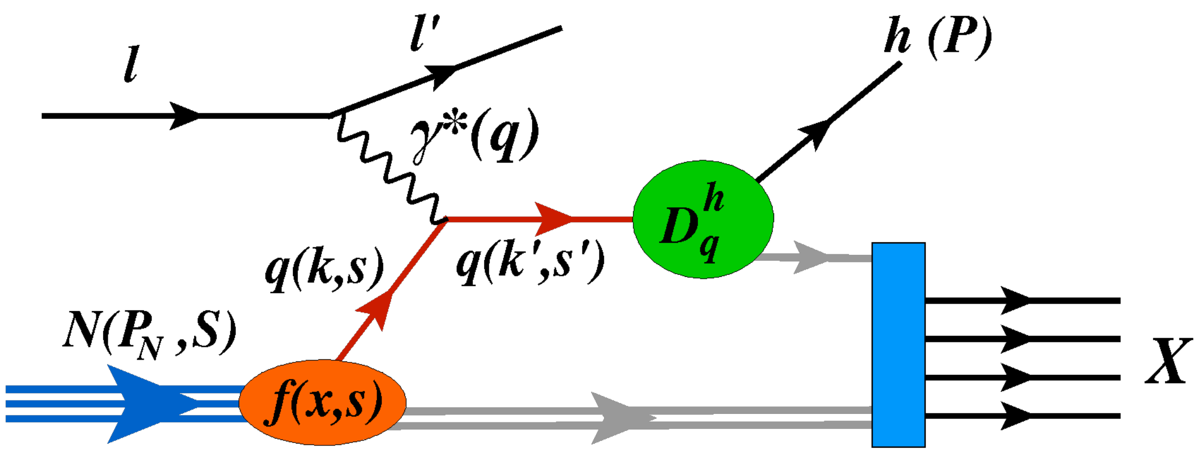
Summary of Parallel Sessions 2 and 5:

Nucleon and nuclear structure and hadronization
Collective effects in nucleons and nuclei

Convenors:

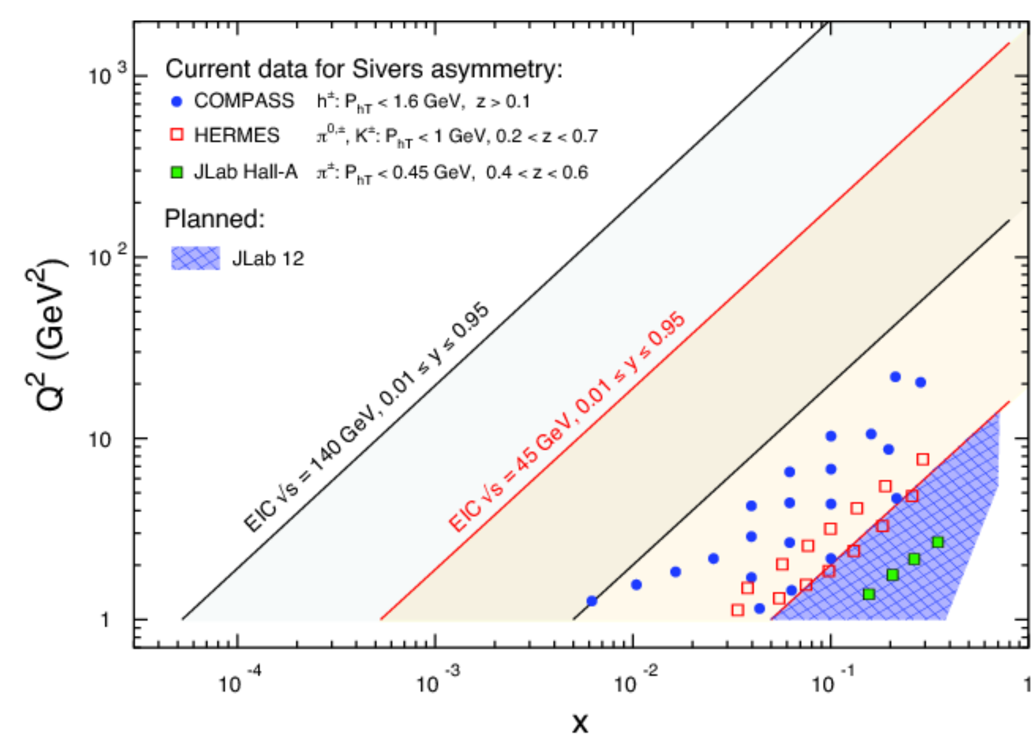
Gunar Schnell, Hrayr Matevosyan,
Marta Ruspa, Yoshitaka Hatta

SIDIS program in EIC



- *Flavour separation in collinear PDFs.*
- *Polarised PDFs.*
- *TMD (polarized) PDFs.*

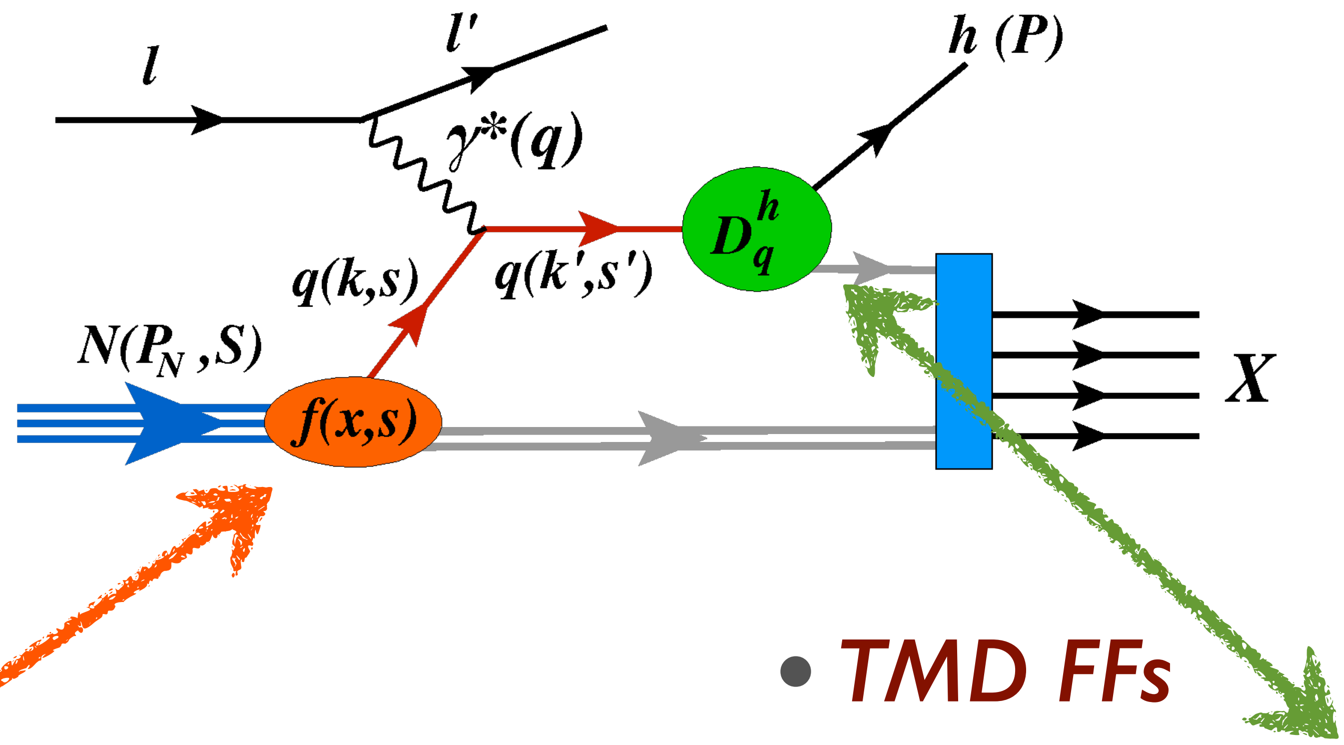
EIC extended kinematic coverage



Accessing TMDs in SIDIS

- ***Measurement of the <u>transverse momentum</u> of the produced hadron in SIDIS provides access to <u>TMD PDFs/FFs</u>.***

  - *SIDIS Process with TM of hadron measured.*



- *TMD PDFs*

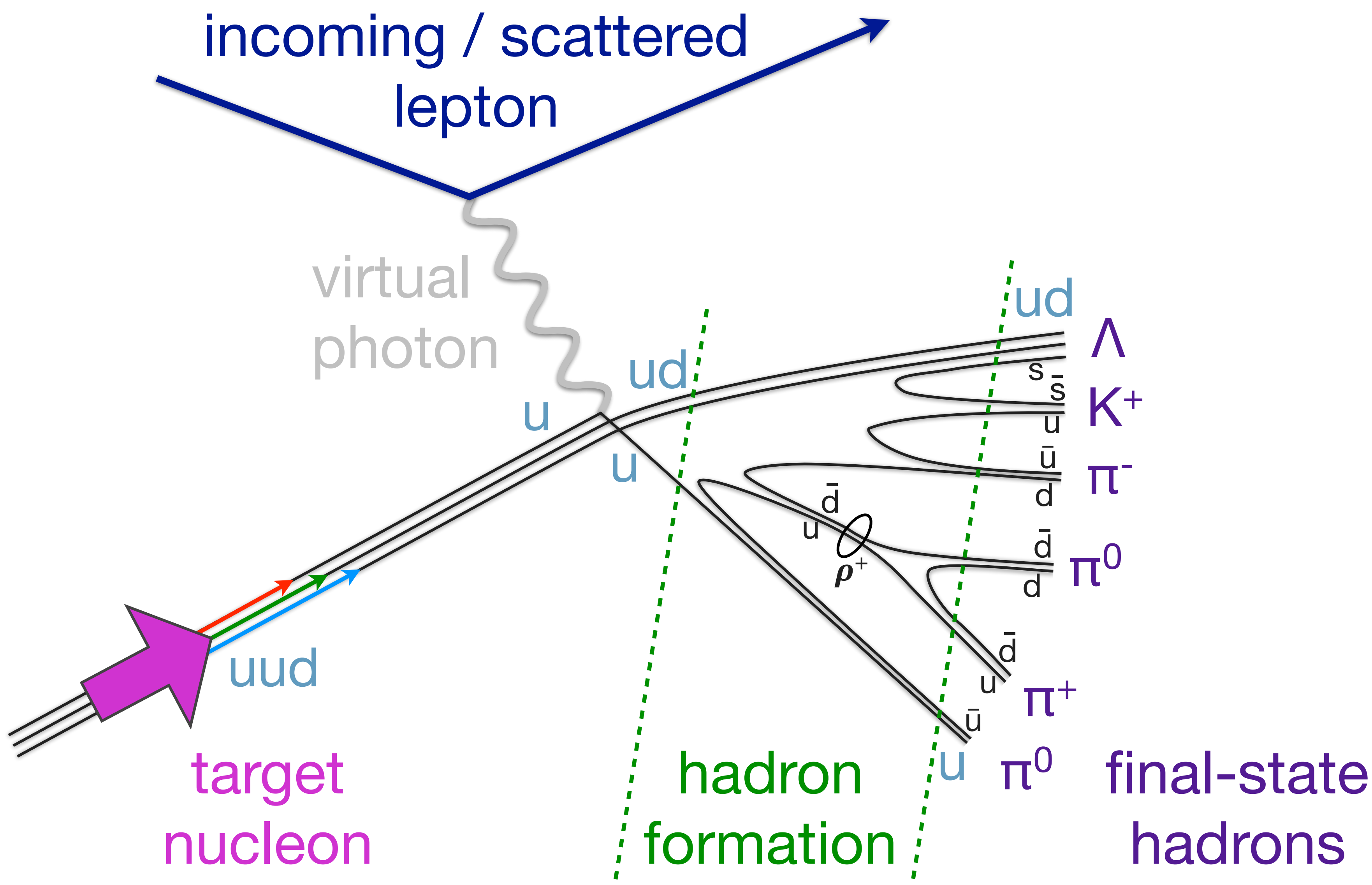
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1 \, h_{1T}^\perp$

- *TMD FFs*

q/h	U
U	D_1
L	
T	$H_1^\perp$

✶unpol/spinless h!

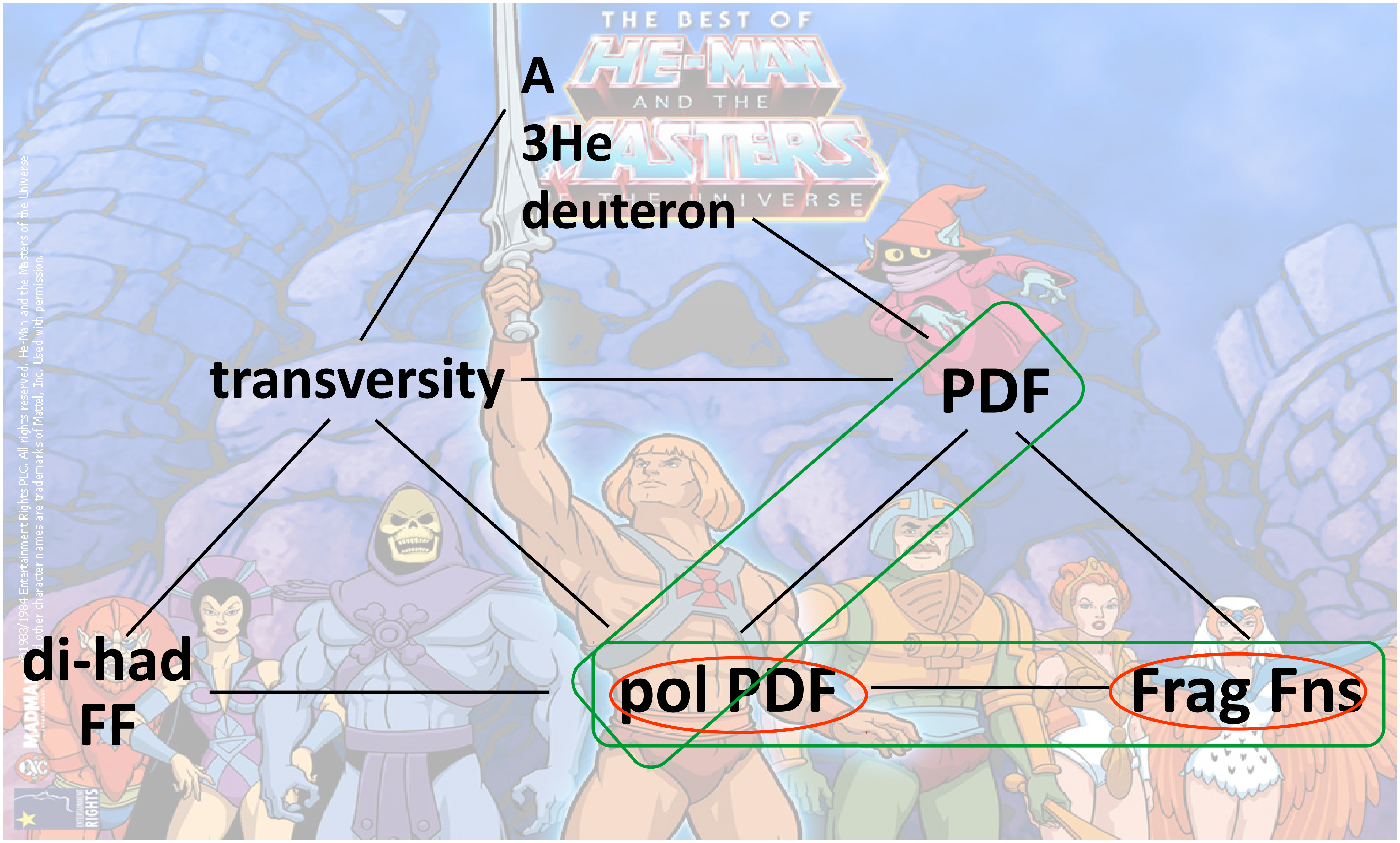
Accessing Parton Properties at EIC



- Need the knowledge on PDFs and (in particular) FFs.
- Their extractions not necessarily independent, but *naturally interlinked*.

Masters of the Universe

A. Accardi



towards “universal” (combined) fits

5+ years: new fitting methods

A. Accardi

- More computing power, efficient implementations
  - **New fitting, analysis methods**
- In traditonal fits:
  - Detailed χ^2 scans, refined statistical analysis
- Monte Carlo fitting methods:
  - **NNPDF**: bootstrap + neural network fit *→ Nocera's talk*
  - **JAM**: bootstrap + Iterative Monte Carlo (IMC) approach

NNFF1.0

→ Sato, Ethier et al (since 2015)

Large number of parameters, trustable uncertainty estimates

- Self organizing maps *→ Liuti et al.*

JAM 17

A. Accardi

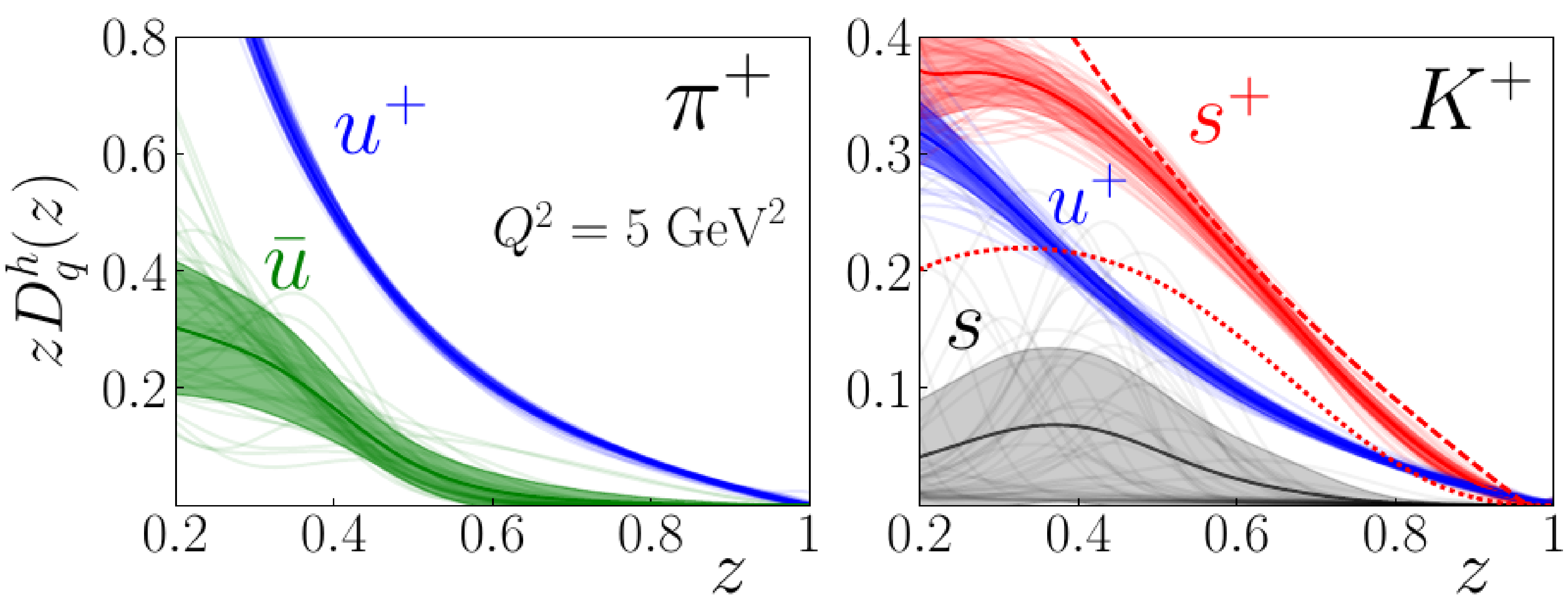
First simultaneous extraction of spin-dependent parton distributions and fragmentation functions from a global QCD analysis

J. J. Ethier,[1,2] N. Sato,[3] and W. Melnitchouk[2]

[1] *College of William and Mary, Williamsburg, Virginia 23187, USA*
[2] *Jefferson Lab, Newport News, Virginia 23606, USA*
[3] *University of Connecticut, Storrs, Connecticut 06269, USA*

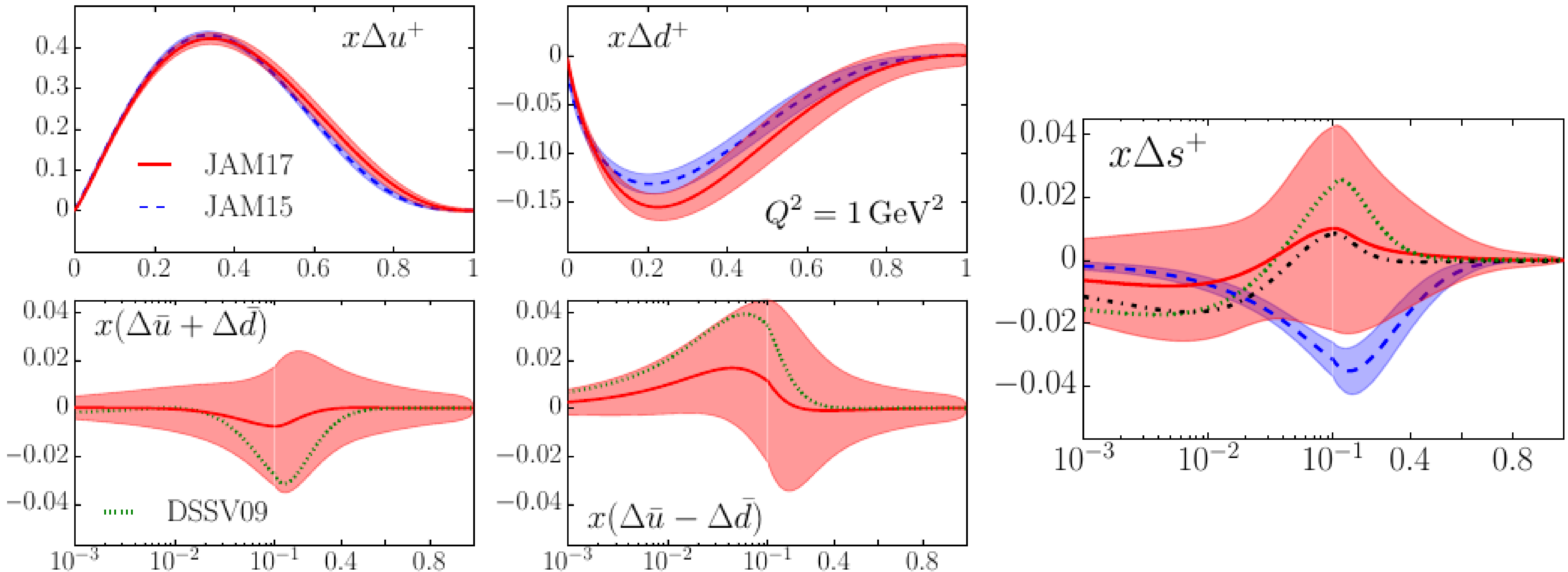
Jefferson Lab Angular Momentum (JAM) Collaboration

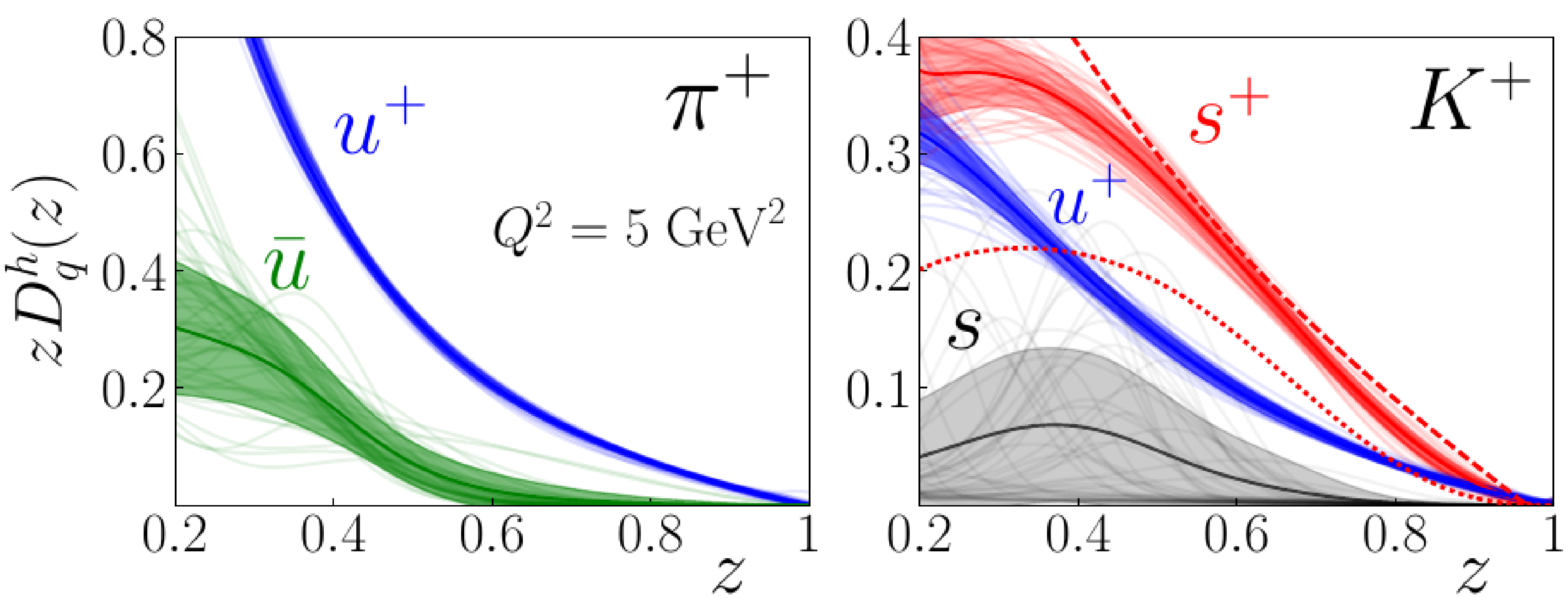
(Dated: May 18, 2017)



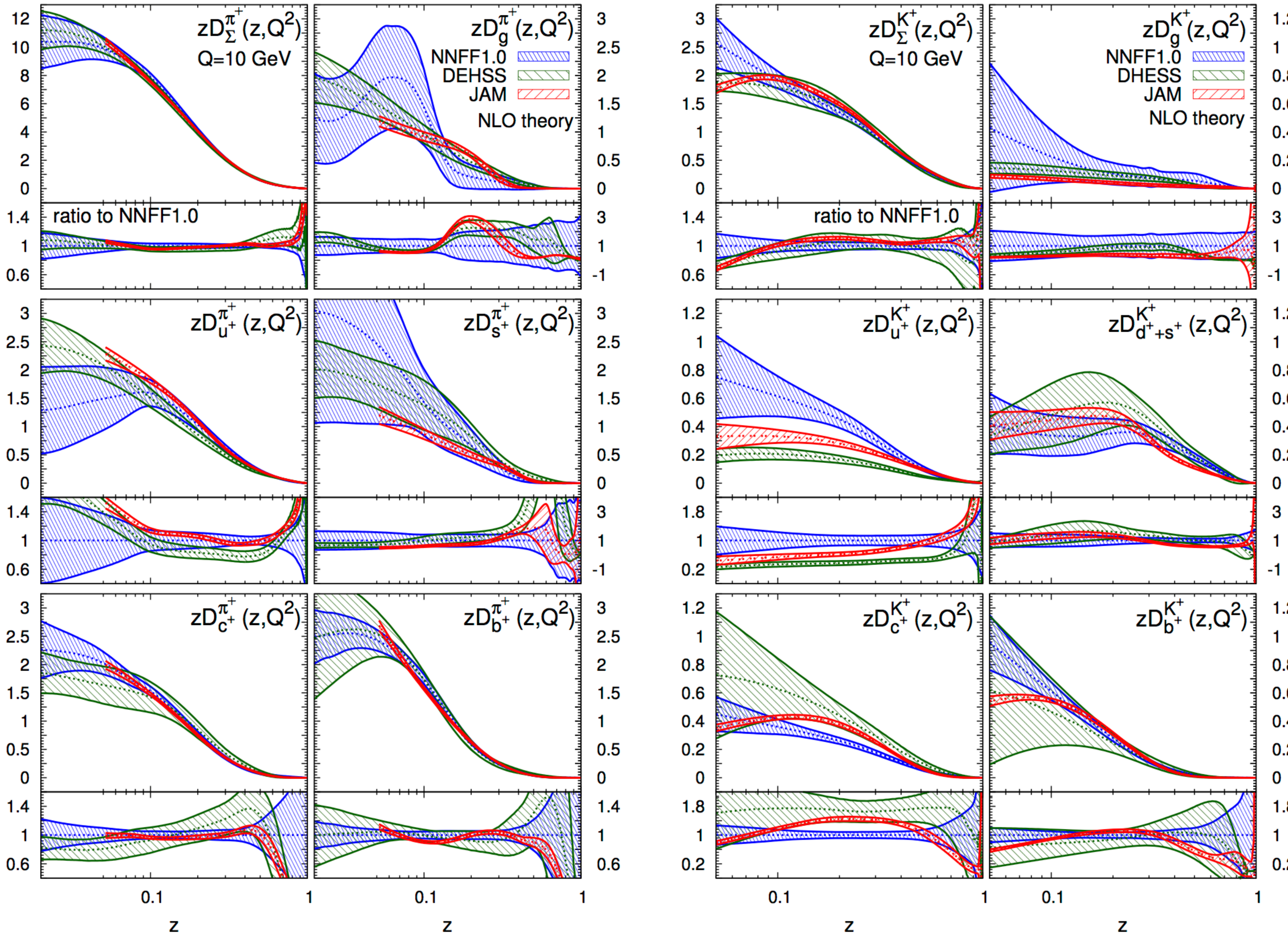
JAM 17

A. Accardi

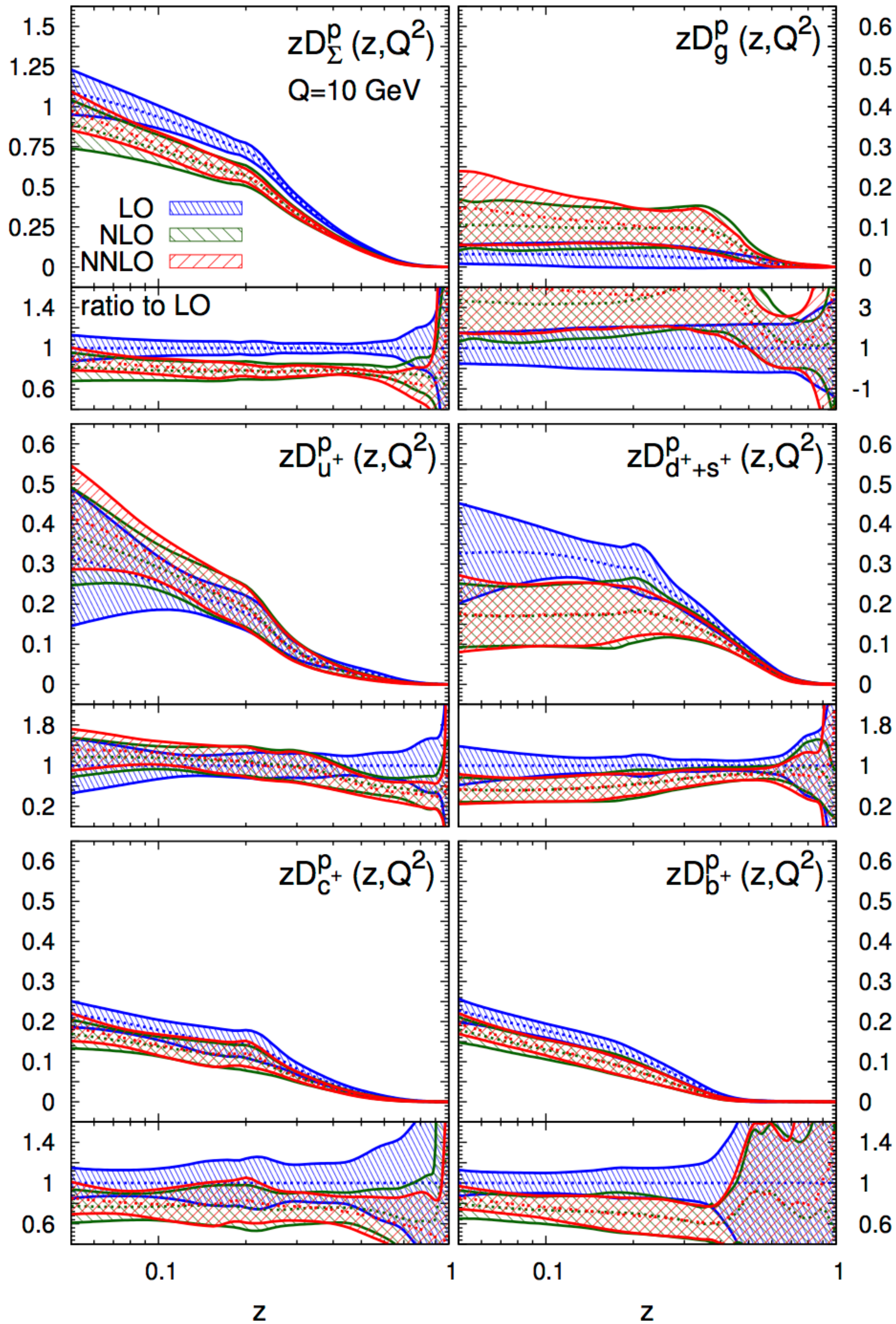




Comparison with other recent FF sets: π^+ and K^+



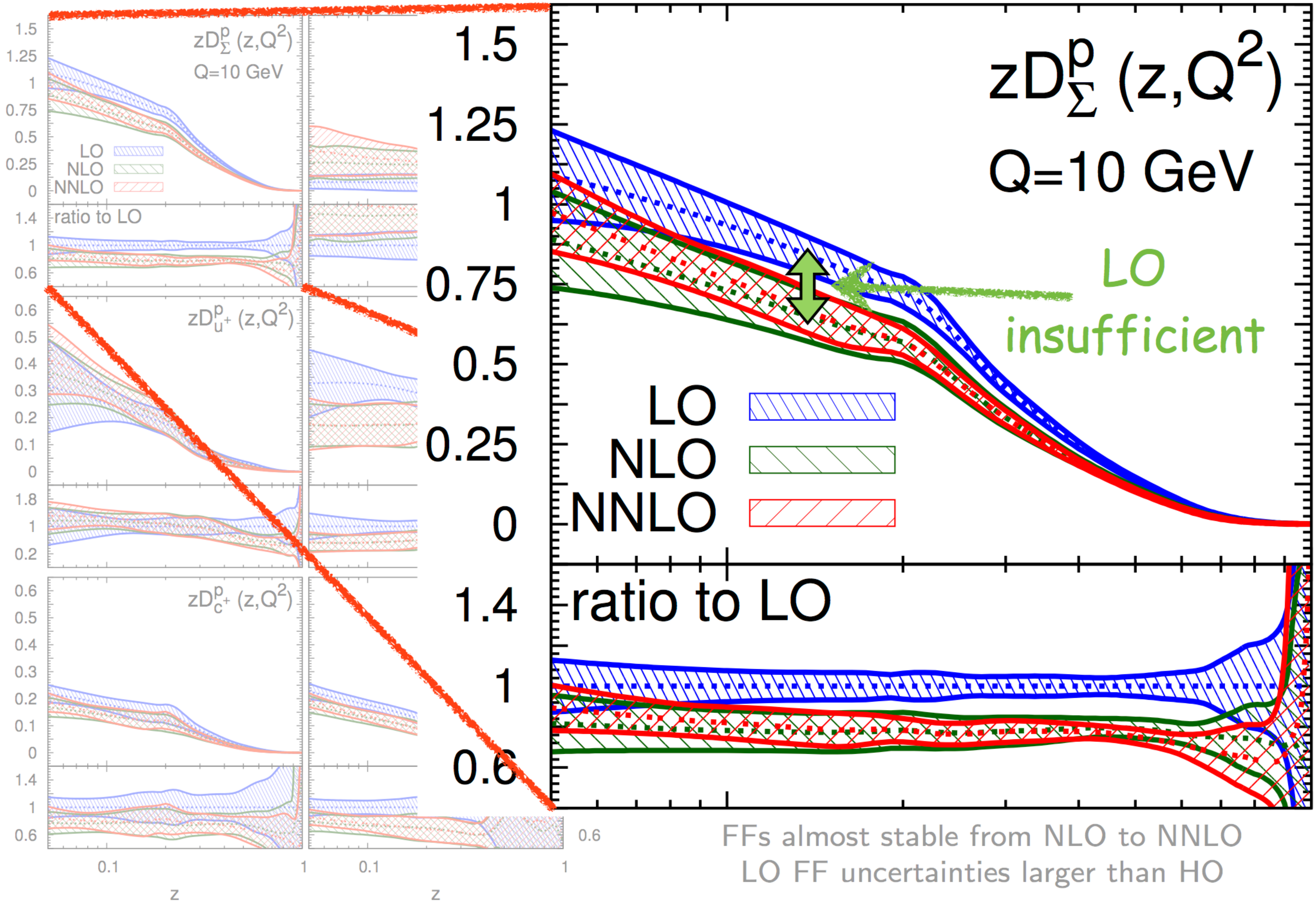
Fit quality vs perturbative order: p



Exp.	$N_{\rm dat}$	LO $\chi^2/N_{\rm dat}$	NLO $\chi^2/N_{\rm dat}$	NNLO $\chi^2/N_{\rm dat}$
BELLE	29	0.10	0.31	0.50
BABAR	43	4.74	3.75	3.25
TASSO12	3	0.69	0.70	0.72
TASSO14	9	1.32	1.25	1.22
TASSO22	9	0.98	0.92	0.93
TPC	20	1.04	1.10	1.08
TPC-UDS	–	–	–	–
TPC-C	–	–	–	–
TPC-B	–	–	–	–
TASSO30	2	0.25	0.19	0.18
TASSO34	6	0.82	0.81	0.78
TASSO44	–	–	–	–
TOPAZ	4	0.79	1.21	1.19
ALEPH	26	1.36	1.43	1.28
DELPHI	22	0.48	0.49	0.49
DELPHI-UDS	22	0.47	0.46	0.45
DELPHI-B	22	0.89	0.89	0.91
OPAL	–	–	–	–
SLD	36	0.66	0.65	0.64
SLD-UDS	36	0.77	0.76	0.78
SLD-C	36	1.22	1.22	1.21
SLD-B	35	1.12	1.29	1.33
TOTAL	360	1.31	1.23	1.17

Excellent perturbative convergence
FFs almost stable from NLO to NNLO
LO FF uncertainties larger than HO

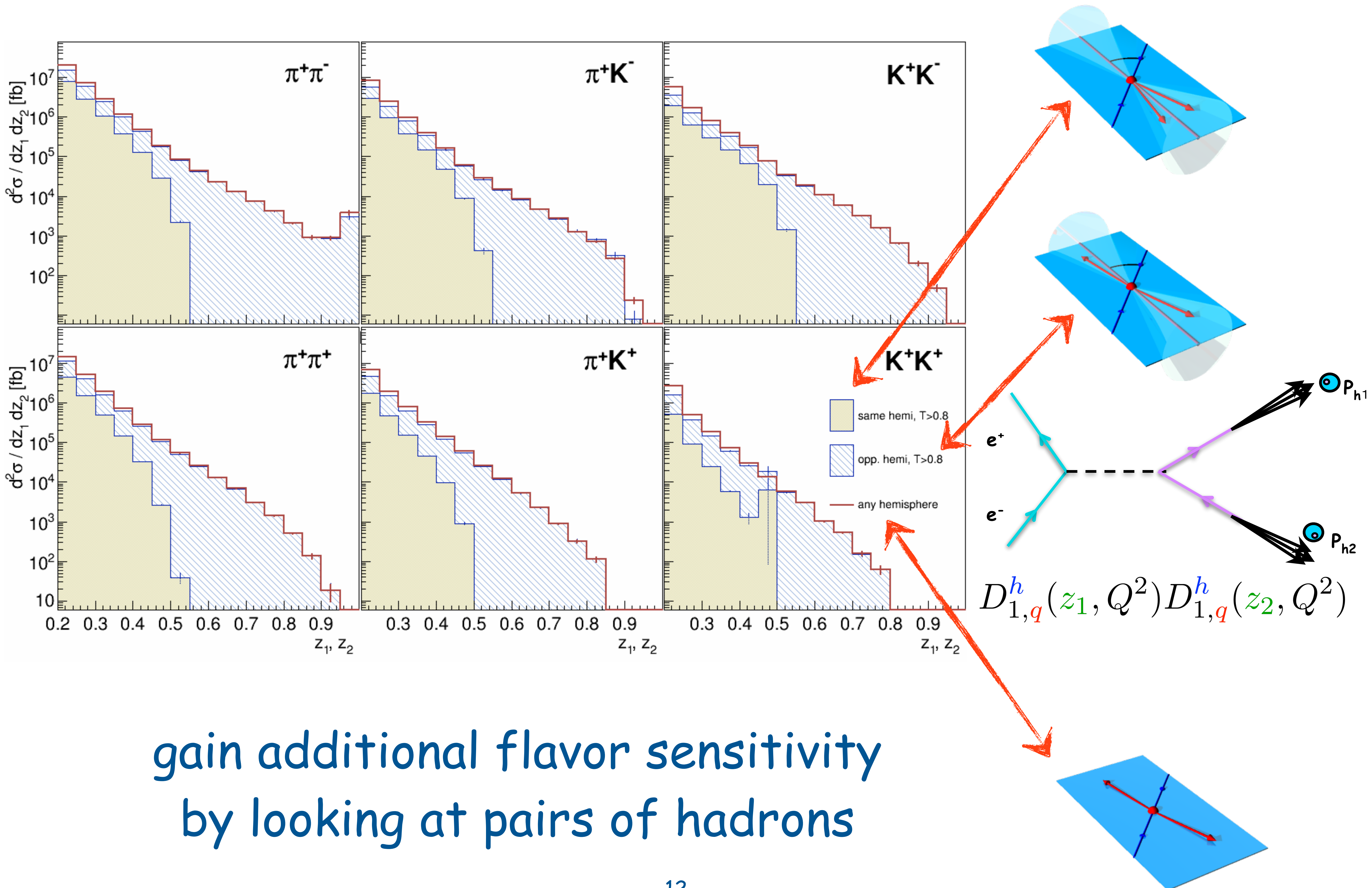
Fit quality vs perturbative order: p



FFs almost stable from NLO to NNLO
LO FF uncertainties larger than HO

Additional FF data from e+e-

R. Seidl

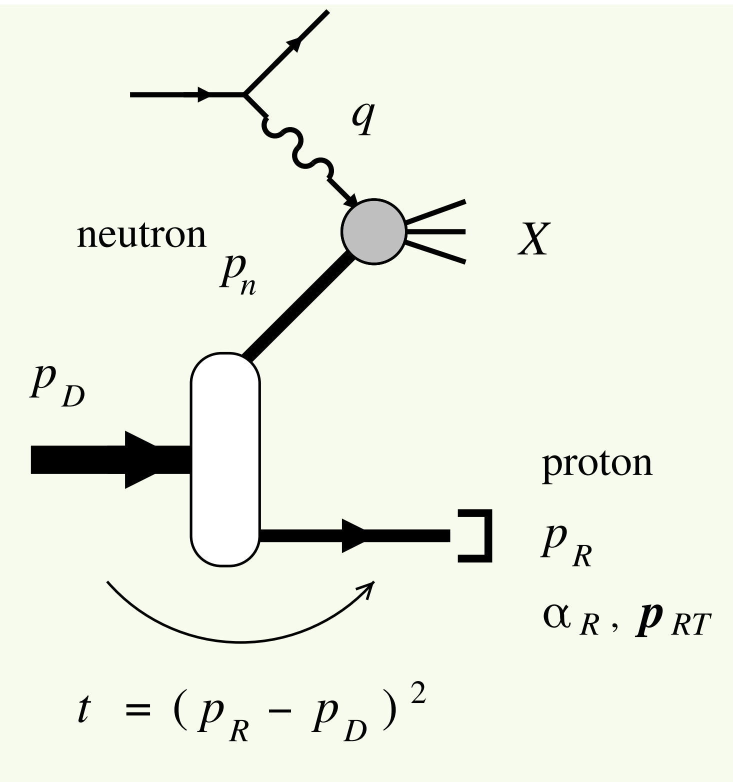


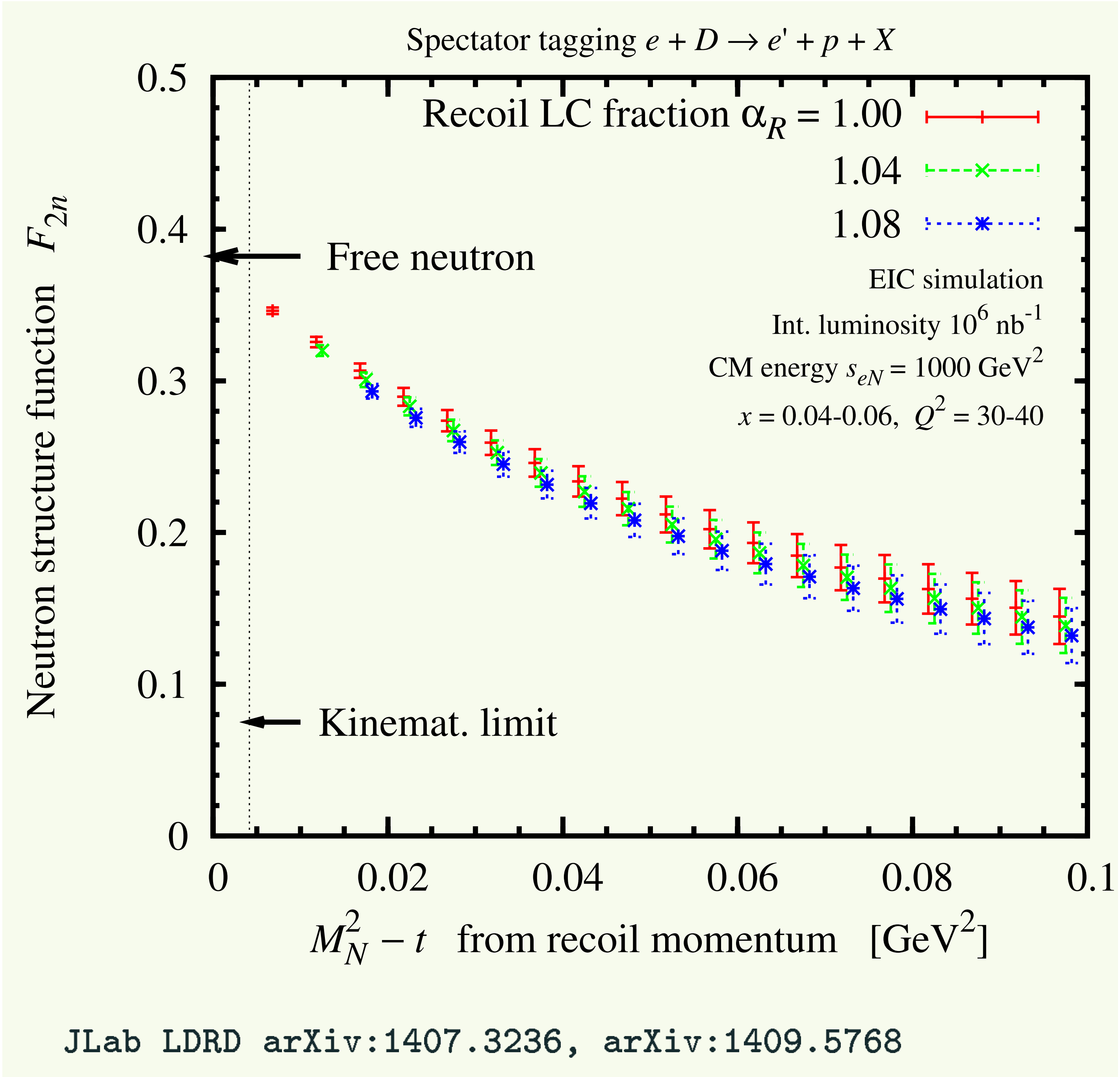
gain additional flavor sensitivity by looking at pairs of hadrons

Tagged Structure Functions

W. Cosyn

detect recoil proton from deuteron target to study neutron structure





Tagged Structure Functions

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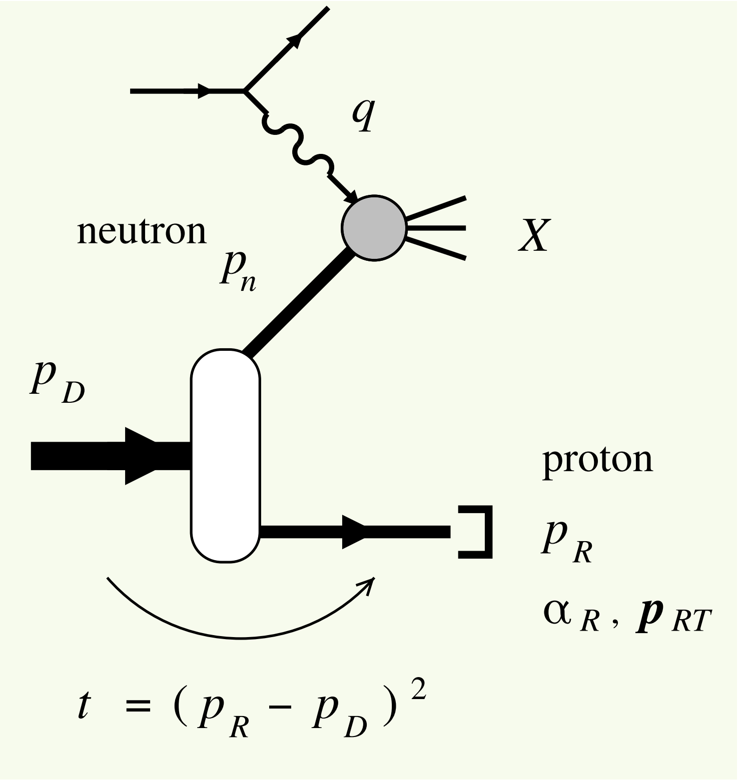
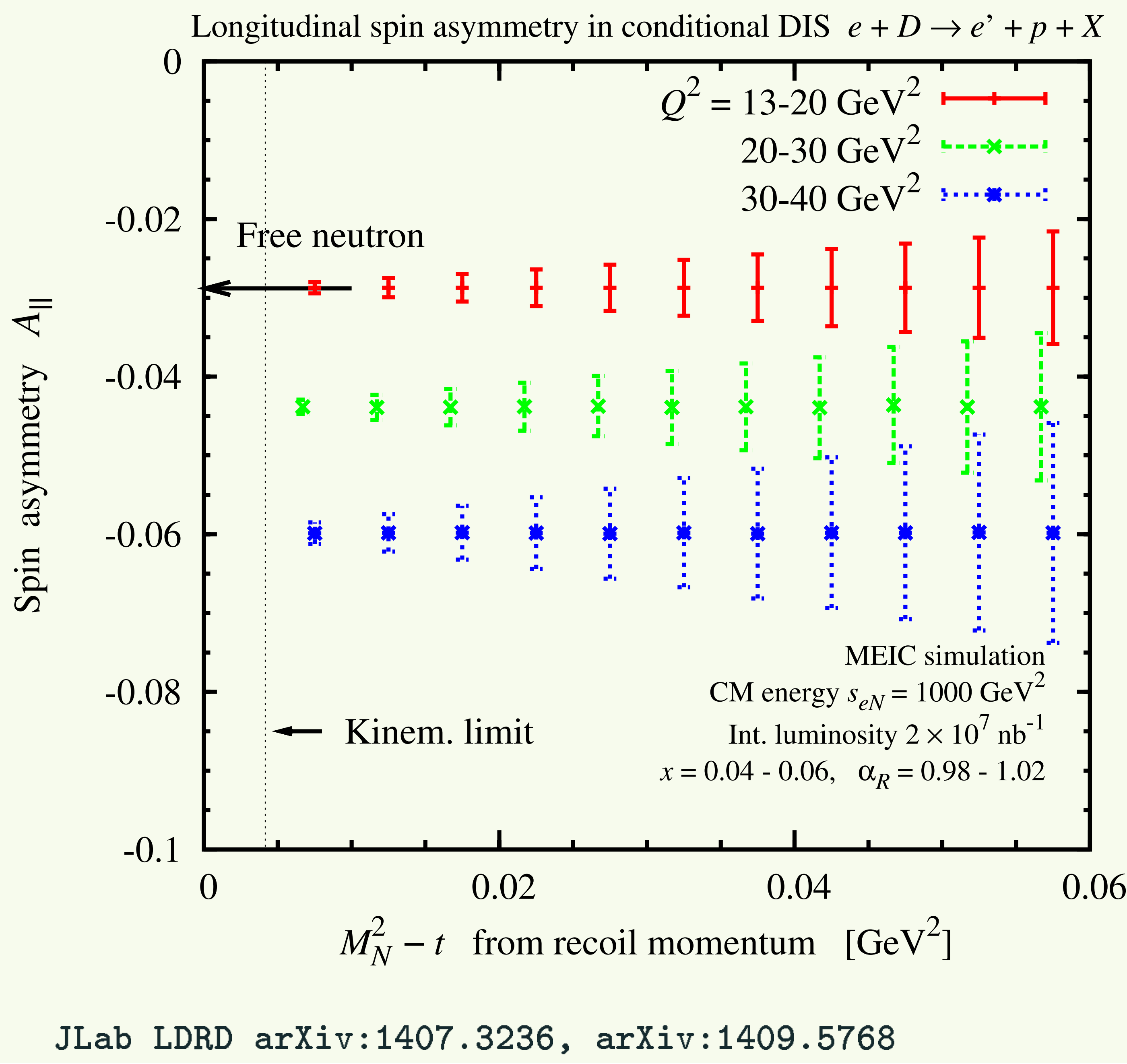
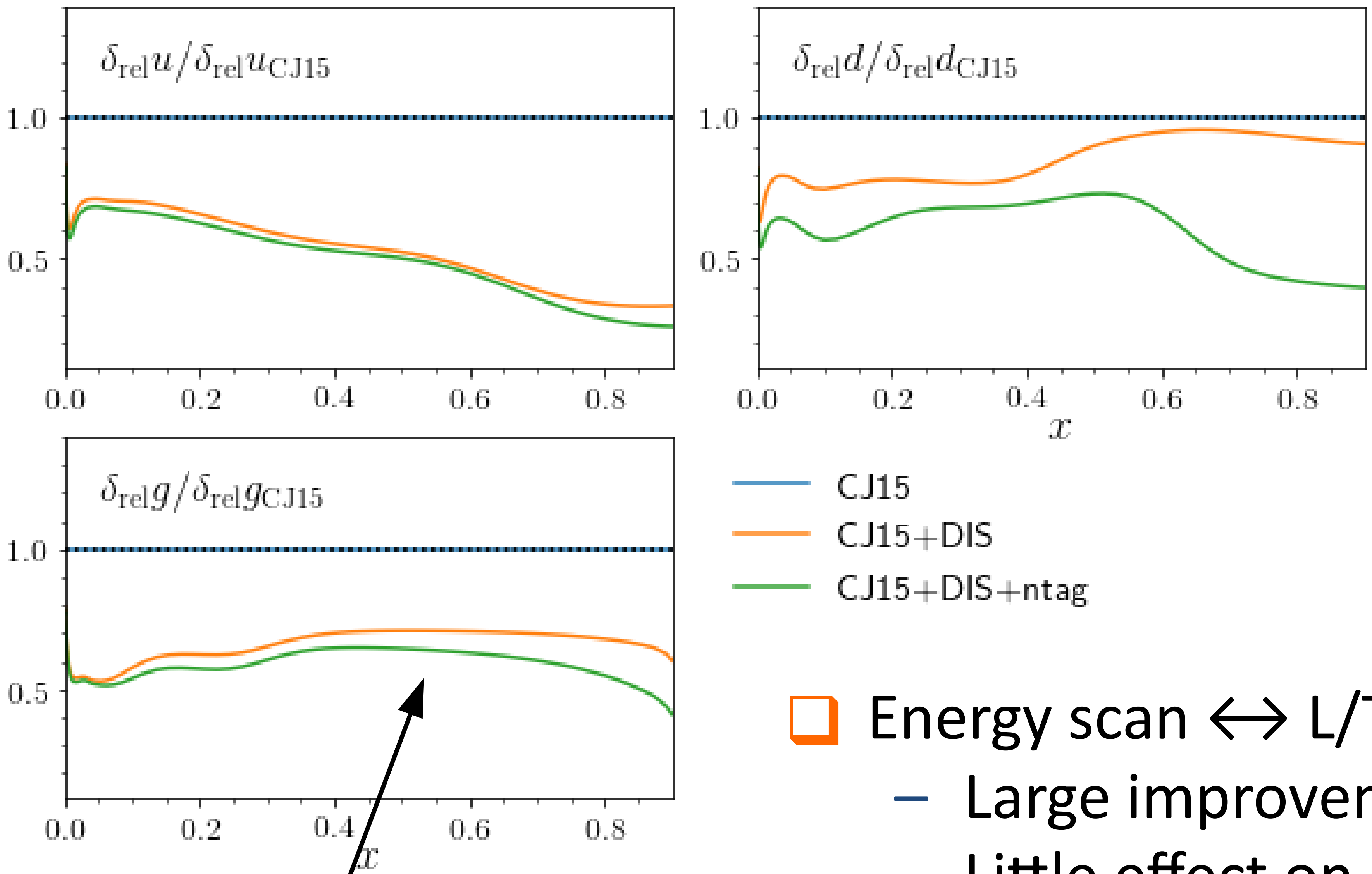




can also look at helicity distributions of neutron

Impact - summary

A. Accardi



40-50% better d-quarks

40-50% better gluons

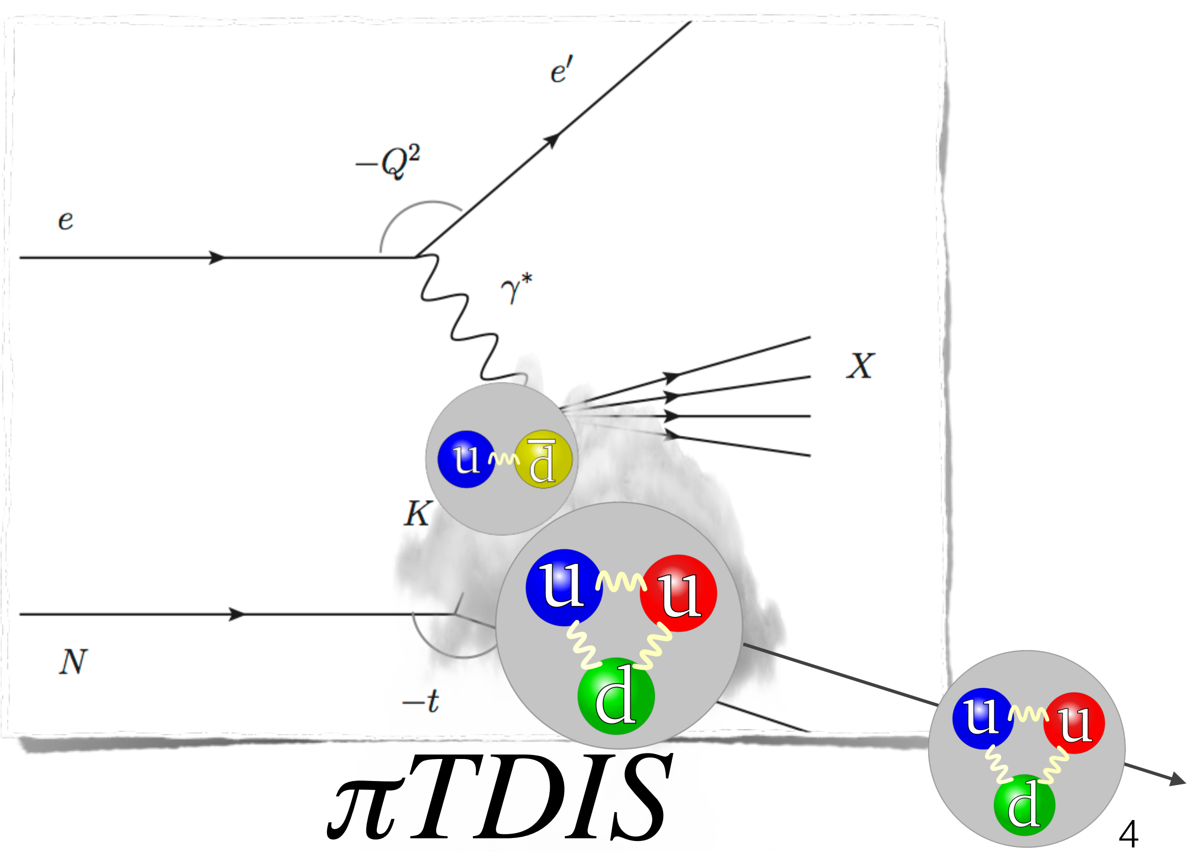
- Energy scan ↔ L/T separation
  - Large improvement in gluon uncertainty
  - Little effect on *d*-quarks
  - (CC have very little effects on u,d,g)
- Tagged neutrons
  - Noticeable improvement for d-quarks u
  - Some effects on gluons

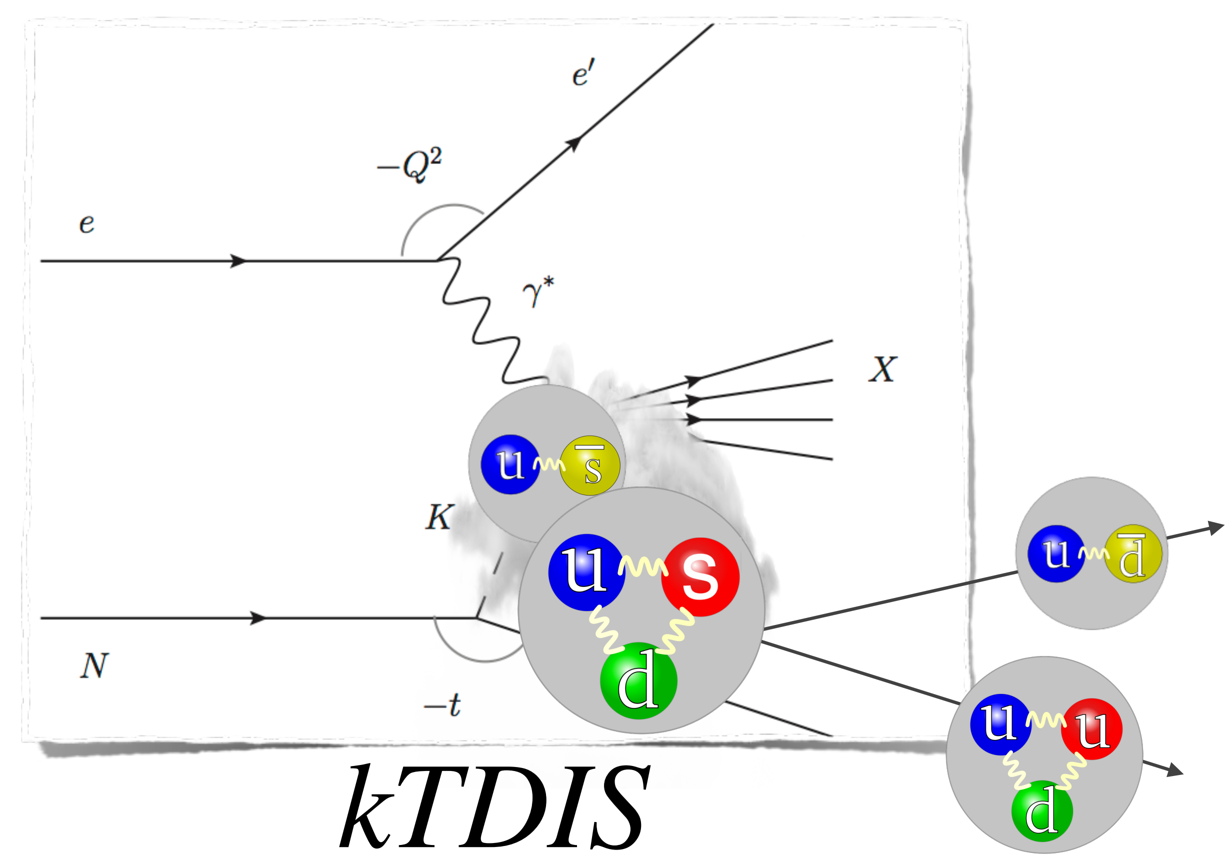
Tagging method to study meson structure

K. Park

Tagged Deep Inelastic Scattering (TDIS)

- Sullivan Process
  .. provides reliable access to a meson target as t becomes space-like (the meson pole dominance of the process)
- Direct measure the mesonic-nucleon content

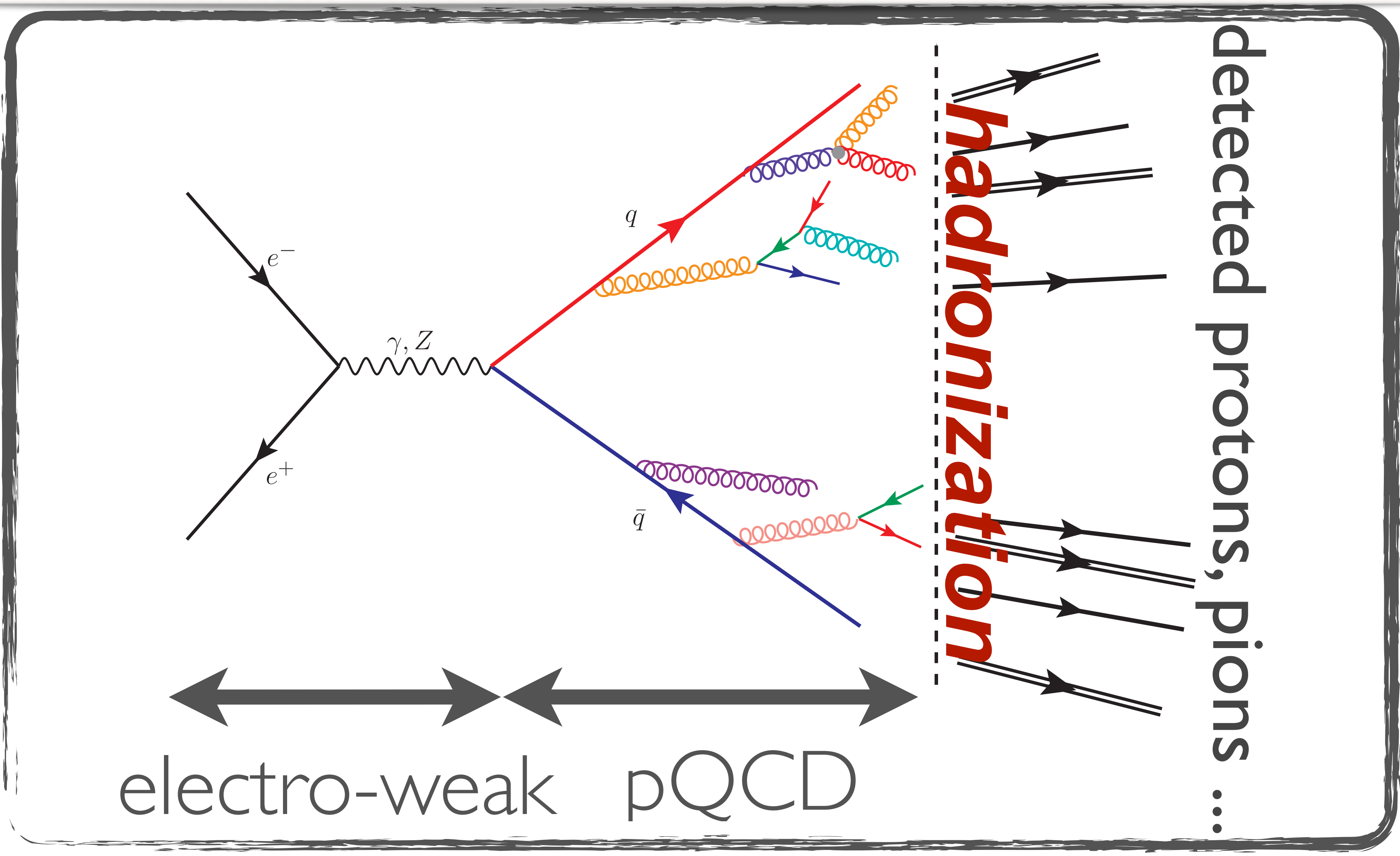




Hadronization

- **The conjecture of *Confinement*:**

✦ ***NO free quarks or gluons have been directly observed:* *only* HADRONS.**



✦ **Hadronization**: describes the process where colored quarks and gluons form colourless hadrons (in deep inelastic scattering).

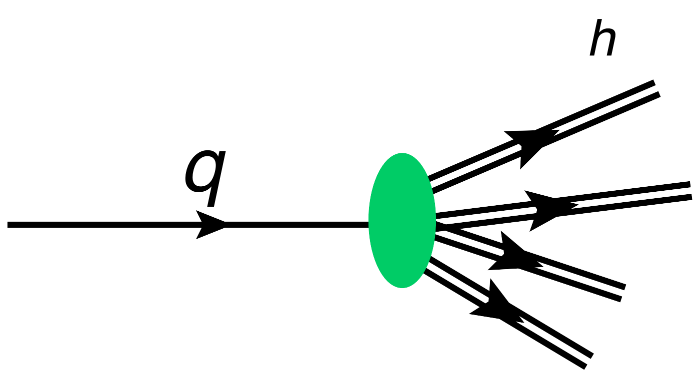
Fragmentation Functions

- **The non-perturbative, universal functions encoding parton hadronization are the: *Fragmentation Functions (FF)*.**

$$\frac{1}{\sigma}\frac{d}{dz}\sigma(e^-e^+ \to hX) = \sum_i \mathcal{C}_i(z,Q^2) \otimes D_i^h(z,Q^2)$$

- Unpolarized FF is the number density for parton *i* to produce hadron *h* with LC momentum fraction **z**.

$$D_i^h(z,Q^2)$$



- **z** is the light-cone mom. fraction of the parton carried by the hadron

$$z = \frac{p^-}{k^-} \approx z_h = \frac{2E_h}{Q} \qquad a^\pm = \frac{1}{\sqrt{2}}(a^0 \pm a^3)$$

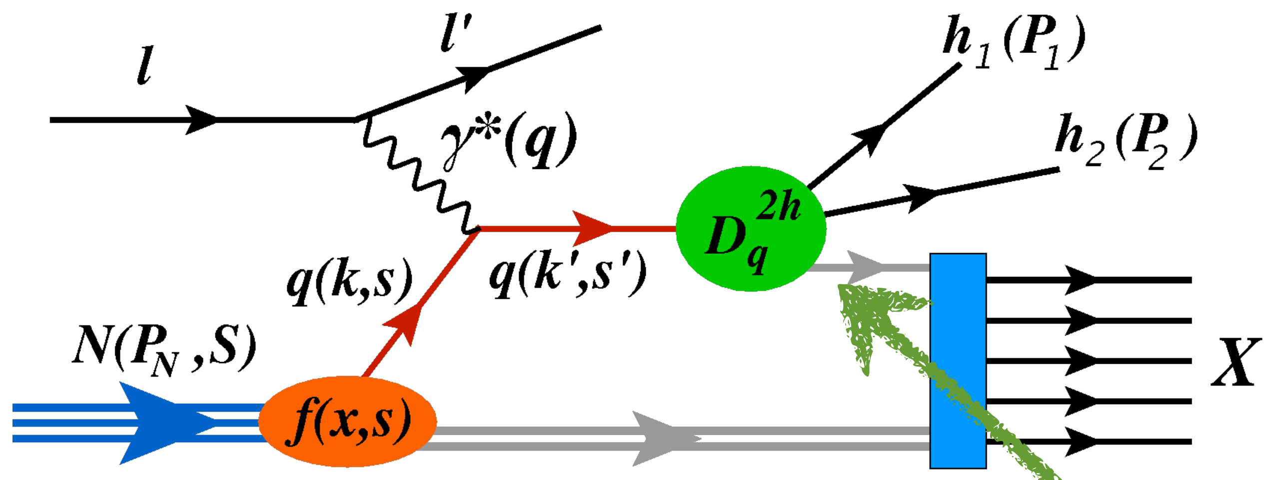
Modelling Hadronization

- ➡ Need to understand the non-perturbative mechanism of hadron formation.
- ➡ To include the *TM dependence and polarization*.
- ➡ Connection between the *one hadron and dihadron FFs*.
- ➡ Implementation in MC generators (PYTHIA, etc).

TMD PDFs with Two-Hadron FFs

- ***Measuring <u>two-hadron</u> semi-inclusive DIS: an additional method for accessing TMD PDFs.***

  - *SIDIS Process with TM of hadrons measured.*



- *TMD PDFs*

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1\, h_{1T}^\perp$

- *TMD DiFFs*

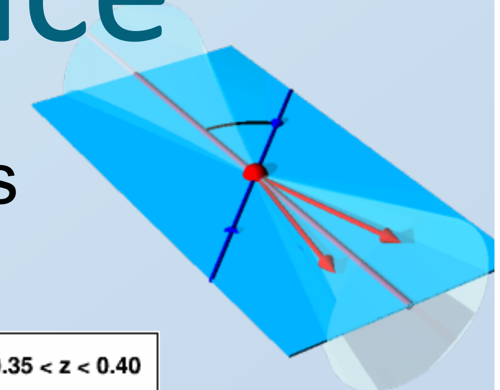
q/h₁h₂	U
U	D_1
L	$G_1^\perp$
T	$H_1^\perp \quad H_1^\sphericalangle$

✶unpol/spinless h!

R. Seidl

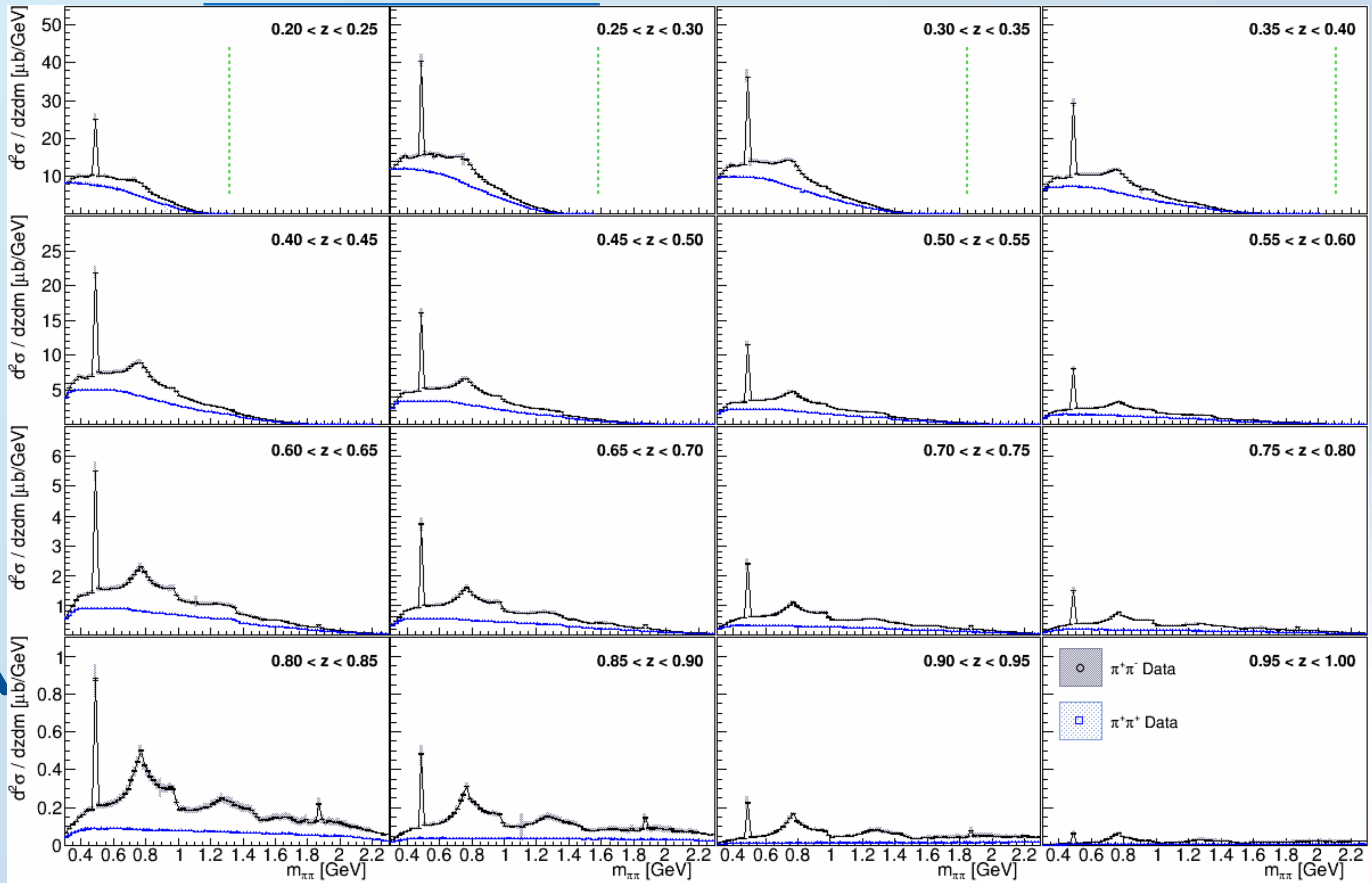
Di-hadron mass dependence

Similar analysis in same hemisphere and mass – combined z binning. Important input for IFF based transversity global analysis



Belle: RS et.al. arXiv:1706.08348

$$\frac{d^2\sigma}{dzdm_{\pi\pi}}$$

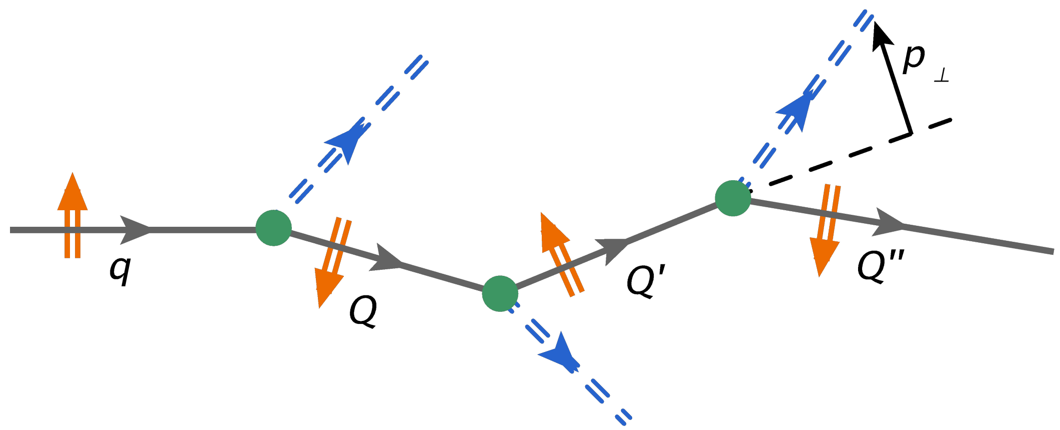


$m_{\pi\pi}$

Quark-jet Model

A. Kotzinian

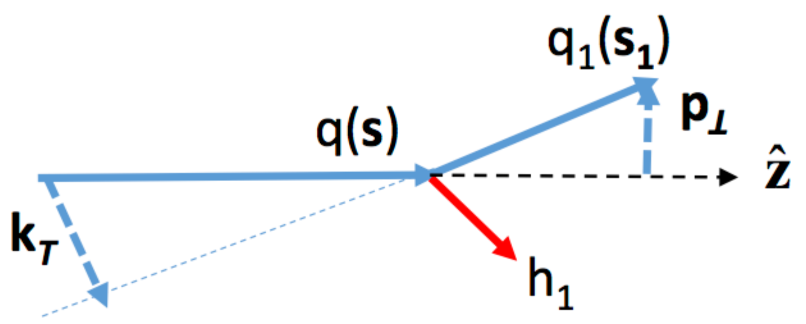
- Recursive framework for quark hadronization based on Field-Feynman model.



- Description of arbitrary quark polarization via spin density matrix formalism.
- Encode spin transfer via 8 TMD quark-to-quark elementary TMD FFs.
- Extraction of the *complete set of one- and two-hadron polarized FFs* for pions.

Quark-jet: Spin Transfer

A. Kotzinian



$$\langle \mathbf{s}_1 \rangle = \frac{\boldsymbol{\beta}(z,\mathbf{p}_\perp;\mathbf{s})}{\alpha(z,\mathbf{p}_\perp;\mathbf{s})}$$

Initial quark polarization \ Final quark polarization	U	L	T
U	$D(z,p_\perp^2)$		$-\frac{\mathbf{k}_T\times\hat{\mathbf{z}}}{\mathcal{M}}D_T^\perp(z,p_\perp^2)$
L		$s_L G_L(z,p_\perp^2)$	$s_L\frac{\mathbf{k}_T}{\mathcal{M}}G_T(z,p_\perp^2)$
T	$-\frac{(\mathbf{k}_T\times\mathbf{s}_T)\cdot\hat{\mathbf{z}}}{\mathcal{M}}H^\perp(z,p_\perp^2)$	$\frac{\mathbf{k}_T\cdot\mathbf{s}_T}{\mathcal{M}}H_L^\perp(z,p_\perp^2)$	$\mathbf{s}_T H_T(z,p_\perp^2)+\frac{\mathbf{k}_T}{\mathcal{M}}\frac{(\mathbf{k}_T\cdot\mathbf{s}_T)}{\mathcal{M}}H_T^\perp(z,p_\perp^2)$

$$\alpha(z,\mathbf{p}_\perp;\mathbf{s}) = D(z,\mathbf{p}_\perp^2) - \frac{1}{M}(\mathbf{k}_T\times\mathbf{s}_T)\cdot\hat{\mathbf{z}}H^\perp(z,\mathbf{p}_\perp^2)$$

$$\beta_L(z,\mathbf{p}_\perp;\mathbf{s}) = s_L G_L(z,\mathbf{p}_\perp^2) - \frac{1}{M}(\mathbf{k}_T\cdot\mathbf{s}_T)H_L^\perp(z,\mathbf{p}_\perp^2)$$

$$\boldsymbol{\beta}_\perp(z,\mathbf{p}_\perp;\mathbf{s}) = -\frac{\mathbf{k}'_T}{M}D_T^\perp(z,\mathbf{p}_\perp^2) + s_L\frac{\mathbf{k}_T}{M}G_T(z,\mathbf{p}_\perp^2) + \mathbf{s}_T H_T(z,\mathbf{p}_\perp^2) + \frac{\mathbf{k}_T}{M^2}(\mathbf{s}_T\cdot\mathbf{k}_T)H_T^\perp(z,\mathbf{p}_\perp^2)$$

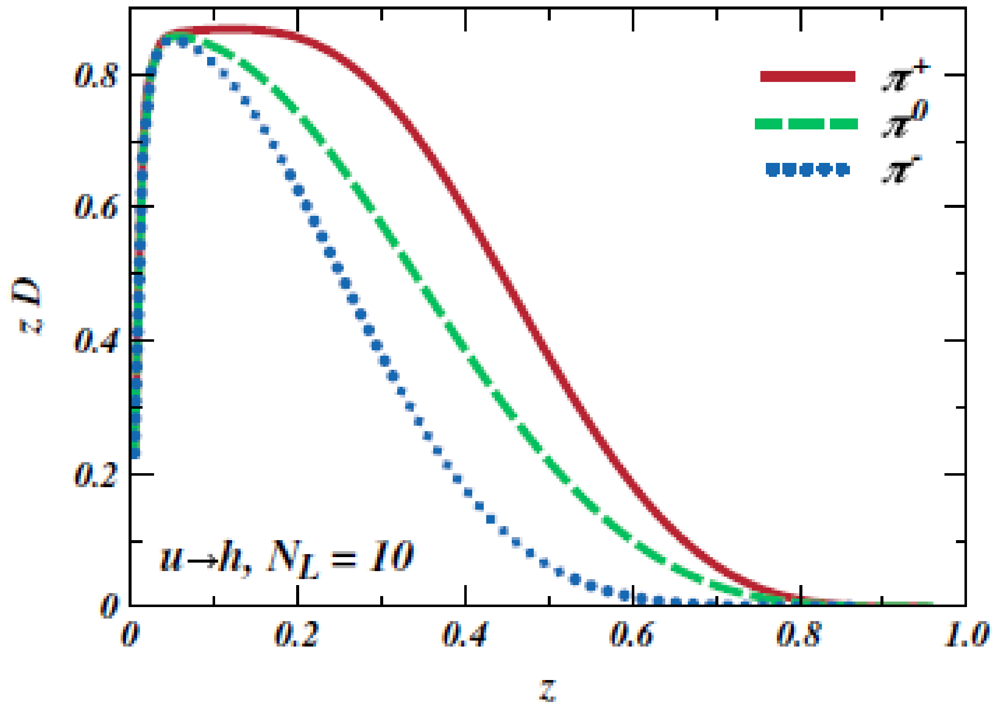
Polarized quark to unpolarized hadron SF

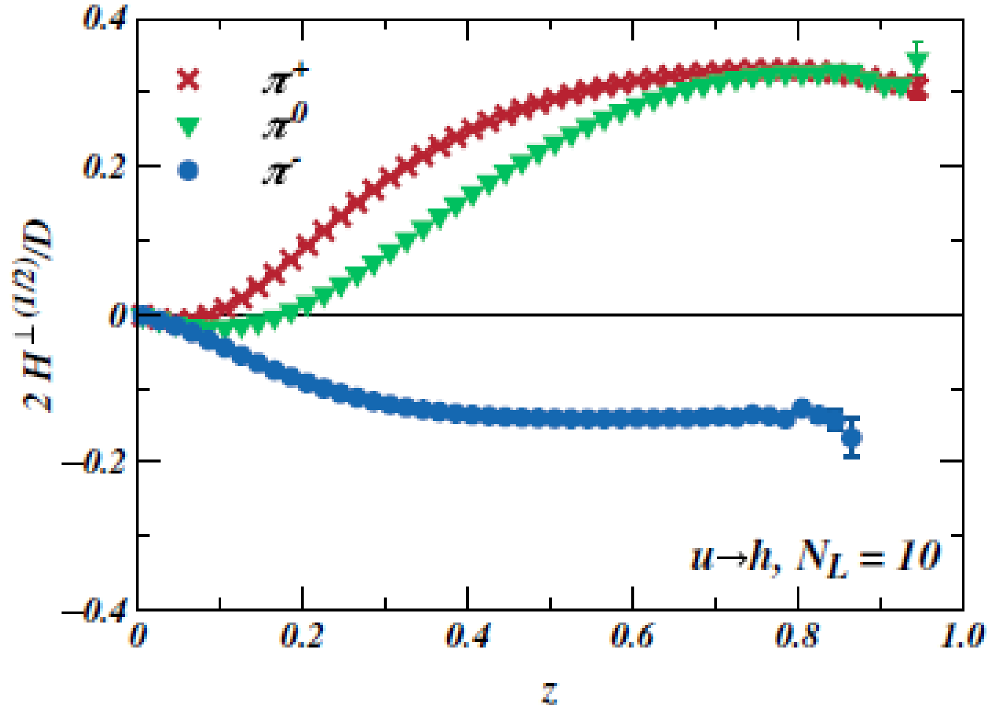
$$F^{q\to h_1}(z,\mathbf{p}_\perp;\mathbf{s}) = F^{q\to q_1}(1-z,-\mathbf{p}_\perp;\mathbf{s}_1=0,\mathbf{s}) = D(1-z,\mathbf{p}_\perp^2) + \frac{1}{M}(\mathbf{k}_T\times\mathbf{s}_T)\cdot\hat{\mathbf{z}}H^\perp(1-z,\mathbf{p}_\perp^2)$$

Quark-jet: Results

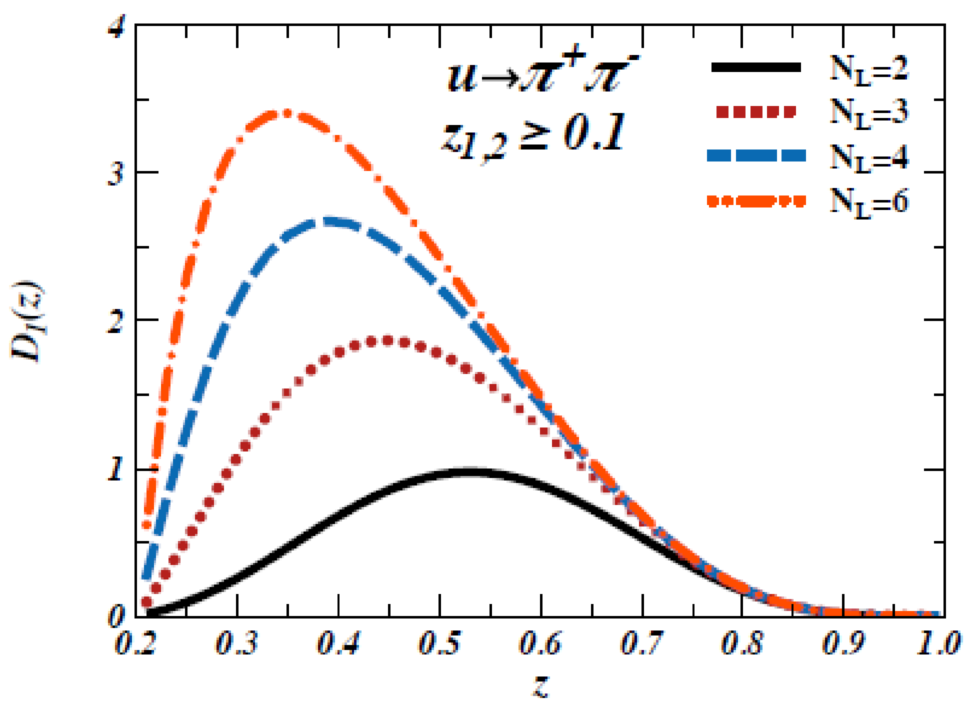
A. Kotzinian

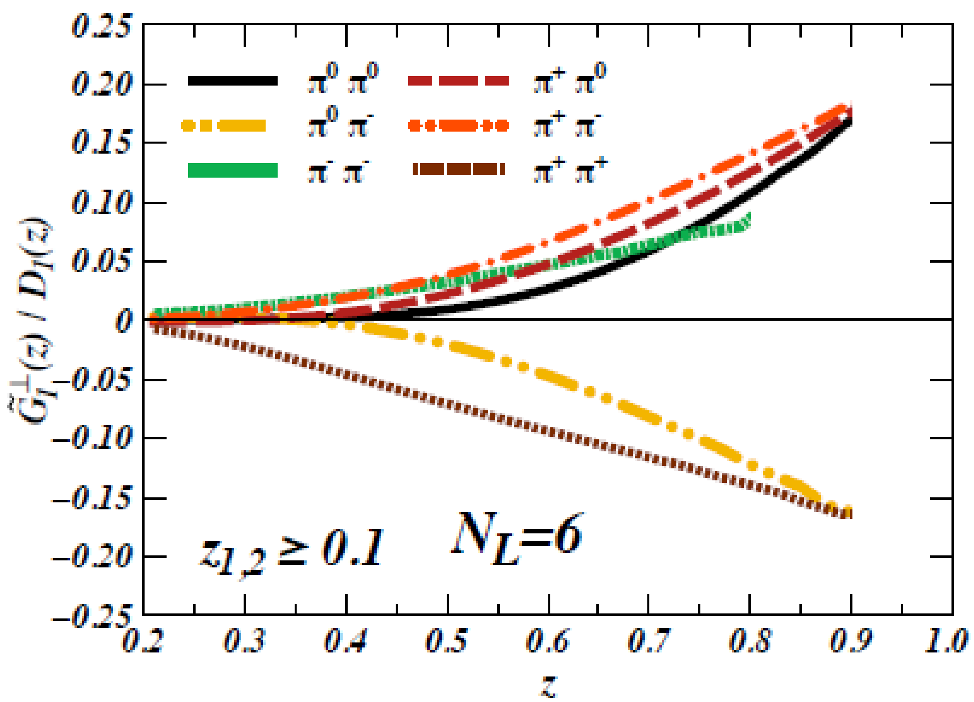
One hadron: Collins effect





Two hadron: Helicity-dependent DiFF

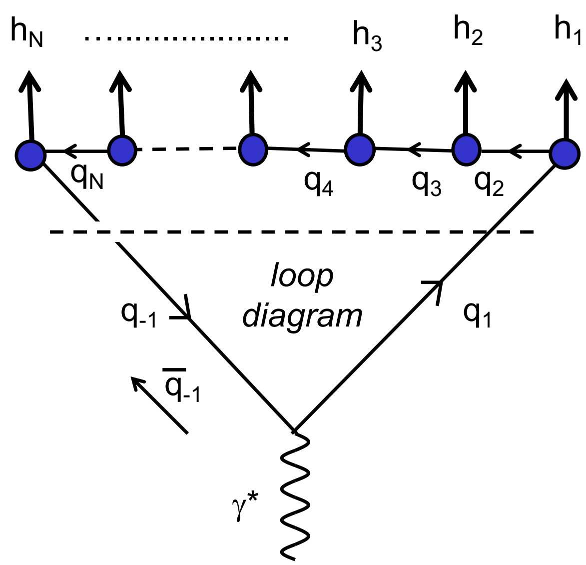




Recursive quark fragmentation with spin

X. Artru

- **Complete description of hadronization in hard process: Quark Multiperipheral model satisfying LR symmetry.**

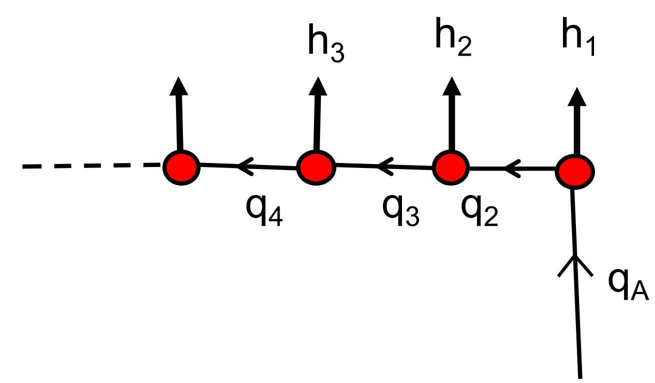


Recursive model

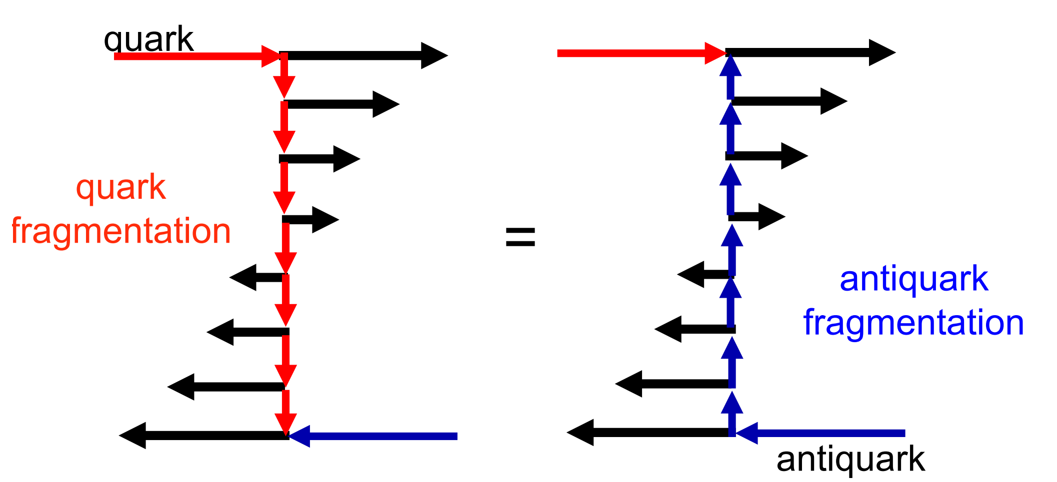
$q_A\,(k_A) \to h_1(p_1) + q_2(k_2)$,

$q_2\,(k_2) \to h_2(p_2) + q_3(k_3)$,

… etc.

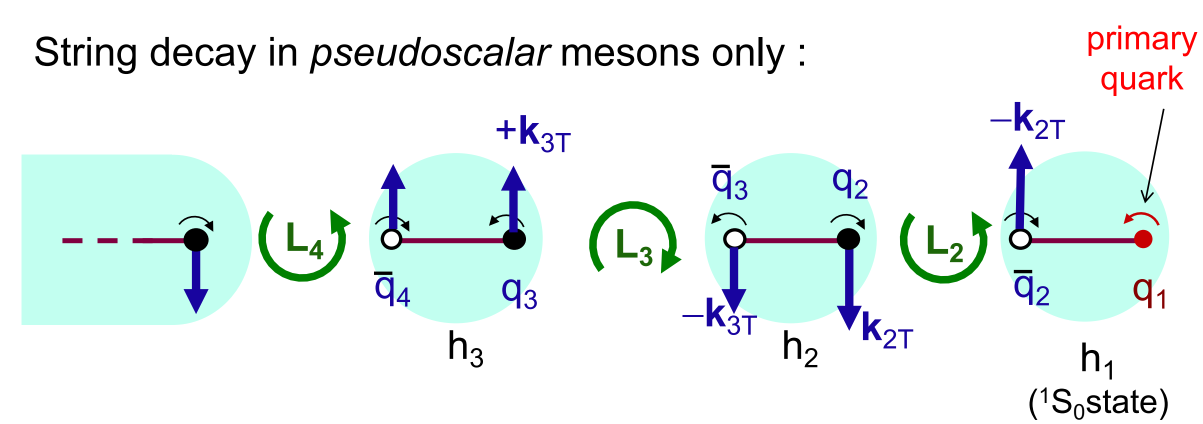


Symmetry under *quark* ***L****ine* ***R****eversal* (or *"Left-Right"* symmetry)



Iteration of the *string* + $^3P_0$ mechanism

String decay in *pseudoscalar* mesons only :



X. Artru

Synthesis of string and 3P0 inputs (pseudoscalar mesons only)

$T_{q'hq}(k',k) = C_{q'hq}$ ← Flavor

$\times \exp(-\tfrac{1}{2} b_T \mathbf{k}'^2_T)$ ← transverse momentum cutoff

$\times (1-Z)^{a/2} \exp(-b_L \varepsilon^2/2Z)$ ← string model

$\times (\mu + \sigma_z \boldsymbol{\sigma}.\mathbf{k}'_T)$ ← $^3P_0$

$\times \sigma_z$ ← Pseudoscalar

$\times \hat{u}_q^{-1/2}(\mathbf{k}_T)$ ← reduced single quark density matrix

$$\hat{u}_q(\mathbf{k}_T) = \Sigma_h \int dZ/Z \; d^2\mathbf{p}_T \;\; \mathbf{t}^\dagger \; \mathbf{t}$$

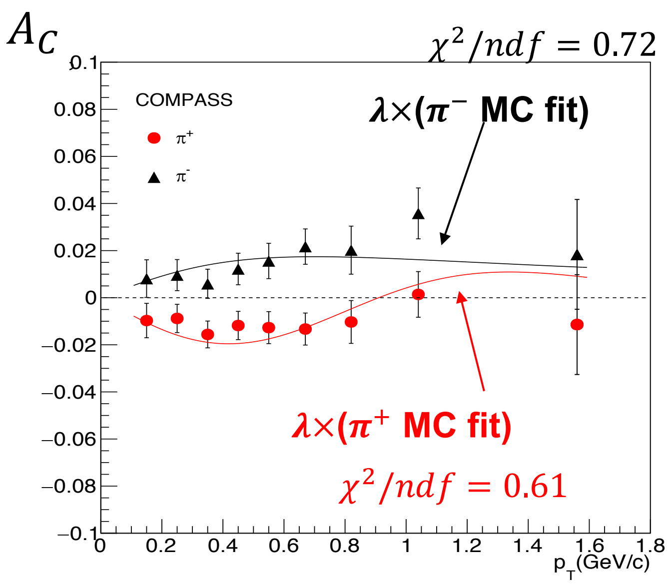
$$= [\hat{u}_0(\mathbf{k}_T^2) + \hat{u}_1(\mathbf{k}_T^2)\, \boldsymbol{\sigma} \cdot (\mathbf{z} \times \mathbf{k}_T) / |\mathbf{k}_T| \,]$$

($\mathbf{t}$ = T without the last line)

Comparison with COMPASS data

X. Artru

Single hadron: Collins asymmetry



- λ is a scale parameter estimated minimizing

$$\chi^2 = \sum_i \frac{\left(A_{C\,i} - \lambda f_{\pi^-}(p_{T,i})\right)^2}{\sigma_i^2}$$

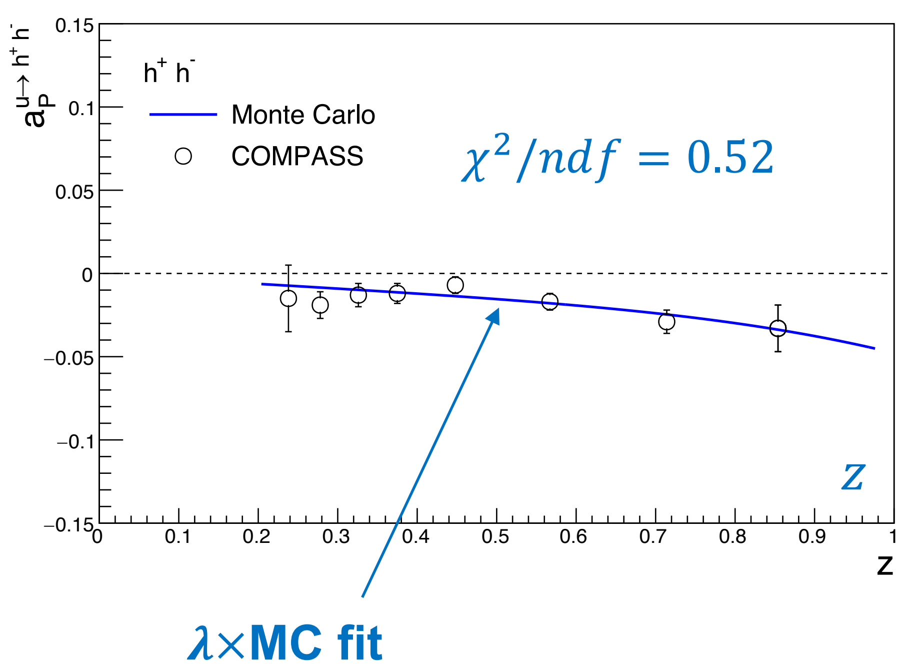
- $\lambda \sim \langle h_1^u / f_1^u \rangle$

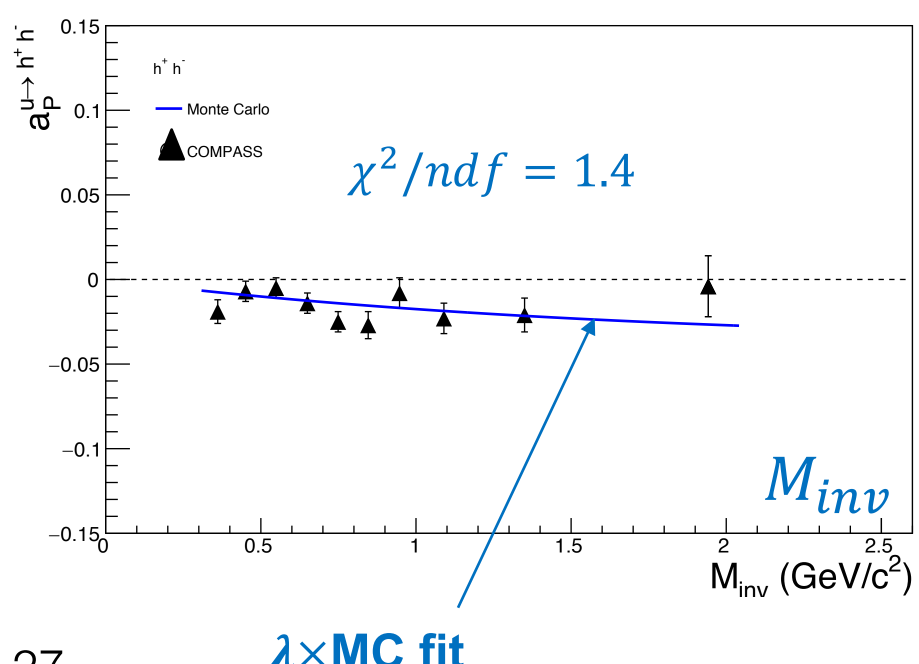
- $f_{\pi^-}(p_T)$: preceding MC fit for π^-
- A_C: experimental value of the π^- asymmetry
- σ: statistical error

$\boldsymbol{\lambda = 0.055 \pm 0.010}$

Dihadron: IFF

- Same λ also for 2h asymmetries



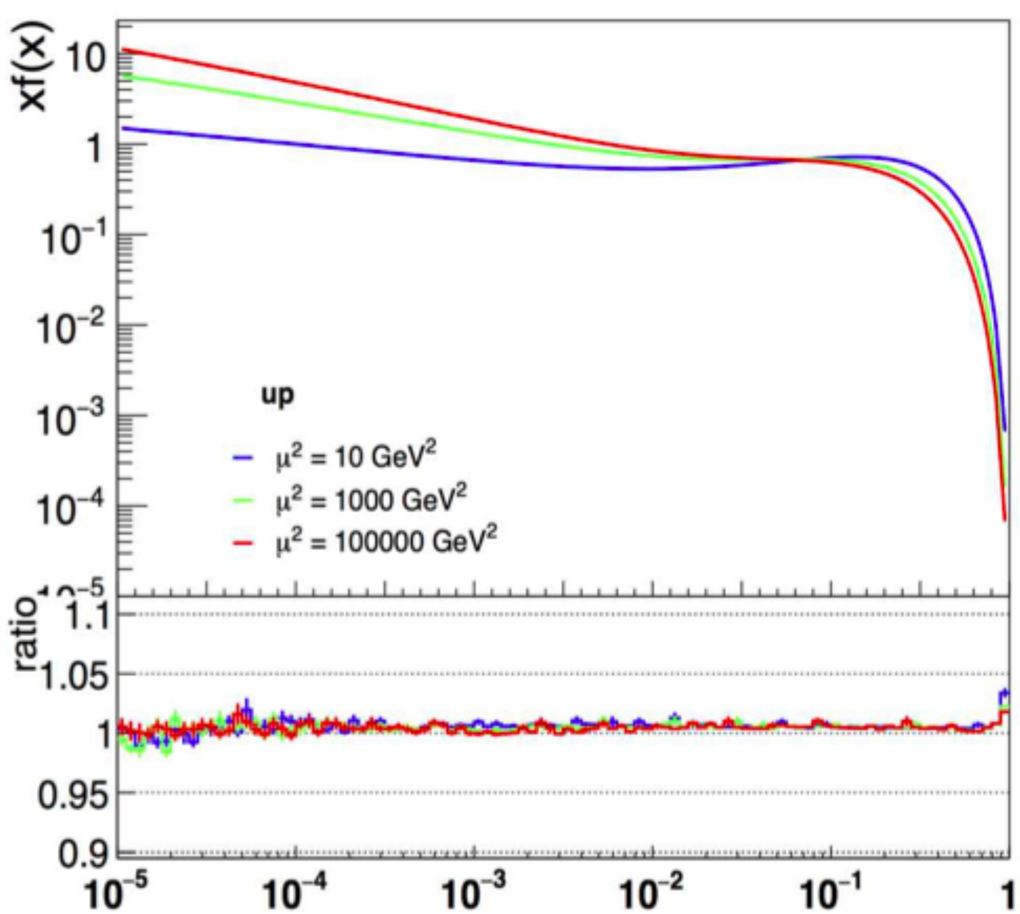


Parton Branching Solution for QCD Evolution Equations

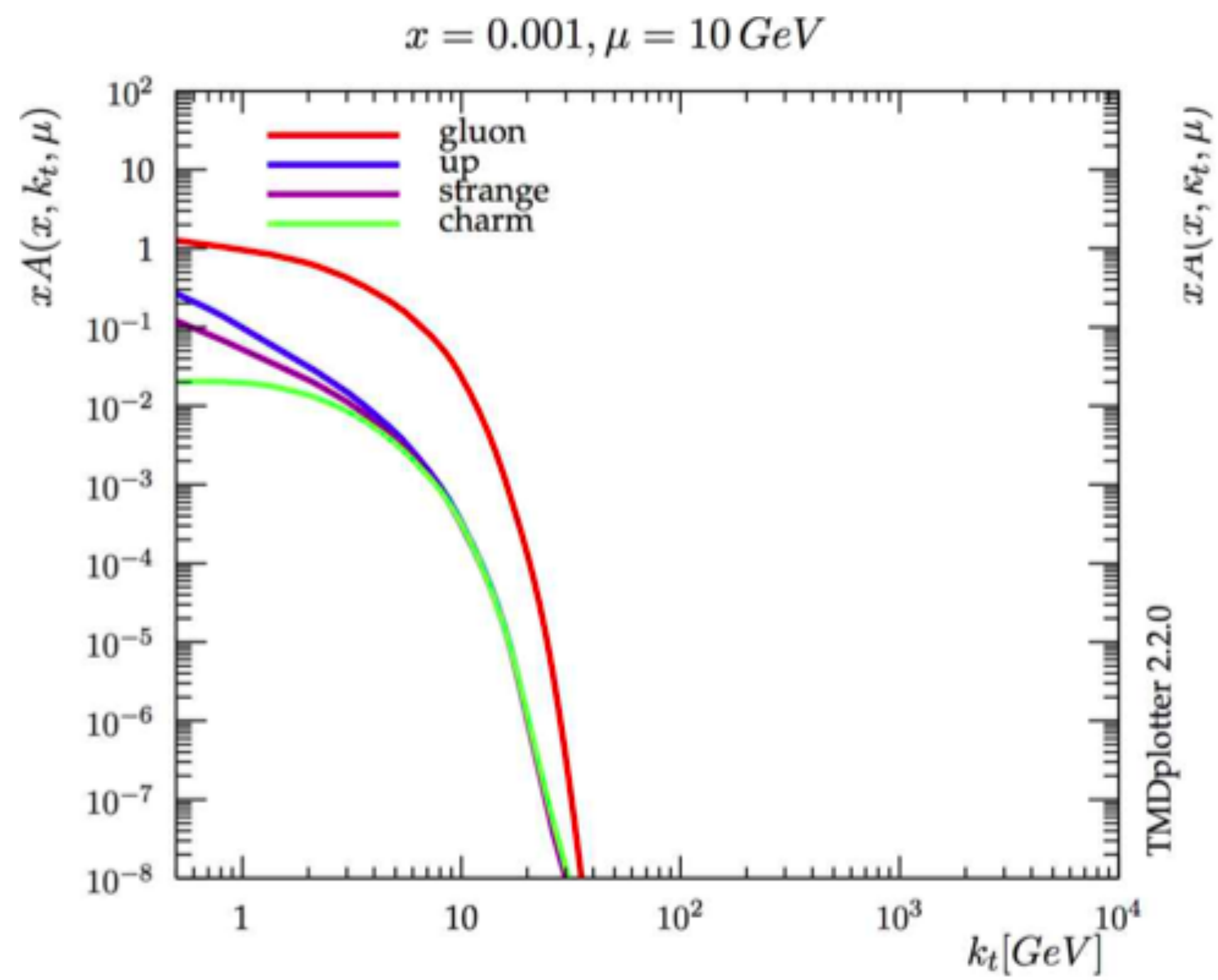
F. Hautmann

- Consistent with “orthodox” solutions up to *NNLO* at high precision.
- Provides the complete final partonic state with k_T.
- Determination of TMD for all flavours up to NLO: NO free parameters.
- TMD evolution implemented in xFitter - applicable for DIS processes.

Validation: vs DGLAP at NLO

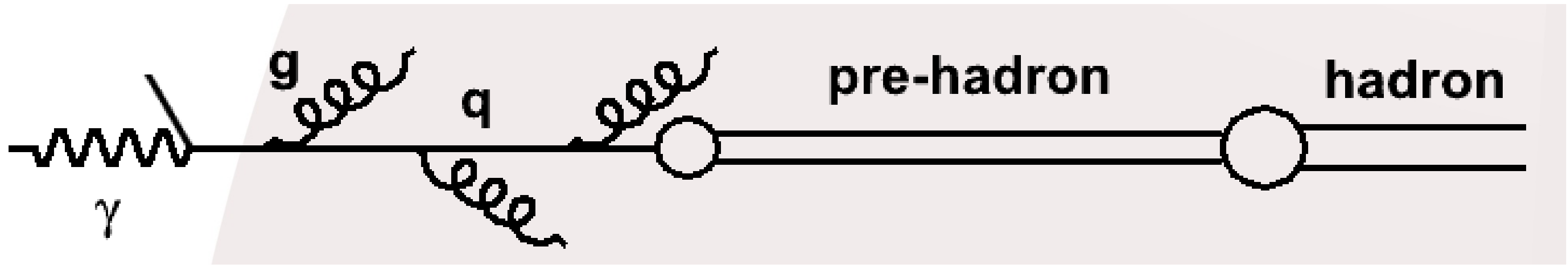


All flavours of TMDs

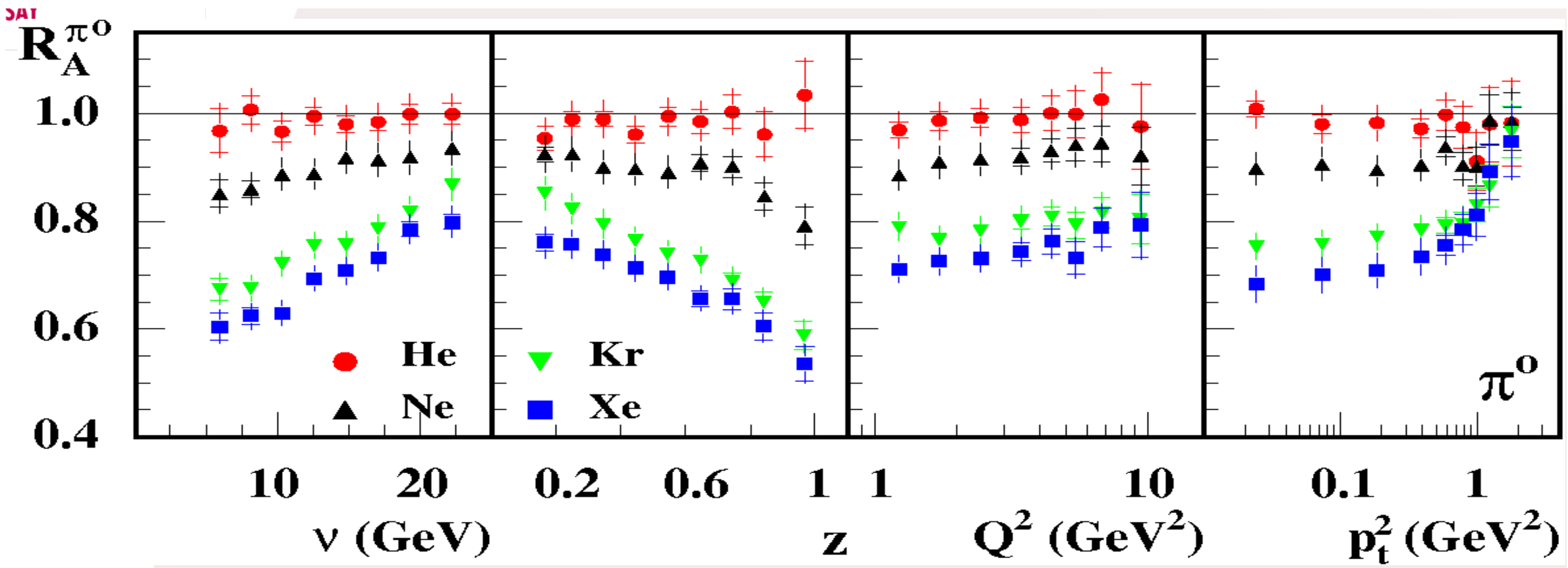


Hadronization in Nuclear Medium

R. Dupre

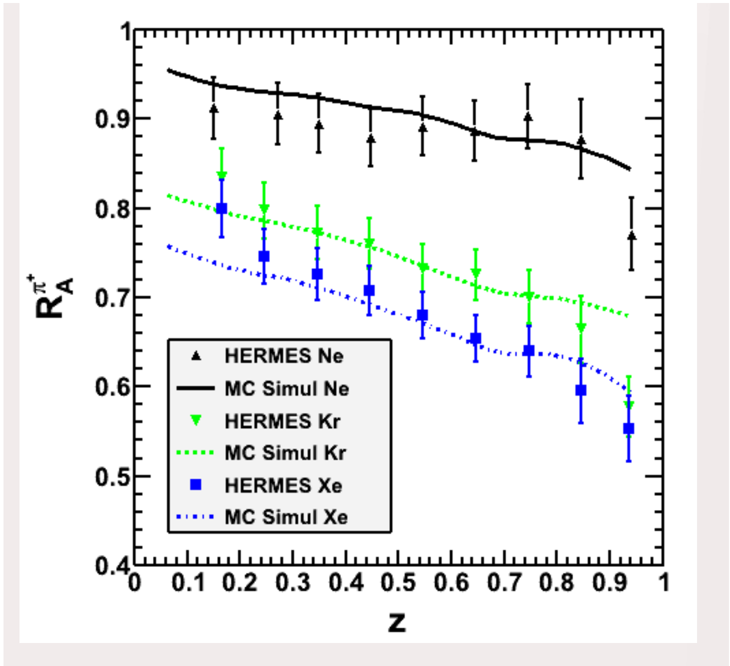


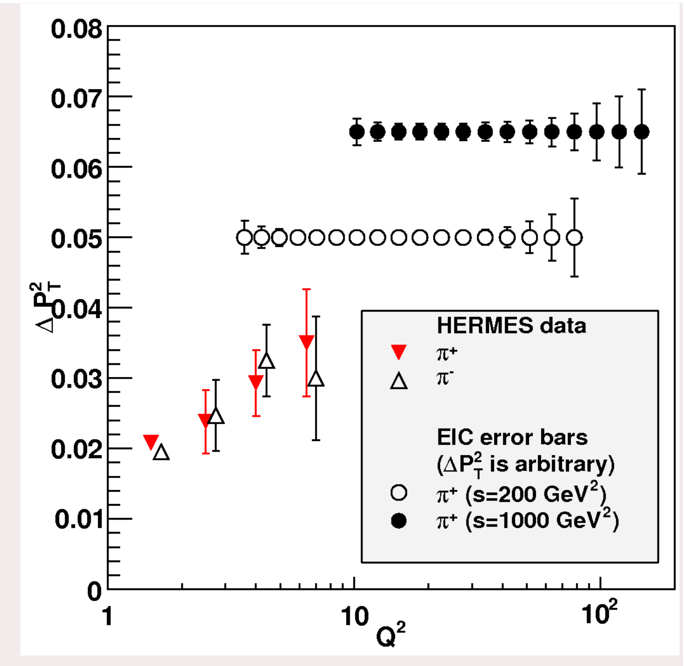
HERMES data on multiplicity ratios to D



MC with parton energy loss in medium

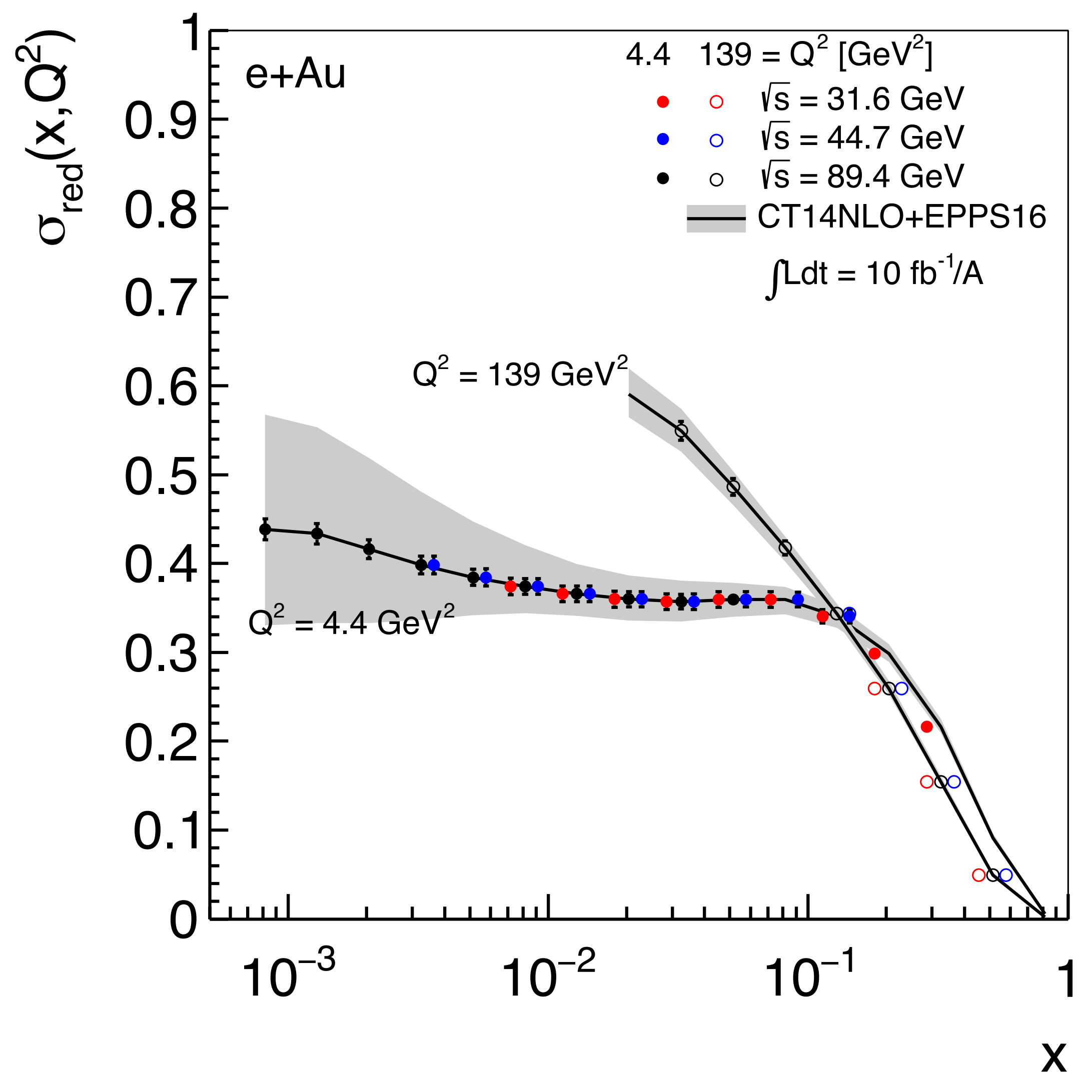
Q^2 evolution with EIC projections

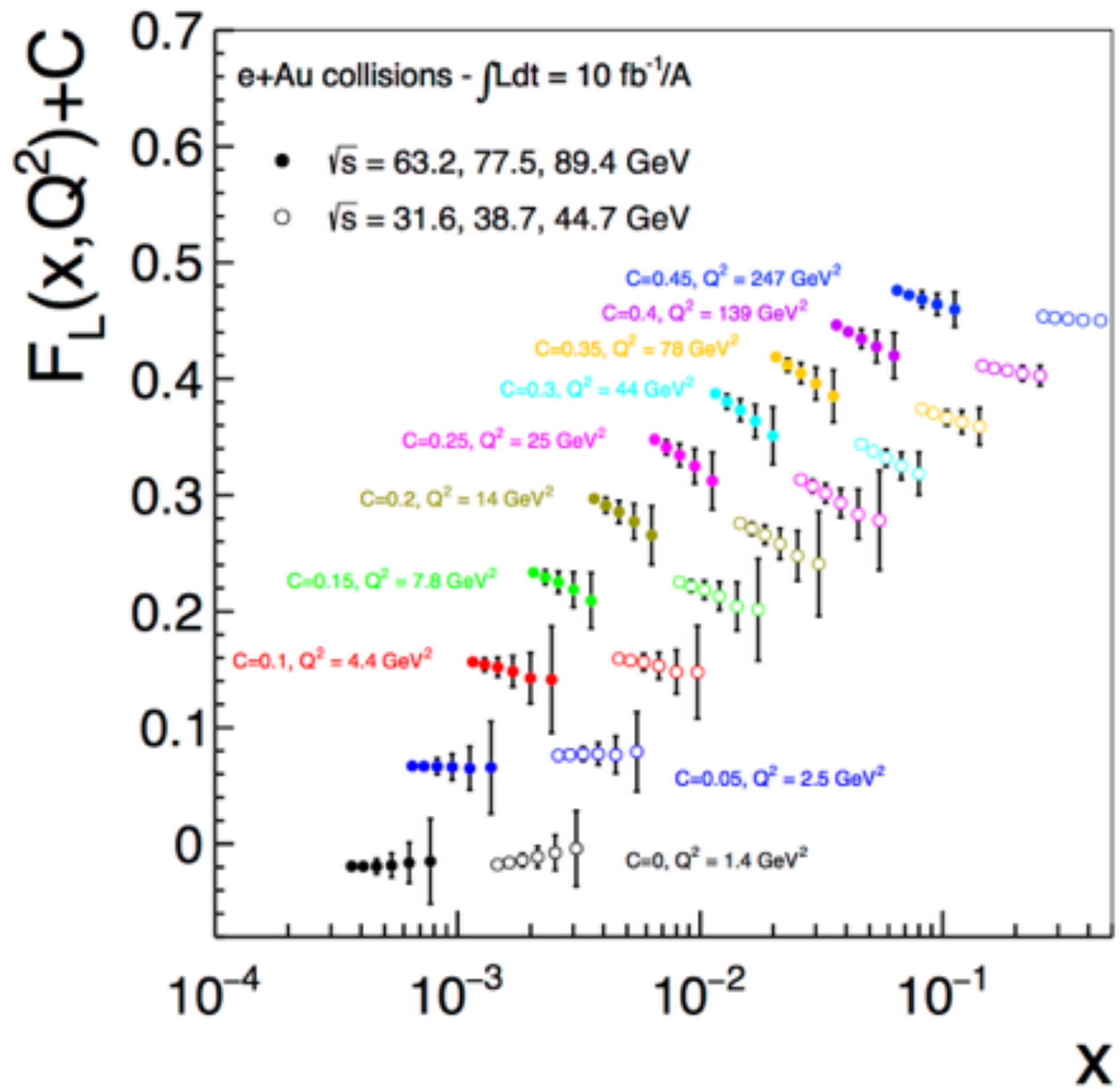




Impact of EIC on nuclear PDFs

S. Fazio

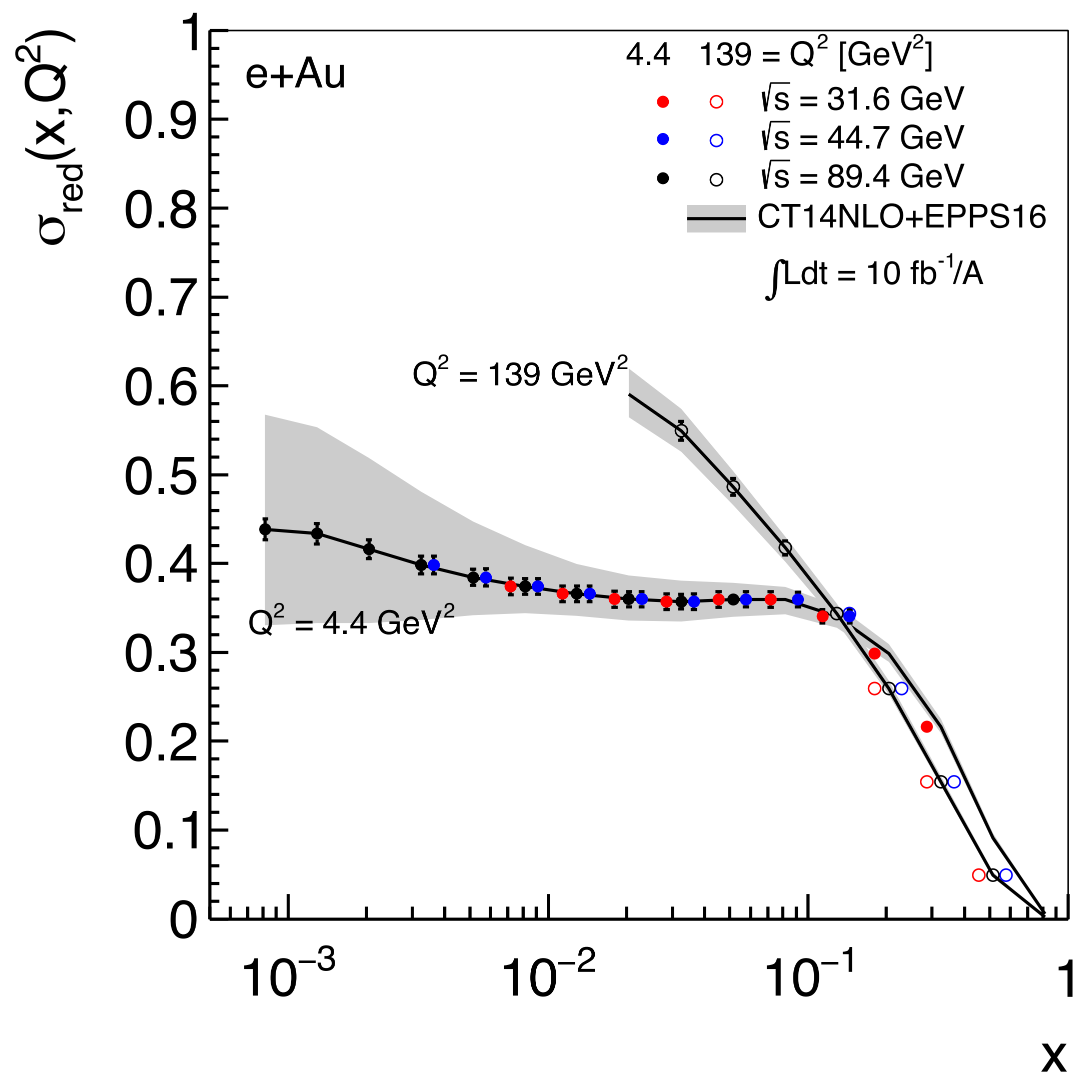


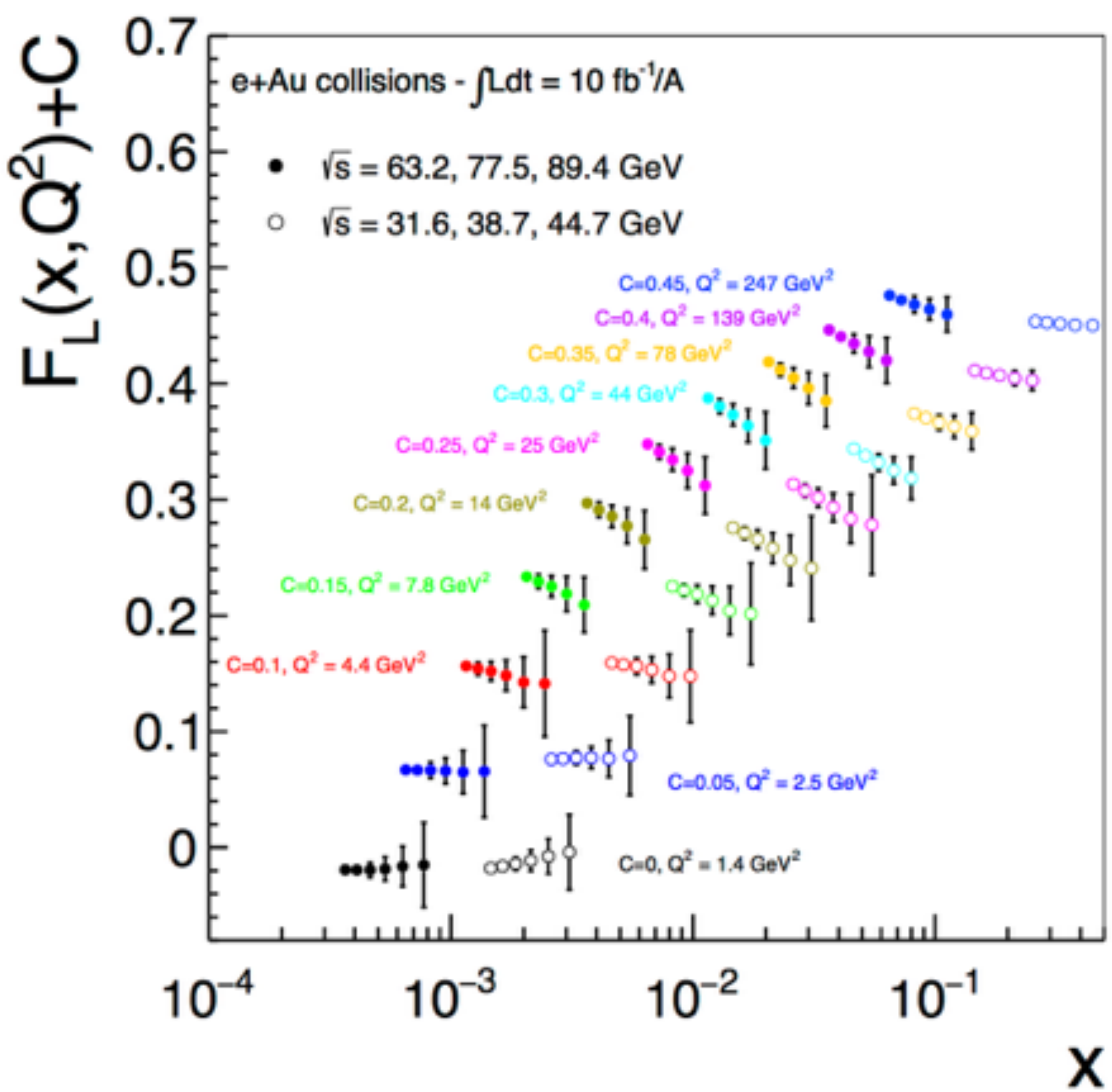


An EIC at its highest energy provides a factor 10 larger reach in Q^2 and low-x compared to available data

Impact of EIC on nuclear PDFs

S. Fazio





An EIC at its highest energy provides a factor 10 larger reach in Q^2 and low-x compared to available data

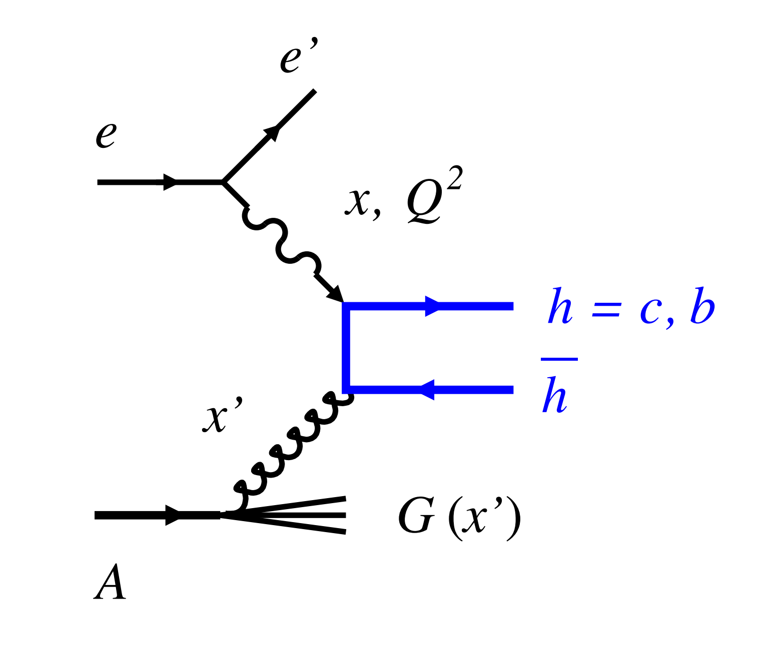
additional charm tagging will further help constraining gluon especially at high (gluon) x

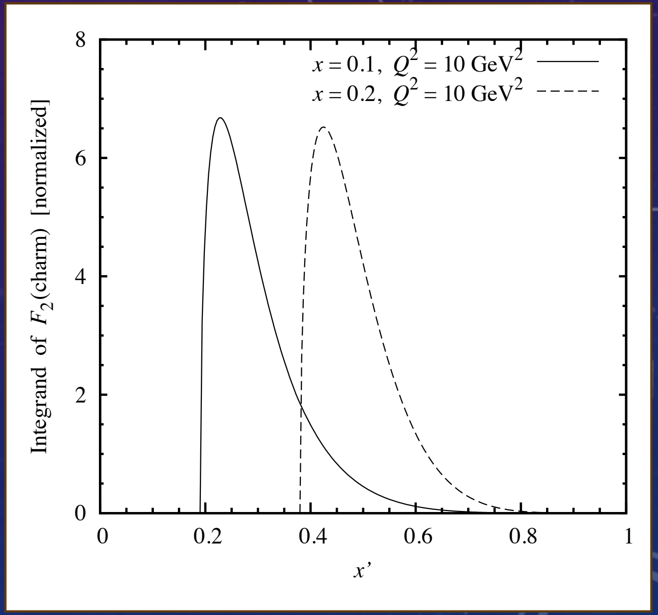
Nuclear gluon densities via *open charm*

C. Hyde

OPEN CHARM: A DIRECT PROBE OF GLUONS

- EIC:
  - Nuclei
  - CM Energy
  - Luminosity
    - Count rate reach to "high"-x
    - Small branching fractions
  - Particle ID, vertexing

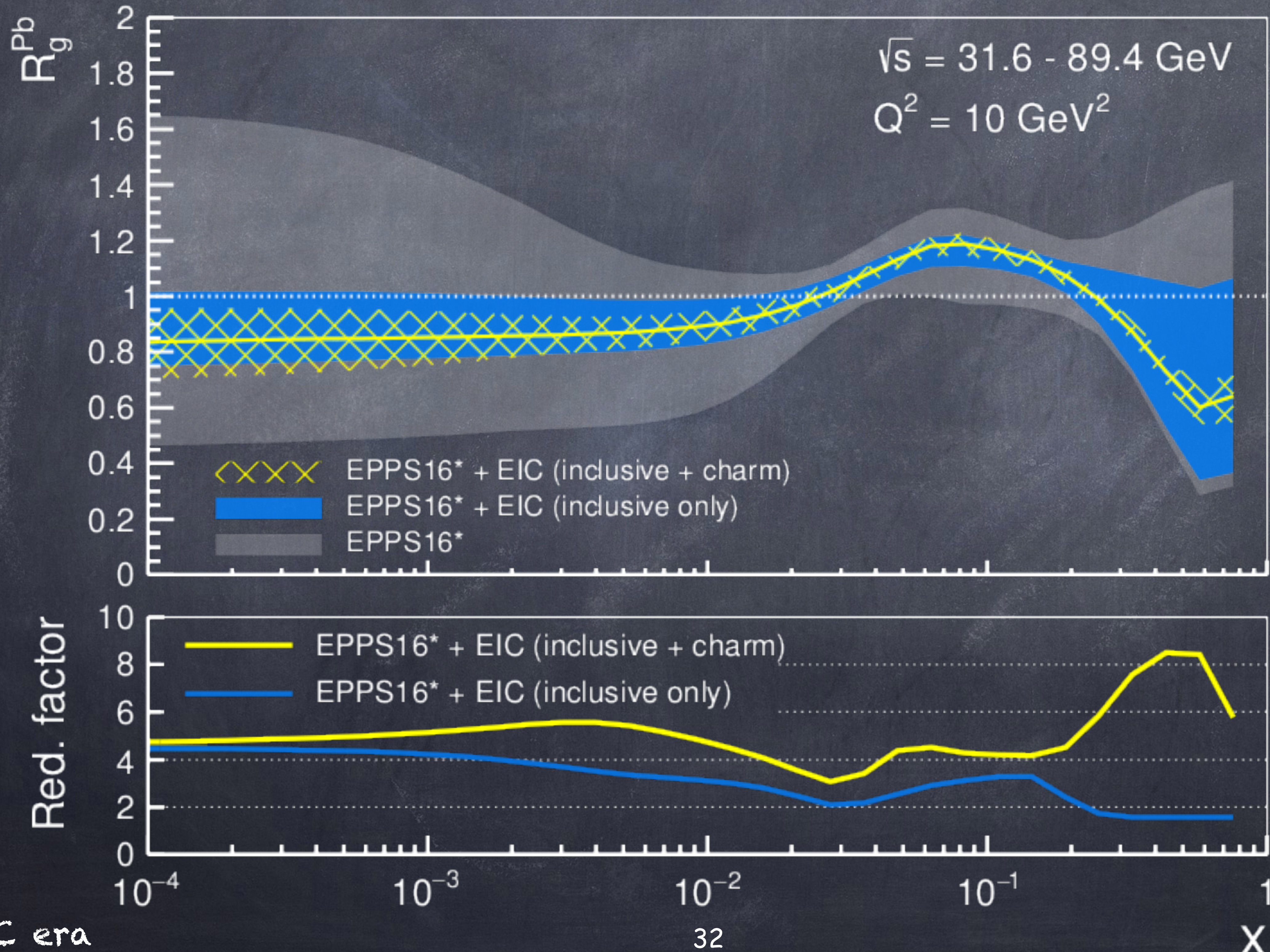




$$x_{\text{gluon}} = x' \geq \frac{4m_h^2 + Q^2}{W^2} \qquad W^2 \gg Q^2$$

with a higher energy realization of an EIC

P. Zurita

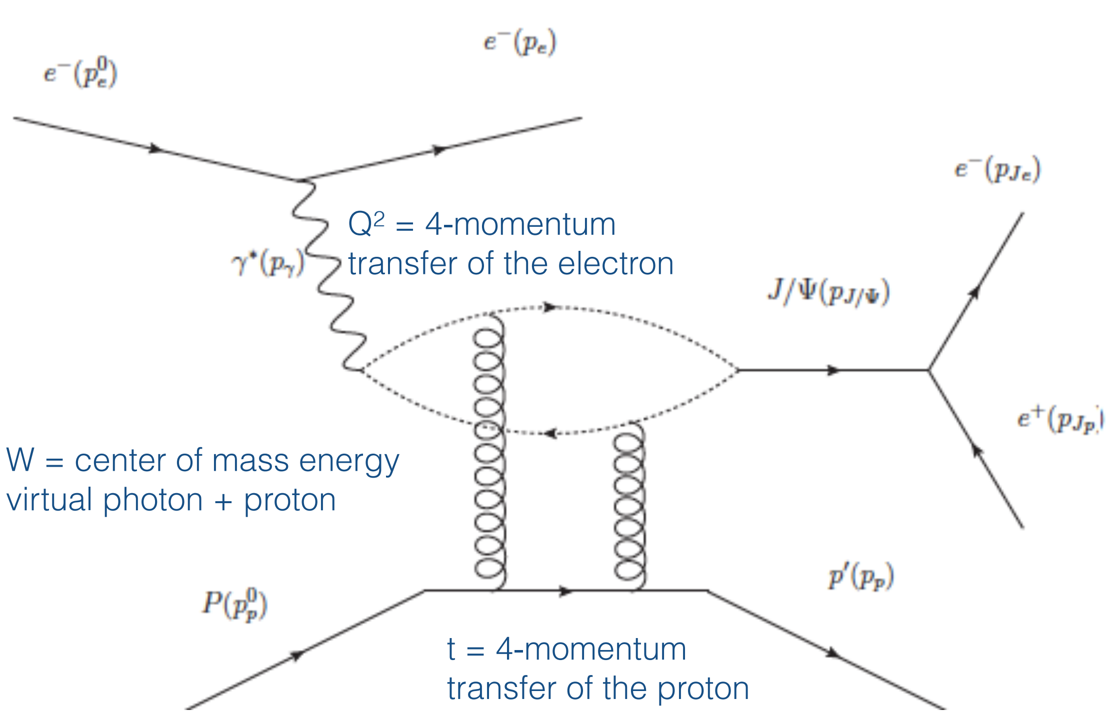


MODELS RELATE TRACE ANOMALY TO J/Ψ PRODUCTION NEAR THRESHOLD

e.g. D. Kharzeev, *EPJ* C9 459 (1999)

N. Feege

Photo-production of J/Ψ



J/Ψ and Υ production near threshold at EIC