Systematics of high-energy photonuclear cross section and challenges in extensive air shower physics

based on *Phys. Rev. D* **113**, 083026 (2026) & some new results

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List of abbreviations

– *CR = cosmic[-]ray[s],*
– *EAS = extensive air shower,*
– *(U)HE = (ultra-)high-energy,*
– *PNR = photonuclear reaction*
– *TPR = true positive rate*

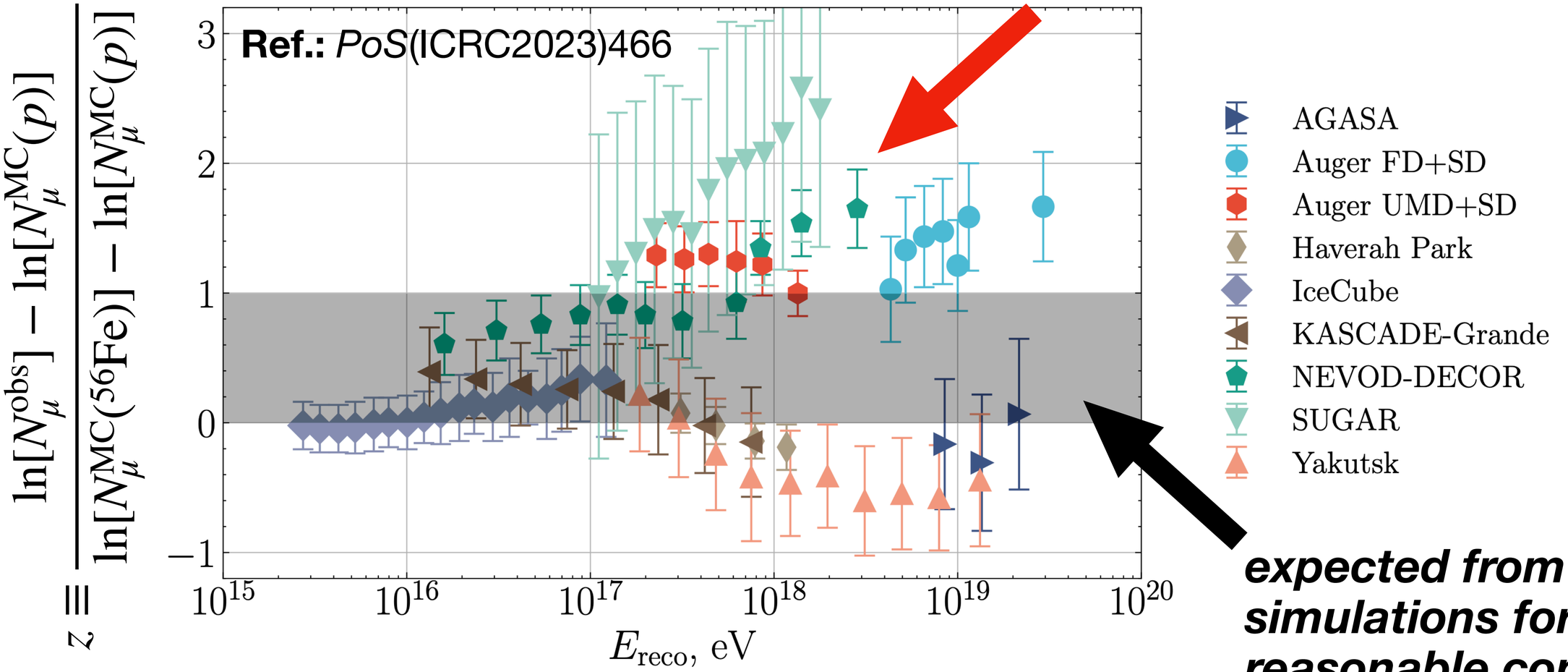
Outline of the talk

– *Motivation & Method*

– *Challenge 1: CR(?!) excess from Cygnus*
– *Challenge 2: UHECR composition and muon excess*
– *Challenge 3: searches for UHE photons*

Motivation & Method: Muon excess

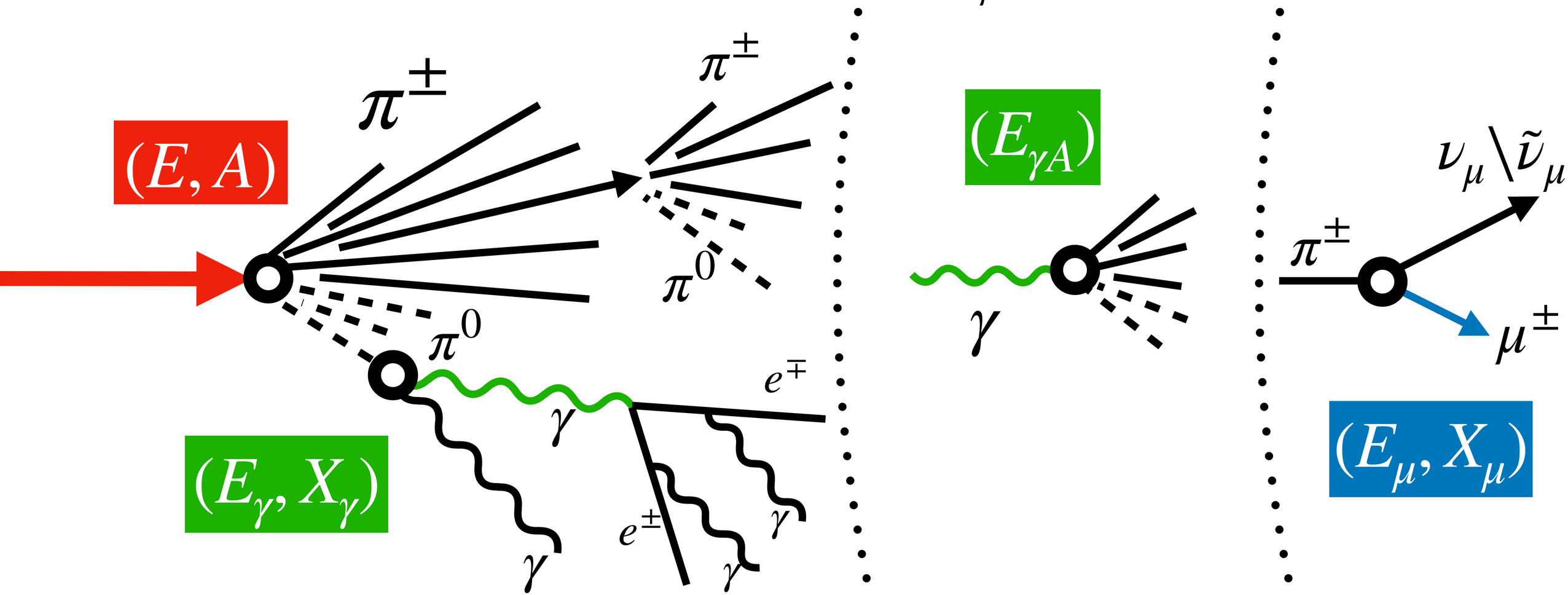
«muon excess»



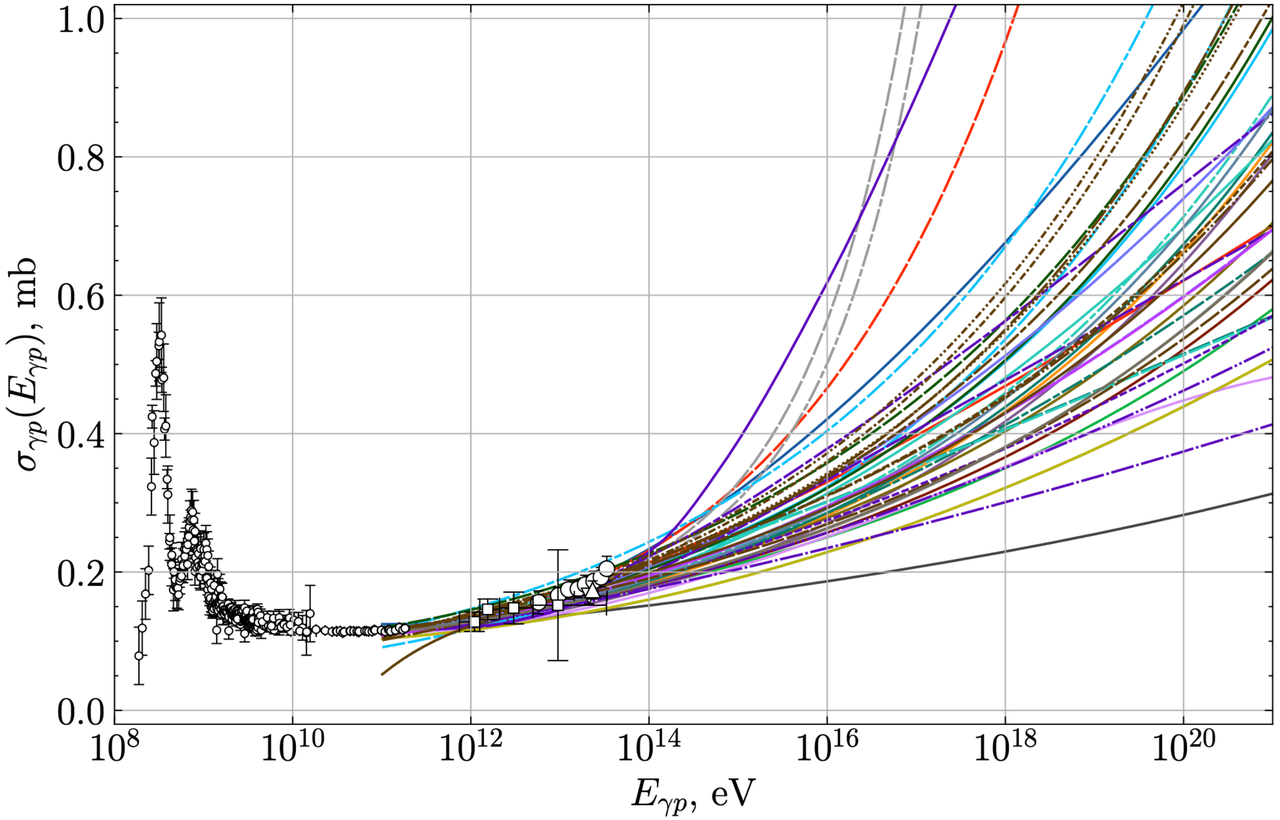
expected from simulations for any reasonable composition

Motivation & Method: PNRs and muons in EASs

It is believed that PNRs contribution to N_μ is within $(4\ldots11)\,\%$

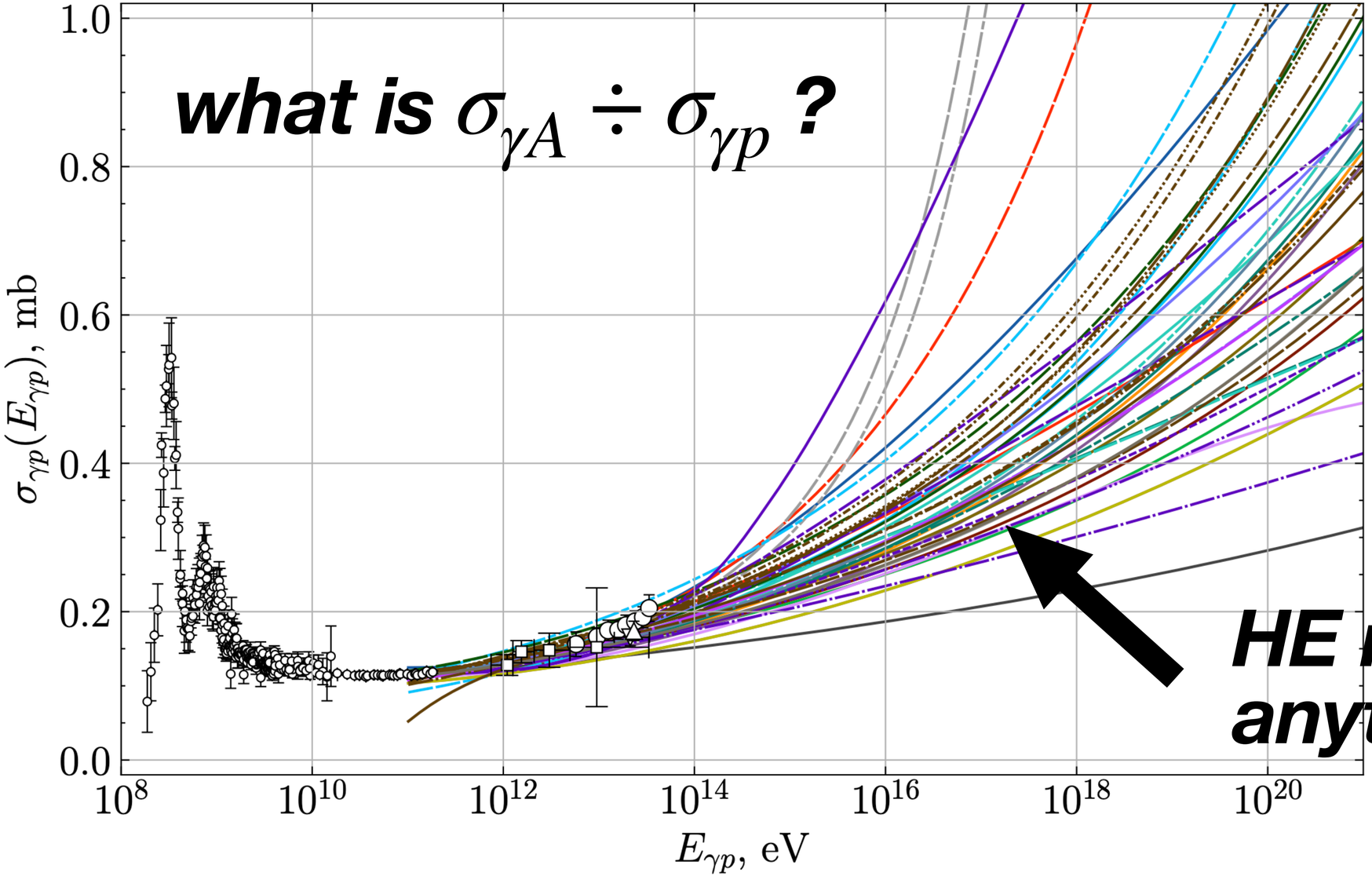


Motivation & Method: PNR cross section



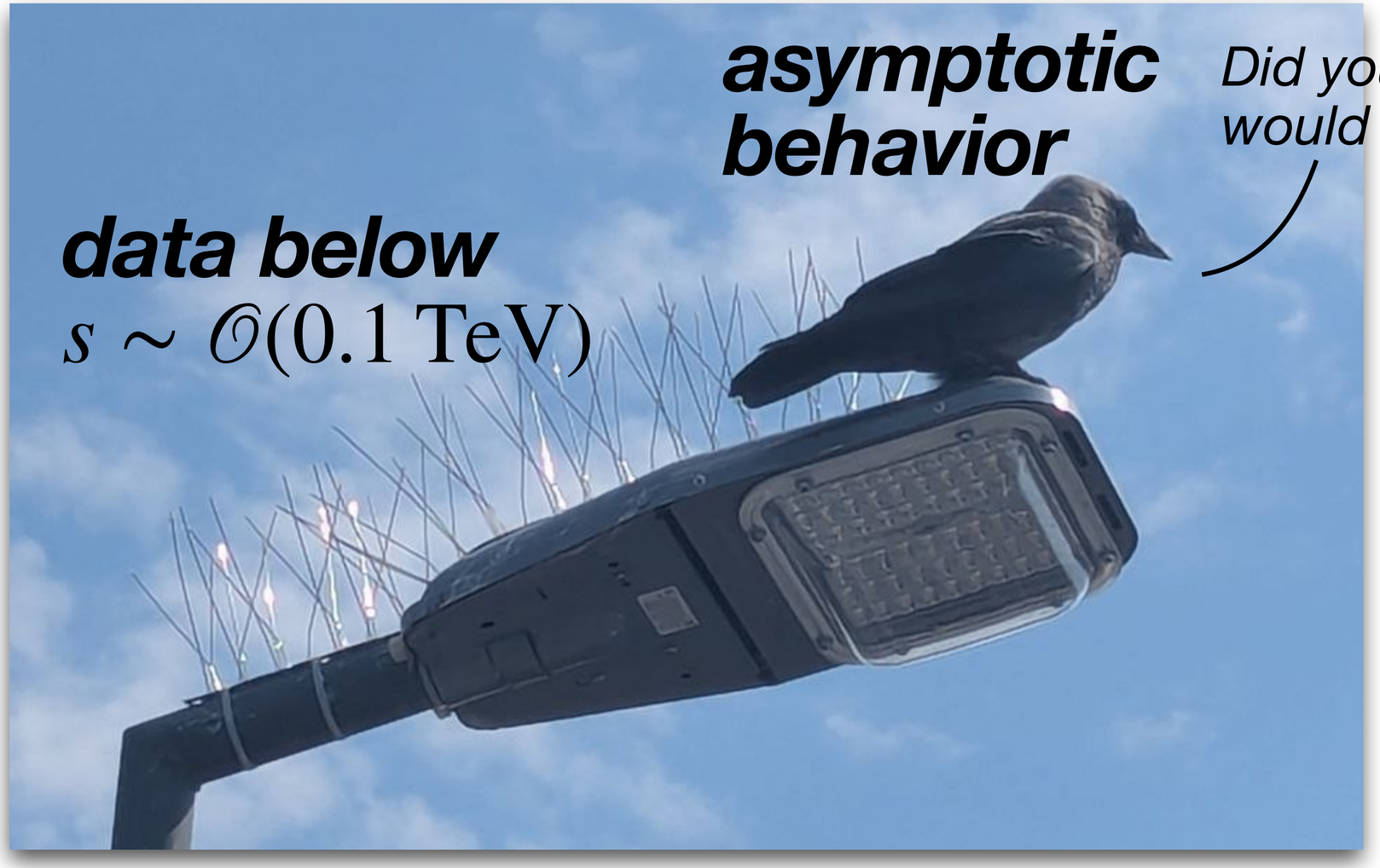
AIRES
CONEX
CORSIKA7
GEANT4
GEANT4(Manual)
SOPHIA
AbramowiczLevinLevyMaor'1991
DonnachieLandshoff'1992
DonnachieLandshoff'1998
DonnachieLandshoff'2001
CapellaKaidalovMerinoTranThanhVan'1994
AbramowiczLevy'1997(ALLM97)
ZEUS'1999(ZEUSREGGE)
ZEUS'2011(A[RCAL]=1.0)
ZEUS'2011(A[RCAL]=0.8)
BlockGregoresHalzenPancheri'1999
CudellEzhelaKangLugovskyTkachenko'2000(RRP)
CudellEzhelaKangLugovskyTkachenko'2000(RRL1)
CudellEzhelaKangLugovskyTkachenko'2000(RRL2)
COMPETE'2002(RRP[nf]L2[u])
COMPETE'2002(RRL[nf])
COMPETE'2002(RRE[nf])
ButkevichMikheyev'2002(γp)
ButkevichMikheyev'2002(γp/2+γn/2)
BUST'2003(μA)
BlockHalzen'2004(Fit1)
BlockHalzen'2004(Fit2)
NovoseltsevNovoseltsevaVereshkov'2009(ScalingViolation)
GodboleGrauPancheriSrivastava'2009(FF)
GodboleGrauPancheriSrivastava'2009(BNγ,Lower)
GodboleGrauPancheriSrivastava'2009(BNγ,Upper)
GodboleGrauPancheriSrivastava'2009(BNF,Lower)
GodboleGrauPancheriSrivastava'2009(BNF,Center)
GodboleGrauPancheriSrivastava'2009(BNF,Upper)
HümmerRügerSpanierWinter'2010
BlockDurandHa'2014
HHT'2017(HHT-ALLM)
HHT'2017(HHT-ALLM-FT)
HHT'2017(HHT-REGGE)
HHT'2017(HHT-REGGE-3p-.85)
HHT'2017(HHT-REGGE-4p)
HHT'2017(HHT-REGGE-FT-4p)
HHT'2017(HHT-REGGE-PHP-5p)
HHT'2017(HHT-REGGE-PHP-FT-5p)
HHT'2017(ZEUSREGGE-update)
GámezGutiérrezMartínezMasip'2020
low-energy data'1968–78
BUST'2003 (μA)
H1'1995 (ep)
ZEUS'2002 (ep)
ZEUS'1999 (ep, $Q^2 \neq 0$)

Motivation & Method: PNR cross section



HE region: anything goes…

Motivation & Method: PNR cross section



Motivation & Method: PNR cross section $\mapsto N_\mu$

Ref.: *Phys. Rev. D* **113**, 083026 (2026), by NM

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}\ln E_\gamma\,\mathrm{d}X_\gamma}$$

HE photons distribution within an EAS, which depends on $(E, A, E_\gamma, X_\gamma)$

$$\frac{\mathrm{d}N'_{\mu(\leftarrow\gamma A)}}{\mathrm{d}\ln E_{\gamma A}}$$

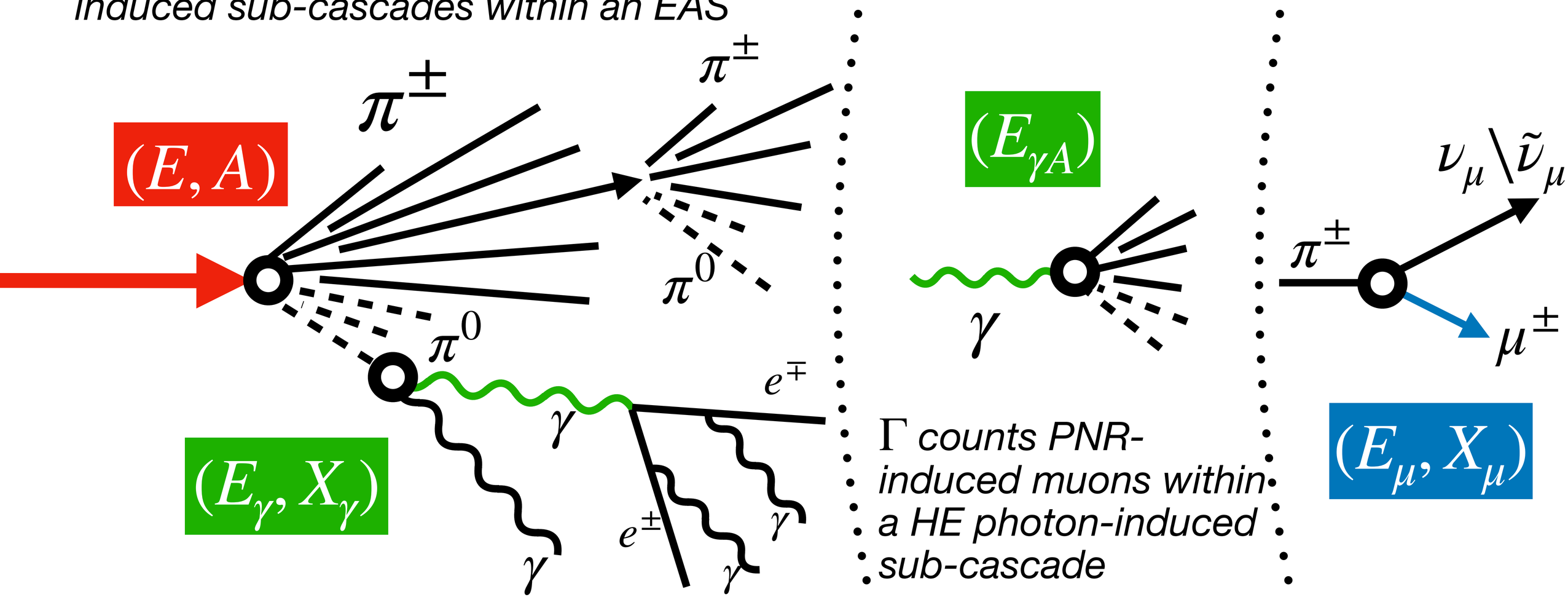
Number-of-muons distribution induced by (grand)^{N}parent HE PNR reactions, which is $\Gamma(E_\gamma, E_{\gamma A}, X_\mu - X_\gamma)\cdot\bar\sigma_{\gamma A}(E_{\gamma A})$*, where* Γ *does not depend on* $\bar\sigma_{\gamma A}$

$$\frac{\mathrm{d}N_{\mu(\leftarrow\gamma A)}}{\mathrm{d}\ln E_{\gamma A}} = \int\limits_{\ln E_{\gamma A}}^{\ln E} \mathrm{d}\ln E_\gamma \int\limits_0^{X_\mu} \mathrm{d}X_\gamma \left[\frac{\mathrm{d}N_\gamma}{\mathrm{d}\ln E_\gamma\,\mathrm{d}X_\gamma}\times\frac{\mathrm{d}N'_{\mu(\leftarrow\gamma A)}}{\mathrm{d}\ln E_{\gamma A}}\bigg|_{X_\mu - X_\gamma}\right]$$

$$=: G(E, A, E_{\gamma A}, X_\mu)\cdot\sigma_{\gamma A}(E_\gamma) = A\cdot G(E/A, 1, E_{\gamma A}, X_\mu)\cdot\sigma_{\gamma A}(E_\gamma)$$

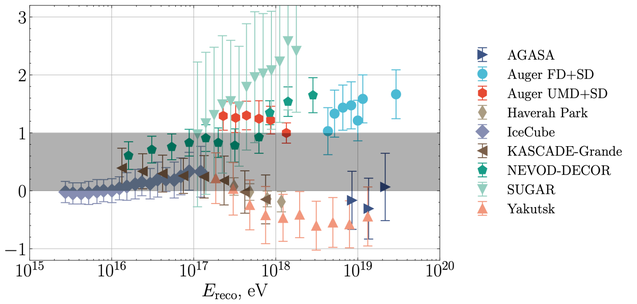
Motivation & Method: PNR cross section $\mapsto N_\mu$

G integrates Γ over all HE photon-induced sub-cascades within an EAS

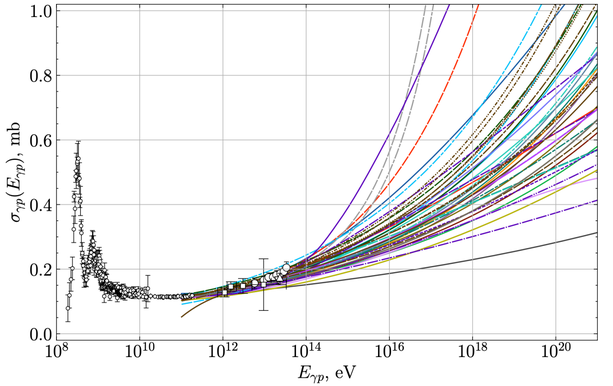


Γ counts PNR-induced muons within a HE photon-induced sub-cascade

Motivation & Method: Summary



– we are obviously in trouble with describing the muon content of EASs at HE region



– HE PNR cross section is extremely uncertain

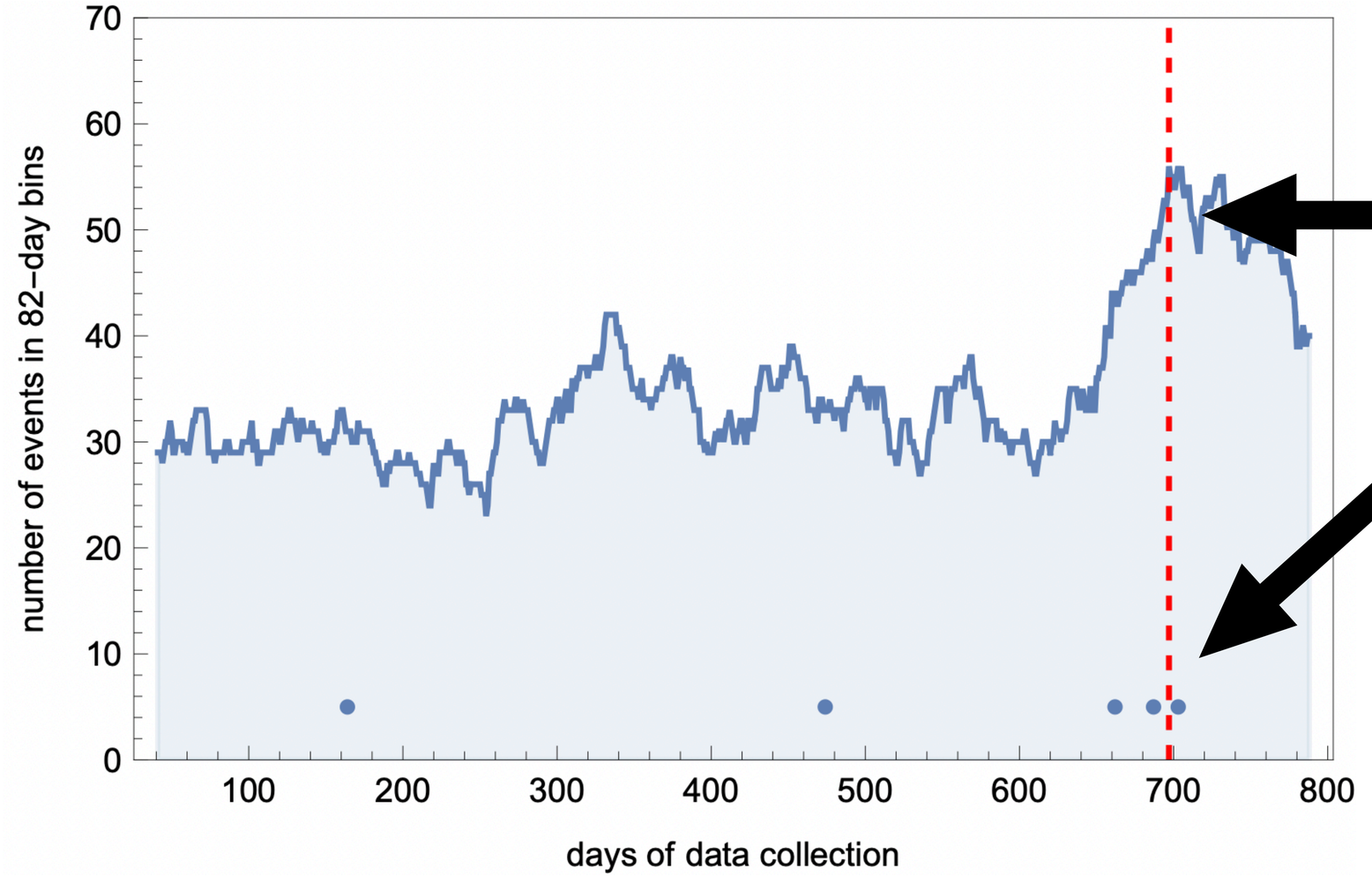
– HE PNRs are guaranteed to contribute to the muon content of EASs

*– now **we know this contribution** without the need to average over an infinite number of simulations!*

$$\frac{\mathrm{d}N_{\mu(\leftarrow\gamma A)}}{\mathrm{d}\ln E_{\gamma A}} = \int\limits_{\ln E_{\gamma A}}^{\ln E} \mathrm{d}\ln E_\gamma \int\limits_0^{X_\mu} \mathrm{d}X_\gamma \left[\frac{\mathrm{d}N_\gamma}{\mathrm{d}\ln E_\gamma\, \mathrm{d}X_\gamma} \times \frac{\mathrm{d}N'_{\mu(\leftarrow\gamma A)}}{\mathrm{d}\ln E_{\gamma A}} \bigg|_{X_\mu - X_\gamma} \right] =: G(E, A, E_{\gamma A}, X_\mu) \cdot \sigma_{\gamma A}(E_\gamma) = A \cdot G(E/A, 1, E_{\gamma A}, X_\mu) \cdot \sigma_{\gamma A}(E_\gamma)$$

Challenge 1: CR(?!) excess from Cygnus

Ref.: *Astrophys. J. Lett.* 916 (2021) 2, L22 (by Carpet-3 Collaboration)
Astrophys. J. Lett. 921 (2021) 1, L10 (by A.M. Bykov *et al.*)



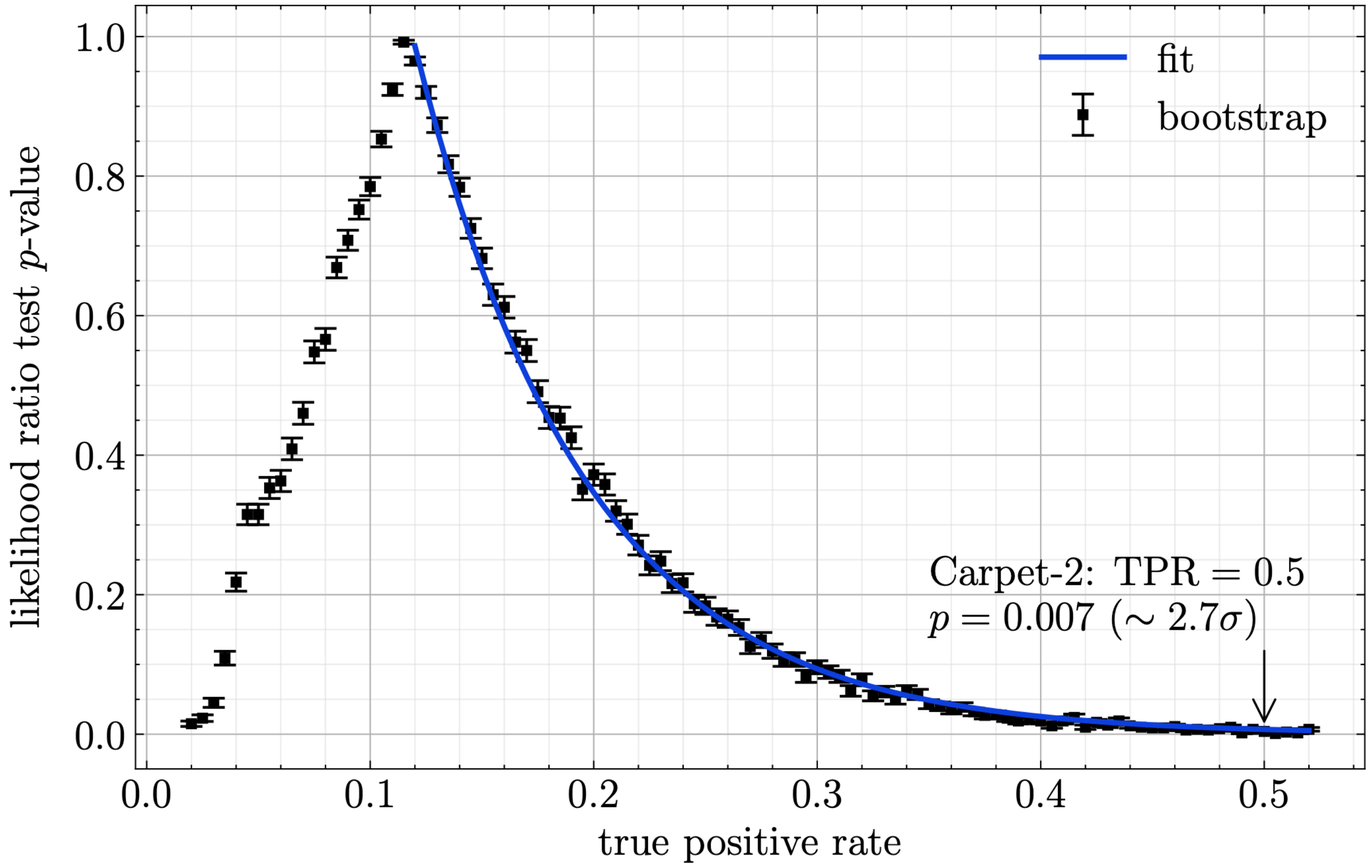
total excess: ~24

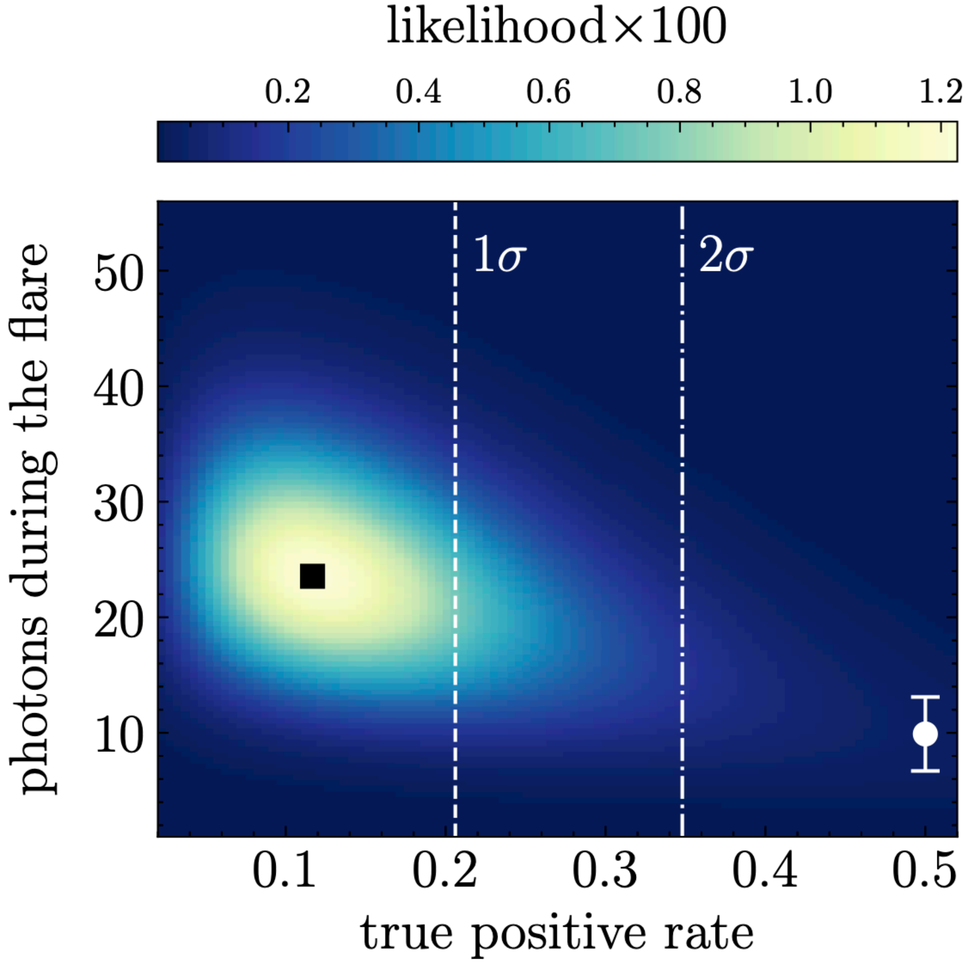
photon candidates (muon-poor EASs): 3
total photons: ~10

~14 events unexplained — cosmic rays?!

Challenge 1: CR(?!) excess from Cygnus

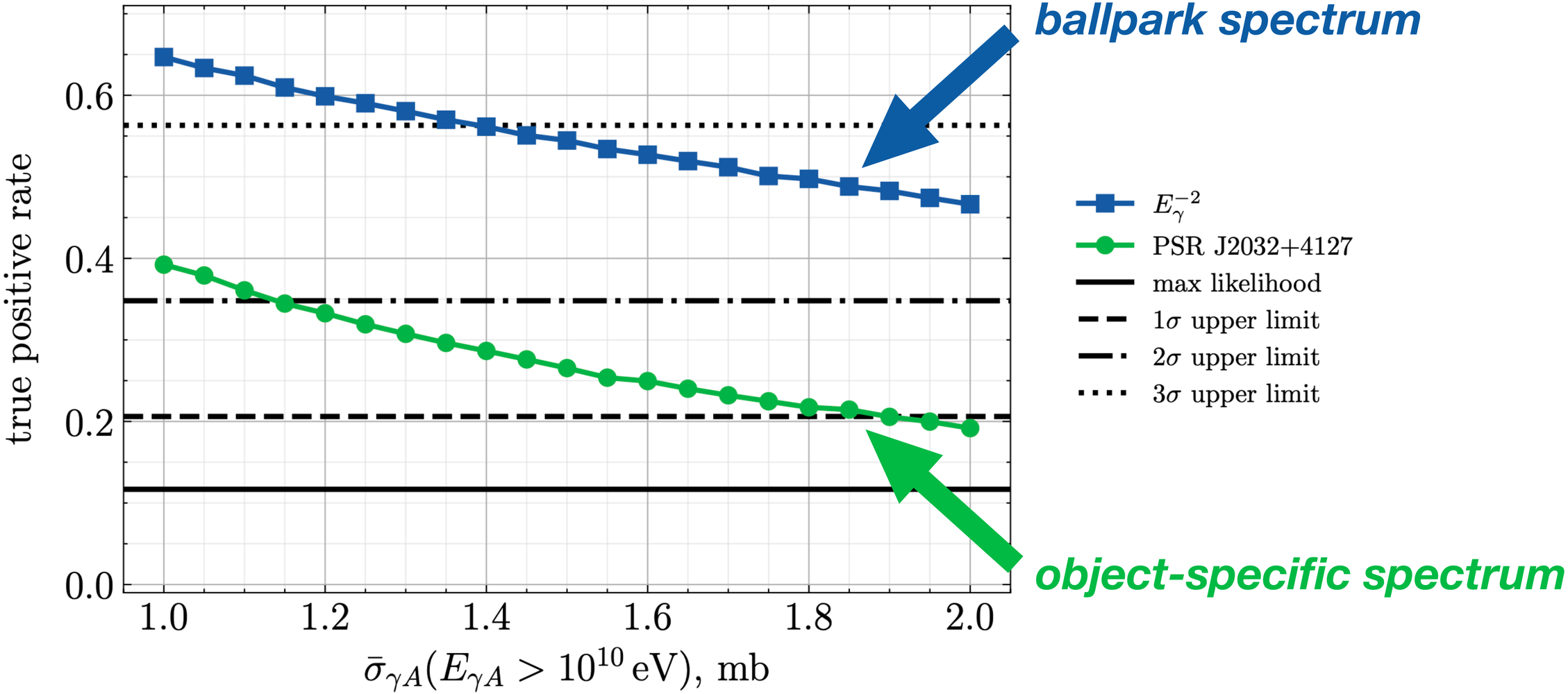
Random coincidence of the flare with a Poissonian positive fluctuation in CR flux: $\sim 2.7\sigma$ tension





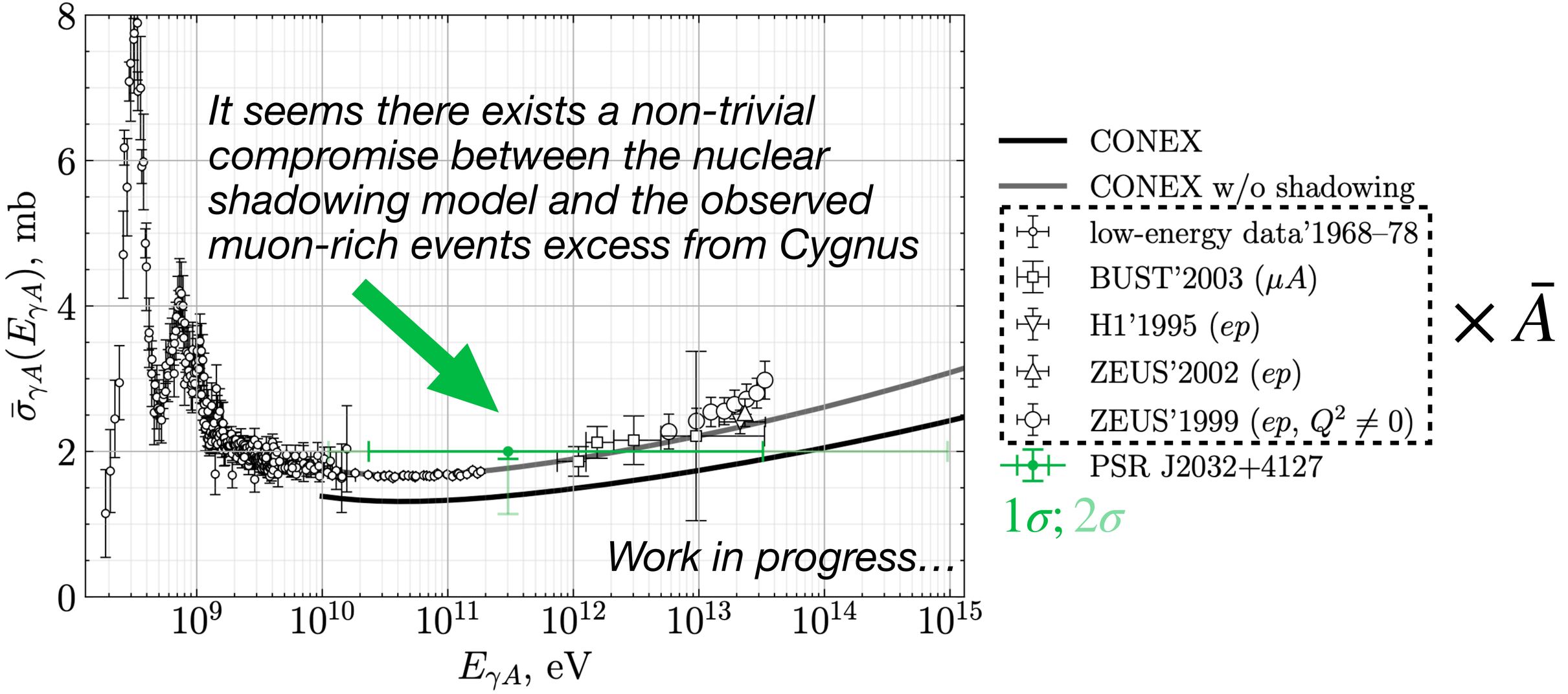
Challenge 1: CR(?!) excess from Cygnus

What if HE PNR cross section is actually larger and TPR is lower?



Challenge 1: CR(?!) excess from Cygnus

One can constrain the HE PNR cross section HE photon flares!



Challenge 2: UHECR composition and muon excess

Let us consider a family of HE PNR cross section models such that:

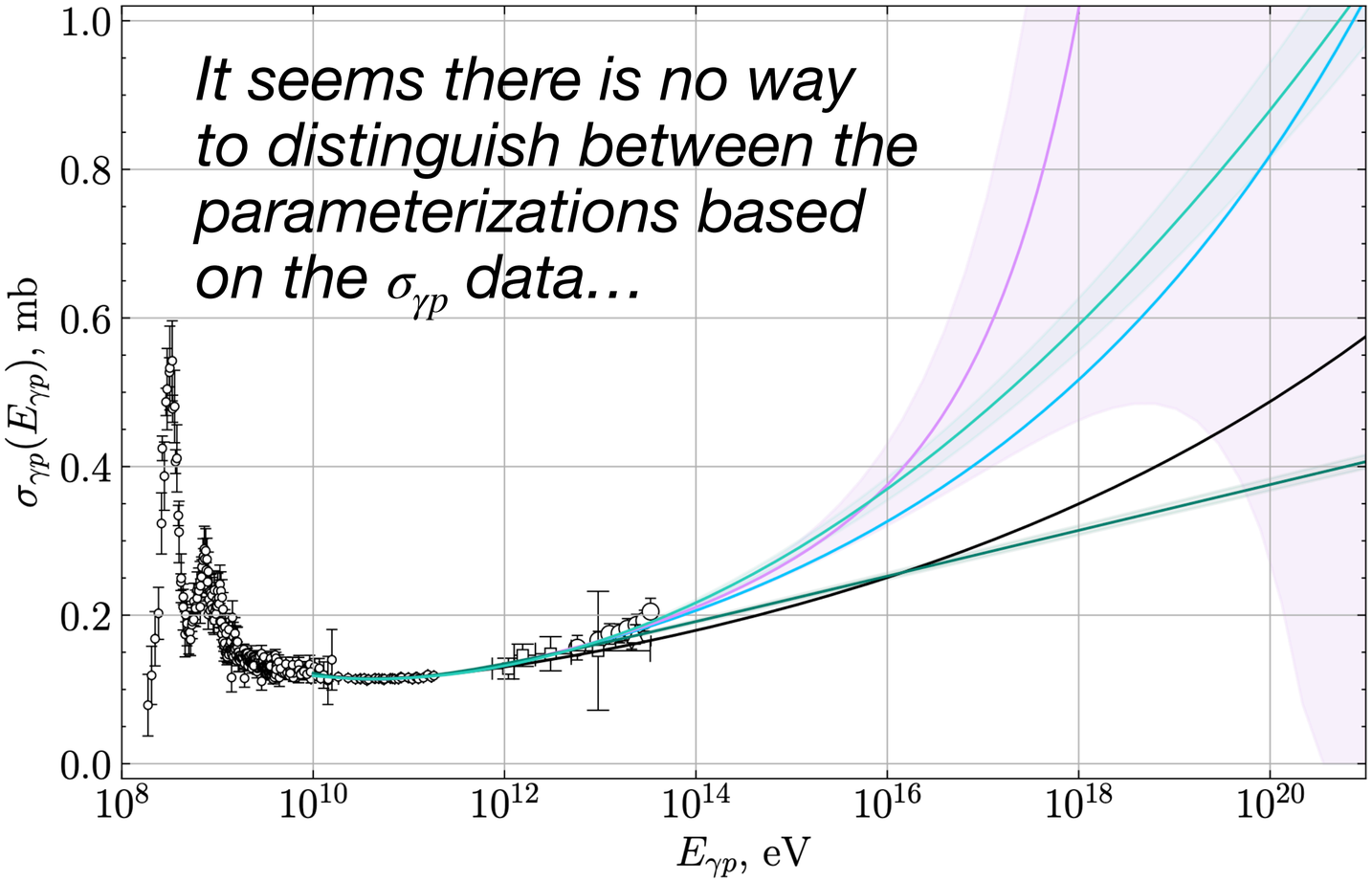
(a) parametrization is smooth and has some physical motivation
(b) parametrization is universal above $E_{\gamma A} \sim 10\,\mathrm{GeV}$
(c) cross sections do not contradict to $\sigma_{\gamma p}$ *data at* $E_{\gamma A} \gtrsim 10\,\mathrm{GeV}$

→

Soft Pomeron, $\sigma_{\gamma p} \sim \mathcal{O}(s^{0.1})$
Hard Pomeron, $\sigma_{\gamma p} \sim \mathcal{O}(s^{0.5})$
Froissart, $\sigma_{\gamma p} \sim \mathcal{O}(\ln s)$
Saturated Froissart, $\sigma_{\gamma p} \sim \mathcal{O}(\ln^2 s)$

Using our method, we maximize the N_μ *enhancement subject to the constraints (a–c) and obtain upper bounds on the positive systematic uncertainty of* N_μ

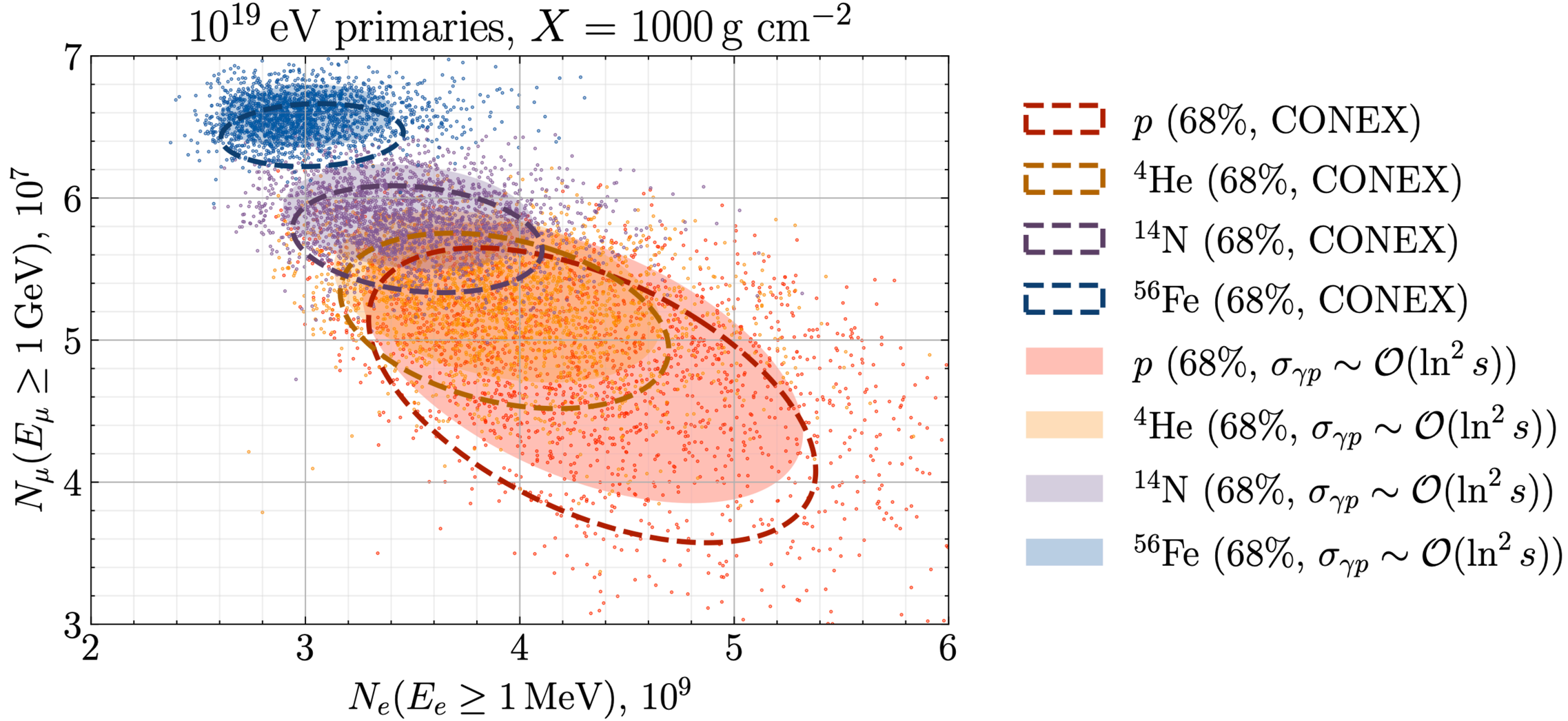
Challenge 2: UHECR composition and muon excess



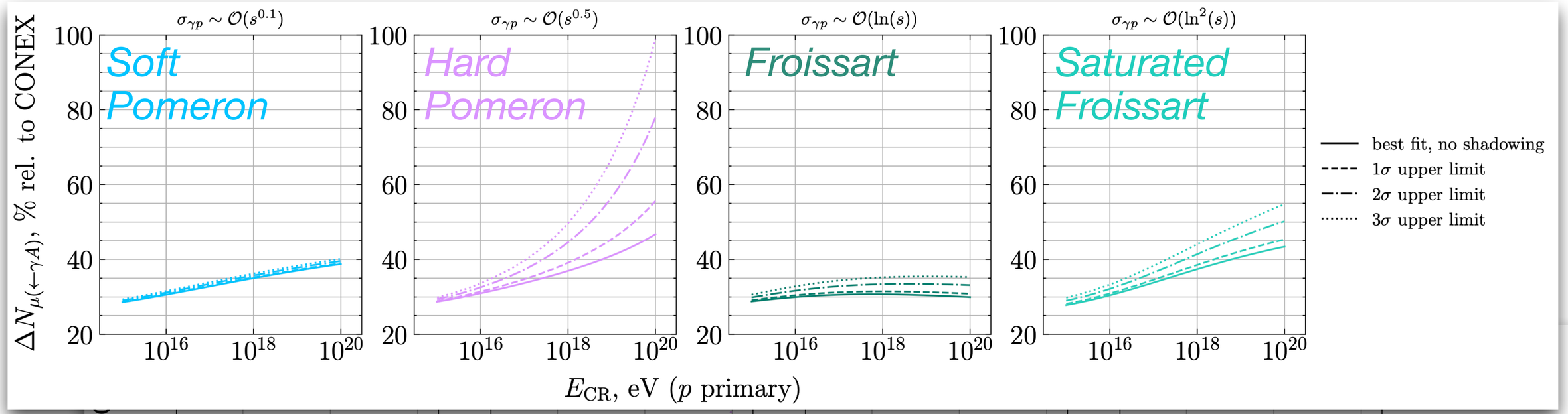
- CONEX
- $\sigma_{\gamma p} \sim \mathcal{O}(s^{0.1})$ *Soft Pomeron*
- $\sigma_{\gamma p} \sim \mathcal{O}(s^{0.5})$ *Hard Pomeron*
- $\sigma_{\gamma p} \sim \mathcal{O}(\ln(s))$ *Froissart*
- $\sigma_{\gamma p} \sim \mathcal{O}(\ln^2(s))$ *Saturated Froissart*
- low-energy data'1968–78
- BUST'2003 (μA)
- H1'1995 (ep)
- ZEUS'2002 (ep)
- ZEUS'1999 (ep, $Q^2 \neq 0$)

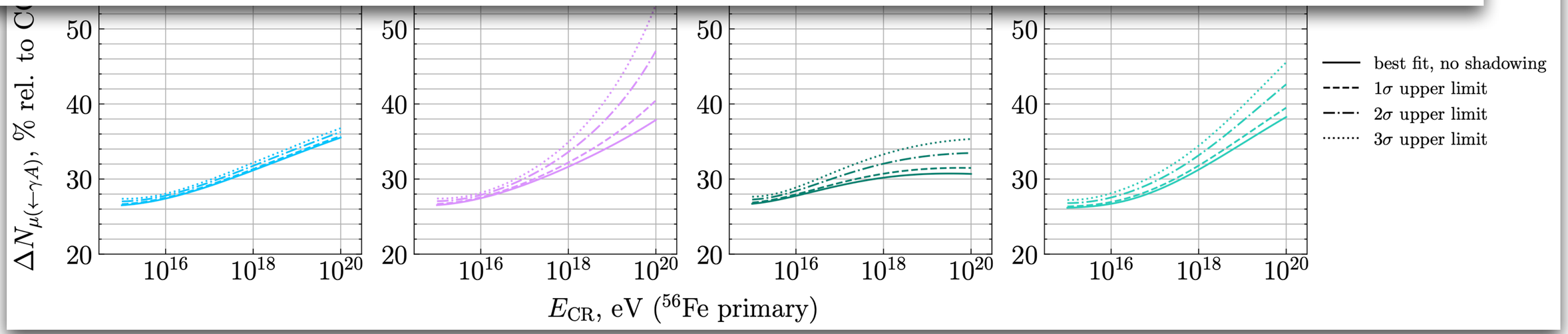
Challenge 2: UHECR composition and muon excess

$A_{\rm reco} > A_{\rm true}$ *even for Saturated Froissart,* $\sigma_{\gamma p} \sim \mathcal{O}(\ln^2 s)$ *model!*

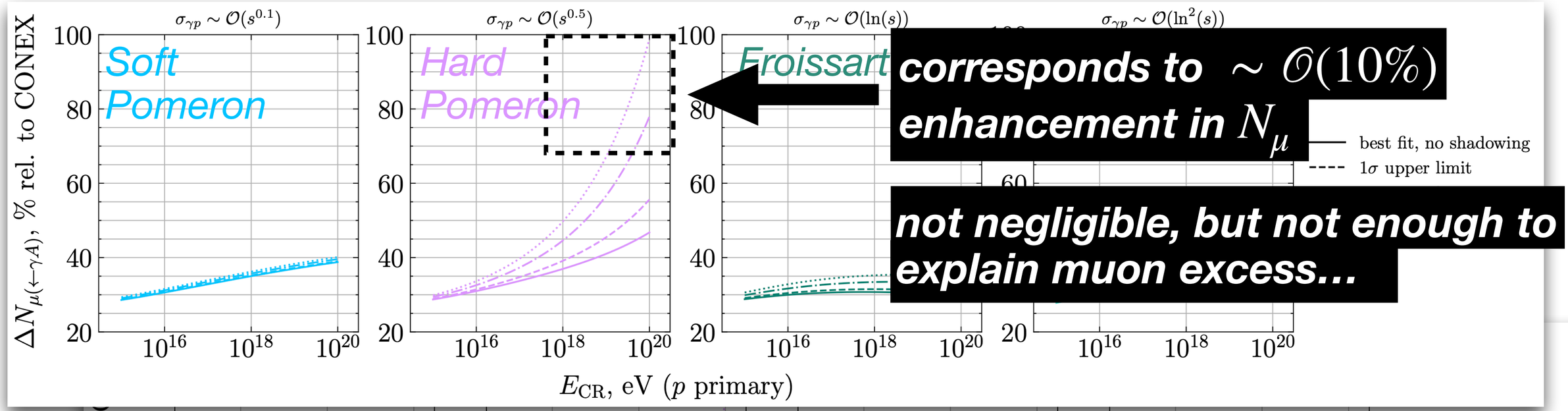


Challenge 2: UHECR composition and muon excess



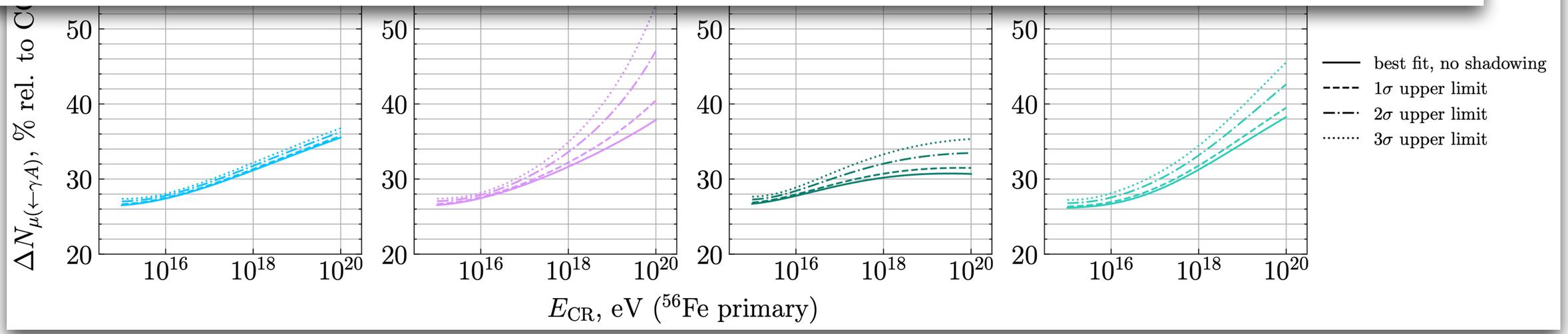


Challenge 2: UHECR composition and muon excess



corresponds to $\sim \mathcal{O}(10\%)$ enhancement in N_μ

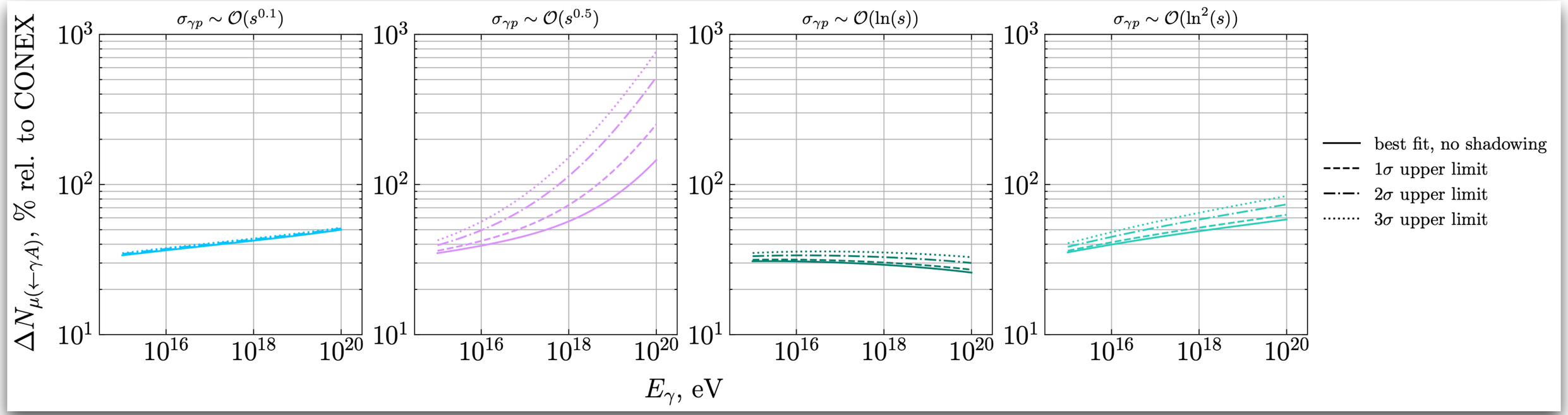
not negligible, but not enough to explain muon excess…



Challenge 3: searches for UHE photons

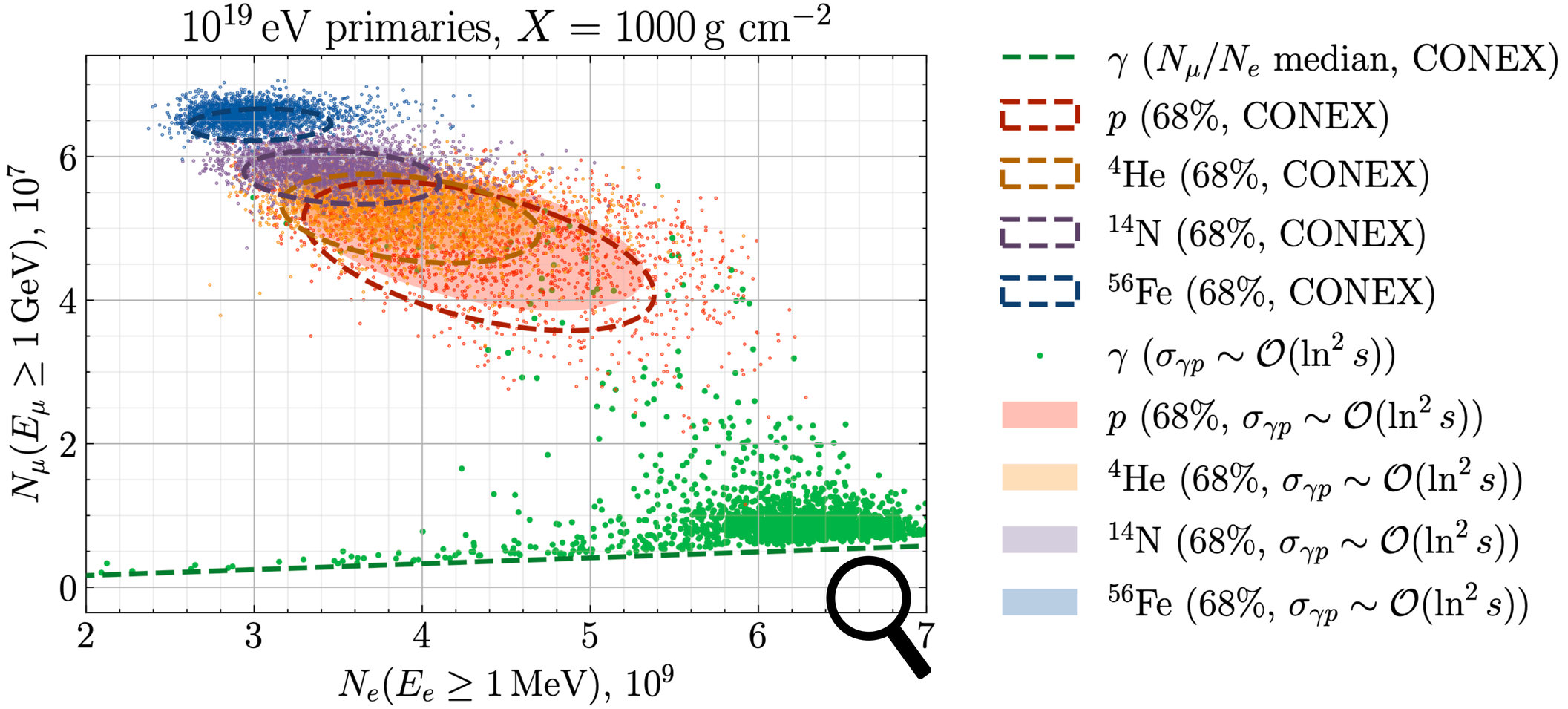
The approach is exactly the same as for CR

*Note the logarithm scale and note that muons from HE PNRs dominate in photon-induced EASs' muon content — the systematic uncertainty is **MUCH** larger!*



Challenge 3: searches for UHE photons

*There may be **NO** photon-induced EASs in the region of their search… UHE photon flux should be readdressed!*



Summary: What have we learned?

*– There is an important interplay between the HE PNR cross section behavior (which is **VERY** uncertain!) and modern challenges in EAS physics*

– We have developed a method to study this interplay

– Using this method, one can (at least!):

— constrain HE PNR cross section from photon-induced EASs,

— estimate the systematic uncertainty of the reconstructed UHECR composition and of the UHE photon flux

Thank you!