Central Exclusive Production of Two-Pseudoscalar Final States at COMPASS

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for the
COMPASS Collaboration

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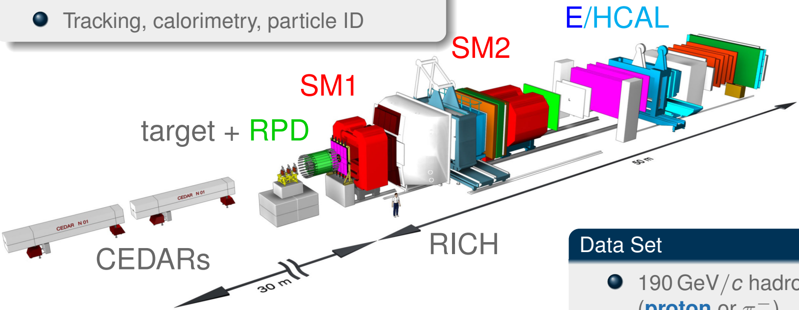
COMPASS
Großgeräte der physikalischen Grundlagenforschung

Outline

The COMPASS Experiment

Multi-Purpose Setup

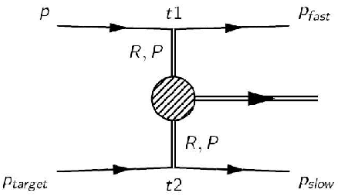
- Fixed-target experiment @ CERN SPS
- Two-stage magnetic spectrometer
- Broad kinematic range
- Tracking, calorimetry, particle ID



Data Set

- 190 GeV$/c$ hadron beam (**proton** or π^-)
- Liquid H_2 target
- Trigger on recoil proton

Central Exclusive Production



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

- Proton beam impinging on liquid hydrogen target
- Double-Pomeron Exchange as glue-rich environment
  $\Rightarrow$ Production of non-$q\bar{q}$-mesons (Glue Balls, Hybrids) at central rapidities

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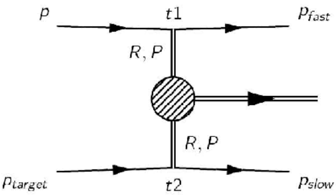

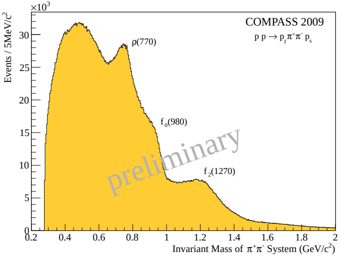

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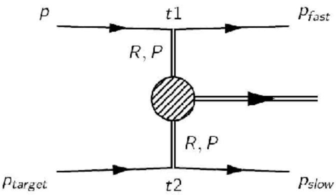

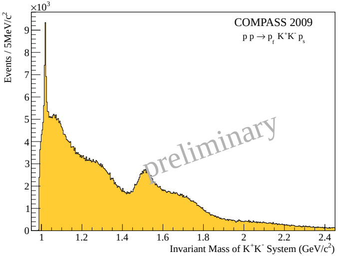

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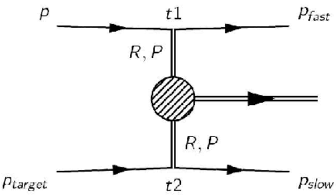

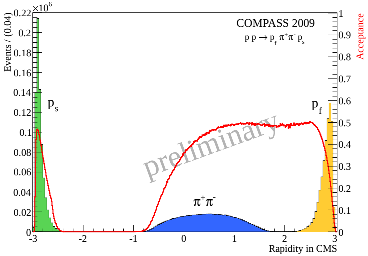

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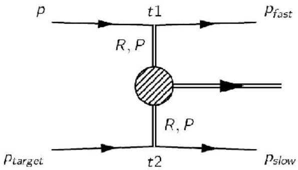
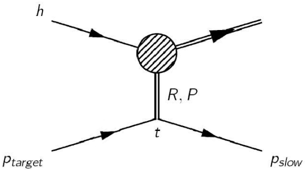
- Decay into two-pseudoscalar final state ($\pi^+\pi^-$, $\pi^0\pi^0$, K^+K^-, $\eta\,\eta$, ..)
- Rapidity gap between p_s and the central system X introduced by the principal trigger

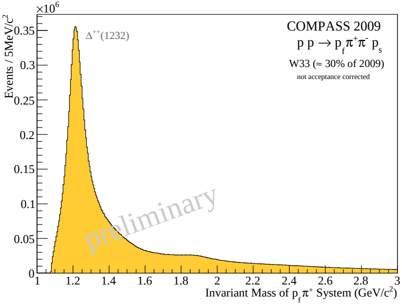
Central Exclusive Production





Kinematic Selection

- $M(p\pi) > 1.5\,\mathrm{GeV}/c^2$



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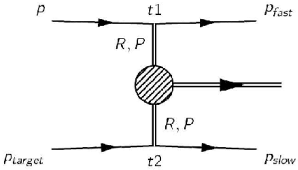
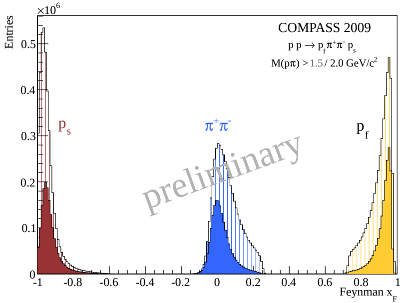


Kinematic Selection

- $x_F(p_f) > .9$



Central Exclusive Production

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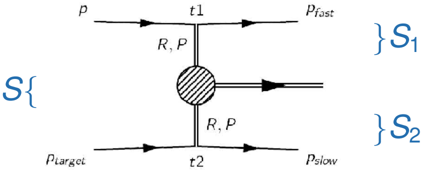
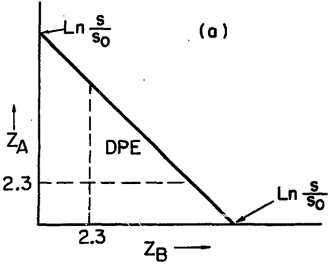




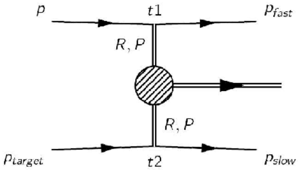
Kinematic Selection

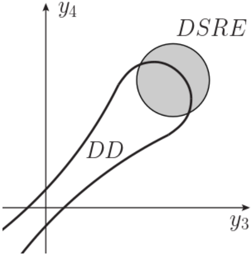
- $Z_{A,B} > 2.3$

- $Z_A = \ln \frac{s}{s_1}$
- $Z_B = \ln \frac{s}{s_2}$

D.M. Chew, [Nucl. Phys. B 82 (1974)]

Central Exclusive Production





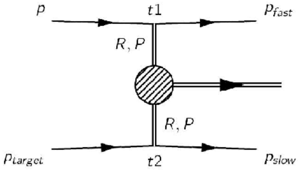
Kinematic Selection

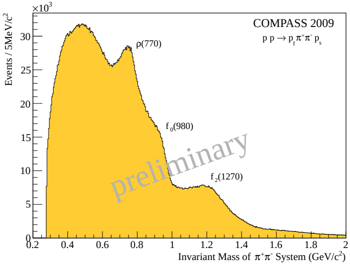
- $|y(\pi)| < 1$

- DD: double diffraction (= central production)
- DSRE: diffractive single resonance excitation

P. Lebiedowicz and A. Szczurek, [Phys. Rev. D 81 (2010)]

Central Exclusive Production





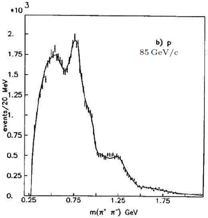
Kinematic Selection

- $M(p\pi) > 1.5\,\text{GeV}/c^2$
- $x_F(p_f) > .9$
- $Z_{A,B} > 2.3$
- $|y(\pi)| < 1$
- ...

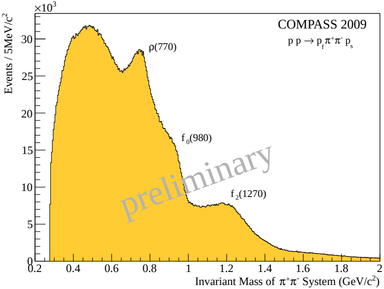
Large overlap of the cuts, weak dependence of the results (CEP sample by all definitions, but not pure DPE!)

$\sqrt{s}$-Dependence

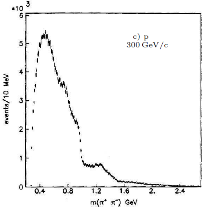
T.A. Armstrong et al. [Z. Phys. C51 (1991)]



$\sqrt{s} = 12.7\,\text{GeV}/c^2$



$\sqrt{s} = 18.9\,\text{GeV}/c^2$

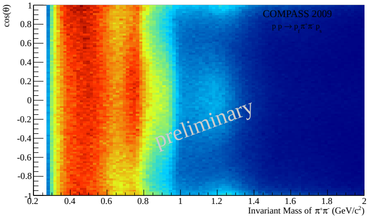


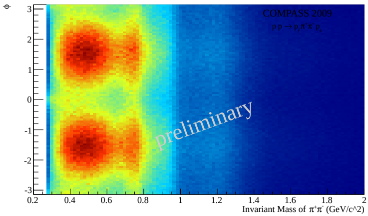
$\sqrt{s} = 23.7\,\text{GeV}/c^2$

- Production of $\rho(770)$ disappears rapidly with increasing $\sqrt{s}$
- Low mass enhancement (σ) and $f_0(980)$ remain practically unchanged
  $\rightarrow$ characteristic for s-independent Pomeron-Pomeron scattering

Two-Body Partial-Wave Analysis in Mass Bins

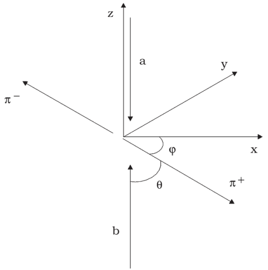
Partial-Wave Analysis





$X \rightarrow \pi^+\pi^-$

- **Assumption:** collision of two space-like exchange particles ($\mathbb{P}, \mathbb{R}$)
- Decay fully described by $M(\pi^+\pi^-)$, $\cos(\theta)$ and ϕ



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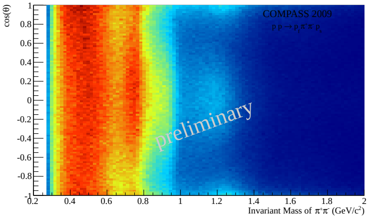
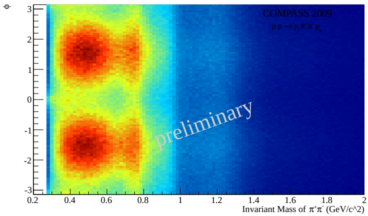
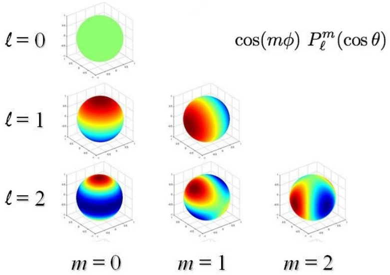




$X \to \pi^+\pi^-$

- **Assumption:** collision of two space-like exchange particles ($\mathbb{P}$, $\mathbb{R}$)
- Decay fully described by $M(\pi^+\pi^-)$, $\cos(\theta)$ and ϕ
- Fit complex production amplitudes in mass bins to match spin contributions and interference pattern



Construction of Wave-Set

Strong Interaction Conserves Parity

- Linear combination of spherical harmonics as eigenstates of reflectivity ϵ, limiting the spin projection $m \geq 0$, waves with opposite ϵ do not interfere

$$Y_m^{\epsilon\ell}(\theta,\phi) = c(m)\left[Y_m^\ell(\theta,\phi) - \epsilon(-1)^m Y_{-m}^\ell(\theta,\phi)\right]$$

Naturality

- Minus-sign was chosen historically, such that reflectivity coincide with exchanged naturality η for reaction with pion beam
- Here: correspondence only for product of naturality of exchange particles
- If at least one Pomeron is involved, natural transfer corresponds to $\epsilon = -1$

S.-U. Chung, [Phys. Rev. D 56 (1997)]

Partial-Wave Decomposition

Expand intensity $I(\theta, \phi)$ in terms of partial-waves for narrow mass bins:

$$I(\theta, \phi) = \sum_{\varepsilon} \left| \sum_{\ell m} T_{\varepsilon \ell m} Y_m^{\varepsilon \ell}(\theta, \phi) \right|^2$$

- Complex transition amplitudes $T_{\varepsilon \ell m}$, no assumption on mass-dependence
- Spectroscopic notation: ℓ_m^{ϵ}
- Significant contributions only from $\ell = S, P, D$, $m \leq 1$

⇒ **Maximum Likelihood Fit in Mass Bins**

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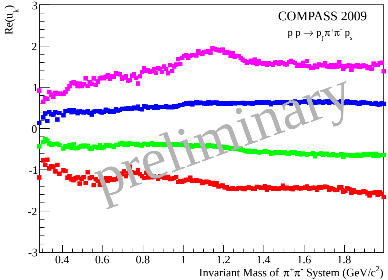
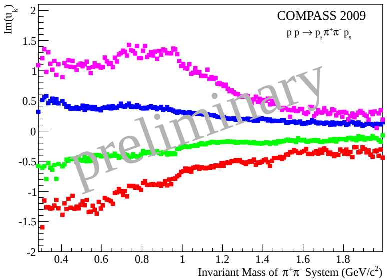
Inherent Ambiguities of Two-Pseudoscalar Final State

- Intensity can also be expressed as a 4^{th}-order polynomial
- Complex conjugation of the roots ('Barrelet zeros') results in the same angular distribution, i.e. the same likelihood

S.-U. Chung, [Phys. Rev. D 56 (1997)]

Barrelet Zeros





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

⇒ 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)

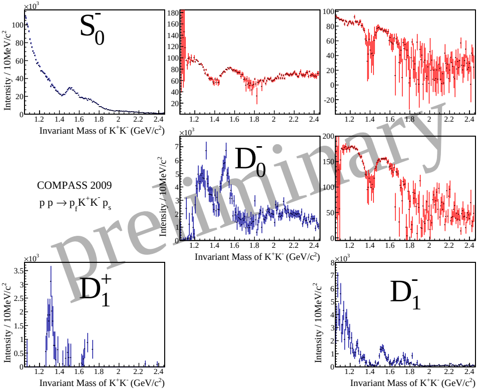
$\pi^0\pi^0$ System

- 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



- Odd waves do not play a significant role above the ϕ(1020)-mass
  $\Rightarrow$ Reduction of ambiguities
- Interpretation only with mass-dependent parametrisation

Mass-Dependent Parametrisation of K^+K^--System

Parametrisation

S_0-Wave

- Relativistic Breit-Wigner parametrisation: $f_0(1370)$, $f_0(1500)$, $f_0(1710)$

D_0-Wave

- Relativistic Breit-Wigner parametrisation: $f_2(1270)$, $f_2'(1525)$

Non-resonant contribution

- Phase space factor $q^\ell \cdot \sqrt{\frac{q}{m^2}}$ with breakup momentum q
- Exponential damping factor $\exp(-\alpha q - \beta q^2)$ with fit parameters α, β

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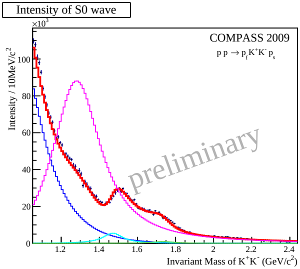
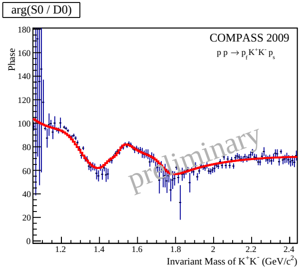
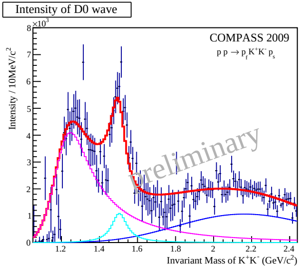
In total: 27 parameters

Intensities and Phase







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

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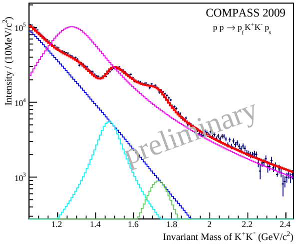

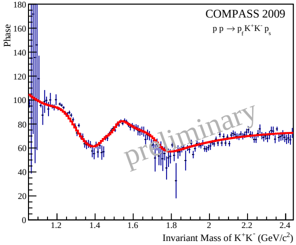

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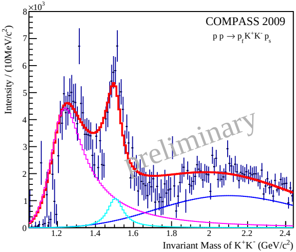

Conclusion

Summary

- **Central production** of two-pseudoscalar final states (not pure DPE)
- Order-of-magnitude **larger sample** than previous experiments (for charged channels)
- Performed **acceptance corrected PWA**
- Studied **mathematically ambiguous** solutions
- Simple **mass-dependent parametrisation** can describe the K^+K^- fit
- Breit-Wigner parameters mostly consistent with **PDG values**

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- **Unitary models** (K-matrix, ..)
- **Combined fit** of all available channels
- Include production kinematics (t_1, t_2, φ)
- Information about the **composition** of supernumerous scalar resonances

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Thank you for your attention!

'Glueball Filter'

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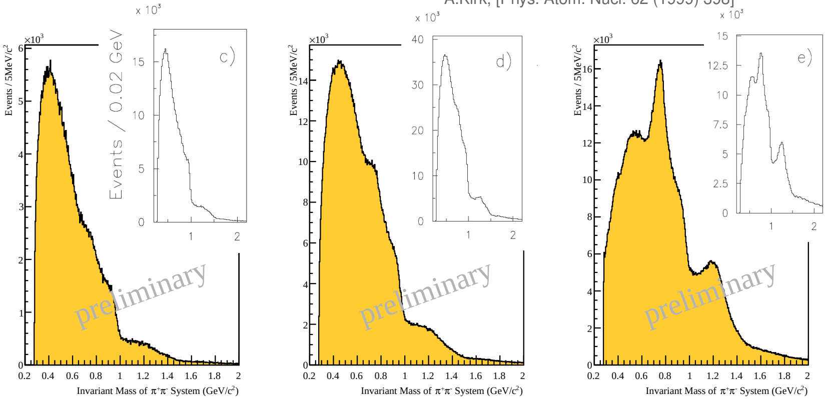
A.Kirk, [Phys. Atom. Nucl. 62 (1999) 398]



$dP_T \leq 0.2\,\mathrm{GeV}/c$ $0.2 \leq dP_T < 0.5\,\mathrm{GeV}/c$ $dP_T \geq 0.5\,\mathrm{GeV}/c$

- $dP_T = |\vec{p}_{T_1} - \vec{p}_{T_2}|$ in *pp* centre-of-mass
- Only scalar signals remain for small *dPt*

Maximum Likelihood Fit in Mass Bins

Maximise likelihood function

$$\ln L = \sum_{i=1}^{N} \ln I(\theta_i, \phi_i) - \int d\Omega\, I(\theta, \phi)\, \eta(\theta, \phi)$$

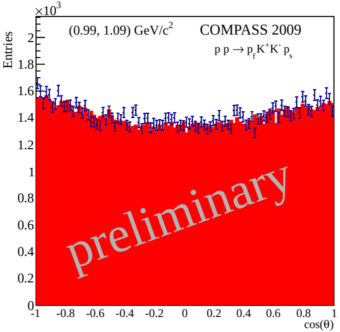
- by choosing $T_{\varepsilon \ell m}$ such that the intensity fits the observed N events
- the normalisation integral is evaluated by a phase-space Monte Carlo sample
- with the acceptance $\eta(\theta, \phi)$

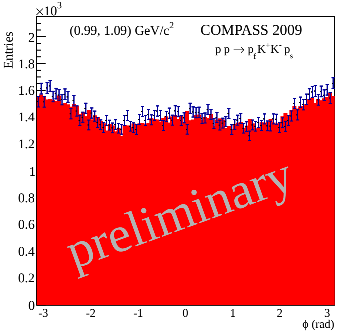
Barrelet Zeros

- Through variable transformation $u = \tan(\theta/2)$, angular distribution for this wave set can be written as a function of $|G(u)|^2$ with
  $G(u) = a_4 u^4 - a_3 u^3 + a_2 u^2 - a_1 u + a_0$
  where coefficients a_i are functions of amplitudes
- or with in terms of 4 complex roots u_i (*'Barrelet zeros'*)
  $G(u) = a_4 (u - u_1)(u - u_2)(u - u_3)(u - u_4)$
- *Laguerre's method* to find polynomial roots numerically
- Complex conjugation of one/more of these roots result in the same measured angular distribution
  $\rightarrow$ **8 different ambiguous solutions** (same likelihood per definition!)

Techniques of amplitude analysis for two-pseudoscalar systems
S.U. Chung, [Phys. Rev. D 56 (1997), 7299]

Evaluation of Fit with Weighted MC





- Blue: data, red: weighted MC

Evaluation of Fit with Weighted MC

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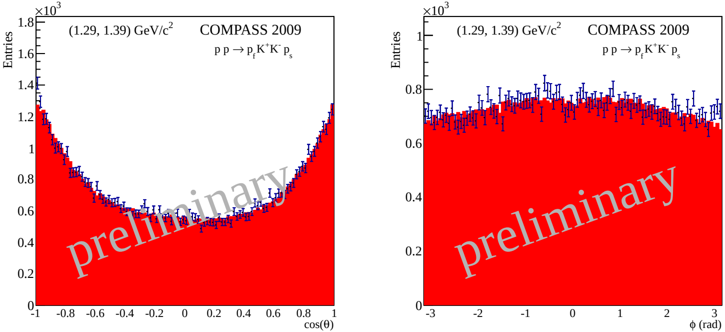

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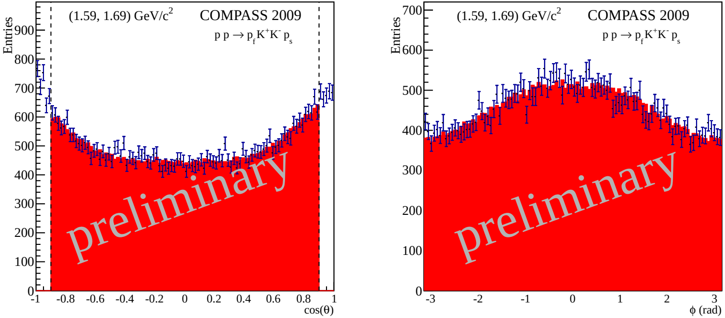

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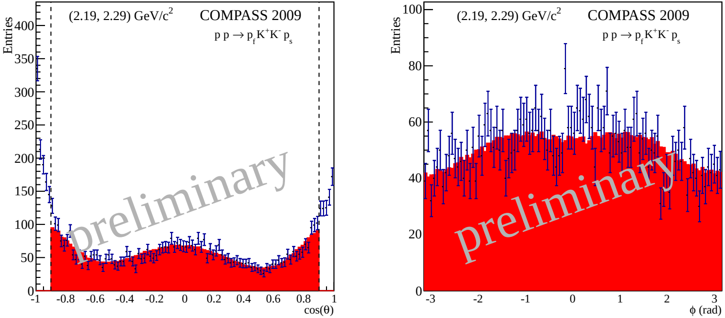

- Blue: data, red: weighted MC
- Peaking distribution for $|cos(\theta)| > 0.9$ for masses above $2\,\text{GeV}/c^2$ cannot be described by fit (limited wave set)
- Signature of diffractive dissociation background