Dark sector particle searches
and
Directional Detection
with
Gas Time Projection Chambers

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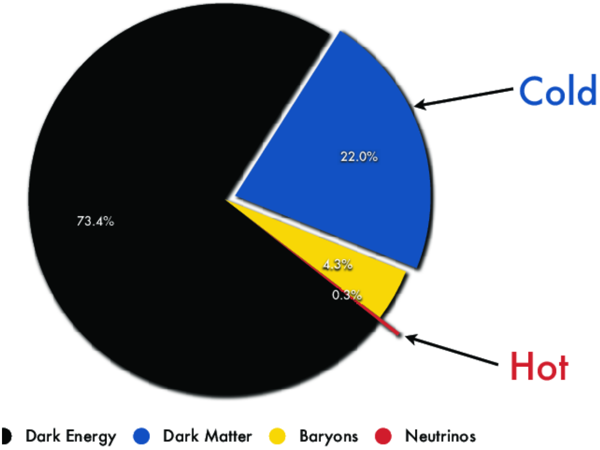
Personal details

	Professional Experience
2010–present	**University of Hawai'i, Honolulu, USA.**
	Post-doc in Experimental Physics.
2008-2010	**University of Basel, Basel, Switzerland.**
	Post-doc in Experimental Physics.
2001–2007	**University of Basel, Basel, Switzerland.**
	Graduate student in Experimental Physics.
	Collaborations
2010–present	Belle and Belle II (Tsukuba, Japan).
2010–present	Directional Dark matter Detector - D^3 (Honolulu, HI, USA).
2010–2013	Dark Matter Time Projection Chamber - DMTPC (Carlsbad, NM, USA).
2008–2010	Crystal Ball and Travel Around Photon Spectrometer - A2 (Mainz, Germany).
2001–2010	Crystal Barrel and TAPS - CB-ELSA/TAPS (Bonn, Germany).
	Education
2001–2007	**University of Basel, Basel, Switzerland.**
	Ph.D. in Experimental Physics - “SUMMA CUM LAUDE”
1999–2000	**University of Haute-Alsace, Mulhouse, France.**
	Diplôme d'Etude Approfondie (DEA) de physique subatomique.
1998–1999	**Louis Pasteur University, Strasbourg, France.**
	Maîtrise de Chimie-Physique.

We know there is dark matter / Introduction



- Can Belle/Belle II and/or a directional detection detector contribute to the dark sector particle searches ?

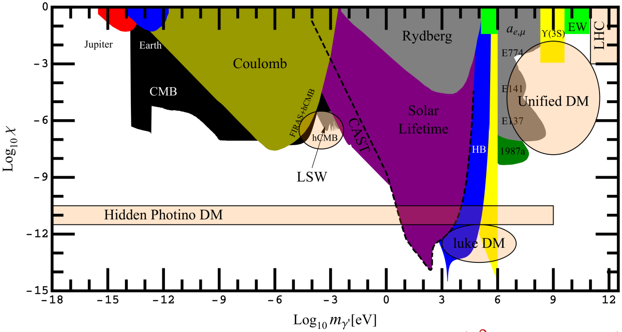
Dark gauge boson / Introduction

to be distinguished from dark matter or WIMP, coupling to SM fermions via EM current are:

- searched since the late 80's, it may or may not exist but
- many theorists think there is a larger dark sector,

  hence recent strong interest in dark sector models (Unified DM)
- introduce a vector boson A, and often a dark Higgs h' by a Higgs mechanism
  - plot below shows astrophysical and cosmological, constraints and experimental limits:

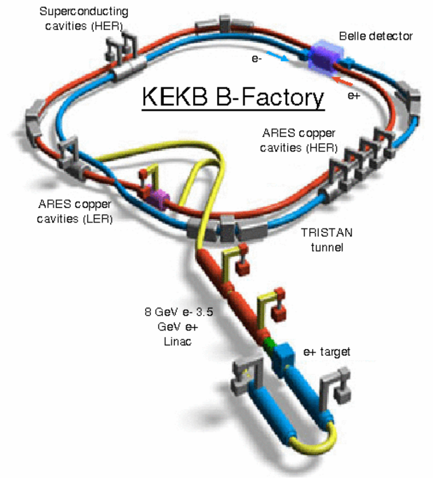
    kinetic mixing vs. A boson mass J. Jaeckel and A. Ringwald - arXiv:1002.0329v1
    - ★ kinetic mixing: χ/ϵ

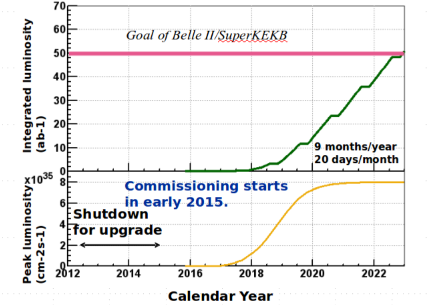


=> BaBar, Belle and Belle II can cover region between few 10's of MeV/c^2 and 10 GeV/c^2

SuperKEKB, the intensity frontier

- Belle/Belle II experiment at KEK/super KEK B-factory in Tsukuba, Japan
- Belle@KEKB L $= 977$ fb^{-1} at $\Upsilon(1S, 2S, 3S, 4S, 5S)$ and continua
- Belle II@superKEKB L$_{projected}$ $= 40$ ab^{-1} at $\Upsilon(1S, 2S, 3S, 4S, 5S, 6S)$ and continua





$$L = \frac{\gamma_{\pm}}{2 e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{\pm y}}{\beta_y^*}\left(\frac{R_L}{R_y}\right)$$

- nano-beam scheme extremely small β_y^* low emittance
- beam current x 2

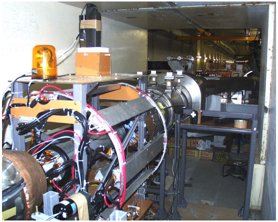
S. Kurokawa and E. Kikutani NIM A 499, 1 (2003)

superKEKB luminosity will generate huge beams-induced background

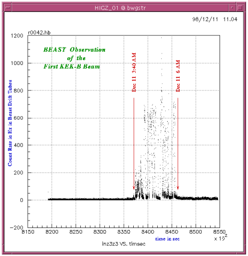
Beam commissiong detectors before Belle

aka BEAST used in 1998 to monitor radiation level and particle rates during KEKB commissioning

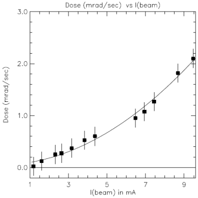
- BEAST in the cave



- first beam



- rate

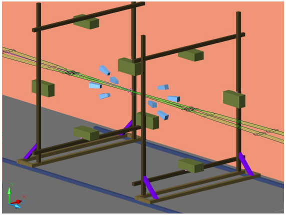


- provided important feedback to accelerator group during commissioning, and ensured background levels acceptable before Belle roll-in
- located at IP composed of PIN diodes, MOSFETs, Drift tubes, CsI and two Silicon Strip Ladders
- but did not prevent synchrotron radiation from damaging first beampipe

Beam commissioning detectors before/during Belle II

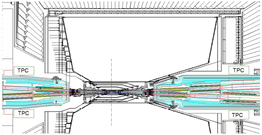
- measure instantaneous and integrated radiation dose at position of Belle II subdetectors
- measurements of luminosity and background levels during beam commissioning
- synchrotron and neutron backgrounds were unexpectedly problematic in Belle, we would like to measure
- details understanding and Monte Carlo simulation validation of beam-induced backgrounds
    - Touschek: intra-bunch scattering, electron/positron deviates from beam-bunch by Coulomb scattering
    - Coulomb (beam-gas scattering): electron/position scattering with residual gas-atoms
    - Radiative Bhabha process propagate along beam axis and interact with magnet iron
    - synchroton radiation: emitted by the beam since α E_e^2 and B^2, High Energy Ring beam dominat
    - also two-photon and beam-beam but not critical background

- phase 1



- non magnetic support structure (Rosen, Hawaii)
- BGO crystals for luminosity monitoring (Wang, NTU)
- Diodes for radiation monitoring (Cinabro, Wayne / Marinas, Bonn)
- few PXD, SVD modules (MPI, KEK)
- CDC prototype (Uno, KEK)

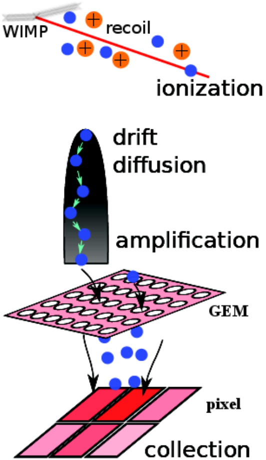
- phase 2



- microTPCs for directional neutron detection, xrays, tracks (Vahsen, Hawaii)
- thermal neutron detection system (Roney, Victoria)

Gas Time Projection Chambers (TPCs)

Time Projection Chamber as fast neutrons/WIMPs detector filled with gas



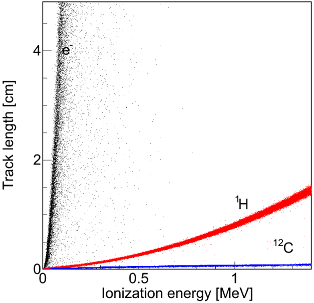
- fast neutrons not detected directly
- but through their scattering product with
- the gas-nucleus by elastic scattering
  $n + A_{rest} \rightarrow n' + A_{recoil}$
- nuclear recoil ionizes gas along track
- electric field moves charges
- amplification (by 2 GEMs)
- readout (FE-I4B pixel chips)
  - 2D charge distribution
  - + timing information
  - + known drift velocity => 3D hit information
  - + known GEMs gain (and QF) => energy

=> we reconstruct the nuclear recoil (θ,ϕ,E)

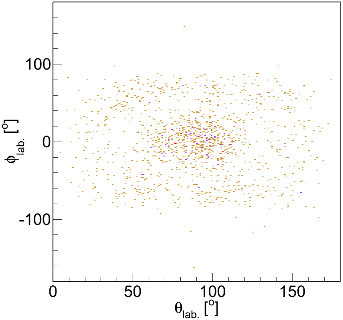
Directional detection concept

3D-direction and total ionization energy measurements of nuclear recoil allow

- dE/dx topology (iso-butane at 1 atm)



- nuclear recoil "profil"
  - not energy weighted
  - distribution points back to neutron direction (along x-axis)



$$E_{recoil} = E_{neutron}^{incident} \cdot \frac{2m_{recoil}.m_{neutron}}{(m_{recoil}+m_{neutron})^2}.(1+cos\psi_{cm})$$

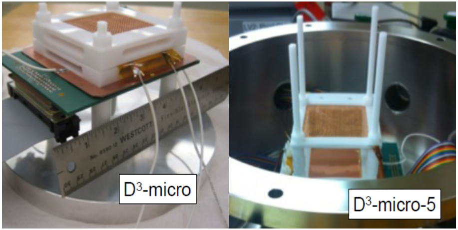
with $\psi_{cm} = 2\ \psi_{lab.}$, ψ_{lab} opening angle between indicident neutron and nuclear recoil ($cos\psi_{lab} = \frac{\vec{n}\vec{A}}{n.A}$)

pre-prototype-micro-TPC / TPC characterisation

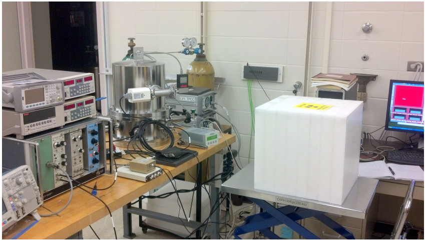
R&D with a pre-prototype TPC: S.E. Vahsen et al. http://arxiv.org/abs/1110.3401

- volume from ∼ 0.61 cm^3 to ∼ 2.5 cm^3
- charge amplified by 2 GEMs
- detected by ATLAS Pixel Chip FE-I3

- inside vacuum vessel
  NB: white material corresponds to delrin



- vaccum vessel + neutron source



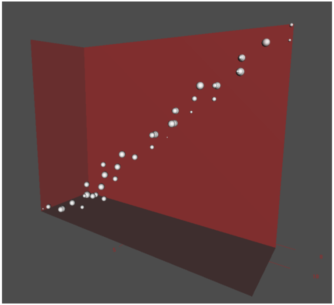
- stable operation for more than a year, large datasets recorded
  - commissioning w/ Ar:C0$_2$:70:30; muons, x-rays, alpha-particles (11,12)
  - detailed calibration & directional neutron detection w/ He:C0$_2$:70:30 (Fall 12-now)

ATLAS Pixel Chip electronics / TPC characterisation

High gain + ATLAS Pixel Chip electronics allows full 3D tracking

- track range (position resolution)
- track dE/dx (topology)
- track total ionization energy (energy resolution)
- track direction (angular resolution)

- cosmic-ray trak: ∼ 7 mm and 2 keV measured by micro-D^3 prototype



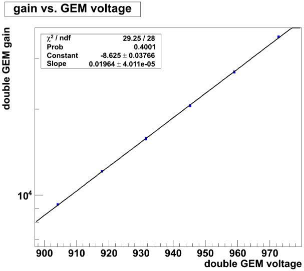
- FE-I3 low-noise and low-threshold
  - chip size 0.84 cm x 0.76 cm
  - pixel size 50 μm x 400 μm
  - 18 column x 160 row
  - 400 ns time range with 16 graduation
  - threshold 3000 e^-
  - 100k e^- charge range with 128 graduation
- FE-I4 low-noise and low-threshold
  - chip size 2 cm x 1.68 cm
  - pixel size 50 μm x 250 μm
  - 80 column x 336 row
  - 1600 ns time range with 64 graduation
  - thresold 1400 e^-
  - 100k e^- charge range with 16 graduation

- virually no noise
- high-single electron efficiency => suitable for low-mass WIMP search

Gain resolution and stability / TPC characterisation

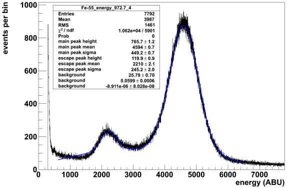
High gain w/o sparking for weeks, measurement w/ pulseheight analyzer

- gain vs voltage

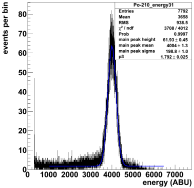


- sufficient gain to achieve single-electron sensitivity if needed
- good gain resolution for MeV-scale signals, adequate even for few-keV signals!

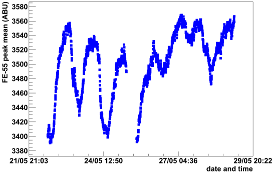
- ^{55}Fe/x-rays source
  $\sigma_{gain} = 11\ \%$ at 3 keV
  $\sigma_{gain} = 8\ \%$ at 5.9 keV



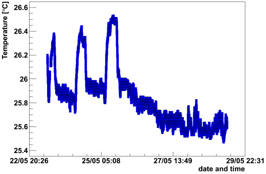
- ^{210}Po/alpha source
  $\sigma_{gain} = 5\ \%$ at 5 MeV



- 5.9 keV x-ray peak vs. time

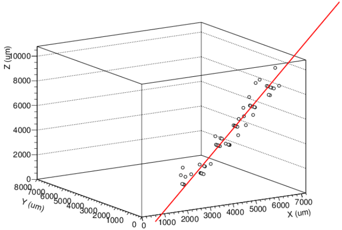


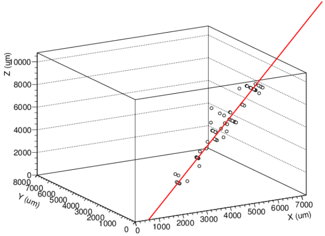
- temperature vs. time

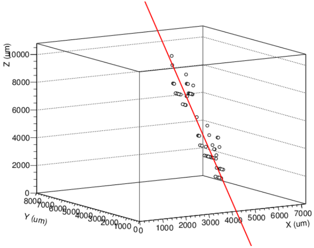


3D point resolution / TPC characterisation

10k events of cosmics recorded with Ar:CO_2:70:30 at 1 atm, use such events to measure detector point resolution ($< 200\ \mu$m)





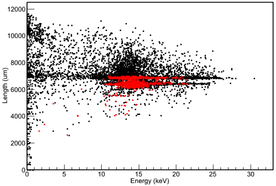


=> based on measured point resolution, expect angular resolution on nuclear recoils $\sim$ 1 degree

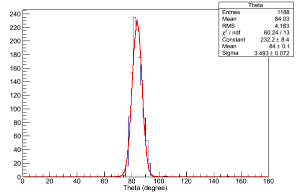
Angular resolution, nuclear recoils / TPC characterisation

^{210}Po alpha-source inside vacuum vessel, He:CO$_2$:70:30 at 1 atm, plots below show how well we can locate it:

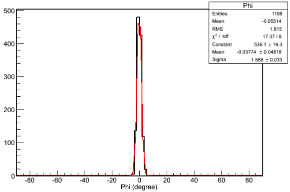
- track length vs. total ionization energy



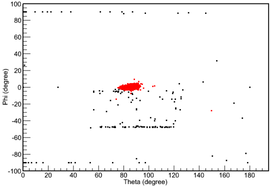
- polar angle distribution



- azimuthal angle distribution

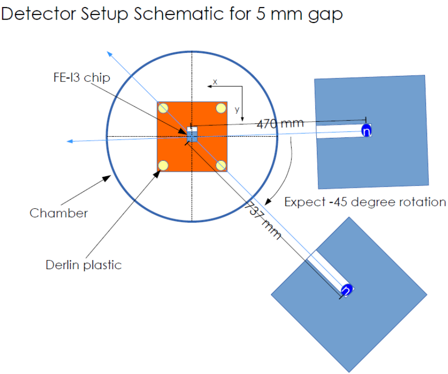


- azimuthal vs polar angles



- selected events clearly point back to a single source
- No BG after good-track selection
- consistent with $\sigma(\theta,\phi)$ detector $< 1^o$

neutron setup / TPC characterisation

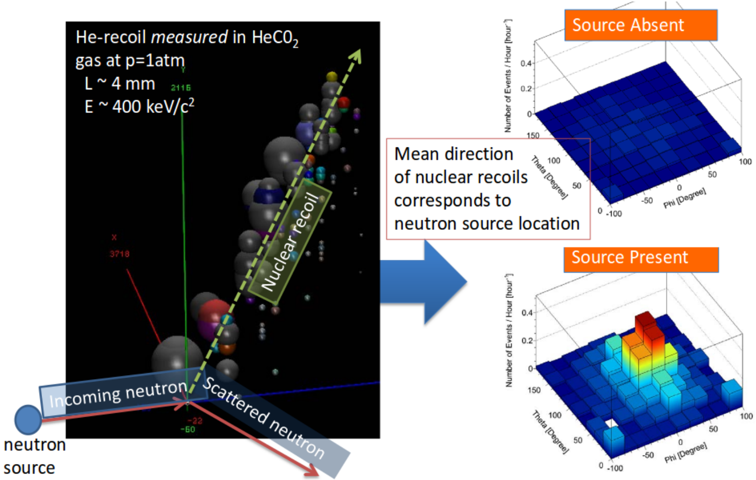


4 settings of the source:

- theta = 90 degrees and phi = 0 degrees
- theta = 90 degrees and phi = 45 degrees
- theta = 90 degrees and phi = -45 degrees
- theta = 65 degrees and phi = 45 degrees

Directional Neutron Detection / TPC characterisation

DCube-micro-5 (He:CO_2:70:30 in 1 atm with FE-I3 board) measurement in LAB. with a pseudo neutron beam emitted by ^{252}Cf-source



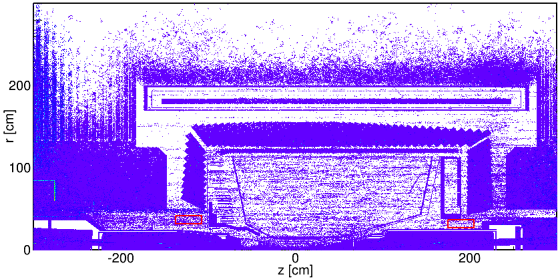
Mean direction of nuclear recoils corresponds to neutron source location

=> recoil angular distribution points back to the neutron direction

Micro-TPC conceptual design / Micro-TPC design

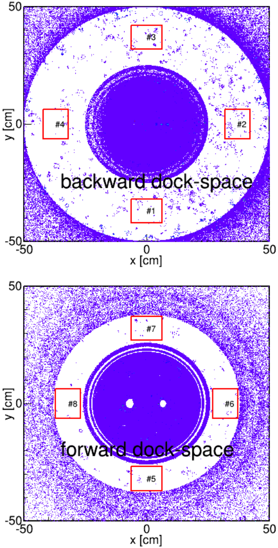
TPCs positioned to disentangle the different sources of neutrons by measuring the angular distribution of the recoil nucleus.

- “phase 2” top view - TPCs located in dock-spaces



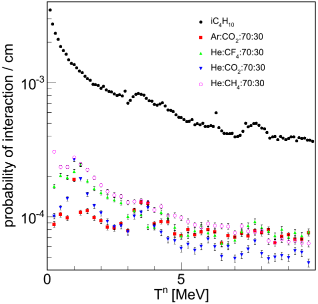
- 8 TPC chambers 10.12 x 12.7 x 30 cm^3
- active volume 5$\times$5$\times$25 cm^3
- surface from 0.72 x 0.8 to 4 x 3.36 cm^2 can be instrumented
- E $\|$ B (0.3 to 0.9 kV/cm [depending of the chip and gas] $\|$ 1.5 T)

- “phase 2” R-phi view

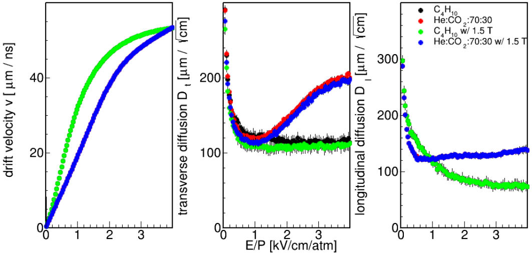


Gas choice / Micro-TPC desgin

- good neutron detection efficiency
- attachment coefficient low
- gas gain o(100)
- simulate gas / gas mixture with
  - iC_4H_{10} (flammable and explosive)
  - $Ar:CO_2$
  - $He:CO_2$
  - $He:CF_4$
  - $He:CH_4$ (flammable, but not explosive)



- Gas parameters calculation by MAGBOLTZ and effect of 1.5 T magnetic field

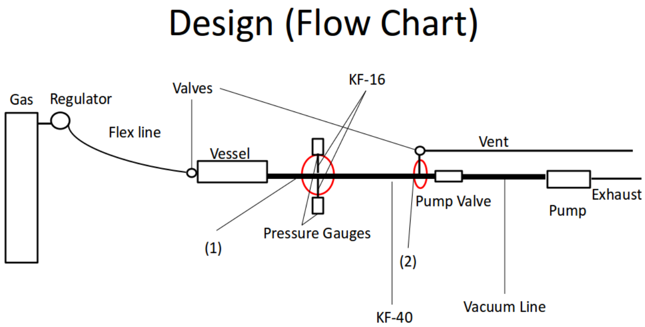


- B-field has negligle effect (for gases with small drift velocity)
- we want E || B
- if not E || B => diffusion and drift velocity more complex form

=> best trade off between safety, efficiency, gas propertires and track length is given to $He:CO_2$:70:30 at 1 atm

Gas system / Micro-TPC design

- gas
- regulator
- gas in/out
- exhaust
- mechanical overpressure release
  - gas system designed by Michael Hedges



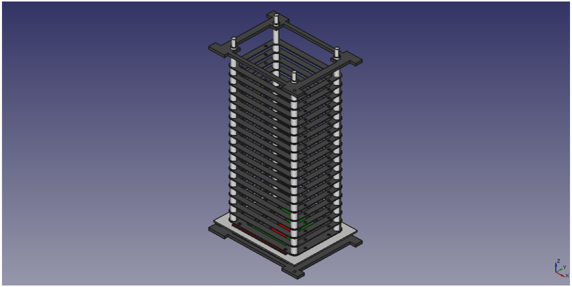
=> all parts ordered

Field cage (FC) / Micro-TPC design

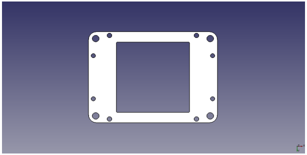
FC encircles sensitive volume and produced the electric field, it is composed of:

- an anode plane, field-shaping rectangular rings and a cathode
- connected to a resistor chain creating a linearly degrading potential

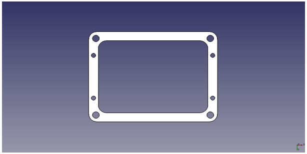
- full structure
  - 7 mm/10 mm gap between each rectangular rings
  - 15 cm drift gap
  - rings are 1 cm from the vessel wall



- cathode



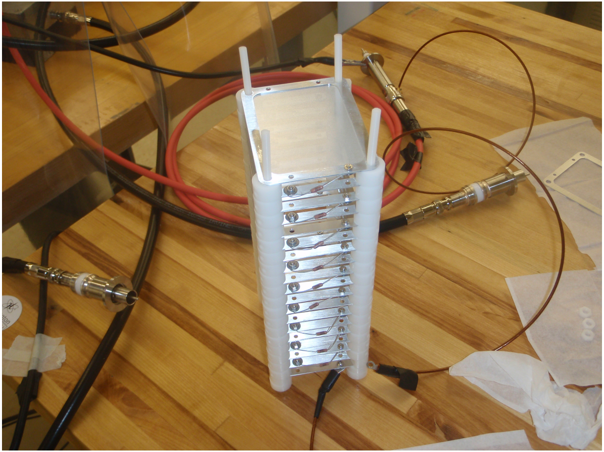
- rectangular ring



- anode: rectangular ring at which is glued a mesh

v_{drift} [μm/ns]	D_t [$\mu m/\sqrt{cm}$]	E [kV/cm]	V_{anode} [kV]
10	124.3	0.53	$7.95+V_{GEM_2^{top}}$

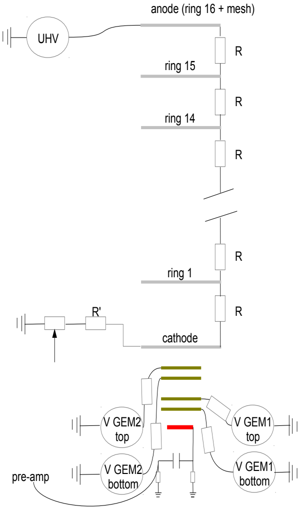
Field cage (FC) / Micro-TPC design



v_{drift} [μm/ns]	D_t [$\mu m/\sqrt{cm}$]	E [kV/cm]	V_{anode} [kV]
10	124.3	0.53	$7.95+V_{GEM_2^{top}}$

HV bias / Micro-TPC desgin

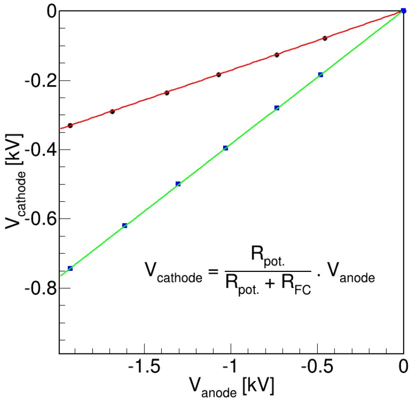
- circuit diagram



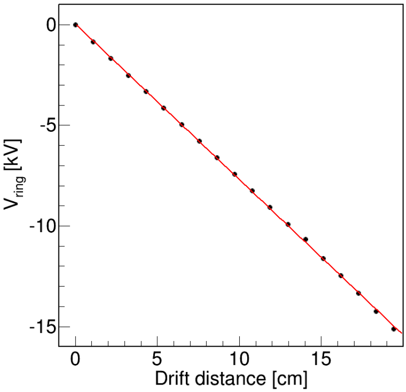
- R = 4 MΩ ± 0.1 % => R^{total} = 64 MΩ
- GEM HV range between 900 V and 2000 V
- $V_{anode}^{max} = 10.48$ kV
- $I = 132.5\ \mu A$
- R' = 15.16 MΩ
- $15.16 \leq R' + R_{potentiometer} \leq 45$ MΩ
- $V_{cathode} = V_{GEM_2^{top}} + 530$ V/cm x 0.06 cm
- $V_{anode} = V_{cathode} + 530$ V/cm x 16 cm
- $V_{cathode} = \frac{R' + R_{potentiometer}}{R' + R_{potentiometer} + R} . V_{anode}$
- procedure to set the field:
  - set first GEM HV
  - tune offline $R_{potentiometer}$ to the desired value
  - connect potentiometer box cables and switch on UHV
  - set V_{anode}

HV bias check / Micro-TPC design

- potentiometer range



- field measurement at 15 kV



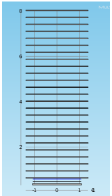
- $V_{anode} \, . \, 0.171 \leq V_{cathode} \leq V_{anode} \, . \, 0.386$
- sparking at Feedthrough level above 15 kV
- field homogeneity below 3%, measurement limited by voltometer precision

Radial displacement (Δr) / Micro-TPC design

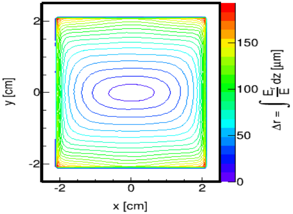
Electric field should be as uniform as possible to minimize distortions of the reconstructed tracks

- $\Delta r(x,y) = \int_{z=0}^{z_{max}/2} \frac{E_r(x,y,z)}{E(x,y,z)} dz$ with
  - z drift distance
  - E_r radial field
  - E field
- Finite Element Method (FEM) used to study the uniformity (in COMSOL)

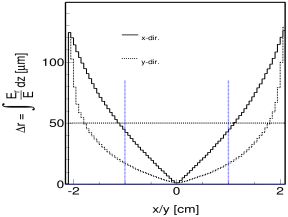
- field cage in COMSOL



- Δr vs. x vs. y



- Δr for x=0 and y=0, blue dashed lines represent one chip



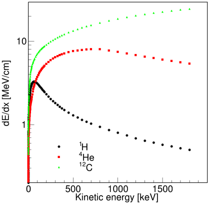
- point resolution in r$\phi < 125\ \mu m$ in the 15 cm drift gap
- point resolution in z $< 250\ \mu m$ in the 15 cm drift gap

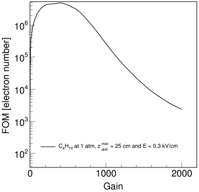
Gain gas optimization / Micro-TPC design

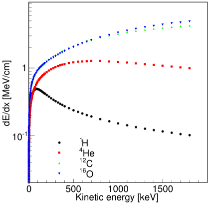
To achieve the highest possible detection of the primary ionization, GEMs are used to amplify the signal.

- GEMs are gate-less, can operate continuously and have intrasic ion feedback suppression
- gain has to be adapted to the amount of ionization

- iso-butane at 1 atm
  - SRIM dE/dx
  - gain FOM
- He:CO_2:70:30 at 1 atm
  - SRIM dE/dx
  - gain FOM







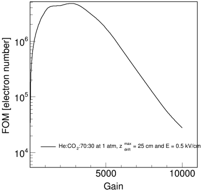


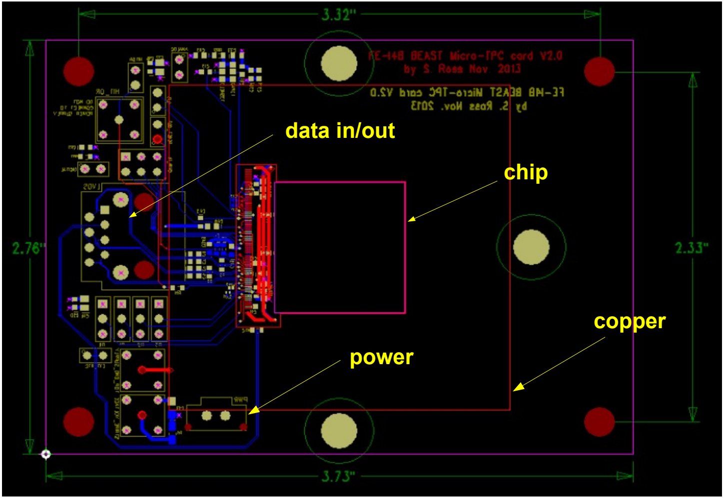
Table: Average electron number per pixel and optimal gain for He:CO_2:70:30 and C_4H_{10} at 1 atm.

gas	He in He:CO_2:70:30	H in C_4H_{10}
electron number per pixel	171	1294
optimal gain	2800	600

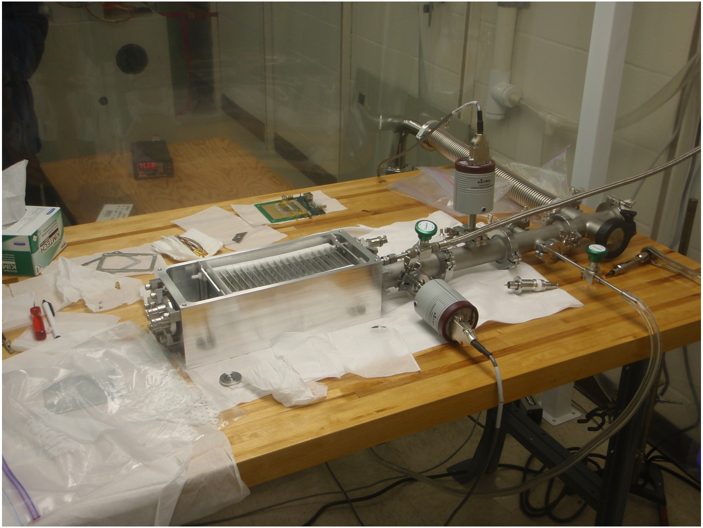
Electronics / Micro-TPC design

We will use FE-I4B with a single chip for the first prototype:

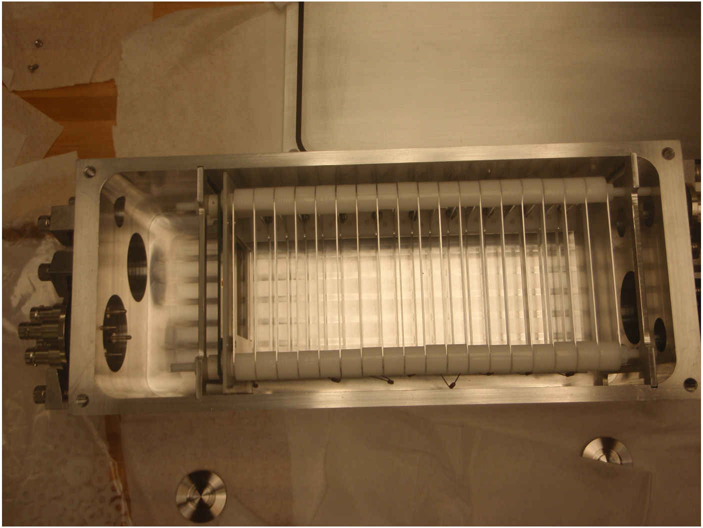
- board



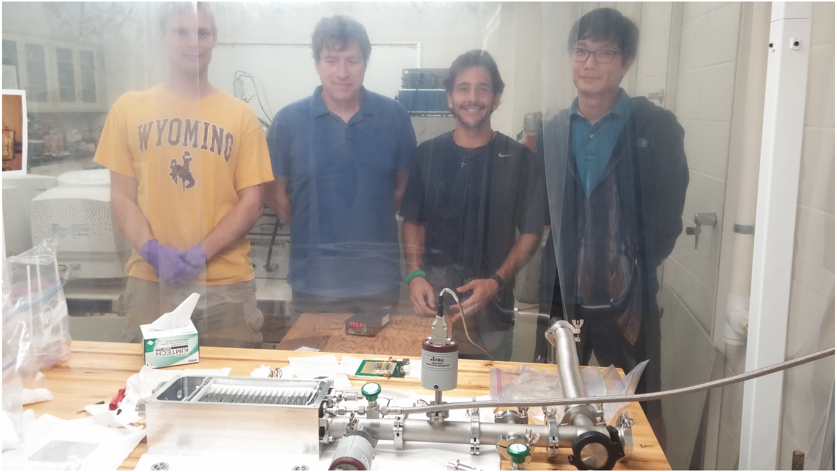
Nice picture I / Micro-TPC design



Nice picture II / Micro-TPC design



Nice picture III / Micro-TPC design

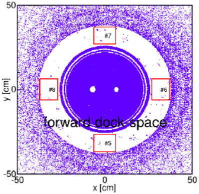


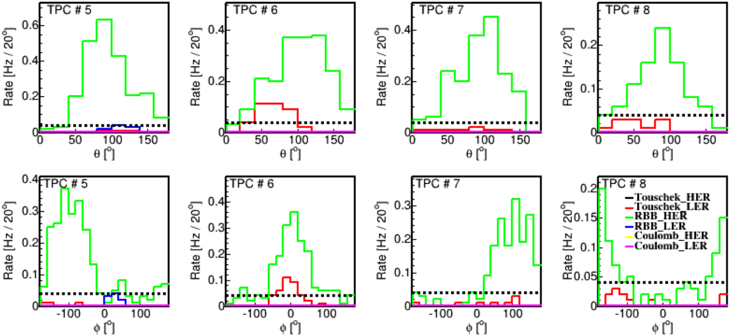
Left to right: Gas System, Speaker, Machine Shop and USBpix-DAQ/LV/HV

Recoil angle rate distribution in forward TPC

MC simulation with 1 chip and He:CO_2:70:30 at 1 atm

- RBB LER dominates at end of phase2
- with single beams
  - no RBB
  - measure Touschek
  - with vacuum bump Coulomb can be measured

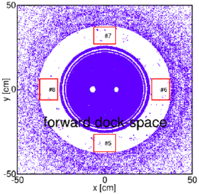


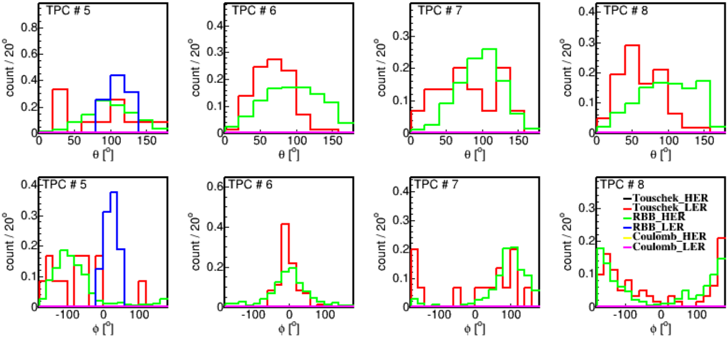


Recoil angle re-normalized distribution in forward TPC

MC simulation with 1 chip and He:CO_2:70:30 at 1 atm

- re-normalized distributions
- clear difference visible

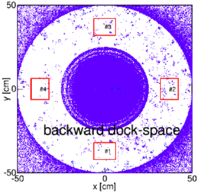


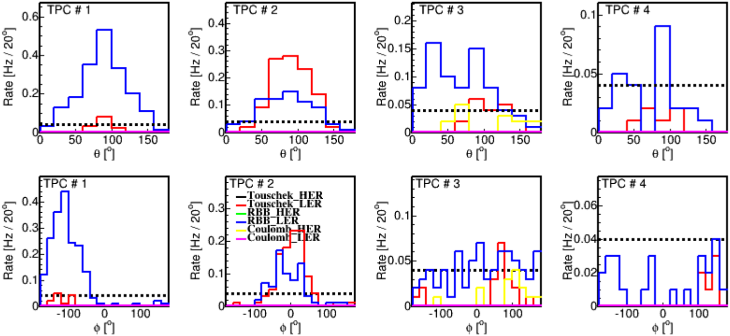


Recoil angle rate distribution in backward TPCs

MC simulation with 1 chip and He:CO_2:70:30 at 1 atm

- RBB LER dominates at end of phase2
- with single beams
    - no RBB
    - measure Touschek
    - with vacuum bump Coulomb can be measured

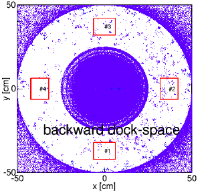


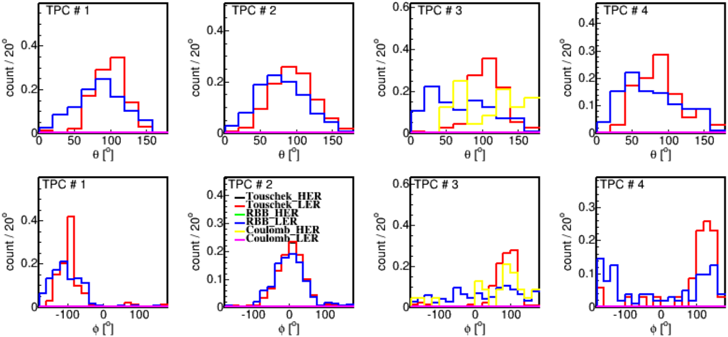


Recoil angle re-normalized distribution in backward TPCs

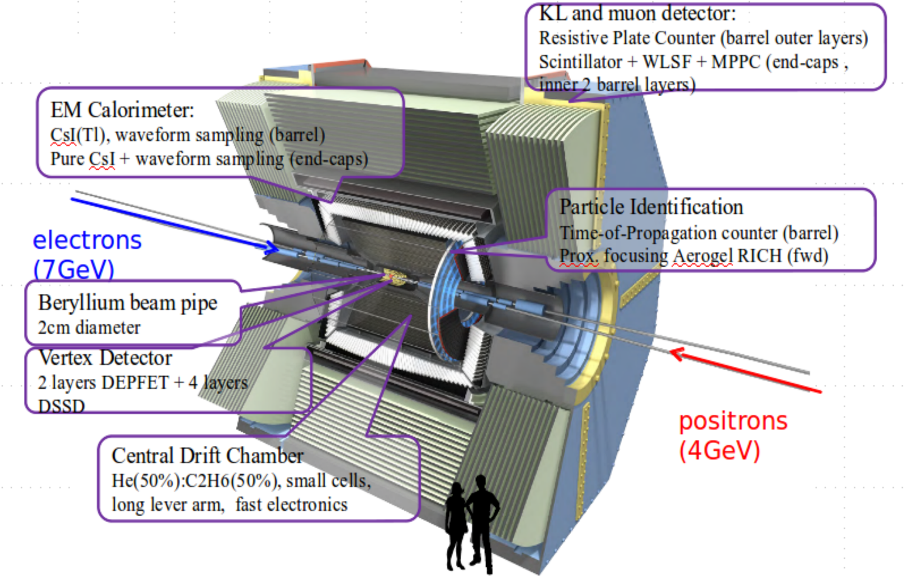
MC simulation with 1 chip and He:CO$_2$:70:30 at 1 atm

- re-normalized distributions
- clear difference visible





Belle/Belle II setups

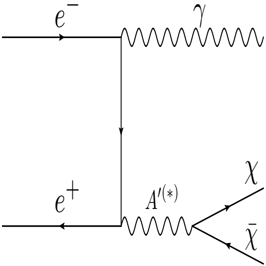


Radiative channels

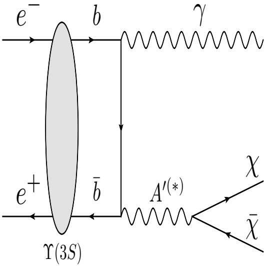
Belle may have or/and Belle II may produce dark matter, χ, dark photon (dark gauge boson), A; and dark Higgs h' as long as the mass of each is low in the following channels:

- Radiative decay:
- $e^+e^- \to \gamma X$
- $e^+e^- \to \Upsilon(nS) \to \gamma X$
    - $X = \chi\bar{\chi}$
    - $X = A$
    - $A \to l^+l^-$ or hadrons or dark matter

★ two body decays



★ upsilon decays



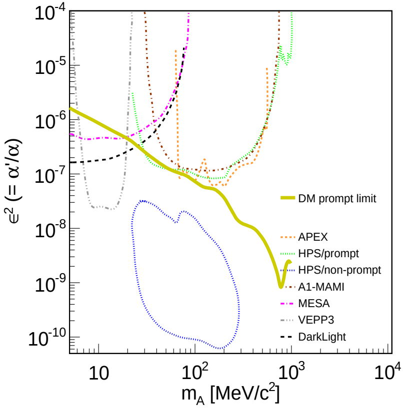
NB: dark photon or dark gauge boson has no normalized name and letter: γ', A ,A' or U

Radiative channels, γA

6 experiments have been approved/commissioned and will cover region between 1 MeV/c^2 and 1 GeV/c^2

- all experiments will look for a prompt decay and $A \rightarrow l^+ l^-$ by detecting the leptons
- HPS will also look for a displaced vertex.
- Belle/Belle II could set a limit between 200 MeV/c^2 and 10 GeV/c^2

- predicted sensitivity



- VEPP3/Russia (new setup), $e^+ + p \rightarrow \gamma A$
- APEX/USA-JLAB (new setup), $e^- +$ nucleus $\rightarrow \gamma A$
- HPS/USA-JLAB, $e^- +$ nucleus $\rightarrow \gamma A$
- DarkLight/USA-JLAB (new setup), $e^- +$ H $\rightarrow \gamma A$
- A1-MAMI/Germany, $e^- +$ nucleus $\rightarrow \gamma A$
- MESA/Germany (new accelerator and setup), $e^- +$ nucleus $\rightarrow \gamma A$

A not necessarely prompt

Radiative channels, γA

6 experiments have been approved/commissioned and will cover region between 1 MeV/c^2 and 1 GeV/c^2

- all experiments will look for a prompt decay and $A \to l^+ l^-$ by detecting the leptons
- HPS will also look for a displaced vertex.
- Belle/Belle II could set a limit between 200 MeV/c^2 and 10 GeV/c^2

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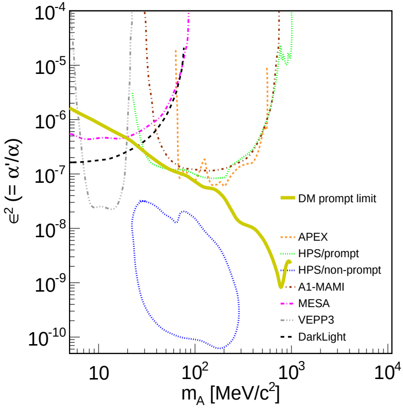
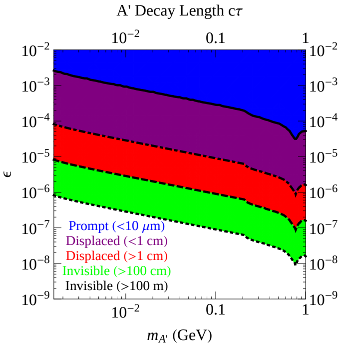


- plot shows lifetime of A as a function of its mass m_A and ϵ
  R. Essig et al, arXiv:0903.3941



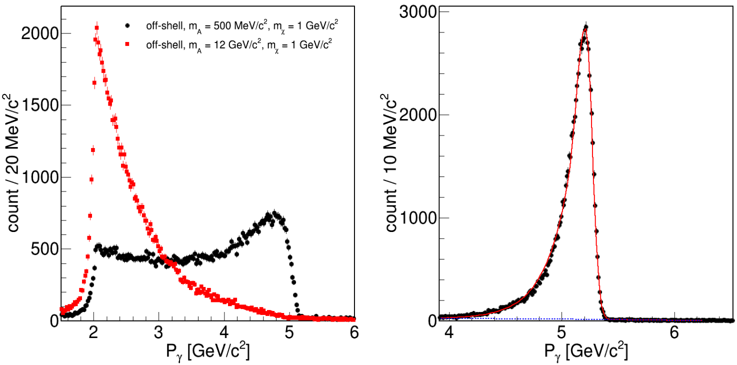
MC simulation of signal signature / Radiative decay

Dark matter can be produced in two modes:

- off-shell i.e. $e^+e^- \to \gamma\chi\bar{\chi}$
- on-shell i.e. $e^+e^- \to \gamma A, A \to \chi\bar{\chi}$
- simulated photon spectra for W(e^+e^-) = 10 GeV/c^2

▶ off-shell case

▶ on-shell case, m_A = 1 GeV/c^2

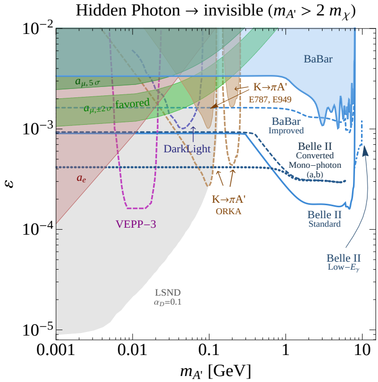


- off-shell signature => broad energy distribution
- on-shell signature => mono-photon, as displaced vertex decaying into leptons

Belle II predicted sensitivity / Radiative decay

Determined by R. Essig et al. arXiv:1309.5084 for 50 ab^{-1}

- Belle II Standard with prescaled trigger of 100
- Belle II Converted Mono-photon (a,b) no prescaled trigger but $\varepsilon(\gamma \to e^+e^-) = 5$ % instead of 1 %



At start of Belle II physics run, photon trigger (not prescaled) might be implemented

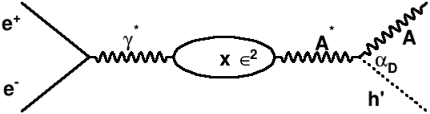
furthermore luminosity much lower than at designed luminosity

Higgs-strahlung channels

Belle may have or/and Belle II may produce dark matter, χ, dark photon (dark gauge boson), A; and dark Higgs h' as long as the mass of each is low in the following channels:

- Higgs-strahlung:
- $e^+e^- \to Ah'$
  - if $m(h') > 2m(A)$, $h' \to AA$
  - if $m(A) < m(h') < 2m(A)$, $h' \to l^+l^-$ or hadrons
  - if $m(h') < m(A)$, $h' \to$ dark matter
  - $A \to l^+l^-$ or hadrons or dark matter

- Higgs-strahlung decays

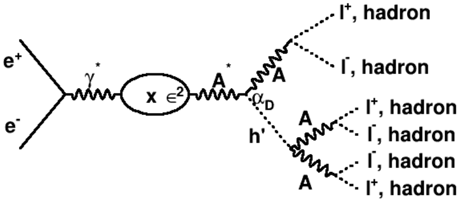


- α_D coupling between the dark Higgs and the dark photon
- $\alpha' = \frac{g'^2}{4\pi}$ fine structure for the dark photon
- g' coupling of the dark photon to electrons (or SM)
- $\epsilon = \frac{g'}{e}$ and $\epsilon^2 = \frac{\alpha'}{\alpha}$
- $\alpha = \frac{e^2}{4\pi} \sim \frac{1}{137}$ the electromagnetic coupling

Search for the dark photon and dark Higgs at Belle

Presented today: A and h' prompt and $m_{h'} > 2m_A$

for $0.1 < m_A < 3.5$ GeV/c^2 and $0.2 < m_{h'} < 10.5$ GeV/c^2



α_D: dark sector constant
ϵ^2: kinetic mixing

- channels presented today
  - $3e^+3e^-$, $3\mu^+3\mu^-$, $2e^+2e^-\mu^+\mu^-$, $2\mu^+2\mu^-e^+e^-$
  - $3\pi^+3\pi^-$, $2\pi^+2\pi^-e^+e^-$, $2\pi^+2\pi^-\mu^+\mu^-$
  - $2e^+2e^-\pi^+\pi^-$, $2\mu^+2\mu^-\pi^+\pi^-$, $e^+e^-\mu^+\mu^-\pi^+\pi^-$
  - $2e^+2e^-X$, $2\mu^+2\mu^-X$, $e^+e^-\mu^+\mu^-X$

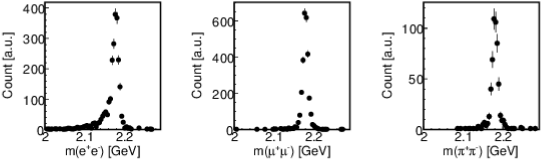
- if A coupling to h' unity
- Higgs-strahlung channel most sensitive to A since QED background low
- than other decays e.g.: $e^+e^- \to A\gamma$ with huge QED background

Analysis strategy / Higgs-strahlung channels

Full reconstruction of exclusive six-lepton/hadron final states from $e^+e^- \to Ah' \to AAA$

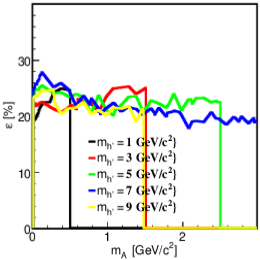
- final state identification
  - 6 charged tracks
  - 3 pairs of opposite charge

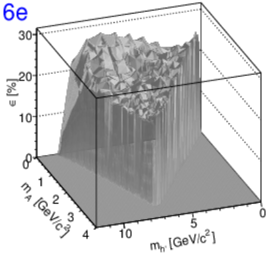
- signal reconstruction
  - impact parameters and χ^2 vertex fit cuts
  - require energy conservation
  - calculate invariant mass for each combinations of leptons/hadrons consistent with three distinct $A \to l^+l^-$ or hadrons
  - keep combinations with three masses "equal"
  - plots below show signal Monte Carlo simulation events surviving selection with $m_{h'} = 5$ GeV/c^2 and $m_A = 2.19$ GeV/c^2

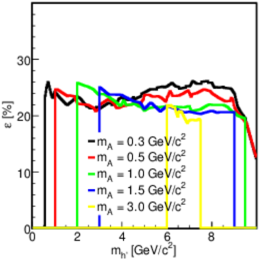


Detection efficiency / Higgs-strahlung channels

e.g. $e^+e^- \to Ah' \to AAA \to 3e^+3e^-$



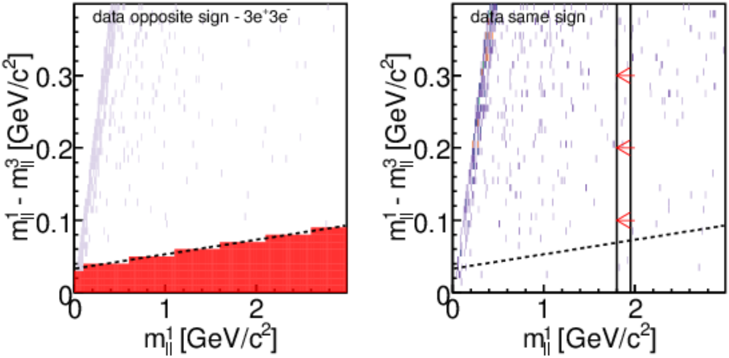




Background estimation strategy / Higgs-strahlung channels

Data driven background estimation

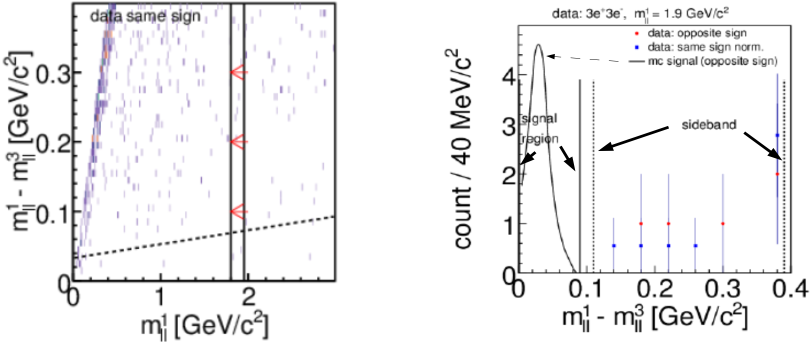
- estimate background using "same sign" events $e^+e^- \rightarrow Ah' \rightarrow A(l^+l^+)A(l^+l^+)A(l^-l^-)$
- order masses of lepton pairs $m^1_{ll} > m^2_{ll} > m^3_{ll}$ and plot $m^1_{ll} - m^3_{ll}$ vs. m^1_{ll}
- select region in m_{ll} and predict background there using same sign
    - $e^+e^- \rightarrow 3e^+3e^-$



- opposite sign = signal, signal box blinded (red)

Background estimation method / Higgs-strahlung channels

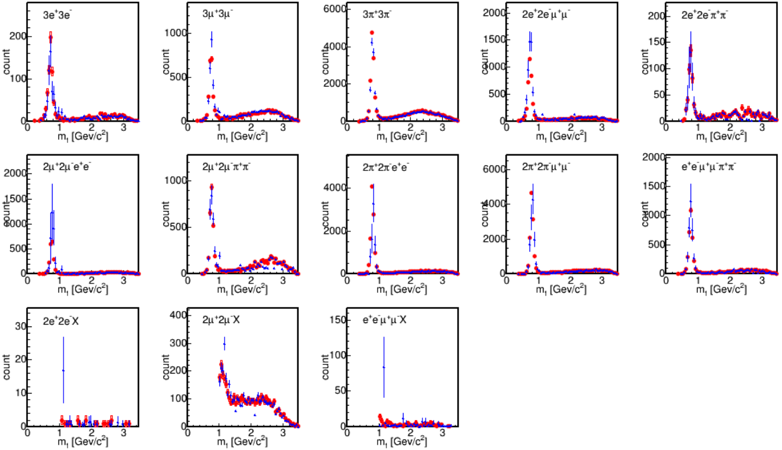
- sideband used to normalize same sign to opposite sign
- background estimated from the number of counts in the signal region of the same sign distributions
  - projection on $m_{ll}^1 - m_{ll}^3$ for $m_{ll}^1 = 1.9$ GeV/c^2



MC simulation test / Higgs-strahlung channels

MC simulation of $e^+e^- \to \rho^0\rho^0 l^+l^-$ or hadrons produced in phase space

- red opposite sign
- blue same sign

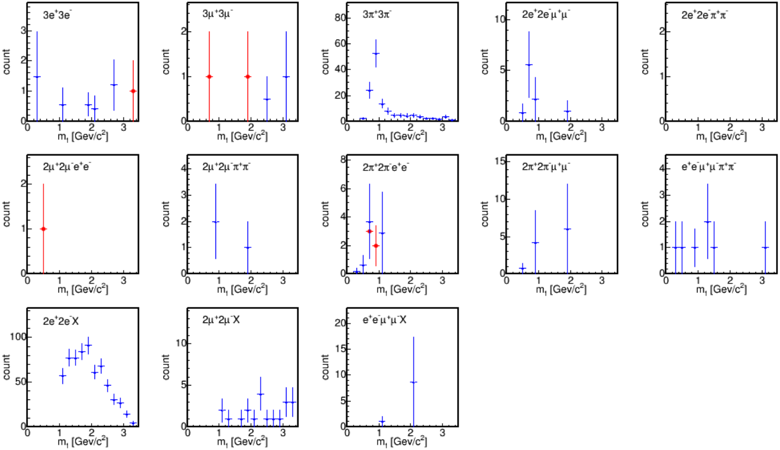


=> background estimation method verified successfully with MC

Background estimation results / Higgs-strahlung channels

Data control sample with the 4 boxes already open:

- red opposite sign
- blue same sign



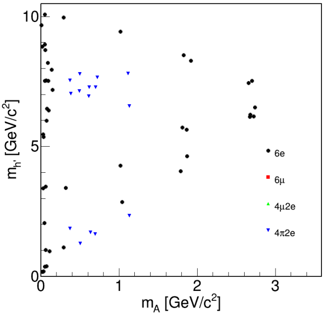
Background estimation results / Higgs-strahlung channels

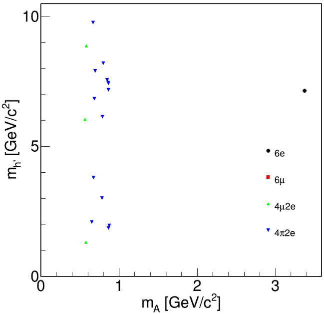
Comparison between predicted Belle background and Belle number of events measured

Final state	6e	6μ	$4\mu 2e$	$4\pi 2e$
Belle expected	4.75 ± 1.31	1.64 ± 1.12	0	7.4 ± 4
Belle measured	1	0	1	5

=> Number of events measured consistent with background expectation

- same sign (predicted)
- opposite sign (measured)



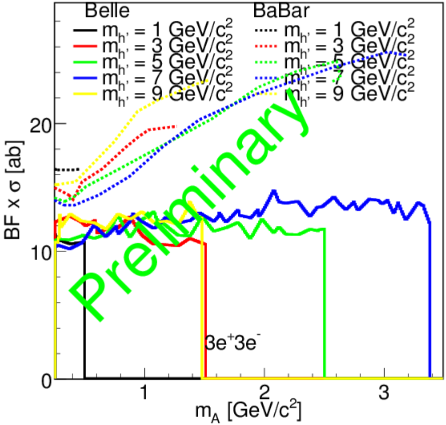


background: Standard Model 2γ processes with ρ's or ω's in the final state

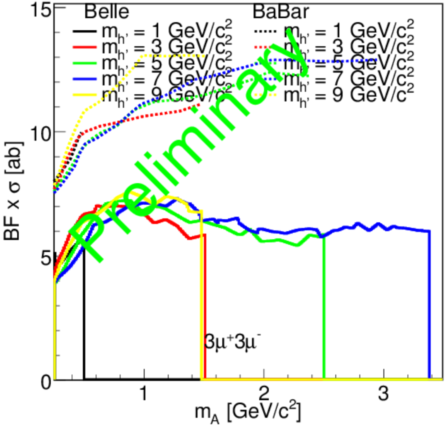
Belle limits / Higgs-strahlung channels

- Belle preliminary limits for $L = 980$ fb^{-1}
- BaBar limits for $L = 520$ fb^{-1} BaBar Collaboration - arXiv:1202.1313

- $e^+e^- \to 3e^+3e^-$



- $e^+e^- \to 3\mu^+3\mu^-$

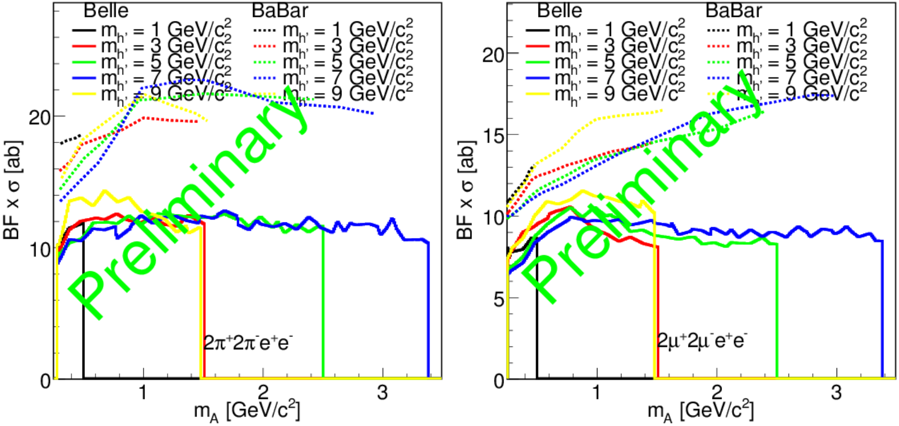


- upper limit (90 % CL) determined by Bayesian inference method with the use of Markov Chain Monte Carlo A. Caldwell et al., CPC 180 (2009) 2197-2209
- Belle limit scales nearly linearly with integrated luminosity

Belle limit / Higgs-strahlung channels

Compare to BaBar limits BaBar Collaboration - arXiv:1202.1313

- $e^+e^- \to 2\pi^+2\pi^-e^+e^-$
- $e^+e^- \to 2\mu^+2\mu^-e^+e^-$

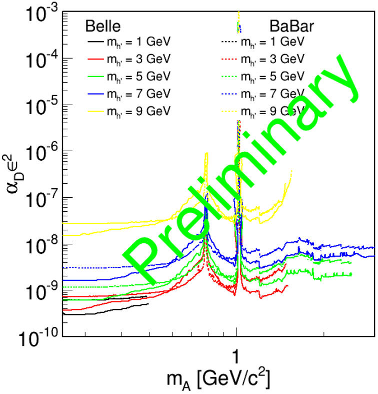


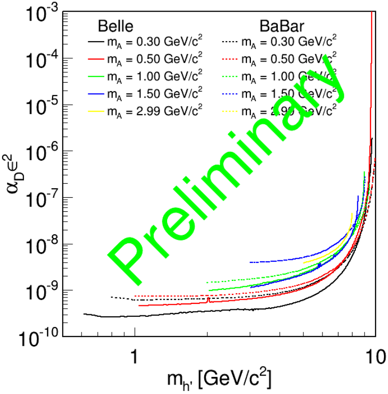
=> Belle II will scales nearly linearly with integrated luminosity or with square root of integrated luminosity in presence of background

Combined sensitivity to the product of $\alpha_D\epsilon^2$

Belle combined sensitivity compared to BaBar combined limit

- dark photon 90 % CL sensitivity
- dark Higgs 90 % CL sensitivity

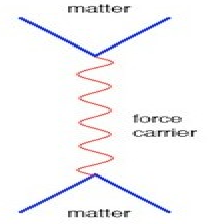


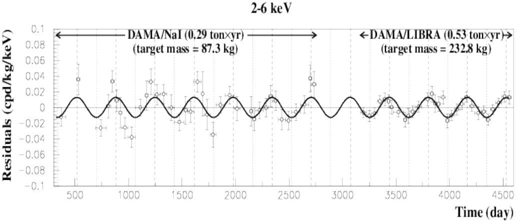


Branching fractions and couplings versus cross section, dark photon and dark Higgs masses fallow B. Batell et al. arXiv:0903.0363 (2009)

Annual modulation ?

- DM can explain observed anomalies in astrophysical data and dark matter experiments
  - annual modulation due to the Earth's orbit around the Sun as the Sun orbits the galactic center ? DAMA/LIBRA, Eur. Phys. J. C 56: 333-355 (2008)





- scattering cross section $\sigma \propto \frac{1}{(q^2 - M_*^2)^2}$ with q: momentum transfer ($q^2 = 2 m_{nucleus} E_{recoil}^{nucleus}$) and M_*: carrier particle = A or W, Z
  - $M_* \to 0$ then $\sigma \propto \frac{1}{q^4}$, long range interaction $=>$ $\frac{d\sigma}{dE_{recoil}^{nucleus}} \propto \frac{1}{(m_{nucleus} E_{recoil}^{nucleus})^2}$
  - $M_* \gg q$ then $\sigma \propto \frac{1}{M_*^4}$, contact term interaction
- for $M_{WIMP} = 10$ GeV/c^2 and $m_{Na(I)} = 22(129)$ GeV/c^2, $q^{max} \sim 30(100) MeV/c^2$ $=> m_A \ll 1\ GeV/c^2 \ll M_{WIMP}$ and modulation amplitude enhanced

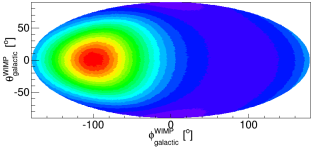
Daily oscillation / Dark matter directional detection

If annual modulation observed by DAMA/LIBRA is caused by WIMPs due to:

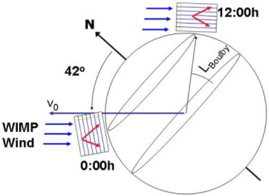
- Earth's orbit around the Sun as the Sun orbits the galactic centre
- since Earth's rotation a daily oscillation in the mean direction of the WIMPs must be observed as well
    - passing from TPC coordinate to galactic coordinate enforce daily osciallation
    - at least 10 recoil events to measure WIMP direction

      => strong constrain, no known background with this signature

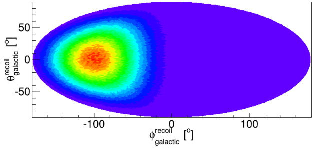
- WIMP flux in galactic coordinate



- daily oscillation scheme



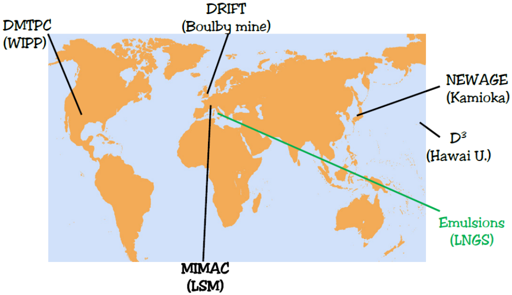
- F recoil angular distribution in galactic coordinate



=> use daily oscillation to clean and identify the WIMP signal

Current projects / Dark matter directional detection

Time Projection Chamber as WIMP detector filled with gas



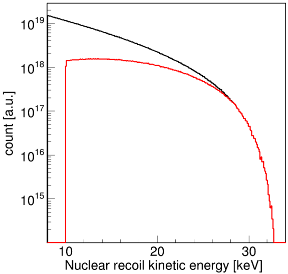
- low target mass, normally need very large gas volume
- but low track reconstruction threshold changes situation for low-mass WIMPs with only 1-10 m^3 volume
- several groups attempting directional detection with gas TPC. Advantages of our approach are:
  - 3D tracking => better DM identification & alpha BG rejection
  - single electron efficiency => expect very low track-recons. threshold
  - basically free of noise

Low-pressure operation / Dark matter directional detection

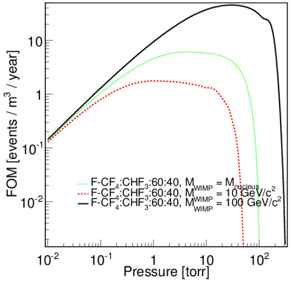
To measure low WIMP mass, eg 10 GeV/c^2:

- gas with target nucleus close to wanted WIMP mass and TPC friendly
  => Fluorine as target and gas CF$_4$ or gas mixtures CF$_4$:CHF$_3$ or CF$_4$:CS$_2$
- operate at extremely low-pressure, increase track length, $\mathrm{L(at\ P)} = \mathrm{L(at\ P_0)} \times \frac{P_0}{P}$,
  but diffusion $\sigma(\mathrm{at\ P}) = \sigma(\mathrm{at\ P_0}) \times \sqrt{\frac{P_0}{P}}$
- find best trade off between the target mass and track length so that the directional sensitivity is maximized I. Jaegle et al. http://arxiv.org/abs/1110.3444

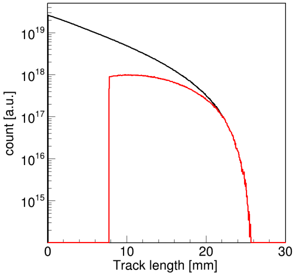
- ▶ F recoil kinetic energy
  red line: 3D-dir. and 10 keV thres.



- ▶ optimal pressure
  => 1.5 torr for 10 GeV/c^2 WIMP



- ▶ F track length at 1.5 torr
  red line: 3D-dir. and 10 keV thres.

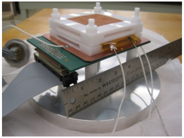


- operation at low-pressure with high gain ∼ 100k has been demonstrated in A.Breskin et al., NIM 217, 131 (1983), NIMA 433 476 (1999) and C.K. Shalem et al., NIMA 558 468-474 (2006)

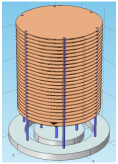
Future plan / Dark matter directional detection

Building this year a 10l volume detector

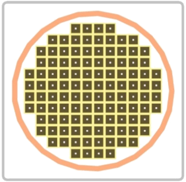
- build and run smoothly



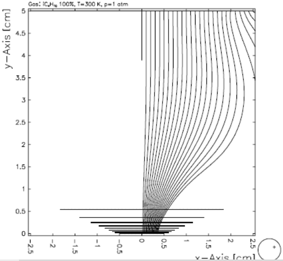
- building this year



- planned



- electrostatic focusing of drift charge
S.Ross et al. IEEE proceedings 2012

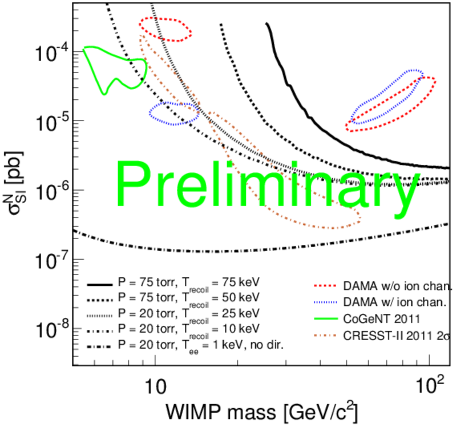


- to reduce the readout price
  - larger pixel chips
  - electrostatic focusing of drift charge
- existing ATLAS DAQ
- negative ion drift or gas w/ slow drift velocity

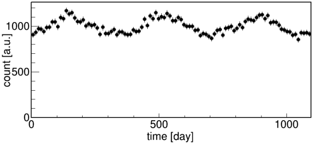
Reach plot for 3 years and 3 m^3

Preliminary reach plot shows advantages of low track energy threshold and possible golden scenario

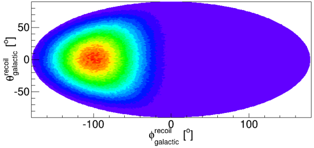
- observe annual modulation
- sub-sample of data for daily oscillation search



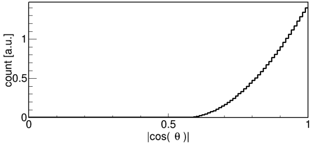
- annual modulation



- F recoil angular distribution in galactic coordinate



- angle between F recoil and WIMP direction



Conclusion

Belle and Belle II can contribute to the dark sector particles searches for the prompt and displaced vertex cases

- radiative decays
  - with 50 ab^{-1}, Belle II might reach sensitivity to rule out a prompt dark photon and dark Higgs decays into leptons or hadrons
  - expected background in Belle II is not known
- search in Belle data set for dark photon and dark Higgs in the mass ranges:
  - $0.1 < m_A < 3.5$ GeV/c^2
  - $0.2 < m_{h'} < 10.5$ GeV/c^2
  - we found that:
    - background is small, implying
    - limit scales nearly linearly with integrated luminosity
    - Belle II expected to scale nearly linearly with integrated luminosity or square root of integrated luminosity

TPC:

- TPC characterisation shows very promising results
- MC simulation
  - beams-induced background, different background can be disentangled
  - measurement of WIMPs direction might be possible at low pressure

Thanks for your attention.