The Search for Pentaquarks

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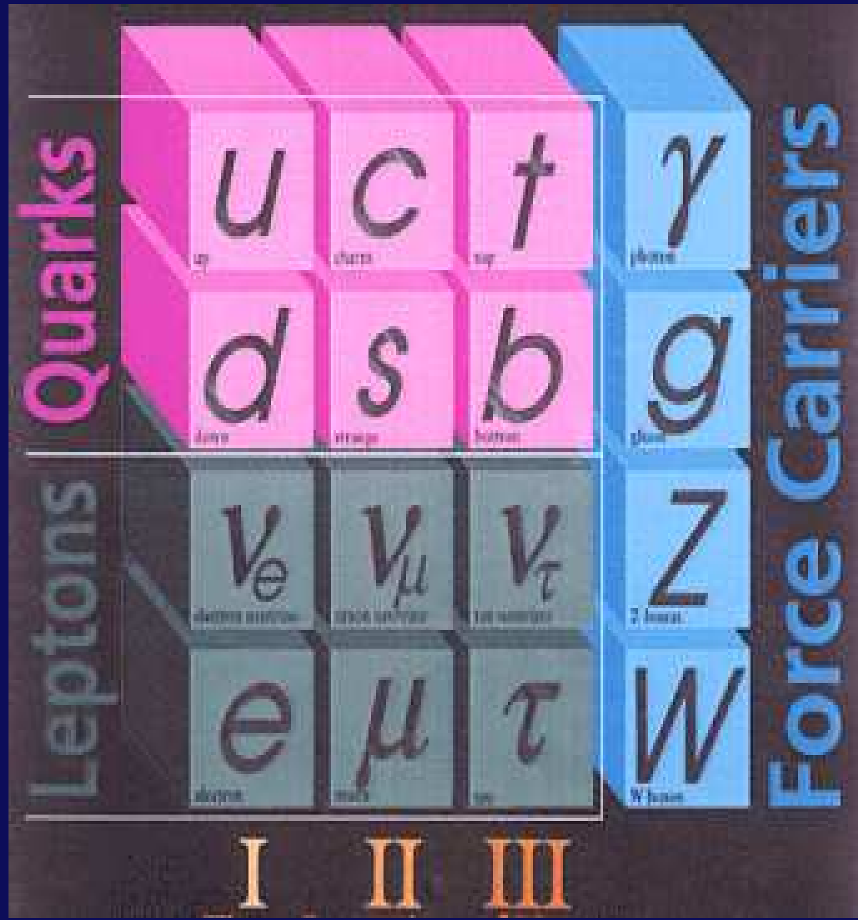
Standard Model



Forces:

- Three forces: strong, weak, electromagnetism
- Four force carriers: gluon (g) for strong, $W^{\pm}$ and Z^0 for weak, and γ for EM
- Quantum Electrodynamics (QED) combined with weak theory makes up *electroweak* theory
- Quantum Chromodynamics (QCD) modeled on QED to describe the strong force

Matter:

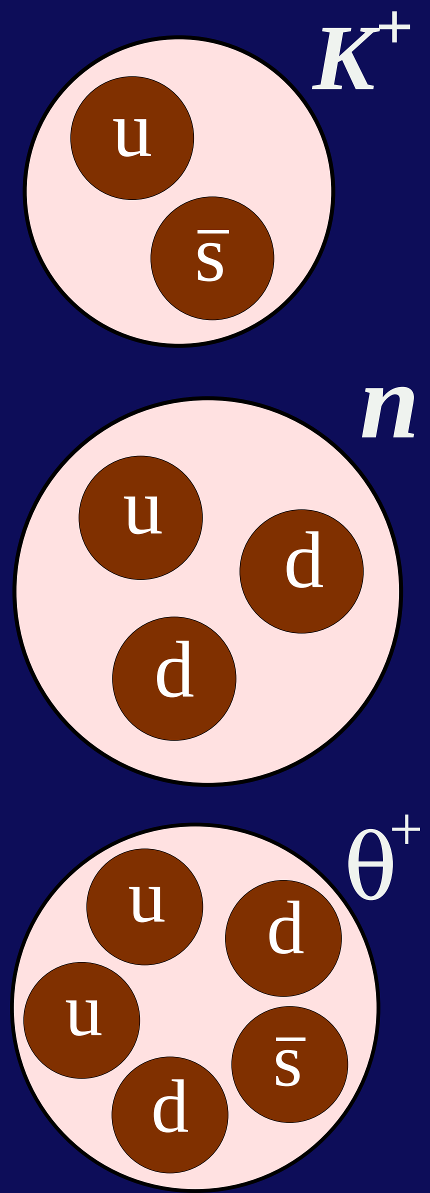
- 3 pairs of quarks: affected by all forces
- 3 pairs leptons: not affected by strong force (no EM for ν either)
- Also have antiparticles for each

The strong force (QCD)

- Based on QED replacing photon and 1 electric charge with gluon and 3 color charges
- Quarks carry color charge: red (r), green (g), or blue (b)
- Antiquarks carry anti-color charge: $\bar{r}$, $\bar{g}$, $\bar{b}$
- 8 gluons; also carry color charge like $r\bar{g}$ or $\bar{r}g$
- Since gluons carry color they self-interact making QCD *non-Abelian* as opposed to the *Abelian* EM theory QED (γ is neutral)
- Leads to an interaction strength α_s which increases with increasing distance (or decreasing momentum transfer)
- Two interesting consequences:
  1. *Confinement* — Only color neutral (white) particles can be observed
  2. *Asymptotic freedom* — At short distances (high Q^2) the interaction strength is small so particles are "free" and perturbative QCD is possible ($\alpha_s \sim 0.1$)

Color neutral states?

- Nearly all quark containing particles can be understood as mesons or baryons
- Mesons contain a quark and an antiquark $(q\bar{q})$
- Baryons contain 3 quarks (qqq) or 3 antiquarks $(\bar{q}\bar{q}\bar{q})$
- These are the two simplest color neutral combinations
- Why not tetraquarks $(qq\bar{q}\bar{q})$, pentaquarks $(qqqq\bar{q})$, baryonium $(qqq\bar{q}\bar{q}\bar{q})$, dibaryons $(qqqqqq)$, glueballs (ng), or hybrids $(q\bar{q}g)$?
- Many theories for these *exotic* states have been proposed
- *crypto-exotic* states have the same quantum numbers as normal states
- *manifestly exotic* states have quantum numbers inaccessible to normal states



Putting quarks together

- Define *isospin* (I) similarly to intrinsic spin (and I_3 like s_z)

$$u = |\tfrac{1}{2}, \tfrac{1}{2}\rangle$$
$$\bar{u} = |\tfrac{1}{2}, -\tfrac{1}{2}\rangle$$
$$d = |\tfrac{1}{2}, -\tfrac{1}{2}\rangle$$
$$\bar{d} = -|\tfrac{1}{2}, \tfrac{1}{2}\rangle$$

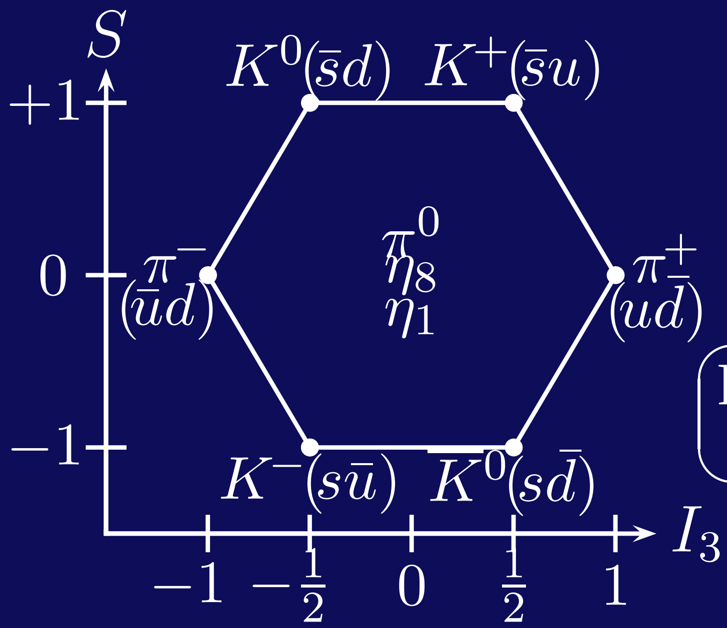
Can be combined ⟹ into an $I = 1$ triplet and $I = 0$ singlet

$$\pi^+ = |1, 1\rangle = -u\bar{d}$$
$$\pi^0 = |1, 0\rangle = \sqrt{\tfrac{1}{2}}(u\bar{u} - d\bar{d})$$
$$\pi^- = |1, -1\rangle = d\bar{u}$$
$$X^0 = |0, 0\rangle = \sqrt{\tfrac{1}{2}}(u\bar{u} + d\bar{d})$$

- Identical to $SU(2)$ decomposition $\mathbf{2} \otimes \overline{\mathbf{2}} = \mathbf{3} \oplus \mathbf{1}$
- Adding s quark leads to $SU(3)$ and new quantum number *strangeness* (S)
  - Mesons $(q\bar{q})$ decompose as $\mathbf{3} \otimes \overline{\mathbf{3}} = \mathbf{8} \oplus \mathbf{1}$
  - Baryons (qqq) decompose as $\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1}$

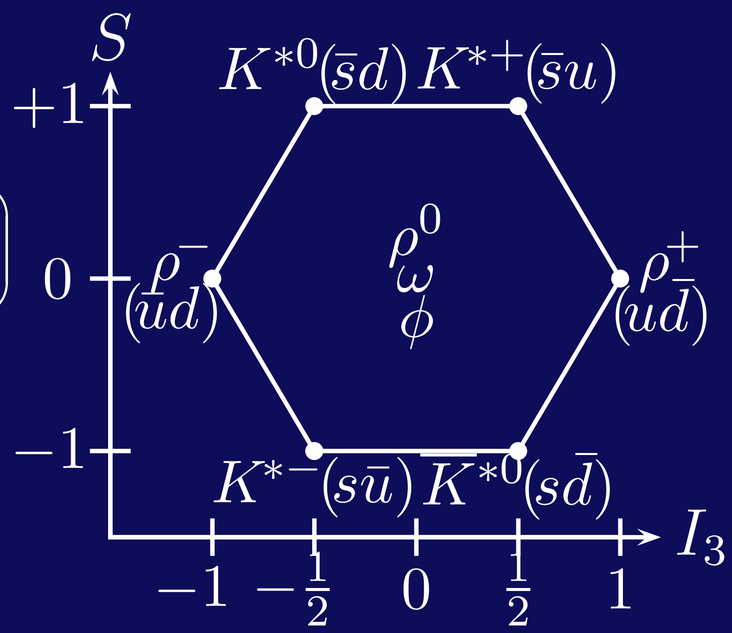
The resulting multiplets

Mesons

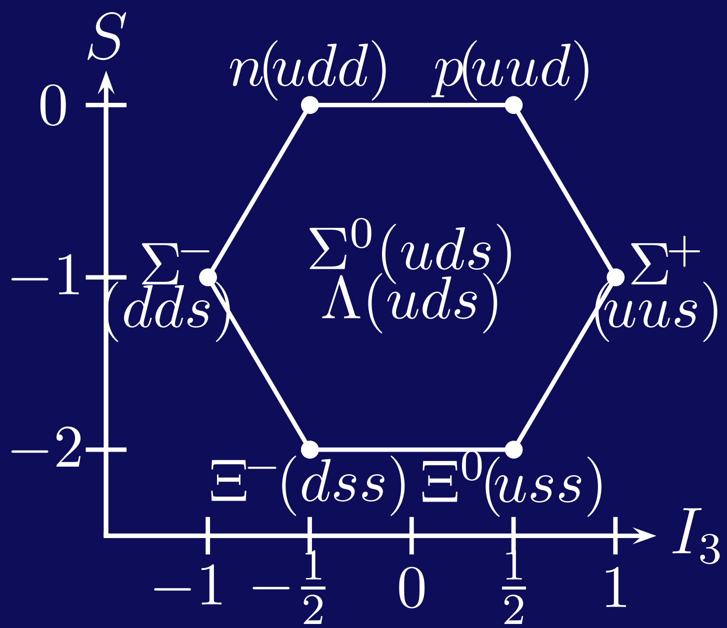


Pseudoscalar
$J^{PC} = 0^{-+}$

Vector
$J^{PC} = 1^{--}$

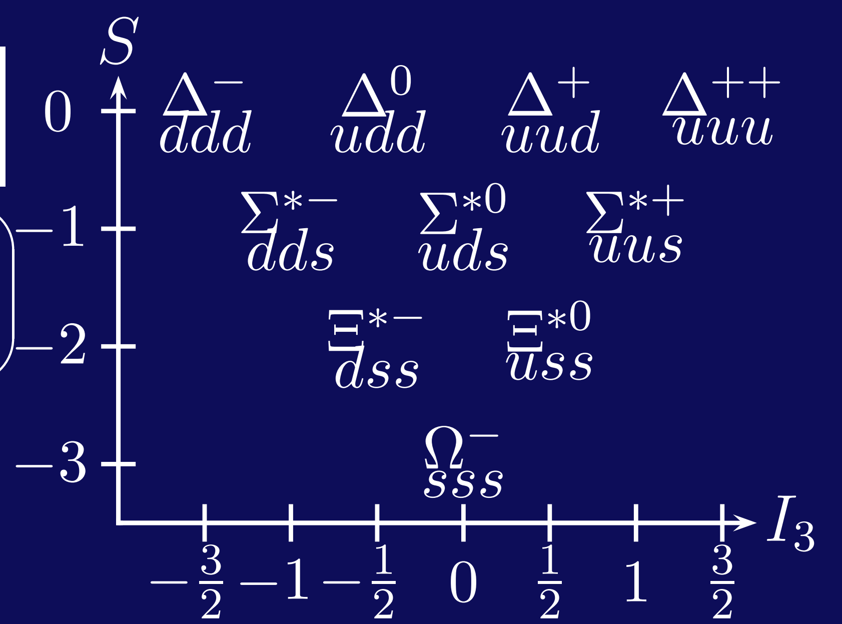


Baryons



Octet
$J^P = \frac{1}{2}^+$

Decuplet
$J^P = \frac{3}{2}^+$

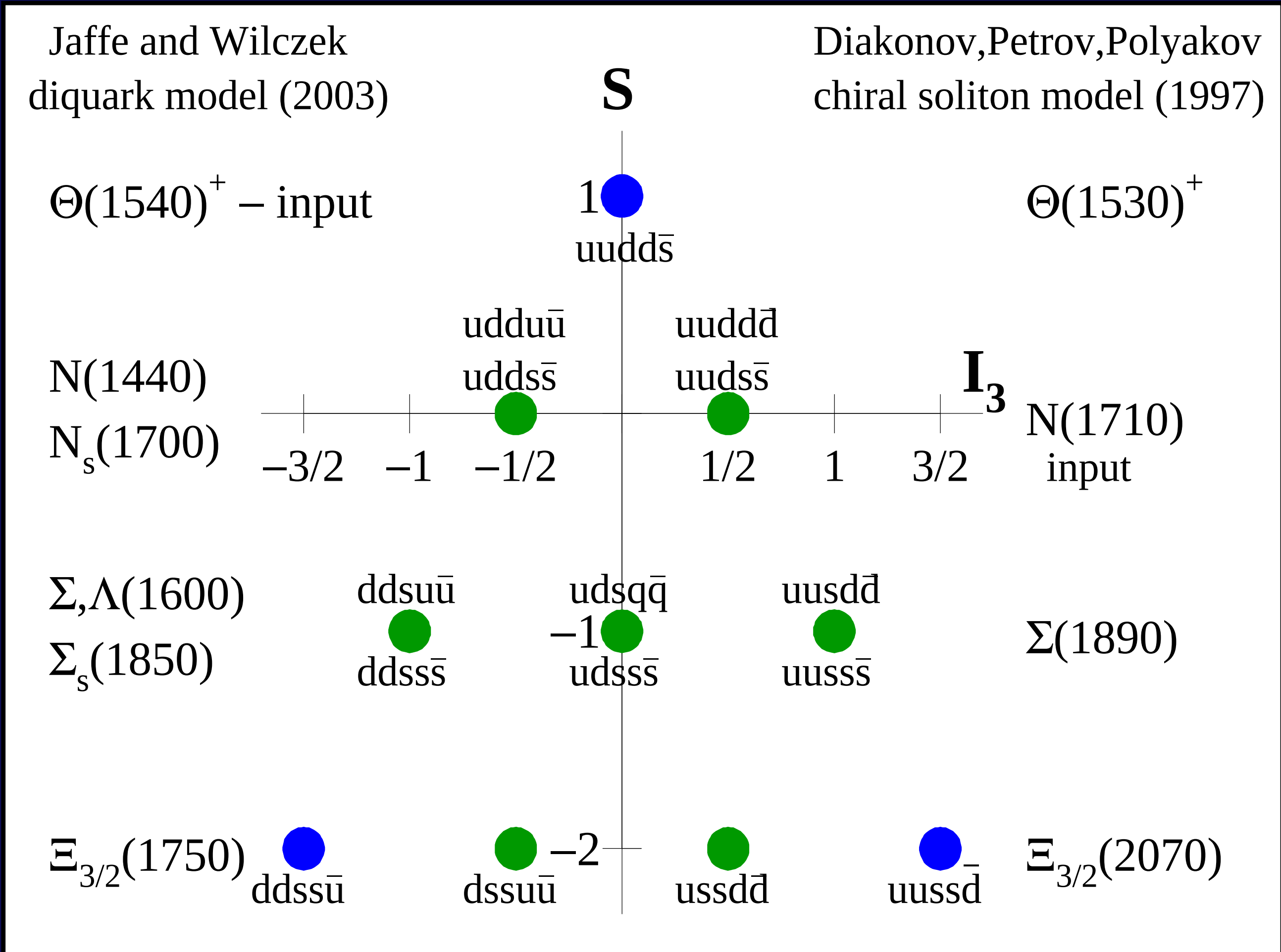


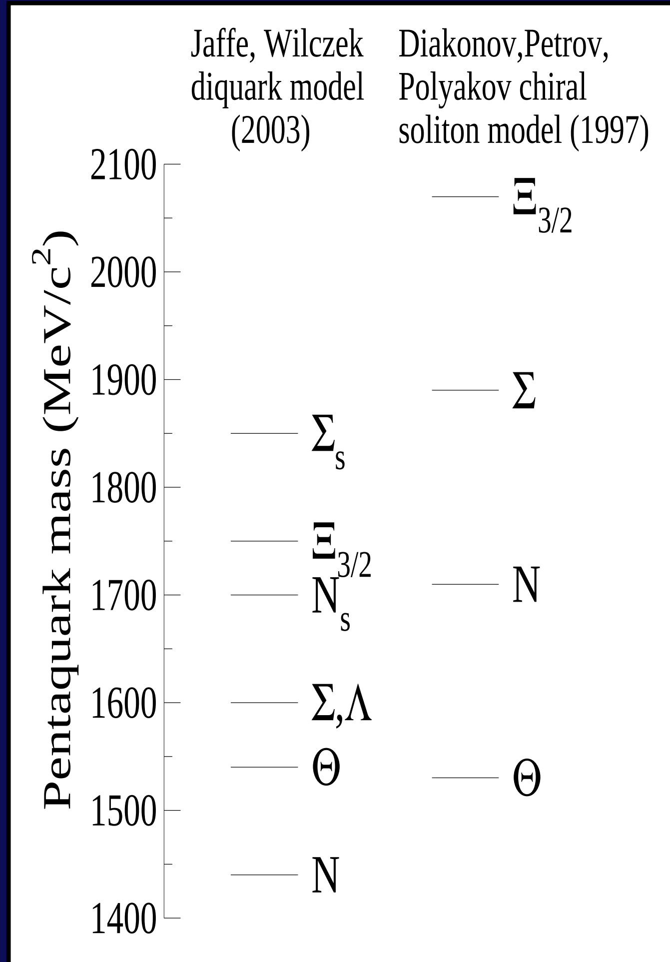
Pentaquark anti-decuplet

Combining 4 quarks and 1 antiquark gives

$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} \otimes \overline{\mathbf{3}} = (3)\mathbf{1} \oplus (8)\mathbf{8} \oplus (4)\mathbf{10} \oplus (2)\overline{\mathbf{10}} \oplus (3)\mathbf{27} \oplus \mathbf{35}$$

Anti-decuplet $\overline{\mathbf{10}}$ shown below ● = manifestly exotic, ● = crypto-exotic

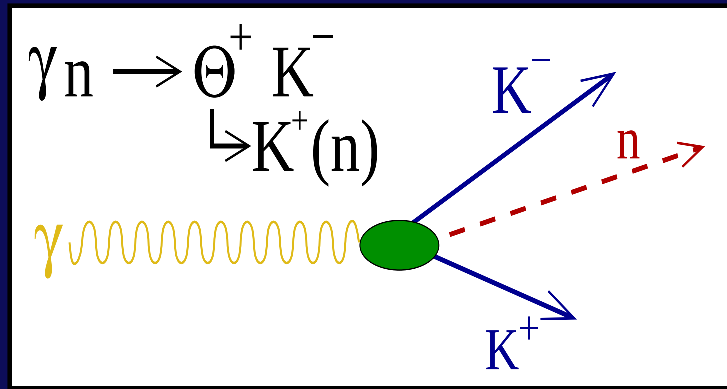


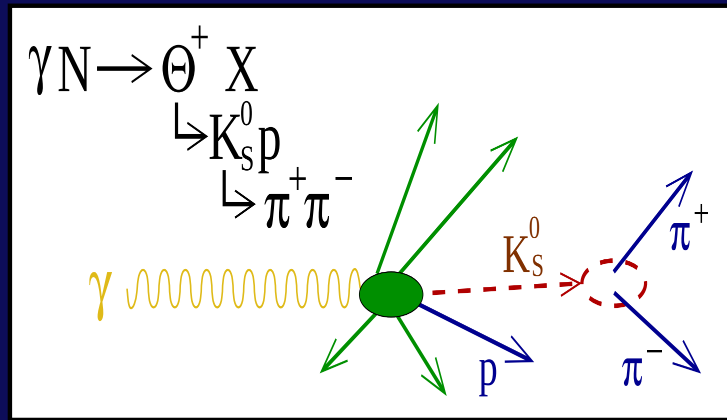


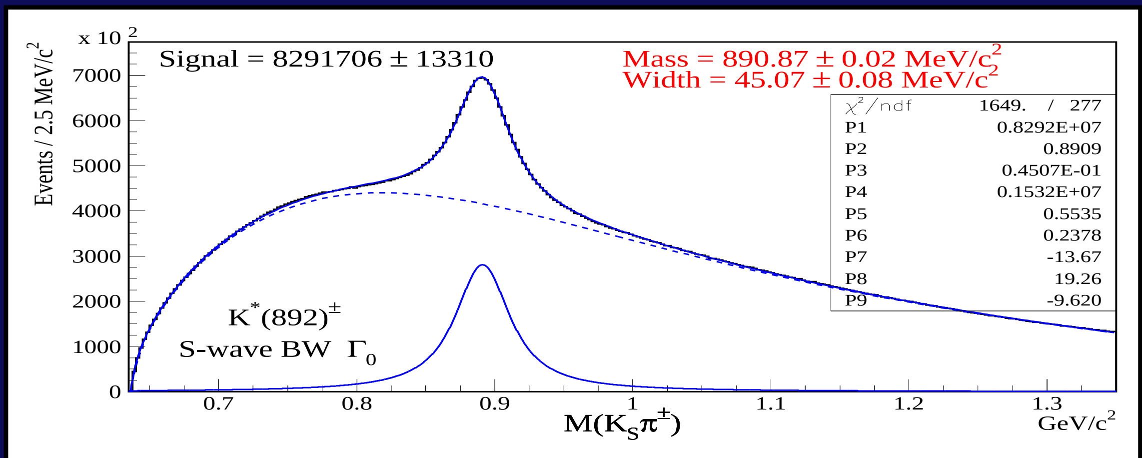
Experimental particle physics 101

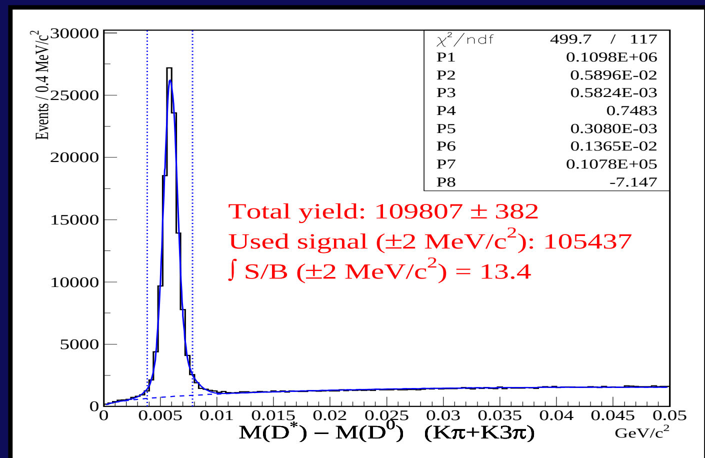
Production and Reconstruction:

- Generally, stable particles bore us
- We like to smash things and create exotic particles which decay in 10^{-25} to 10^{-12} s
- Use decay products to reconstruct event
- Parent particle mass from $m^2 = E^2 - p^2$
- Peaks in mass spectrum indicate particles
- Width of peaks from two sources:
  1. Breit-Wigner width from uncertainty principle: $\Gamma = 1/\tau$
  2. Gaussian resolution due to detector









Experimental particle physics 101

Lies, Damn Lies, and Statistics:

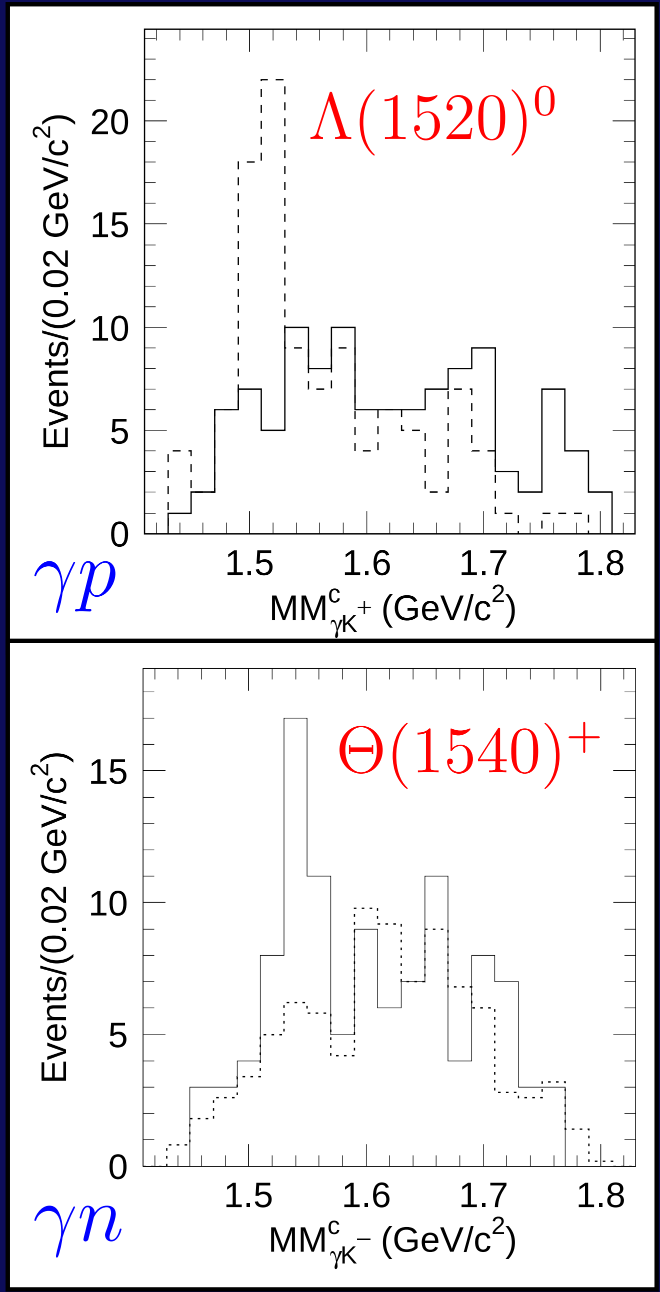
- What is necessary to prove discovery?
- If probability that background caused excess is sufficiently small, claim discovery
  1. Estimate amount of background expected, B
  2. Compute Poisson probability that B could fluctuate into at least the amount observed $(S + B)$
  3. Convert to "significance" in σ based on Gaussian distribution
  4. If greater than 3–5 σ, claim discovery
  5. For large B, $S/\sqrt{B}$ gives significance directly

Two additional points to note:

1. Upper limits are at the 95% confidence level
2. In some places the charge-conjugate state is implied

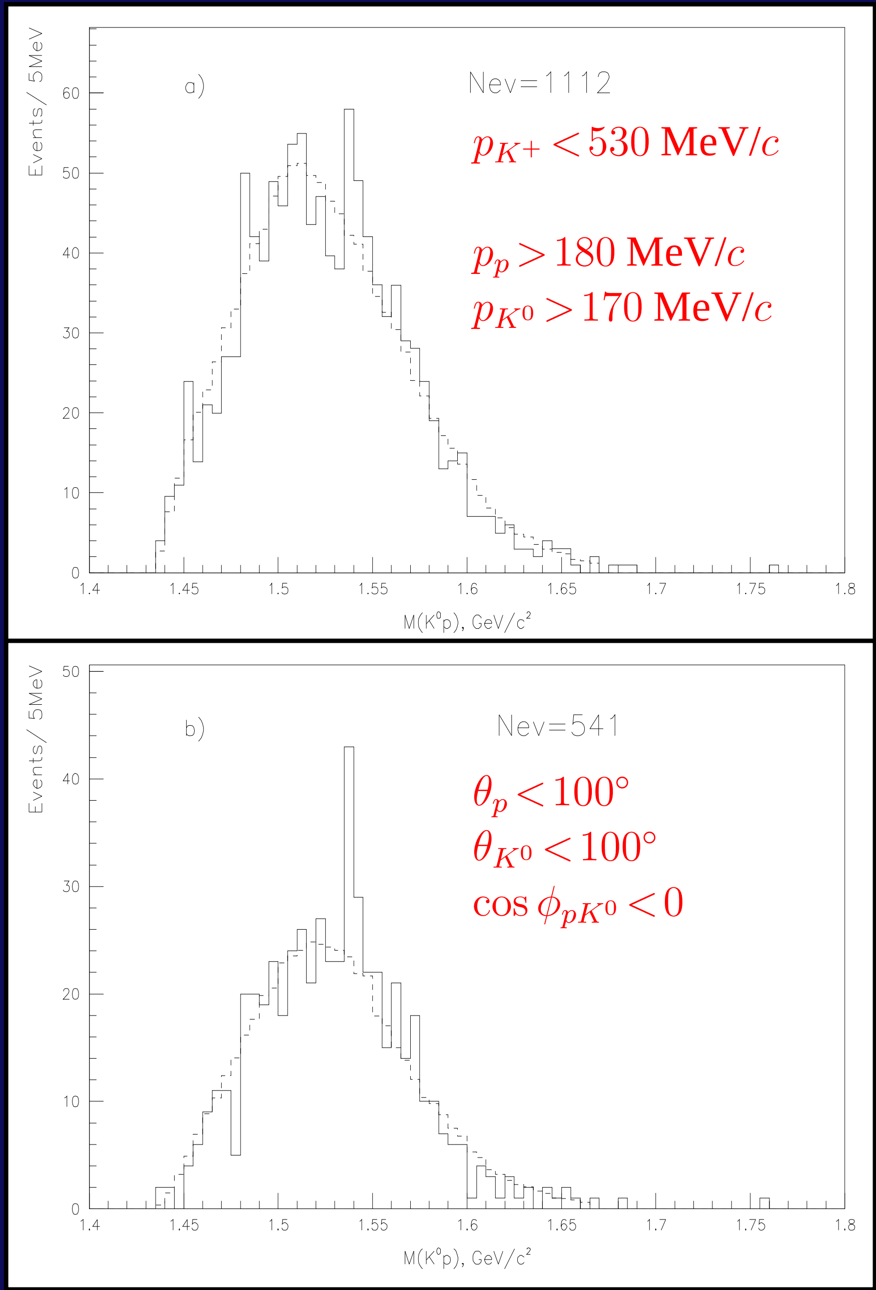
First observation: LEPS (1/03)

- 1.5–2.4 GeV tagged photons from laser backscattered off 8 GeV electrons
- Study $\gamma n \to K^+ K^- n$ in ^{12}C (n inferred)
- Distinguish γp events by looking for recoil p
- Plot missing masses: $MM_{\gamma K^+}$ & $MM_{\gamma K^-}$
- $\gamma p \to \Lambda(1520) K^+ \to p K^- K^+$ in $MM_{\gamma K^+}$
- 36 events w/. $1.51 < MM_{\gamma K^-} < 1.57$ GeV/c^2
- Expect 17 background
- Quote $19/\sqrt{17} = 4.6\,\sigma$ signficance
- Interpretation: $\Theta^+(uudd\bar{s}) \to n(udd) K^+(u\bar{s})$
- 462 citations in last 20 months = 0.8/day



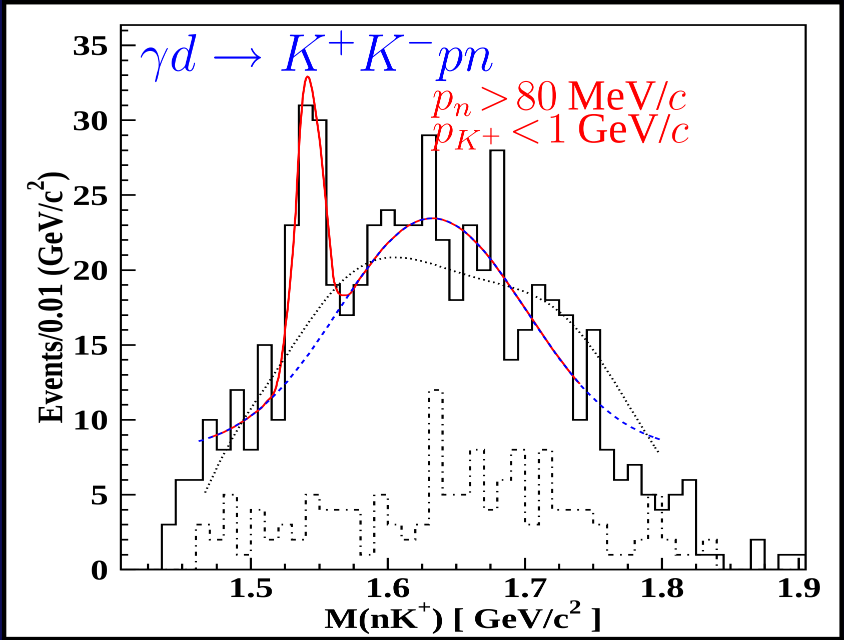
Second observation: DIANA (4/03)

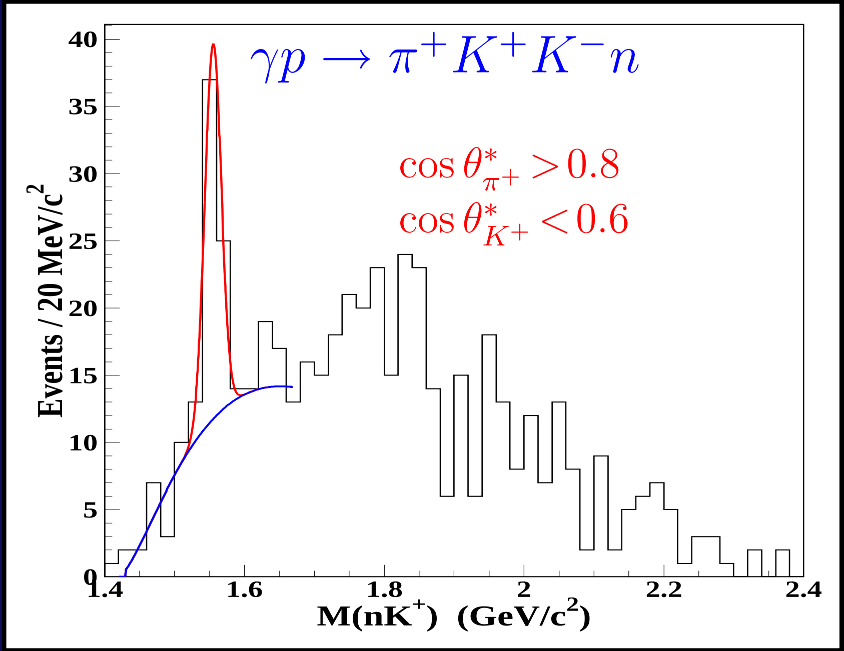
- 300–750 MeV/c K^+ beam interact in Xe bubble chamber
- $K^+ n \to p K^0$ and $K^0 \to \pi^+\pi^-$
- No B–field; momentum obtained from distance traveled
- 73 events in two high bins
- Expect 44 background
- Quote $29/\sqrt{44} = 4.4\,\sigma$ signficance
- Interpretation:
  $\Theta^+(uudd\bar{s}) \to p(uud)K^0(d\bar{s})$



Observations 3 & 6: CLAS (7/03,11/03)

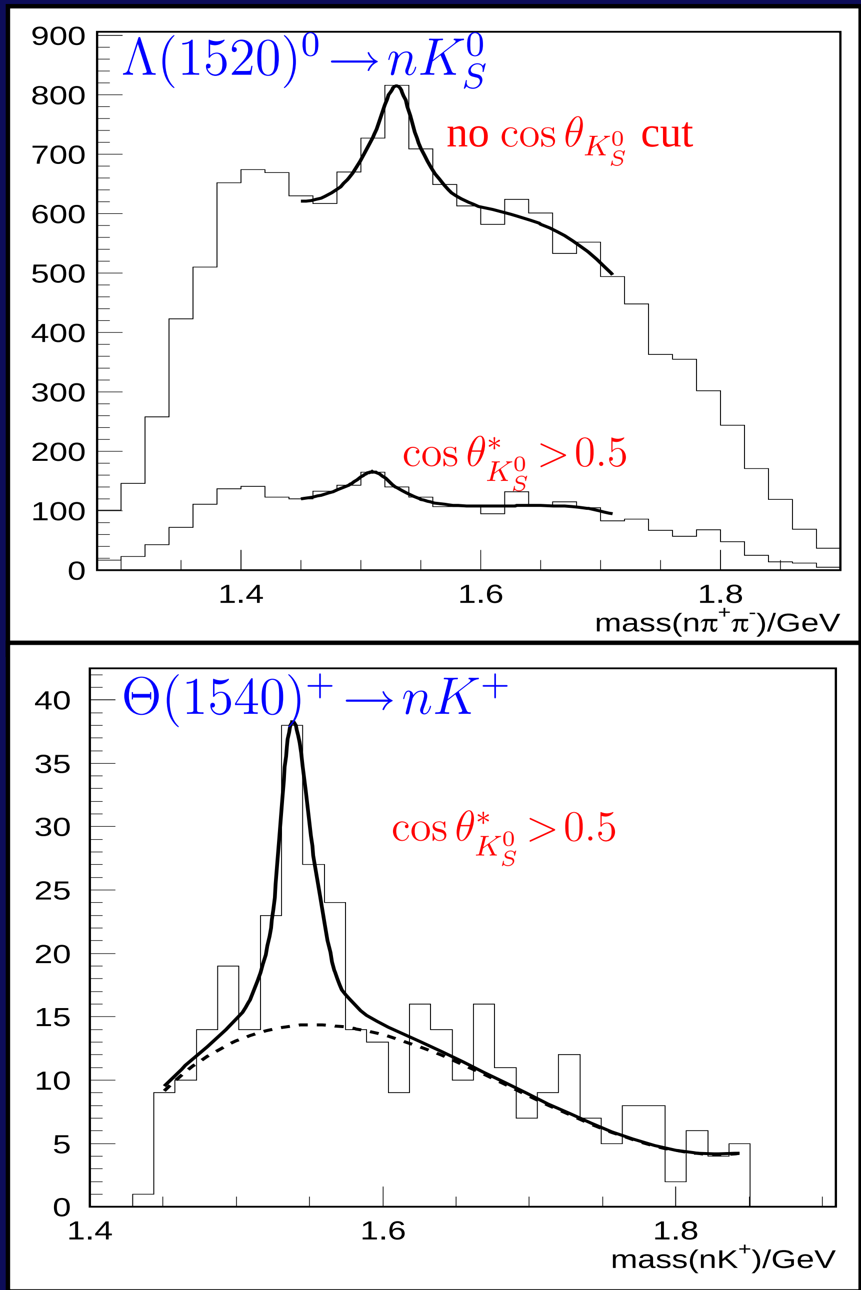
- Tagged γ beam from e^- bremsstrahlung
- d analysis: $\gamma d \to K^+K^-pn$ with $1.5 < E_\gamma < 3$ GeV
- p analysis: $\gamma p \to \pi^+K^+K^-n$ with $3 < E_\gamma < 5.5$ GeV
- n from E and p conservation
- d analysis: cuts on momentum
- p analysis: cuts on angles
- d analysis: 43 signal, $5.2 \pm 0.6\,\sigma$
- p analysis: 41 signal, $7.8 \pm 1.0\,\sigma$
- $\Theta^+(uudd\bar{s}) \to n(udd)K^+(u\bar{s})$ from interesting production mechanisms





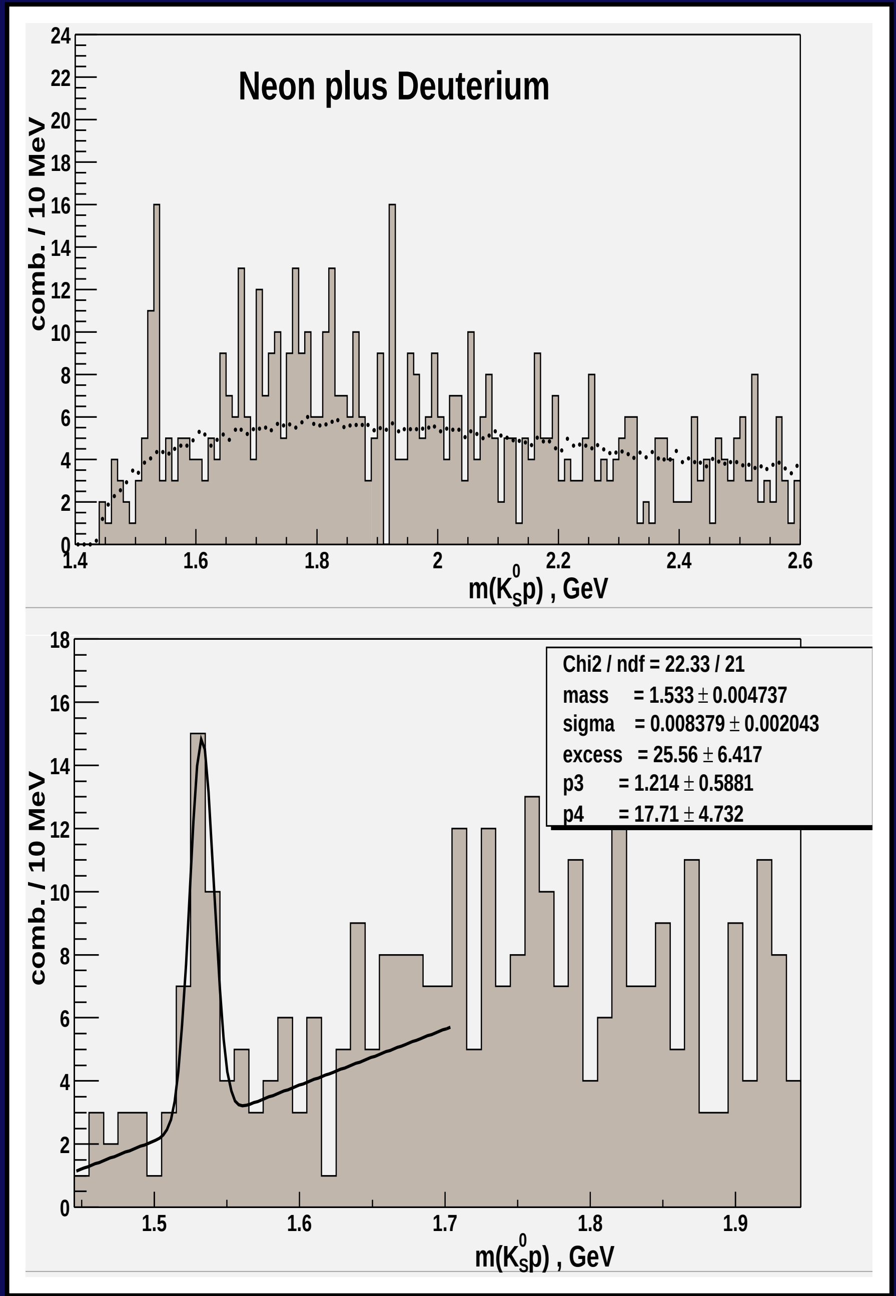
Observation 4: SAPHIR (7/03)

- LH_2 target and tagged γ from e^- bremsstrahlung
- $\gamma p \longrightarrow n K_S^0 K^+$
- $0.9 < E_\gamma < 2.6$ GeV
- Kinematic n reconstruction
- Cut on K_S^0 mass and production angle
- $\Lambda(1520)^0 \rightarrow n K_S^0$ in top plot: 620 ± 90 events
- $\Theta(1540)^+ \rightarrow n K^+$ in bottom plot: 63 ± 13 events = $4.8\,\sigma$



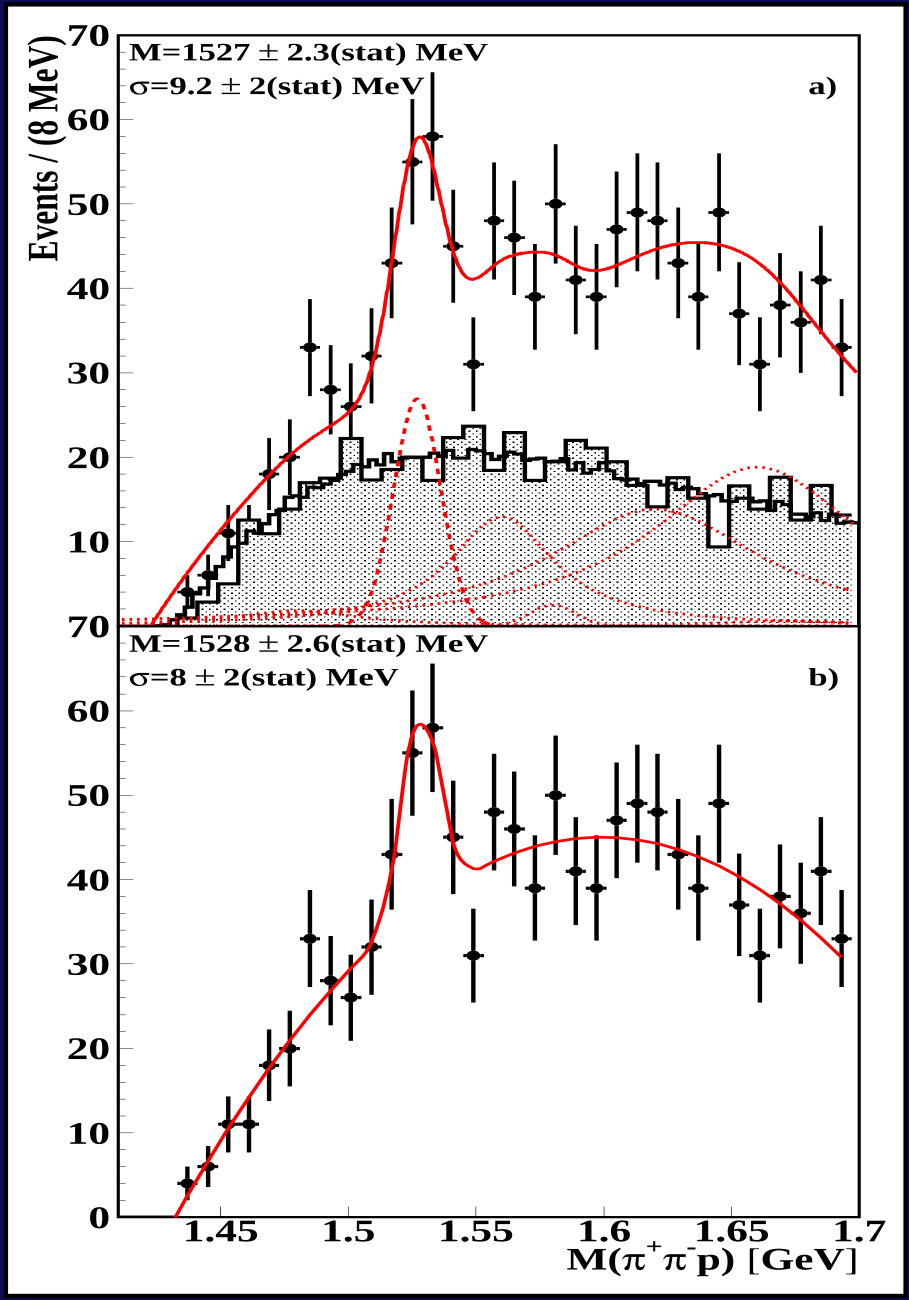
Observation 5: Asratyan *et al.* (9/03)

- ν and $\bar{\nu}$ with $30 < E_\nu < 140$ GeV
- Bubble chambers filled with H_2, D_2, Ne–H_2
- $\nu N \to p K^0_S \mu X$
- Sample has $p_\mu > 4$ GeV/c
- Require $300 < p_p < 900$ MeV/c
- No signal in H_2 so combine deuterium and neon data
- Fit finds 25.6 ± 6.4 events
- 19 signal over 8 background, $6.7\,\sigma$
- $\Theta(1540)^+ \to p K^0_S$ is crypto-exotic: can be $\Sigma^+(uus) \to p(uud)\overline{K}^0(\bar{d}s)$



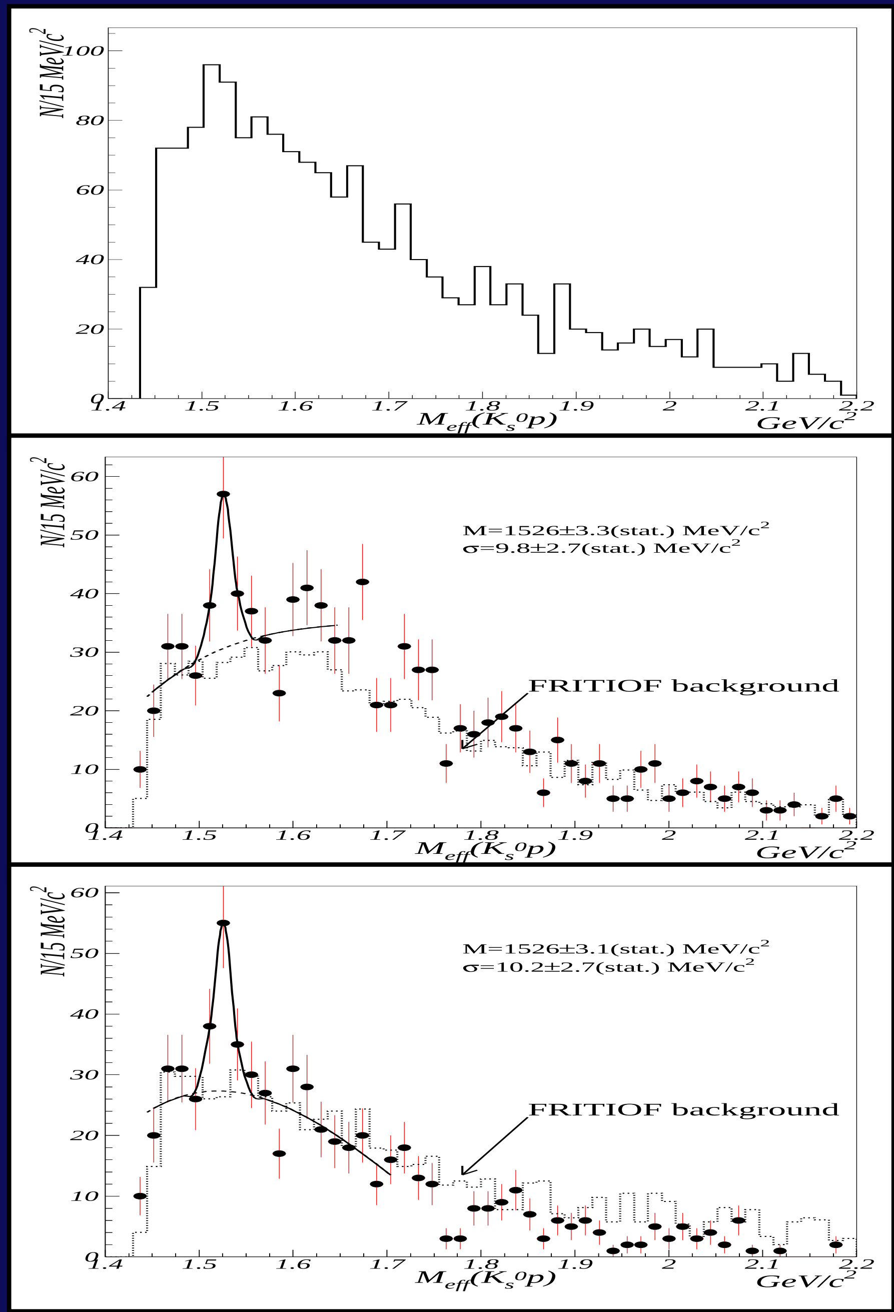
Observation 7: HERMES (12/03)

- 27.6 GeV e^+ on deuterium gas at HERA
- $\gamma d \to p K^0_S X$
- Cut on K^0_S mass and $1 < p_\pi < 15$ GeV/c
- Restrict proton momentum to 4–9 GeV/c
- Various fits find 52–79 events with $S/\sqrt{B} = 4.2$–$6.3\ \sigma$ and $S/\delta S = 3.4$–$4.3\ \sigma$
- $\Theta(1540)^+ \to p K^0_S$ is crypto-exotic: can be $\Sigma^+(uus) \to p(uud)\overline{K}^0(\bar{d}s)$



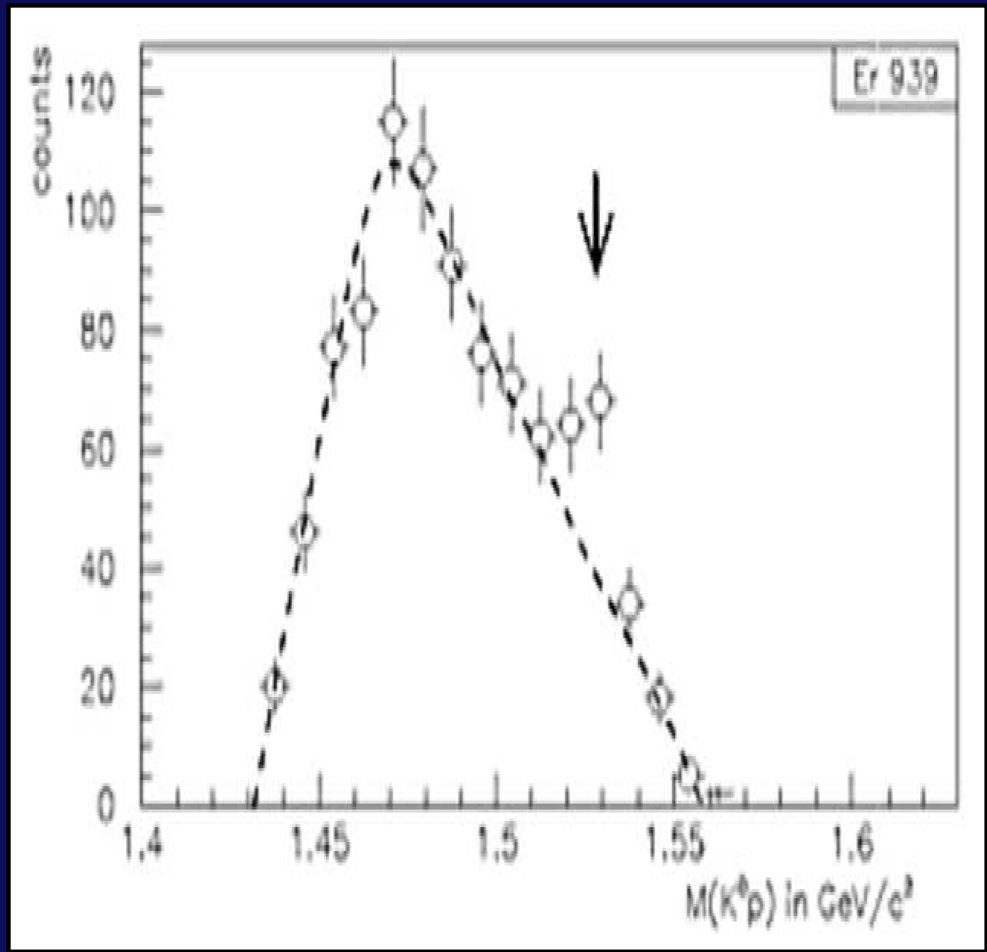
Observation 8: SVD (1/04)

- 70 GeV/c p on C, Si, Pb targets
- $pN \to pK^0_S X$
- Select p with $4 < p_p < 21$ GeV/c and Čerenkov ID
- Middle plot adds K^0_S mass cut and Θ^+ angle cut
- Bottom plot adds $p_{K^0_S} < p_p$ cut
- 50 events over 78 background gives $50/\sqrt{78} = 5.6\,\sigma$
- $\Theta(1540)^+ \to pK^0_S$ is crypto-exotic: can be $\Sigma^+(uus) \to p(uud)\overline{K}^0(\bar{d}s)$



Observation 9: COSY–TOF (3/04)

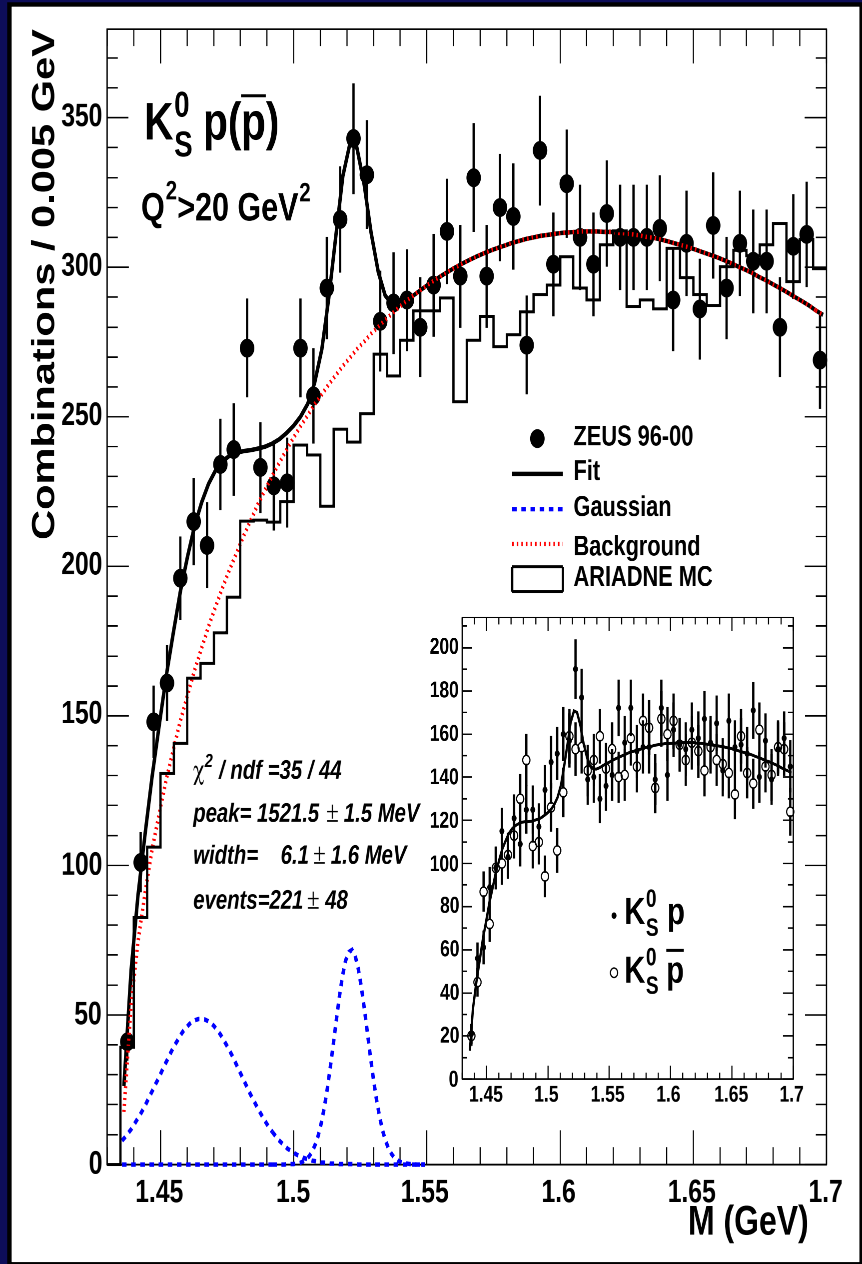
- $3\,\mathrm{GeV}/c\ p$ on LH_2
- $pp \to \Sigma^+ K^0 p$
- Cuts on $K^0_S \to \pi^+\pi^-$ mass and Σ^+ mass
- Some kinematic constraints
- Report $S/\sqrt{B} = 5.7$, $S/\sqrt{S+B} = 4.7$, $S/\sqrt{S+2B} = 3.7$
- Implies ~ 60 events over ~ 105 background



- $\Theta(1540)^+ \to pK^0_S$ is manifestly exotic due to Σ^+ and no energy for additional strange particles

Observation 10: ZEUS (3/04)

- ep collisons at $\sqrt{s} \sim 300$ GeV
- $\gamma p \rightarrow p K_S^0 X$ in deep inelastic scattering
- Cut on K_S^0 mass, p_T, and $|\eta|$
- Require $p_p < 1.5\,\mathrm{GeV}/c$ to separate from π with dE/dx
- 221 ± 48 events $(4.6\,\sigma)$
- Monte Carlo studies find fluctuation likelihood of $6 \times 10^{-5} = 4.0\,\sigma$
- $\Theta(1540)^+ \rightarrow p K_S^0$ is crypto-exotic



What are the odds?

Experiment	Significance	Prob	Prob min	Prob max
LEPS	$4.6^{+1.2}_{-1.0}\,\sigma$	4×10^{-6}	3×10^{-4}	7×10^{-9}
DIANA	$4.4\,\sigma$	1×10^{-5}		
CLAS–*d*	$5.2 \pm 0.6\,\sigma$	2×10^{-7}	4×10^{-6}	7×10^{-8}
SAPHIR	$4.8\,\sigma$	2×10^{-6}		
Asrtyan *et al.*	$6.7\,\sigma$	2×10^{-11}		
CLAS–*p*	$7.8 \pm 1.0\,\sigma$	6×10^{-15}	1×10^{-11}	1×10^{-18}
HERMES	$5 \pm 1\,\sigma$	6×10^{-7}	6×10^{-5}	2×10^{-9}
SVD	$5.6\,\sigma$	2×10^{-8}		
COSY–TOF	$5 \pm 1\,\sigma$	6×10^{-7}	6×10^{-5}	2×10^{-9}
ZEUS	4.0–$4.6\,\sigma$	6×10^{-5}	6×10^{-5}	4×10^{-6}
Total		8×10^{-73}	2×10^{-62}	6×10^{-86}

The probability of all observations being due to background is 10^{-62}–10^{-86}, a 17–20 σ effect and equivalent to:

- Flipping heads 207–288 times in a row
- Red Sox winning next 39–54 World Series
- 4–5 people in this room being killed by lightning in the next month
- DOE changing its mind about cancelling BTeV

What are the “real” odds?

Is this the same kind of “slam dunk case” George Tenet presented to President Bush about Iraqi WMD?

- Most experiments use $\sqrt{B}$ for background fluctuation when B is small (Poisson)
- Most experiments assume B is perfectly well known. If B estimation uncertainty is σ_B then $\sqrt{B} \to \sqrt{B+\sigma_B^2}$
- Presumably experiments would accept a range of masses and widths; accepting 10 different masses increases probability of background mimicing signal by 10 — can only really be answered by Monte Carlo techniques
- What about effect of setting cuts to enhance a bump? Very difficult to account for:
  1. “A peak appears most clearly when requiring $\cos\theta^*_{\pi^+} > 0.8, \ldots$”
  2. “The data also show that K^+ momenta greater than 1.0 GeV/c are associated with an invariant mass of the nK^+ system above ~ 1.7 GeV/c^2. Events with a K^+ momentum above 1.0 GeV/c were removed to reduce this background.”

Better estimations of significance

- Use Poisson statistics for background fluctuation probability
- Account for statistical uncertainty of B estimation
- Assume any signal between 1510–1570 MeV/c^2 accepted; divide 60 MeV/c^2 by resolution and divide probability by result

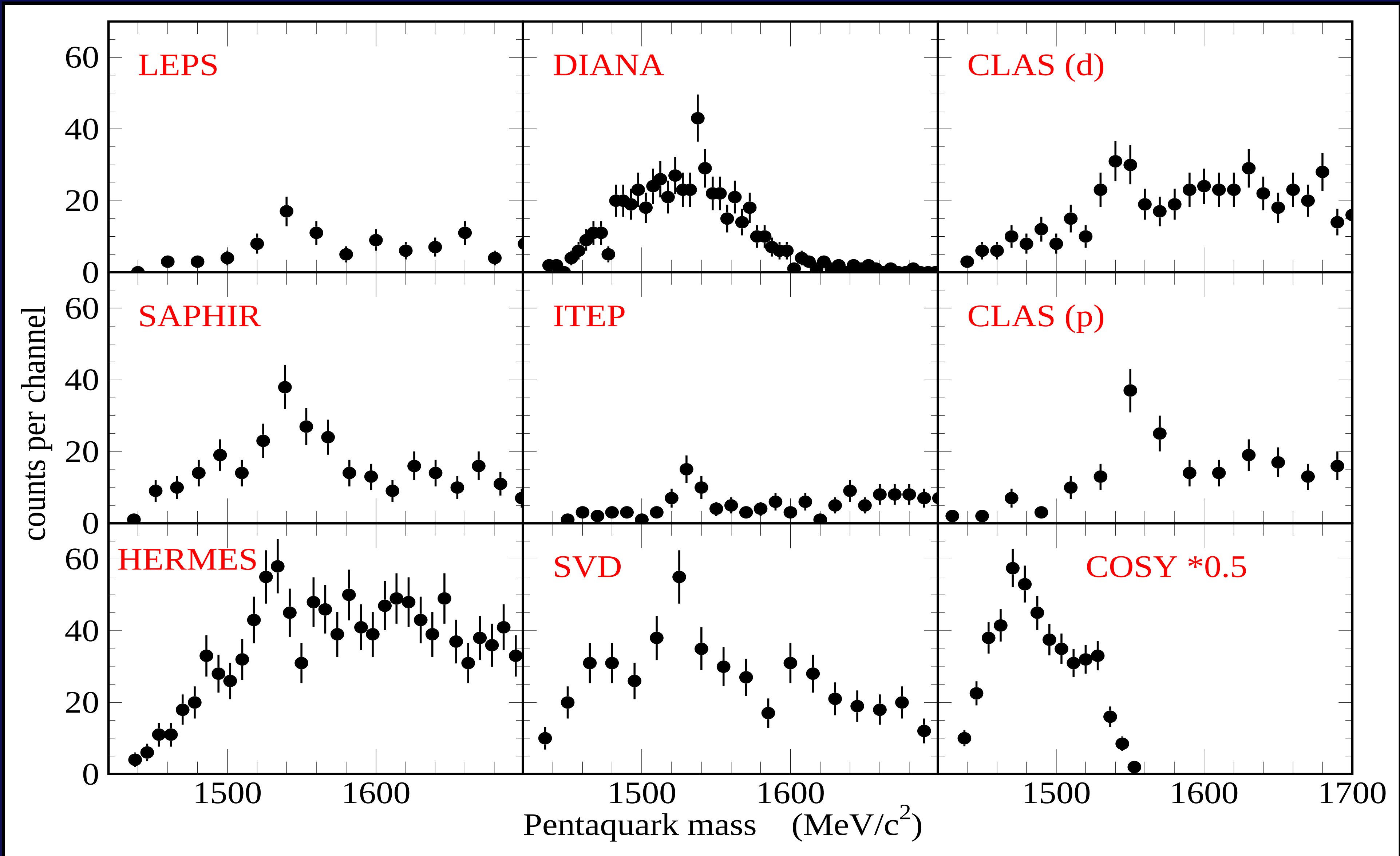
Experiment	$S/\sqrt{B}$	Poisson	$+\sigma_B$	+Mass ambiguity	Prob
LEPS	$4.6\,\sigma$	$4.0\,\sigma$	$3.3\,\sigma$	$2.9\,\sigma$	3×10^{-3}
DIANA	$4.4\,\sigma$	$3.9\,\sigma$	$3.8\,\sigma$	$3.0\,\sigma$	3×10^{-3}
CLAS–d	$5.8\,\sigma$	$5.2\,\sigma$	$4.9\,\sigma$	$4.6\,\sigma$	5×10^{-6}
SAPHIR	$7.3\,\sigma$	$6.4\,\sigma$	$5.7\,\sigma$	$5.4\,\sigma$	5×10^{-8}
Asrtyan *et al.*	$6.7\,\sigma$	$5.2\,\sigma$	$4.9\,\sigma$	$4.5\,\sigma$	7×10^{-6}
CLAS–p	$7.8\,\sigma$	$6.4\,\sigma$	$5.7\,\sigma$	$5.4\,\sigma$	6×10^{-8}
HERMES	$4.7\,\sigma$	$4.4\,\sigma$	$4.3\,\sigma$	$3.7\,\sigma$	2×10^{-4}
SVD	$5.7\,\sigma$	$5.1\,\sigma$	$4.7\,\sigma$	$4.0\,\sigma$	5×10^{-5}
COSY–TOF	$5.9\,\sigma$	$5.4\,\sigma$	$5.4\,\sigma$	$5.1\,\sigma$	4×10^{-7}
ZEUS	$6.1\,\sigma$	$6.1\,\sigma$	$5.9\,\sigma$	$5.3\,\sigma$	1×10^{-7}
Total				$15\,\sigma$	4×10^{-52}

New probability of 4×10^{-52} still seems impressive. However:

- Does not account for selecting cuts to enhance signal
- Does not account for the acceptance of various widths
- Multiplying probabilities is only correct if due to same effect

Is this a convincing case?

Plots with errors and without fits (courtesy Pochodzall – hep-ex/0406077):



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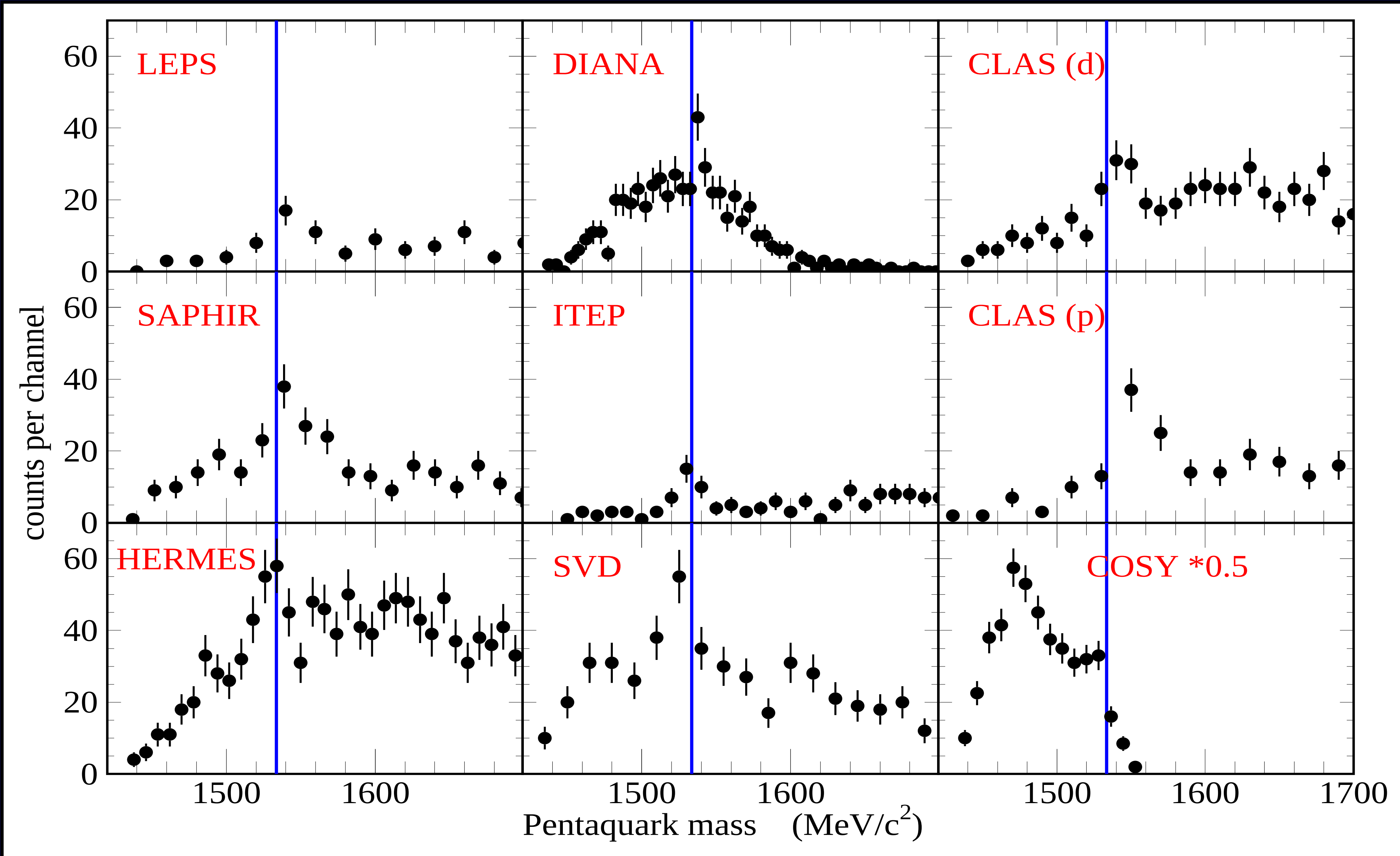
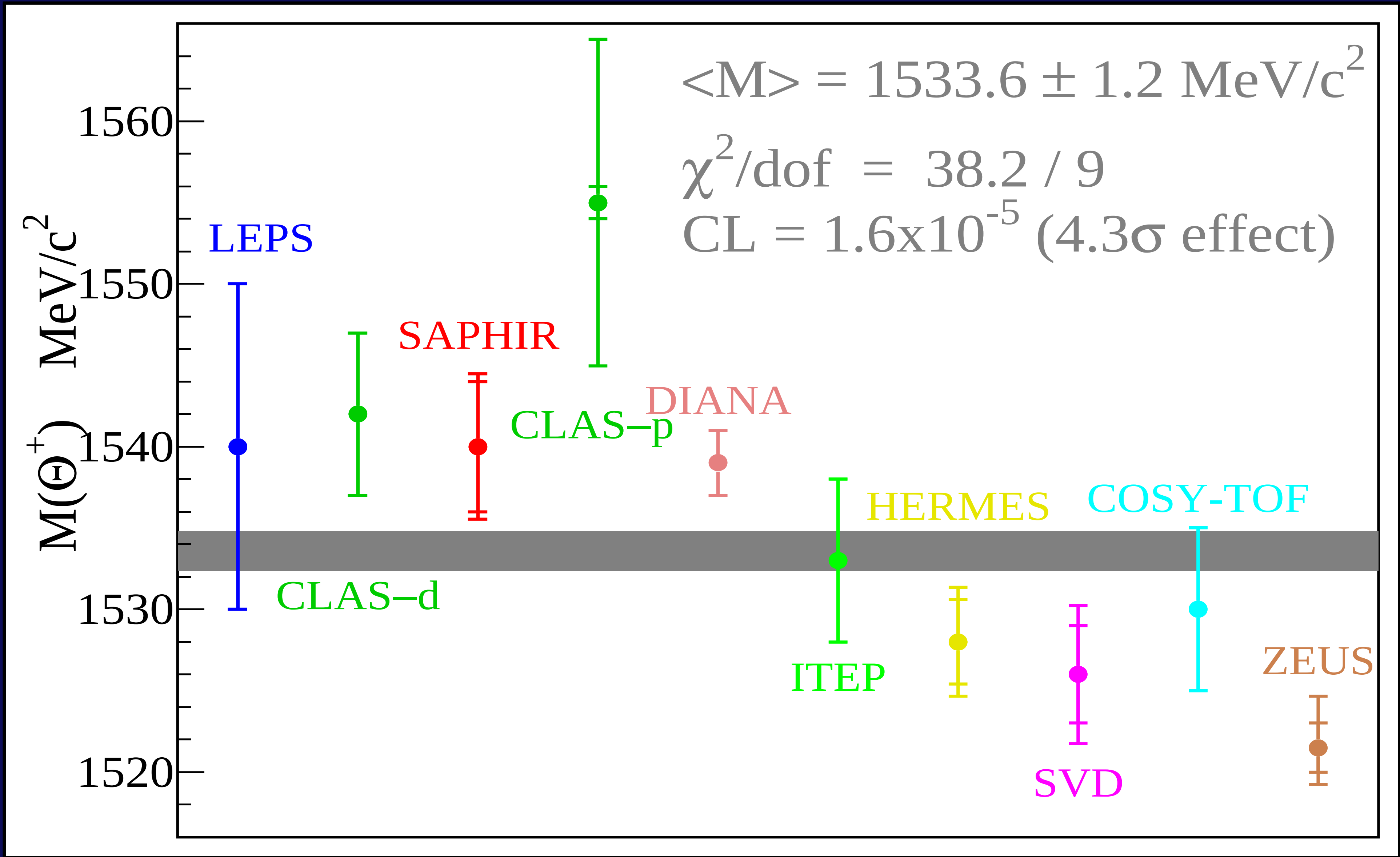


Summary of Θ^+ mass measurements

Lack of agreement on mass does not build confidence:



Summary of observations

- 10 observations, all at the $\sim 4\,\sigma$ level
- The measured masses disagree at the $5\,\sigma$ level (CL = 10^{-5})
- All observed widths are consistent with resolution (1–20 MeV/c^2)
- Most results from γN but also νN and pN production
- Choice of cuts often not well motivated
- Evolution of signal versus cuts rarely given
- Finally, there exist many theories on how these peaks may be artifacts
- Need more experimental data to confirm or refute

Enter FOCUS: a photoproduction fixed-target experiment designed to study charm particles

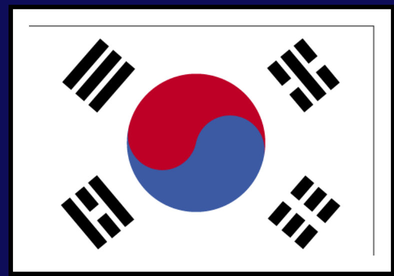
A FOCUS Group

Centro Brasileiro de Pesquisas Físicas,
Rio de Janeiro

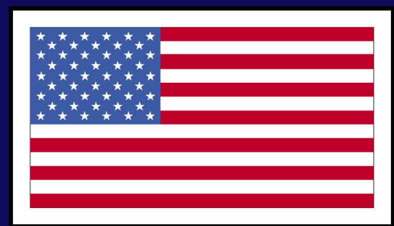
Laboratori Nazionali di Frascati dell'INFN
INFN and Università degli Studi di Milano
INFN and Università degli Studi di Pavia

CINVESTAV, México City
Universidad Autonoma de Puebla, Puebla
University of Guanajuato, Guanajuato

University of Puerto Rico, Mayaguez



Korea University, Seoul
Kyungpook National University, Taegu



University of California, Davis
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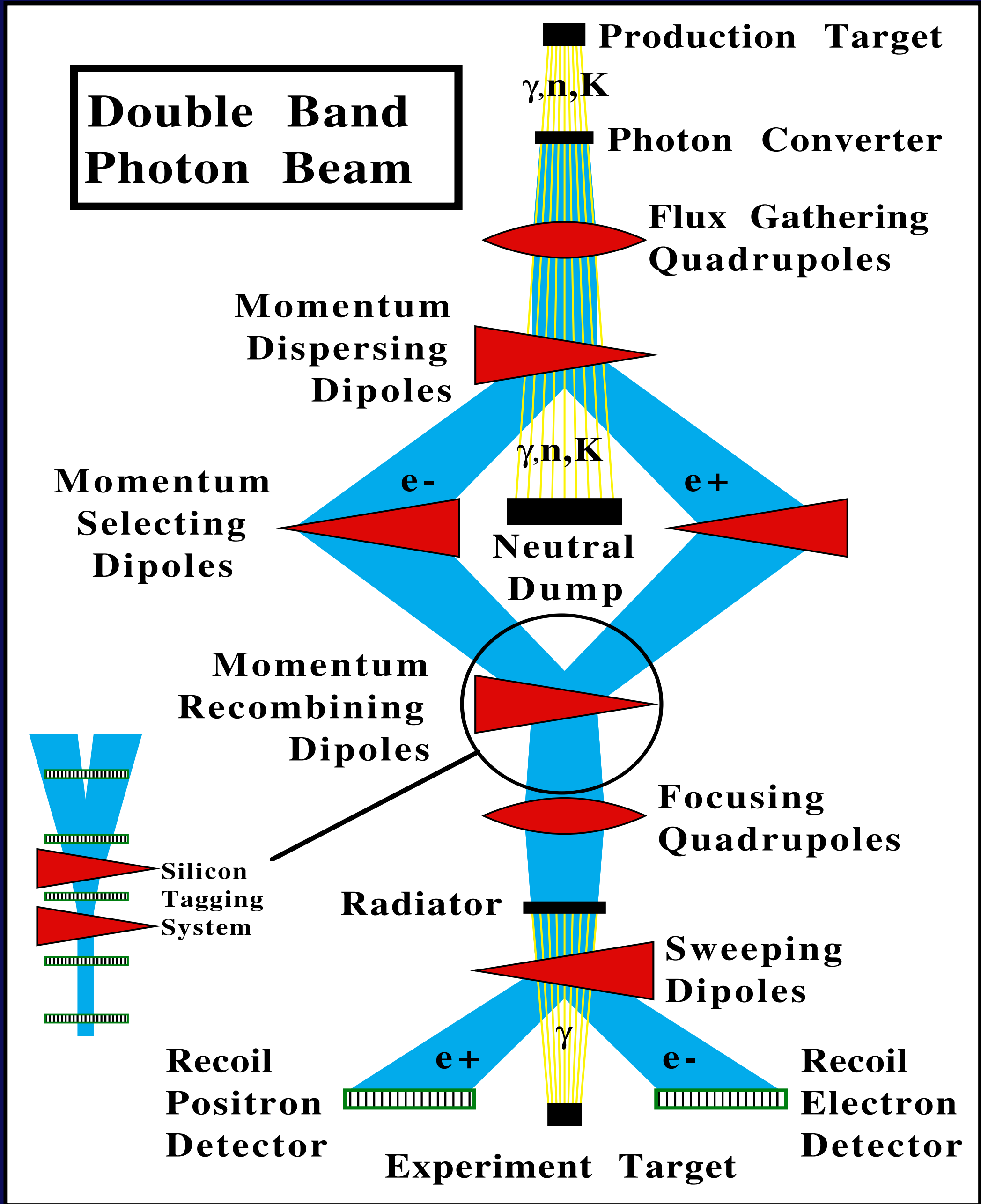
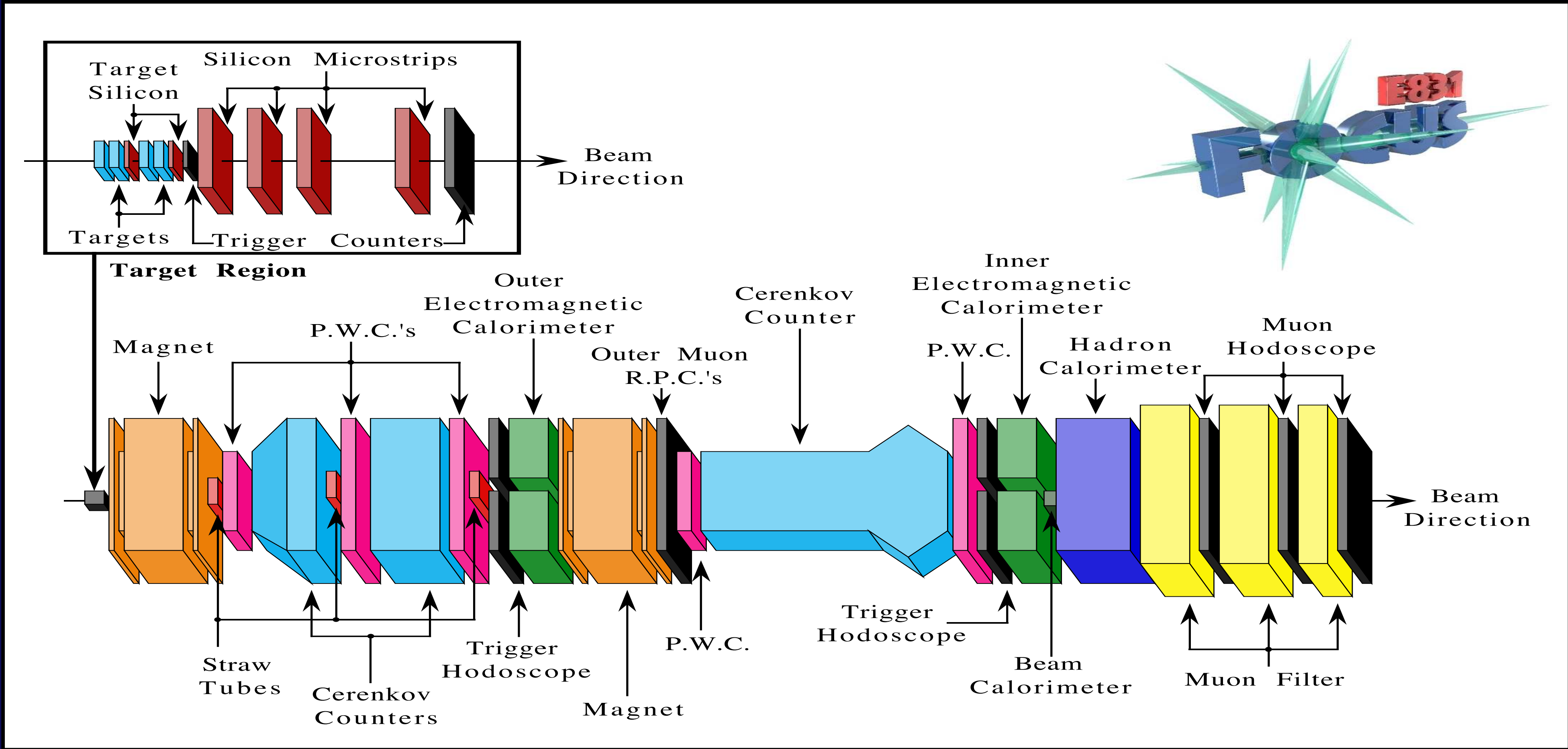
University of Illinois, Urbana-Champaign
University of North Carolina, Ashville
University of South Carolina, Columbia
University of Tennessee, Knoxville
Vanderbilt University, Nashville
University of Wisconsin, Madison

FOCUS the light

- 800 GeV protons impact liquid deuterium target
- Charged particles swept out
- Photons converted to $e^{\pm}$ which are bent around a neutral dump
- Lepton momentum measured by silicon system
- $e^{\pm}$ energy $\sim$300 GeV with $\pm$15% acceptance
- $e^{\pm}$ bremsstrahlung provides photons on experimental BeO target
- $e^{\pm}$ swept out and energy measured
- 20 s spill every minute with $e^{\pm}$ at 53 MHz



The FOCUS Detector



- 16 silicon planes with 25 – 100 μm pitch provide production and decay vertex separation plus lifetime resolution
- Two magnets and five wire chambers measure momentum
- Three Čerenkov counters, two electromagnetic calorimeters, two muon detectors, and one hadron calorimeter provide particle ID

FOCUS Trigger/Reconstruction

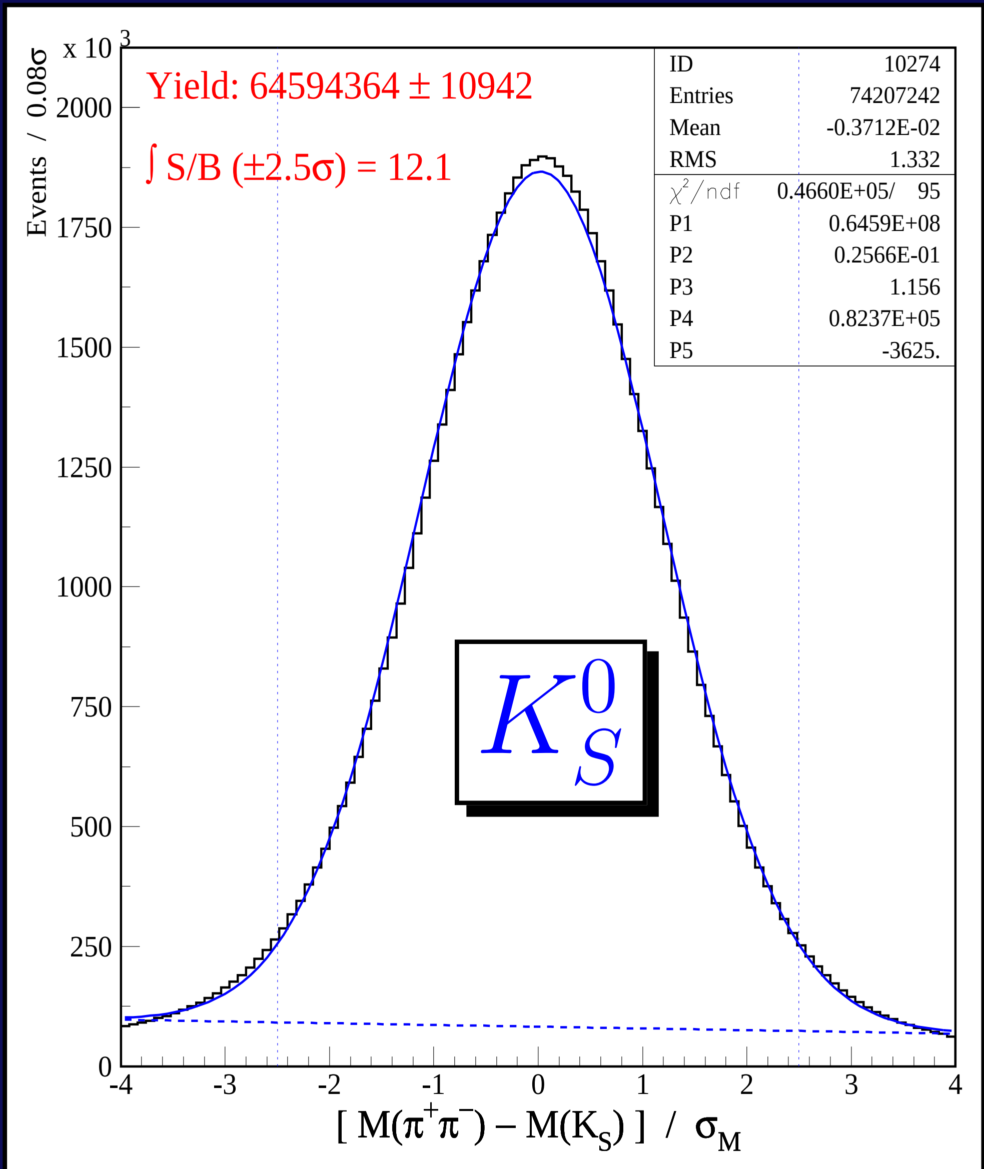
- 5 MHz of electromagnetic interactions in target ($\gamma \to e^+e^-$)
- 10 kHz of hadronic events, 100 Hz of charm events
- Open trigger requires hadronic energy ($\gtrsim 25$ GeV) and charged tracks outside beam region
- Up to 40,000 events/spill written to tape
- Recorded 7 billion events in 1996–7 Fermilab fixed-target run on 6,000 tapes
- First pass reconstruction finished at Fermilab in 1998
- Second pass at Vanderbilt and Colorado reduced and split data into six streams of 250 tapes – finished 3/99

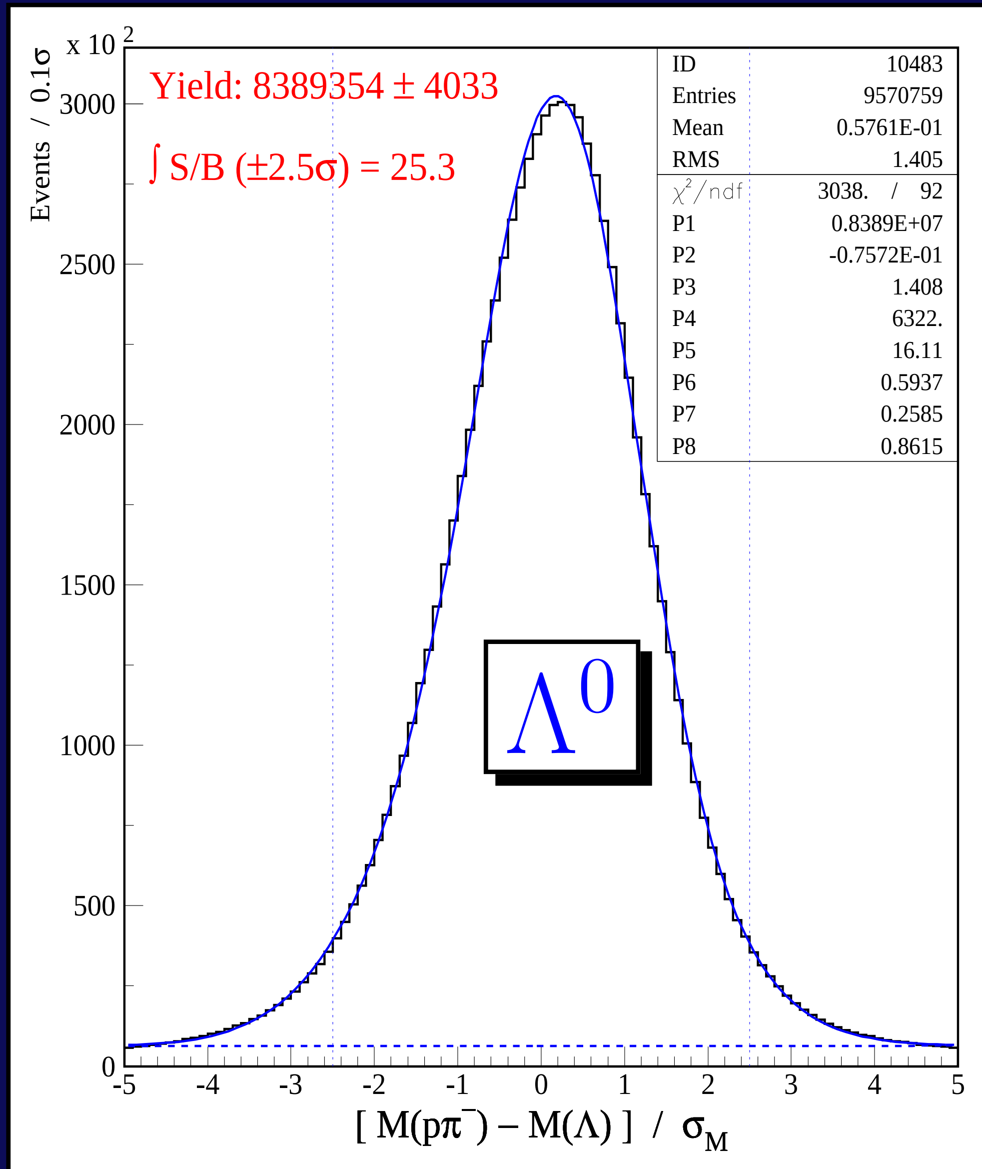
FOCUS search for $\Theta(1540)^+ \to \mathrm{pK^0_S}$

- Search for $\Theta(1540)^+ \to pK^0_S$ and compare to $K^*(892)^+ \to K^0_S\pi^+$ and $\Sigma(1385)^\pm \to \Lambda^0\pi^\pm$ (similar topology)
- Reconstruct $K^0_S \to \pi^+\pi^-$ and $\Lambda^0 \to p\pi^-$ (called vees)
- Use Čerenkov ID on fast track to separate K^0_S and Λ^0
- Remaining good quality tracks must be consistent with one vertex (CL>1%) suppressing charm decays and reinteractions
- Various minor clean up cuts applied to vees and charged tracks
- Mass of K^0_S or Λ^0 candidate within 2.5σ of nominal mass
- Very stringent Čerenkov ID cut applied to proton in pK^0_S (misid $\sim$0)

FOCUS Vee samples

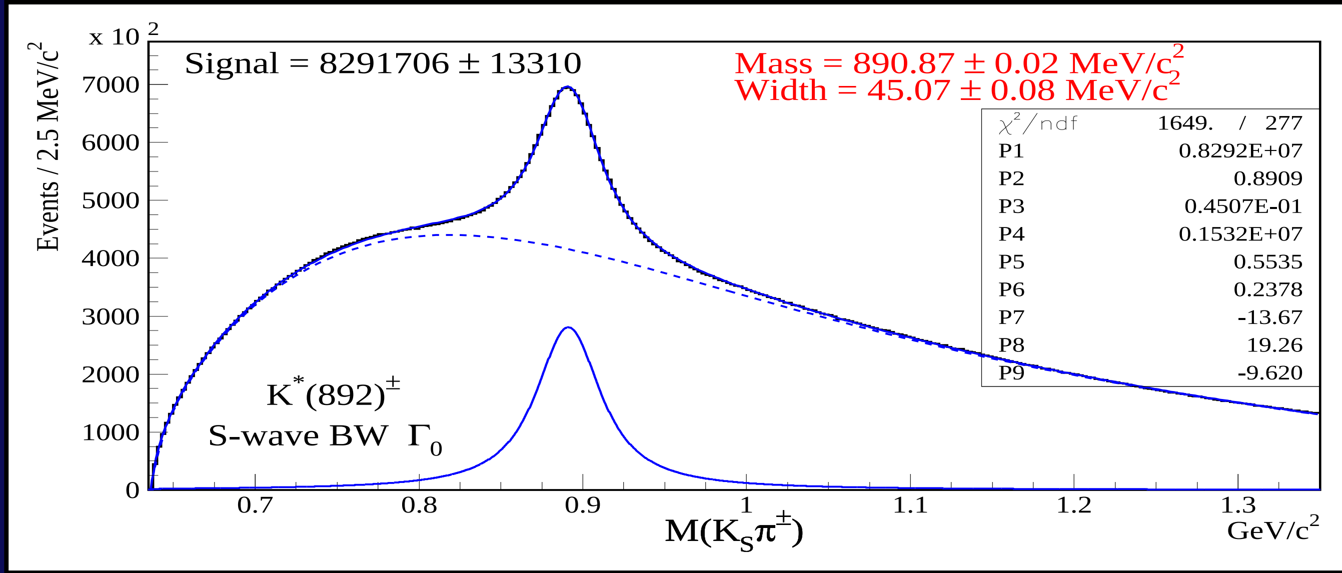
FOCUS sample of vee candidates ($K_S^0 \to \pi^+\pi^-$ & $\Lambda^0 \to p\pi^-$)



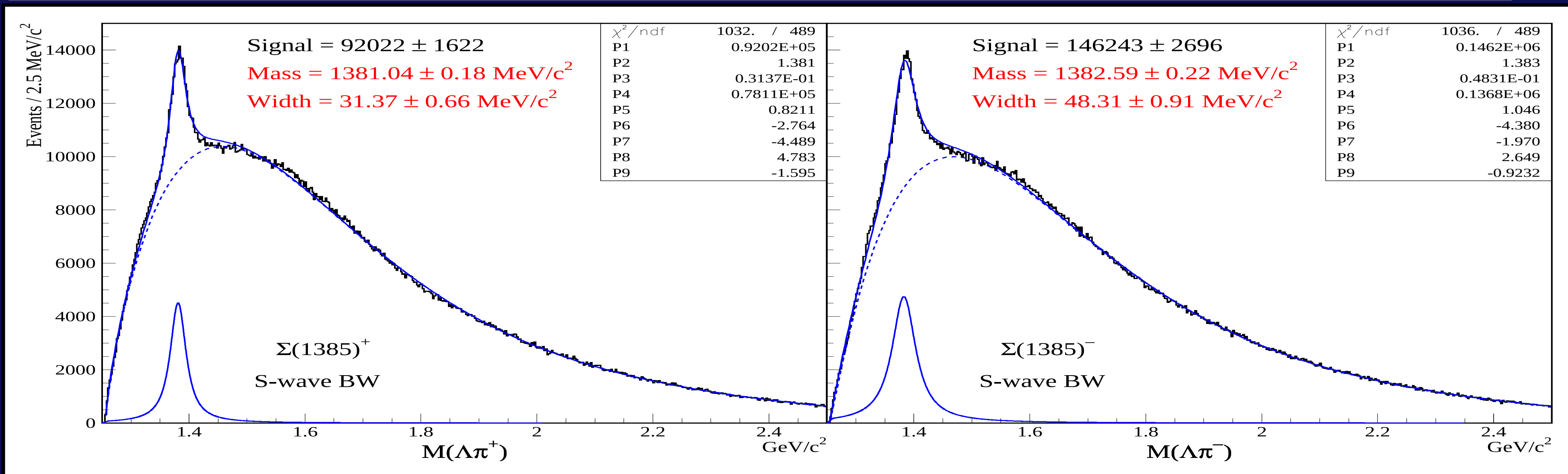


$K^*(892)^+ \to K^0_S\pi^+$ & $\Sigma(1385)^\pm \to \Lambda\pi^\pm$

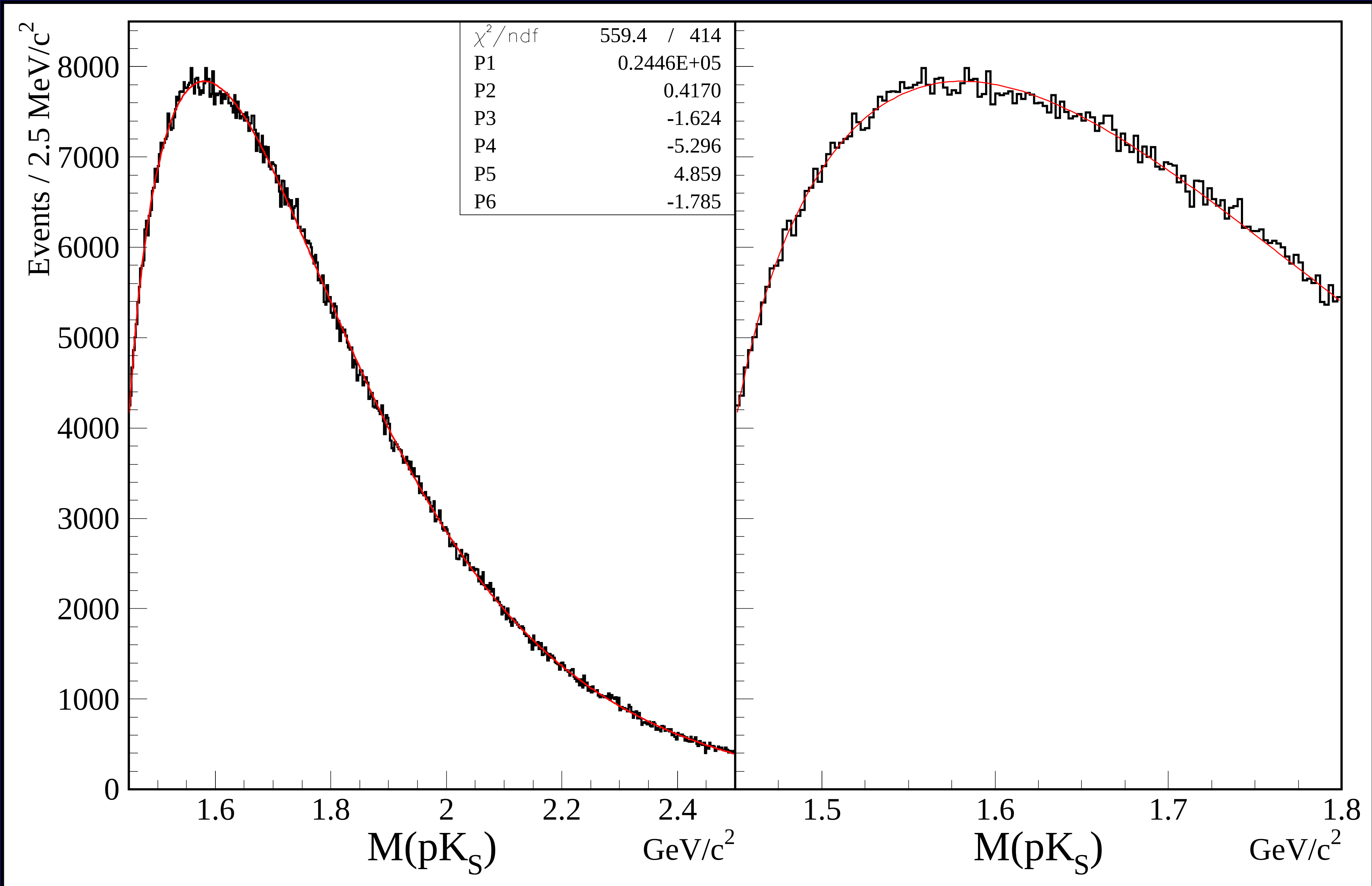
Signal shape:
S-wave Breit-Wigner with energy independent width convoluted with detector resolution



Background shape: $q^a \exp\left(bq + cq^2 + dq^3 + eq^4\right),\ \ q \equiv M(\Lambda\pi) - M(\Lambda) - m_\pi$



FOCUS search for $\Theta^+ \rightarrow pK^0_S$



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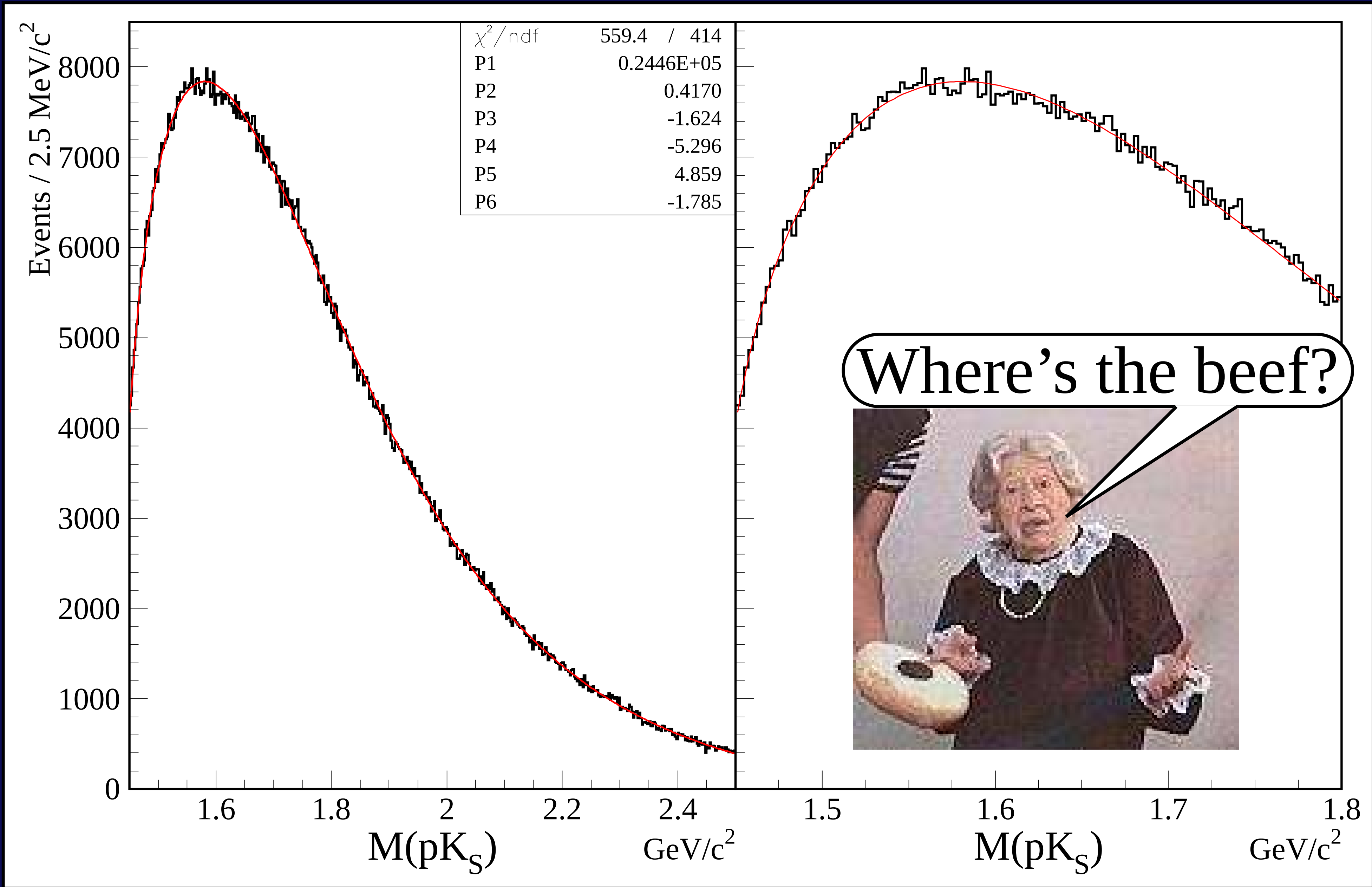
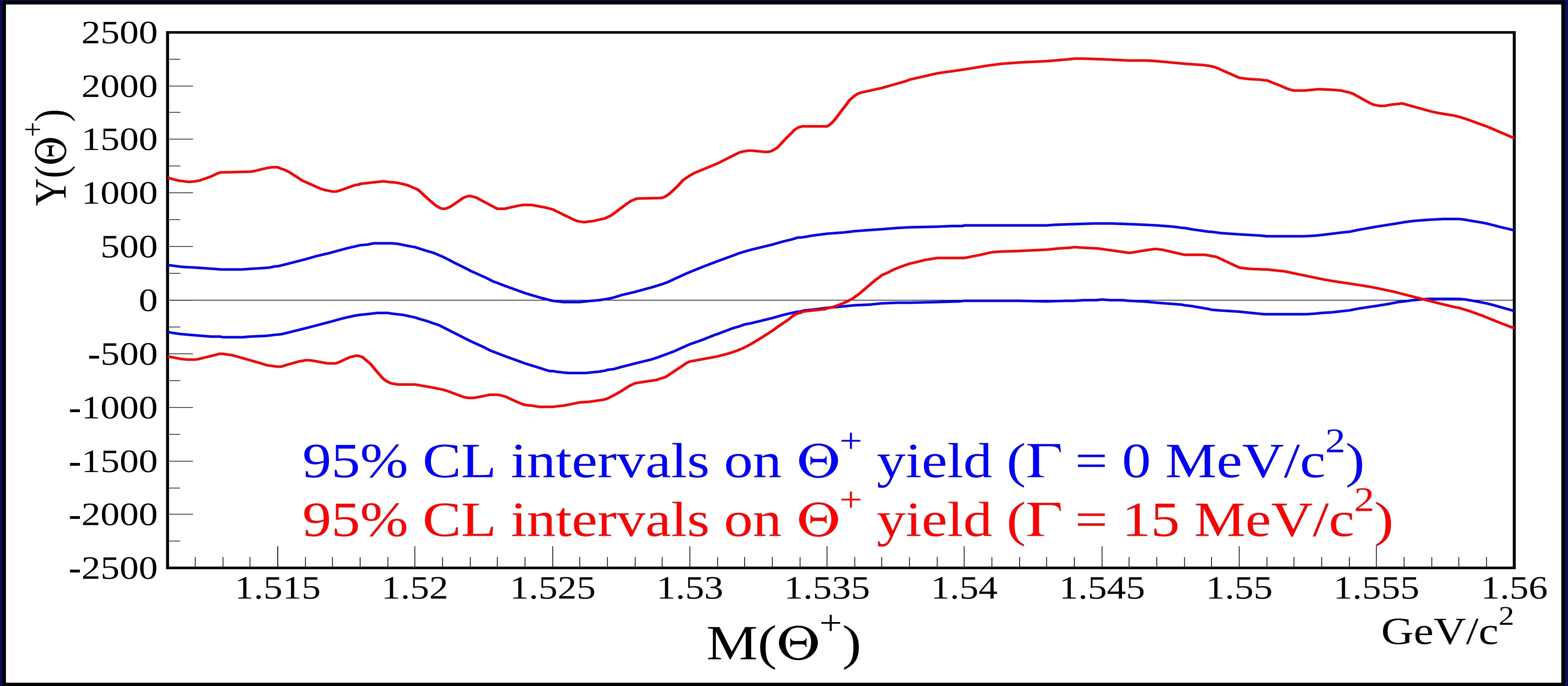


Limits on $\Theta^+ \to pK^0_S$ yield



- Fit for signal in $1\,\text{MeV}/c^2$ steps from 1511 to 1560 MeV/c^2
- Find where $-2\ln\mathcal{L}$ changes by 3.84 (95% CL) w.r.t minimum as yield is varied
- Include mass resolution $\sigma = 2.4\text{–}3.1\,\text{MeV}/c^2$ in fits with $\Gamma = 0$ and $\Gamma = 15\,\text{MeV}/c^2$

Convert to production

Accounting for acceptance and inefficiency

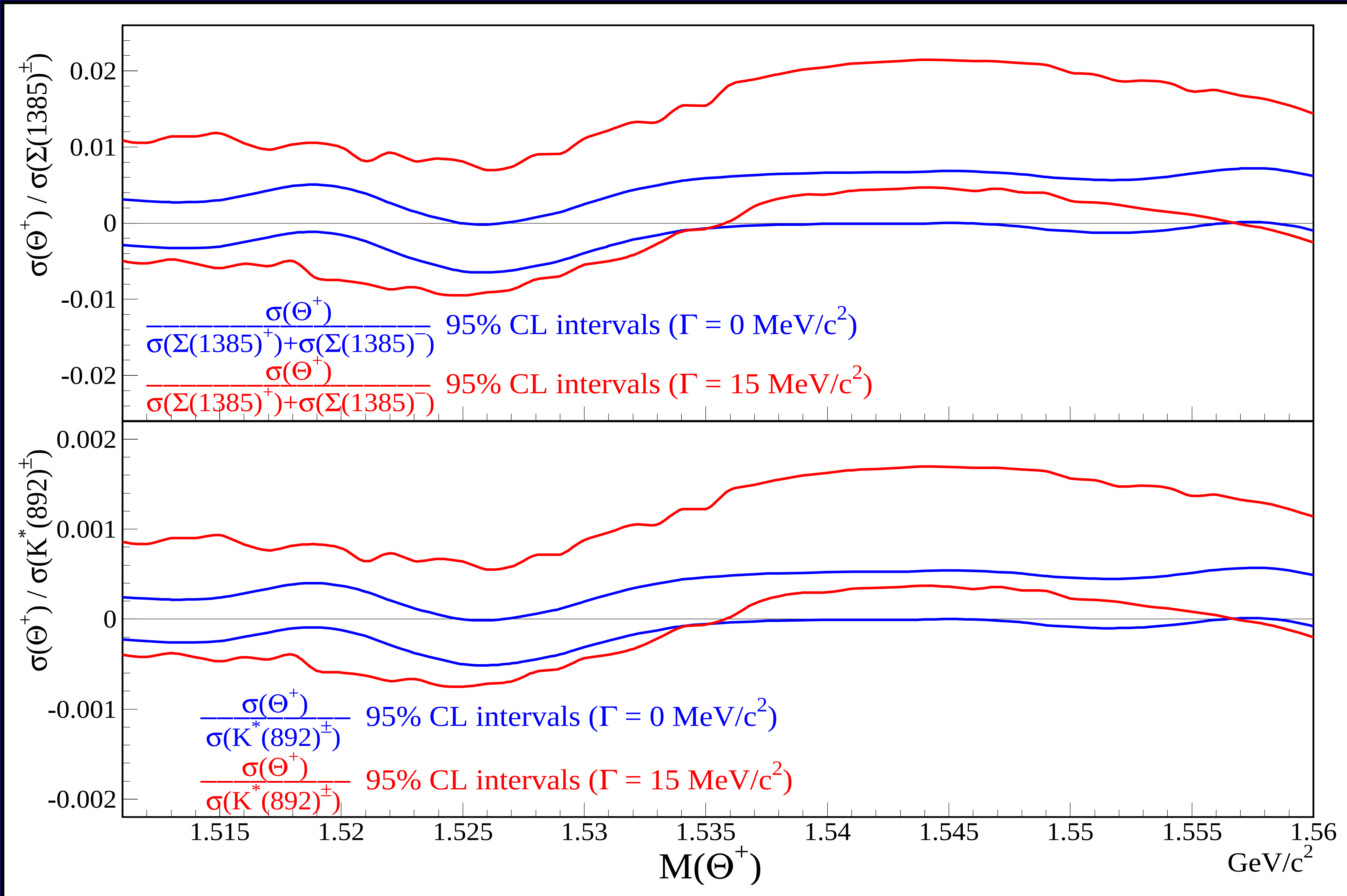
- Ratio $\Theta(1540)^+$ production to $K^*(892)^+$ & $\Sigma(1385)^\pm$ production
- Need ratio of acceptance+efficiency — from Monte Carlo program
- FOCUS acceptance depends on unknown production mechanism
- Assume reasonable production model: $\Theta(1540)^+$ produced like $\Sigma(1385)^+$ — largest source of uncertainty
- Use PYTHIA event generator to model production and FOCUS simulation to account for acceptance and efficiency

Also need to account for branching ratios

Decay	B.R.
$K^*(892)^+ \to \overline{K}^0\pi^+$	66.6%
$K^0_S \to \pi^+\pi^-$	68.6%
$\overline{K}^0 \to K^0_S$	50.0%

Decay	B.R.
$\Lambda^0 \to p\pi^-$	63.9%
$\Sigma(1385)^\pm \to \Lambda^0\pi^\pm$	88.0%
$\Theta(1540)^+ \to p\overline{K}^0$	50.0%

Limits on Θ^+ production



Summary of $\Theta(1540)^+$ results

Experiment	Yield $\Theta(1540)^+$	σ_{M_Θ} MeV/c^2	Yield $\Lambda(1520)^0$	Yield/10^3 K_S^0	Yield/10^3 K^{*+}	Yield/10^3 $\Sigma(1385)^\pm$
LEPS γn	19 ± 3	18	25			
DIANA K^+Xe	29	3.3		25		
CLAS γd	43	12	212			
SAPHIR γp	63 ± 13	12	630			
Asratyan νN	26 ± 6	8.5		6		
CLAS γp	41 ± 10	12			1.4	
HERMES ed	59 ± 16	6	710	1		
SVD pN	50	3			0.3	0.2
COSY-TOF pp	$\sim$60	10		1		
ZEUS ep	221 ± 48	2	$\sim$2000	867		
FOCUS γN	< 695	2.8		65000	8300	238
ALEPH e^+e^-	< 140	4	2874	1200	100	
BABAR e^+e^-	$\lesssim 500$	2	40000			
BELLE e^+e^-	< 120	2	15519			
CDF $p\bar{p}$	< 154	2.6	8191	2300	52	
E690 pp	< 25	1.5	5000		15	
HERA-B pN	$\lesssim 30$	3.9	5600	4900		
HyperCP X^+N	< 406	11		80		
SPHINX pN	< 125	10	25000			2.5

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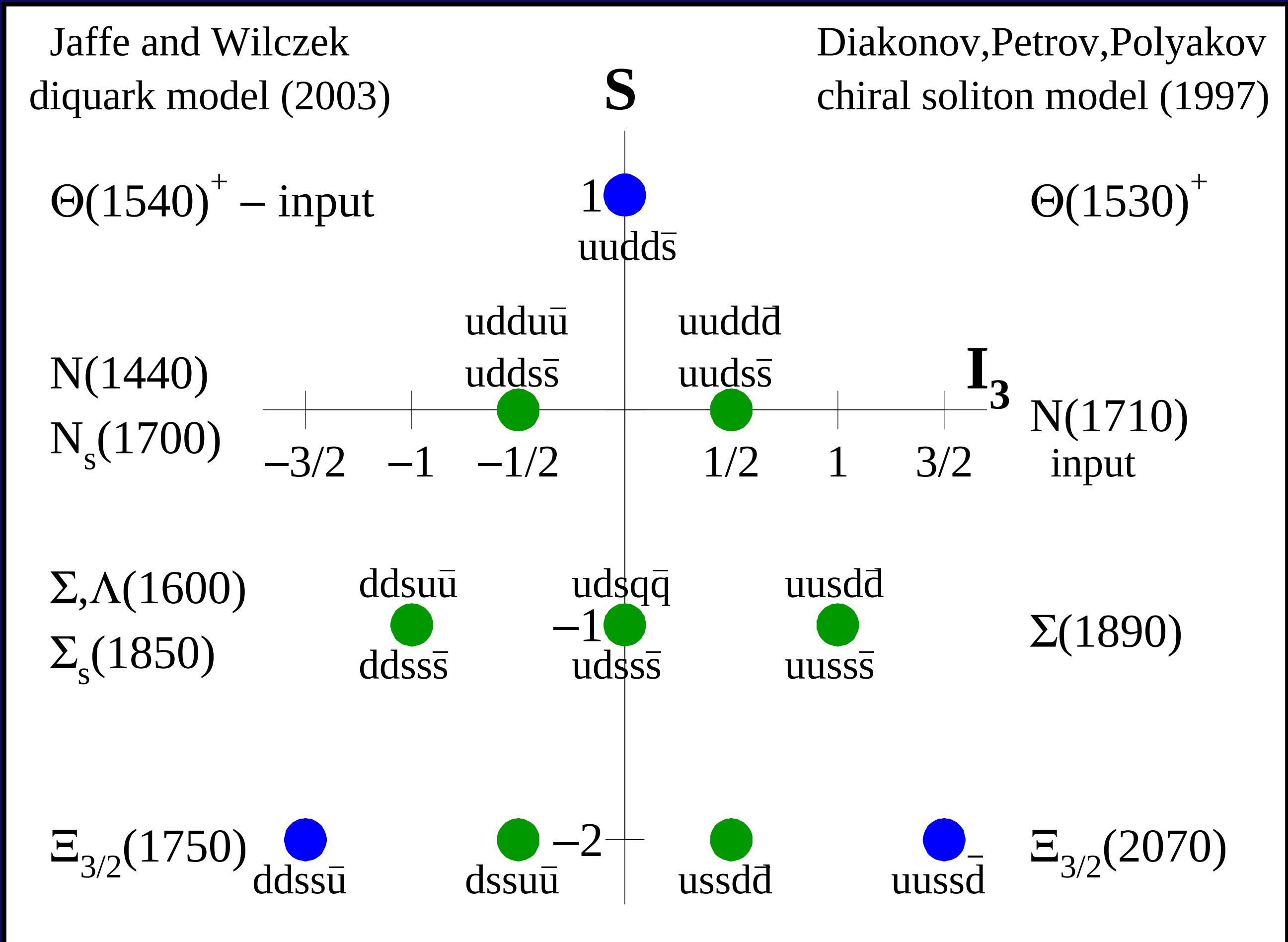
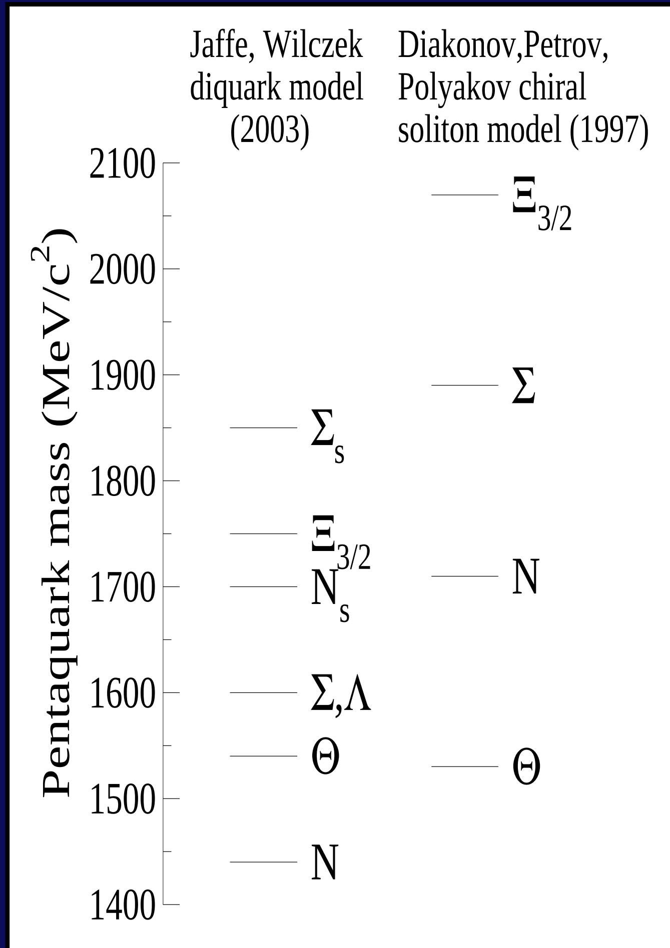
What about other pentaquarks?

- $\Theta(1540)^+$ evidence is quite shaky





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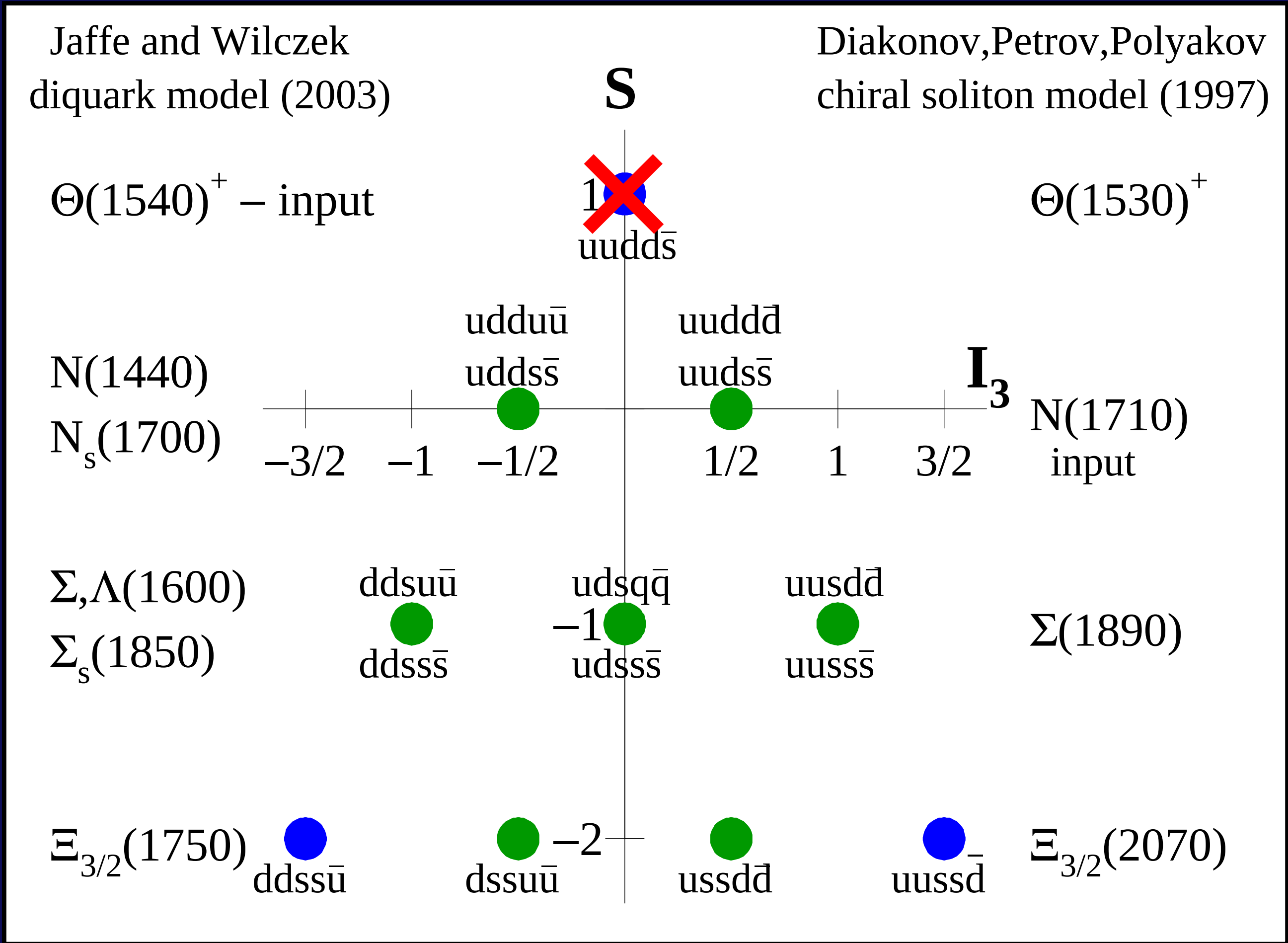
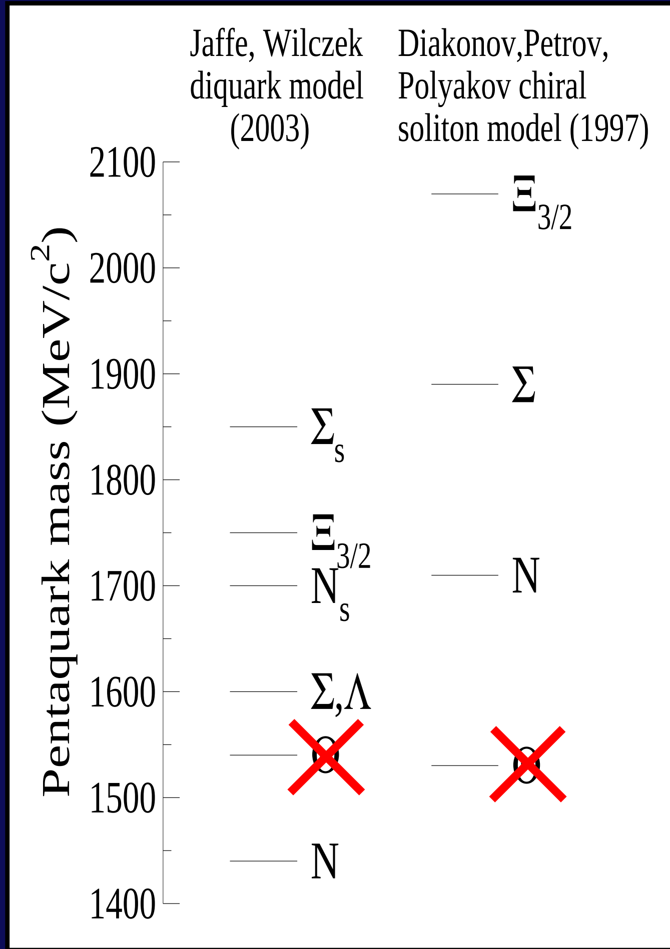
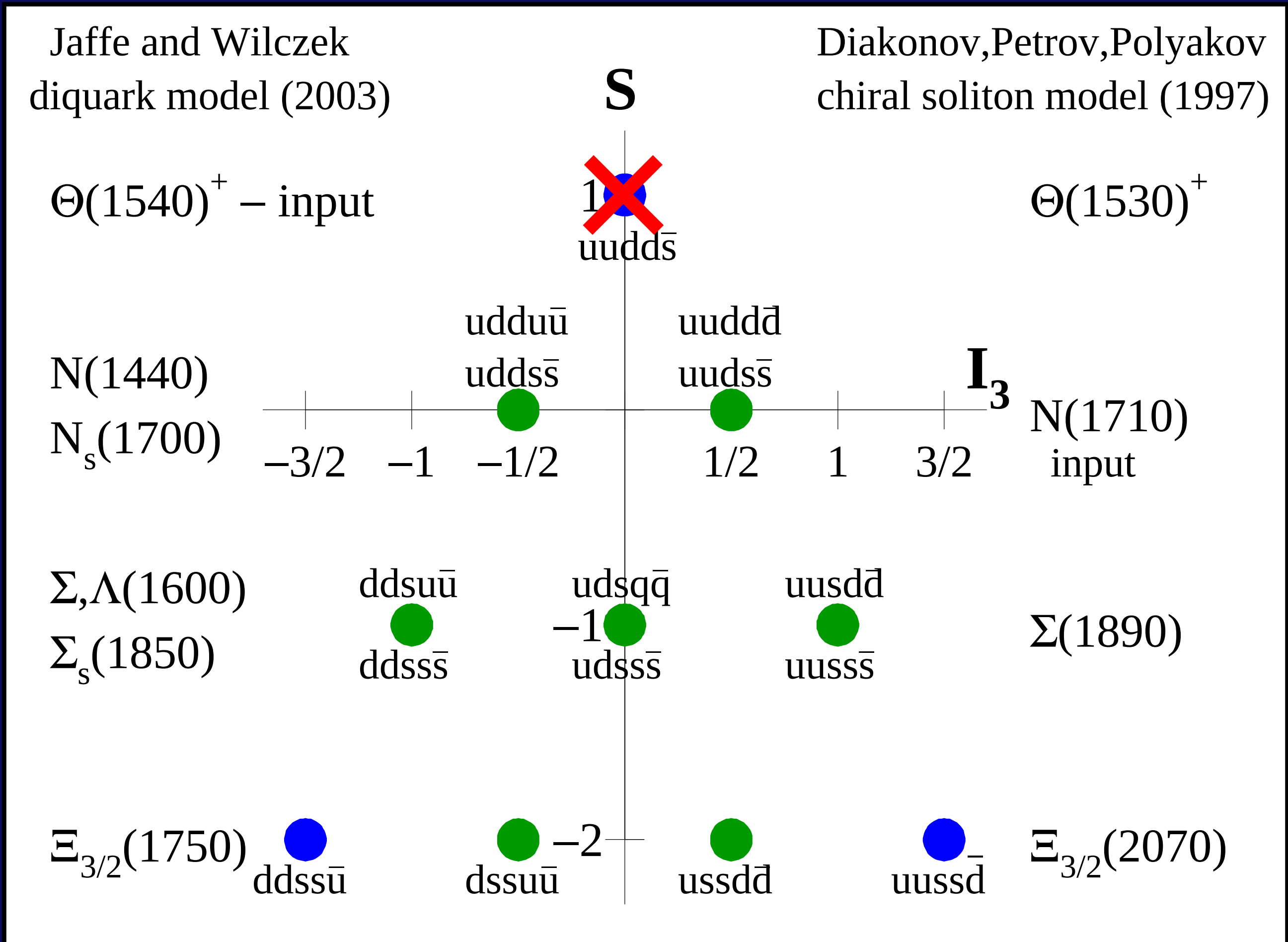
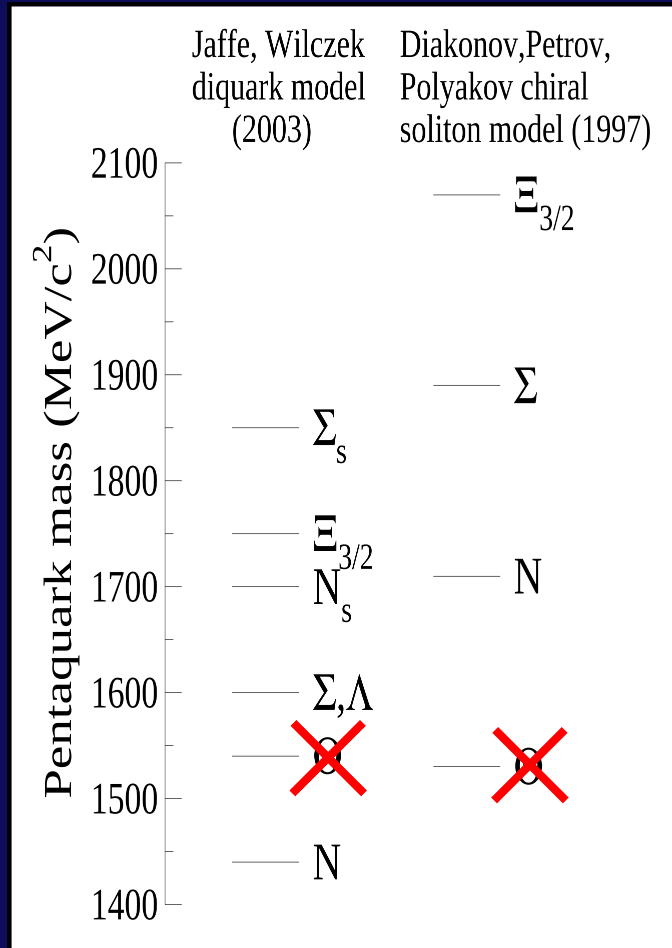




What about other pentaquarks?

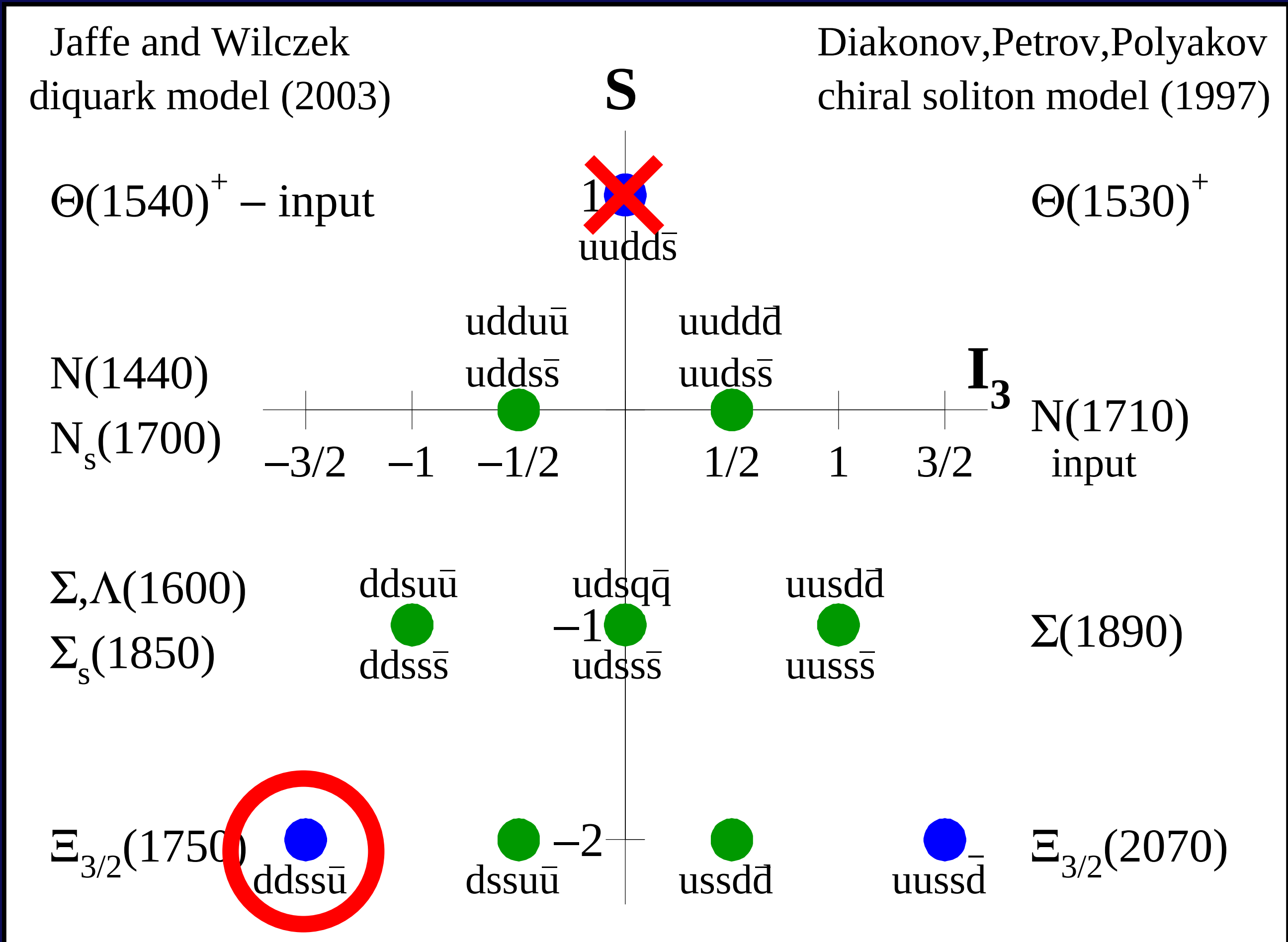
- $\Theta(1540)^+$ evidence is quite shaky
- What about other states?

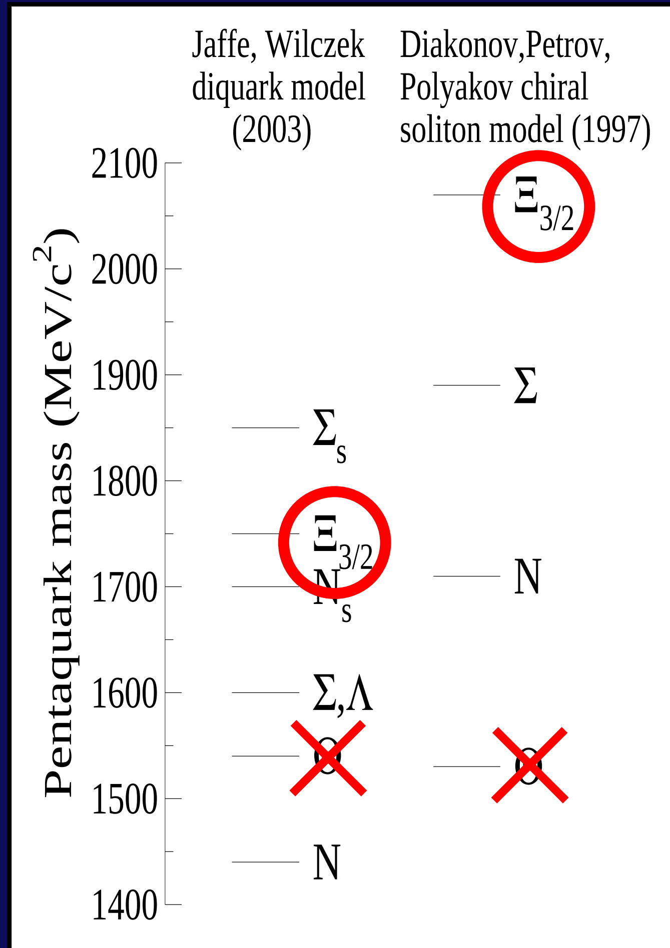




What about other pentaquarks?

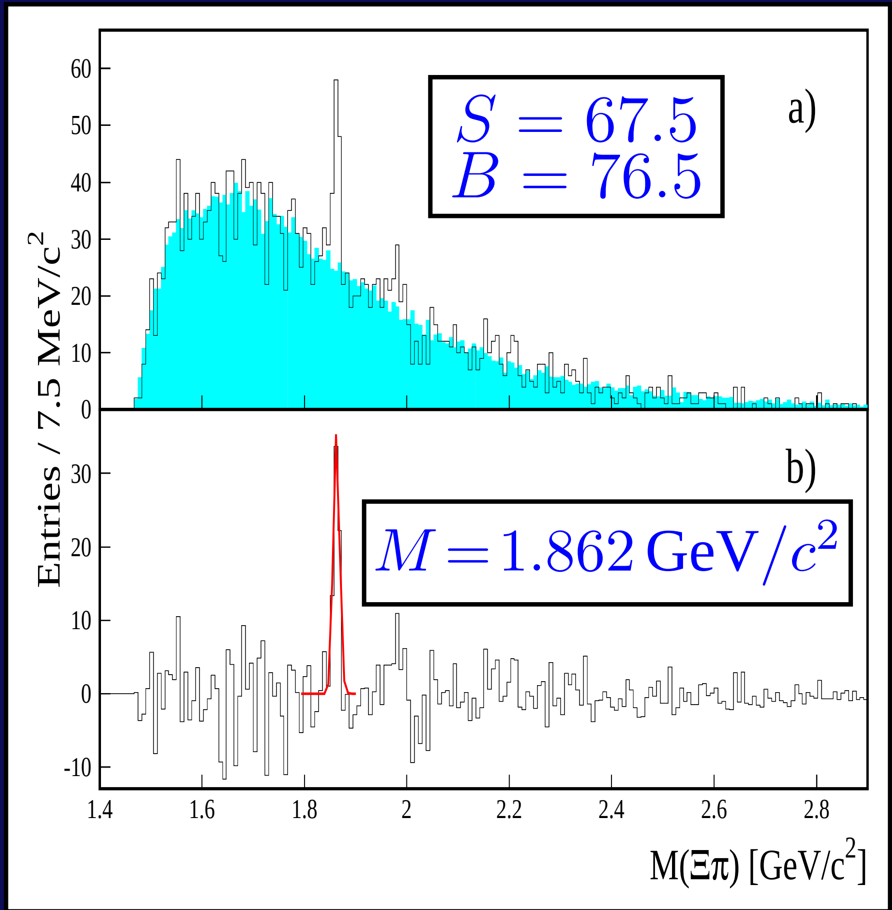
- $\Theta(1540)^+$ evidence is quite shaky
- What about other states?
- $\Xi_{3/2}^{--}(dd s s \overline{u})$ is manifestly exotic
- Possible decay: $\Xi^{--} \rightarrow \Xi^- \pi^-$, $\Xi^- \rightarrow \Lambda^0 \pi^-$

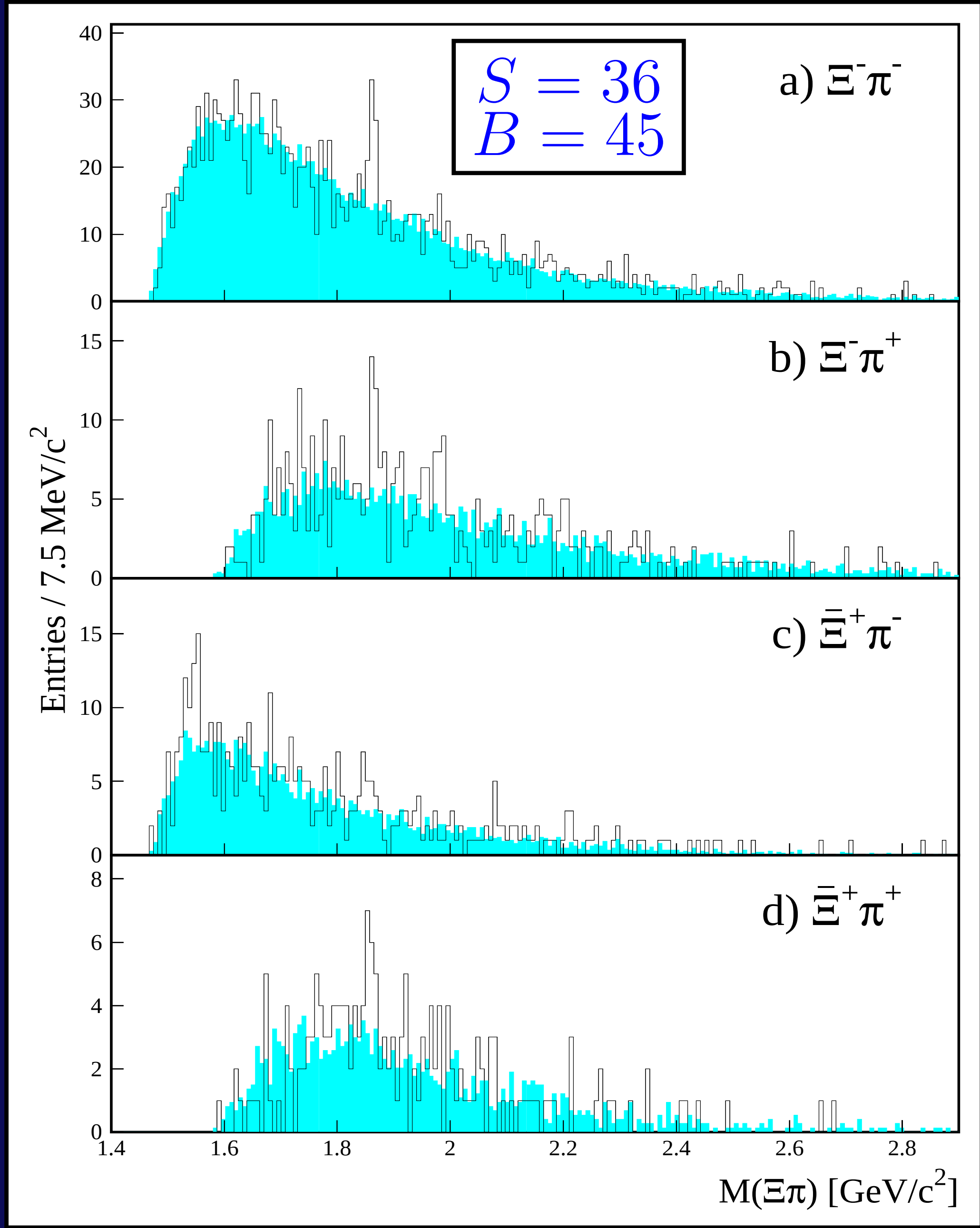




NA49 observation of $\Xi_{3/2}(1862)^{--}$

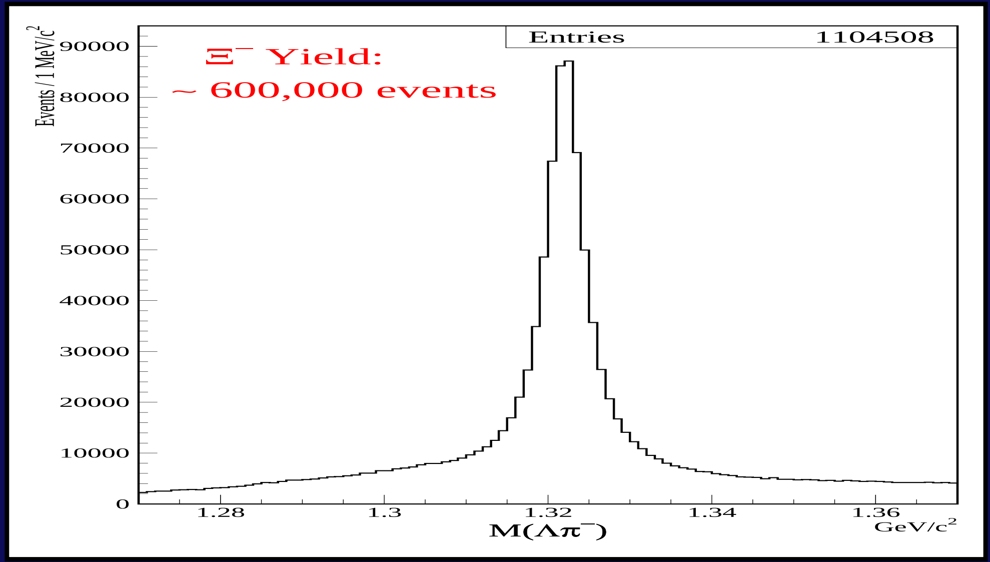
NA49 uses 158 GeV p on LH_2; evidence for $\Xi_{3/2}(1862)^{--}(dds s\bar{u})$ and $\Xi_{3/2}(1862)^0$ decaying $\Xi^-\pi^\pm$

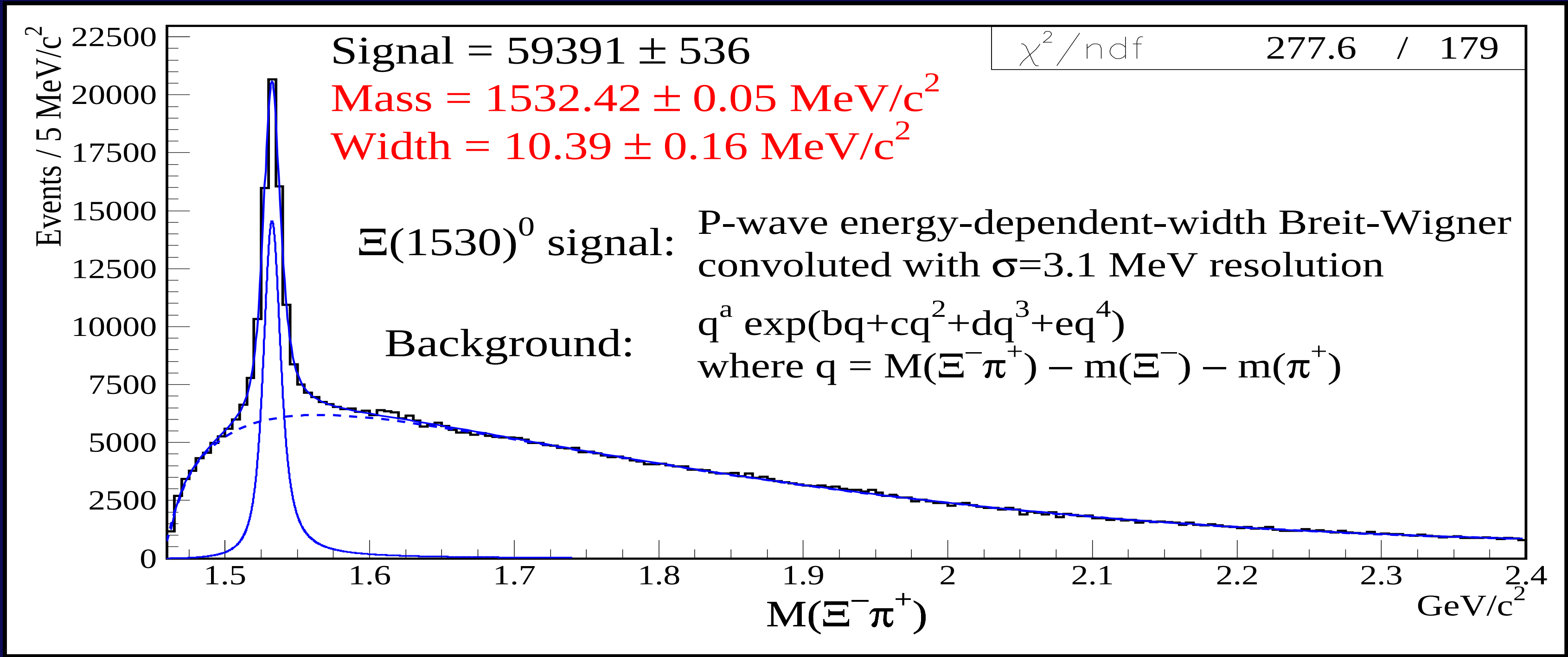




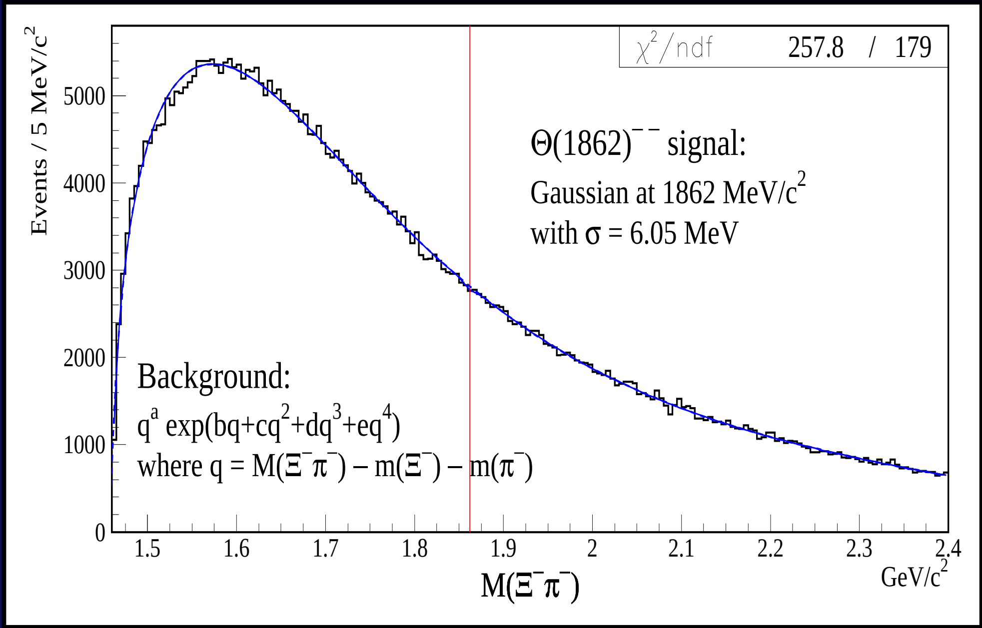
FOCUS search for $\Xi_{3/2}(1862)^{--} \to \Xi^- \pi^-$

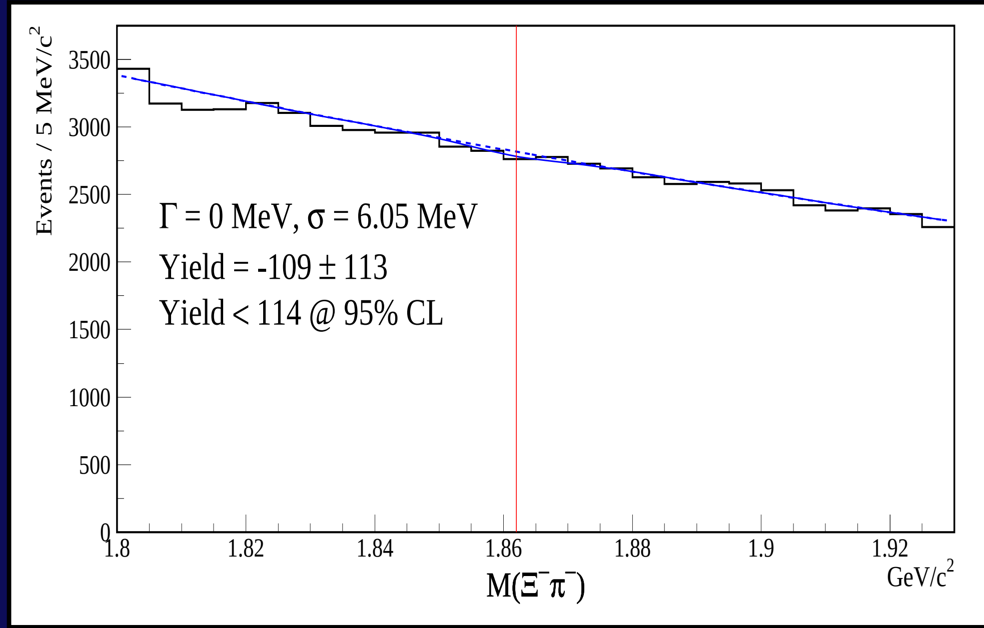
- $\sim$600,000 $\Xi^- \to \Lambda^0 \pi^-$ sample
- Vertex Ξ^- with $\pi^\pm$ and find production vertex
- Require $< 4\sigma$ separation between vertices
- In $\Xi^- \pi^+$, observe $\sim$60,000 $\Xi(1530)^0$ candidates





Results of search for $\Xi_{3/2}(1862)^{--}$





- Convert limit of < 114 events @ 95% CL to cross section ratio w.r.t. $\Xi(1530)^0$ assuming production like $\Xi(1530)^0$
- Efficiency ratio is $\frac{\epsilon(\Xi_{3/2}(1862)^{--}\rightarrow\Xi^-\pi^-)}{\epsilon(\Xi(1530)^0\rightarrow\Xi^-\pi^+)} = 0.78$
- Also account for $BR(\Xi(1530)^0 \rightarrow \Xi^-\pi^+) = 2/3$
- Thus, for a $\Xi_{3/2}(1862)^{--}$ produced like $\Xi(1530)^0$ we obtain the limit:

$$\frac{\sigma(\Xi_{3/2}(1862))\times \mathrm{BR}(\Xi_{3/2}(1862)\rightarrow\Xi^-\pi^-)}{\sigma(\Xi(1530))} < 0.16\% \text{ @ } 95\% \text{ CL}$$

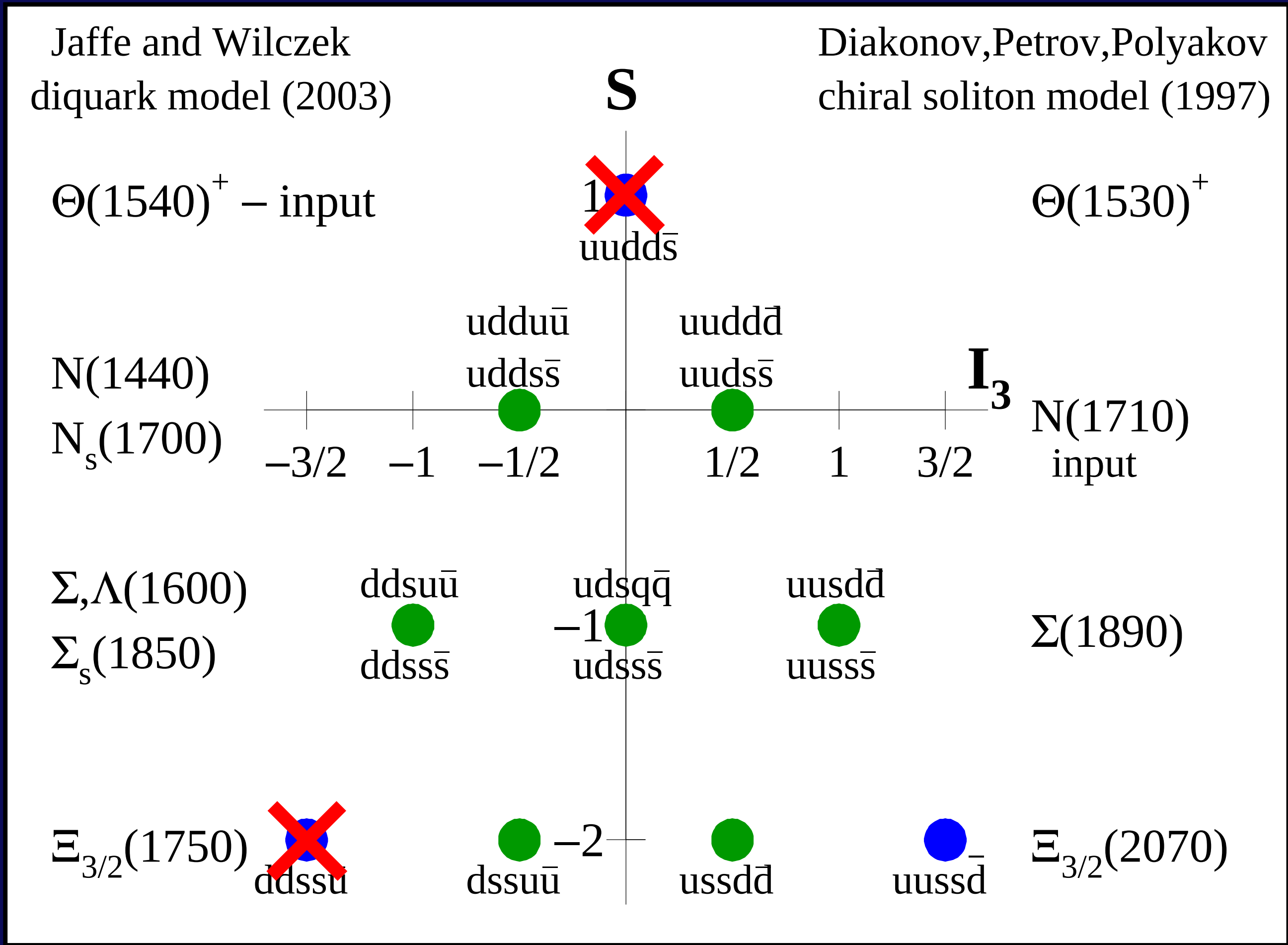
Summary of $\Xi_{3/2}(1862)^{--}$ searches

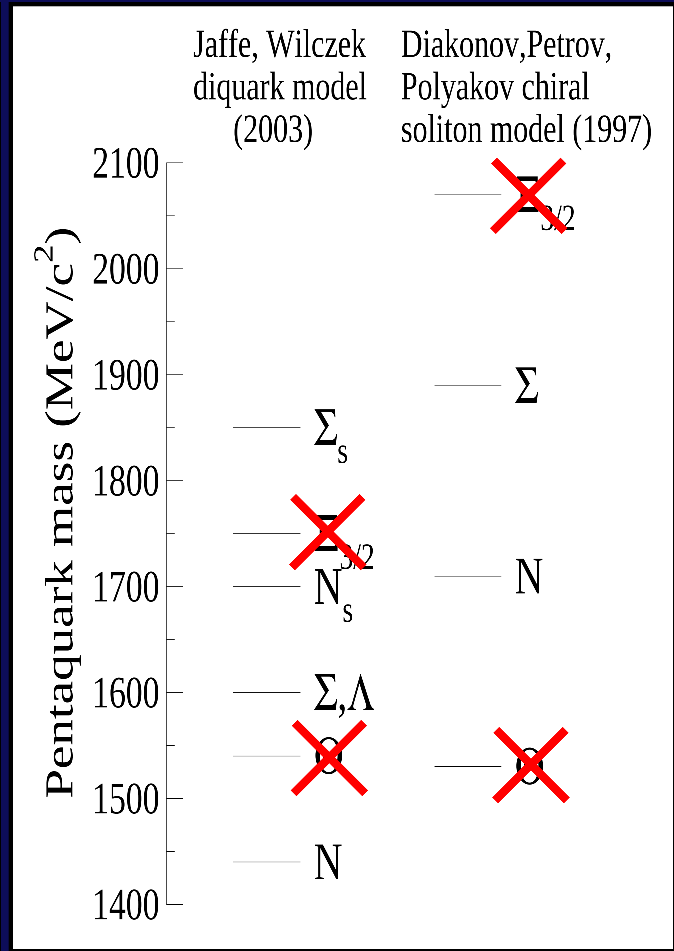
Experiment	Yield $\Xi_{3/2}(1862)^{--}$	Yield $\Xi(1530)^0$	$\frac{\sigma\left(\Xi_{3/2}(1862)^{--}\right) \cdot \mathrm{BR}}{\sigma\left(\Xi(1530)^0\right)}$
NA49 pp	~ 45	~ 150	$\sim 30.00\,\%$
FOCUS γN	< 114	59391 ± 536	$< 0.16\,\%$
ALEPH e^+e^-		322 ± 33	$< 8.00\,\%$
BABAR e^+e^-	$\lesssim 80$	~ 5000	$< 0.50\,\%$
CDF $p\overline{p}$	< 63	2182 ± 92	$< 4.00\,\%$
E690 pp	< 200	70000	$< 0.30\,\%$
HERA-B pN			$< 0.60\,\%$
HERMES ed	< 5	35 ± 11	$< 19.00\,\%$
WA89 $\Sigma^-,\pi^- N$		63000	$< 1.40\,\%$
ZEUS ep	< 6	192 ± 30	$< 19.00\,\%$

- FOCUS has the best limit on the ratio of $\Xi_{3/2}(1862)^{--}$ production relative to $\Xi(1530)^0$ production
- All results in serious disagreement with NA49 observation

That's two down!

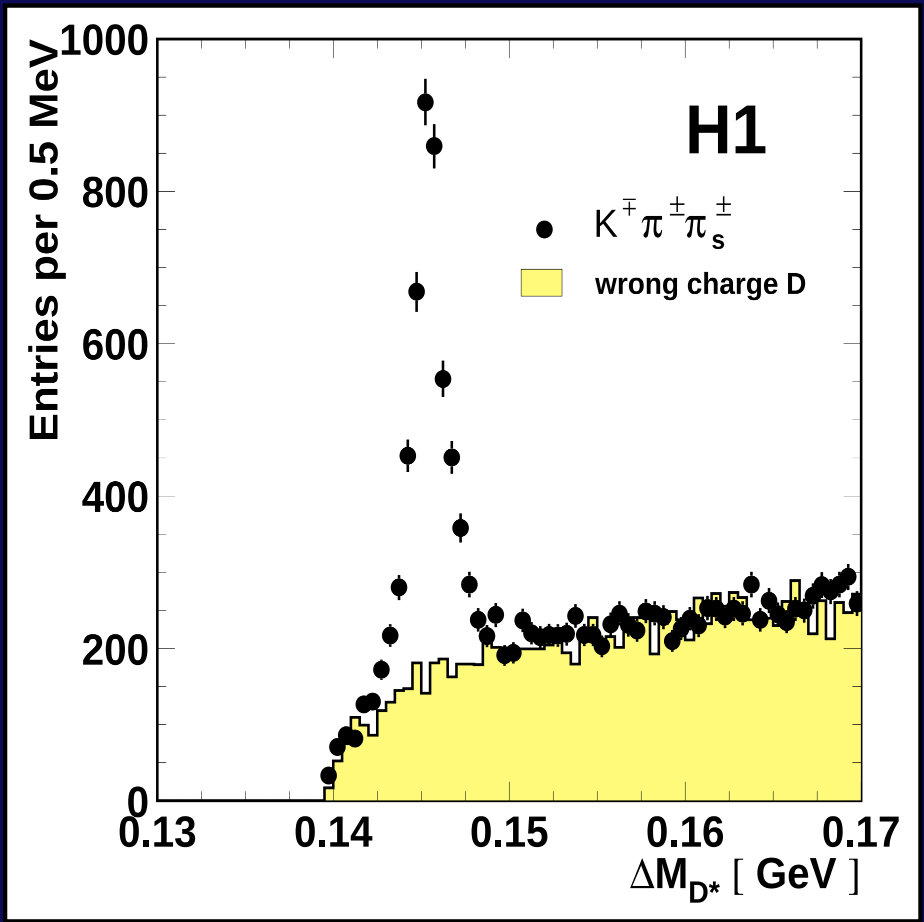
- Evidence for $\Theta(1540)^+$ and $\Xi^{--}_{3/2}(1862)$ seems rather weak

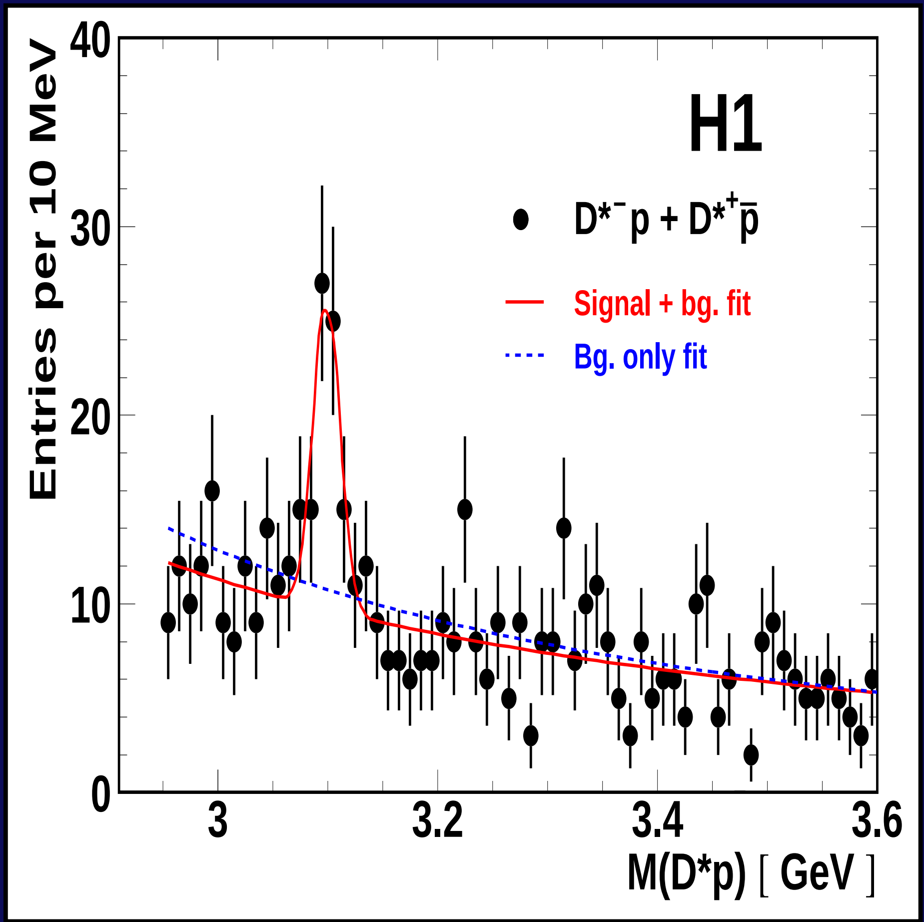




But wait, there's more: $\Theta_c^0(uudd\bar{c})$

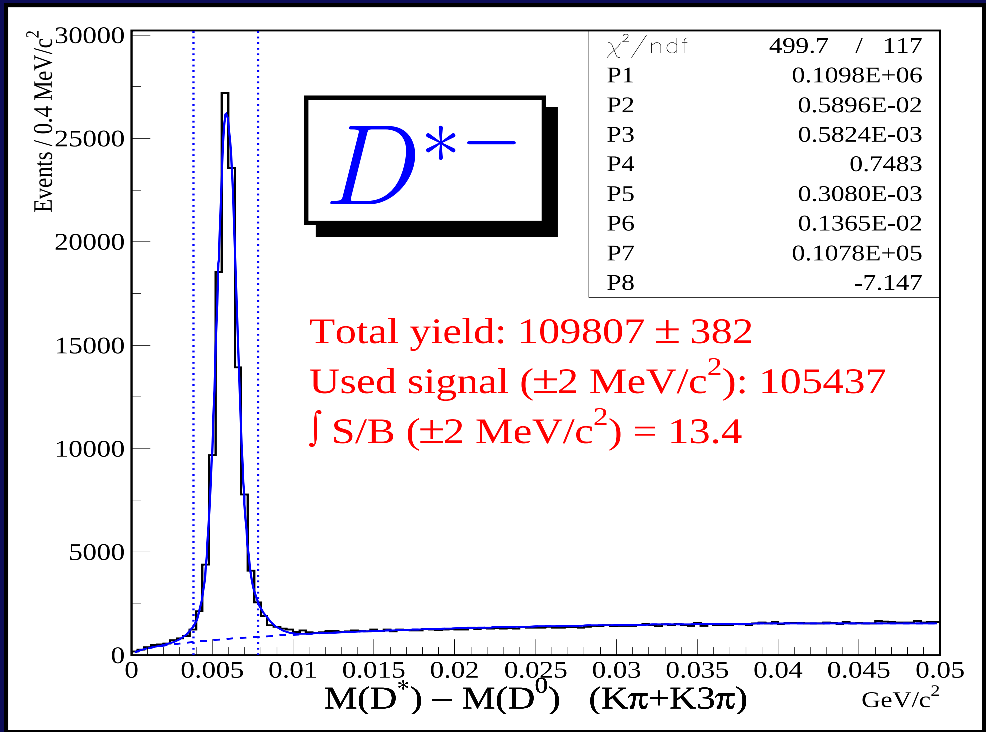
- Pentaquarks can have charm or beauty quarks too . . .
- Just replace $\bar{s}$ in $\Theta^+(uudd\bar{s})$ with $\bar{c}$ to get $\Theta_c^0(uudd\bar{c})$
- H1 at HERA finds $\Theta_c^0 \to D^{*-}p$ where $D^{*-} \to \overline{D}^0\pi_s^-$, and $\overline{D}^0 \to K^+\pi^-$
- Θ_c^0 yield of 50.6 ± 11.2 from $\sim$3500 D^{*-} candidates

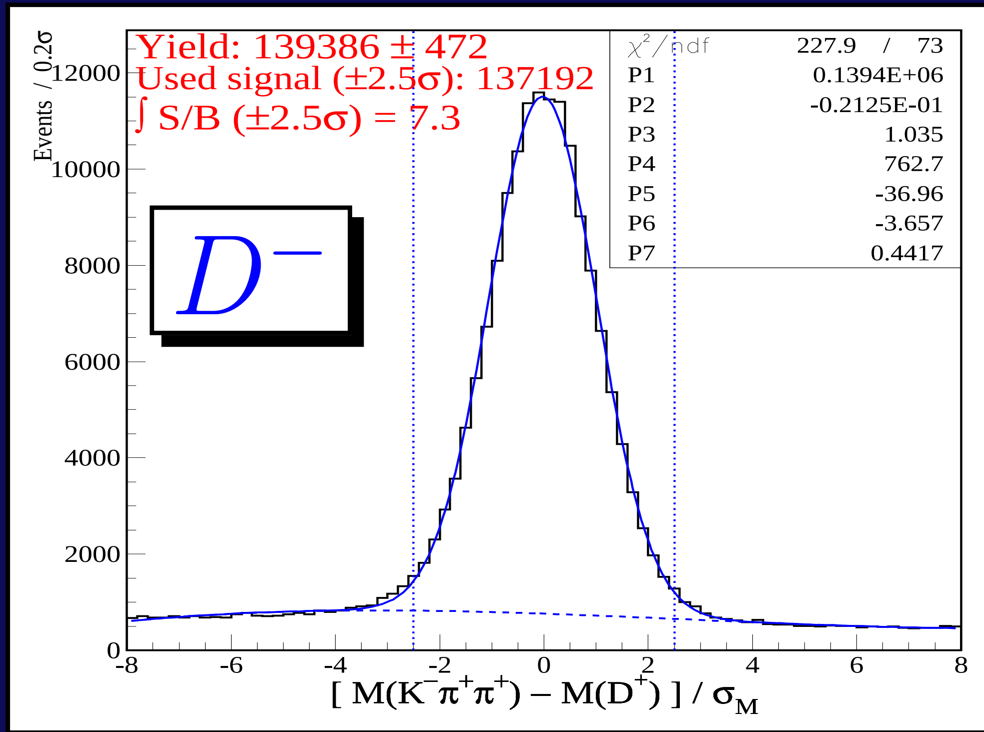




FOCUS search for Θ_c^0

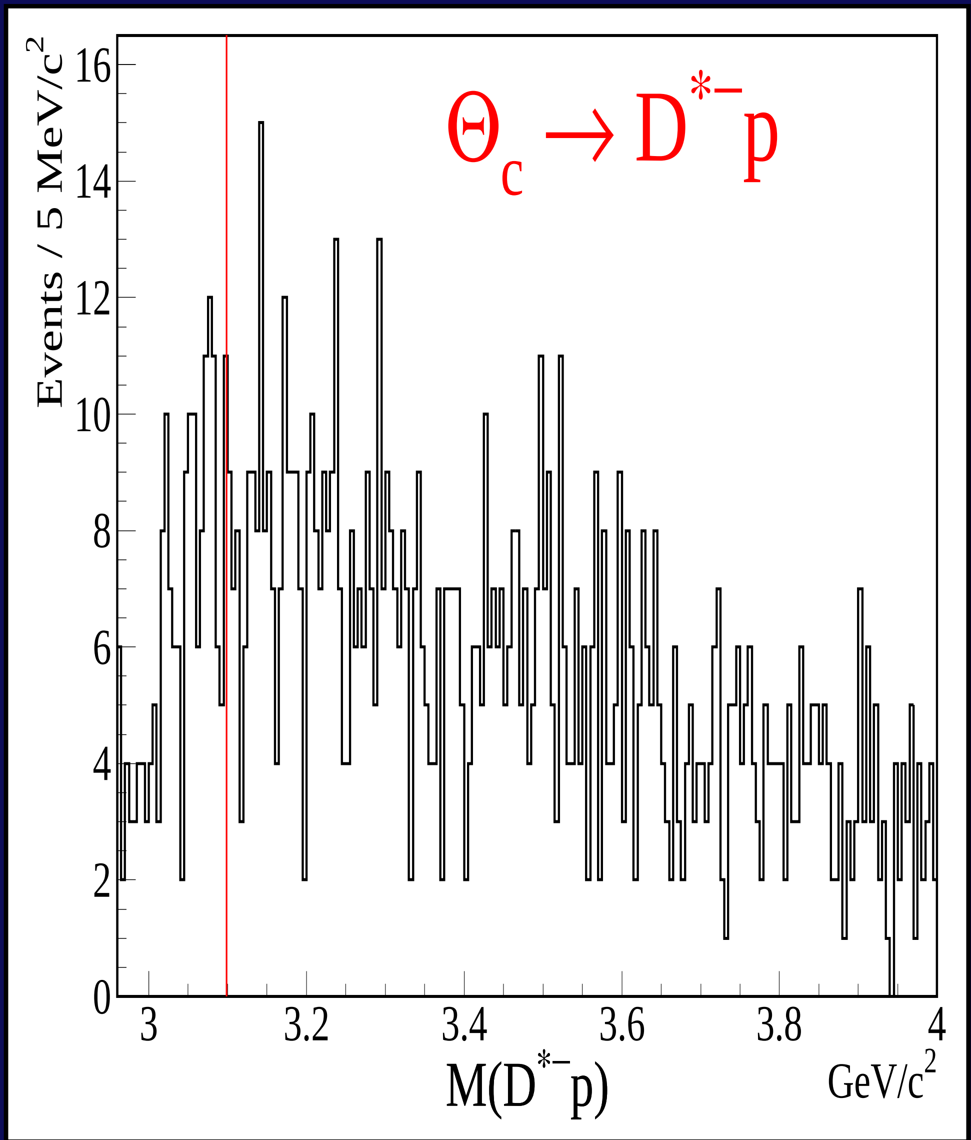
- Search for $\Theta_c^0 \rightarrow D^{*-}p$ (H1 mode) and also $\Theta_c^0 \rightarrow D^-p$
- Standard charm reconstruction for D
- Select $D^{(*)-}$ candidates in signal region
- Stringent requirement on proton ID

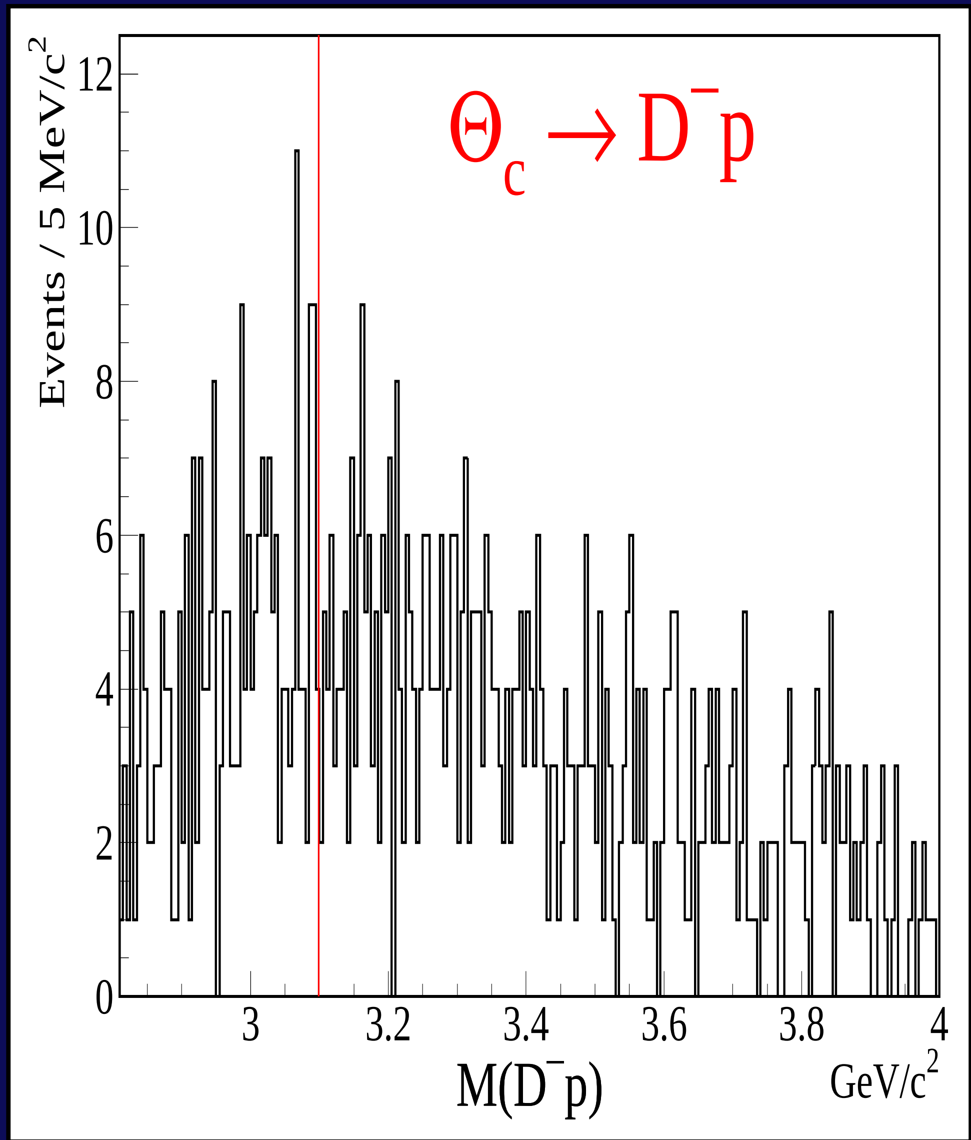




FOCUS Θ_c^0 mass plots

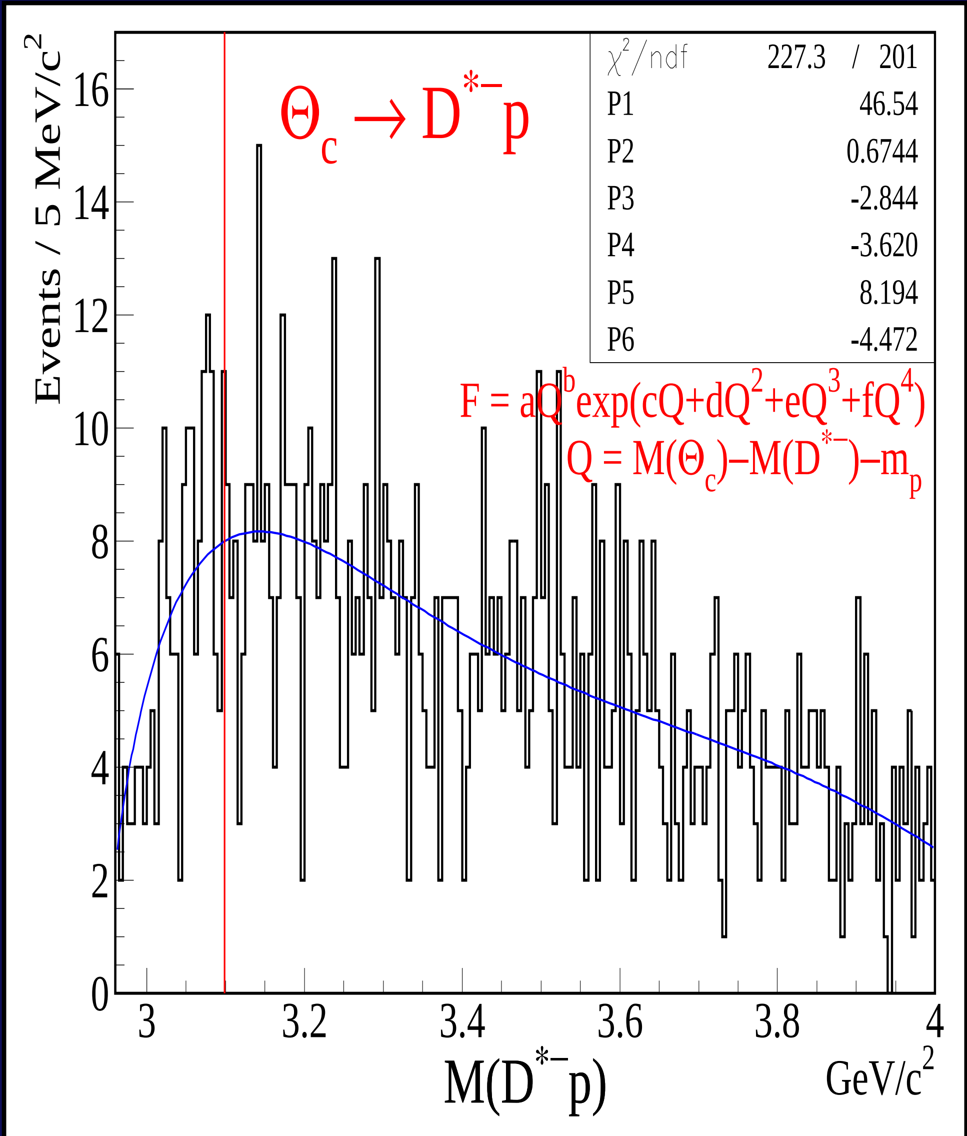
Nothing to see here, move along

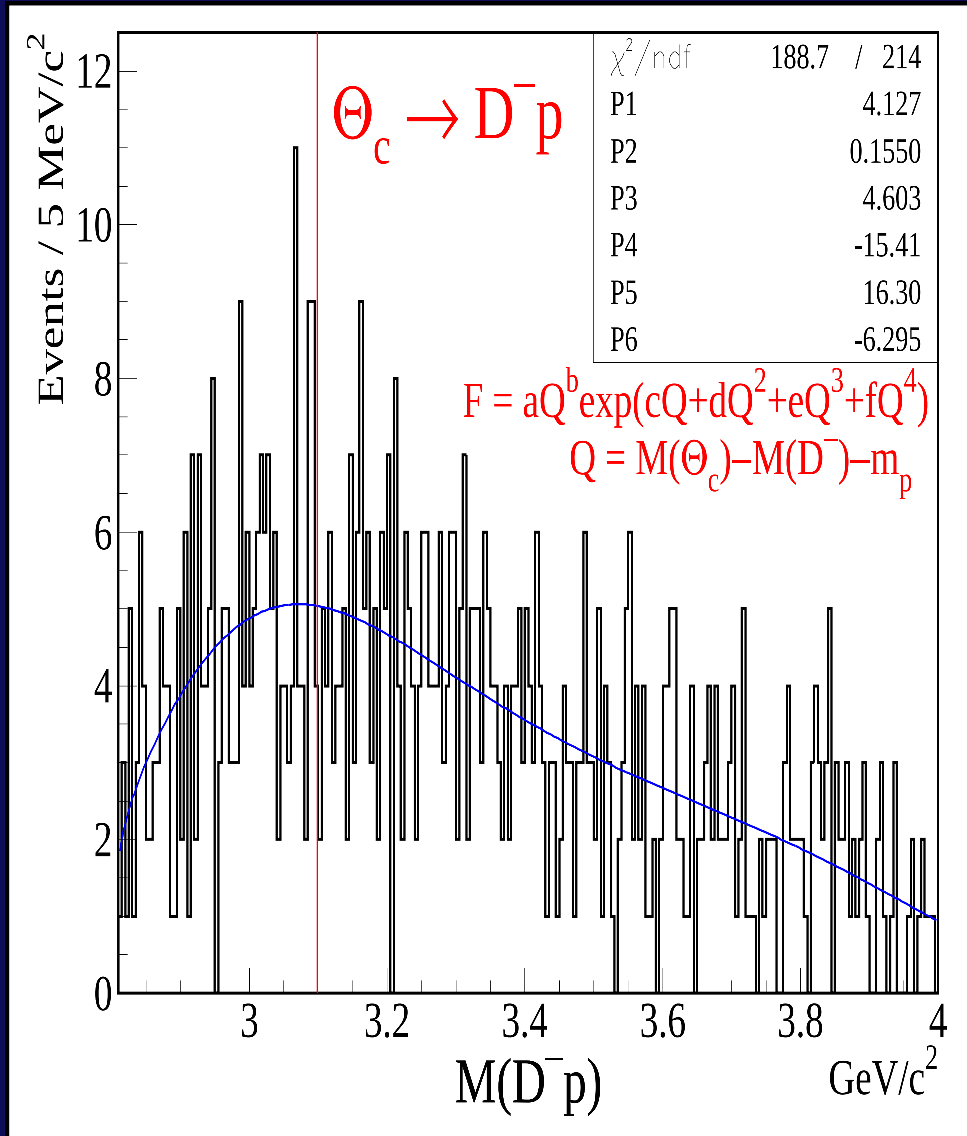




FOCUS Θ_c^0 mass plots

Background shape: $q^a \exp\left(bq+cq^2+dq^3+eq^4\right),\ q\equiv M(\Theta_c^0)-M(D^{(*)-})-m_p$



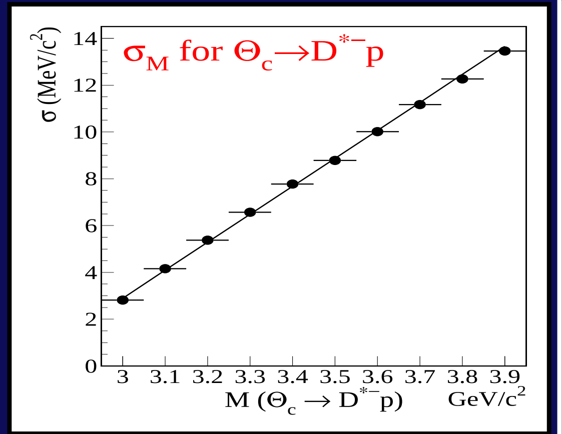


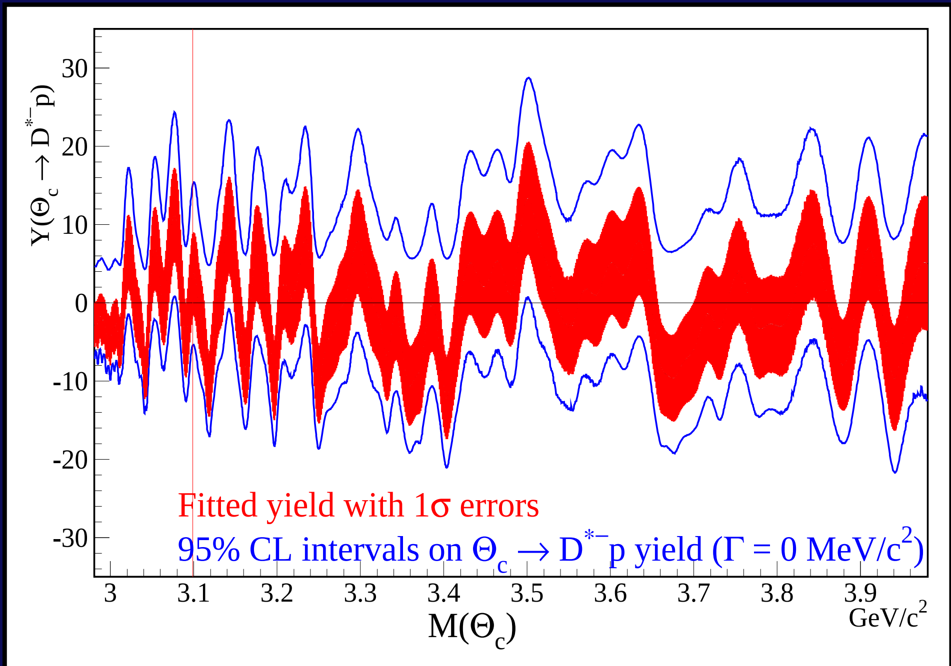
Obtaining limits on FOCUS yields

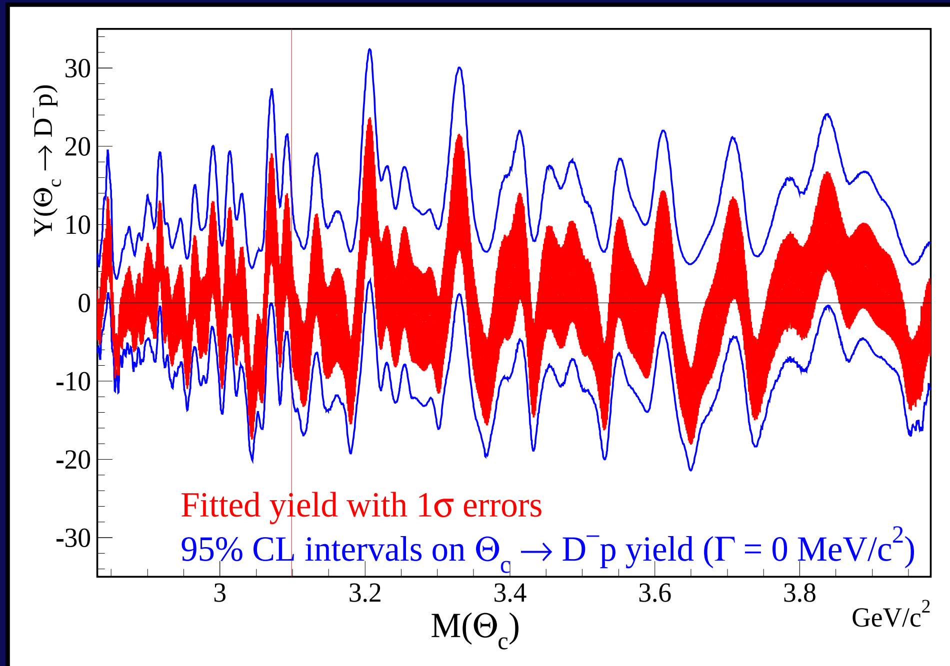
Perform ∼1000 fits in 1 MeV/c^2 steps over mass range

Red band shows 1-σ errors
Blue curve shows 95% CL upper & lower limits; UL from integrating 95% of likelihood above $Y = 0$, LL from $\Delta 2 \log \mathcal{L} = 3.84$

Gaussian σ in fit obtained from resolution (via Monte Carlo)





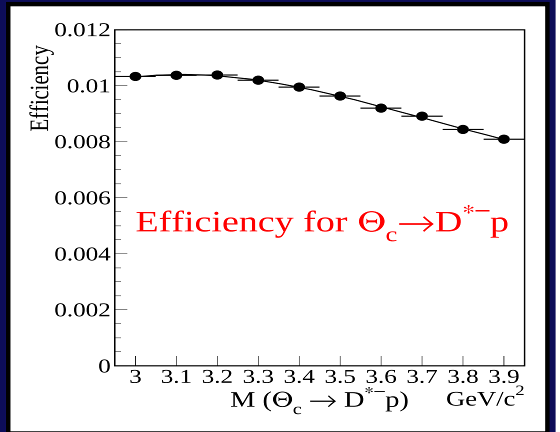


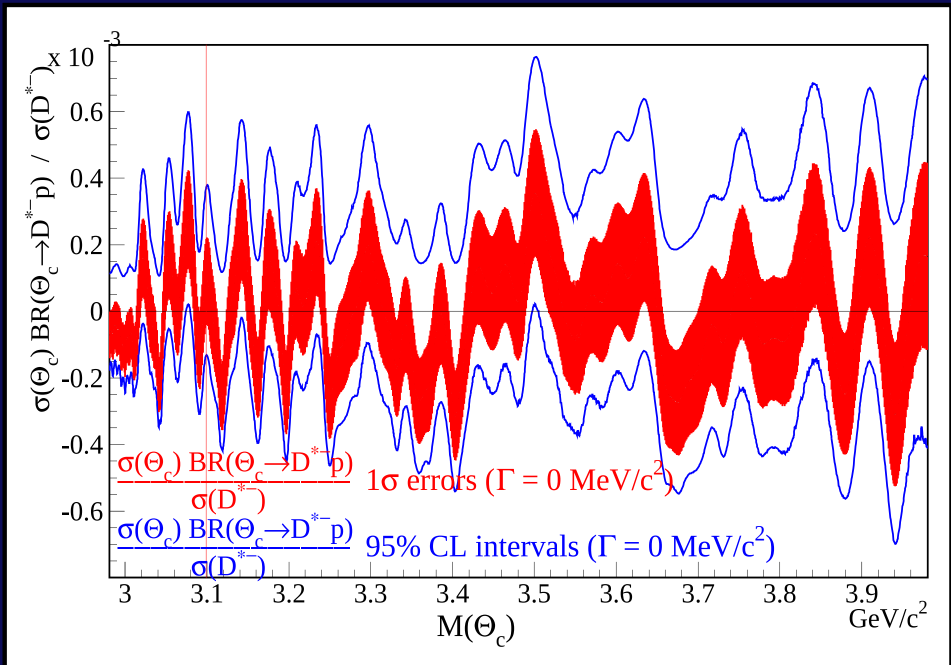
Convert yield limit to cross section

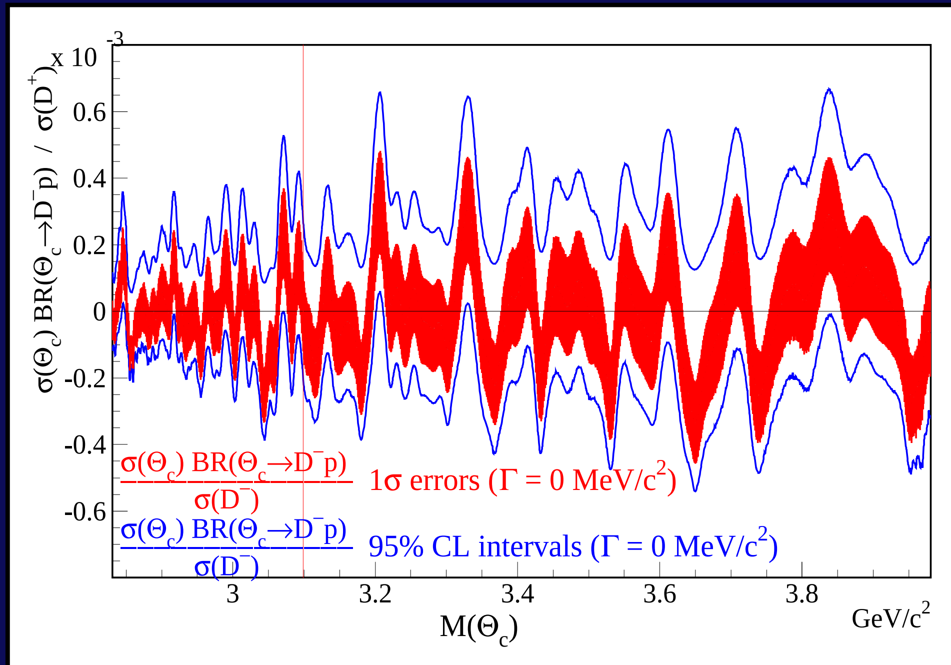
Correct for efficiency and acceptance

Assume Θ_c^0 produced like $3.1\,\mathrm{GeV}/c^2$ Ξ_c^0. Ratio production to single charm.

$\Theta_c \to D^{*-}p$ efficiency from Monte Carlo; D^-p is similar







Summary of charm pentaquark results

Experiment	$Y(\Theta_c)$	$Y(D^{*-})$	$Y(D^-)$	$\frac{\sigma(\Theta_c \to D^{*-})}{\sigma(D^{*-})}$	$\frac{\sigma(\Theta_c \to D^-)}{\sigma(D^-)}$
H1 ep	50.6 ± 11.2	$\sim$3500		~ 1 %	
FOCUS γN	< 15	105000	137000	< 0.04 %	< 0.04 %
ALEPH e^+e^-		$\sim$4300	$\sim$5400	< 0.31 %	< 1.80 %
CDF $p\overline{p}$	< 27	537000			
ZEUS ep		$\sim$60000		< 0.23 %	

- FOCUS result is in serious disagreement with H1 observation for $\Theta_c \to D^{(*)-}p$
- ZEUS has identical production and similar experiment; claims H1 signal excluded at $9\,\sigma$

Conclusions

January, 2003 — March, 2004 saw 12 pentaquark observation papers submitted; PRL, PLB, PAN published 4, 5, 2 (1 pending for PAN)

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Second half of 2004 saw the emergence of many negative results from experiments with better statistics and mass resolution

While pentaquarks may exist, we still lack strong evidence

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January, 2003 — March, 2004 saw 12 pentaquark observation papers submitted; PRL, PLB, PAN published 4, 5, 2 (1 pending for PAN)

Inspired many believers such as Wilczek: *The discoveries of manifestly exotic particles, which have been sought for decades, clearly open a new chapter in strong interaction physics.*

Interesting theories involving chiral solitons, diquarks, triquarks, flux tubes, strings, lattice QCD, QCD sum rules were all brought to bear

Second half of 2004 saw the emergence of many negative results from experiments with better statistics and mass resolution

While pentaquarks may exist, we still lack strong evidence

We should keep in mind a quote from Jorge Santayana (borrowed from a pentaquark talk by Ted Barnes): *Scepticism is the chastity of the intellect, and it is shameful to surrender it too soon or to the first comer*