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Spin dependence of small angle scattering

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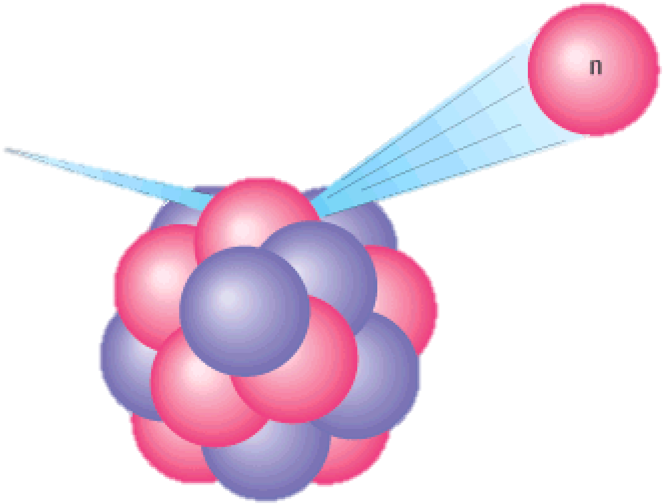
Outline

- Motivation & introduction
- Spin asymmetry in *pA*
- Spin asymmetry in *pp*
- Conclusions



Motivations

- **Study spin-flip hadronic interaction**
  - Spin and **spin-flip** interaction of Pomeron?
  - Influence of Reggeons at available experimental data?

- **Nuclear effects in elastic pA collisons**
  - Disagreement of pAu data with theory?

- Study of single spin asymmetry as function of energy or target

- **Theory review**

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Hadron spin-flip interaction?

- **Hadronic spin-flip interaction** is well known from low energies via Reggeons such as ρ or a_2.
- But at higher energies, the **Pomeron** is dominant, at least a general agreement is about the dominant spin non-flip hadronic interaction in the community.
- However, there is not *general agreement* about the **pomeron spin**.

- But can we measure the **Pomeron** spin-flip interaction at intermediate energies of RHIC in the fix-target configuration where data are available?
  - Not sure, since no one is able to reliable calculate the contribution from the Reggeons.

Why nuclear target?

Reggeons – experimental data mostly from RHIC ($E_{LAB} = 100\ \mathrm{GeV} \approx \sqrt{s} = 14\ \mathrm{GeV}$). Can be expected a significant contribution from the iso-vector Reggeons.

If we use the nucleus with zero isospin (e.g. Carbon), these Reggeons are excluded. For other nuclei are suppressed as $1/A$.

B. Kopeliovich, hep-ph/9801414

However, previous theoretical attempts fail to explain the recent data from the RHIC on polarized proton-gold scattering, exposing a nontrivial t-dependence of single spin asymmetry.

=> interesting physics itself, nuclear effects??

Single spin asymmetry

Study of the single spin asymmetry $A_N(t)$ in the CNI region.

$$A_N \frac{d\sigma}{dt} = 2\mathrm{Im}[\phi_{++}\phi_{+-}^*]$$

$$\frac{d\sigma}{dt} = |\phi_{++}|^2 + |\phi_{+-}|^2$$

ϕ_{++} - Non-flip amplitude
ϕ_{+-} - Spin-flip amplitude

CNI (Coulomb-nuclear interference) region = a kinematical region of very low 4-momentum transfer squared, *-t,* where the interference electromagnetic-hadron terms dominates

B.Z.Kopeliovich, B.G.Zakharov, Phys.Lett. **B**226 (1989) 156

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How to calculate it?

The interference with EM amplitude.

$\phi = \phi^h + \phi^{em}$ Dominant term: $A_N \sim \mathrm{Im}\phi^{\mathrm{h}}_{++} \mathrm{Re}\phi^{\mathrm{em}}_{+-}$

Coulomb spin-flip and non-flip amplitude are known, as well as non-flip hadronic amplitude from data.

$$\phi^h = \phi_{++}\left(1 + i\frac{\sqrt{-t}}{m_N}\vec{\sigma}\cdot\vec{n}\, r_5\right)$$

Spin-flip hadron amplitude can be parametrized by factor

$$r_5 = \frac{m_p\, \phi_{+-}}{\sqrt{-t}\ \mathrm{Im}\ \phi_{++}}$$

Assuming $r_5 = 0$ the asymmetry *$A_N(t)$* can be fully predicted.

L.I.Lapidus & B.Kopeliovich Sov. J. Nucl. Phys. 19(1974) 114

Let's start with *pA*.

At RHIC fix-target configuration.

Experimental data for *pC*, *pAl*

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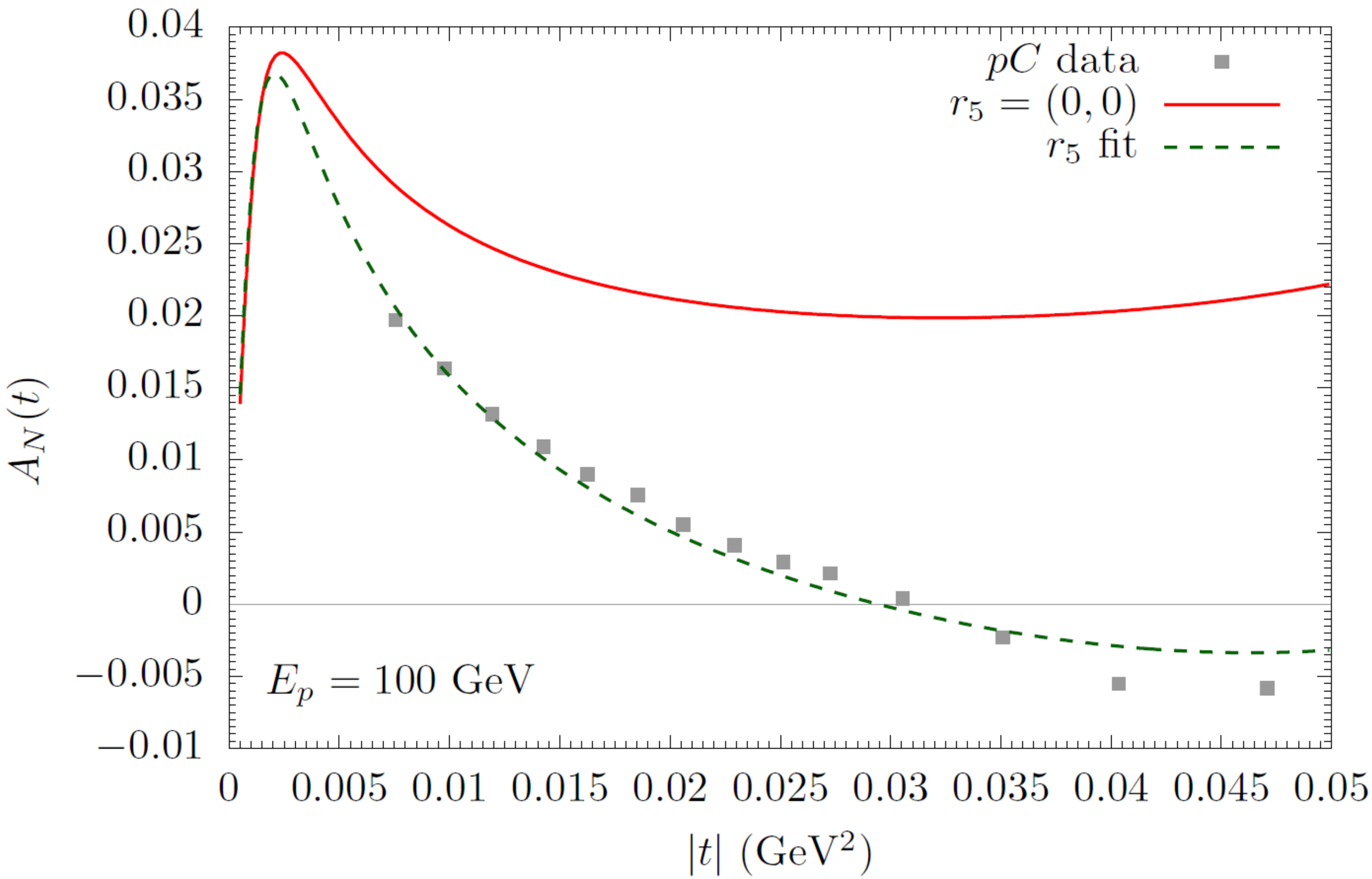

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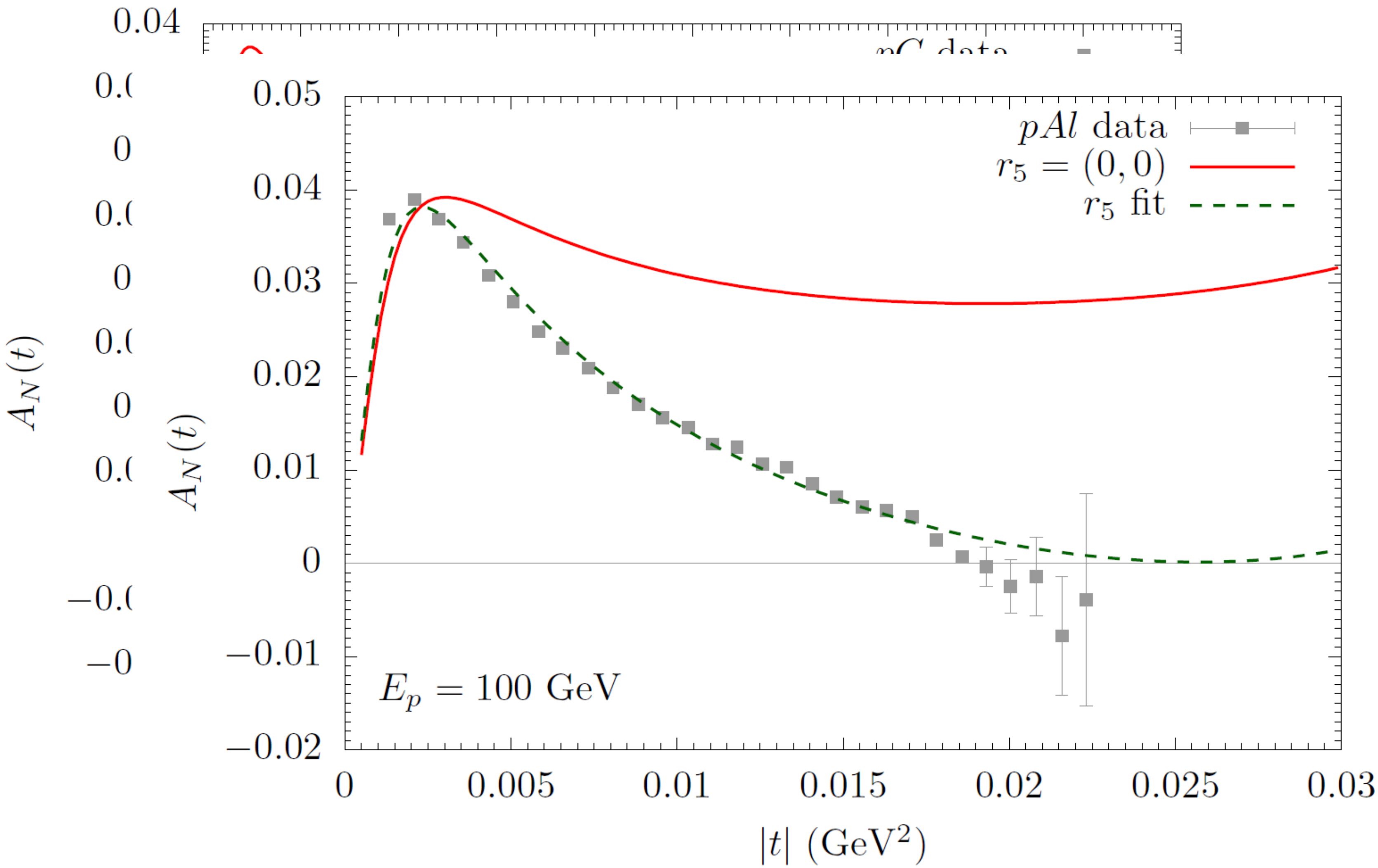
Experimental data for *pC*, *pAl*



Experimental data for *pC*, *pAl*

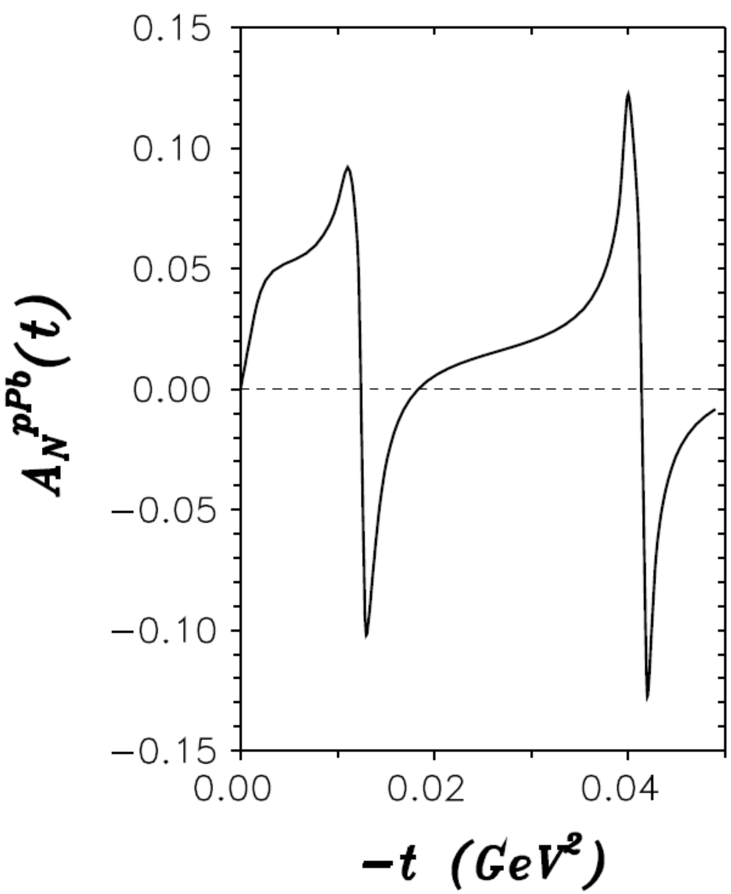
***pC*:** $r_5 = -0.051 \pm 0.001 - i0.014 \pm 0.014$

***pAl*:** $r_5 = -0.100 \pm 0.003 - i0.183 \pm 0.096$

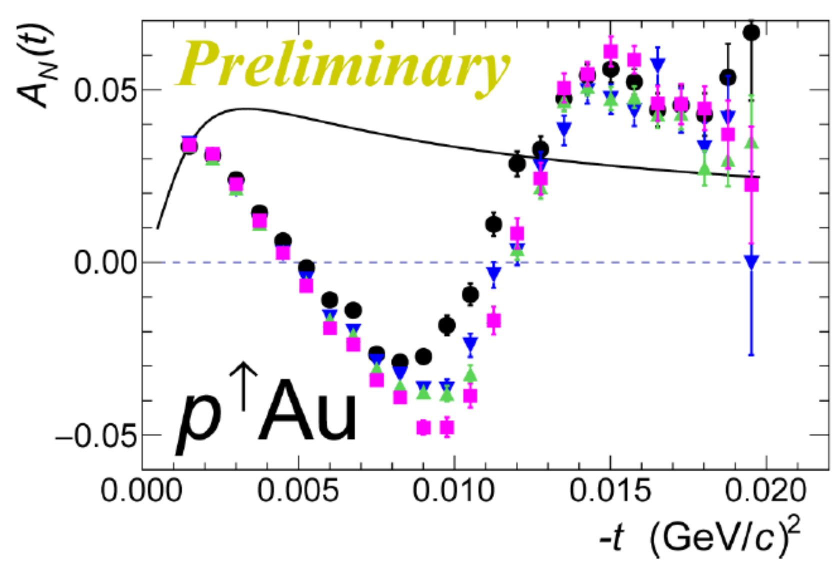
- With the current theory we can find such r_5 that fit the data
- With $r_5 = 0$ we are above the experimental data!?
  - Compare with *pp!*
- One could expect r_5 closer to each other.

…but the Gold is the challenge

Estimation of $r_{5,\mathbb{P}}$ form Carbon is sufficient, for Gold the situation is more complicated. However, take a look at it…



B. Kopeliovich, hep-ph/9801414



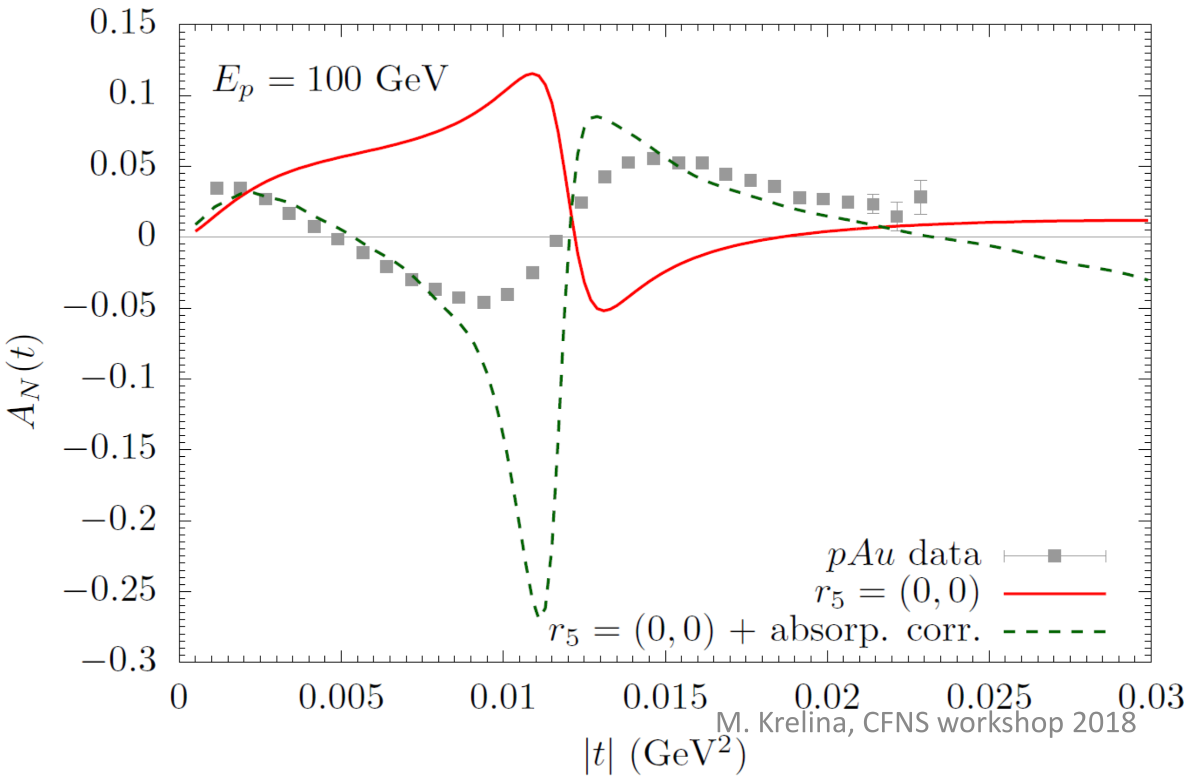
From a talk by Andrei Poblaguev (SPIN2016)

Data has nearly inverse trend than theoretical calculations.

Wrong EM form factor

We found that the source of the trouble is the incorrect electromagnetic form factor, where we discovered the importance of the absorption

$$\phi_{\text{em}}(q) = \sqrt{\pi} Z \alpha_{em} \left(\frac{2}{q^2} + \frac{\mu_p - 1}{q} \right) F_A^{em}(q^2) e^{i\delta_{pA}} \otimes \boldsymbol{e^{-\frac{1}{2}\sigma_{tot}^{pp} T_A(b)}}$$

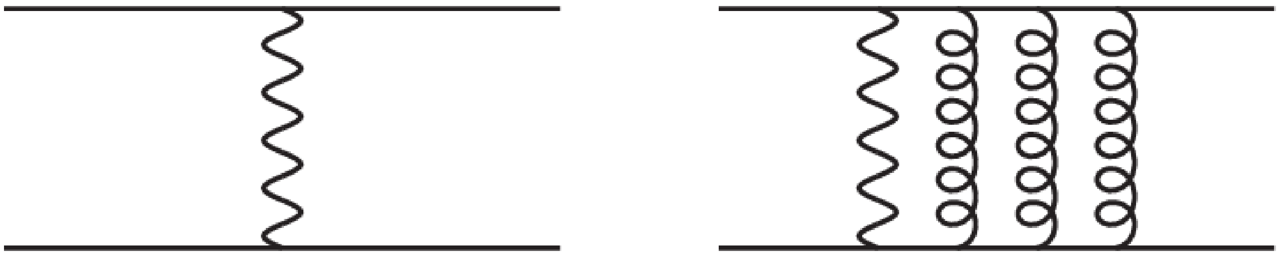


The electromagnetic amplitude gets the main contribution from the ultra-peripheral collisions, $b > R_A$, while the hadronic amplitude is non-zero only at small impact parameters, $b < R_A$.

Due to the coherence in the momentum space.

Absorptive correction

- Absorptive correction on inelastic collisions is a natural part of the Glauber formula
- But EM formfactor corresponds to *eA* collisions where we have no correction on inelastic collisions
  - Significant only for small distance in the range of Pomerons
- Can be applied also for *pp*!!



Other corrections

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To have a full description we should add other corrections such as Gribov correction or nucleon-nucleon correlations.

Gribov corrections – effectively decrease the *pA* cross section

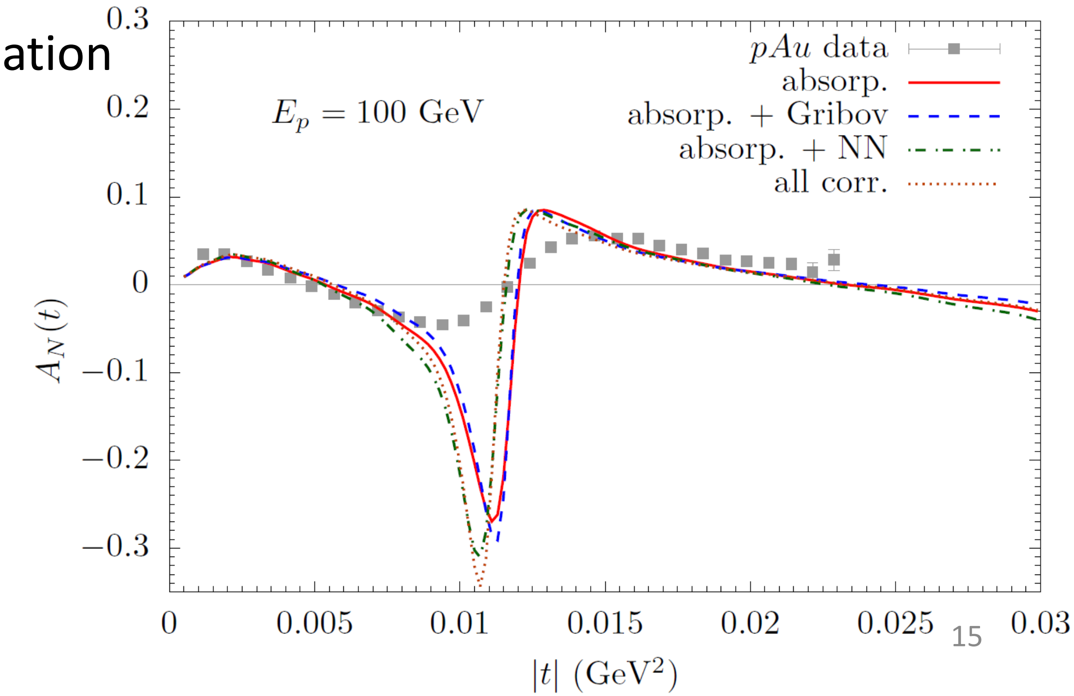
B. Z. Kopeliovich, Int. J. Mod. Phys. A31 no. 28n29, (2016) 1645021, arXiv:1602.00298 [hep-ph].
B. Z. Kopeliovich, I. K. Potashnikova, and I. Schmidt, Phys. Rev. C73 (2006) 034901, arXiv:hep-ph/0508277 [hep-ph].

NN correlations – effectively reduce the nuclear thickness function

M. Alvioli, C. Ciofi degli Atti, B. Z. Kopeliovich, I. K. Potashnikova, and I. Schmidt, Phys. Rev. C81 (2010) 025204, arXiv:0911.1382 [nucl-th].

Odderon – only Born approximation

B. G. Zakharov, Sov. J. Nucl. Phys. 49, 860 (1989), [Yad. Fiz.49,1386(1989)]



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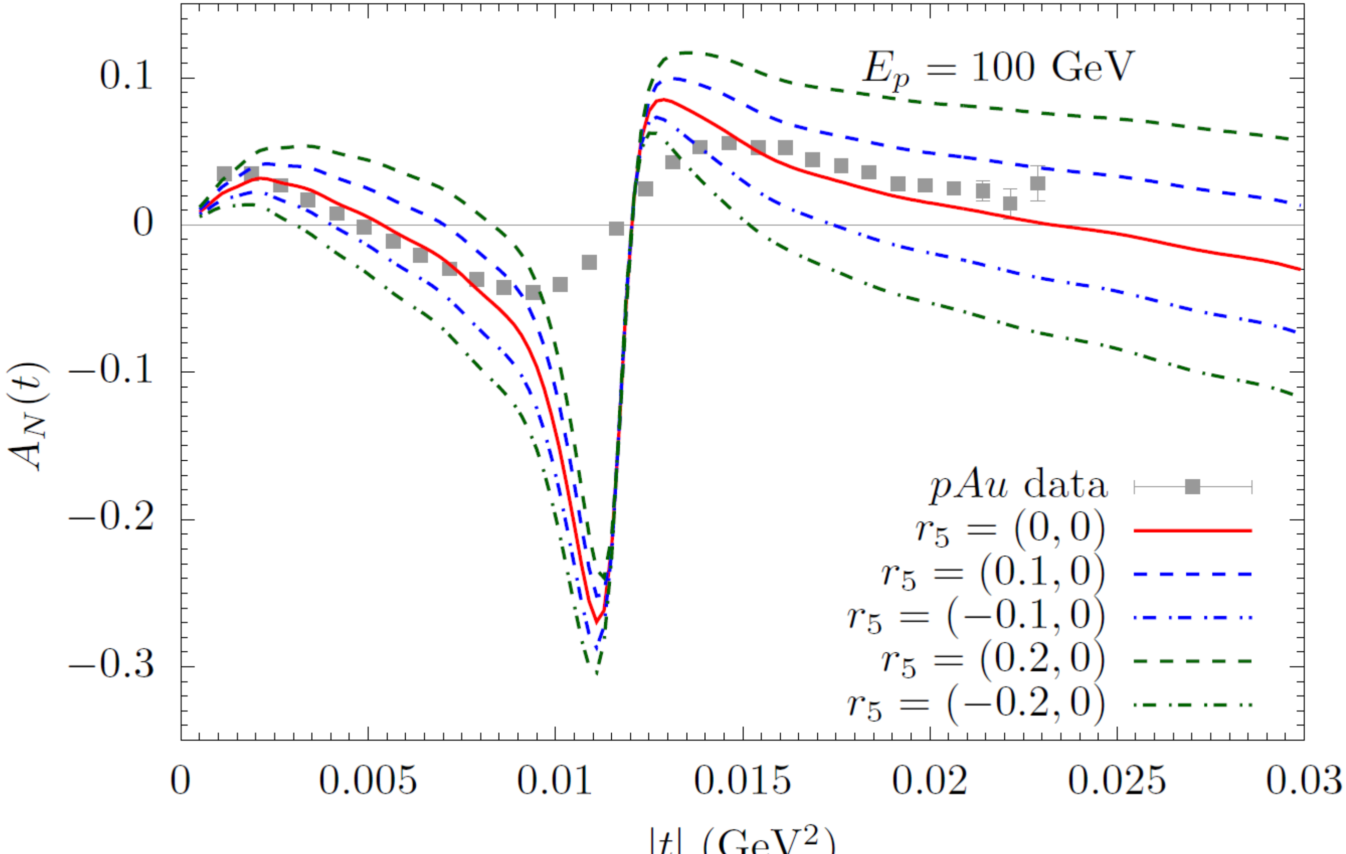
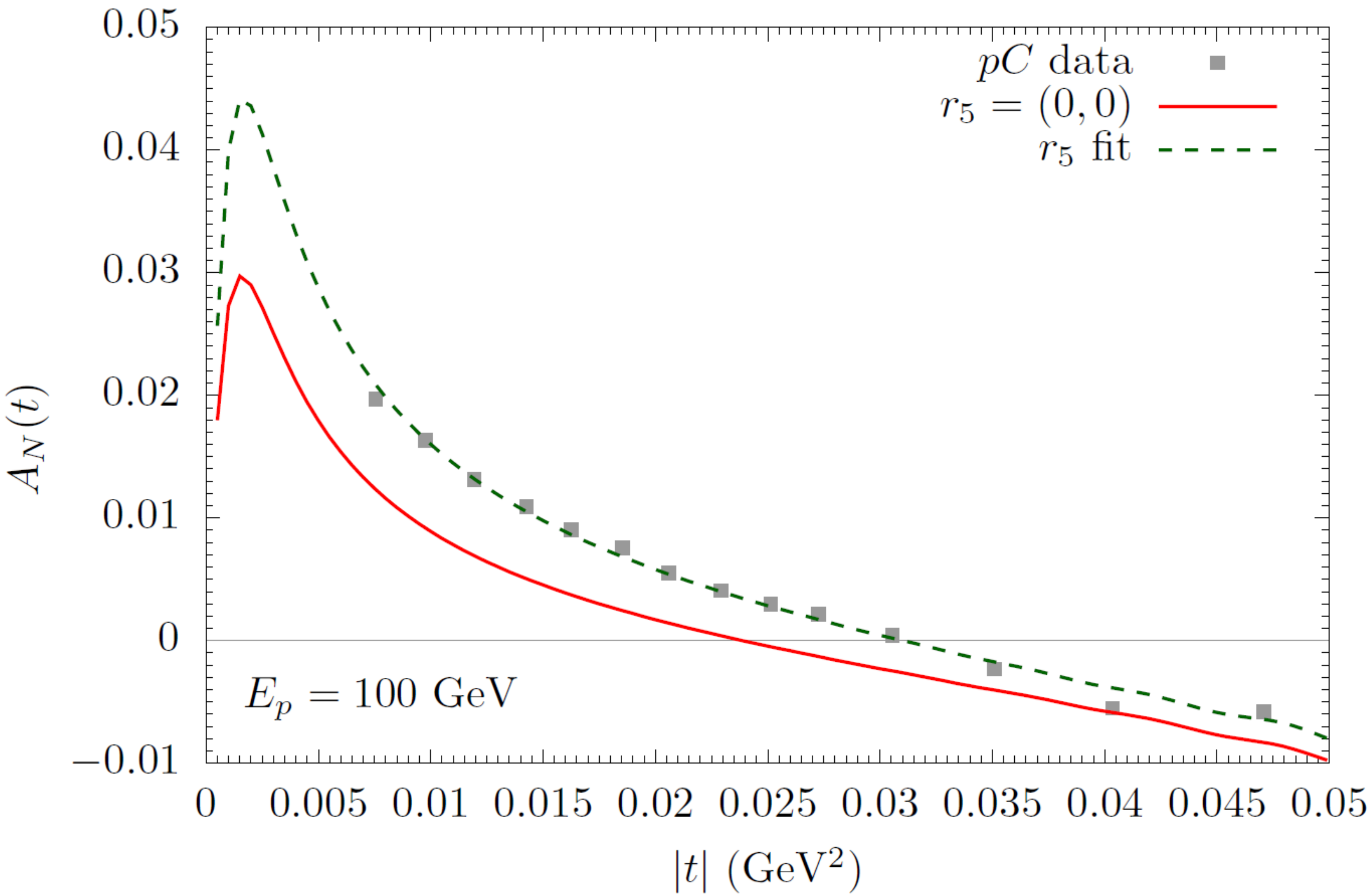
Further adjustments

Finally, we can make some adjustment by non-zero $\boldsymbol{r_5}$

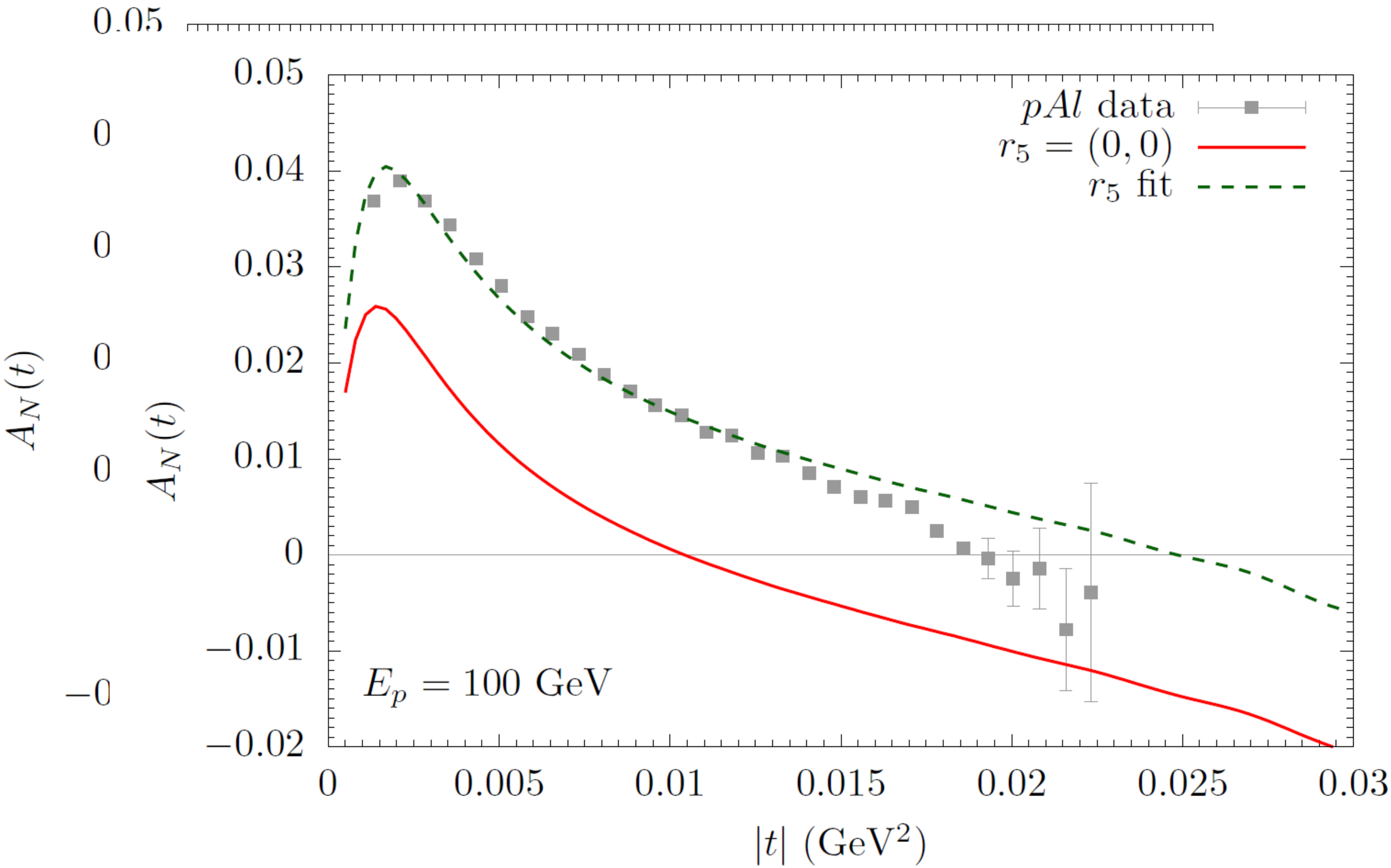


The result looks reasonable, good agreement at low and high *t*, good position of the cross points.

pC, pAl with absorption correction



pC, *pAl* with absorption correction



Let us check the *pp* elastic scattering.

At fix-target lower energy configurations.

pp data from H-JET

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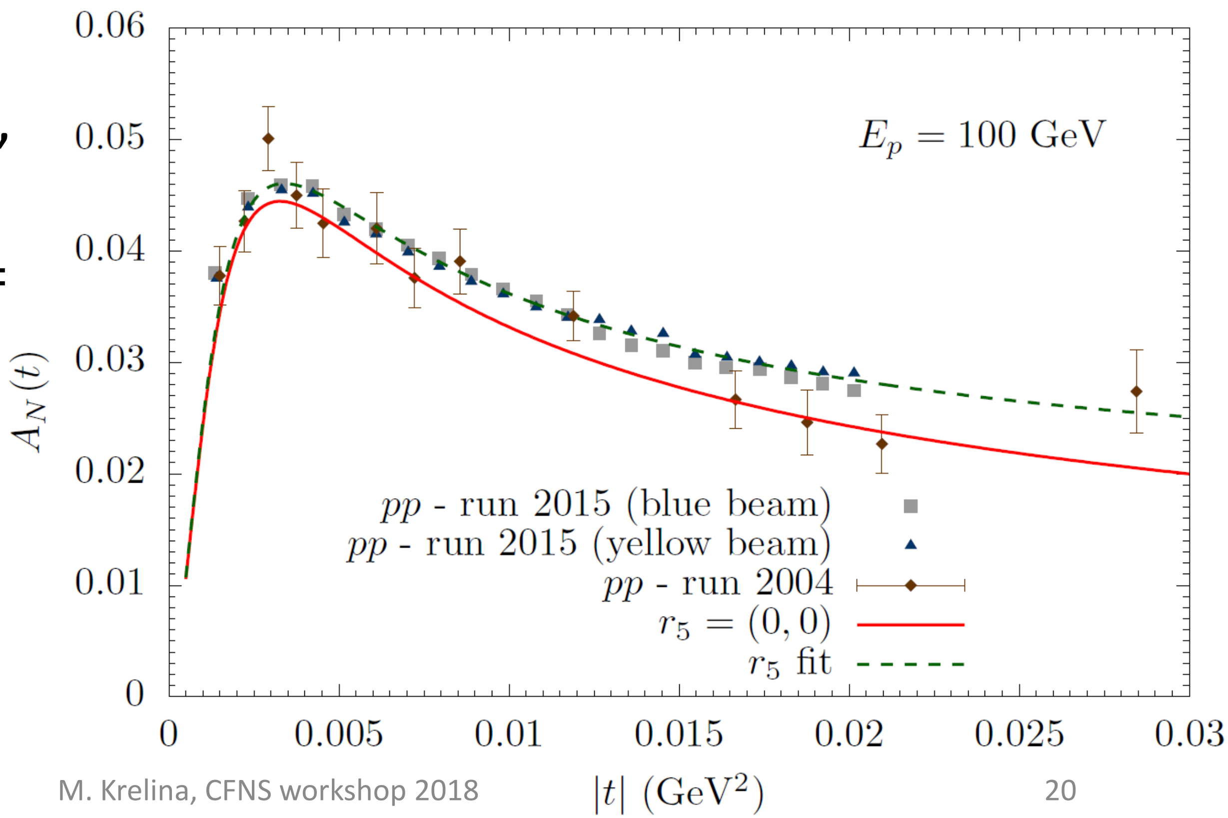
Combined r_5 fit result

$$r_5 = -0.0077 \pm 0.0031 - i0.0294 \pm 0.0126$$
$$r_5 = -0.0068 \pm 0.0032 - i0.0285 \pm 0.0130$$

Small experimental errors, however still low energy ($E_{LAB} = 100$ GeV $\approx \sqrt{s} = 14$ GeV) → possible contribution from Reggeons



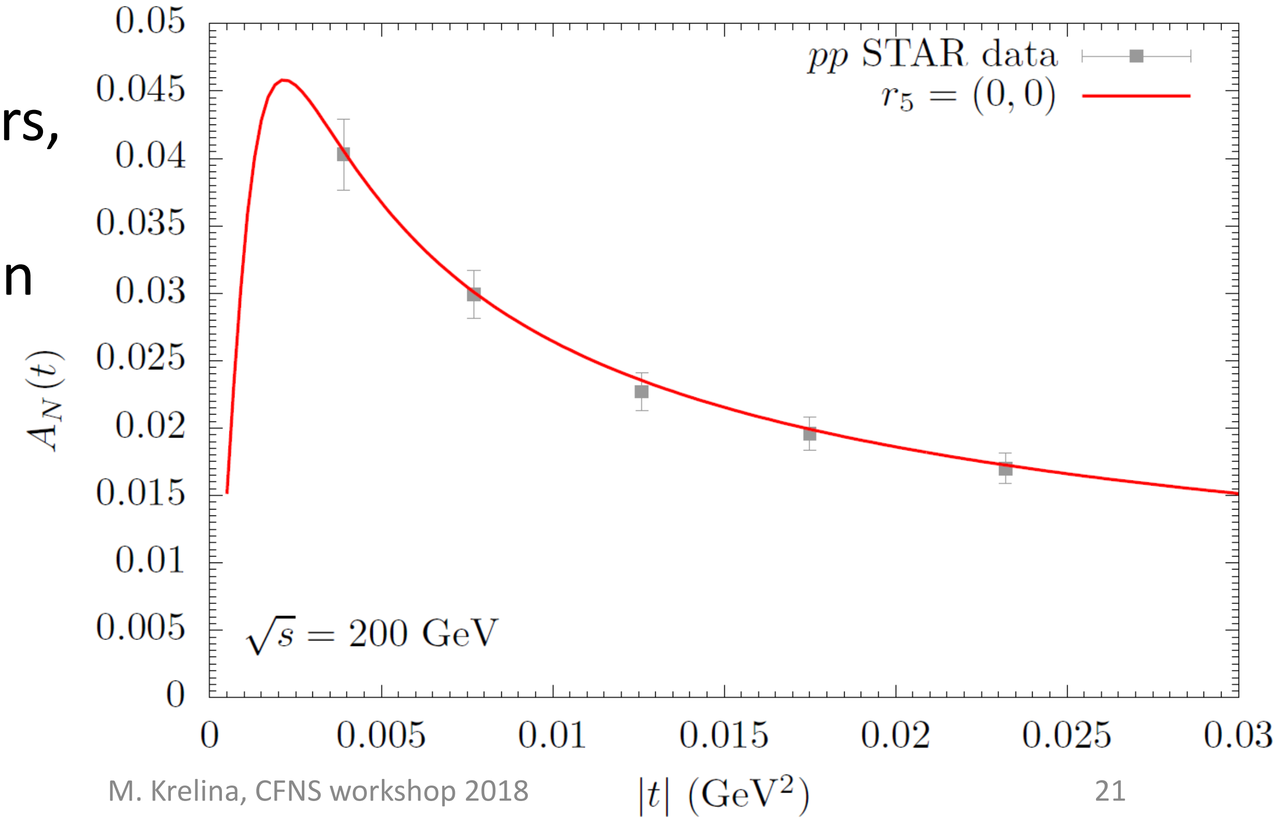
pp data from STAR

Combined r_5 fit result

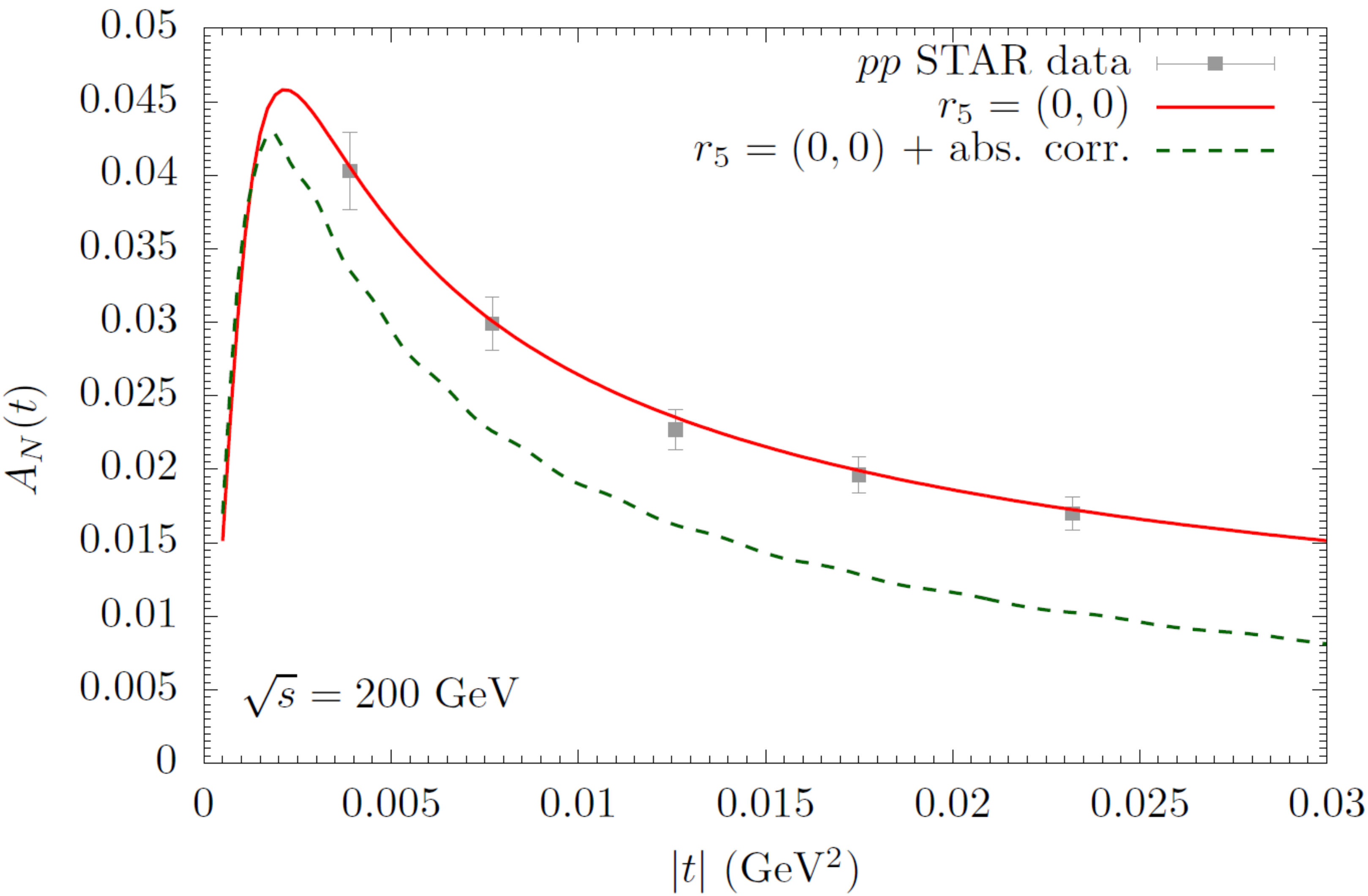
$$r_5 \approx 0$$

Zero r_5 ?! No Pomeron spin flip interaction?!

Small experimental errors, high energy ($\sqrt{s} = 200$ GeV) → contribution from Reggeons are not expected



pp with absorption correction



Wrong EM form factor again…

We checked carefully also the theory for *pp*. Many other works study the single spin asymmetry use the following simplified formula

N. H. Buttimore, B. Z. Kopeliovich, E. Leader, J. Soffer, T. L. Trueman; Phys.Rev.D59 (1999) 114010

$$\frac{m\,A_N}{\sqrt{-t}}\,\frac{16\pi}{\sigma_{\rm tot}^2}\,\frac{d\sigma}{dt}\,e^{-Bt} = \left[\kappa\,(1-\delta\rho+{\rm Im}\,r_2-\delta\,{\rm Re}\,r_2)-2\,({\rm Im}\,r_5-\delta\,{\rm Re}\,r_5)\right]\frac{t_c}{t}$$

$$-2(1+{\rm Im}\,r_2)\,{\rm Re}\,r_5+2(\rho+{\rm Re}\,r_2)\,{\rm Im}\,r_5,$$

$$\frac{16\pi}{\sigma_{\rm tot}^2}\,\frac{d\sigma}{dt}\,e^{-Bt} = \left(\frac{t_c}{t}\right)^2-2(\rho+\delta)\frac{t_c}{t}+(1+\rho^2)(1+\beta^2)\,,$$

Where authors assumed the EM form factor in the following form

$$G^2(t) = e^{-\frac{1}{2}B|t|}.$$

This by default is no problem. But…

Wrong EM form factor again…

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… when you change the energy of the collision, you change the slope parameter $\boldsymbol{B}$.
$\Rightarrow$ That effectively change also the EM form factor.

From Hofstadter:

- Electromagnetic form factor can be obtained from the electron-proton scattering
- Nucleon electromagnetic form factors are related to the charge and magnetization distribution inside the nucleon.
- => the slope of the electric form factor determines the charge radius of the nucleon.
- => from that follows, that the EM form factor is **energy independent**

The change of fitted r_5 is small, but important is that the physics is wrong.

$$G^2(t) = \exp\left[-\frac{|t|\langle r_{em}^2\rangle}{3}\right]$$

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We are finishing.

Let’s see the final results and conclusions!

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Global results

mode	Energy	note	year	Re r_5	Im r_5
pp	21,321	STAR (stat err)	2012	-0.0342 ± 0.0024	-0.1500 ± 0.0272
pp	21,321	STAR (stat+sys err)	2012	-0.0337 ± 0.0047	-0.1413 ± 0.0582
pp	255	HJET blue (stat err)	2017	-0.0290 ± 0.0008	-0.0623 ± 0.0046
pp	255	HJET yellow (stat err)	2017	-0.0301 ± 0.0008	-0.0564 ± 0.0045
pp	100	HJET blue (stat err)	2015	-0.0459 ± 0.0014	-0.0219 ± 0.0050
pp	100	HJET yellow (stat err)	2015	-0.0485 ± 0.0013	-0.0162 ± 0.0049
pC	100	RHIC (stat err)	2004	0.0321 ± 0.0006	-0.3851 ± 0.0165
pAl	100	HJET (stat err)	2015	0.0758 ± 0.0005	-0.3227 ± 0.0044
pZr	100	HJET blue (stat err)	2018	0.1111 ± 0.0007	-0.4929 ± 0.0064
pZr	100	HJET yellow (stat err)	2018	0.1126 ± 0.0008	-0.4766 ± 0.0065
pRu^*	100	HJET blue (stat err)	2018	0.1087 ± 0.0008	-0.4539 ± 0.0061
pRu^*	100	HJET yellow (stat err)	2018	0.1125 ± 0.0008	-0.4077 ± 0.0062

Conclusions

- We study the CNI region to see the effect of spin-flip hadronic amplitude.
- Indicated small r_5 in pp at RHIC does not report about Pomeron spin-flip interaction, it is a combination of Pomeron and Reggeon.
- We are interested in the nuclear target because of exclusion or suppression of Reggeons at low energies.
- A more complicated situation in case of the Gold target. Unexpected experimentally measured t dependence.
- A novel mechanism of interference of electromagnetic UPC with central hadronic collisions is proposed attempting at explanations of pAu data for CNI generated AN(t) We included other expected correction.
- Finally, we have a good agreement at low and high t, good position of the crossing points.
- Nevertheless, an accurate determination of r_5 from pAu data is not possible so far.
- Importance of the absorption correction also for pp. The other revision of the EM form factor is necessary.
- Non-zero r_5 from STAR at high energy with the absorption.

Thank you for your attention

Back slide – formulas - pp

$$\frac{d\sigma}{dt} = 2\pi \left\{ |\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2 \right\},$$

$$A_N \frac{d\sigma}{dt} = -4\pi \mathrm{Im} \left\{ (\phi_1 + \phi_2 + \phi_3 - \phi_4)\phi_5^* \right\}$$

$$\phi_1(s,t) = \langle + + |M| + + \rangle$$

$$\phi_2(s,t) = \langle + + |M| - - \rangle$$

$$\phi_3(s,t) = \langle + - |M| + - \rangle$$

$$\phi_4(s,t) = \langle + - |M| - + \rangle$$

$$\phi_5(s,t) = \langle + + |M| + - \rangle$$

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Back slide – formulas - pp

$$\phi_1^h = \frac{\sigma_{tot}^{pp}}{8\pi}(\rho_{pp} + i)e^{-\frac{1}{2}B|t|},$$

$$\phi_2^h = r_2\frac{\sigma_{tot}^{pp}}{4\pi}(\rho_{pp} + i)e^{-\frac{1}{2}B|t|} = r_5^2\frac{t}{m_p^2}\frac{\sigma_{tot}^{pp}}{8\pi}(\rho_{pp} + i)e^{-\frac{1}{2}B|t|} \approx 0,$$

$$\phi_3^h = \frac{\sigma_{tot}^{pp}}{8\pi}(\rho_{pp} + i)e^{-\frac{1}{2}B|t|},$$

$$\phi_4^h = -r_4\frac{t}{m_N^2}\frac{\sigma_{tot}^{pp}}{8\pi}(\rho_{pp} + i)e^{-\frac{1}{2}B|t|} \approx 0,$$

$$\phi_5^h = r_5\frac{\sqrt{-t}}{m_N}\frac{\sigma_{tot}^{pp}}{8\pi}e^{-\frac{1}{2}B|t|},$$

$$e^{i\delta_{pp}}\phi_1^{em} = -\frac{\alpha_{em}}{|t|}G^2(t)e^{i\delta_{pp}},$$

$$e^{i\delta_{pp}}\phi_2^{em} = \frac{\alpha_{em}(\mu_N - 1)^2}{|t|}G^2(t)e^{i\delta_{pp}} \approx 0,$$

$$e^{i\delta_{pp}}\phi_3^{em} = -\frac{\alpha_{em}}{|t|}G^2(t)e^{i\delta_{pp}},$$

$$e^{i\delta_{pp}}\phi_4^{em} = -\frac{\alpha_{em}(\mu_N - 1)^2}{|t|}G^2(t)e^{i\delta_{pp}} \approx 0,$$

$$e^{i\delta_{pp}}\phi_5^{em} = -\frac{\alpha_{em}(\mu_N - 1)}{2m_N\sqrt{-t}}G^2(t)e^{i\delta_{pp}},$$

$$G^2(t) = \exp\left[-\frac{|t|\langle r_{em}^2\rangle}{3}\right]$$

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Back slide – formulas - pA

$$A_N \frac{d\sigma^{pA}}{dt} = 2\mathrm{Im}(f_{++}^{pA} f_{+-}^{pA,*}),$$

$$\frac{d\sigma^{pA}}{dt} = |f_{++}^{pA}|^2 + |f_{+-}^{pA}|^2.$$

$$f_{++}^{pA,h} = \sqrt{\pi}\frac{\sigma_{tot}^{pA}}{4\pi} F_A^h(q^2),$$

$$f_{+-}^{pA,h} = \sqrt{\pi} r_5 \frac{q}{m_N} \frac{\sigma_{tot}^{pA}}{4\pi} \mathrm{Im} F_A^h(q^2),$$

$$e^{i\delta_{pA}} f_{++}^{pA,em} = \sqrt{\pi}\frac{2Z\alpha_{EM}}{q^2} F_A^{em}(q^2) e^{i\delta_{pA}},$$

$$e^{i\delta_{pA}} f_{+-}^{pA,em} = \sqrt{\pi}\frac{Z\alpha_{EM}}{m_N q}(\mu_p - 1) F_A^{em}(q^2) e^{i\delta_{pA}}.$$

Back slide – formulas - pA

$$F_A^h(q^2) = \frac{2i}{\sigma_{tot}^{pA}} \int d^2b\, e^{i\vec{q}\cdot\vec{b}} \left[1 - e^{-\frac{1}{2}\sigma_{tot}^{NN}(1-i\rho_{pp})T_A^h(b)}\right]$$
$$= \frac{4i\pi}{\sigma_{tot}^{pA}} \int db\, b J_0(qb) \left[1 - e^{-\frac{1}{2}\sigma_{tot}^{NN}(1-i\rho_{pp})T_A^h(b)}\right]$$

$$T_A^h(b) = \frac{2}{\sigma_{tot}^{hN}} \int d^2s \frac{\sigma_{tot}^{hN}}{4\pi B_{hN}} \exp\left(-\frac{s^2}{2B_{hN}}\right) T_A(\vec{b} - \vec{s})$$

Back slide – formulas - absorption

$$f^{em,pA}(b) = \sqrt{\pi} Z \alpha_{em} \left[2G_1(b^2) + \frac{\mu_p - 1}{m_N} G_2(b^2) \right],$$

$$G_1(b^2) = \int d^2q e^{i\vec{b}\cdot\vec{q}} \frac{1}{q^2} F_A^{em}(q^2) e^{i\delta_{pA}(q^2)}$$

$$G_2(b^2) = \int d^2q e^{i\vec{b}\cdot\vec{q}} \frac{1}{q} F_A^{em}(q^2) e^{i\delta_{pA}(q^2)}$$

$$\begin{aligned} f^{em,pA}(b) &= \sqrt{\pi} Z \alpha_{em} \left[2G_1(b^2) + \frac{\mu_p - 1}{m_N} G_2(b^2) \right] S(b) \\ &= \sqrt{\pi} Z \alpha_{em} \left[2G_1(b^2) + \frac{\mu_p - 1}{m_N} G_2(b^2) \right] e^{-\frac{1}{2}\sigma_{tot}^{pp} T_A^{eff}(b)} \end{aligned}$$

$$f^{em,pA}(q^2) = \frac{1}{2\pi} \int d^2b e^{-i\vec{b}\cdot\vec{q}} f^{em,pA}(b)$$