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AMBER
Apparatus for Meson and Baryon Experimental Research

AMBER Phase II: QCD physics beyond colliders

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For the AMBER Collaboration

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Physics beyond Colliders - Emergent Phenomena

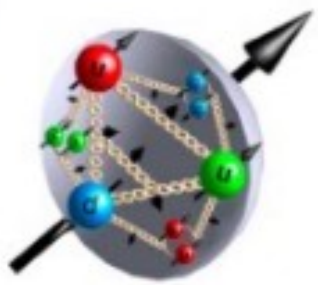
Pion

- $M_\pi \sim 140$MeV
- Spin 0
- 2 light valence quarks

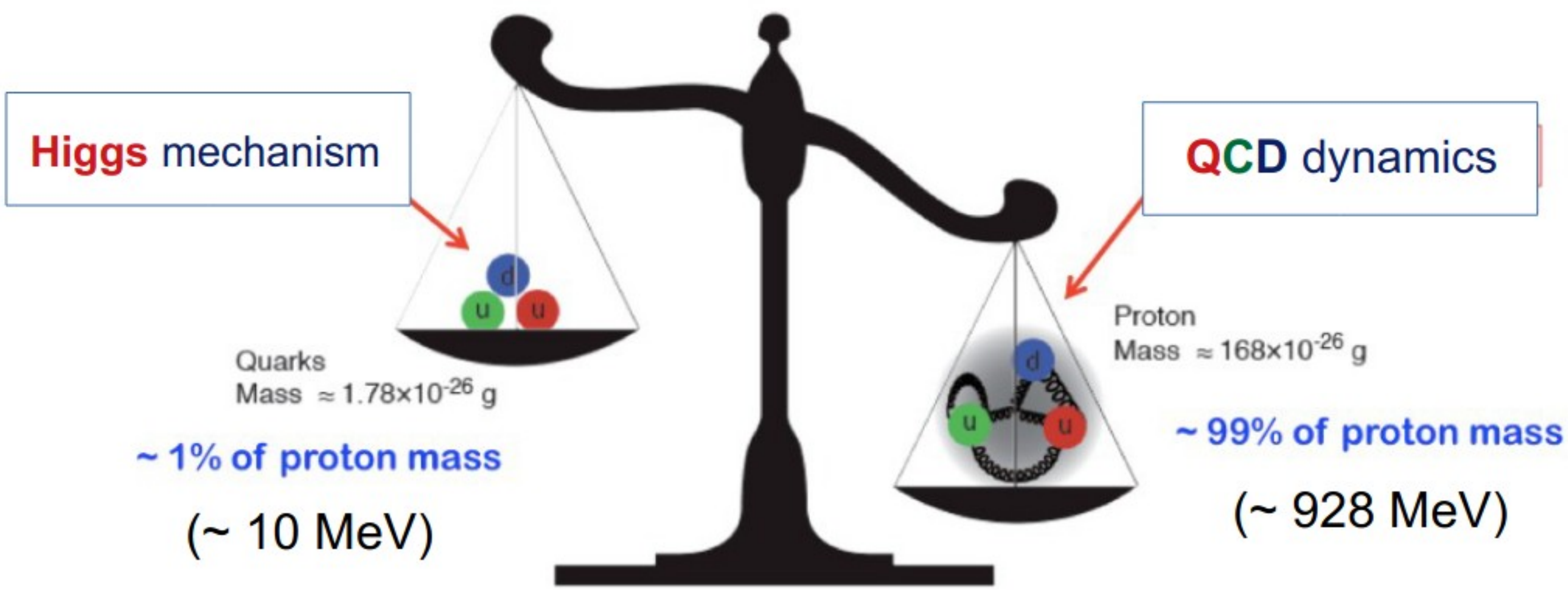
Kaon

- $M_K \sim 490$MeV
- Spin 0
- 1 light and 1 "heavy" valence quarks

Proton



- $M_p \sim 940$MeV
- Spin 1/2
- 3 light valence quarks



Explore QCD in detail to understand emergent phenomena

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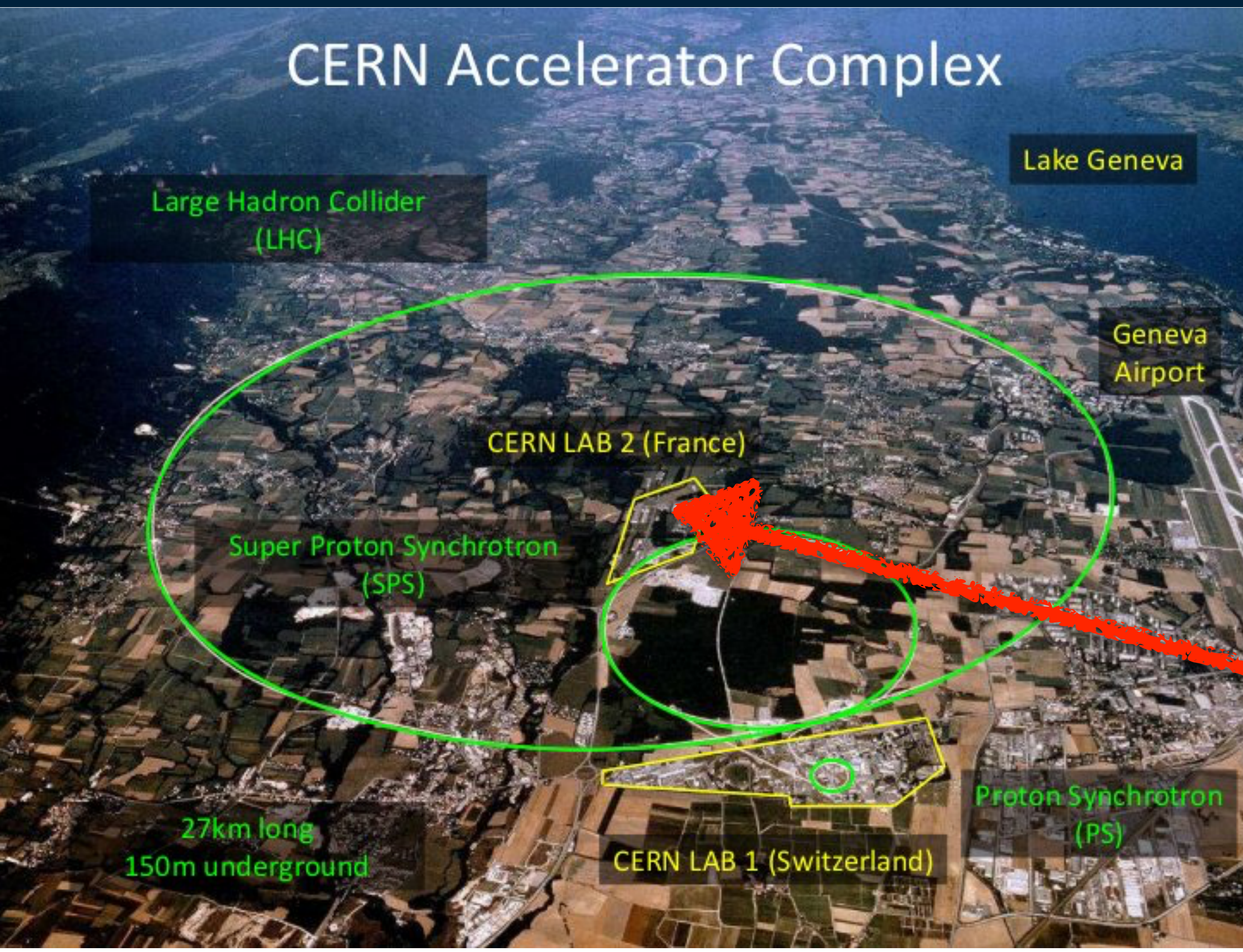

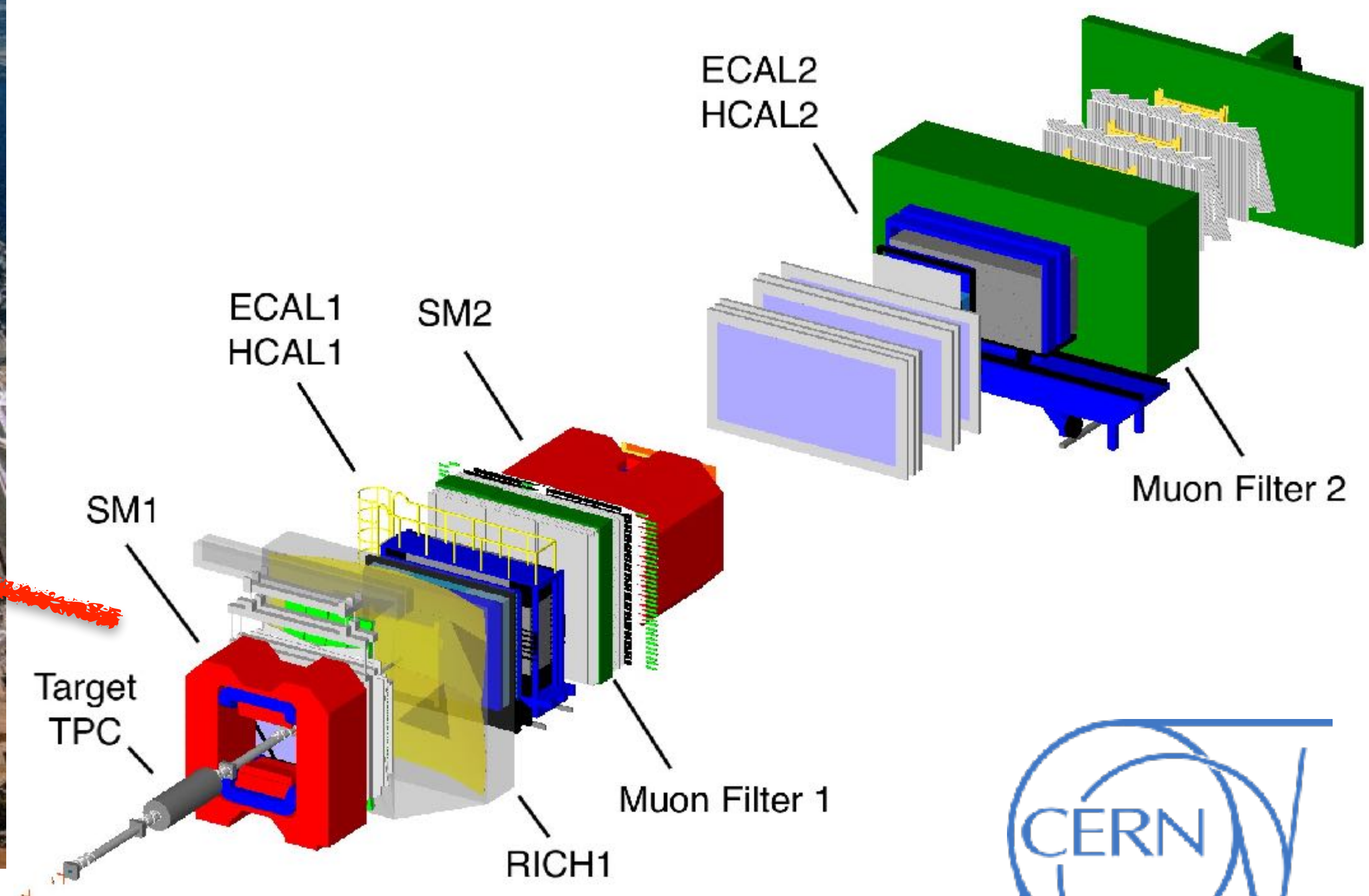

Use M2 beam in the CERN/SPS North Area
Versatile beams (muons and hadrons of both charges)
Beam momenta ranging from 50 - 280 GeV/c
Intensity limited by radiation protection

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	Beam	Target	Additional Hardware	
Proton radius measurement	***100 GeV muons***	***high pressure Hydrogen***	***active target TPC, tracking stations (SciFi, Silicon)***	Phase 1 (approved)
Antiproton production cross section	***50 GeV - 280 GeV protons***	***LH_2, LHe***	***Liquid He target***	
Drell-Yan measurements with pions	***190 GeV charged pions***	***Carbon, Tungsten***		
Drell-Yan measurements with Kaons	***~100 GeV charged Kaons***	***Carbon, Tungsten***	***vertex detectors, ‘active absorber’***	Phase 2 (in preparation)
Prompt photon measurements	***> 100 GeV charged Kaon/pion beams***	***LH_2, Nickel***	***hodoscopes***	
K-induced spectroscopy	***50 GeV - 100 GeV charged Kaons***	***LH_2***	***recoil ToF, forward PID***	

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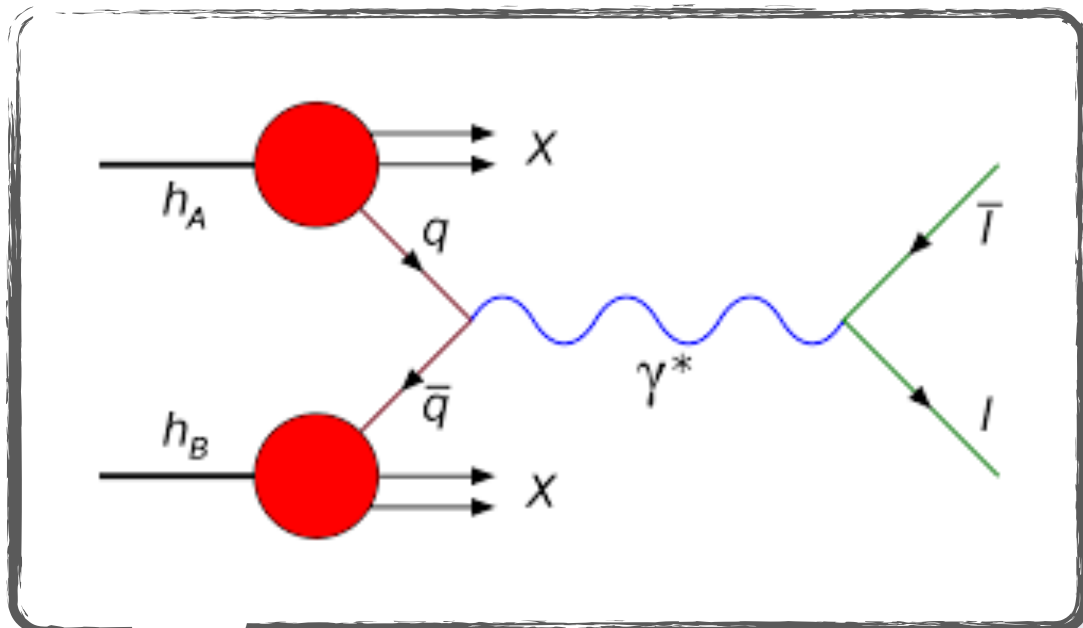

		Target	Additional Hardware
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se		LH_2, LHe	Liquid He target
Dre Yan mea urements with pion	190 GeV charged pions	Carbon, Tungsten	
Drell-Yan measurements with Kaons	~100 GeV charged Kaons	Carbon, Tungsten	vertex detectors, 'active absorber'
Prompt photon measurements	> 100 GeV charged Kaon/pion beams	LH_2, Nickel	hodoscopes
K-induced spectroscopy	50 GeV - 100 GeV charged Kaons	LH_2	recoil ToF, forward PID

Phase 1 (approved)

Phase 2 (in preparation)

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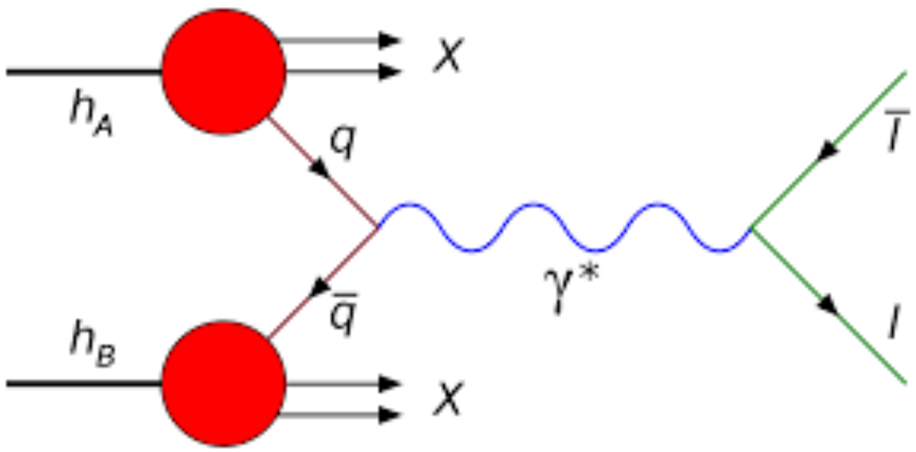

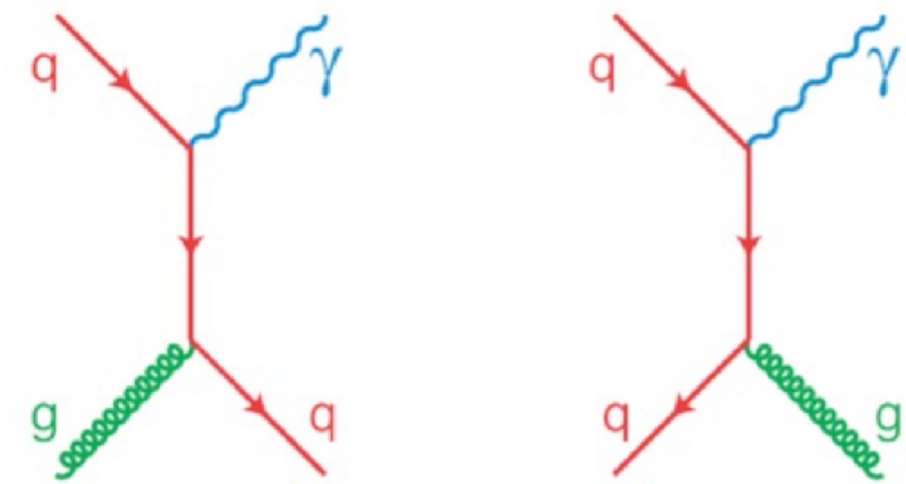

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se			
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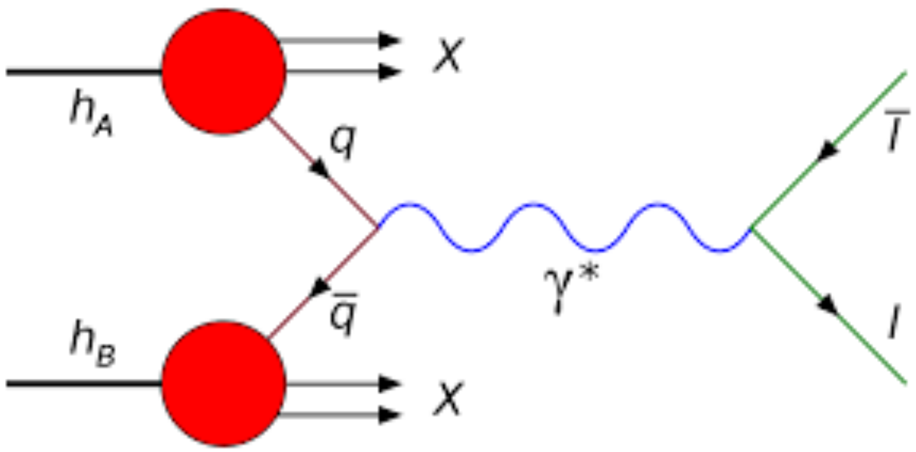

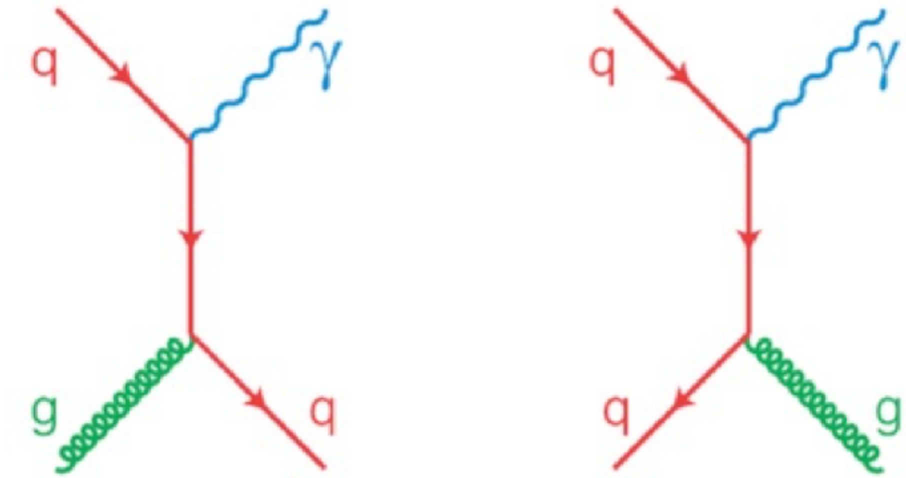

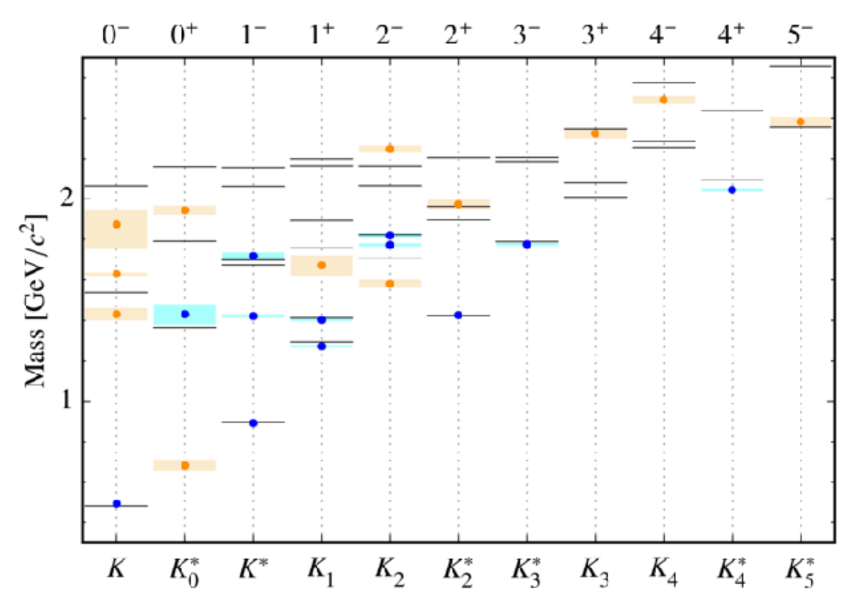

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		LH...	
se...			
Dre... ...an mea... ...urements with pion...	190 GeV charg... pions	Carbon, Tungst...	
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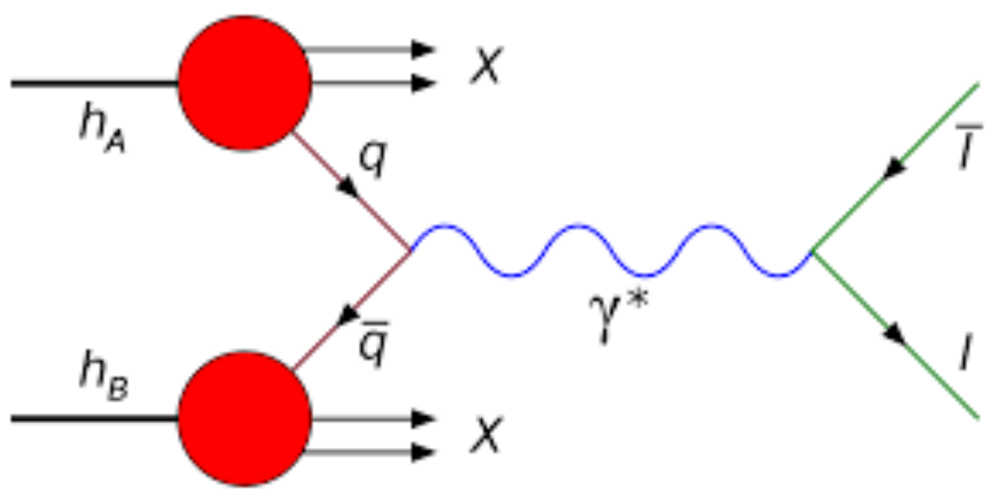
K-induced spectroscopy	50 GeV... charged Kaons	LH_2	recoil ToF, forward PID

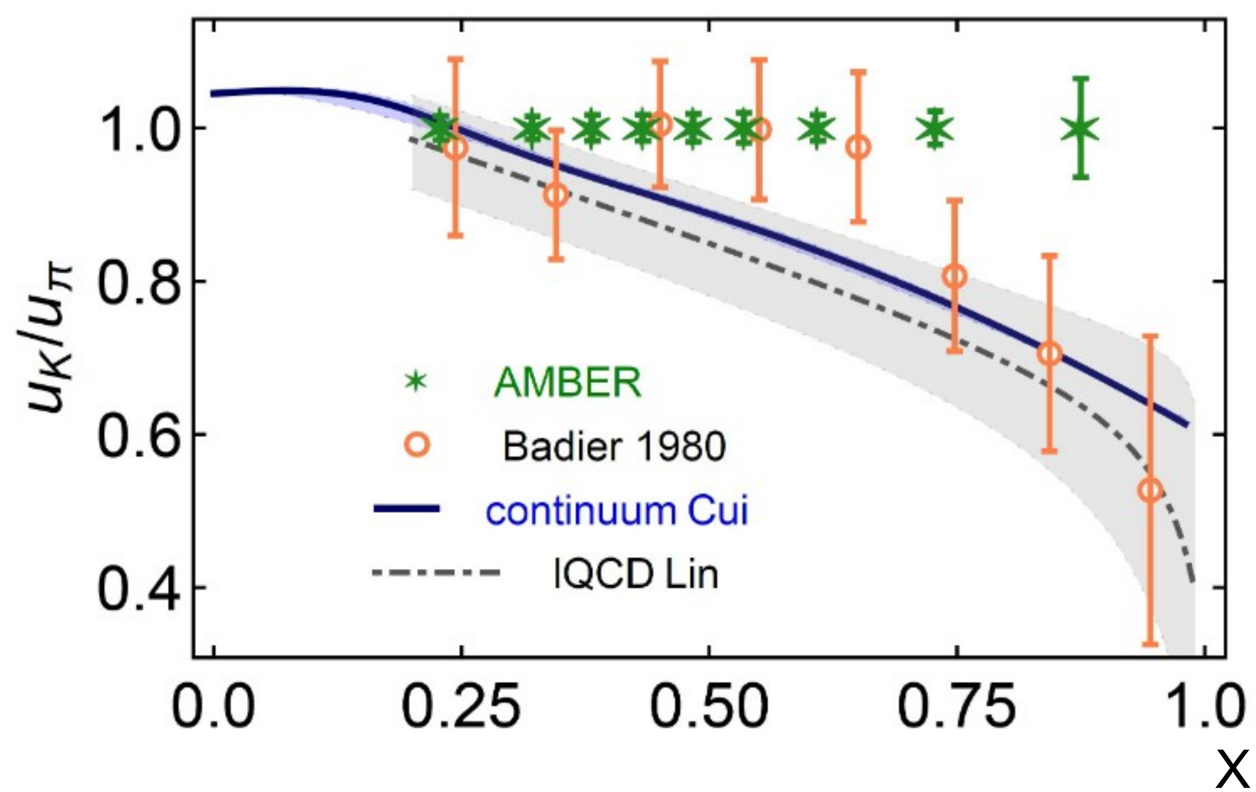
Phase 1 (approved)

Phas... (in p...

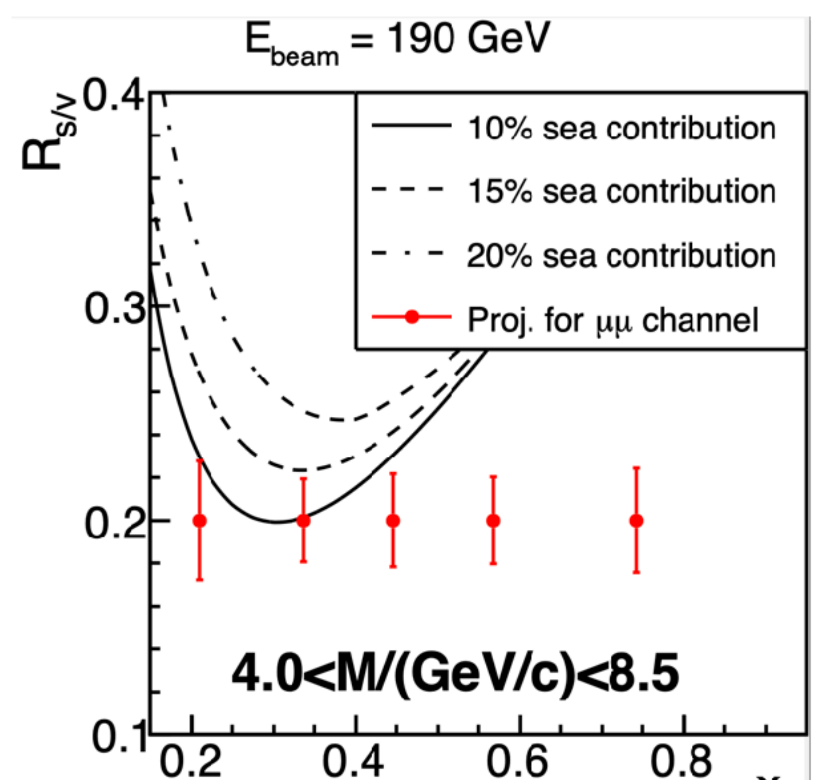
From Pions to Kaons - Drell Yan process

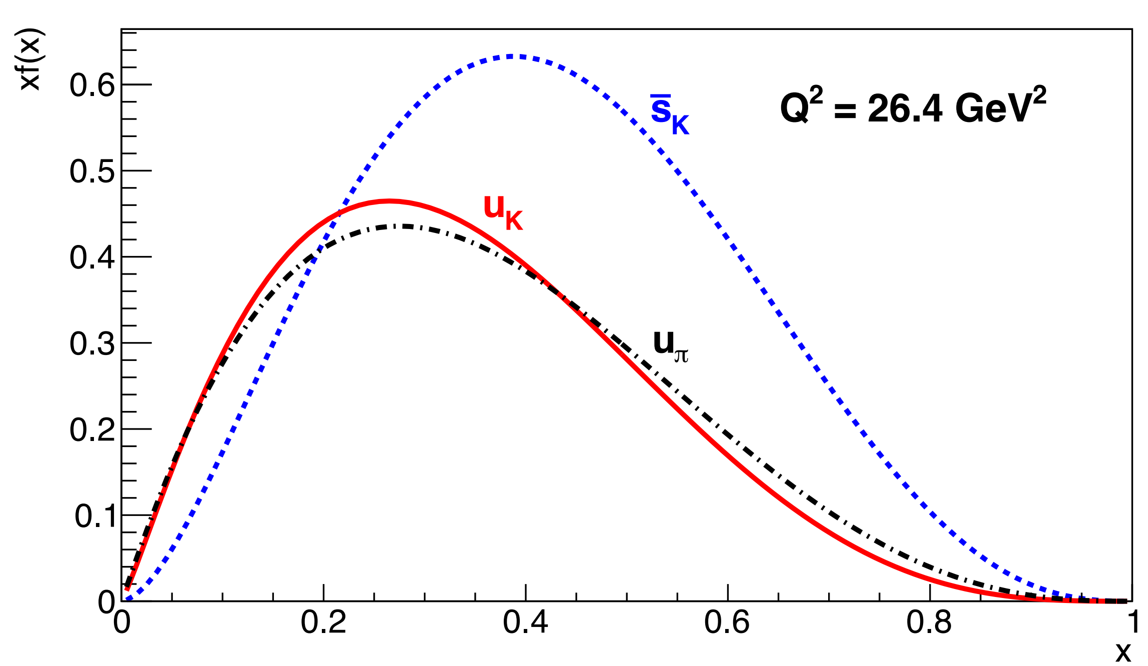


Z-F. Cui, *et al.* EPJC80(2020)1064, H-W. Lin *et al.*, PRD103(2021)014516

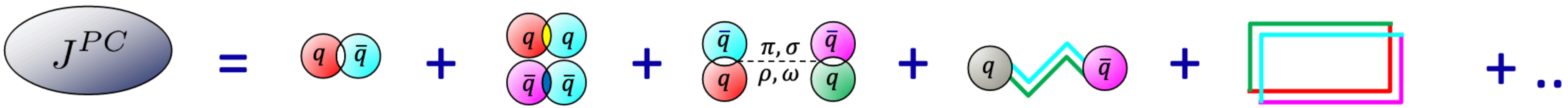


Inclusive di-lepton measurement





Meson spectroscopy



$(q\bar{q})_0$ $(qq)_8(\bar{q}\bar{q})_8$ $(q\bar{q})_0(q\bar{q})_0$ $(q\bar{q})_8 g$ $(gg)_0$

Tetraquark Molecule Hybrid Glueball

Where are they?

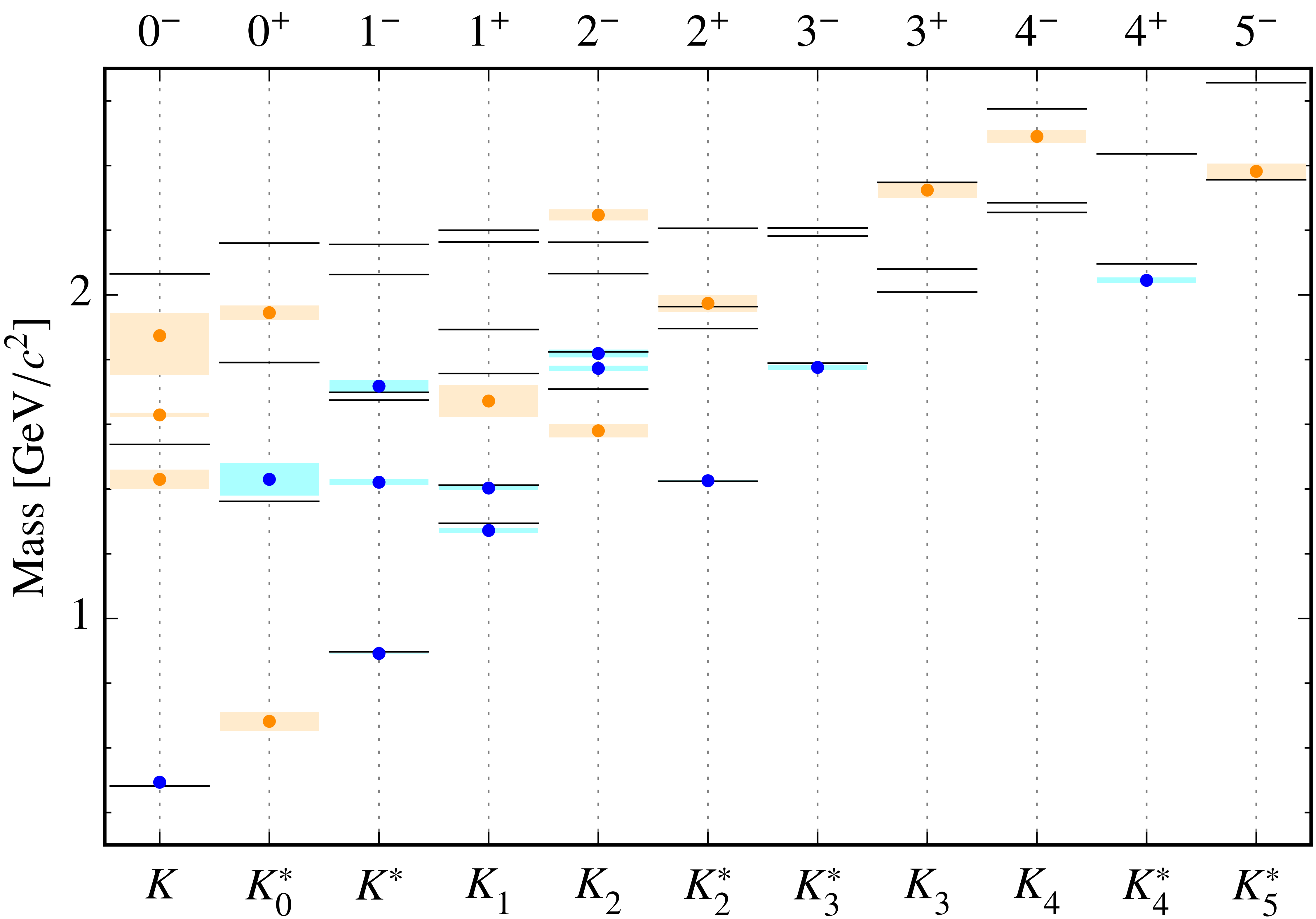
How to identify them?

- Spin-exotic: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, \ldots$
- Supernumerary states
- Flavor-exotic: $|Q|, |I_3|, |S|, |C| \geq 2$
- Comparison with models, lattice

Need:

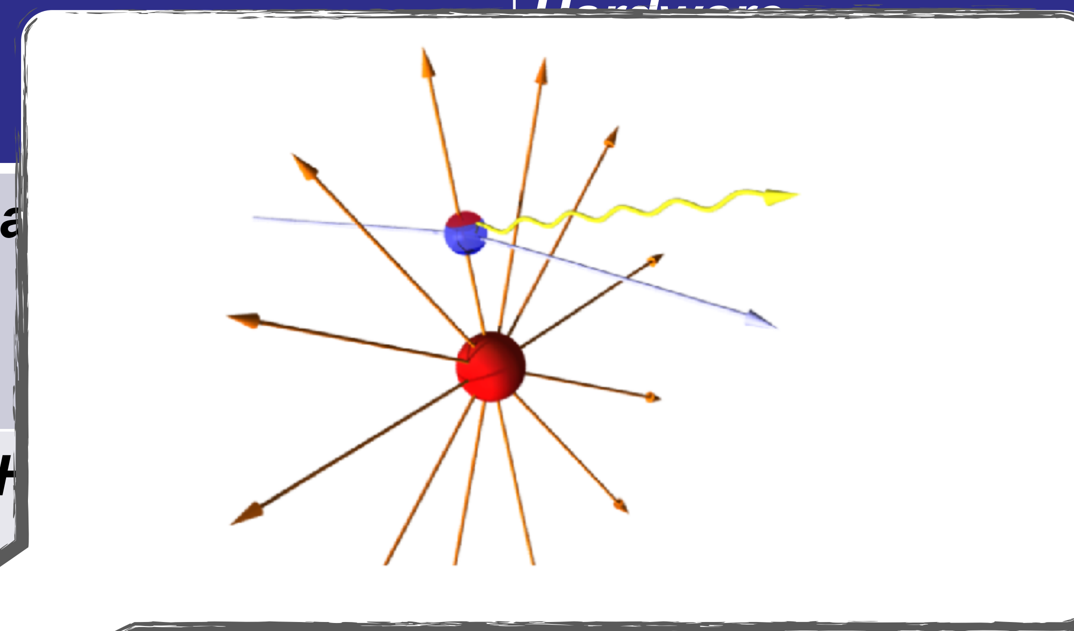
- Large data sets with small statistical uncertainties
- Complementary experiments
  - production mechanisms
  - final states
- Advanced analysis methods
  - reaction models
  - theoretical constraints

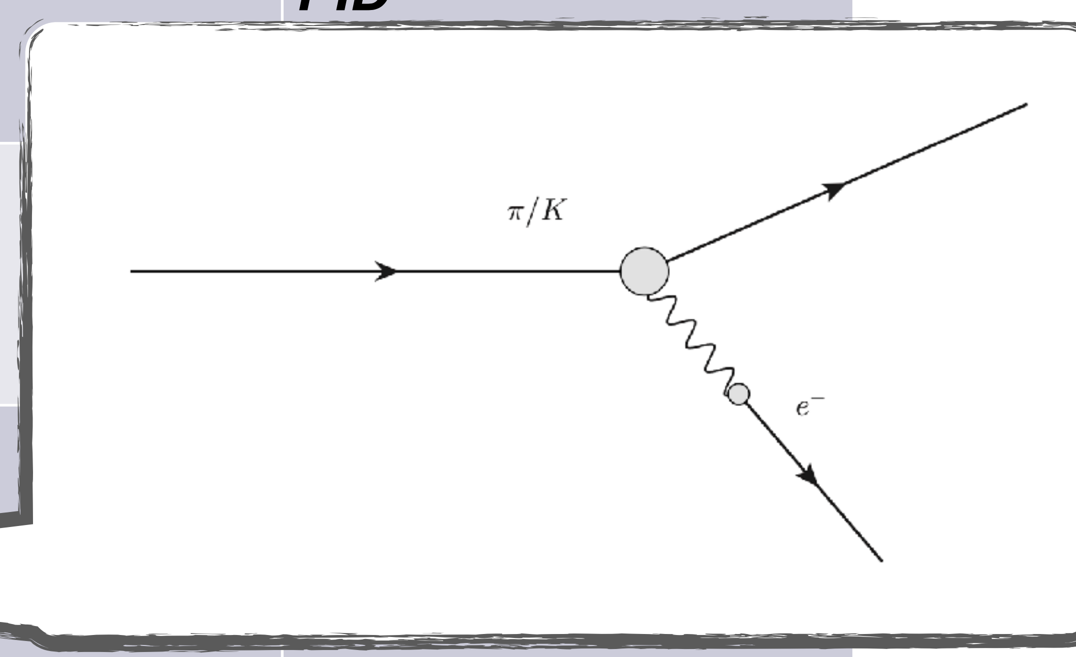
Kaonic mass spectrum



And there is more

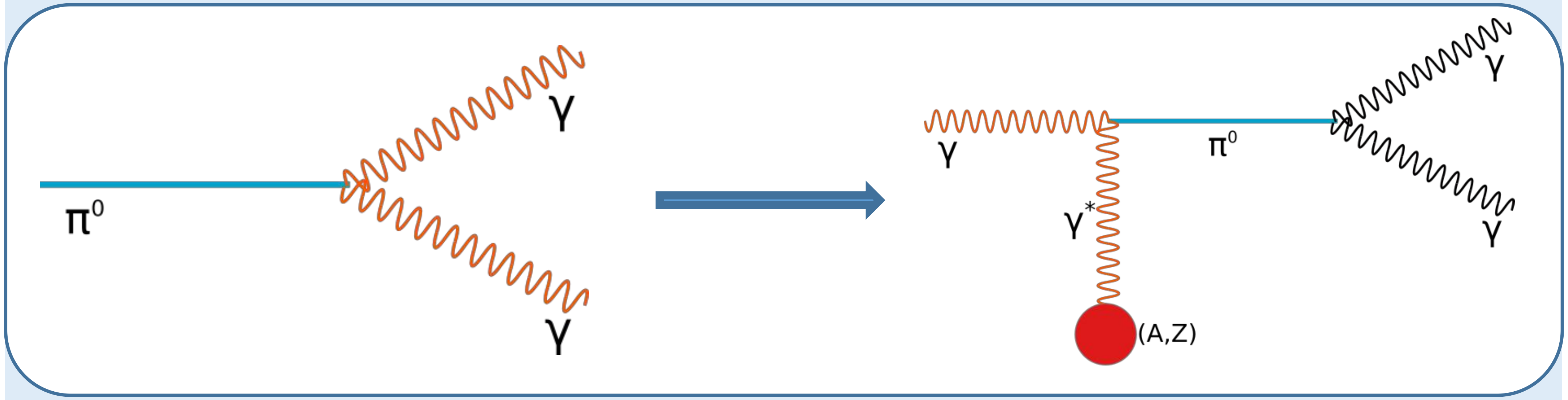
	Beam	Target	Additional
Drell-Yan measurements with Kaons	~100 GeV charged Kaons	Ca	
Prompt photon measurements	> 100 GeV charged Kaon/pion beams	LH	
K-induced spectroscopy	50 GeV - 100 charged	LH_2	recoil ToF, forward PID
Primakoff reactions	~ 100 GeV charged Kaons	Nickel	
Meson radii	50 GeV to 280 GeV charged pions and Kaons		



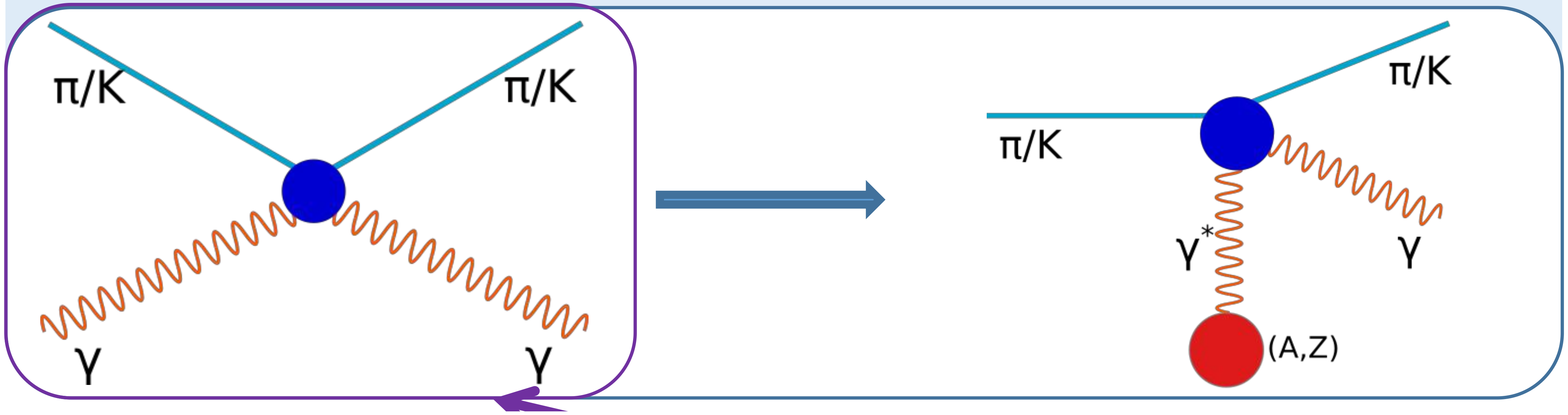


Prompt Photons and Primakoff Effect

Initial idea of Henry Primakoff:
Electromagnetic field of nucleus = photon target!



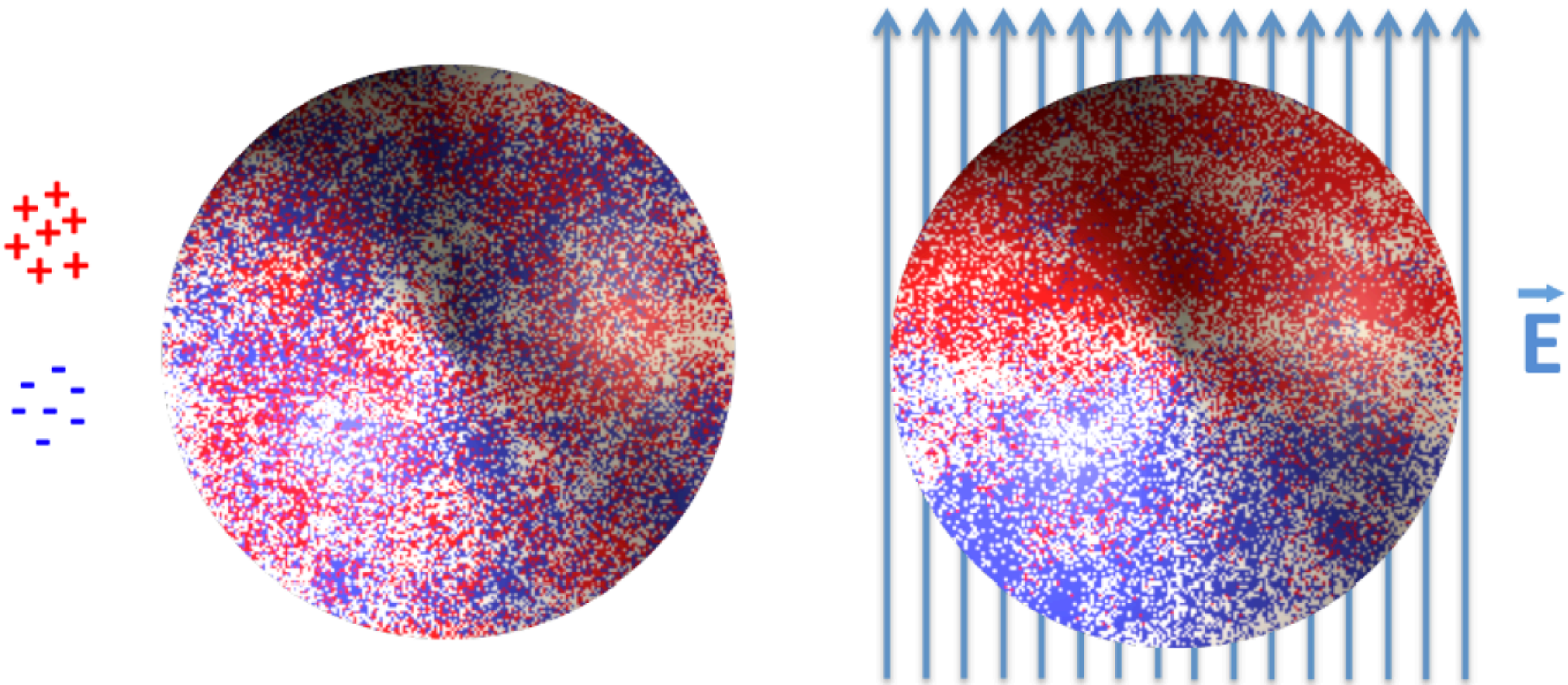
Also applicable to compton scattering:



graphics from A. Maltsev, EHM Workshop 2021

Kaon polarisabilites at AMBER

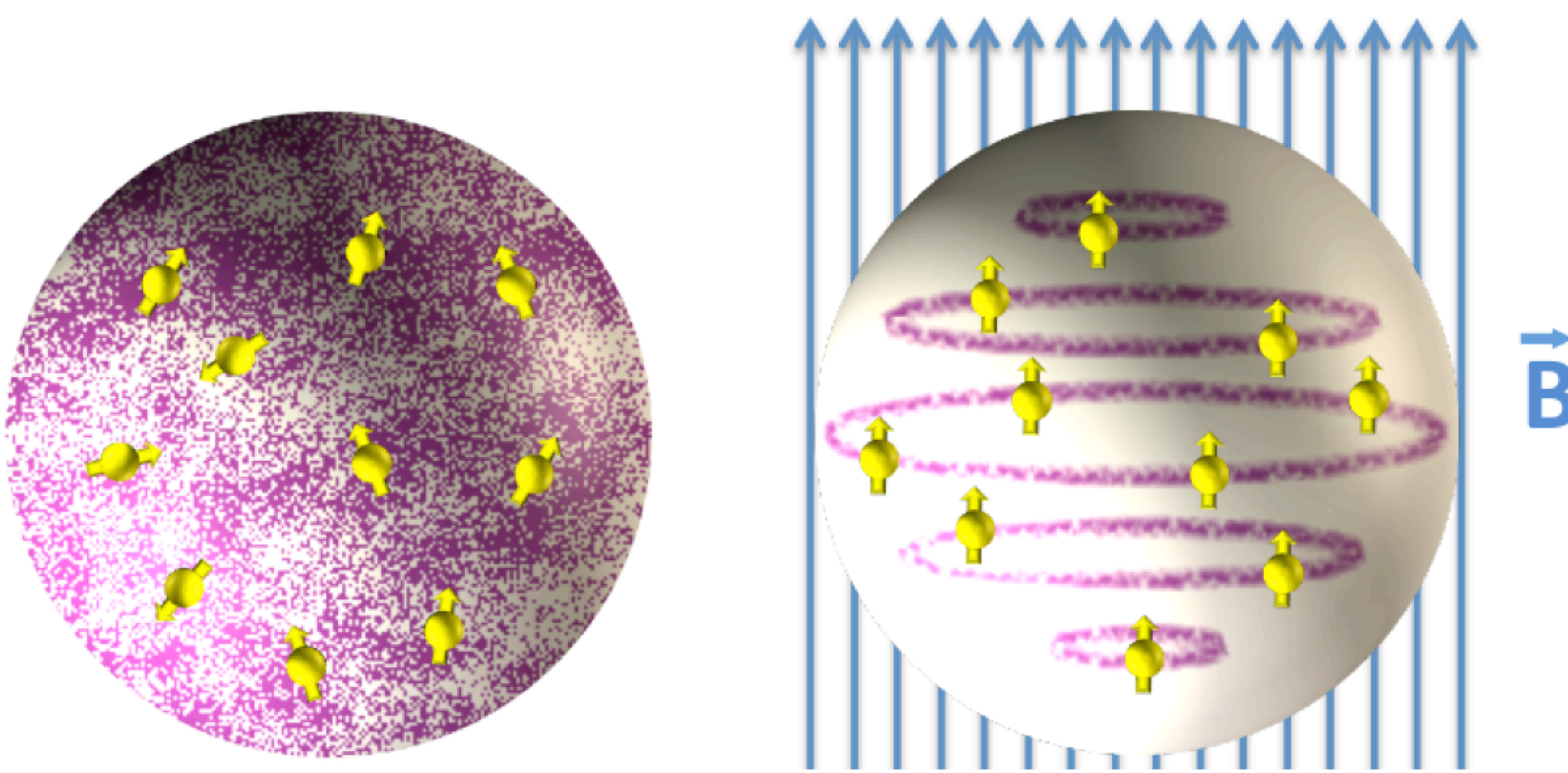
pictures from Temple Univ



"stretchability"

$\vec{d}_{E\ \text{induced}} \sim \alpha\, \vec{E}$

External field deforms the charge distribution



"alignability"

$\vec{d}_{M\ \text{induced}} \sim \beta\, \vec{B}$

$\beta_{para} > 0$

$\beta_{diam} < 0$

Paramagnetic: proton spin aligns with the external magnetic field

Diamagnetic: π-cloud induction produces field counter to the external one

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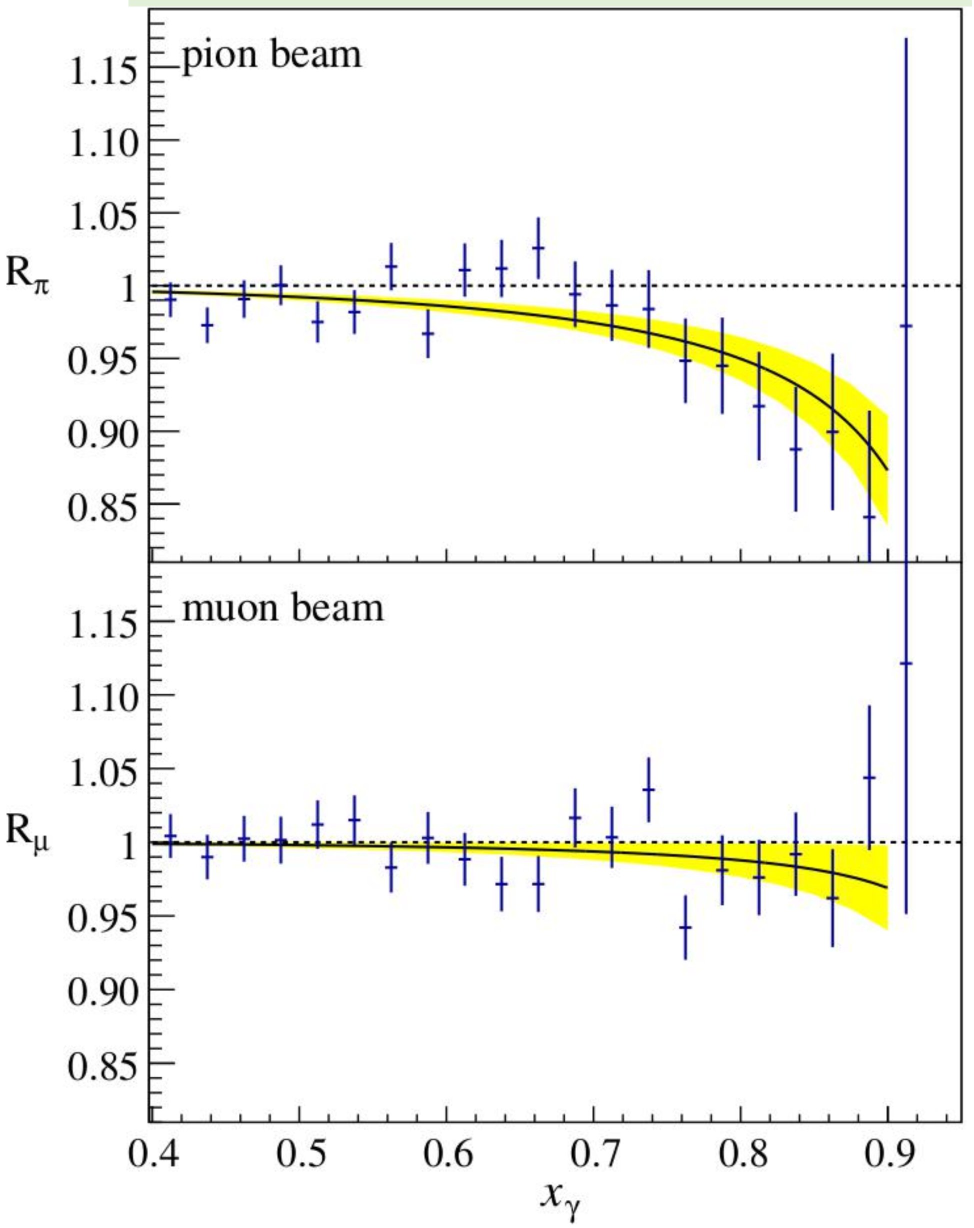
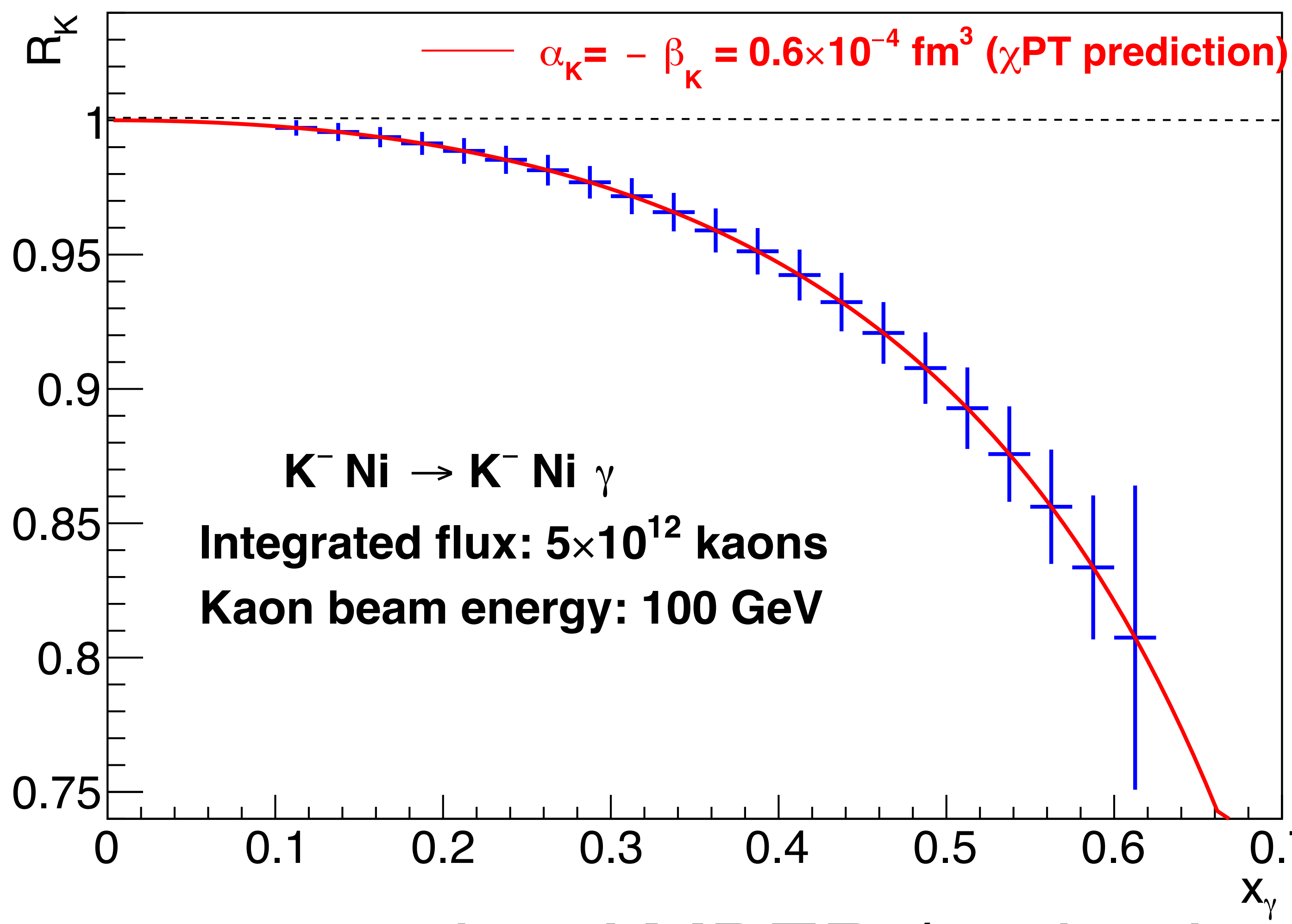
Kaon polarisabilites at AMBER

PRL 114, 062002 (2015)



α_π at COMPASS

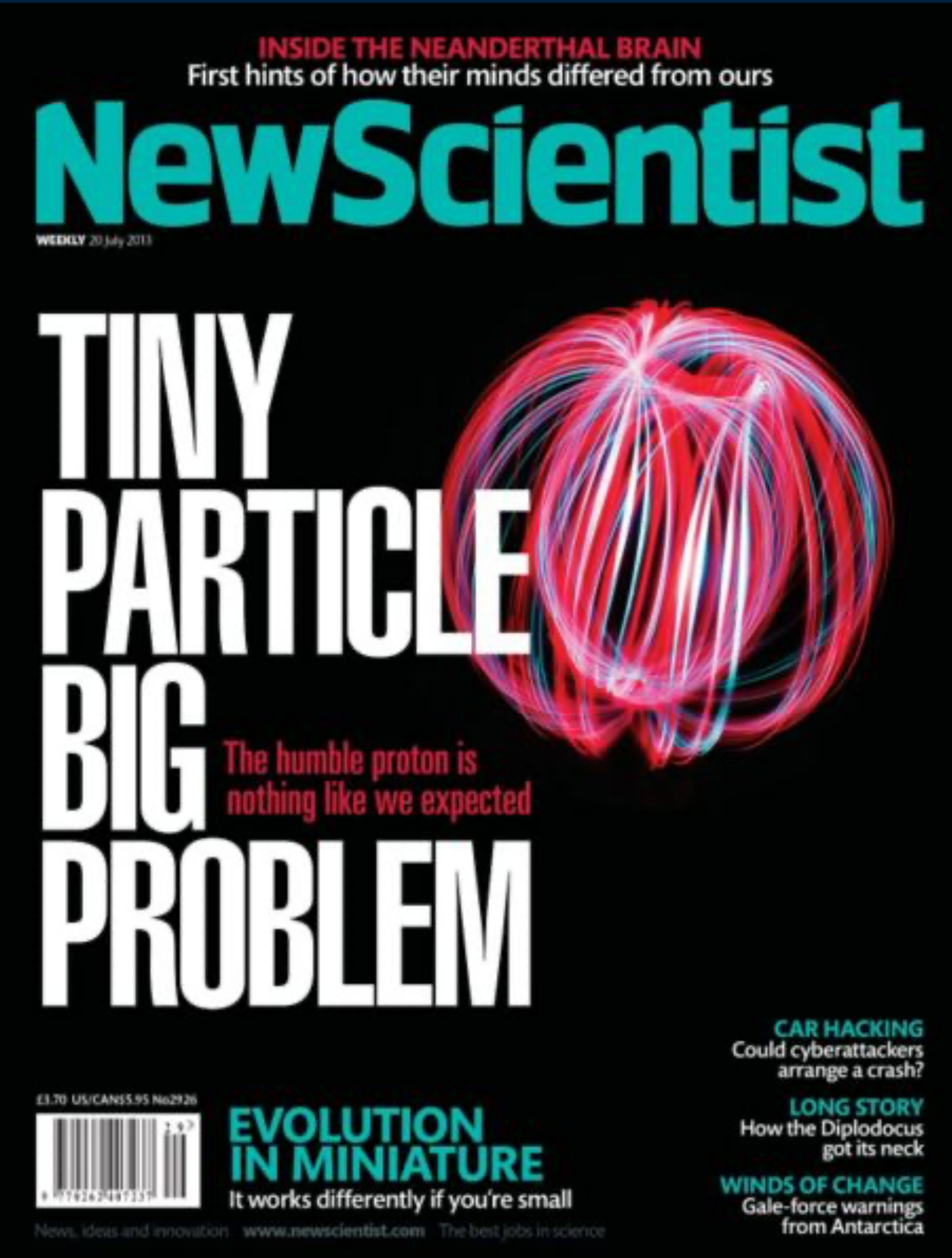
$\alpha_\pi = (2.0 \pm 0.6 \pm 0.7) \times 10^{-4} fm^3$



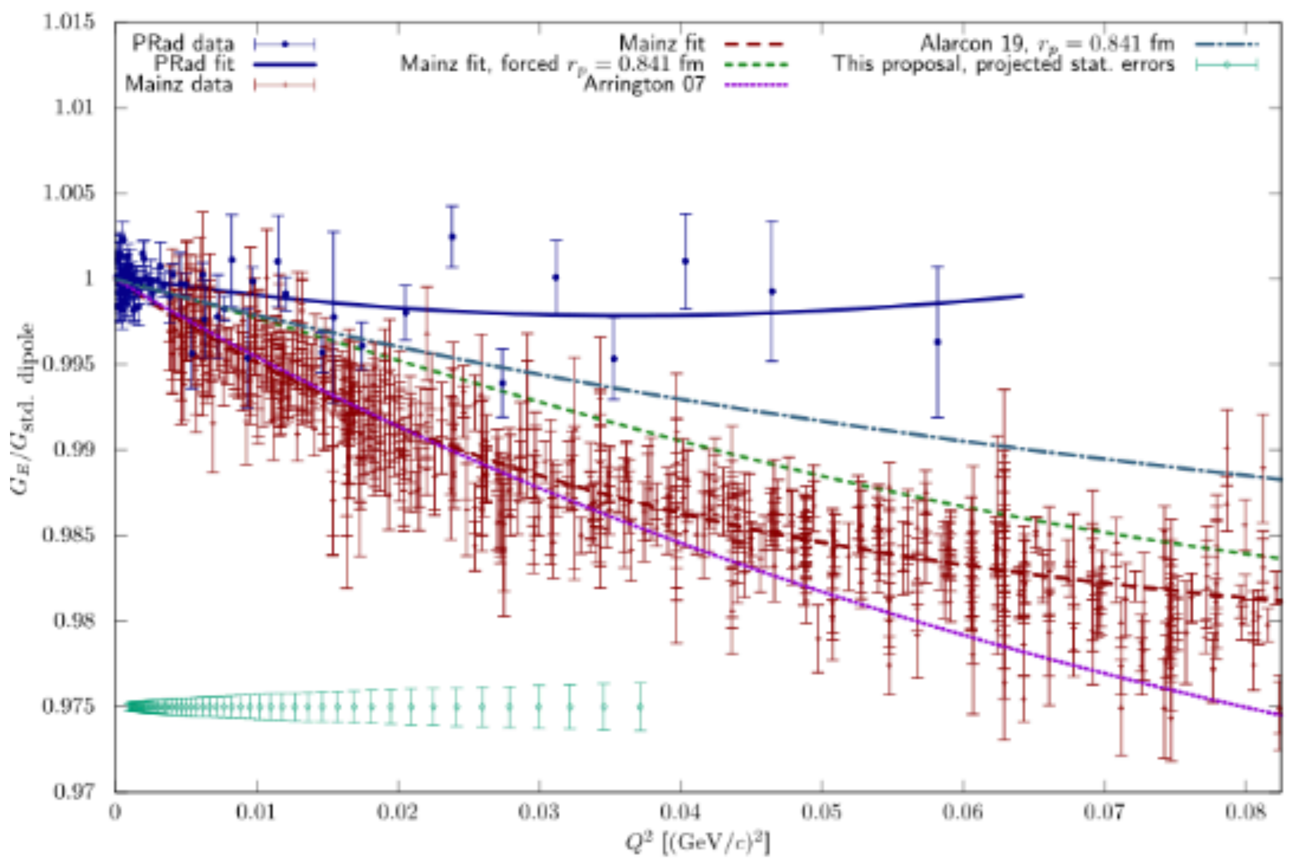
α_K extracted at AMBER (projection)

- Expected statistical accuracy in α_K-β_K: $\sigma = 0.03 \times 10^{-4}$ fm^3
- Unique measurement
- Prediction α_K-β_K~1-4x10^{-4}fm^3

Hadron charge radii

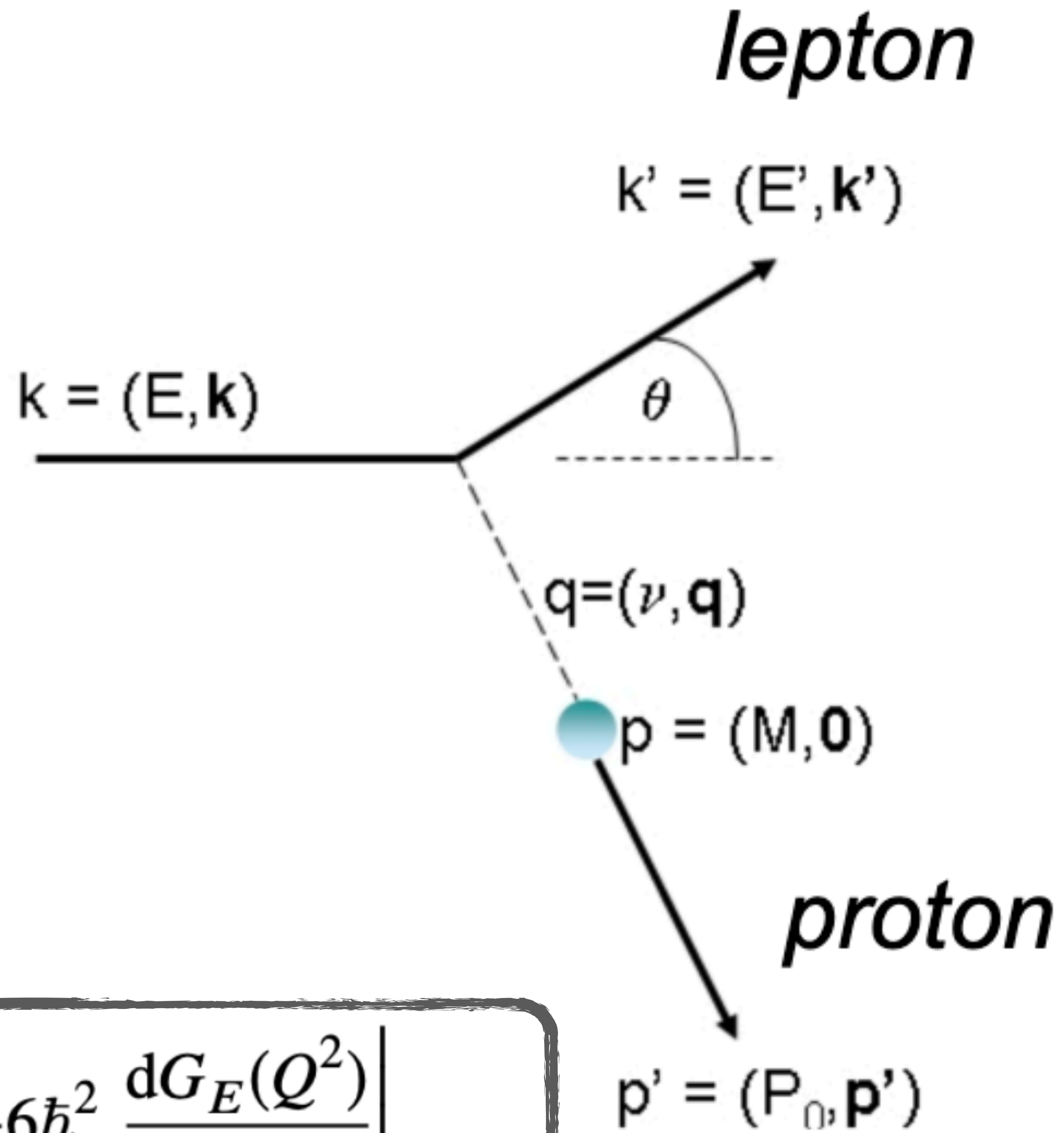


Hadron charge radii

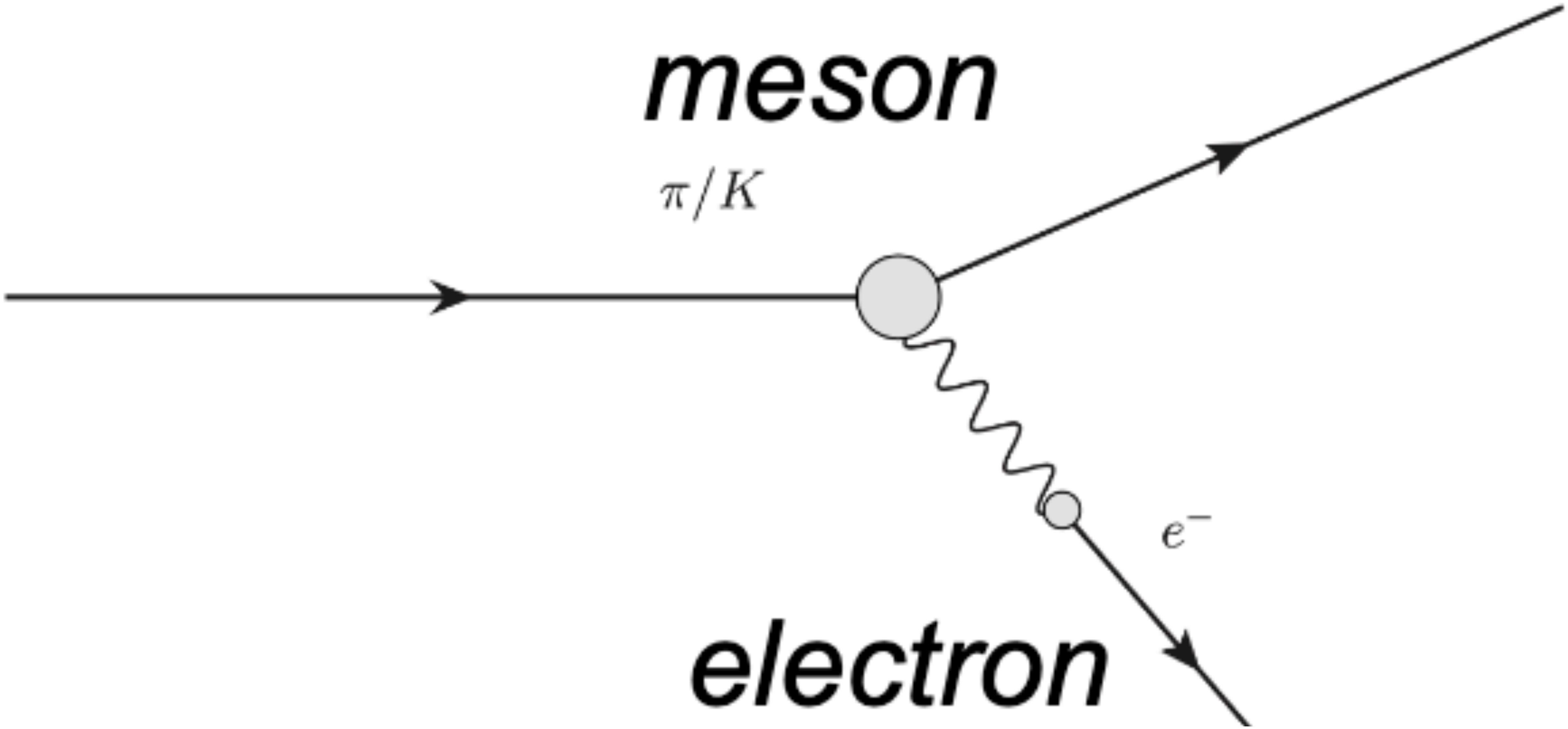


$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4} R \left(\varepsilon G_E^2 + \tau G_M^2\right)$$

$$\langle r_E^2 \rangle = -6\hbar^2 \left.\frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2}\right|_{Q^2\to 0}$$



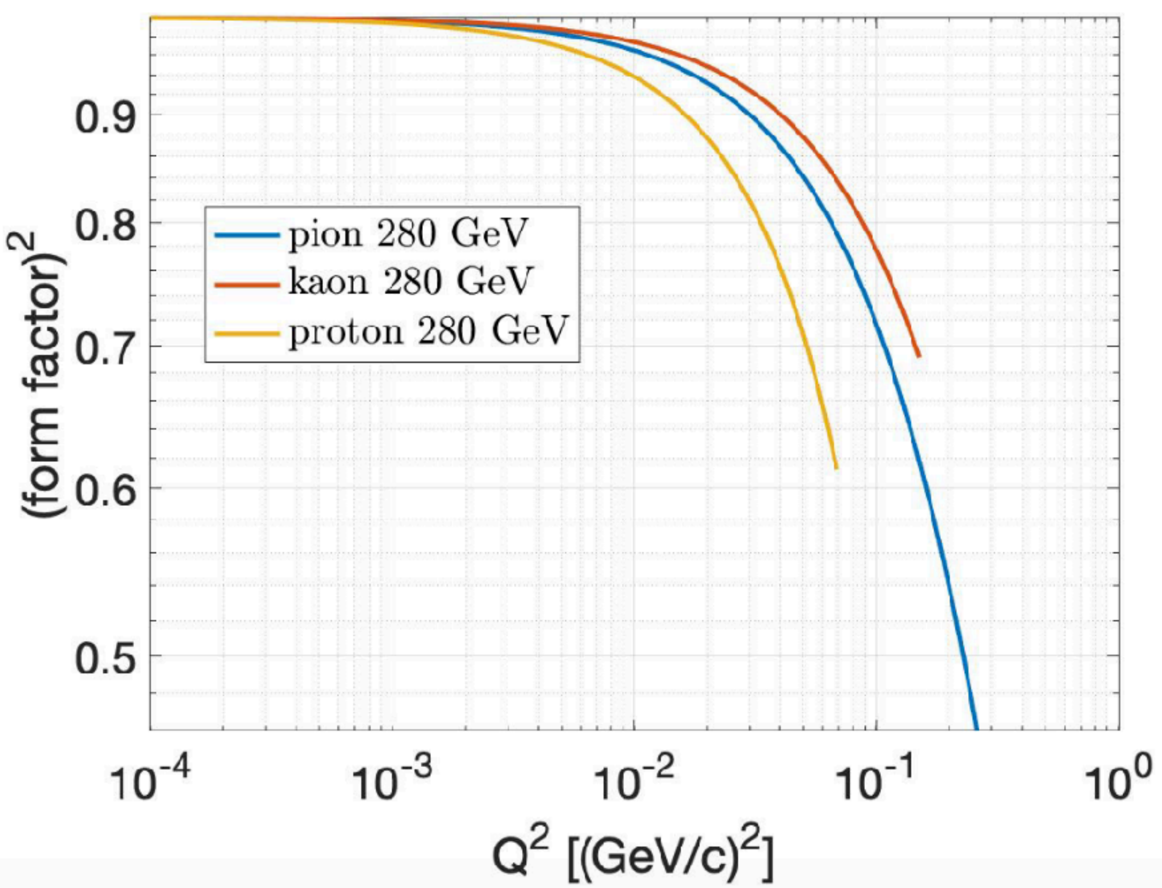
Hadron charge radii



$$\langle r_E^2 \rangle = -6\hbar^2 \left. \frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2} \right|_{Q^2 \to 0}$$

Q^2 range and radius effect

- large values of Q^2: higher sensitivity to charge distribution —> $< r_E^2 >$
- small values of Q^2: smaller extrapolation uncertainties to $Q^2 = 0$ and $\frac{dF(Q^2)}{dQ^2}|_{Q^2=0}$



Beam	E_{beam} [GeV]	Q^2_{max} [GeV²]	Relative charge-radius effect on σ(Q²)
π	280	0,268	~54%
K	280	0,15	~30%
K	80	0,021	~5%
K	50	0,009	~2-3%
p	280	0,070	~28%

Q^2 range and radius effect

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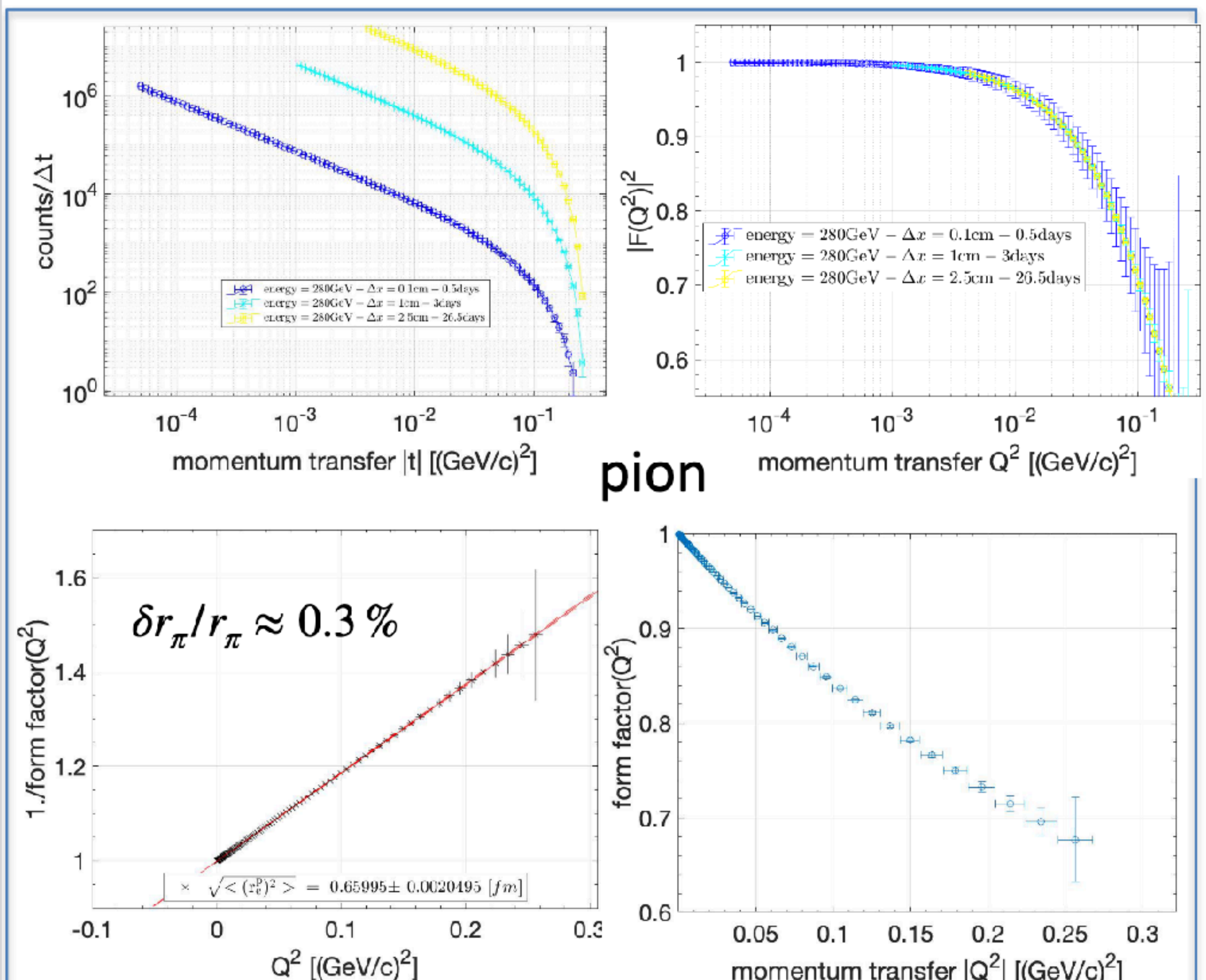
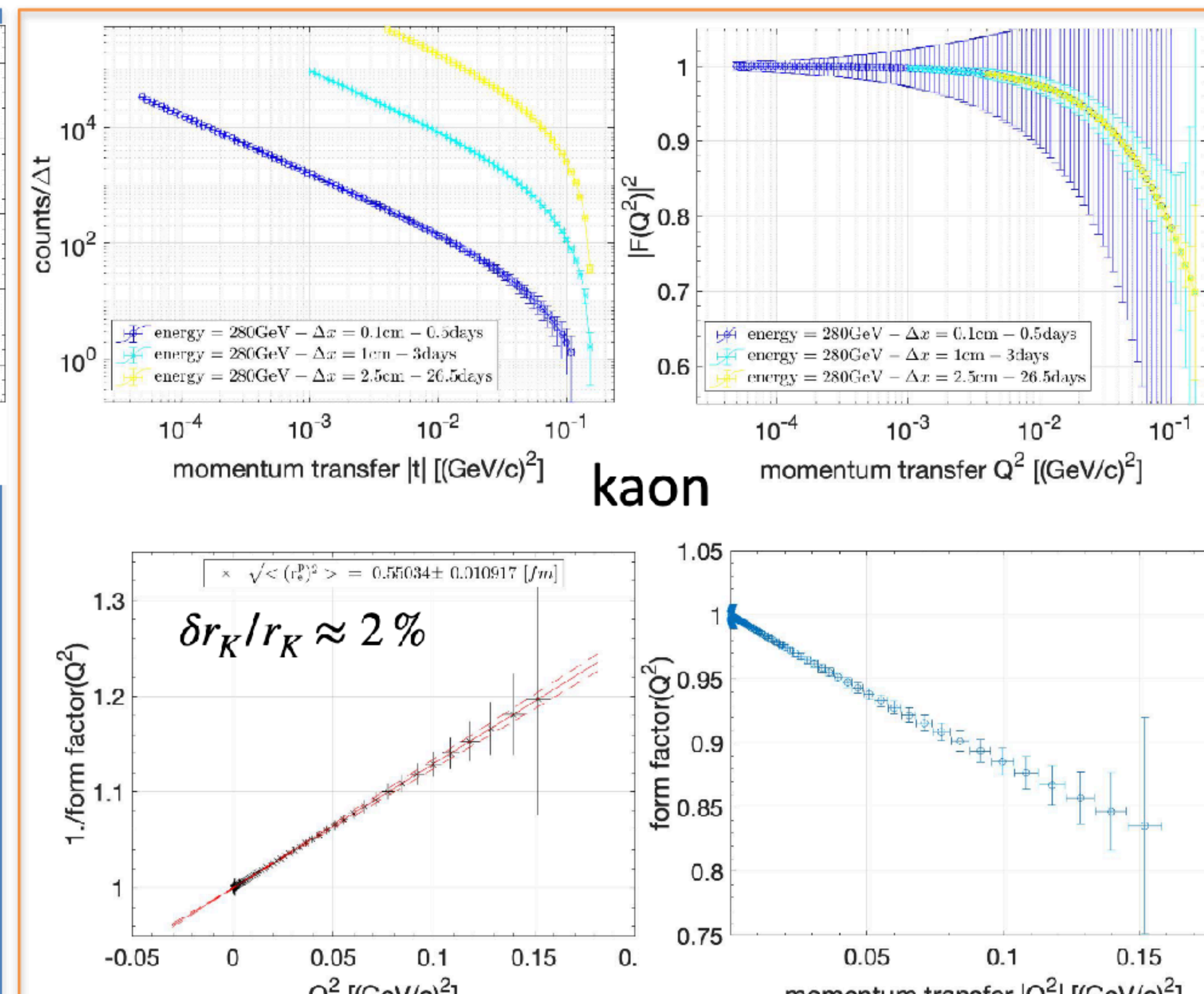
- large values of Q^2: higher sensitivity to charge distribution —> $< r_E^2 >$
- small values of Q^2: smaller extrapolation uncertainties to $Q^2 = 0$ and $\frac{dF(Q^2)}{dQ^2}|_{Q^2=0}$
    - Assume 30 days of beam time (100% efficiency) - use pole description for FF





Summary and Conclusion

- Understanding QCD means understanding the properties of Baryons and Mesons
- Unique opportunities to study QCD provided by CERN M2 beam line with high energy and high intensity π/K/p beam
- AMBER Phase 2 focussing on
  - Drell-Yan with Kaons and Kaon structure
  - Kaon induced meson spectroscopy
  - Meson polarisabilities using Primakoff reactions
  - Meson radii in inverse kinematics

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