Central Production of Light Scalar Mesons at COMPASS

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for the
COMPASS Collaboration

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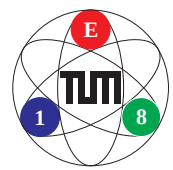

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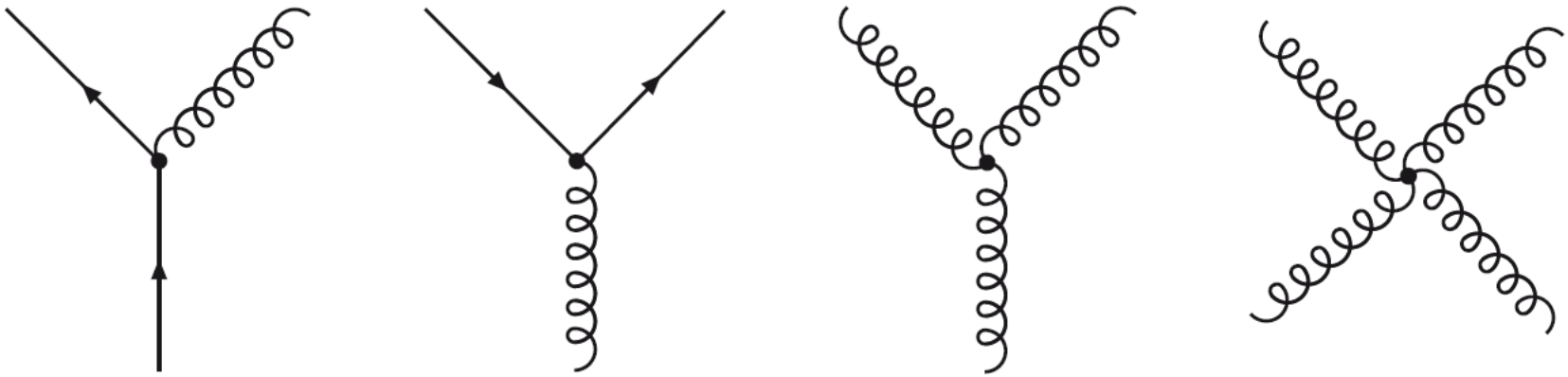
Context: Strong Interaction

Quantum Chromodynamics (QCD)

- Degrees of freedom: quarks and gluons
- Confinement: only colour-neutral objects can be observed
- Baryons (qqq, $\bar{q}\bar{q}\bar{q}$) and Mesons ($q\bar{q}$) as the relevant degrees of freedom



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- Glueballs and other exotic hadrons predicted by many approximations

Tetraquark

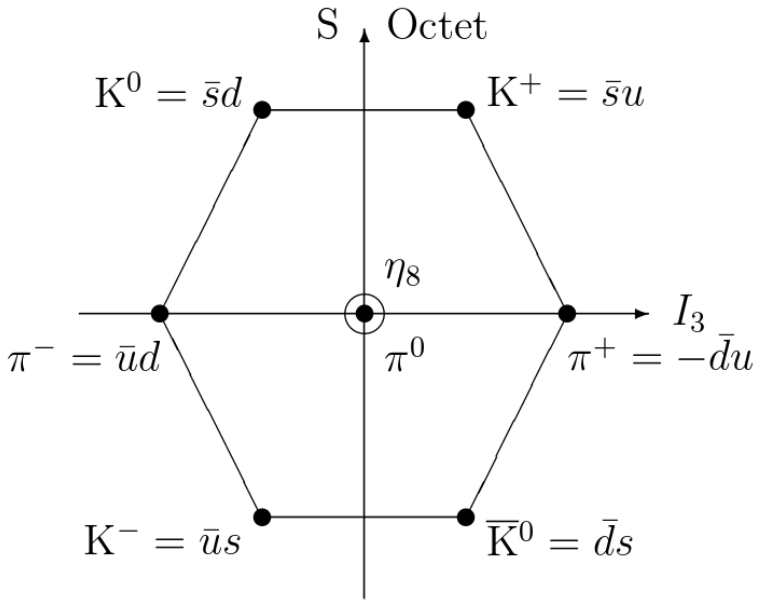
QCD hybrid

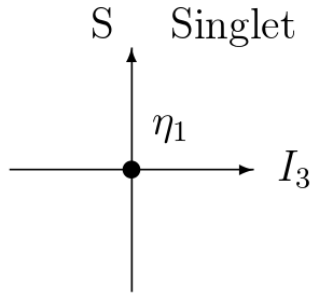
Where are they?

Prediction of the Standard Model that has not yet been confirmed experimentally!

Light-Quark Meson Spectroscopy

- Flavour SU(3): Mesons are grouped into $3 \otimes 3 = 8 \oplus 1$ nonets

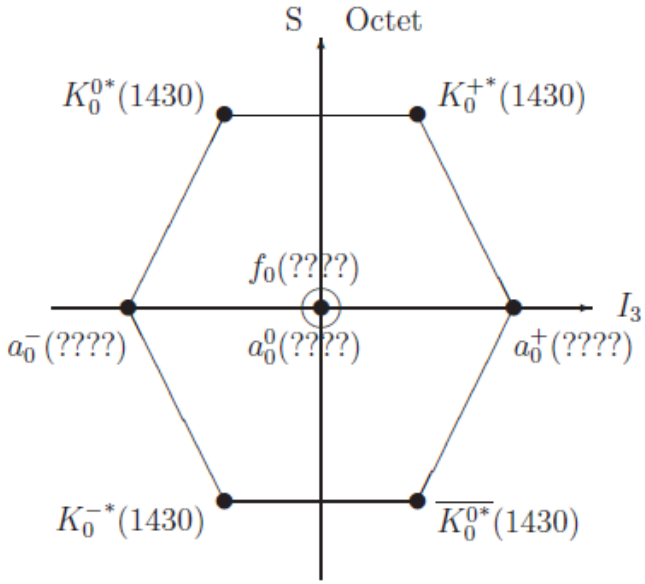


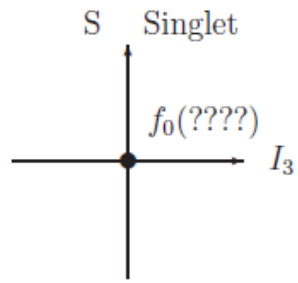


Light-Quark Meson Spectroscopy

- Flavour SU(3): Mesons are grouped into $3 \otimes 3 = 8 \oplus 1$ nonets
- Scalar isoscalar mesons ($I^G\, J^{PC} = 0^+\, 0^{++}$):
  $f_0(500)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$, ...

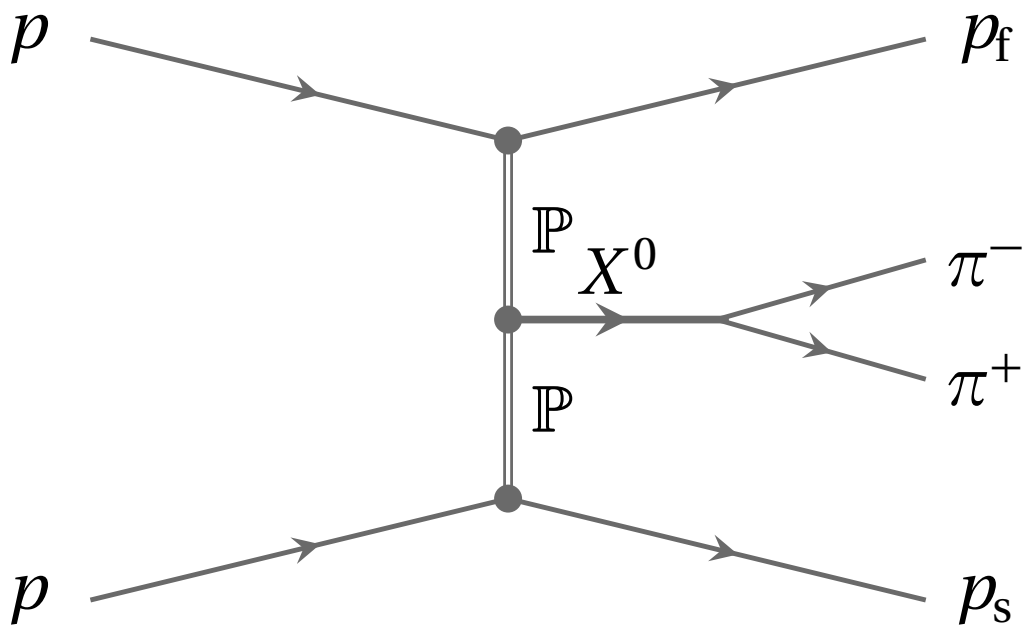
'ground state nonet of scalar mesons as most physicists in the field would agree upon'
E. Klempt [arXiv:hep-ex/0101031]





- **Super-numerous f_0 states** not at all understood by quark models
  $\Rightarrow$ Mixing with **Glueballs?**

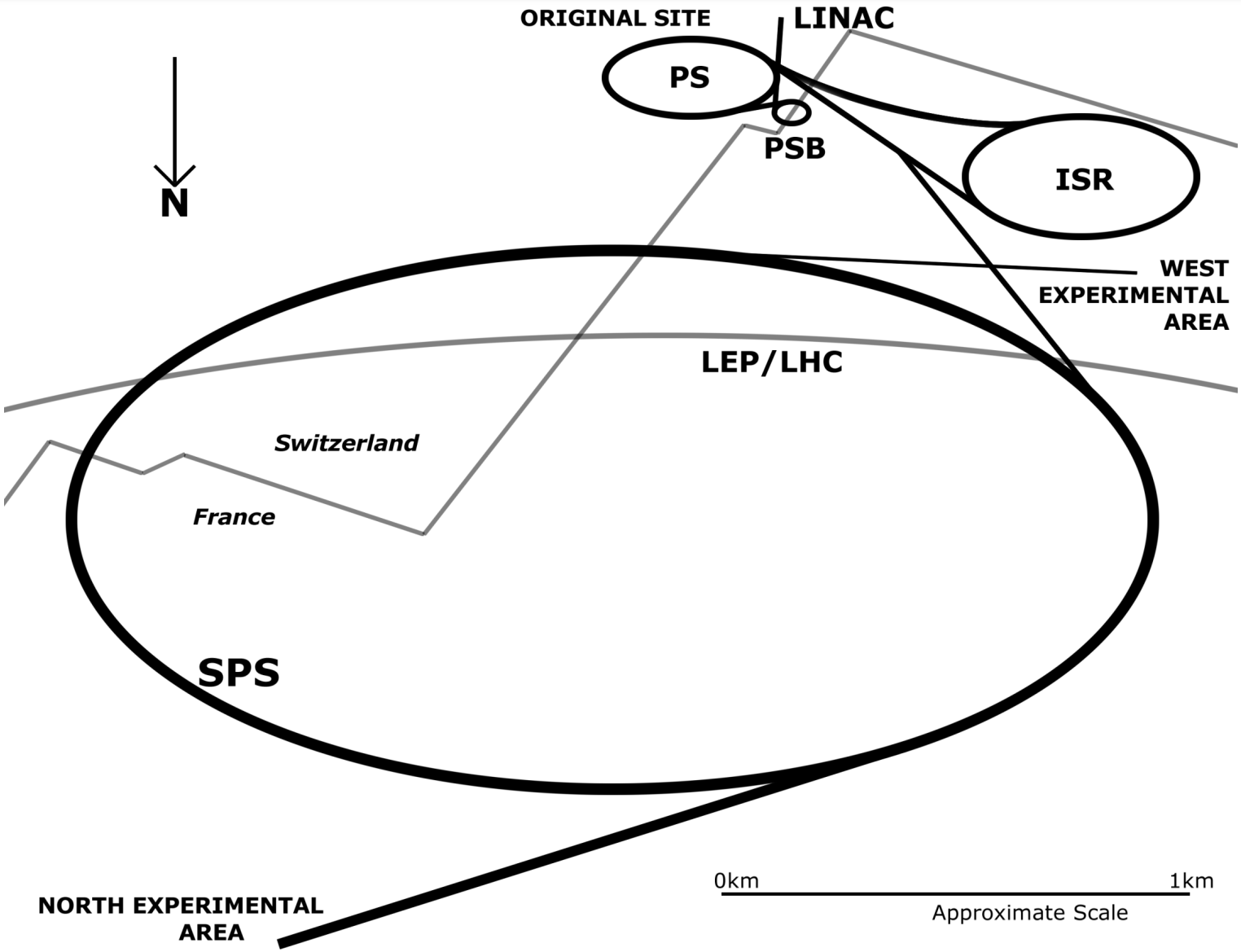
Central Production



$p\,p \to p_{\text{fast}}\,X\,p_{\text{slow}}$

- Proton beam impinging on proton target, both **stay intact** and are detected
- Double-Pomeron production of meson system (**gluon-rich environment**)
- Decay into two pseudoscalar mesons ($\boldsymbol{\pi^+\pi^-}$, $\pi^0\pi^0$, K^+K^-, $\eta\,\eta$, ..)

Central Production at CERN



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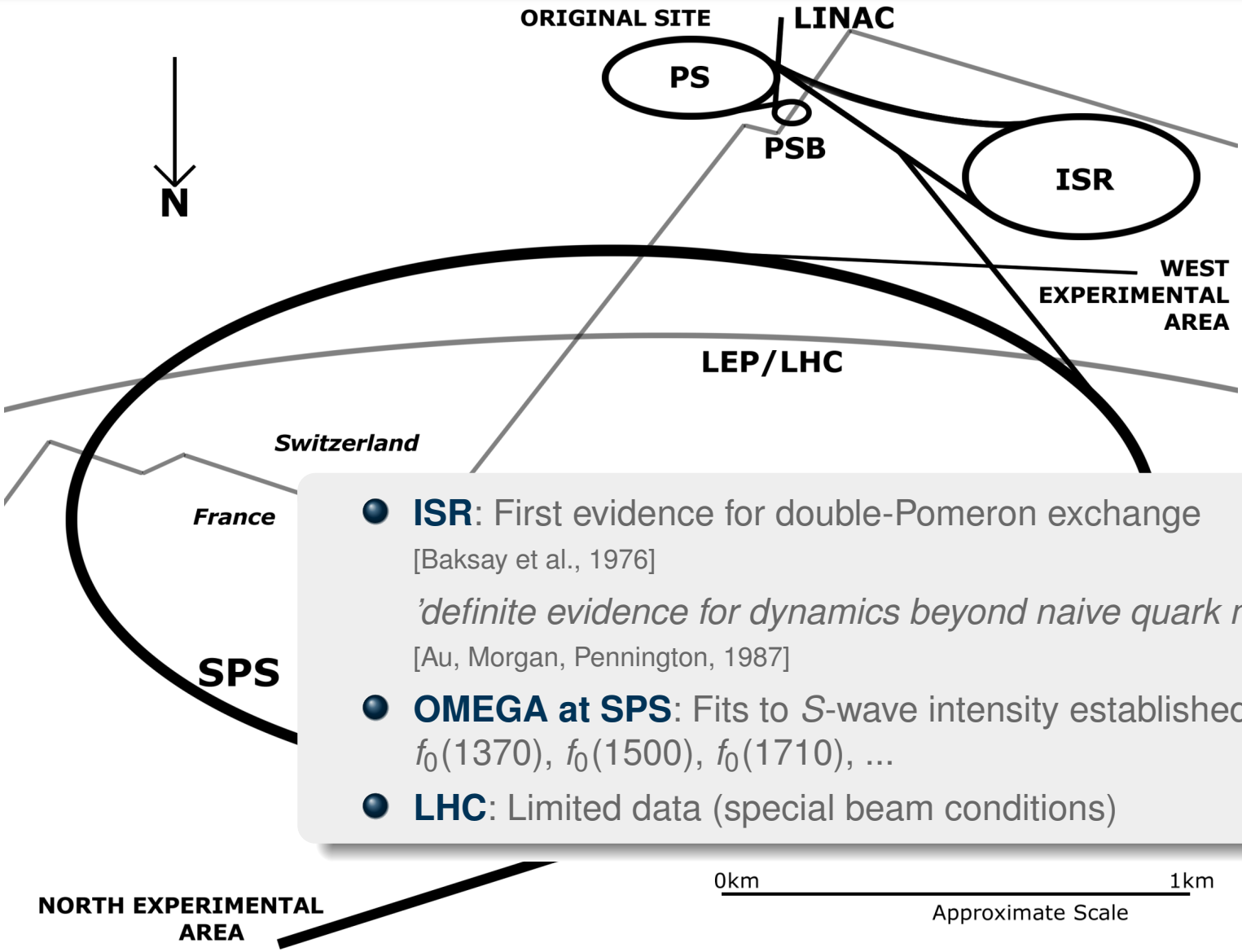

- **ISR**: First evidence for double-Pomeron exchange
  [Baksay et al., 1976]
  'definite evidence for dynamics beyond naive quark model'
  [Au, Morgan, Pennington, 1987]
- **OMEGA at SPS**: Fits to S-wave intensity established
  $f_0(1370)$, $f_0(1500)$, $f_0(1710)$, ...
- **LHC**: Limited data (special beam conditions)

COMPASS at CERN SPS

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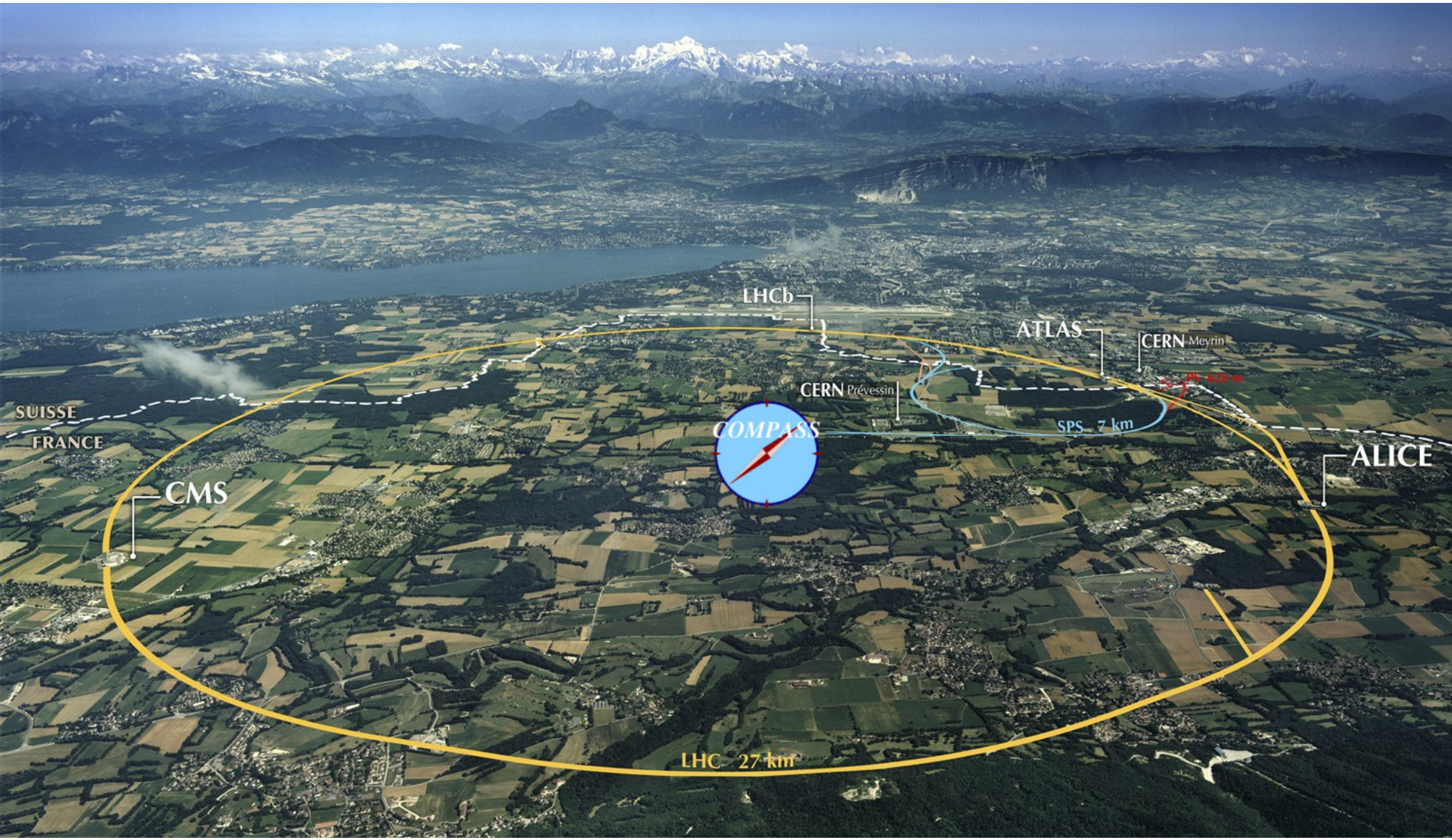

The COMPASS Experiment

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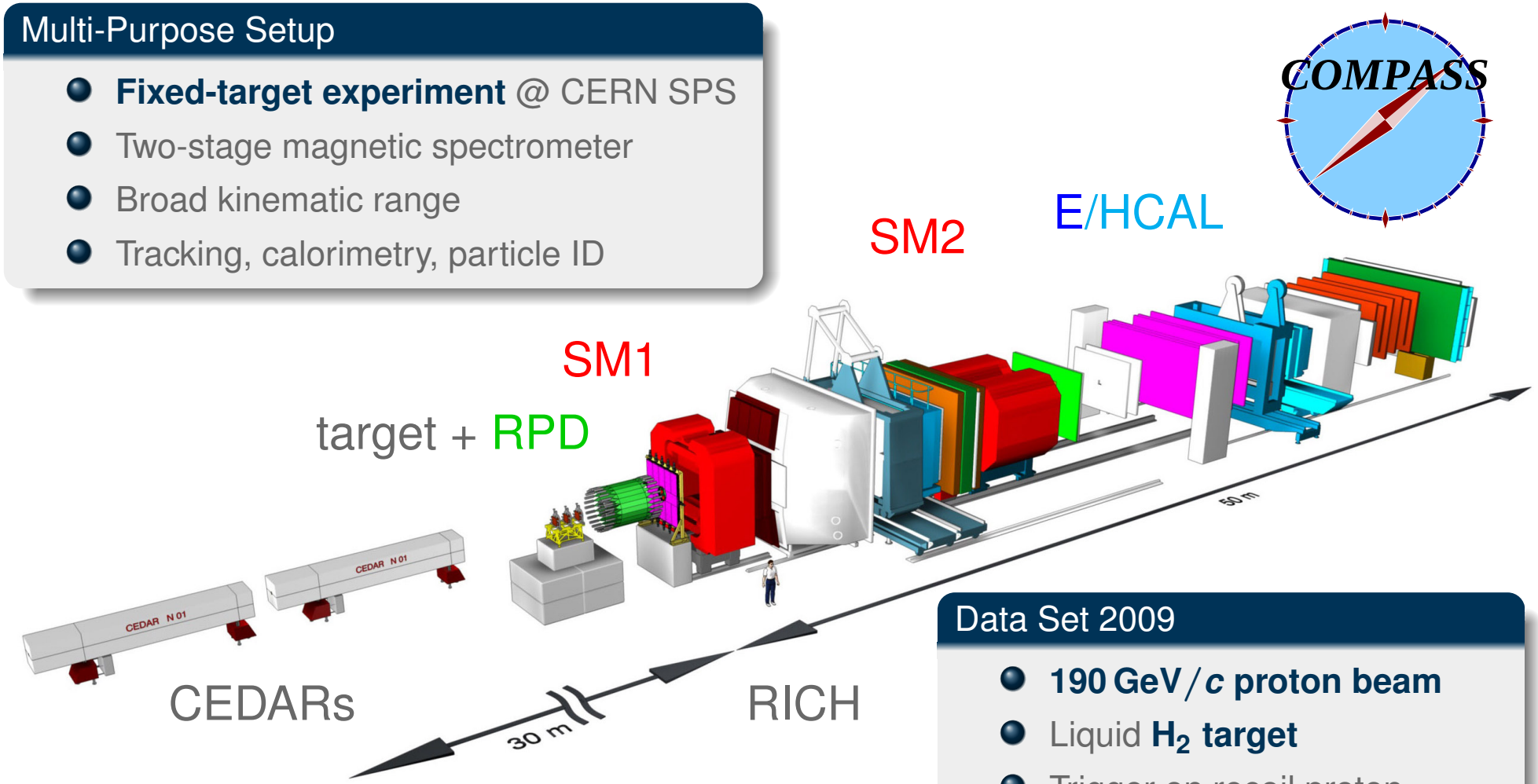
Multi-Purpose Setup

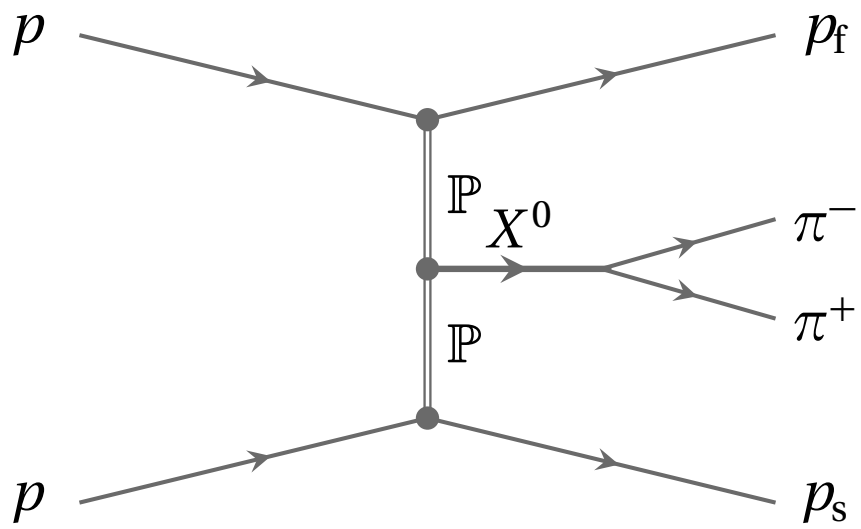
- **Fixed-target experiment** @ CERN SPS
- Two-stage magnetic spectrometer
- Broad kinematic range
- Tracking, calorimetry, particle ID



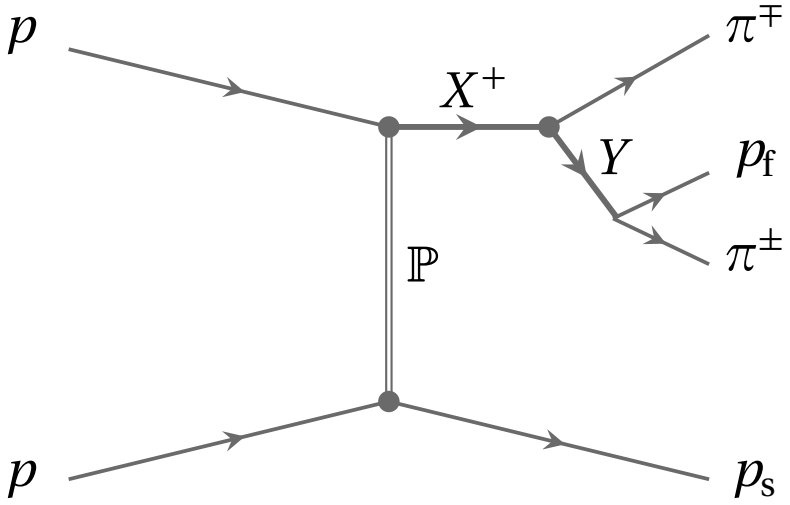
Data Set 2009

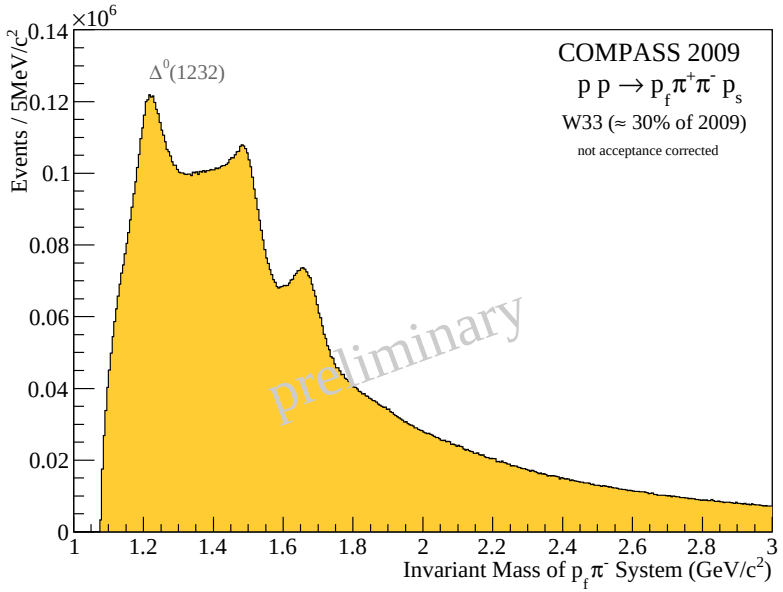
- **190 GeV/c proton beam**
- Liquid **H_2 target**
- Trigger on recoil proton

Central Production of Two-Pseudoscalar Final States



Central Production of $\pi^+\pi^-$ System





- Baryon resonances in $p_f\pi^\pm$ subsystems
  $\rightarrow$ **Diffractive dissociation** of the beam proton as dominant process

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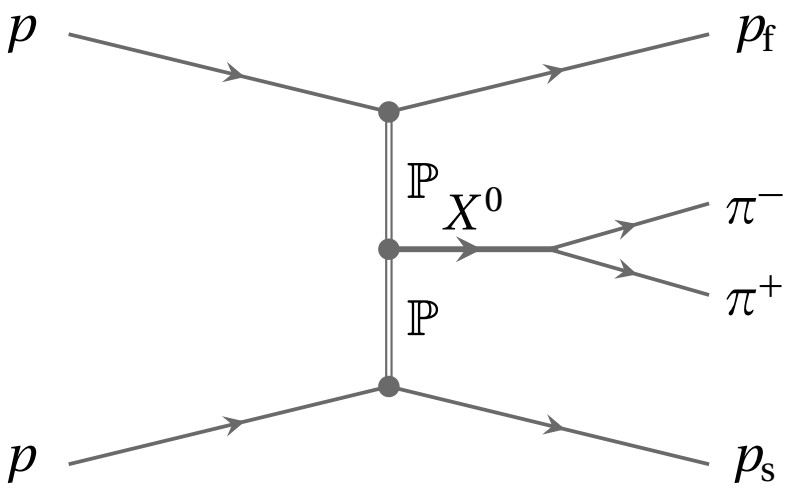

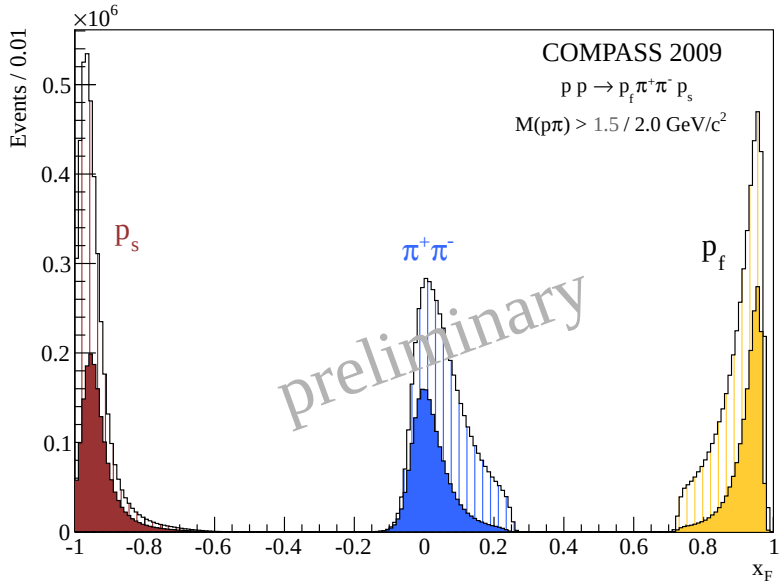

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  $\rightarrow$ **Diffractive dissociation** of the beam proton as dominant process
- **Kinematic separation** between p_f and $\pi^\pm$
- Separation between p_s and $\pi^\pm$ by trigger on recoil proton p_s

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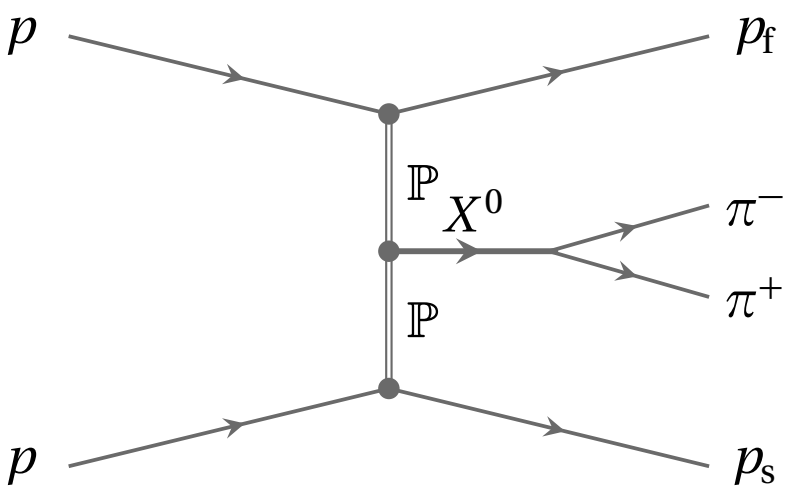
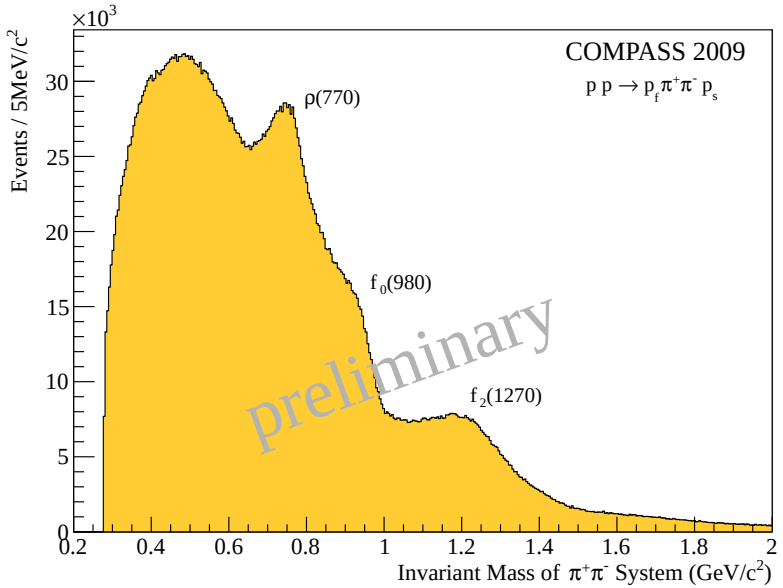
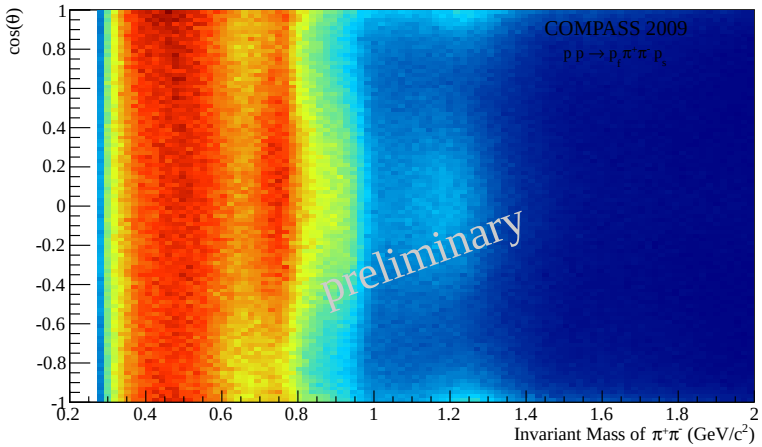


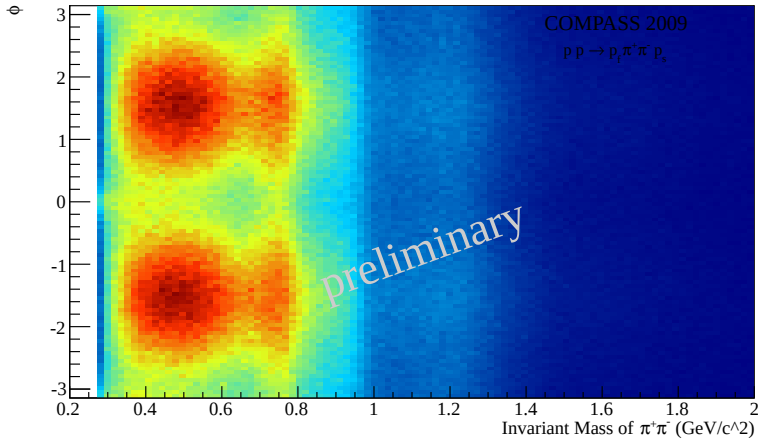


- Baryon resonances in $p_f\pi^\pm$ subsystems
  $\rightarrow$ **Diffractive dissociation** of the beam proton as dominant process
- **Kinematic separation** between p_f and $\pi^\pm$
- Separation between p_s and $\pi^\pm$ by trigger on recoil proton p_s
- $\rho(770)$ production $\rightarrow$ kinematic selection cannot isolate pure DPE sample

$\Rightarrow$ **Two-Body Partial-Wave Analysis (PWA)**

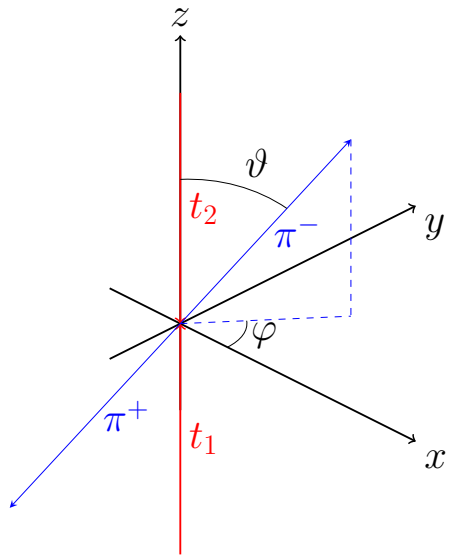
Partial-Wave Analysis



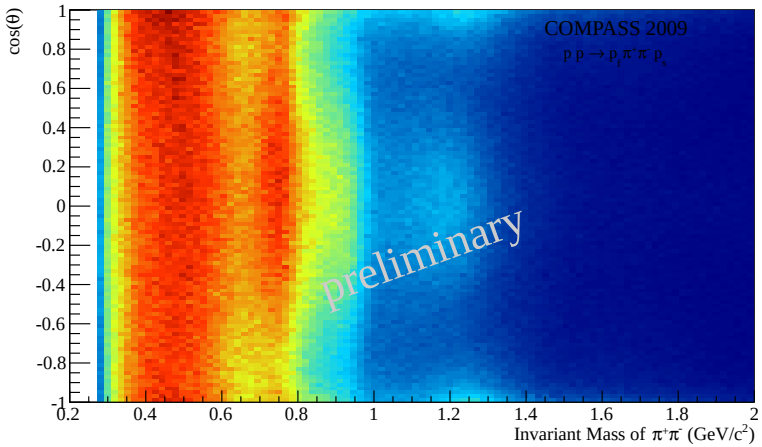


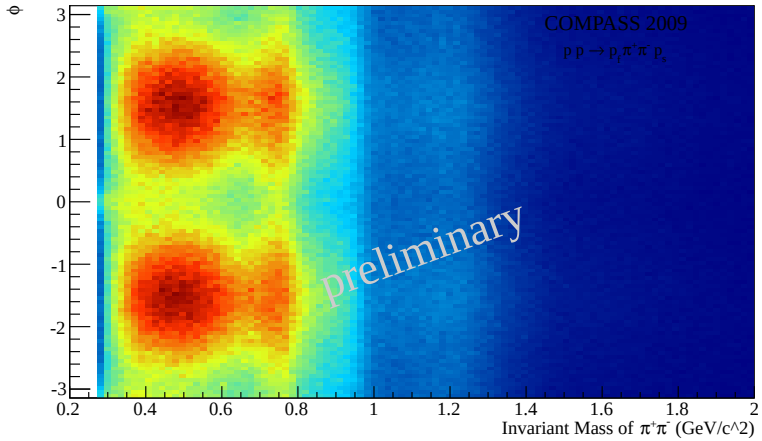
$X^0 \to \pi^+\pi^-$

- **Assumption:** collision of two space-like exchange particles
- Decay of X^0 fully described by $M(\pi^+\pi^-)$, $\cos\vartheta$ and φ



Partial-Wave Analysis





$X^0 \to \pi^+\pi^-$

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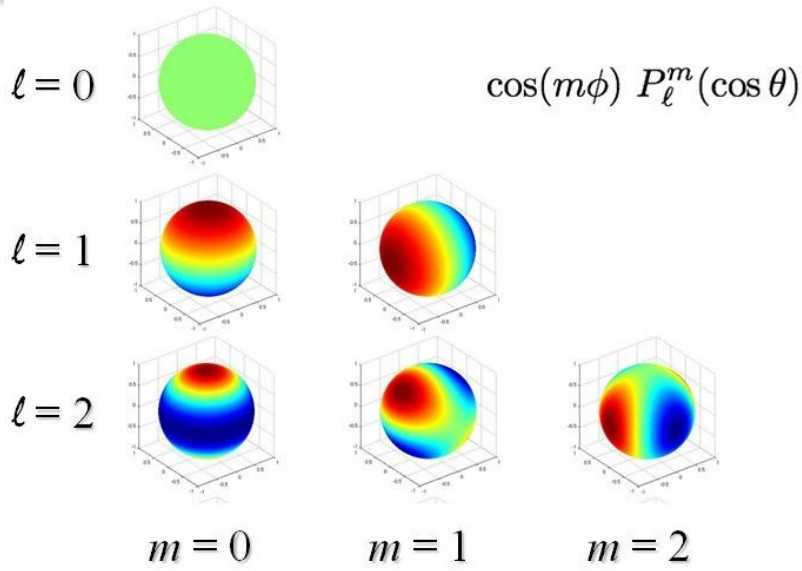
- Decompose into complex-valued amplitudes (spherical harmonics) with definite spin and parity



Partial-Wave Decomposition

Expand intensity $I(\vartheta, \varphi)$ into partial-wave amplitudes in narrow mass bins ($10\,\mathrm{MeV}/c^2$):

$$I(\vartheta, \varphi) = \left| \sum_{LM} T_{LM} Y_M^L(\vartheta, \varphi) \right|^2$$

- Quantum-mechanical interference between amplitudes with same $|\mathrm{i}\rangle$ and $|\mathrm{f}\rangle$
- Complex-valued transition amplitudes T_{LM}, no assumption on mass-dependence
- Significant contributions only from $L = S, P, D$ and $M \leq 1$

$\Rightarrow$ **Maximum Likelihood Fit in Mass Bins**

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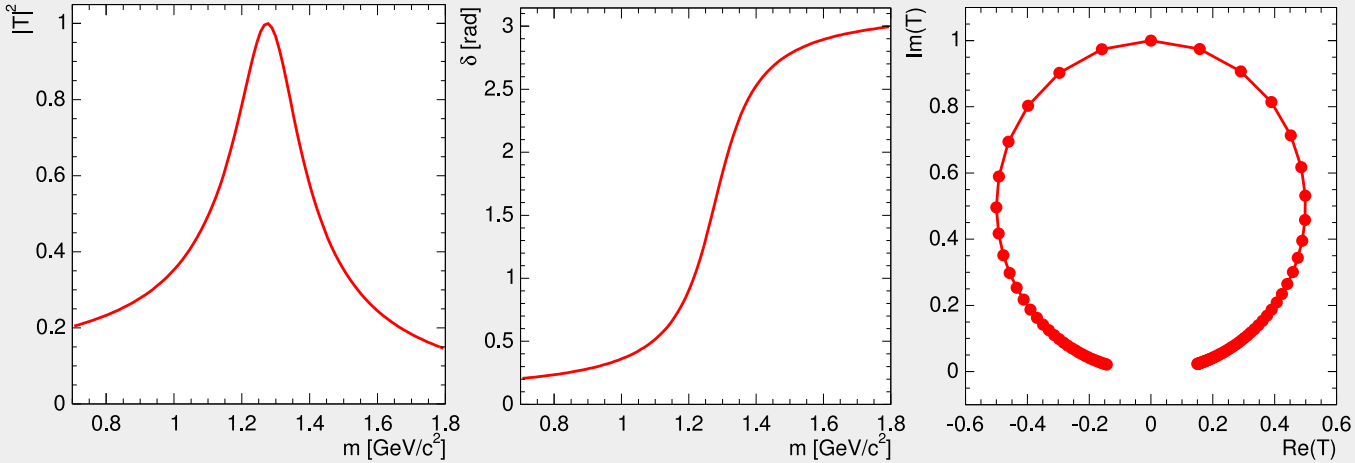
$\Rightarrow$ **Maximum Likelihood Fit in Mass Bins**

- Physical observables: **intensities** $|T_{LM}|^2$ and **relative phases** ($\rightarrow$ Model)

Model Parametrisation

Resonance: Relativistic Breit-Wigner Function

[K. Peters, arXiv:hep-ph/0412069]



$\mathcal{R}_{\text{dyn}}(m) = \frac{m_0\sqrt{\Gamma_0}\sqrt{\Gamma(m;L)}}{m_0^2 - m^2 - im_0\Gamma(m;L)}$ with the **parameters m_0, Γ_0** and the dynamical width $\Gamma(m, L)$

Non-Resonant Contribution: Phase Space with Exponential Damping

$\mathcal{N}(m) = \left(\frac{q}{m}\right)^L \cdot \sqrt{\frac{q}{m}} \cdot \exp(-\alpha q^2)$ with breakup momentum q and **parameter α**

- Sum with complex-valued coefficient (**strength + phase**) for each component

Mass-Dependence of K^+K^-

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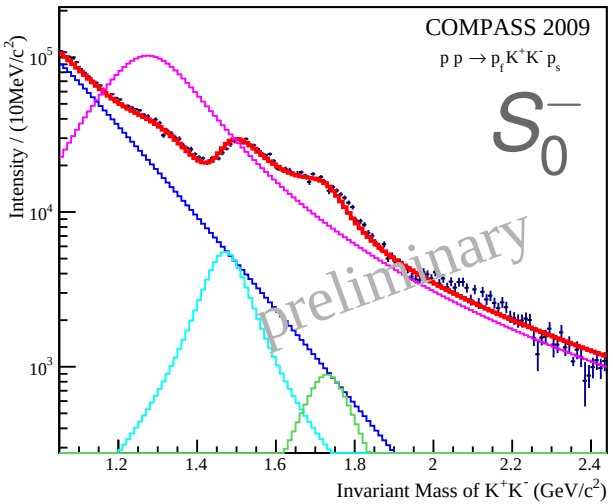
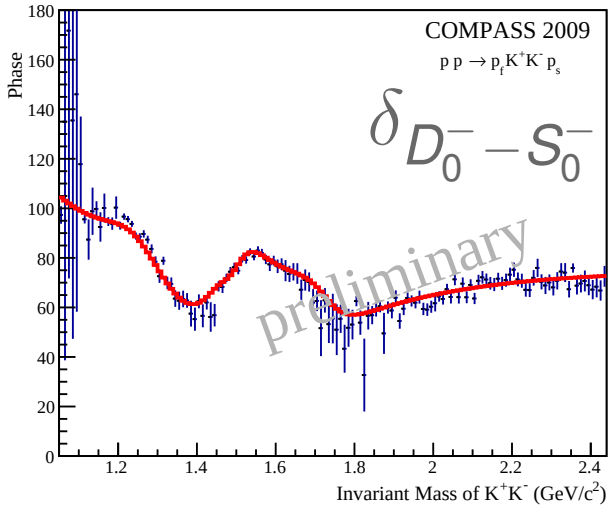
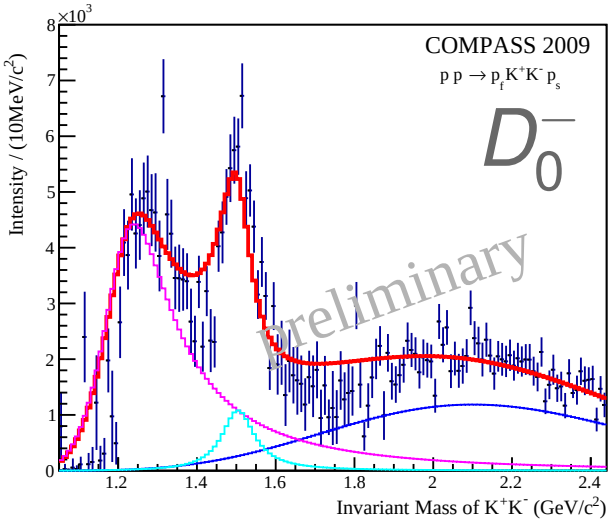
$f_0(1370)$
$f_0(1500)$
$f_0(1710)$





- BW contributions
- non-resonant contribution
- **coherent sum**



$f_2(1270)$
$f_2'(1525)$

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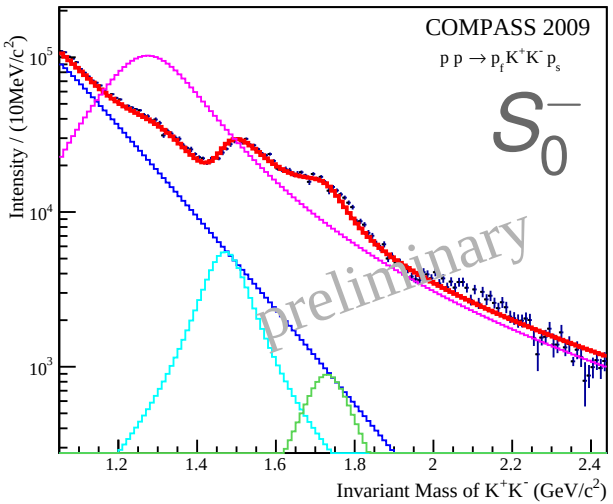

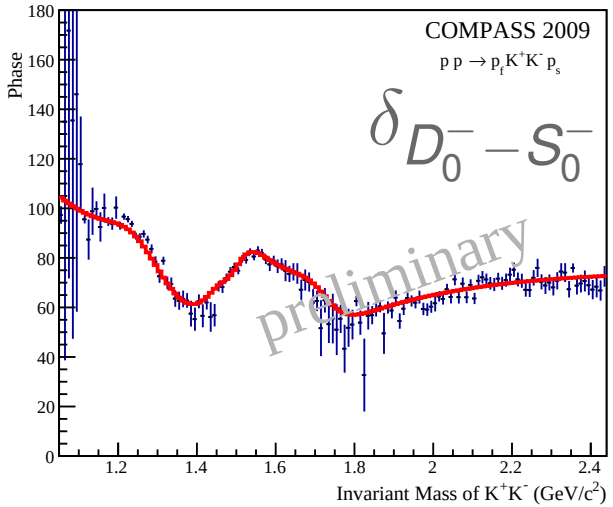

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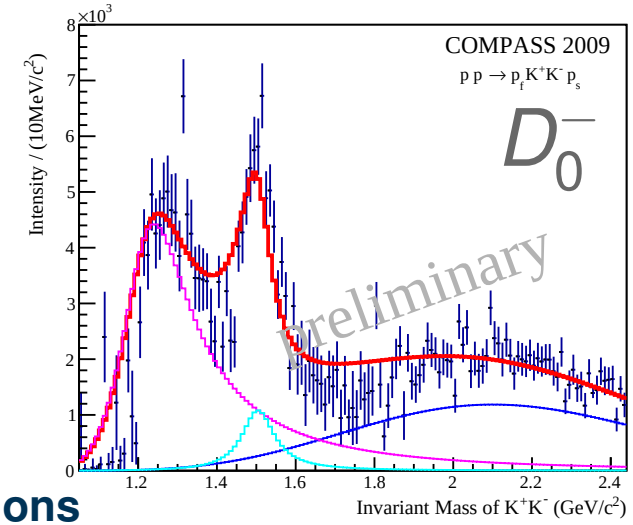

$f_2(1270)$
$f_2'(1525)$

Even better:

coupled channels, unitary models ⇒ **pole positions**

Conclusion

COMPASS is a unique experiment to study
light-quark hadron spectroscopy

- **Large samples** and **precision data** outperform previous experiments
- **Novel analysis schemes** provide insight in hadron dynamics
- **Consistent picture of scalar sector** through combination of different approaches

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- Implications for **BSM searches** (e.g. CPV in heavy meson decays)

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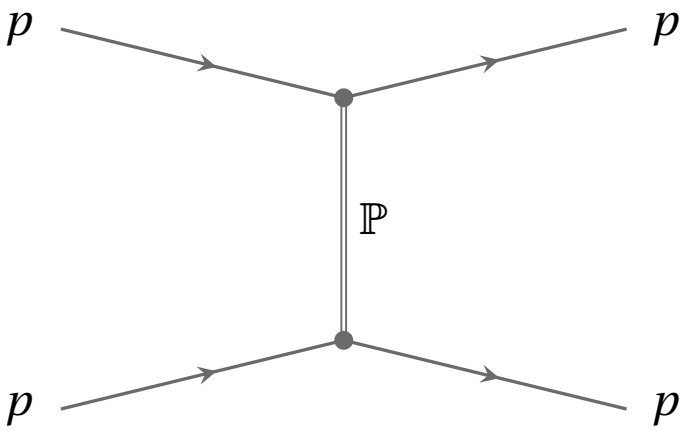
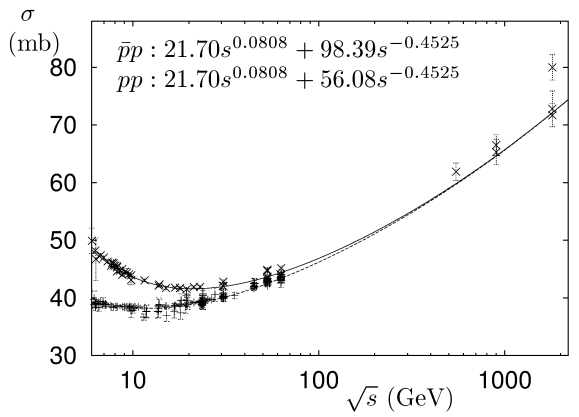
Thank you for your attention!

Backup Slides

Regge Theory



S. Donnachie et al. (2002)



Phenomenological Theory of Hadron Scattering

- Postulation of Pomeron $\mathbb{P}$ necessary for scattering above $\sqrt{s} \approx 10\,\text{GeV}$
- **Which observed particles, if any, correspond to the Pomeron?**

How does Regge theory emerge from QCD at long distances?

Ambiguities

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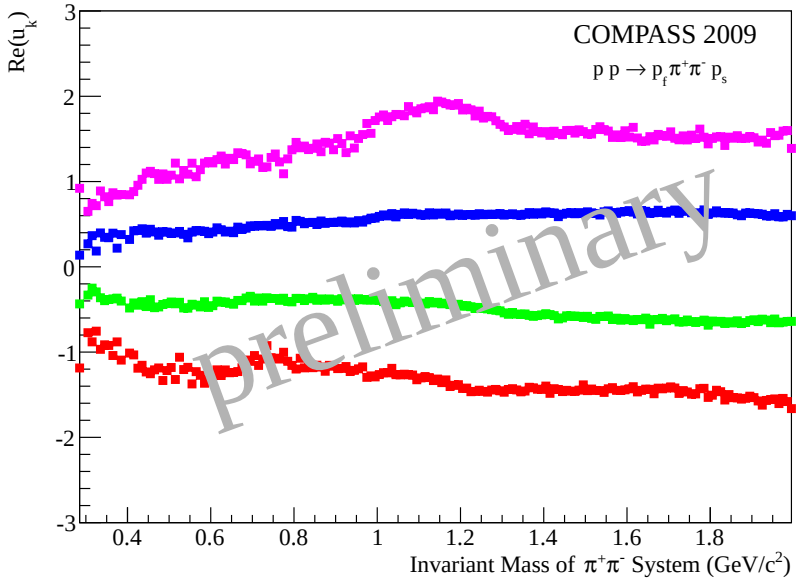
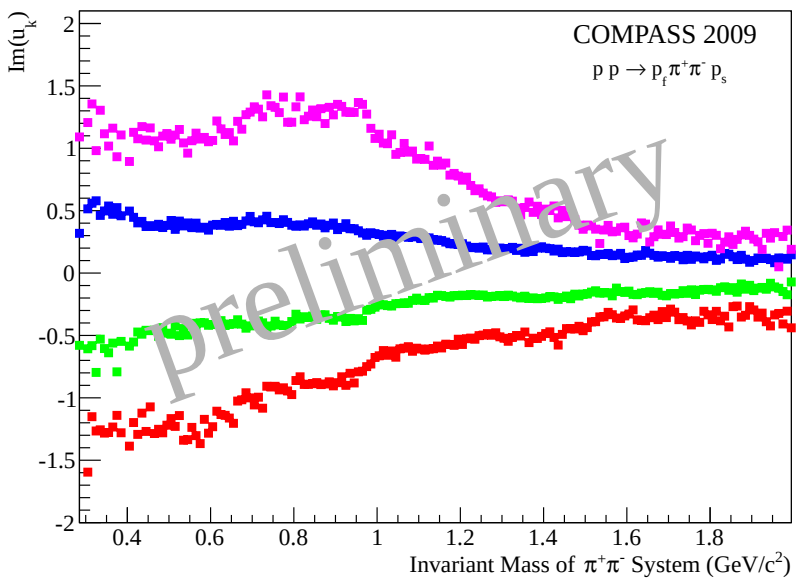
- 8 mathematically ambiguous solutions result in the same angular distribution
- Analytical computation via method of Barrelet Zeros





- Real (left) and imaginary (right) part of polynomial roots
- Well separated, imaginary parts do not cross the real axis

$\Rightarrow$ Solutions can be uniquely identified and linked from mass bin to mass bin

Ambiguities in the $\pi\pi$ Systems

$\pi^+\pi^-$ System

- 8 different solutions can be calculated analytically
- Differentiation requires additional input
  (e.g. behaviour at threshold, physics content)

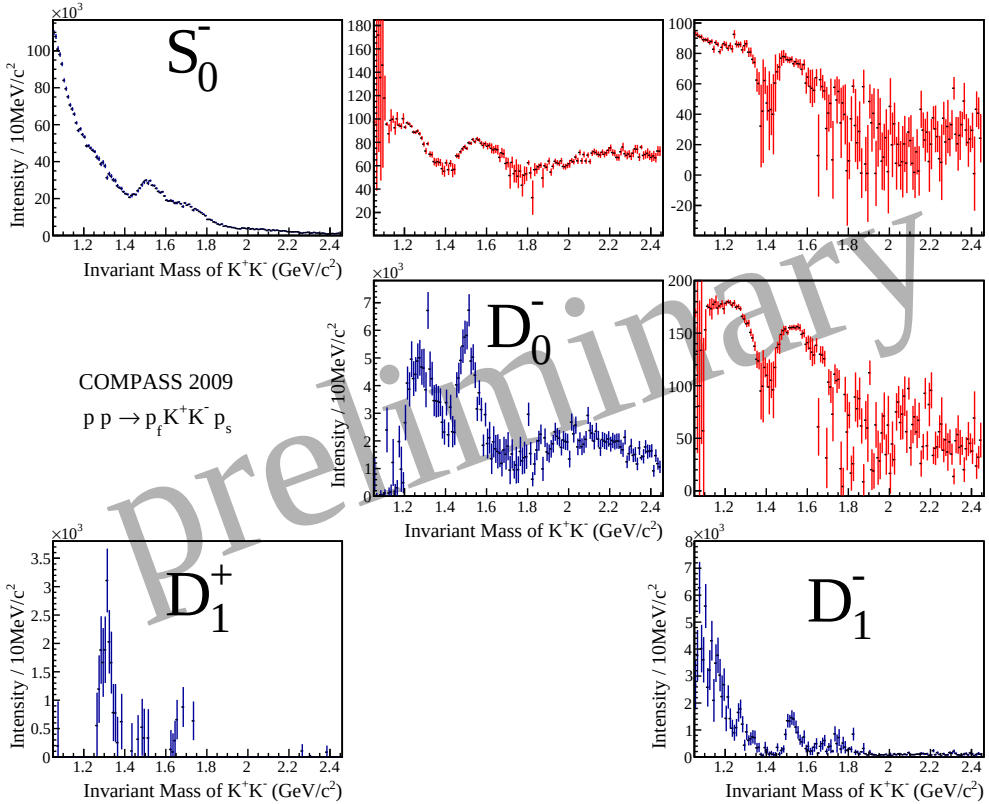
$\pi^0\pi^0$ System

- Identical particles, only even waves allowed
- Reduces number of ambiguities to 2

Combination of $\pi\pi$ Systems

- Consistent picture of the reaction, measured with different parts of experimental setup
- Interpretation with mass dependent parametrisation under way!

Fit to the K^+K^- System



- Similar partial-wave analysis of K^+K^--system
- Odd waves do not play a significant role above the $\phi(1020)$-mass
  $\Rightarrow$ Reduction of ambiguities