PION NUCLEUS DRELL–YAN PROCESS

AND

PARTON TRANSVERSE MOMENTUM IN THE PION

INT Program INT-18-3

Probing Nucleons and Nuclei in High Energy Collisions

Week 2

A. Courtoy

Instituto de Física
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Instituto de Física

OUTLINE

- Drell-Yan in πN scattering
- Focus on the W-term
  - ➡ Drell-Yan with transverse momentum
  - ➡ Pion dynamics
  - ➡ Effects on DY cross section

in collaboration with
Federico Ceccopieri,
Santiago Noguera
& Sergio Scopetta

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- Drell-Yan in πN scattering
- Focus on the W-term
  - ➡ Drell-Yan with transverse momentum
  - ➡ Pion dynamics → Focus of the pion
  - ➡ Effects on DY cross section

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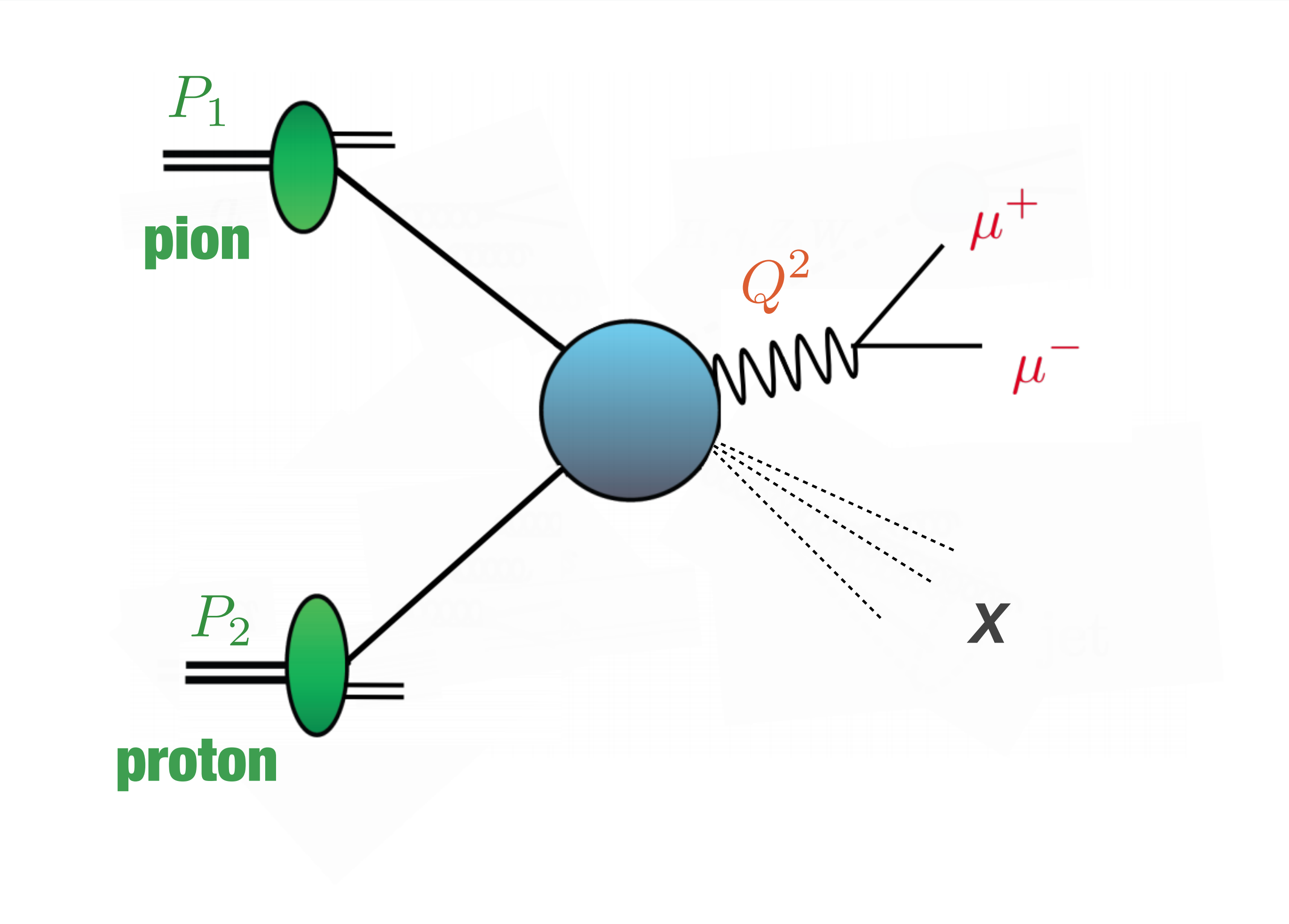


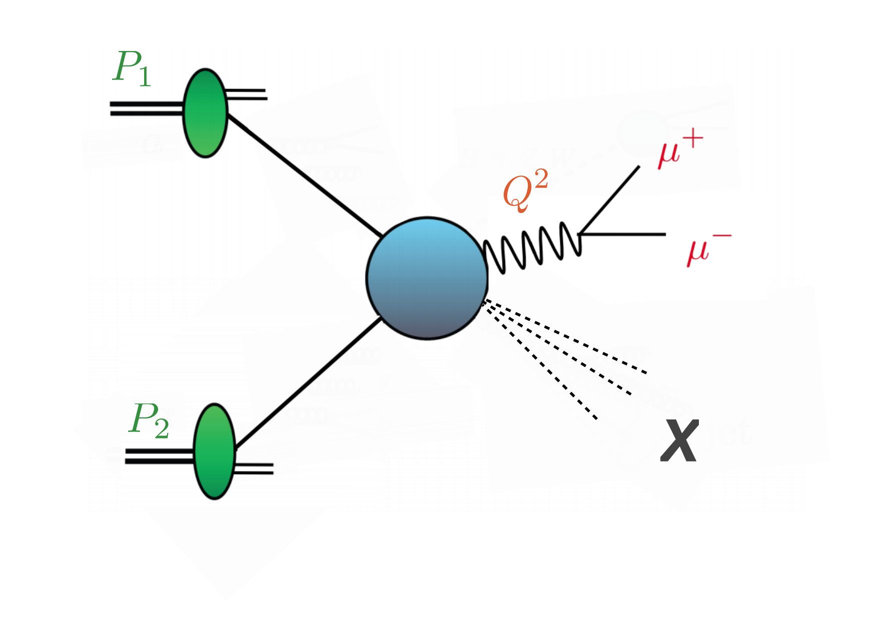
$$Q^2 = M^2$$
$$s = 2P_1 \cdot P_2$$

$$\tau = \frac{Q^2}{s} \equiv \text{finite as } Q^2, s \to \infty$$

Pion DY

Pion-proton Drell-Yan differential cross-section

$$d\sigma = \sum_{ab} \int dx_a \int dx_b \, f_a^{\pi}(x_a,\mu) f_b(x_b,\mu) \, d\hat{\sigma}_{ab}(x_a P_a, x_b P_b, Q, \alpha_s(\mu), \mu)$$



$$x_a x_b = \tau$$

$$Q^2 = M^2$$

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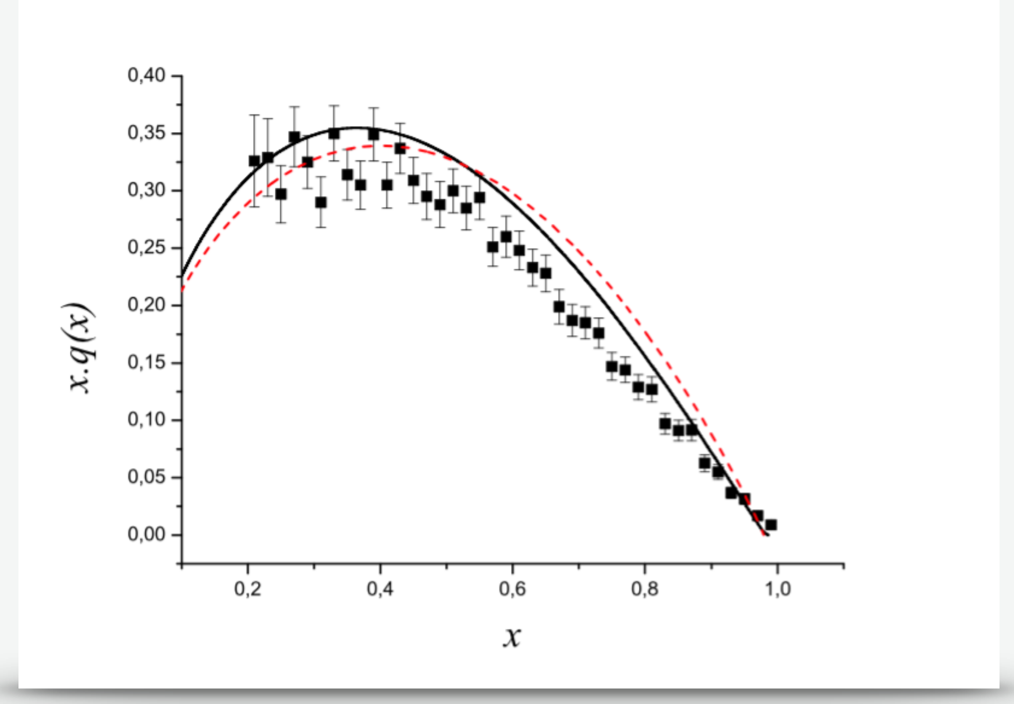
Pion-proton Drell-Yan:
main source of information on pion structure

E615 extraction
(joint proton and pion PDF)

Momentum fraction carried by valence quarks
→ allows Q_0 fixing



Nambu - Jona-Lasinio (NJL)
with MSRS PDFs (1992)

$$Q_0 = 0.29\text{GeV} \quad , \quad \text{for the LO evolution;}$$
$$Q_0 = 0.43\text{GeV} \quad , \quad \text{for the NLO evolution.}$$

$$\Lambda_{\text{LO}} = 0.174\,\text{GeV}$$
$$\Lambda_{\text{NLO}} = 0.246\,\text{GeV}$$

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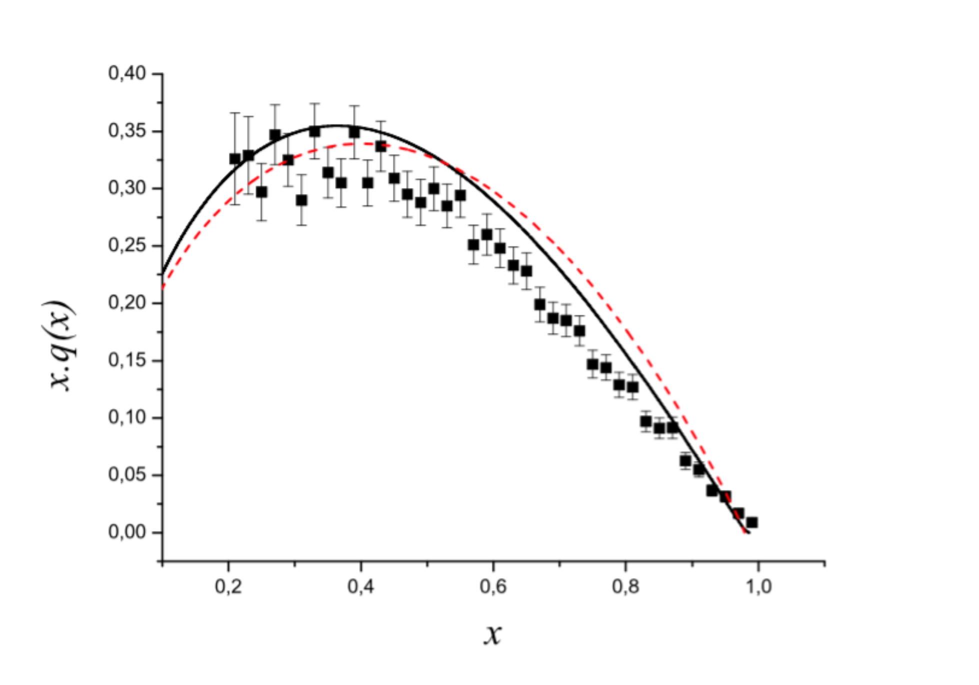

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The exercice should be repeated for the new pion PDF of PRL121,152001.

THE PION IN NJL

Successful results and predictions in the past

Pion means chiral low-energy model

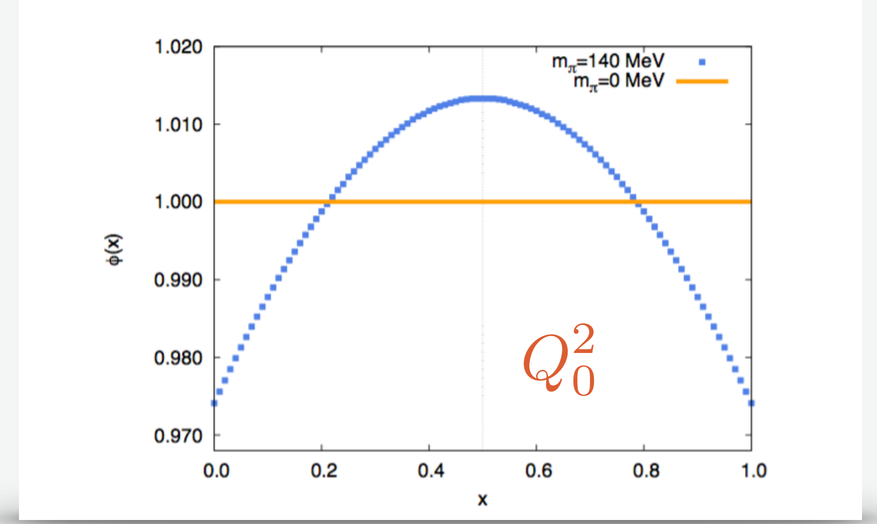
Decent approach of QCD

Why NJL?

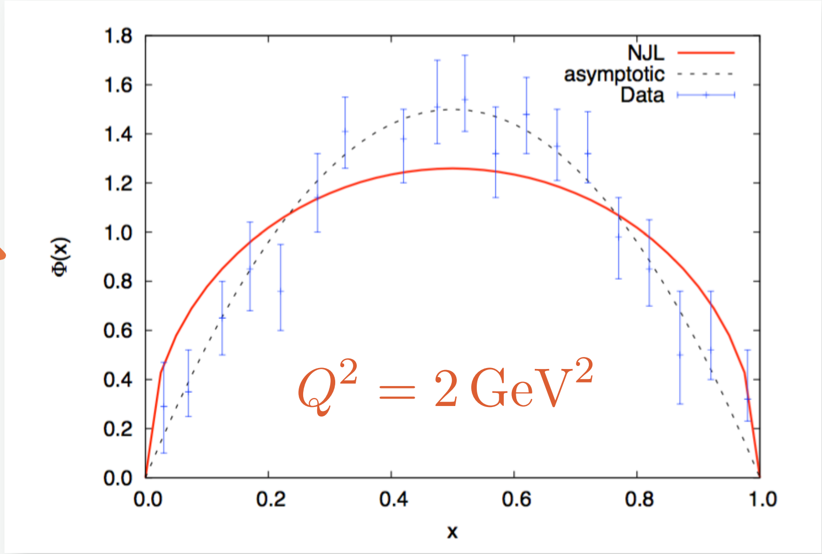
- Quarks dof
- Constituent quarks mass from gap equation
- Pion as a Goldstone mode
- Pion as a Bound-State in the sense of Bethe-Salpeter $\vec{\chi}_P(p) \; = \; -g_{\pi qq}\, iS(p)\,\gamma_5\vec{\tau}\, iS(p-P)$
- Choice of a covariant regularization scheme (here we use Pauli-Villars)

Ruiz-Arriola, Broniowski, Gamberg, Noguera, Scopetta, Courtoy,…

THE PION IN NJL:
DISTRIBUTION AMPLITUDE



Mind the scale of y-axis!



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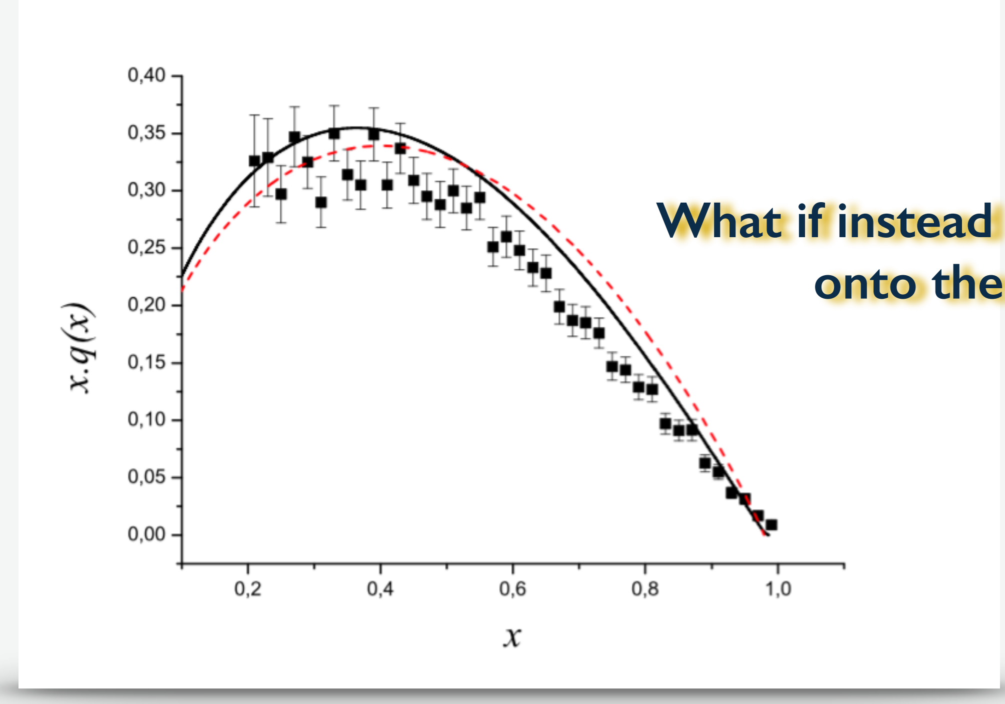

What if instead we map the pion PDF onto the DY X-section?

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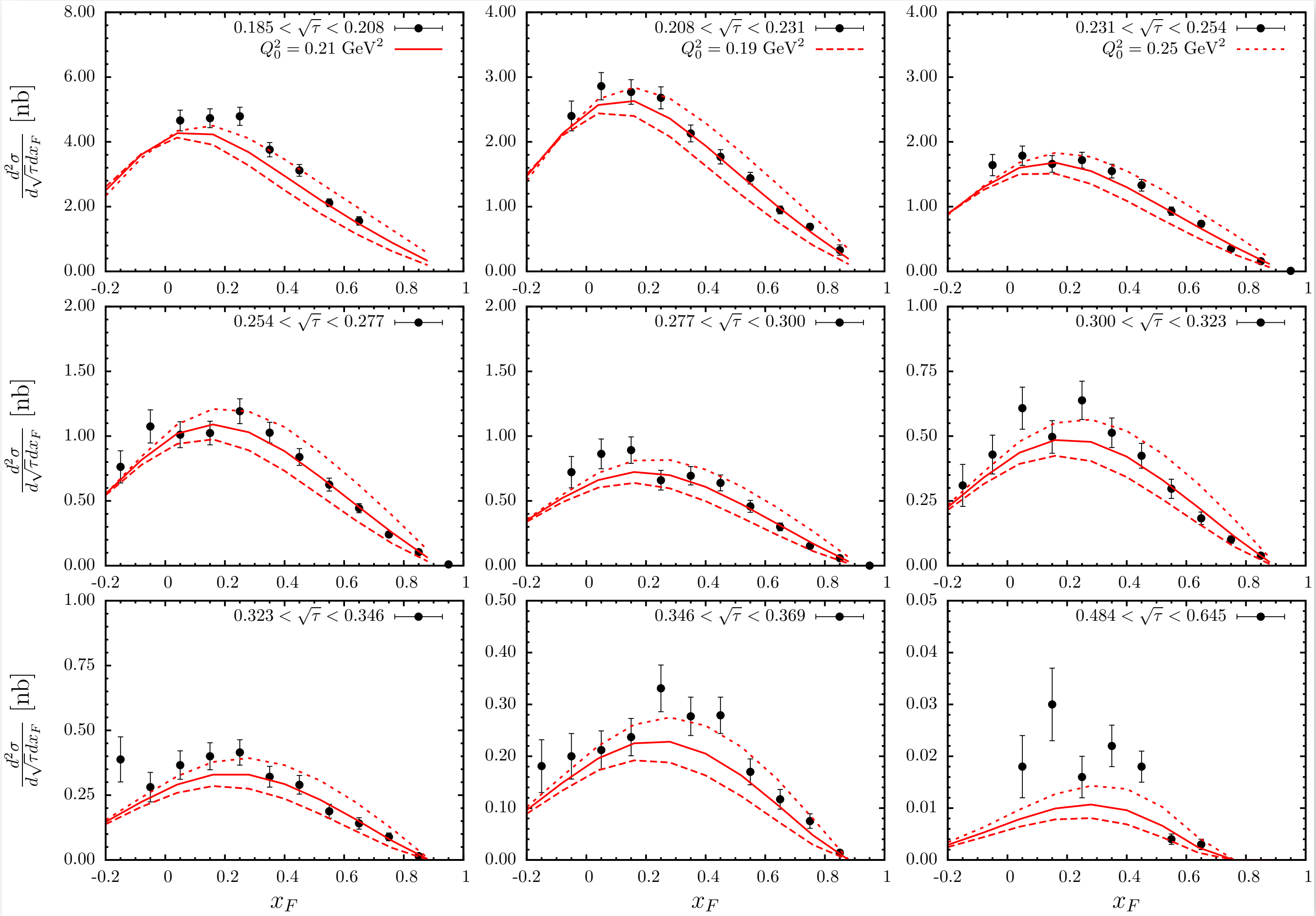
Determination of NJL's scale

Comparison of integrated X-section with theory at NLO:

- pion from NJL
- proton from CTEQ06M

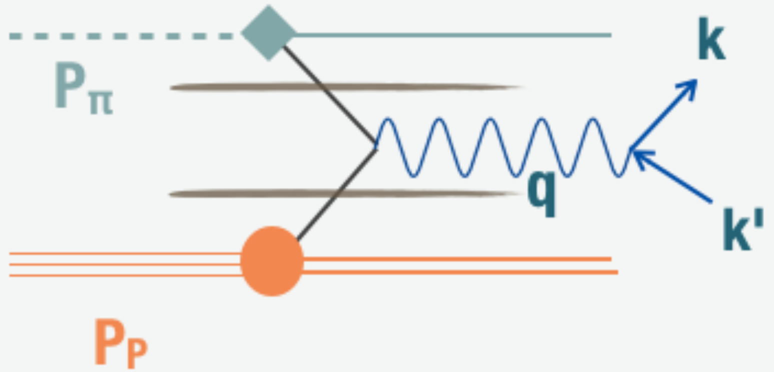


We find

Q_0^2=0.21 GeV^2 / Q_0=0.46 GeV

with χ^2/dof=2

DRELL-YAN WITH TRANSVERSE MOMENTUM



See talks by Fulvio and Nobuo

With measured Q_T of order Q

$$\frac{d\sigma}{dQ^2\,dy\,dQ_T^2} = \frac{4\pi^2\alpha^2}{9Q^2 s}\sum_{a,b}\int_{x_\pi}^{1}\frac{d\xi_\pi}{\xi_\pi}\int_{x_P}^{1}\frac{d\xi_P}{\xi_P}\,T_{ab}(\cdots)f_{a/\pi}(\xi_\pi,\mu)f_{b/P}(\xi_P,\mu)$$

$$q^2 = (k+k')^2$$

$$x_\pi = \frac{Q^2}{2P_\pi\cdot q}, \quad x_P = \frac{Q^2}{2P_P\cdot q}$$

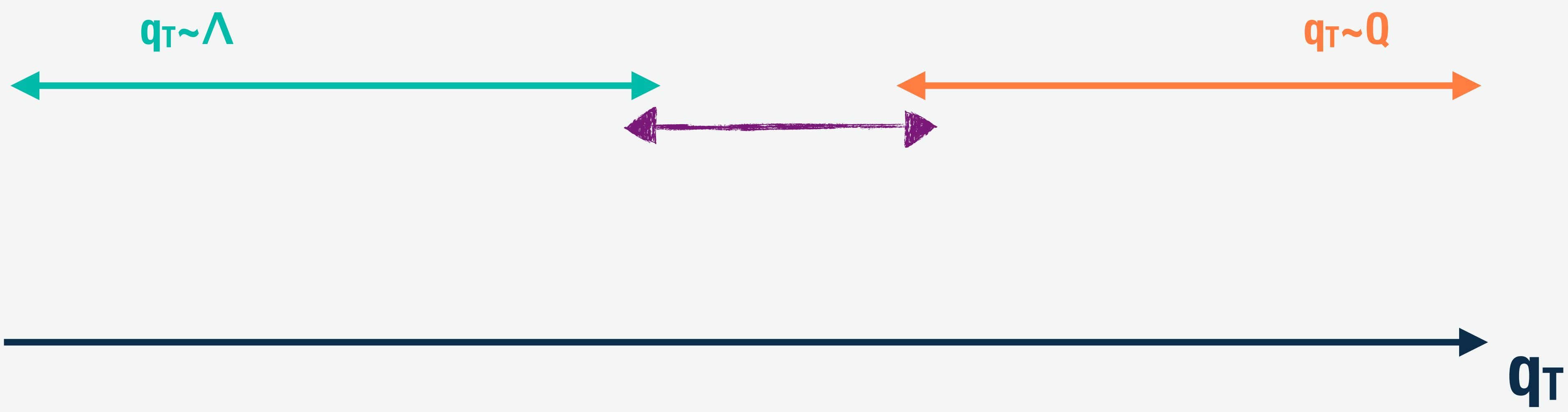
$$\tau = \frac{Q^2}{s} \text{ fixed and finite as } Q^2, s\to\infty$$

$$q^\mu = (x_\pi P_\pi^+,\, x_P P_P^-,\, \vec{q}_T)$$

$$y = \frac{1}{2}\ln\frac{x_\pi}{x_P}$$

REGION OF TRANSVERSE MOMENTUM

$Q^2 >> \Lambda^2$



Pion DY

[Collins, Soper & Sterman, Nucl.Phys.B250]

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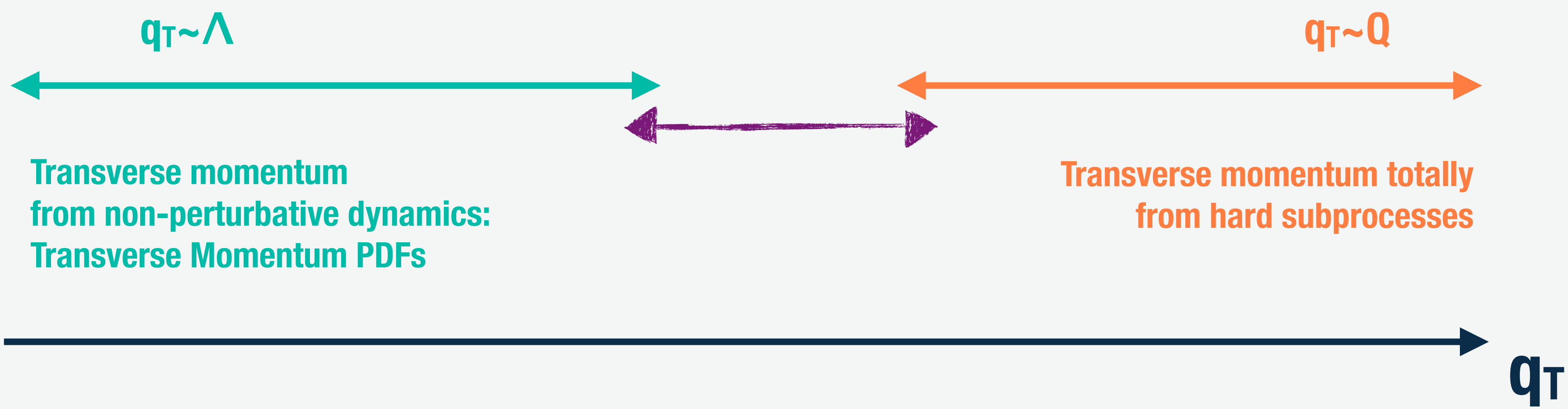

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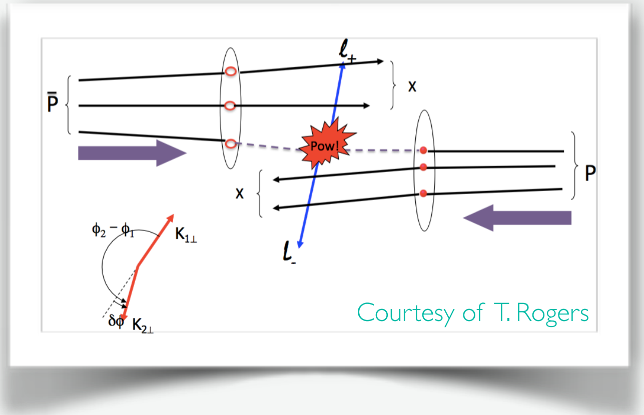

$q_T \sim \Lambda$

$q_T \sim Q$

Transverse momentum
from non-perturbative dynamics:
Transverse Momentum PDFs

Transverse momentum totally
from hard subprocesses

q_T

Pion DY

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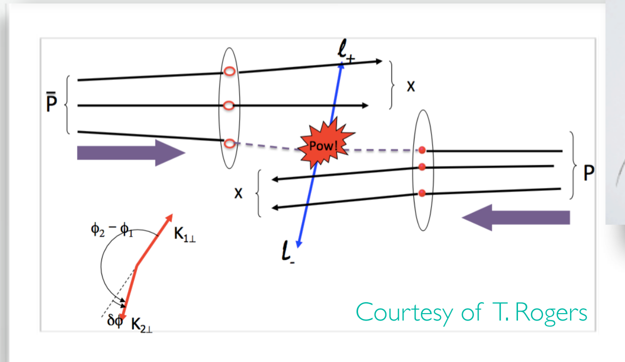

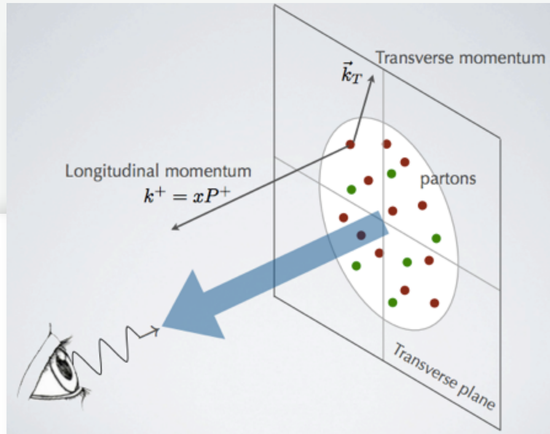

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FULL REGION

$$\frac{d\sigma}{dQ^2\,dy\,dQ_T^2} = \frac{4\pi^2\alpha^2}{9Q^2 s}\int \frac{d^2b}{2\pi^2} e^{i\vec{Q}_T\cdot\vec{b}} \sum_{a,b}\int_{x_\pi}^1 \frac{d\xi_\pi}{\xi_\pi}\int_{x_P}^1 \frac{d\xi_P}{\xi_P} f_{a/\pi}(\xi_\pi,\mu_b) f_{b/P}(\xi_P,\mu_b)$$

$$\times\ \exp\left(-C_F\,\frac{\alpha_s(q)}{2\,\pi}\int_{b_0^2/b^2}^{Q^2}\frac{dq^2}{q^2}\left[2\ln\frac{Q^2}{\mu^2}-3\right]+\text{H.O}\right)$$

$$\times\sum_j e_j^2\, C_{ja}(x_\pi/\xi_\pi, b; 2e^{-\gamma};\mu_b)\, C_{jb}(x_P/\xi_P, b; 2e^{-\gamma};\mu_b)$$

$$\times e^{S_{\rm NP}^{\pi}(b)}\ e^{S_{\rm NP}^{P}(b)}$$

Taming b~1/Λ:

- **b-prescription**

$$\mu_b = 2e^{-\gamma}/b^\star$$
$$b^\star = b/\sqrt{1+b^2/b_{\rm max}^2}$$

NLL

Pion DY

[Collins, Soper & Sterman, Nucl.Phys.B250]

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Ideally, we'd use

- **full TMD for both hadrons**
- **either from pheno. or similar models**

But,

- **no pheno proton TMD available** (when we started this…)
- **no model similar to NJL for the proton**

NLL

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[Collins, Soper & Sterman, Nucl.Phys.B250]

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NLL

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[Collins, Soper & Sterman, Nucl.Phys.B250]

STRATEGY

- use a phenomenologically estimated $f_{b/P}(\xi_P;\mu_b) \times e^{S^P_{\rm NP}(b)}$
    - PDF from CTEQ6M
    - NP + b-prescription from [Konychev & Nadolsky, Phys. Lett. B 633, 710 (2006)]
- use the pion TMD from the NJL model $f_{a/\pi}(\xi_\pi, \vec{b}; \zeta_\pi, \mu_b)$
    - [Noguera, S. Scopetta, JHEP 1511, 102 (2015)]
    - redefine the hadronic scale of PDF from DY integrated data
    - interpret the k_T-dependence of the model onto the (unintegrated) DY data

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from now on: $e^{S^P_{\rm NP}(b)} \to S^P_{\rm NP}(b)$

THE NON-PERTURBATIVE PART

$$\frac{d\sigma}{dQ^2\,dy\,dQ_T^2} \sim \frac{4\pi^2\alpha^2}{9Q^2 s}\left\{(2\pi)^{-2}\int d^2b\, e^{iQ_T\cdot b}\sum_j e_j^2 \tilde{W}_j(b_*;Q,x_A,x_B)_{\text{pert}}\right.$$

$$\times \exp\left[-\ln(Q^2/Q_0^2)g_1(b) - g_{j/A}(x_A,b) - g_{j/B}(x_B,b)\right]$$

One parameterization of the non-perturbative contribution

Here: $S_{NP}^{\pi W}(b) = S_{NP}^{\pi}(b)\sqrt{S_{NP}^{pp}(b)}$

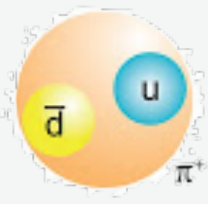
purely comes from
the dynamics of the model

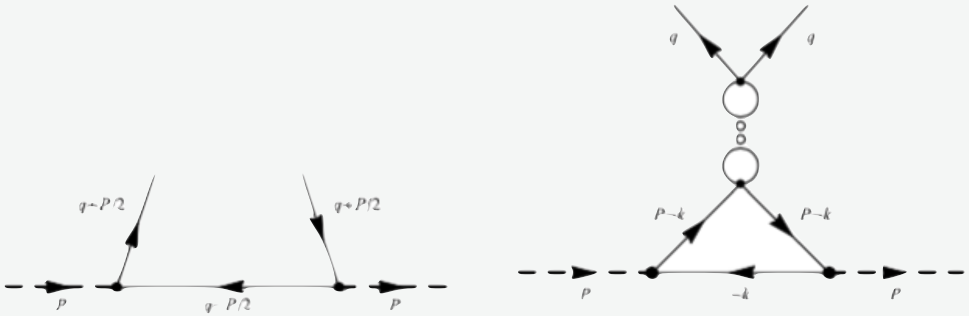
- $S_{NP}^{pp}(b)$
  $= \exp\{-[a_1 + a_2\ln(M/(3.2\,\text{GeV})) + a_3\ln(100x_1x_2)]b^2\}.$
- $b_\star(b, b_{max}) = \frac{b}{\sqrt{1+\left(\frac{b}{b_{max}}\right)^2}}$ with $b_{max} = 1.5\,\text{GeV}^{-1}$

FULL TRANSVERSE MOMENTUM DEPENDENCE FOR THE PION

$$f(x;\mu) \times \exp(g_{j/P}(b)) = f(x,b;\mu)$$

TMD PDFs





$$f_{1,\pi}\left(x,k_T^2\right) = \frac{3}{4\,\pi^3}\, g_{\pi qq}^2\, \theta\left(x\right)\, \theta\left(1-x\right) \sum_{i=0}^{2} c_i \times \left\{ \frac{1}{k_T^2 + M_i^2 - m_\pi^2\, x\left(1-x\right)} + \frac{m_\pi^2\, x\left(1-x\right)}{\left[k_T^2 + M_i^2 - m_\pi^2\, x\left(1-x\right)\right]^2} \right\}$$

[Noguera & Scopetta, JHEP11, 102]

THE PION IN A CHIRAL MODEL

$$f_\pi(x,b;\mu) \xrightarrow{chiral\ lim} f'_\pi(x;\mu) f''_\pi(b)$$

Our interpretation: $\exp(g_{j/\pi}(b)) = f''_\pi(b)$

→ no "$g_1(b)$" is this model picture

$$\begin{aligned} f''_\pi(b) &= \frac{3}{2\pi^2}\left(\frac{m}{f_\pi}\right)^2 \sum_{i=0,2} \int dk_T\, k_T\, J_0(bk_T) \frac{a_i}{k_T^2 + m_i^2} \\ &= \frac{3}{2\pi^2}\left(\frac{m}{f_\pi}\right)^2 \sum_{i=0,2} a_i K_0(m_i\, b) \end{aligned}$$

[Noguera & Scopetta, JHEP11, 102]

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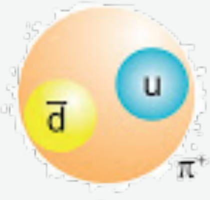
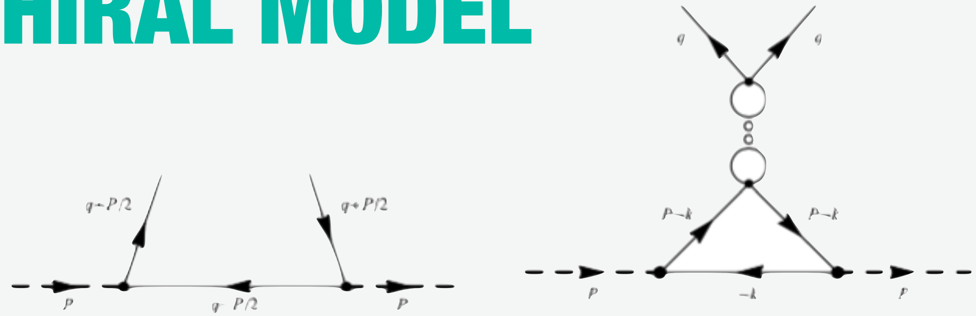
$$= \frac{3}{2\pi^2}\left(\frac{m}{f_\pi}\right)^2 \sum_{i=0,2} a_i K_0(m_i\, b)$$

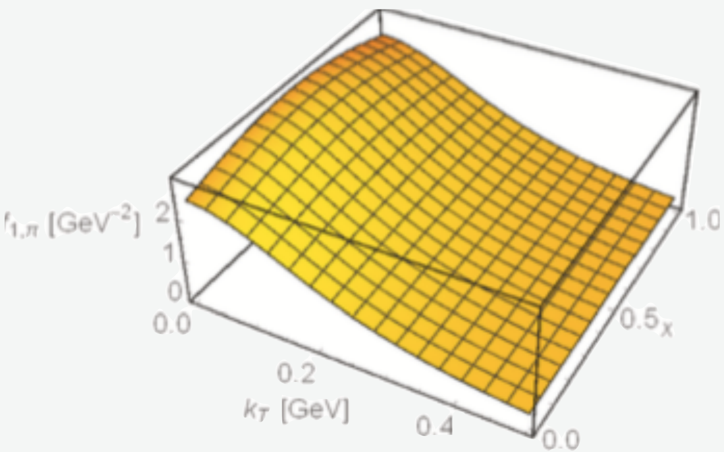
We assumed that factorization of the transverse momentum occurs at Q_0 only.

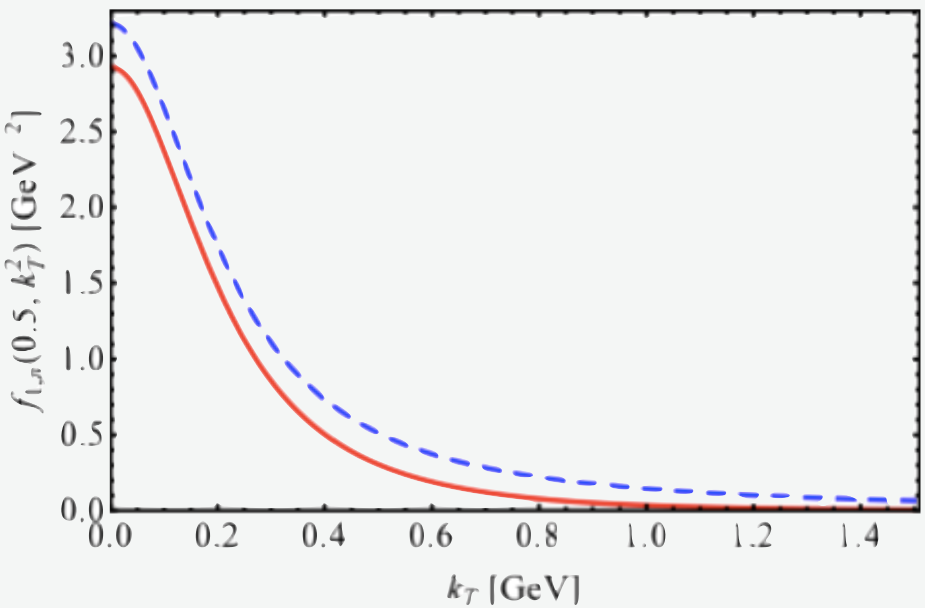
[Noguera & Scopetta, JHEP11, 102]

THE PION IN A CHIRAL MODEL





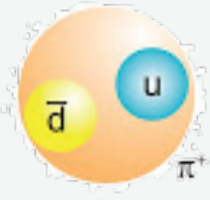


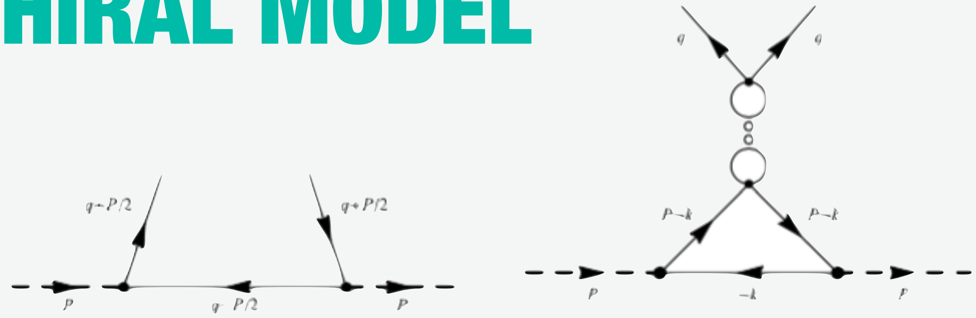


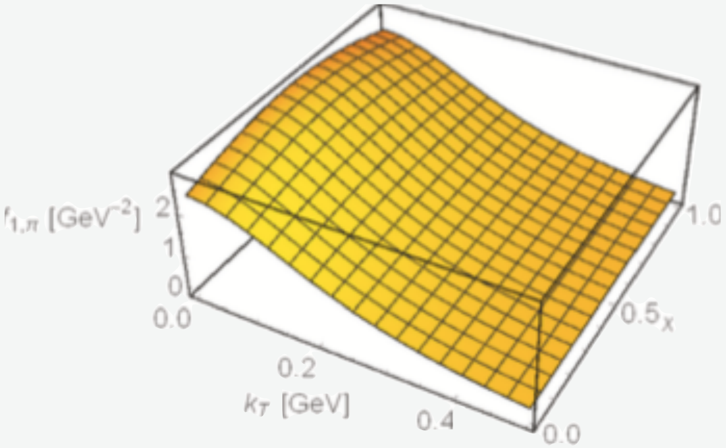
Pion DY

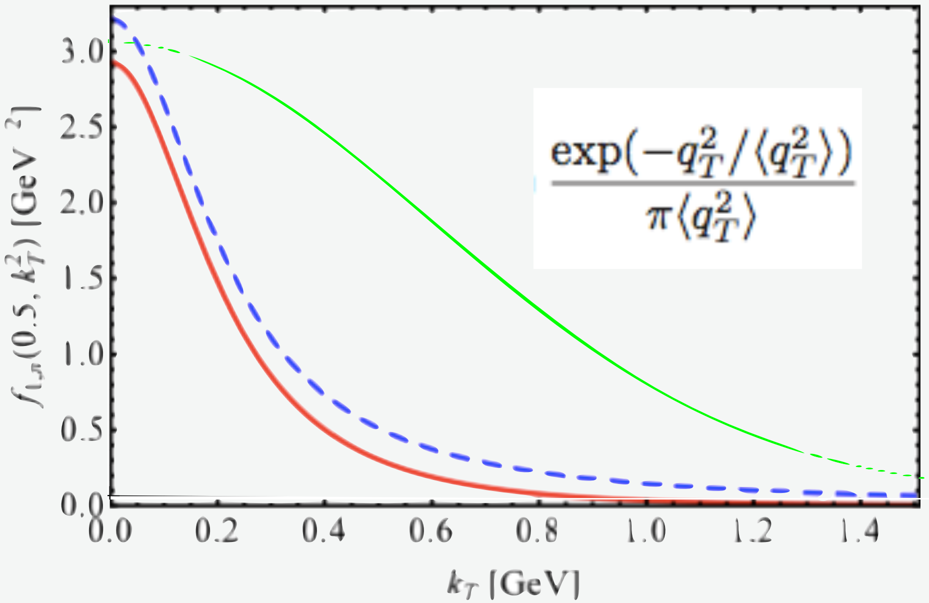
[Noguera & Scopetta, JHEP11, 102]

THE PION IN A CHIRAL MODEL





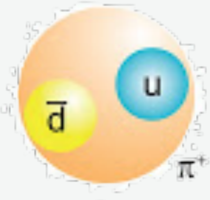


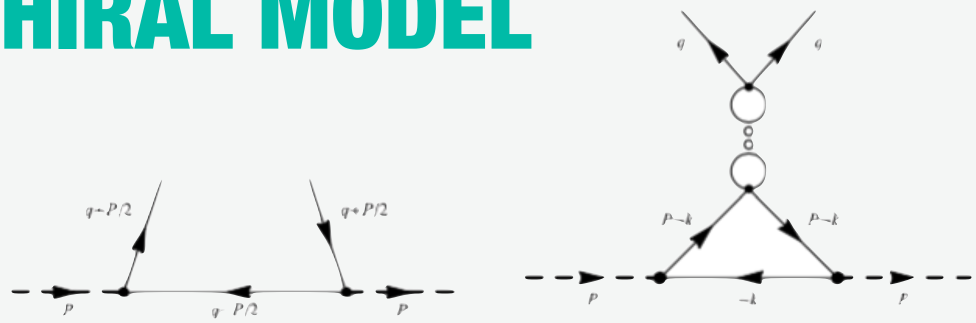


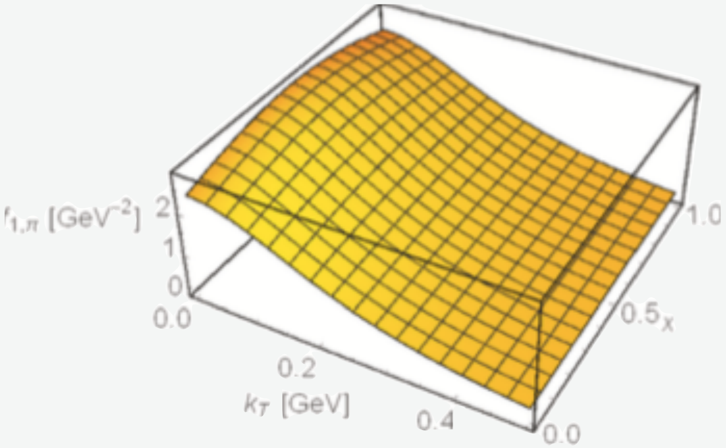
Pion DY

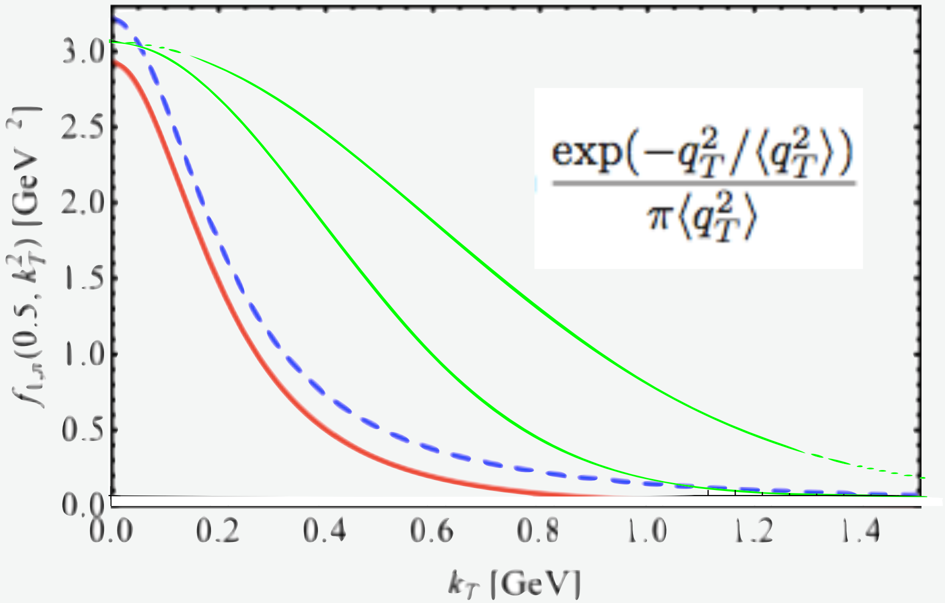
[Noguera & Scopetta, JHEP11, 102]

THE PION IN A CHIRAL MODEL





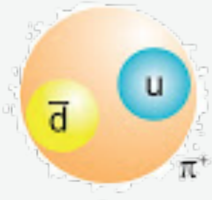


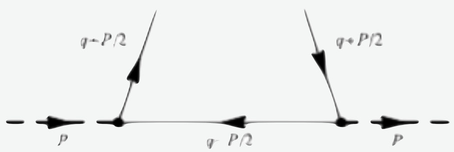


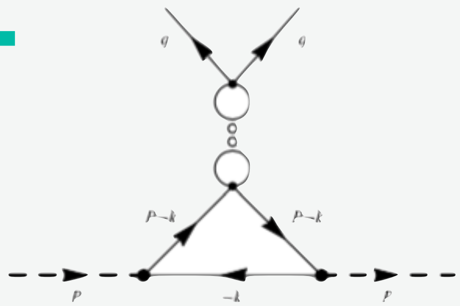
Pion DY

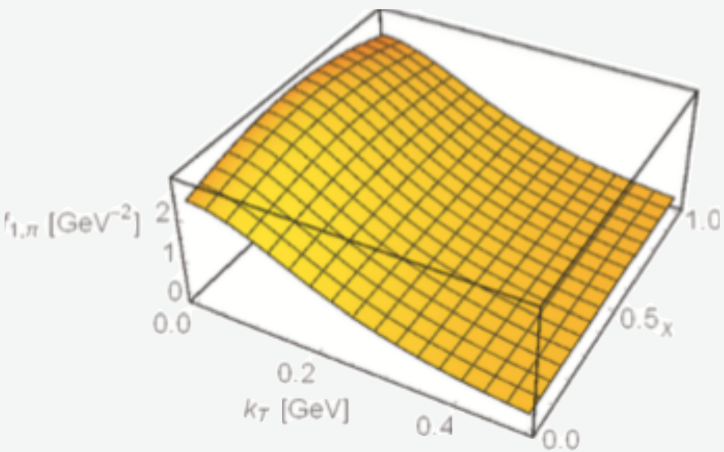
[Noguera & Scopetta, JHEP11, 102]

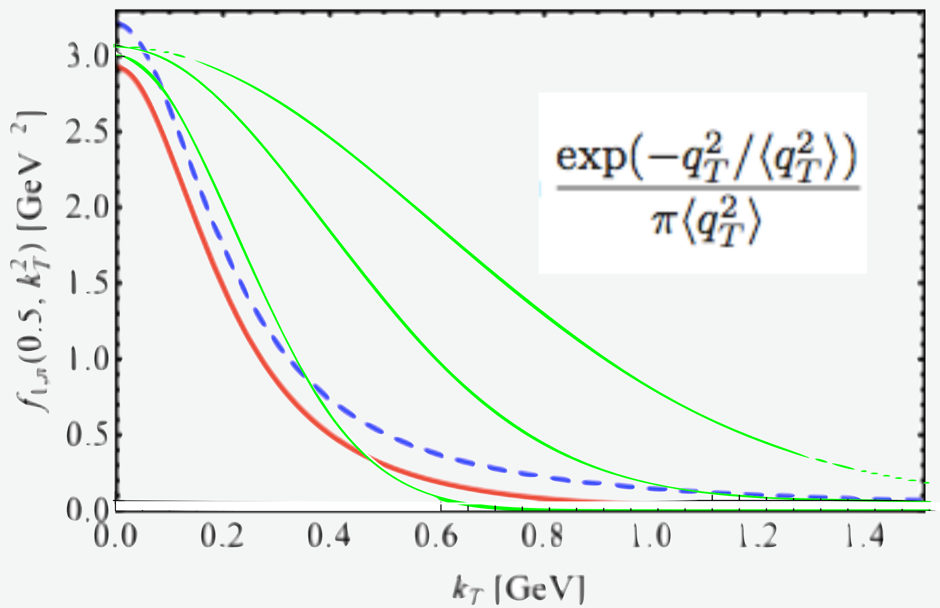
THE PION IN A CHIRAL MODEL







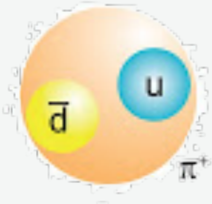


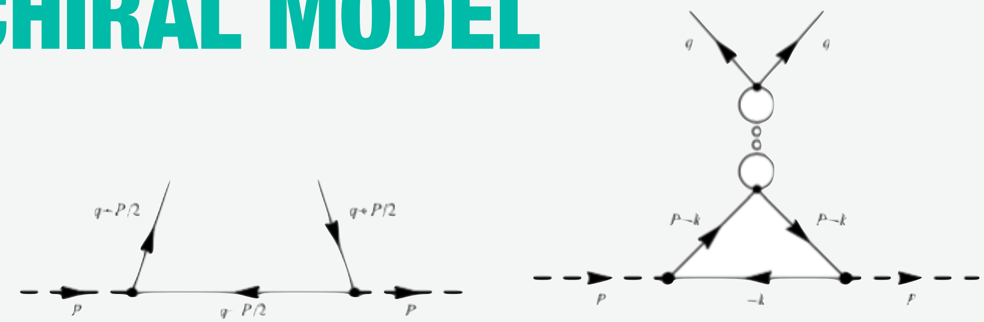


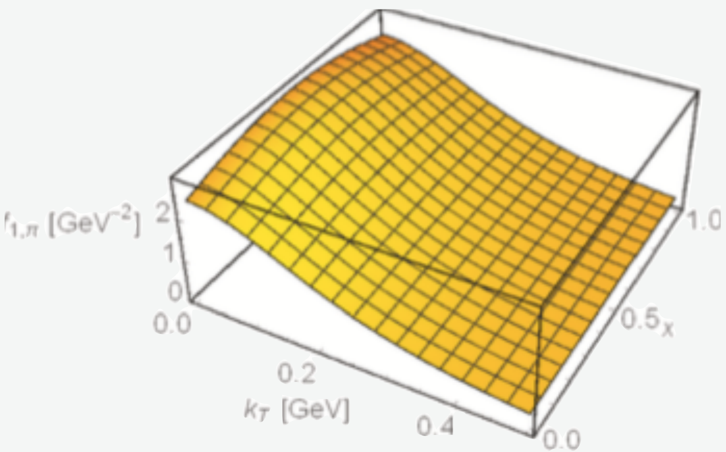
Pion DY

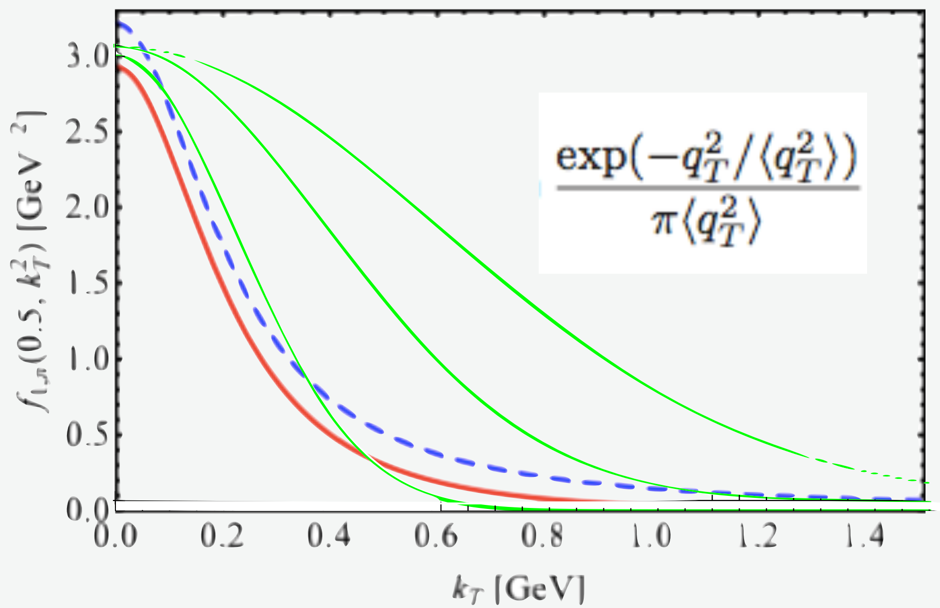
[Noguera & Scopetta, JHEP11, 102]

THE PION IN A CHIRAL MODEL





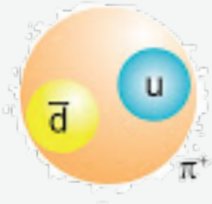


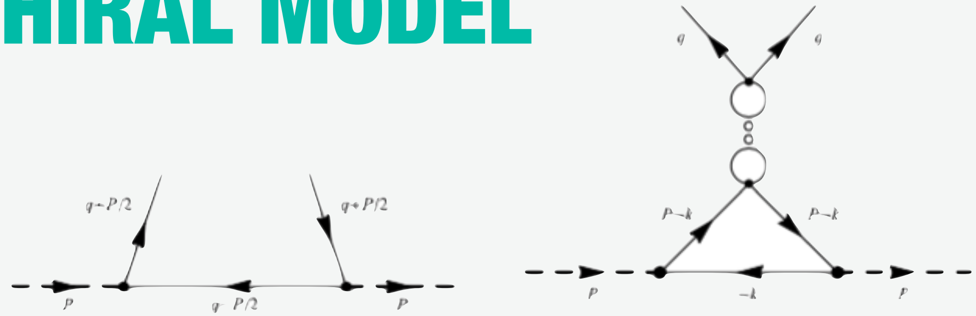


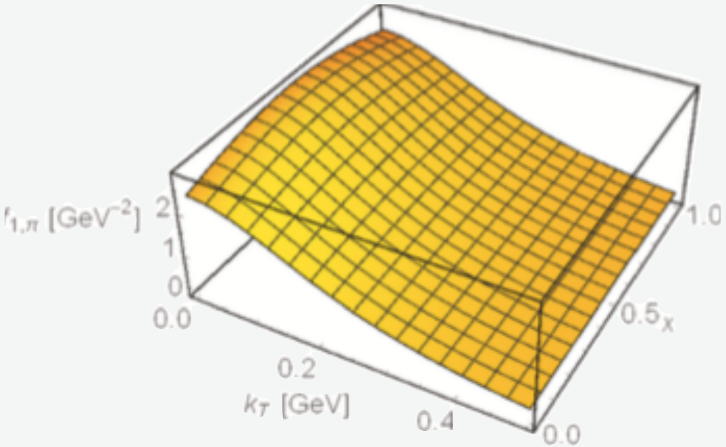
Pion dynamics→ differs from a gaussian

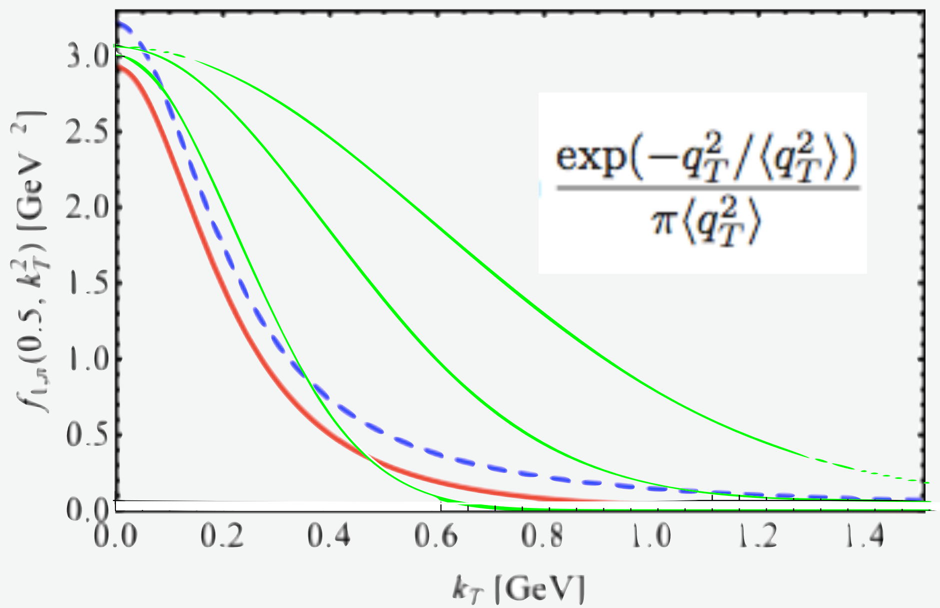
[Noguera & Scopetta, JHEP11, 102]

THE PION IN A CHIRAL MODEL







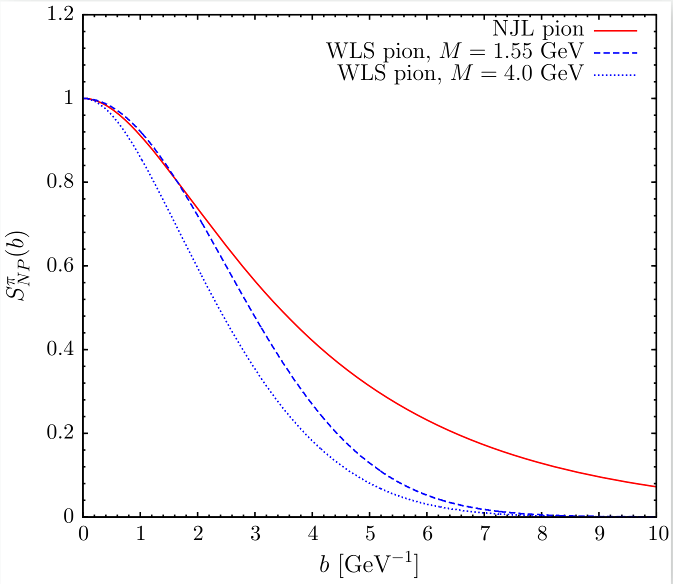


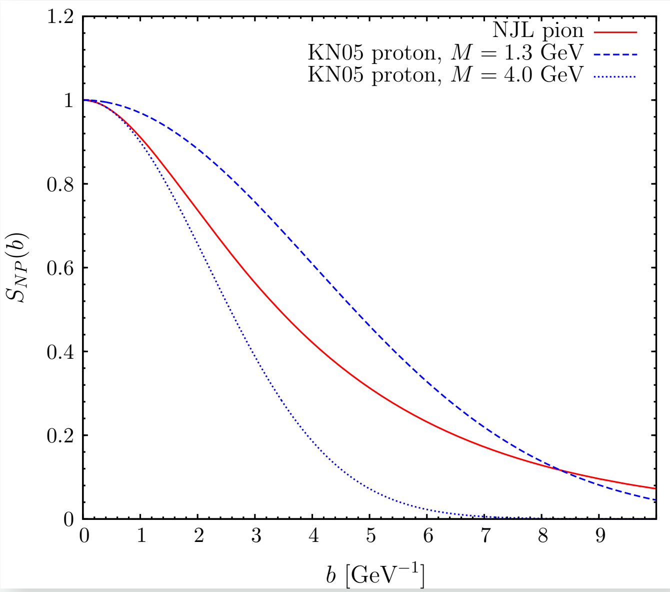
Pion dynamics→ differs from a gaussian

Transverse profile→ no dpdce on x or M

[Noguera & Scopetta, JHEP11, 102]

PION TRANSVERSE PROFILE





$$S^{f_1^{q/\pi}}_{\mathrm{NP}} = g_1^{\pi} b^2 + g_2^{\pi} \ln\frac{b}{b_*} \ln\frac{Q}{Q_0}$$

Fit of pion Sudakovs'
[Wang & et al, JHEP08-137]

$$S^{pp}_{NP}(b) \tag{12}$$
$$= \exp\{-[a_1 + a_2 \ln(M/(3.2\,\mathrm{GeV})) + a_3 \ln(100 x_1 x_2)] b^2\}.$$

Fit of proton's
[Konychev, P.M. Nadolsky, Phys. Lett. B 633, 710]

DRELL-YAN WITH PION DYNAMICS

Next-to-Leading Log

$$\sigma_{DY\pi N} \equiv \frac{d\sigma}{d\tau\, dy\, dp_T^2} = \sum_q \frac{\sigma^0_{q\bar{q}}}{2} \int_0^\infty db\, b\, J_0(bp_T)\; e^{S(b,b_{max},Q,C_1)}\; e^{S^\pi_{NP}(b)}\; e^{S^N_{NP}(b)} \,.$$

$$\cdot \left[\left(f^\pi_{q_a}(x_a,\mu_b) \otimes C_{aa'} \right) \left(F^N_{\bar{q}_b}(x_b,\mu_b) \otimes C_{bb'} \right) + q \leftrightarrow \bar{q} \right] ,$$

Wilson coeff. at order α_s
CTEQ6M PDFs evolved at NLO

Proton b_{max}=0.86 GeV^{-1}
Pion b_{max}=educated guess/adjusted to data
= b_0/Q_0=2.44 GeV^{-1}
☑ stability upon variation of regulator

Pion DY

[Ceccopieri & Trentadue, Phys.Lett.B741]
[Ceccopiero, A.C, Noguera & Scopetta, EPJC78, 8, 644]

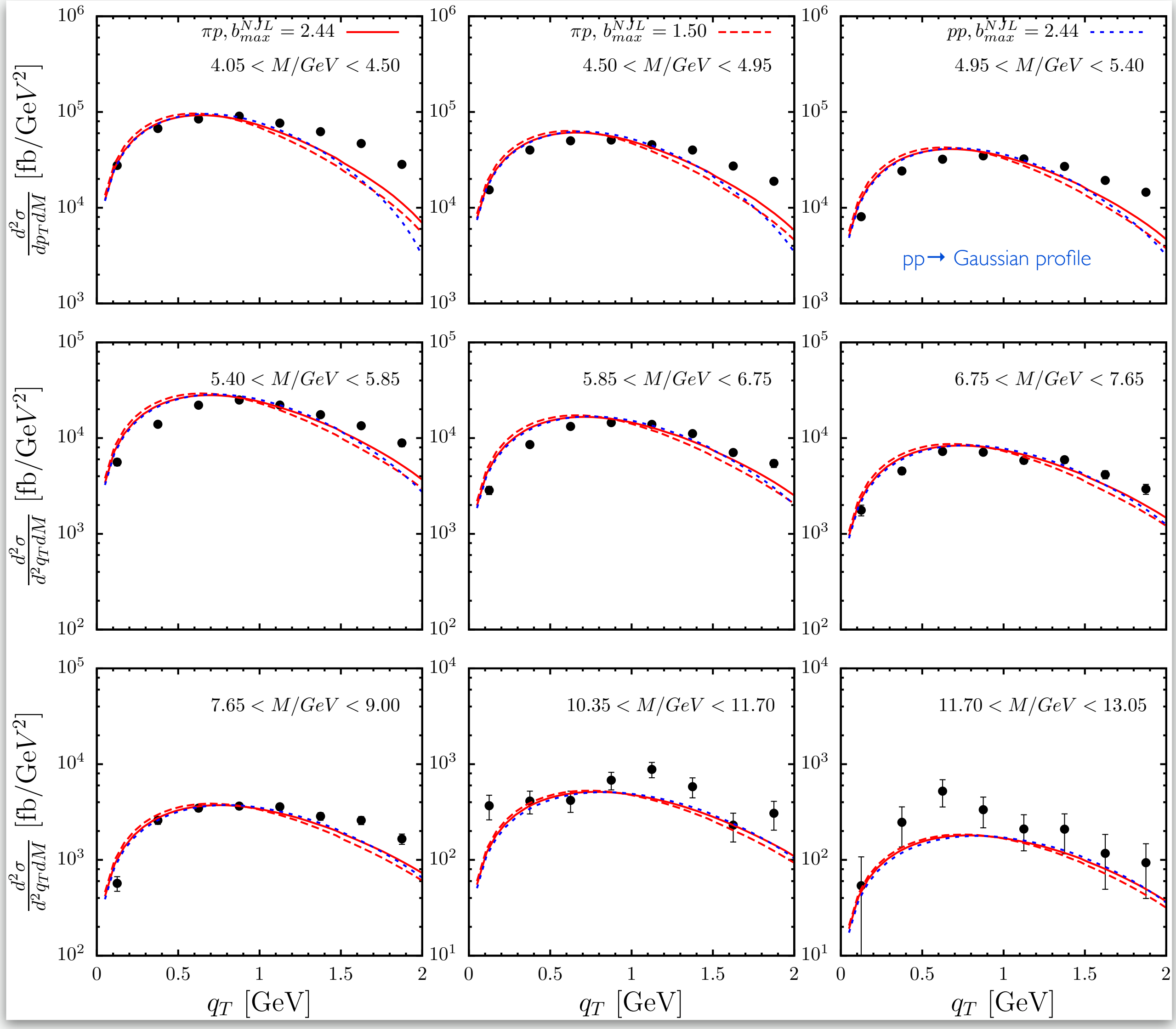
$\pi^- W$ DRELL-YAN

Cross section in Q-bins

- ☑ overall magnitude
- ☑ small qT
- ☑ stability upon b-prescription

- ☐ higher qT
- ☐ Gaussian profile ~indistinguishable

No free parameters
Only Q_0 is fixed beforehand



with KN param.

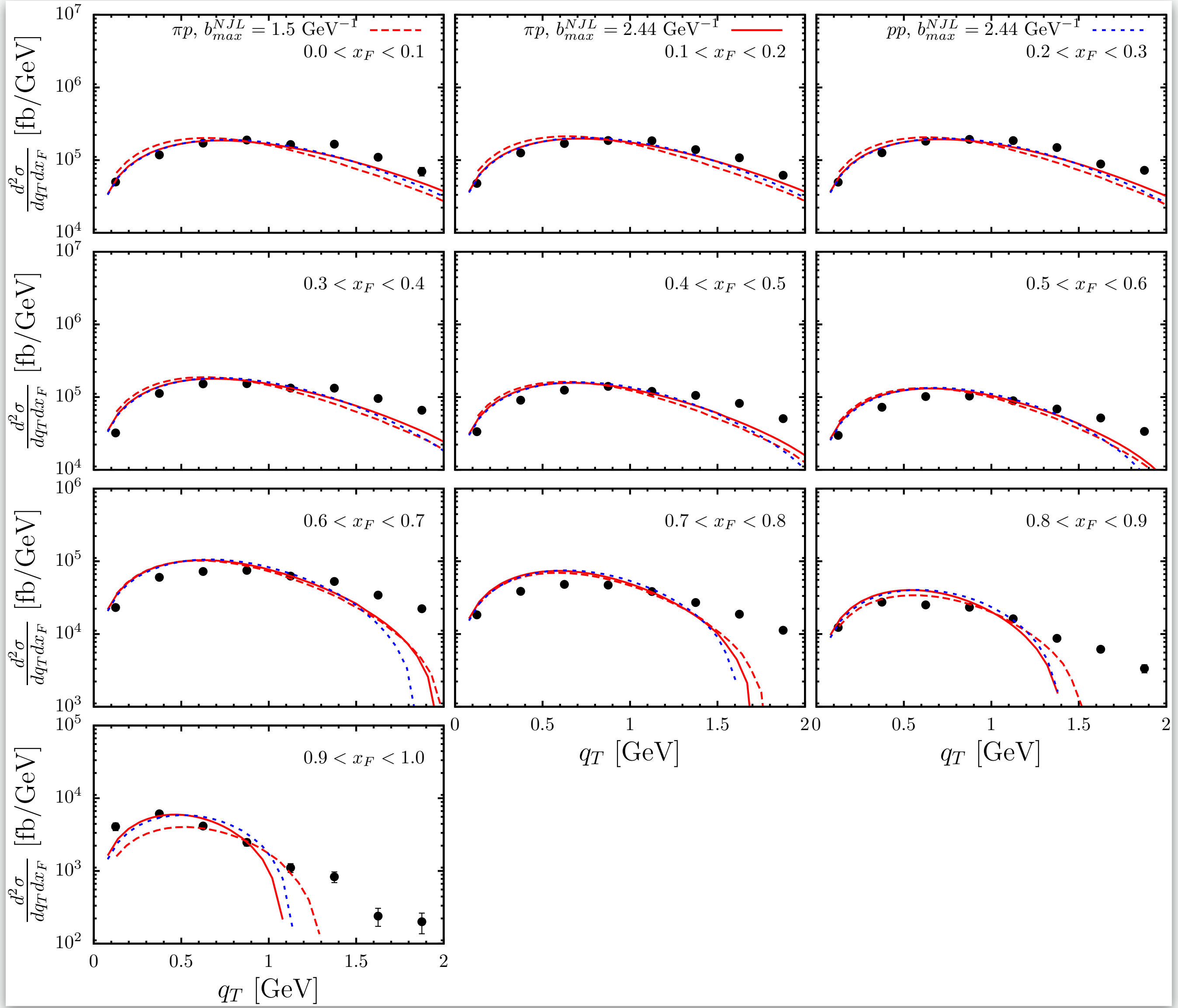
Pion DY

$\pi^- W$ DRELL-YAN

Cross section in x-bins

- ☑ overall magnitude
- ☑ small qT
- ☑ stability upon b-prescription

- ☐ higher qT
- ☐ Gaussian profile ~indistinguishable

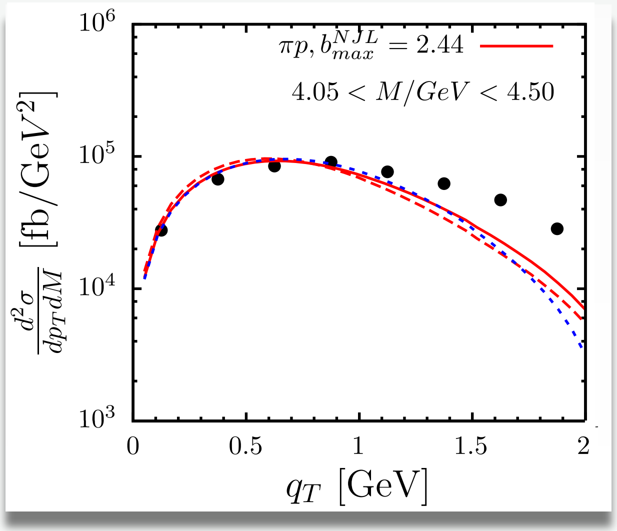


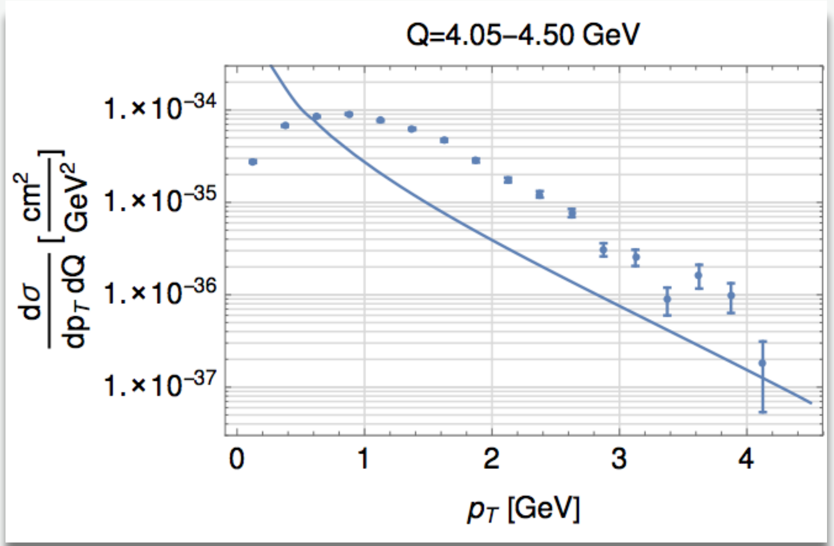
No free parameters
Only Q_0 is fixed beforehand

with KN param.

W WITHOUT `FO´

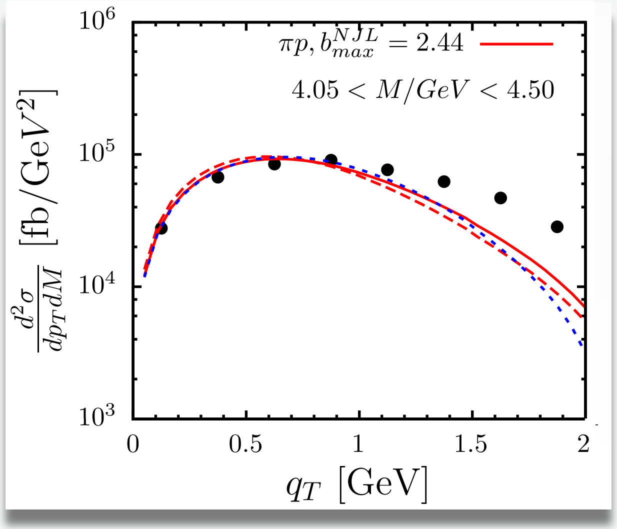
COMPLEMENTING FULVIO'S CONSIDERATIONS



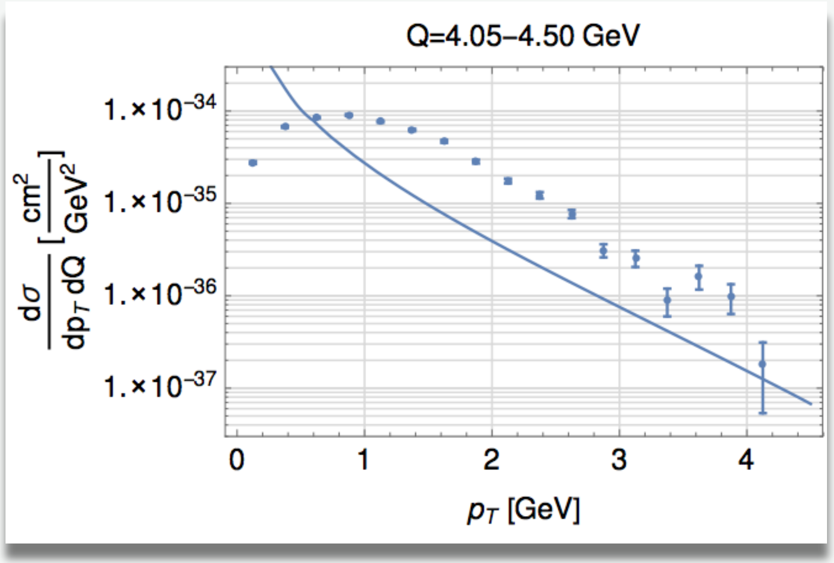


W WITHOUT `FO´

COMPLEMENTING FULVIO'S CONSIDERATIONS



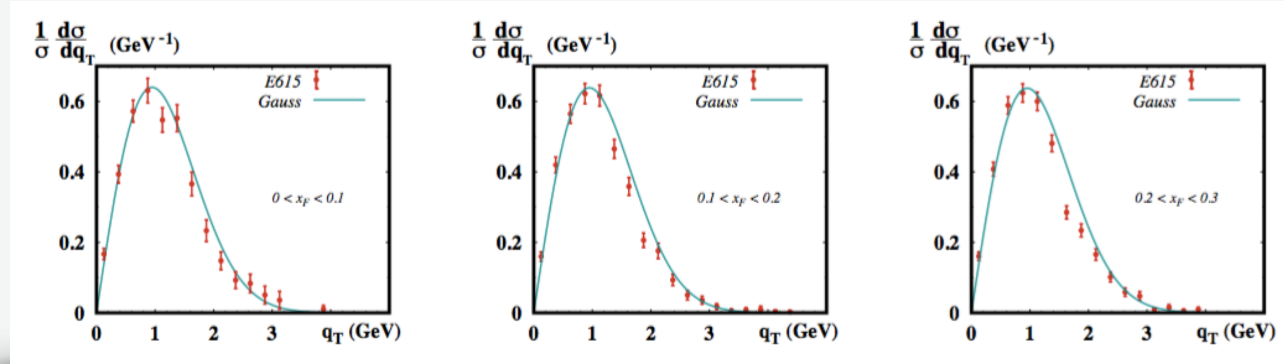
Pieces/hints/room to accomodate info in the low-qT regime…



…but we don't understand the pQCD regime properly.

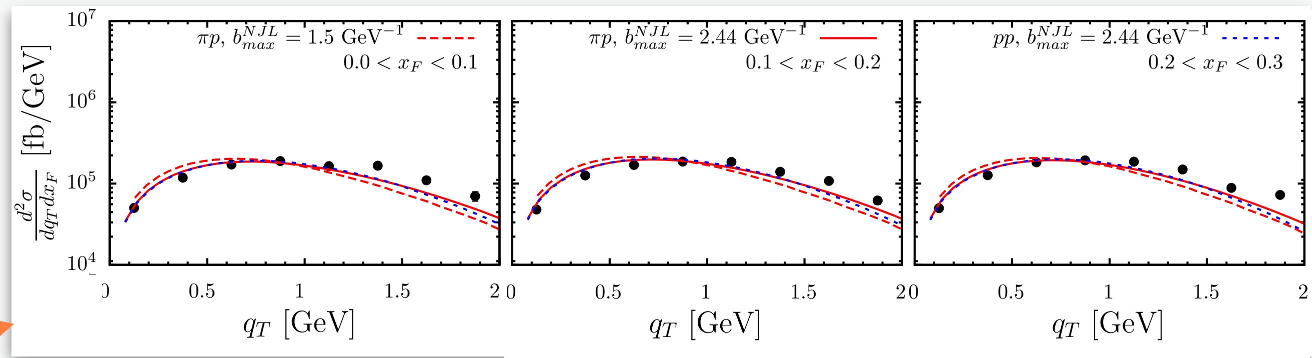
Possible piece of solution from Nobuo's talk.

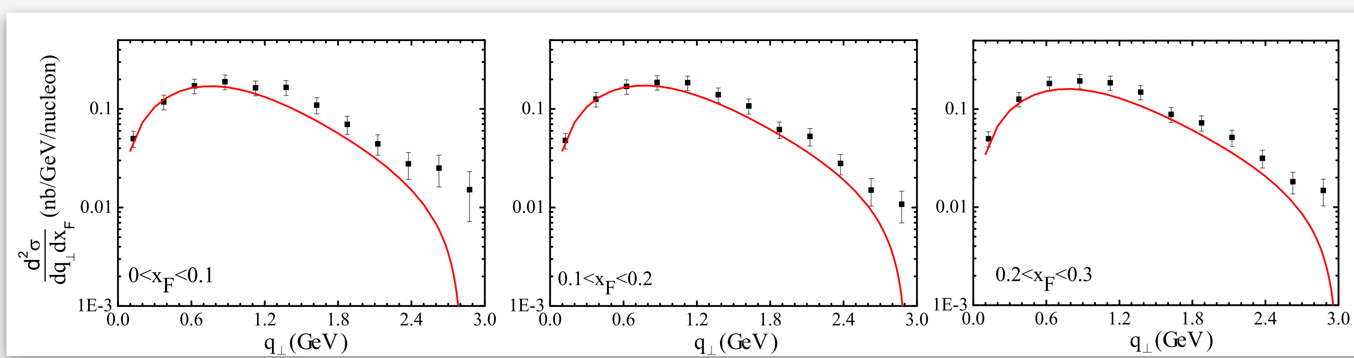
$\pi^- W$ DRELL-YAN



Only gaussian

[Pasquini & et al, Phys.Rev.D90]



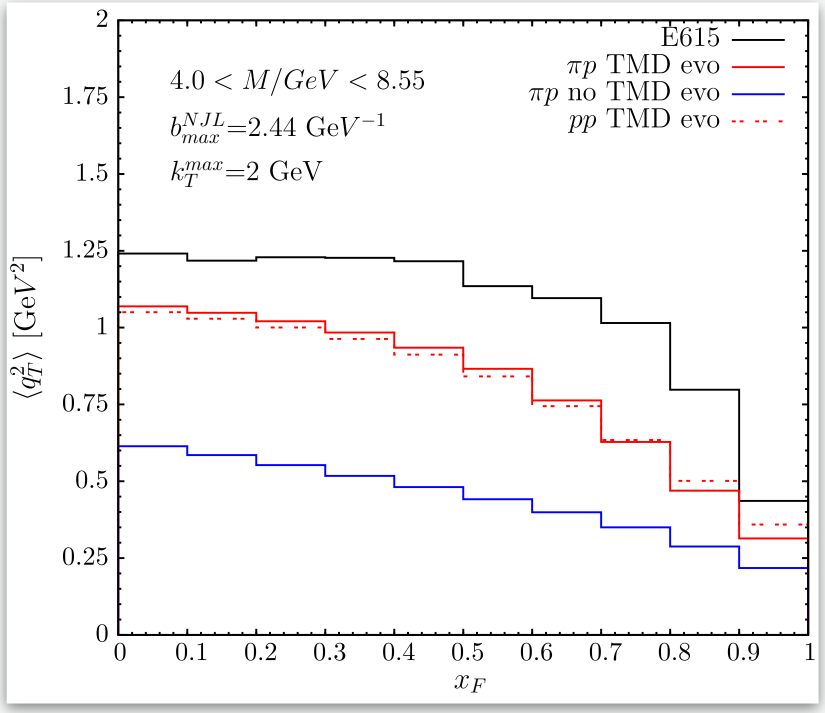


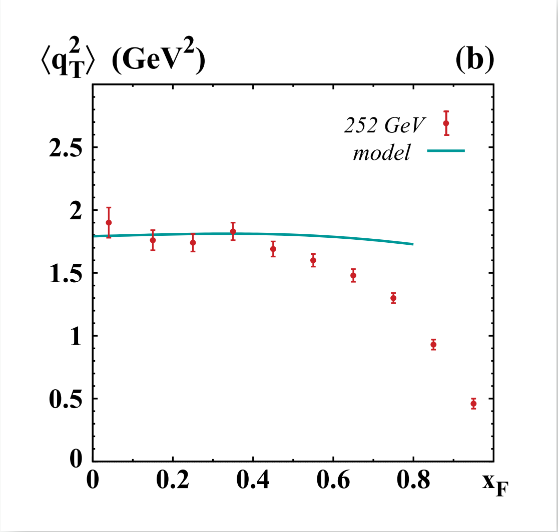
Fit

[Wang & et al, JHEP08-137]

Pion DY

$\pi^- W$ DRELL-YAN

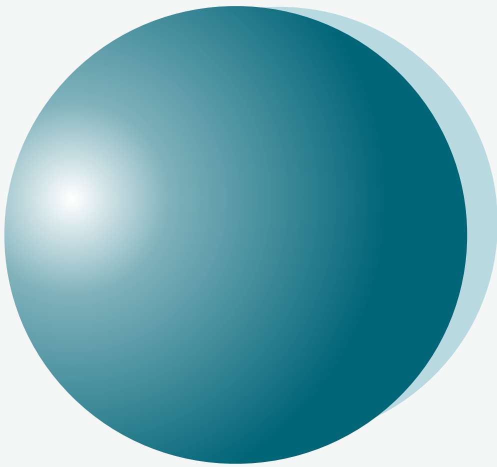


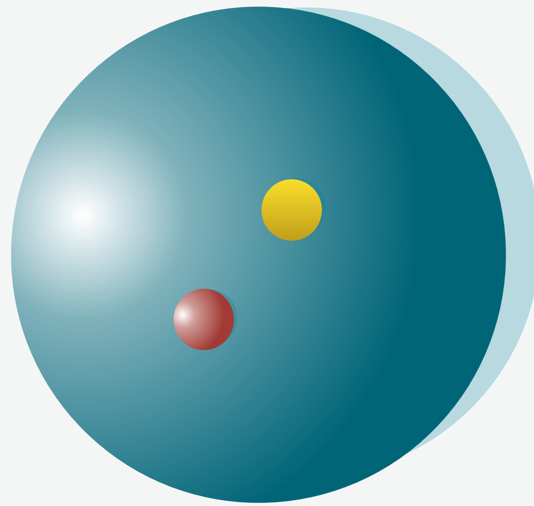


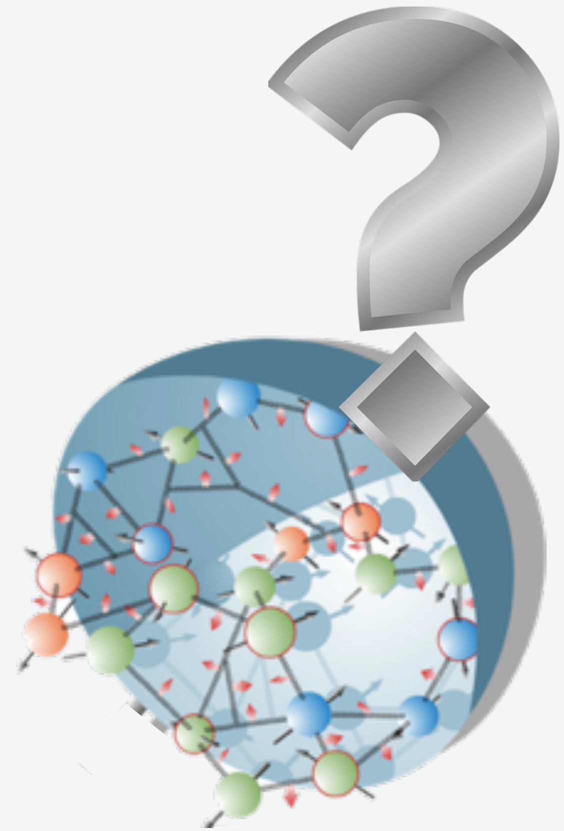
[Pasquini & et al, Phys.Rev.D90]

CSS evolution affects the transverse mmt distribution.

PION STRUCTURE FROM DY?



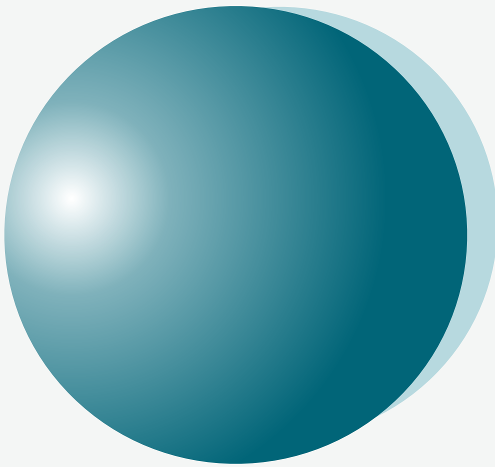


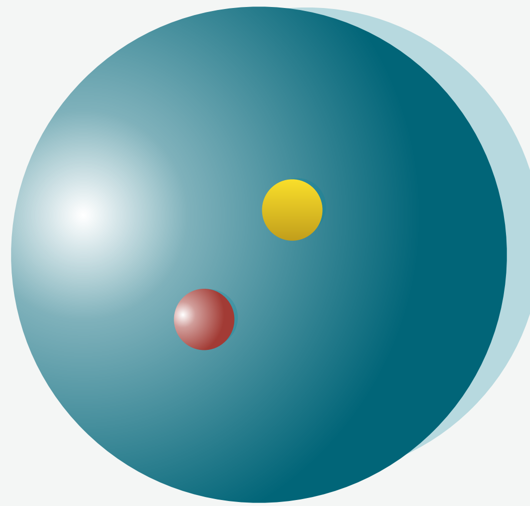


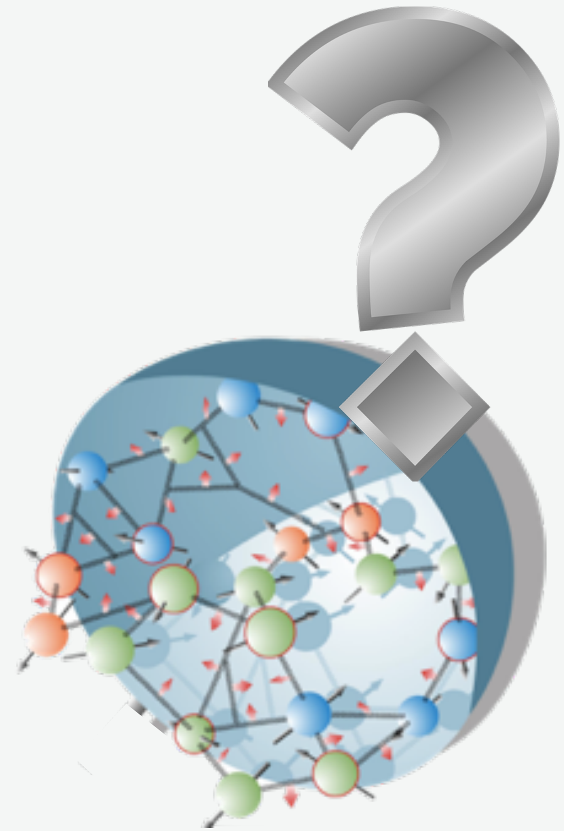
Degrees of freedom change governed
by the chiral symmetry.

Pion DY

CAN THE PION HELP THE PROTON?







- Fixing NP params. at low qT
- Less theoretical uncertainties from the pion
- Less “nice and symmetric” expression

CONCLUSIONS

- Pion-proton collision to $\mu^+\mu^-$
- We have included pion nonperturbative dynamics in DY cross section
- Slight change in shape w.r.t. pure gaussians
- Need to understand another function: $g_K(b)$

Importance of nonperturbative inserts in perturbative evolution!

Exciting physics ahead!

EIC PHYSICS

- Use knowledge on the pion to
  - lower proton uncertainties
  - disentangle possible symmetry effects
- Go to pion target SIDIS to test framework
  - relevant at JLab

- Relevant for COMPASS
- Use knowledge on pion to fix NP parameters
- Redefine/evaluate the hadronic scale from TMD pheno.