PHENOMENOLOGY OF DIHADRON FRAGMENTATION FUNCTIONS

MWPF 2015, Mazatlán

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Consejo Nacional de Ciencia y Tecnología

HADRONIZATION

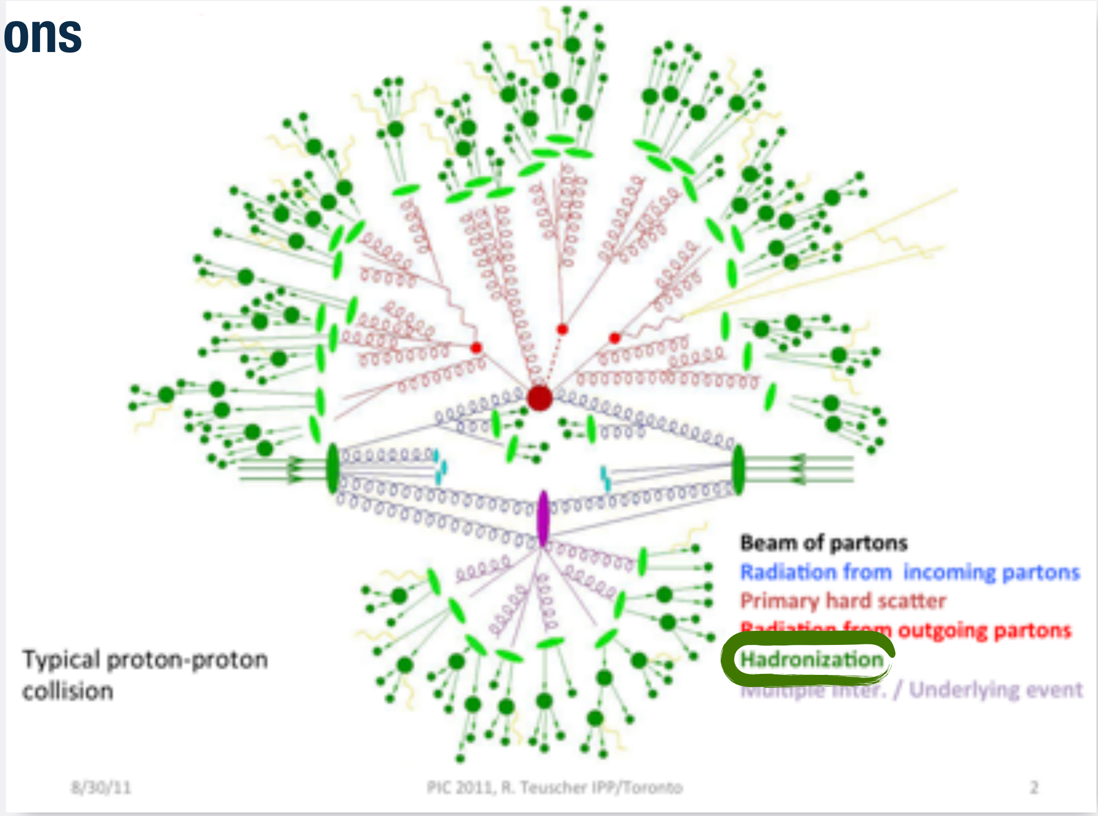
Well, what's with it?

- (nearly) All visible matter is made up of quarks and gluons but quarks and gluons are not visible
- Hadron mass from ~massless quarks and massless (?) gluons
  - ➡ consequence of many-body quark-gluon dynamics
- It seems we don't understand QCD Lagrangian
  - ➡ So what about confinement and hadronization?
- So, what can we do?

HADRONIZATION

- No free partons ➡ hadronization happens very often
- e.g. at LHC
- Coupled to parton distributions

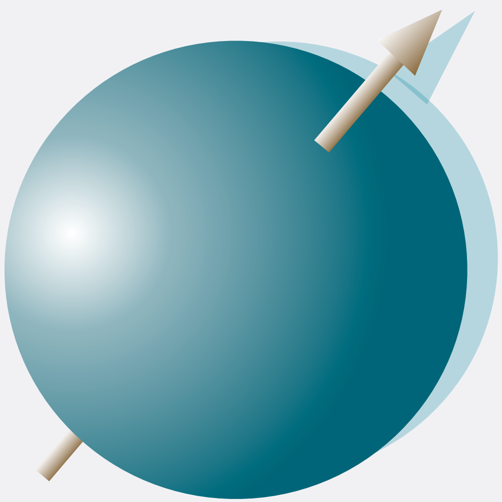
1. Concept of Factorization
2. Concept of ``hard scale"

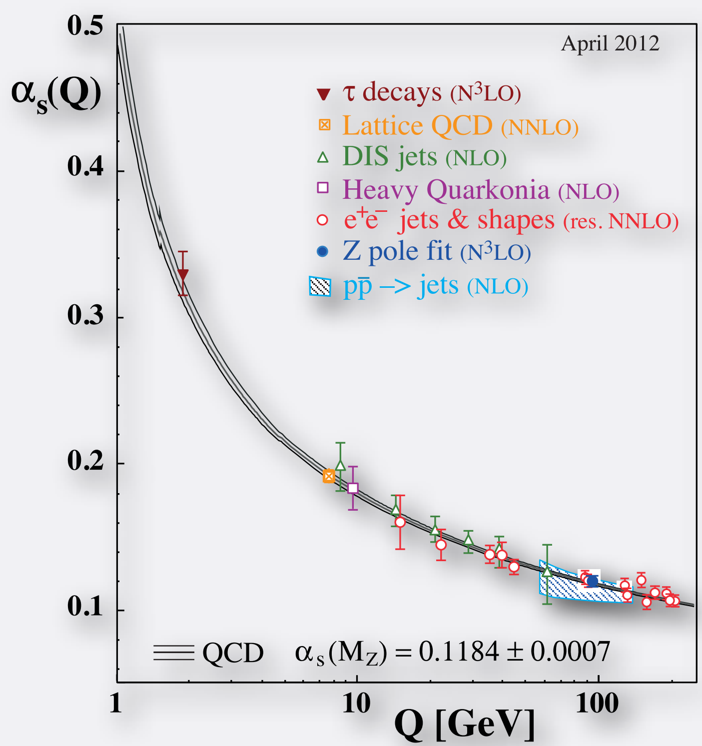


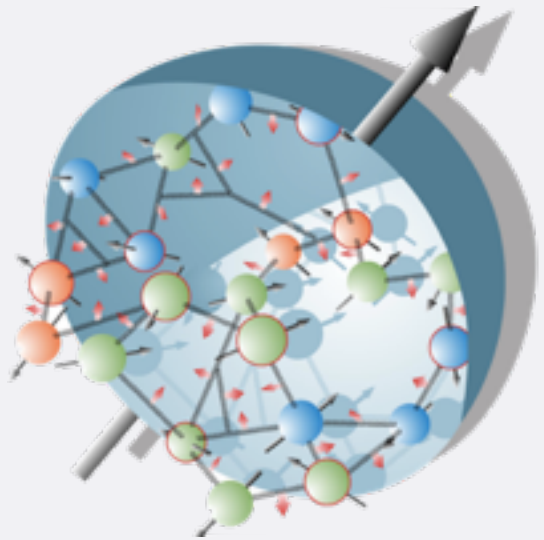
THE TWO REGIMES OF QCD

"The duality of the strong interactions"

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



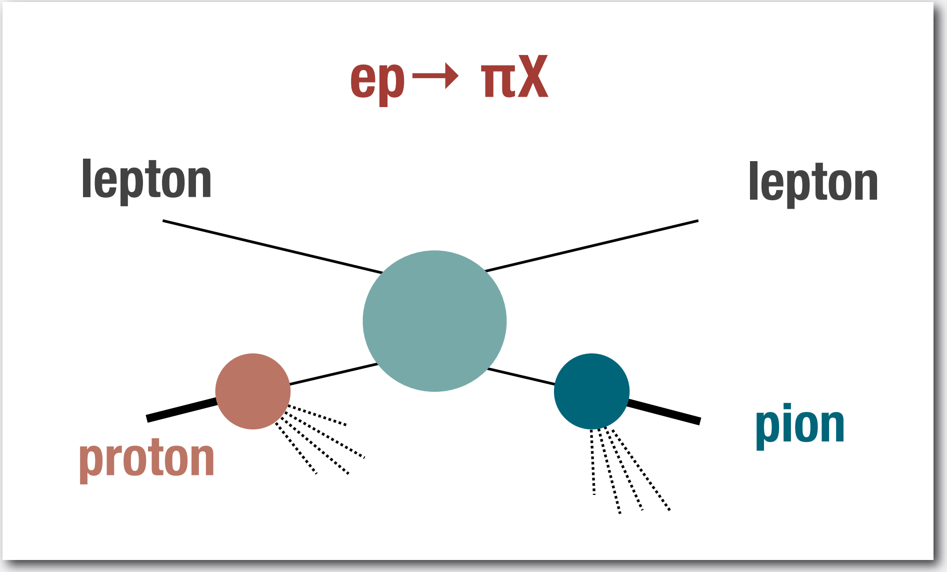


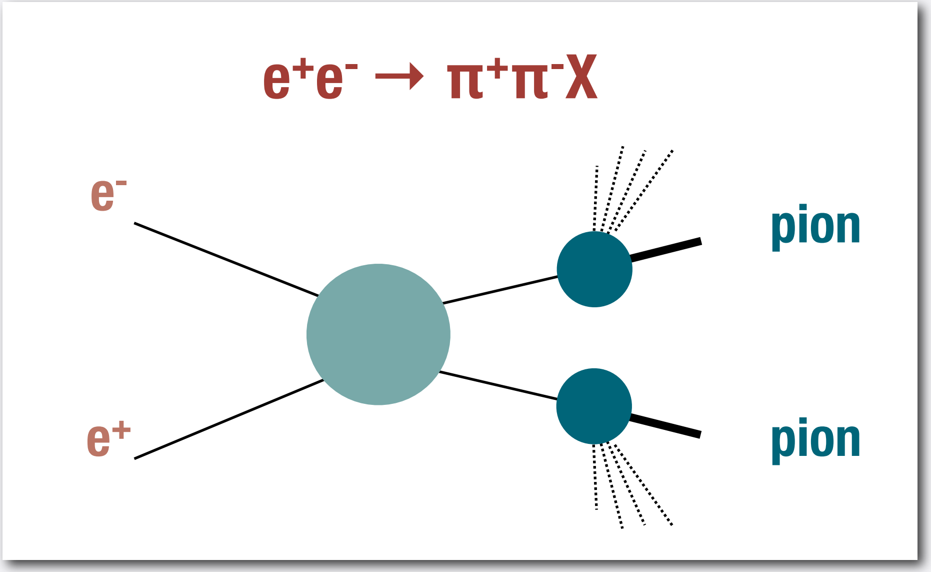


Resolution

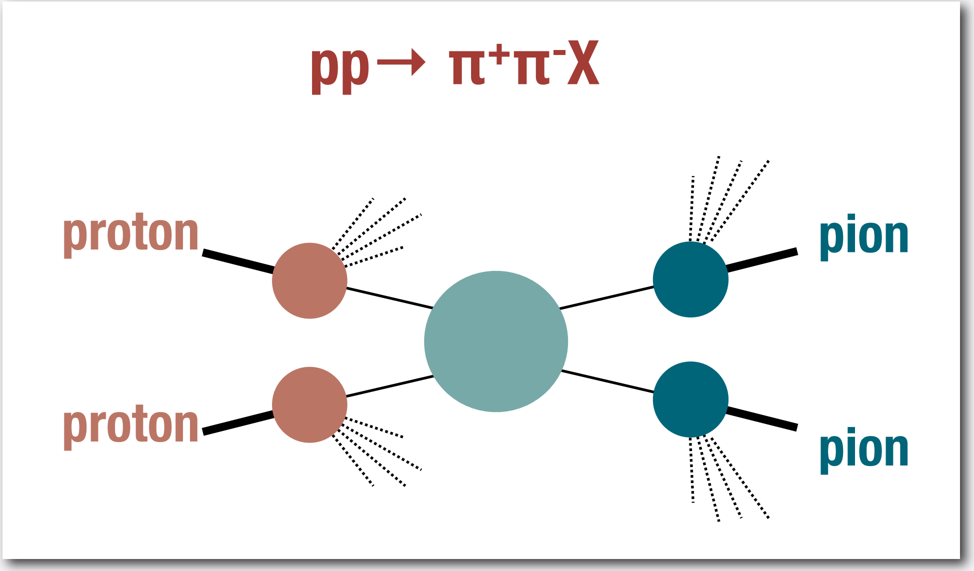
PROCESSES TO ACCESS FRAGMENTATION

Inclusive hadron yields





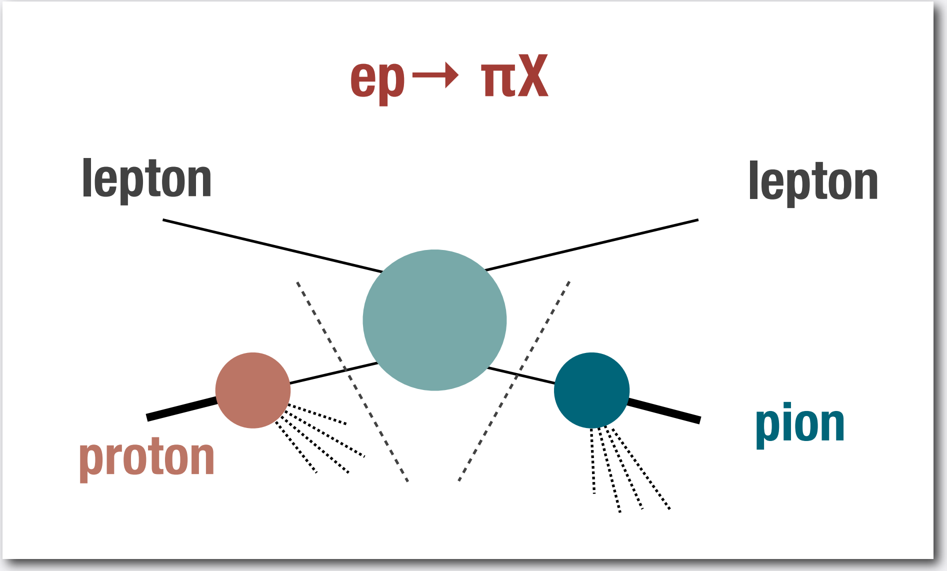
X=all the undetected stuffs



Kinematical regimes that allow for factorization

PROCESSES TO ACCESS FRAGMENTATION

Inclusive hadron yields



Pink Blob=Parton Distribution Function

Blue Blob=Fragmentation Function

Turquoise Blob=Hard Scattering

Kinematical regimes that allow for factorization

X=all the undetected stuffs

NON-PERTURBATIVE FUNCTIONS

Parametrizing the unknown

Parton distribution functions (PDFs)
→ Probability to find a parton *q* with momentum fraction *x* at a scale μ in a proton

Define all the relevant Lorentz structures.

Evaluate with non-perturbative tools and/or global fits.

Fragmentation functions (FFs)
→ Probability to find a pion with momentum fraction *z* at a scale μ in a parton *q*

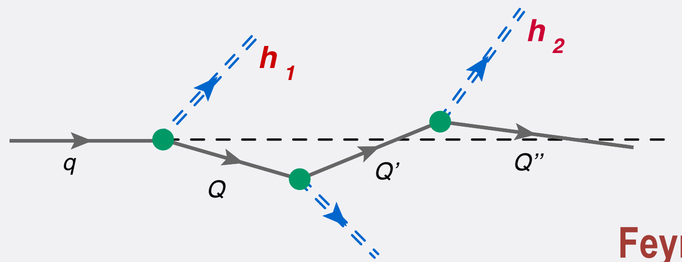
HERE I WANT TO FOCUS ON SPIN EFFECTS

MODELS FOR FRAGMENTATION

Jet models ➜ infinite number of substeps

Comparing versions of Monte Carlo

- Monte Carlo
  - Pythia
  - Herwig
  - Sherpa
  - ...
- Models
  - Cascade
    - various vertices...
  - 1 quark dominance
    - spectator
    - ...
- First principles: sum rule



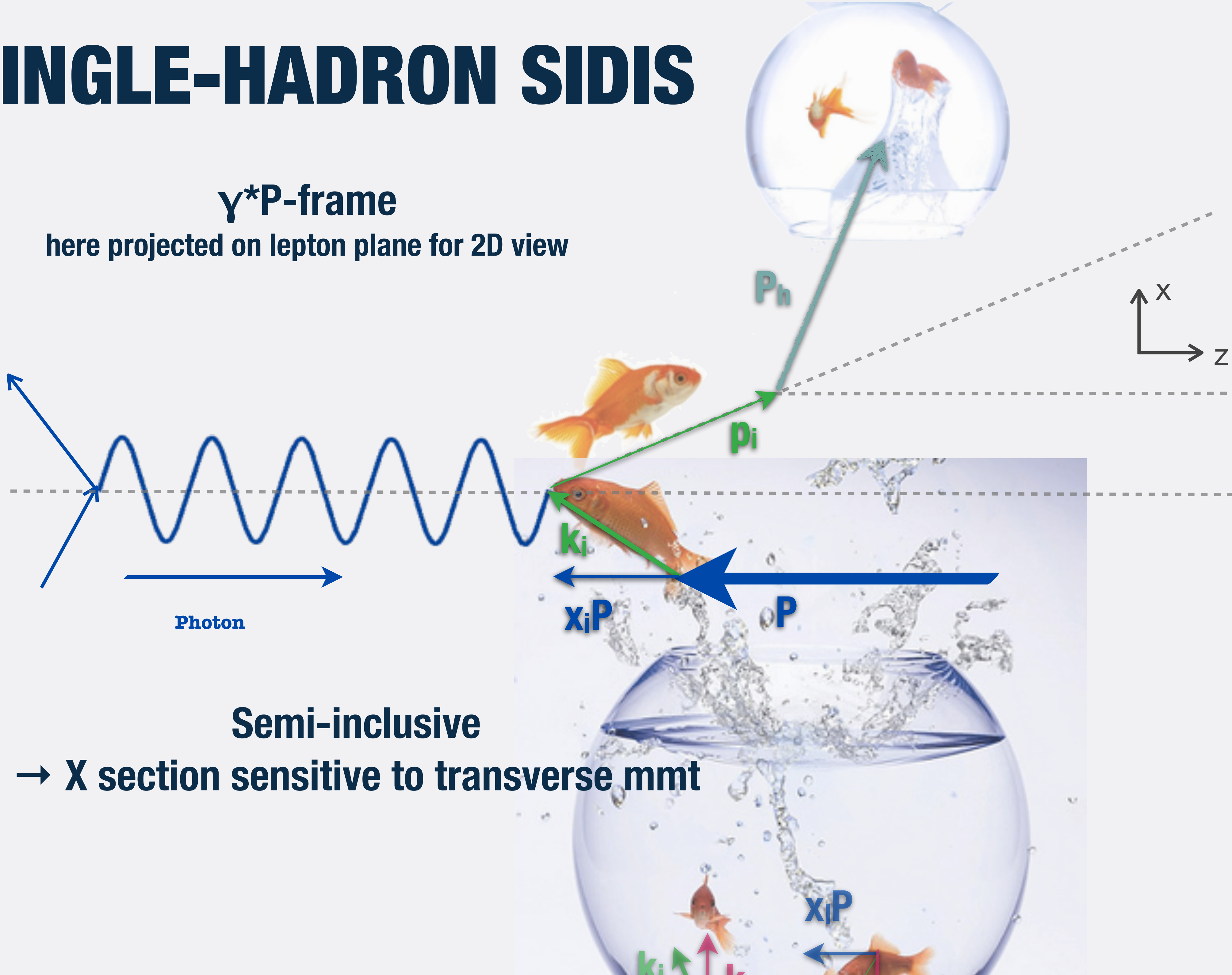
Feynman cascade model

$$\sum_h \int_0^1 dz\, z\, D_i^h(z, Q^2) = 1$$

SINGLE-HADRON SIDIS

γ*P-frame

here projected on lepton plane for 2D view



Semi-inclusive

→ X section sensitive to transverse mmt

SINGLE-HADRON SIDIS

γ*P-frame

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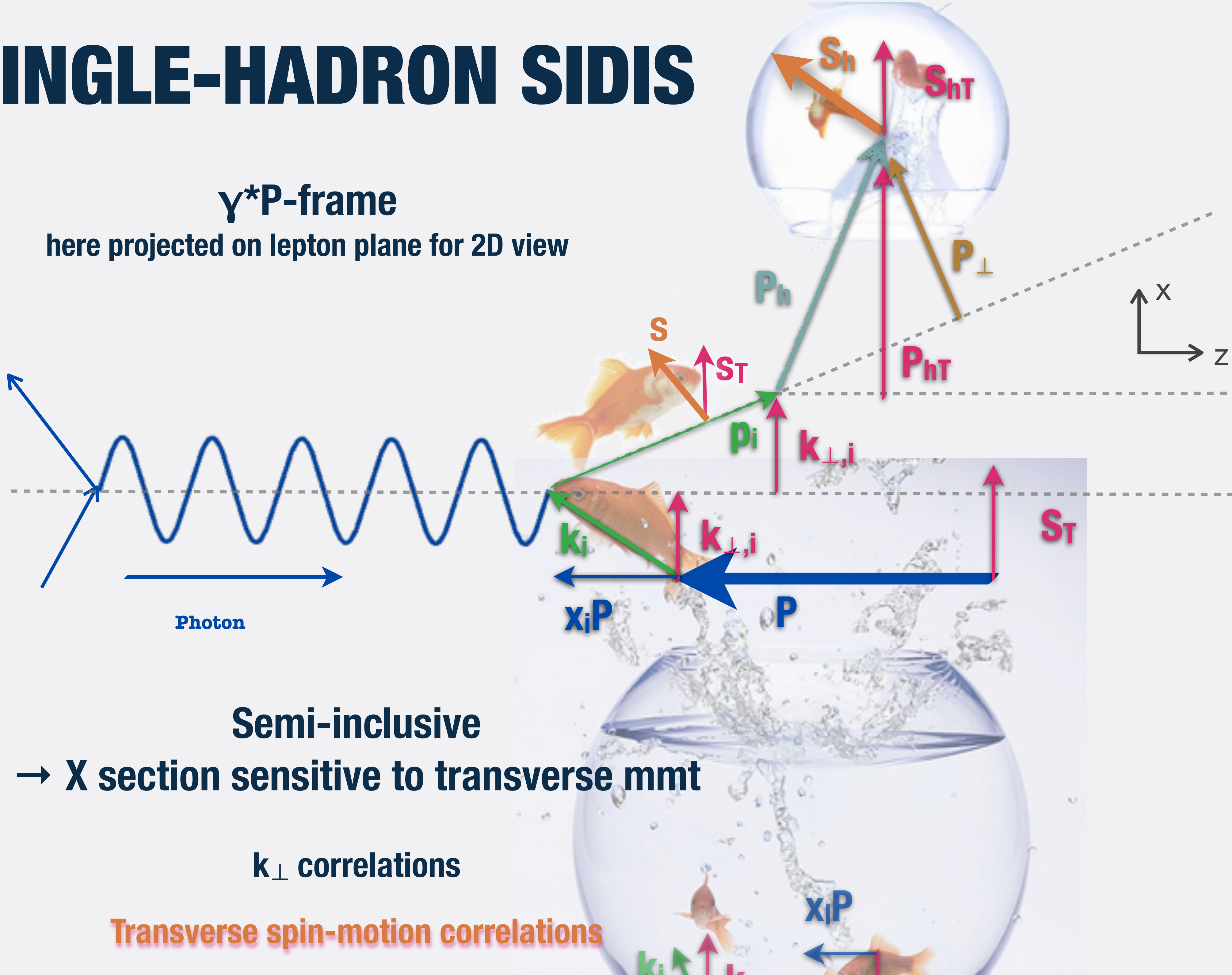


Semi-inclusive

→ X section sensitive to transverse mmt

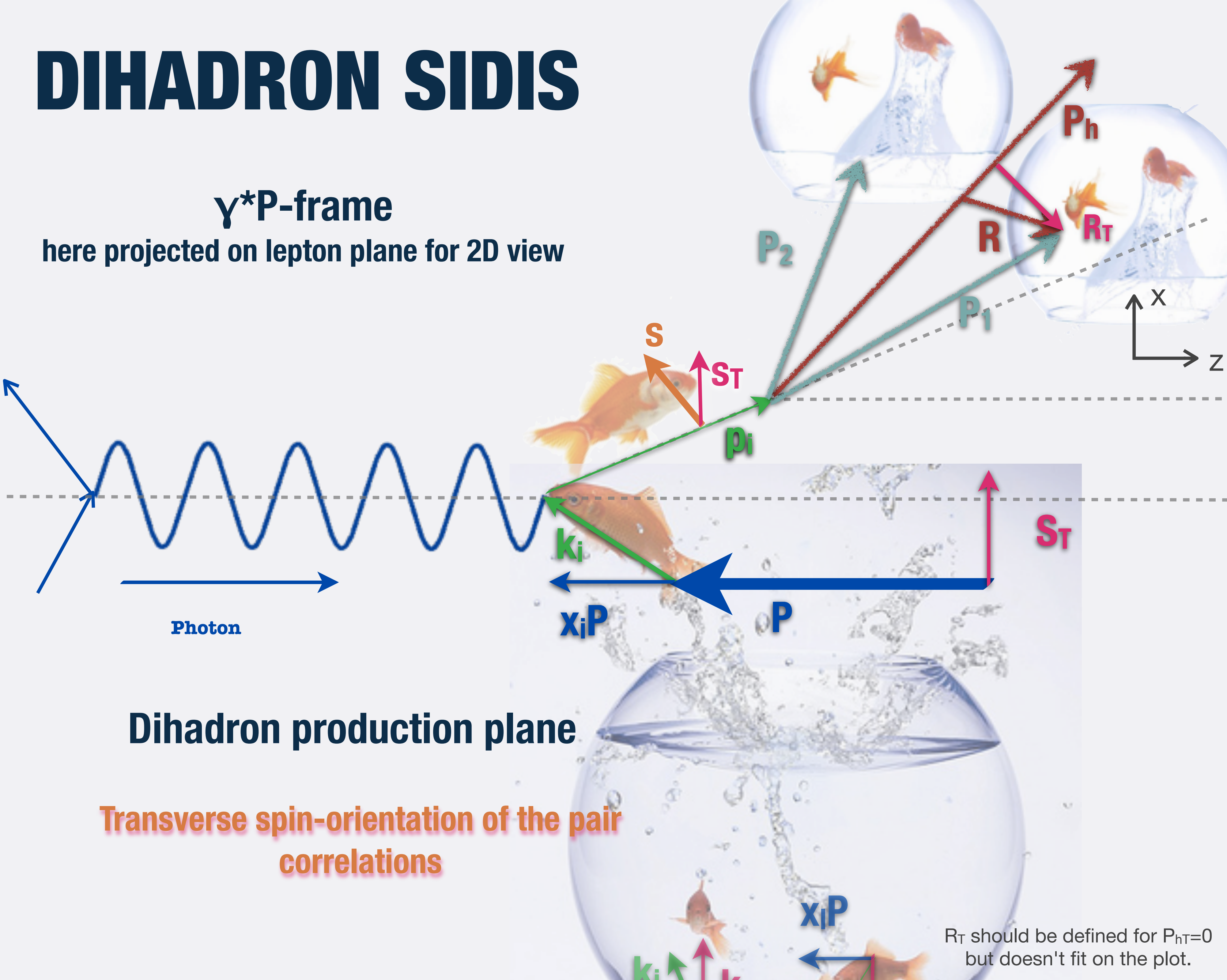
$k_{\perp}$ correlations

Transverse spin-motion correlations

DIHADRON SIDIS

γ*P-frame

here projected on lepton plane for 2D view



Dihadron production plane

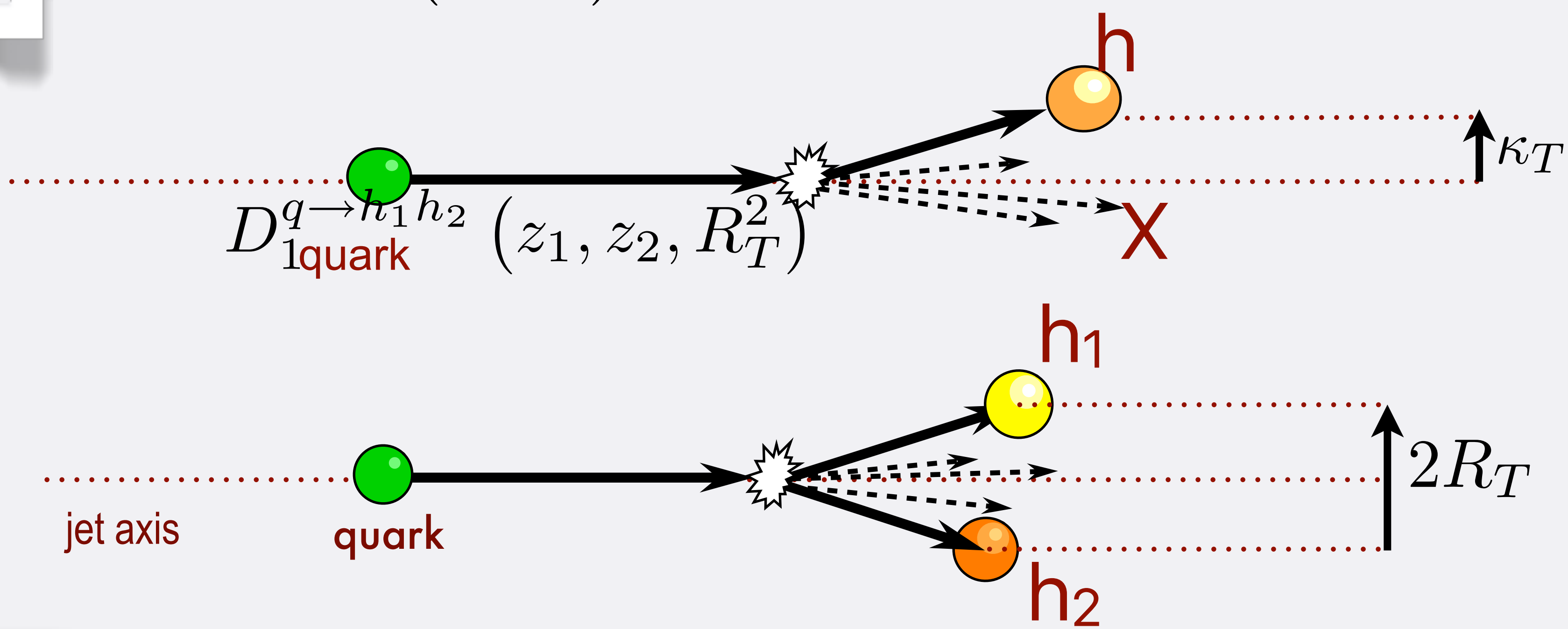
Transverse spin-orientation of the pair correlations

R_T should be defined for P_{hT}=0 but doesn't fit on the plot.

UNPOLARIZED FF

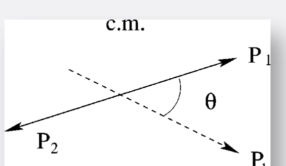
TMD FF

$$D_1^{q\to h}\left(z,\kappa_T^2\right)$$



$$D_1^{q\to h_1 h_2}\left(z_1,z_2,R_T^2\right)$$

DiFF

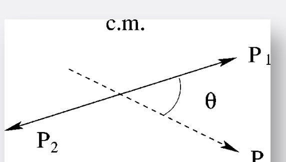


$$\frac{|\boldsymbol{R}|}{M_h}=\frac{1}{2}\sqrt{1-\frac{4m_\pi^2}{M_h^2}}$$

SPIN DEPENDENT DIFF

$$H_1^{\sphericalangle}(z, M_h)$$

transverse pol. of the fragm. quark → **angular distribution** of hadron pairs in the transverse plane



$$\frac{|\boldsymbol{R}|}{M_h} = \frac{1}{2}\sqrt{1 - \frac{4m_\pi^2}{M_h^2}}$$

SINGLE-HADRON & DIHADRON SIDIS

Transverse mmt dep.

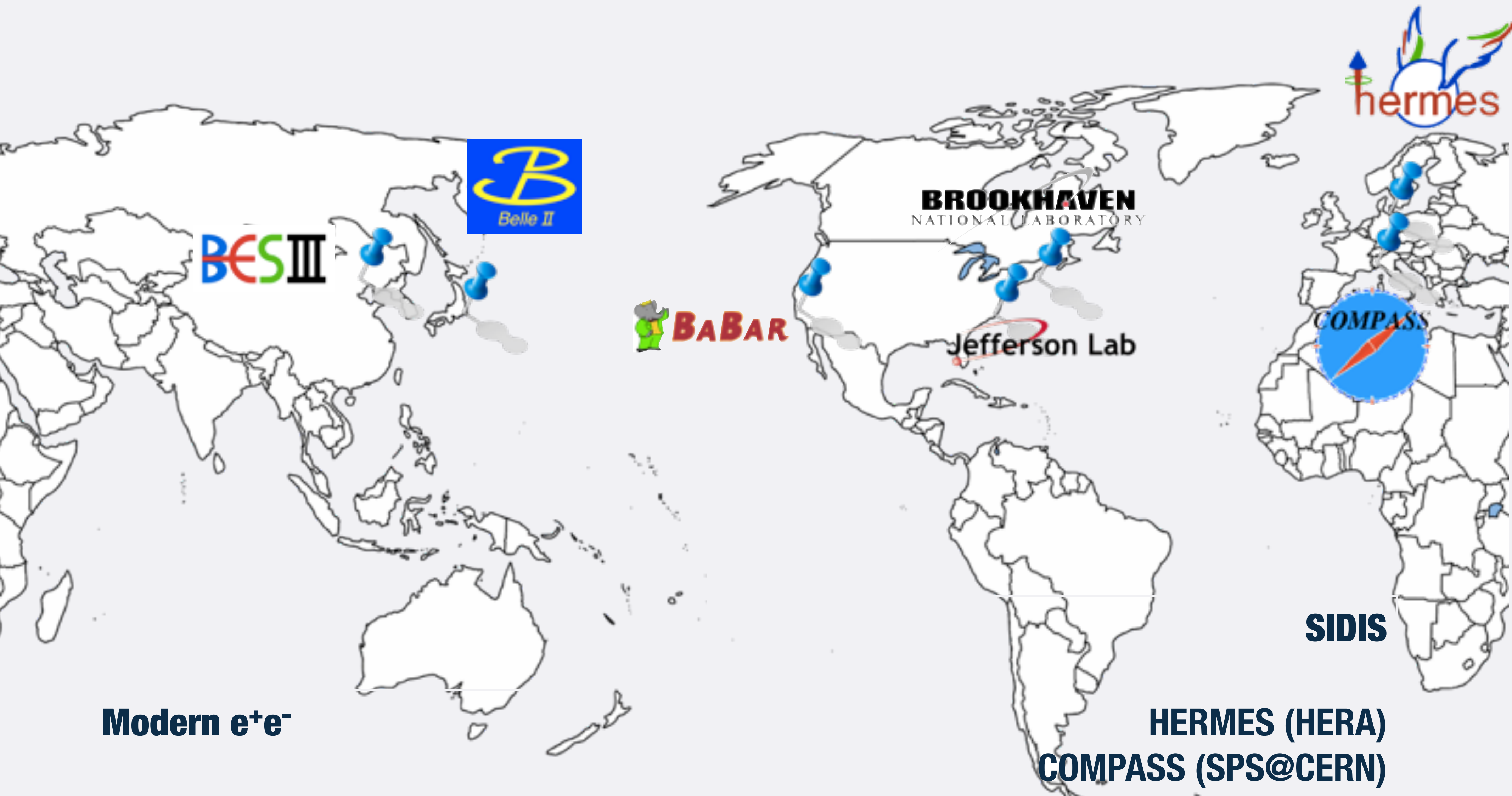
$$d\sigma \propto \sum_q [\mathrm{PDF}^q \otimes \mathrm{FF}^q] \left(x, z, P_{h\perp}^2\right)$$

- TMD Fragmention and Distribution functions
- Convolution
- More Lorentz structures
- 3D ``tomography"

Collinear

$$d\sigma \propto \sum_q \mathrm{PDF}^q(x) \times \mathrm{DiFF}^q\,(z, M_h)$$

- Collinear Distribution functions
- Simple product
- 1D ``tomography"



SIDIS

HERMES (HERA)
COMPASS (SPS@CERN)
CLAS(JLab)

Future
CLAS12(JLab)
SoLID(JLab)
EIC(??)

Modern e^+e^-

Belle/Belle II (KeK)
BaBar (SLAC)
BES (BEPC)

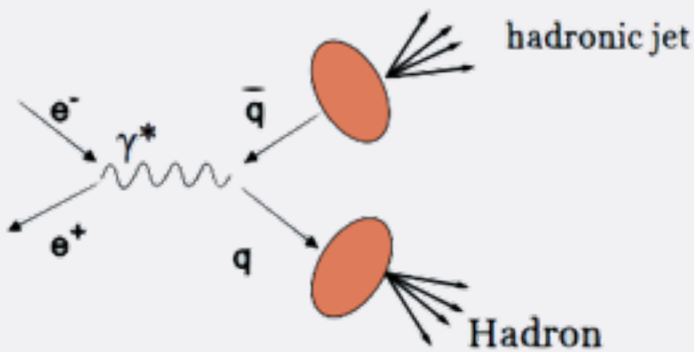
pp @BNL
DY @COMPASS

INTERPLAY & COLLABORATION BETWEEN TWO FIELDS

LED TO FIRST SUCCESS IN SPIN PHYSICS!

SI PION PAIRS PRODUCTION @ BELLE

[Belle Collaboration, PRL107]



$$A_{e^+e^-}(z, M_h^2, \bar{z}, \bar{M}_h^2) \propto \frac{\sum_q e_q^2 H_{1,\,sp}^{q\to\pi^+\pi^-}(z, M_h^2)\,\bar{H}_{1,\,sp}^{q\to\pi^+\pi^-}(\bar{z}, \bar{M}_h^2)}{\sum_q e_q^2 D_1^{q\to\pi^+\pi^-}(z, M_h^2)\,\bar{D}_1^{q\to\pi^+\pi^-}(\bar{z}, \bar{M}_h^2)}$$

Extraction/fit of DiFFs

- Hadron multiplicities
- Define
  - fitting procedure
  - statistical model
  - first principles constraints?
- Build functional form
- Account for QCD evolution

[A.C., Bacchetta, Radici, Bianconi, Phys.Rev. D85]
[Radici, A.C., Bacchetta, Radici, Guagnelli, JHEP 1505]

SI PION PAIRS PRODUCTION @ BELLE

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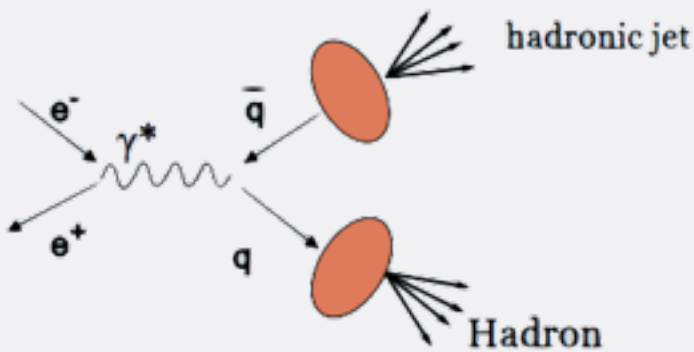

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Extraction/fit of DiFFs

- from Artru-Collins asymmetry
- Define
  - fitting procedure
  - statistical model
  - first principles constraints?
- Build functional form
- Account for QCD evolution

[A.C., Bacchetta, Radici, Bianconi, Phys.Rev. D85]
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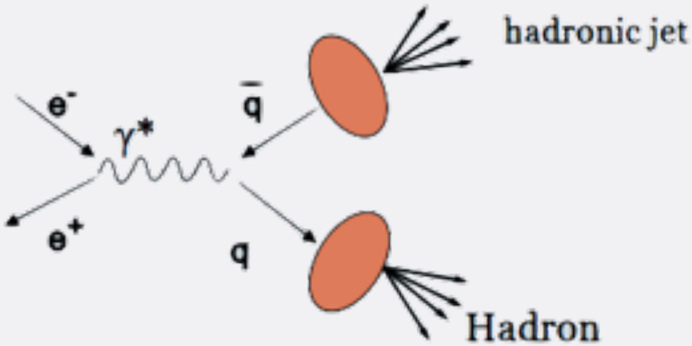

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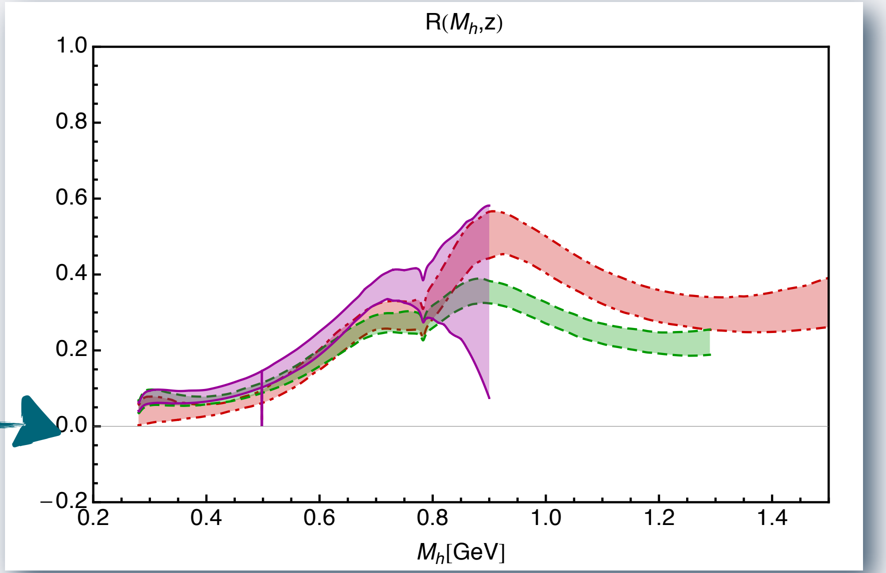
$$R(z, M_h) = \frac{|\mathbf{R}|}{M_h}\,\frac{H_{1,sp}^{\sphericalangle u}(z, M_h; Q_0^2)}{D_1^u(z, M_h; Q_0^2)}$$



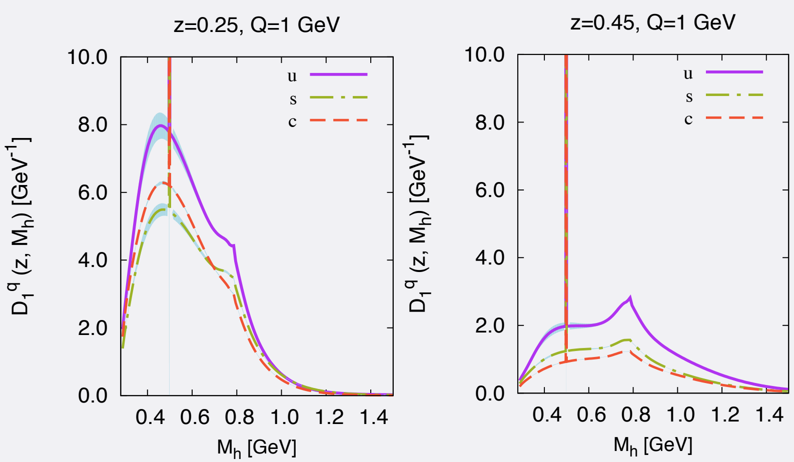
[A.C., Bacchetta, Radici, Bianconi, Phys.Rev. D85]
[Radici, A.C., Bacchetta, Radici, Guagnelli, JHEP 1505]

FITS & MODELS FOR DIFF

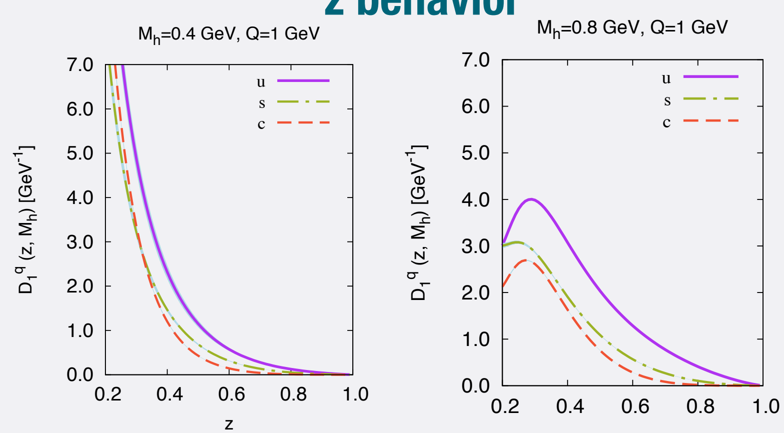
$q \rightarrow \pi^+\pi^- X$

Fitting PYTHIA at Belle

M_h behavior

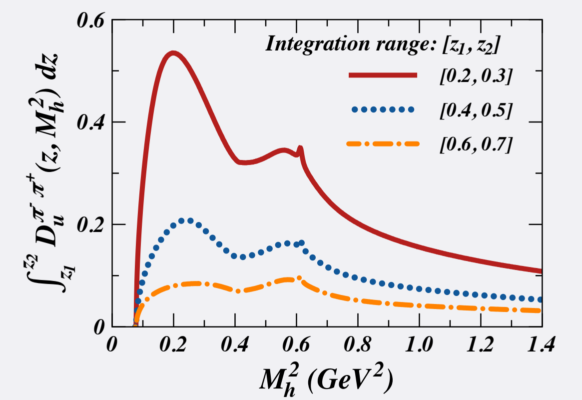


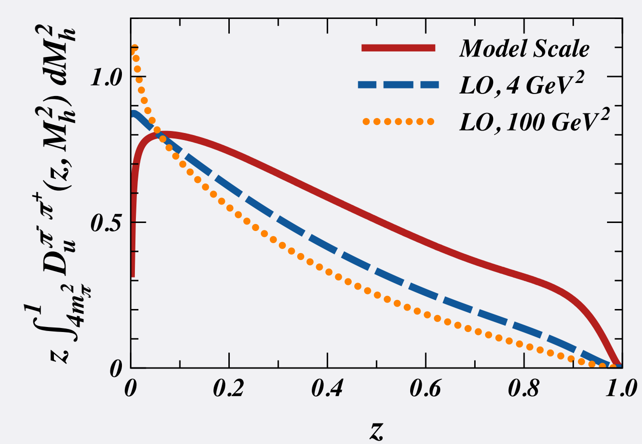
z behavior



[A.C., Bacchetta, Radici & Bianconi, PRD85]

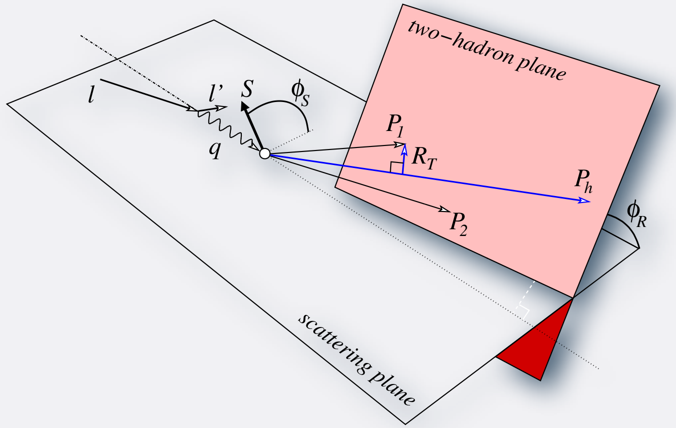
NJL-jet based MC event generator





[H. Matevosyan et al., PRD88]

DIHADRON SIDIS



Beam pol.

Target pol.

- **A_{UT}**

$$A_{UT}^{\sin(\phi_R+\phi_S)\,\sin\theta}(x,y,z,M_h;Q) = -\frac{B(y)}{A(y)}\,\frac{|\mathbf{R}|}{M_h}\,\frac{\sum_q e_q^2\, h_1^q(x;Q^2)\, H_{1,sp}^{\sphericalangle\, q}(z,M_h;Q^2)}{\sum_q e_q^2\, f_1^q(x;Q^2)\, D_1^q(z,M_h;Q^2)}$$

[Jaffe, Jin, Tiang, PRL 80]
[Radici, Jakob & Bianconi, PRD65]

- **A_{LU}**

$$A_{LU}^{\sin\phi_R\,\sin\theta}(x,y,z,M_h,Q) = -\frac{W(y)}{A(y)}\,\frac{M}{Q}\,\frac{1}{2}\,\frac{|\mathbf{R}|}{M_h}\,\frac{\sum_q e_q^2\left[x e^q(x)\, H_{1,sp}^{\sphericalangle,q}(z,M_h) + \frac{M_h}{zM}\, f_1^q(x)\,\tilde{G}_{sp}^{\sphericalangle,q}(z,M_h)\right]}{\sum_q e_q^2\, f_1^q(x)\, D_{1,ss+pp}^q(z,M_h)}$$

[Bacchetta & Radici, PRD69]

- **A_{UL}**

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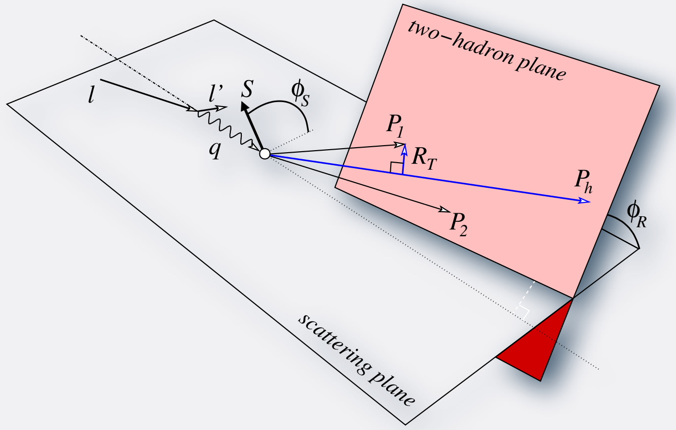
DIHADRON SIDIS



☑ **A$_{UT}$ @ HERMES & COMPASS**

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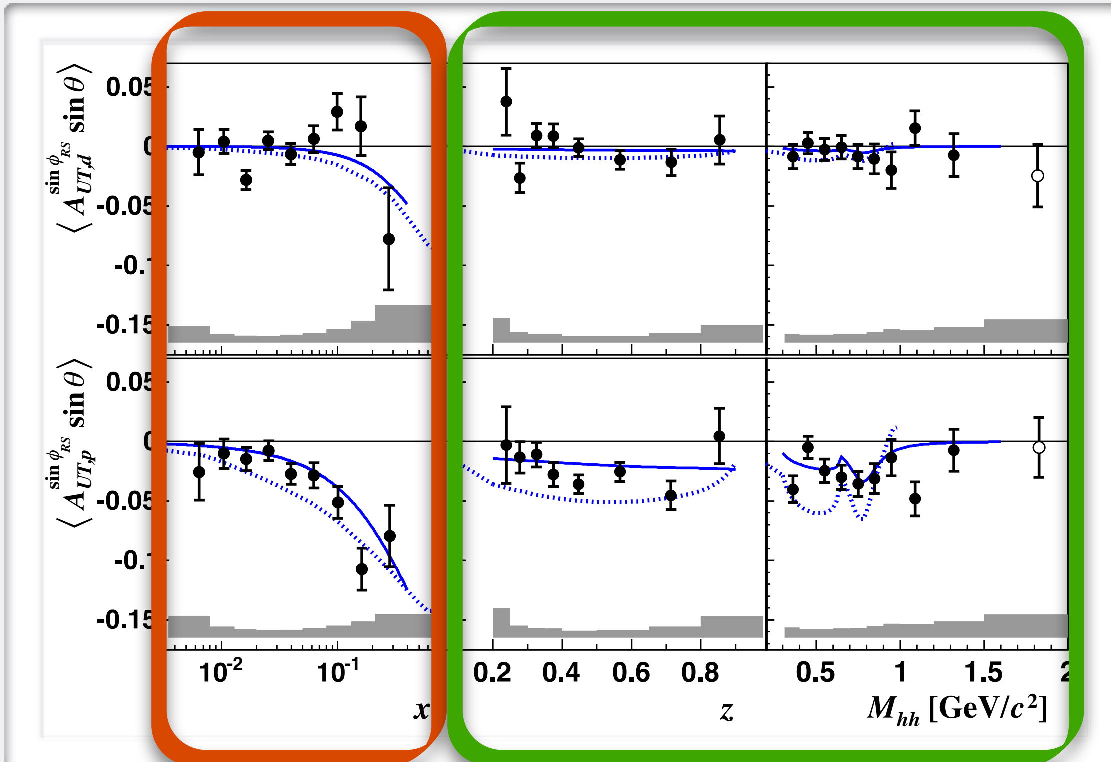
DIHADRON SIDIS ON PROTON & DEUTERON

2002-4 Deuteron Data

2007 Proton Data



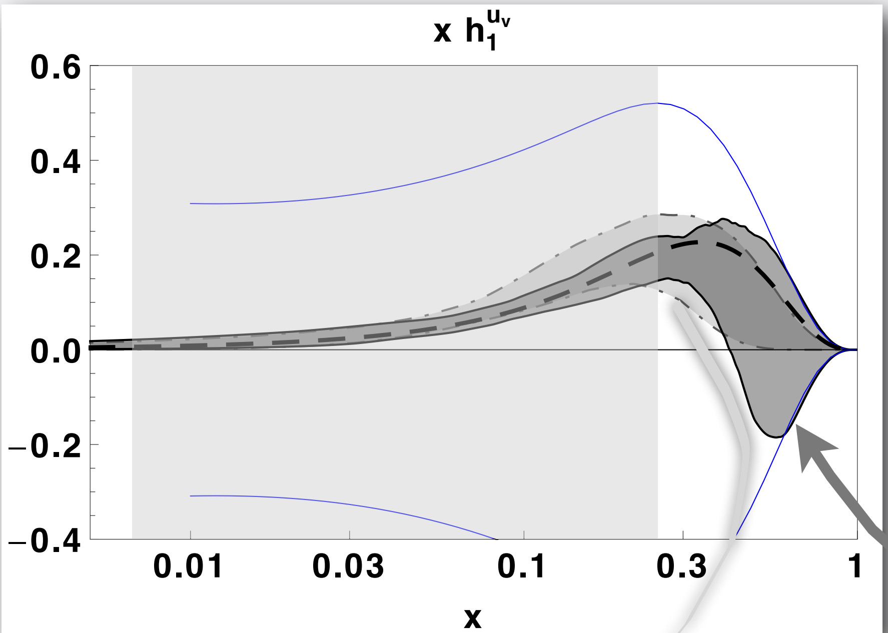
(z, M_h)-dpdence determined by DiFF from Belle

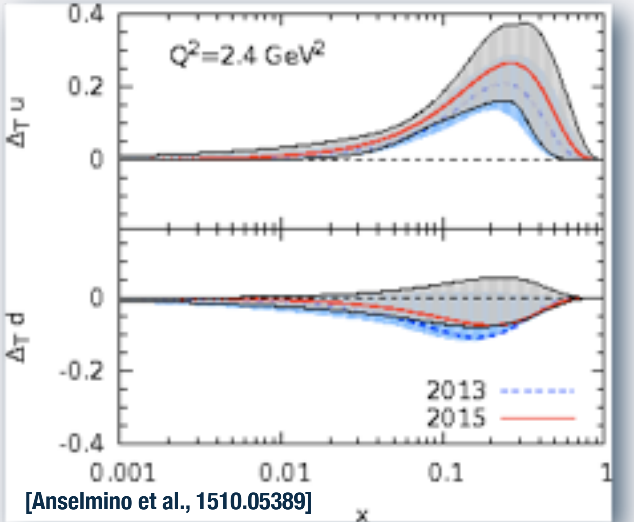
[A.C., Bacchetta, Radici, Bianconi, Phys.Rev. D85]

x-dependence only from Transversity

$$A_{\mathrm{DIS}}(x,z,M_h^2,Q^2) = -C_y \frac{\sum_q e_q^2\, h_1^q(x,Q^2)\, \frac{|\bar{R}|}{M_h}\, H_{1,sp}^{q\to\pi^+\pi^-}(z,M_h^2,Q^2)}{\sum_q e_q^2\, f_1^q(x,Q^2)\, D_1^{q\to\pi^+\pi^-}(z,M_h^2,Q^2)}$$

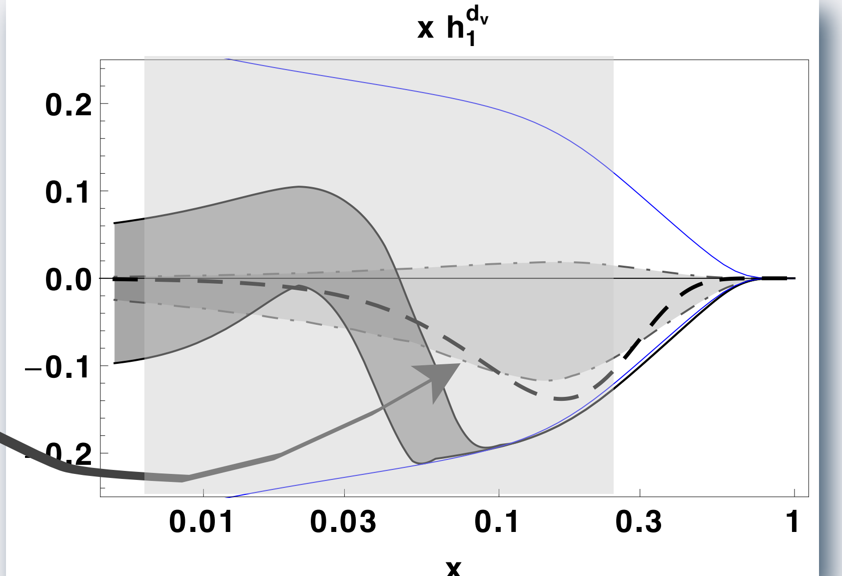
STATE-OF-THE-ART TRANSVERSITY





Pavia @2.4 GeV^2 flexible-0.125

Torino 2013 @2.4 GeV^2



Kang et al central value

Discrepancy in the d distribution

New proton data don't change that!

[Radici, A.C., Bacchetta, Radici, Guagnelli, JHEP 1505]

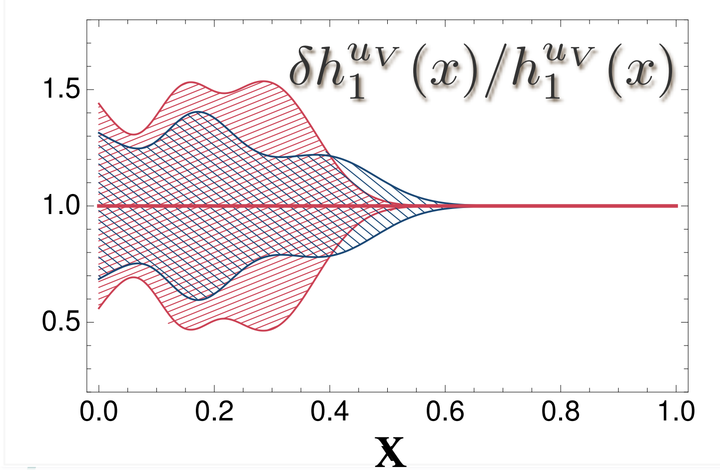
FUTURE OF THE TRANSVERSITY

Proposal for CLAS12 PR12-12-009

A 12 GeV Research Proposal to Jefferson Lab (PAC 39)

Measuremen[...] [...]oduction in SID[...] [...]get

A. Courtoy†
† Co-spokesperson



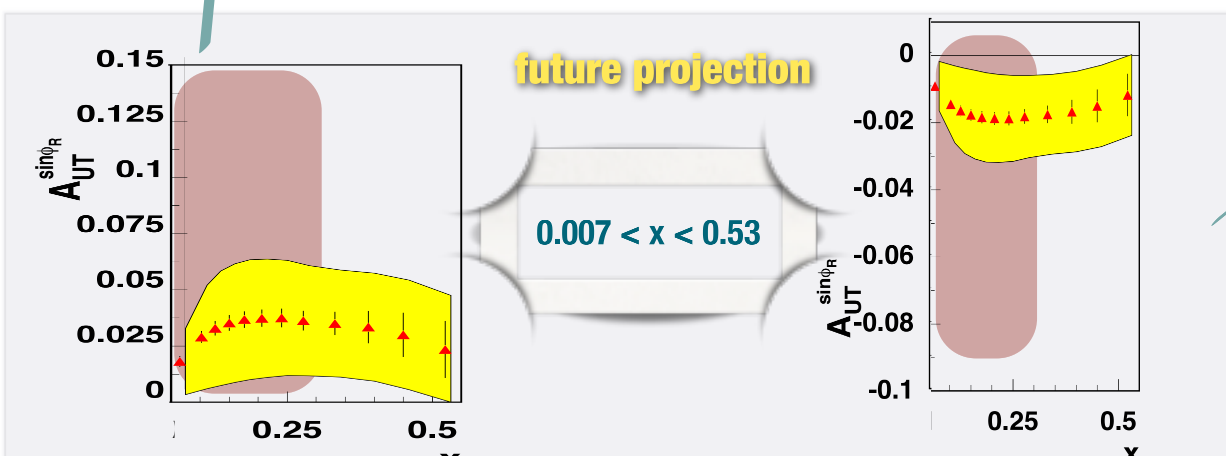
Analysis Proposal for SoLID

Dihadron Electroproduction in DIS with Transversely Polarized ^{3}He Target at 11 and 8.8 GeV

June 2, 2014

(A Proposal to Jefferson Lab (PAC 42))

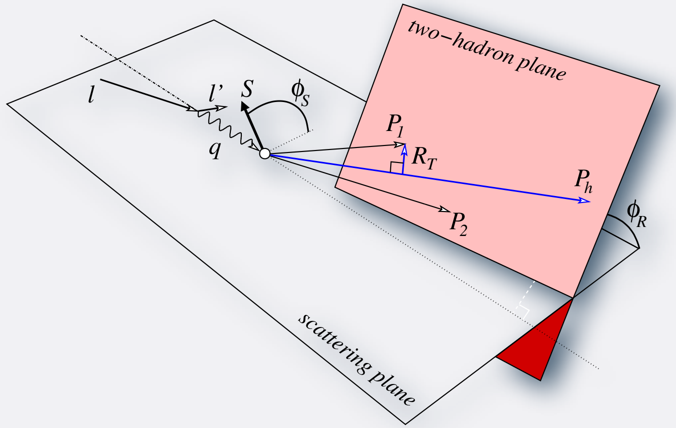
A. Courtoy†
† Co-spokesperson



Improve determination of tensor charge!

$$\int_0^1 dx\, h_1^{q_V}(x) = \delta q$$

DIHADRON SIDIS



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@ CLAS12 & SoLID

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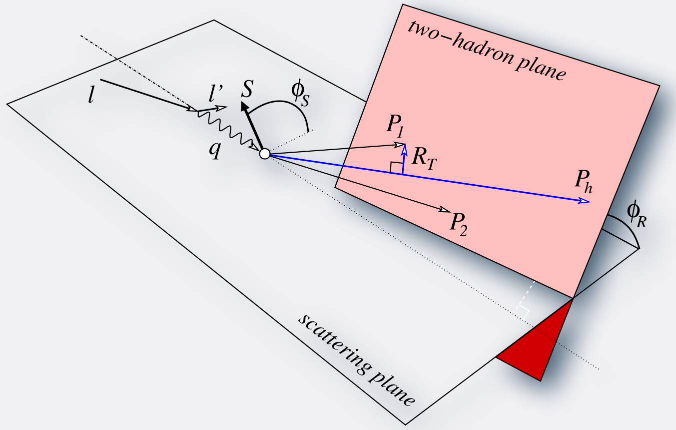
DIHADRON SIDIS



☑ **A$_{UT}$** @ HERMES & COMPASS
@ CLAS12 & SoLID

$$A_{UT}^{\sin(\phi_R+\phi_S)\,\sin\theta}(x,y,z,M_h;Q) = -\frac{B(y)}{A(y)}\frac{|\mathbf{R}|}{M_h}\frac{\sum_q e_q^2\, h_1^q(x;Q^2)\, H_{1,sp}^{\sphericalangle\, q}(z,M_h;Q^2)}{\sum_q e_q^2\, f_1^q(x;Q^2)\, D_1^q(z,M_h;Q^2)}$$

[Jaffe, Jin, Tiang, PRL 80]
[Radici, Jakob & Bianconi, PRD65]

☑ **A$_{LU}$** @CLAS & CLAS12

$$A_{LU}^{\sin\phi_R\,\sin\theta}(x,y,z,M_h,Q) = -\frac{W(y)}{A(y)}\frac{M}{Q}\frac{1}{2}\frac{|\mathbf{R}|}{M_h}\frac{\sum_q e_q^2\left[x e^q(x)\, H_{1,sp}^{\sphericalangle,q}(z,M_h) + \frac{M_h}{zM}\, f_1^q(x)\, \tilde{G}_{sp}^{\sphericalangle,q}(z,M_h)\right]}{\sum_q e_q^2\, f_1^q(x)\, D_{1,ss+pp}^q(z,M_h)}$$

[Bacchetta & Radici, PRD69]

☑ **A$_{UL}$** @CLAS

$$A_{UL}^{\sin\phi_R\,\sin\theta}(x,y,z,M_h,Q) = -\frac{V(y)}{A(y)}\frac{M}{Q}\frac{1}{2}\frac{|\mathbf{R}|}{M_h}\frac{\sum_q e_q^2\left[x h_L^q(x)\, H_{1,sp}^{\sphericalangle,q}(z,M_h) + \frac{M_h}{zM}\, g_1^q(x)\, \tilde{G}_{sp}^{\sphericalangle,q}(z,M_h)\right]}{\sum_q e_q^2\, f_1^q(x)\, D_{1,ss+pp}^q(z,M_h)}$$

BEAM SPIN ASYMMETRY@CLAS

GOAL: extract e(x)

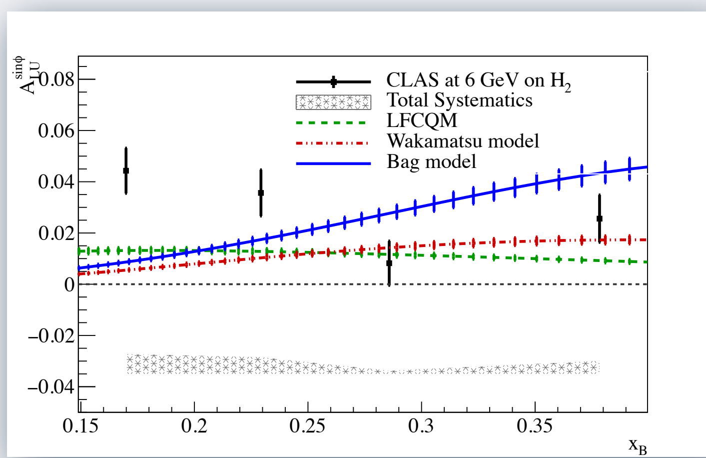
higher-twist PDF e(x) unknown

higher-twist DiFFs unknown

$$A_{LU}^{\sin\phi_R}(x,z,m_{\pi\pi};Q,y) = -\frac{W(y)}{A(y)}\,\frac{M}{Q}\,\frac{|\mathbf{R}|}{m_{\pi\pi}}\,\frac{\sum_q e_q^2\left[x e^q(x,Q^2)\, H_{1,sp}^{\sphericalangle,q}(z,m_{\pi\pi},Q^2) + \frac{m_{\pi\pi}}{M}\, f_1^q(x,Q^2)\, \tilde{G}_{sp}^{\sphericalangle,q}(z,m_{\pi\pi},Q^2)\right]}{\sum_q e_q^2\, f_1^q(x,Q^2)\, D_{1,ss+pp}^q(z,m_{\pi\pi},Q^2)}$$

leading-twist DiFFs known

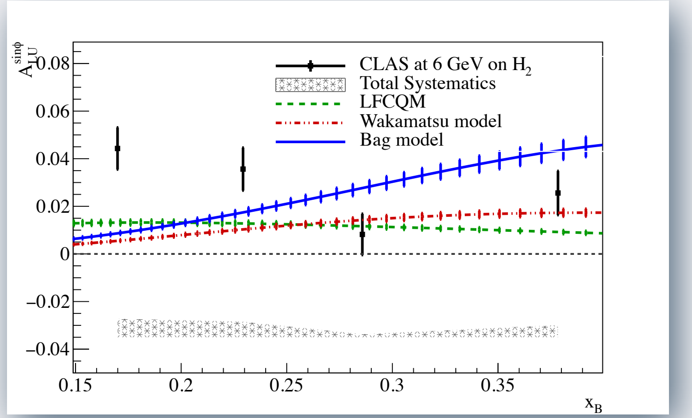
...from CLAS data

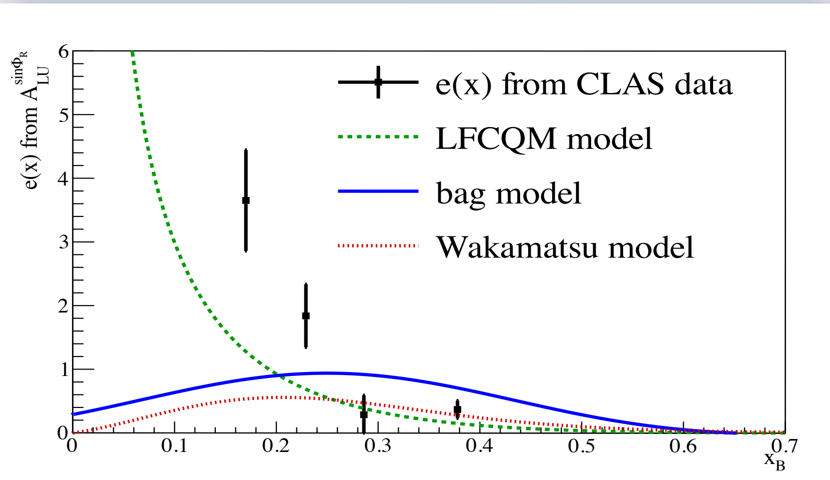


Silvia Pisano's analysis e1-f

FIRST TRY EXTRACTION

Assume no dynamical higher-twist in the fragmentation part





leading-twist DiFFs
known from PAVIA fit

$$A_{LU}^{\sin\phi_R}(x_i, m_{\pi\pi\,i},, z_i; Q_i, y_i) = -\frac{W(y_i)}{A(y_i)}\,\frac{M}{Q_i}\,\frac{x_i\left[\frac{4}{9}e^{u_V}(x_i, Q_i^2) - \frac{1}{9}e^{d_V}(x_i, Q_i^2)\right]\, n_{u,i}^{\uparrow}(Q_i^2)}{\sum_{q=u,d,s} e_q^2\, f_1^q(x_i, Q_i^2)\, n_{q,i}(Q_i^2)}$$

[AC et al, arXiv:1405.7659]

TWIST-3 PDF @CLAS12

Analysis Proposal for CLAS12

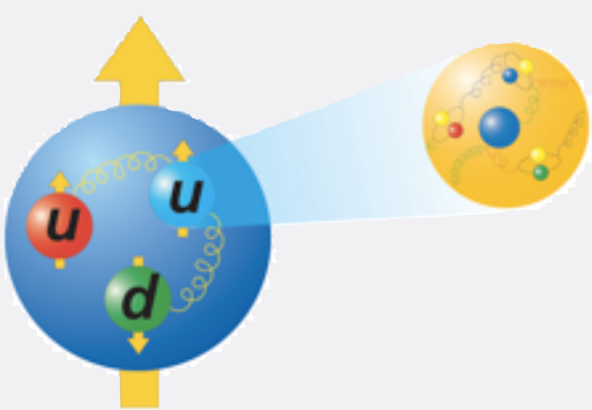
Higher-twist collinear structure of the nucleon through di-hadron SIDIS on unpolarized hydrogen and deuterium

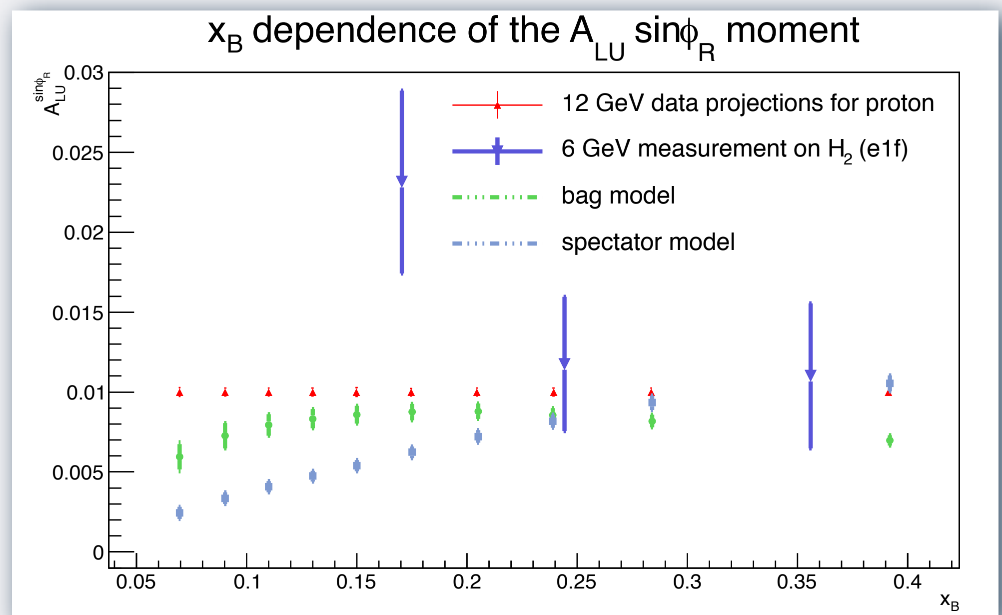
A 12 GeV Research Proposal to Jefferson Lab (PAC 42)

E12-06-112B
Silvia Pisano & A.C.

e(x)

- related to the scalar charge
- quark-gluon correlation
- quark mass term





BSM FUNDAMENTAL INTERACTIONS?

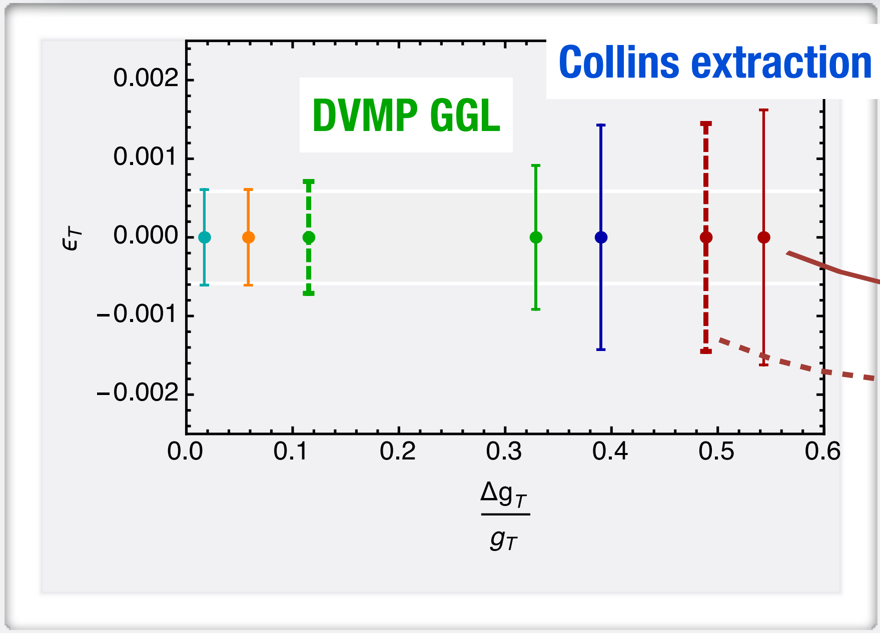
Example: New fundamental interaction from beta decay?

$$\Delta\mathcal{L}_{eff} = G_F V_{ud}\sqrt{2}\,\epsilon_S g_S\,\bar{p}n\cdot\bar{e}(1-\gamma_5)\nu_e$$
$$-4G_F V_{ud}\sqrt{2}\,\epsilon_T g_T\,\bar{p}\sigma_{\mu\nu}n\cdot\bar{e}\sigma^{\mu\nu}(1-\gamma_5)\nu_e$$

[Cirigliano et al., NPB 830]

Could we do the same with g_S?

$$\int_{-1}^{1} dx\, h_1^{u_V-d_V}(x) = g_T$$



Present DiFF extraction

Future DiFF extraction

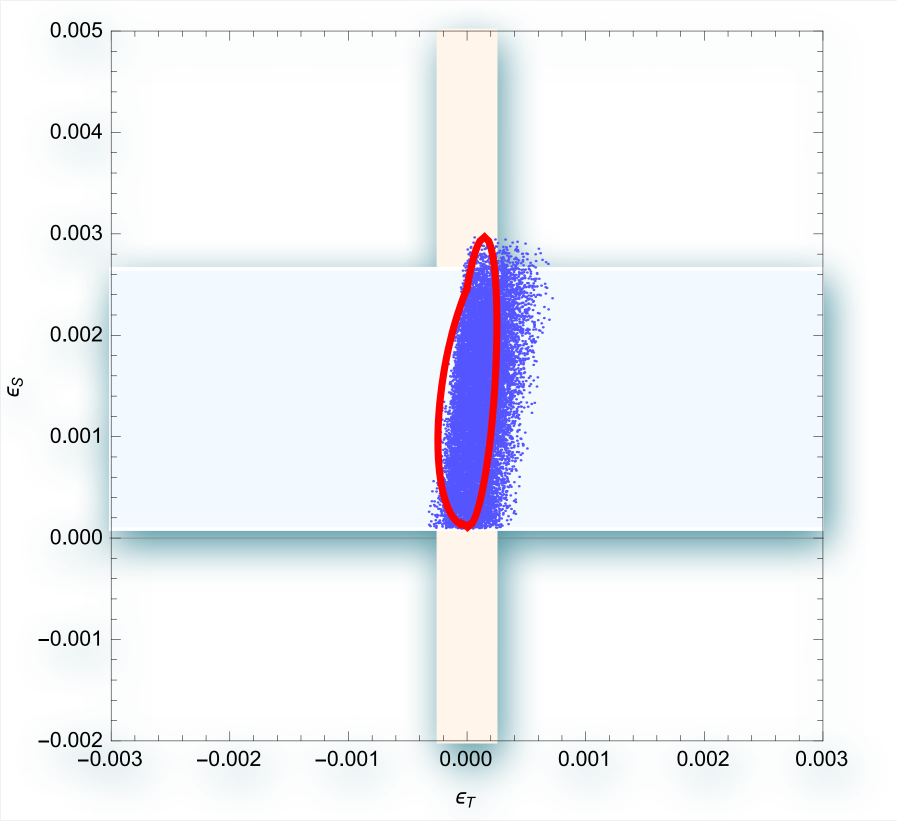
[AC,Baessler,Gonzalez-Alonso,Liuti, PRL 115]

BSM FUNDAMENTAL INTERACTIONS?

ε_T vs. ε_S plane from beta decay observables

with **ε_S=0.0011(21)** at 90% CL from Gonzalez & Camalich, PRL112.

with **$\langle g_T \rangle$=0.839(357)** from GGL & Pavia new



- **1σ errors**
- **Hessian in blue & pink**
- **Rfit method in red**
- **Scatter plot in blue**
- **MC 1D gives $\langle \varepsilon_T \rangle$ =0.0012 ±...**

[AC,Baessler,Liuti, in progress]

CONCLUSIONS

✓ Hadronization and confinement are of high importance

✓ Here: Dihadron Fragmentation Functions

- Dihadron SIDIS is a good tool to
    - access to scalar, tensor hadronic structures
    - glimpse of quark-gluon correlations
- **Future:** get more info on DiFF from e^+e^- & SIDIS (multiplicities,...)

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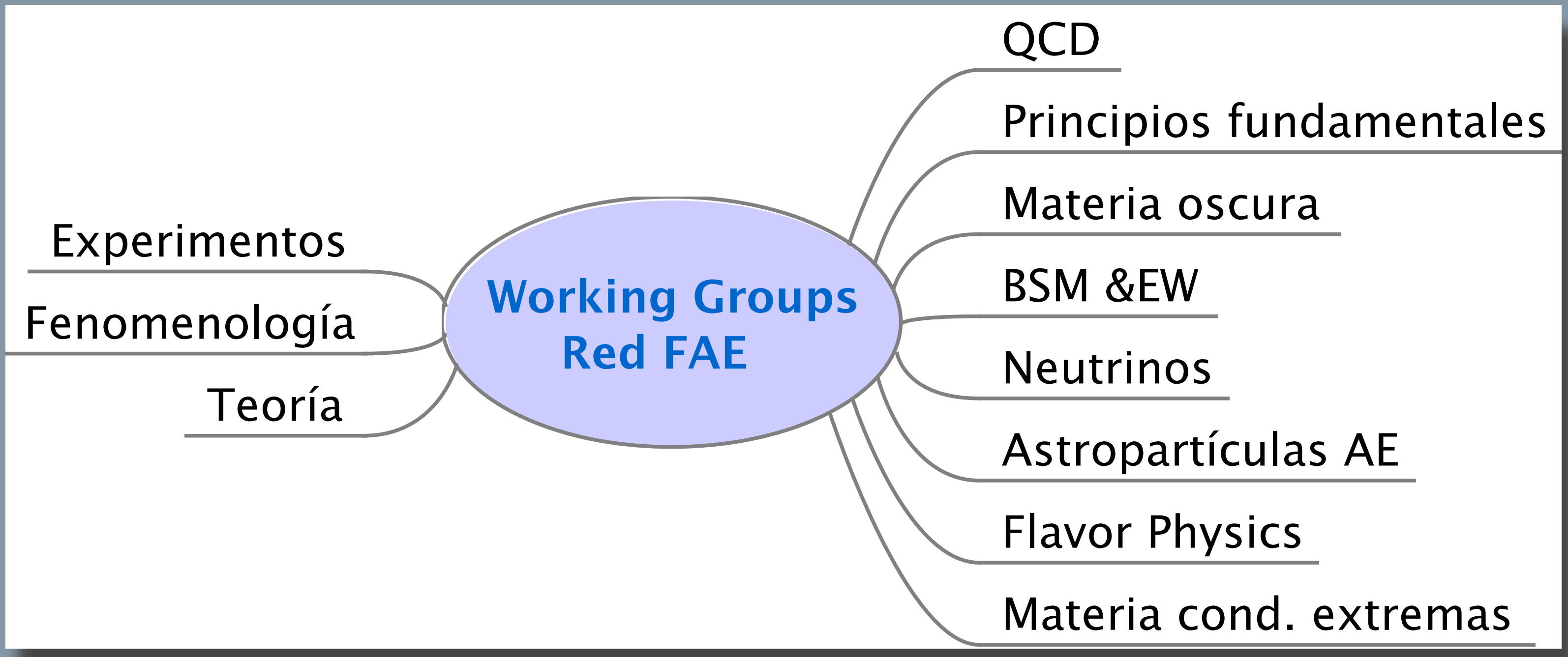
Red FAE



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Coordinador: Aurore Courtoy