Single hadron multiplicities in SIDIS @ COMPASS

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On behalf of the COMPASS collaboration

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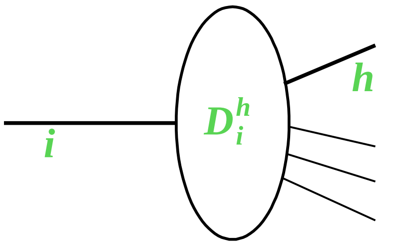
COMPASS

Motivation: FFs

- SIDIS $lN \to lhX$ gives access to **Fragmentation Functions (FFs)**

- **Collinear** FFs $D_i^h(z, Q^2)$ describe the collinear transition
  of a parton i
  into a hadron h carrying energy fraction $z = E_h/E_i$.



  - Non-perturbative universal objects.
    Factorisation: FF $\otimes$ parton-level X-section [$\otimes$ PDF] $(+$ *power suppressed...*$)$
  - Scale evolution: $dD_q^h(z, Q^2)/dlnQ^2 = [P_{qq} \otimes D_q^h + P_{gq} \otimes D_g^h](z, Q^2)$

- FFs are needed in analyses with a hadron in the final state
  (*when a hadron is* ***inclusively*** *detected in* ***hard*** *scattering*)

- Cleanest way to access FFs: e^+e^- annihilation. However. . .
  . . . only sensitive to $q + \bar{q}$, flavour separation limited.
  - In SIDIS, $q/\bar{q}$ and flavour separation possible. However. . .
    . . . FFs are convoluted with PDFs.
  - pp: $pp \to hX$ at high pT: little flavour/charge separation, but with gluon at leading order
    $pp \to (jet\ h)X$, see PRD 92 (2015),
  - SIDIS data are crucial to understand parton fragmentation

Motivation: PDFs

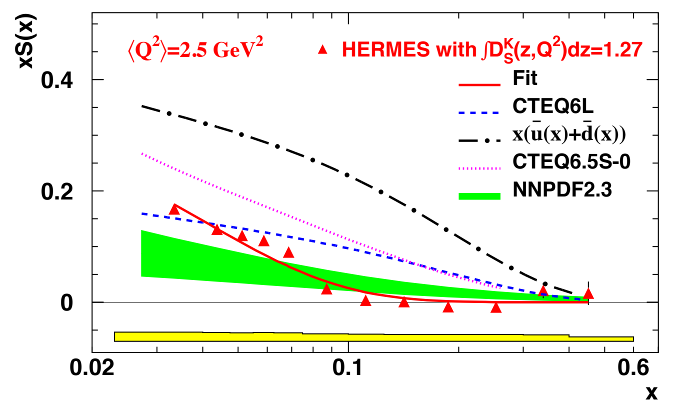
$$(\Delta)\sigma^h \overset{\text{LO}}{\propto} \Sigma\, e_q\, (\Delta)q(x,Q^2) \int D_q^h(z,Q^2)dz$$ ⇒ **Tagging of quark flavour**

- **Polarised PDFs (pPDFs)**
  - SIDIS data in several global QCD fits of pPDFs, *e.g.*:

    DSSV*: PRL 113 (2014)), JAM17: PRL 119 (2017), NNPDFpol1.1: NP B887 (2014)

- **PDFs**: well known. . . but for **Strangeness**
  - LO extraction of $S(x)$ $(S = s + \bar{s})$ @ high x

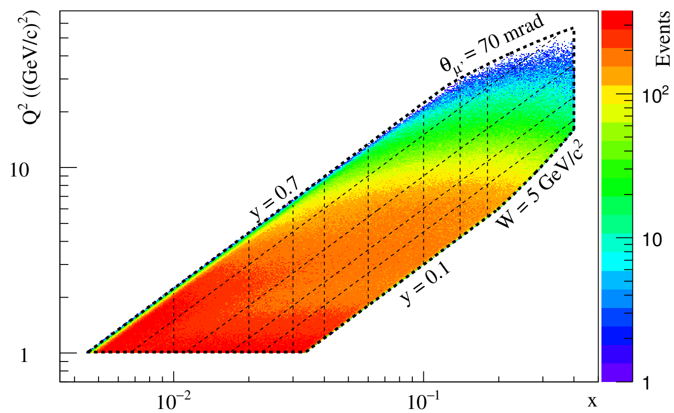
    from HERMES d data: PRD 89 (**2014**)



  - **Simultaneous** fit of FFs and PDFs, by JAM and DSS groups

Multiplicity Measurement in SIDIS

- Multiplicity is number of hadrons ***per*** inclusive DIS event



$$\frac{dM^h(x,z,Q^2)}{dz} = \frac{d^3\sigma^h(x,z,Q^2)/dxdzdQ^2}{d^2\sigma^{DIS}/dxdQ^2}$$

- Measurements need to be corrected for various effects:
  - Spectrometer acceptance. . .
    . . . taking p_T and azimuth ϕ_h into account
  - ParticleID efficiency and purity
  - Radiative effects
  - Diffractive vector meson production
    (***Subtracted*** *based on Handbag Model by Goloskokov and Kroll using MC generator HEPGEN*)
  - Feed-down from weak decays of charmed hadrons
    (*Negligible in our measured z range* $(z > 0.2)$)

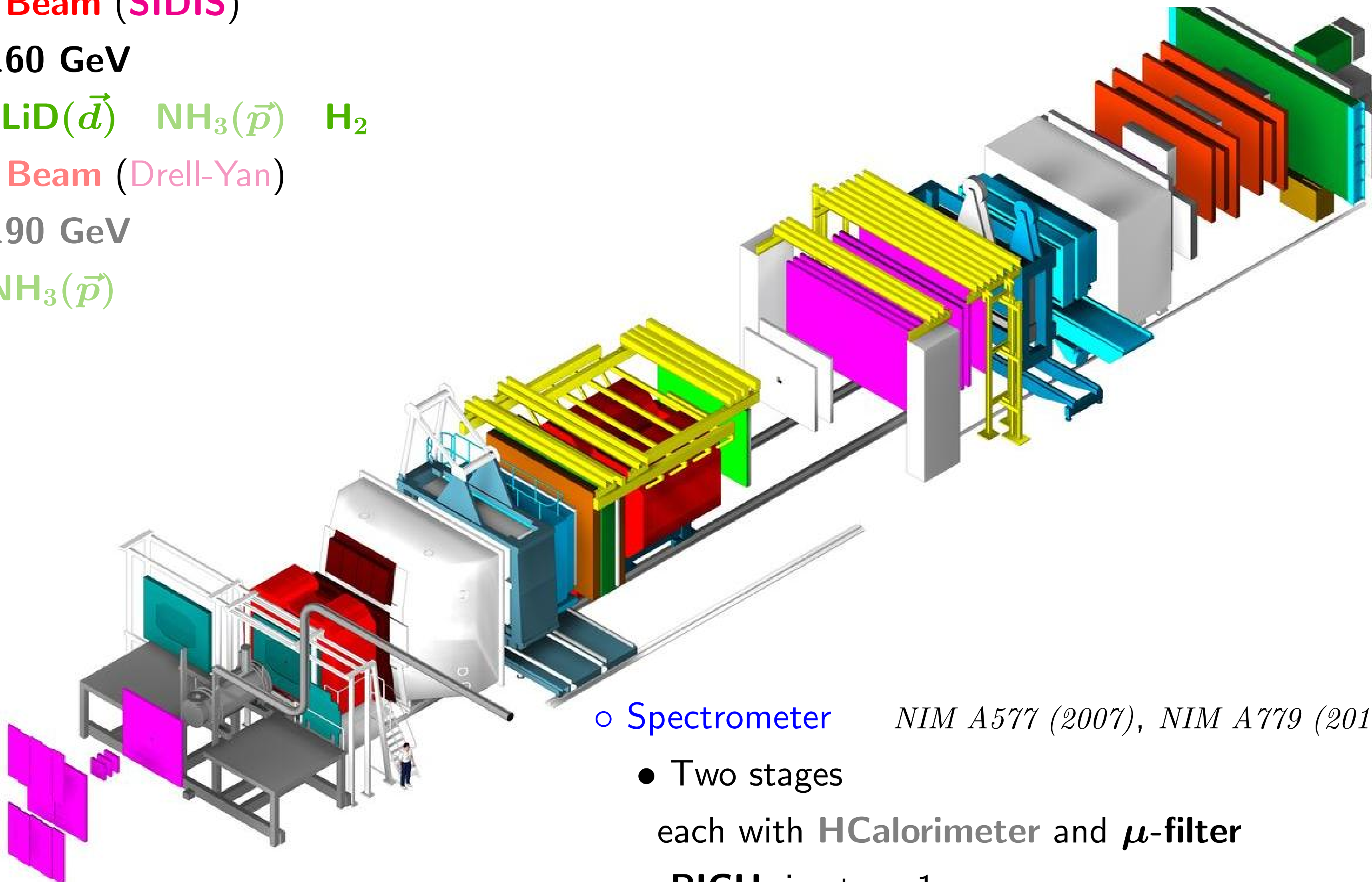
Multiplicity Measurement in SIDIS (*cont'd*)

- **Radiative Corrections**: Three approaches considered:
  1. **TERAD**(*i.e.* **Incl.DIS**)-based + empirical correction for hard photon. . .
     . . . impact on kinematics and phase-space of SIDIS
     Used in earliest analyses
  2. **RADGEN**-based: **Monte Carlo generation of radiative events**. . .
     . . . impact on kinematics on a *per* event basis
     Disagreement w/ COMPASS data ⇒ **Abandoned**
  3. **DJANGOH**-based: **Monte Carlo generation of radiative events**. . .
     Good agreement w/ COMPASS data ⇒ **Retained in latest analysis**
  - Ongoing discussion I. Akushevich, A. Afanasev (*RADGEN*) and H. Spiesberger (*DJANGOH*): Novel Probes of the Nucleon Structure, JLab, MCEGs for future ep and eA facilities, DESY

- **Acceptance correction**
  - 3D, along $\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}$
    $\boldsymbol{z}$-dependent $\boldsymbol{y}$ bin-width to stay w/in momentum range of RICH particleID
  - $\boldsymbol{p_T}$: Reasonably flat acceptance along $\boldsymbol{p_T}$
  - $\boldsymbol{\phi_h}$: Relying of extensive $\boldsymbol{\phi_{lab}}$ coverage of COMPASS. . .
    . . . to integrate out $\boldsymbol{cos\phi_h}$, $\boldsymbol{cos2\phi_h}$ and $\boldsymbol{sin\phi_h}$ modulations.

COMPASS: Spectrometer

- $\mu^{\pm}$ **Beam** (**SIDIS**)
  - **160 GeV**
  - **^{6}LiD($\vec{d}$) NH$_3$($\vec{p}$) H$_2$**
- π^{-} **Beam** (Drell-Yan)
  - **190 GeV**
  - **NH$_3$($\vec{p}$)**



- Spectrometer *NIM A577 (2007), NIM A779 (2015)*
  - Two stages
    each with **HCalorimeter** and **μ-filter**
  - **RICH**: in stage 1
  - **ECalorimeters**(0,1,2)

Multiplicity of $\pi^{\pm}$ on isoscalar target (^{6}LiD)

- PLB764 (2017) 1
- **3D binning**: $\boldsymbol{x \times y \times z}$
- LO QCD Fit,

  using Hirai, Kumano software with:

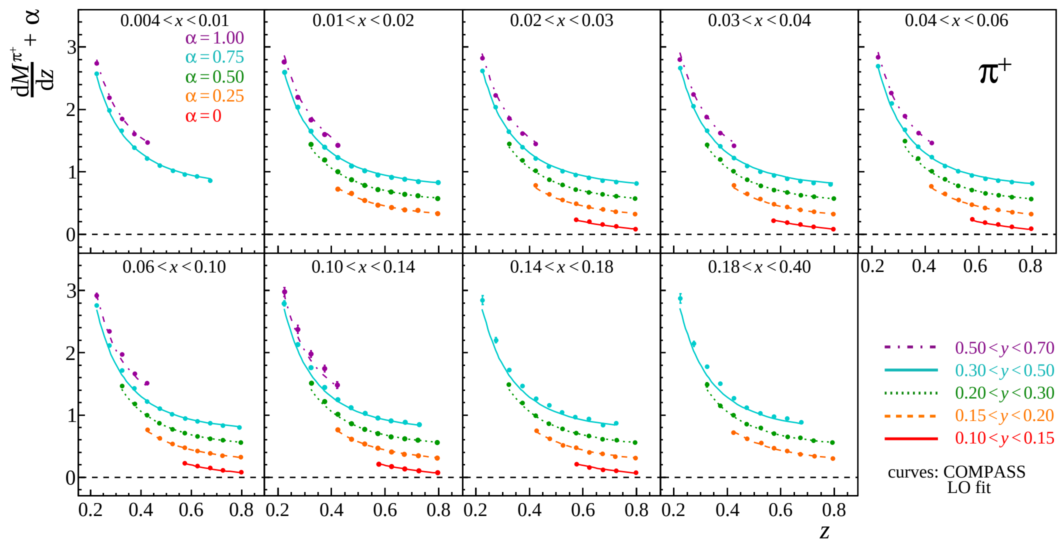
  $$\boldsymbol{D^{\pi}_{fav} = D^{\pi^+}_{u} = D^{\pi^+}_{\bar{d}}}\ \textit{and c.c.}$$

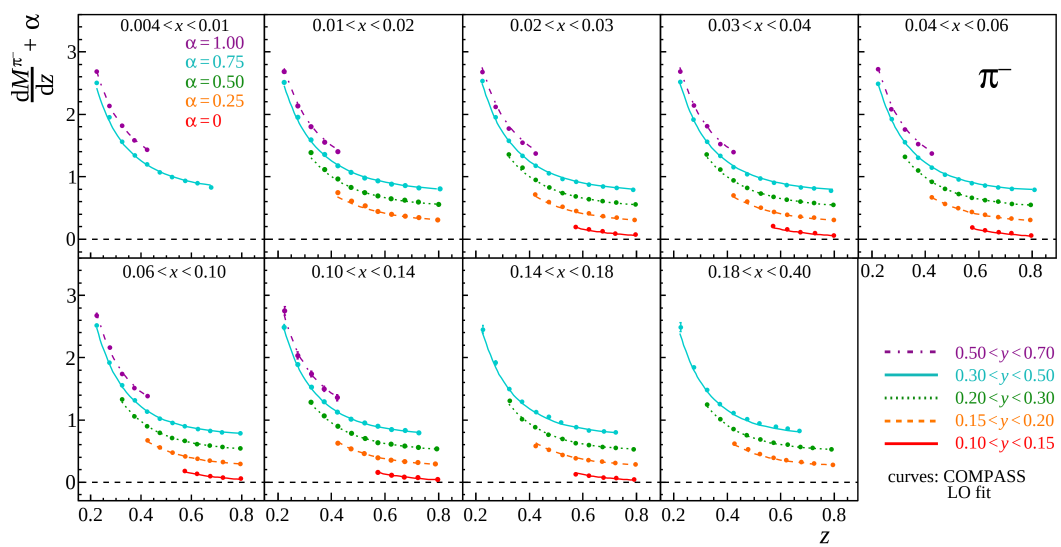
  $$\boldsymbol{D^{\pi}_{g}}\quad (\textit{in } \boldsymbol{Q^2} \textit{ evolution only})$$

  Simplification:

  $$\boldsymbol{D^{\pi}_{unf} = D^{\pi^{\pm}}_{q}},\ \forall \text{ non-valence } \boldsymbol{q}$$

- Also unidentified $\boldsymbol{h^{\pm}}$





Multiplicity of $K^{\pm}$ on isoscalar target (^{6}LiD)

- PLB767 (2017) 133

- LO QCD Fit

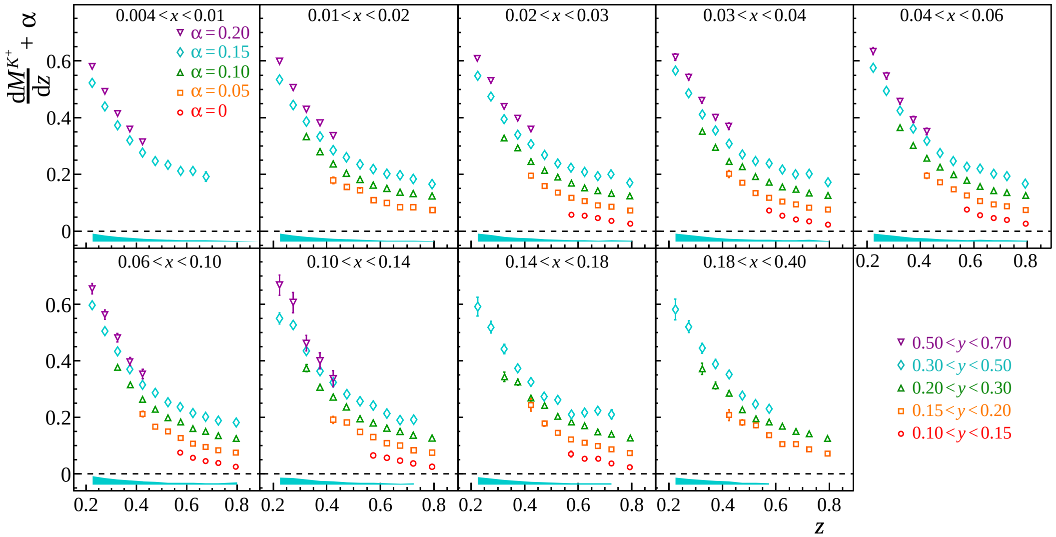
$D^K_{fav} = D^{K+}_u$ *and c.c.*

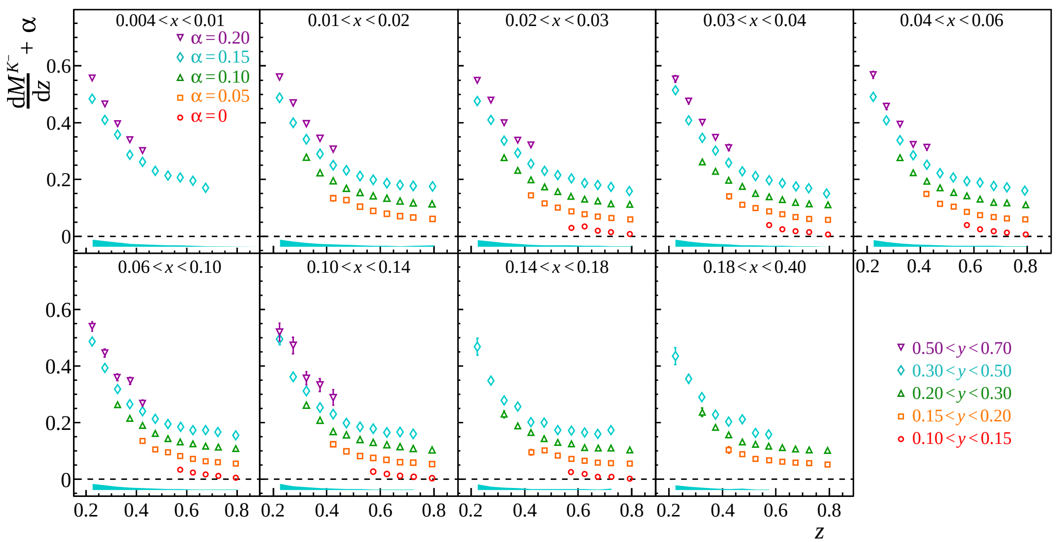
$\boldsymbol{D^K_{str} = D^{K^+}_{\bar{s}}}$ *and c.c.*

D^K_g

$D^K_{unf} = D^{K^{\pm}}_q$, $\forall$ non-valence q

unstable $\Rightarrow$ *not displayed*





Comparison w/ Other SIDIS Measurements

- **EMC**: $h^{\pm}$ ZPC52 (1991), **HERMES**: $\pi^{\pm}$, $K^{\pm}$ PRD87 (2013), **JLab E00-108**: $\pi^{\pm}$: PRC85 (2012)

- Sum/Ratio of **integrals** (*over measured z range*) **averaged over y** / **integrated over Q^2**

$$\mathscr{M} = \int \frac{dM}{dz} dz \qquad (\mathscr{D} = \int D dz)$$

LO pQCD + **simplifying assumptions** yield simple expressions and **provide guidance**

(*Shown is the* ***isoscalar target*** *case*)

∘ $\boldsymbol{\mathscr{M}^{\pi^+} + \mathscr{M}^{\pi^-}} \overset{\text{LO}}{=} \mathscr{D}^{\pi}_{fav} + \mathscr{D}^{\pi}_{unf} - \frac{2S}{5Q+2S}(\mathscr{D}^{\pi}_{fav} - \mathscr{D}^{\pi}_{unf}) \simeq \boldsymbol{\mathscr{D}^{\pi}_{fav} + \mathscr{D}^{\pi}_{unf}}$

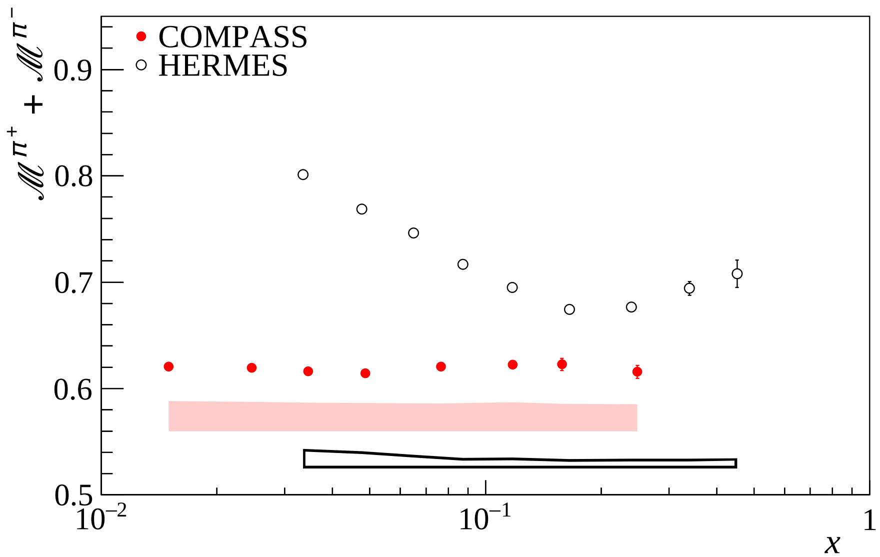
$$Q = u + \bar{u} + d + \bar{d},\ S = s + \bar{s}$$

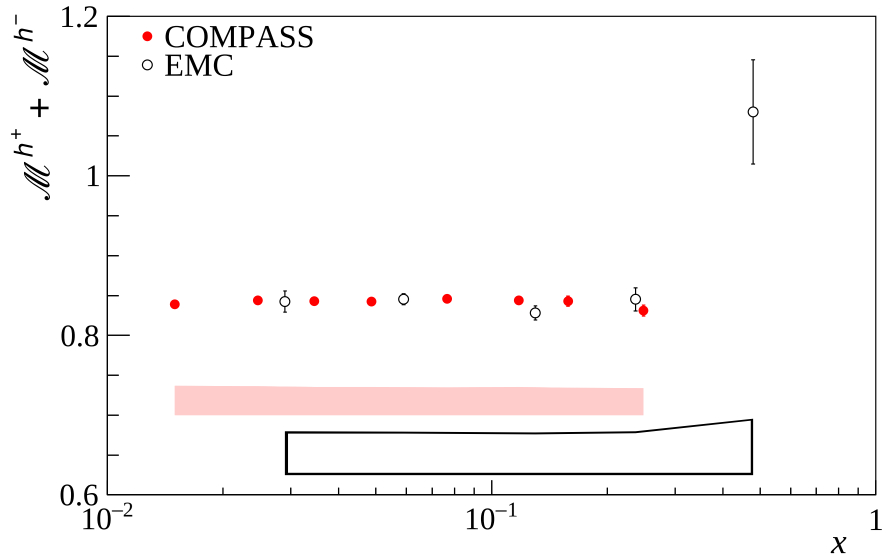
⇒ depends on x only weakly *via* $\mathscr{D}(Q^2)$ evolution and x/Q^2 correlation at fixed target.

∘ $5(\mathscr{M}^{K^+} + \mathscr{M}^{K^-}) \overset{\text{LO}}{\simeq} 4\mathscr{D}^{K}_{fav} + 6\mathscr{D}^{K}_{unf} + S/Q\ \mathscr{D}^{K}_{S}$

Comparison w/ Other SIDIS Measurements: π Multiplicity Sum

- COMPASS data averaged over y





$\Rightarrow$ Discrepancy w/ HERMES, beyond systematics uncertainty

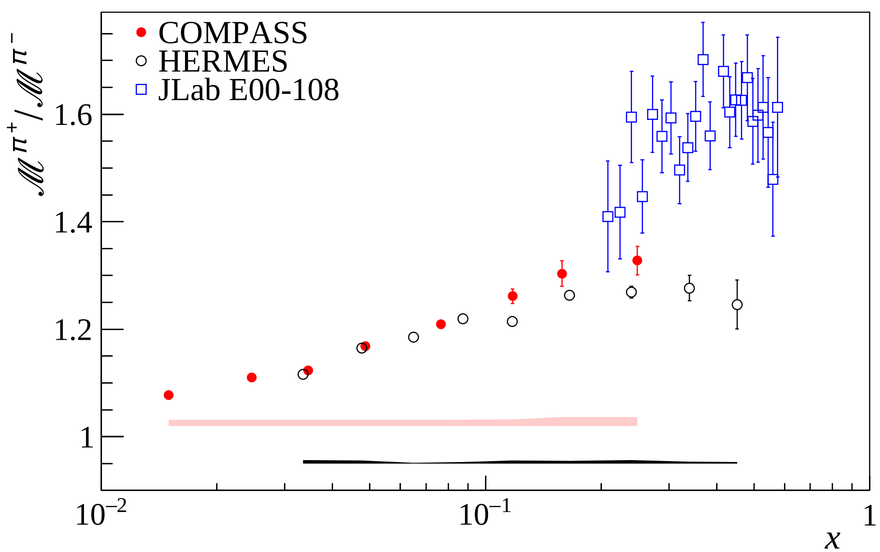
$\Rightarrow$ COMPASS (*averaged over* y) and EMC agree w/ LO pQCD prediction

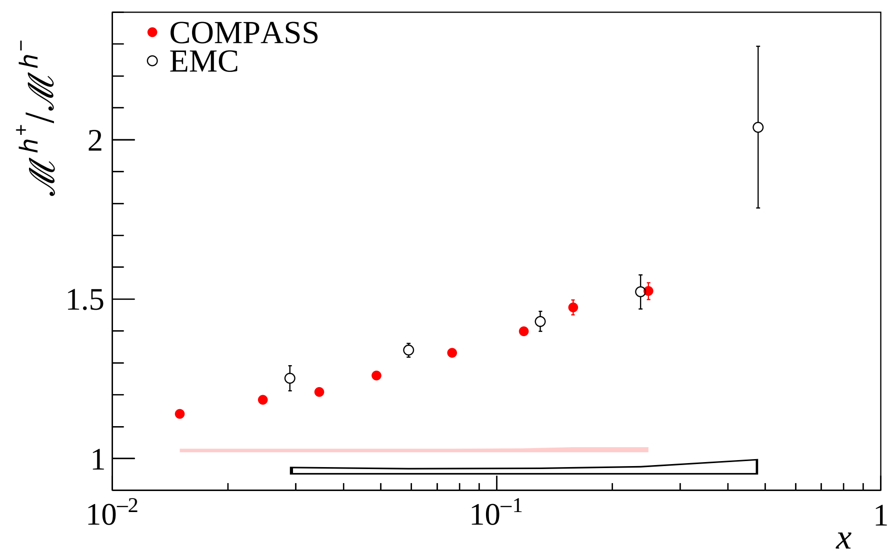
Caveat: ∘ **One of two available HERMES data sets**, *viz.* $\boldsymbol{x \times z}$ as opposed to $\boldsymbol{Q^2 \times z}$

∘ Q^2 differs among the experiments

π^+/π^- Multiplicity Ratio

- The ratio π^+/π^- is interesting because of cancellation of many systematic errors.





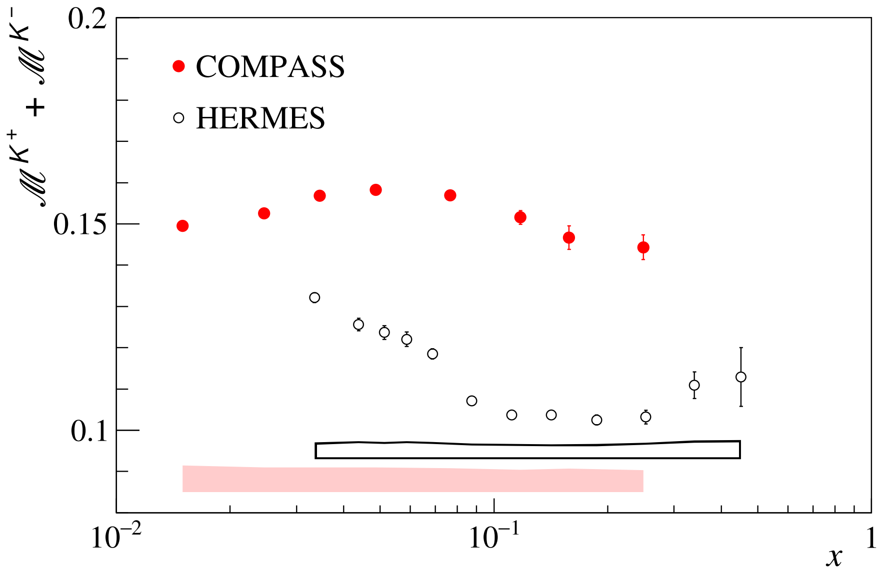
⇒ Agreement with HERMES, w/in uncertainty

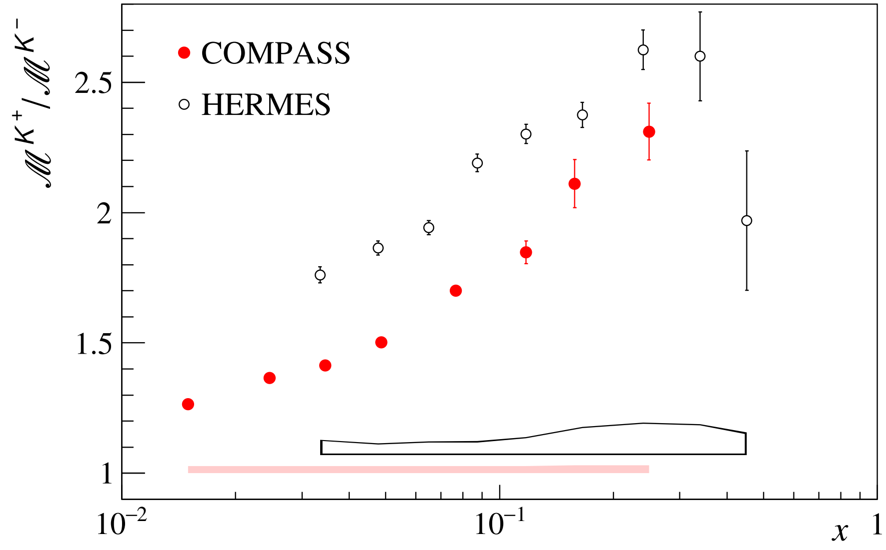
⇒ HERMES vs. JLab discrepancy at high x likely due to different W range

and possible higher twist contribution

K Multiplicity Sum and Ratio

- Comparison w/ **HERMES $x \times z$ data set**





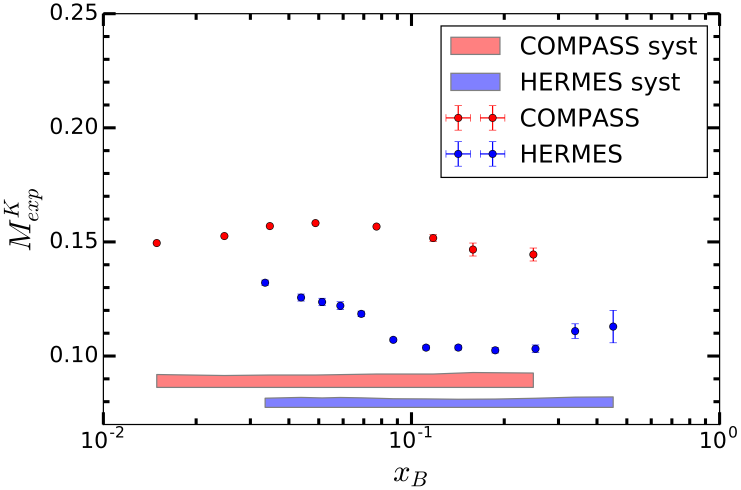
$\Rightarrow$ Significant differences between COMPASS and HERMES

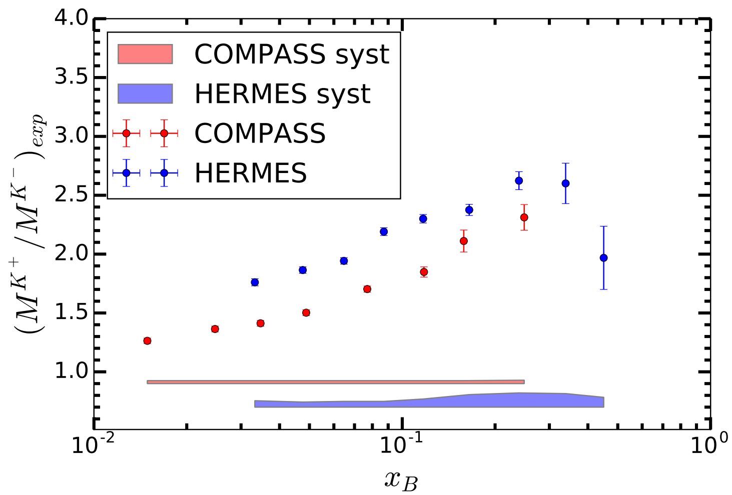
- Shape of $\mathscr{M}^{K^+} + \mathscr{M}^{K^-}$
- Mean value of $\mathscr{M}^{K^+} + \mathscr{M}^{K^-}$, while at high x it's, approx., a combination of $\mathscr{D}_q$

  ($Note$: *COMPASS on top, contrary to* π *case*)
- Ratio, whereas there's agreement for pions

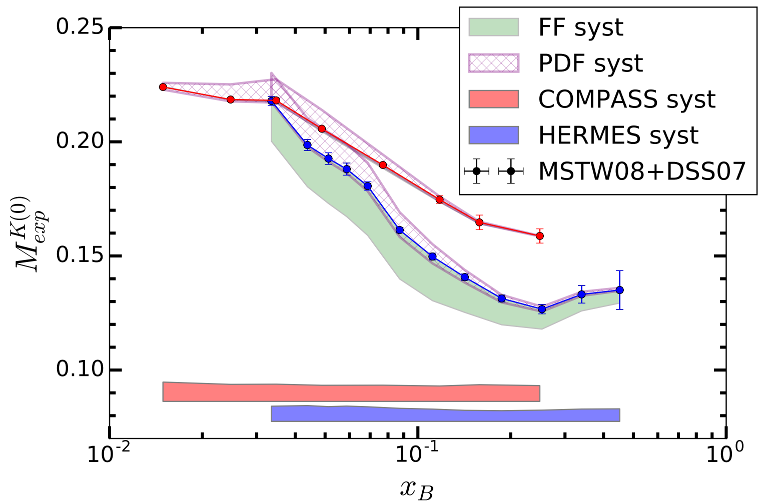
- Guerrero and Accardi PRD97 (2018): discrepancy suppressed by Hadron Mass Corrections

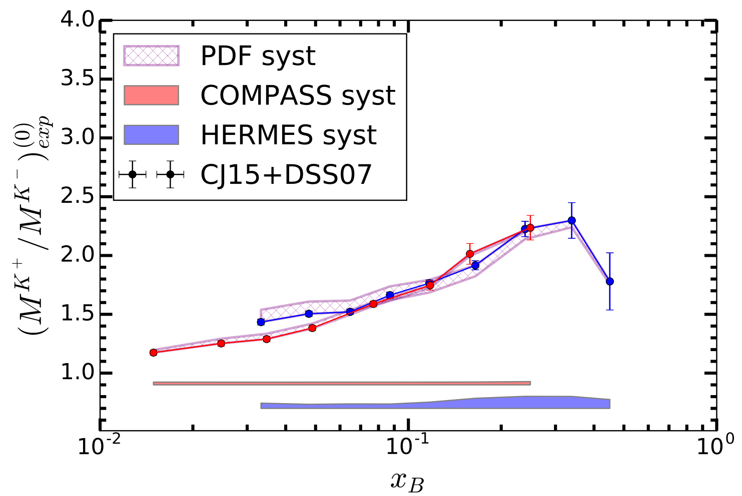
J. V. Guerrero and A. Accardi, PRD97 (2018) 114012





Experimental data





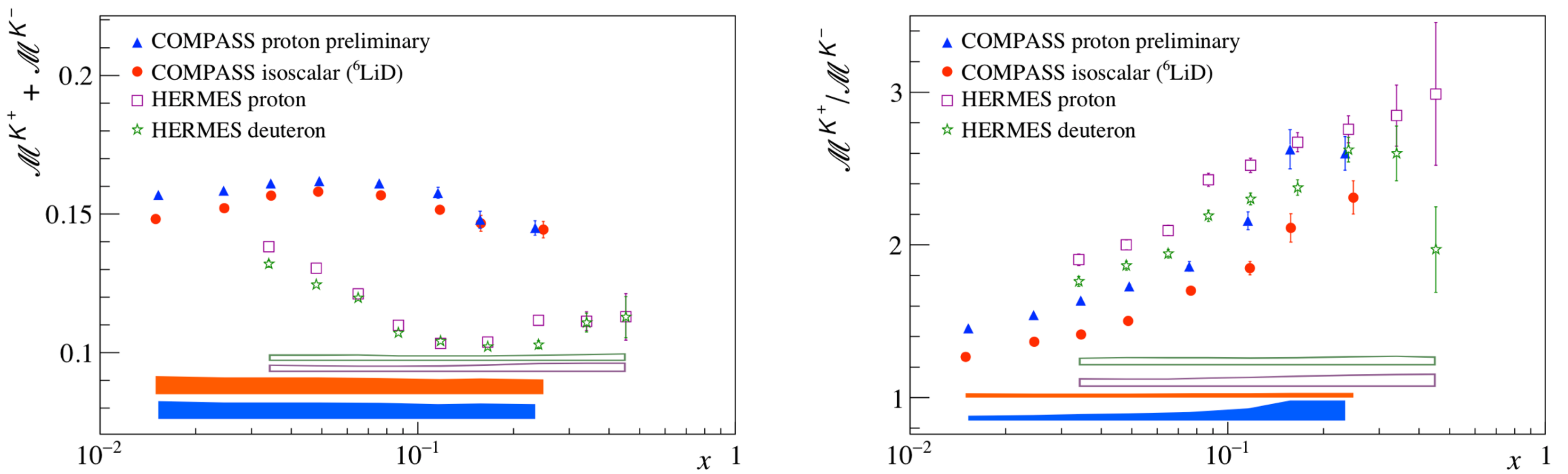
Massless parton multiplicities

(*@ common energy*)

K from p target (*preliminary*)

- Result from 2016 run *More to come from the 2017 run*
- **RC by Event Generator DJANGOH by H. Spiesberger**

  ⇒ Expecting better control on RC ⇒ associated systematics reduced
- Comparison w/ **HERMES p $x \times z$ data set**



⇒ **Confirmation of COMPASS *vs.* HERMES discrepancy**

- $\boldsymbol{p}$ sitting $\sim$ 5%(*sum*)/10 %(*ratio*) above $\boldsymbol{d}$ as expected (*different PDFs involved*)

Experimental Status of FFs: Global QCD Fits

- Global fits exploit universality by **combining** data sets from **several processes**:
  - **DEHSS** = De Florian, Sassot, Stratmann *et al.*: PRD91 (2015), PRD95 (2017):
    e^+e^-, pp and **SIDIS**.
  - **NNPDF**: Bertone *et al.*: EPJC78 (2018): e^+e^-, $pp(\bar{p})$.
  - **HKKS** = Hirai, Kawamura, Kumano, Saito PTEP (2016): e^+e^-.
  - **LSS** = Leader, Sidorov, Stamenov PRD93 (2016): **SIDIS**.
  - **AKK** = Albino, Kniehl, Kramer NPB803 (2008): e^+e^-, $pp(\bar{p})$.

- Exploit SIDIS full potential *via* combined fit of FFs, PDFs and/or pPDFs
  - **JAM17** Ethier, Sato, Melnitchouk: PRL119 (2017) (e^+e^-, **SIDIS = COMPASS only**)
  - Borsa, Sassot, Stratmann: PRD96 (2017)

    Help clarify PDFs of strange sea, COMPASS/HERMES disagreement

K^-/K^+ Multiplicity Ratio at high z

- PLB786 (2018) 390

- Ratio?
  - Ratio cancels out many of the systematics

  $\Rightarrow$ Can explore otherwise experimentally difficult SIDIS high z

- Ratio of Kaons, as opposed to pions?
  - Diffractively produced vector meson decays . . .

  . . . dominate at **high z** in pion case ($\rho^o \to \pi^+\pi^-$)

  . . . stay w/in 0.3< z <0.7 in kaon case ($\phi \to K^+K^-$)
  because break-up momentum is small.

- **Domain of validity of pQCD + independent fragmentation in SIDIS?**

  What SIDIS data to consider in global fit?

K^-/K^+ at high z: Predictions

- At LO in pQCD, on a $\boldsymbol{p}$ **target**:
  - $$\frac{dM^{K^-}}{dM^{K^+}} \stackrel{\text{LO}}{=} \frac{4\bar{u}D_{fav} + (4u + \bar{d} + d + \bar{s})D_{unf} + sD_{str}}{4uD_{fav} + (4\bar{u} + d + \bar{d} + s)D_{unf} + \bar{s}D_{str}}$$

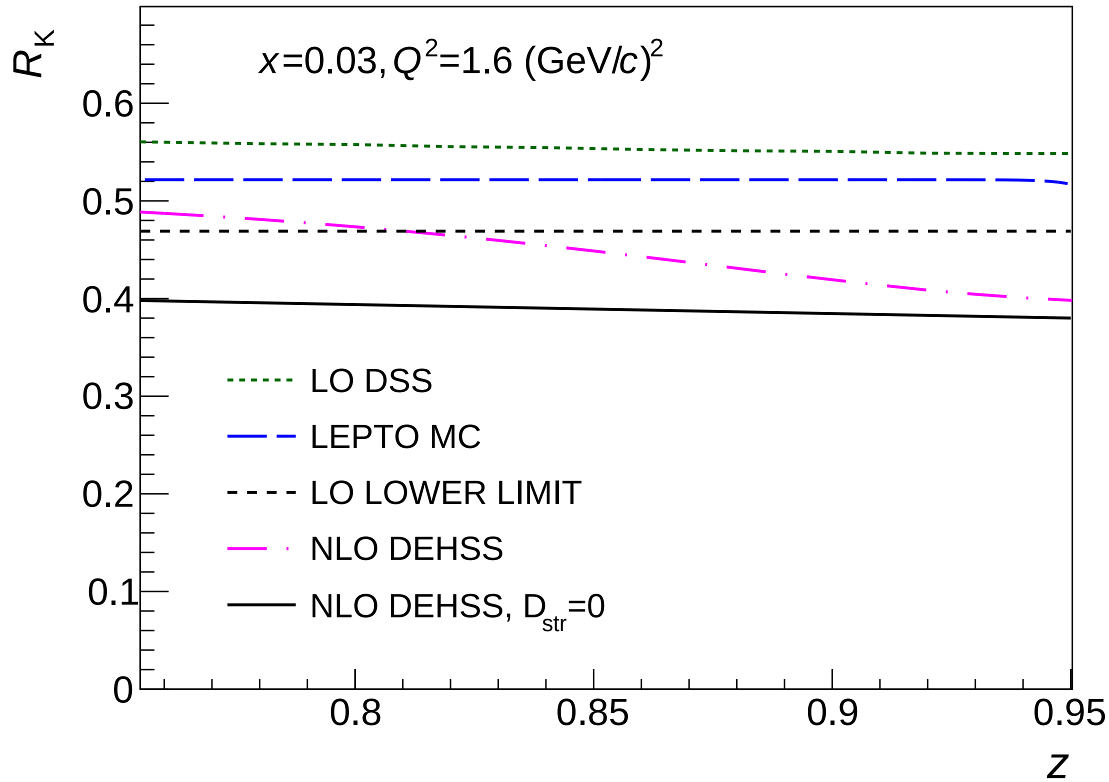
    Neglecting D_{unf} ($since\ high\ z$), and trivial simplifications:

    $$\frac{dM^{K^-}}{dM^{K^+}} \stackrel{\text{LO}}{\simeq} \frac{4\bar{u}D_{fav} + sD_{str}}{4uD_{fav} + \bar{s}D_{str}} > \frac{\bar{u}}{u}$$
  - On a $\boldsymbol{d}$ **target**:

    $$\boldsymbol{R_K = \frac{dM^{K^-}}{dM^{K^+}} > \frac{\bar{u} + \bar{d}}{u + d}}$$

- At NLO,
  - Reasonably safe lower bound obtained by setting $D_{str} = 0$, working around dispersion among PDF and FF sets.

K^-/K^+ at high z: Predictions

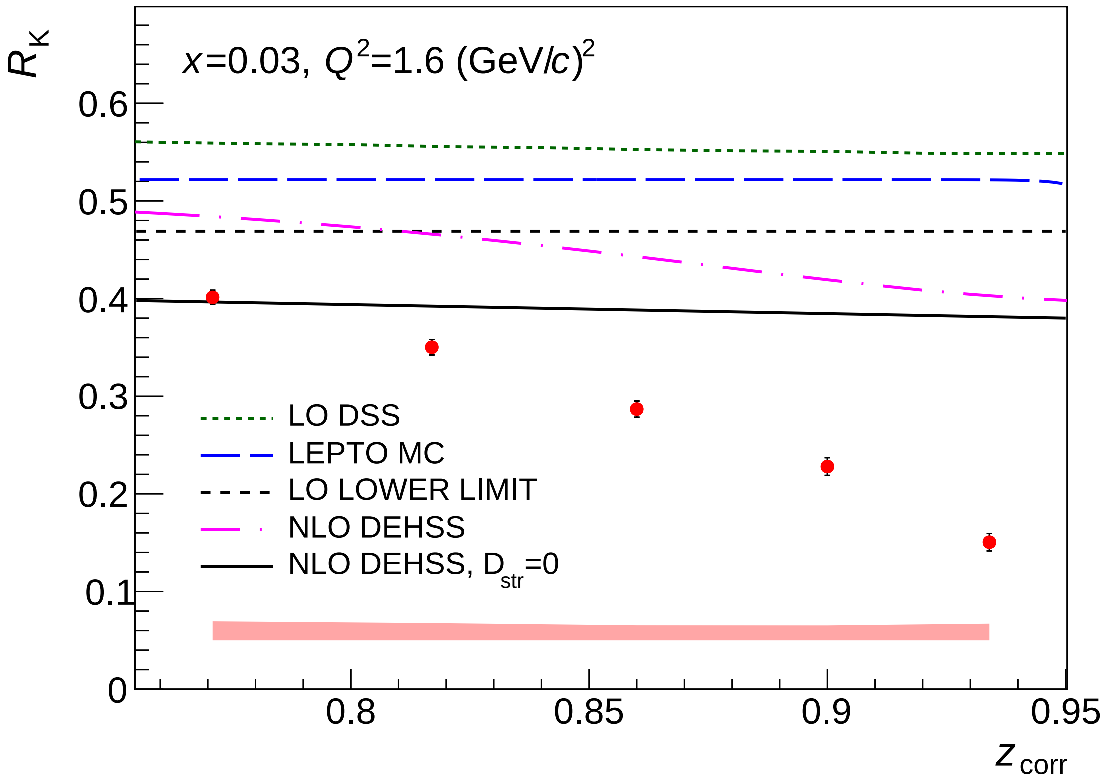


- Model calculations (*in addition to lower limits*)

  LO DSS07, NLO DEHSS

  LEPTO, w/ $H^K_{q/N}(x, z, Q^2)$ fragmentation ansatz

K^-/K^+ at high z: COMPASS Results *vs.* Predictions



PLB 786 (2018)

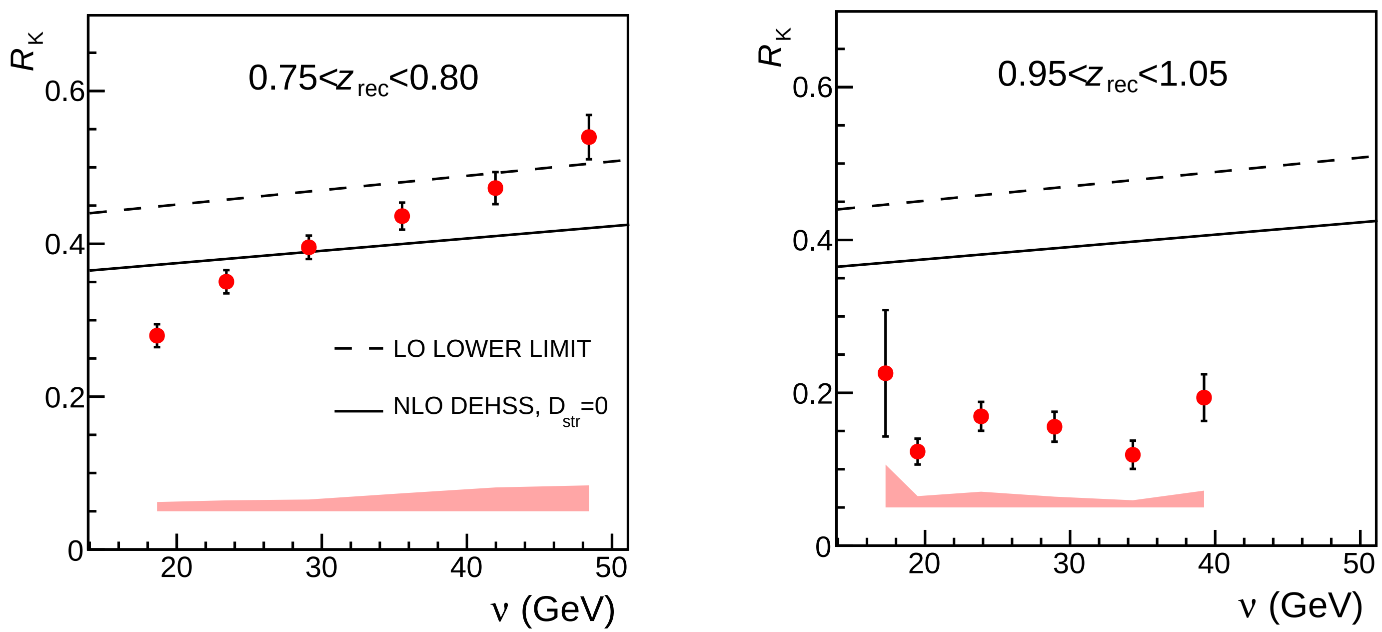
⇒ Clear disagreement w/ models. Violation of LO and NLO limits

(*Safe result: all effects, here unaccounted for, in theory, tend to further increase disagreement.*)

- (*Note: Similar result @ higher* x, *w/* $R_K(x<0.05)/R_K(x>0.05)$ *flat*)

K^-/K^+ at high z: COMPASS Results *vs.* photon energy ν

- R_K in 5 bins of z (*2 shown*)
  compared to LO and NLO lower limits



PLB 786 (2018)

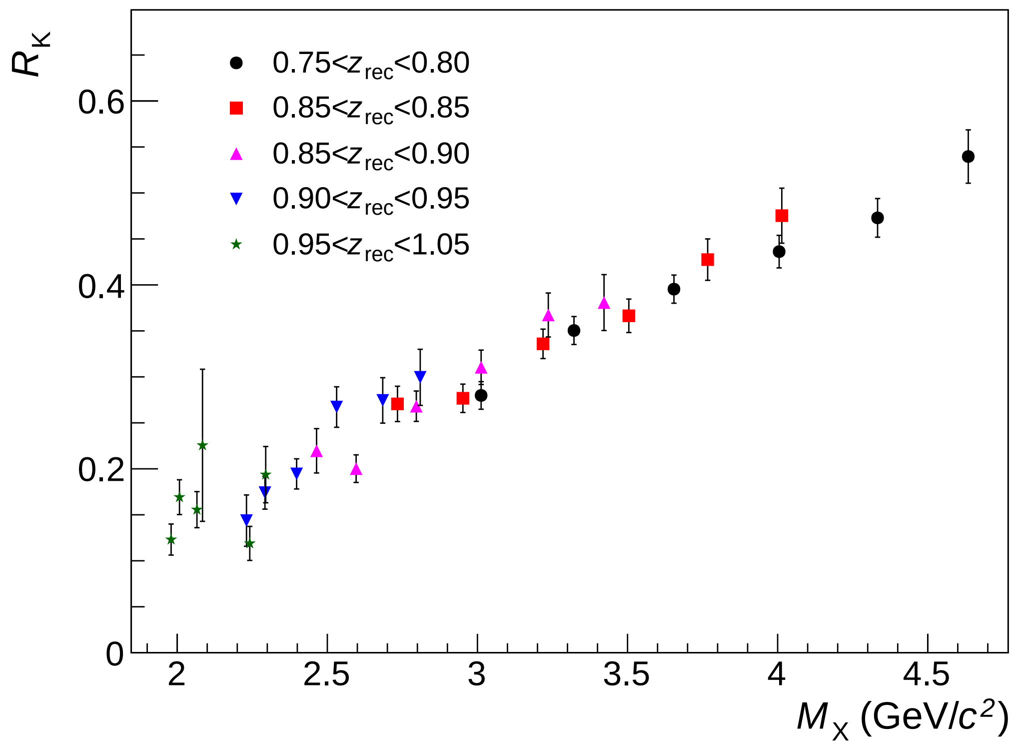
- Strong **dependence upon ν** ($beyond\ expected\ from\ x(\nu)$)

  Not foreseen w/in independent fragmentation in pQCD

⇒ **Low ν high z: Applicability of independent fragmentation pQCD questionable**

K^-/K^+ at high z: COMPASS Results *vs.* Missing Mass

- Missing Mass M_X: $M_X^2 \approx 2M\nu(1-z)$



PLB 786 (2018)

- M_X nicely expresses both z and ν dependences

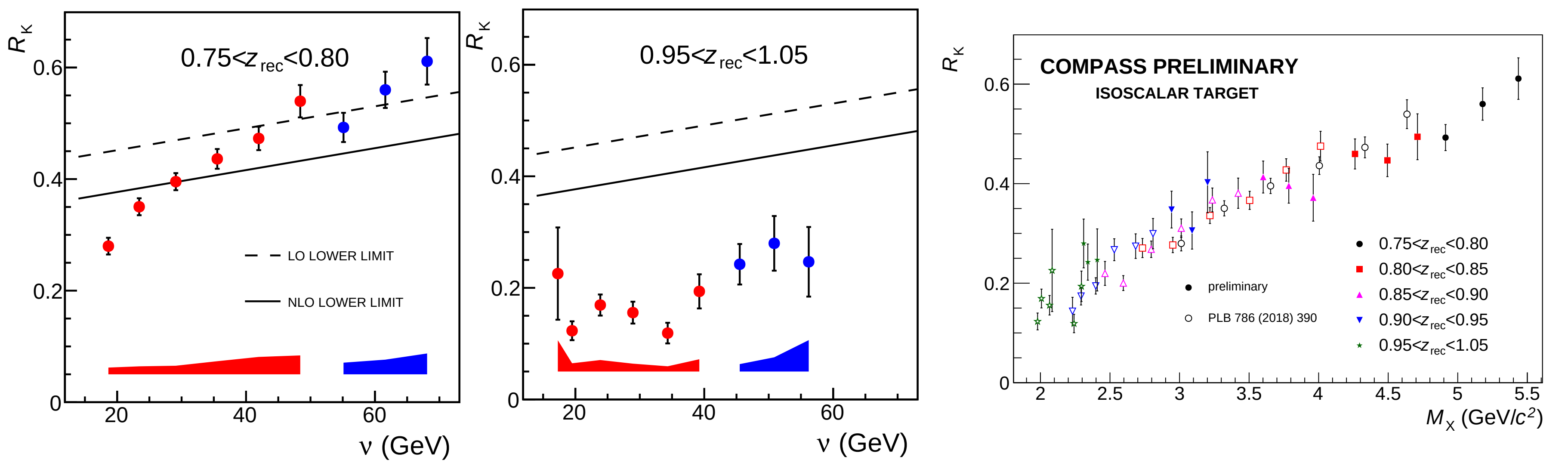
⇒ Low ν high z: Independent fragmentation is what becomes invalid

Fragmentation becomes sensitive to phase space for hadronisation of target remnants

K^-/K^+ at high z: Extended ν range ($Preliminary$)

- RICH pID range extended: [12,40] $\rightarrow$ [12,55] GeV/c

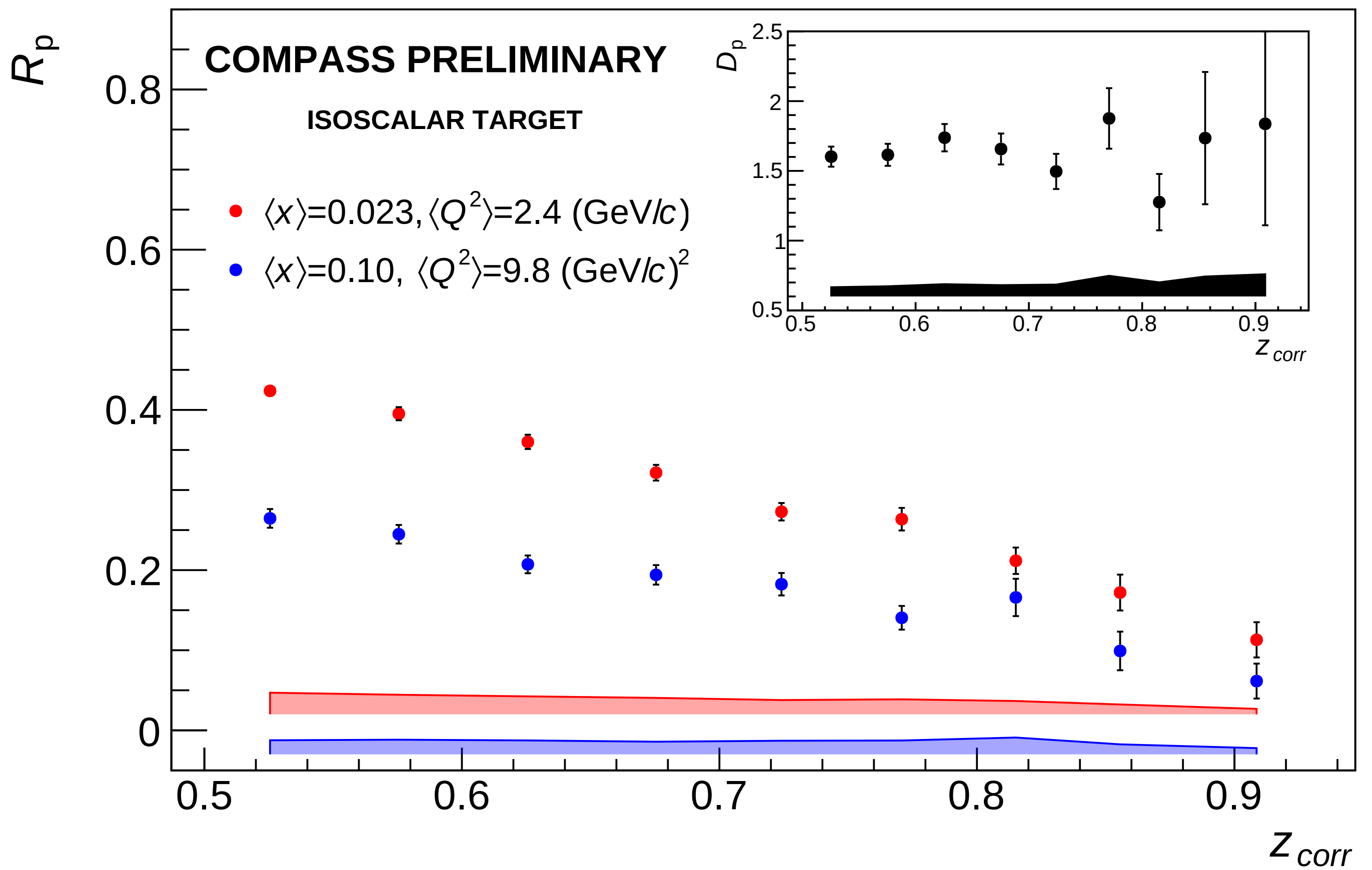
  ($thanks\ to,\ in\ part,\ Machine\ Learning\ techniques$)



$\Rightarrow$ Extended range nicely completes the picture

w/ signs of saturation of R_K and restoration of independent fragmentation

p^-/p^+ at high z ($Preliminary$)

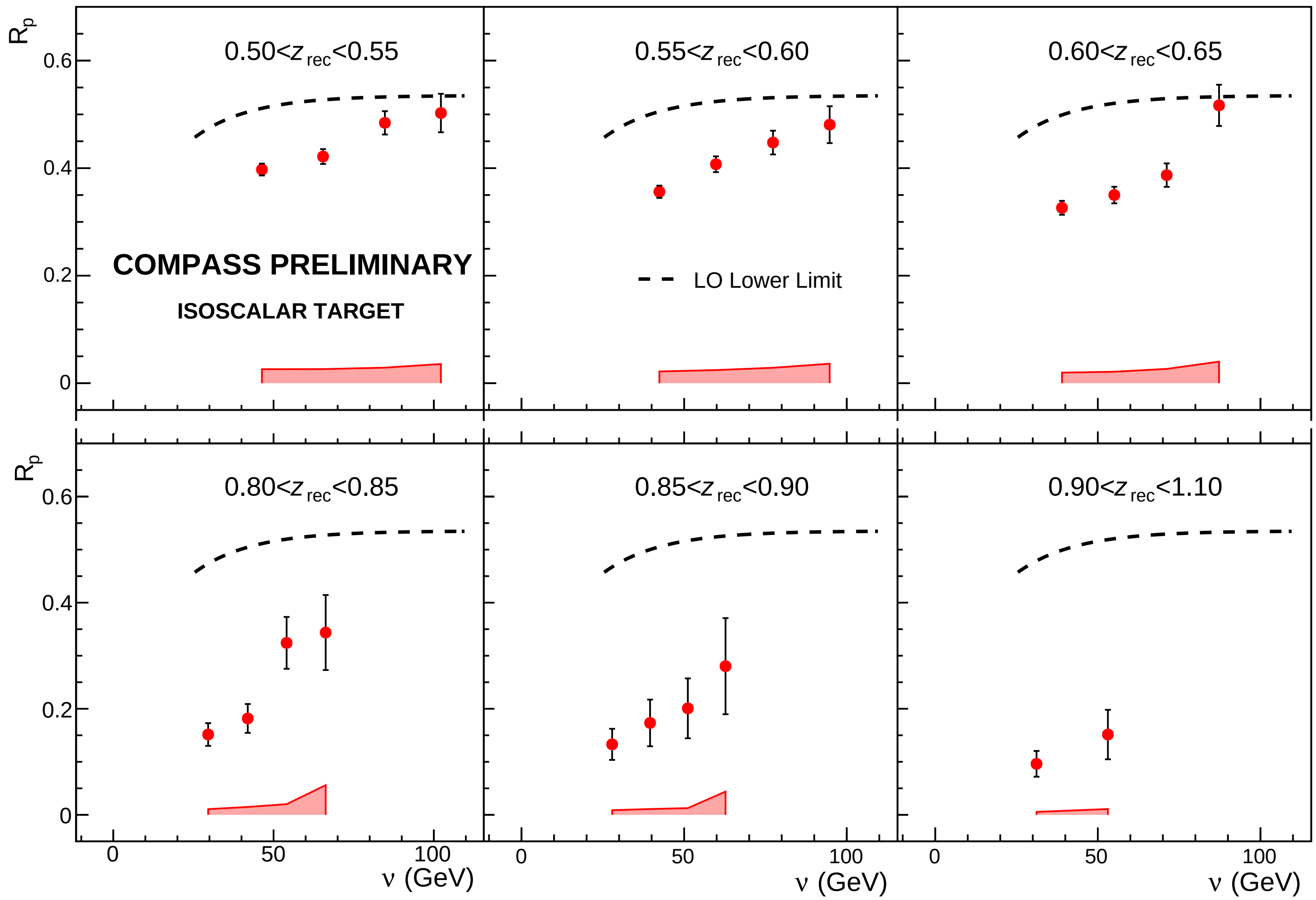


⇒ Well below LO pQCD limits, *viz.*: 0.51 and 0.28

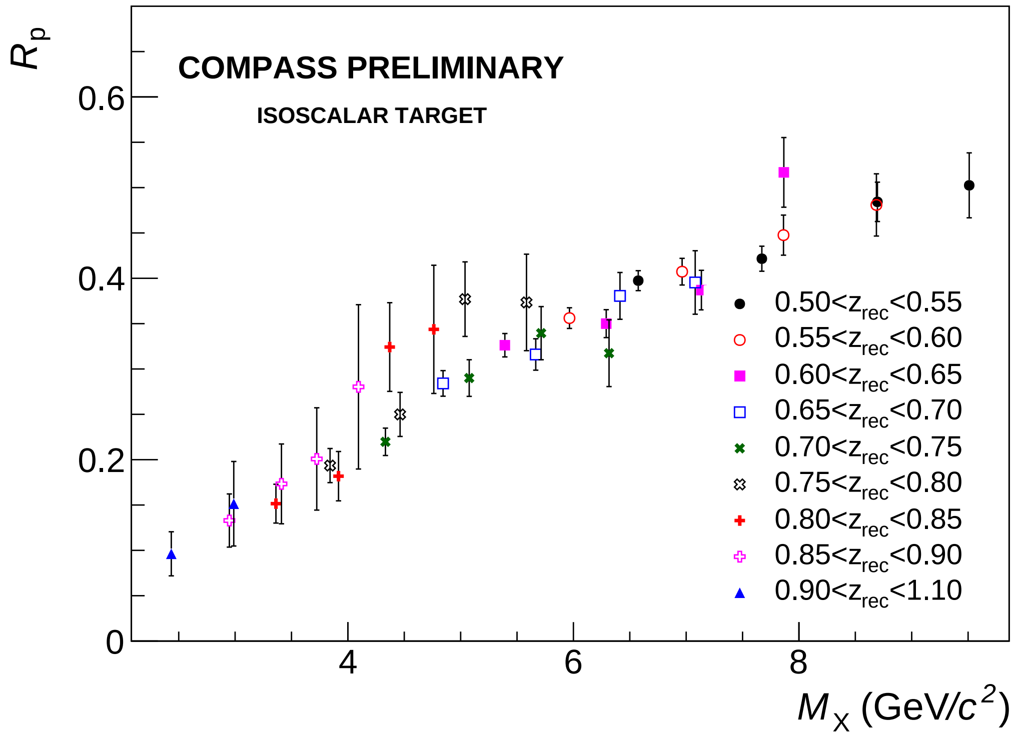
($Note$: Q^2 $reaches$ $\sim$$10$ GeV^2)

p^-/p^+ at high z vs. ν (*Preliminary*)

- R_p in 9 bins of z (*6 shown*)
- Compared to LO limit



p^-/p^+ at high z *vs.* Missing Mass



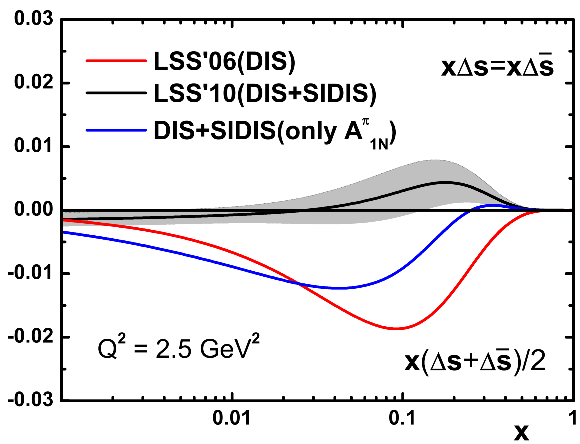
- As for K, M_X nicely expresses both z and ν dependences
- Hint that scaling variable is $(M_X - Thr)/M_h$

h^-/h^+: Conclusions

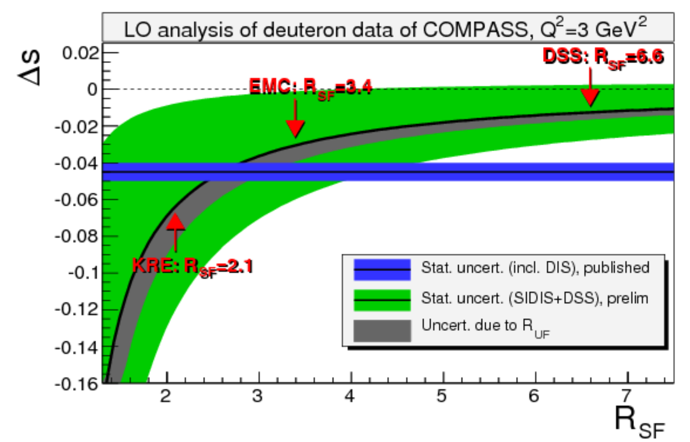
- In COMPASS, we're sitting in a corner region of the phase space. . .
  . . . but at lower energy, larger region is affected

$\Rightarrow$ This gives interesting insights:

- ◦ Possible explanation for HERMES/COMPASS K discrepancy
  supplementing (*w/ some overlap?*) HMC alla Accardi/Guerrero.
- ◦ @ low ν positive contribution from Δu may mistaken for ΔS
  $\Rightarrow$ biasing the extraction of ΔS from polarised DIS+SIDIS



LSS, PRD 84 (2011)



Δs dependence upon $R_{SF} = \mathscr{D}_s/\mathscr{D}_u$

- ◦ K and p account for 20-25% of all hadrons.
  $\Rightarrow$ Analyses based on unidentified hadrons, *e.g.* TMD, may be biased

Outlook

- The region of applicability of pQCD in SIDIS should be revisited

- COMPASS: More results from 2016-17 runs: on proton target, $\sim$.5 fb^{-1}

Spares