Process dependence of the gluon Sivers function in inclusive pp collisions: **Phenomenology**

in progress

U. D'Alesio in collaboration with
Carlo Flore, Francesco Murgia,
Cristian Pisano and Pieter Taels

Outline

- SSAs in pp collisions dominated by gluons in the initial state:

  - $pp \to h\,X$ at mid-rapidity

  Heavy quark (charm) production

  - $pp \to D\,X$
  - $pp \to J/\psi\,X$

- TMD scheme: w/o initial/final state interactions

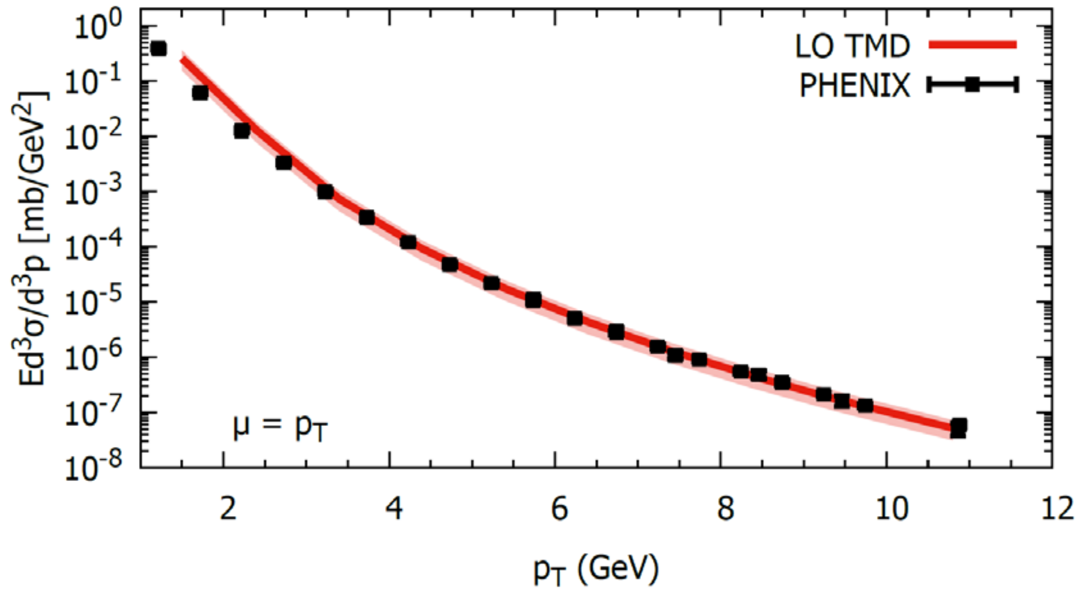
  GPM: one universal GSF

  CGI-GPM: 2 GSFs and process dependent

- A strategy to constrain the Gluon Sivers function(s)
- Comparisons with data and predictions ($pp \to \gamma\,X$)
- Concluding remarks

$pp \to \pi X$ at mid-rapidity

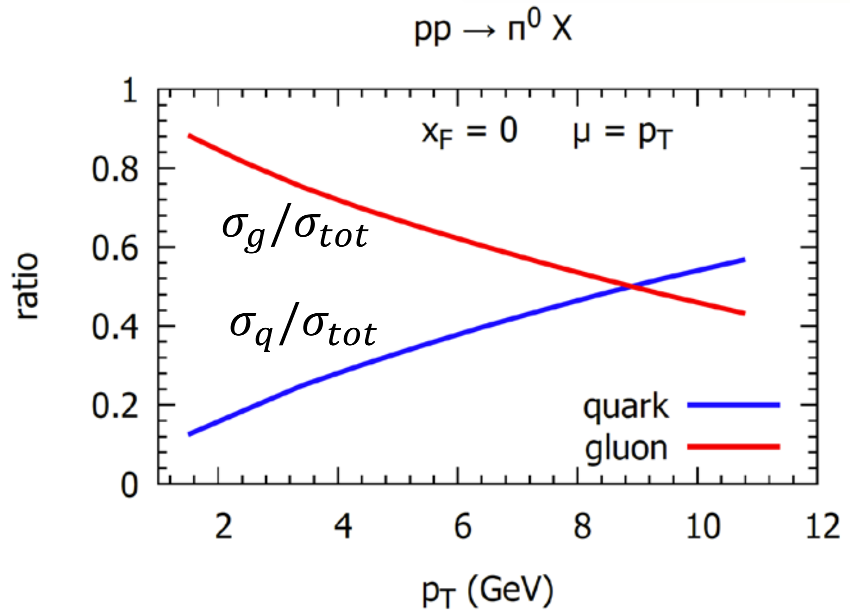
- Unpolarised xsec at LO in a TMD scheme



PHENIX Coll. (2007)

$pp \to \pi X$ at mid-rapidity

- Unpolarised xsec at LO in a TMD scheme
- Gluon dominance up to $p_T \sim$ 4-5 GeV



- SSAs in a TMD scheme:
  - Collins effect compatible with zero
  - Quark Sivers effect small and almost zero from SIDIS fits

→ Access to the GSF

[Anselmino, UD, Melis, Murgia (2006)]

$pp \to D\,X$

- At LO 2 partonic processes (only charm fragmentation)

  - $q\,\bar{q} \to c\,\bar{c}$ (sub-leading)

  - $g\,g \to c\,\bar{c}$

- SSAs in a TMD scheme ($p^{\uparrow}p \to D\,X$)

  [Anselmino, Boglione, UD, Leader, Murgia (2004);

  UD, Murgia, Pisano, Taels (2017)]

$q^{\uparrow}\bar{q} \to c\,\bar{c}$: s-channel NO spin transfer ⟹ NO Collins effect

Quark Sivers effect very small/almost zero from SIDIS fits

⟹ Access to the GSF

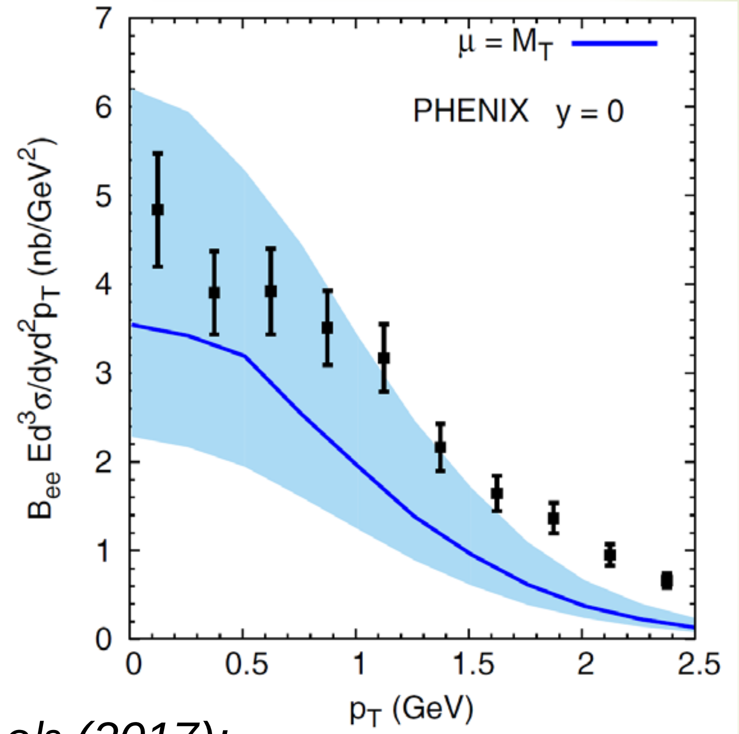
Study within a twist-three approach:
Kang, Qiu, Vogelsang, Yuan (2008); Koike, Yoshida (2011)

$pp \to J/\psi\, X$

- At LO one partonic process

  - $g\, g \to c\, \bar{c}$

  Color-Singlet Model



- SSAs in a TMD scheme

  → Access to the GSF

[UD, Murgia, Pisano, Taels (2017); Godbole et al. (2017)]

Basic formalism (I)

Color-gauge Invariant GPM

$$\mathrm{d}\Delta\sigma^{\mathrm{CGI}} \sim \left\{ \left(-\frac{k_{\perp a}}{M_p}\right) f_{1T}^{\perp g(f)}(x_a, k_{\perp a}) \cos\phi_a \otimes H_{ab\to cd}^{\mathrm{Inc}(f)} + \left(-\frac{k_{\perp a}}{M_p}\right) f_{1T}^{\perp g(d)}(x_a, k_{\perp a}) \cos\phi_a \otimes H_{ab\to cd}^{\mathrm{Inc}(d)} \right\} \otimes c \to hadron$$

Generalised parton model

$$\mathrm{d}\Delta\sigma^{\mathrm{GPM}} \sim \left(-\frac{k_{\perp a}}{M_p}\right) f_{1T}^{\perp g}(x_a, k_{\perp a}) \cos\phi_a. \otimes H_{ab\to cd}^{U} \otimes c \to hadron$$

$$\Delta^N f_{a/p^\uparrow}(x_a, k_{\perp a}) = -2\frac{k_{\perp a}}{M_p} f_{1T}^{\perp a}(x_a, k_{\perp a})$$

Sivers function

Basic formalism (I)

- Three fundamental elements

- The GSF $f_{1T}^{\perp g}(x_a, k_{\perp a})$
- The azimuthal phase (integrated over) $\cos\phi_a$
- The hard scattering piece $H_{ab\to cd}^{\rm Inc}$

Basic formalism (II)

$$\left|\frac{k_{\perp a}}{M_p} f_{1T}^{\perp a}(x_a, k_{\perp a})\right| \leq f_{a/p}(x_a, k_{\perp a})$$

Positivity bound

$$\left(-\frac{k_{\perp a}}{M_p}\right) f_{1T}^{\perp g}(x_a, k_{\perp a}) = \mathcal{N}_g(x) f_{g/p}(x) \; h(k_\perp) \frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle}$$

$-f_{1T}^{\perp g}(x)$

$|\mathcal{N}_g(x)| \leq 1$

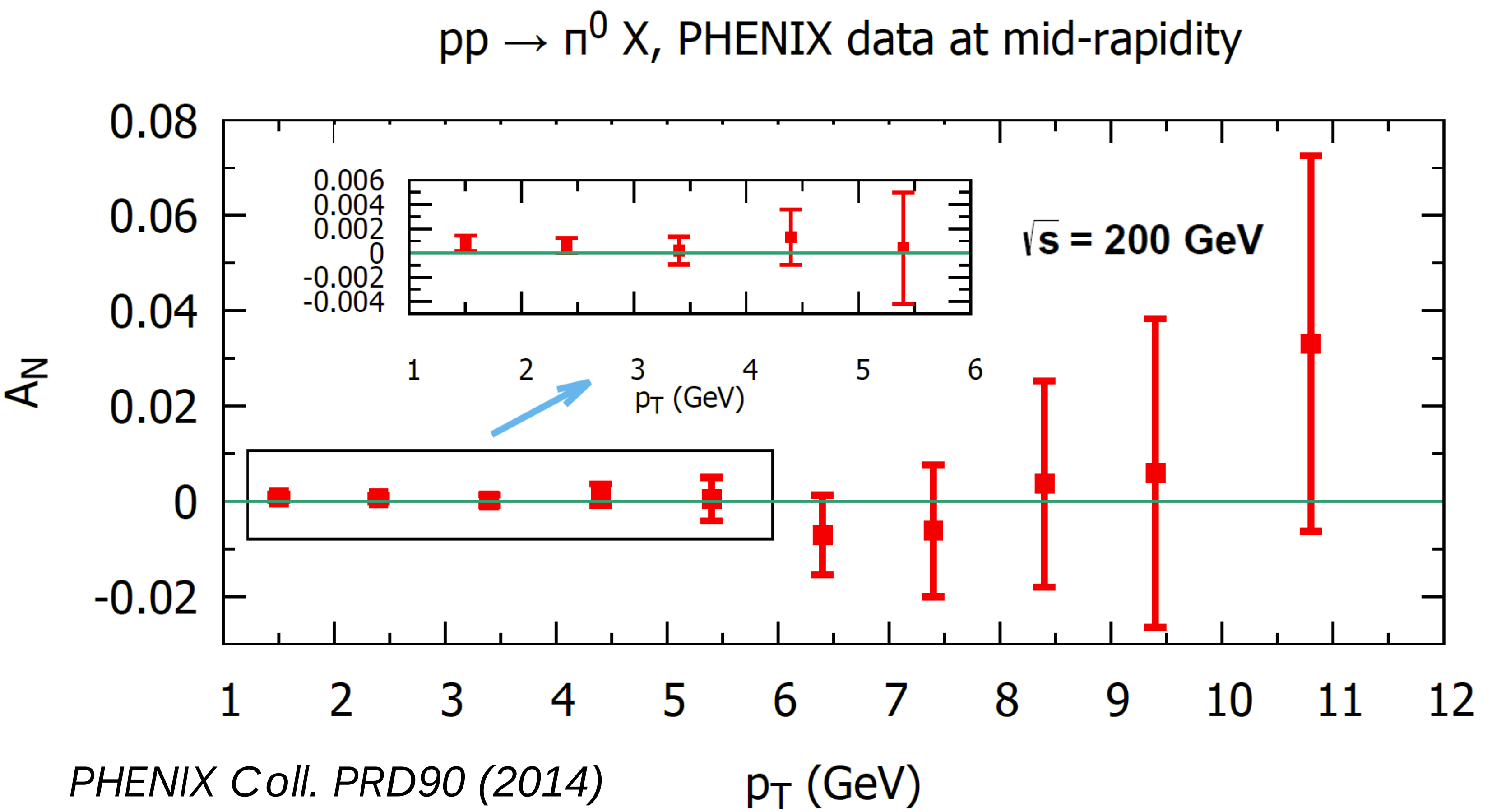
$h(k_\perp) \leq 1$

Parametrization (Gaussian k_T dep.)

$$f_{1T}^{\perp(1)g(f/d)}(x) = \int d^2\boldsymbol{k}_\perp \frac{k_\perp^2}{2M_p^2} f_{1T}^{\perp g(f/d)}(x, k_\perp) = -\Delta^N f_{g/p^\uparrow}^{(1)}(x)$$

1st k_T - moment

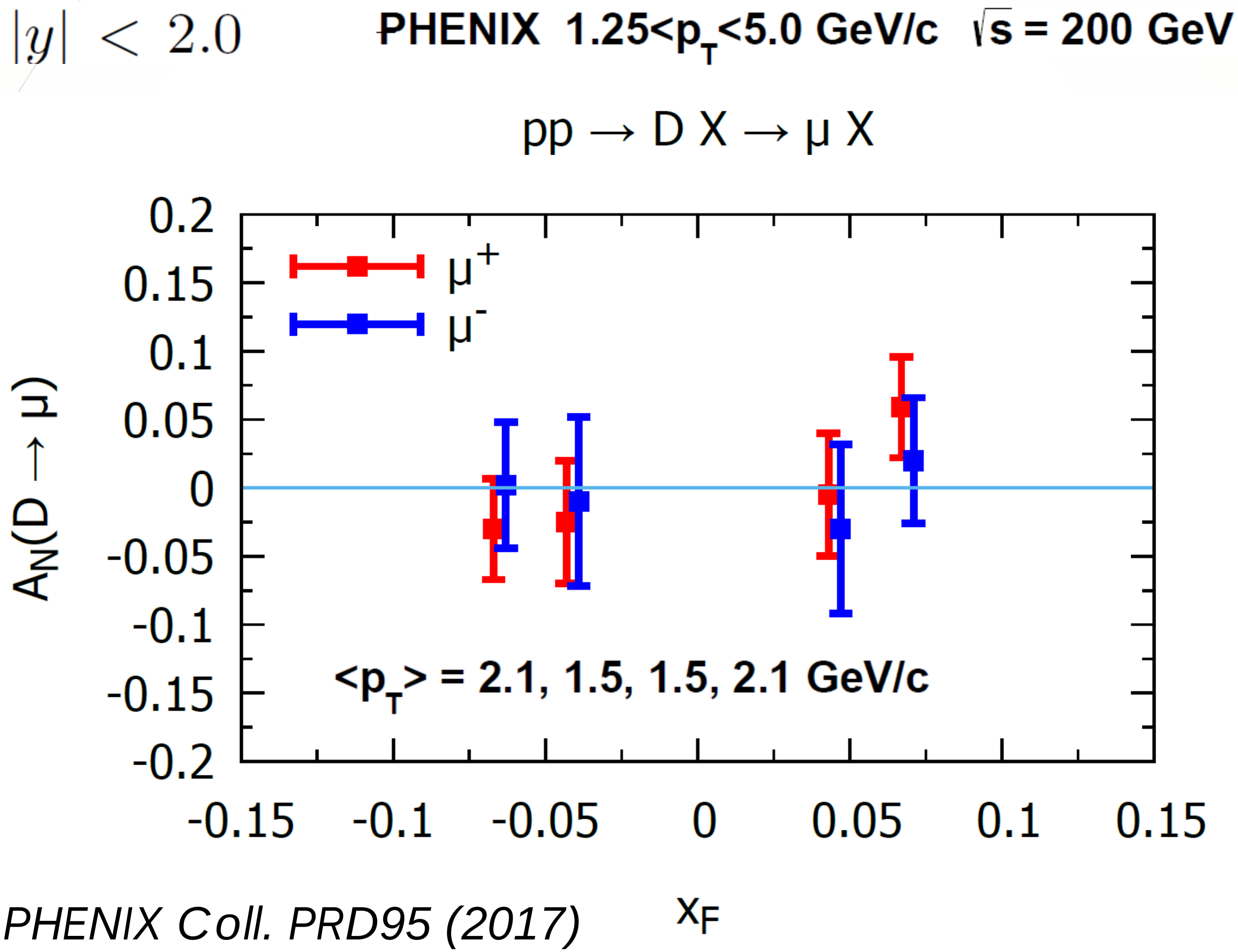
Pion SSA Data



PHENIX Coll. PRD90 (2014)

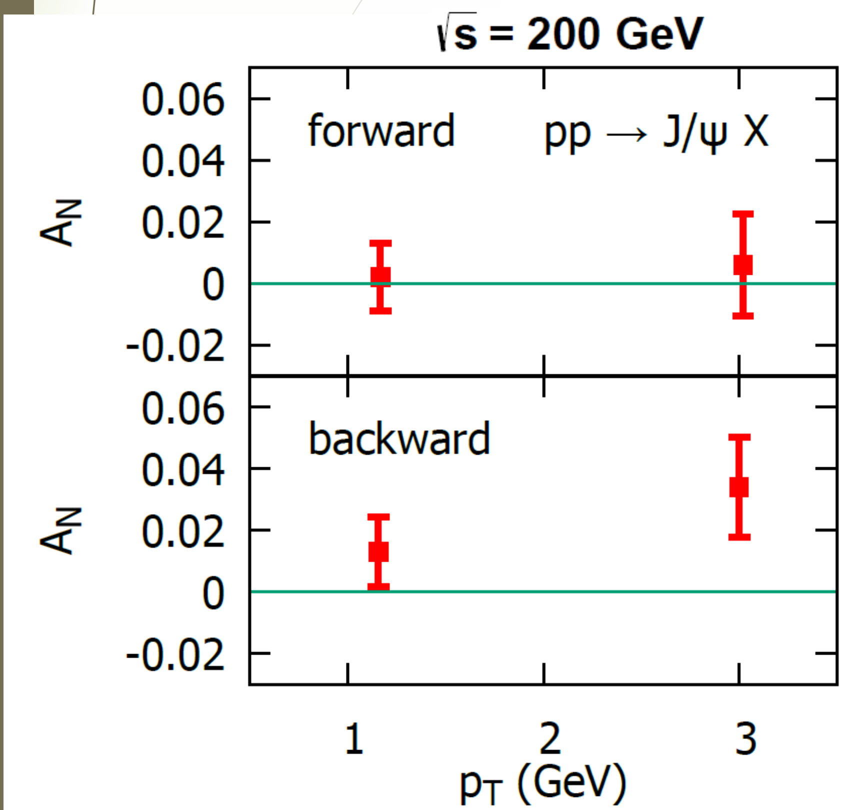
Muon SSA data from D production

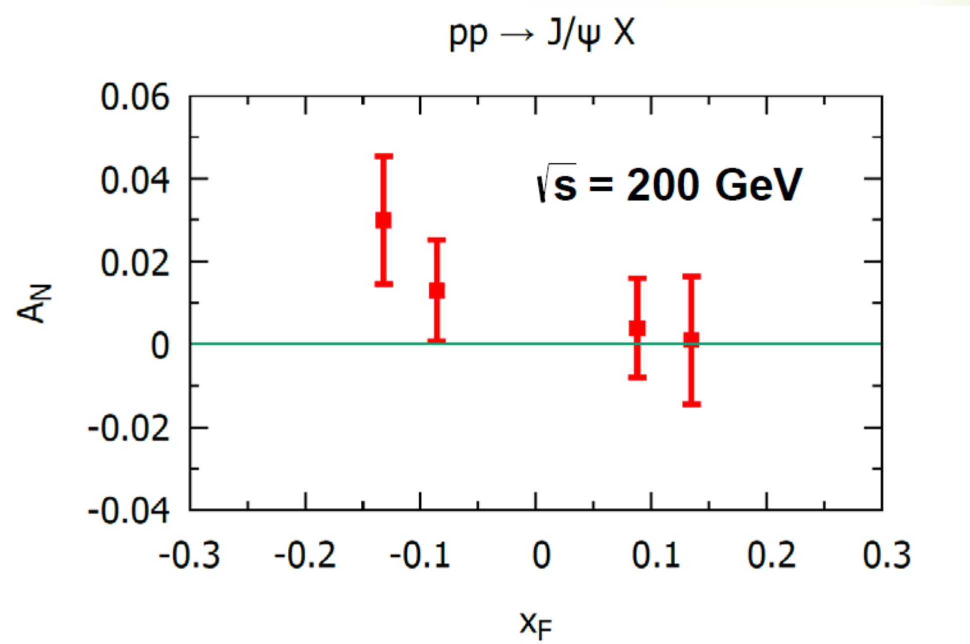
$1.4 < |y| < 2.0$



PHENIX Coll. PRD95 (2017)

SSA data for J/ψ production





$\sqrt{s_{NN}}$ **= 200 GeV,** $|y| \in [1.2, 2.2]$

PHENIX Coll. PRD98 (2018)

STRATEGY

- GPM: one universal Gluon Sivers function

1. Bound from pion SSA data (the most precise set)
2. Comparison with the rest of the data

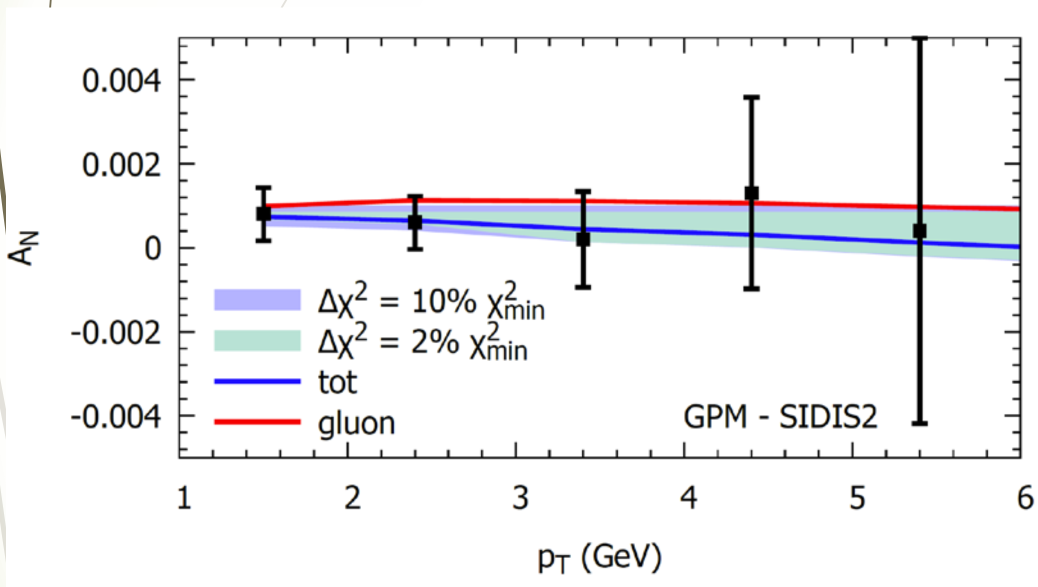
UD, Murgia, Pisano (2015)

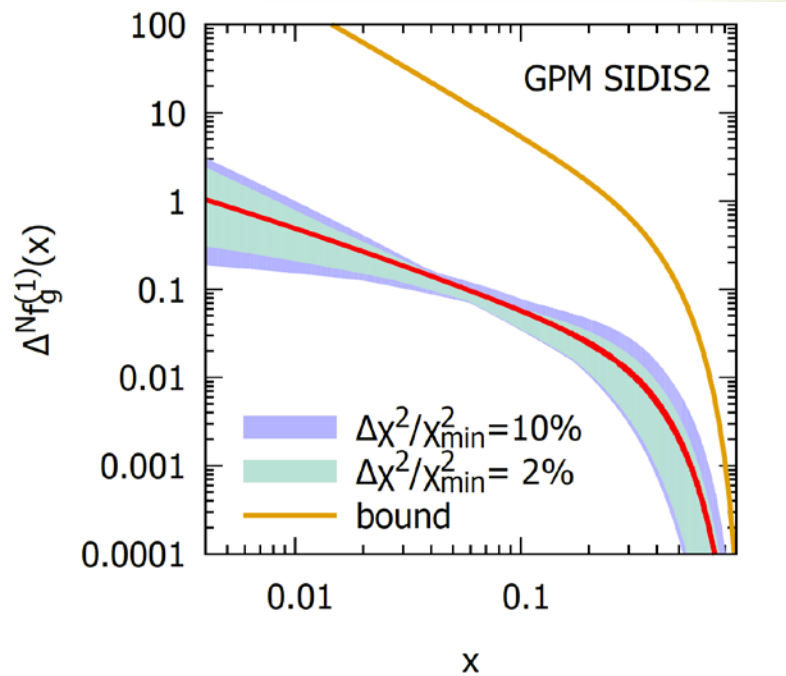
- CGI-GPM: two types of gluon Sivers functions

1. use of (at least) two independent sets of data
2. "saturated" GSFs → dynamical suppression
3. Conservative scenarios and process dependence

GPM vs. pion SSA data

UD, Murgia, Pisano JHEP09 (2015)

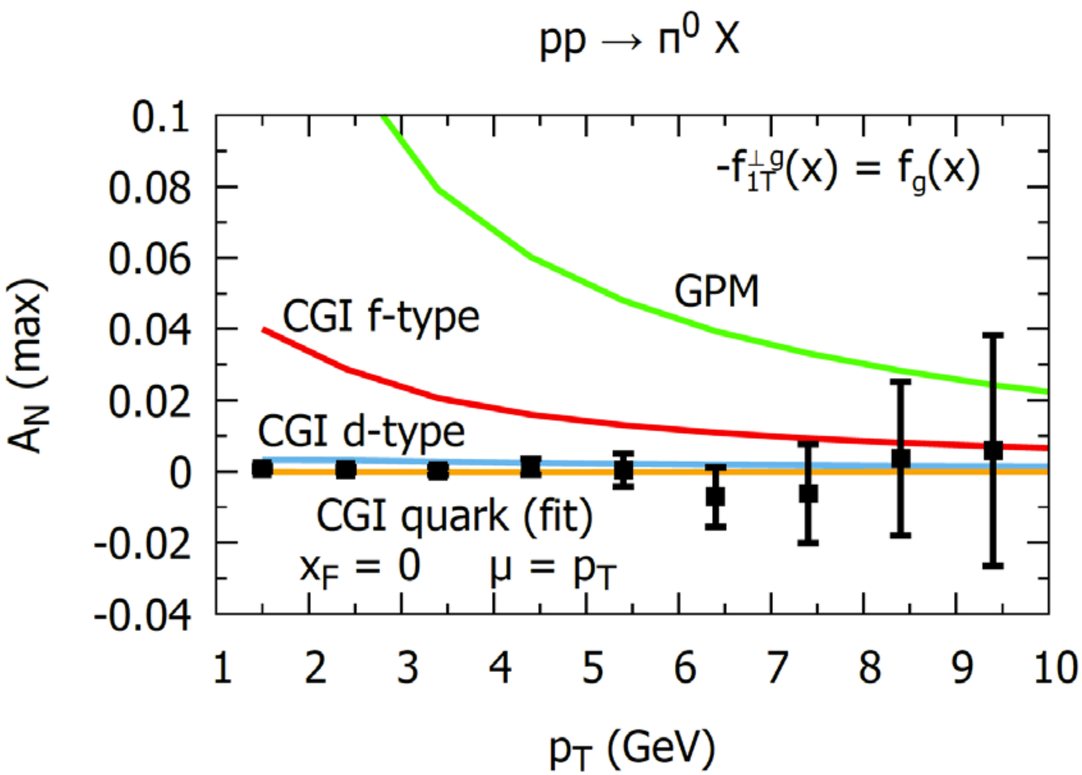




$$\mathcal{N}_g(x) = N_g x^{\alpha}(1-x)^{\beta}\,\frac{(\alpha+\beta)^{(\alpha+\beta)}}{\alpha^{\alpha}\beta^{\beta}} \qquad h(k_\perp) = \sqrt{2e}\,\frac{k_\perp}{M'}\,e^{-k_\perp^2/M'^2}$$

Free parameters: $N_g\ \alpha\ \beta\ M'$

CGI-GPM vs. pion SSA data



CGI

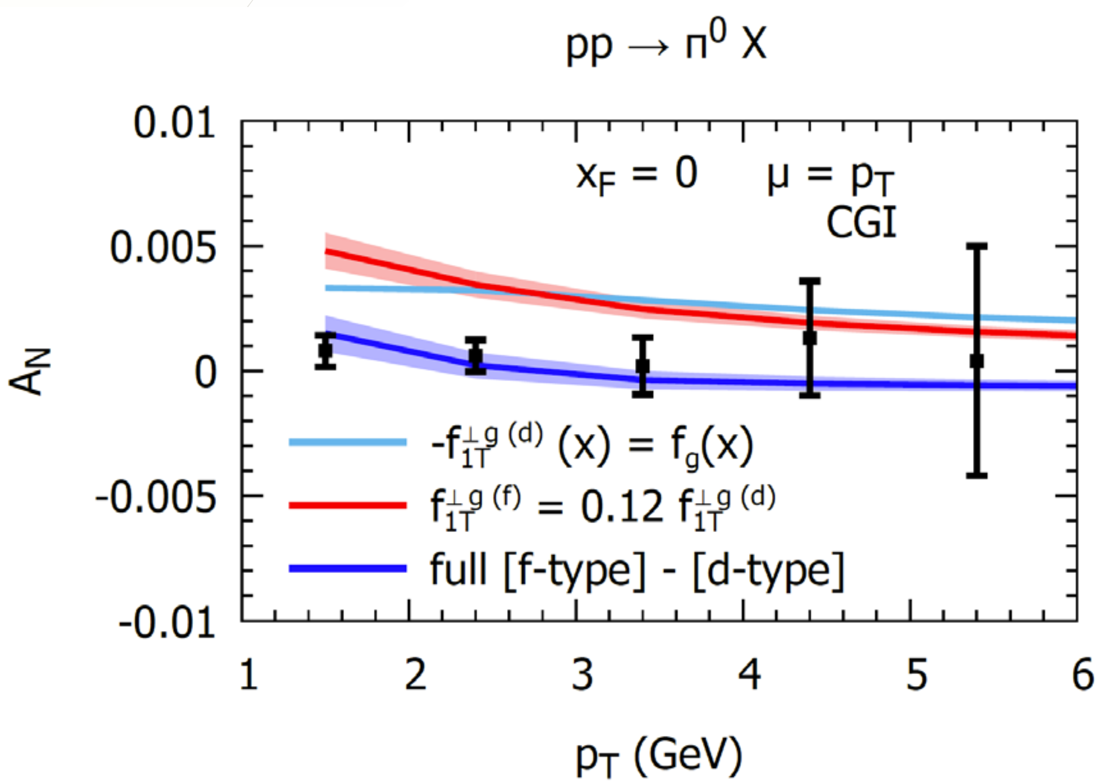
- d-type contr. dynamically suppressed relative sign btw gq and $g\bar{q}$ partonic xsec and NO gg contribution

GSF Scenarios

1. All zero
2. Relative cancelation, btw f-type and d-type

All GSFs saturated and "positive"

Constraint on f-type GSF



1. d-type saturated
2. f-type reduced w.r.t. d-type

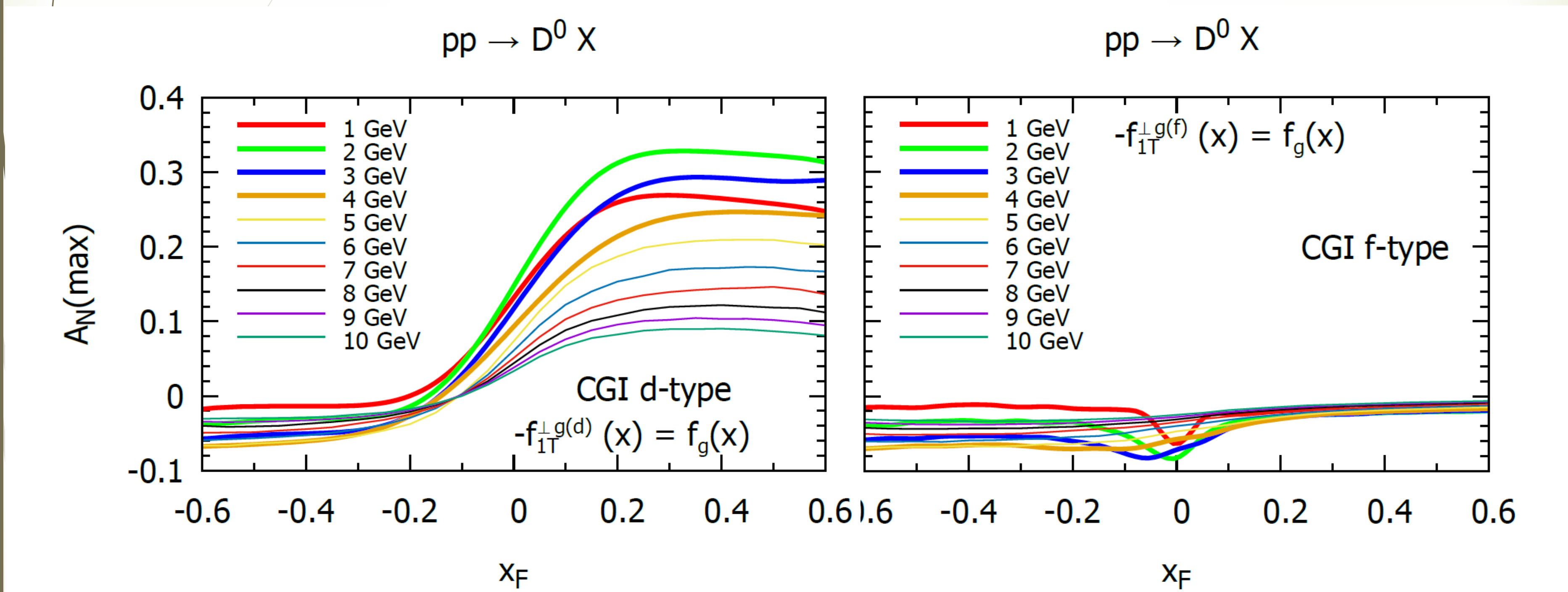
Notice: full result assuming d-type saturated, “negative”, and opposite in sign w.r.t. f-type (positive)

First results (from pion data)

- d-type contribution dynamically suppressed
- Constraint on f-type w.r.t. d-type contribution
- Assuming no information on d-type → saturated
- f-type/d-type = –0.12 [relative sign]
- GSFs: smaller |d-type| ➡ smaller |f-type|

But which sign each and which size?

D meson SSAs: f- and d-type saturated

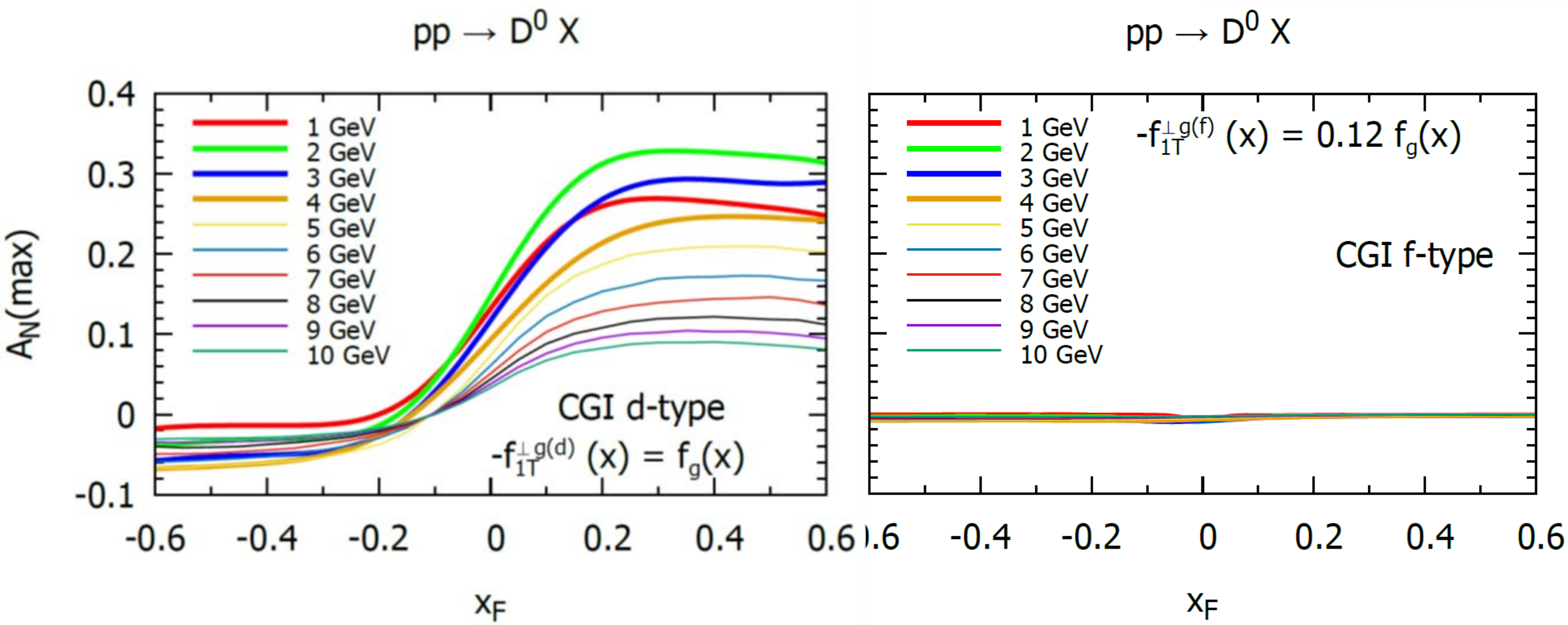


f-type dynamically suppressed at $x_F > 0$

$H^{\mathrm{Inc}(f)}_{gg\to c\bar{c}}$ $\sim t^2/s^2$ vs. $H^{\mathrm{Inc}(d)}_{gg\to c\bar{c}}$ $\sim (t^2 - u^2)\,/\,s^2$ and $|t| \ll |u|$

at $x_F < 0$ both suppressed by the azimuthal phase factor

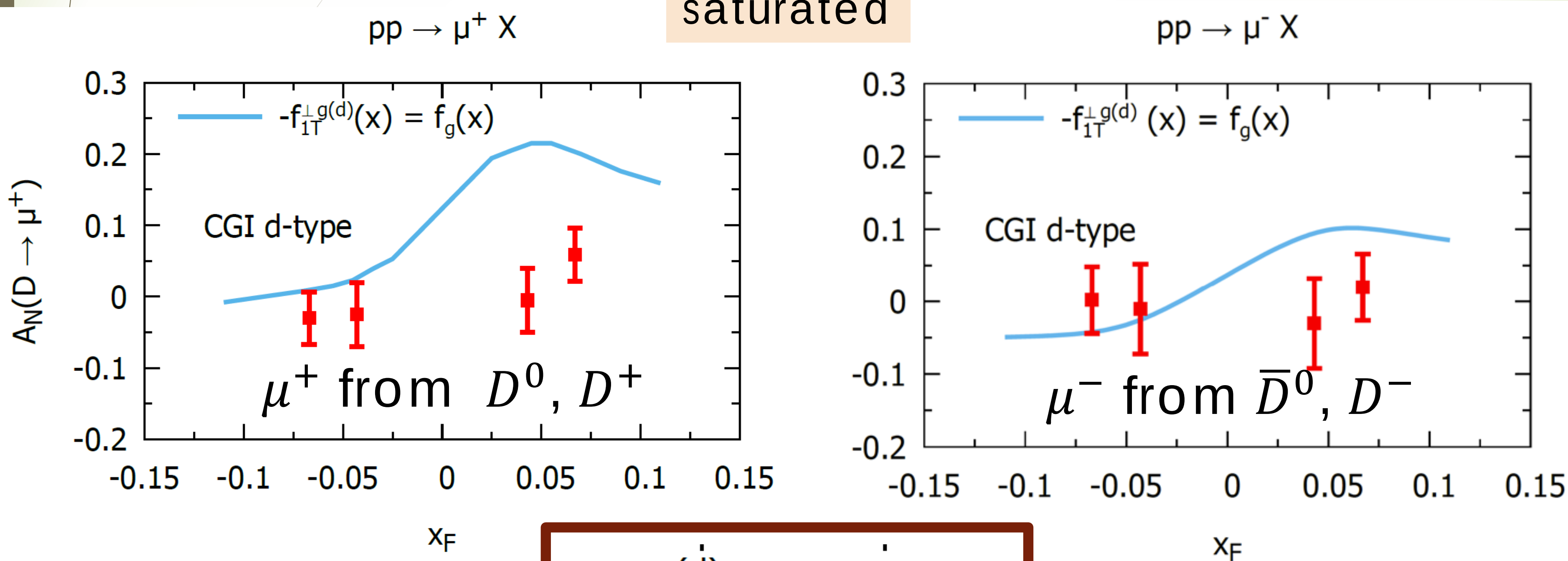
D meson SSAs: f-type from pion SSA



D meson SSAs driven by the d-type GSF
if f-type GSF reduced as from pion SSAs → Focus on d -type

Muon(D) SSAs from d-type GSF

saturated



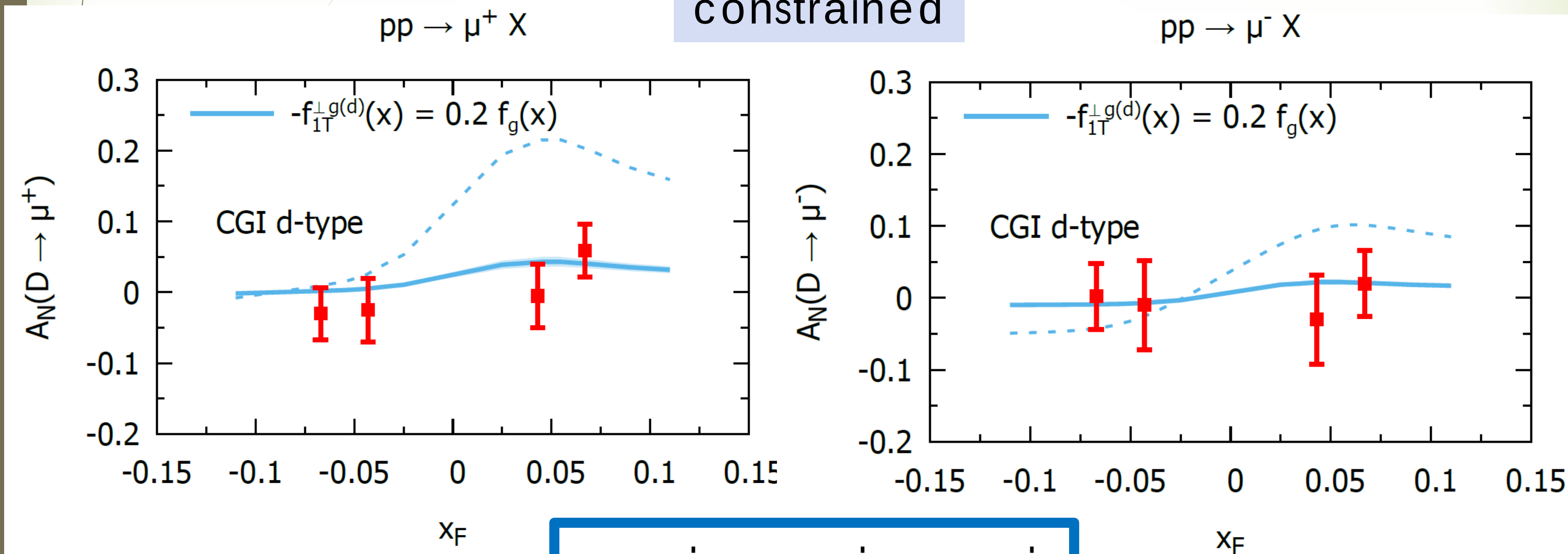
$$-f_{1T}^{\perp g(d)}(x) = f_g(x)$$

D meson kinematics $1 < p_T < 6$ GeV and $|x_F| < 0.6$

$D \to \mu$ conversion kindly provided by **Jeongsu Bok** (PHENIX)

Muon(D) SSAs from d-type GSF

constrained



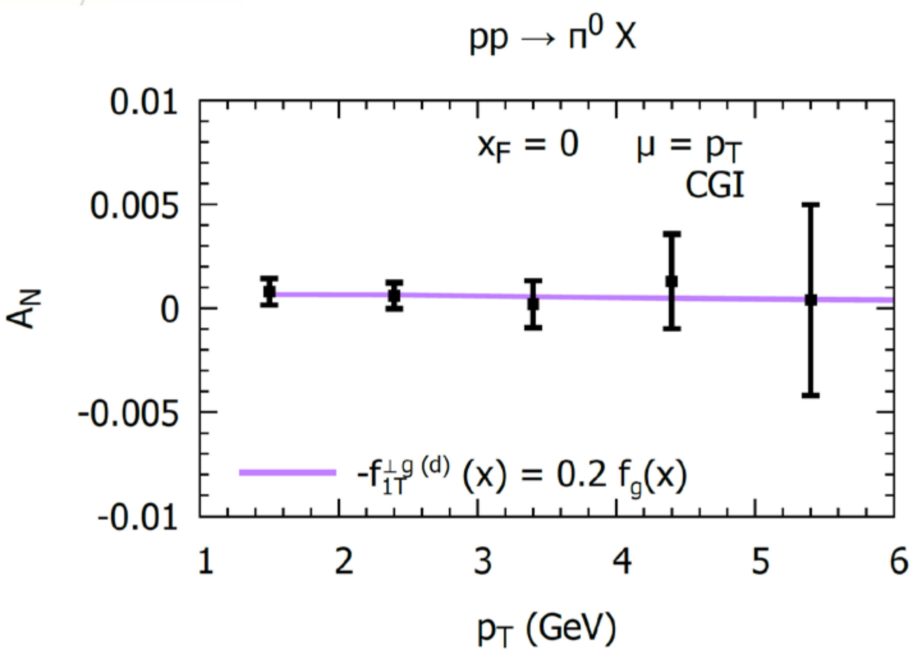
$$-f_{1T}^{\perp g(d)}(x) = 0.2\, f_g(x)$$

Constraint on d-type GSF:
reduced by 0.2 and “positive” (one data point)

From D to pion SSAs (I)

- **Scenario 1**: d-type "positive"

$$-f_{1T}^{\perp g\,(d)}(x) = +0.2\, f_g(x)$$



This scenario implies:

- pion SSA data described by d-type contribution
- f-type GSF compatible with zero

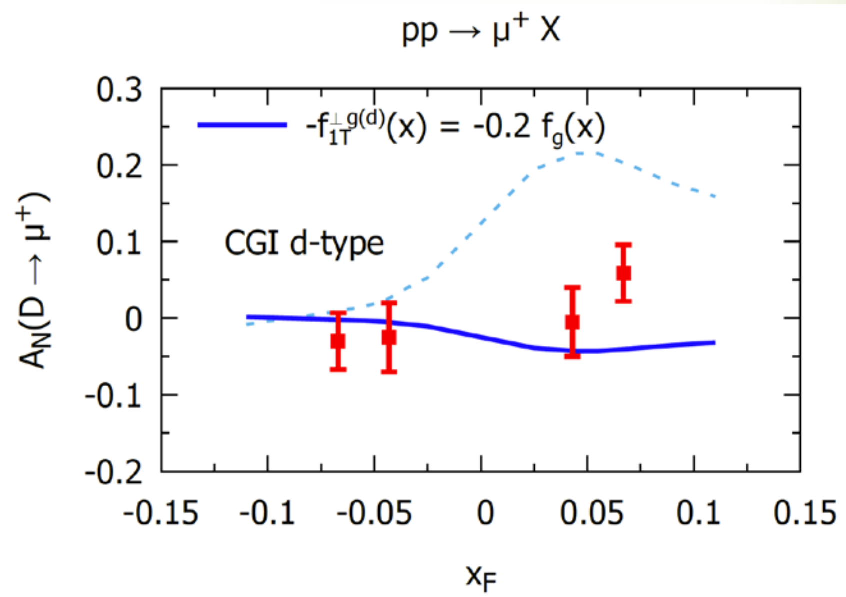
From D to pion SSAs (II)

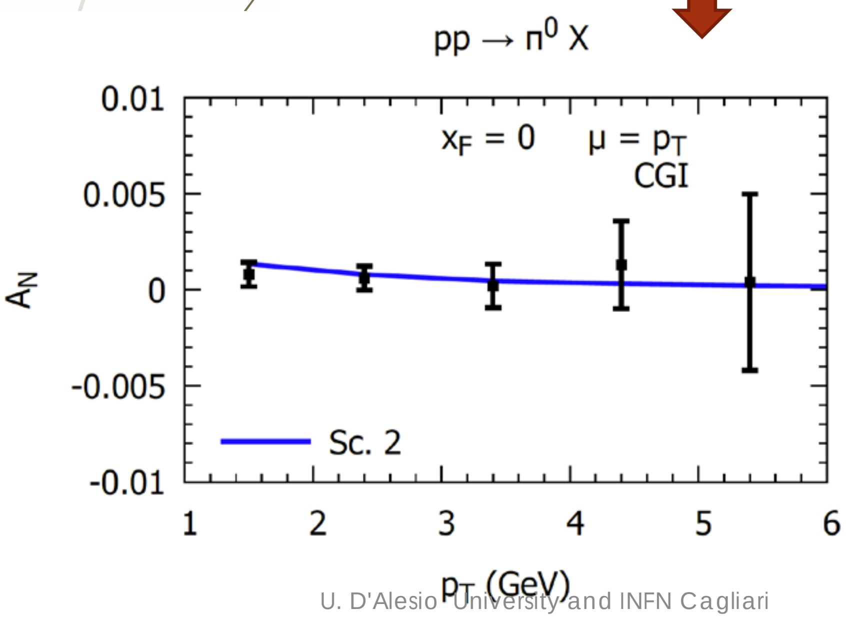
Let's explore more scenarios:

- d-type GSF "negative"

$$-f_{1T}^{\perp g\,(d)}(x) = -\,0.2\, f_g(x)$$

$$-f_{1T}^{\perp g\,(f)}(x) = 0.05\, f_g(x)$$





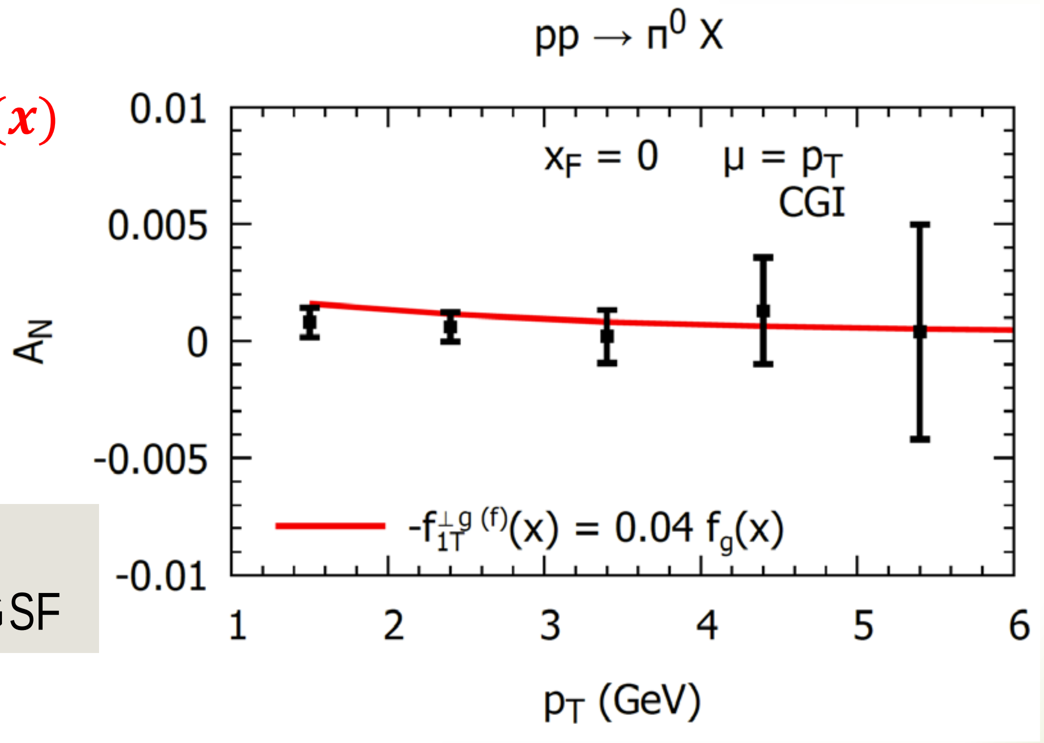
Scenario 2

From D to pion SSAs (III)

Scenario 3:

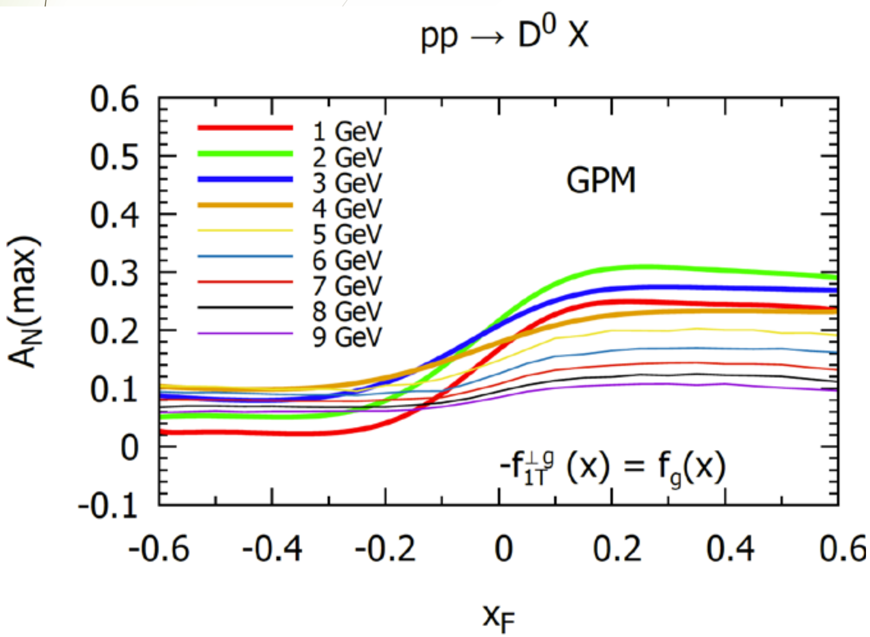
- d-type GSF ≅ 0

$$-f_{1T}^{\perp g\,(f)}(x) = 0.04\, f_g(x)$$

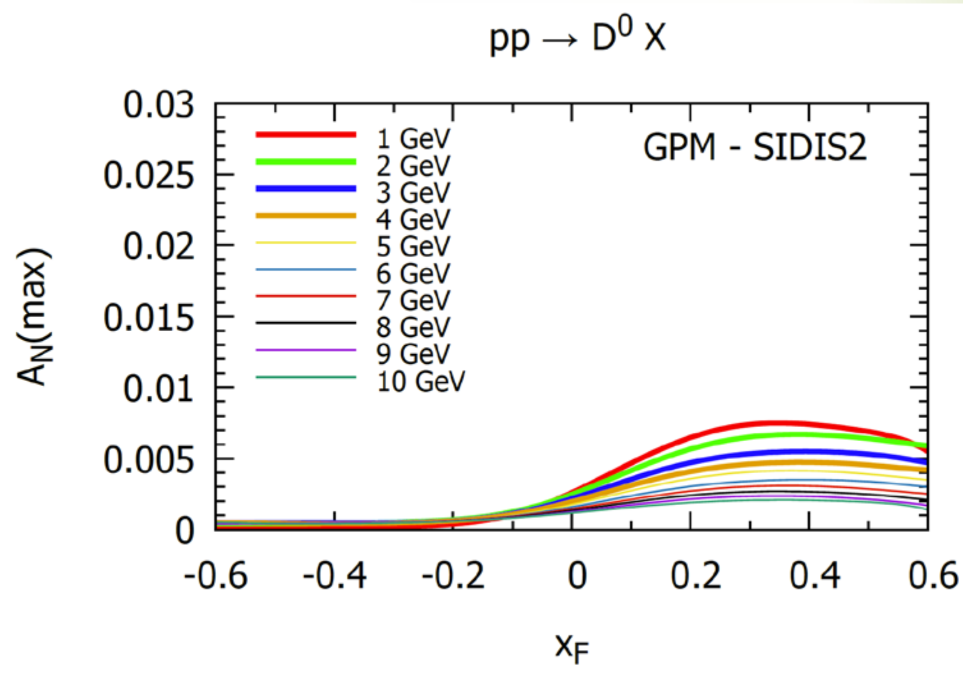


Similar to Sc. 2 concerning f-type GSF

D meson SSAs in GPM



Saturated



extracted from pion SSAs

GPM: muon SSAs compatible with zero and data

GSFs from pion and meson D SSAs

1. $-f_{1T}^{\perp g\,(d)}(x) = +0.2\, f_g(x)$

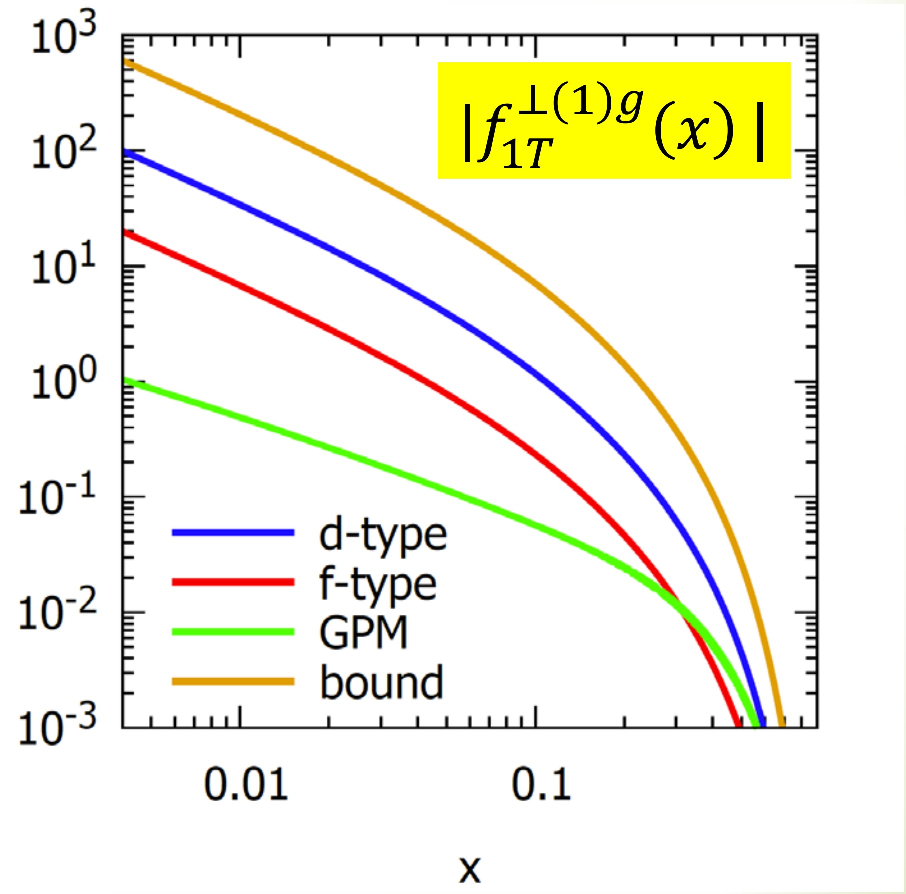
   $f_{1T}^{\perp g\,(f)}(x) \cong 0$

2. $-f_{1T}^{\perp g\,(d)}(x) = -0.2\, f_g(x)$

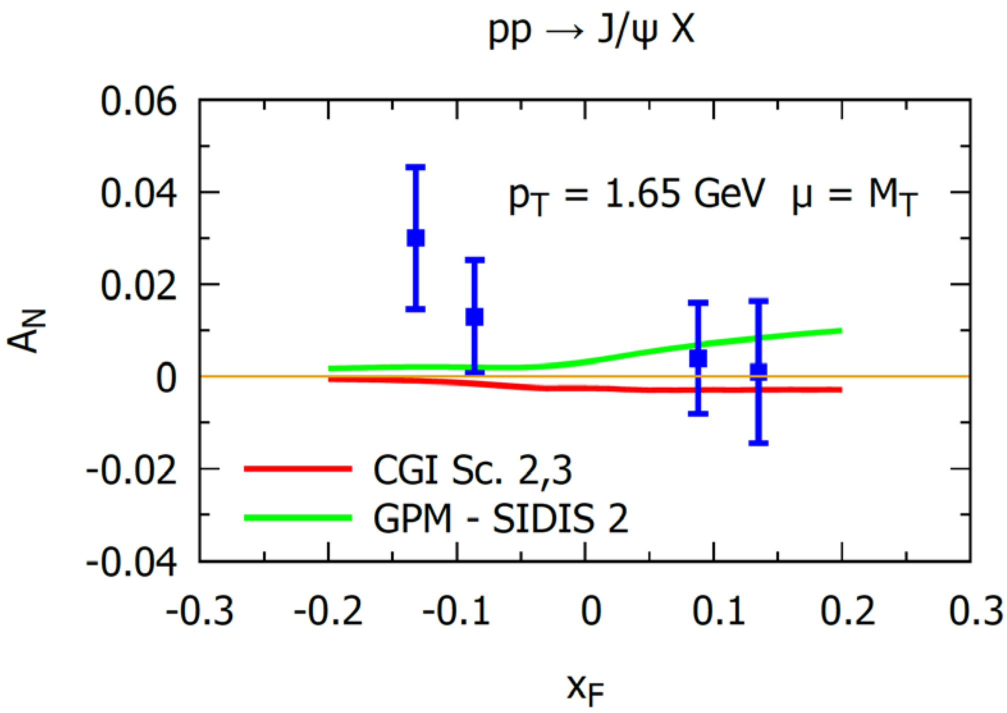
   $-f_{1T}^{\perp g\,(f)}(x) = 0.05\, f_g(x)$

3. $f_{1T}^{\perp g\,(d)}(x) \cong 0$

   $-f_{1T}^{\perp g\,(f)}(x) = 0.04\, f_g(x)$

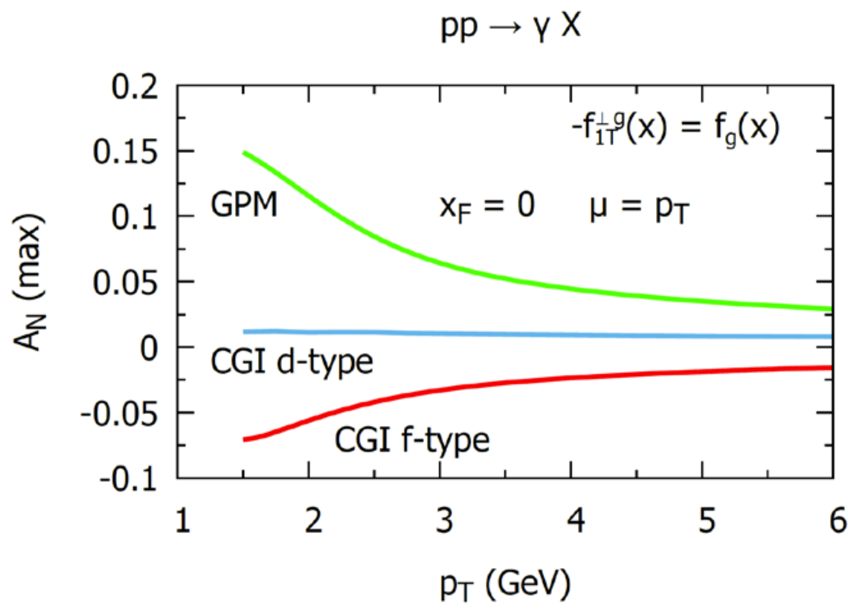


Predictions for J/ψ SSAs



CGI:
only f-type contribution

Predictions for photon SSAs mid-rapidity



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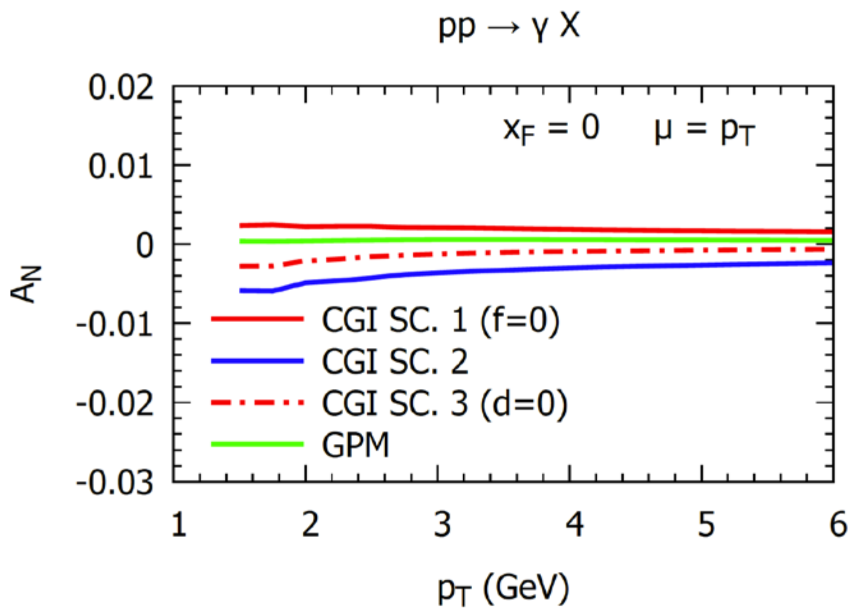
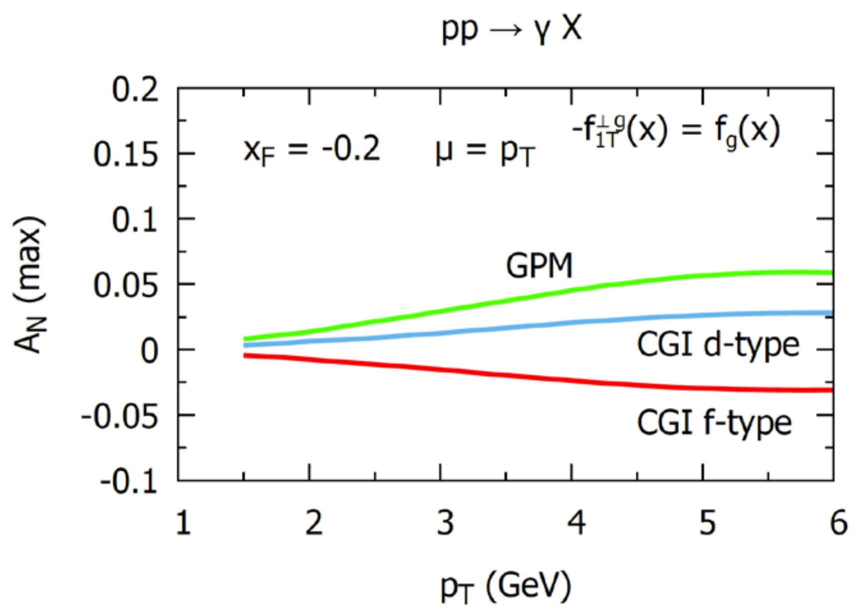


From pion and D SSAs

Predictions for photon SSAs backward-rapidity



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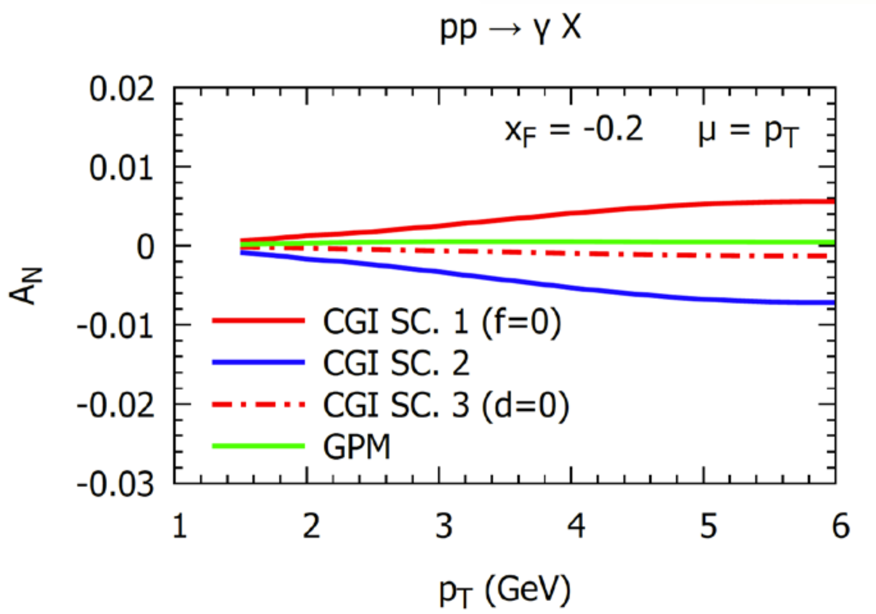


From pion and D SSAs

Concluding Remarks

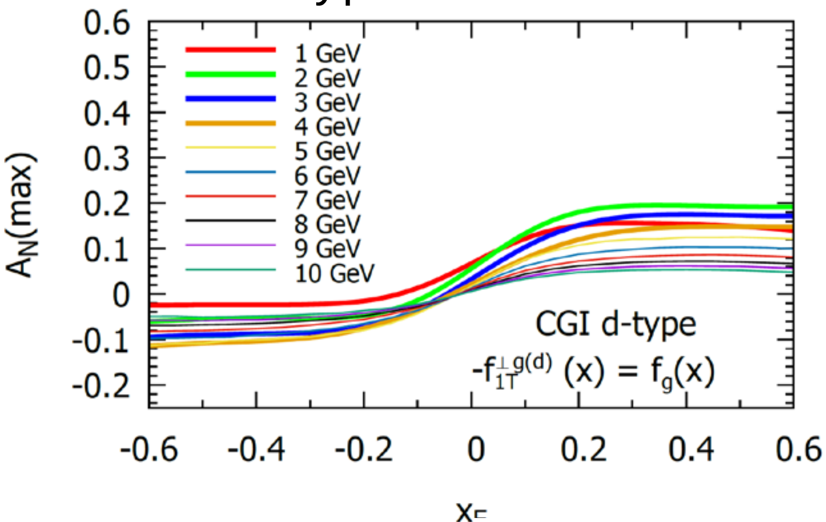
- SSA in inclusive *pp* processes (gluon dominated) within a **TMD scheme**:
  - GPM approach: one universal GSF
  - CGI-GPM: two GSFs (f/d) and process dependent
  - Combined analysis of pion and D meson SSAs:

    d-type / f-type contribution dynamically suppressed
- Present measurements (pion, D and J/ψ SSAs):
  - almost compatible with zero
  - allow for a first "constraint" of the GSF(s)
  - no discrimination between approaches/GSFs
- More (more precise) data to improve our knowledge on gluon TMDs (RHIC, LHCb, COMPASS, EIC…)

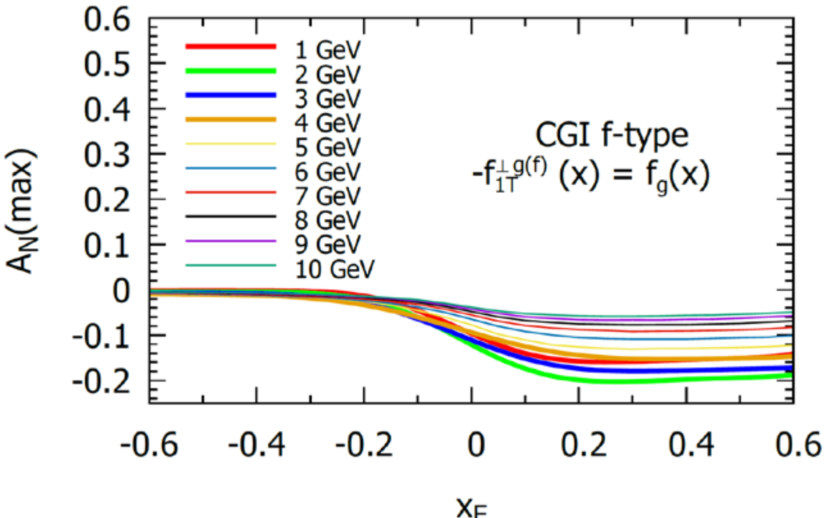
Back-up slides

$\bar{D}$ meson SSAs

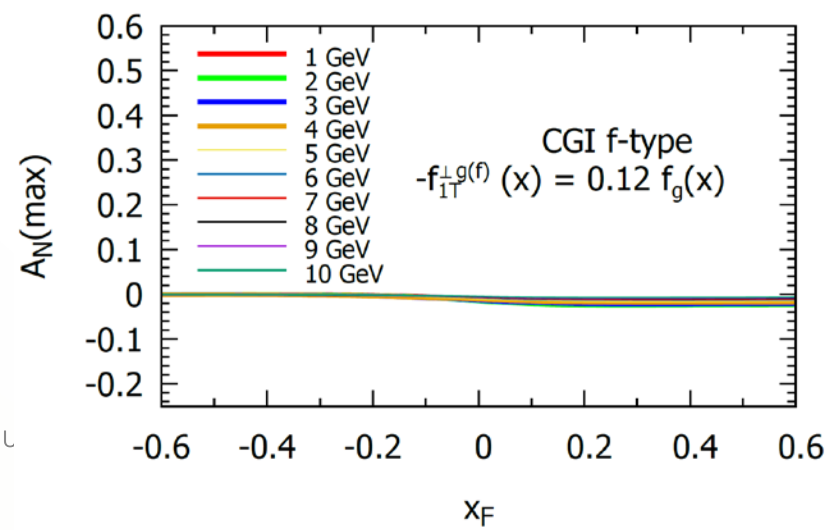
d-type saturated



f-type saturated

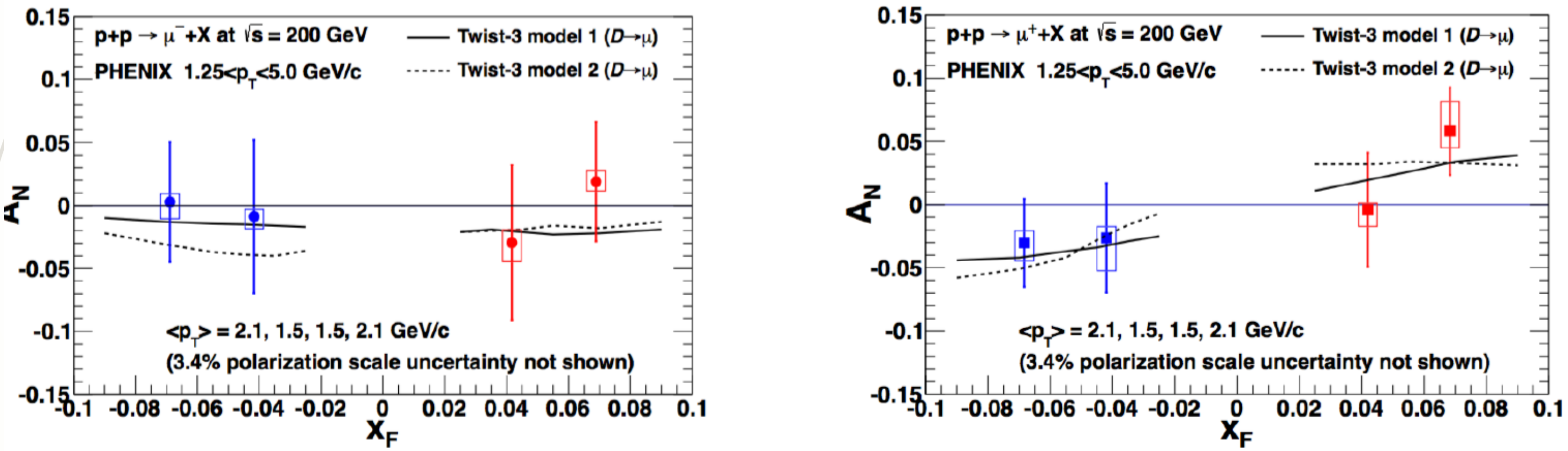


f-type reduced (pion SSAs)



Twist-three results for D(muon) SSAs

Phys.Rev.D. 95, 112001 (2017) PHENIX collaboration



$A_N(D)$ from Y. Koike and S. Yoshida, *Phys. Rev. D84, 014026 (2011)*