10 Years MITP

Bethe Center for Theoretical Physics

UNIVERSITÄT BONN

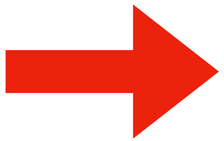
Light Long-lived Particles

Herbi Dreiner — University of Bonn

Work performed with: Jordy de Vries, Florian Domingo, Julian Günther
Dominik Köhler, Saurabh Nangia, Zeren Simon Wang
Guanghui Zhou

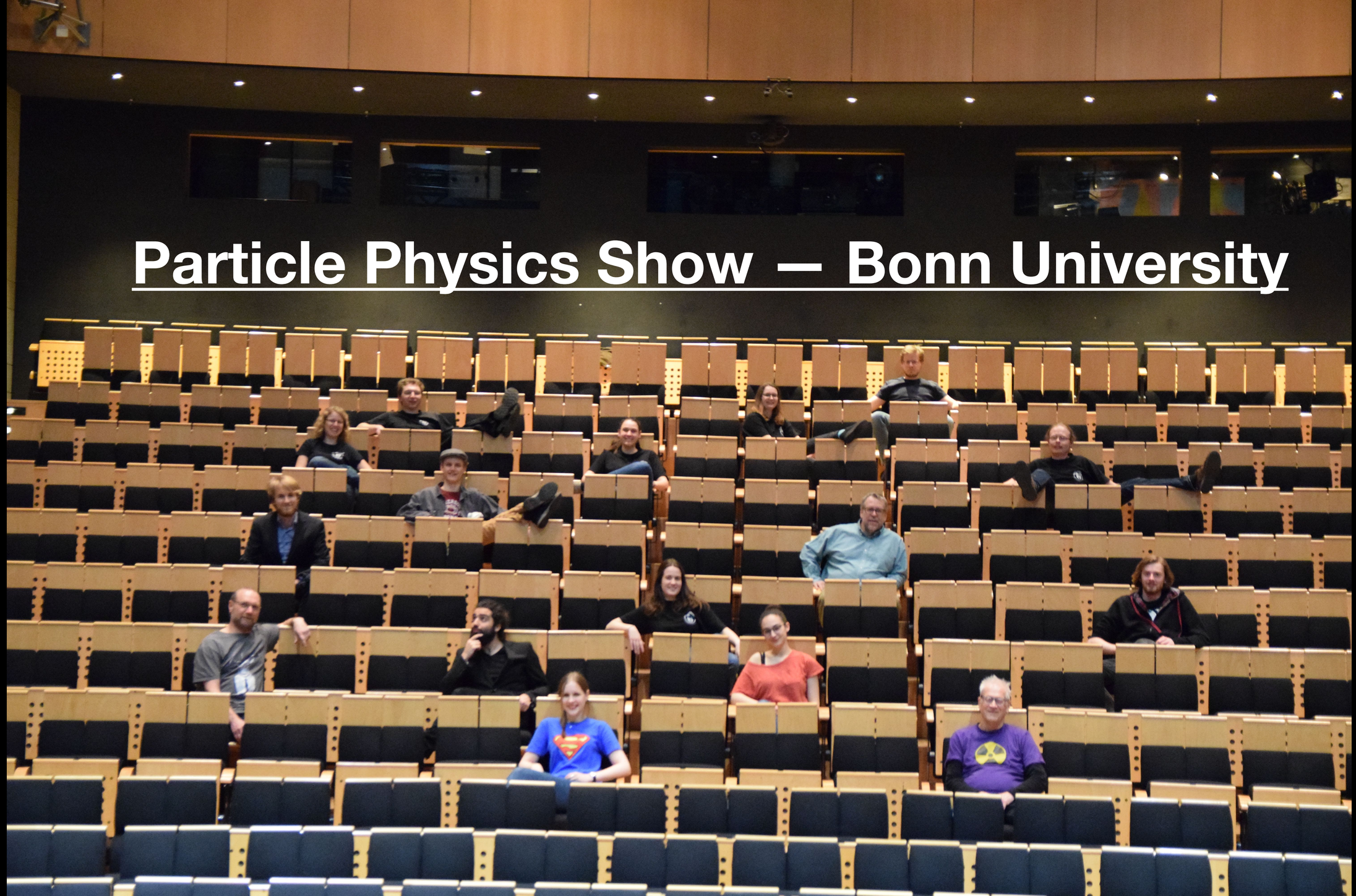
Mainz Institute for Theoretical Physics

- 10 Years of MITP!
- We have benefitted also greatly in Bonn.
- Have personally been to 5 workshops
- Have sent many students & postdocs to workshops and schools
- **Physik im Theater!**



Physik im Theater - Staatstheater Mainz

Particle Physics Show — Bonn University




Fund-
Roter Knopf:
Nicht
drücken!
Niemals!


Roter Knopf:
Nicht
drücken!


Roter Knopf:
Nicht
drücken!
Niemals!


sachen
Roter Knopf:
Nicht
drücken!


What's (the) Matter?
Die Teilchenphysik-Show
Prof. Herbert Dreiner und Studierende
der Rheinischen Friedrich-Wilhelms Universität Bonn
Einführung: Matthias Neubert, MITP Direktor
JG|U
mitp
Roter Knopf: Nicht drücken!
Niemals!

Light Long-Lived Particle: Supersymmetric Neutralino

(Photon, Z-boson; Higgs-1, Higgs-2) SUSY $(\tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0,\ \tilde{\chi}_4^0)$ Neutralinos

(Spin-1) (Spin-0) (Spin-½)

lightest neutralino

(mostly Bino)

Choudhury, HD, Richardson, Sarkar; *Phys.Rev.D* 61 (2000) 095009

Dedes, HD, Richardson; *Phys.Rev.D* 65 (2001) 015001

Light Neutralino: mass constraints

- LEP searches: $M_{\chi_1^0} \gtrsim 46\,\mathrm{GeV}$

- However, this is based on chargino searches, and assumption:

SUSY GUTs: $M_1 = \frac{5}{3}\tan^2\theta_W M_2 \approx \frac{1}{2}M_2$

- Drop assumption, and set determinant of neutralino mass matrix to 0

$$M_1 = \frac{M_2 M_Z^2 \sin(2\beta)\sin^2\theta_W}{\mu M_2 - M_Z^2 \sin(2\beta)\cos^2\theta_W}.$$

always has solutions

Light Neutralino: mass constraints

- Constraints: invisible Z-width
- Radiative corrections

} avoided, since neutralino dominantly bino

- Massless neutralino consistent with all constraints:

HKD, Heinemeyer, Kittel (Granada), Langenfeld, Weber, Weiglein: *Eur.Phys.J.C* 62 (2009) 547

- Strictest constraint from Supernova and White Dwarf cooling:

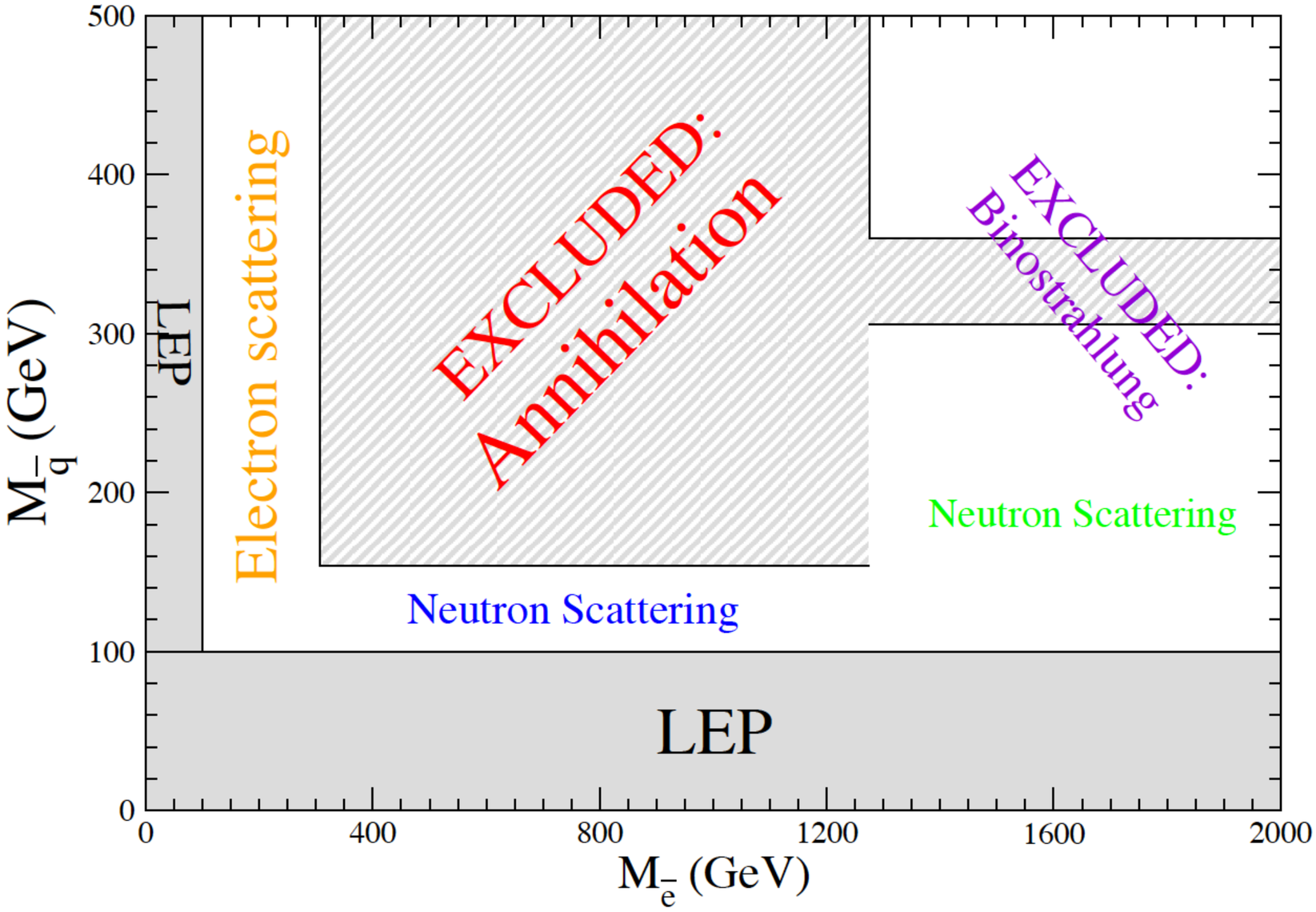
$$m_{\tilde{q}} > 600\,\mathrm{GeV}$$

$$m_{\tilde{e}} > 1100\,\mathrm{GeV}$$

C. Hanhart, HKD, et al: *Phys.Rev.D* 68 (2003) 055004

HKD, J. Fortin, L. Ubadi; *Phys.Rev.D 88 (2013) 043517*

Supernova Cooling Constraints



Cosmological Bounds

excluded for stable χ_1^0:

$$0.7\ \text{eV} < M_{\tilde{\chi}_1^0} < 24\ \text{GeV}$$

Cowsik-McClelland

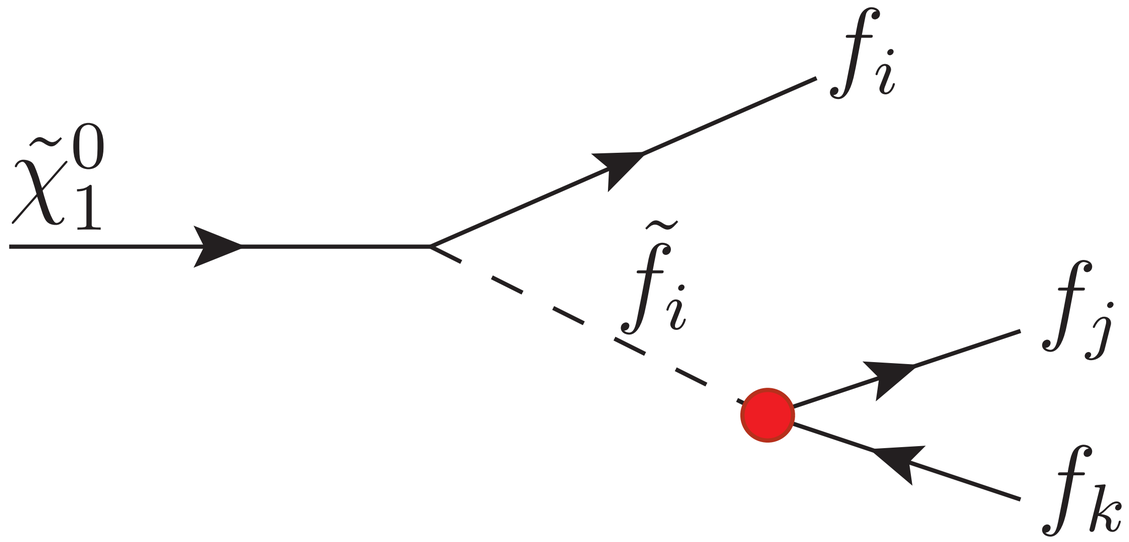
Lee-Weinberg

- In this range χ_1^0 must decay, R-Parity Violation

$$W_{\text{RPV}} = \kappa_i L_i H_u + \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c,$$

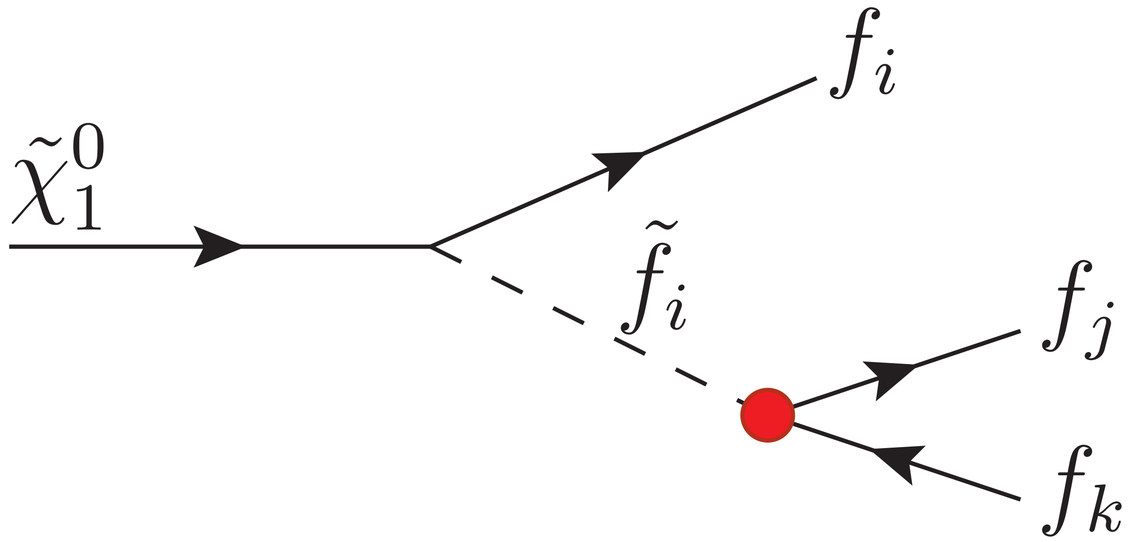
Neutralino no longer dark matter candidate — axino

LSP Decay — Heavy Neutralino



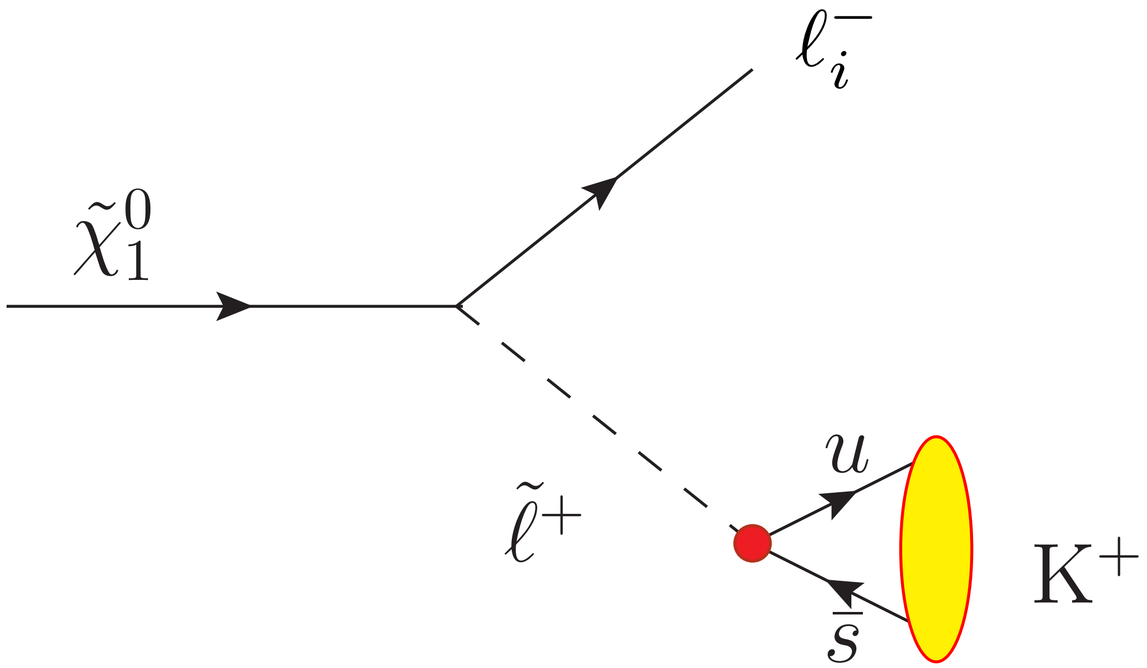
- UDD: 3 jets
- LQD: 2 jets + 1 lepton
- LLE: 2 charged leptons + 1 neutrino

LSP Decay — Lighter Neutralino



- UDD: ~~3 jets~~ baryon + meson
- LQD: ~~2 jets + 1 lepton~~ 1 meson + 1 lepton
- LLE: 2 charged leptons + 1 neutrino

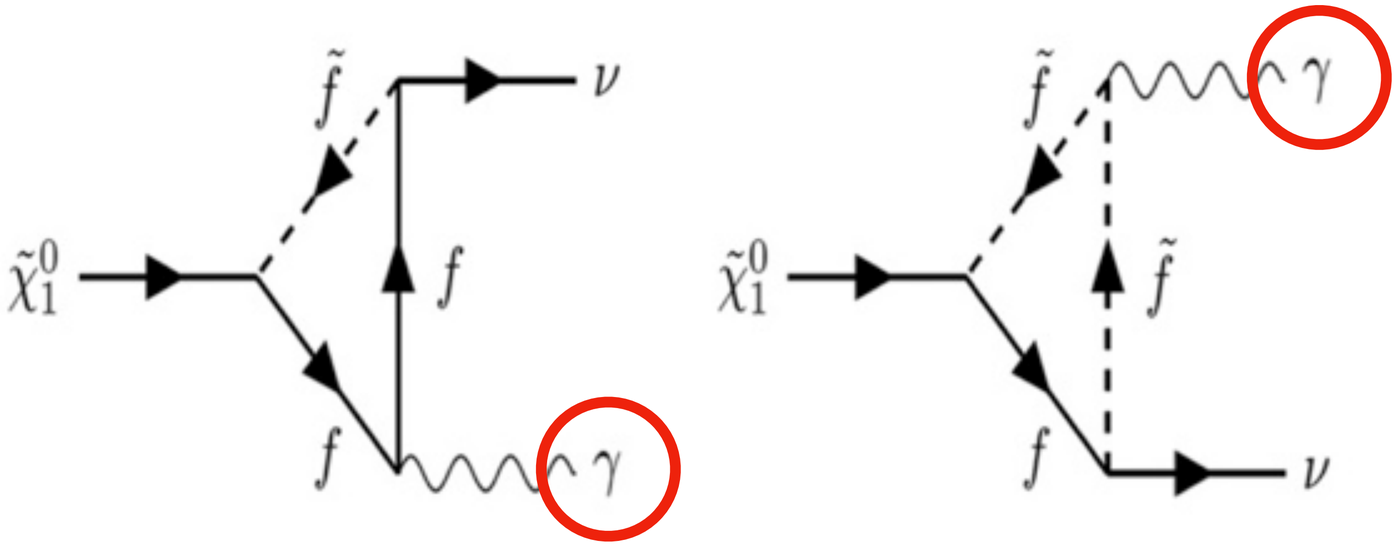
LSP Decay — Lighter Neutralino



$$L_i Q_1 \bar{D}_2$$

LSP Decay — Even Lighter Neutralino

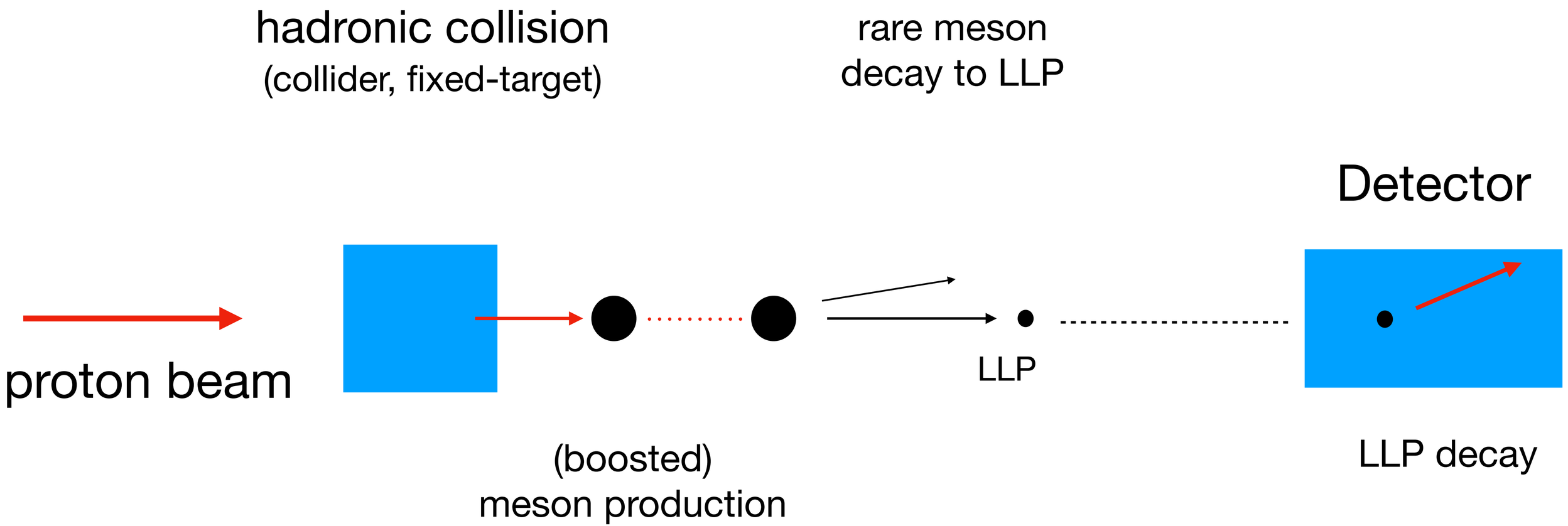
$$\tilde{\chi}_1^0 \to \gamma + \nu$$



$$L_i L_j \bar{E}_j, \quad \text{or} \quad L_i Q_j \bar{D}_j$$

Light Long-Lived Particles (LLPs): 1. Colliders

Basic idea for detection:



FASER

Benchmark Scenarios for FASER

HD, Köhler, Nangia, Wang; *JHEP* 02 (2023) 120

$$\tilde{\chi}_1^0 \to \gamma + \nu$$

Scenario	$m_{\tilde{\chi}_1^0}$	Production $\left(\lambda^{\rm P}_{ijk}\right)$	Decay $\left(\lambda^{\rm D}_{ijj}\right)$	Current Constraints
B1	30 MeV	$\lambda'_{211}\,(M=\pi^\pm,\pi^0)$	λ'_{333}	$\lambda'_{211}<0.59\left(\frac{m_{\tilde{d}_R}}{1\,\text{TeV}}\right),\ \lambda'_{333}<1.04$
B2	75 MeV	$\lambda'_{212}\left(M=K^\pm,K^0_{L/S}\right)$	λ'_{333}	$\lambda'_{212}<0.59\left(\frac{m_{\tilde{s}_R}}{1\,\text{TeV}}\right),\ \lambda'_{333}<1.04$
B3	200 MeV	$\lambda'_{112}\left(M=K^\pm,K^0_{L/S}\right)$	λ_{322}	$\lambda'_{112}<0.21\left(\frac{m_{\tilde{s}_R}}{1\,\text{TeV}}\right),\ \lambda_{322}<0.7\left(\frac{m_{\tilde{\mu}_R}}{1\,\text{TeV}}\right)$
B4	300 MeV	$\lambda'_{221}\left(M=D^\pm,K^0_{L/S}\right)$	λ_{233}	$\lambda'_{221}<1.12,\ \lambda_{233}<0.7\left(\frac{m_{\tilde{\tau}_R}}{1\,\text{TeV}}\right)$
B5	500 MeV	$\lambda'_{222}\left(M=D_S^\pm\right)$	λ'_{222}	$\lambda'_{222}<1.12$
B6	1 GeV	$\lambda'_{313}\,(M=B^\pm,B^0)$	λ'_{333}	$\lambda'_{313}<1.12,\ \lambda'_{333}<1.04$

Table 1. Benchmark scenarios considered in this paper. The neutralino is produced through the rare decay of the meson M via the coupling $\lambda^{\rm P}_{ijk}$: $M \to \tilde{\chi}_1^0 + \ell\,(\nu)$. The neutralino decay is as in eq. (2.4) via the coupling $\lambda^{\rm D}_{ijj}$. The photon energy in the neutralino rest frame is $E_\gamma = m_{\tilde{\chi}_1^0}/2$, but can range from $\mathcal{O}\,(0.1)$ to $\mathcal{O}\,(1)$ TeV at FASER. In the furthest-to-the-right column, we list the current best bounds on the couplings, see for example, ref. [38].

$$BR(\tilde{\chi}_1^0 \to \gamma + \nu)$$

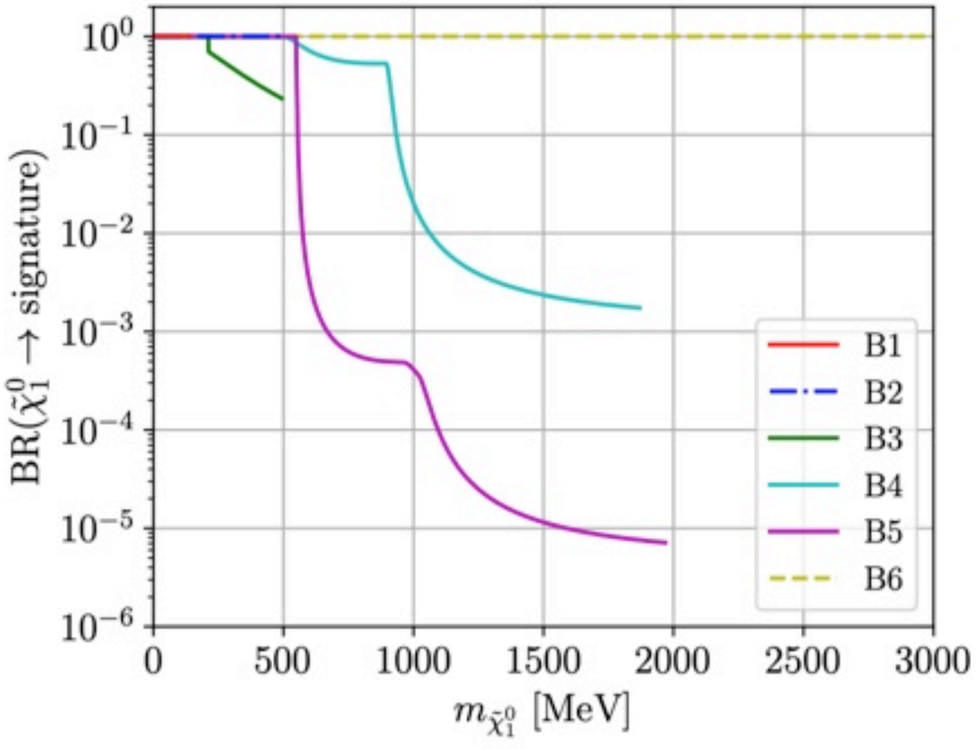


Figure 2. Branching ratios of the lightest neutralino into the single-photon signature, with varying neutralino mass.

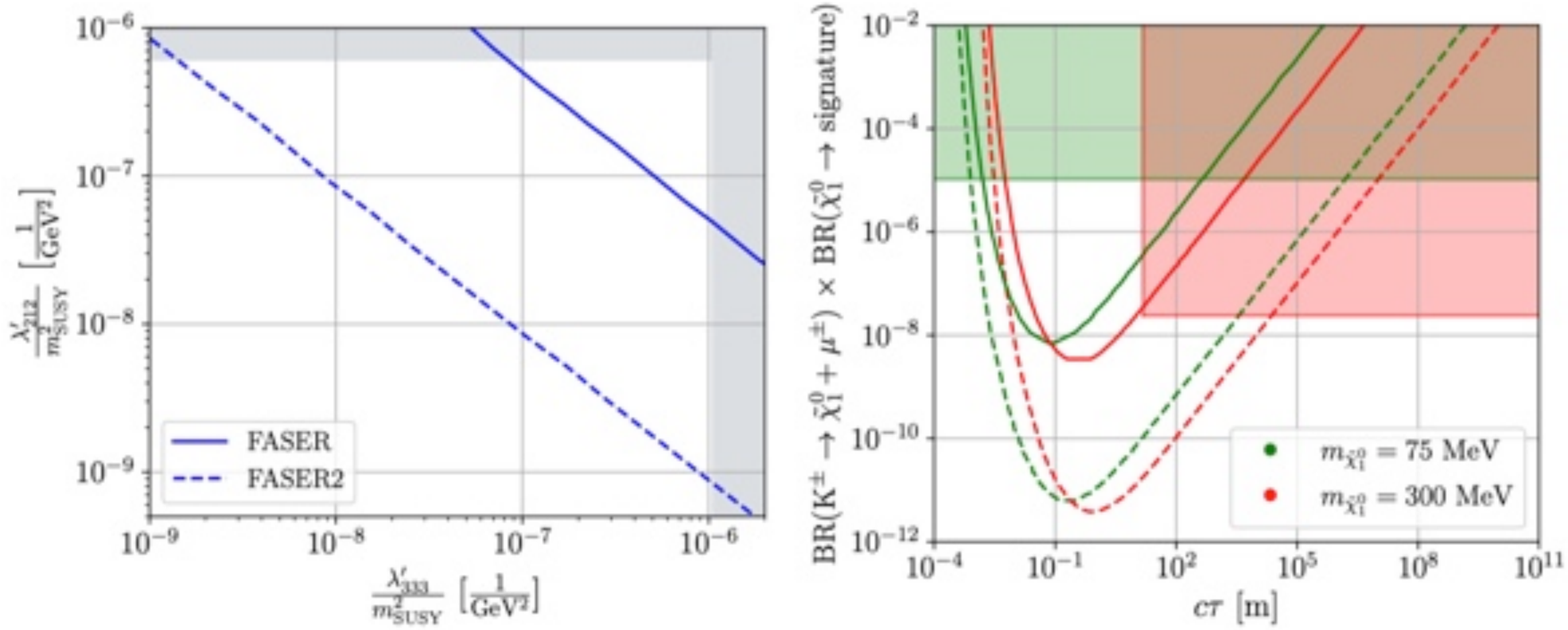
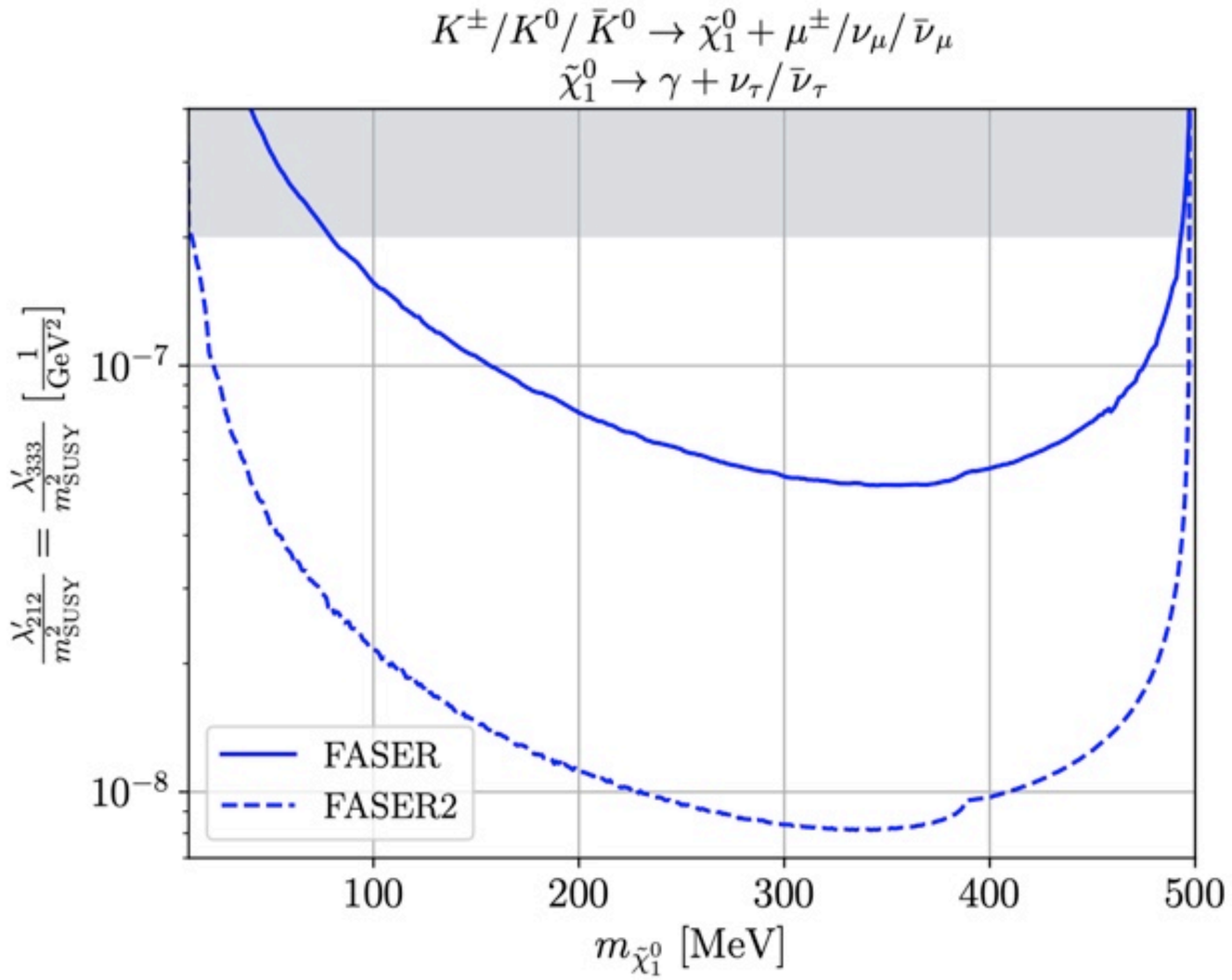
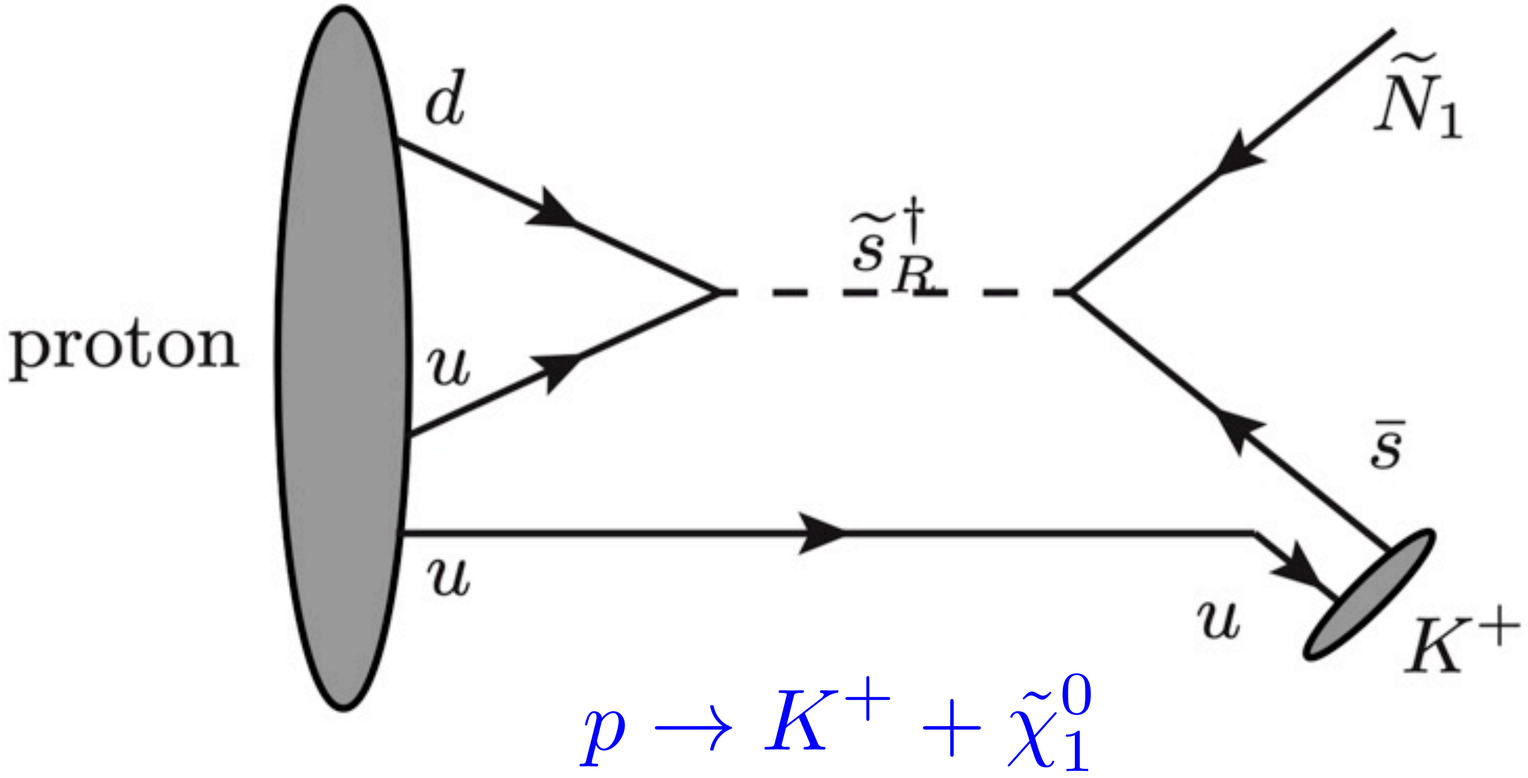


Figure 5. As in figure 3 but for the benchmark scenario **B2** with $m_{\tilde{\chi}^0_1} = 75\,\text{MeV}$, *cf.* table 1. The right plot shows the sensitivity reach in $\text{BR}(K^\pm \to \tilde{\chi}^0_1 + \mu^\pm) \times \text{BR}(\tilde{\chi}^0_1 \to \text{signature})$ as a function of the neutralino decay length, $c\tau$, for $m_{\tilde{\chi}^0_1} = 75$ and $300\,\text{MeV}$.

Benchmark 2


$K^{\pm}/K^0/\bar{K}^0 \to \tilde{\chi}_1^0 + \mu^{\pm}/\nu_\mu/\bar{\nu}_\mu$
$\tilde{\chi}_1^0 \to \gamma + \nu_\tau/\bar{\nu}_\tau$
$\frac{\lambda'_{212}}{m^2_{\rm SUSY}} = \frac{\lambda'_{333}}{m^2_{\rm SUSY}}$ $\left[\frac{1}{\rm GeV^2}\right]$
10^{-7}
10^{-8}
FASER
FASER2
100
200
300
400
500
$m_{\tilde{\chi}_1^0}$ [MeV]

2. Novel Proton Decay Signature



$$p \to K^+ + \tilde{\chi}_1^0$$

From Book:
From Spinors to Supersymmetry,
Dreiner, Haber, Martin!!!!

- Nucleon decay in the R-parity violating MSSM

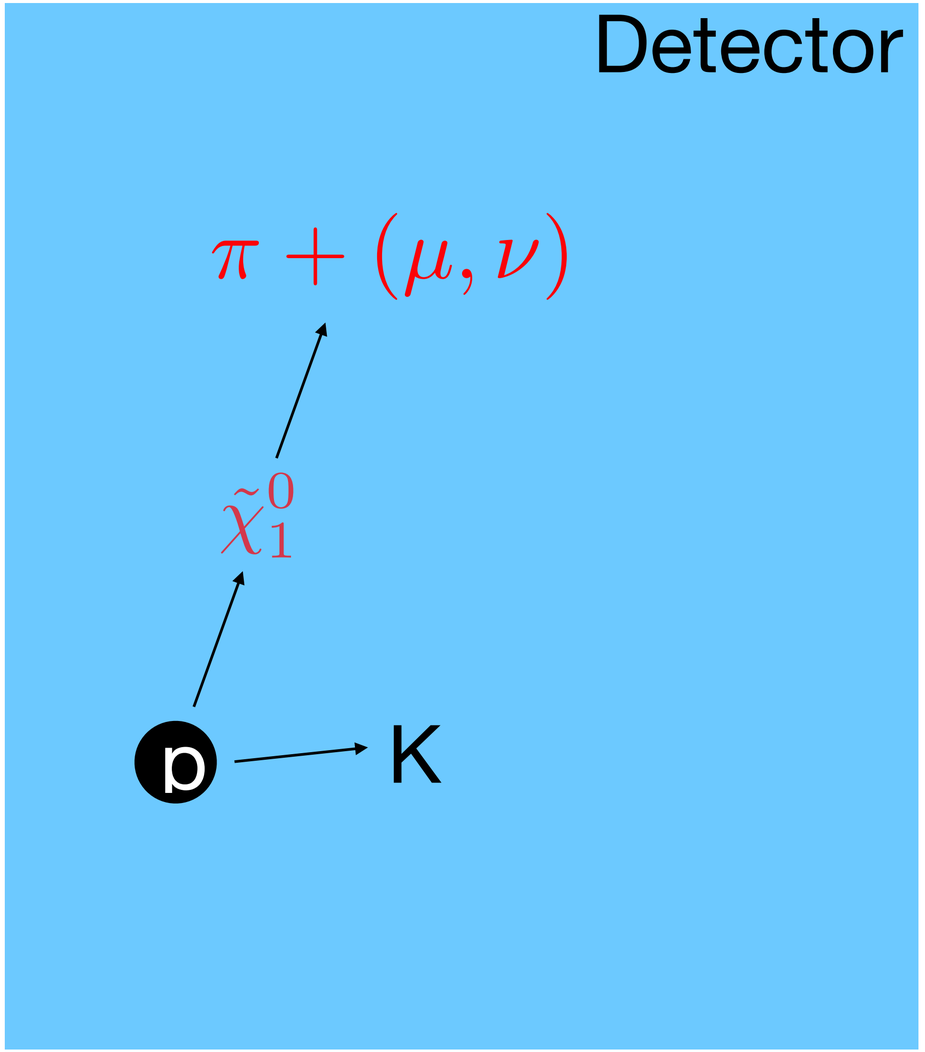
  Nidal Chamoun, Florian Domingo, HKD; PRD. 104 (2021) 015020

- A Novel Proton Decay Signature at DUNE, JUNO and Hyper-K

  HKD, Saurabh Nangia, Dominik Köhler, Apoorva Shah; (to appear shortly)

Proton Decay - Novel Decay Signature - Work in Progress

ith: Cai-Dian Lü, Apoorva Shah, Saurabh Nangia, Dominik Köhler



$$\tilde{\chi}_1^0 \to \pi + (\mu, \nu)$$

$$\tilde{\chi}_1^0 \to \gamma + \nu$$

Upcoming Detectors

	Super-K	Hyper-K	JUNO	DUNE
Geometry	Cylindrical 42 m height×39 m diameter	Cylindrical 60 m height×74 m diameter	Spherical 35.4 m diameter	Cuboidal (4 modules) 58.2 m×14 m×12 m
Detector Material	Water	Water	LABs	Liquid Argon
Working Principle	Cherenkov	Cherenkov	Scintillation	Scintillation
Fiducial Mass	22.5 kt	187 kt	20 kt	40 kt
No. of Protons	$\sim 7.5 \times 10^{33}$	$\sim 6.3 \times 10^{34}$	$\sim 6.9 \times 10^{33}$	$\sim 1.1 \times 10^{34}$
$\epsilon_{inv.}$	$\mathcal{O}(10)\,\%$	$\mathcal{O}(10)\,\%$	37%	30%

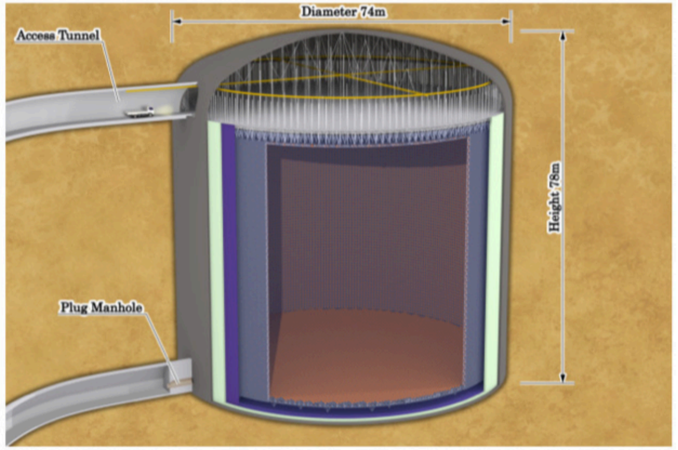


Figure 1: Hyper-K

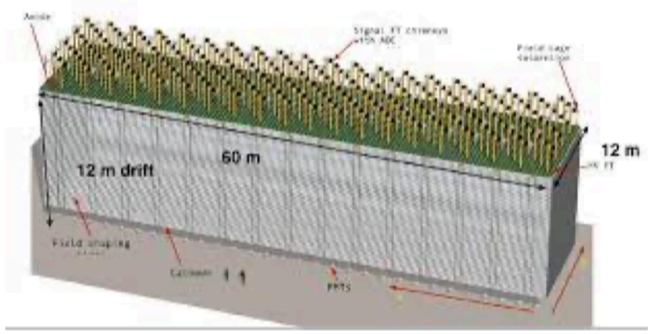


Figure 2: DUNE

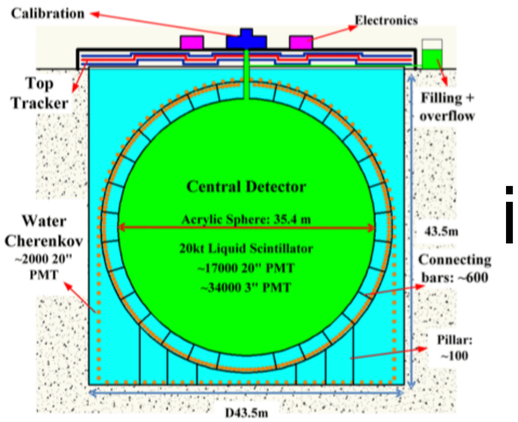


Figure 3: JUNO

includes CAS

Benchmarks

Scenario	$m_{\tilde{\chi}_1^0}$	Proton Decay	$\tilde{\chi}_1^0$ Decay $\left(\lambda^D_{ijk}\right)$	Product Bound	Min. $c\tau_{\tilde{\chi}_1^0}$
B1	$0 - 400\,\mathrm{MeV}$	$\lambda''_{121} < 5 \times 10^{-7} \left(\frac{m_{\tilde{q}}}{\tilde{\Lambda}\mathrm{TeV}}\right)^{5/2}$	–	–	∞
B2	$0 - 400\,\mathrm{MeV}$	$\lambda''_{121} < 5 \times 10^{-7} \left(\frac{m_{\tilde{q}}}{\tilde{\Lambda}\mathrm{TeV}}\right)^{5/2}$	$\lambda'_{333} < 1.04$	$\lambda'_{333}\lambda''_{121} < 10^{-9}$	$\sim 1600\,\mathrm{m}$
B3	$0 - 400\,\mathrm{MeV}$	$\lambda''_{121} < 5 \times 10^{-7} \left(\frac{m_{\tilde{q}}}{\tilde{\Lambda}\mathrm{TeV}}\right)^{5/2}$	$\lambda_{233} < 0.7 \left(\frac{m_{\tilde{\tau}_R}}{1\,\mathrm{TeV}}\right)$	$\lambda_{233}\lambda''_{121} < 10^{-21}$	$\sim 180\,\mathrm{m}$
B4	$150 - 400\,\mathrm{MeV}$	$\lambda''_{121} < 5 \times 10^{-7} \left(\frac{m_{\tilde{q}}}{\tilde{\Lambda}\mathrm{TeV}}\right)^{5/2}$	$\lambda'_{211} < 0.59 \left(\frac{m_{\tilde{d}_R}}{1\,\mathrm{TeV}}\right)$	$\lambda'_{211}\lambda''_{121} < 6 \times 10^{-25}$	$\sim 11\,\mathrm{m}$
B5	$150 - 400\,\mathrm{MeV}$	$\lambda''_{121} < 5 \times 10^{-7} \left(\frac{m_{\tilde{q}}}{\tilde{\Lambda}\mathrm{TeV}}\right)^{5/2}$	$\lambda'_{311} < 1.12$	$\lambda'_{311}\lambda''_{121} < 4 \times 10^{-24}$	$\sim 30\,\mathrm{m}$

(rad)

$\tilde{\chi}_1^0 \to \pi^\pm + \mu^\mp, \;\; \pi^0 + \nu_\mu$

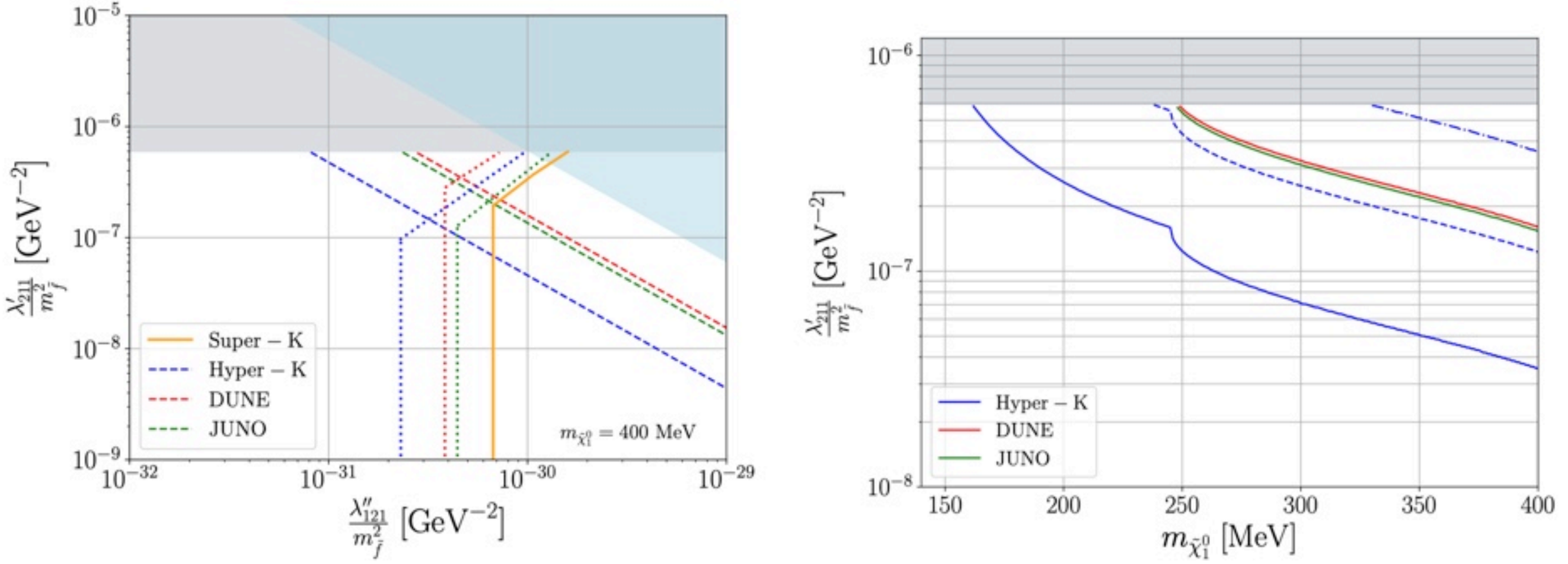


Figure 7: Sensitivity reach/Super-K limit for benchmark **B4**. The existing single-bound on λ'_{211} from Table 2 is shown in gray, the product-bound is in blue (both with $m_{\tilde{f}} = 1\,\text{TeV}$), while the bound on λ''_{121} lies outside the scale of the plot. *Left:* As in left plot of Fig. 5 but for benchmark **B4**. *Right:* As in right plot of Fig. 4 but for benchmark **B4**. The solid, dashed, and dot-dashed lines correspond to 3-, 30- and 90-event isocurves, respectively.

P.S.

Completing 2nd book: Popular Physics Book

Faszinierende Teilchenphysik

Springer Verlag

Co-Authors: Philip Bechtle (Bonn)
Florian Bernlochner (Bonn)
Josef Jochum (Tübingen)
Christoph Hanhart (FZ Jülich, Bonn)
Jörg Pretz (Aachen, FZ Jülich)