UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

Centro Científico Tecnológico de Valparaíso

ATLAS EXPERIMENT

ACT 1406 Theory Meets Experiment at LHC

Spin Dependence in Proton-Nucleus Elastic Scattering

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Outline

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

Motivation

Measurement of elastic (CNI region) scatterings at high energies used to be used for polarization measurement, e.g. in AGS, RHIC

Today it is interesting physics itself. Latest results show non-zero spin-flip hadronic part in *pp* collisions.

Origin of spin-flip hadronic part:

- Spin-flip pomeron?
- Reggeon (main source of the spin flip at medium energy)?
- Odderon?
- Other mechanism?

What is CNI region?

Elastic scattering = very low 4-momentum transfer squared, *-t,* = very small angles

CNI (Coulomb-nuclear interference) region = a kinematical region where the interference electromagnetic-hadron terms dominates

Measurable = single-spin asymmetry $A_N(t)$ = left-right asymmetry

Expected very small, only few percent

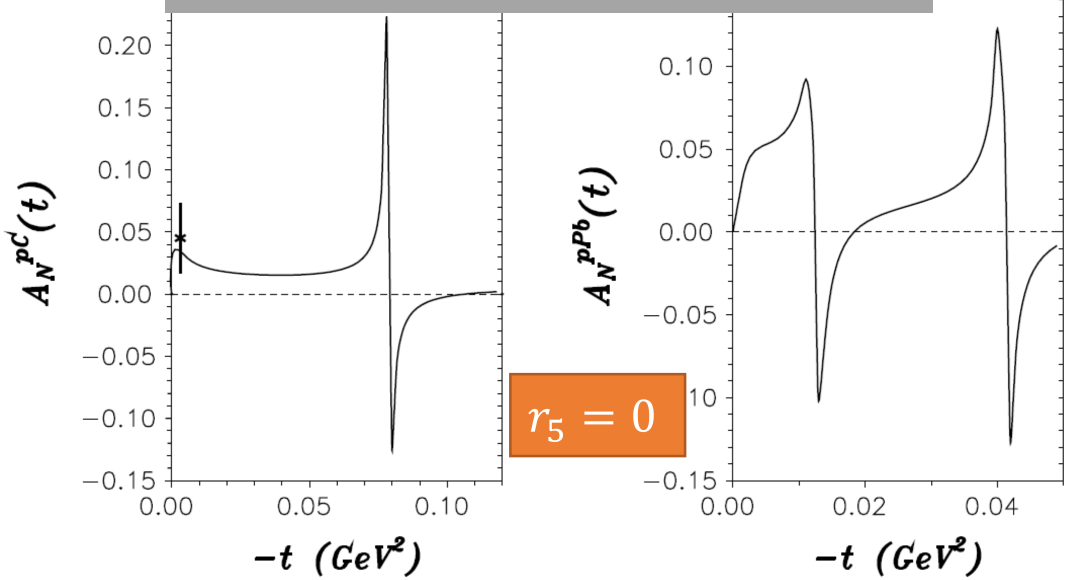
$$A_N \frac{d\sigma^{pp}}{dt} = 2\mathrm{Im}[(\phi_1 + \phi_2 + \phi_3 - \phi_4)\phi_5^*]$$

$$\frac{d\sigma^{pp}}{dt} = |\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2$$

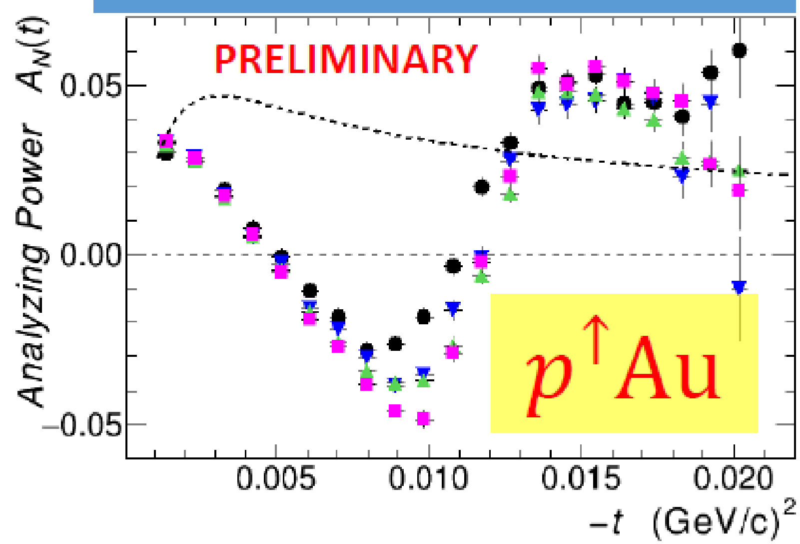
Current status

New data = from *pC* polarimeter & HJET (*pp, pAu, pAl*) @ RHIC (*pAu* at different energies from BES)

Predictions for *pC, pPb* by B. Kopeliovich, ArXiv:hep-ph/9801414, 1998



22nd International Spin Simposium, A. Poblaguev, at 10, 20, 31, 100 GeV. Dashed line: pp prediction with r_5=0



pp elastic scattering theory

Spin-flip EM amplitude – well known, caused by the proton's magnetic moment.

Spin-flip hadronic amplitude – nobody know.

Introduce parameter r_5 that need to be **fit**

$$r_5 = \frac{m_p\, \phi_5}{\sqrt{-t}\ \mathrm{Im}\ \phi_+}$$

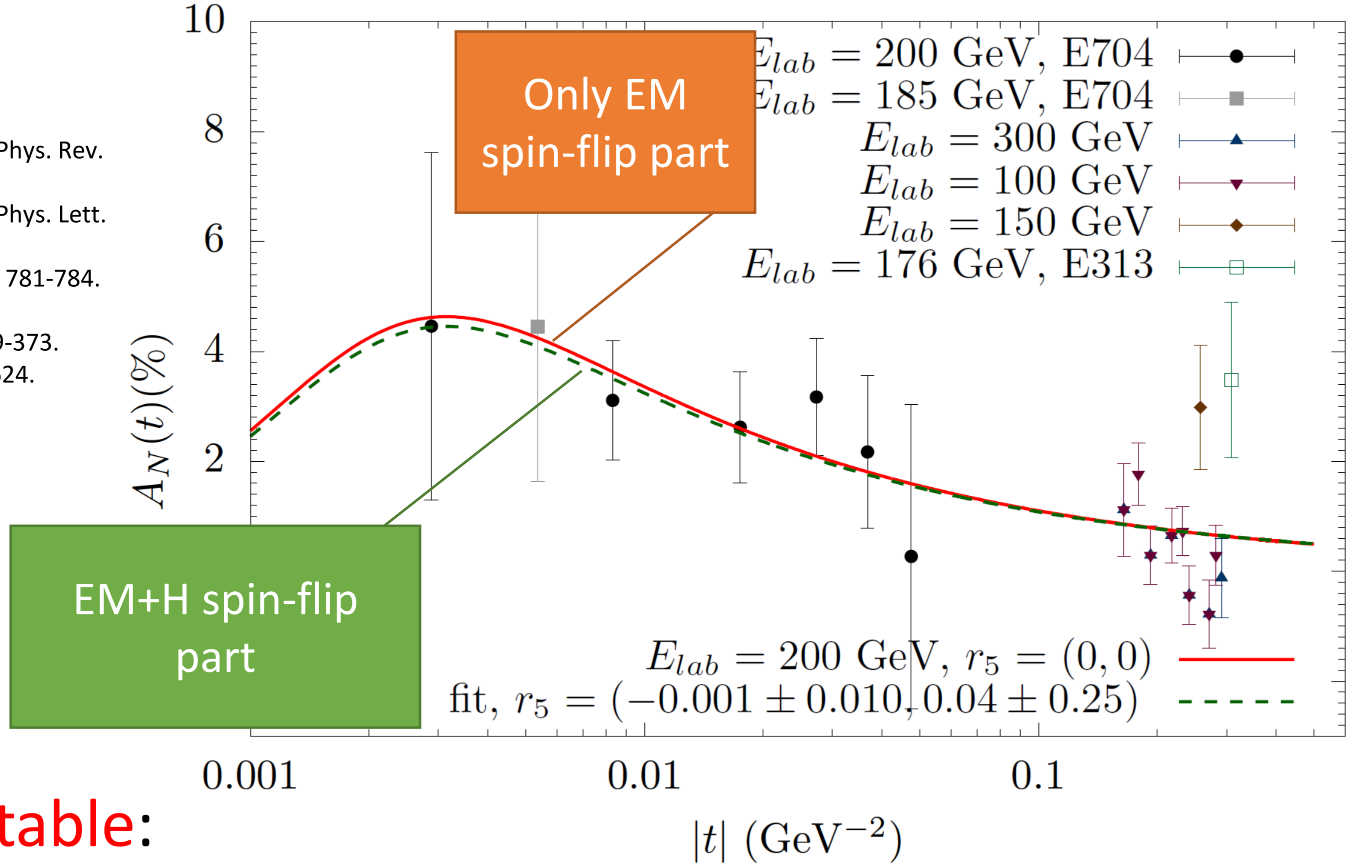
ϕ_+ - non-flip amplitude
ϕ_5 - single spin-flip amplitude

where

$$\phi_+ = \tfrac{1}{2}(\phi_1 + \phi_3)$$

pp $A_N(t)$ and old measurements

Data:
- E581/704 Collaboration, N. Akchurin et al., Phys. Rev. D48 (1993) 3026-3036.
- E581/704 Collaboration, N. Akchurin et al., Phys. Lett. B229 (1989) 299-303.
- J. H. Snyder et al., Phys. Rev. Lett. 41 (1978) 781-784. [Erratum: Phys. Rev. Lett.41,1256(1978)].
- G. Fidecaro et al., Phys. Lett. B76 (1978) 369-373.
- M. Corcoran et al., Phys. Rev. D22 (1980) 2624. [Erratum: Phys. Rev.D24,3010(1981)].

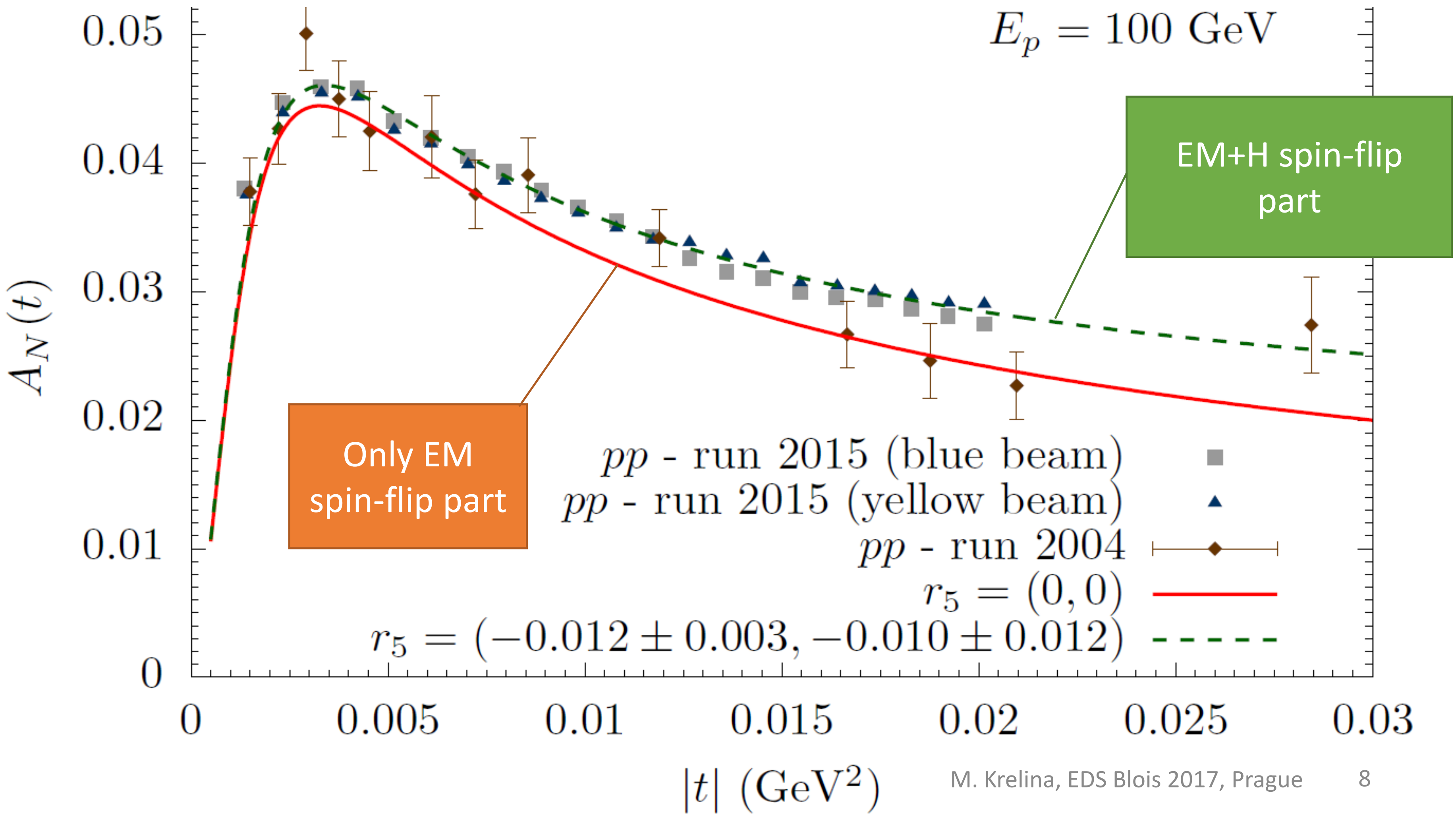


Fit of r_5 not trustable:

- Neglected t dependence of r_5 (valid only for $tB \ll 1$, i.e. $t <$ 0.1 GeV)
- Huge errors of small t data

pp $A_N(t)$ @ RHIC

Situation has changed by measurement at RHIC. Evidence of **non-zero spin-flip hadronic amplitude**



Spin asymmetry in *pA* interactions

Spin asymmetry for elastic proton-nucleus interaction:

$$A_N \frac{d\sigma^{pA}}{dt} = 2\mathrm{Im}\left[f_{++}^{pA} f_{+-}^{pA,*}\right]$$

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

Goal: predict *pA* $A_N(t)$ using r_5 from *pp.*

Theoretical predictions of $A_N(t)$ for *pA* done almost **20 years ago with no available data**.

- *B. Z. Kopeliovich*, High-energy polarimetry at RHIC, in Workshop on Polarimetry at RHIC, (1998), arXiv:hep-ph/9801414 [hep-ph].
- *N. H. Buttimore, B. Z. Kopeliovich, E. Leader, J. Soer, and T. L. Trueman*, Phys. Rev. D59 (1999) 114010, arXiv:hep-ph/9901339 [hep-ph].
- *B. Z. Kopeliovich and T. L. Trueman*, Phys. Rev. D64 (2001) 034004, arXiv:hep-ph/0012091 [hep-ph].

Spin-flip hadronic amplitude in *pA I.*

Old papers:

Predicted that non-flip and spin-flip parts of hadronic amplitude have the same nuclear form factor = r_5^{pA} is not subjected to any nuclear effects!

$$r_5^{pA} = \frac{m_p f_{+-}^{pA}}{\sqrt{-t}\,\mathrm{Im}\, f_{++}^{pA}}$$

Our statement: ***r_5* is subjected to nuclear effects**!

Spin-flip hadronic amplitude in *pA* I.

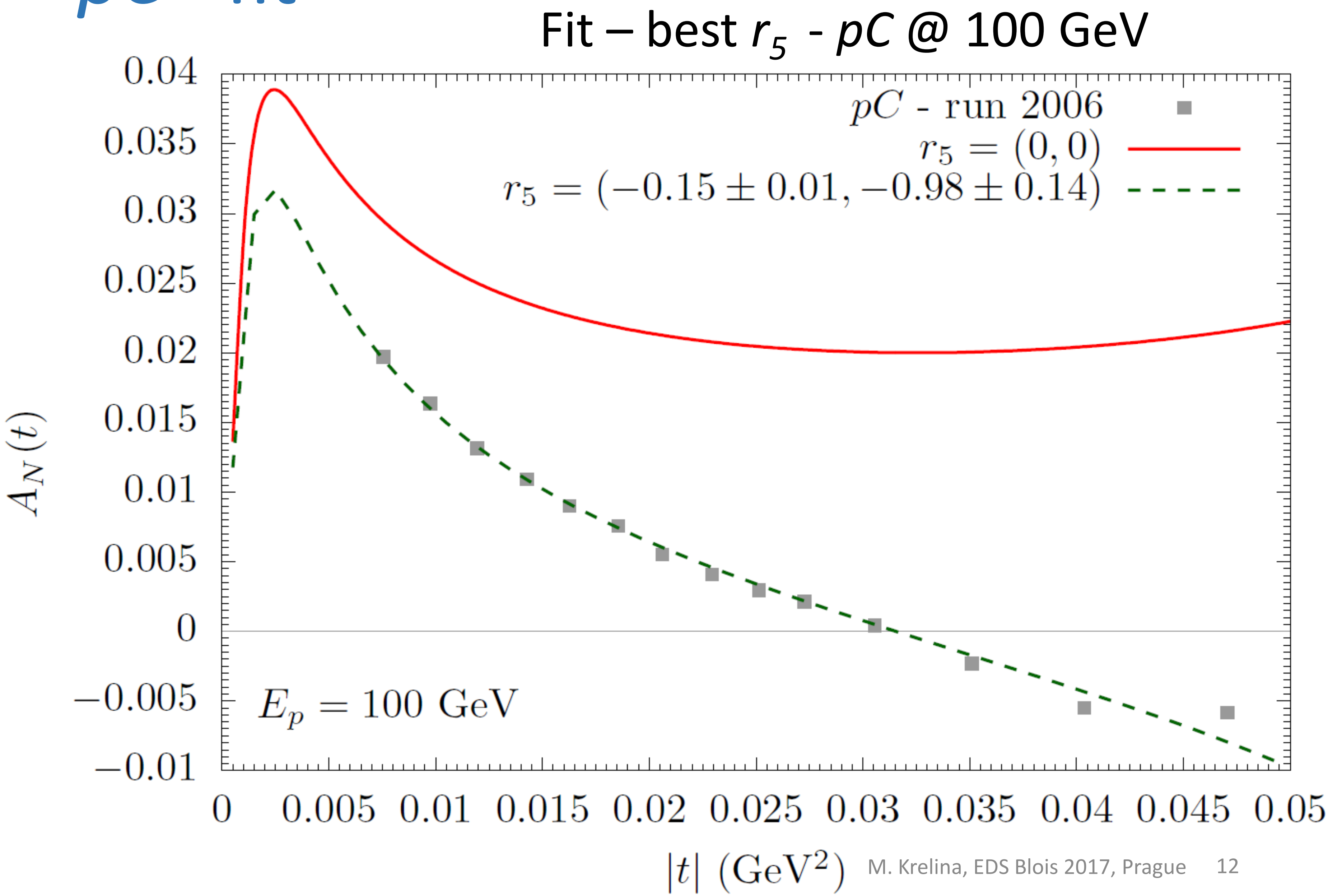
Idea:

We factorize out one spin-flip interaction from Glauber elastic scattering amplitude

$$\tilde{F}(\vec{b}) = 1 - \exp\left[-\int d^2 s\, T_A(\vec{b})\Gamma(\vec{b}-\vec{s})\right]$$
$$+ \boldsymbol{T_A}(\vec{\boldsymbol{b}})\boldsymbol{\phi_5}(\vec{\boldsymbol{q}}) \exp\left[-\int d^2 s\, T_A(\vec{b})\Gamma(\vec{b}-\vec{s})\right]$$
$$= \tilde{F}^{++}(\vec{b}) + \tilde{F}^{+-}(\vec{b})$$

Next: We can try to fit r_5 to existing *pA* data…

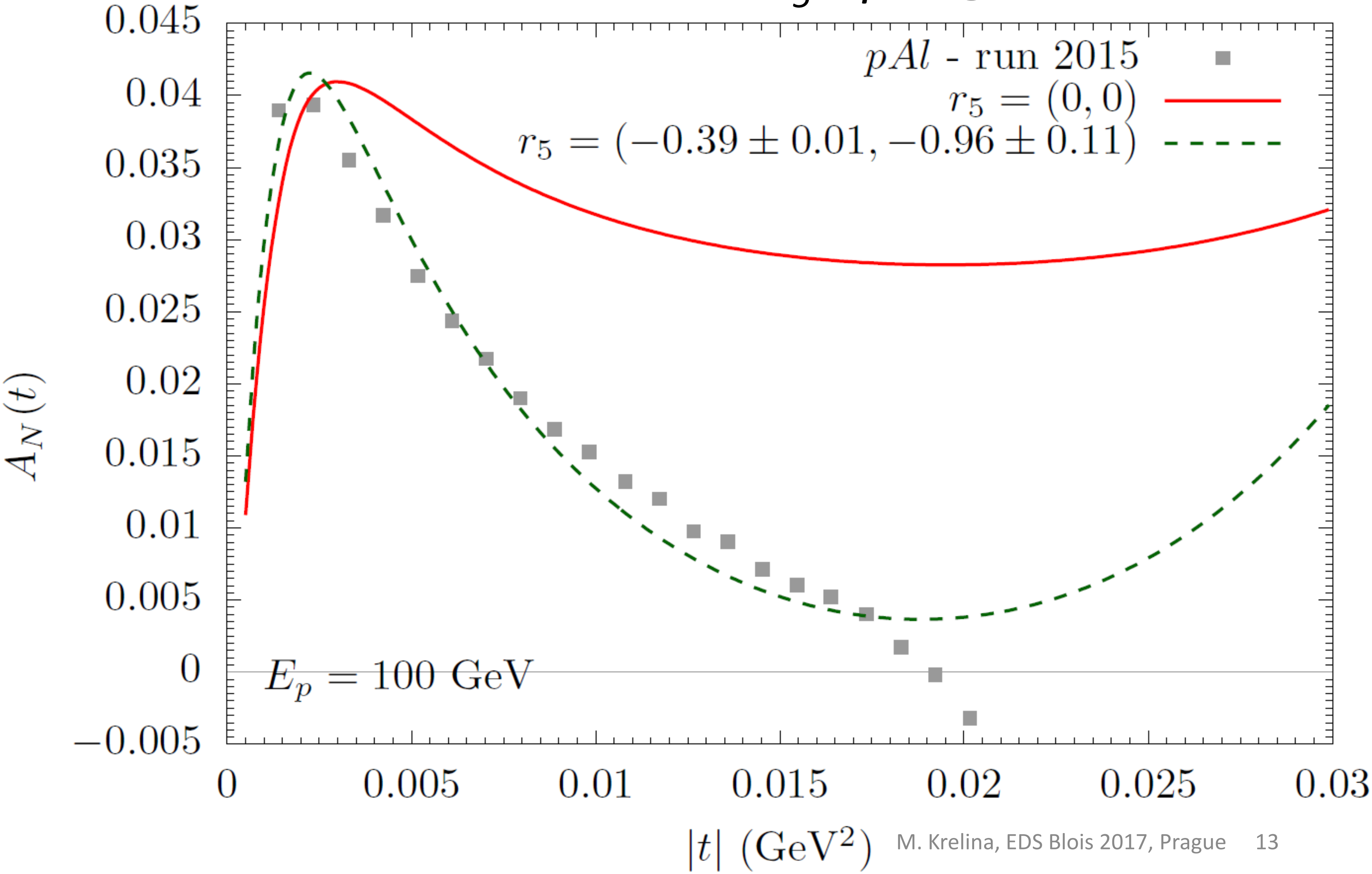
pC - fit



Fit – best r_5 - pC @ 100 GeV
pC - run 2006
$r_5 = (0, 0)$
$r_5 = (-0.15 \pm 0.01, -0.98 \pm 0.14)$
$E_p = 100$ GeV
$A_N(t)$
$|t|$ (GeV^2)
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
−0.005
−0.01
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05

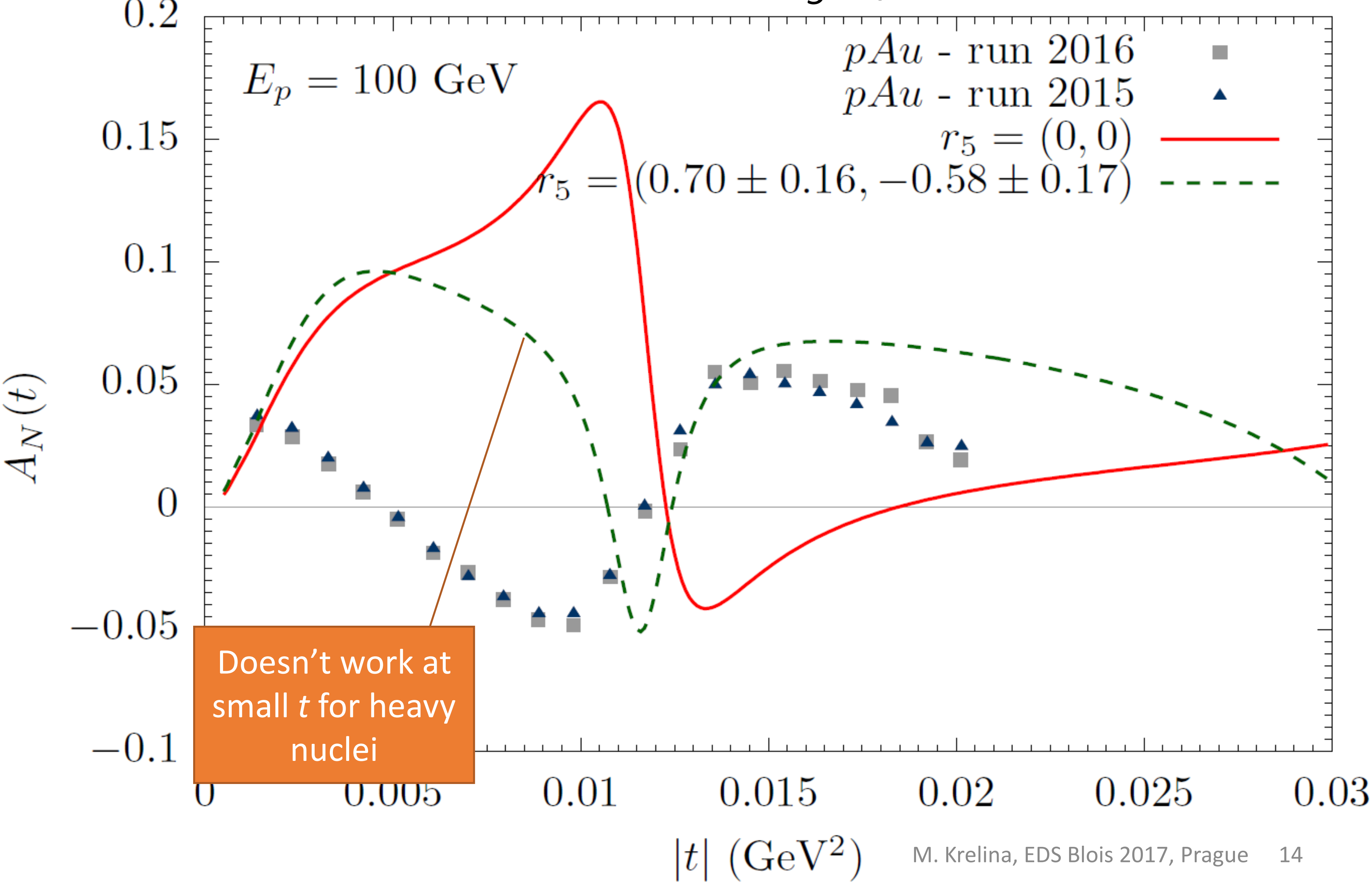
pAl - fit

Fit – best r_5 - *pAl* @ 100 GeV



pAu - fit

Fit – best r_5 - *pAu* @ 100 GeV



pp – *pA* inconsistency

Fit of r_5 on *pA* is far from r_5 on *pp*.

- One would not expected so big different between *pC* and *pp*
  - Looks more like problem with data
- This is the main puzzle in *pp/pA* for elastic spin-flip interactions

Why data on heavy nuclei are not in agreement?

- More tricky, more freedom in selecting of nuclear parametrizations, Coulomb phase, real part, …
- Sensitivity on nuclear density
  - Well studied for Carbon
  - For Gold only one parametrization from 1956!

Conclusions

- *pp* data with small errors available, can fit r_5
- r_5 independent on t only for small t, approx. t<0.1
- We fitted significant real part of r_5 in *pp*
- Formulation of r_5 dependence in *pA* is not right → reformulation
  - Factorizing out one spin-flip interaction
  - This interaction dominates at the edge of the nucleus
- r_5 fit for *pC* is not in correspondence with r_5 in *pp*
  - *This inconsistency is independent on the r_5 formulation (old or new)*
- We see no easy solution of this puzzle
  - It looks to us more like an inconsistency in available data
- Not work for heavy nuclei – more tricky

Thank you for your attention

Acknowledgement

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pp elastic scattering theory I.

Five independent helicity amplitudes:

$$\begin{aligned}\phi_1(s,t) &= \langle ++|M|++\rangle,\\ \phi_2(s,t) &= \langle ++|M|--\rangle,\\ \phi_3(s,t) &= \langle +-|M|+-\rangle,\\ \phi_4(s,t) &= \langle +-|M|-+\rangle,\\ \phi_5(s,t) &= \langle ++|M|+-\rangle,\end{aligned}$$

Cross section & **single-spin asymmetry *$A_N(t)$*:**

$$\frac{d\sigma}{dt} = \frac{2\pi}{s(s-4m_p^2)}\left\{|\phi_1|^2+|\phi_2|^2+|\phi_3|^2+|\phi_4|^2+|\phi_5|^2\right\}$$

$$A_N\frac{d\sigma}{dt} = -\frac{4\pi}{s(s-4m_p^2)}\,\mathrm{Im}\left\{(\phi_1+\phi_2+\phi_3-\phi_4)\phi_5^*\right\}$$

pp amplitudes

$$
\begin{aligned}
\phi_1^h &= \frac{\sigma_{tot}^{pp}}{8\pi} s(\rho_{pp}+i)e^{-\frac{1}{2}B|t|},\\
\phi_2^h &= r_2\frac{\sigma_{tot}^{pp}}{4\pi} s(\rho_{pp}+i)e^{-\frac{1}{2}B|t|} = r_5^2\frac{t}{m_p^2}\frac{\sigma_{tot}^{pp}}{8\pi} s(\rho_{pp}+i)e^{-\frac{1}{2}B|t|} \approx 0,\\
\phi_3^h &= \frac{\sigma_{tot}^{pp}}{8\pi} s(\rho_{pp}+i)e^{-\frac{1}{2}B|t|},\\
\phi_4^h &= -r_4\frac{t}{m_p^2}\frac{\sigma_{tot}^{pp}}{8\pi} s(\rho_{pp}+i)e^{-\frac{1}{2}B|t|} \approx 0,\\
\phi_5^h &= r_5\frac{\sqrt{-t}}{m_p}\frac{\sigma_{tot}^{pp}}{8\pi} s(\rho_{pp}+i)e^{-\frac{1}{2}B|t|},\\
e^{i\delta_{pp}}\phi_1^{em} &= -\frac{s\alpha_{EM}}{|t|}G^2(t)e^{i\delta_{pp}},\\
e^{i\delta_{pp}}\phi_2^{em} &= \frac{s\alpha_{EM}(\mu-1)^2}{|t|}G^2(t)e^{i\delta_{pp}} \approx 0,\\
e^{i\delta_{pp}}\phi_3^{em} &= -\frac{s\alpha_{EM}}{|t|}G^2(t)e^{i\delta_{pp}},\\
e^{i\delta_{pp}}\phi_4^{em} &= -\frac{s\alpha_{EM}(\mu-1)^2}{|t|}G^2(t)e^{i\delta_{pp}} \approx 0,\\
e^{i\delta_{pp}}\phi_5^{em} &= -\frac{s\alpha_{EM}(\mu-1)}{2m_p\sqrt{-t}}G^2(t)e^{i\delta_{pp}},
\end{aligned}
$$

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

pp amplitude parameters

$\sqrt{s}$ (GeV)	σ_{tot}^{pp} (mb)	ρ_{pp}	B (GeV^{-2}) [6]
6.56 (22 GeV in LAB) AGS	39.015	-0.241	10.48
20	39.193	-0.021	11.7
40	41.346	0.051	12.57
62.3	43.482	0.082	12.97
200	51.688	0.126	14.47
7000	97.283	0.137	19.90

Spin-flip hadronic nuclear form factor

Our statement: ***r_5* is subjected to nuclear effects**!

Non-flip hadronic form factor:

$$\tilde{F}(\vec{b}) = 1 - \exp\left[-\int d^2s\, T_A(\vec{s})\Gamma(\vec{b}-\vec{s})\right]$$

Now, let's **factorize out one interaction**:

$$\begin{aligned}
\tilde{F}(\vec{b}) &= 1 - \int \prod_{j=1}^{A} d^3q_j\, \rho_j(\vec{q}_j)(1-\Gamma_j(\vec{b}-\vec{s}_j)) \\
&= 1 - \left[\int d^3q\, \rho_j(\vec{q})(1-\Gamma(\vec{b}-\vec{s}))\right]\left[\int \prod_{j=2}^{A} d^3q_j\, \rho_j(\vec{q}_j)(1-\Gamma_j(\vec{b}-\vec{s}_j))\right] \\
&= 1 - \exp\left[-\int d^2s\, T_A(\vec{s})\Gamma(\vec{b}-\vec{s})\right] + T_A(b) f^{pp,5}(\vec{q}) \exp\left[-\int d^2s\, T_A(\vec{s})\Gamma(\vec{b}-\vec{s})\right] \\
&= \tilde{F}^{nf}(\vec{b}) + \tilde{F}^{sf}(\vec{b})
\end{aligned}$$

pA amplitudes I.

All pA amplitudes:

$$
\begin{aligned}
f_{++}^{pA,h} &= \frac{\sigma_{tot}^{pA}}{4\sqrt{\pi}} F_A^h(q^2), \\
f_{+-}^{pA,h} &= r_5 \frac{\sqrt{-t}}{m_p} \frac{\sigma_{tot}^{pp}}{8\sqrt{\pi}} (\rho_{pp} + i) F_A^{h,5}(q^2, r_5), \\
e^{i\delta_{pA}} f_{++}^{pA,em} &= \frac{2\sqrt{\pi} Z \alpha_{EM}}{q^2} F_A^{em}(q^2) e^{i\delta_{pA}}, \\
e^{i\delta_{pA}} f_{+-}^{pA,em} &= \frac{\sqrt{\pi} Z \alpha_{EM}}{m_N q} (\mu_p - 1) F_A^{em}(q^2) e^{i\delta_{pA}},
\end{aligned}
$$

pA amplitudes II.

Form factors:

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

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

$$F_A^{h,5}(q^2, r_5) = \int d^2b e^{i\vec{q}\cdot\vec{b}} T_A^h(b) e^{-\frac{1}{2}\sigma_{tot}^{NN}(1-i\rho_{pp})T_A(b)}$$

Other factors:

$$\delta_{pA} = \alpha_{EM} Z_1 Z_2 e^{2\omega}\left[2E_1(2\omega) - E_1(\omega)\right],$$

$$\omega = \frac{1}{4}q^2 B_{pA},$$