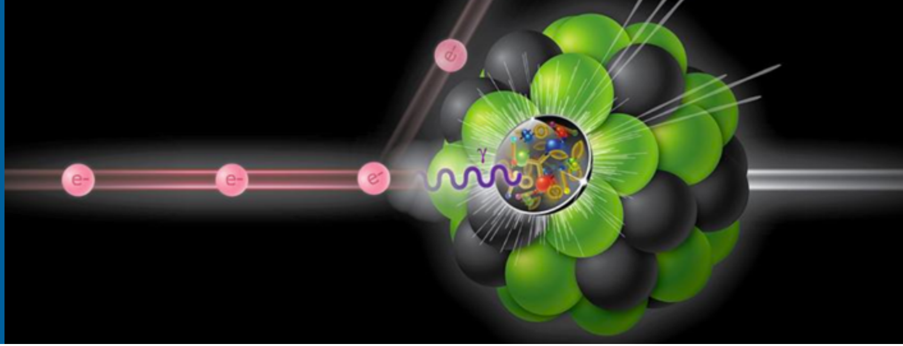
Argonne NATIONAL LABORATORY

Center for Frontiers of Nuclear Science:
Workshop on Pion and Kaon Structure at the EIC



COMPLEMENTARITY OF EXPERIMENTS AND THEORETICAL METHODS

PAUL E REIMER

U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

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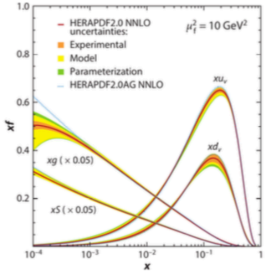
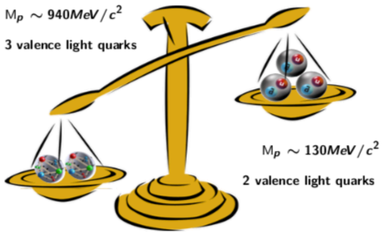
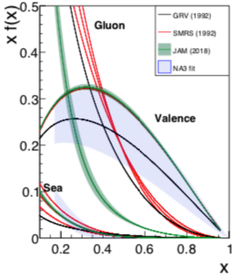
Motivation

How to explain the origin of the mass of composite hadrons?







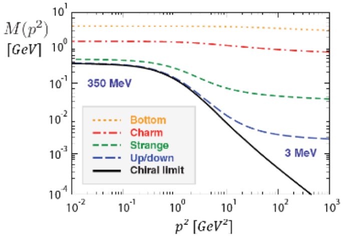
…nucleon and the **pion PDFs**

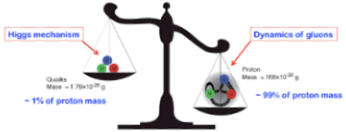
…**erstand the hadrons mass budget.**

…udy their structure!

The incomplete Hadron: Mass Puzzle

"Mass without mass!"





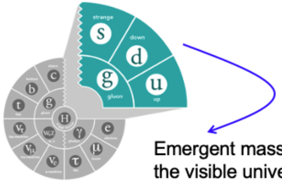
The light quarks acquire (most of) their masses as effect of the gluon cloud.

The strange quark is at the boundary - both emergent-mass and Higgs-mass generation mechanisms are important.

Proton: Mass ~ 940 MeV
preliminary LQCD results on mass budget, or view as mass acquisition by DCSB

Kaon: Mass ~ 490 MeV
at a given scale, less gluons than in pion

Pion: Mass ~ 140 MeV
mass enigma – gluons vs Goldstone boson

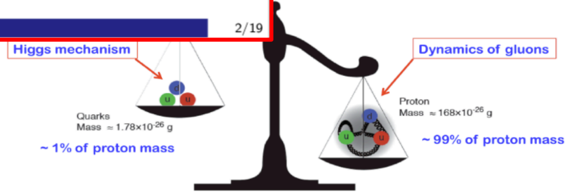


Emergent mass of the visible universe

→ *also see talks by Craig Roberts, Jianwei Qiu, …*

Proton Mass

…ates the mass of visible world:



Higgs mechanism is not enough!!! *"Mass without mass!"*

❑ **How does QCD generate the nucleon mass?**

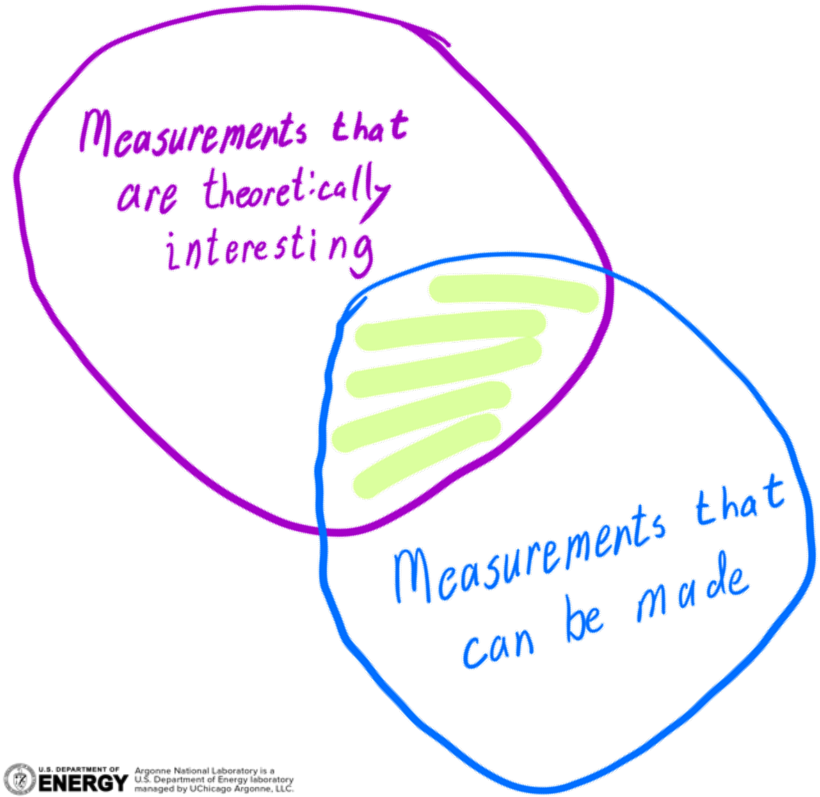
"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

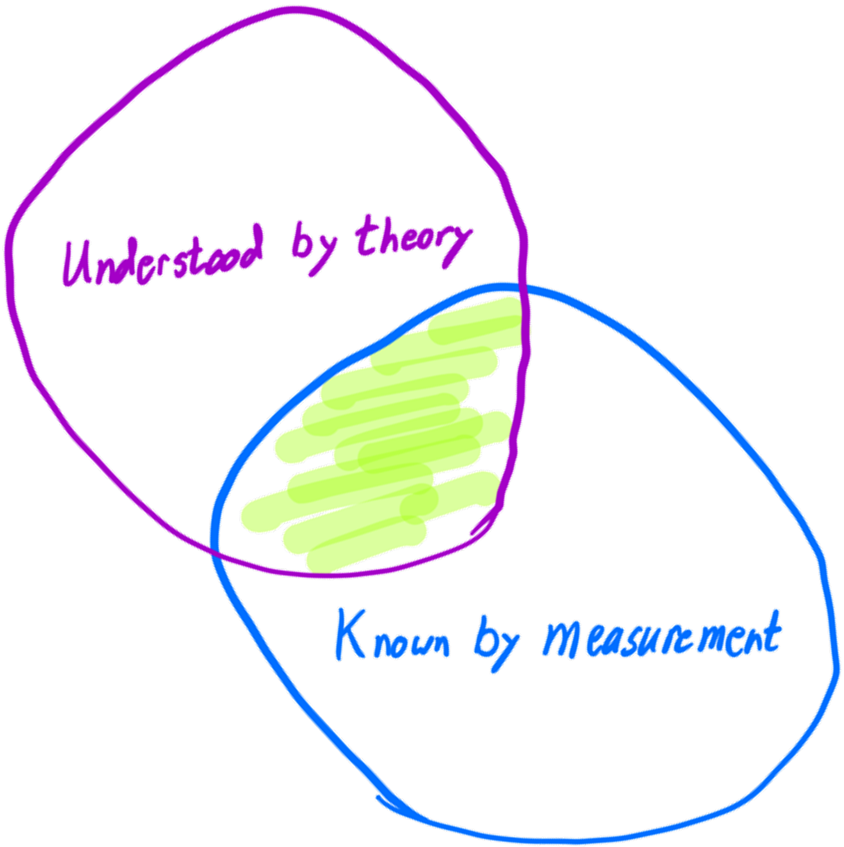
REACHING FOR THE HORIZON

The 2015 Long Range Plan for Nuclear Science

How to quantify and verify this, theoretically and experimentally?

COMPLEMENTARITY OF EXPERIMENTS AND THEORETICAL METHODS





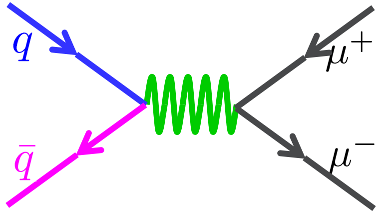
Status: pion and kaon structure functions

Pion

- Pointwise behaviour of pion’s valence-quark distribution function: agreement between predictions from lQCD and symmetry-preserving QCD-consistent continuum analyses
- Amongst existing phenomenological studies of pion structure functions, only one employs a next-to-leading-order analysis that includes threshold resummation. This study is unique in producing a valence-quark DF that is consistent with large-*x* QCD and matches continuum and lattice prediction
- General disagreement between phenomenological results and theory predictions for the pion’s valence-quark DF feeds into uncertainty about pion’s glue and sea distributions
- Resolution of these conflicts must await
  - Improved phenomenological analyses that include threshold resummation
  - New data that constrains the pion’s glue and sea distributions.

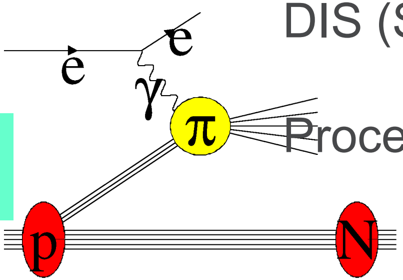
World Data on pion structure function F_2^{π}

Pion Drell-Yan

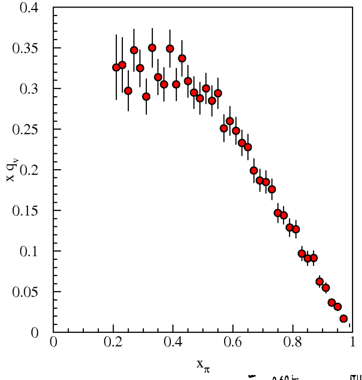


Amount of data is limited…

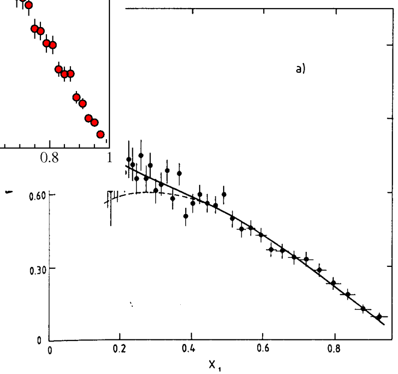
DIS (Sullivan Process)

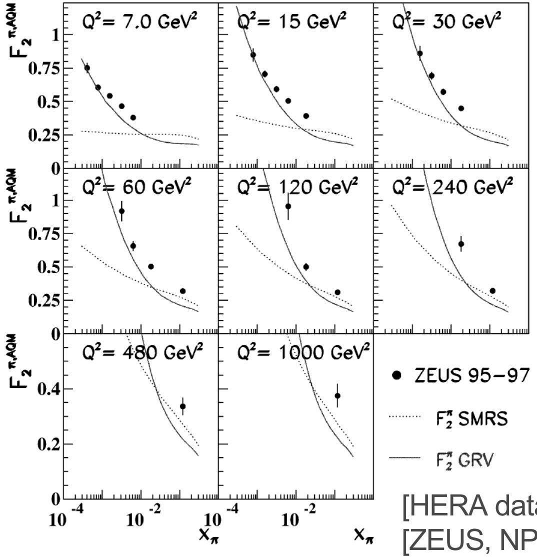


FNAL E615



CERN NA3





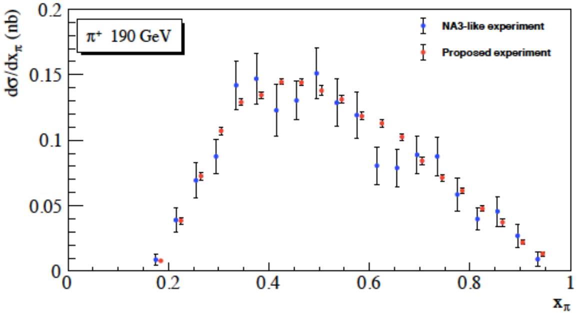
[HERA data [ZEUS, NPB637 3 (2002)]

→ also see talks by Oleg Denisov, Vincent Andrieux, Richard Trotta, Rachel Montgomery, …

Tanja Horn

EHM

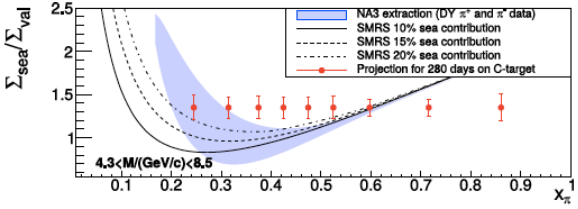
COMPASS++/AMBER (PION INDUCED DY) (VINCENT)

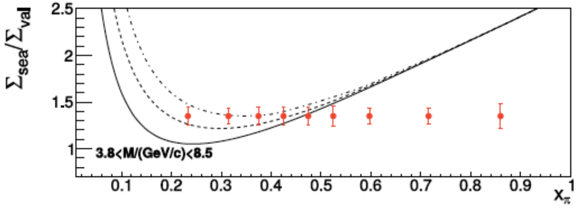


Pion structure in pion induce DY
Expected accuracy as compared to NA3

- $\Sigma_V = \sigma^{\pi^- C} - \sigma^{\pi^+ C}$: only valence-valence
- $\Sigma_S = 4\sigma^{\pi^+ C} - \sigma^{\pi^- C}$: no valence-valence
- Collect at least a **factor 10 more statistics** than presently available
- Minimize nuclear effects on target side
  - Projection for 2×140 days of Drell-Yan data taking
  - π^+ to π^- 10:1 time sharing
  - 190 GeV beams on Carbon target ($1.9\lambda^{\pi}_{int}$)
  - Improvement of shielding to double the intensity is under investigation

PHASE-1





Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (part/sec)	DY mass (GeV/c^2)	DY events
E615	20 cm W	252	π^+ π^-	17.6×10^7 18.6×10^7	4.05 – 8.55	5000 30000
NA3	30 cm H_2	200	π^+ π^-	2.0×10^7 3.0×10^7	4.1 – 8.5	40 121
	6 cm Pt	200	π^+ π^-	2.0×10^7 3.0×10^7	4.2 – 8.5	1767 4961
NA10	120 cm D_2	286 140	π^-	65×10^7	4.2 – 8.5 4.35 – 8.5	7800 3200
	12 cm W	286 194 140	π^-	65×10^7	4.2 – 8.5 4.07 – 8.5 4.35 – 8.5	49600 155000 29300
COMPASS 2015 COMPASS 2018	110 cm NH_3	190	π^-	7.0×10^7	4.3 – 8.5	35000 52000
This exp	75 cm C	190	π^+	1.7×10^7	4.3 – 8.5 4.0 – 8.5	21700 31000
		190	π^-	6.8×10^7	4.3 – 8.5 4.0 – 8.5	67000 91100
	12 cm W	190	π^+	0.4×10^7	4.3 – 8.5 4.0 – 8.5	8300 11700
		190	π^-	1.6×10^7	4.3 – 8.5 4.0 – 8.5	24100 32100

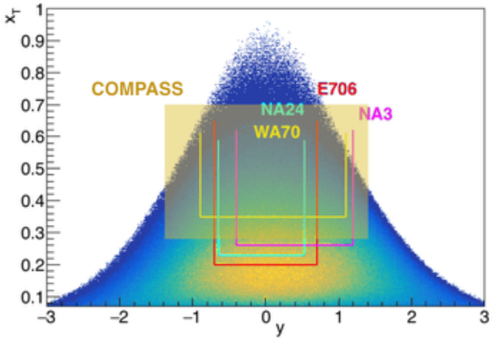
Isoscalar target + *Both positive and negative beams* + *High statistics*

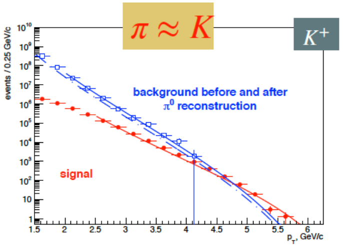
COMPASS++/AMBER (Prompt Photons)
(Charles)

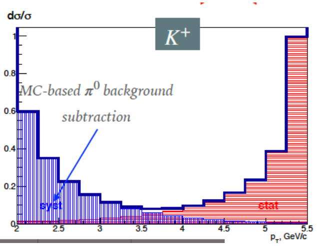
At the moment there is no experimental information about gluon contribution in kaon. Calculations based on Dyson-Schwinger equations predict 6 times smaller contribution at hadronic scale in respect to pion (Phys. Rev. D93 (7) (2016) 074021)

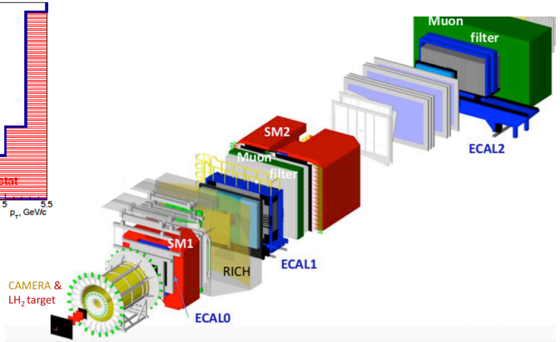
Pythia-based MC simulation for prompt photons production was used for preliminary estimation of kinematic range accessible at COMPASS. It was compared with corresponding ranges accessible by previous experiments with pion beams.

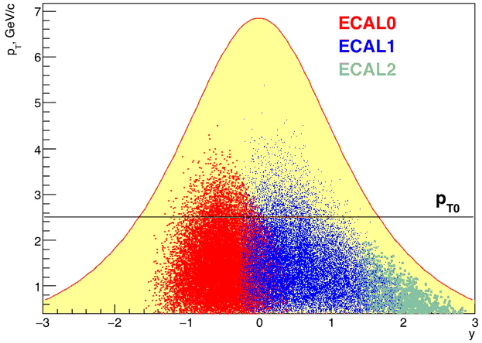
Possibilities to identify signal and reject background were tested. Some optimization of the setup from point of the material budget was tested.



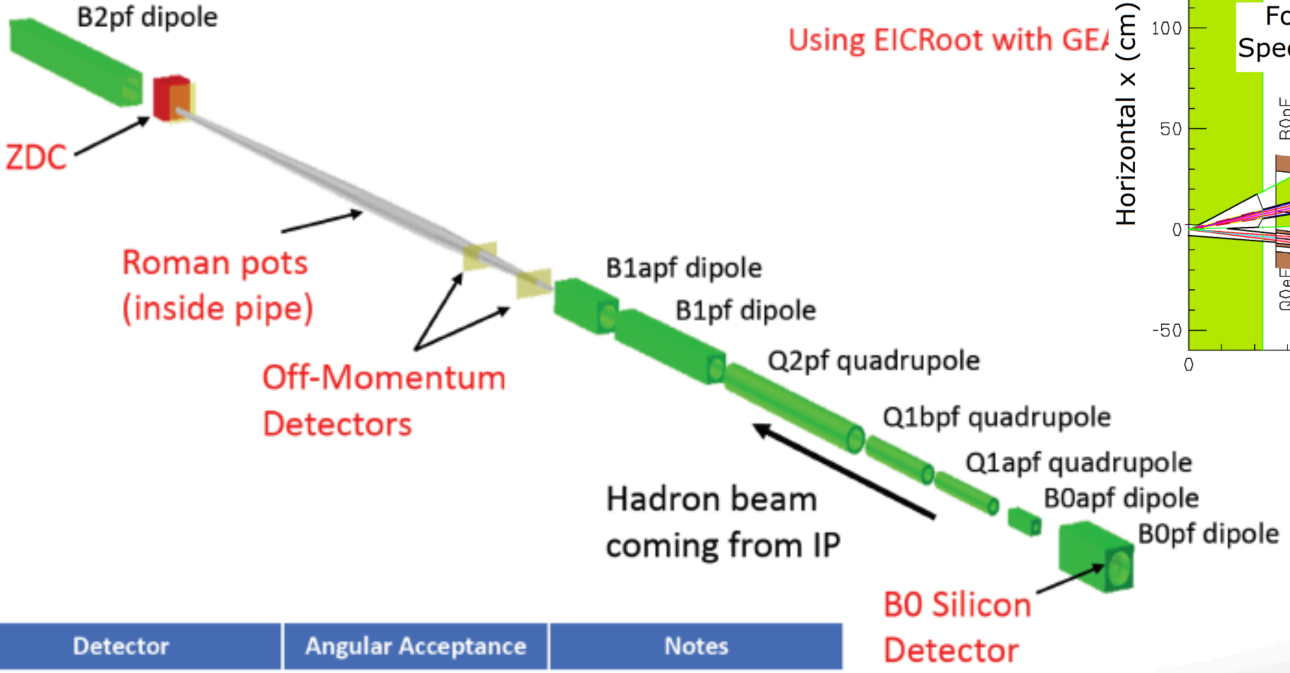


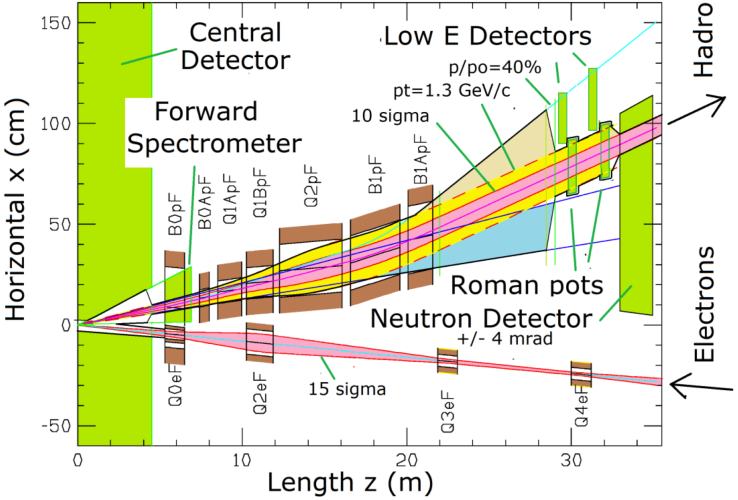






Far-Forward Region Layout





Detector	Angular Acceptance	Notes
ZDC	$\theta < 5.5$ mrad	About 4.0 mrad at $\varphi \sim \pi$
Roman Pots	$0.0 < \theta < 5.0$ mrad	Need 10σ cut.
Off-Momentum Detectors	$0.0 < \theta < 5.0$ mrad	Roughly $.4 < x_L < .6$
B0 Sensors	$5.5 < \theta < 20.0$ mrad	Still need to optimize.

$$x_L = \frac{p_{z,nucleon}}{p_{z,beam}}$$

Yulia Furletova

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Status: pion and kaon structure functions

Kaon

- Very little empirical information available on K DFs ⇒ no recent phenom. inferences.
  - Valence-quark distributions: results from models and a single, recent lQCD study
  - Kaon's glue and sea distributions: no results
- Hence, symmetry-preserving continuum QCD predictions sketched here for entire array of kaon DFs currently stand alone.
- One piece of available experimental information: $u_K(x)/u_\pi(x)$
  - Continuum prediction for ratio is consistent with the data.
  - But, given the large errors, this ratio is very forgiving of even large differences between various calculations of the individual DFs used to produce the ratio.
    - Modern, precise data is critical if this ratio is to be used as a path to understanding the Standard Model's Nambu-Goldstone modes;
    - Results for $u_\pi(x;\zeta_5)$, $u_K(x;\zeta_5)$ separately would be better.

Status: pion and kaon structure functions

Kaon

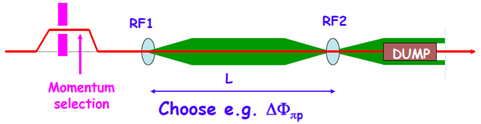
- Glue and Sea – Predictions:
  - DFs very similar to those in the pion
  - Detailed comparison requires the use of mass-dependent splitting functions.
  - Development underway … Preliminary conclusions:
    i. Light-front momentum fraction carried by s-quarks in the kaon increases by ~ 10%;
    ii. Compensated by a commensurate decrease in fractions carried by glue (−1%) and sea (−2%).

Oleg Denisov

COMPASS++/AMBER (kaon induced DY) (Vincent)

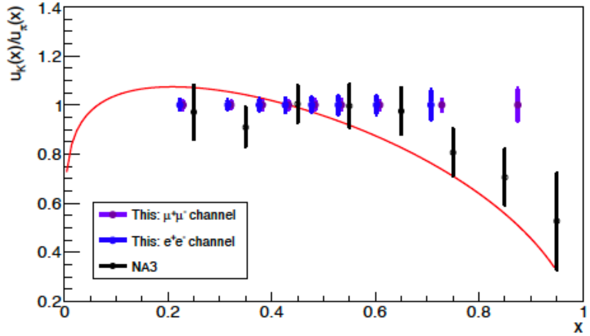
Extremely important to compare the gluon content of kaon and pion (emergent mass)

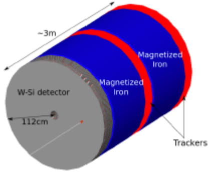
- **First ever DY measurements that could lead to kaon PDFs**
- Achievable statistics depends on beam energy and on kaon beam purity. Assuming I=7×10^7 s^{-1} with 30% kaons:
  - 40 kevents (K^-) and 5 kevents (K^+) @ 100 GeV
  - 25 kevents (K^-) and 3 kevents (K^+) @ 80 GeV



$\Delta\Phi = 2\pi\,(L\, f\, /\, c)\,(\beta_1^{-1} - \beta_2^{-1})$ with $\beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2p^2$

Projected statistical errors after 140 days of running, compared to NA3 stat. errors





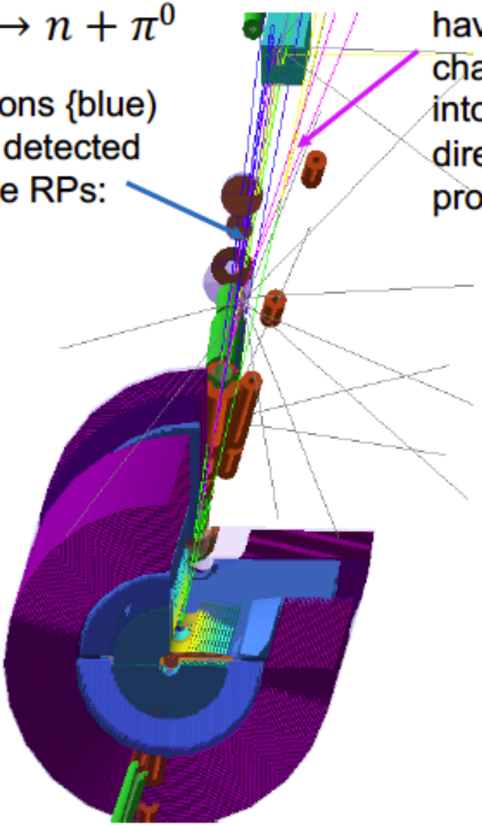
Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$	e^+e^-
NA3	6 cm Pt	K^-		200	4.2 – 8.5	700	0
This exp.	100 cm C	K^-	2.1×10^7	60	4.0 – 8.5	12,000	8,000
				70	4.0 – 8.5	18,000	10,900
				80	4.0 – 8.5	25,000	13,700
				100	4.0 – 8.5	40,000	17,700
				120	4.0 – 8.5	54,000	20,700
		K^+	2.1×10^7	60	4.0 – 8.5	1,000	600
				70	4.0 – 8.5	1,800	900
				80	4.0 – 8.5	2,800	1,300
				100	4.0 – 8.5	5,200	2,000
				120	4.0 – 8.5	8,000	2,400
This exp.	100 cm C	π^-	4.8×10^7	60	4.0 – 8.5	31,000	20,500
				70	4.0 – 8.5	50,800	25,400
				80	4.0 – 8.5	65,500	29,700
				100	4.0 – 8.5	95,500	36,000
				120	4.0 – 8.5	123,600	39,800

Lambda decays (275 GeV) see next talk by Richard Trotta

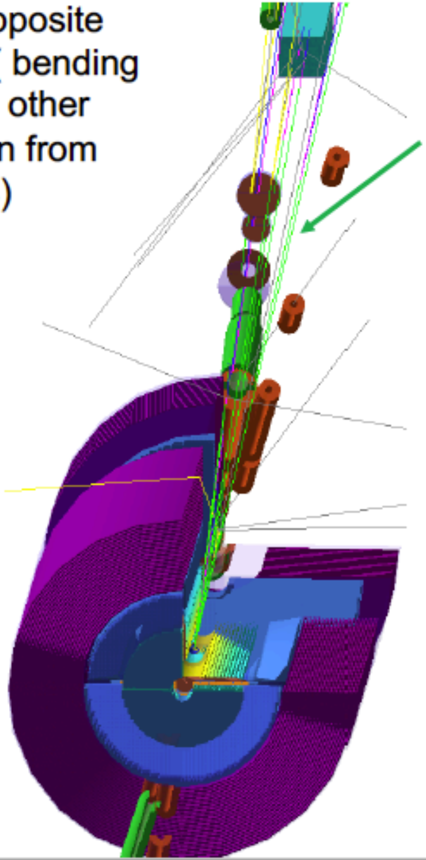
$$\Lambda \rightarrow p + \pi^-$$
$$\Lambda \rightarrow n + \pi^0$$

Protons {blue) are detected in the RPs:

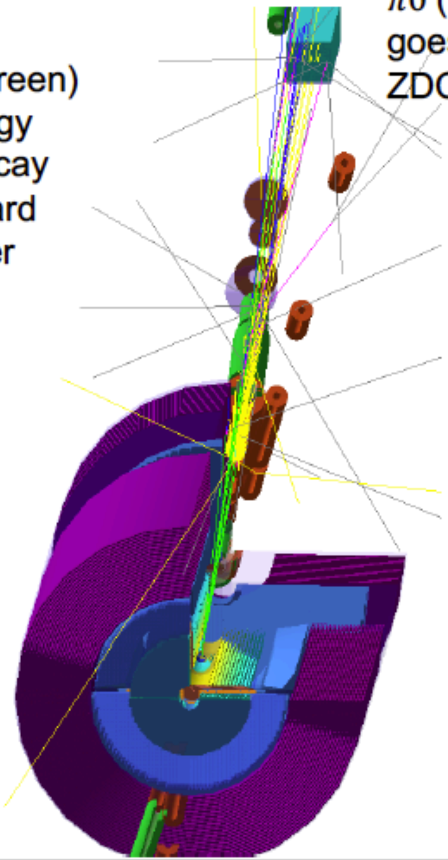
π^- {magenta) have opposite charge(bending into an other direction from protons)



Ca 30% of Lambdas (green) at high energy does not decay before forward spectrometer



Neutrons {gray) and fraction of $\pi 0$ (yellow) goes into ZDC



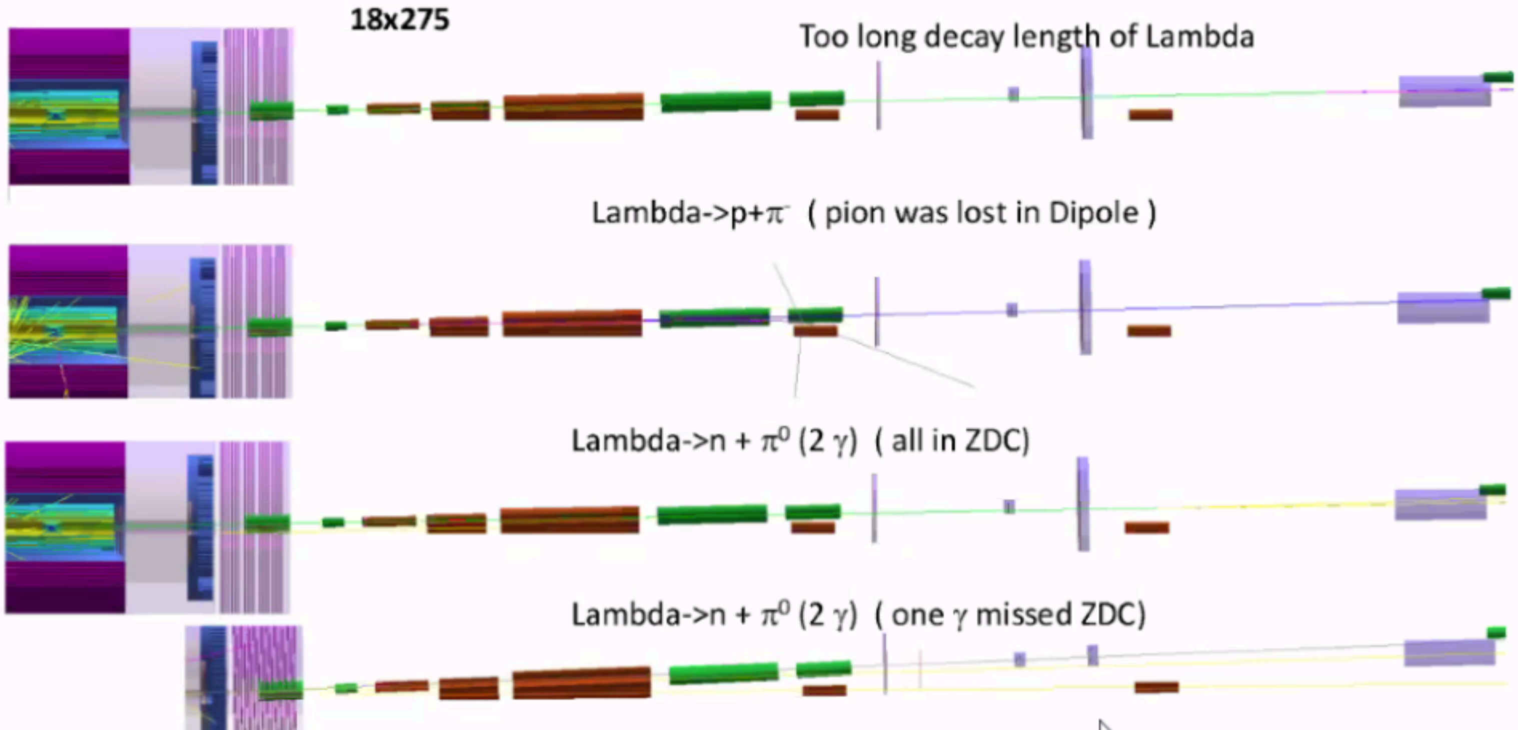
Lambda Final State

$\Lambda \rightarrow p+\pi-$: very challenging!

- need additional particle tracking between dipoles and ZDC

$\Lambda \rightarrow n+\pi^0$: looks promising

- need additional high-res/granularity EMCal+tracking before ZDC



Richard Trotta

NEEDS: pion and kaon structure functions

- Standard Model's (pseudo-) Nambu-Goldstone modes – pions and kaons – are basic to the formation of everything from nucleons, to nuclei, and on to neutron stars.
- Hence, new-era experiments capable of discriminating between the results from models, phenomenology and QCD-connected predictions should have high priority.
- Phenomenological methods needed to proceed from data to DFs must match modern experiments in precision.
- Theory: continuum and lattice analyses of the pion's valence-quark DF are converging on the same form, confirming the longstanding QCD expectation
  - But, lattice results for the pion's glue and sea distributions would be very valuable.
- Even more true for the kaon.
  - Only one extant lattice study of kaon DFs
  - Addressing solely valence distributions
  - Disagreeing in many respects with continuum predictions
  - Conflict with large-x QCD

  ⇒ Many opportunities are available.

Pion and Kaon Structure

- ❑ **Pion decays, and there is no stable pion target**
- ❑ **Pion beam:**

  Talking advantage of time-dilation, $\pi + p \to \ell^+\ell^- + X$ Drell-Yan process

  Precision of pion structure depends on our knowledge of proton structure

  Nuclear--WM

- ❑ **Lattice QCD:**

  – using a vector-axial-vector correlation as an example

$$\frac{1}{2}\left[T^{\mu\nu}_{v5}(\xi,p) + T^{\mu\nu}_{5v}(\xi,p)\right] = \frac{\xi^4}{2}\langle h(p)|\left(\mathcal{J}^\mu_v(\xi/2)\,\mathcal{J}^\nu_5(-\xi/2) + \mathcal{J}^\mu_5(\xi/2)\,\mathcal{J}^\nu_v(-\xi/2)\right)|h(p)\rangle$$

$$\equiv \epsilon^{\mu\nu\alpha\beta} p_\alpha \xi_\beta \widetilde{T}_1(\omega,\xi^2) + (p^\mu \xi^\nu - \xi^\mu p^\nu)\widetilde{T}_2(\omega,\xi^2)$$

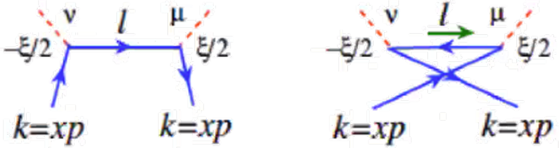
Vanishes under T

✧ **Collinear factorization:**

$$\widetilde{T}_i(\omega,\xi^2) = \sum_{f=q,\bar{q},g}\int_0^1 \frac{dx}{x} f(x,\mu^2)\, C^f_i(\omega,\xi^2;x,\mu^2) + \mathcal{O}\left[|\xi|/\text{fm}\right]$$

✧ **Lowest order coefficient functions:**

$$C^{q(0)}_1(\omega,\xi^2;x) = \frac{1}{\pi^2}\, x\left(e^{ix\omega} + e^{-ix\omega}\right)$$



$$T_1(\tilde{x},\xi^2) \equiv \int \frac{d\omega}{2\pi} e^{-i\tilde{x}\omega}\widetilde{T}_1(\omega,\xi^2)$$

$$= \frac{1}{\pi^2}\left(q(\tilde{x},\mu^2) - \bar{q}(\tilde{x},\mu^2)\right) \equiv \frac{1}{\pi^2} q_v(\tilde{x},\mu^2)$$

Sufian et al.
PRD99 (2019) 074507

Jainwei Qiu
Screen shot