Strangeness production with FOPI @ SIS 18 (GSI/Darmstadt)

Introduction / Motivation / History of strangeness in heavy-ion collisions @ SIS 18 (kaons in dense matter)

Detector

New results – correlations (with respect to the bulk, with other reaction products)

Perspective

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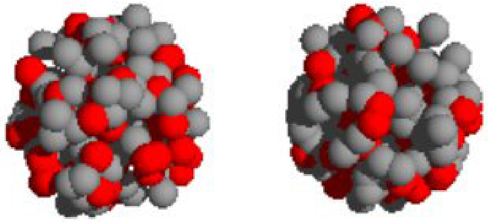
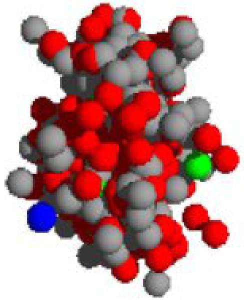
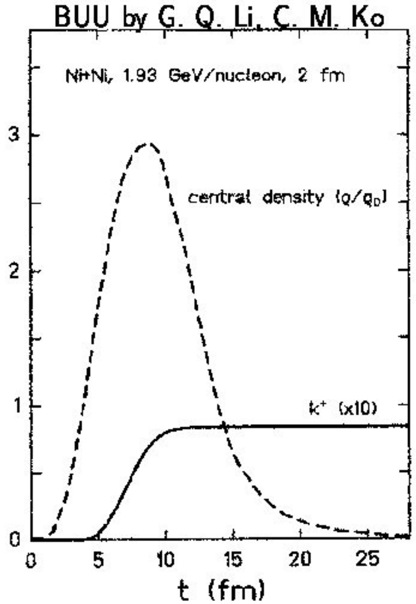
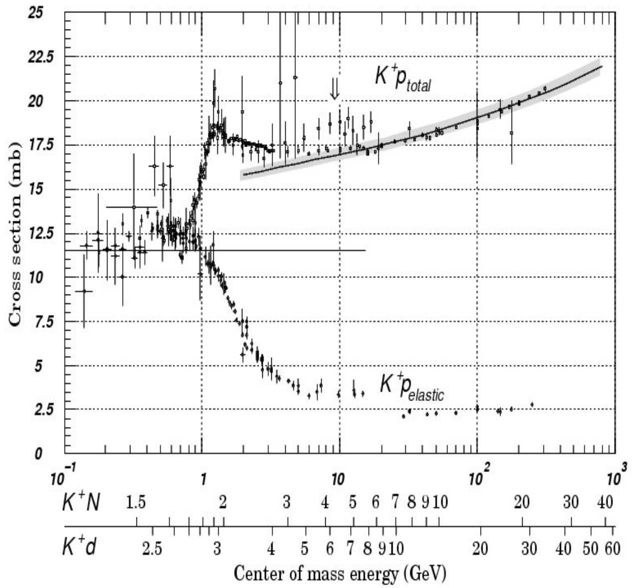
FOPI Collaboration

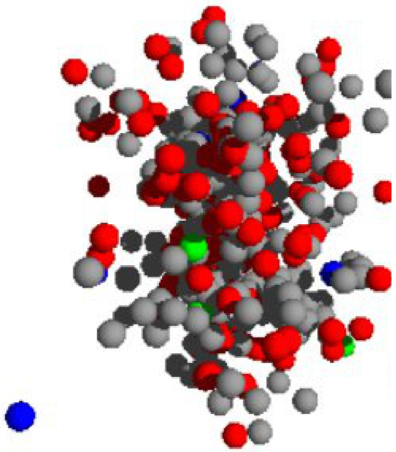
Heavy-ion collisions @ SIS 18 (up to 2 AGeV)
Modifications of kaons

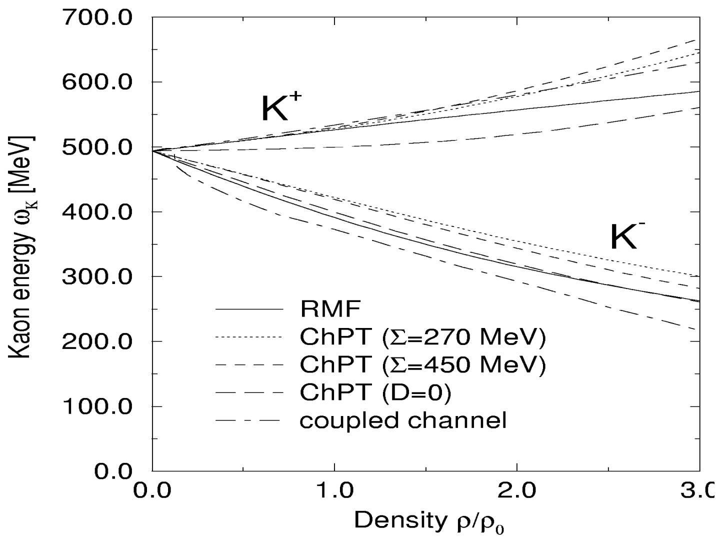












Strangeness produced in the early stage

High density of the medium ($3\rho_0$)

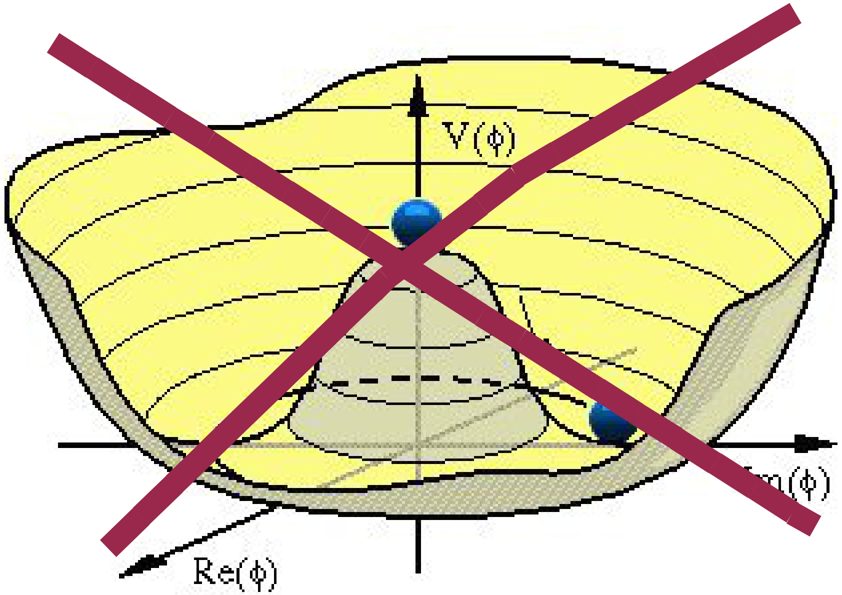
Messengers from the dense phase

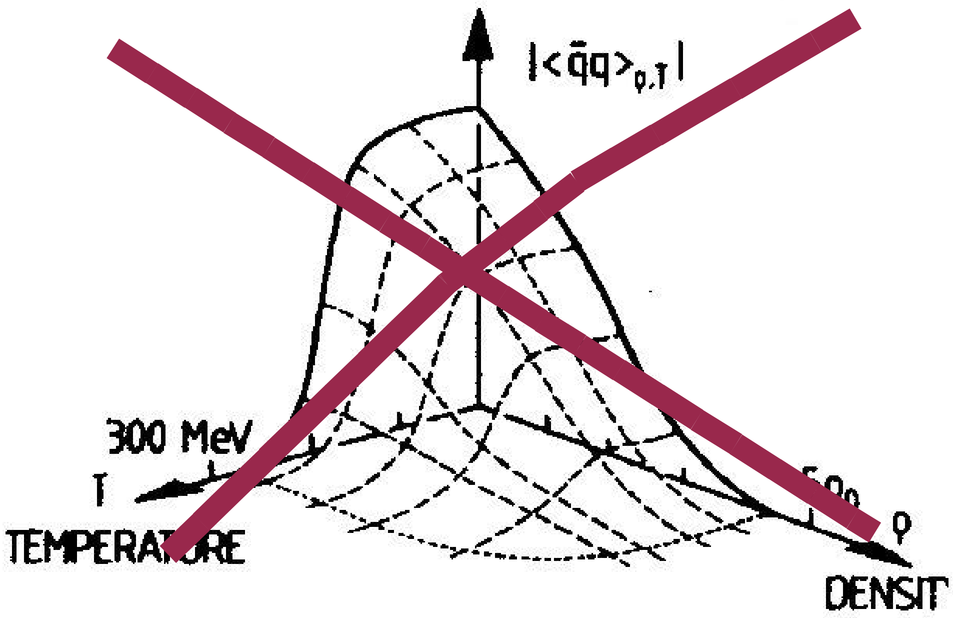
Modifications of mass/KN potential expected

Affects production and propagation

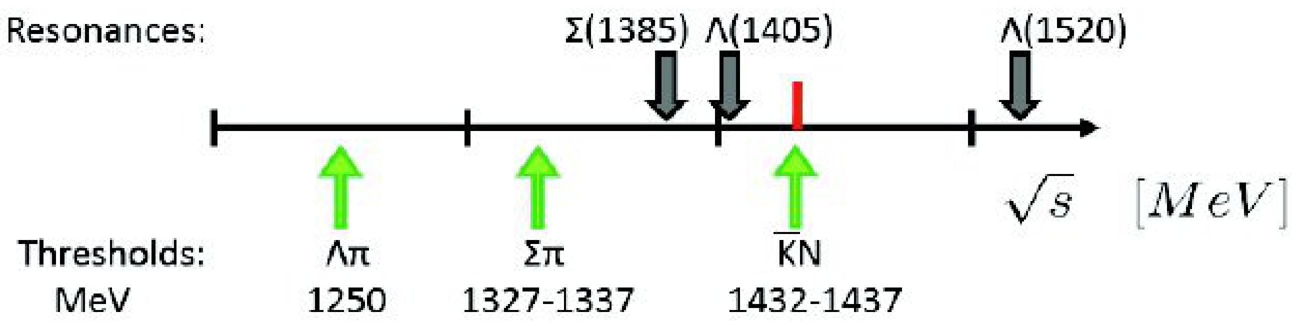
Puzzling esp. in the case of K-

Restoration of spontaneously broken chiral symmetry ?





Not necessarily



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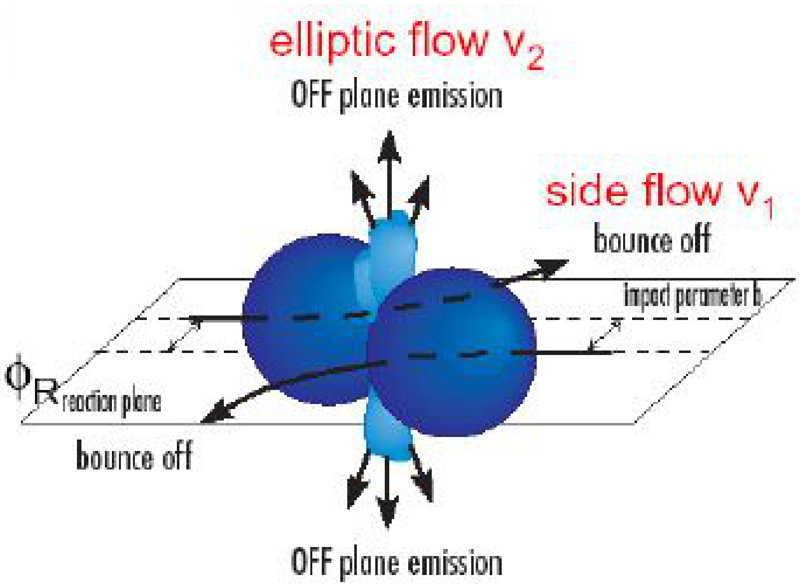
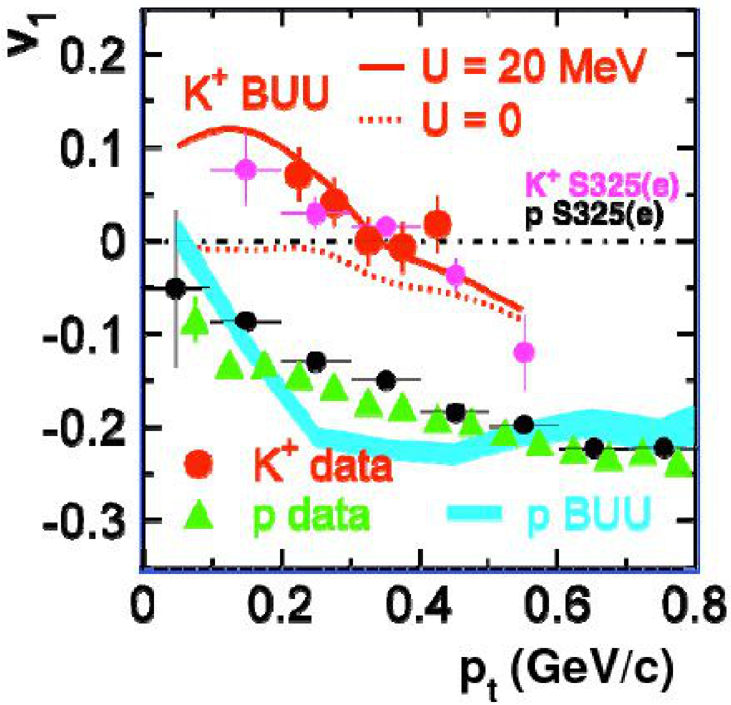
Evidence for in-medium modifications

E.g. flow





New data are consistent with earlier data in range $-1.2 < y^{(0)} < -0.65$, σ_{geo}=200mb

P.Crochet et al., PLB 486, 6 (2000)

Former conclusion:

Data favor the presence of repulsive potential $U(\rho=\rho_0)$ = 20 MeV

Model dependant (comparison to BUU transport)

... and much, much, much more

(FOPI, KaoS)

Strangeness program of FOPI

Data from elementary reactions

K^0 , Λ production and phase space distributions in

π^- + C, Al, Cu, Sn, Pb @ 1.15 GeV/c, (S273, 2004)

K^0 , K^+, K^-, ϕ, Λ production in

π^- + LH_2, C, Pb @ 1.7 GeV/c, (S339, 2011)

Kaonic bound state ppK^- in

p + p @ 3 GeV, 80M (S349, 2009)

Systematics of strangeness data from heavy-ion reactions

K^0 , K^+, K^-, ϕ, K^*, Λ, $\Sigma*(1385)$ production and flow

System	beam energy	events	(proposal, year)
Ni + Ni	1.93 AGeV,	100M	(S261, 2003)
Al + Al	1.91 AGeV,	200M	(S297, 2005)
Ni + Ni	1.91 AGeV,	80M	(S325, 2008)
Ni + Pb	1.91 AGeV,	100M	(S338, 2009)
Ru+ Ru	1.7 AGeV,	210M	(S338, 2009)

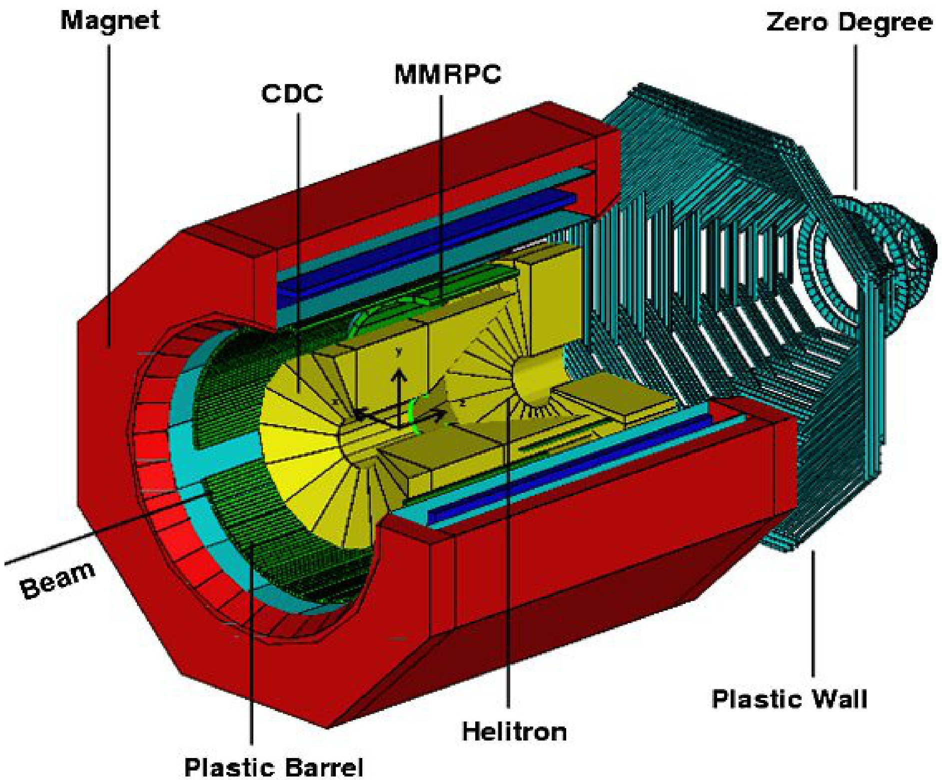
Search for

Kaonic bound states

Hypernuclei

in heavy-ion reactions

FOPI is a very good detector



General purpose

Complete azimuthal symmetry, large acceptance

Helitron+Wall : 1.2^0 - 30^0

CDC+Barrel : $\Theta_{lab} > 35^0$

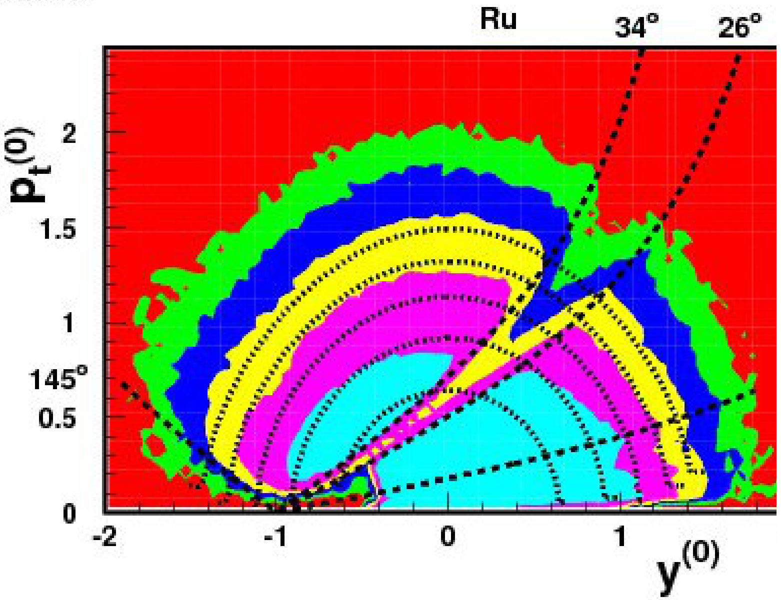
B =0.6 T

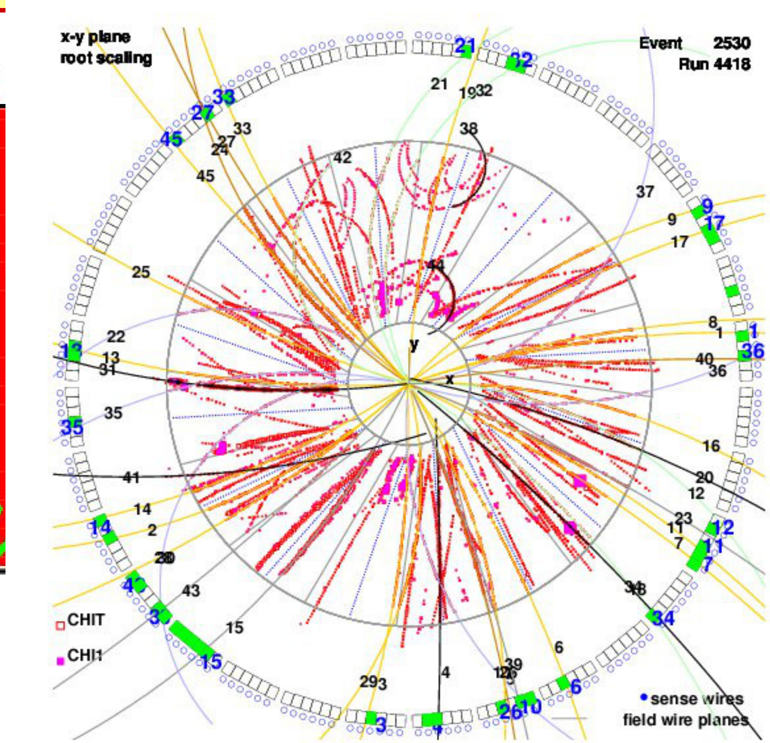
Fixed target exepriment
(variable target position)

Heavy-ions and elementary

Direct detection of charged particles
fragments, pions (95% efficiency)

IPNE Bucharest, Romania
ITEP Moscow, Russia
CRIP/KFKI Budapest, Hungary
LPC Clermont-Ferrand, France
Korea University, Seoul, Korea
GSI Darmstadt, Germany
IReS Strasbourg, France
FZ Rossendorf, Germany
Univ. of Heidelberg, Germany
Univ. of Warsaw, Poland
RBI Zagreb, Croatia





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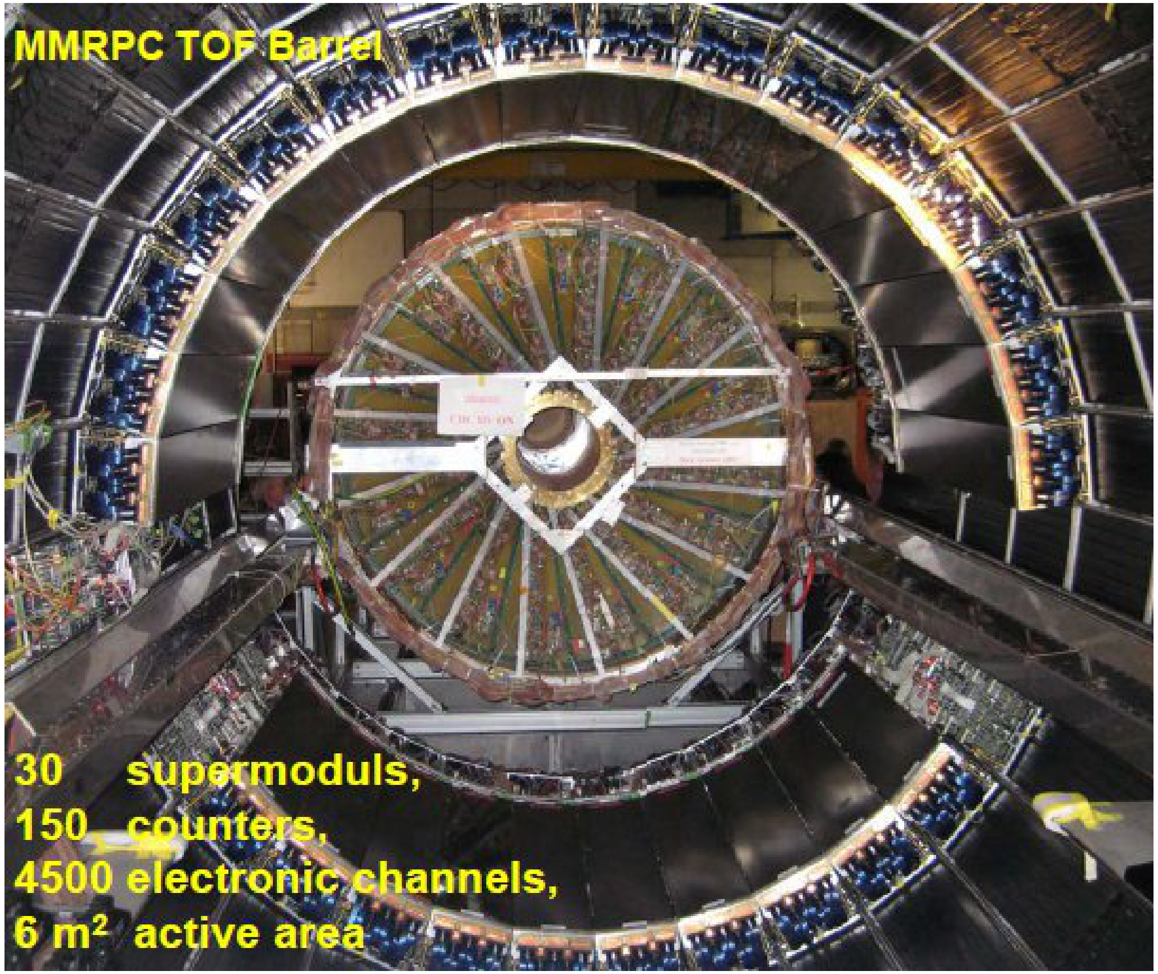
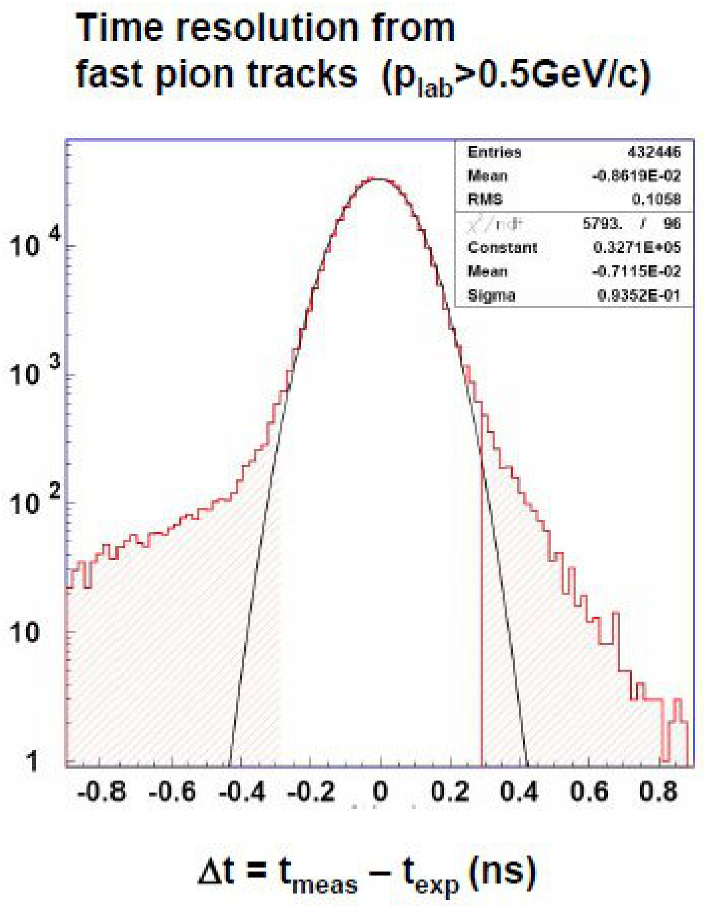
Resistive Plate Chambers - TOF Barrel

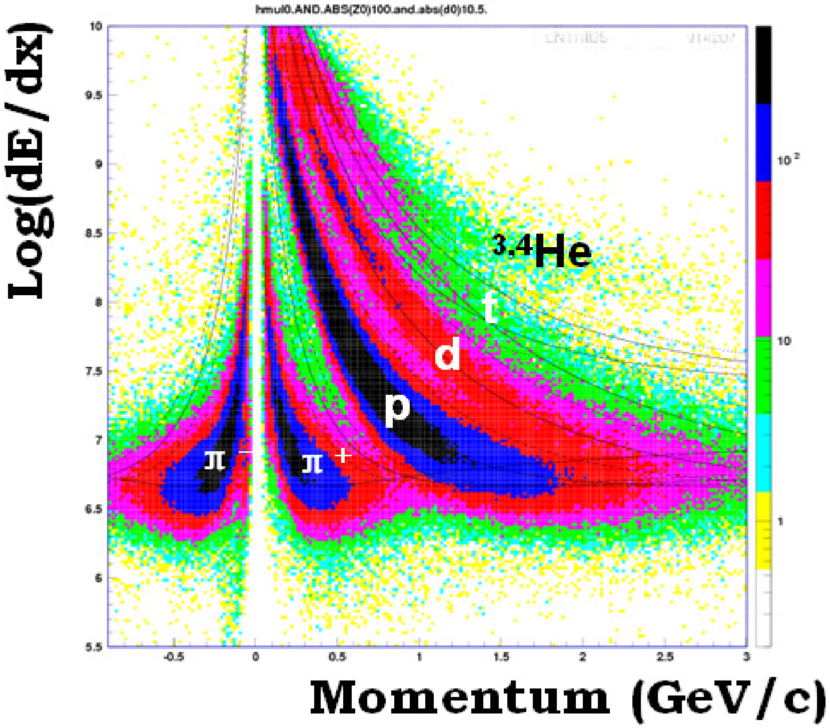


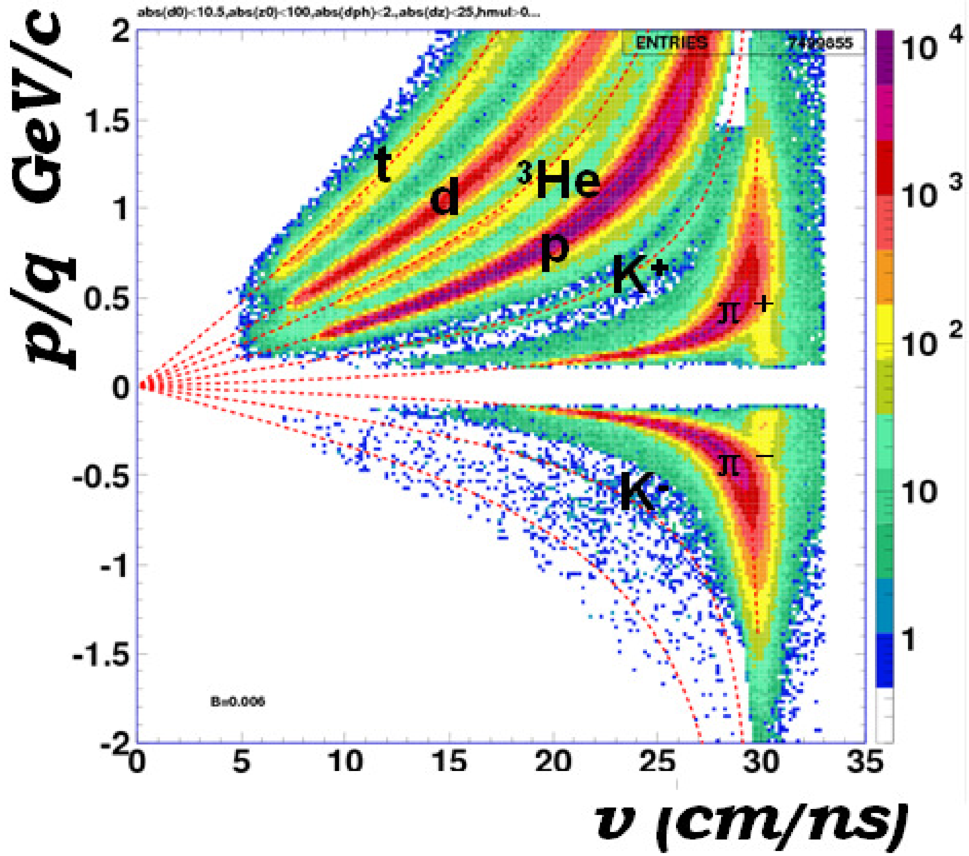


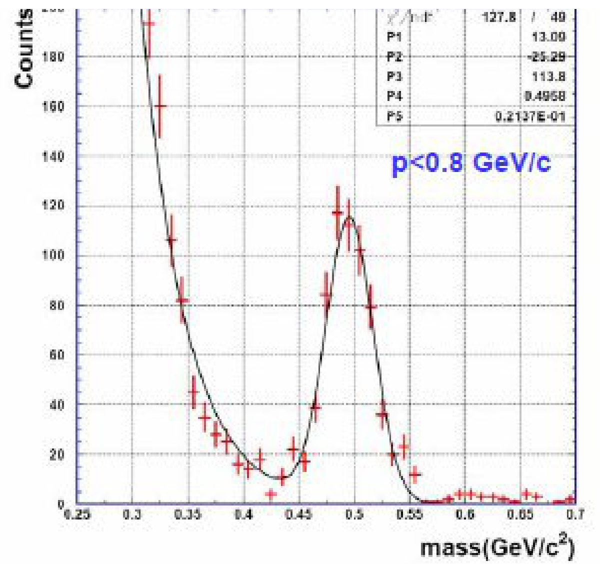
Performance:
σ_{system} ~ 90 ps
σ_{RPC} ~ 65 ps

First RPC-TOF system in the world
Prototyping the TOF system of CBM @ FAIR

Identification of charged particles





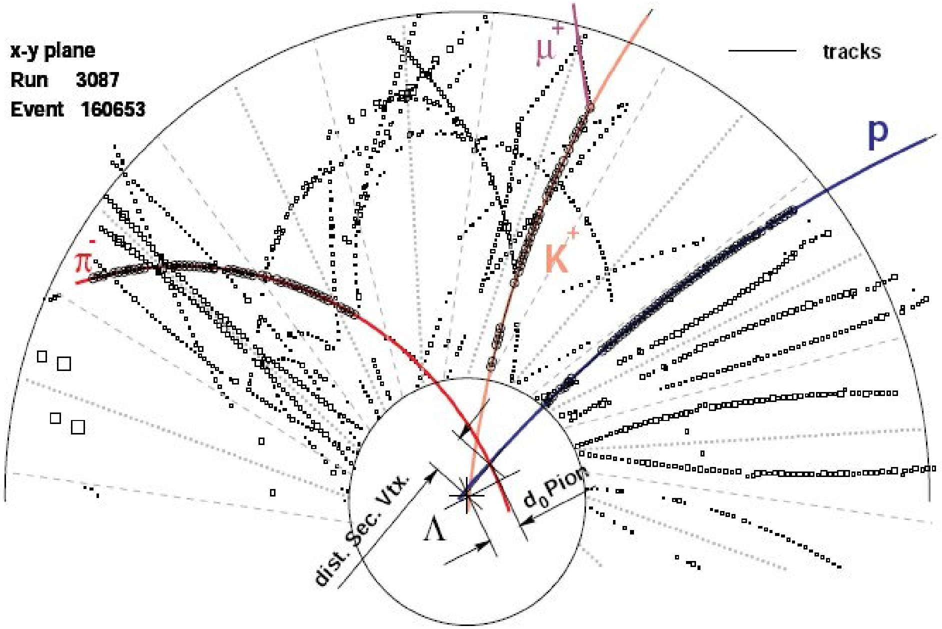


... up to 1 GeV/c – CDC-TOF essential

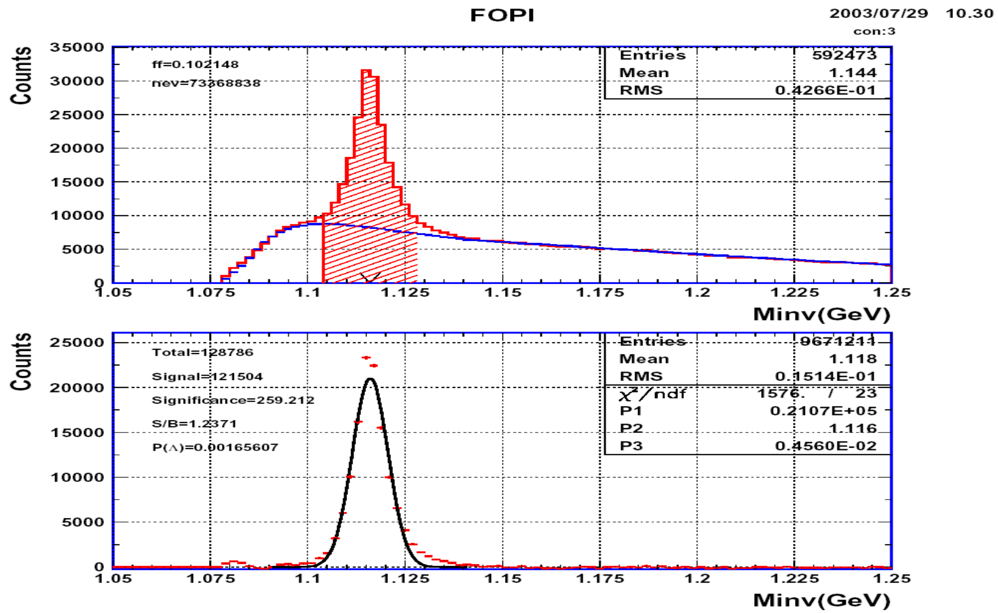
in the CDC/TOF acceptance
(mid-rapidity not fully covered)

Extended thanks to RPC

Identification of particles by decay



$\Lambda \;\; \rightarrow \pi^- \, p$ (64%) ,$c\tau$=7.9cm



Background reconstructed by event mixing

Topological cuts decisive for the amount of background (S/B ~ 10 no problem)

Mass resolution (in the case of weak decay) σ>4 MeV
(depending on momenta of daugthers, intrinsic width not extracted)

Integrated flow of K+ and K- in peripheral coll.

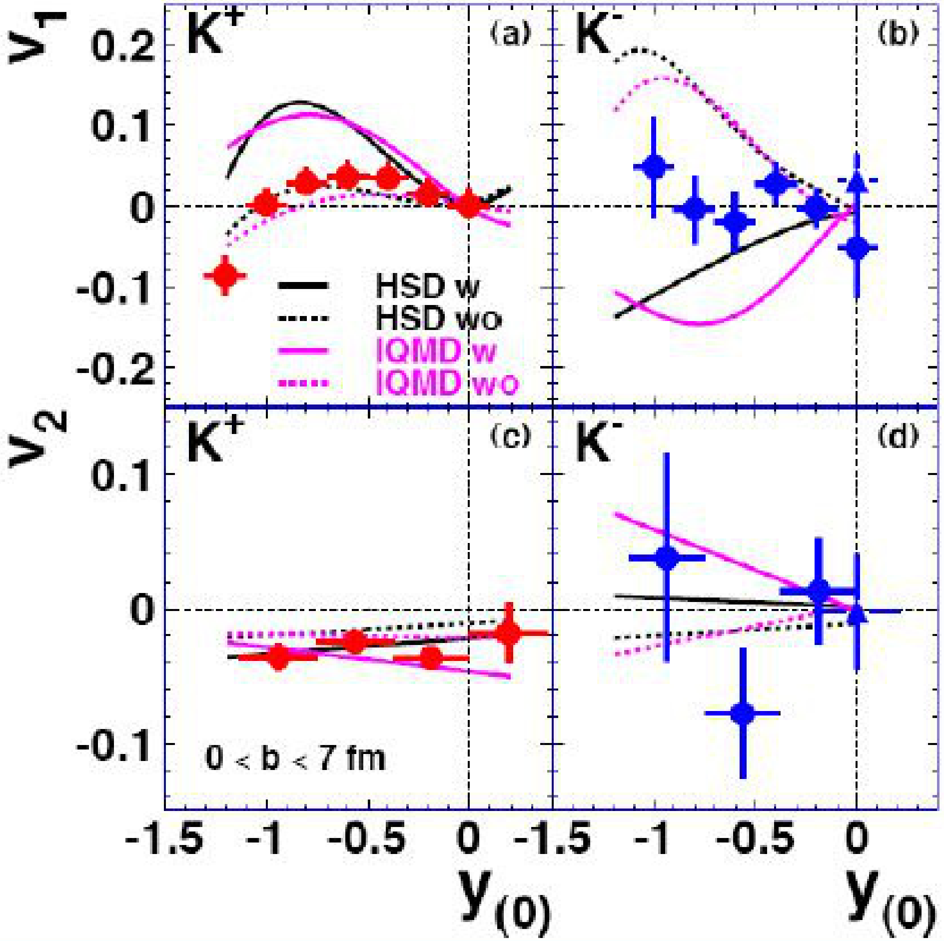
Ni+Ni at 1.91 AGeV
(S325 + S325e data)
σ = 1.5 b
b_{geo}= 7 fm

Models with FOPI acceptance filter

Potentials with linear density dependence.

At $\rho=\rho_0$:

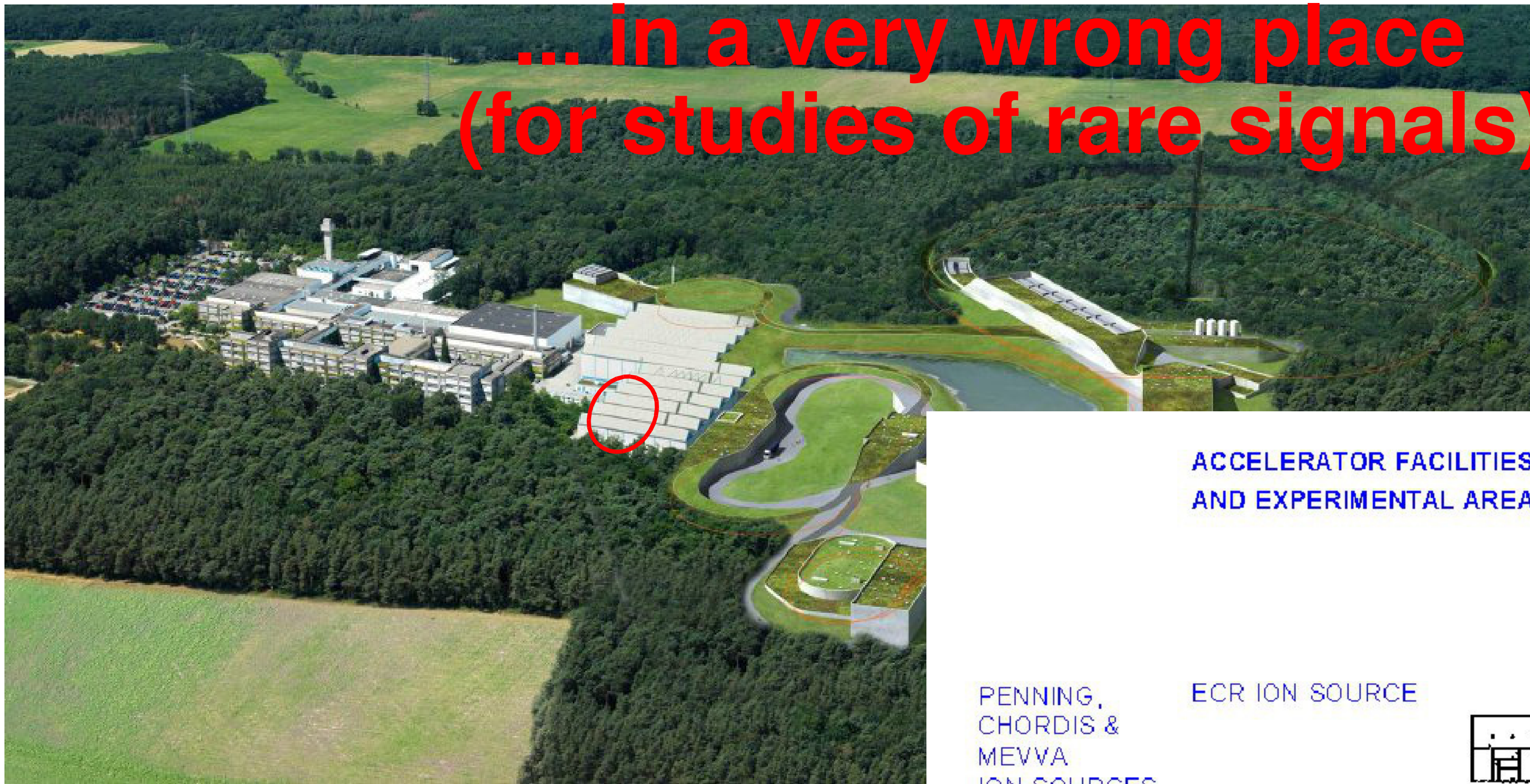
$U_{HSD}(K^+)$	20 MeV
$U_{IQMD}(K^+)$	40 MeV
$U_{HSD}(K^-)$	50 MeV
$U_{IQMD}(K^-)$	90 MeV

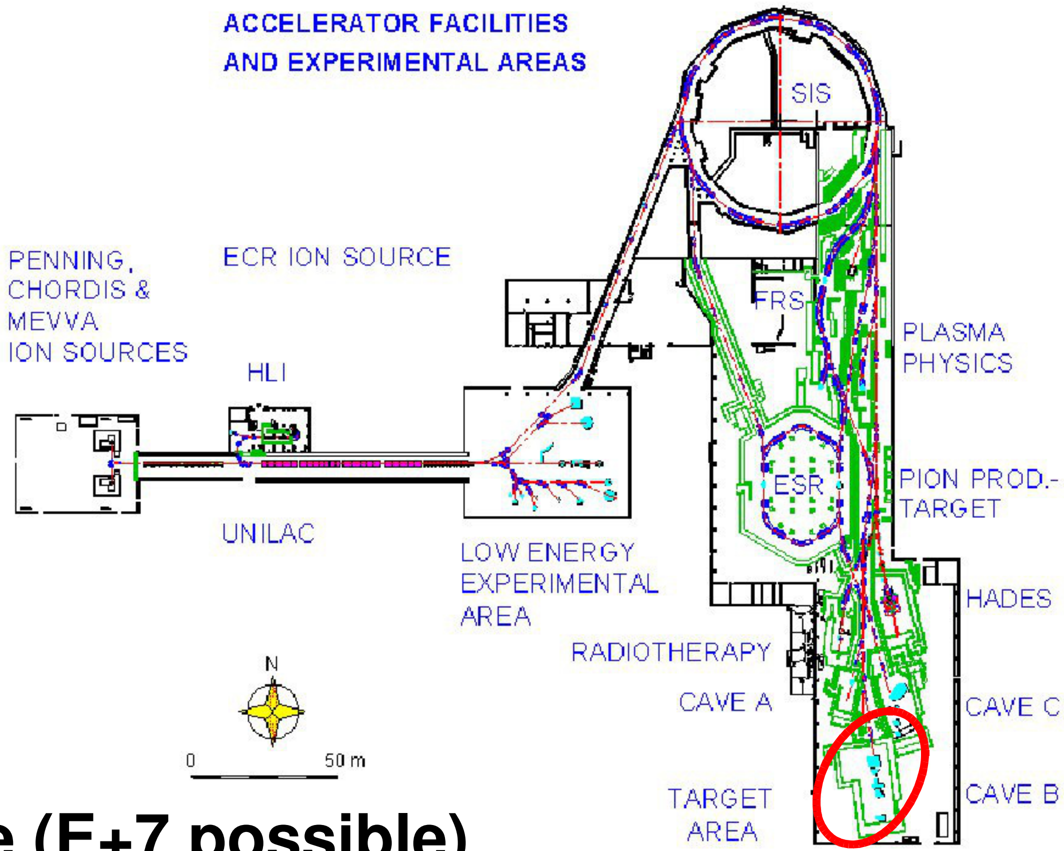


K^+ sideflow much smaller than expectation from model calculations.
K^- sideflow compatible with zero, in variance with model expectiations.
K^+ - elliptic flow negativ ⟶ out of plane emission.
K^- - elliptic flow consistent with zero.

The problem came back, theorist stepped back

FOPI is avery good detector...
... in a very wrong place
(for studies of rare signals)





Beams C, ... , Au, p, π

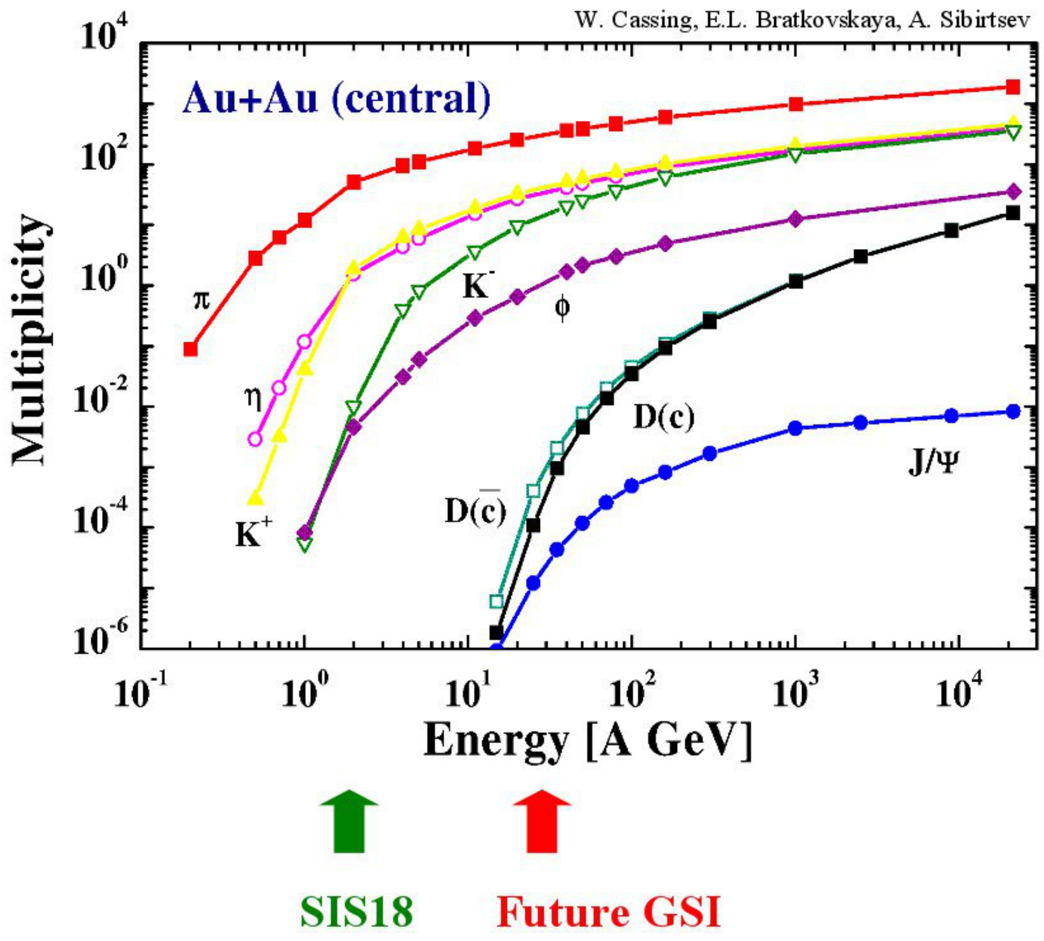
Energies 100 AMeV – 3,5 AGeV

Intensities up to E+11/s
(space-charge limit for N)

Radiation protection is an issue (E+7 possible)

What is more rare at SIS than strangeness ?

Nothing - wrong answer



Multi-strangeness, correlations – good answer

Trivial correlations
reconstruction of $\phi(1020)$ -> K+K-

Ni+Ni @ 1.9 AGeV

E_{trh}(NN->NNϕ)~ 2.6 GeV

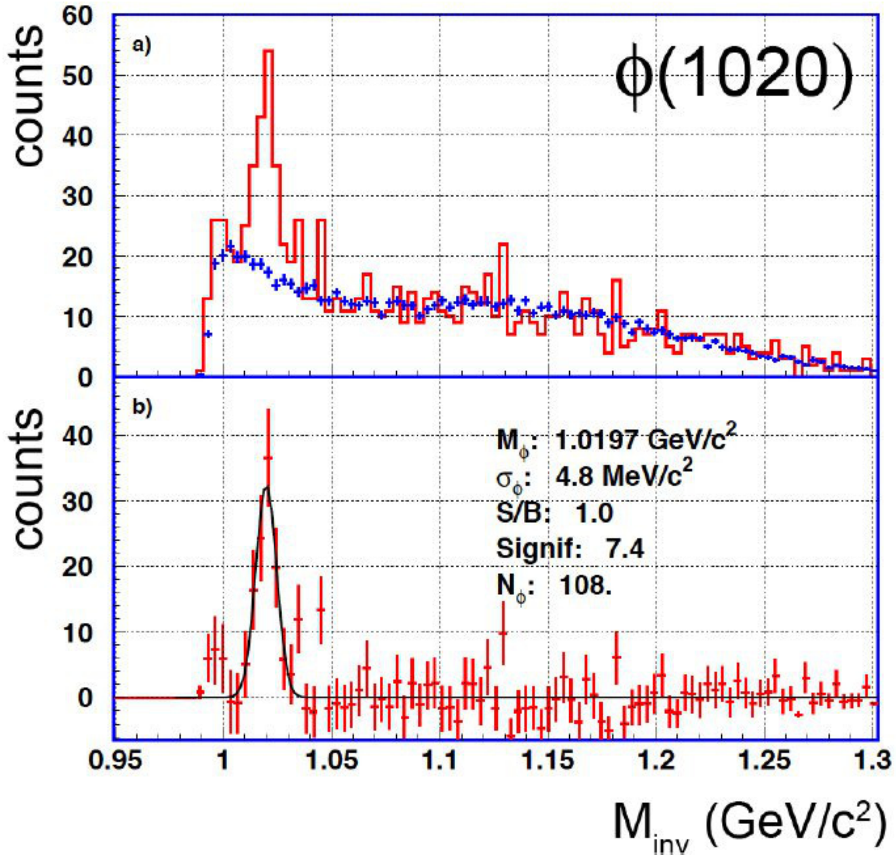
Background from mixed-events

S/B~1

100 ϕ in 4.*10^8 events

Efficiency from MC

First sub-thresh. measure of ϕ(1020)

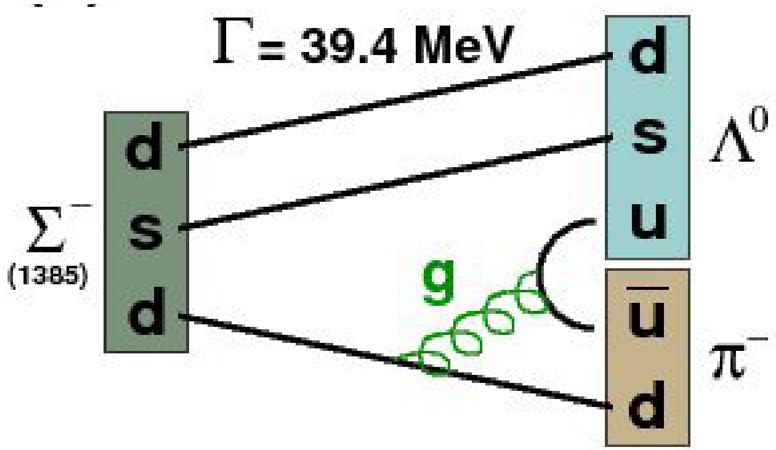


Taking into account $\phi \to K^+K^-$ branching ratio: $(48.9 \pm 0.5)\%\ldots$

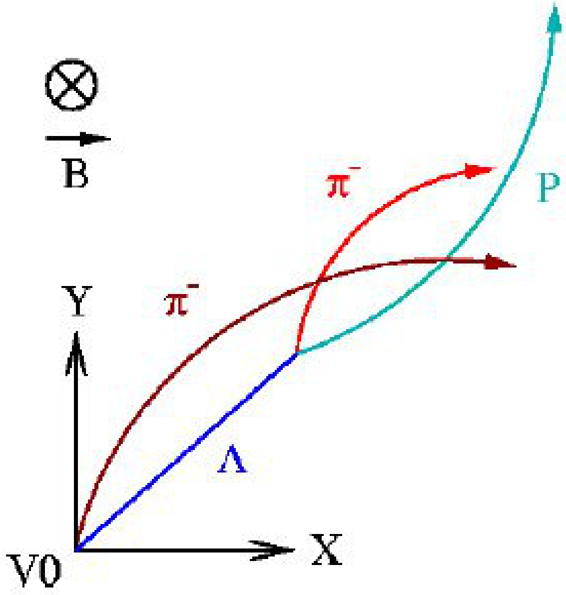
$$\left(\mathbf{14} \pm 4^{+2}_{-1}\right)\%$$

$\ldots$ K^- mesons comes from ϕ decays.

Λ^0 π trivial correlations - not trivial reconstruction



$\Sigma^{-,+}$(1385) -> Λ^0+$\pi^{-,+}$,with B.R. 87%



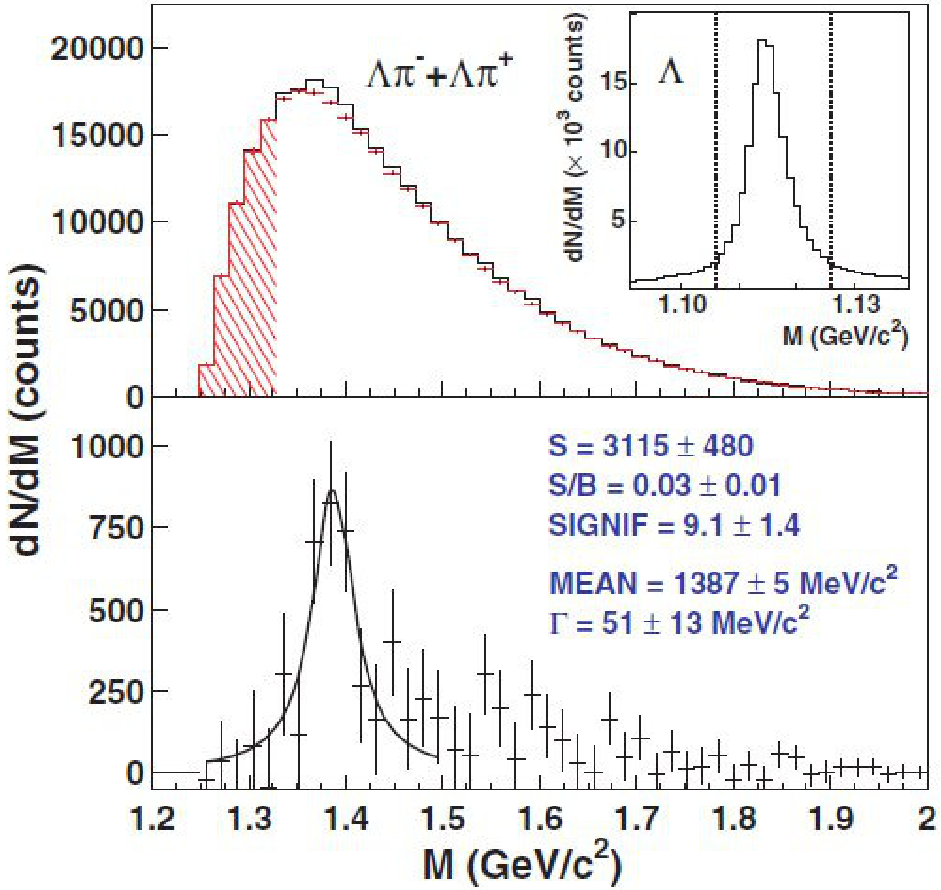
$\pi(\Lambda)$	$p(\Lambda)$	Λ	$\pi(\Sigma^{*\pm})$
0<m1<0.5	0.6<m2<1.5	1.106<m<1.126	0.05<m3<0.35
|d01|>1.9	|d02|>0.8	|d0|<0.5	|d0|<1
nh1>25	nh2>30	4<dv0v2<20	nh3>37
σxy1<0.1	σxy2<0.1	|Δφ|<4	σxy3<0.1
pt1>0.1	pt2>0.2	pt>0.3	pt3>0.1
σz1<20	σz2<20	|dvz12|<30	σz3<20
|z01|<50	|z02|<50	CTR	|z03|<25

More than 30 selection cuts

Distance to vertex decisive

Rejection of intersecting tracks & rotation of events to the R.P. -> description of the background

First sub-threshold measurement of Σ*



Al+Al @ 1.9 AGeV

E_{trh}~ 2.33 GeV

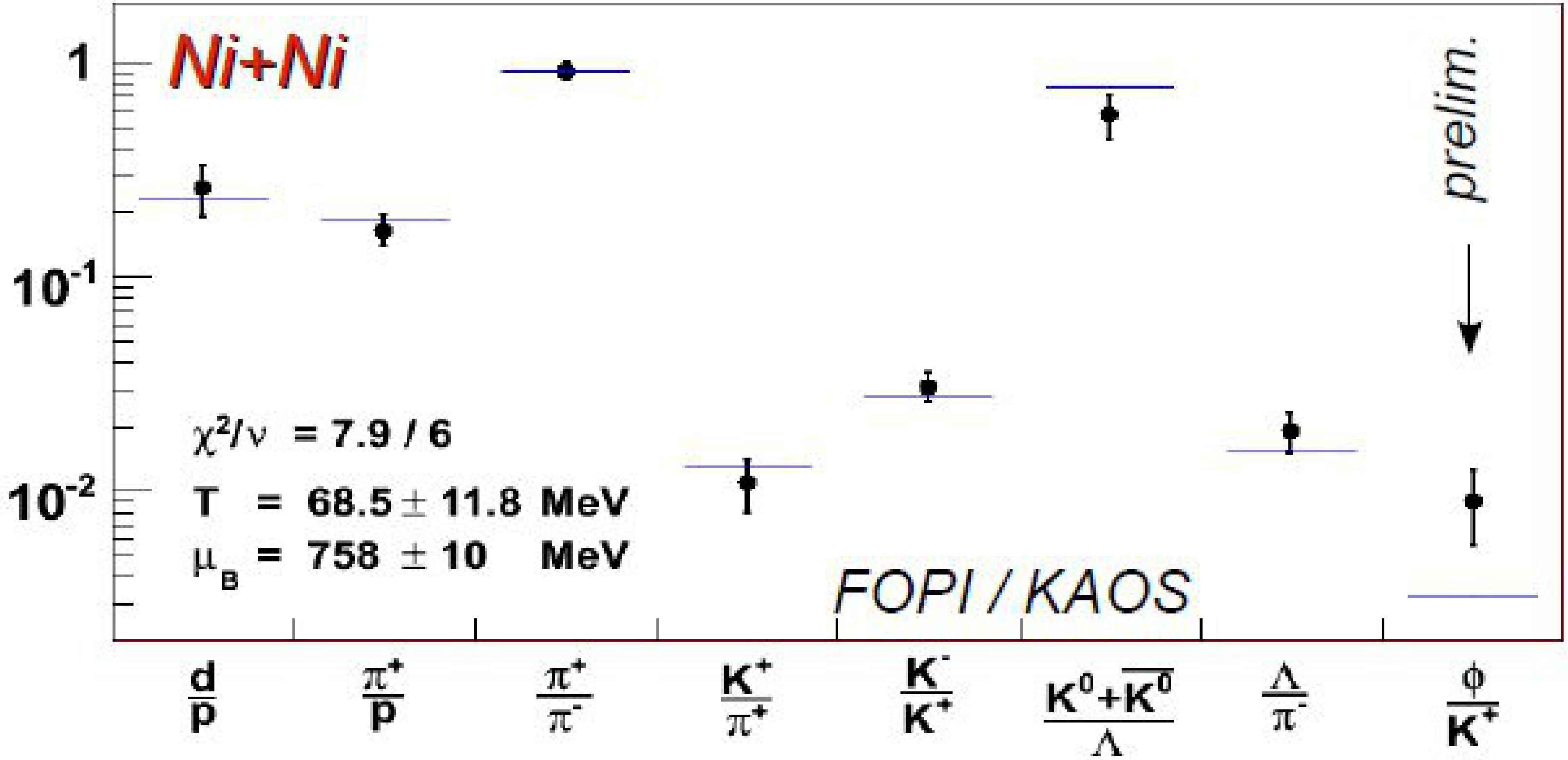
3000 Σ in 4*10^8 events

S/B~0.03

Width agrees with PDG

Similar analysis for $K^*(892)^0$ -> $K^+\pi^-$

Good enough to (positively?) verify models



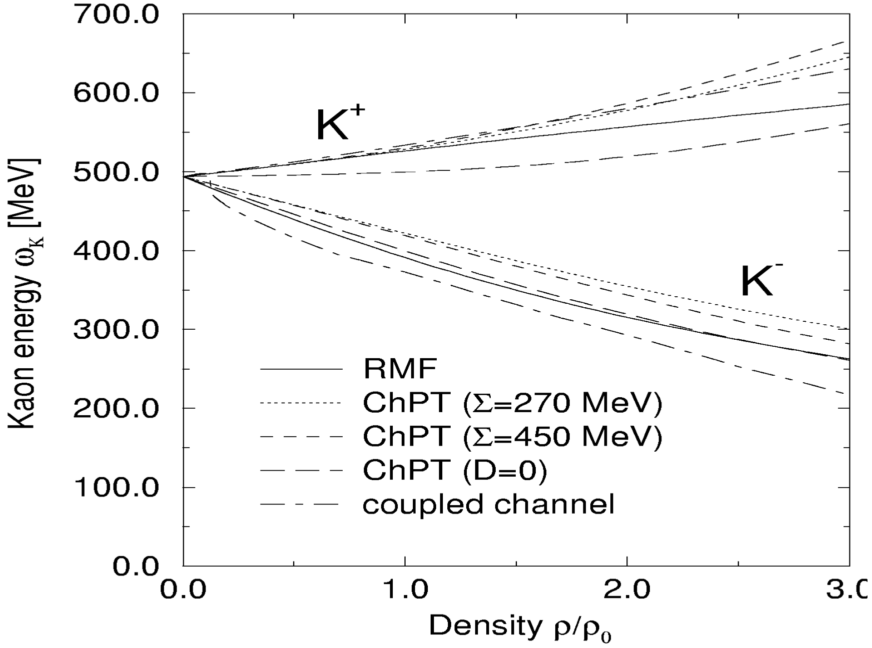
All independent ratios from one experiment

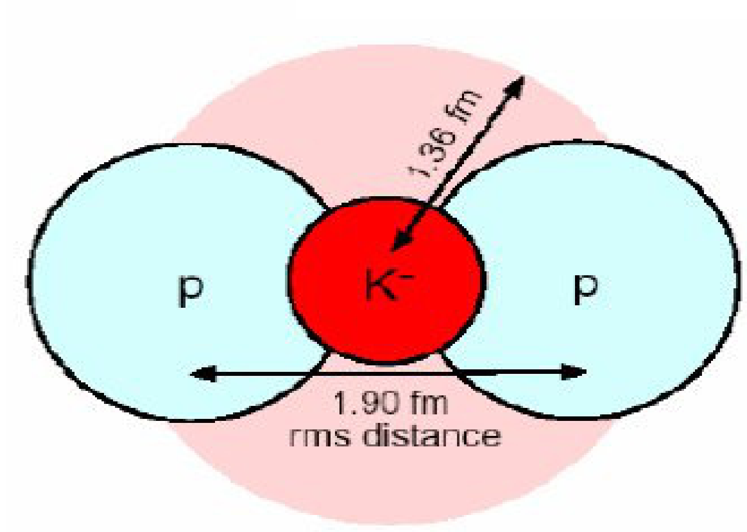
Some of them deep sub-threshold

Statistical model does quite well, except the ϕ

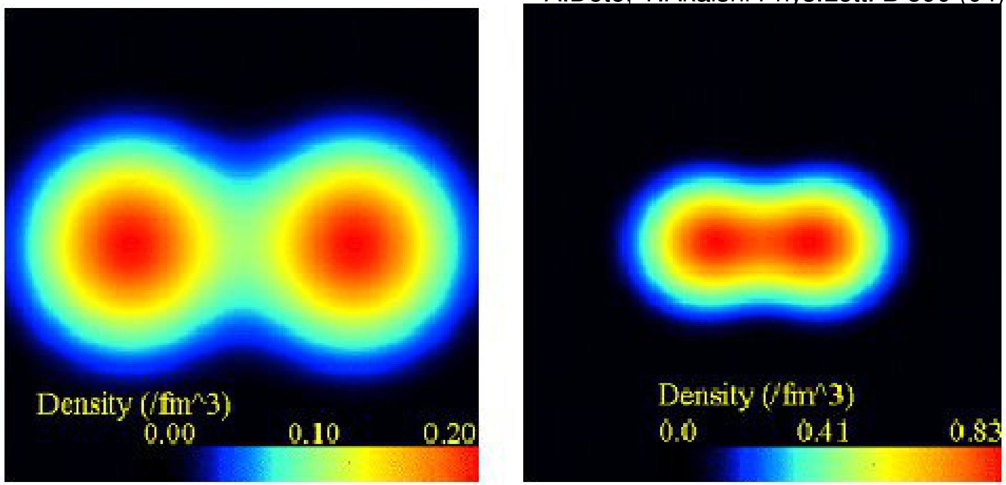
Do kaons modify the matter ?

Strong K-N attraction





A.Dote, Y.Akaishi Phys.Lett. B 590 (04)



(a) ^{8}Be (b) ^{8}BeK$^-$

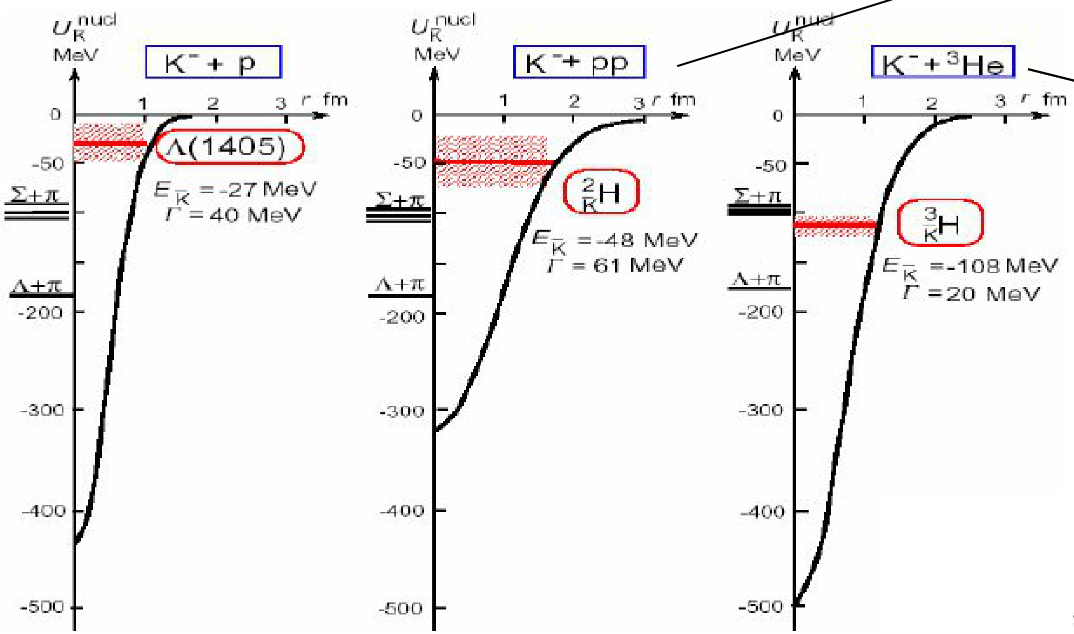
Compact and dense

Deeply bound kaonic clusters

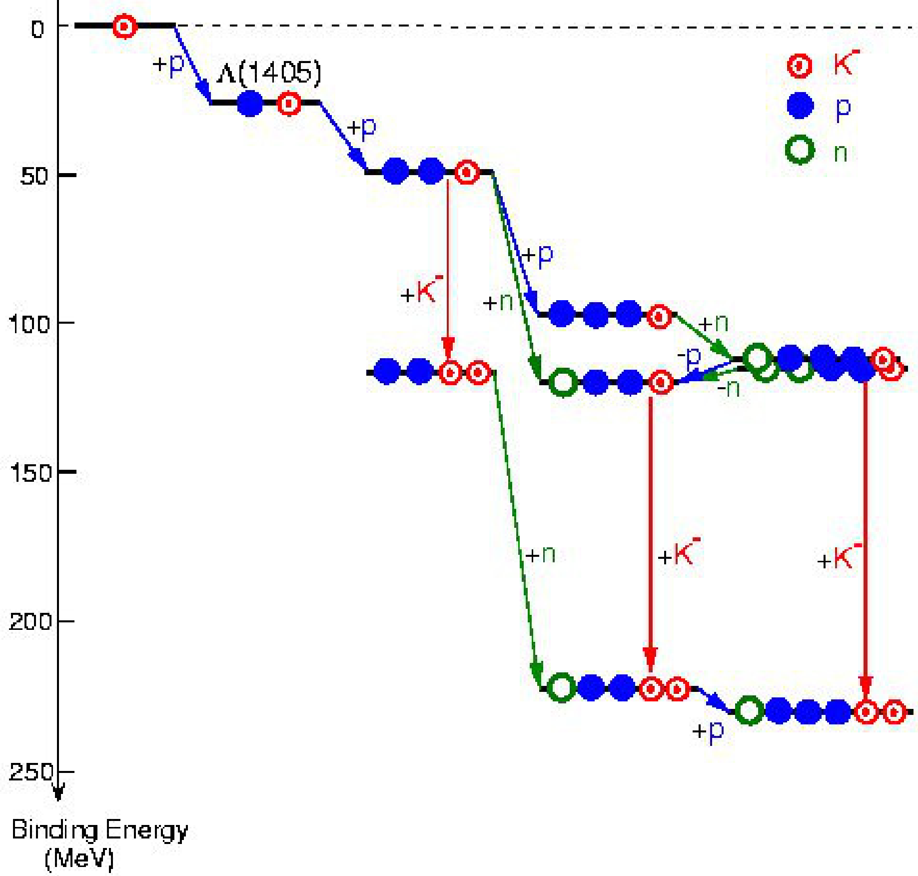
Correlations A+Λ

ppK- -> pΛ

nppK- -> dΛ



T.Yamazaki et al., Phys.Lett.B587, 167 (2004)



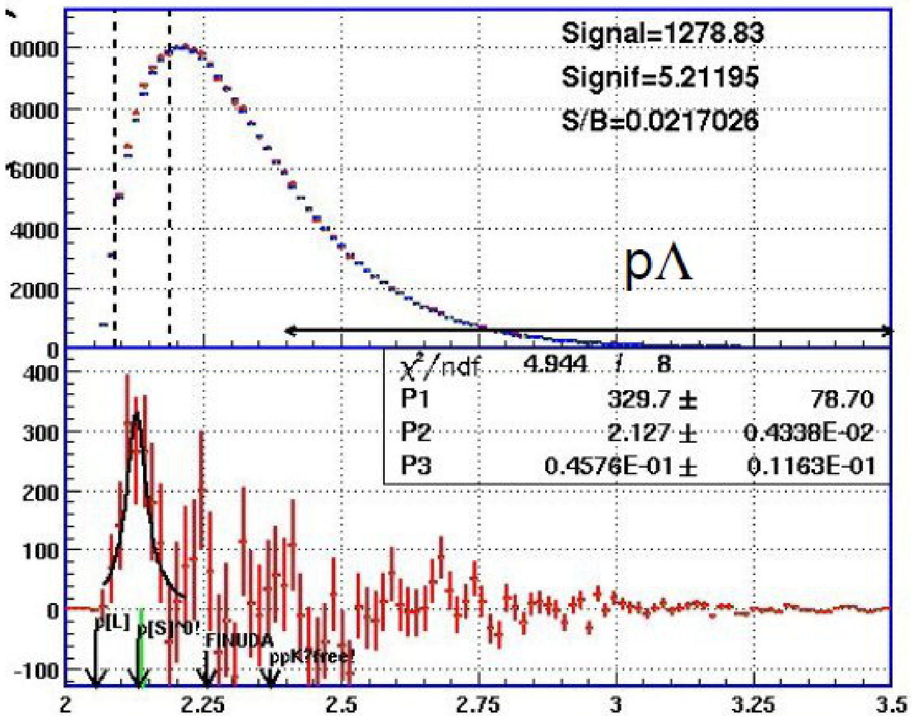
Search for the decays: Λ + A

pΛ outcome of FOPI

Excess found,
 but about 100 MeV too much bound

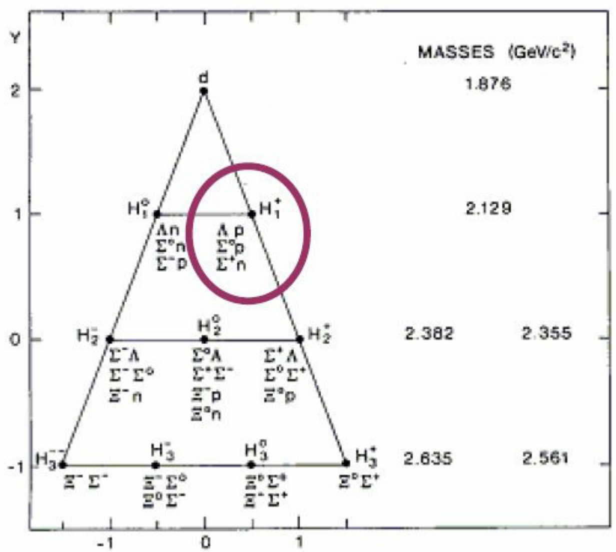
No evidence of a ppK- cluster

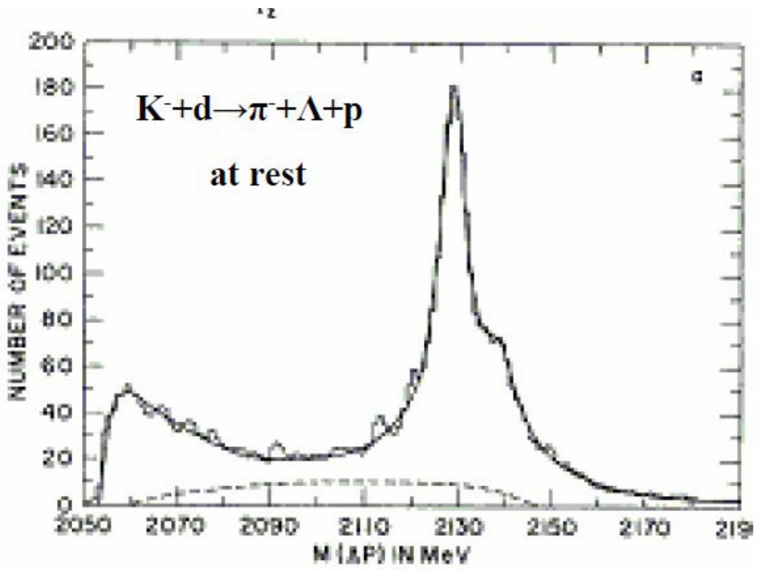
Could be a final-state interaction



Or a strange di-baryon

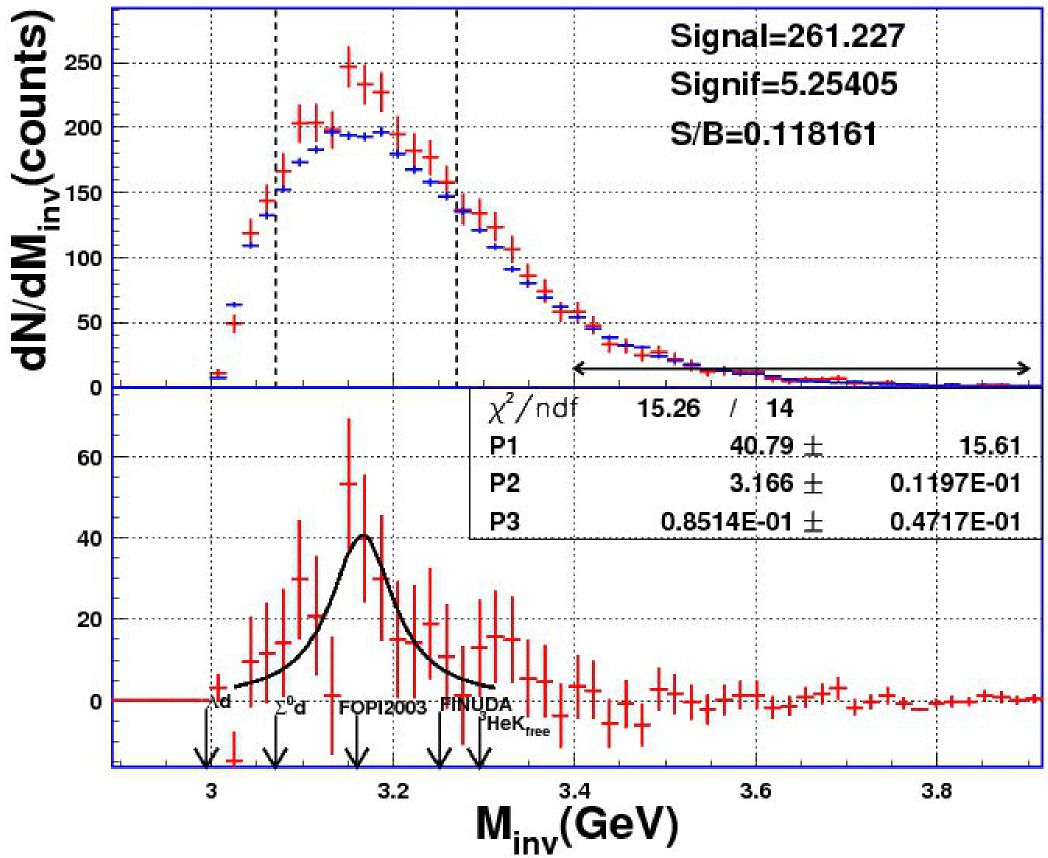
R.J. Oakes, PR 131 (1963) 2239





T.H. Tan, PRL 23 (1969) 395

nppK- -> dΛ outcome of FOPI



Excess visible

Not at the threshold

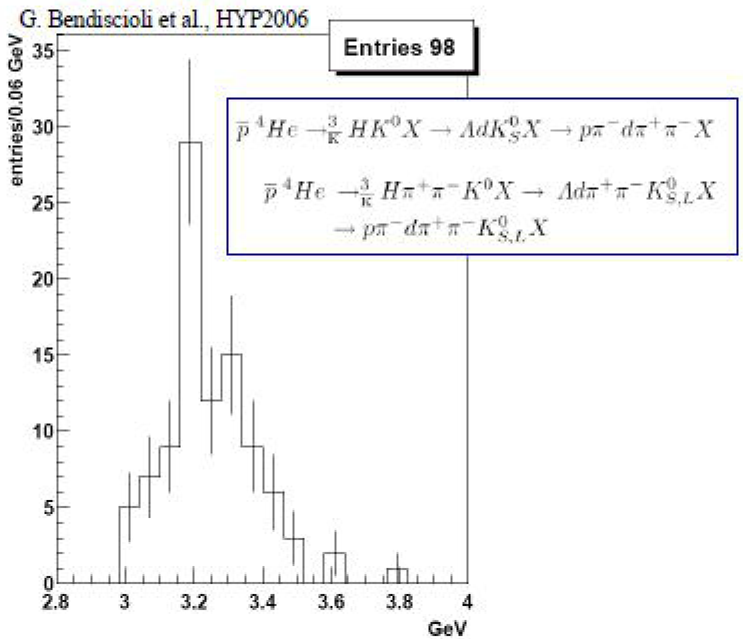
Not due to the cusp effect

Binding energy & width compatible to predictions

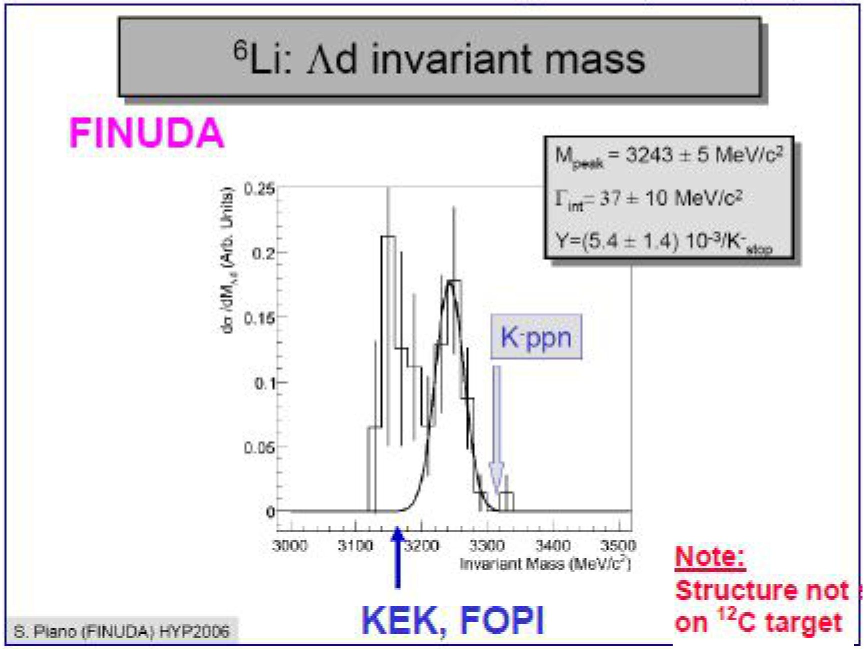
Significance large

... compared to other experiments

OBELIX



M. Agnello et al., PLB 654, 80 (2007)



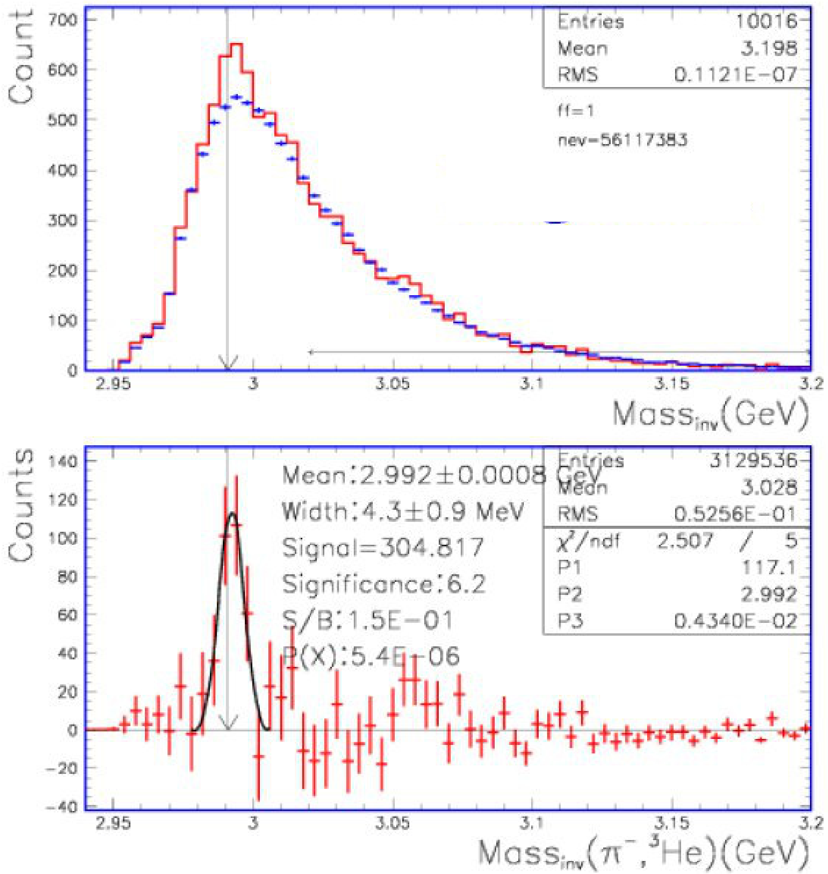
		M (MeV)	Γ (MeV)	P/Λ	P/(IN)	Sign (σ)
FOPI	HI: Al+Al	-	-	-	-	-
	HI: Ni+Ni	3149 ± 15 3166 ± 12	100 ± 49 85 ± 47	$1.3 \cdot 10^{-2}$	$1.0 \cdot 10^{-5}$	4.9 5.2
FINUDA	K^- stopped on ^{6}Li	3251 ± 6	37 ± 14		$4.4 \cdot 10^{-3}$	3.9
KEK E549	K^- stopped in LHe	-	-	-	-	-
Obelix	$\bar{p}$ stopped in ^{4}He	3190 ± 15	< 60.		$>0.4 \cdot 10^{-4}$	2.6

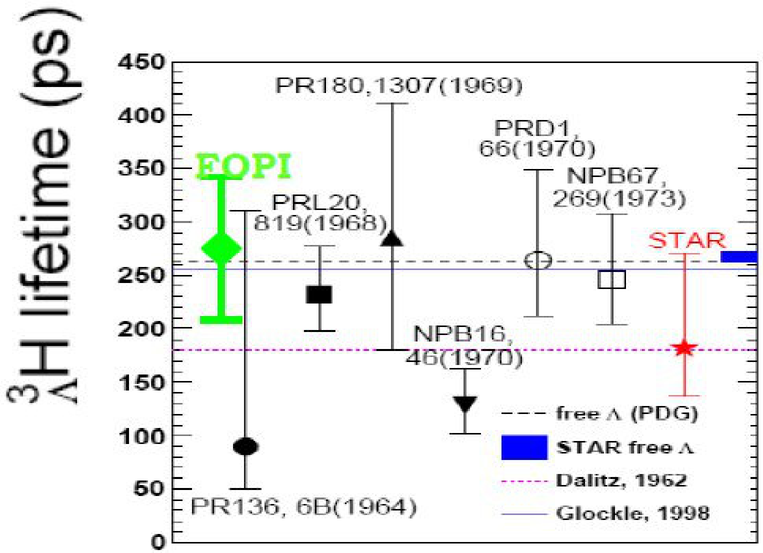
The result certainly needs more attention

Not every structure in inv. mass corresponds to a real signal

dΛ is also a hypernucleus !

Mesonic 2body decay $^{3}_{\Lambda}H \rightarrow {}^{3}He+\pi^{-}$ in Ni+Ni @ 1.9 AgeV





$6*10^{7}$ events, 50% central

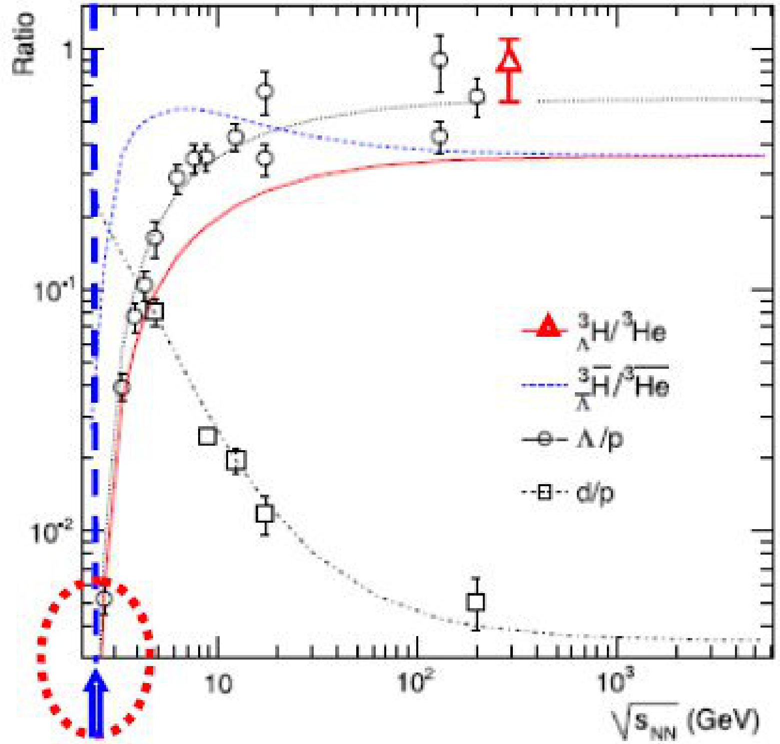
Detection rate: 10^{-6}/event

S/B ~ 10^{-1}, Significance ~ 6

Lifetime agrees with world-data

Comparison to thermal model

Particle	${}^{3}_{\Lambda}He/{}^{3}He$	${}^{3}_{\Lambda}He/\Lambda$	$t/{}^{3}He$
Region A	1.5×10^{-2}	0.42	1.44
Error	5.7%	6.74%	0.16%
Region B	$<2.0\times10^{-3}$	$<1.3\times10^{-2}$	0.97
Error	23.7%	23.5%	0.14%
Thermal model	2.0×10^{-3}	2.8×10^{-2}	1.1

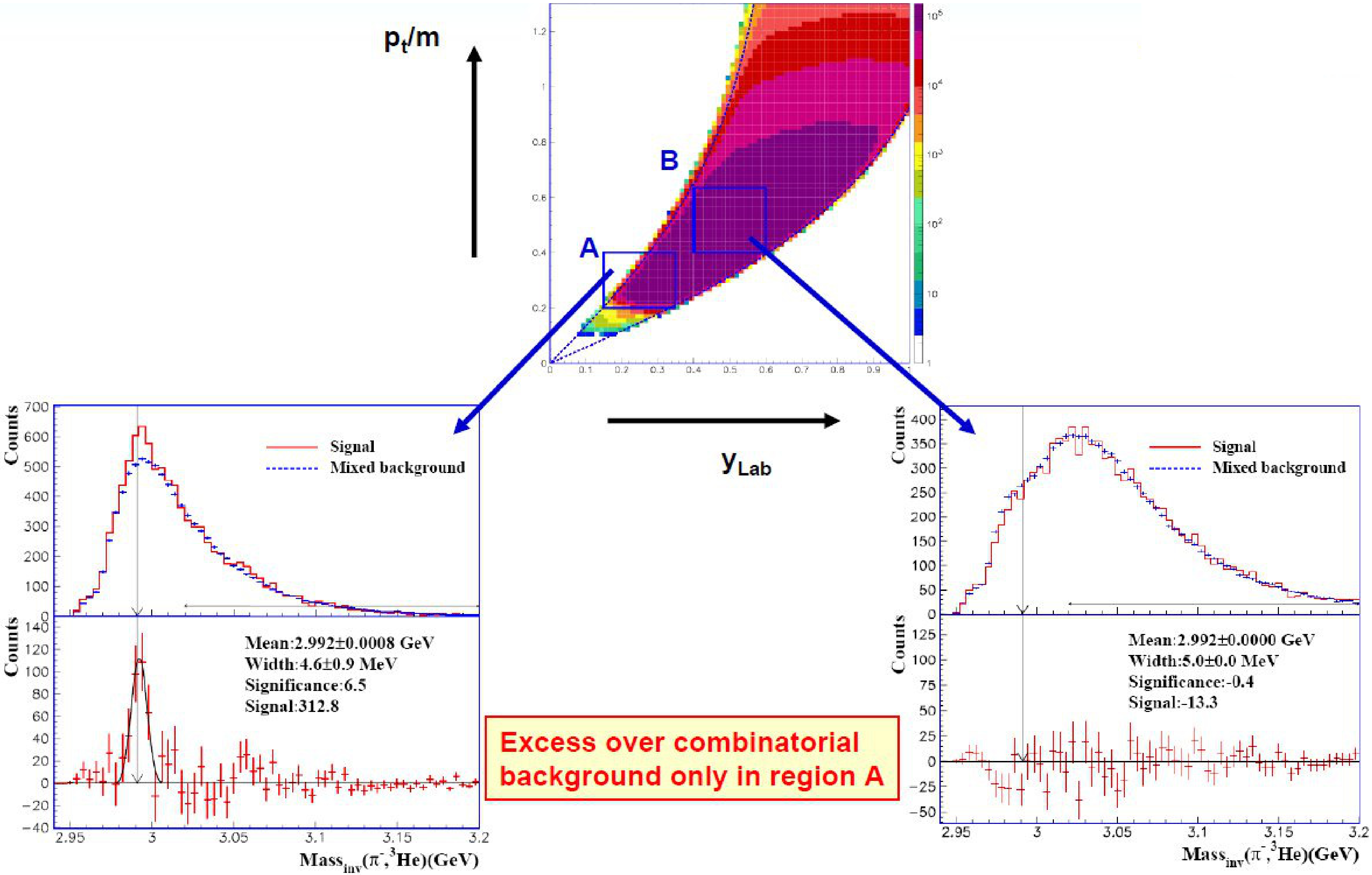


A. Andronic et al, PLB 697 (2011) 203

Thermal model fails (an order of magnitude)

(Limited experimental acceptance)

Phase-space distribution

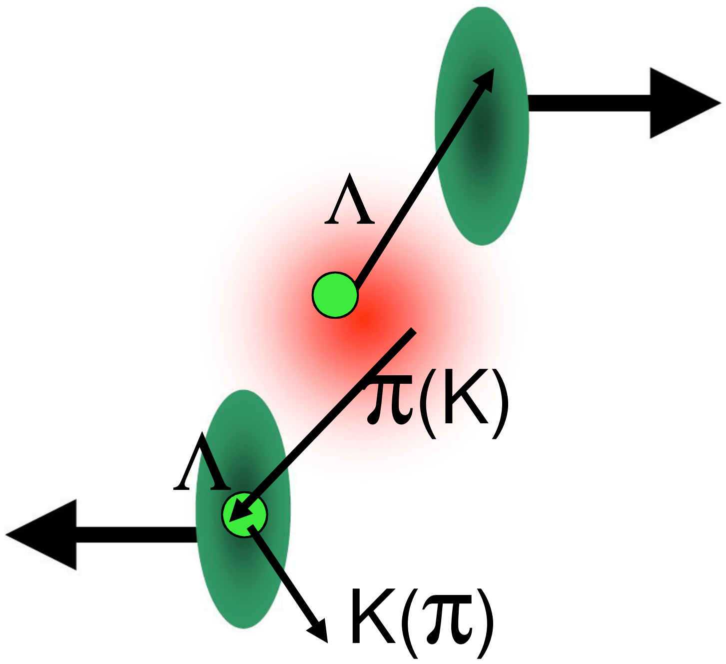


Production mechanism

$^{12}C + ^{12}C@2\ AGeV$

	$^{4}_{\Lambda}H$	$^{4}_{\Lambda}He$	$^{5}_{\Lambda}He$
total yield (μb)	2.2	4	1.4
pionic contribution (μb)	0.3	0.2	0.03

T. Gaitanos et al. / Physics Letters B 675 (2009) 297
(GiBUU+SMM)



Only an idea of theorists

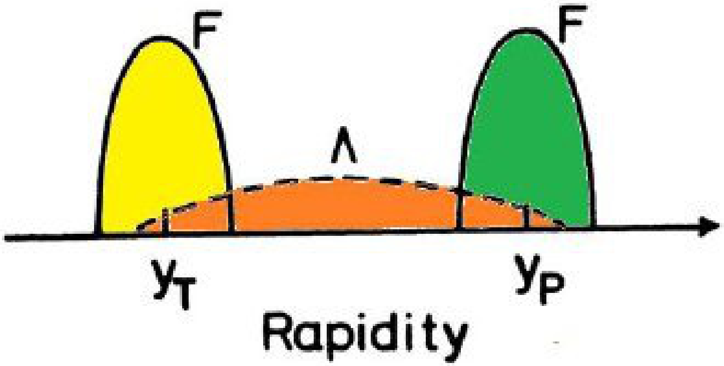
No experimental verification

Coalescence

$$\frac{\gamma}{\sigma_r}\frac{d^3\sigma(\Lambda F)}{dk_c^3} = \left(\frac{m_\Lambda + m_F}{m_\Lambda m_F}\right)^3 S_{\Lambda F}\left(\frac{\gamma}{\sigma_r}\frac{d^3\sigma^{(\Lambda)}}{dk_c^3}\right)\left(\frac{\gamma}{\sigma_r}\frac{d^3\sigma^{(F)}}{dk_c^3}\right)$$

H.Bando et al. NPA 501,1900 (1989)

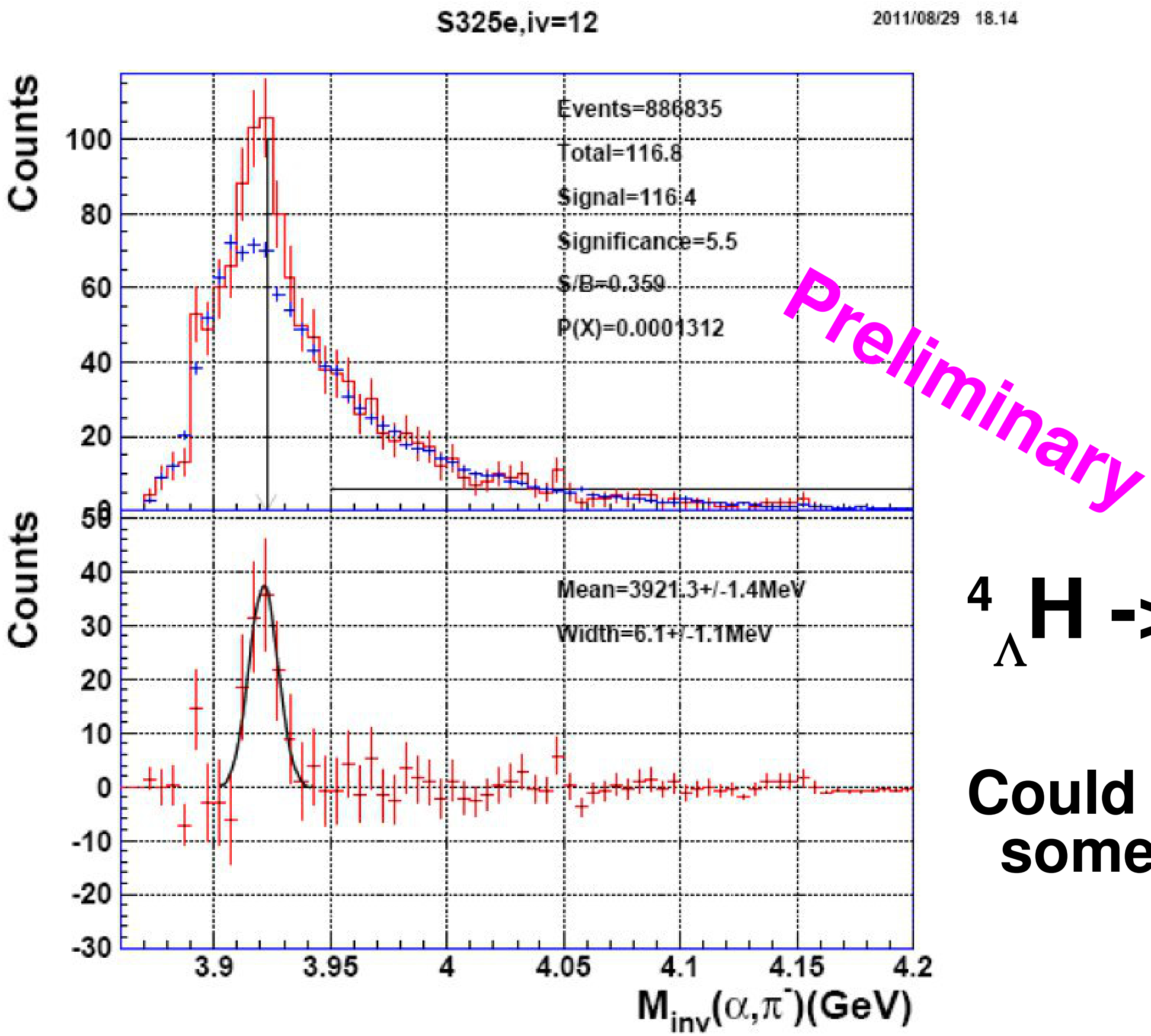
Coalescence process ($\Lambda X \rightarrow {}_{\Lambda}Y$)



Particle	$P({}^3_\Lambda He)$	$P(\Lambda)$	$P(d)$	$S_{\Lambda F}$	Error
Region A	3.4×10^{-4}	8.0×10^{-4}	1.7×10^{-1}	2.5	6.8%
Region B	$< 3.0 \times 10^{-5}$	2.1×10^{-3}	1.6×10^{-1}	$< 8.8 \times 10^{-2}$	23.6%

Coalescence does not work very well

More hyper-nuclei



$^{4}_{\Lambda}H \rightarrow \alpha+\pi^-$

Could be a prelude to something heavier ?

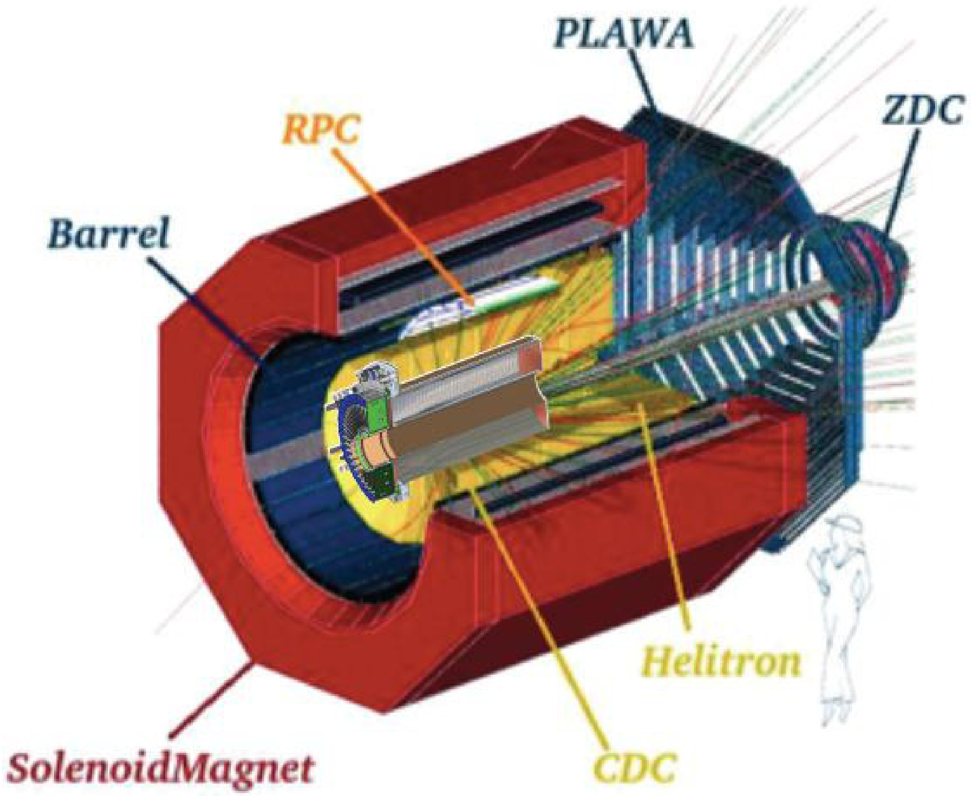
Advantages of hyper-nuclei production in heavy-ion collisions

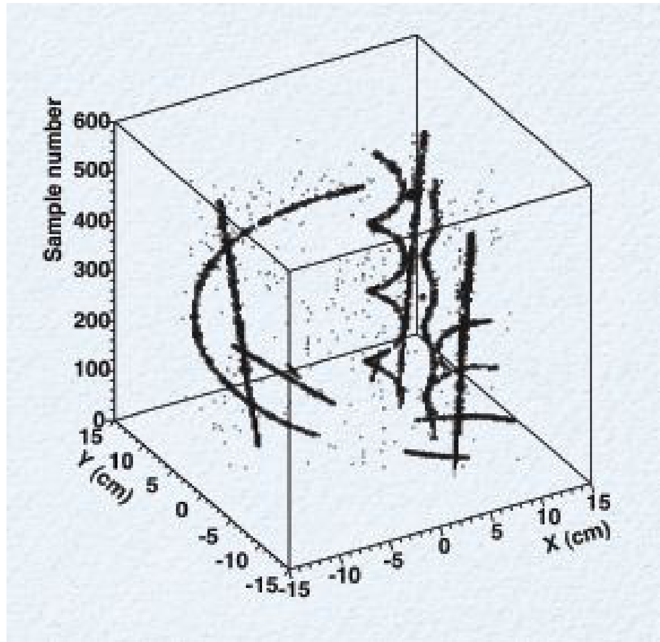
Large momentum transfer and recoil
- **(more) precise lifetime measurement**
- **small detectors in fixed-target experiments**

Rare fragments
- **population of n/p-rich isotopes**

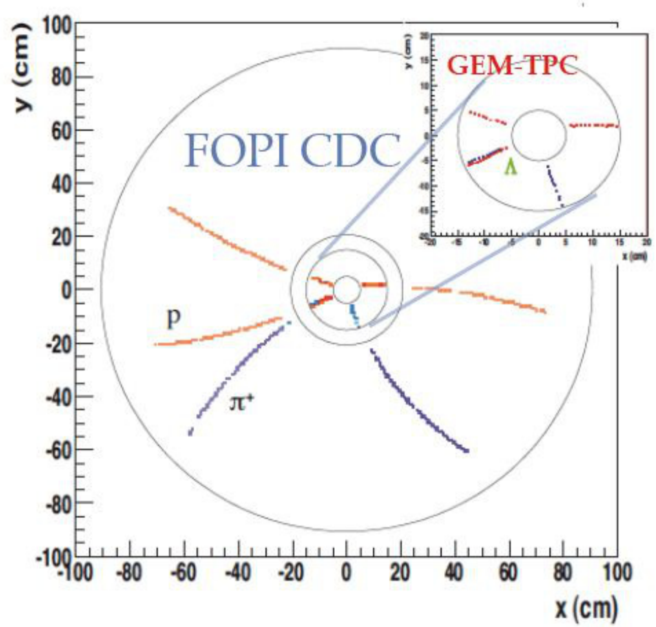
Multi-strange objects
- **production of XXΛ-Hypernuclei**

FOPI ? tomorrow ?!

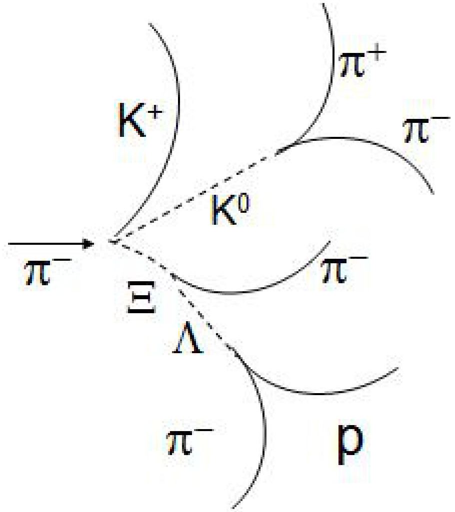




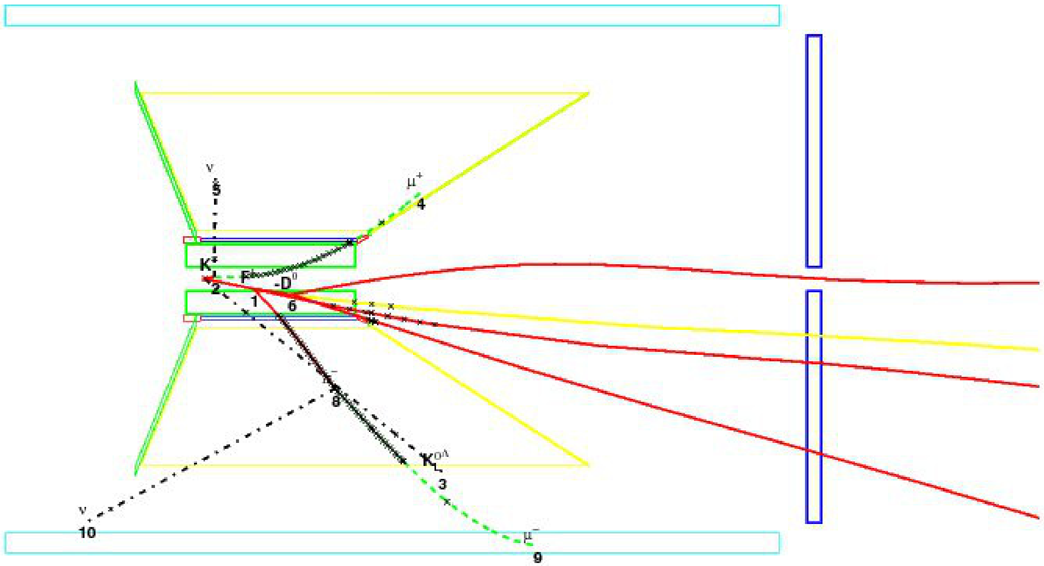
Installation and operation of the PANDA prototype GEM-TPC with a supreme spatial resolution and forward geometrical acceptance



Ready to go for double strangeness production



Production of Ξ^- in π induced reactions at 2.5 GeV/c



Production of $^{6}_{\Lambda\Lambda}He$ in ^{3}He+C @ 2.7 AGeV

$^{6}_{\Lambda\Lambda}He \rightarrow {}^{6}_{\Lambda}Li + \pi^-$

$^{6}_{\Lambda}Li \rightarrow {}^{6}Be^* + \pi$-

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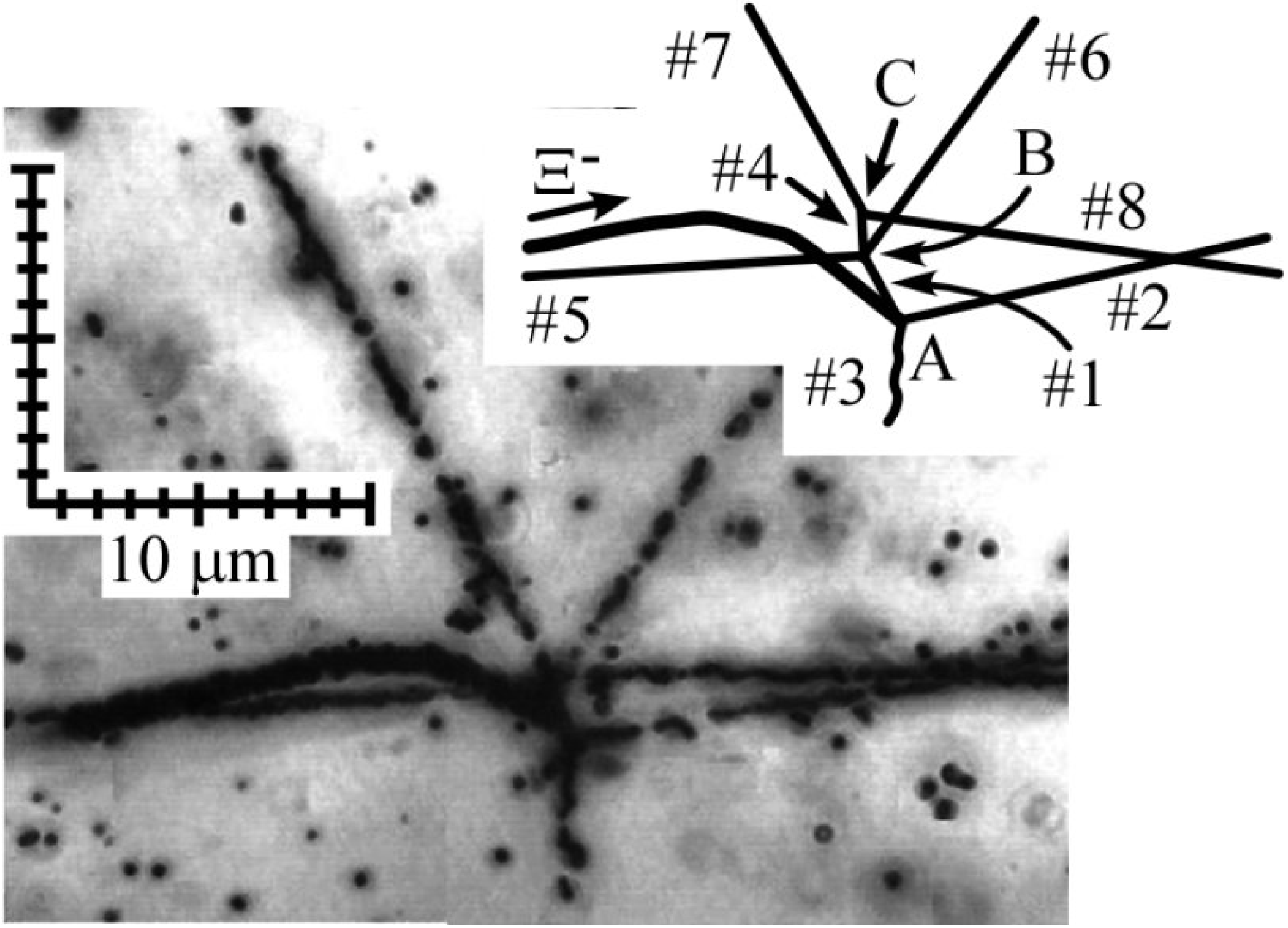
FOPI Collaboration

ΛΛ Hypernuclei



Unfortunately FOPI will never see them

The program has been turned down

Last Slide