PION NUCLEUS DRELL–YAN PROCESS

AND

PARTON TRANSVERSE MOMENTUM IN THE PION

JLab Theory Seminar

9/5/18

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OUTLINE

- Drell-Yan in πN scattering
- Drell-Yan with transverse momentum
  - Pion dynamics
  - Effects on DY cross section
- Outlook

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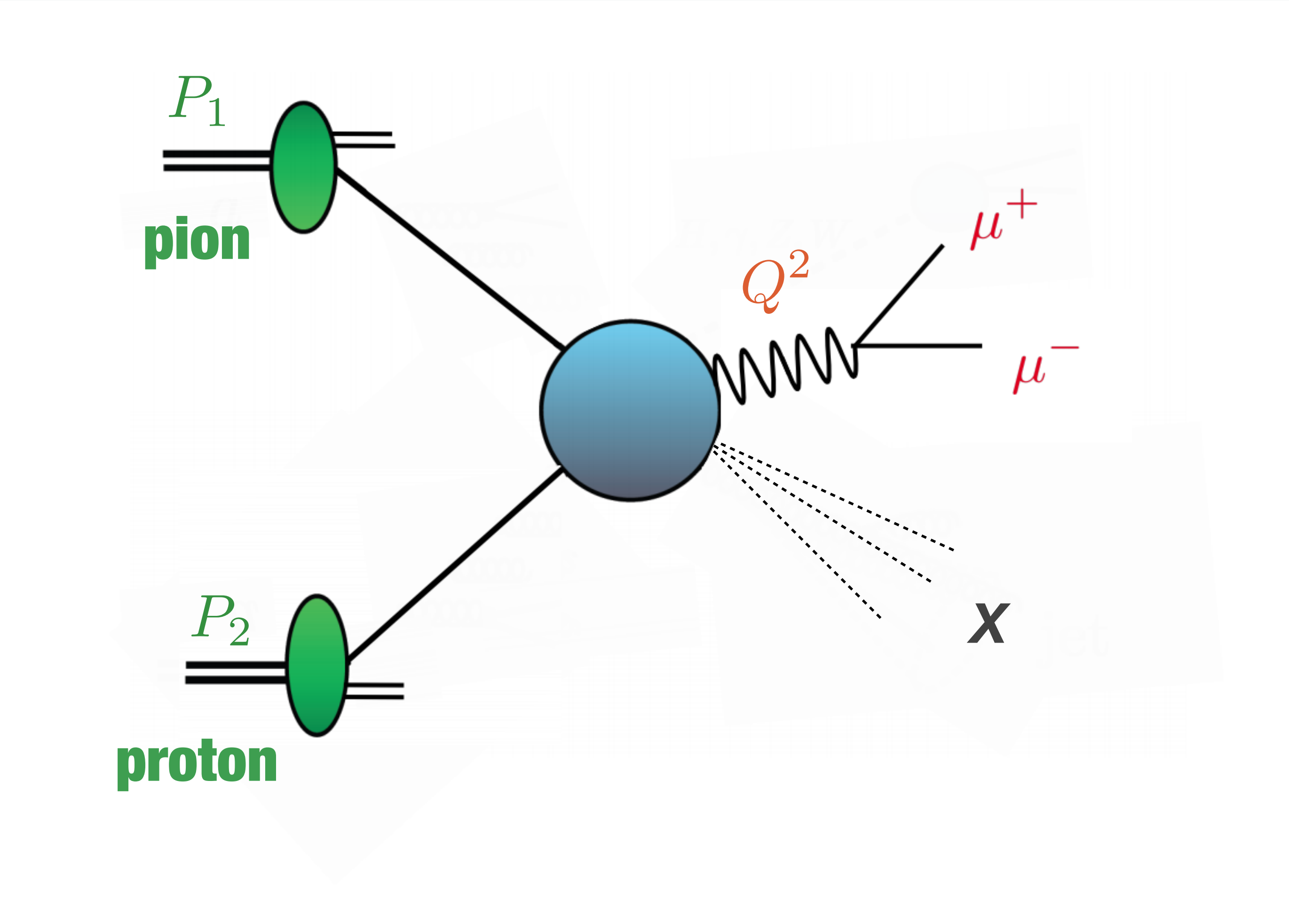
Based on
Eur.Phys.J. C78 (2018) no.8, 644
with F.A. Ceccopieri, S. Noguera & S. Scopetta

FOCUS ON THE PION



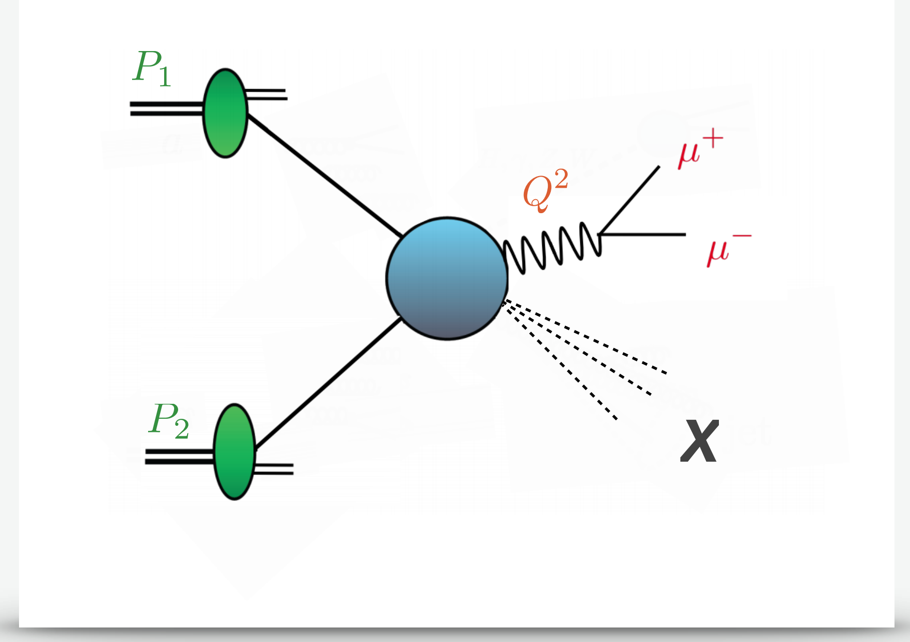
$$Q^2 = M^2$$
$$s = 2P_1 \cdot P_2$$

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

Pion DY

Pion-proton Drell-Yan differential cross-section

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



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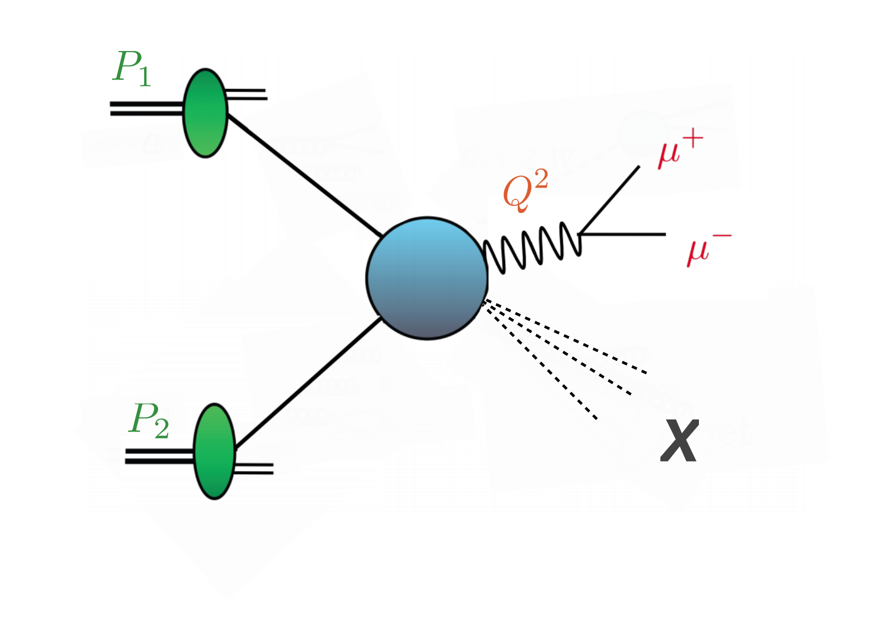
Pion PDF



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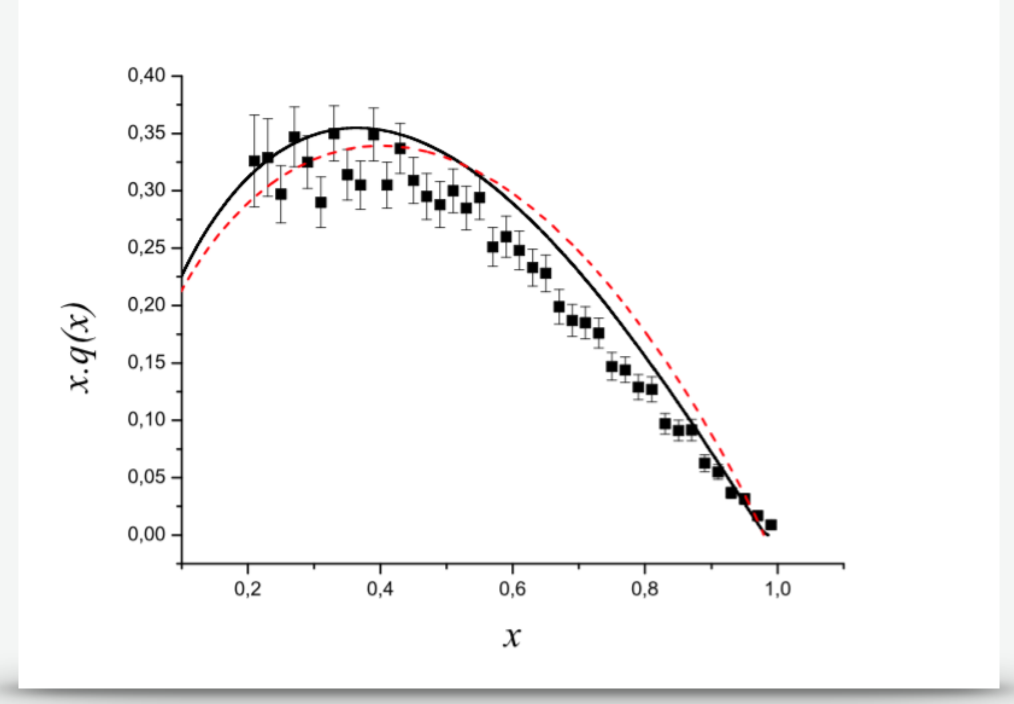
Pion DY

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)

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

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

Pion DY

THE PION IN NJL

Distribution Functions as Functions of x

Calculation in QCD not possible ⟶ Nonperturbative Objects

Approaching QCD by Models, Effective theories,... ⟶ not an exact calculation

Pion → Chiral Low-Energy Models

Why NJL?

- Quarks degrees of freedom
- Relation current ⇔ constituent quarks
- Pion as a Goldstone mode
- Pion as a Bound-State in the sense of Bethe-Salpeter
- Choice of a covariant regularization scheme

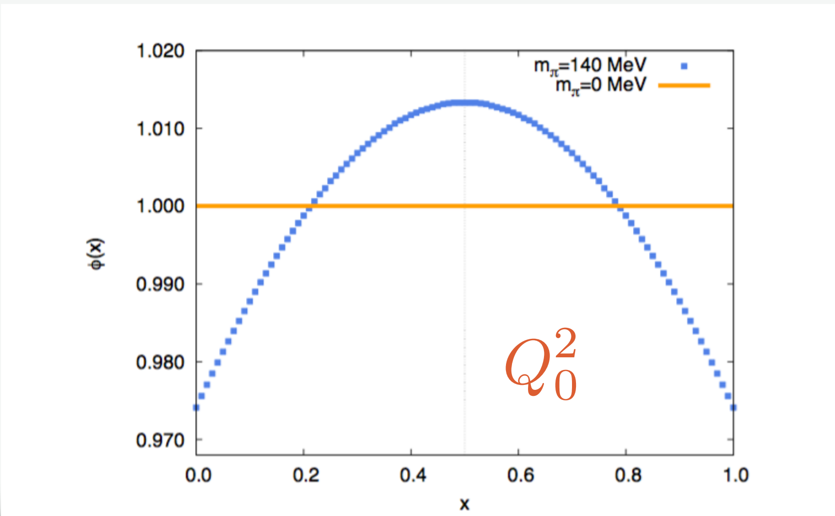
Long story of successful results and predictions

Why are we confident about the use of NJL?

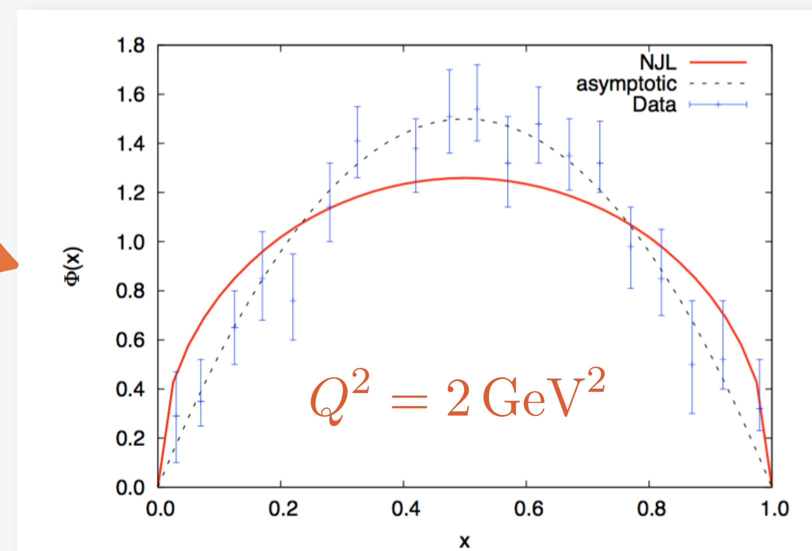
- Calculations of PDFs in NJL ⟶ OK
- Non perturbative QCD ⟶ Evolution of initial PDF
- Comparison with data ⟶ OK

[Noguera & Scopetta, JHEP11, 102]

THE PION IN NJL:
DISTRIBUTION AMPLITUDE



Mind the scale of y-axis!



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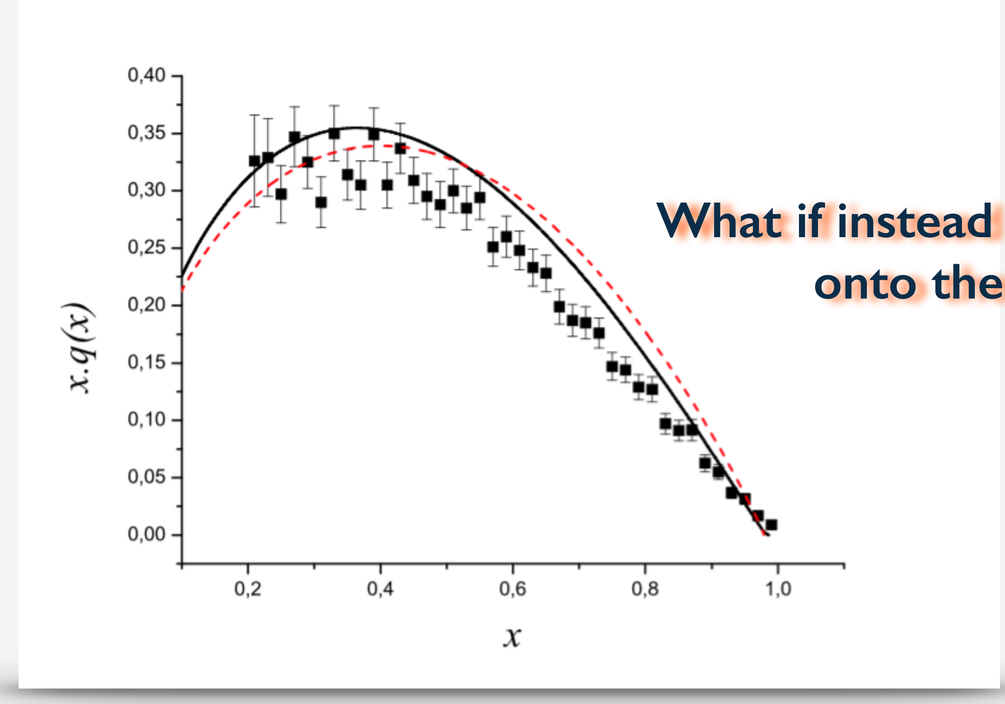

What if instead we map the pion PDF onto the DY X-section?

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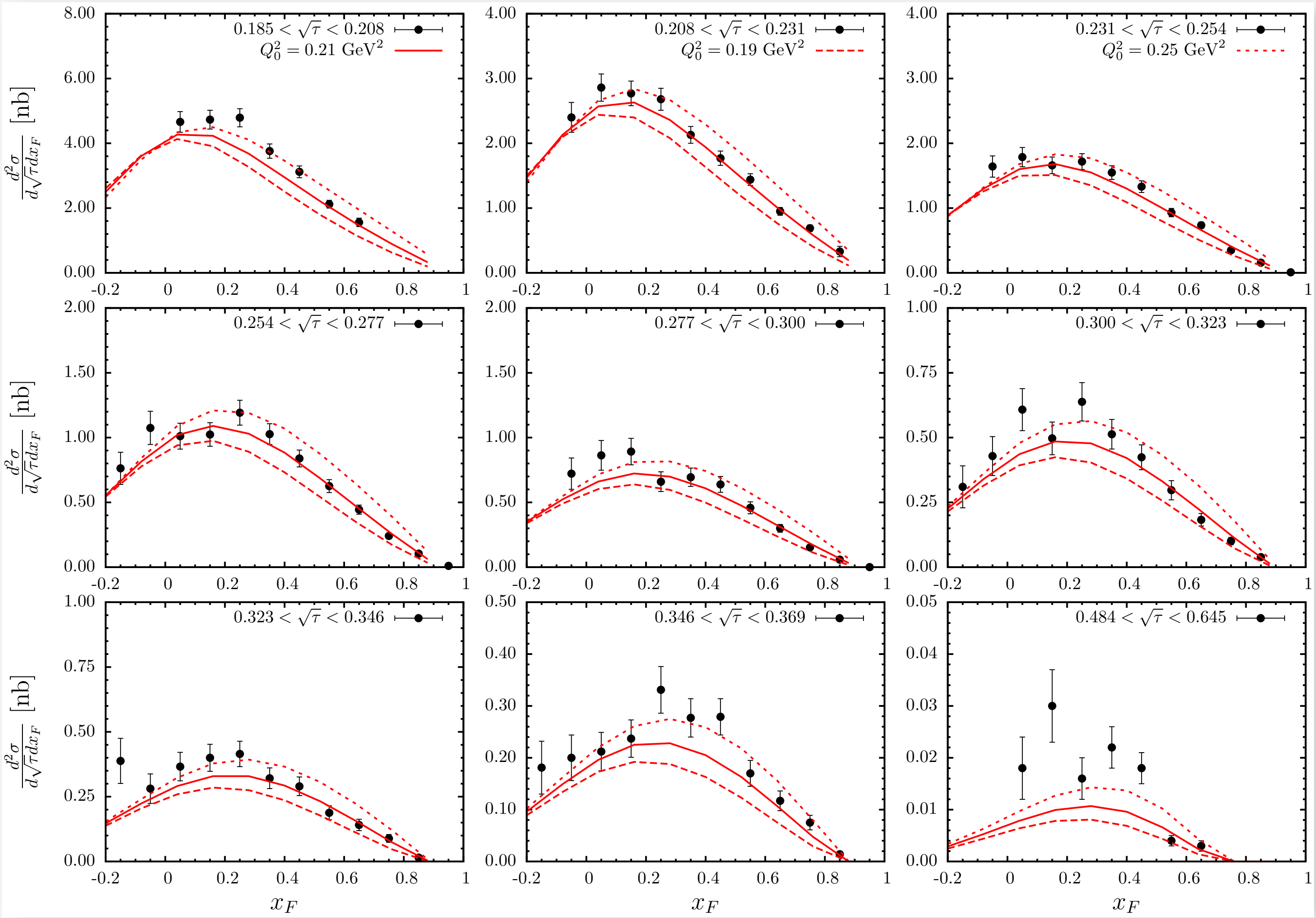
Pion DY

Determination of NJL's scale

Comparison of integrated X-section with theory at NLO:

- pion from NJL
- proton from CTEQ06M

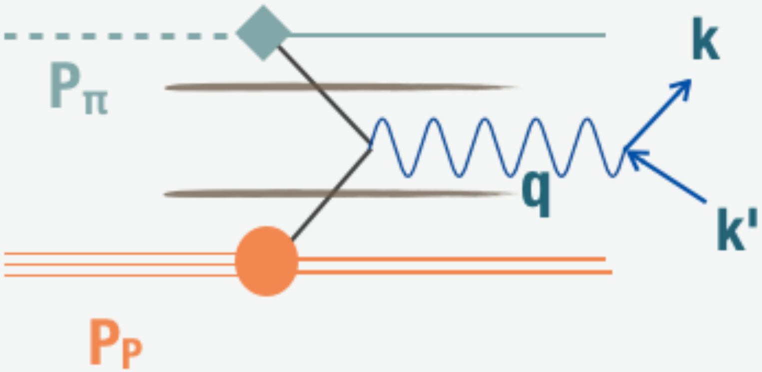


We find

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

with χ^2/dof=2

DRELL-YAN WITH TRANSVERSE MOMENTUM



With measured Q_T of order Q

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

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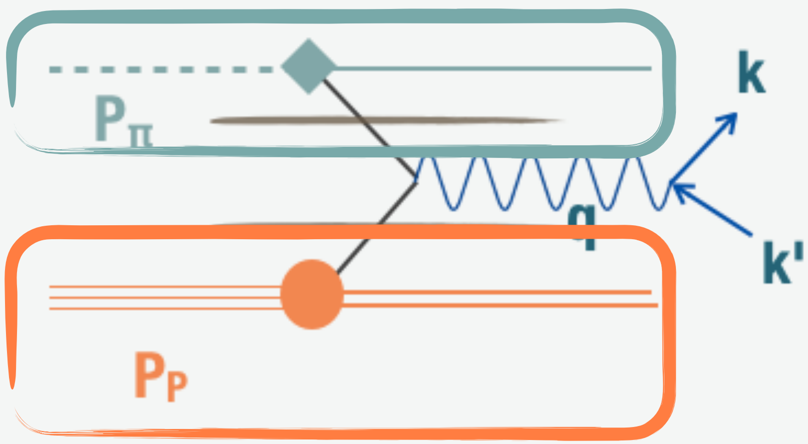

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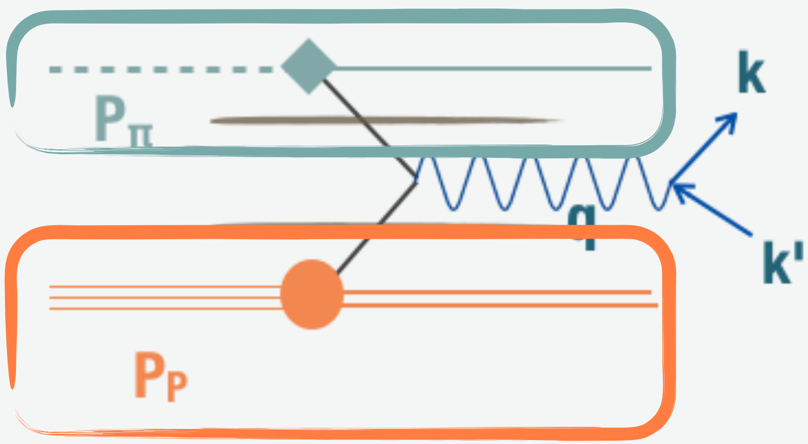

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$$q^2 = (k + k')^2$$

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

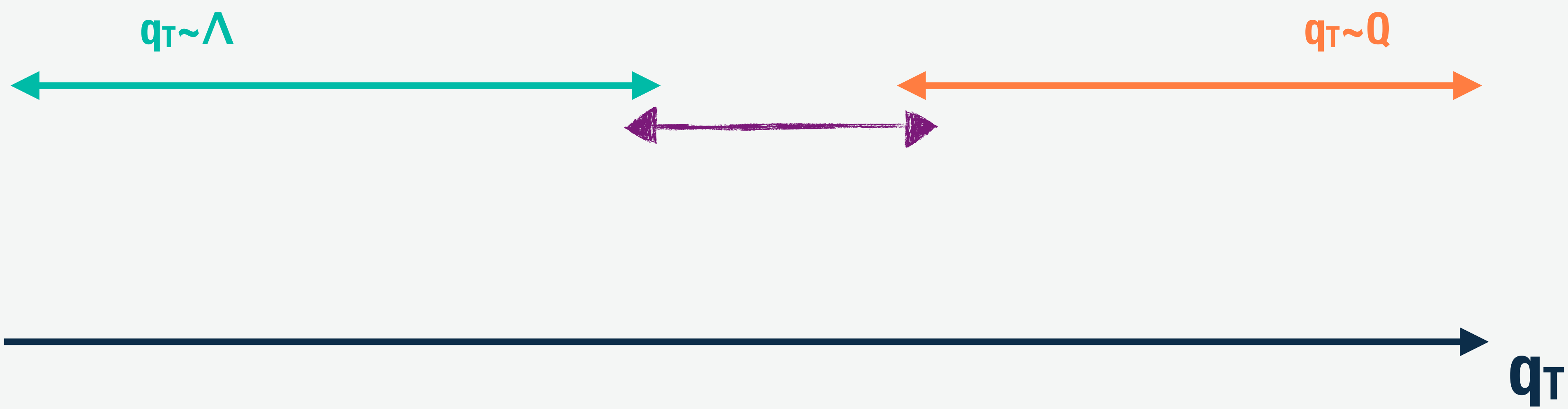
$$\tau = \frac{Q^2}{s} \text{ fixed and finite as } Q^2, s \to \infty$$

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

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

REGION OF TRANSVERSE MOMENTUM

$Q^2 >> \Lambda^2$



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

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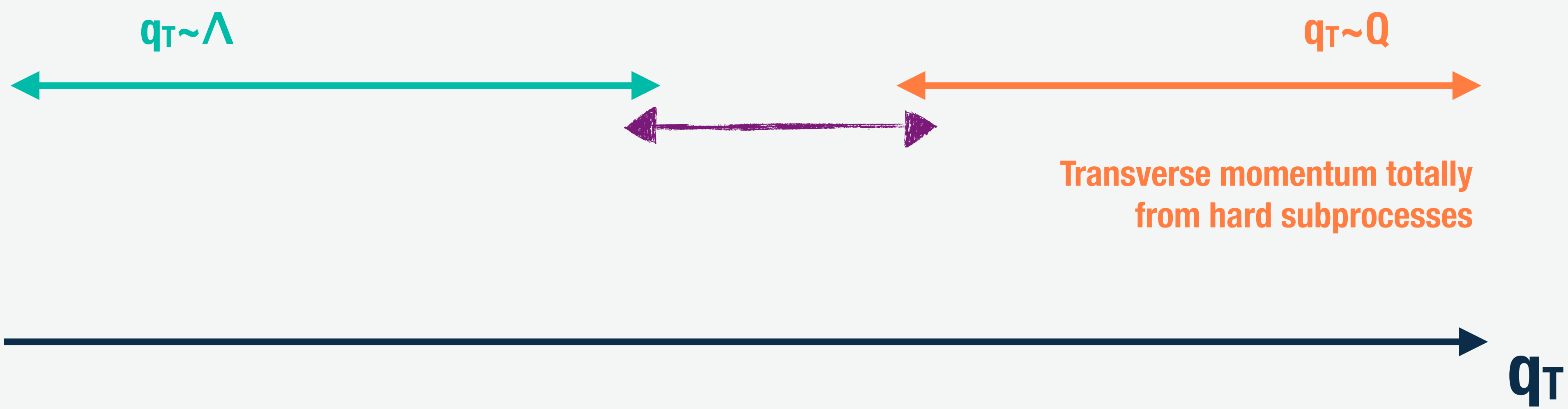

[Collins, Soper & Sterman, Nucl.Phys.B250]

REGION OF TRANSVERSE MOMENTUM

$Q^2 >> \Lambda^2$

$q_T \sim \Lambda$

$q_T \sim Q$

Transverse momentum
from non-perturbative dynamics:
Transverse Momentum PDFs

Transverse momentum totally
from hard subprocesses

q_T

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

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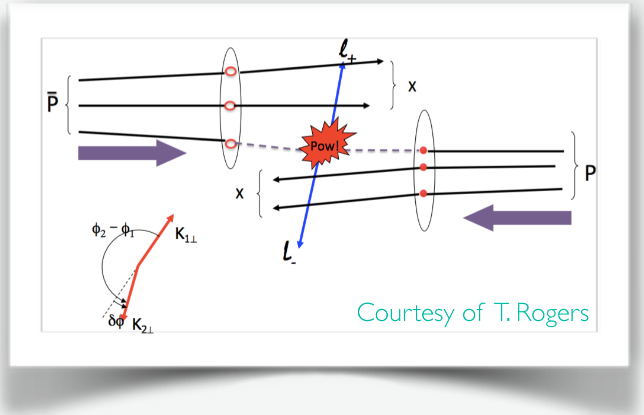

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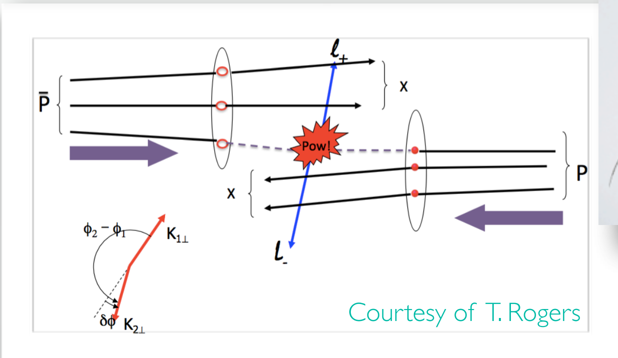

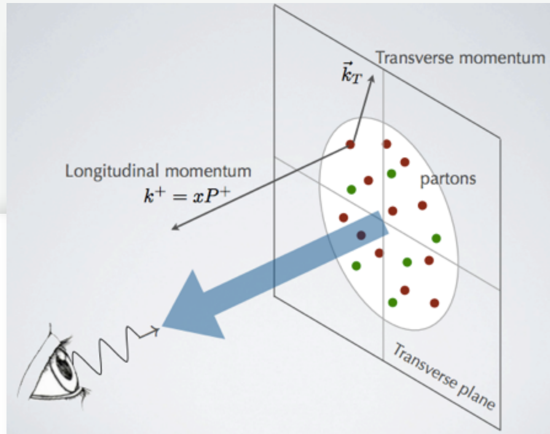

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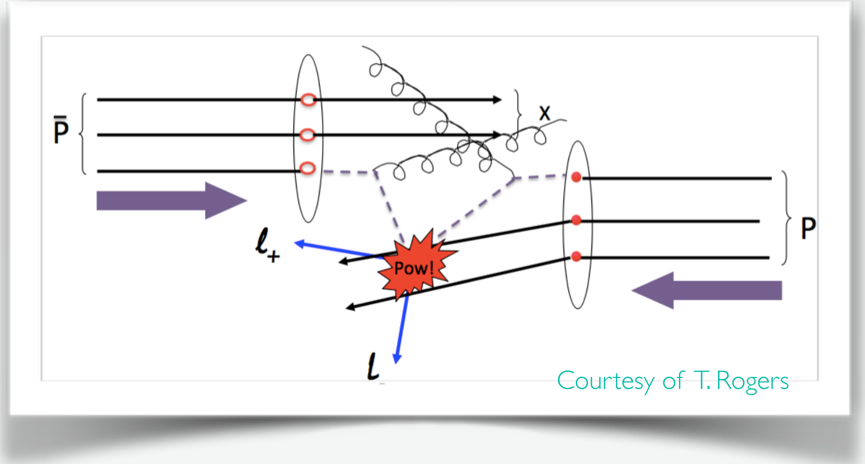
[Collins, Soper & Sterman, Nucl.Phys.B250]

Pion DY

PERTURBATIVE CORRECTIONS

Q_T appears at NLO



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$$\times \sum_j e_j^2\, C_{ja}(x_\pi/\xi_\pi, b; Qb; \mu)\, C_{jb}(x_P/\xi_P, b; Qb; \mu)$$

$$C_{ja}(x_\pi/\xi_\pi, b; Qb; \mu) = \delta_{ja}\delta\left(x_\pi/\xi_\pi - 1\right) + \frac{\alpha_s(\mu)}{\pi} C_{ja}^{(1)} + \cdots$$

FULL REGION

$q_T \sim \Lambda$ $q_T \sim Q$

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

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

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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NLL

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

FULL REGION

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$$
\begin{aligned}
\frac{d\sigma}{dQ^2\,dy\,dq_T^2} = \frac{4\pi^2\alpha^2}{9Q^2 s} \int \frac{d^2 b}{2\pi^2}\, e^{i\vec{q}_T\cdot\vec{b}} \sum_{a,b} \sum_j e_j^2 \\
\times \int_{x_\pi}^{1} \frac{d\xi_\pi}{\xi_\pi} \int_{x_P}^{1} \frac{d\xi_P}{\xi_P} f_{a/\pi}(\xi_\pi, \vec{b}; \zeta_\pi, \mu_b)\, f_{b/P}(\xi_P, \vec{b}; \zeta_P, \mu_b) \\
\times \exp\left(-C_F \frac{\alpha_s(q)}{2\,\pi} \int_{b_0^2/b^2}^{Q^2} \frac{dq^2}{q^2} \left[2\ln\frac{Q^2}{\mu^2} - 3\right] + \mathrm{H.O}\right) \\
\times C_{ja}\left(x_\pi/\xi_\pi, \vec{b}; 2e^{-\gamma}; \mu_b\right) C_{jb}\left(x_P/\xi_P, \vec{b}; 2e^{-\gamma}; \mu_b\right)
\end{aligned}
$$

NLL

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

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NLL

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$$

$$
\times \int_{x_\pi}^{1} \frac{d\xi_\pi}{\xi_\pi} \int_{x_P}^{1} \frac{d\xi_P}{\xi_P} \boxed{f_{a/\pi}(\xi_\pi, \vec{b}; \zeta_\pi, \mu_b) f_{b/P}(\xi_P, \vec{b}; \zeta_P, \mu_b)}
$$

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

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

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

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

STRATEGY

- use a phenomenologically estimated $f_{b/P}(\xi_P; \mu_b) \times e^{S_{\rm NP}^P(b)}$
  - 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

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

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

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

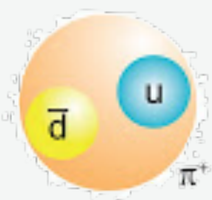
- $S_{NP}^{pp}(b)$
  $= \exp\{-[a_1 + a_2 \ln(M/(3.2\,\mathrm{GeV})) + a_3 \ln(100 x_1 x_2)]b^2\}.$

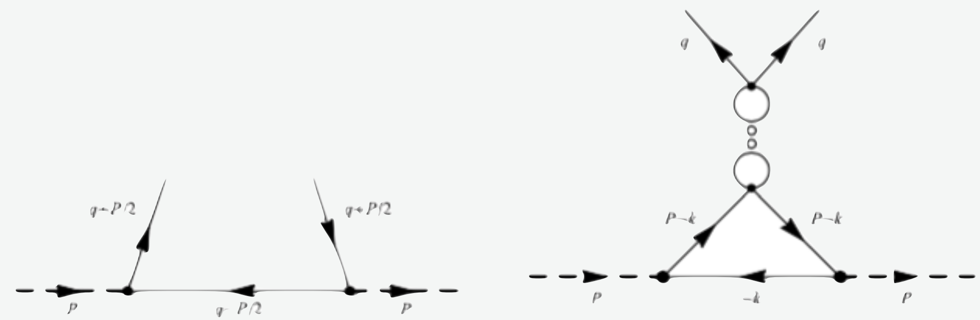
- $b_\star(b, b_{max}) = \dfrac{b}{\sqrt{1+\left(\frac{b}{b_{max}}\right)^2}}$ with $b_{max} = 1.5\,\mathrm{GeV}^{-1}$

FULL TRANSVERSE MOMENTUM DEPENDENCE FOR THE PION

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

TMD PDFs





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

Pion DY

[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]

THE PION IN A CHIRAL MODEL

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

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

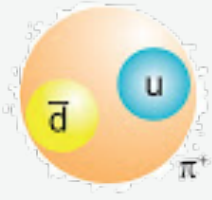
→ **no "$g_1(b)$" is this model picture**

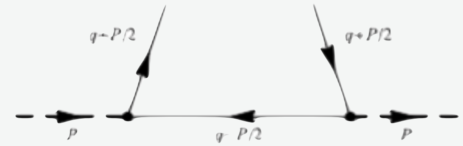
$$\begin{aligned} f''_\pi(b) &= \frac{3}{2\pi^2}\left(\frac{m}{f_\pi}\right)^2 \sum_{i=0,2} \int dk_T\, k_T\, J_0(bk_T)\frac{a_i}{k_T^2+m_i^2} \\ &= \frac{3}{2\pi^2}\left(\frac{m}{f_\pi}\right)^2 \sum_{i=0,2} a_i K_0(m_i\, b) \end{aligned}$$

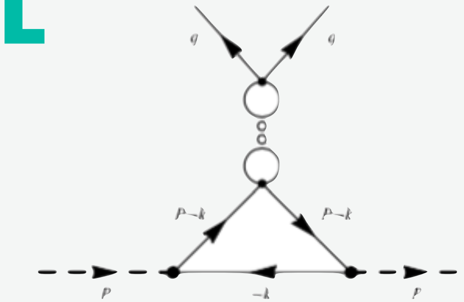
We assumed that factorization of the transverse momentum occurs at Q_0 only.

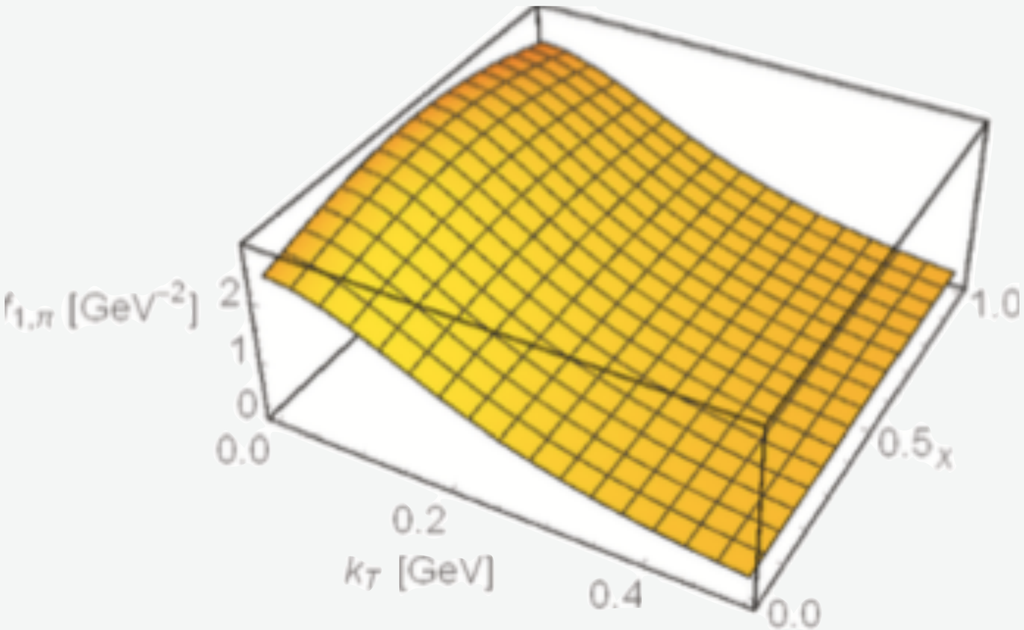
[Noguera & Scopetta, JHEP11, 102]

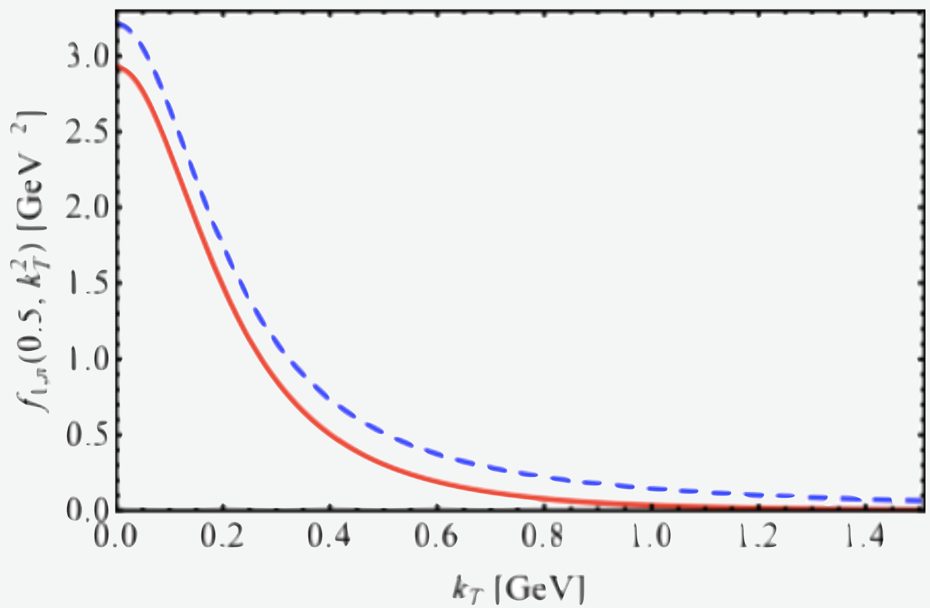
THE PION IN A CHIRAL MODEL







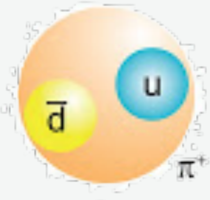


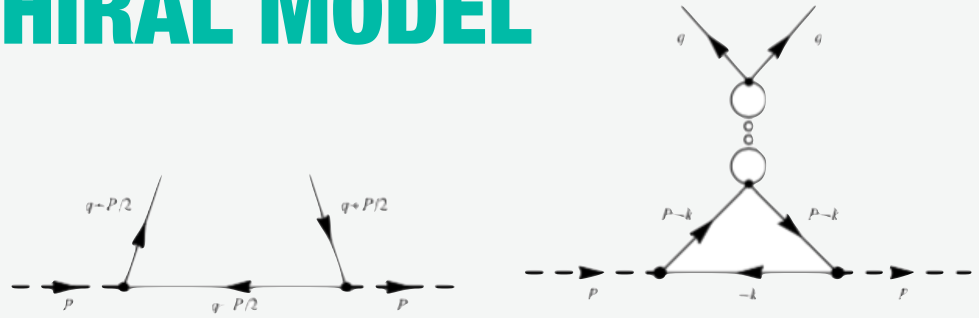


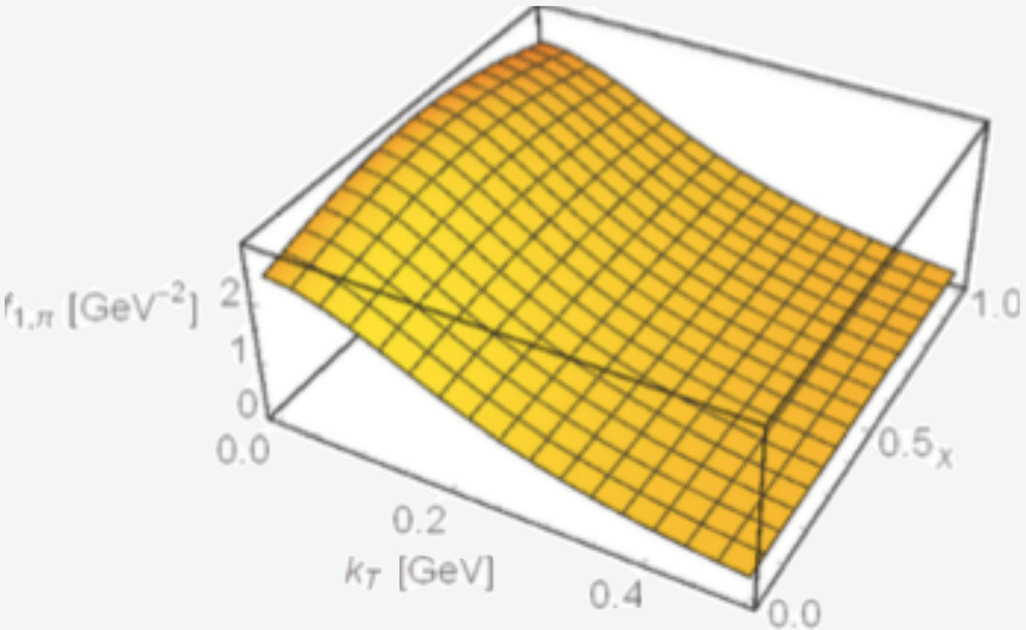
Pion DY

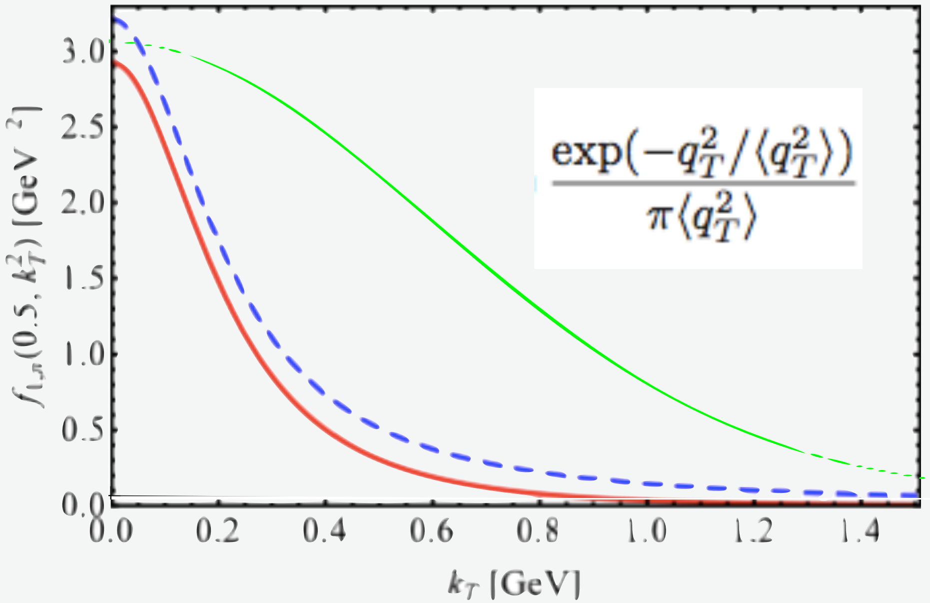
[Noguera & Scopetta, JHEP11, 102]

THE PION IN A CHIRAL MODEL





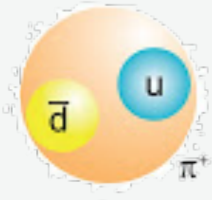


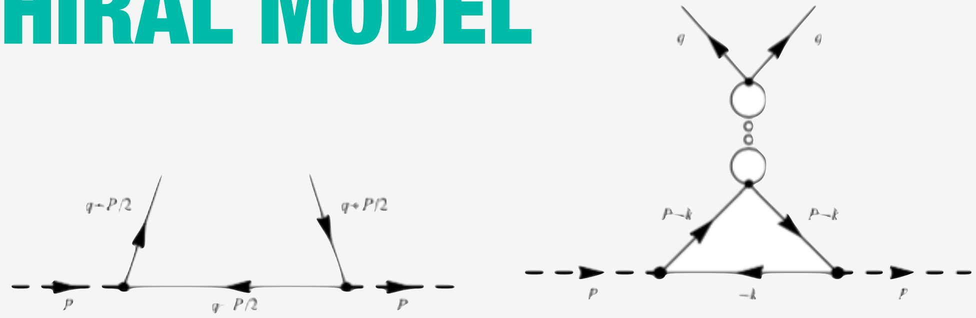


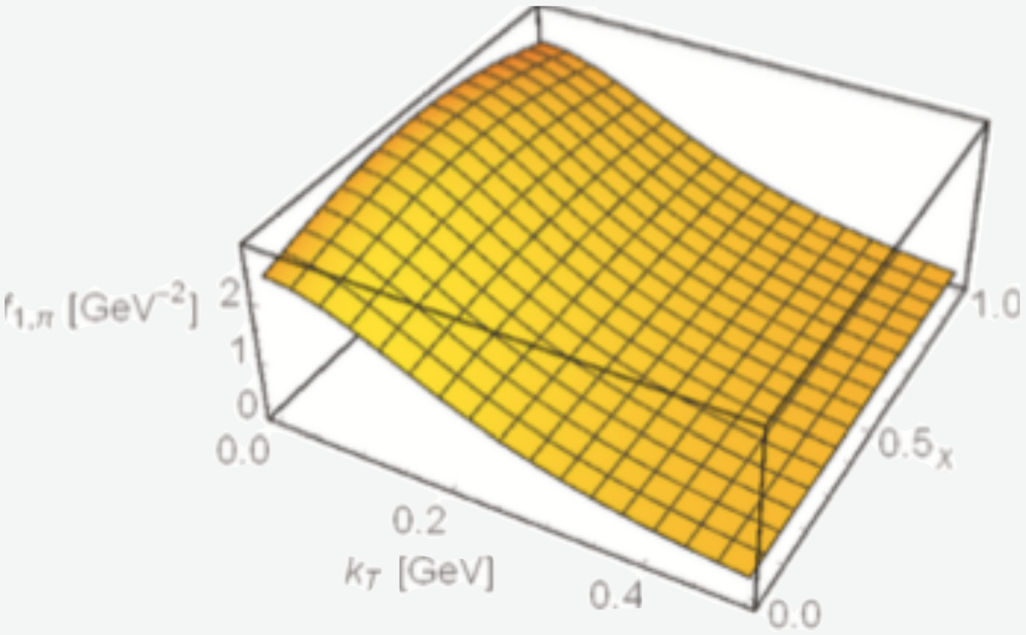
Pion DY

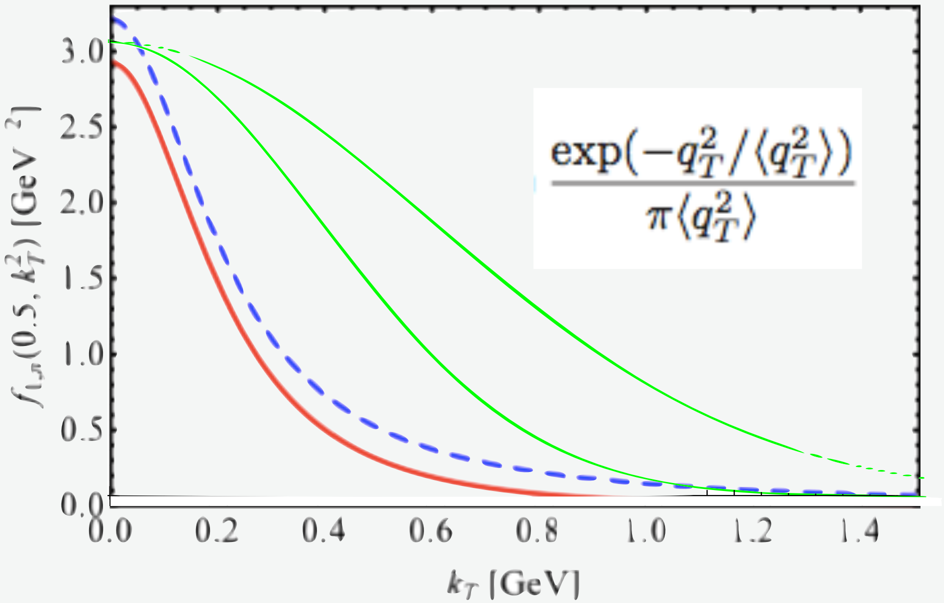
[Noguera & Scopetta, JHEP11, 102]

THE PION IN A CHIRAL MODEL





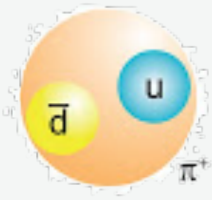


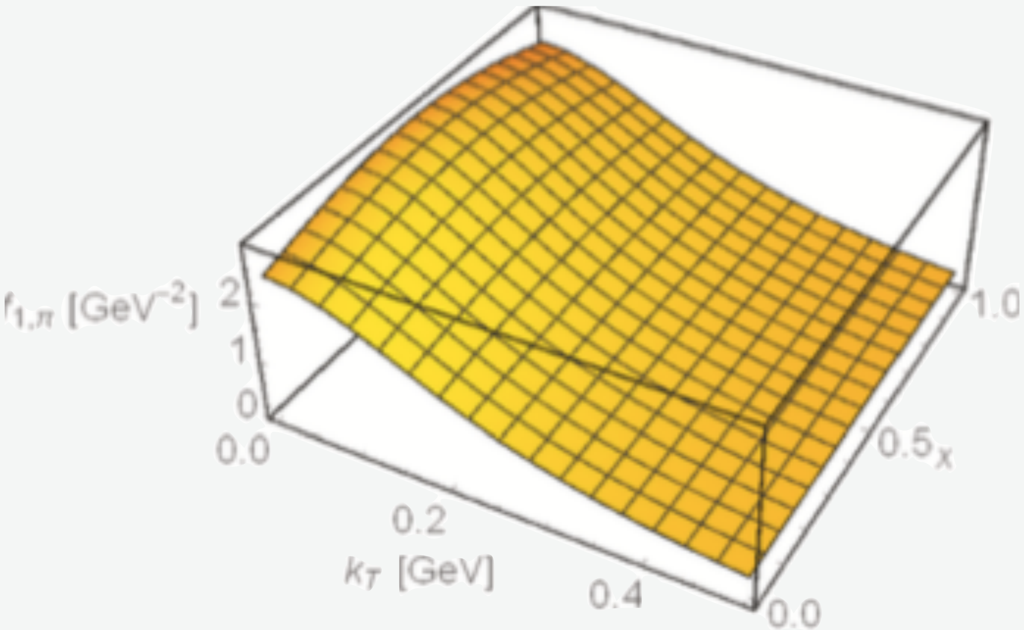


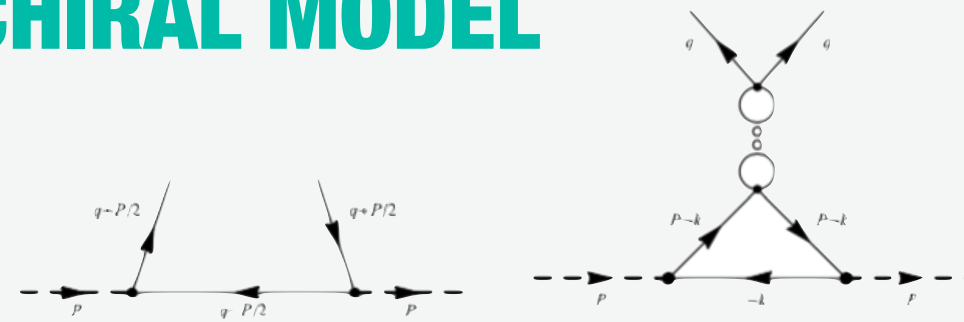
Pion DY

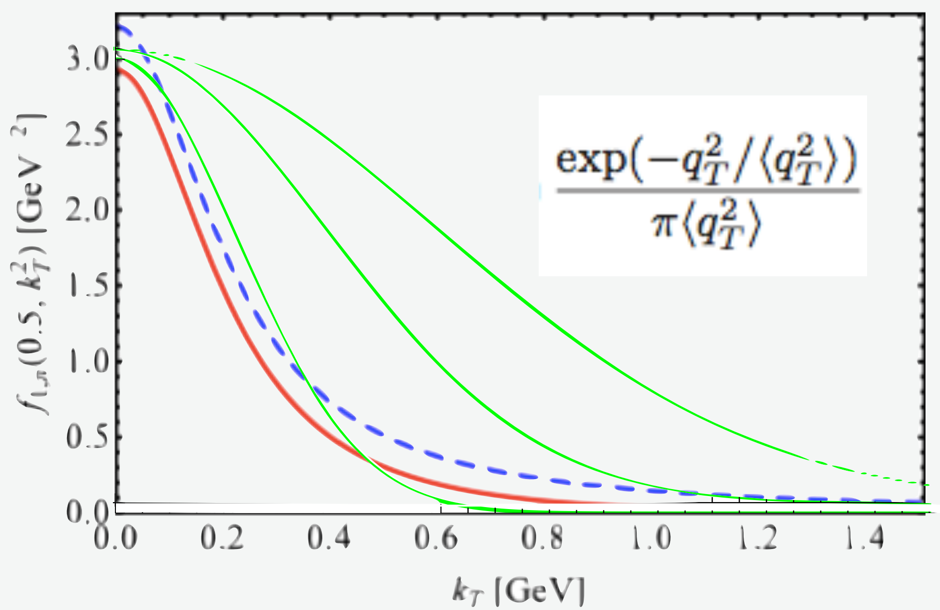
[Noguera & Scopetta, JHEP11, 102]

THE PION IN A CHIRAL MODEL





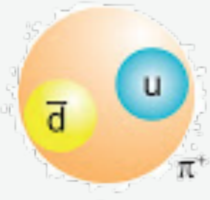


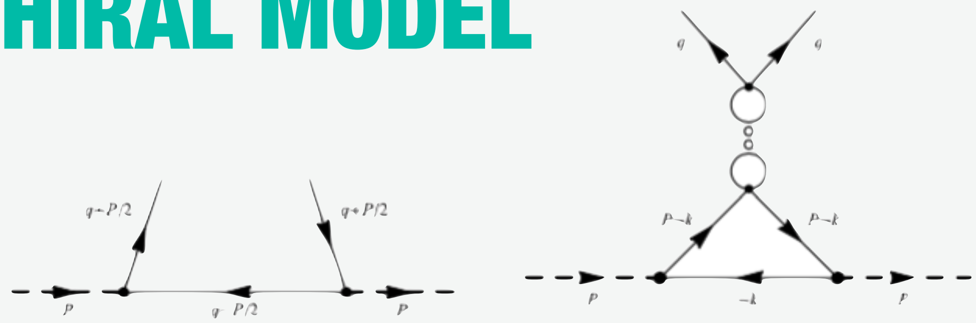


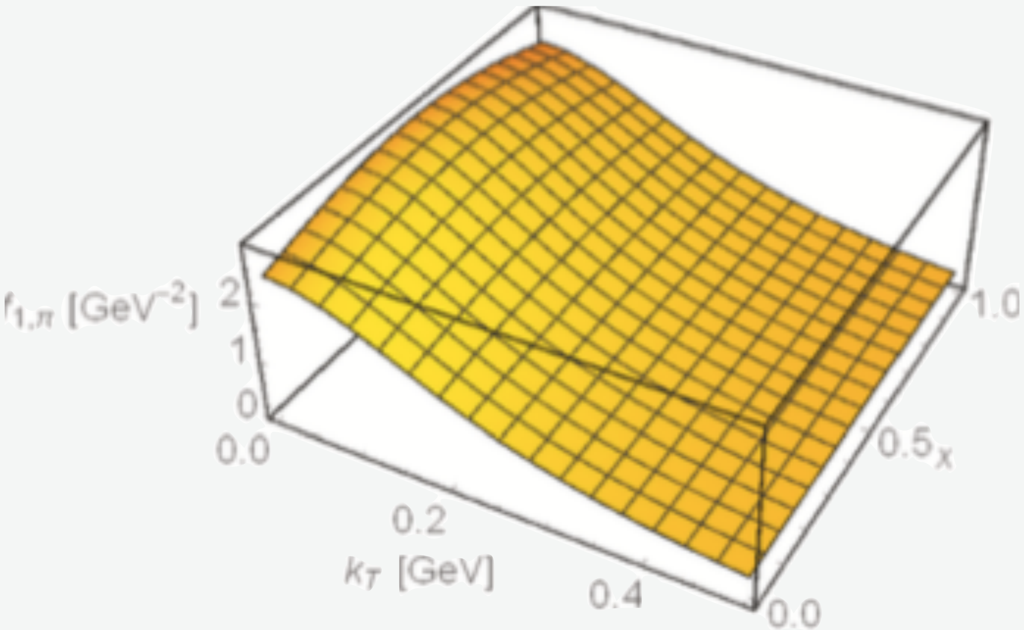
Pion DY

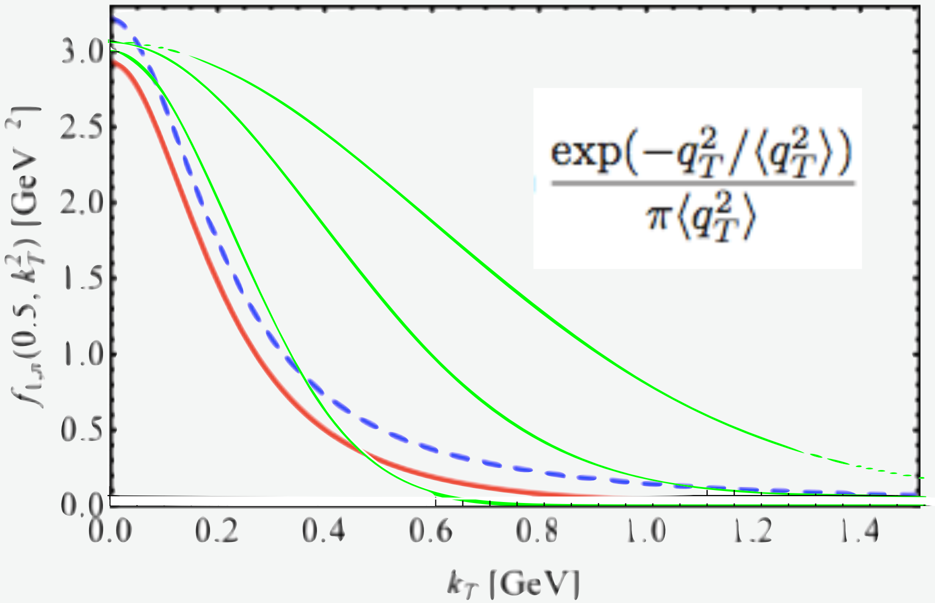
[Noguera & Scopetta, JHEP11, 102]

THE PION IN A CHIRAL MODEL







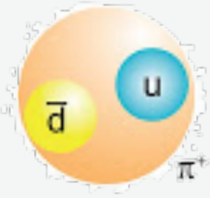


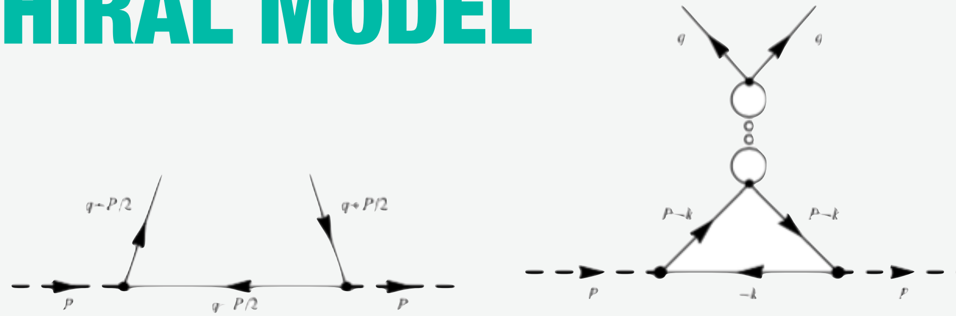
Pion dynamics→ differs from a gaussian

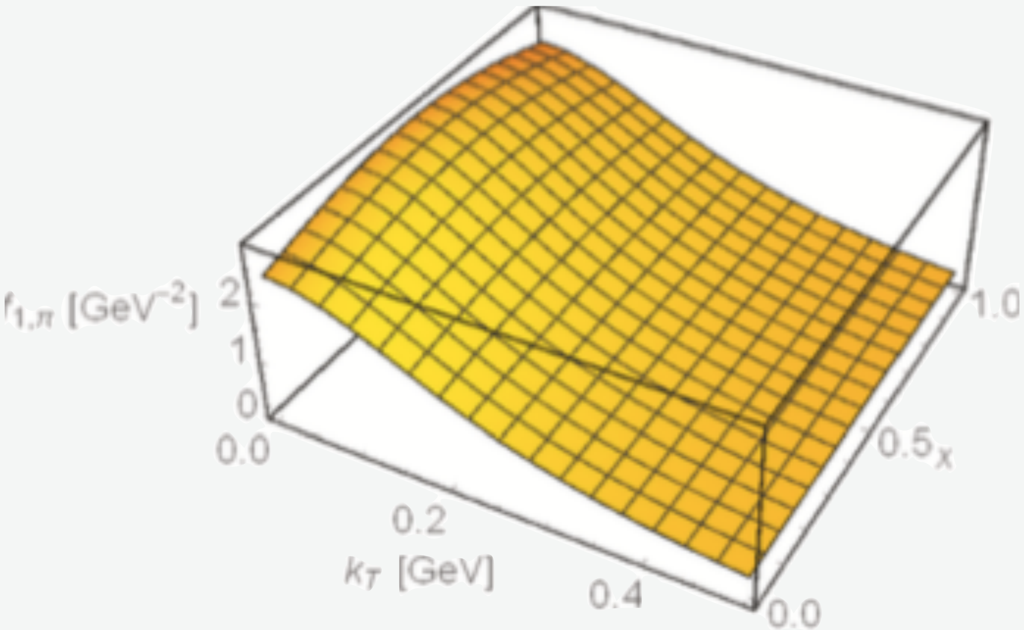
Pion DY

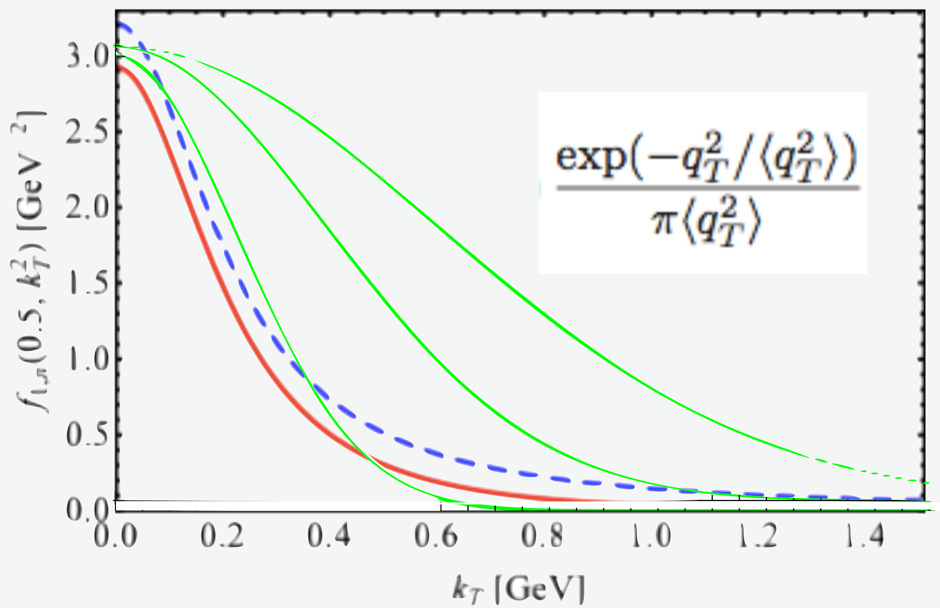
[Noguera & Scopetta, JHEP11, 102]

THE PION IN A CHIRAL MODEL









Pion dynamics→ differs from a gaussian

Transverse profile→ no dpdce on x or M

Pion DY

[Noguera & Scopetta, JHEP11, 102]

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

[Ceccopieri & Trentadue, Phys.Lett.B741]
[Ceccopiero, A.C, Noguera & Scopetta, in preparation]

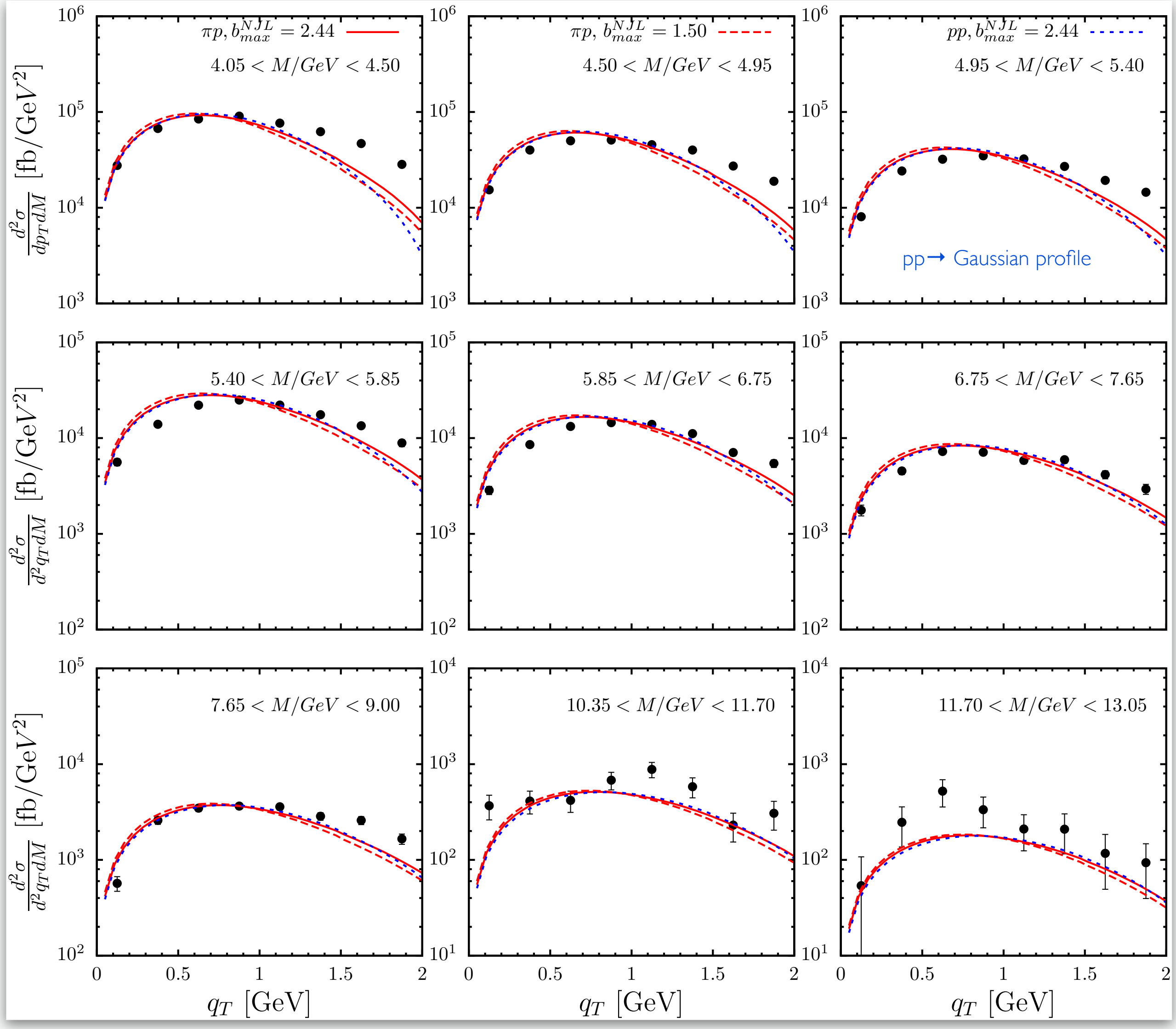
$\pi^- W$ DRELL-YAN

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



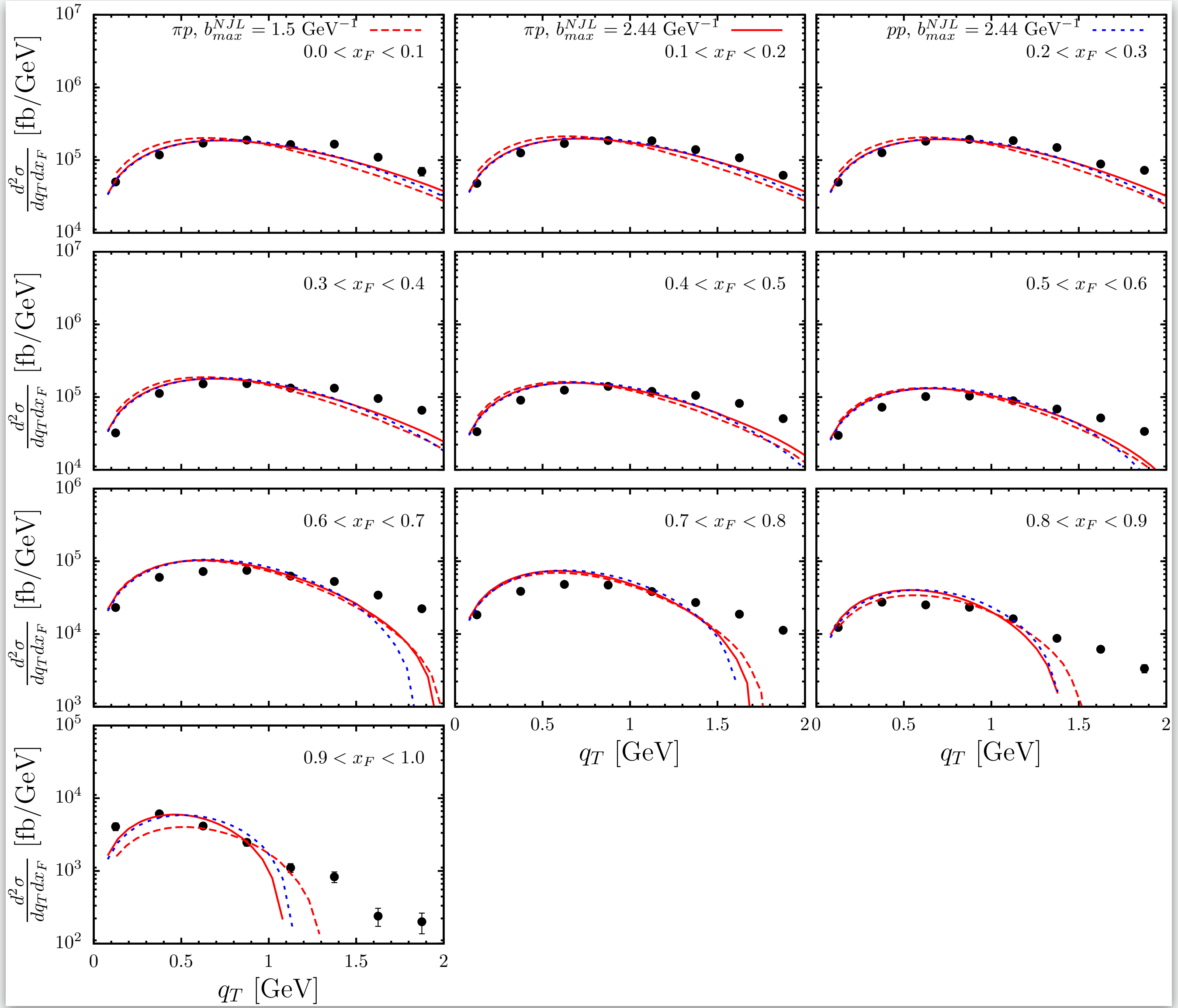
with KN param.

$\pi^- W$ DRELL-YAN

Cross section in x-bins

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

- ☐ higher qT
- ☐ Gaussian profile ~indistinguishable

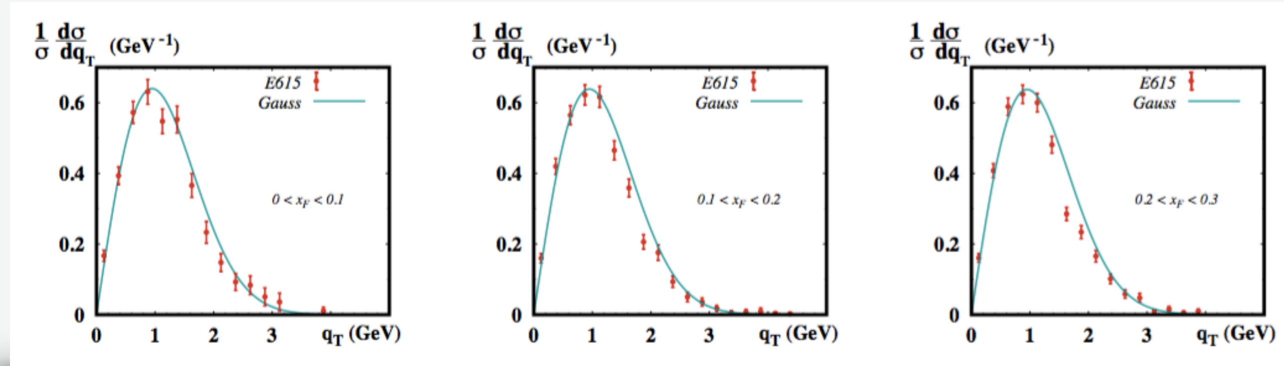


No free parameters
Only Q_0 is fixed beforehand

with KN param.

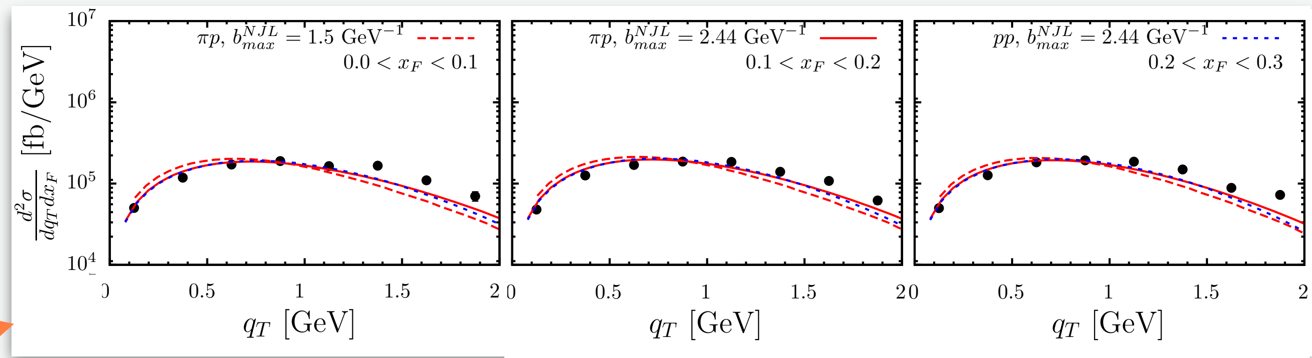
Pion DY

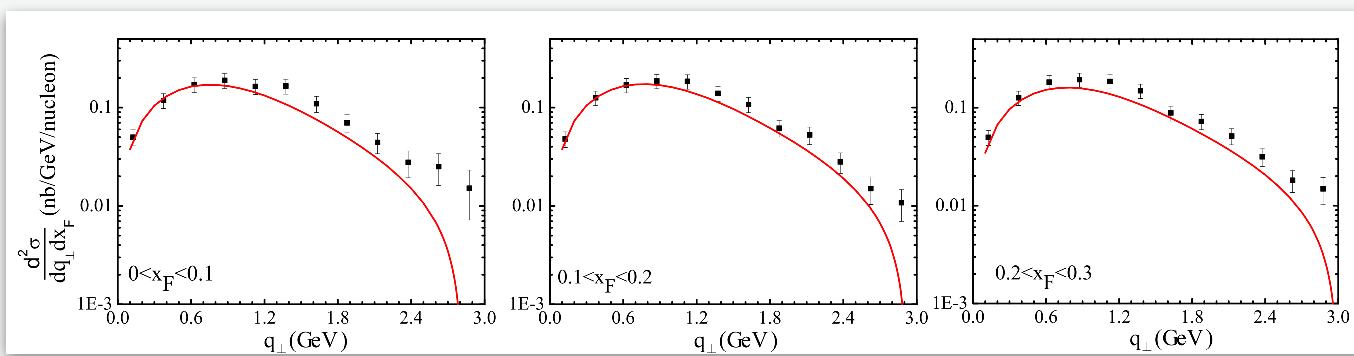
$\pi^- W$ DRELL-YAN



Only gaussian

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



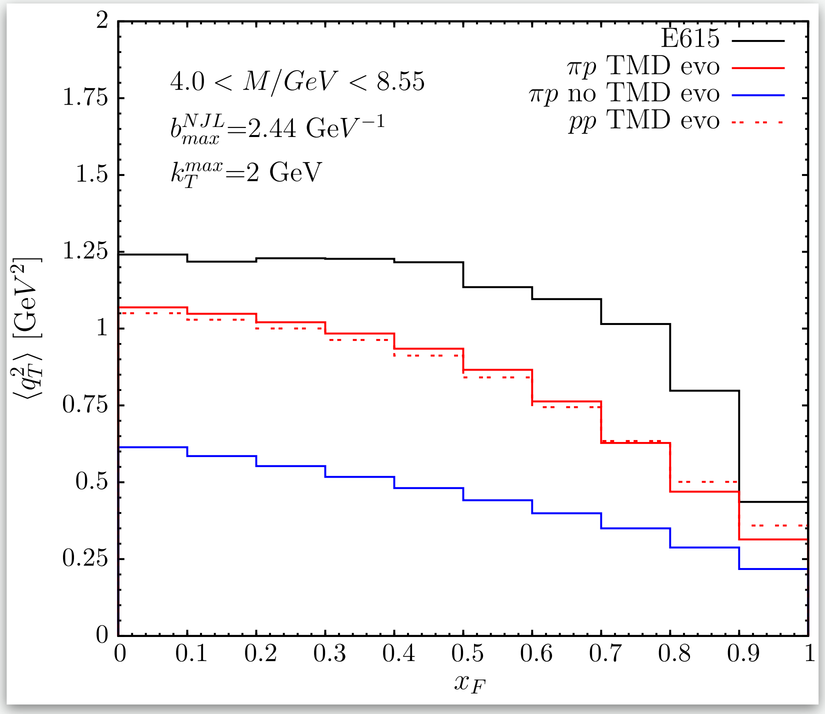


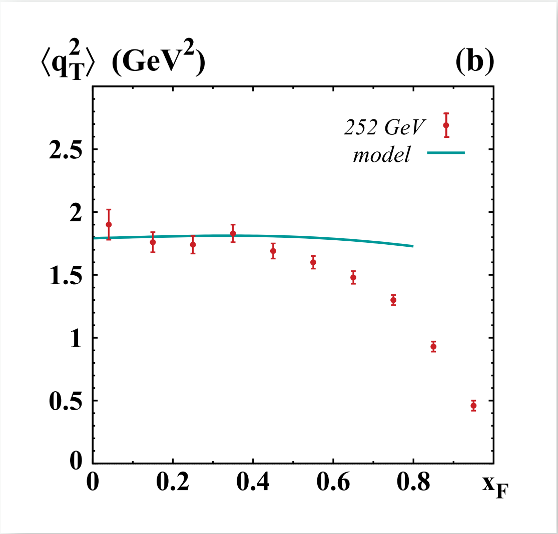
Fit

[Wang & et al, JHEP08-137]

Pion DY

$\pi^- W$ DRELL-YAN

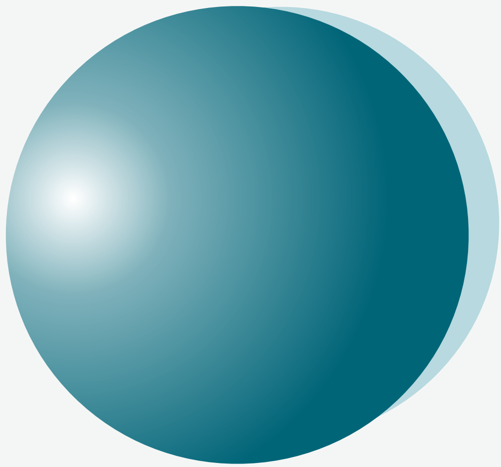


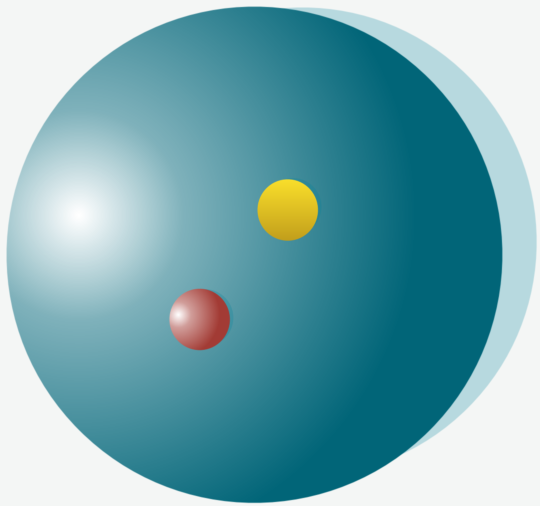


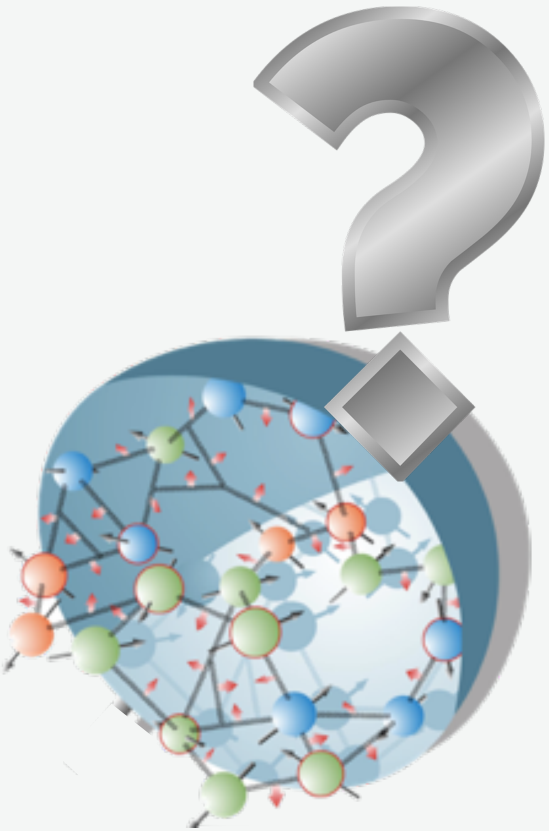
[Pasquini & et al, Phys.Rev.D90]

CSS evolution affects the transverse mmt distribution.

PION STRUCTURE FROM DY?







Degrees of freedom change governed by the chiral symmetry.

Resolution

Pion DY

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!

OUTLOOK

- Predictions for COMPASS-II
- Go to polarized case
  - T-odd TMDs and universality
- Go to the modern TMD description of the factorized form

$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\,\mathrm{d}\Omega} = {} & \frac{2}{s}\sum_j \frac{\mathrm{d}\hat{\sigma}_{j\bar{j}}(Q,\mu_Q,\alpha_s(\mu_Q))}{\mathrm{d}\Omega}\int \mathrm{d}^2\boldsymbol{b}_\mathrm{T}\, e^{i\boldsymbol{q}_\mathrm{T}\cdot\boldsymbol{b}_\mathrm{T}}\,\tilde{f}_{j/A}(x_A,\boldsymbol{b}_\mathrm{T};Q_0^2,\mu_{Q_0})\,\tilde{f}_{\bar{j}/B}(x_B,\boldsymbol{b}_\mathrm{T};Q_0^2,\mu_{Q_0}) \\
& \times \exp\left\{\left[-g_K(b_\mathrm{T};b_\mathrm{max}) + \tilde{K}(b_*;\mu_{b_*}) - \int_{\mu_{b_*}}^{\mu_{Q_0}}\frac{\mathrm{d}\mu'}{\mu'}\gamma_K(\alpha_s(\mu'))\right]\ln\frac{Q^2}{Q_0^2}\right\} \\
& \times \exp\left\{\int_{\mu_{Q_0}}^{\mu_Q}\frac{\mathrm{d}\mu'}{\mu'}\left[2\gamma_j(\alpha_s(\mu');1) - \ln\frac{Q^2}{(\mu')^2}\gamma_K(\alpha_s(\mu'))\right]\right\}
\end{aligned}
$$

[Collins & Rogers, PRD91]

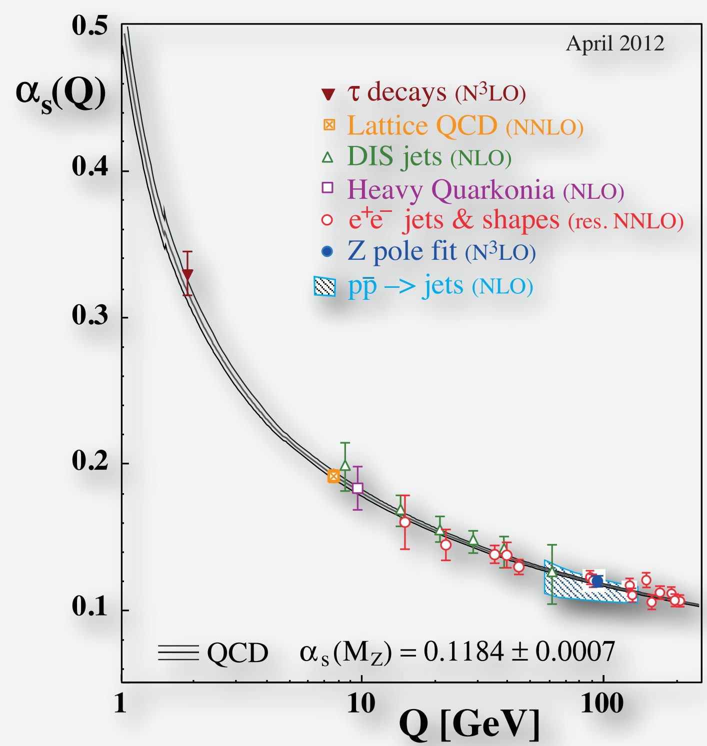
- Use knowledge on pion to fix NP parameters
- Redefine/evaluate the hadronic scale from TMD pheno.

BACKUP SLIDES

THE THEORY OF THE STRONG INTERACTIONS

QM: $\hat{H} = \hat{H}_0 + \lambda \hat{H}_1 + \cdots \;, \quad \lambda << $

QCD: $$A = A_0 + \frac{\alpha_s(Q)}{4\pi} A_1 + \left(\frac{\alpha_s(Q)}{4\pi}\right)^2 A_2 + \cdots$$



Confinement

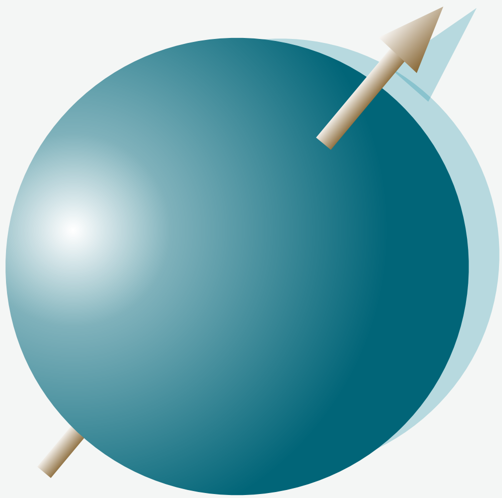
Asymptotic freedom

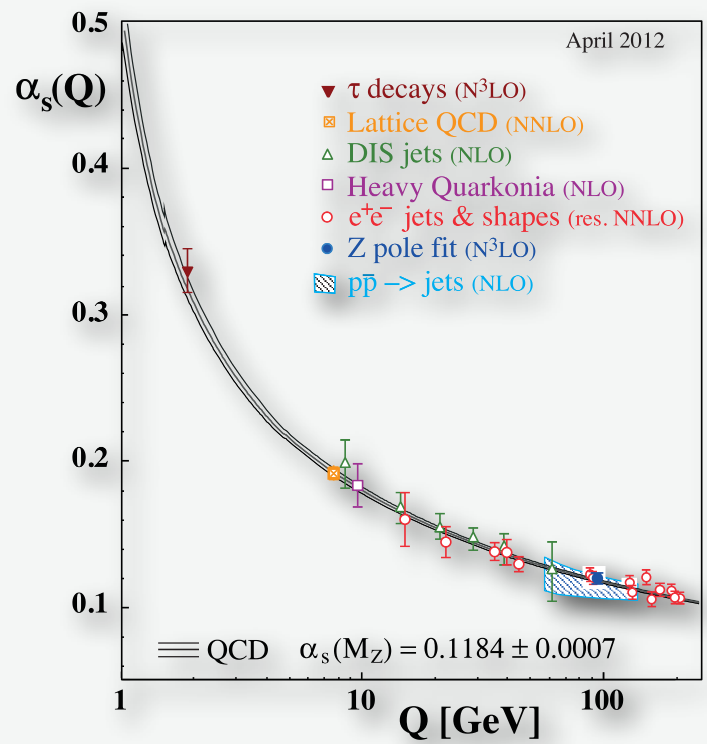
Pion DY

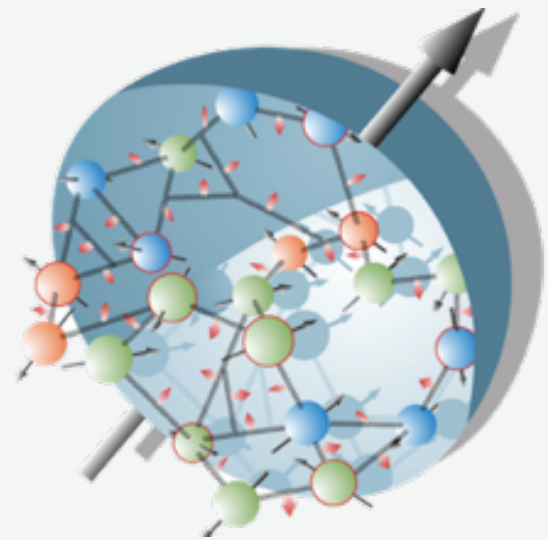
Resolution

HADRON STRUCTURE

$$A = A_0 + \frac{\alpha_s(Q)}{4\pi} A_1 + \left(\frac{\alpha_s(Q)}{4\pi}\right)^2 A_2 + \cdots$$



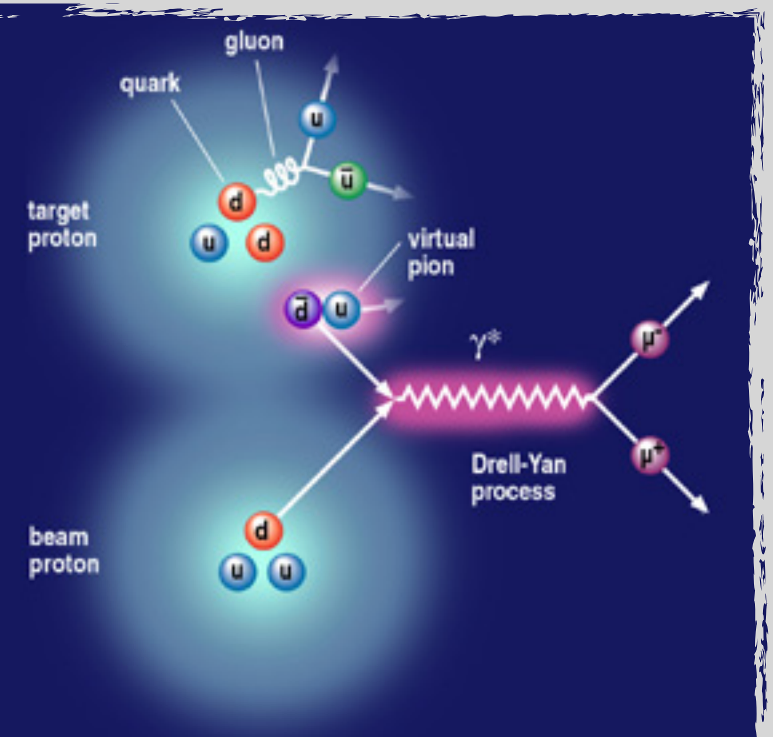


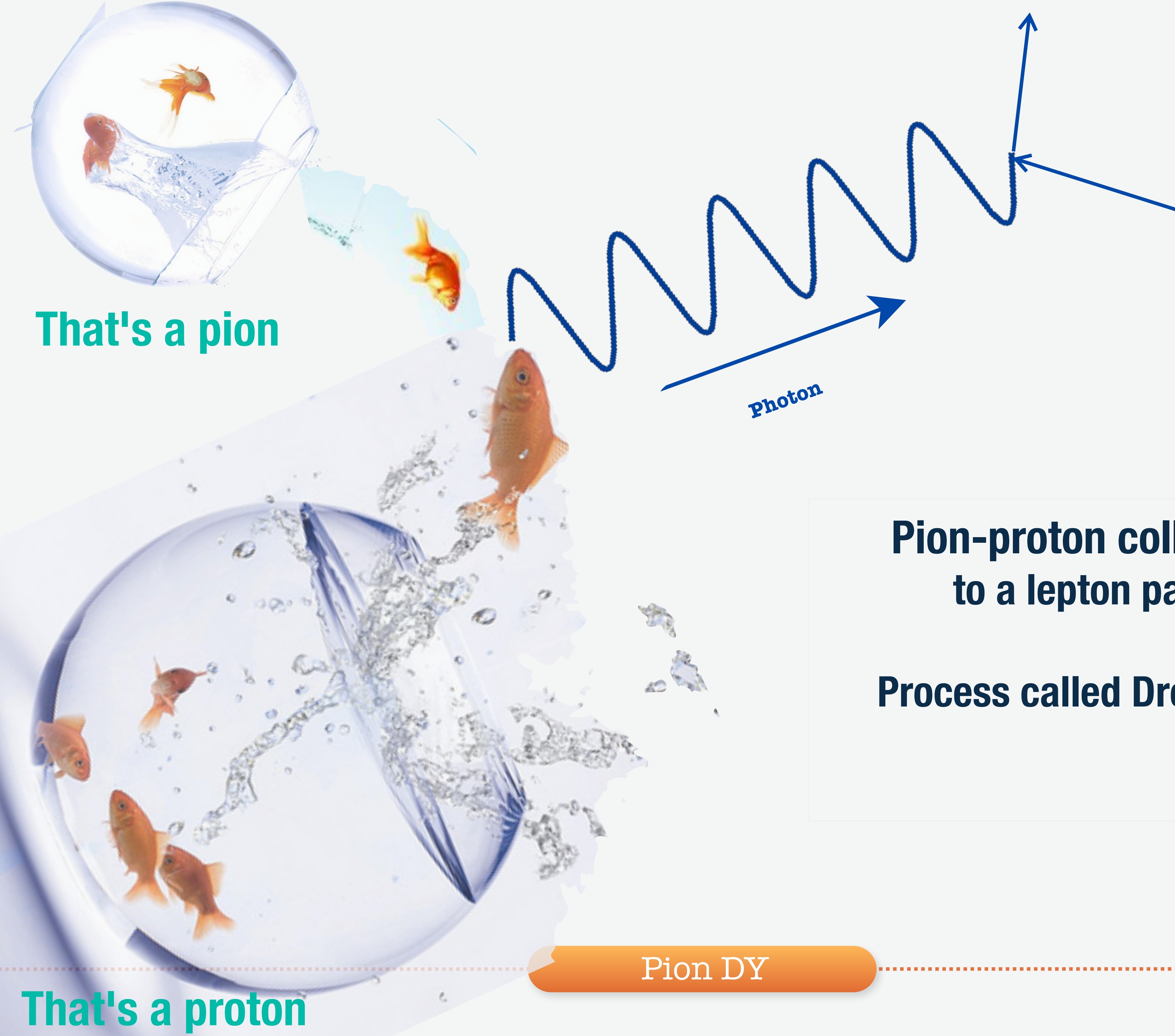


Pion DY

Resolution

DRELL-YAN PROCESSES

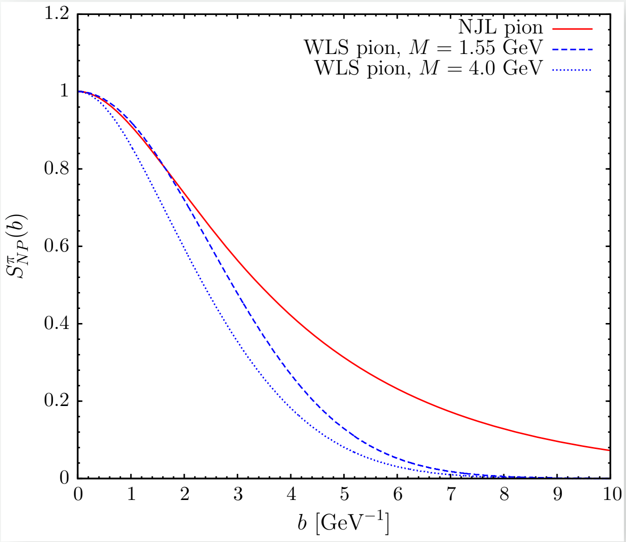


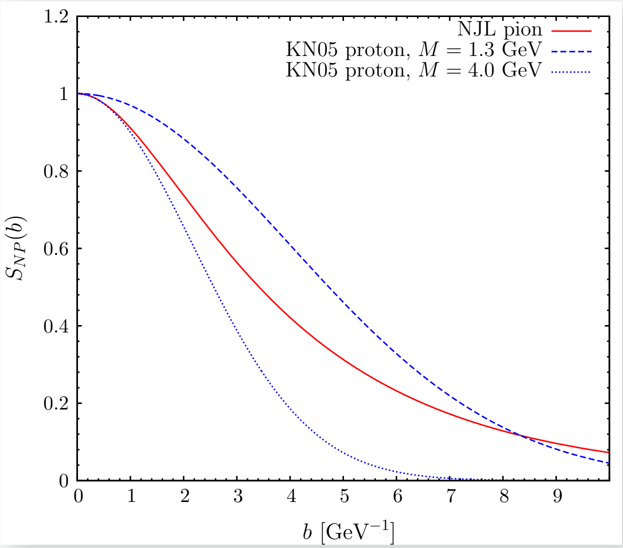


Pion-proton collision
to a lepton pair

Process called Drell-Yan

TRANSVERSE PROFILE





Pion DY