Summary of WG5: Spin and 3D Structure

Conveners: Yoshitaka Hatta, Yoshiyuki Miyachi, Qinghua Xu

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Laboratori Nazionali di Frascati

DIS2022 Santiago de Compostela – 6/5/22

Courtesy of F.Cuicchio INFN

List of Speakers

52 talks: 23 experimental and 29 theoretical

Jan Matousek
Matteo Cerutti
Patrick Barry
Andrea Simonelli
Miguel Arratia
Bakur Parsamyan
Abhiram Kaushik
Dillon Scott Fitzgerald
Navagyan Ghimire
Maxime Defurne
Johannes Vincenzo Giarra
Jakob Schönleber
Oskar Grocholski
Paweł Sznajder
Andreas Metz
Scott Wissink
Yiyu Zhou
Daniel Adamiak

Michael Murray
Sergio Leal Gómez
Alexey Vladimirov
Francesco Giovanni Celiberto
Zhongling Ji
Shohini Bhattacharya
Miguel Echevarria
David Frenklakh
Aurore Courtoy
Charles Hyde
Daria Sokhan
Olga Bessidskaia Bylund
Zhite Yu
Qintao Song
Ted Rogers
Fanyi Zhao
Fatma Pinar Aslan
Kemal Tezgin
Poona Choudhary
Stefan Diehl

Kei Nagai
Shunzo Kumano
Yajin Zhou
Wai Kin Lai
Amol Pawar
Ting Lin
Xilin Liang
Yi Yu
Taoya Gao
Yukun Song
Ralf Seidl
Kim Minho

Disclaimer

Many interesting subjects and lots of interesting results
Apologies if we have missed some topic or if I am not accurate in reporting your results

Longitudinal Spin

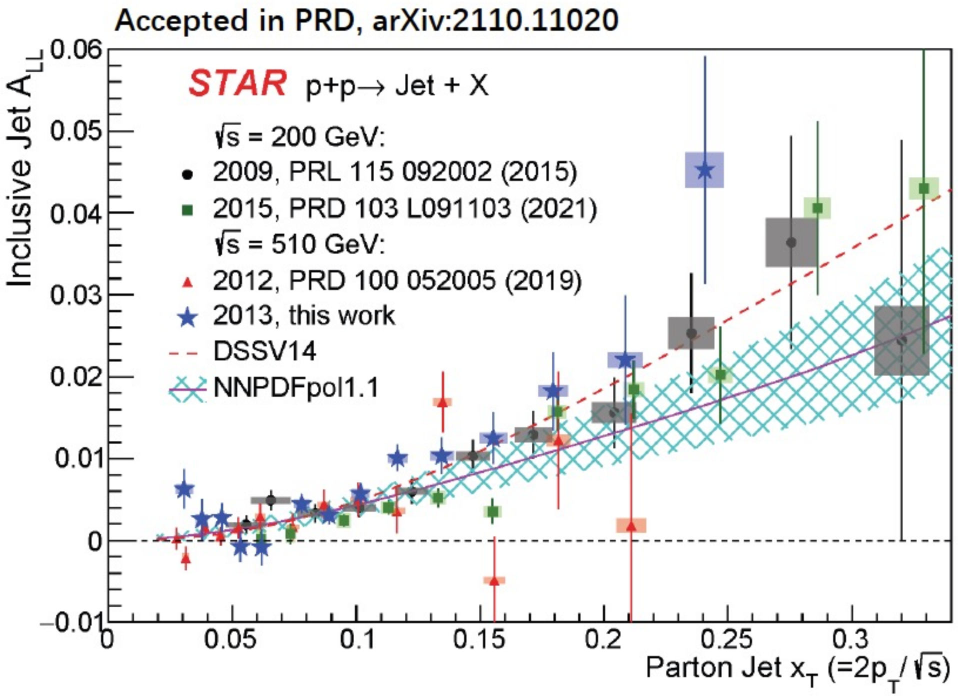
Courtesy of F.Cuicchio INFN

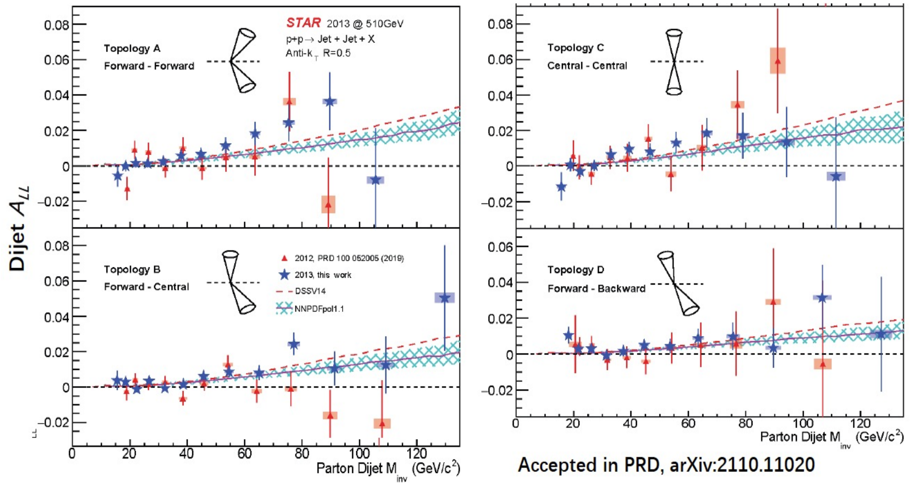
..n.co.uk

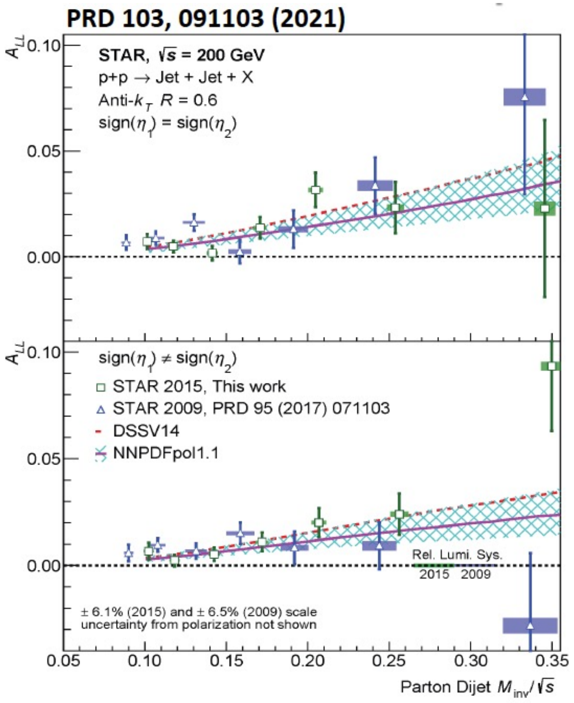
Jet spin asymmetries: probing gluon helicity distribution

Does the gluon spin contribute significantly to that of the proton?

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$







-Results from 510 GeV push down to lower x_T

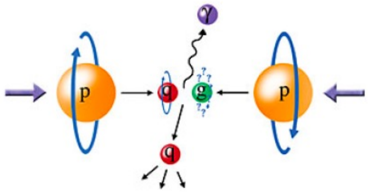
-Overall consistency seen among STAR data sets, a slight preference for DSSV14

Midrapidity dijets at 510 GeV … and 200 GeV

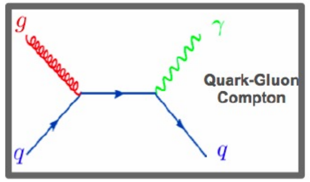
➡ Midrapidity results indicate ~40% of the proton's spin may be due to contributions from the spins of gluons that each carry at least 5% of the proton's momentum. Consistency old and new data will allow combined analysis

Zhonglin Ji

Measurement of Direct Photon Cross Section and Double Helicity Asymmetry at 510 GeV in pp Collisions



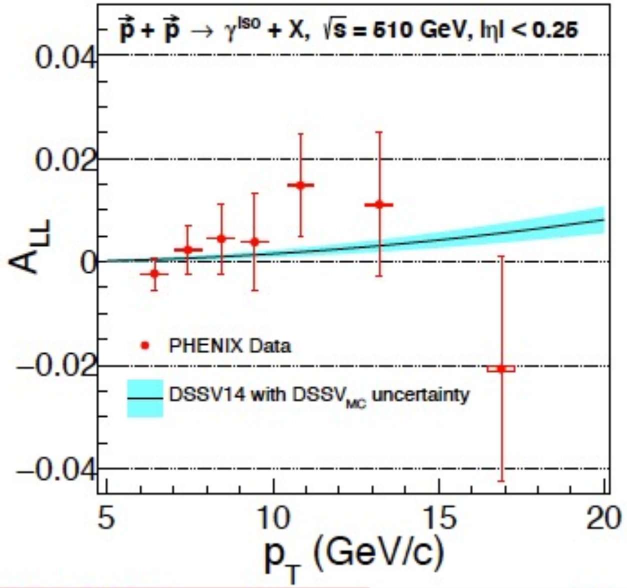
$$A_{LL}^{pp\to\gamma X} \sim \frac{\Delta q(x_q)}{q(x_q)} \cdot \frac{\Delta g(x_g)}{g(x_g)} \cdot a_{LL}^{qg\to\gamma q}$$

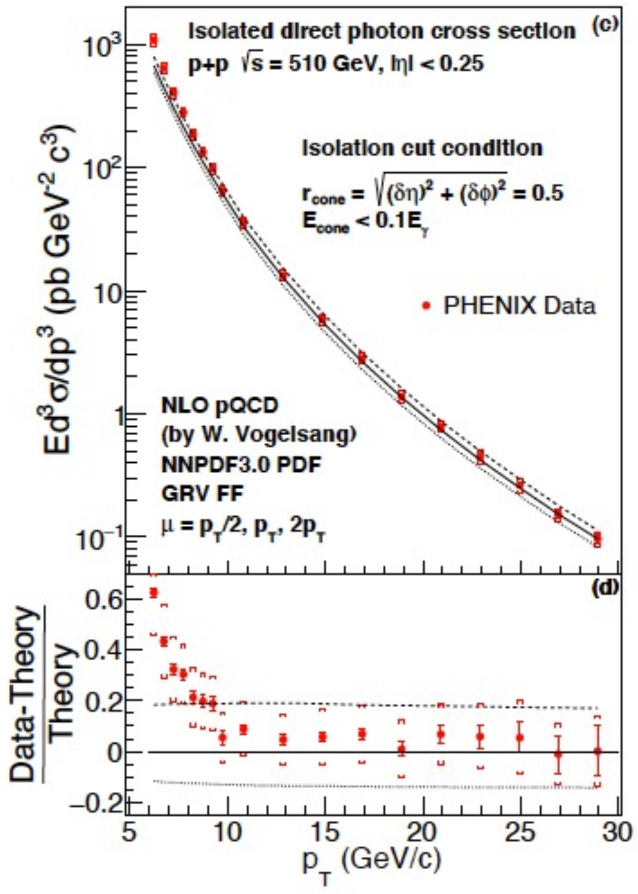


First published direct photon A_{LL}

"golden" channel

- Gluon spin is important for proton spin decomposition.
- Direct photons have little fragmentation contributions.
- First direct photon xsec and A_{LL} at 510 GeV.
- Independent constraint on the gluon spin contribution.





Transversity and Transverse Spin Asymmetries

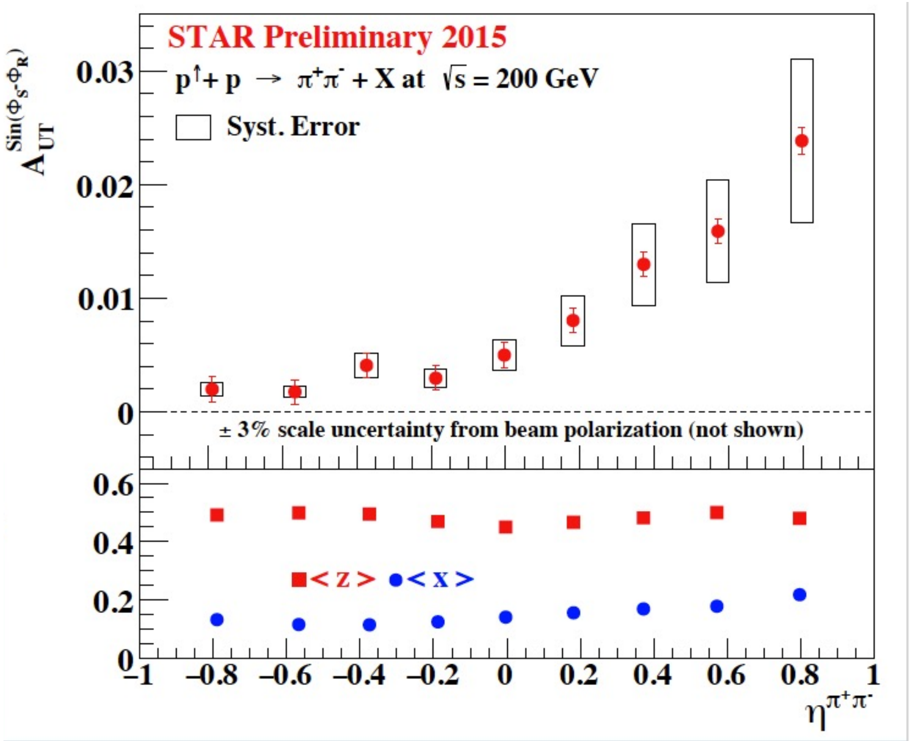
Courtesy of F.Cuicchio INFN

Probing transversity with **Interference Fragmentation Function** and **Collins asymmetry** in pp collisions

STAR

Navagyan Ghimire

Preliminary results of IFF asymmetry for charged pion pair in pp 200 GeV

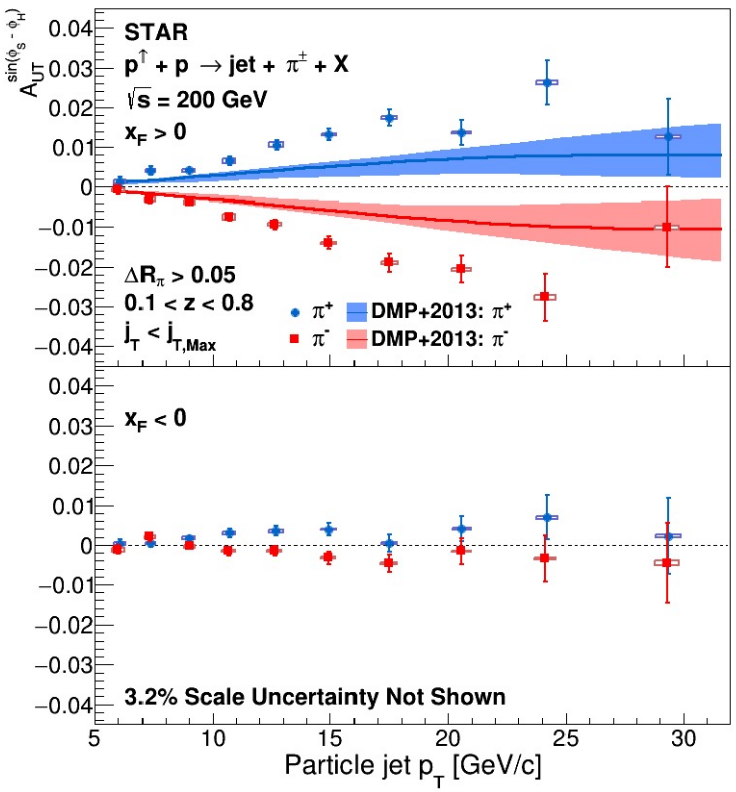


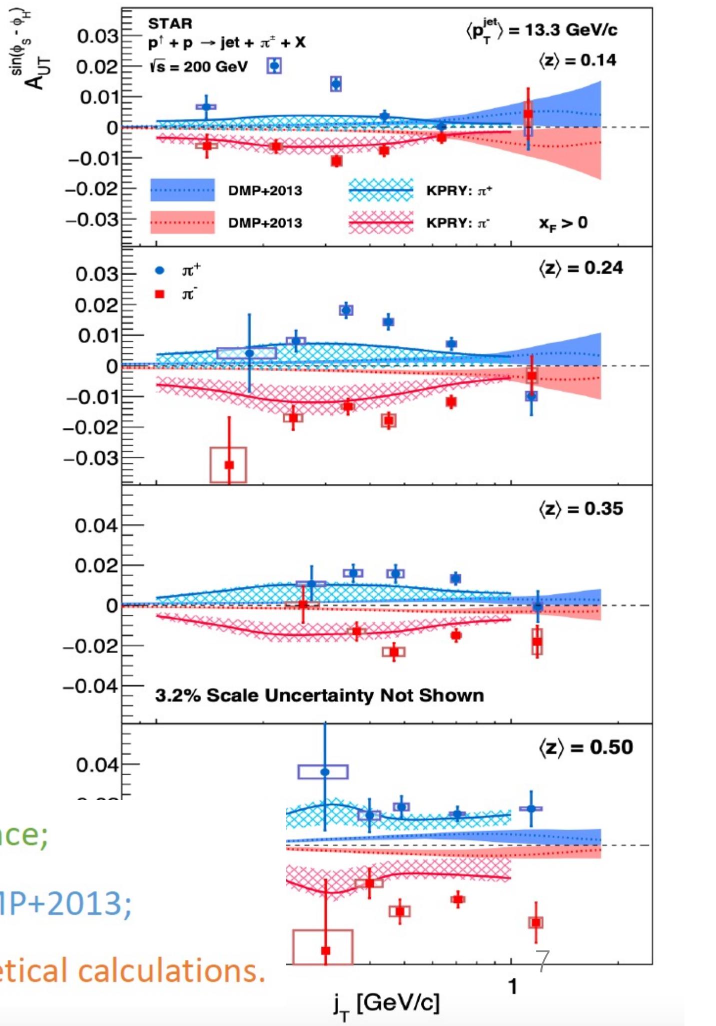
Strong rise of A_{UT} signal towards higher η_{pair} where we reach the highest value of x

Significant reduction of the PID uncertainty is expected by including TOF

Ting Lin

$\pi\pm$ Azimuthal Distribution in Jets: most precise results of Collins asymmetry in pp at 200 GeV from STAR 2012+2015 data



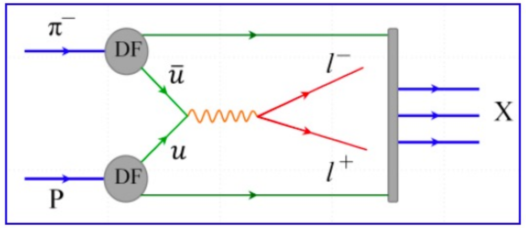


- Collins TMD FF is sensitive to the (j_T, z) dependence;
- Our results slightly favor the KPRY model than DMP+2013;
- Sizable differences between data and both theoretical calculations.

Transverse spin asymmetries in SIDIS and Drell-Yan

Bakur Parsamyan

New preliminary results on Sivers asymmetry in pion induced Drell-Yan with 2015+2018 COMPASS data



Sivers DY TSA

$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$

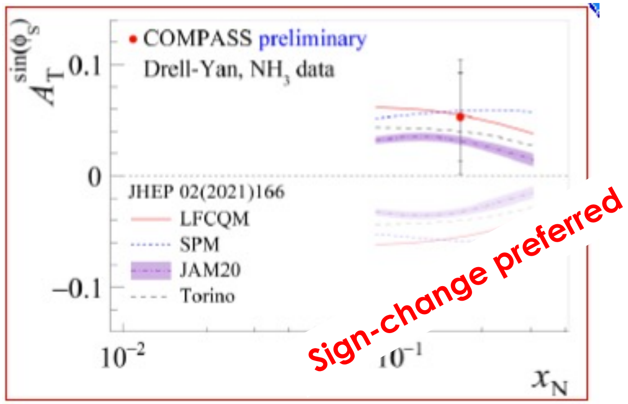
Transversity DY TSA

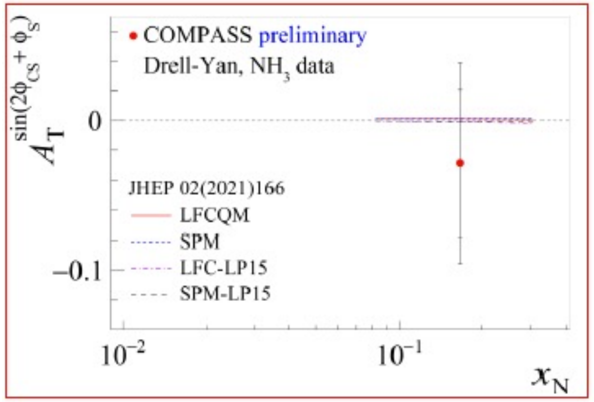
$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$

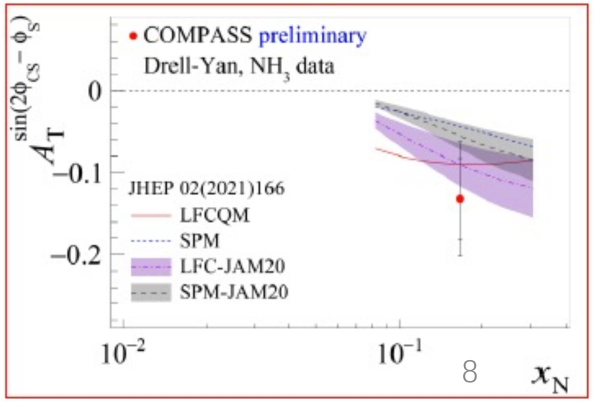
Pretzelosity DY TSA

$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$

2015 + 2018 data **NEW!**

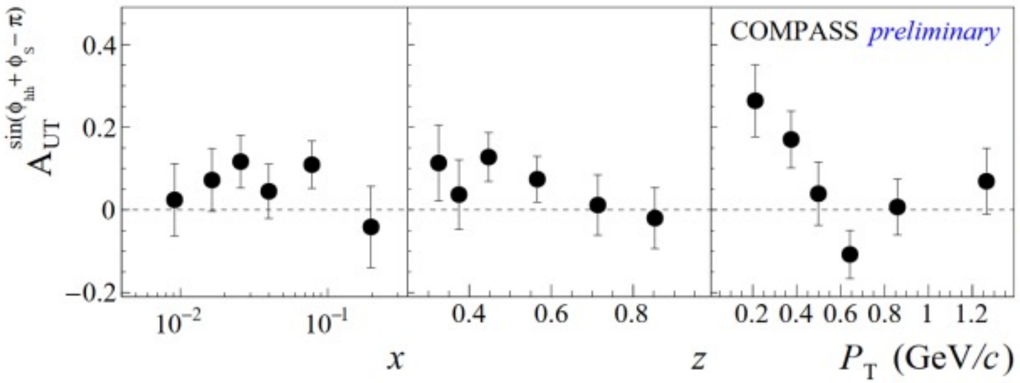


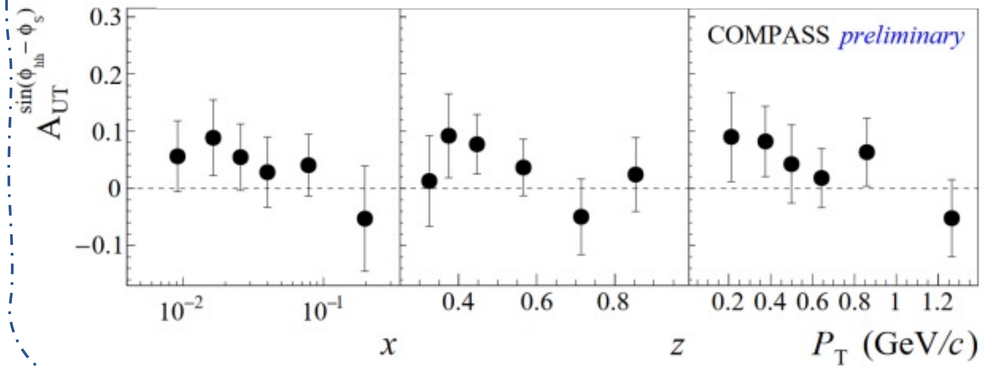




1st results of …

COLLINS ASYMMETRY FOR $\rho 0$
- indication for a positive asymmetry
- opposite to π+ and π0 as predicted by the models
- Large effect at small P_T



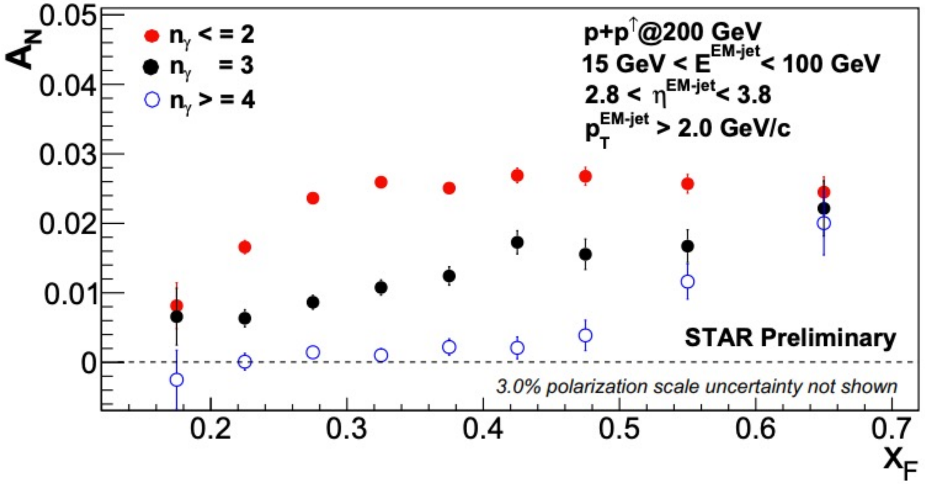


SIVERS ASYMMETRY FOR $\rho 0$
- indication for a positive asymmetry
- similar to π0 as expected from the models

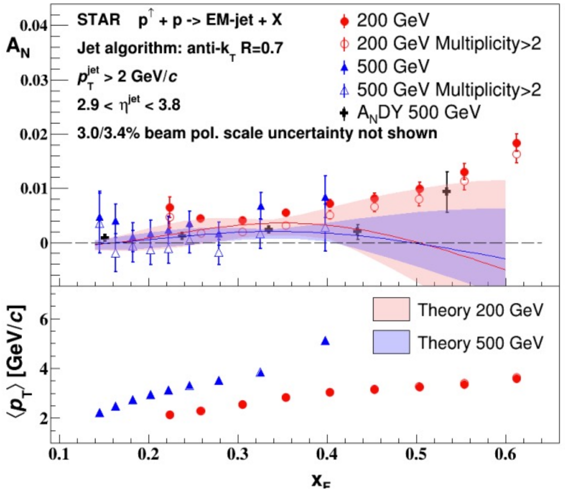
TSSA for forward inclusive and diffractive electromagnetic (EM) jets in pp collisions

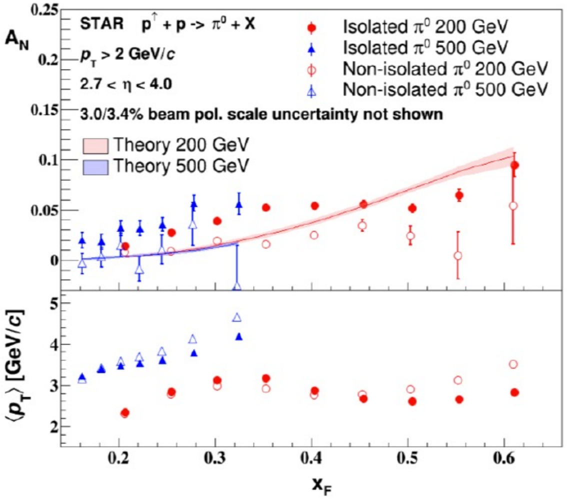
Xilin Liang

The EM-jet A_N decreases with photon multiplicity



EM-jet or isolated π^0 have larger A_N



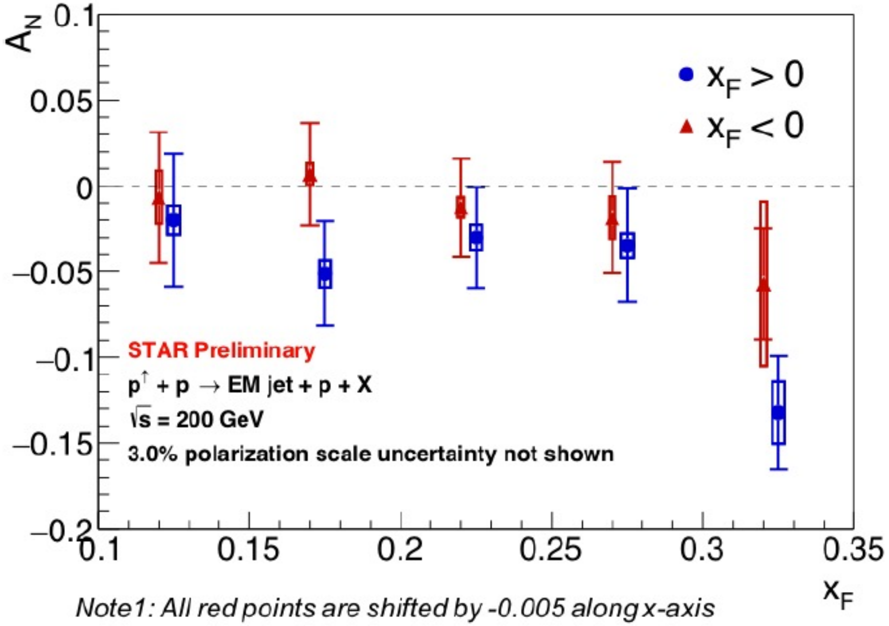


↔ any contribution from diffractive process? ↔

New preliminary results on the diffractive EM-jet A_N

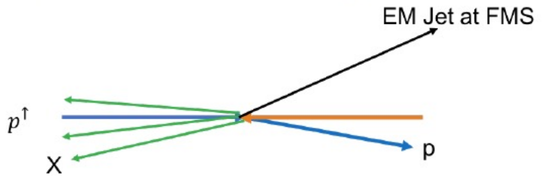
non-zero diffractive EM-jet A_N

Negative sign? → theory inputs needed

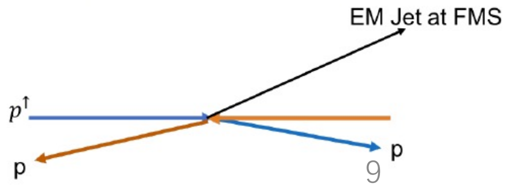


Note1: All red points are shifted by -0.005 along x-axis

① Only 1 proton track on FMS side and no proton track on the away side.



② Only 1 proton track on FMS side and only 1 proton track on away side.

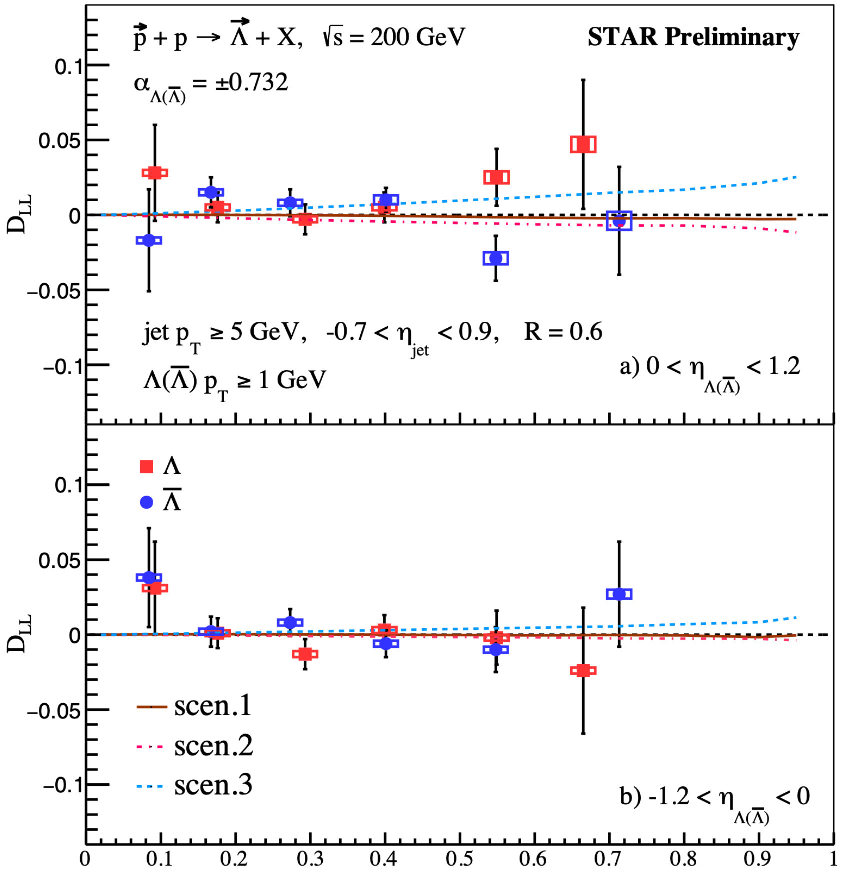


Longitudinal and transverse polarization of Λ hyperon in pp

Yi Yu

Taoya Gao

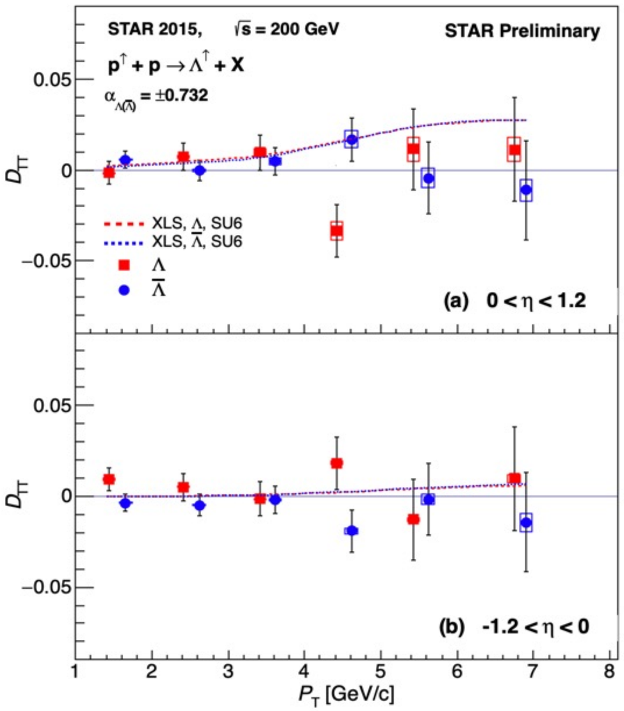
New results of longitudinal spin transfer D_{LL} versus z

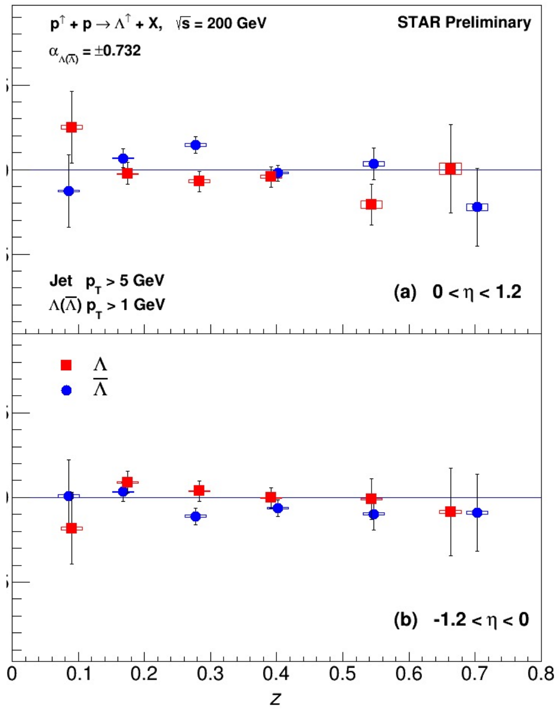


$$z = \frac{p_\Lambda \cdot p_{jet}}{|p_{jet}|^2}$$

Sensitive to polarized FF and strange quark helicity

Results of transverse spin transfer D_{TT} vs. z for $\Lambda(\bar{\Lambda})$ in pp collisions





→ connected to transversity & FF

D_{TT} is consistent both with the model predictions and with zero

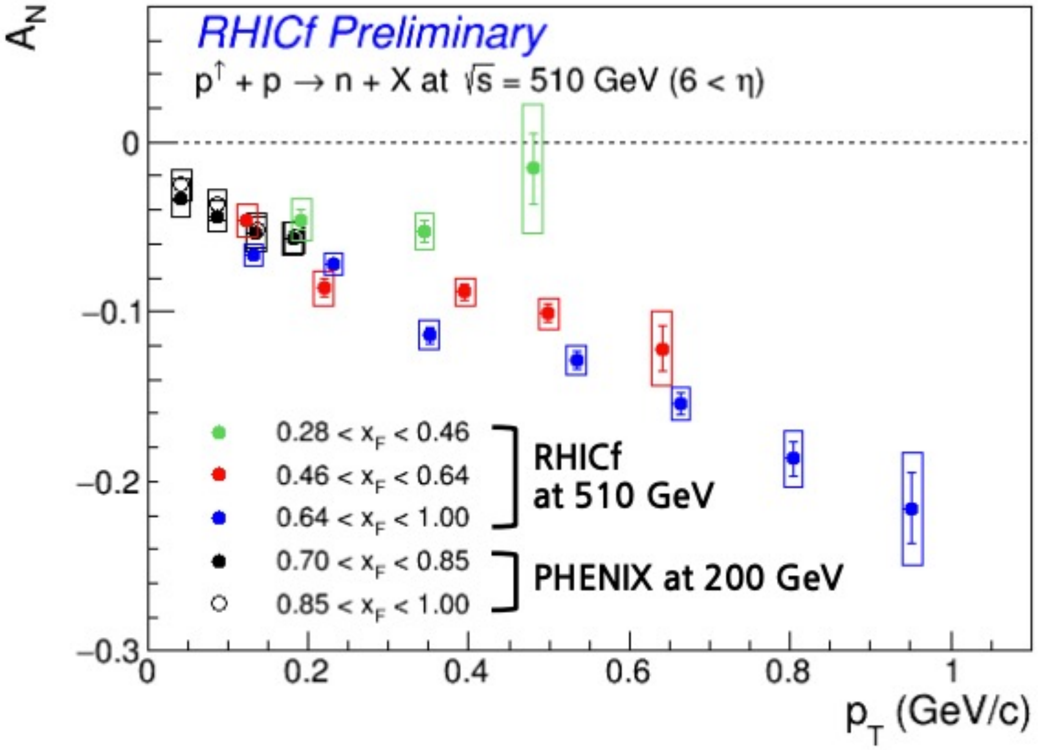
Ongoing analysis of Λ polarizing fragmentation function in unpolarized pp collisions at STAR

Transverse spin asymmetries for very forward neutron in pp/pA

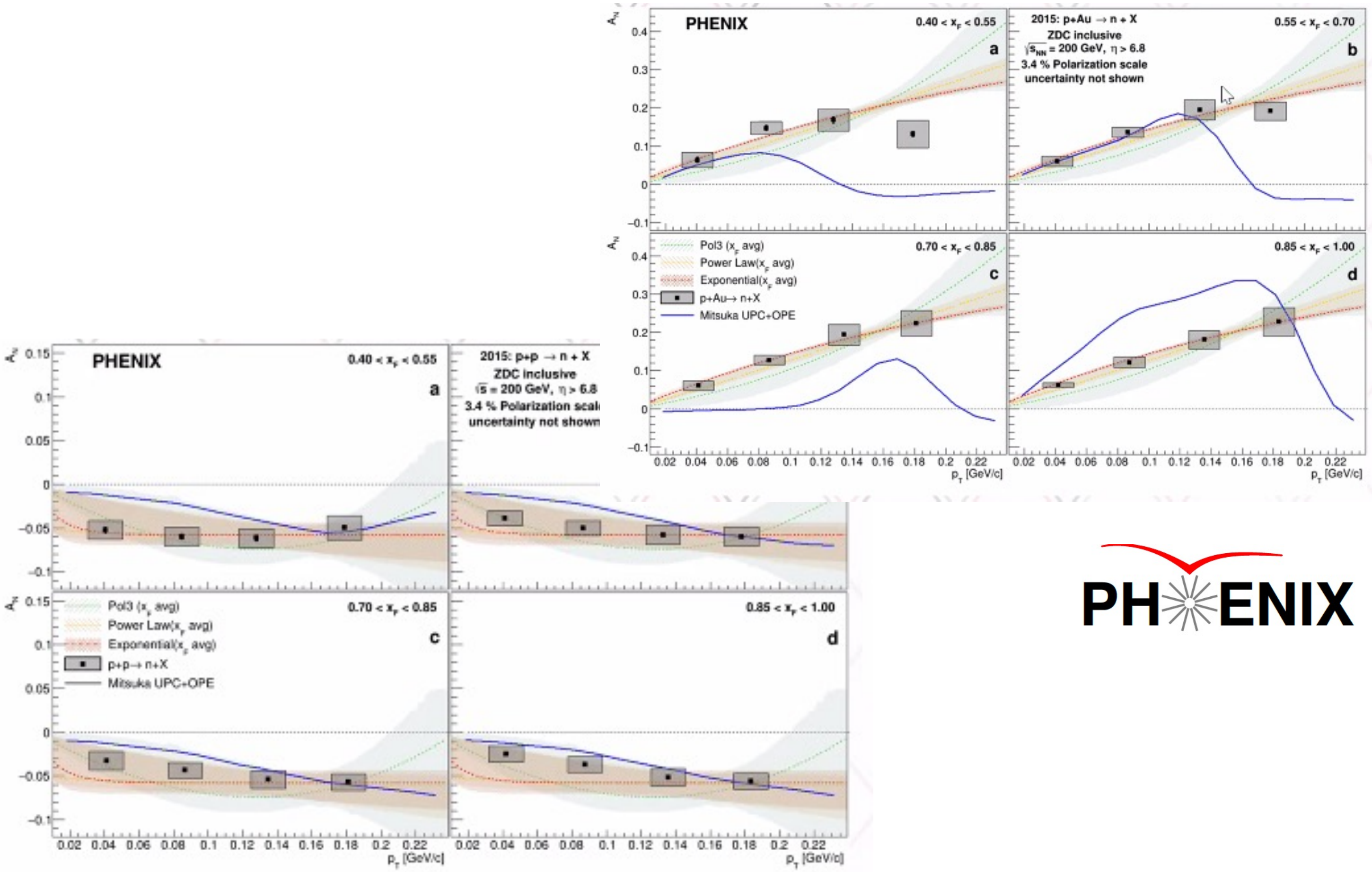
Minho Kim

Ralf Seidl

A_N of forward neutron in pp at 510 GeV at RHICf :



A_N of forward neutron in pp/pAl/pAu at 200 GeV



At high x_F → A_N increases

It seems there is an x_F dependence at high p_T

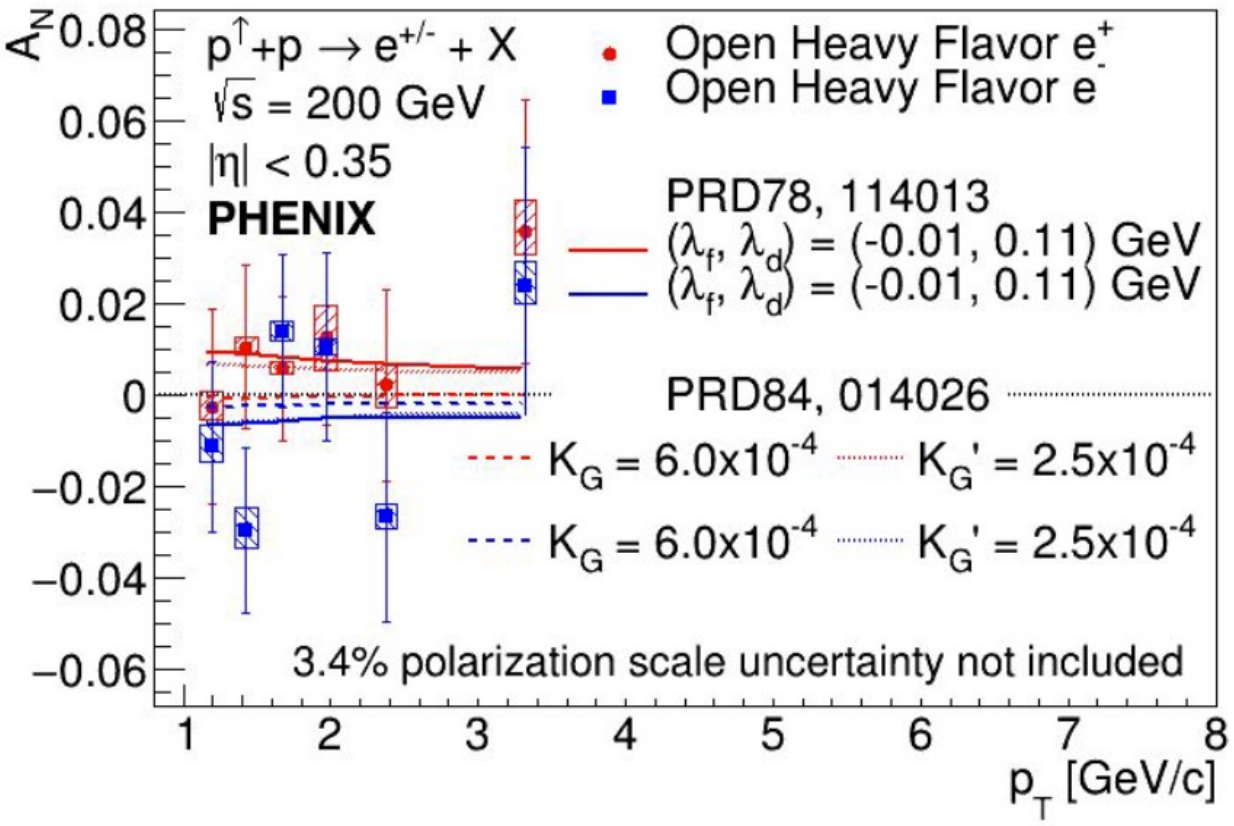
A_N increases with p_T consistently, with a weak x_F dependence, in particular at lower p_T

Transverse spin asymmetries for heavy flavor electron/positron

Dillon Fitzgerald

PHENIX

A_N of Open Heavy Flavor Electron and Positron provides access to nonperturbative spin-momentum correlations for gluons (contributions from twist-3 ggg correlators and antisymmetric and symmetric ggg correlators)



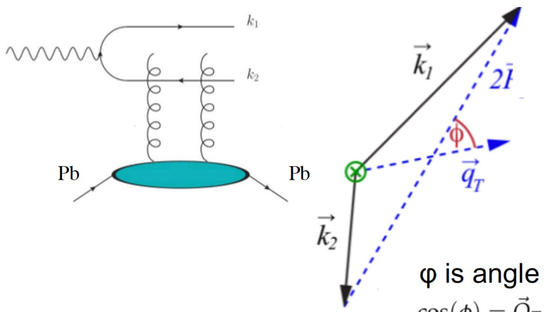
Data is consistent with theoretical predictions for best-fit parameters and with zero across the measured p_T range

Spin Independent

Courtesy of F.Cuicchio INFN

Michael Murray

Angular correlations within dijets from photon-lead collisions



Vector sum of 2 jets:

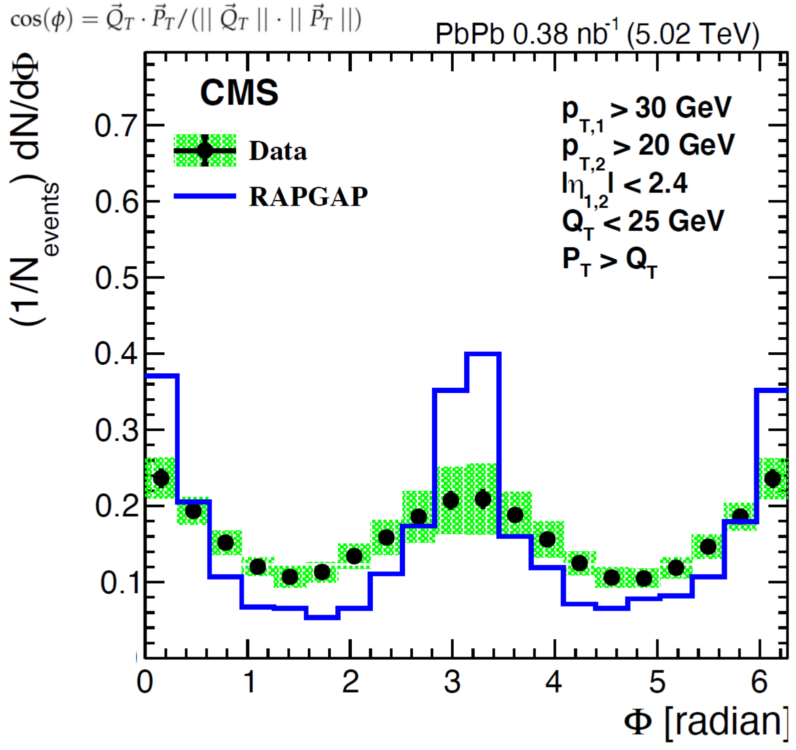
$$\vec{Q}_T = \vec{k}_1 + \vec{k}_2$$

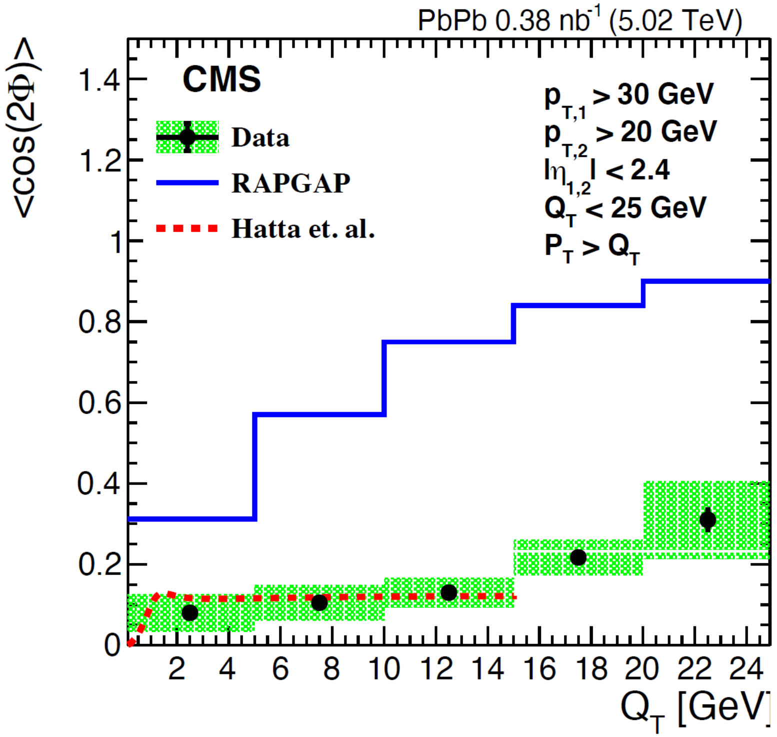
Vector difference of 2 jets:

$$\vec{P}_T = \frac{1}{2}(\vec{k}_1 - \vec{k}_2)$$

φ is angle between P_T and Q_T

$\cos(\phi) = \vec{Q}_T \cdot \vec{P}_T / (|| \vec{Q}_T || \cdot || \vec{P}_T ||)$





Hatta et. al.

Angular correlations are present in data

$\langle\cos(2\phi)\rangle$ in data is below back-to-back expectation and RAPGAP prediction

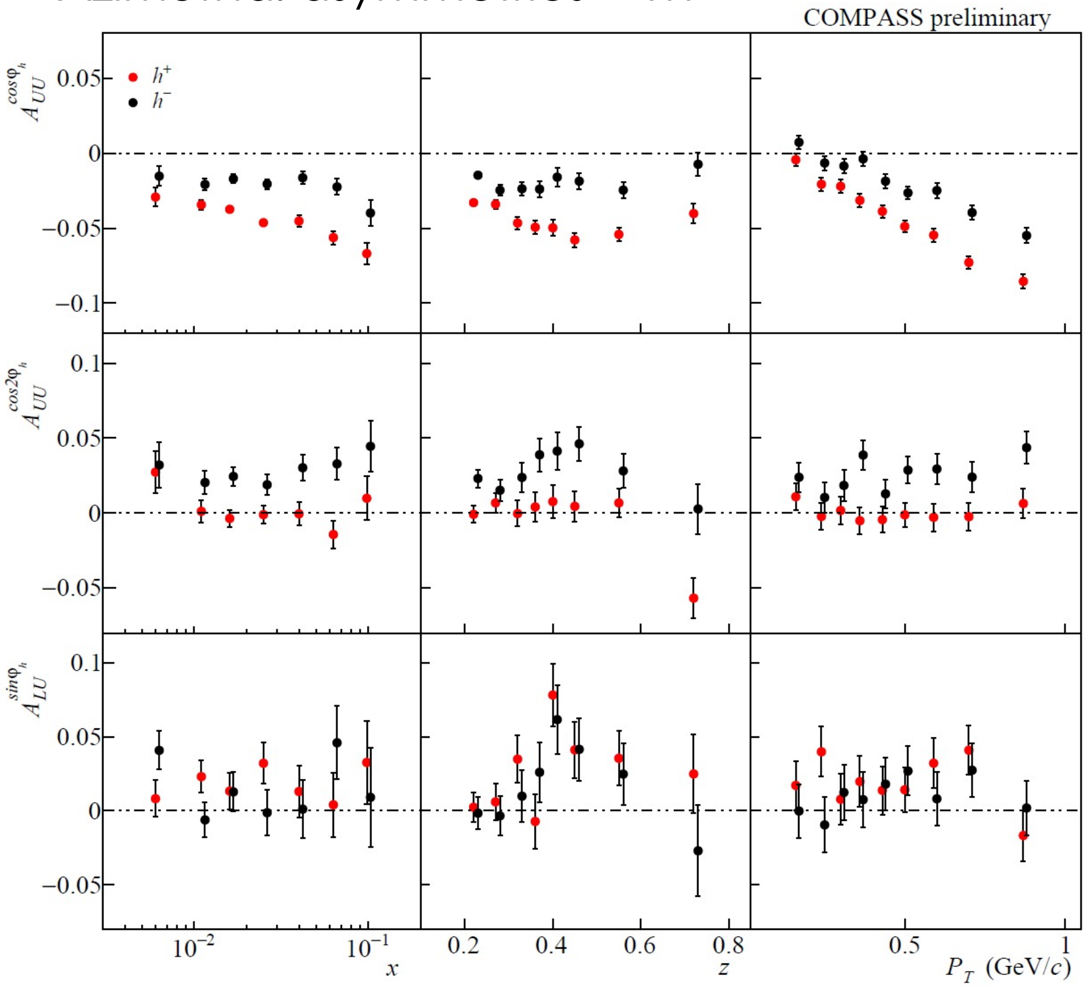
$\langle\cos(2\phi)\rangle$ constant for $Q_T > 2$ GeV as in the Hatta calculations which includes soft gluon radiation (standard TMD framework) and no effect from elliptic gluons

Jan Matousek

Unpolarized SIDIS

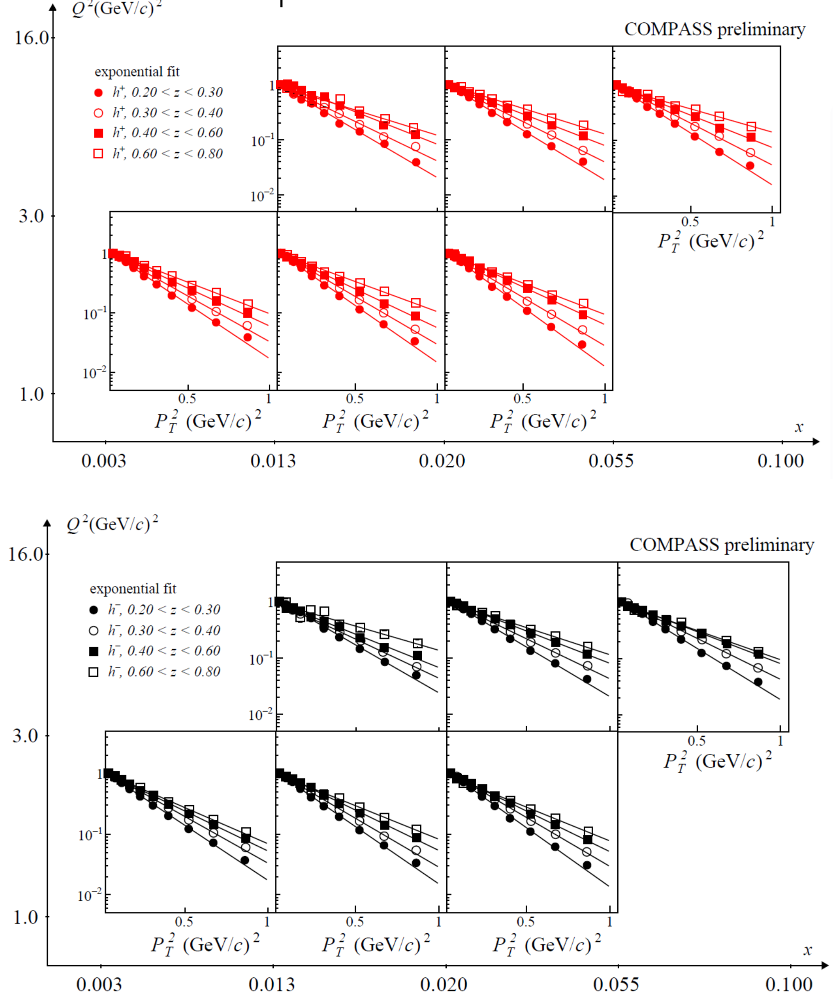
New preliminary results (August 2020) on liquid H_2 target (11% of stat.)

Azimuthal asymmetries – 1h



Strong kinematic dependences, differences between h^{+-}, qualitative agreement with published deuteron results

P_T distributions

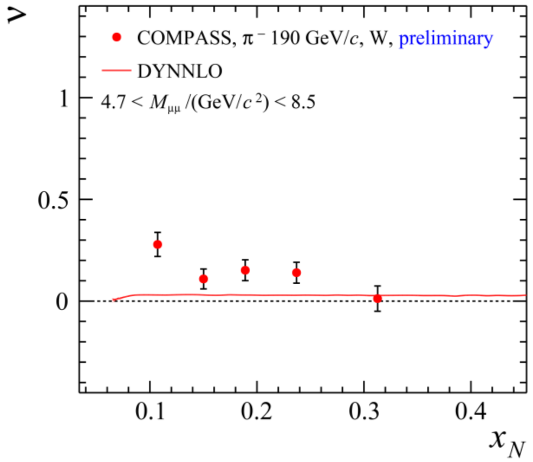


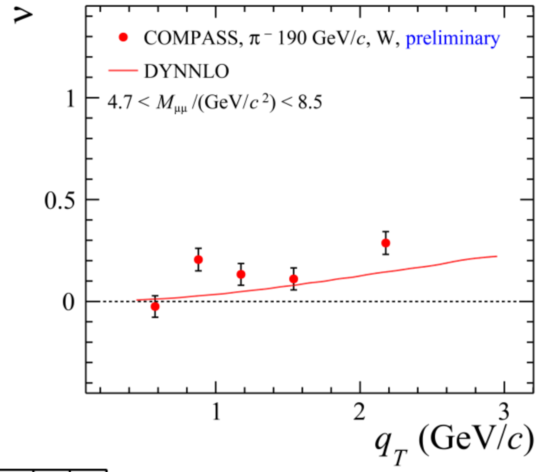
Sensitive to k_T and $p_\perp$ dependence of f1 and D1

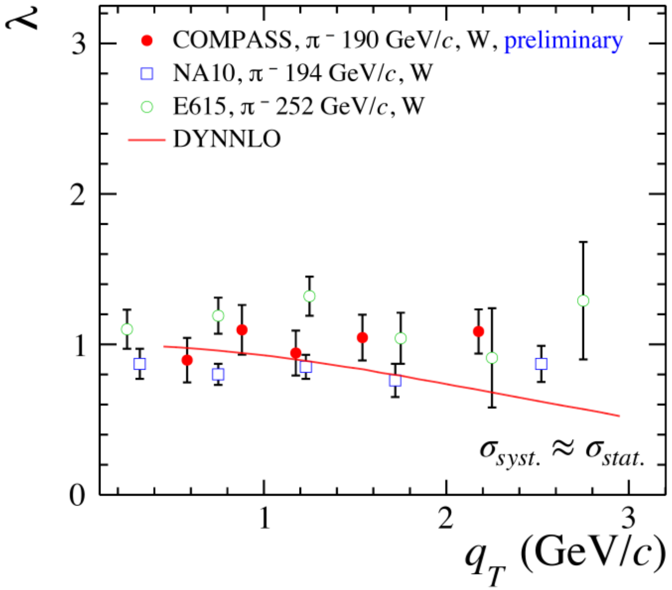
Angular distribution of Drell–Yan cross section

Bakur Parsamyan

DY-2018: tungsten data, NH_3 analysis in progress



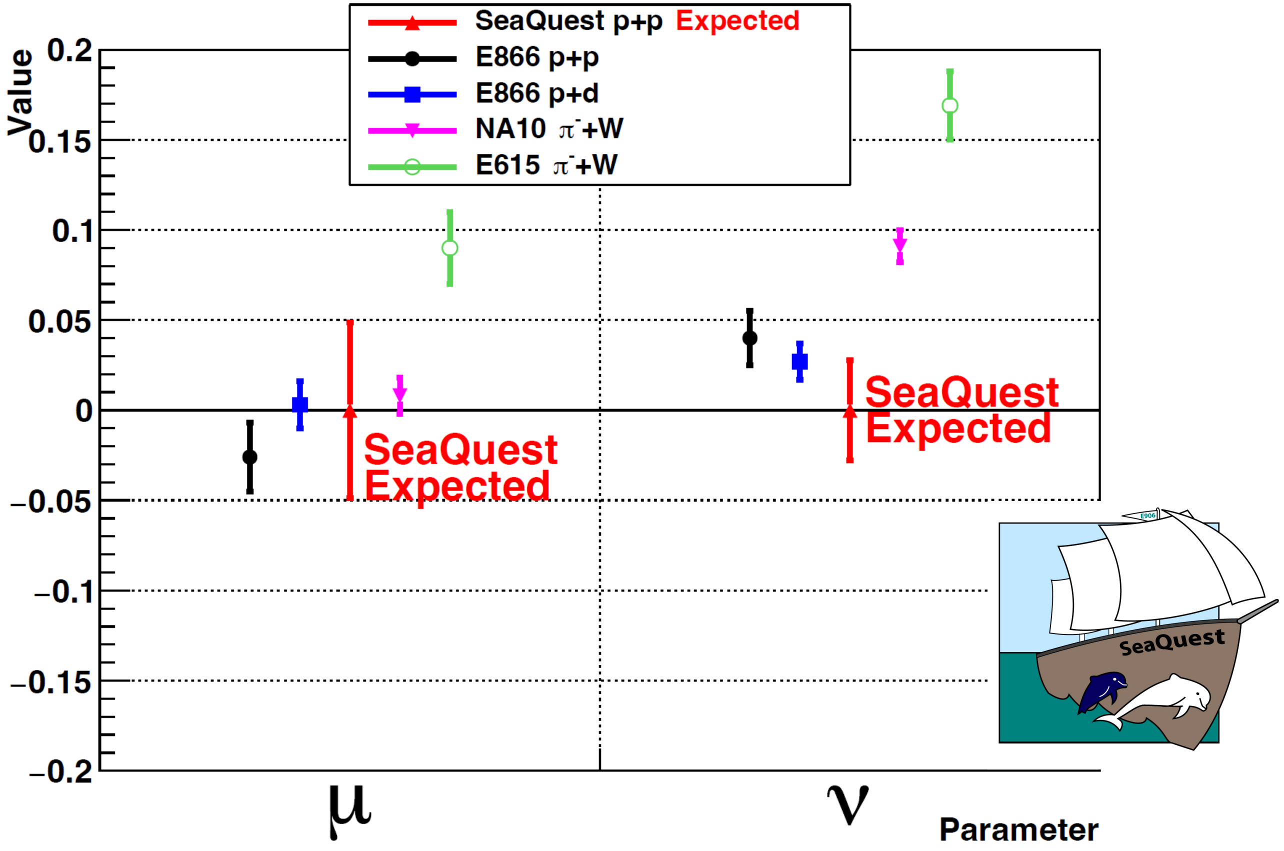




$$\frac{d\sigma}{d\Omega} \propto 1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi$$

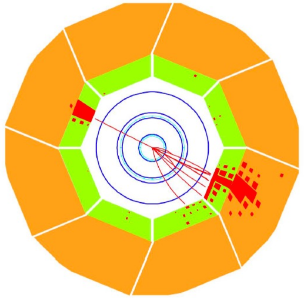
- Naively, $\lambda = 1$, $\mu = \nu = 0$ ($d\sigma \propto 1+\cos^2\theta$) at leading order

Kei Nagai

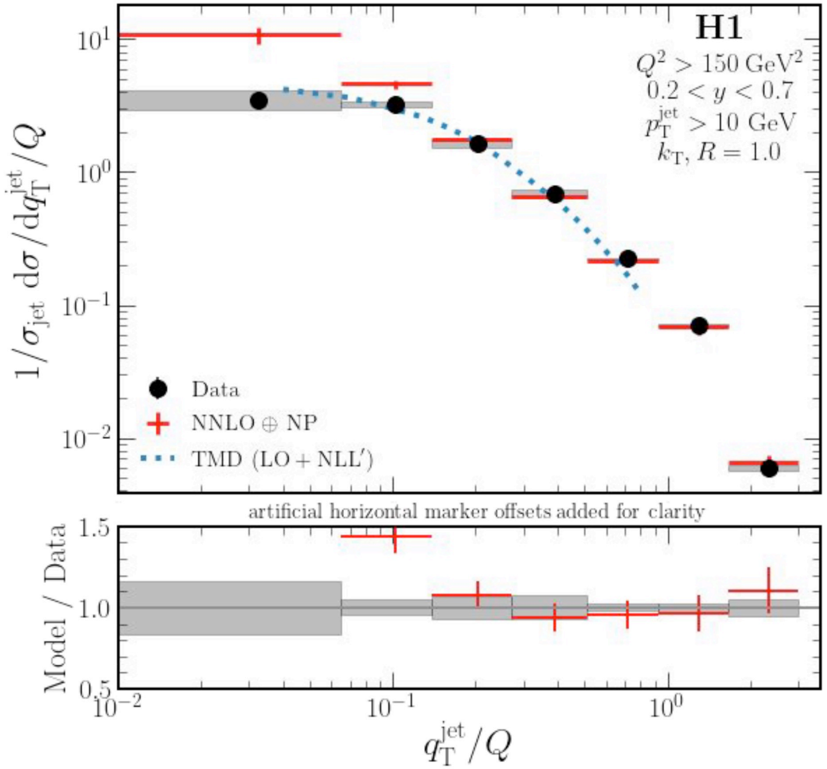


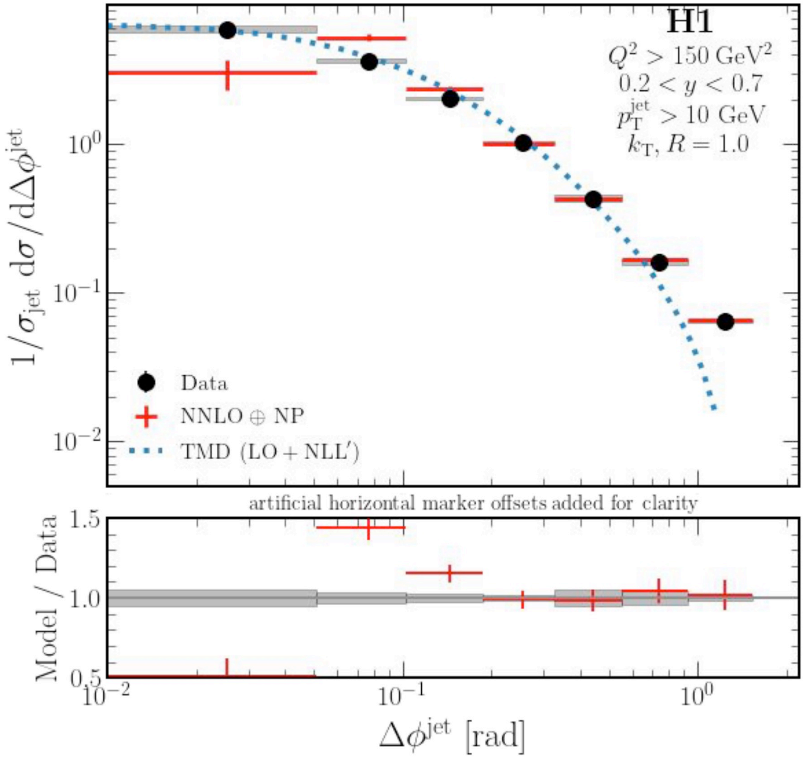
Lepton-Jet correlation in DIS

Miguel Arratia



lepton jet momentum and azimuthal imbalance in DIS
→ provides a new way to constrain TMD PDFs and their evolution





"matching" between collinear and TMD frameworks
First time seen in DIS!

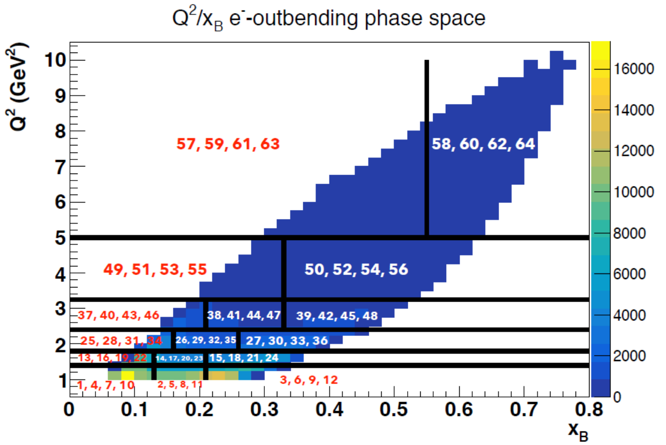
GPDs

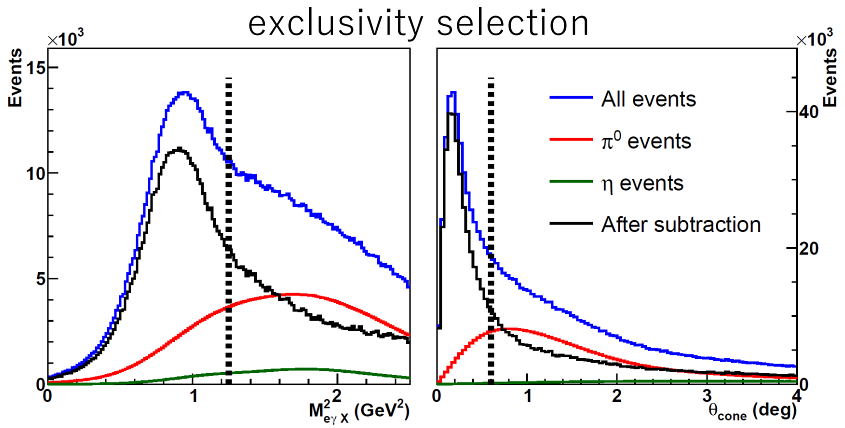
Courtesy of F.Cuicchio INFN

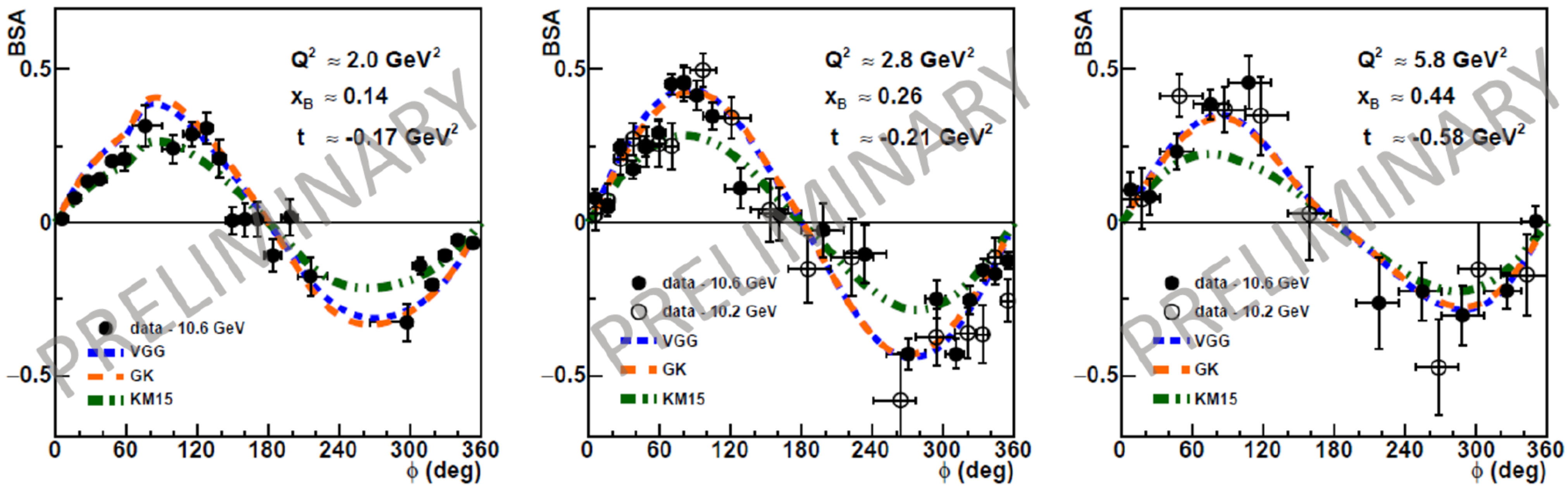
DVCS Beam Spin Asymmetries with CLAS12

Maxime DEFURNE

The data shown represents approximately 25% of the beam time allocated to DVCS study with an unpolarized target.



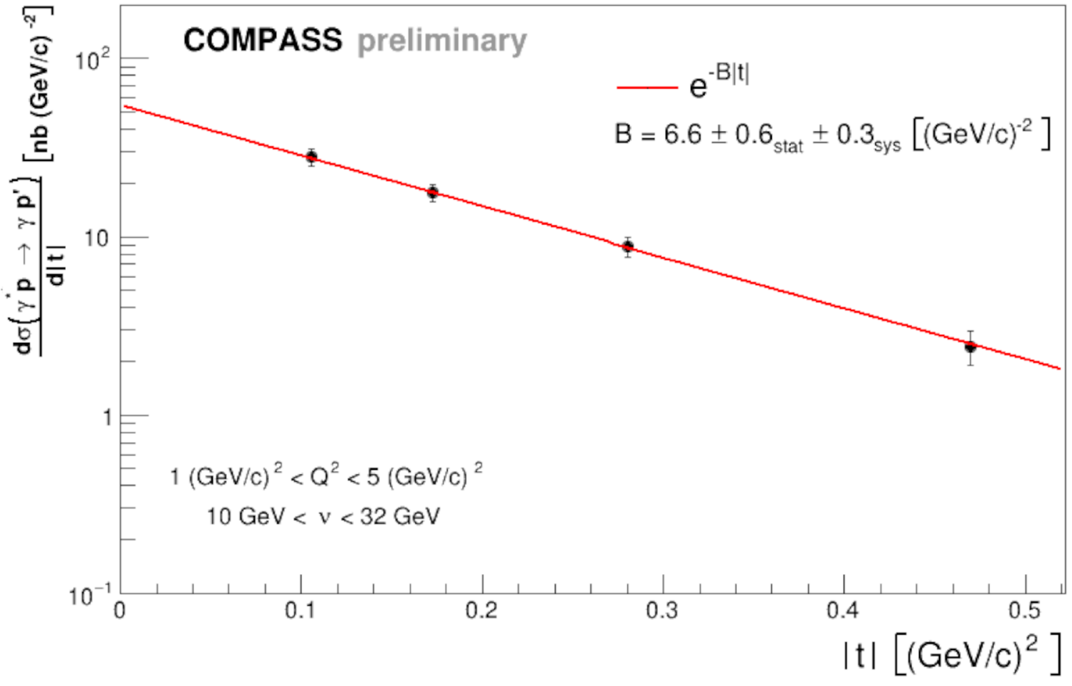


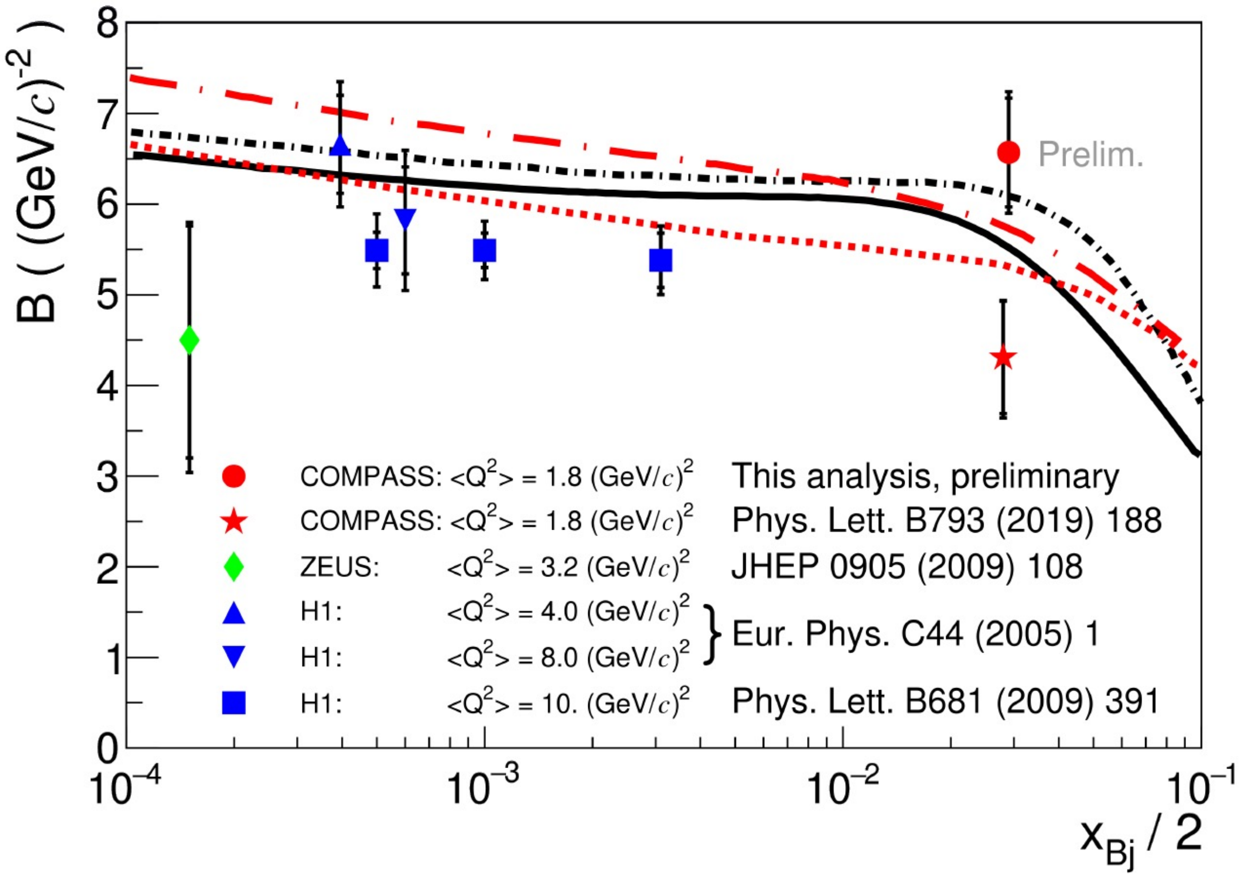


In many bins, data agrees with KM15 predictions except in some bins at large x_B where data agrees better with GK/VGG models

DVCS cross section t-slope

Full statistics of 2016 and 2017
(about 3 times more than 2016)



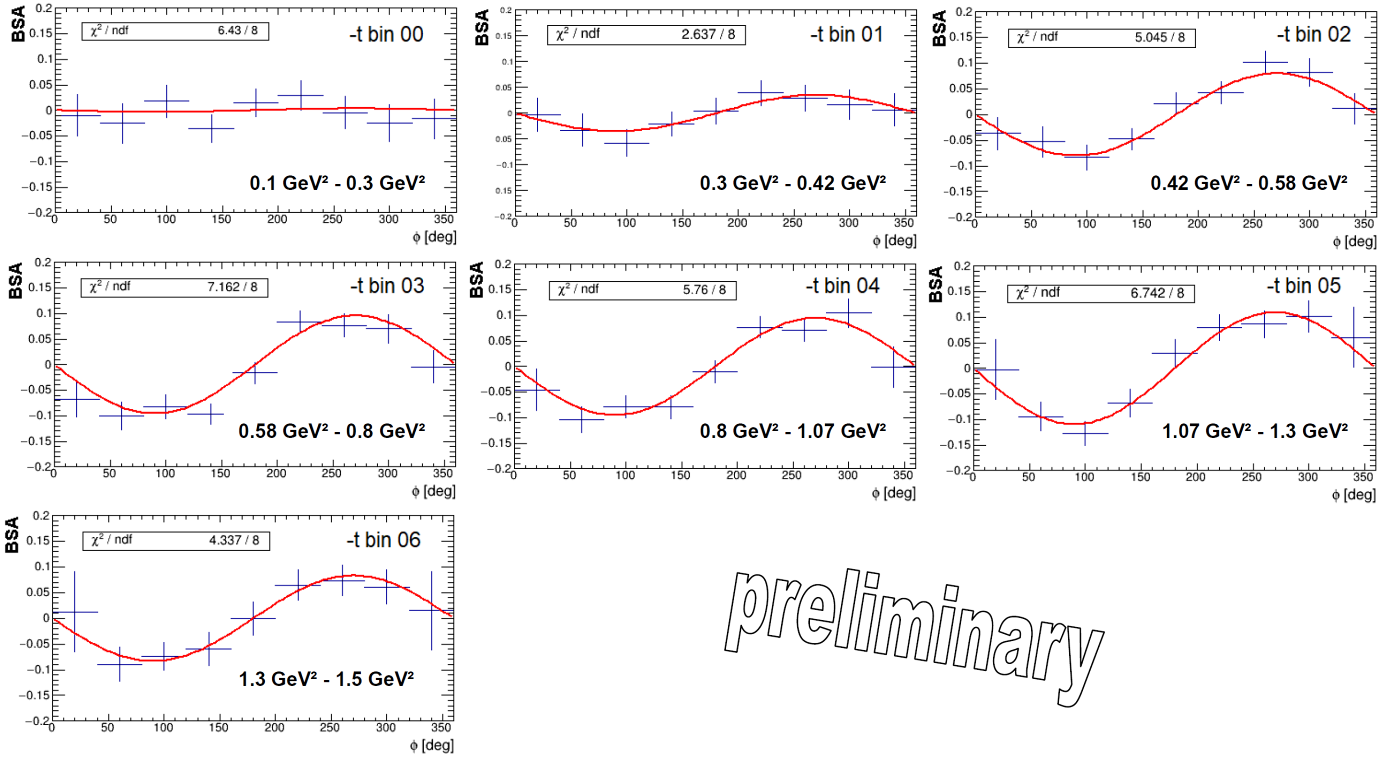


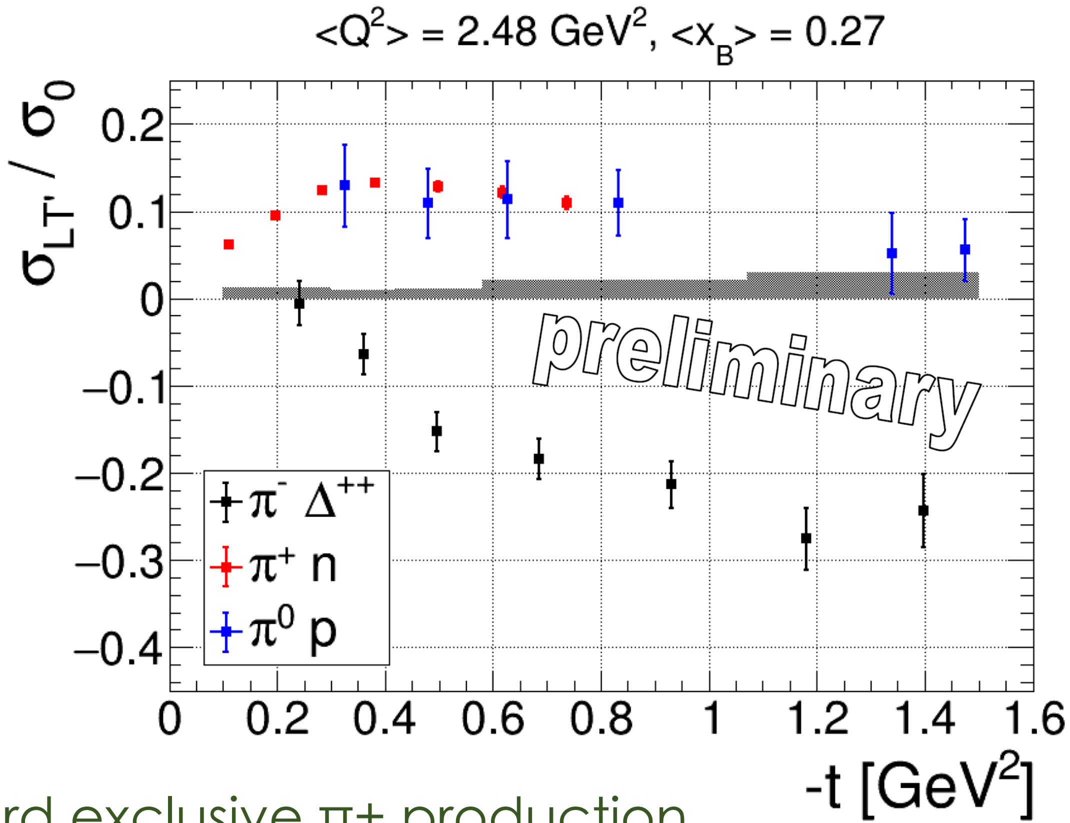
… some "tension" between old and new data

Stefan Diehl

Hard exclusive $\pi^- \Delta^{++}$ electroproduction off the proton (CLAS12)

Beam Spin Asymmetries (Q^2 and x_B integrated)



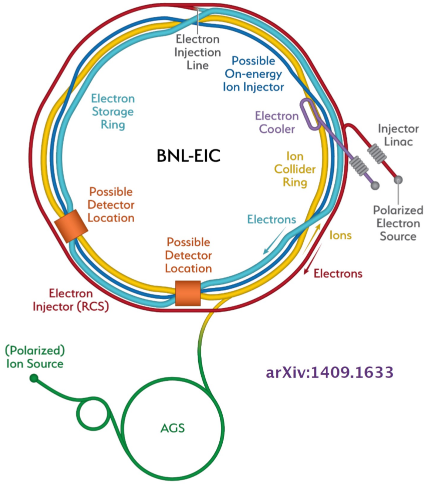


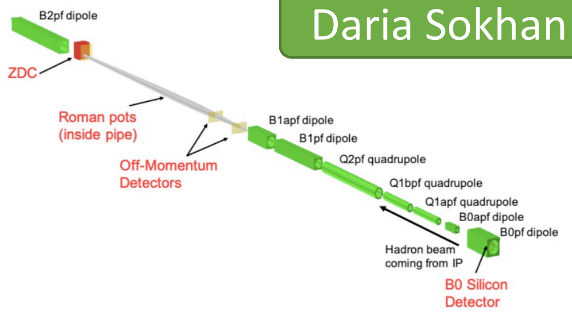
BSA clearly negative and ~ 2 times larger than for the hard exclusive π+ production

→ potential first "clean" observable sensitive to p-Δ transition GPDs

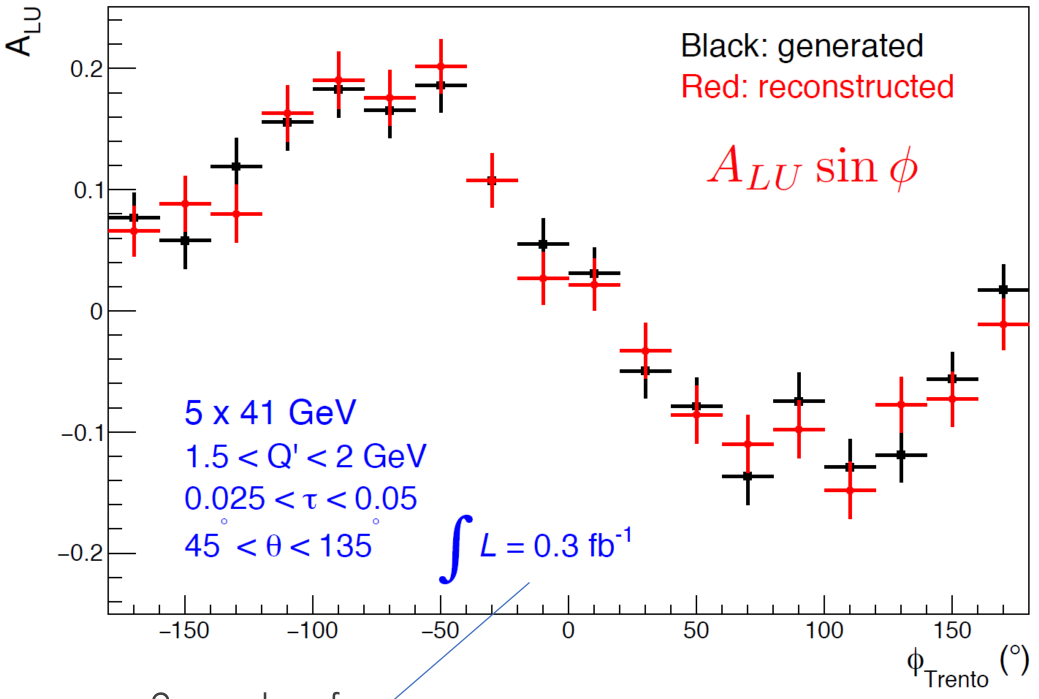
Time-like Compton scattering at the Electron-Ion Collider

Daria Sokhan



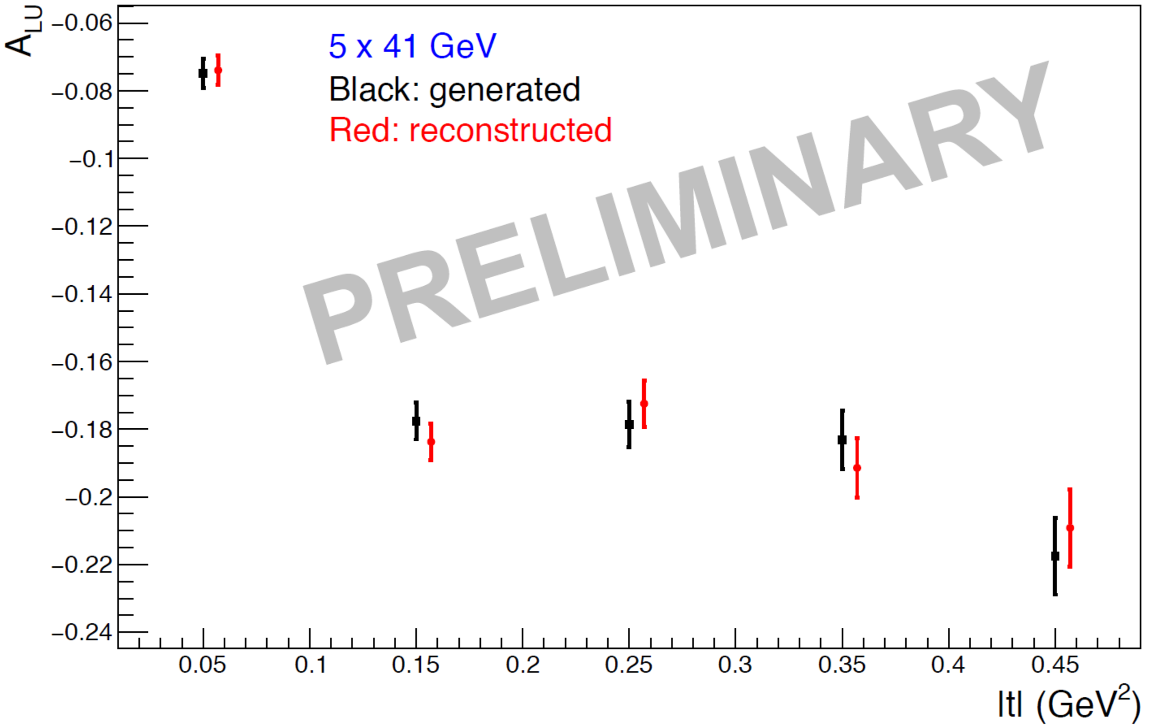


Expected precision on Beam Spin Asymmetries at EIC



2 weeks of running

Very good agreement between generated and reconstructed asymmetries



Measurement of BH-TCS interference is possible at EIC with good acceptance and efficiency

Theory

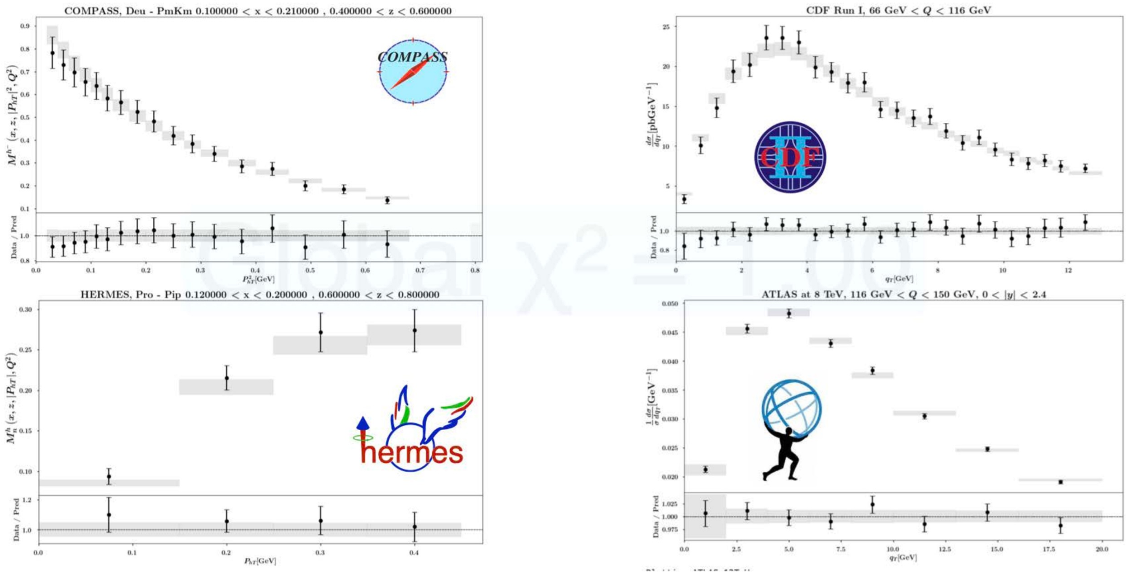
Courtesy of F.Cuicchio INFN

TMD global analysis

Patrick Barry

Matteo Cerutti

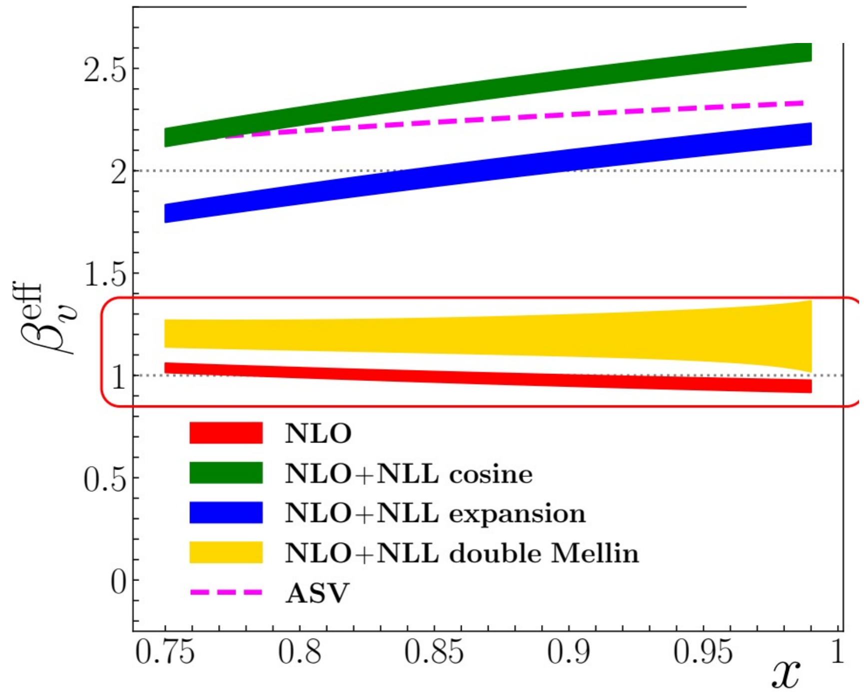
High precision TMD global analysis



- Global analysis of Drell-Yan and Semi-Inclusive DIS data sets: ***2031*** data points
- Perturbative accuracy: ***N^3LL^-***
- ***Normalisation*** of SIDIS multiplicities beyond NLL
- Number of fitted parameters: ***21***
- Extremely good description: $\chi^2/N_{data} \simeq 1.00$

Pion PDF & TMD global analysis from pion-induced Drell-Yan with threshold resummation

$q_v(x) \propto (1-x)^{\beta}$



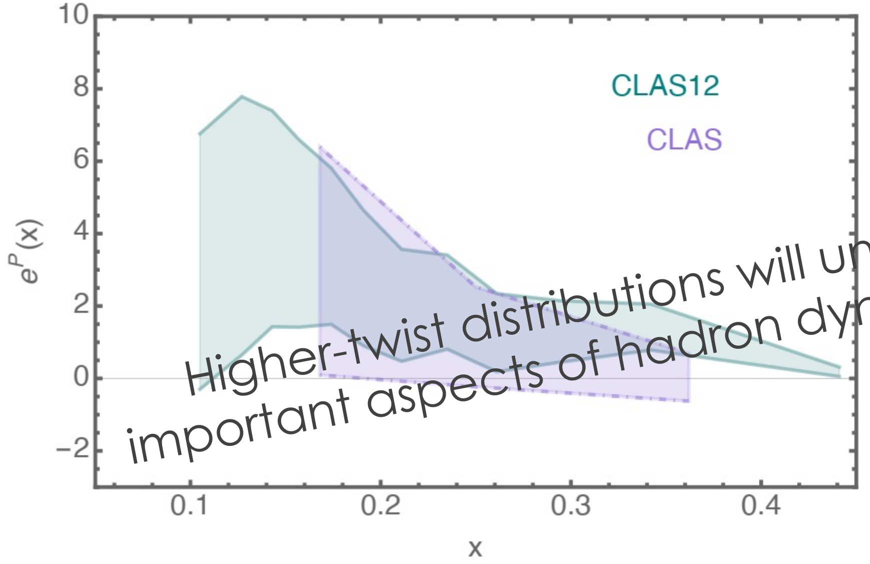
Inclusion of q_T-dependent DY data slightly constrains the sea quark distribution

Then, extend framework to LHC data and nucleon PDFs

Helicity, scalar PDFs

Aurore Courtoy

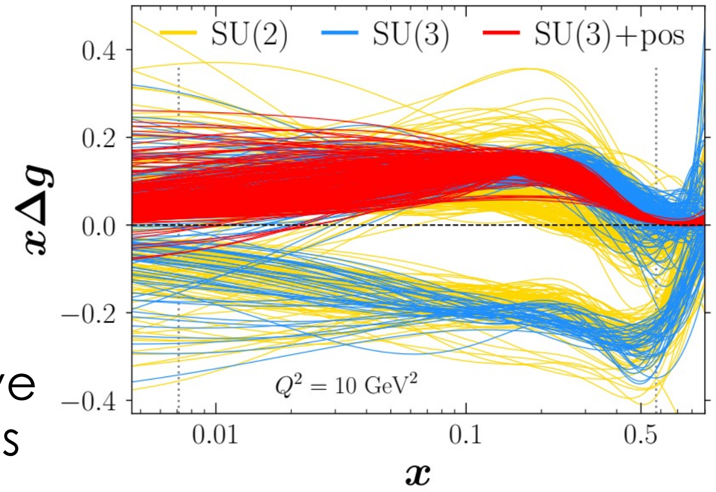
First extraction of twist-3, scalar $e(x)$ from CLAS beam-spin asymmetry data



Higher-twist distributions will unveil important aspects of hadron dynamics

STAR A_{LL}^{jets} data do not exclude negative Δg

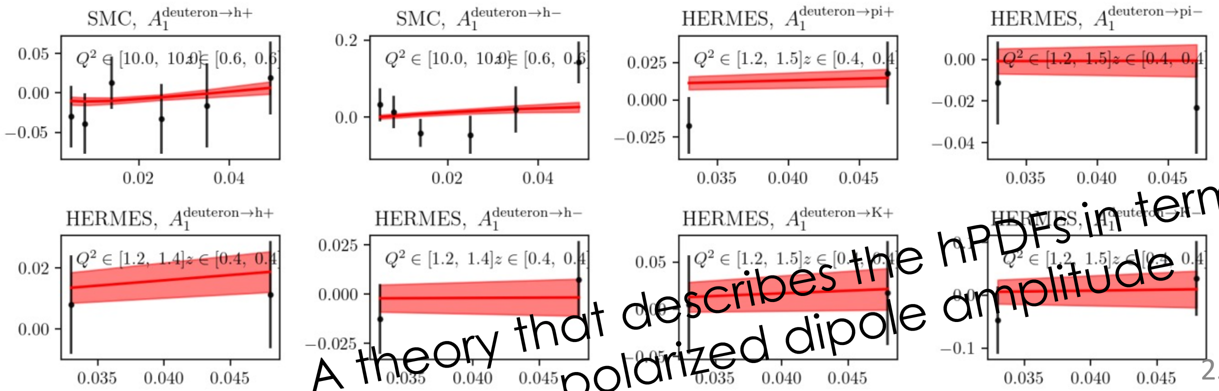
Yiyu Zhou



The assumption of positive Δg puts a significant bias

Daniel Adamiak

First global analysis of polarized world SIDIS data with small-x evolution



A theory that describes the hPDFs in terms of the polarized dipole amplitude

Ted Rogers

Renormalization of collinear and TMD pdfs

Positivity is not a general property of MS-bar renormalized PDFs

Power corrections in TMD factorization

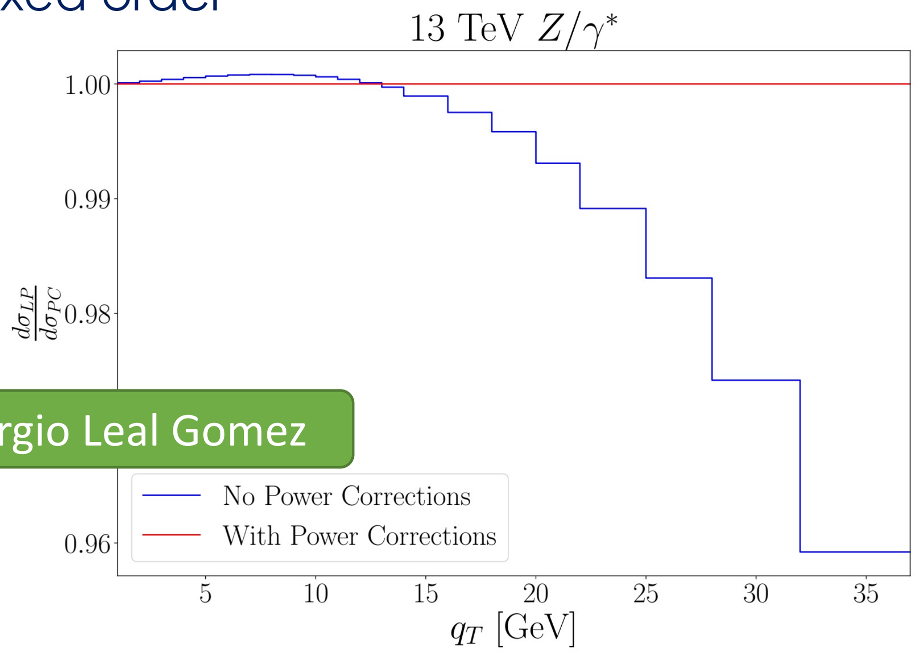
$$d\sigma = H \otimes F \otimes F + \mathcal{O}(q_T/Q) + \mathcal{O}(q_T^2/Q^2)$$

Leading: standard TMD factorization

Next-to-Leading Power (NLP)

NNLP

Soft Collinear Eff. Th. (SCET) approach, focus on DY analytic calculation of power corrections at fixed order



Sergio Leal Gomez

Electroweak corrections are subleading compared to power corrections

Alexey Vladimirov

OPE approach, all processes

NLP corrections factorizable in terms of twist-3 TMD

$$\int dz e^{-ip_+ \sum_i x_i z_i} \langle p, s | \underbrace{\bar{q}[z_1 n + b, z_2 n + b] F_{\mu+}[.., \infty]}_{\text{tw-2}} \gamma^+ \underbrace{[\infty, z_3 n] q}_{\text{tw-1}} | p, \rangle$$

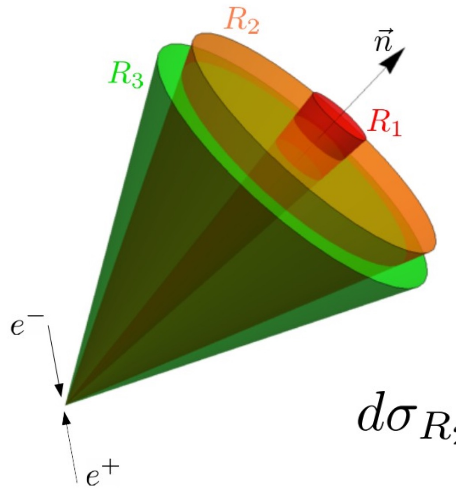
NLO evolution & coefficient functions derived

Shunzo Kumano

General analysis of twist-3,4 TMD and FF for spin-1 particles

New (G)TMD observables

Factorization for thrust distribution in e+e- in Region 2
→ Access to TMD fragmentation functions

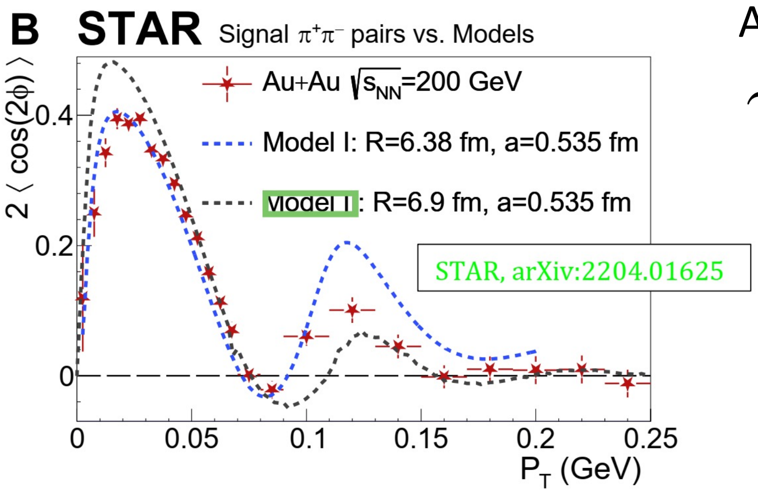


Andrea Simonelli

$$d\sigma_{R_2} \sim H \cdot J \cdot \frac{\mathcal{S}}{\mathcal{Y}_L} \cdot \widetilde{D}_{j\to h}$$

Yajin Zhou

Linearly polarized photon TMD in UPC



Azimuthal asymmetries in

$$\gamma \to \rho^0 \to \pi^+\pi^-$$

$\cos 2\phi$ Well explained by QED effects

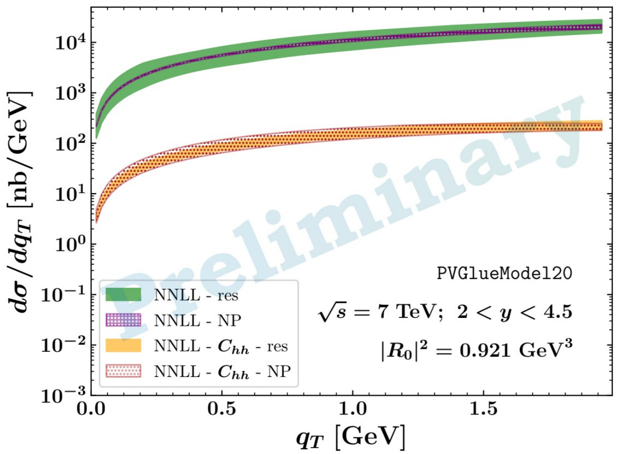
$\cos 4\phi$ Need QCD (Wigner) contributions?

Amol Pawar

$\cos 2\phi$ asymmetry in J/psi + jet production from linearly polarized gluon distribution

Francesco Celiberto

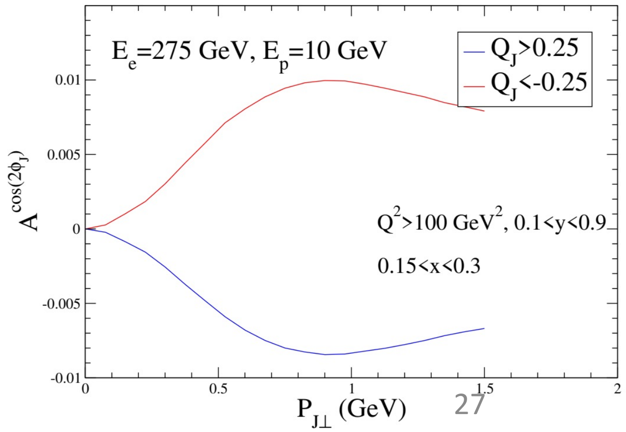
$\eta_{b,c}$ production at LHC from gluon TMD at NNLL



Wai Kin Lai

Probing T-odd TMDs (Sivers, Boer-Mulders) using T-odd jet function in SIDIS

$$F_{UU}^{\cos(2\phi_J)} \sim h_1^\perp \otimes J_T$$

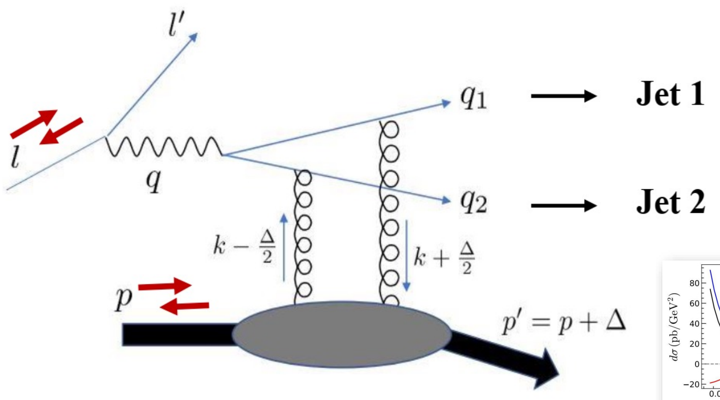


Nucleon spin & mass sum rule

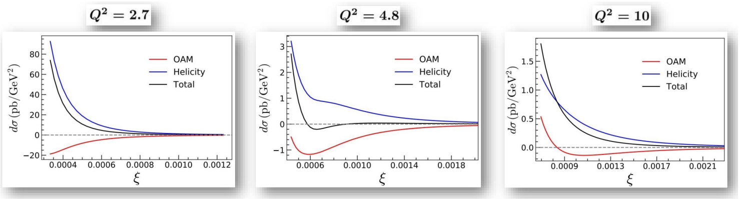
Miguel Echevarria

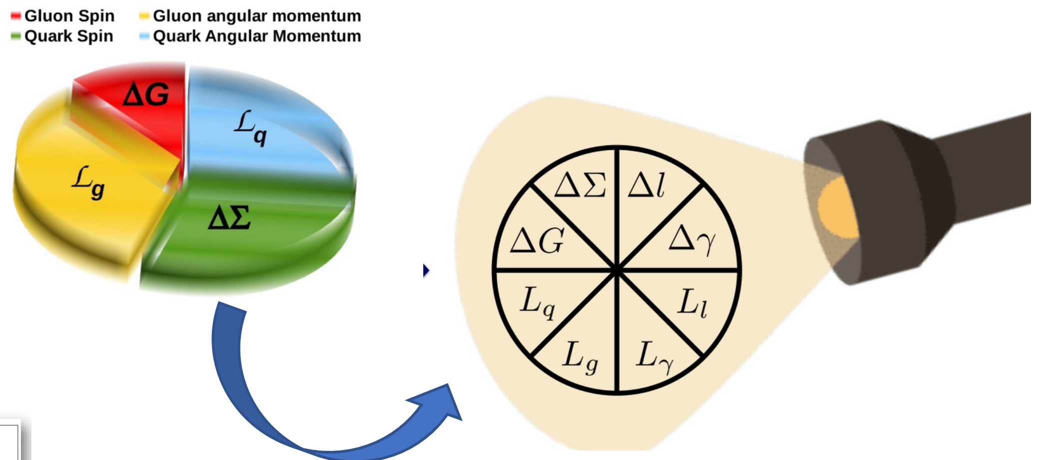
Extend the nucleon spin sum rule to QCD x QED

Double spin asymmetry in dijet production at the EIC
→ Novel observable for gluon orbital angular momentum

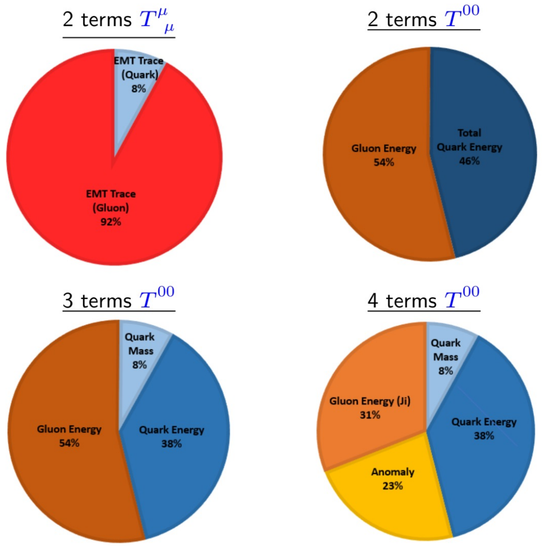


Shohini Bhattacharya





Calculated all the new 1-loop DGLAP splitting functions

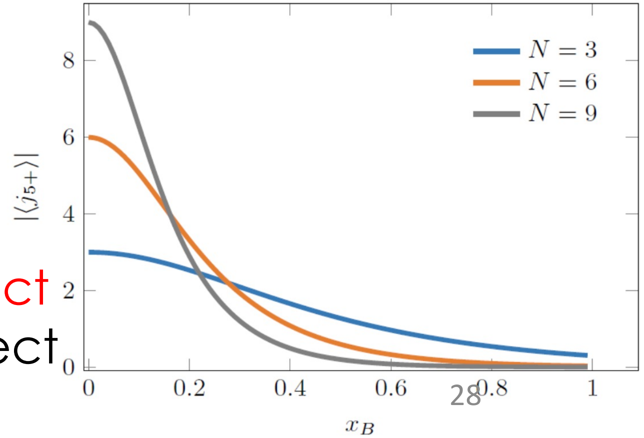


Andreas Metz

Different proton mass sum rules: 2-term, 3-term, 4-term decompositions

David Frenklakh

Helicity distribution in 2D QCD ('t Hooft model), exact
Enhanced by topological effect at small x



Single spin asymmetry

Abhiram Kaushik

Old, naive estimate of partonic SSA

$$A_N \sim \alpha_s \frac{m_q}{P_{hT}}$$

New, complete 2-loop calculation in SIDIS

$$A_N \sim \alpha_s \frac{xM_N}{P_{hT}} g_T(x)$$

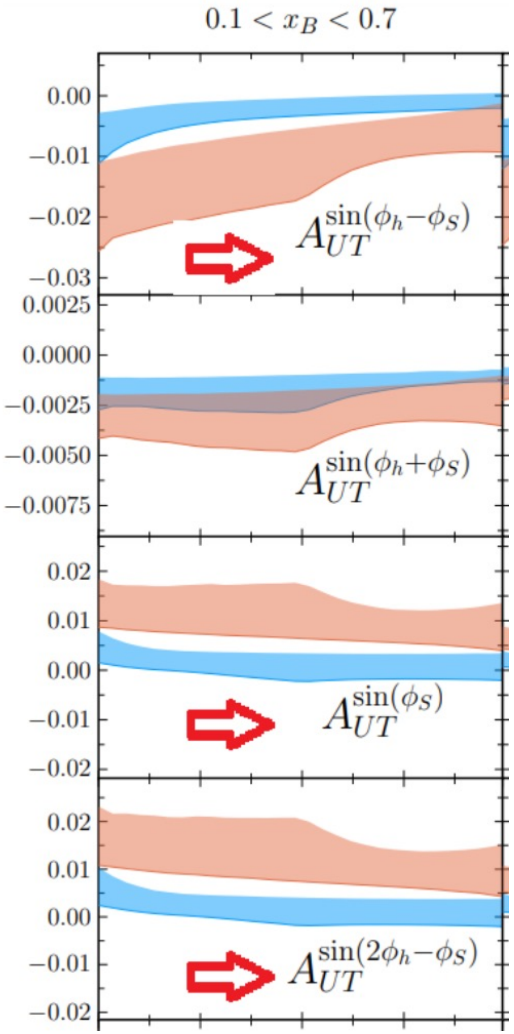
Up to 2% asymmetry for

$\sin(\phi_h - \phi_S)$ (Sivers)

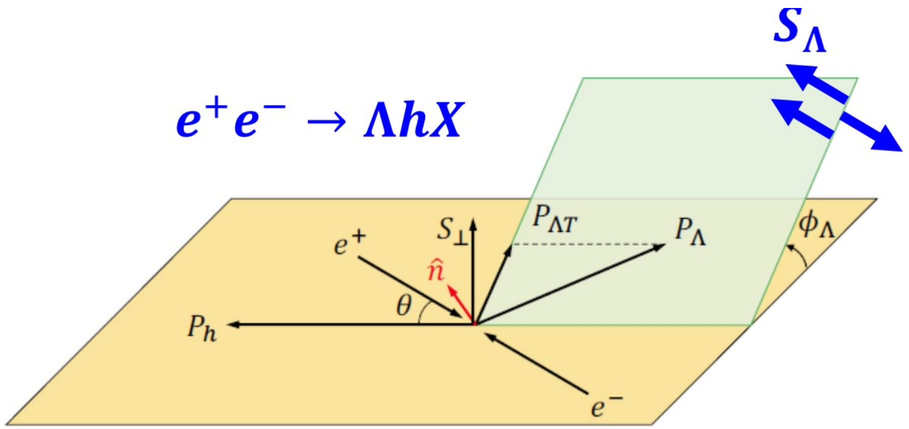
$\sin(\phi_S)$

$\sin(2\phi_h - \phi_S)$

in SIDIS at the EIC



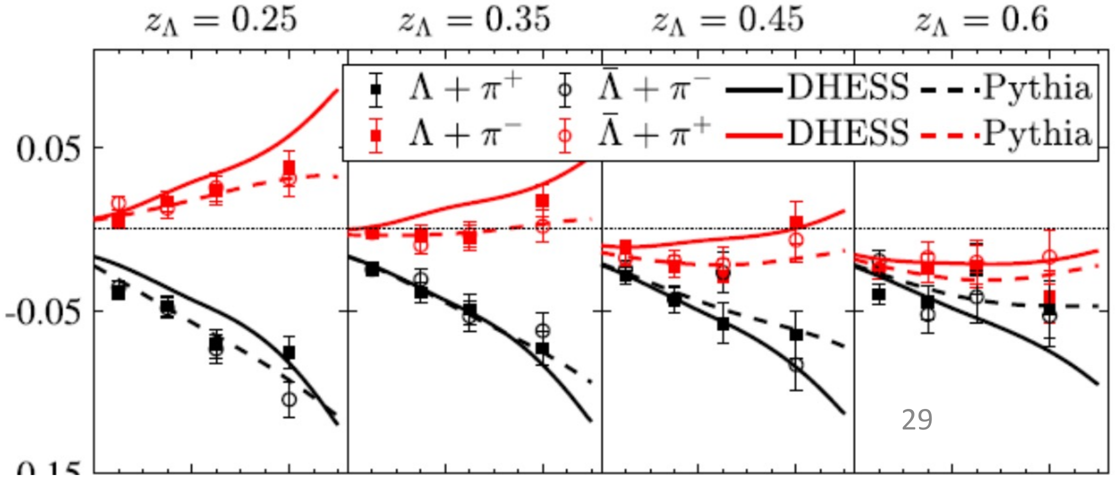
Λ polarization w.r.t. the production plane



Yukun Song

Possible origin: spin-dep. TMD FF?
Respect isospin symmetry!

Belle

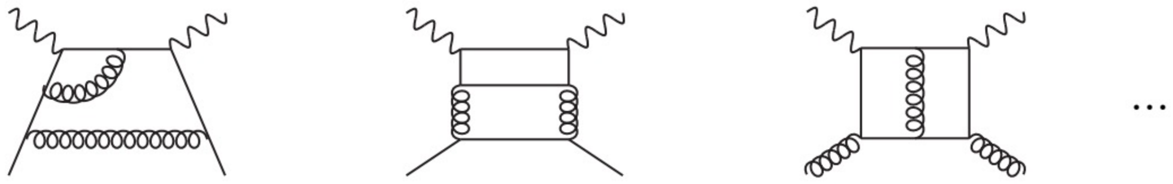


High precision DVCS

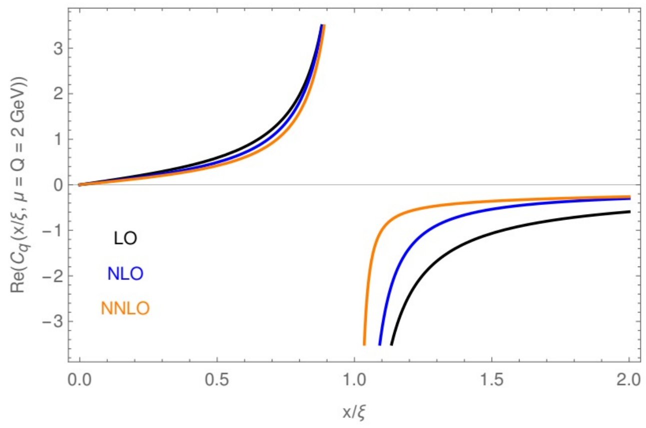
Jakob Schoenleber

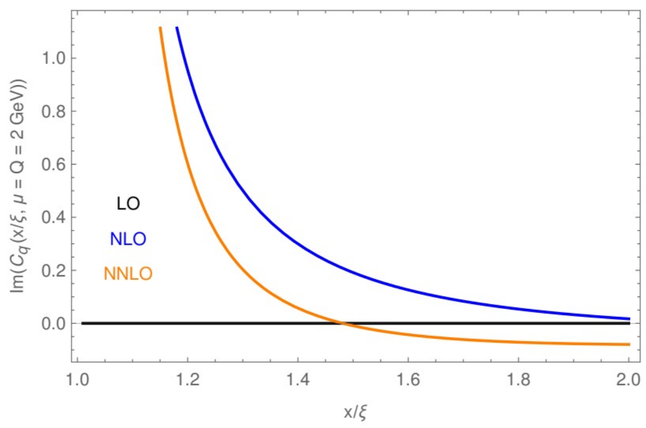
DVCS Compton form factor, 2 loops, 70 diagrams

$$\mathcal{H} = \sum_{q=u,d,s} \frac{1}{\xi}\int_{-1}^{1} dx\; \underline{C_q(x/\xi, Q, \mu)} H_q(x,\xi,t,\mu) + \frac{1}{\xi^2}\int_{-1}^{1} dx\; \underline{C_g(x/\xi, Q, \mu)} H_g(x,\xi,t,\mu)$$



$$\begin{aligned}
\mathrm{T}^{(C_F)}(z) = \frac{1}{z^2\bar{z}^2}\Bigg\{ & z^2\Big(- H_{2,1}(z) + 2H_{2,2}(z) - \frac{23}{2}H_{3,0}(z) - \frac{17}{2}H_{2,0,0}(z) - 11H_{2,1,0}(z) - \frac{23}{2}H_{0,0,0,0}(z) \\
& - 9H_{1,0,0,0}(z) - 9H_{1,1,0,0}(z)\Big) + \frac{1}{2}\Big(-3z^2 + 16z + \pi^2(1-2z(z+1)) - 13\Big) H_{1,1}(z) \\
& + 2\Big(z^4 - 2z^3 + z\Big)\Big(H_{1,2}(z) - H_{2,0}(z)\Big) - \frac{1}{4}\Big(\Big(6+7\pi^2\Big)z + 20\Big) zH_{0,0}(z) + \frac{5}{2}(z+1)zH_{0,0,0}(z) \\
& + \Big[-\frac{1}{4}\bar{z}(z(8z-3)+3) - \frac{1}{6}\pi^2(z(7z+4)-2)\Big] H_{1,0}(z) + \frac{1}{4}[z^2(-8(z-2)z-5)+2z-5]H_{1,1,0}(z) \\
& + \bar{z}^2\Big(H_{1,0,0}(z) - \frac{5}{2}H_{1,1,2}(z) + \frac{1}{2}H_{1,2,1}(z) - \frac{5}{2}H_{1,1,1,1}(z) - 2H_{1,3}(z)\Big) \\
& + \frac{5}{2}\bar{z}(z-2)H_{1,1,1}(z) + (2 - z(7z+4))\Big(H_{1,2,0}(z) + H_{1,1,1,0}(z)\Big) - 9z^2H_4\Big(-\frac{\bar{z}}{z}\Big) + 2z^2H_4(z) \\
& - \frac{1}{12}zH_0(z)\Big[24z(z+\zeta(3)) - 6(23z+9) + \pi^2(z(4(z-2)z+3)+5)\Big] \\
& + \frac{1}{24}\bar{z}H_1(z)\Big[12(z(4z-\zeta(3)+15)+\zeta(3)-28) + \pi^2(3 - z(8\bar{z}z+9))\Big] \\
& - \frac{1}{12}\Big[z\Big(24z + 22\pi^2 - 39\Big) + 24\Big] zH_2(z) + \frac{1}{4}[z(8(z-2)z+5)+8]zH_3(z) + 6z^4\zeta(3) \\
& + \frac{1}{3}z^3\Big(\pi^2 - 36\zeta(3)\Big) - \frac{1}{360}z^2\Big[90(\zeta(3)+36) + 195\pi^2 + 103\pi^4\Big] + z\Big(6\zeta(3) + 9 + \frac{\pi^2}{3}\Big)\Bigg\}
\end{aligned}$$





Including three loop evolution is needed to complete NNLO program → three loop singlet evolution is not known yet, but will be available soon.

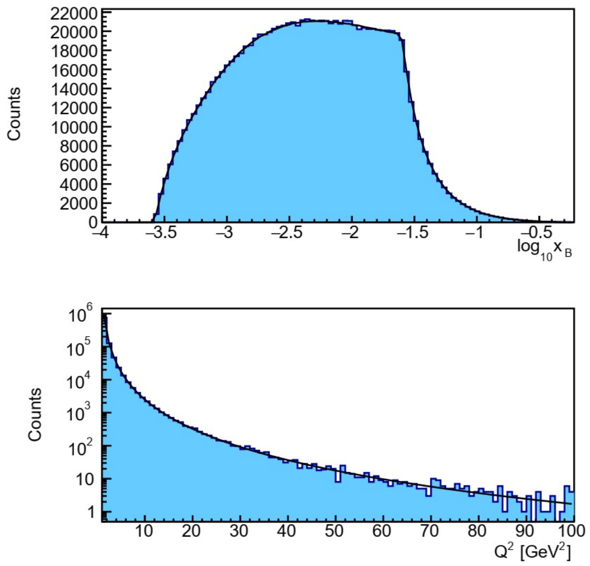
MC and neural network for DVCS

Kemal Tezgin

Pavel Sznajder

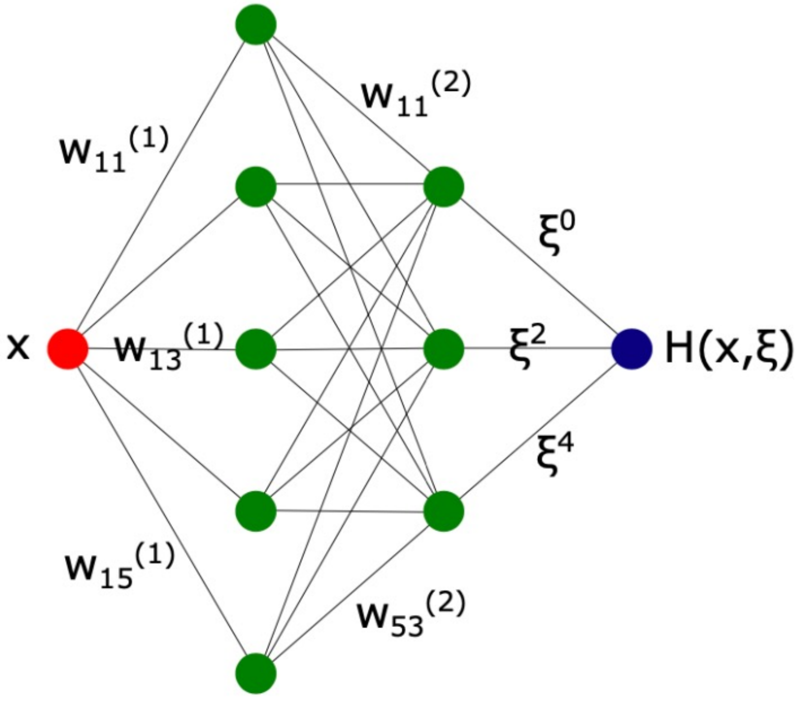
EpIC: a new MC event generator for exclusive reactions

```
<?xml version="1.0" encoding="UTF-8" standalone="yes" ?>

<!-- Scenario starts here -->
<!-- For your convenience and for bookkeeping provide creation date --
<scenario date="2017-07-18" description="Select specific GPD types":

   <!-- Indicate service and its methods to be used -->
   <task service="DVCSGeneratorService" method="generate">

      <!-- General configuration -->
      <!-- Subprocess can be "ALL", "BH" or "DVCS" -->
      <general_configuration>
         <param name="number_of_events" value="1000000" />
         <param name="subprocess_type" value="DVCS" />
      </general_configuration>

      <!-- Kinematic limits -->
      <!-- Limit on 'y' is optional, if not set 0 < y < 1 is assumed
      <kinematic_range>
         <param name="range_xB" value="0.0001|0.6" />
         <param name="range_t" value="-1.0|-0.0" />
         <param name="range_Q2" value="1.0|100.0" />
         <param name="range_phi" value="0.0|2*pi" />
         <param name="range_phiS" value="0.0|2*pi" />
         <param name="range_y" value="0.01|0.95" />
      </kinematic_range>
```



Bridge between models of GPDs and experimental data

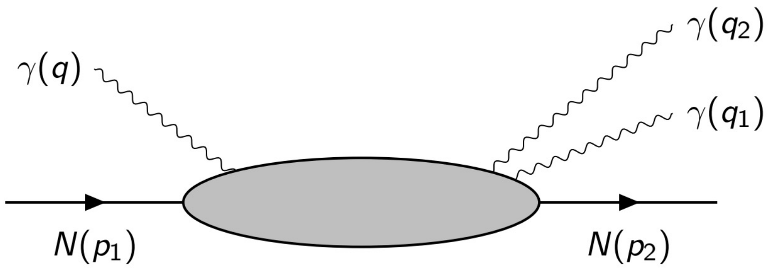
problem of the model dependency of GPDs is still poorly addressed

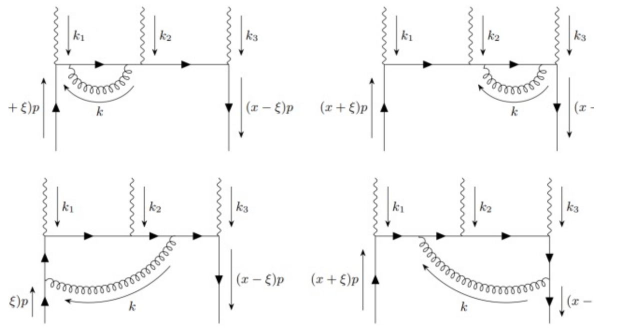


Generate replicas of GPD using NN satisfying all theory constraints

New GPD observables

Oskar Grocholski

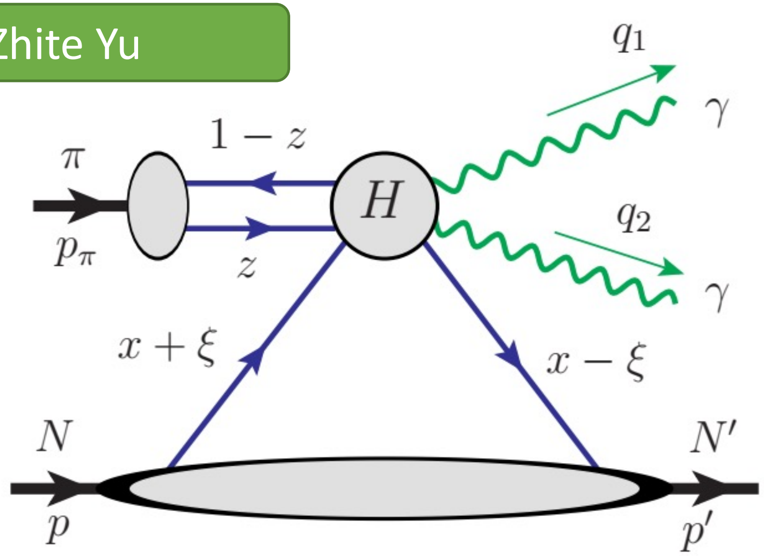




NLO calculation of diphoton photoproduction
Sensitive only to charge-odd GPDs

Exclusive 2-photon production in πN

Zhite Yu



QCD factorization proven

$$\mathcal{M}\left(t,\xi,q_T\right)=\int_{-1}^{1}\mathrm{d}x\,F(x,\xi,t;\mu)\cdot C\left(x,\xi;q_T/\mu\right)$$

GPD

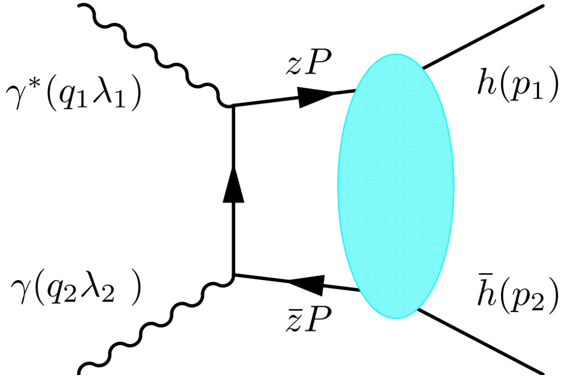
x, q_T dependences do not factorize, unlike in DVCS!

→ stronger constraint on GPD

Qin Tao Song

$\gamma\gamma \to MM$

Access to Generalized Distribution Amplitude of pion (timelike analog of GPD)

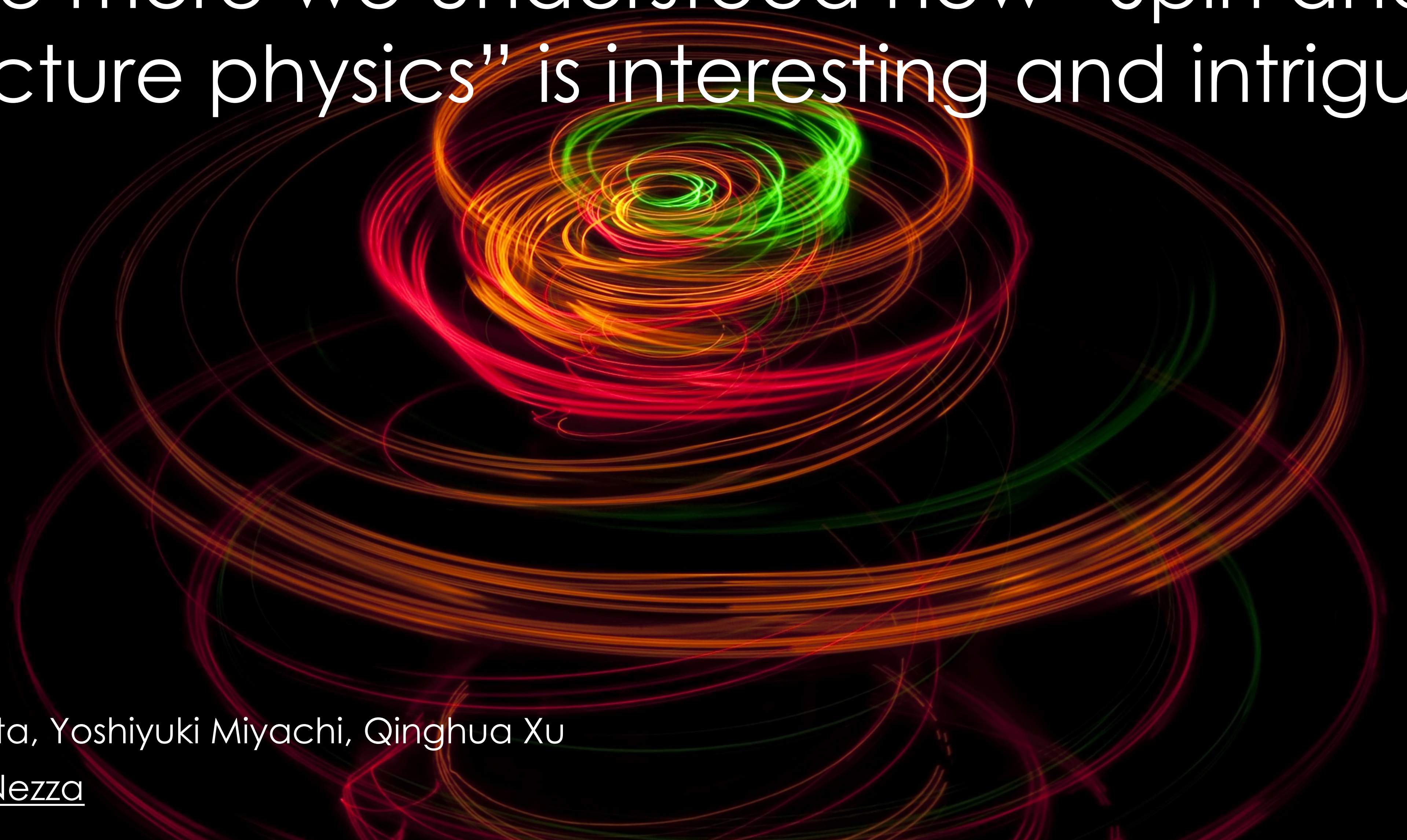


Access to (spacelike) GPD via dispersion relation

→ mass radius, mass distribution, pressure distribution and shear force distribution

little known

An exiting session!
Once more we understood how "Spin and 3D structure physics" is interesting and intriguing



Courtesy of F.Cuicchio INFN

Yoshitaka Hatta, Yoshiyuki Miyachi, Qinghua Xu

Pasquale Di Nezza

An exiting session!

Once more we understood how “Spin and 3D structure physics” is interesting and intriguing

A big thank to Super-Nestor and the LOC for a fantastic conference!

Yoshitaka Hatta, Yoshiyuki Miyachi, Qinghua Xu

Pasquale Di Nezza

Courtesy of F.Cuicchio INFN