Towards 3D Meson Structure - Discussion

What theoretical developments do we already have and what do we need?

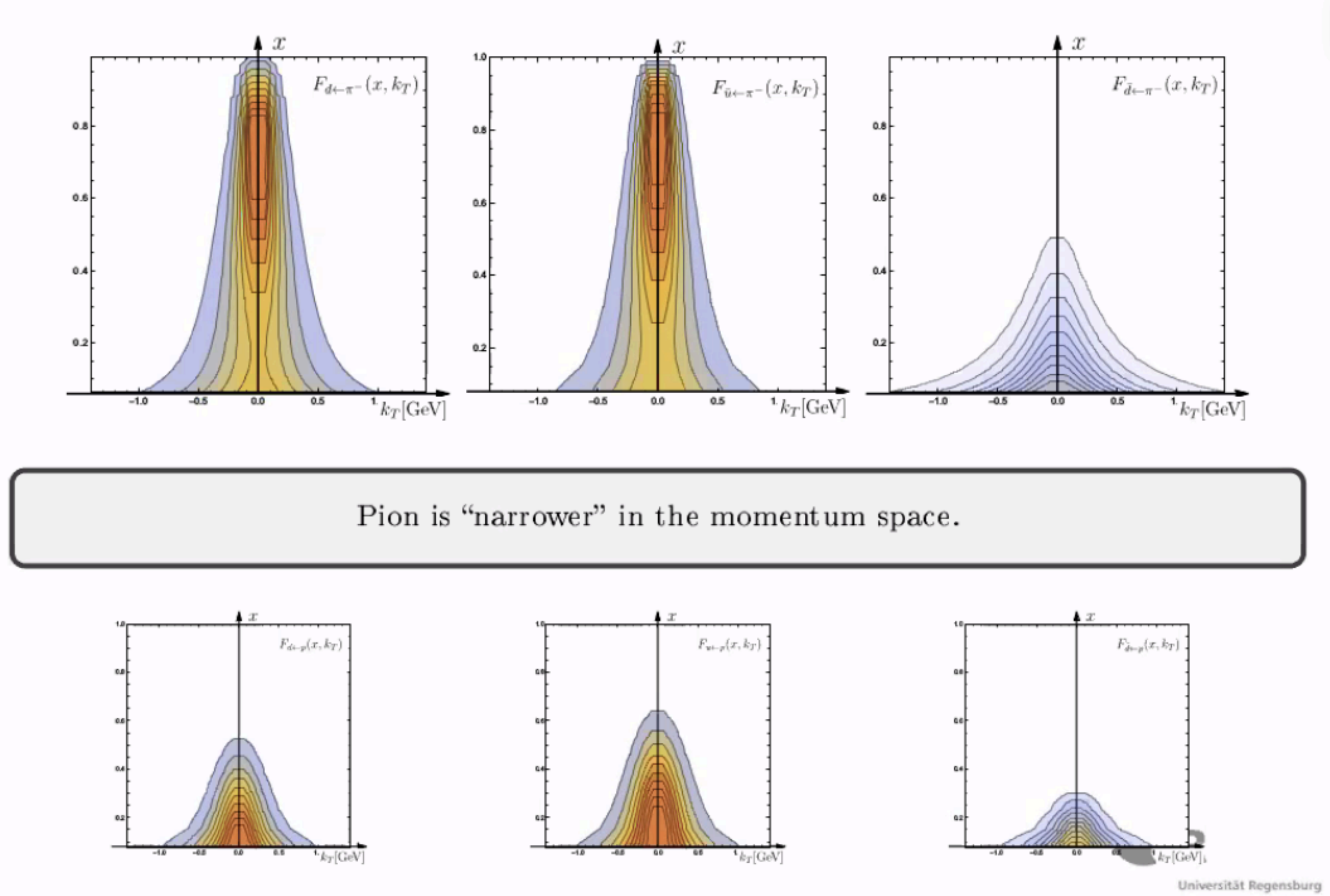
What experimental tools do we have at our disposal?

What would be the ideal measurements and how can we make them?
What are the prospects from EIC?
What can we do in the next 10 years (JLab / COMPASS)?

Where (and what?) are the missing links?

Pion TMDs from pion-induced Drell-Yan

Alexey Vladimirov

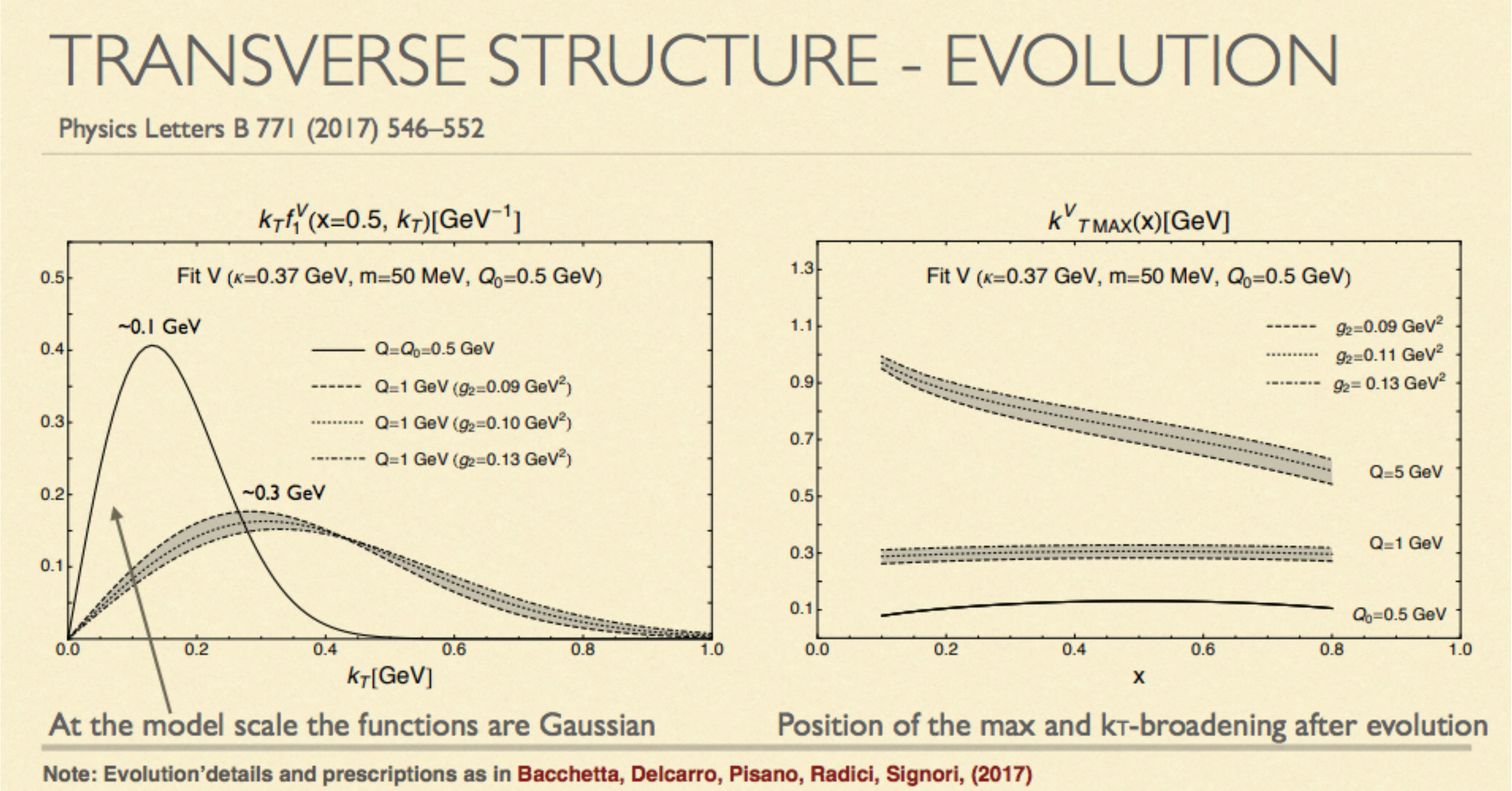


Pion is “narrower” in the momentum space.

Universität Regensburg

Transverse structure of pion in momentum space from AdS/QCD models

Sabrina Cotogno



TRANSVERSE STRUCTURE - EVOLUTION

Physics Letters B 771 (2017) 546–552

At the model scale the functions are Gaussian

Position of the max and kT-broadening after evolution

Note: Evolution'details and prescriptions as in Bacchetta, Delcarro, Pisano, Radici, Signori, (2017)

Spatial and momentum imaging of pion and kaon on the light-front

Chao Shi

Unpolarized TMD PDF

- TMD overlap representation

$$f_{1,\pi}(x,\mathbf{k}_\perp^2)=|\psi_{\uparrow\downarrow}(x,k_\perp^2)|^2+k_\perp^2|\psi_{\uparrow\uparrow}(x,k_\perp^2)|^2$$

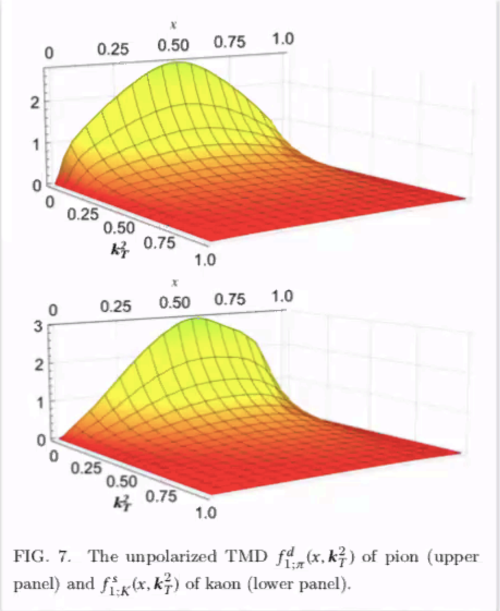
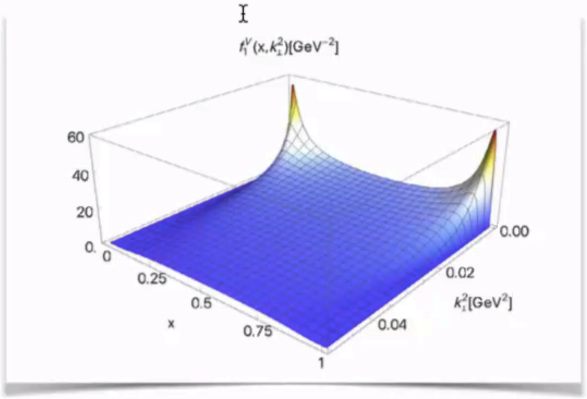


FIG. 7. The unpolarized TMD $f^d_{1;\pi}(x,\boldsymbol{k}_T^2)$ of pion (upper panel) and $f^s_{1;K}(x,\boldsymbol{k}_T^2)$ of kaon (lower panel).

DSE & LF

- Significant strength at low kT , resembles Gaussian-like form.
- The TMD of kaon is slightly broader than pion.
- Smoother as compared to holographic QCD.



Holographic QCD(A Bacchetta, et al, PLB2017)

- At leading twist, the pion has one GPD:

$$H_\pi^q(x,\xi,t)=\frac{1}{2}\int\frac{dz^-}{2\pi}e^{ixP^+z^-}\langle p_2|\bar{\psi}^q(-\frac{z}{2})\gamma^+\psi^q(\frac{z}{2})|p_1\rangle|_{z^+=z_\perp=0}$$

IPD GPD

GPD at zero skewness H(x,ξ=0,Δ)

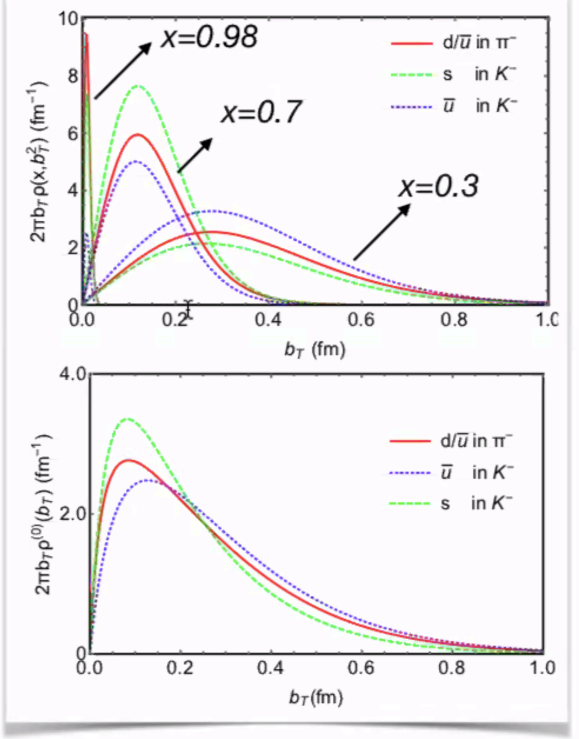
Fourier Transform

Impact Parameter Dependent GPD ρ(x,bT)

Probability density interpretation

x: longitudinal momentum fraction

bT: transverse spatial separation ~ (1-x)($r^1{}_T$-$r^2{}_T$)



- All distributions peek at the center of impact parameter (note the plot has been multiplied with bT)
- heavier s quark is more localized as compared to light u/d quark by ~20%.
- Valence distribution $\rho^{(0)}(b_T)=\rho_q^{(0)}(b_T)-\rho_{\bar{q}}^{(0)}(b_T)$ is scale-independent, as H(x,0,ΔT) evolution is independent of ΔT.

Gravitational Form Factor

GFF: $\langle\pi^+(p')|\Theta^{\mu\nu}(0)|\pi^+(p)\rangle=\frac{1}{2}[P^\mu P^\nu\Theta_2(t)+(g^{\mu\nu}q^2-q^\mu q^\nu)\Theta_1(t)].$

EMT $\Theta^{\mu\nu}=\sum_{q=u,d...}\bar{q}(x)(\gamma^\mu\partial^\nu+\gamma^\nu\partial^\mu)q(x)+(gluons)$

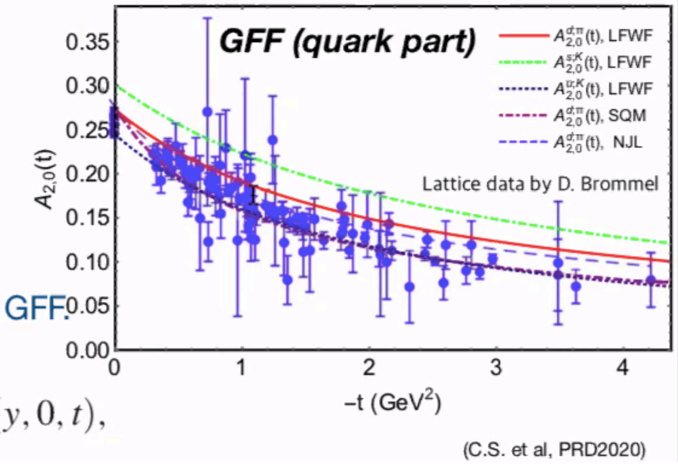
GPD x-moments:

$$\int_{-1}^{1}dxxH'^q(x,0,t)=A^q_{2,0}(t)$$

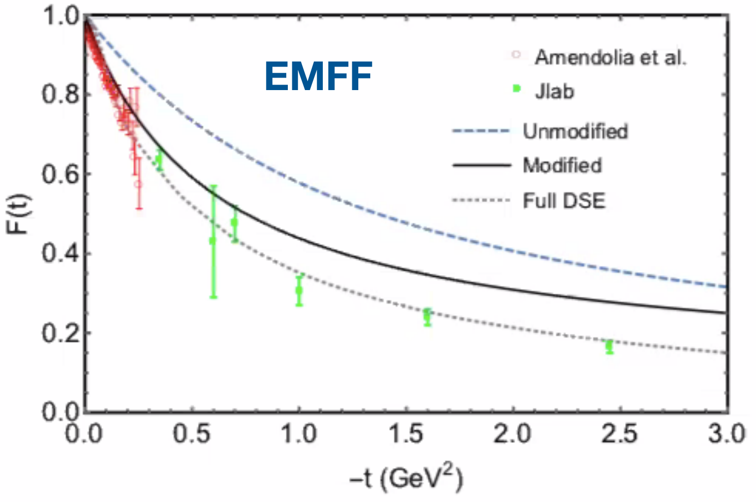
$$A^q_{2,0}(t)=\frac{1}{2}\Theta^q_1(t)$$

- The hidden ERBL region doesn't contribute to GFF.

$$H'_d(x,0,t)=H_d(x,0,t)+\delta(x)\tilde{F}_\rho(t)\int_{-1}^{1}dyH_{I=1}(y,0,t),$$

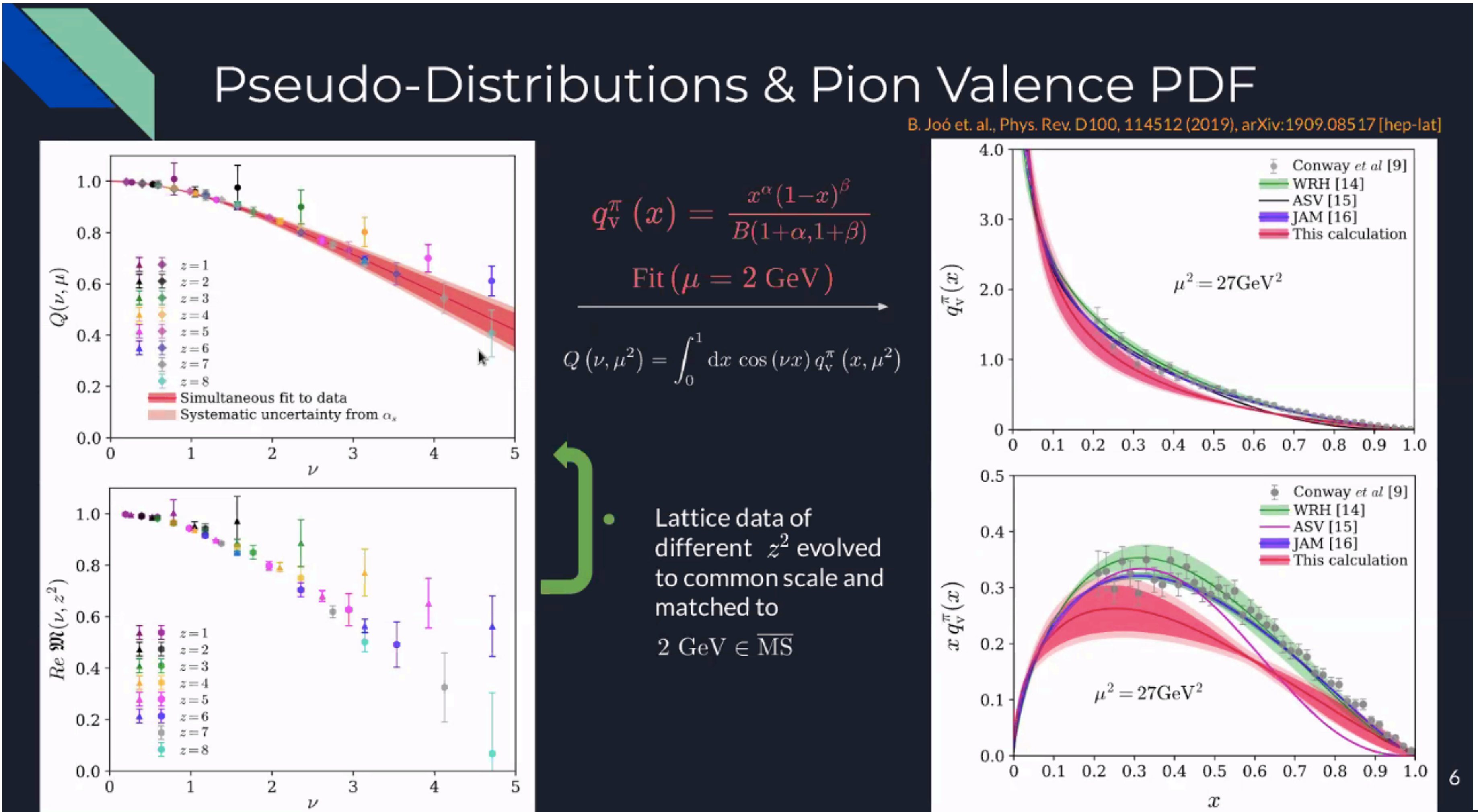


(C.S. et al, PRD2020)



LQCD 3D meson structure prospects

Colin Egerer



Pseudo-Distributions & Pion Valence PDF

B. Joó et. al., Phys. Rev. D100, 114512 (2019), arXiv:1909.08517 [hep-lat]

$$q_v^\pi(x) = \frac{x^\alpha(1-x)^\beta}{B(1+\alpha,1+\beta)}$$

$$\xrightarrow{\text{Fit}\,(\mu = 2\text{ GeV})}$$

$$Q(\nu,\mu^2) = \int_0^1 dx\,\cos(\nu x)\,q_v^\pi(x,\mu^2)$$

- Lattice data of different z^2 evolved to common scale and matched to $2\text{ GeV} \in \overline{\text{MS}}$

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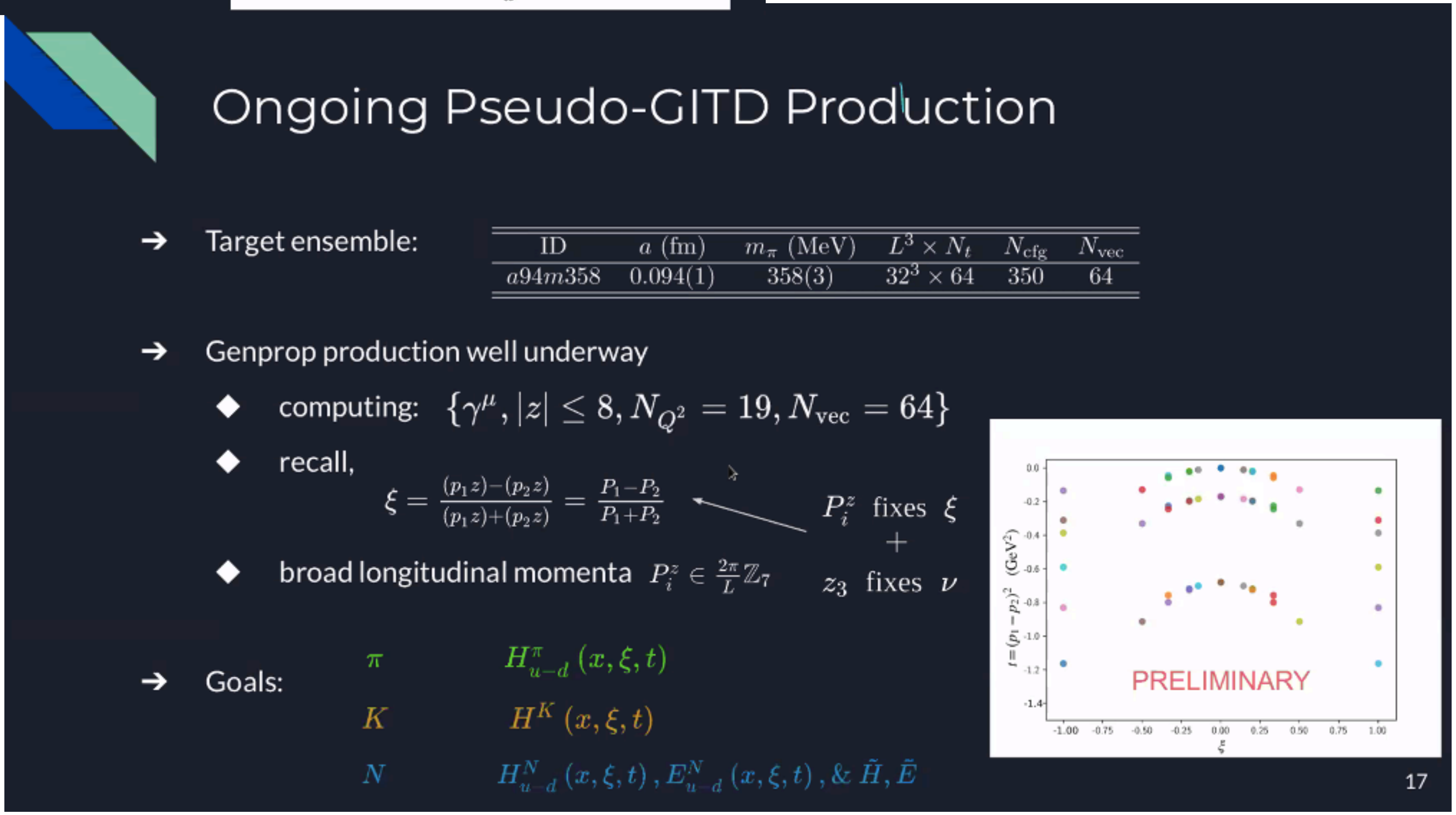

Ongoing Pseudo-GITD Production

→ Target ensemble:

ID	a (fm)	m_π (MeV)	$L^3 \times N_t$	N_{cfg}	N_{vec}
$a94m358$	0.094(1)	358(3)	$32^3 \times 64$	350	64

→ Genprop production well underway

- computing: $\{\gamma^\mu, |z| \le 8, N_{Q^2} = 19, N_{\text{vec}} = 64\}$
- recall,

$$\xi = \frac{(p_1 z)-(p_2 z)}{(p_1 z)+(p_2 z)} = \frac{P_1 - P_2}{P_1 + P_2} \leftarrow P_i^z \text{ fixes } \xi$$

$$+$$

$$z_3 \text{ fixes } \nu$$

- broad longitudinal momenta $P_i^z \in \frac{2\pi}{L}\mathbb{Z}_7$

→ Goals:

π $\quad H^\pi_{u-d}(x,\xi,t)$

K $\quad H^K(x,\xi,t)$

N $\quad H^N_{u-d}(x,\xi,t), E^N_{u-d}(x,\xi,t), \&\ \tilde{H}, \tilde{E}$

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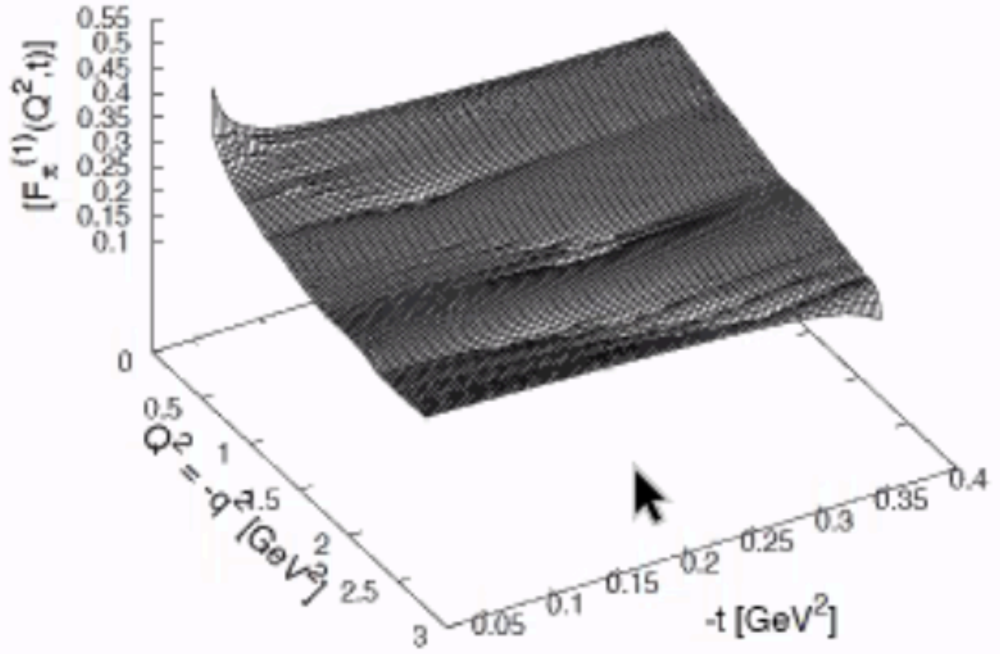
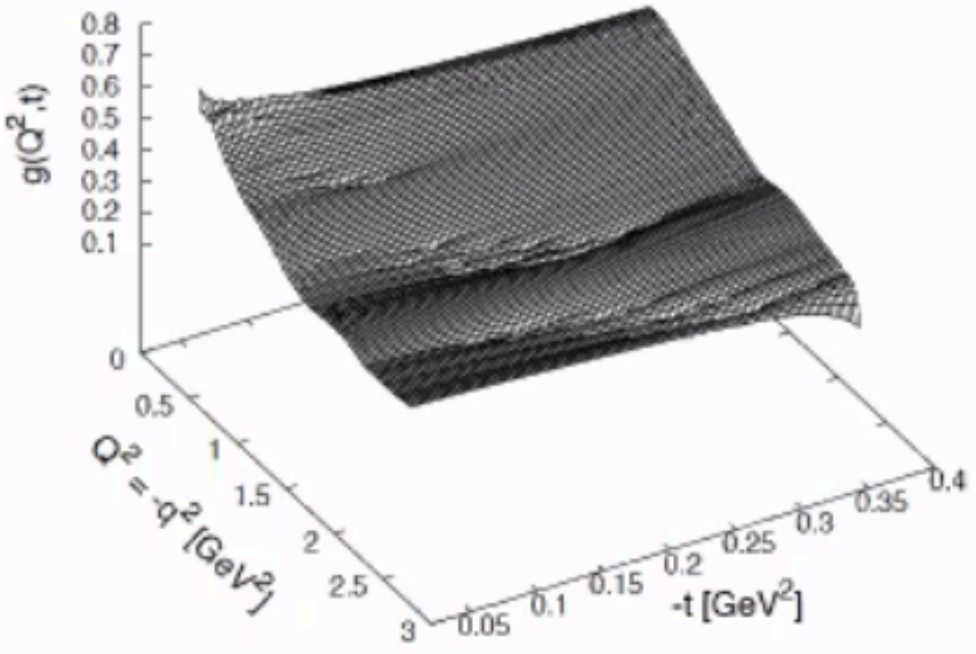
Pion off-shell electromagnetic form factors

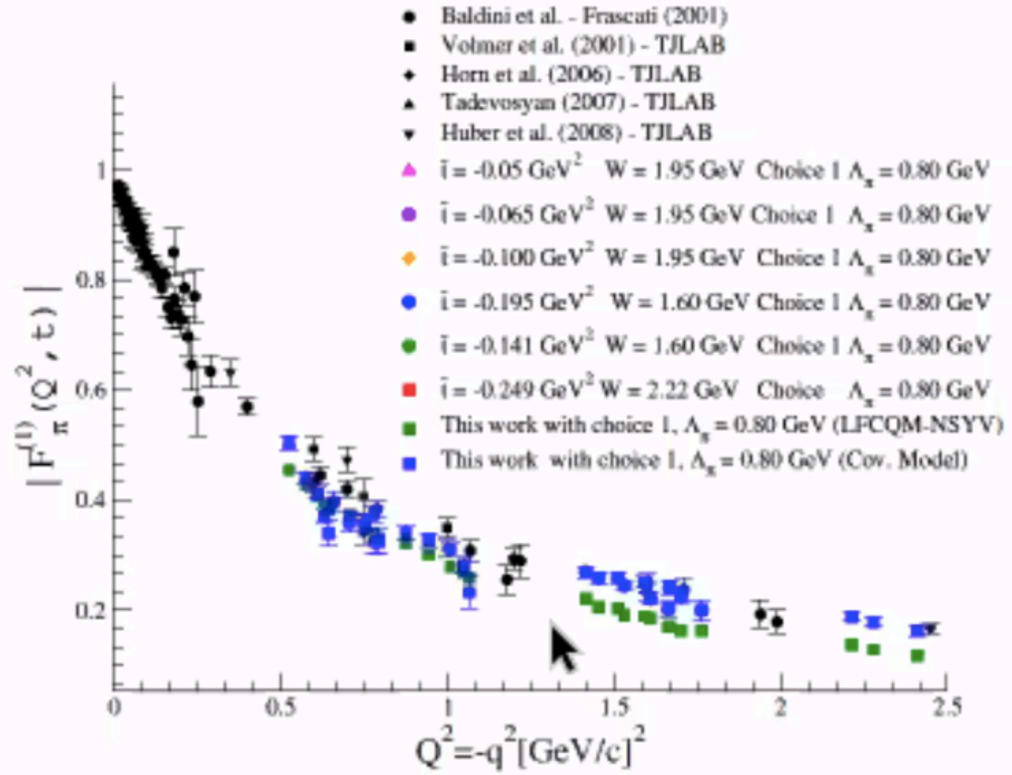
João Pacheco Bicudo Cabral del Melo

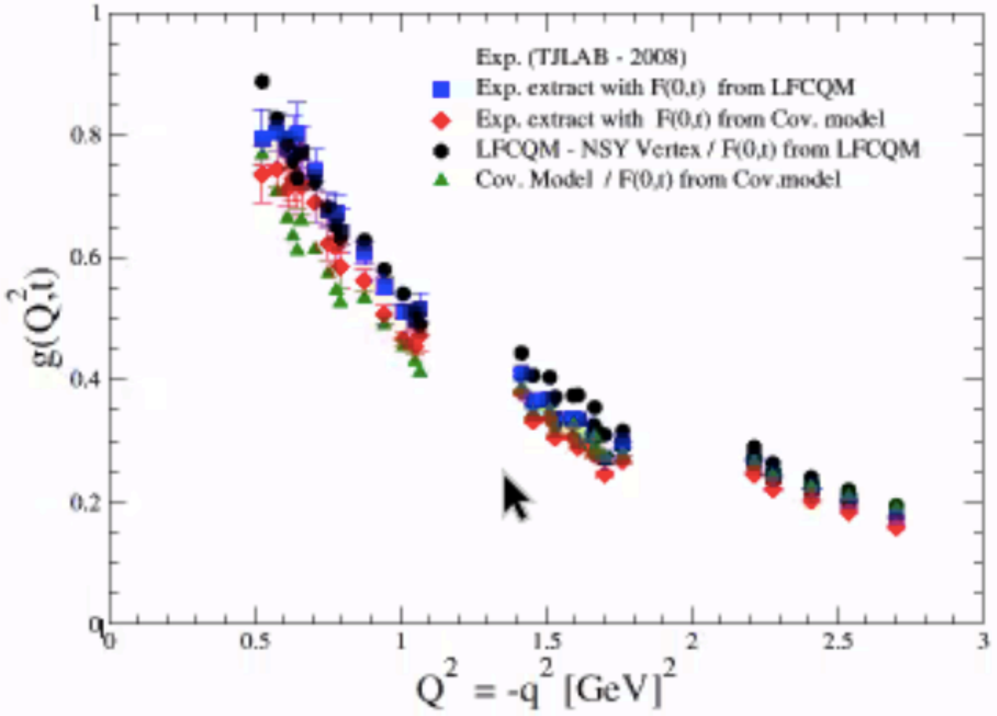




3-D electromagnetic pion form factor $F_1(Q^2, t)$

$F_1(Q^2, t) - F_1(0, t) + Q^2 g(Q \cdot t) = 0$





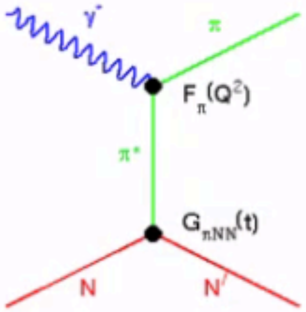
Light meson form factors from exclusive measurements

Stephen Kay

- To access higher Q^2, must measure F_π indirectly
  - Use the "pion cloud" of the proton via pion electroproduction $p(e, e'\pi^+)n$
- At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
- In the Born term model, F_π^2 appears as -

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)}g^2(t)F_\pi^2(Q^2,t)$$

- Drawbacks of this technique -
  - Isolating σ_L experimentally challenging
  - Theoretical uncertainty in F_π extraction $\rightarrow$ Model dependent

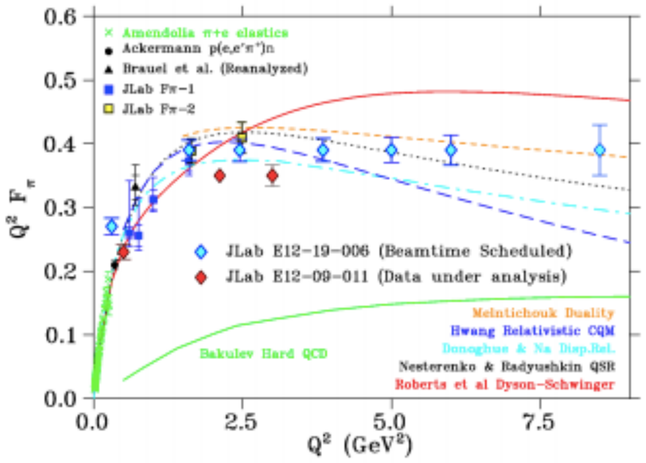


- The physical cross section for the electroproduction process is given by -

$$2\pi\frac{d^2\sigma}{dtd\phi} = \epsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\epsilon(\epsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi,$$

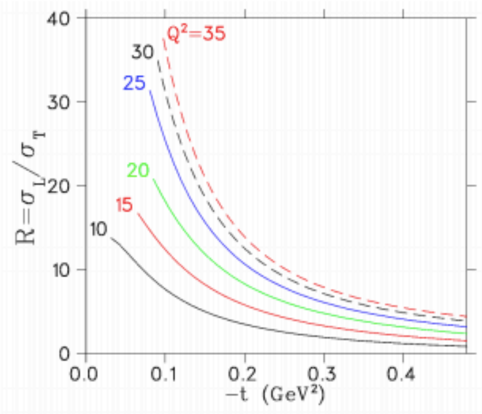
$$\epsilon = \left(1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$

- Measurements of the $p(e, e'\pi^+n)$ reaction at the EIC have the potential to extend the Q^2 reach of F_π measurements even further
- A challenging measurement however
  - Need good identification of $p(e, e'\pi^+n)$ triple coincidences
  - Conventional L-T separation not possible $\rightarrow$ would need lower than feasible proton energies to access low ϵ
- Utilise new EIC software framework to assess the feasibility of the study with updated design parameters
  - Feed in events generated from a DEMP event generator



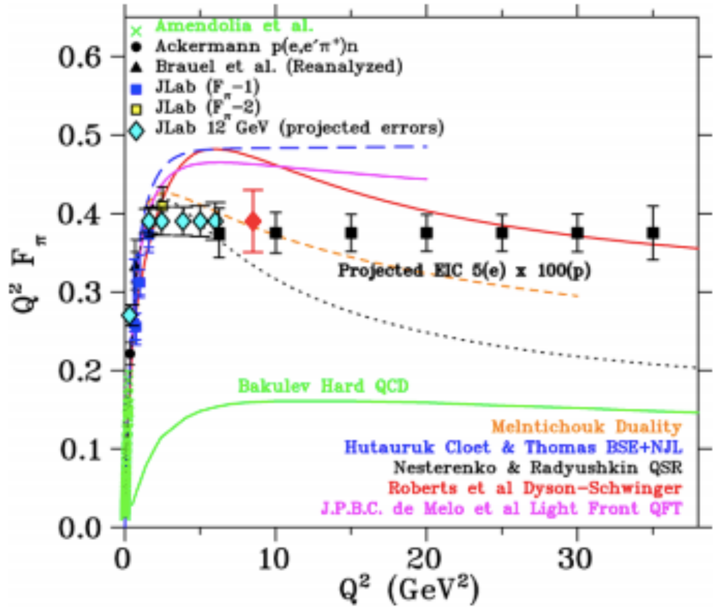
- New low Q^2 point will provide best comparison of the electroproduction extraction of F_π vs elastic $\pi + e$ data

- QCD scaling predicts $\sigma_L \propto Q^{-6}$ and $\sigma_T \propto Q^{-8}$
- At the high Q^2 and W accessible at the EIC, phenomenological models predict $\sigma_L \gg \sigma_T$ at small $-t$
- Can attempt to extract σ_L by using a model to isolate dominant $d\sigma_L/dt$ from measured $d\sigma_{UNS}/dt$
- Critical to confirm the validity of the model used!



Predictions are assuming $\epsilon > 0.9995$ with the kinematic ranges seen earlier

T.Vrancx, J. Ryckebusch, PRC 89(2014)025203



Pion/kaon structure in Primakoff reactions: COMPASS and COMPASS++/AMBER

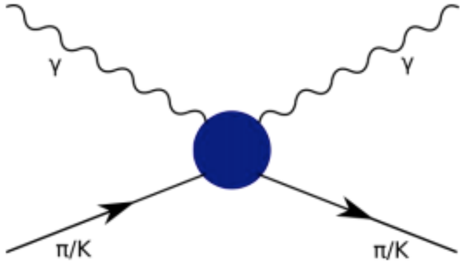
Andrei Maltsev

Compton scattering cross-section:

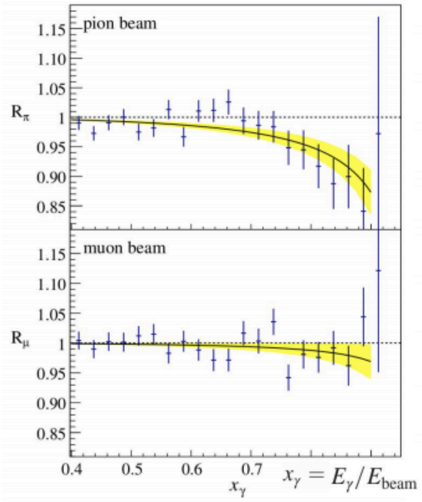
$$\frac{d\sigma}{d\Omega_{\pi\gamma}} = \boxed{\frac{\alpha^2(s^2z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2}} - \frac{\alpha m_\pi^3 (s - m_\pi^2)^2}{4s(sz_+ + m_\pi^2 z_-)}\left(z_-^2(\alpha_\pi - \beta\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta\pi)\right)$$

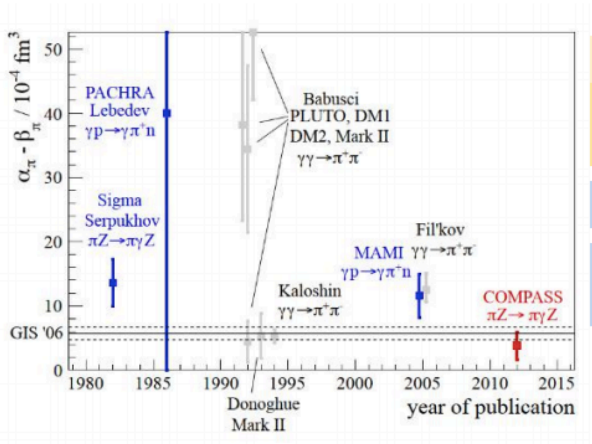
point-like meson

$$z_\pm = 1 \pm \cos\theta_{cm}$$



Pion polarizability at COMPASS





assuming $\alpha_\pi + \beta_\pi = 0$:

COMPASS: $\alpha_\pi=(2.0\pm0.6_{stat}\pm0.7_{syst})\times10^{-4}$ fm³

χPT: $\alpha_\pi \approx 2.8\times10^{-4}$ fm³

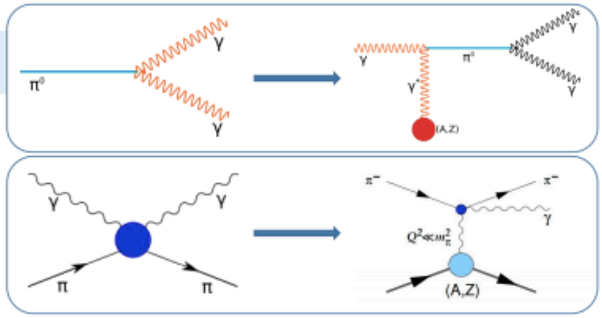
Serpukhov: $\alpha_\pi = 6.8 \pm 1.4_{stat} \pm 1.2_{syst}$ 10^{-4} fm³

PRL 114, 062002 (2015)

2012 data are still under analysis: new results on pion polarizability are expec

How to access polarizabilities in experiment?

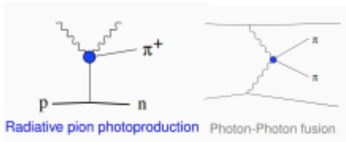
Idea of Henry Primakoff:
EM field of nucleus = photon target!



Assuming: one-photon exchange, $Q^2 \ll m_\pi^2$
Weizsäcker-Williams approximation:

$$\frac{\mathrm{d}\sigma_{\pi^- + (Z,A) \to (Z,A) + \pi^-\gamma}}{\mathrm{d}s\mathrm{d}t\mathrm{d}Q^2} = \frac{Z^2\alpha}{\pi(s - m_\pi^2)} \cdot F_{eff}^2(Q^2) \cdot \frac{Q^2 - Q_{min}^2}{Q^4} \cdot \frac{\mathrm{d}\sigma_{\pi\gamma\to\pi\gamma}}{\mathrm{d}t}$$

$$Q_{\min} = (s - m_\pi^2)/2E_{\text{beam}}$$

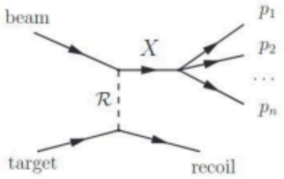


Extract polarizabilities from $\pi^- + (Z,A) \to \pi^- + \gamma + (Z,A)$

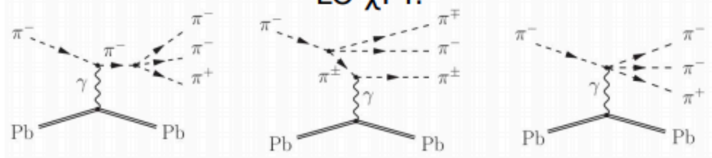
$$R_\pi = \left(\frac{d\sigma_{\pi\gamma}}{dx_\gamma}\right) \Big/ \left(\frac{d\sigma_{\pi\gamma}^0}{dx_\gamma}\right) = 1 - \frac{3}{2}\frac{m_\pi^3}{\alpha}\frac{x_\gamma^2}{1 - x_\gamma}\alpha_\pi, \quad x_\gamma = E_\gamma/E_{\text{beam}}$$

Chiral dynamics in πγ→πππ

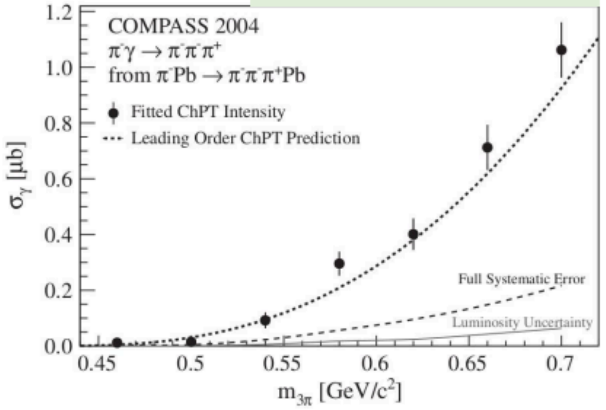
χPT test: **π⁻γ→π⁻π⁻π⁺**
cross section at threshold



LO χPT:



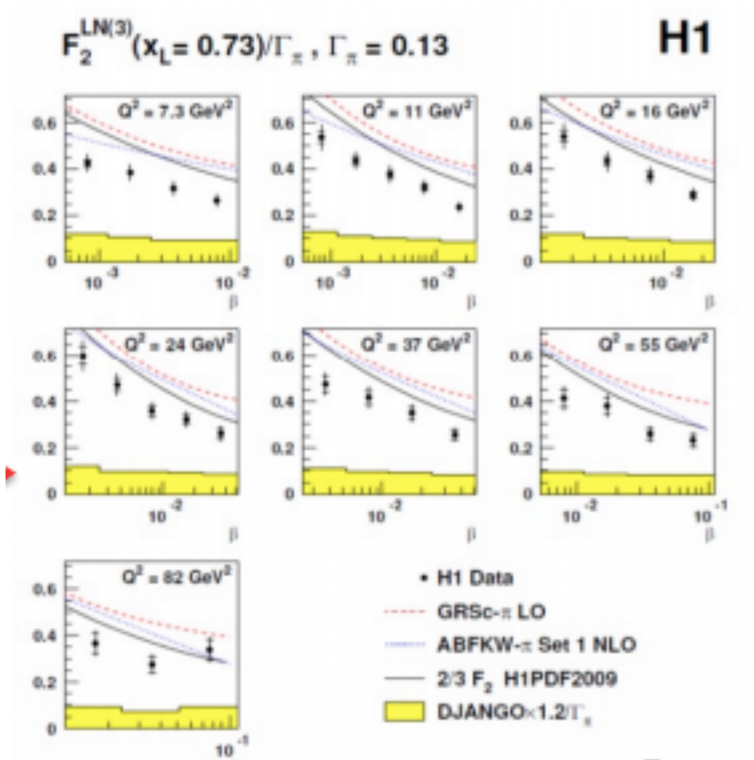
PRL 108, 192001 (2012)



Also possible to study **π⁻γ→π⁻π⁰π⁰**

Further prospects for pion structure measurements at EIC

Thia Keppel



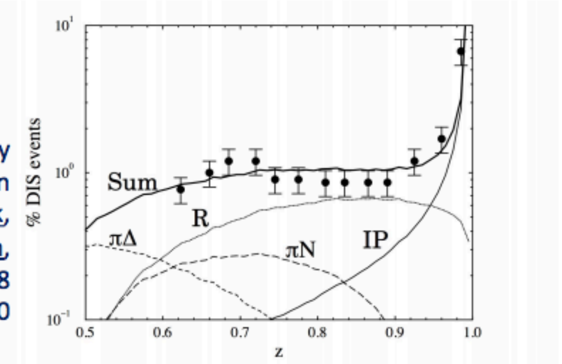
DESY 09-185 Eur. Phys. J. C68 (2010) 381

A lot of fascinating questions remain!

- Understand diffractive difference
- Identify/subtract diffractive component (from all targets)
- Identify/subtract/learn about theoretical "backgrounds"
  - Deploy neutron and proton (and other?) beams
  - Deploy multiple tags – p,n,.., study isospin expectations
  - Expand kinematic range – in x,Q,t,z,..
- Will need close experiment-theory collaboration, large and disparate data set to disentangle
- COMPASS data will help

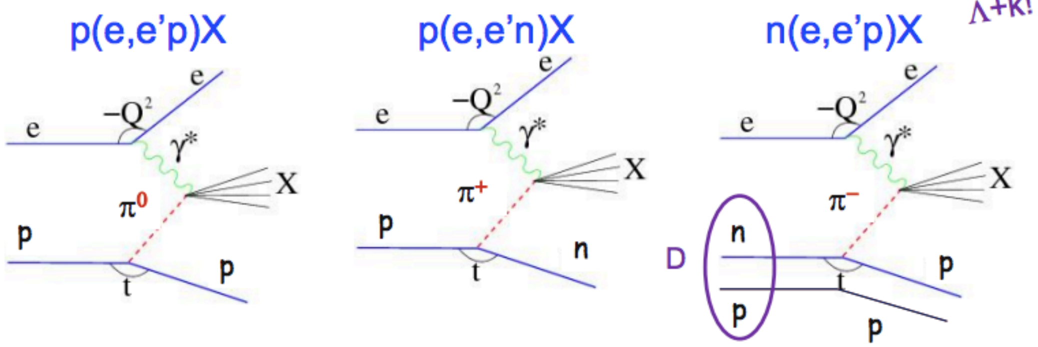
The EIC will enable all of this ☺

Analysis of preliminary ZEUS (leading proton tag) data by Szczurek, Nikolaev and Speth, Phys. Lett. B428 (1998) 383-390

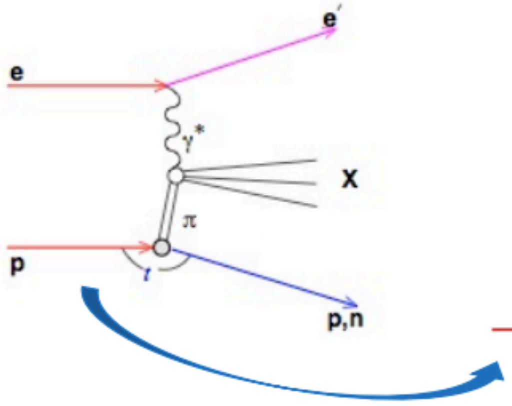


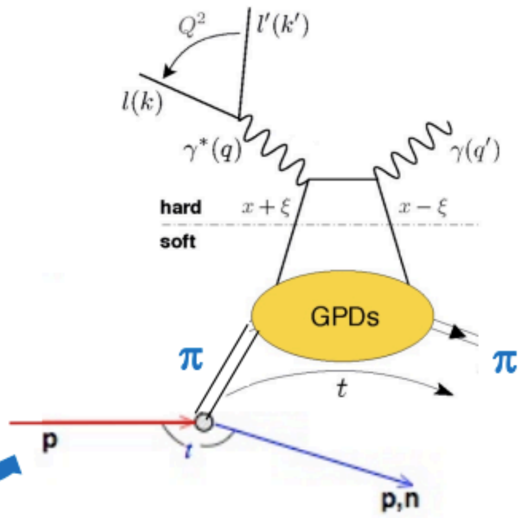
- Important to measure tagged p *and* n *and* d!

Also Λ+k!



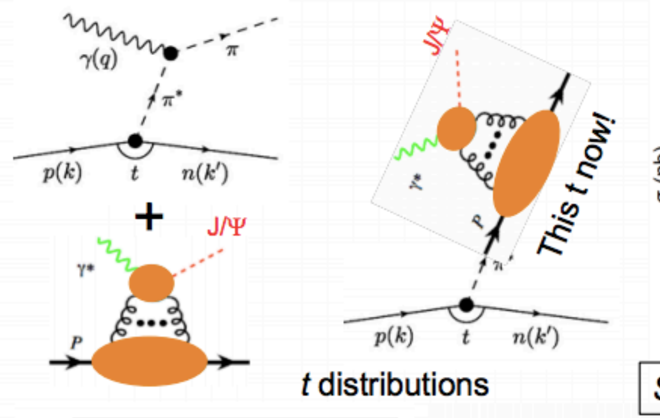
Effective Pion Target

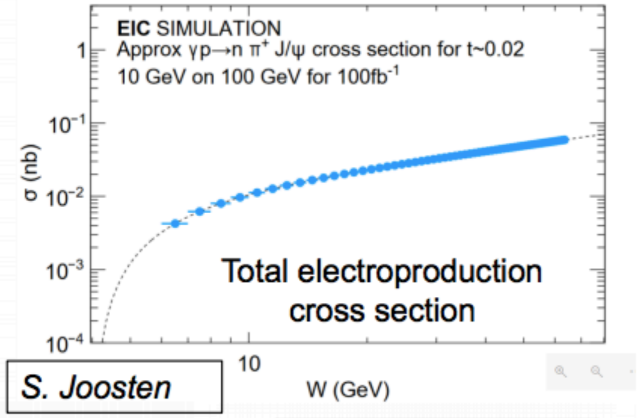




Deeply Virtual Compton Scattering *from a pion*

Elastic J/Ψ production *off the pion* at an EIC





S. Joosten

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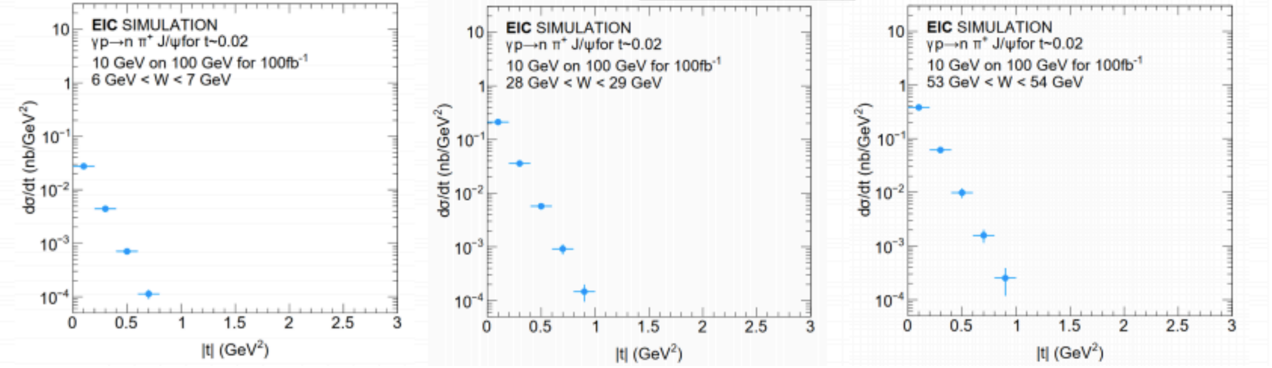

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