Kaon Spectroscopy with Kaon Beam

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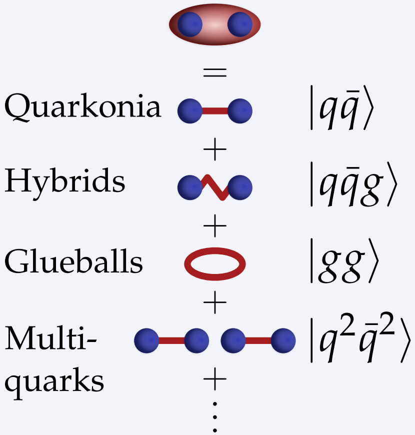
Mini Workshop for a QCD Facility at the SPS after 2021
CERN, 20. Jun 2018

The Quest for exotic Forms of Matter



- In principle, QCD permits color-neutral meson-like states in addition to $|q\bar{q}\rangle$

Physical mesons

- Linear superpositions of *all* allowed basis states

Exotic mesons

- States with small or vanishing $|q\bar{q}\rangle$ component
- Appear either as supernumerous states or mix with conventional states with same quantum numbers

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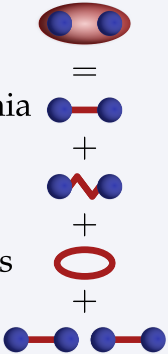

$=$

Quarkonia $|q\bar{q}\rangle$

$+$

Hybrids $|q\bar{q}g\rangle$

$+$

Glueballs $|gg\rangle$

$+$

Multi-quarks $|q^2\bar{q}^2\rangle$

$+$

$\vdots$

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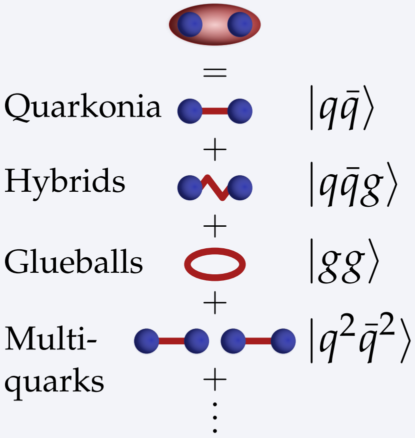

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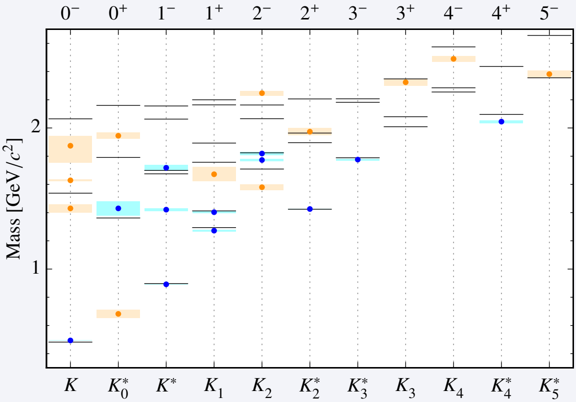
Why Kaon Spectroscopy?

PDG 2016: 25 kaon states below 3.1 GeV / c^2

- Only 12 kaon states in summary table, 13 need confirmation
- Many predicted quark-model states still missing
- Some hints for supernumerous states



[Courtesy of S. Wallner, TUM]

Why Kaon Spectroscopy?

Many kaon states need confirmation

- Little progress in the past
  - Most PDG entries more than 30 years old
  - Since 1990 only 4 kaon states added to PDG (only 1 to summary table)

Kaon spectrum crucial to understand light-meson spectrum

- Identify supernumerous states by completing $SU(3)_{flavor}$ multiplets
  - E.g. $J^P = 0^+$ multiplet with $a_0(980)$, $K_0^*(800)$ [or κ], $f_0(500)$ [or σ], and $f_0(980)$ is hypothesized to be tetra-quark multiplet
  - But $K_0^*(800)$ still disputed

Kaon spectrum required to analyze heavy-meson decays

- E.g. search for CP violation in multi-body decays
  e.g. $B^\pm \to D^0 K^\pm$ with $D^0 \to K_S^0 \pi^+ \pi^-$
  - Dalitz-plot amplitude analysis requires accurate knowledge of resonances in $K_S^0 \pi^\pm$ subsystems

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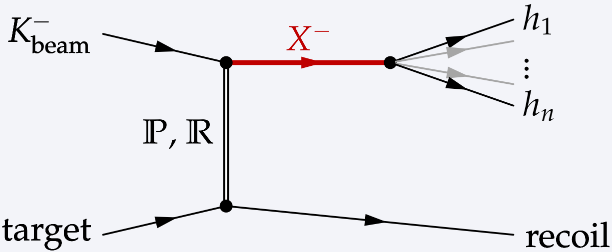
Production of excited Kaons



- High-energy kaon beam on stationary target (proton or nucleus)
- Excitation of beam kaon into X via Pomeron/Reggeon exchange
- Dissociation of X into various n-body mesonic final states
  - $\pi, K, \eta, \eta', \ldots$
- Not very selective: all kaon states can appear as X
- Large cross section

How to get more Data?

Main limitation

- Kaon content of 190 GeV / c h^- beam from current M2 beam line
- Composition: 97 % π^- , 2 % K^- , 1 % $\bar{p}$
- Intensity of K^- component at COMPASS target: $10^5\,\mathrm{s}^{-1}$

Goal

- Increase intensity of kaons by factor > 10
- Would correspond e.g. to $> 10^7$ $K^-\pi^+\pi^-$ events
  (assuming same acceptance as current experimental setup)
  $\Rightarrow$ approximately $10\times$ world data

Possible solution

RF-separated beam at M2 beam line (see talk by J. Bernhard)

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Competition

Kaon beam experiments

- J-PARC K10 beam line
  - Separated $\bar{p}$ and K^- beams with 2 to 10 GeV/c and 10^7 K^- per spill
  - Main focus on hyperon spectroscopy, di-baryons, and study of mesons in nuclear medium
  - Low beam energy
    - Separation between beam and target excitations difficult
    - More complicated production process (various Reggeons)
- Neutral kaon beam at GlueX (Jlab)
  - K_L^0 beam with 0.3 to 10 GeV/c and $10^4\,\mathrm{s}^{-1}$ intensity
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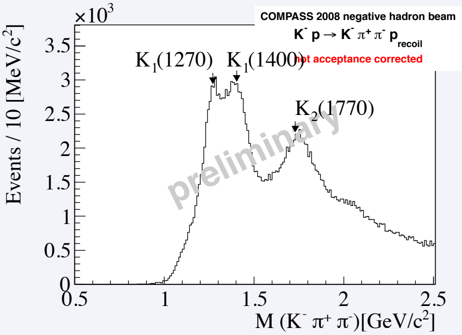
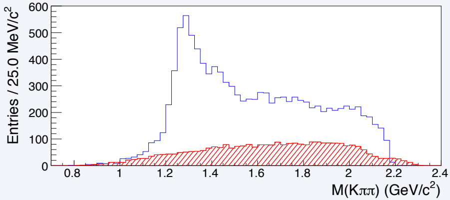
Decays of τ leptons or heavy mesons

- Limited mass reach for charmed mesons and τ leptons
- Mainly BESIII, Belle II, LHCb
- Current data samples typically factor 10 smaller than existing COMPASS data set

COMPASS: $K^- \pi^+ \pi^-$



Belle: $B^+ \to J/\psi K^+ \pi^+ \pi^-$



Belle, PRD **83** (2011) 032005

Competition

Photoproduction: $\gamma\, p \to X\, p$

- GlueX Phase IV proposal (Jlab)
  - 100×10^6 $X \to KK\pi\pi$ events
  - 30×10^6 $X \to KK\pi$ events
- Excited kaons appear in subsystems
  - Could be extracted using freed-isobar method
  - More complicated compared to direct production
  - Possible distortions due to rescattering effects
  - More difficult to find new states

Requirements for experimental Setup

Beam PID

- Upgrade of CEDAR detectors
  $\Rightarrow$ improve rate capability and thermal stability
- CEDAR PID requires precise measurement of beam inclination with resolution $< 40\,\mu\mathrm{rad}$ $\Rightarrow$ silicon beam telescope

Spectrometer

- As uniform acceptance as possible
- High-precision tracking over broad kinematic range
- New vertex detector: precise measurement of vertex position
- Improved RPD: detection of target recoil particle
  - Higher resolution of exclusivity variables

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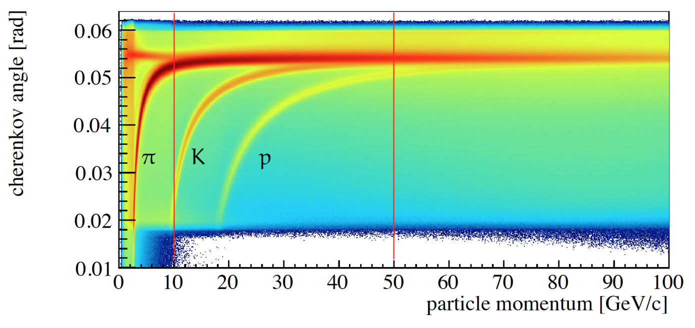
Final-state PID

- Existing RICH 1 kaon ID covers only $10 < p < 50\,\mathrm{GeV}/c$



- More than 50 % of kaons in $K^-\pi^+\pi^-$ outside of acceptance
- Lower beam momentum $\Rightarrow$ more events in RICH 1 acceptance
- *Goal:* extend kaon ID to increase acceptance $\Rightarrow$ RICH 0?

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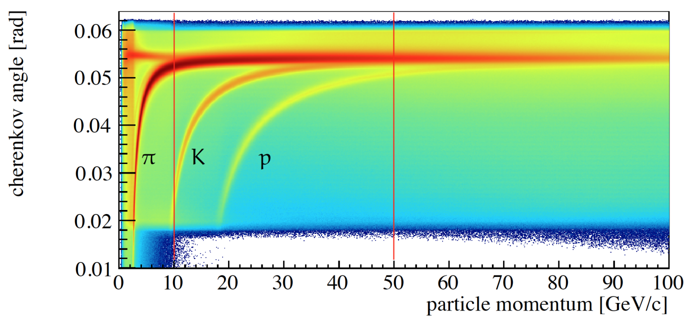

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Electromagnetic calorimeters

- Efficient detection of photons over broad kinematic range is essential
- Gives access to interesting final states: $K^-\eta^{(\prime)}$, $K^-\pi^0\pi^0$, $K^-\omega$, ...

Work in progress

Detailed studies of experimental setup once beam energy is fixed

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Conclusions

Kaon spectroscopy

- Many kaon states
  - Require further confirmation or more precise measurement of their paramaters
  - Have not yet been found

Future program

- *Goal:* collect data set that exceeds existing ones by at least a factor of 10 using high-intensity RF-separated kaon beam
- *High physics potential:* rewrite PDG for kaon states above $1.5\,\mathrm{GeV}/c^2$ (like LASS and WA03 did 30 year ago)
- No direct competitors
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5 Backup slides
- Introduction
- The COMPASS Experiment at the CERN SPS
- *Example:* Analysis of $K^-\pi^+\pi^-$ Final State
- Why do we need even larger data sets?

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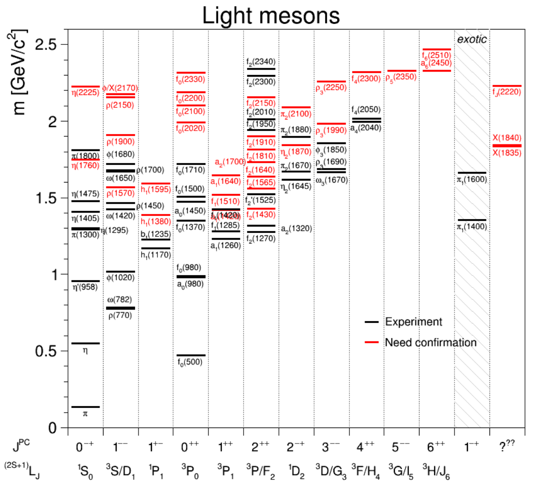
Light-Meson Spectrum



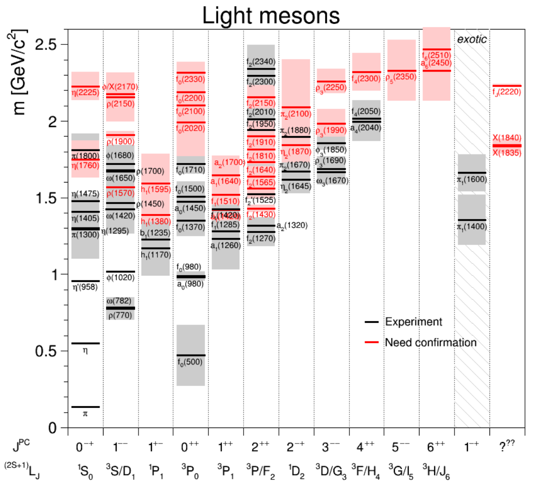
[Courtesy K. Götzen, GSI]

"Light-meson frontier"

- Many states need confirmation in mass region $m \gtrsim 2\,\text{GeV}/c^2$
- Many wide states $\Rightarrow$ overlap and mixing
- Identification of higher excitations becomes exceedingly difficult

Main focus of current COMPASS program

Light-Meson Spectrum



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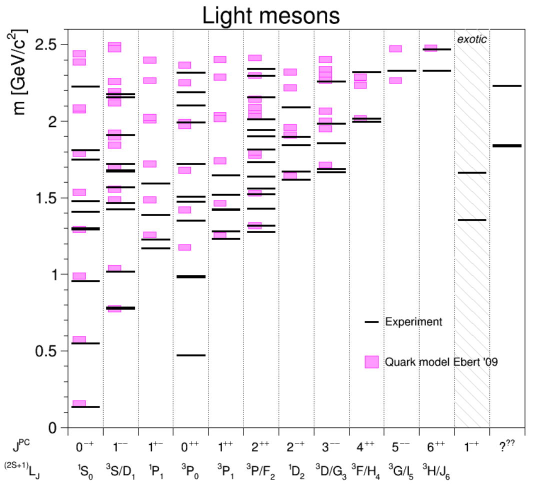

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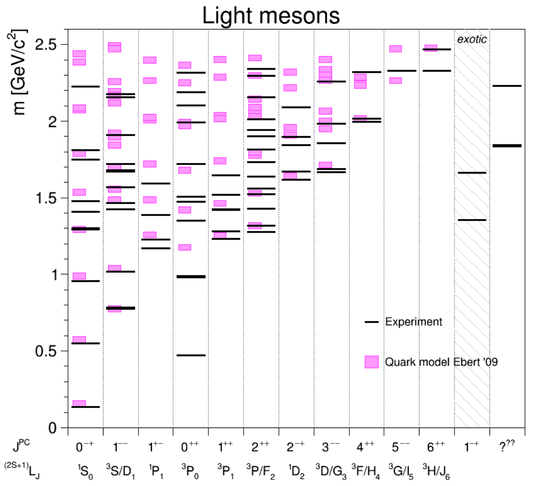

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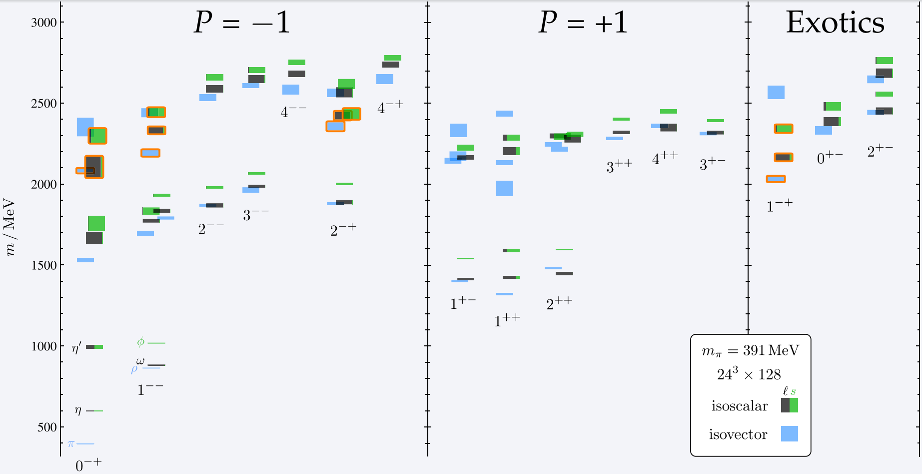
Light-Meson Spectrum from Lattice QCD

State-of-the-art calculation with $m_\pi = 391\ \text{MeV}/c^2$ — Dudek *et al.*, PRD **88** (2013) 094505



- Essentially recovers quark-model pattern
- High towers of excited states
- Additional hybrid-meson super-multiplet

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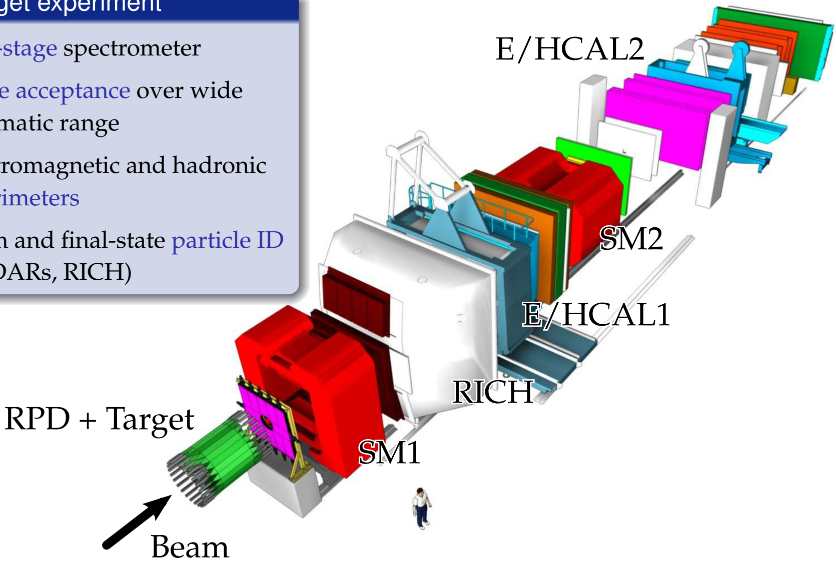
- *Example:* Analysis of $K^-\pi^+\pi^-$ Final State
- Why do we need even larger data sets?

Fixed-target experiment

- Two-stage spectrometer
- Large acceptance over wide kinematic range
- Electromagnetic and hadronic calorimeters
- Beam and final-state particle ID (CEDARs, RICH)



C. Adolph, NIMA **779** (2015) 69

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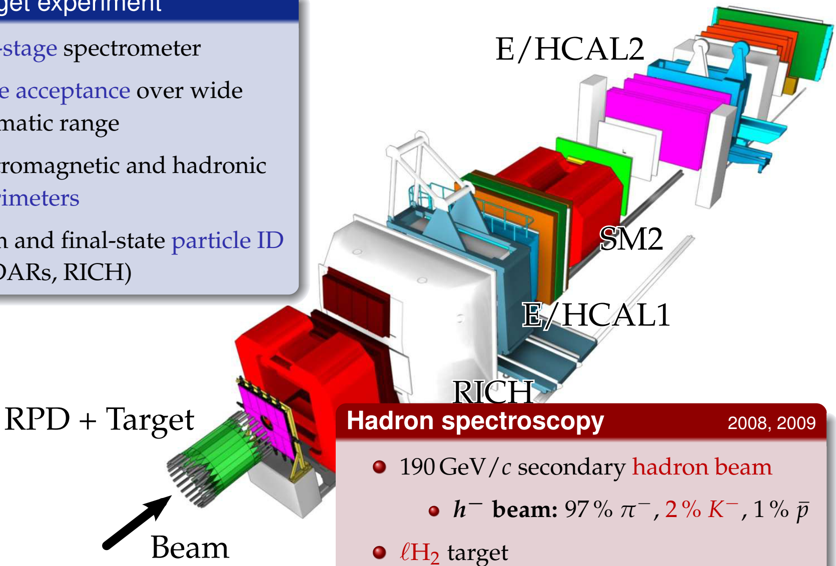

Hadron spectroscopy 2008, 2009

- 190 GeV/c secondary hadron beam
  - h^- **beam:** 97 % π^-, 2 % K^-, 1 % $\bar{p}$
- ℓH_2 target

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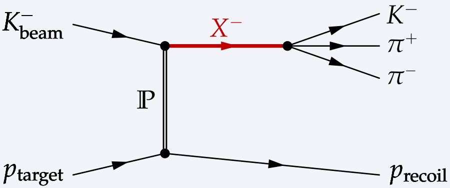

- Diffractive production of excited kaon states X^- that decay into $K^-\pi^+\pi^-$
- Beam-particle ID via Cherenkov detectors (CEDARs)
  - Ca. $50\times$ more π^- than K^- in beam
- Final-state PID via RICH detector
  - Distinguish K^- from π^- over wide momentum range

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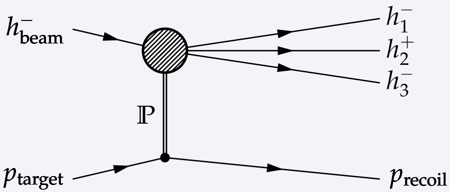

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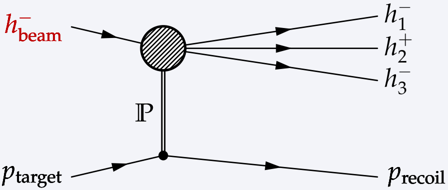

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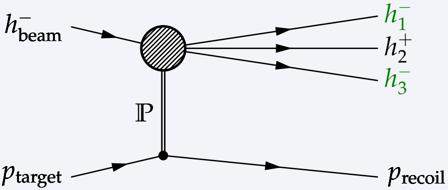

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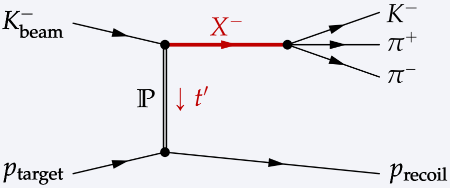
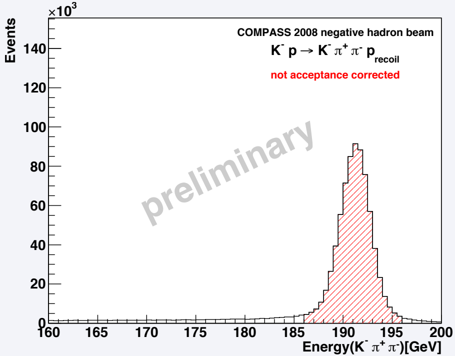
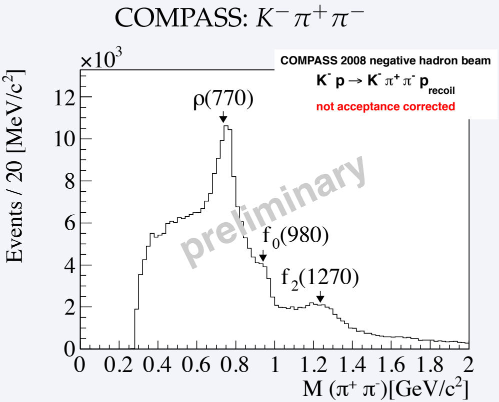
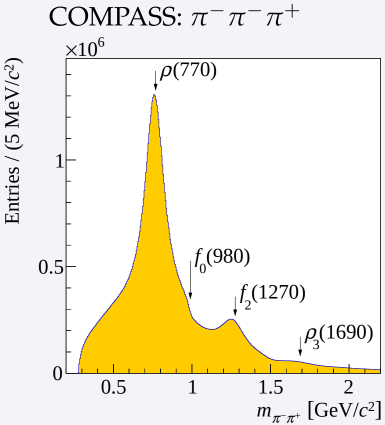


- From 2008 data taking campaign
- 270 000 events
- $0.07 < t' < 0.7\,(\text{GeV}/c)^2$
- Exclusivity ensured by measuring recoil proton
  - Also suppresses target excitations







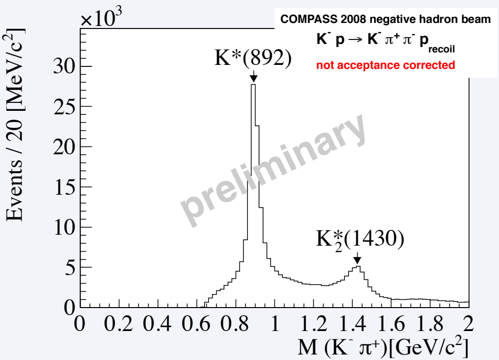
COMPASS, PRD **95** (2017) 032004

- $m_{\pi^-\pi^+}$ spectrum contains states already known from analysis of diffractively produced $\pi^-\pi^-\pi^+$

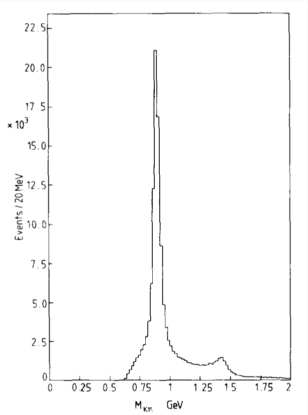
Example: Analysis of $K^-\pi^+\pi^-$ Final State

Invariant Mass of $K^-\pi^+$ Subsystem

COMPASS



WA03 (CERN)



ACCMOR, NPB **187** (1981) 1

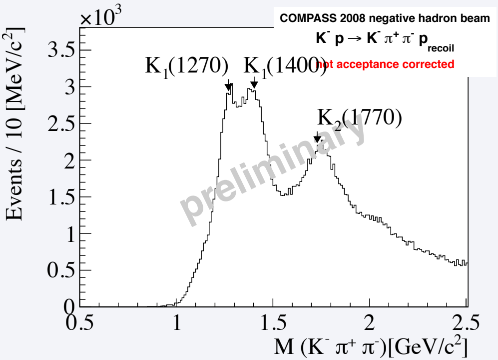
- Clear $K^*(892)$ and $K_2^*(1430)$ signals
- Data set slightly larger than that of most precise previous experiment (WA03)

Example: Analysis of $K^-\pi^+\pi^-$ Final State

Invariant Mass of $K^-\pi^+\pi^-$ System

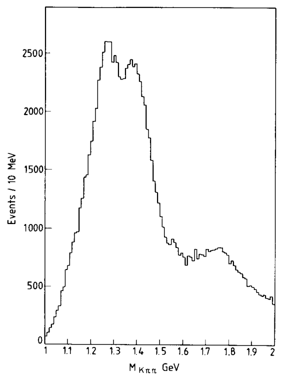
COMPASS

$0.07 < t' < 0.7\,(\mathrm{GeV}/c)^2$



WA03 (CERN)

$0 < t' < 0.7\,(\mathrm{GeV}/c)^2$



ACCMOR, NPB **187** (1981) 1

- Various potential resonance signals
- Need partial-wave analysis (PWA) to disentangle contributions from various J^P quantum numbers

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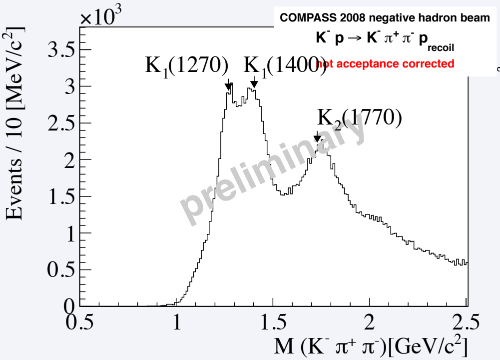
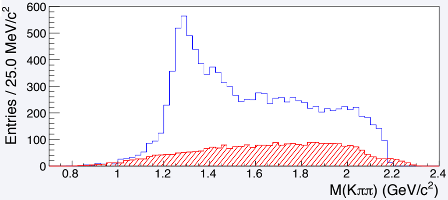


Belle

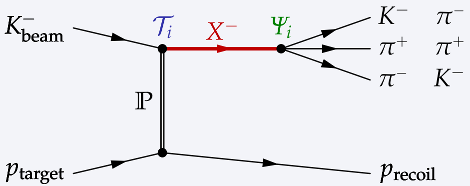
$B^+ \to J/\psi K^+\pi^+\pi^-$



Belle, PRD **83** (2011) 032005

- Various potential resonance signals
- Need partial-wave analysis (PWA) to disentangle contributions from various J^P quantum numbers

Partial-Wave Analysis Method



Ansatz: Factorization of production and decay

$$\mathcal{I}(\tau; m_X) = \left| \sum_i^{\text{waves}} \mathcal{T}_i(m_X)\, \Psi_i(\tau; m_X) \right|^2$$

- Fit model: coherent sum of partial-wave amplitudes
- Decay amplitudes $\Psi_i(\tau; m_X)$
  - Describe kinematic distribution of partial waves
  - Calculated using isobar model and helicity formalism (Wigner D-functions)
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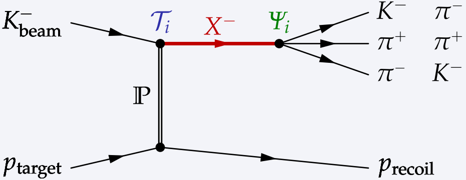

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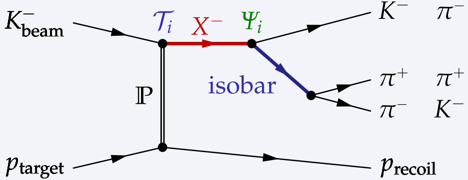
Partial-Wave Analysis Method

C. Adolph *et al.*, PRD **95** (2017) 032004



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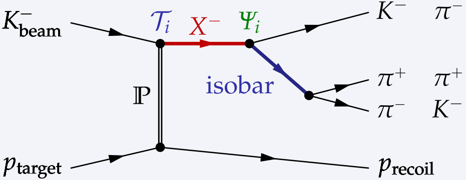

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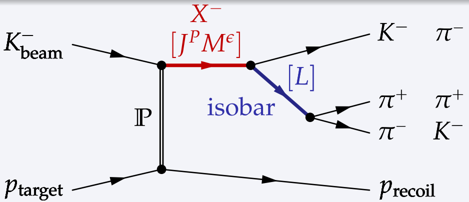
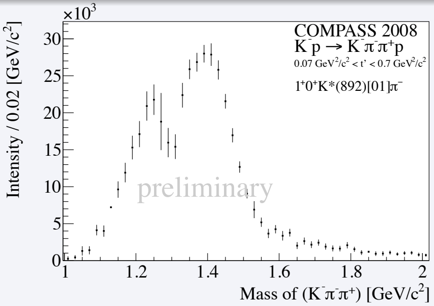
Partial-Wave Analysis of $K^-\pi^+\pi^-$ Final State



PWA model similar to WA03

$$\mathcal{I}(\tau; m_X) = \left| \sum_i^{\text{waves}} \mathcal{T}_i(m_X)\, \Psi_i(\tau; m_X) \right|^2$$

- 6 isobars
  - $\pi^-\pi^+$ subsystem: $f_0(500)$, $\rho(770)$, and $f_2(1270)$
  - $K^-\pi^+$ subsystem: $K_0^*(800)$, $K^*(892)$, and $K_2^*(1430)$
    - $K_0^*(800)$ described by Breit-Wigner amplitude
- 19 waves = combinations of X^- quantum numbers and decay modes

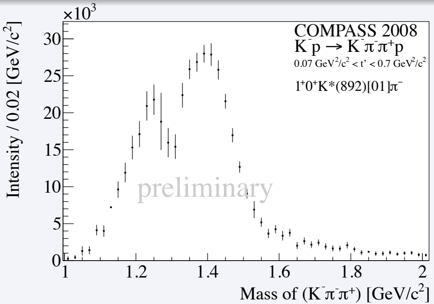


$1^+ \to K^*(892) + \pi^-$ in S-wave

- Clear signals from $K_1(1270)$ and $K_1(1400)$

$2^+ \to K^*(892) + \pi^-$ in D-wave

- Clear signal from $K_2^*(1430)$
- $K_2^*(1980)$?



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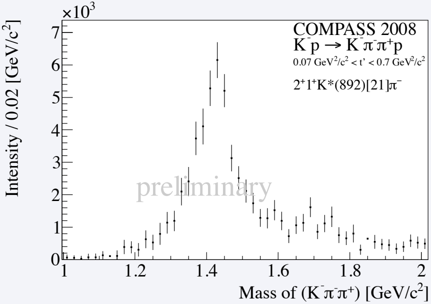

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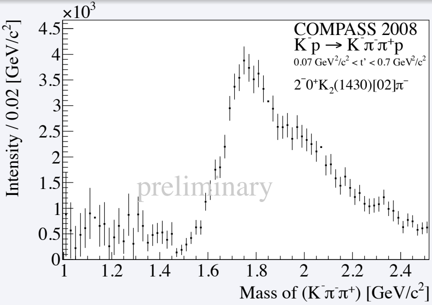
Example: Analysis of $K^-\pi^+\pi^-$ Final State

Results of Partial-Wave Analysis



$2^- \to K_2^*(1430) + \pi^-$ in S-wave

- Possible signals from $K_2(1770)$ and $K_2(1820)$
- $K_2(1580)$ and $K_2(2250)$?

Work in progress: improving analysis

- Improved beam PID + data sample from 2009 run
  $\Rightarrow$ ca. 800 000 $K^-\pi^+\pi^-$ events
  $\Rightarrow$ world's largest data set (4× WA03)
- Improved PWA model $\Rightarrow$ clearer resonance signals
- Resonance-model fit $\Rightarrow$ extraction of $K^-\pi^+\pi^-$ resonances and their parameters

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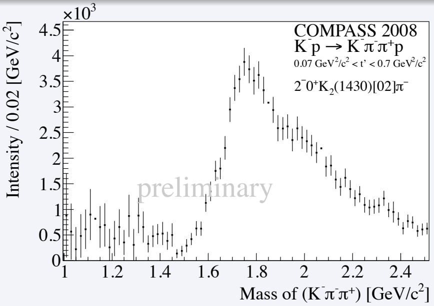

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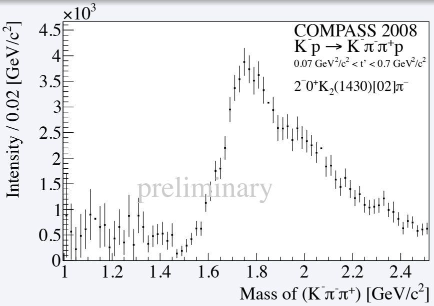

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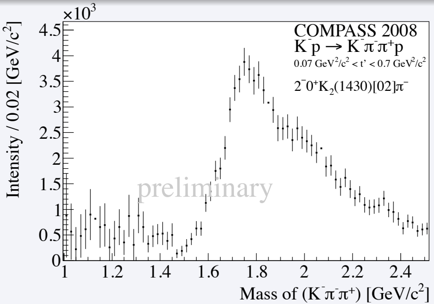

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Further final states accessible by COMPASS

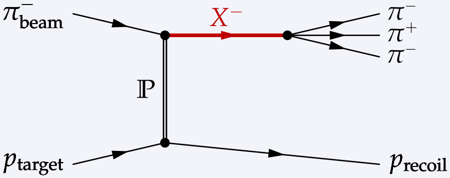
- Isospin partner channel $K^-\pi^0\pi^0$
- $K^-K^+K^-$
- $K^-\pi^0$, $K_S^0\pi^-$, $K^-\eta^{(\prime)}$, $K^-\omega$
- …

Outline

5. Backup slides
   - Introduction
   - The COMPASS Experiment at the CERN SPS
   - *Example:* Analysis of $K^-\pi^+\pi^-$ Final State
   - Why do we need even larger data sets?

Why do we need even larger data sets?

Example: $\pi^- + p \to \pi^-\pi^-\pi^+ + p_{\text{recoil}}$ COMPASS, PRD **95** (2017) 032004



- $50 \times 10^6\ \pi^-\pi^-\pi^+$ events $\Rightarrow$ approx. $10\times$ world data

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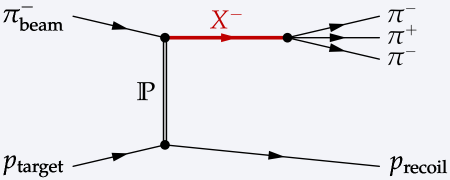

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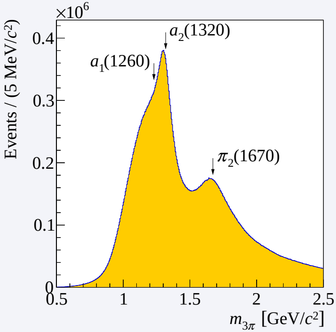

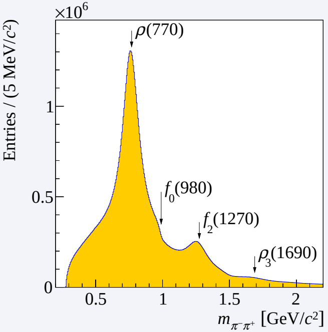

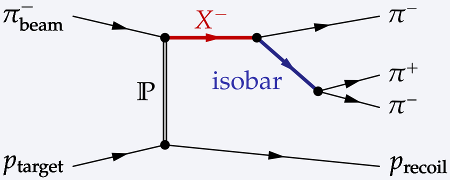

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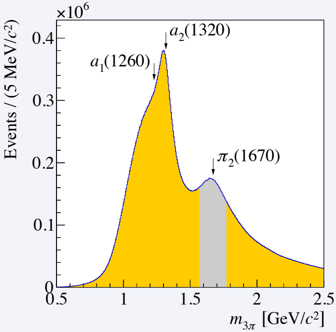
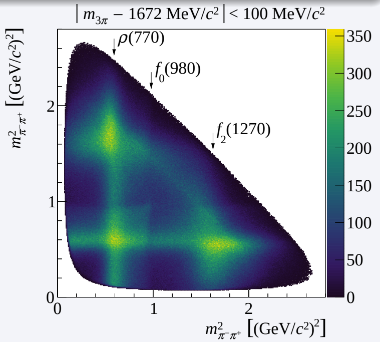


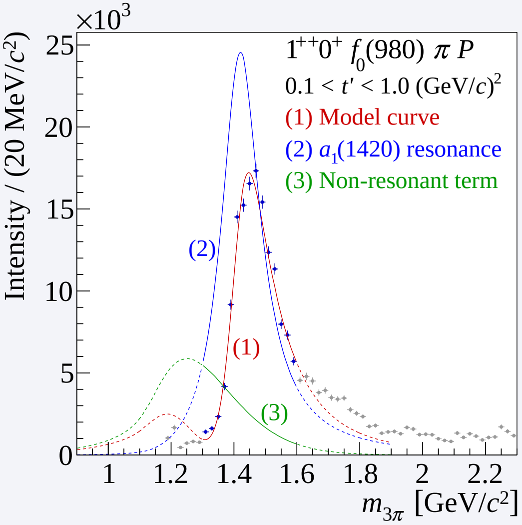


Why do we need even larger data sets?

Example: $\pi^- + p \to \pi^-\pi^-\pi^+ + p_{\text{recoil}}$

Improved sensitivity for small signals

- E.g. surprising find: resonance-like $a_1(1420)$ signal in peculiar decay mode
- Only 0.3 % of total intensity



COMPASS, PRL **115** (2015) 082001

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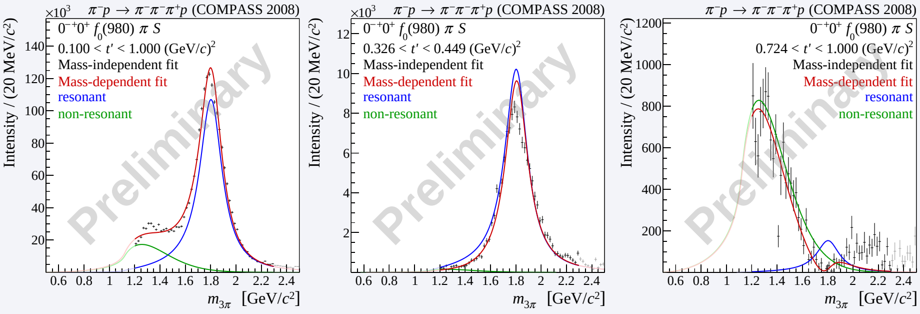
PWA in narrow bins of four-momentum transfer squared t'

- Resolve t' dependence of partial-wave amplitudes
- Improved separation between resonant and nonresonant components in resonance-model fits
- First extraction of t' spectra of resonances from such an analysis $\Rightarrow$ can study production mechanism(s)



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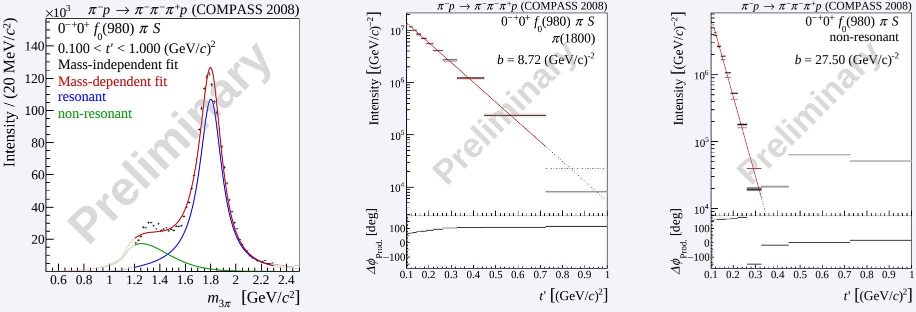

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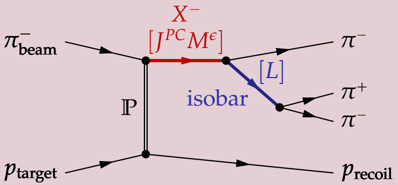
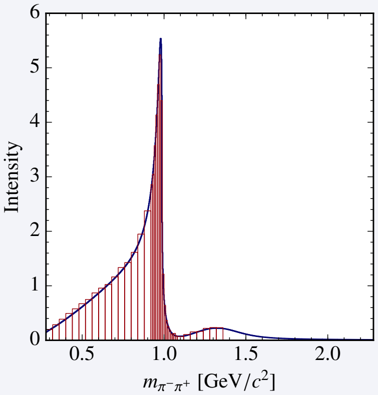
Novel analysis technique "freed-isobar" PWA

[arXiv:1710.09849]



- Conventional PWA requires complete knowledge of isobar amplitude
- *Novel approach:* replace fixed parametrization by step-like function
  - Isobar amplitude determined from data $\Rightarrow$ reduced model dependence
  - E.g. amplitude of $\pi^-\pi^+$ subsystem with $J^{PC} = 0^{++}$ $\Rightarrow f_0(500)$ (?), $f_0(980)$, $f_0(1500)$



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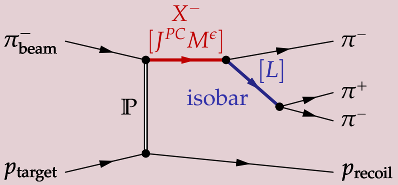

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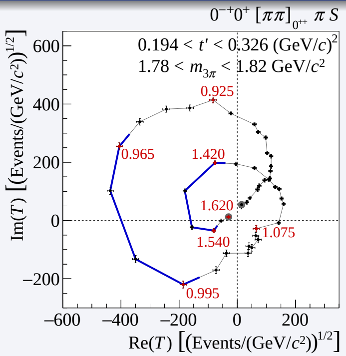

COMPASS, PRD **95** (2017) 032004

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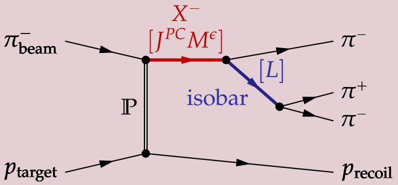

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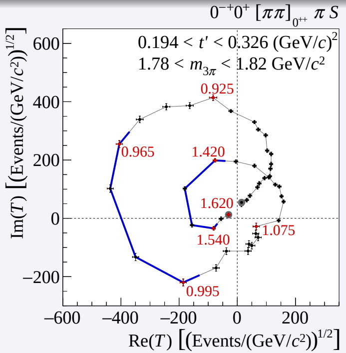
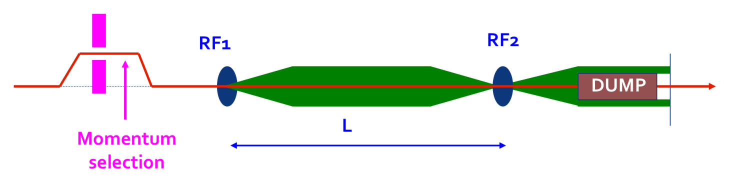


COMPASS, PRD **95** (2017) 032004

- Would allow to study $K^-\pi^+$ subsystem with $J^P = 0^+$ in $K^-\pi^+\pi^-$
- Requires huge data samples

RF-separated Kaon Beam



Possible beam parameters

- Lower beam momentum $\lesssim 100\,\mathrm{GeV}/c$
  - Not an issue: diffractive production depends only weakly on energy
- Estimated kaon intensity: $3.7 \times 10^6\,\mathrm{s}^{-1}$
  - More than factor 35 increase w.r.t. conventional beam line
  - Would correspond to 10 to 20×10^6 $K^-\pi^+\pi^-$ events assuming same acceptance as current experimental setup
    $\Rightarrow$ would be $\approx 10\times$ world data
- More detailed studies needed to determine beam parameters more precisely
- Requires major investment

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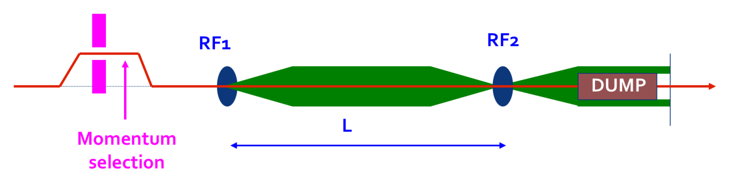

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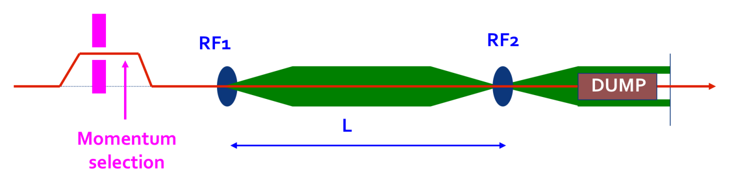

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