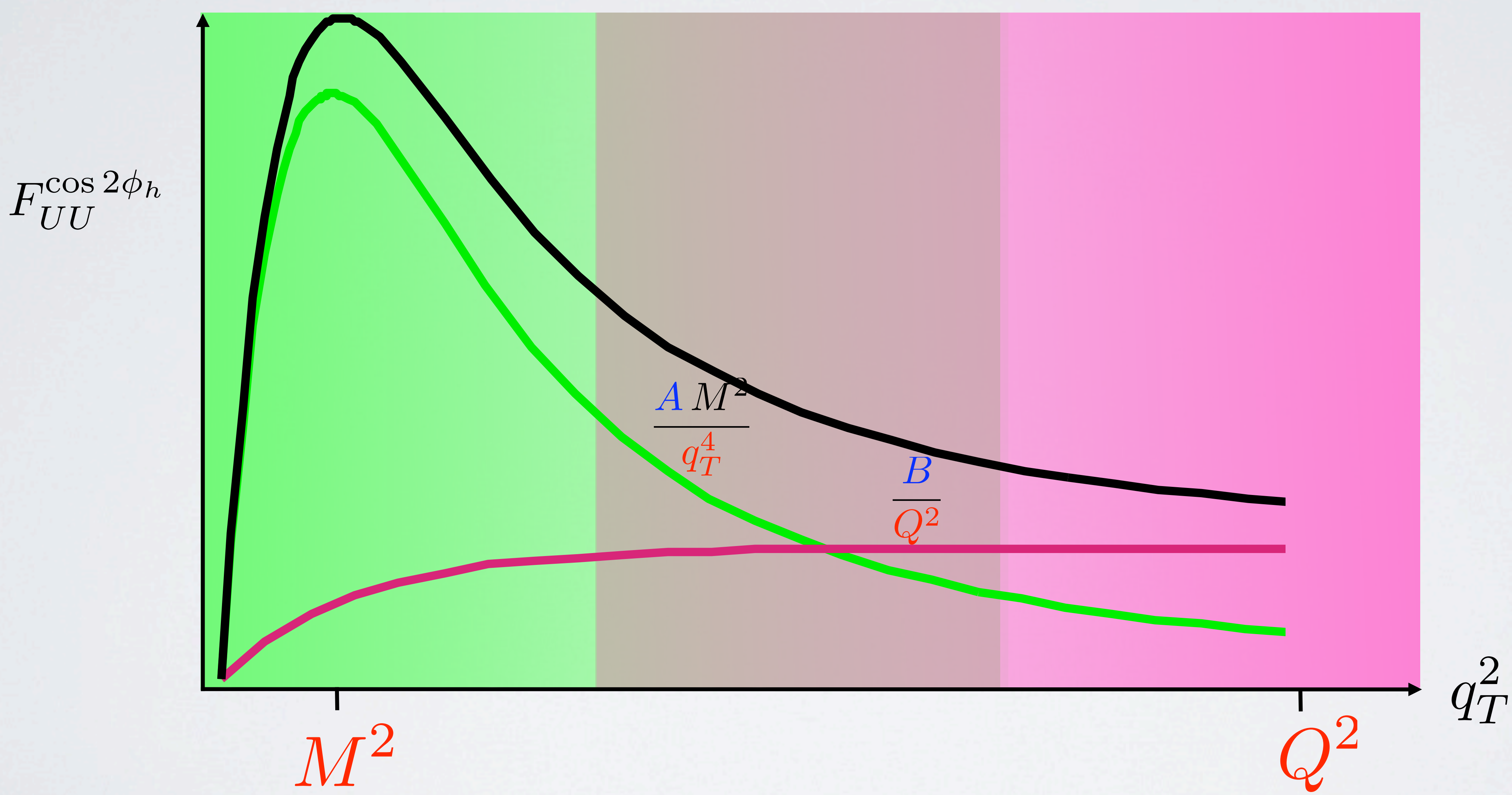
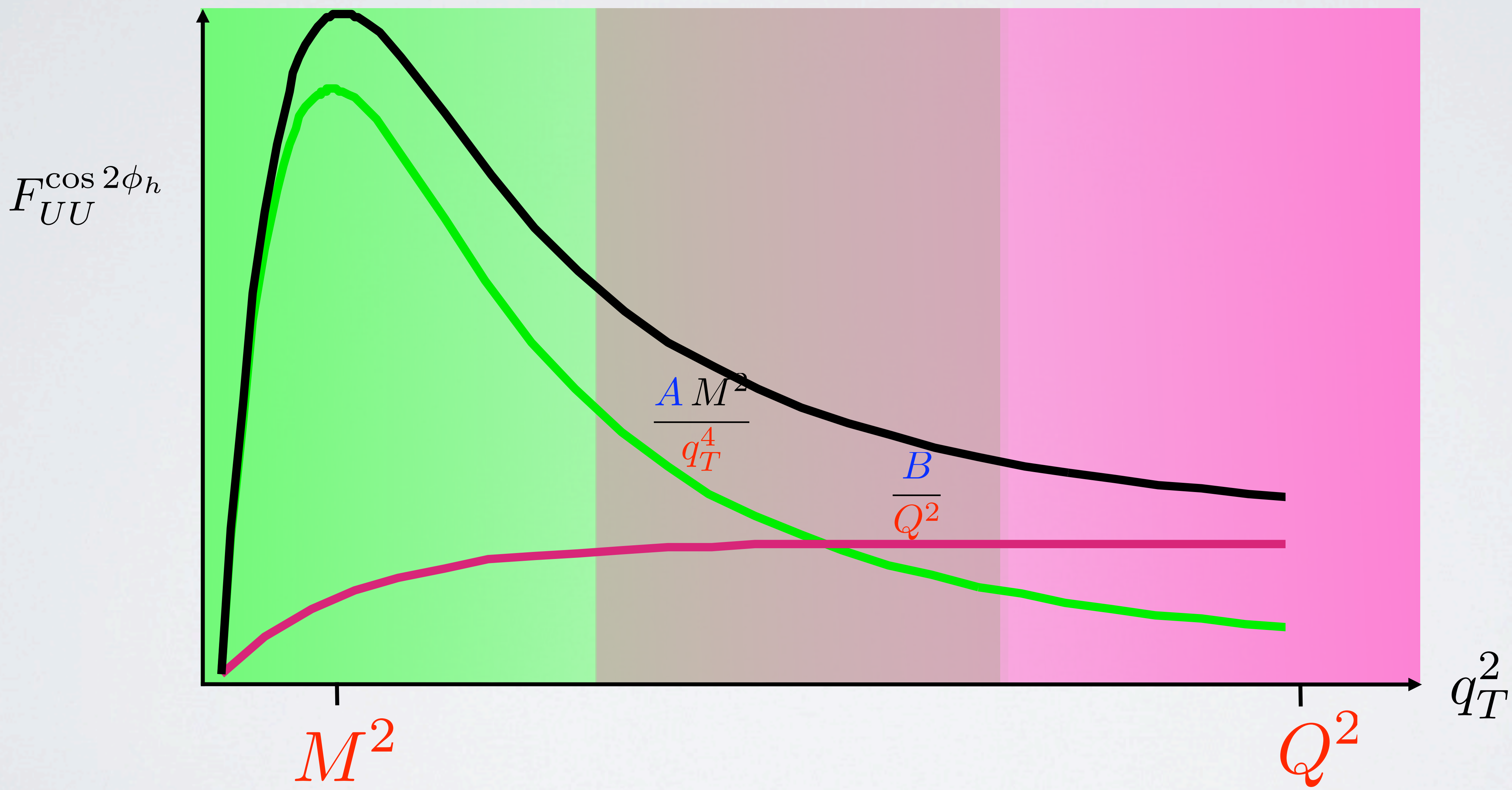
Expected mismatch



Expected mismatch

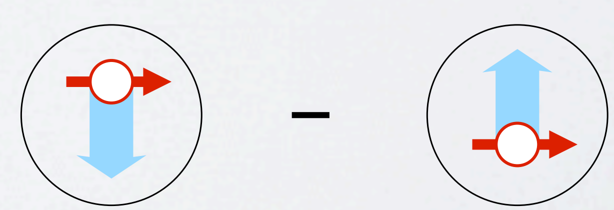


Two distinct mechanisms are involved

TMD description

$$F_{UU}^{\cos 2\phi} = \mathcal{C}\left[\frac{2\left(\vec{h}\cdot\vec{k}_{aT}\right)\left(\vec{h}\cdot\vec{k}_{bT}\right)-\vec{k}_{aT}\cdot\vec{k}_{bT}}{M_a M_b}\, h_1^{\perp}\, \bar{h}_1^{\perp}\right]$$

Boer-Mulders TMD
"spin without spin"



Tuesday, 22 May 2012

TMD description

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Boer-Mulders TMD
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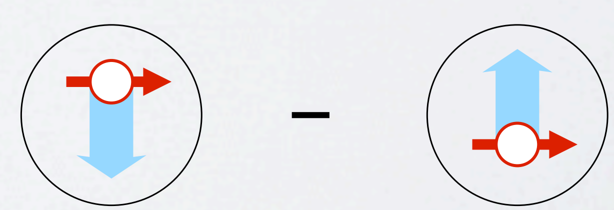
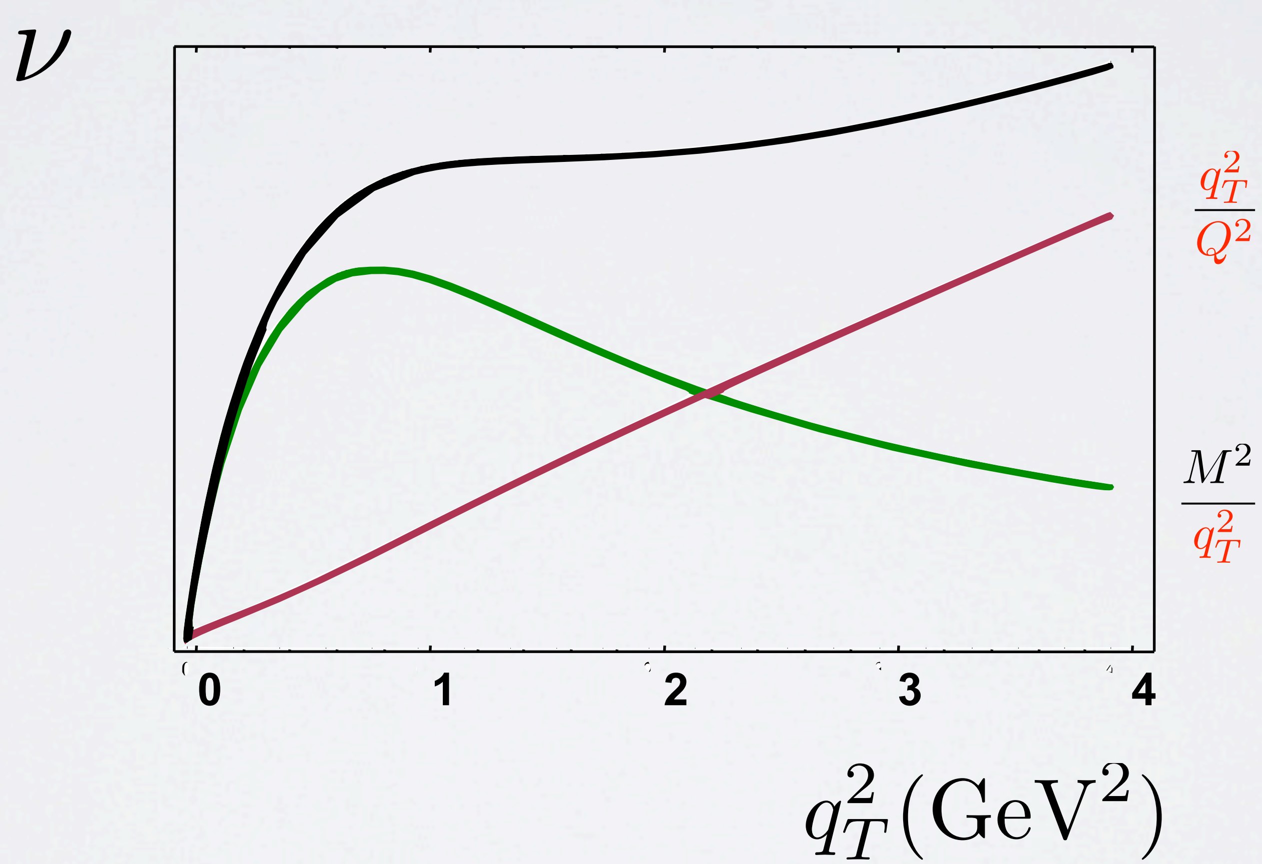
$h_1^{\perp} =$



On the cos2ϕ modulation

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$



Bacchetta, Boer, Diehl, Mulders, JHEP08 (08)

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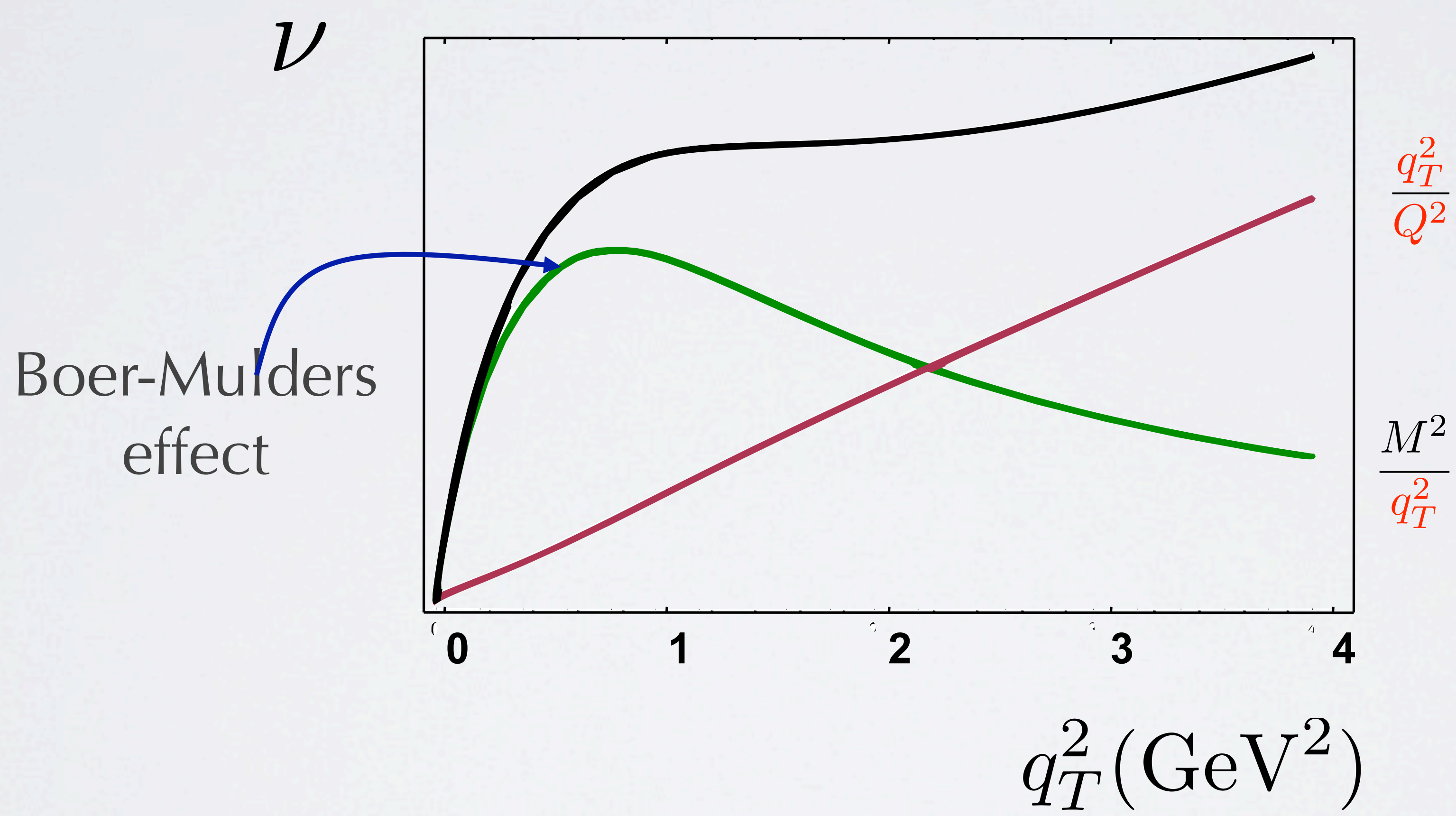

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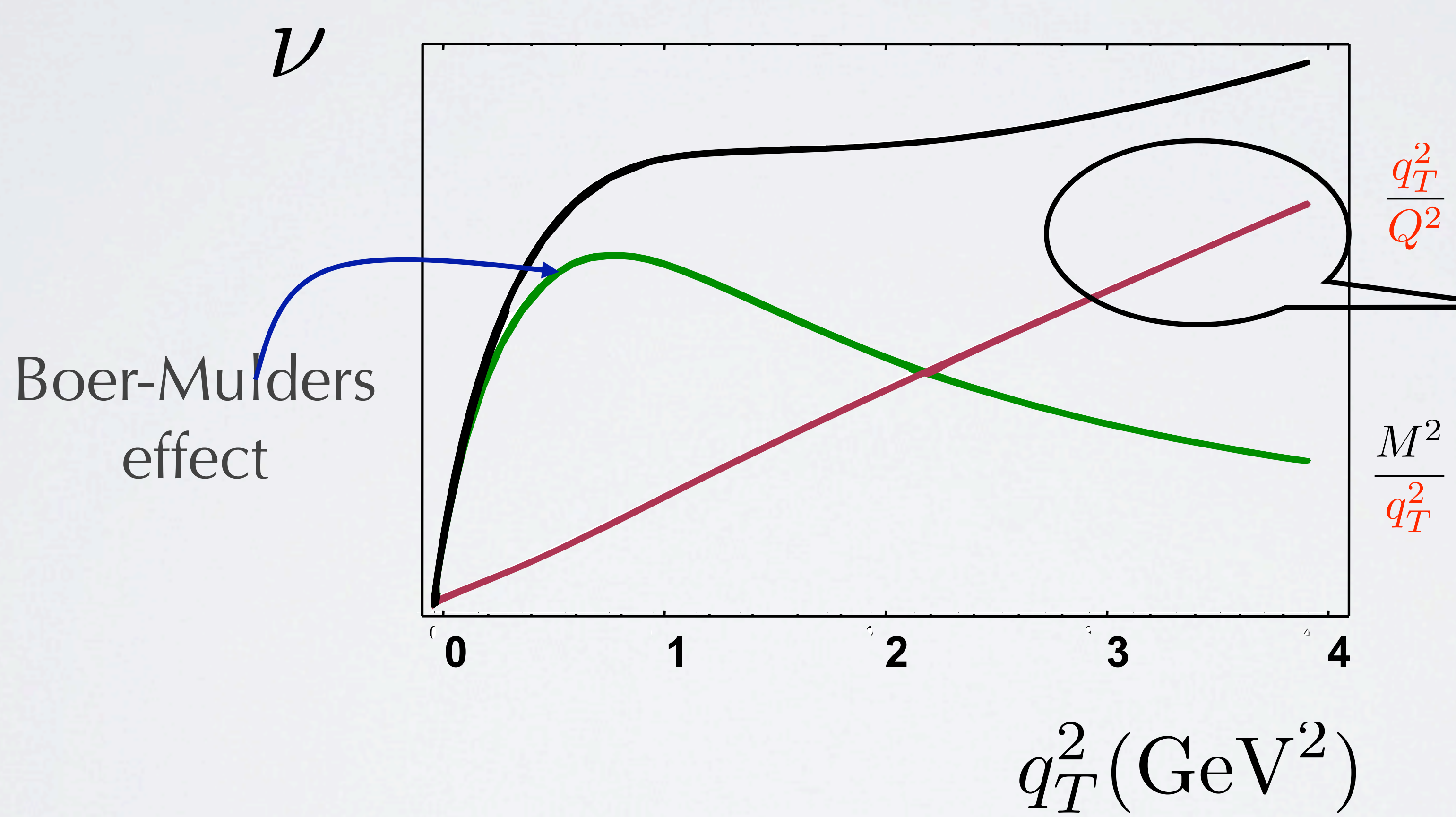

Can be calculated with pQCD. Resummation important.

Boer, Vogelsang, PRD74 (06)

Berger, Qiu, Rodrigues-Pedraza, PRD76 (07)

Bacchetta, Boer, Diehl, Mulders, JHEP08 (08)

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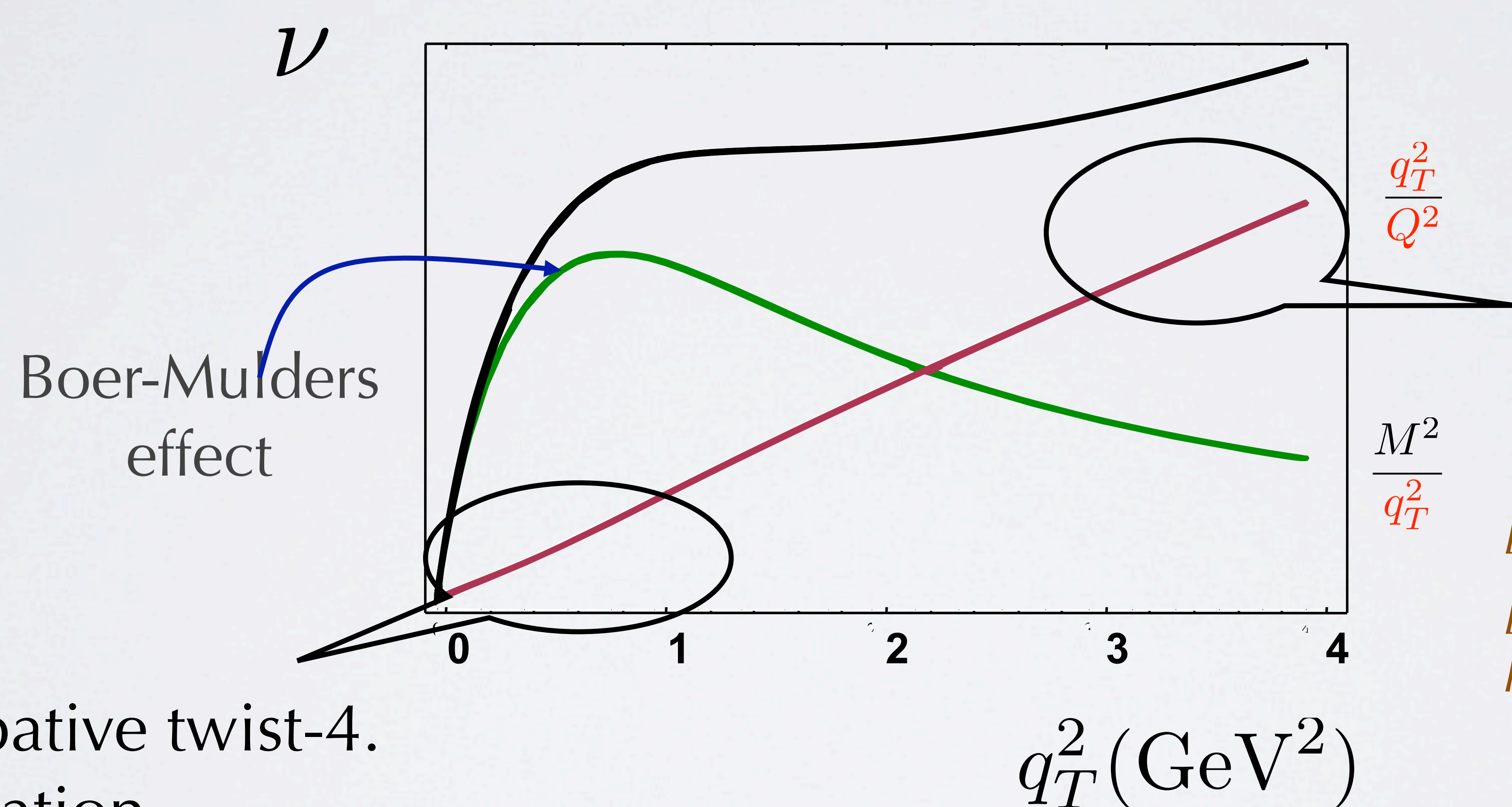


Can be calculated with pQCD. Resummation important.

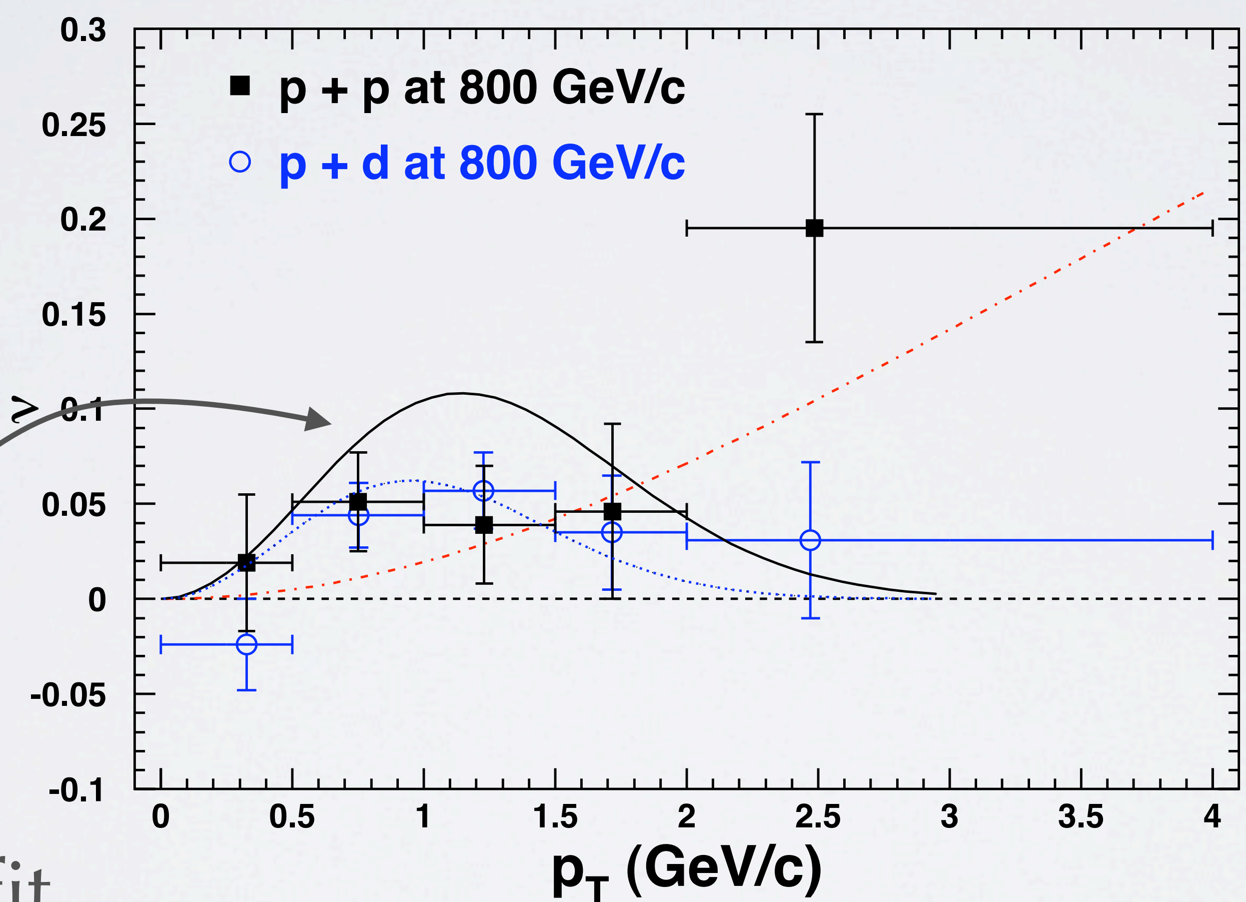
Boer, Vogelsang, PRD74 (06)

Berger, Qiu, Rodrigues-Pedraza, PRD76 (07)

Nonperturbative twist-4.
No factorization.
(Cahn twist-4 can be a model?)

Bacchetta, Boer, Diehl, Mulders, JHEP08 (08)

Phenomenology



pQCD calculation

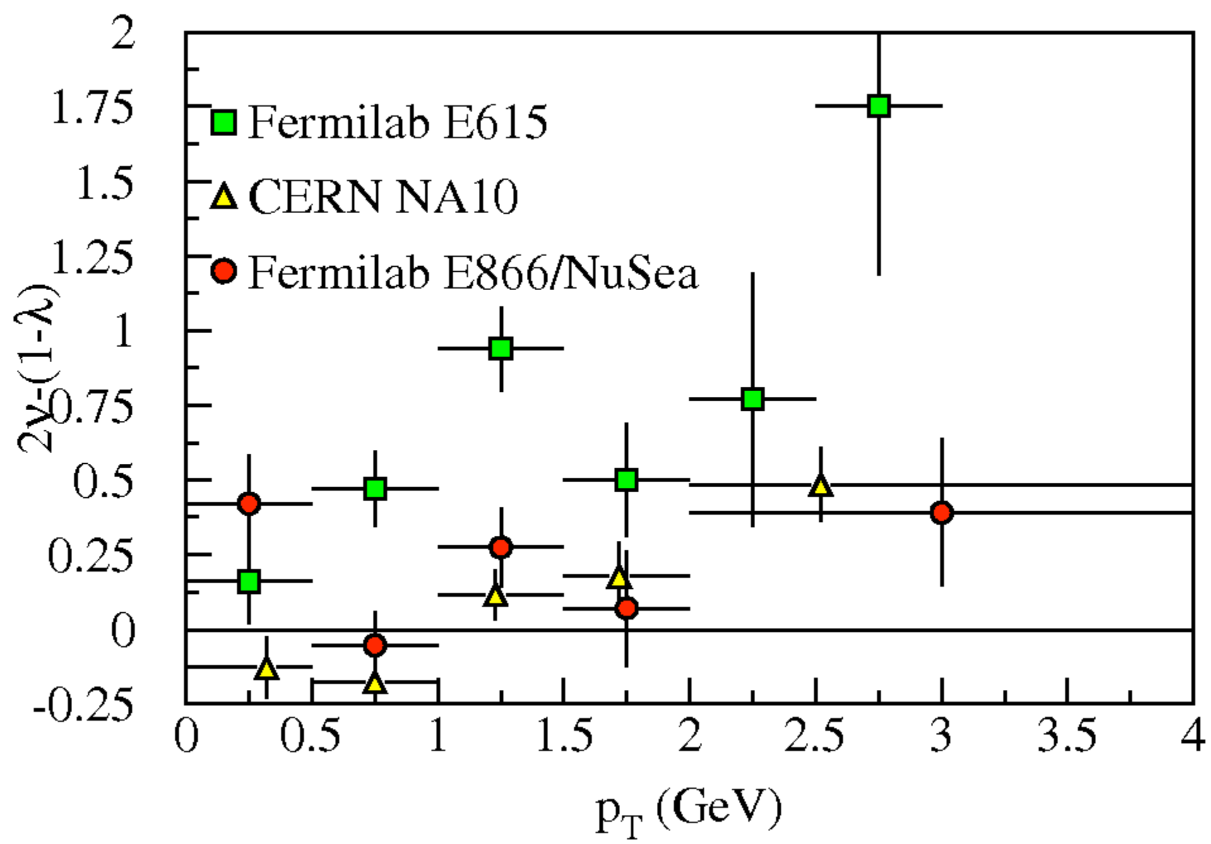
Boer-Mulders fit

Zhang, Lu, Ma, Schmidt, PRD78 (08)

Enzo Barone's talk

Violation of Lam-Tung relation

$$1 - \lambda = 2\nu$$



talk by P. Reimer at DY@BNL workshop

May be a better way to study Boer-Mulders function, since pQCD contributions may cancel

Conclusions

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Already unpolarized Drell-Yan has many rich features related to TMDs...

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see next talk and tomorrow's talks