Experimental check of precise predictions of QCD using π^+K^-, $K^+\pi^-$ and $\pi^+\pi^-$ atoms

L. Nemenov (JINR) on behalf of the DIRAC Collaboration

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QCD Lagrangian and its prediction

The QCD Lagrangians use the $SU(3)_L{*}SU(3)_R$ and $SU(2)_L{*}SU(2)_R$ chiral symmetry breaking.

$$\mathcal{L}(u,d,s) = \mathcal{L}(3) = \mathcal{L}_{sym}(3) + \mathcal{L}_{sym.br.}(3)$$

$$\mathcal{L}(u,d) = \mathcal{L}(2) = \mathcal{L}_{sym}(2) + \mathcal{L}_{sym.br.}(2)$$

$\mathcal{L}_{sym.br.}$ is proportional to m_q

$e^+e^- \rightarrow$ hadrons

QCD provides cross sections with 1% precision

1. Perturbation theory is working at high momentum transfer Q.
2. Unitarity condition.

At large Q, contribution of $\mathcal{L}_{sym.br.}$ to the cross section is proportional to $1/Q^4$.
Therefore these experiments checked only the $\mathcal{L}_{sym}$ prediction precision.

To check the total $\mathcal{L}(3)$ Lagrangian predictions, we must study the low momentum transfer Q processes.

Tools: Lattice calculations and Chiral Perturbation Theory (ChPT)

Lattice----- $\mathcal{L}(3)$, $\mathcal{L}(2)$ ChPT------Effective Lagrangians.

Measurement of the πK scattering length

The S-wave πK scattering lengths $a_{1/2}$ and $a_{3/2}$ in the chiral symmetry world are zero. Therefore the scattering length values $a_{1/2}$ and $a_{3/2}$ are very sensitive to the $\mathcal{L}_{\text{sym.br.}}(3)$.

For Lattice QCD the πK interaction at threshold is a relatively simple process. It gives πK scattering length values with an average precision of 5%.
This precision will be improved in the near future.

There is only one experimental data: DIRAC collaboration observed 349±62 πK atomic pairs (*Phys.Rev.Lett*. 2016) and measured $|\boldsymbol{a_{1/2}-a_{3/2}}|$ with an average precision of 34% (Conference in Chicago, 2016).

Measurement of the πK scattering length

The DIRAC collaboration proposes:

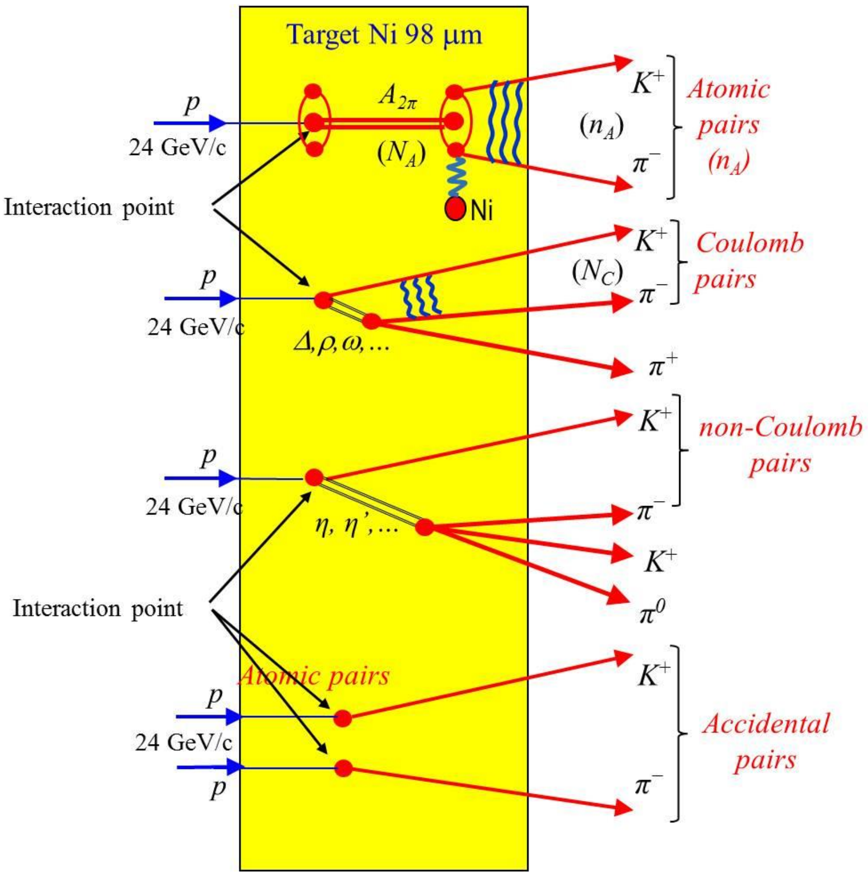
- to measure πK scattering lengths with precision better than 5% and
- to check with this accuracy the Lattice calculation of the total QCD Lagrangian $\mathcal{L}(3)$.

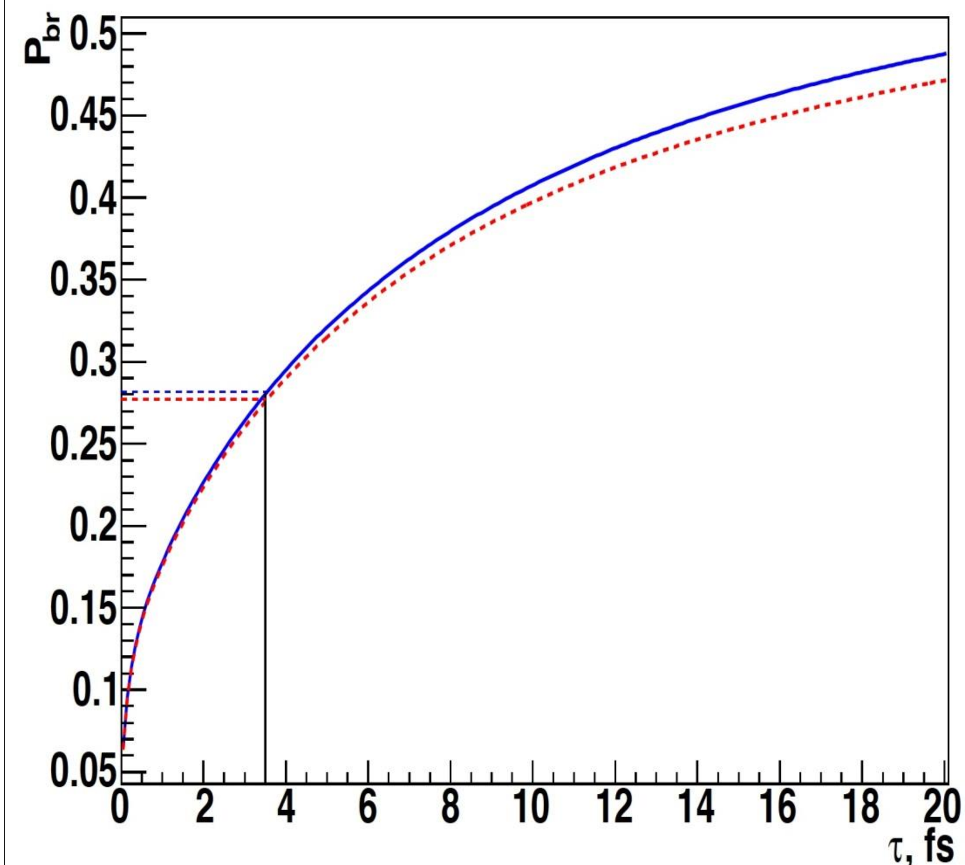
The measurement should be performed with the 450 GeV/c SPS CERN proton beam.

The πK atom lifetime and πK scattering length

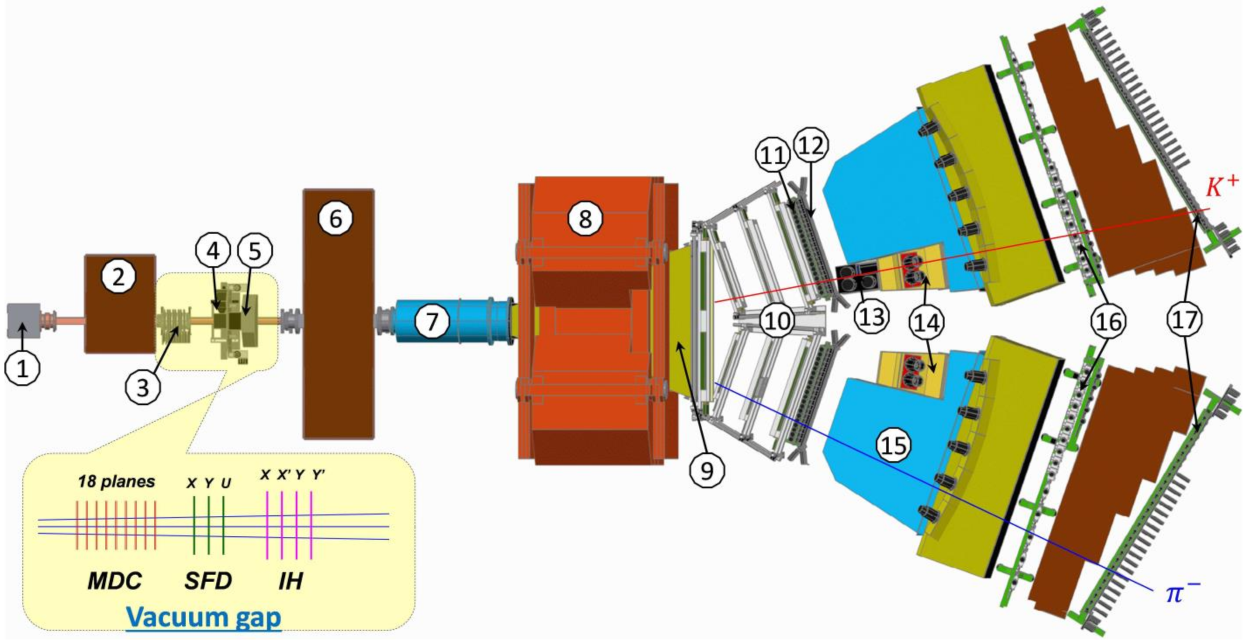
$$\frac{1}{\tau} = R\,|a_{1/2}-a_{3/2}|^2$$

τ_{th} =(3.5±0.4)×10^{-15} s. The evaluation error from this relation for $|a_{1/2}-a_{3/2}|$ is 1%





DIRAC setup, experimental and theoretical data



Experiment	Detected atomic pairs (n_A)	τ (10^{-15} sec)	$a^- = \frac{1}{3}(a_{1/2}-a_{3/2})$	Average error
DIRAC	349±61(stat)±9(syst) =349±62(tot) (5.6σ)	$5.5^{+5.0}_{-2.8}$	$0.072^{+0.031}_{-0.020}$	34%

Theory	P.Buttiker et al., Eur.Phys.J. (2004)	K.Sasaki et al., Phys.Rev. (2014)	Z.Fu, Phys.Rev. (2013)	S.R.Beame et al. Phys.Rev (2008)	C.Lang et al.,Phys.Rev. (2012)	J.Bijnens et al., J. High Energy Phys. (2004)
a^-	0.090±0.005	0.081	0.077	0.077	0.10	0.089
Method	Roy-Steiner equations	Lattice calculations	Lattice calculations	Lattice calculations	Lattice calculations	ChPT, two loops

Dimeson atom production at proton momentum 450 GeV/c

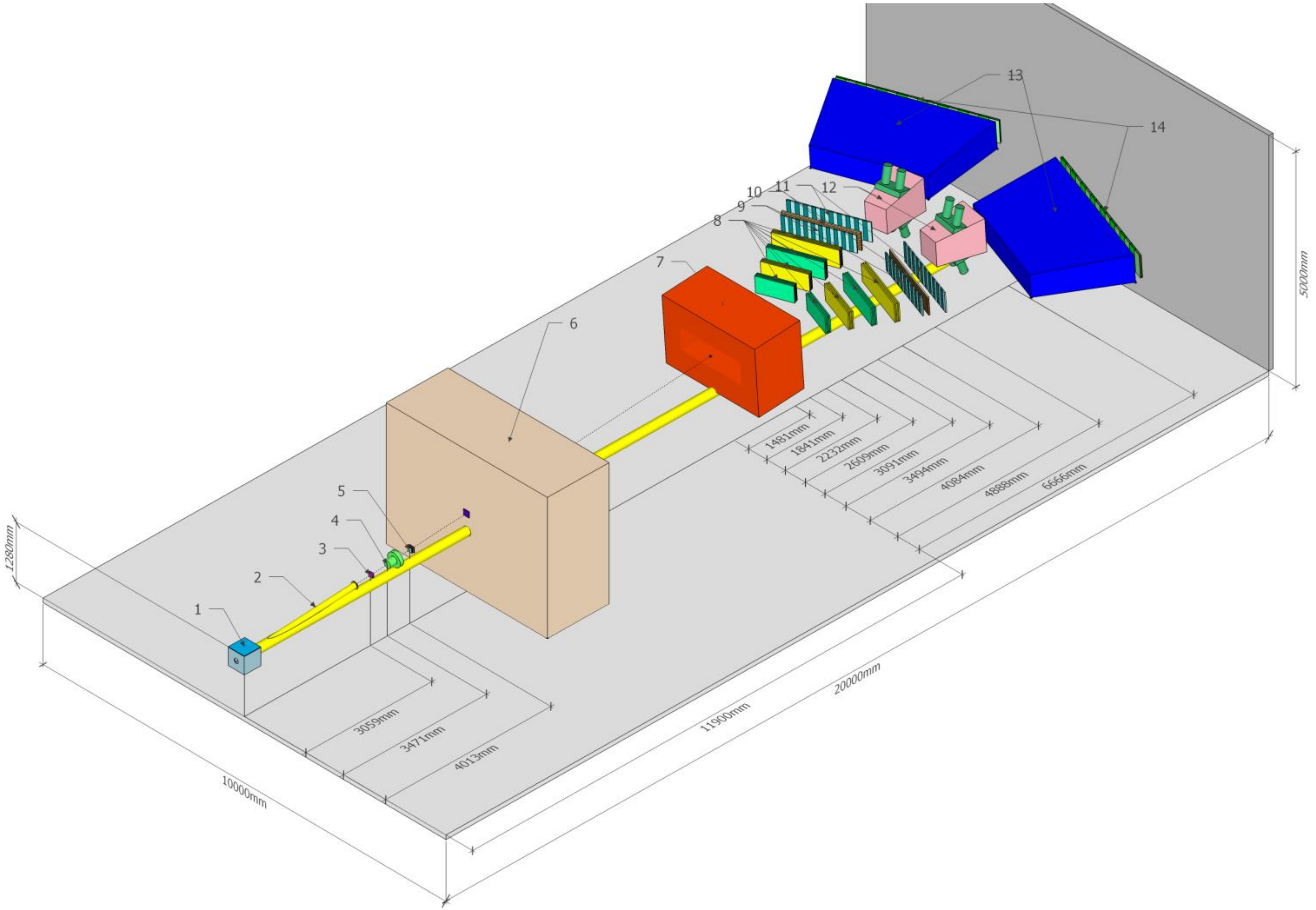
The dimeson atom production in *p*-nucleus interaction can be enlarged by more than an order of magnitude if the incident proton momentum is increased from 24 to 450 *GeV/c*.

With the SPS operation conditions at 450 *GeV/c* ($\theta_{lab} = 4°$) the yield, i.e. the number of produced dimeson atoms $A_{2\pi}$, $A_{\pi^+K^-}$ and $A_{\pi^-K^+}$ per time unit, will be 12±2, 53±11 and 24±5 times higher than in the previous DIRAC experiment (O.Gorchakov, L.Nemenov J. Phys. G: Nucl. Part., 2016).

This significant increase in the $A_{\pi^+K^-}$ and $A_{\pi^-K^+}$ production allows

- to measure with a new DIRAC setup in a comparable running time, $|a_{1/2}-a_{3/2}|$ with a precision better than 5% and
- to check with the same accuracy predictions of the total $\mathcal{L}(3)$ QCD Lagrangian based on the chiral $SU(3)_L*SU(3)_R$ symmetry breaking

The possible scheme of the setup and detectors



SPS beam time for πK scattering length measurement

The data at p_p = 24*GeV/c* and 450*Gev/c* were simulated, processed and analysed (V.Yazkov, DIRAC note, 2016 05).

Experimental conditions on SPS with Ni target

Thin *Ni* target, nuclear efficiency ~ 6×10^{-4}.

The proton beam can be used for other experiments.

Proton beam intensity: 3×10^{11} protons/s

(DIRAC worked at 2.7×10^{11} protons/s)

Number of spills: 4.5×10^{5} with spill duration 4.5 s

Data taking: 3000 spills per 24 hours.

Running time: 5 months

The expected number of πK atomic pairs: n_A=13000

(In the DIRAC experiment was n_A=349±62)

The statistical precision in these conditions for πK scattering length will be: ~5%

The expected systematic error will be at the level of 2%

The expected number of $\pi^+\pi^-$ atomic pairs n_A=400000

The statistical precision of the $\pi^+\pi^-$ scattering length will be: 0.7%

The expected systematic error will be at the level of 2%

$\mathcal{L}(2)$ and Chiral Lagrangian predictions check with short-lived $\pi^+\pi^-$ atoms

- The QCD Lagrangian $\mathcal{L}(2)$ and Chiral Lagrangian describe processes with *u* and *d* quarks, using $SU(2)_L * SU(2)_R$ chiral symmetry breaking.
- From the ChPT prediction for a_0 and a_2, the $\pi^+\pi^-$ atom lifetime in the ground state, given by $1/\tau = R|a_0 - a_2|^2$, is $\tau_{th} = (2.9 \pm 0.1) * 10^{-15}$ s.
- The evaluation error for $|a_0 - a_2|$ from this relation is 0.6%.
- These Lagrangians predict the S-wave $\pi^+\pi^-$ scattering lengths a_0 and a_2.

$\mathcal{L}(2)$ and Chiral Lagrangian predictions check with short-lived $\pi^+\pi^-$ atoms

ChPT	a_0 and a_2 a_0-a_2	2.3% precision 1.5% precision	Colangelo et al. Nucl.Phys.(2001)

Lattice calculations	a_0 a_2	4-10% precision ~1% precision	K.Sasaki et al., Phys.Rev. 2014, Z.Fu, Phys.Rev.(2013), C.Lang et al.,Phys.Rev.(2012), Feng et al., Phys. Lett.(2010), T.Yagy at al., arXiv:1108.2970, S.Beame et al. Phys.Rev(2008)

Experimental values	a_0-a_2	~ 4% precision	J.R.Bateley at al., Eur. Phys. J. (2009), J.R.Bateley at al., Eur. Phys. (2010), Adeva et al., Phys. Lett. (2011)
	a_0 a_2	~ 6% precision ~22% precision	J.R.Bateley at al., Eur. Phys. J. (2009), J.R.Bateley at al., Eur. Phys. (2010)
on SPS	a_0-a_2	~2% precision	DIRAC estimation

QCD and Chiral Lagrangian predictions check with long-lived $\pi^+\pi^-$ atoms

The DIRAC collaboration (Adeva et al., Phys.Lett.(2015) observed 436±61 pion pairs from the long-lived ($\tau \geq 1\times10^{-11}$ sec) $\pi^+\pi^-$ atom breakup (ionisation).

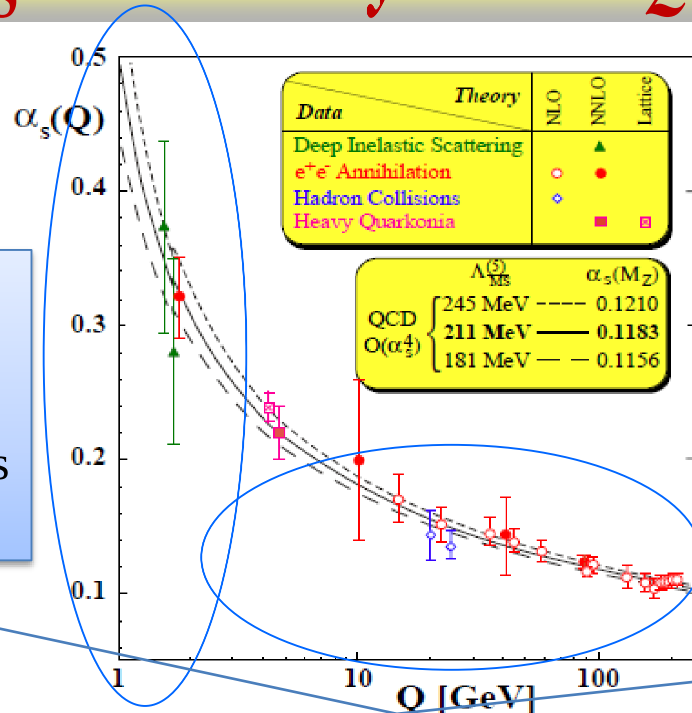
The study of these excited atoms allows to measure the Lamb shift depending on another $\pi\pi$ scattering length combination: $2a_0+a_2$.

The SPS proton beam and the new experimental arrangements makes this measurement possible.

Thank you

Additional slides

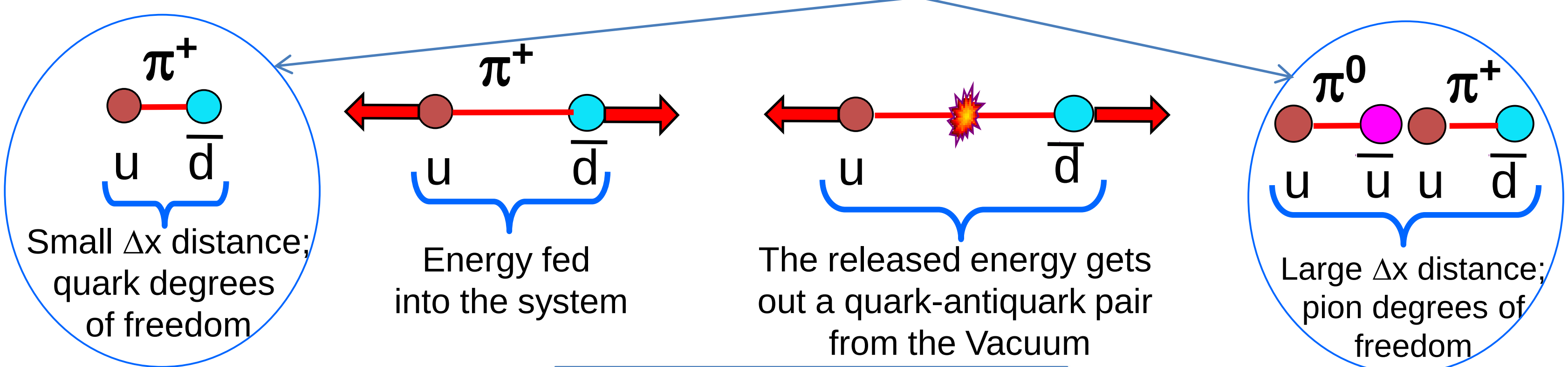
DIRAC search for strong interaction dynamics - Quark confinement



S. Bethke,
J.Phys.G26:R27, 2000

α_S large – small Q^2
"quark confinement"
perturbative QCD not suitable.
Lattice QCD solve field equations
on a space-time lattice by MC.

α_S small – large Q^2
"asymptotic freedom"
and perturbative QCD

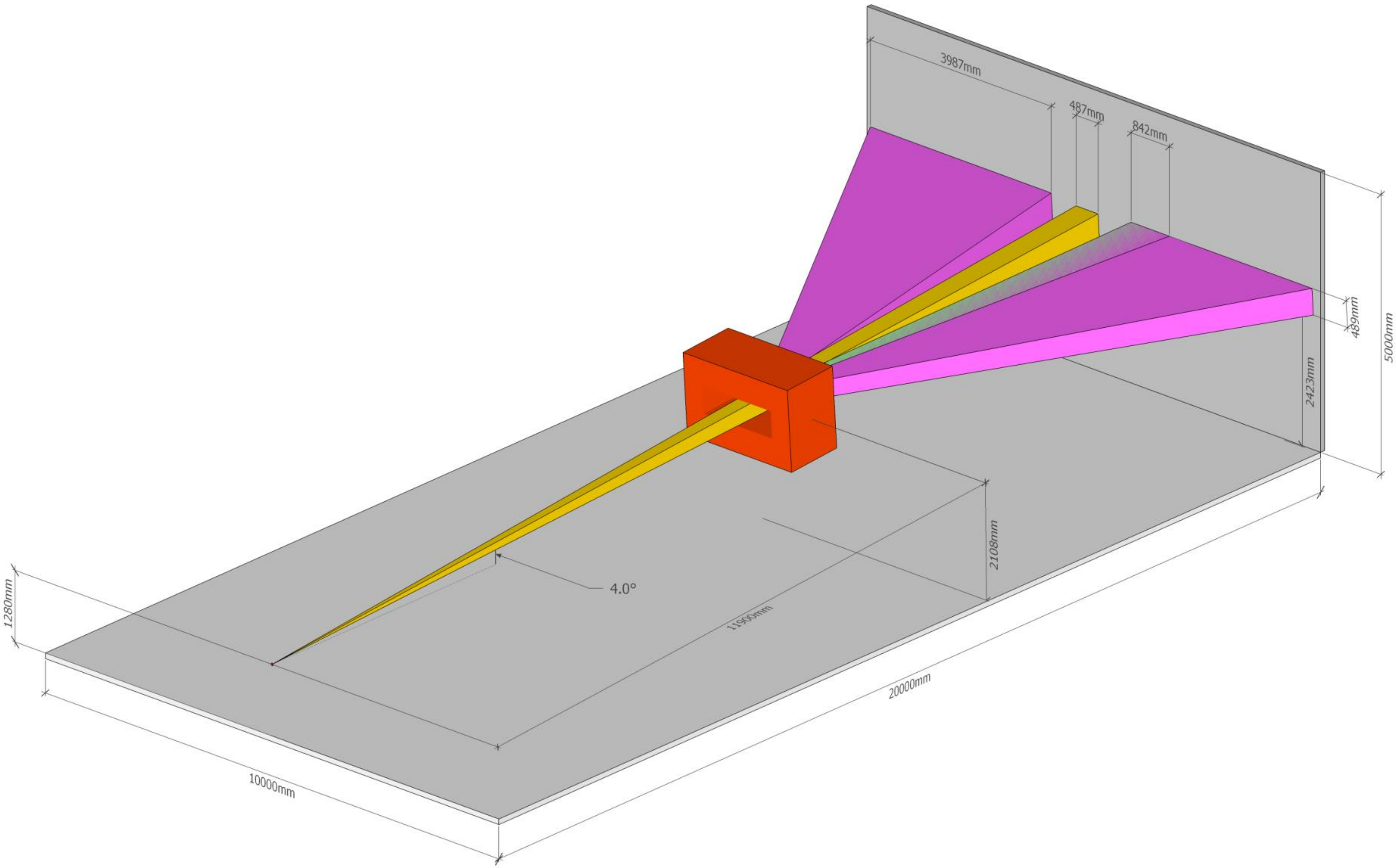


"asymptotic freedom"

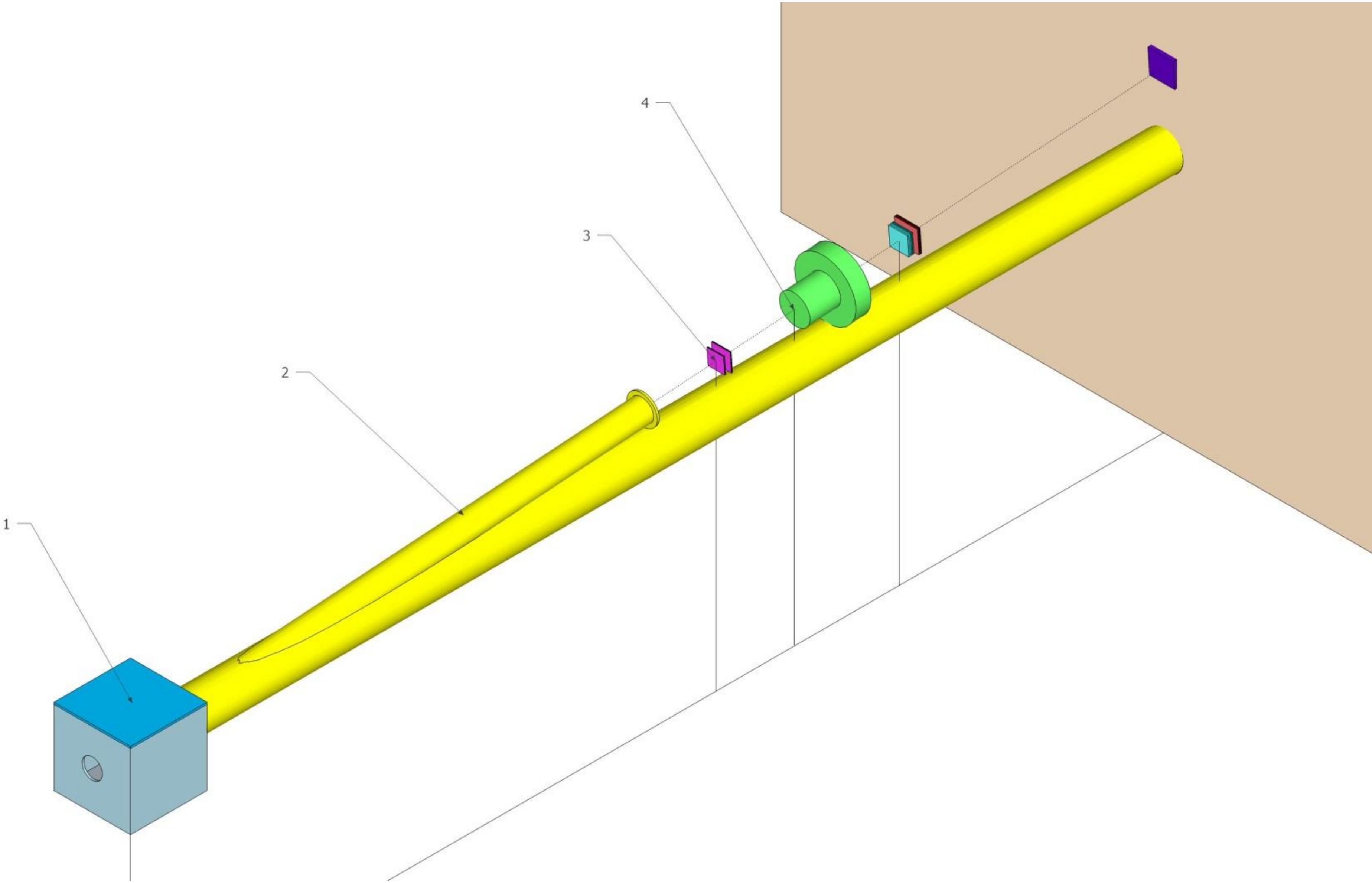
string breaks generate $q\bar{q}$
pair to reduce field energy

"quark confinement"
DIRAC

The possible scheme of the setup and detectors



The possible scheme of the detectors before the magnet



Detectors and dimensions (mm)

Name	Distance to the target	X-size	Y-size	Z-size	Other
Target	0	50	50	0.1	
First Upstream Tracker (Silicon)	3059	86	86		4 planes 2 if pixel
RICH	3471	94	94		
Second Upstream Tracker (Scintillating Fiber)	4013	100	100		
Third Upstream Tracker (Ionization Hodoscope)	4053	120	120		
First Downstream Tracker	13381	746	370		
Second Downstream Tracker	13711	946	380		
Third Downstream Tracker	14132	1133	390		
Forth Downstream Tracker	14509	1326	400		
First Vertical Hodoscope	14991	1471	400		
Horizontal Hodoscope	15594	1545	400		
Second Vertical Hodoscope	15984				
Preshower	18566				
The Wall	20000				