WG2-applications
(TPC survey)

TPCs for Rare Event Searches (‘Rare Decays’ for ECFA)

Diego González Díaz,
01-02-2023
(DRD1 community meeting)

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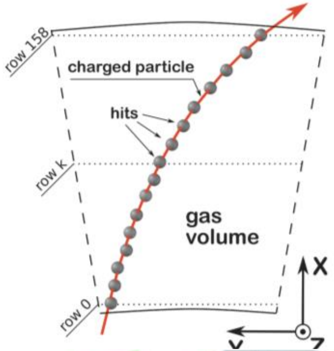
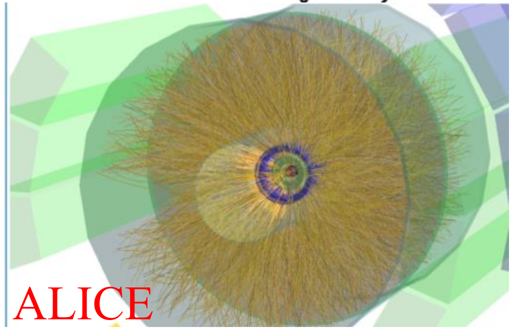
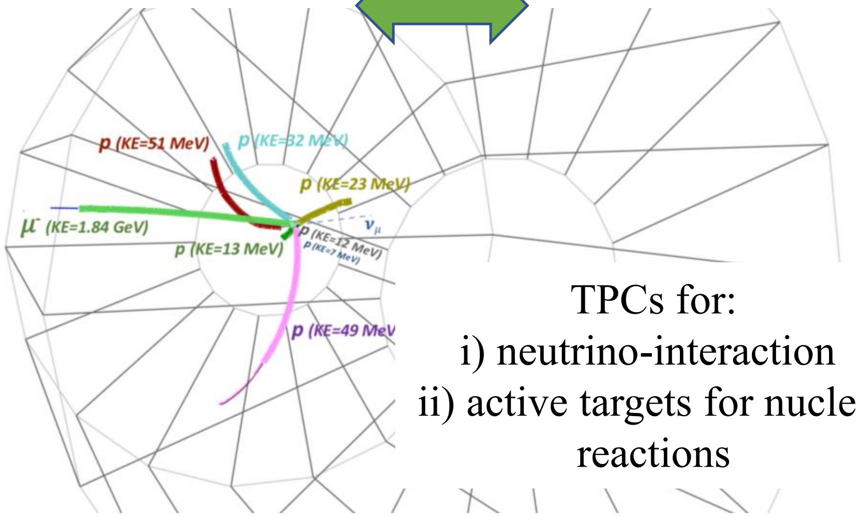
TPC for Tracking



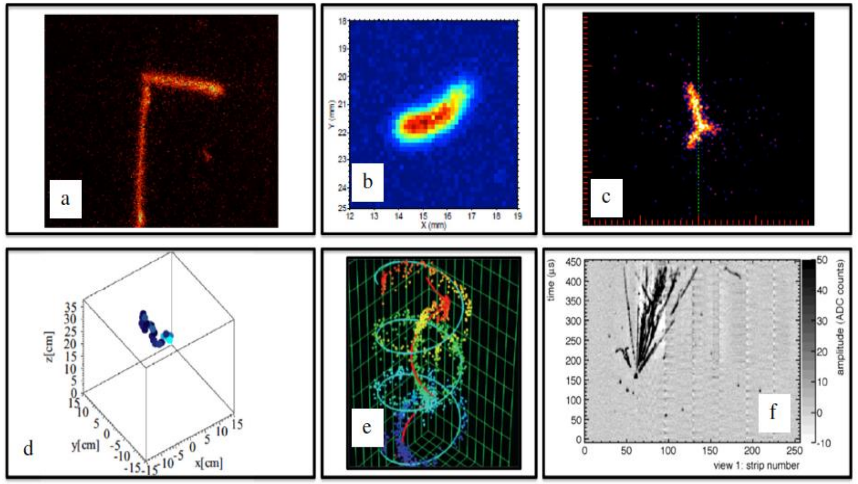


‘TPC == tracker of a spectrometer’



TPCs for:
i) neutrino-interaction
ii) active targets for nuclear reactions

TPC for Rare Events



‘TPC == single reconstruction-tool’

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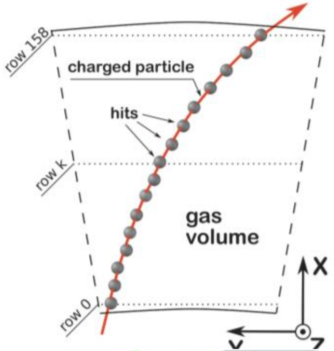
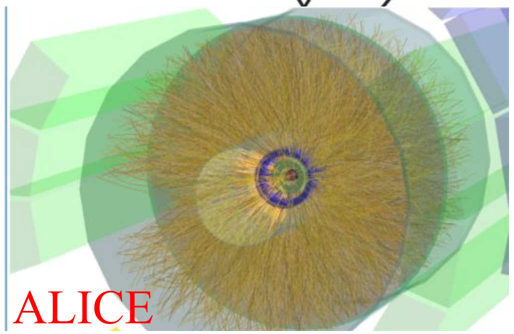
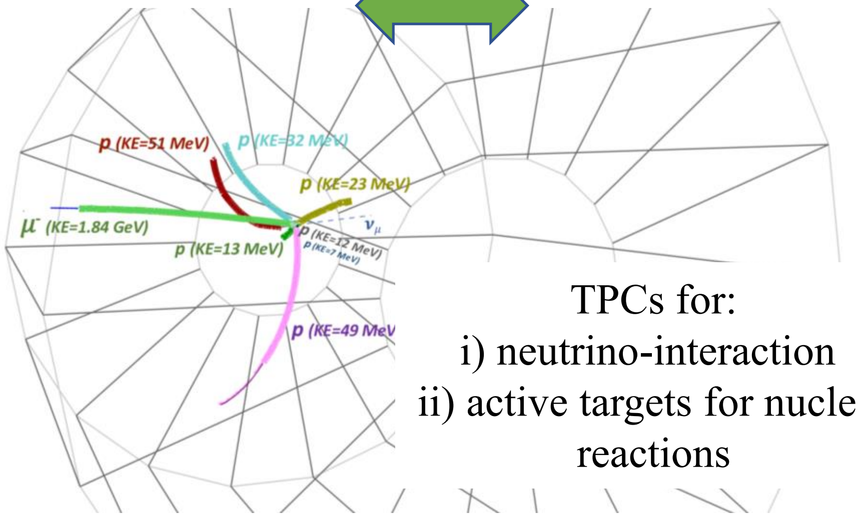




‘TPC == tracker of a spectrometer’

I draw the line here (does not agree with all the opinions in survey!)



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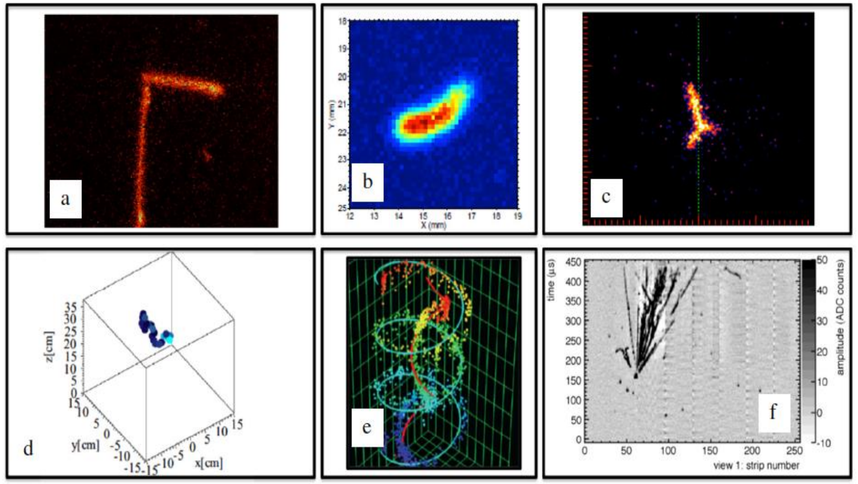
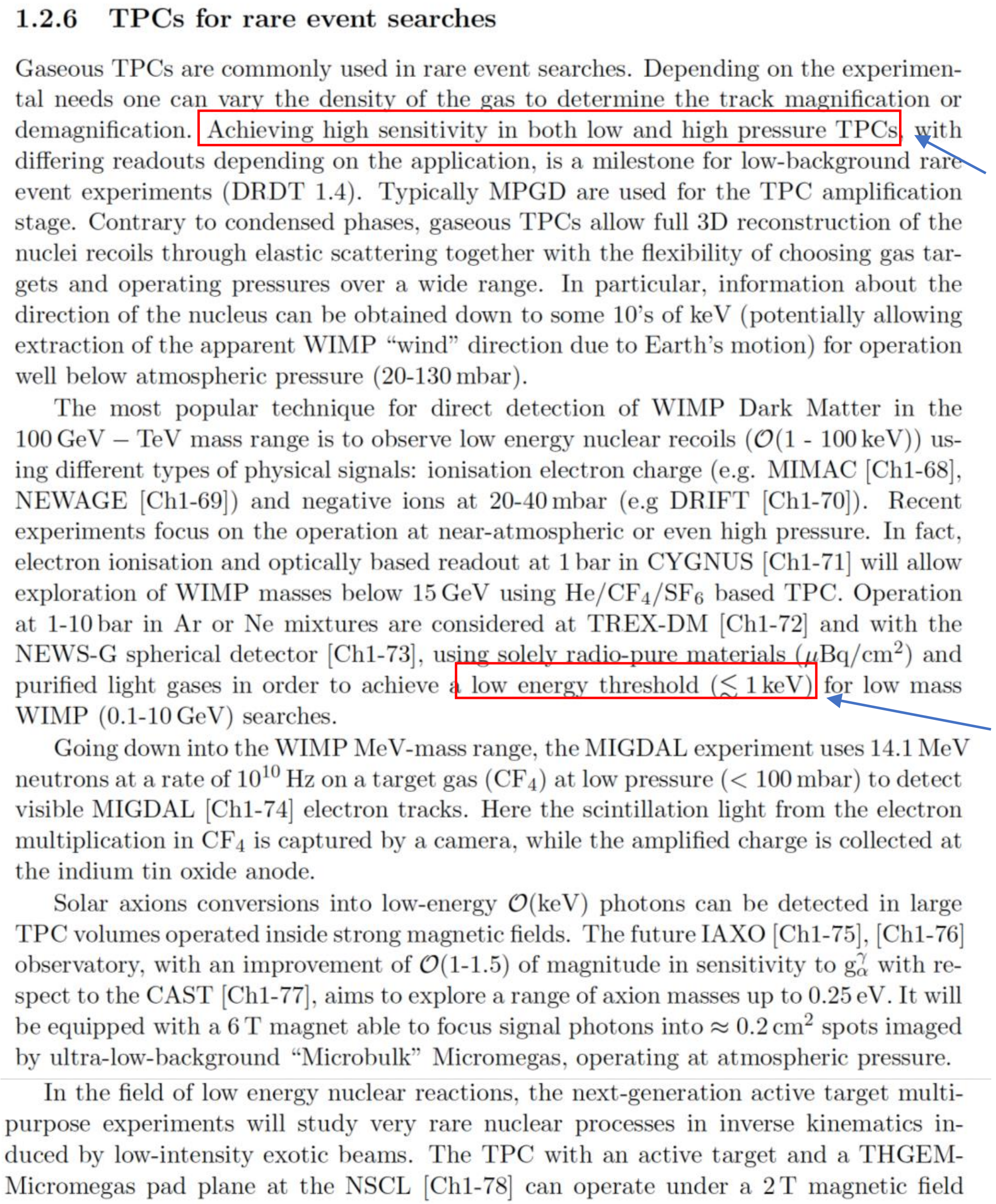


‘TPC == single reconstruction-tool’

I. Challenges (from ECFA)

WG2-applications
(TPC survey)

DRDT 1.4 - Achieve high sensitivity in both low and high-pressure TPCs



1.2.6 TPCs for rare event searches

Gaseous TPCs are commonly used in rare event searches. Depending on the experimental needs one can vary the density of the gas to determine the track magnification or demagnification. Achieving high sensitivity in both low and high pressure TPCs, with differing readouts depending on the application, is a milestone for low-background rare event experiments (DRDT 1.4). Typically MPGD are used for the TPC amplification stage. Contrary to condensed phases, gaseous TPCs allow full 3D reconstruction of the nuclei recoils through elastic scattering together with the flexibility of choosing gas targets and operating pressures over a wide range. In particular, information about the direction of the nucleus can be obtained down to some 10's of keV (potentially allowing extraction of the apparent WIMP "wind" direction due to Earth's motion) for operation well below atmospheric pressure (20-130 mbar).

The most popular technique for direct detection of WIMP Dark Matter in the 100 GeV – TeV mass range is to observe low energy nuclear recoils ($\mathcal{O}$(1 - 100 keV)) using different types of physical signals: ionisation electron charge (e.g. MIMAC [Ch1-68], NEWAGE [Ch1-69]) and negative ions at 20-40 mbar (e.g DRIFT [Ch1-70]). Recent experiments focus on the operation at near-atmospheric or even high pressure. In fact, electron ionisation and optically based readout at 1 bar in CYGNUS [Ch1-71] will allow exploration of WIMP masses below 15 GeV using He/CF$_4$/SF$_6$ based TPC. Operation at 1-10 bar in Ar or Ne mixtures are considered at TREX-DM [Ch1-72] and with the NEWS-G spherical detector [Ch1-73], using solely radio-pure materials (μBq/cm^2) and purified light gases in order to achieve a low energy threshold ($\lesssim 1$ keV) for low mass WIMP (0.1-10 GeV) searches.

Going down into the WIMP MeV-mass range, the MIGDAL experiment uses 14.1 MeV neutrons at a rate of 10^{10} Hz on a target gas (CF$_4$) at low pressure (< 100 mbar) to detect visible MIGDAL [Ch1-74] electron tracks. Here the scintillation light from the electron multiplication in CF$_4$ is captured by a camera, while the amplified charge is collected at the indium tin oxide anode.

Solar axions conversions into low-energy $\mathcal{O}$(keV) photons can be detected in large TPC volumes operated inside strong magnetic fields. The future IAXO [Ch1-75], [Ch1-76] observatory, with an improvement of $\mathcal{O}$(1-1.5) of magnitude in sensitivity to g_a^γ with respect to the CAST [Ch1-77], aims to explore a range of axion masses up to 0.25 eV. It will be equipped with a 6 T magnet able to focus signal photons into ≈ 0.2 cm^2 spots imaged by ultra-low-background "Microbulk" Micromegas, operating at atmospheric pressure.

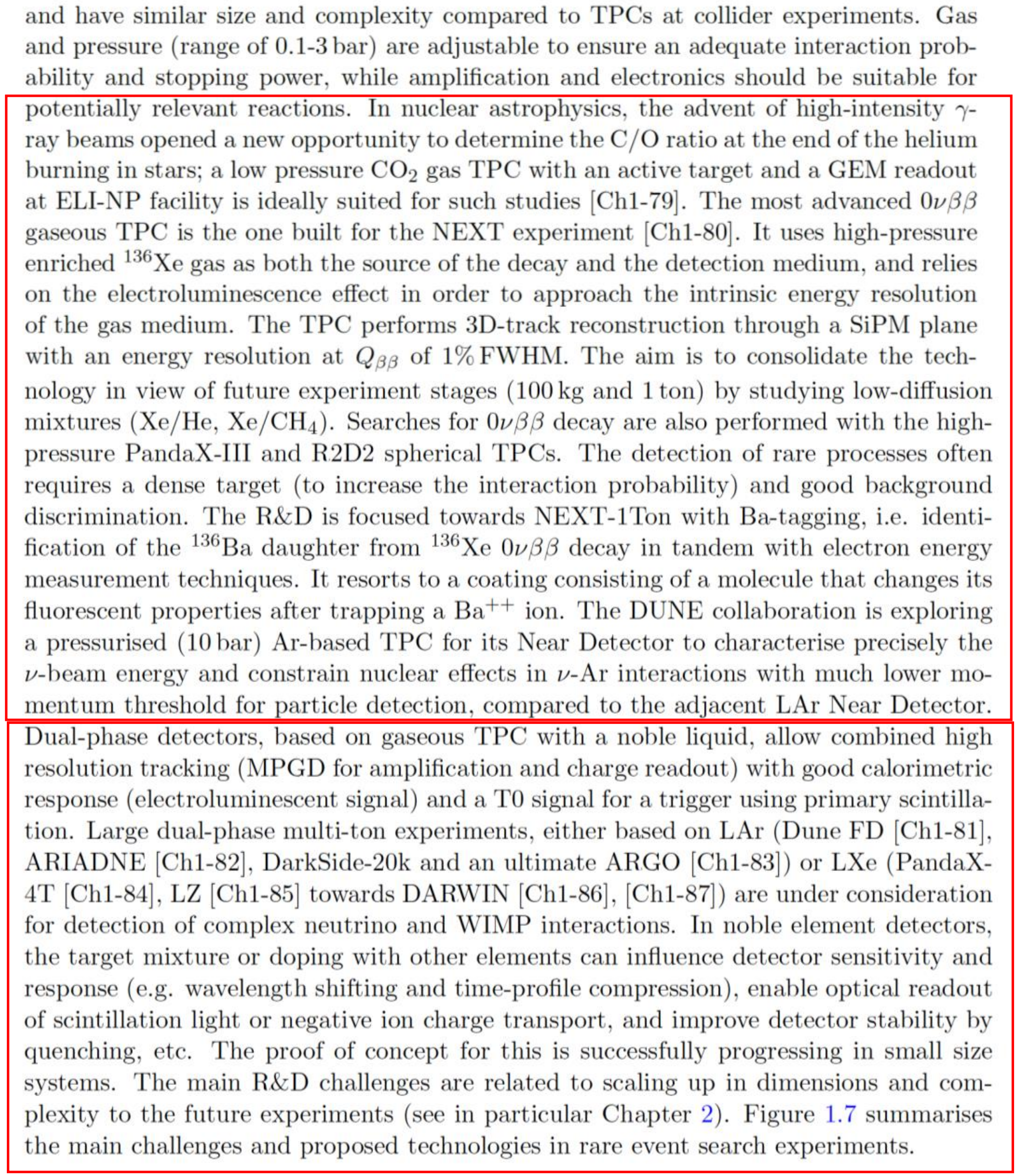
In the field of low energy nuclear reactions, the next-generation active target multi-purpose experiments will study very rare nuclear processes in inverse kinematics induced by low-intensity exotic beams. The TPC with an active target and a THGEM-Micromegas pad plane at the NSCL [Ch1-78] can operate under a 2 T magnetic field

sensitivity across pressure and mixture

new gases and mixtures

keV-threshold at least

dual-phase optimization



and have similar size and complexity compared to TPCs at collider experiments. Gas and pressure (range of 0.1-3 bar) are adjustable to ensure an adequate interaction probability and stopping power, while amplification and electronics should be suitable for potentially relevant reactions. In nuclear astrophysics, the advent of high-intensity γ-ray beams opened a new opportunity to determine the C/O ratio at the end of the helium burning in stars; a low pressure CO$_2$ gas TPC with an active target and a GEM readout at ELI-NP facility is ideally suited for such studies [Ch1-79]. The most advanced $0\nu\beta\beta$ gaseous TPC is the one built for the NEXT experiment [Ch1-80]. It uses high-pressure enriched ^{136}Xe gas as both the source of the decay and the detection medium, and relies on the electroluminescence effect in order to approach the intrinsic energy resolution of the gas medium. The TPC performs 3D-track reconstruction through a SiPM plane with an energy resolution at $Q_{\beta\beta}$ of 1% FWHM. The aim is to consolidate the technology in view of future experiment stages (100 kg and 1 ton) by studying low-diffusion mixtures (Xe/He, Xe/CH$_4$). Searches for $0\nu\beta\beta$ decay are also performed with the high-pressure PandaX-III and R2D2 spherical TPCs. The detection of rare processes often requires a dense target (to increase the interaction probability) and good background discrimination. The R&D is focused towards NEXT-1Ton with Ba-tagging, i.e. identification of the ^{136}Ba daughter from ^{136}Xe $0\nu\beta\beta$ decay in tandem with electron energy measurement techniques. It resorts to a coating consisting of a molecule that changes its fluorescent properties after trapping a Ba^{++} ion. The DUNE collaboration is exploring a pressurised (10 bar) Ar-based TPC for its Near Detector to characterise precisely the ν-beam energy and constrain nuclear effects in ν-Ar interactions with much lower momentum threshold for particle detection, compared to the adjacent LAr Near Detector.

Dual-phase detectors, based on gaseous TPC with a noble liquid, allow combined high resolution tracking (MPGD for amplification and charge readout) with good calorimetric response (electroluminescent signal) and a T0 signal for a trigger using primary scintillation. Large dual-phase multi-ton experiments, either based on LAr (Dune FD [Ch1-81], ARIADNE [Ch1-82], DarkSide-20k and an ultimate ARGO [Ch1-83]) or LXe (PandaX-4T [Ch1-84], LZ [Ch1-85] towards DARWIN [Ch1-86], [Ch1-87]) are under consideration for detection of complex neutrino and WIMP interactions. In noble element detectors, the target mixture or doping with other elements can influence detector sensitivity and response (e.g. wavelength shifting and time-profile compression), enable optical readout of scintillation light or negative ion charge transport, and improve detector stability by quenching, etc. The proof of concept for this is successfully progressing in small size systems. The main R&D challenges are related to scaling up in dimensions and complexity to the future experiments (see in particular Chapter 2). Figure 1.7 summarises the main challenges and proposed technologies in rare event search experiments.

II. R&D topics given in survey for *TPCs for Rare Events* (‘Rare Decays’)

WG2-applications
(TPC survey)

Muon System	Inner and Central tracking	Calorimetry	Photon detection	TOF	Rare decays
● Radiation hardness and stability of large area up to integrated charges of hundreds of C/cm2: - aging issues and discharges; ● Operation in a stable and efficient manner with incident particle flows up to ~10 MHz/cm2: - miniaturisation of readout elements needed to keep occupancy low ● Manufacturing, on an industrial scale, large detectors at low cost, by means of a process of technological transfer to the industry and identifies processes transferable to industries ● Identification of eco-friendly gas mixture and mitigation of the issue related to the operation with high WGP gas mixture: - gas tightness;gas recuperation system;accessibility for repairing ● Study of resistive materials (RPC and MPGD): - higher gain in a single multiplication layer, with a remarkable advantage for assembly, mass production and cost - new material and production techniques for resistive layers for increasing the rate capability ● Thinner layers and mechanical precision over large area	**Drift chambers** ● High rate, unique volume, high granularity, low mass ● Hydrocarbon-free mixture for long-term and high-rate operation ● Prove the cluster counting principle with the related electronics ● Mechanics: new wiring procedure, new wire materials ● Integration: accessibility for repairing **TPC** ● R&D on detector sensors to suppress the IBF ratio ● Optimize IBF together with energy resolution ● Gain optimization: IBF, discharge stability ● Uniformity of the response of the sensors ● Gas mixture: stability, drift velocity, ion mobility, aging ● Influence of Magnetic field on IBF ● High spatial resolution ● Very low material budget (few %) ● Mechanics: thickness minimization but robust for precise electrical properties for stable drift velocity ● Integration: cooling of electronics **Straw chambers** ● Ultra-long and thin film tubes ● “Smart“ designs: self-stabilized straw module, compensating relaxation ● Small diameter for faster timing, less occupancy, high rate capability ● Reduced drift time, hit leading times and trailing time resolutions, with dedicated R&D on the electronics ● PID by dE/dx with “standard“ time readout and time-over-threshold ● 4D-measurement: 3D-space and (offline) track time ● Over-pressurized tubes in vacuum: control the leakage rate to maintain the shape	● Uniformity of the response of the large area and dynamic energy range ● Optimization of weights for different thresholds in digital calorimeters ● Rate capability in detectors based on resistive materials: resistivity uniformity, discharge issue at high rate and in large area detector ● R&D on sub-ns in active elements: resolution stables over wide range of fluxes ● Gas homogeneity and stable over time ● Eco-friendly gas mixture for RPC ● Stability of the gas gain: fast monitoring of gas mixture and environmental conditions ● Mechanics: - large area needed to avoid dead zone: limitation on size and planarity of PCB is an issue - multi-gap with ultra-thin modules: very thin layer of glass and HPL electrodes, gas gap thickness uniformity few micron	● Preserve the photocathode efficiency by IBF and more robust photoconverters ● Gas radiator: alternative to CF4 ● Gas tightness ● Very low noise when coupling large capacitance ● Large dynamic range of the FEE ● Separate the TR radiation and the ionization process ● In TRD use of cluster counting technique and improve it by means of a InGrid	● Uniform rate capability and time resolution over large detector area ● New material for high rate (low resistivity, radiation hardness) - uniform gas distribution - thinner structures: mechanical stability and uniformity ● Eco-gas mixture ● Electronics: Low noise, fast rise time, sensitive to small charge ● Possibly optical readout ● Precise clock distribution and synchronization over large area	● Radio-purity of the materials ● Low background ● High granularity ● For large volume detectors: transparency over large distance ● Pressure stability and control ● Electronics with large dynamic range and flexible configuration. ● Self-trigger capability ● Low noise electronics ● Fast electronics ● Optical readout

we asked the community about these topics!

III. TPCs for Rare Events (stats)

WG2-applications
(TPC survey)

countries	
Australia:	1**(x4, joint australian survey)**
China:	2
Czech Republic:	0 (+1, re-assigned from tracking TPC)
Finland:	1(-1, assigned to tracking TPC)
France:	1(+1, re-assigned from tracking TPC)
Germany:	2
Hungary:	0 (+1 , showed interest after Feb 15th)
Israel:	2
Italy:	5
Japan:	1
Poland:	1
Portugal:	1
Spain:	2 (+1 , showed interest after Feb 15th)
Switzerland:	2
Turkey:	2
UK:	1 (+2 , showed interest after Feb 15th)
US:	1(+1, re-assigned from tracking TPC) (+6, showed interest after Feb 15th)

24 + **1x4** (+2)(+10) /69 submissions

main applications

- direct dark matter detection
- direct dark matter detection (with directionality)
- neutron detection (with directionality)
- X-ray polarimetry
- neutrino oscillations (gas)
- neutrino oscillations (dual-phase)
- neutrinoless double-beta decay
- solar axions
- nuclear interactions (active target) and decays
- X-17 boson studies

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R&D topics

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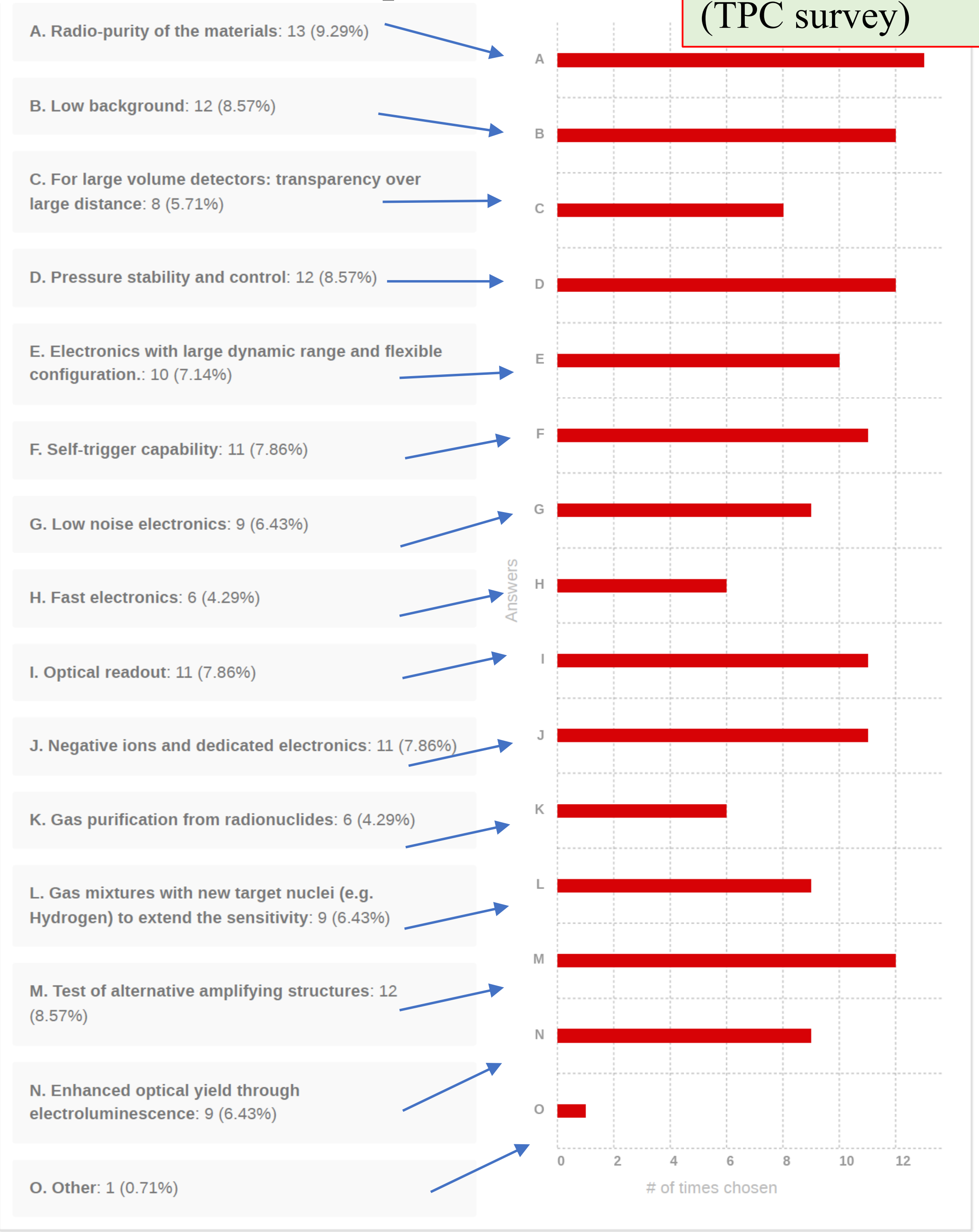
A. Radio-purity of the materials: 13 (9.29%)
B. Low background: 12 (8.57%)
C. For large volume detectors: transparency over large distance: 8 (5.71%)
D. Pressure stability and control: 12 (8.57%)
E. Electronics with large dynamic range and flexible configuration.: 10 (7.14%)
F. Self-trigger capability: 11 (7.86%)
G. Low noise electronics: 9 (6.43%)
H. Fast electronics: 6 (4.29%)
I. Optical readout: 11 (7.86%)
J. Negative ions and dedicated electronics: 11 (7.86%)
K. Gas purification from radionuclides: 6 (4.29%)
L. Gas mixtures with new target nuclei (e.g. Hydrogen) to extend the sensitivity: 9 (6.43%)
M. Test of alternative amplifying structures: 12 (8.57%)
N. Enhanced optical yield through electroluminescence: 9 (6.43%)
O. Other: 1 (0.71%)

III. TPCs for Rare Events (stats)

very balanced choice of topics except for 2! (expected)

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R&D topics

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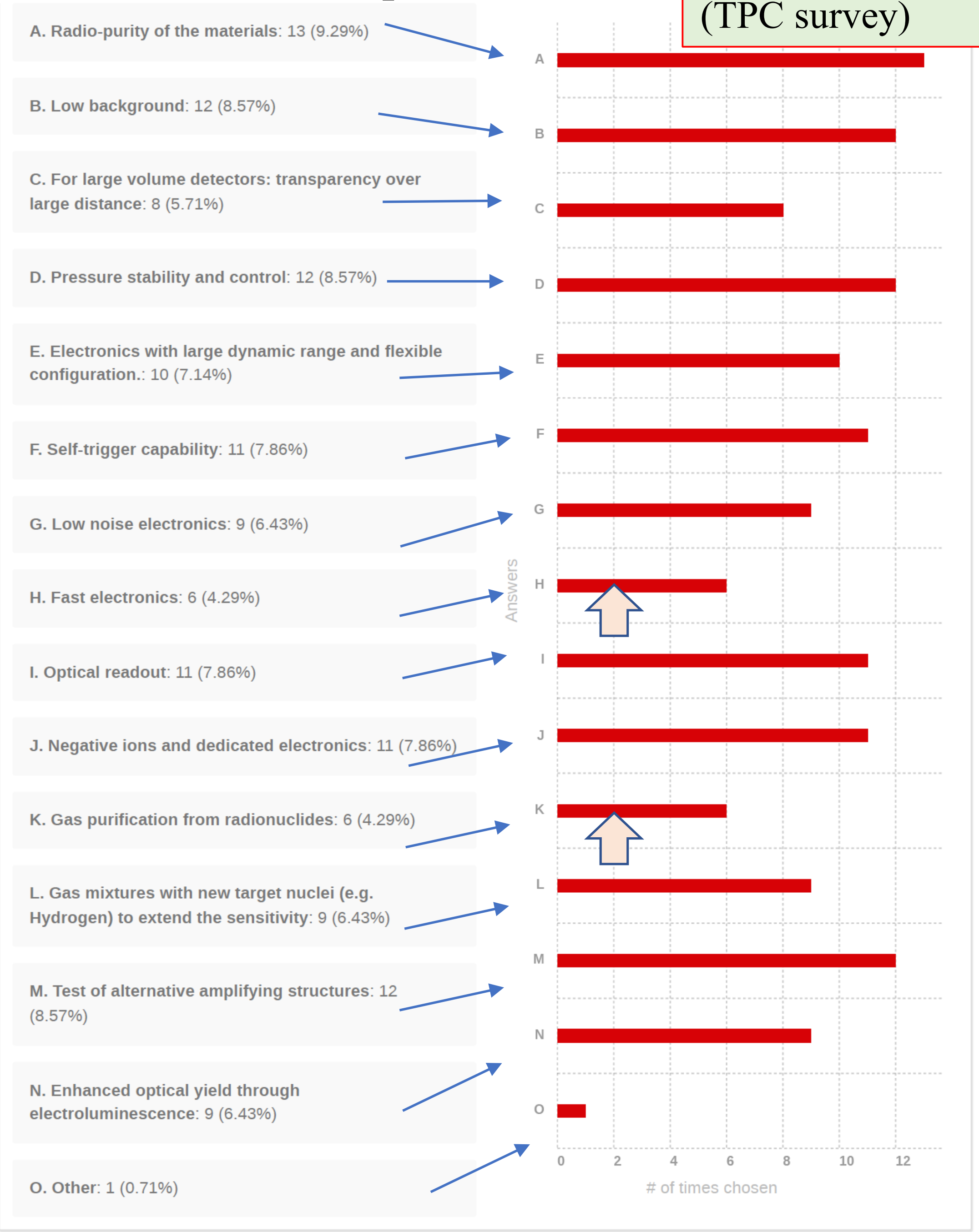

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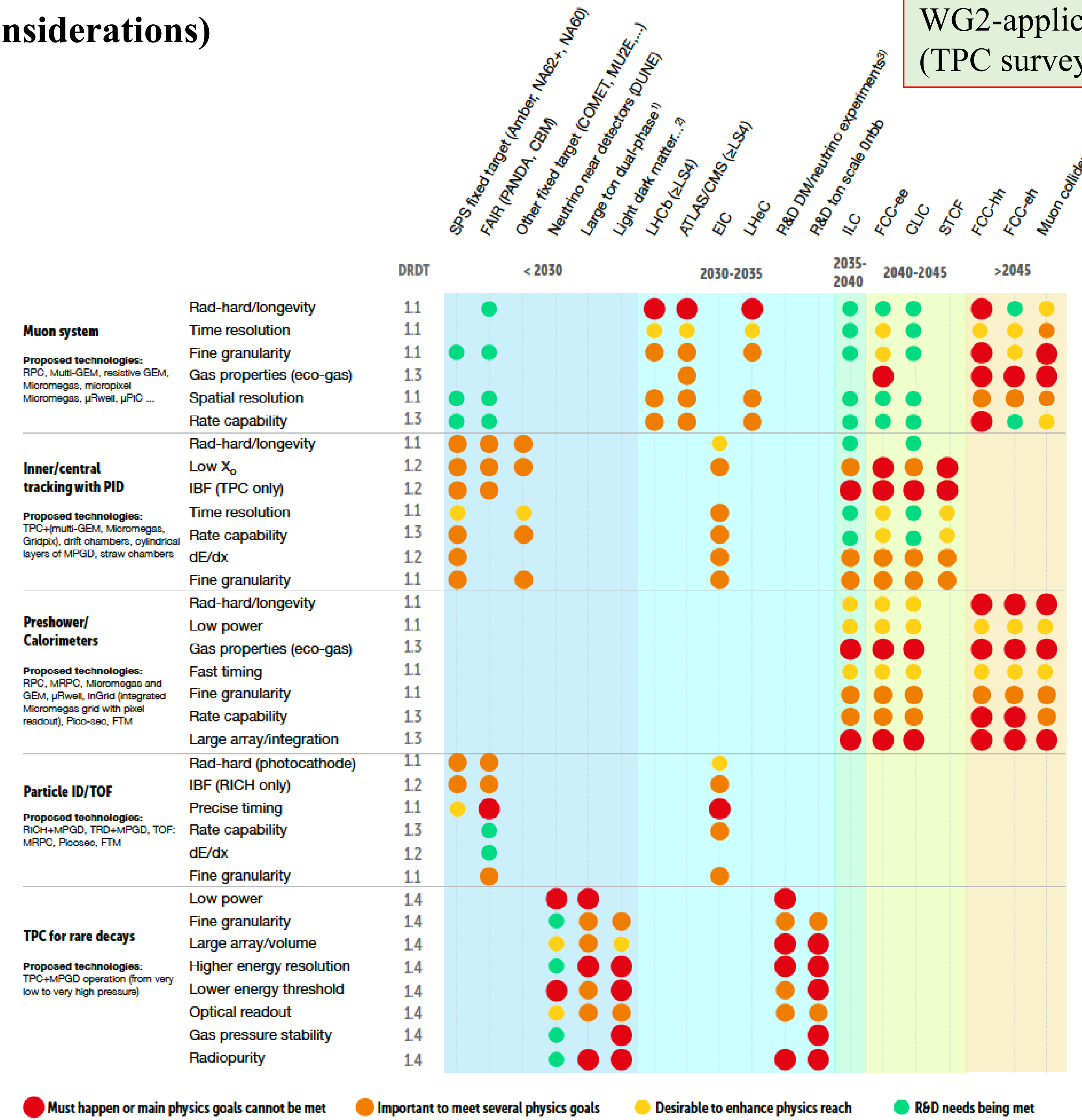

		DRDT	SPS fixed target (Amber, NA62+, NA60)	FAIR (PANDA, CBM)	Other fixed target (COMET, MU2E,...)	Neutrino near detectors (DUNE)	Large ton dual-phase$^{1)}$	Light dark matter...$^{2)}$	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	R&D DM/neutrino experiments$^{3)}$	R&D ton scale 0nbb	ILC	FCC-ee	CLIC	STCF	FCC-hh	FCC-eh	Muon collider
			< 2030						2030-2035						2035-2040	2040-2045			>2045		
Muon system **Proposed technologies:** RPC, Multi-GEM, resistive GEM, Micromegas, micropixel Micromegas, μRwell, μPIC ...	Rad-hard/longevity	1.1		🟢					🔴	🔴		🔴			🟢	🟢	🟢		🔴	🟢	🟡
	Time resolution	1.1							🟡	🟡		🟡			🟢	🟡	🟢		🟡	🟡	🟠
	Fine granularity	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟡	🟢		🔴	🟡	🔴
	Gas properties (eco-gas)	1.3								🟠						🔴			🔴	🔴	🔴
	Spatial resolution	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🟠	🟠	🟠
	Rate capability	1.3	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🔴	🟢	🟡
Inner/central tracking with PID **Proposed technologies:** TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers	Rad-hard/longevity	1.1	🟠	🟠	🟠						🟡				🟢		🟢				
	Low X_o	1.2	🟠	🟠	🟠						🟠				🟠	🔴	🟠	🔴			
	IBF (TPC only)	1.2	🟠	🟠											🔴	🔴	🔴	🔴			
	Time resolution	1.1	🟡		🟡						🟠				🟢	🟡	🟢	🟡			
	Rate capability	1.3	🟠		🟠						🟠				🟢	🟡	🟢	🟡			
	dE/dx	1.2	🟠								🟠				🟠	🟠	🟠	🟠			
	Fine granularity	1.1	🟠		🟠						🟠				🟠	🟠	🟠	🟠			
Preshower/ Calorimeters **Proposed technologies:** RPC, MRPC, Micromegas and GEM, μRwell, InGrid (integrated Micromegas grid with pixel readout), Pico-sec, FTM	Rad-hard/longevity	1.1													🟡	🟡	🟡		🔴	🔴	🔴
	Low power	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Gas properties (eco-gas)	1.3													🔴	🔴	🔴		🔴	🔴	🔴
	Fast timing	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Fine granularity	1.1													🟠	🟠	🟠		🟠	🟠	🟠
	Rate capability	1.3													🟠	🟠	🟠		🔴	🔴	🟠
	Large array/integration	1.3													🔴	🔴	🔴		🔴	🔴	🔴
Particle ID/TOF **Proposed technologies:** RICH+MPGD, TRD+MPGD, TOF: MRPC, Picosec, FTM	Rad-hard (photocathode)	1.1	🟠	🟠							🟡										
	IBF (RICH only)	1.2	🟠	🟠							🟠										
	Precise timing	1.1	🟡	🔴							🔴										
	Rate capability	1.3		🟢							🟠										
	dE/dx	1.2		🟢																	
	Fine granularity	1.1		🟠							🟠										
TPC for rare decays **Proposed technologies:** TPC+MPGD operation (from very low to very high pressure)	Low power	1.4				🔴	🔴						🔴								
	Fine granularity	1.4				🟢	🟠	🟠					🟠	🟠							
	Large array/volume	1.4				🟡	🟠	🟡					🔴	🔴							
	Higher energy resolution	1.4				🟢	🔴	🔴					🔴	🔴							
	Lower energy threshold	1.4				🔴	🟠	🔴					🟠	🔴							
	Optical readout	1.4				🟡	🟠	🟠					🟠	🟠							
	Gas pressure stability	1.4				🟢		🔴						🔴							
	Radiopurity	1.4				🟢	🔴	🔴					🔴	🔴							

🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met

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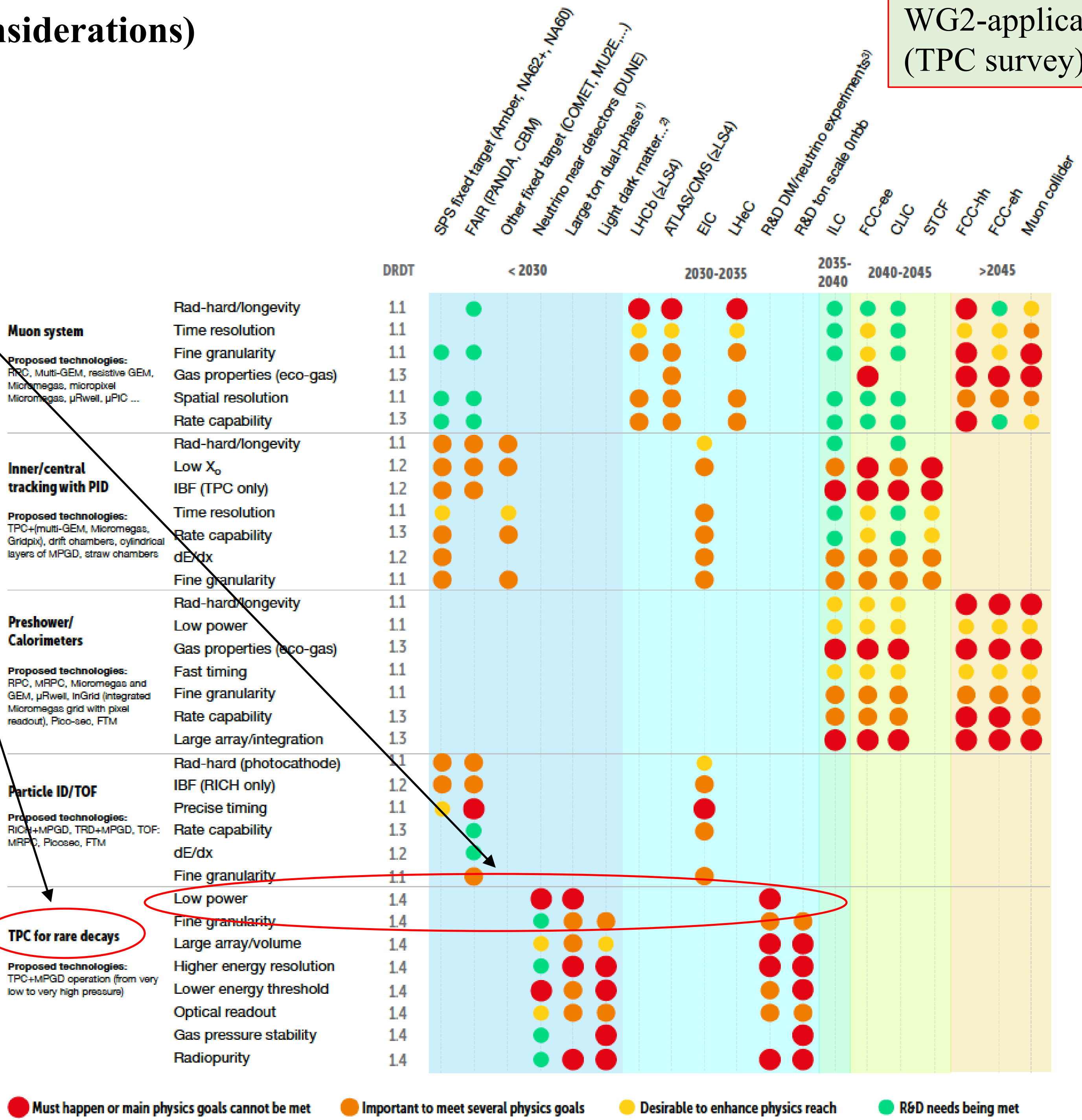

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			SPS fixed target (Amber, NA62+, NA60)	FAIR (PANDA, CBM)	Other fixed target (COMET, MU2E,...)	Neutrino near detectors (DUNE)	Large ton dual-phase$^{1)}$	Light dark matter... $^{2)}$	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	R&D DM/neutrino experiments$^{3)}$	R&D ton scale 0nbb	ILC	FCC-ee	CLIC	STCF	FCC-hh	FCC-eh	Muon collider
Muon system **Proposed technologies:** RPC, Multi-GEM, resistive GEM, Micromegas, micropixel Micromegas, μRwell, μPIC ...	Rad-hard/longevity	1.1		🟢					🔴	🔴		🔴			🟢	🟢	🟢		🔴	🟢	🟡
	Time resolution	1.1							🟡	🟡		🟡			🟢	🟡	🟢		🟡	🟡	🟠
	Fine granularity	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟡	🟢		🔴	🟡	🔴
	Gas properties (eco-gas)	1.3								🟠						🔴			🔴	🔴	🔴
	Spatial resolution	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🟠	🟠	🟠
	Rate capability	1.3	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🔴	🟢	🟡
Inner/central tracking with PID **Proposed technologies:** TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers	Rad-hard/longevity	1.1	🟠	🟠	🟠						🟡				🟢		🟢				
	Low X_0	1.2	🟠	🟠	🟠						🟠				🟠	🔴	🟠	🔴			
	IBF (TPC only)	1.2	🟠	🟠											🔴	🔴	🔴	🔴			
	Time resolution	1.1	🟡		🟡						🟠				🟢	🟡	🟢	🟡			
	Rate capability	1.3	🟠		🟠						🟠				🟢	🟡	🟢	🟡			
	dE/dx	1.2	🟠								🟠				🟠	🟠	🟠	🟠			
	Fine granularity	1.1	🟠		🟠						🟠				🟠	🟠	🟠	🟠			
Preshower/ Calorimeters **Proposed technologies:** RPC, MRPC, Micromegas and GEM, μRwell, InGrid (integrated Micromegas grid with pixel readout), Pico-sec, FTM	Rad-hard/longevity	1.1													🟡	🟡	🟡		🔴	🔴	🔴
	Low power	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Gas properties (eco-gas)	1.3													🔴	🔴	🔴		🔴	🔴	🔴
	Fast timing	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Fine granularity	1.1													🟠	🟠	🟠		🟠	🟠	🟠
	Rate capability	1.3													🟠	🟠	🟠		🔴	🔴	🟠
	Large array/integration	1.3													🔴	🔴	🔴		🔴	🔴	🔴
Particle ID/TOF **Proposed technologies:** RICH+MPGD, TRD+MPGD, TOF: MRPC, Picosec, FTM	Rad-hard (photocathode)	1.1	🟠	🟠							🟡										
	IBF (RICH only)	1.2	🟠	🟠							🟠										
	Precise timing	1.1	🟡	🔴							🔴										
	Rate capability	1.3		🟢							🟠										
	dE/dx	1.2		🟢																	
	Fine granularity	1.1		🟠							🟠										
TPC for rare decays **Proposed technologies:** TPC+MPGD operation (from very low to very high pressure)	Low power	1.4				🔴	🔴						🔴								
	Fine granularity	1.4				🟢	🟠	🟠					🟠	🟠							
	Large array/volume	1.4				🟡	🟠	🟡					🔴	🔴							
	Higher energy resolution	1.4				🟢	🔴	🔴					🔴	🔴							
	Lower energy threshold	1.4				🔴	🟠	🔴					🟠	🔴							
	Optical readout	1.4				🟡	🟠	🟠					🟠	🟠							
	Gas pressure stability	1.4				🟢		🔴						🔴							
	Radiopurity	1.4				🟢	🔴	🔴					🔴	🔴							

🔴 Must happen or main physics goals cannot be met
🟠 Important to meet several physics goals
🟡 Desirable to enhance physics reach
🟢 R&D needs being met

IV. TPCs for Rare Events (feedback to the process)

WG2-applications
(TPC survey)

a diverse community where **most players are already active and doing something** (and often, quite different)

A. Assets that give support to the collaboration:

- Low and high pressure techniques.
- High gas-purity techniques (monitoring and control).
- Underground Facilities and radiopurity techniques.
- Low-outgassing and sealing techniques.
- Neutron beams and neutron generators.
- **GridPix.**

B. Assets that the collaboration can support with:

- R&D on ad-hoc structures (e.g., radiopure and with enhanced properties for negative-ion amplification, scintillation, etc…)
- A stable GridPix production and readout line, accessible to users.
- A high-purity facility in connection with scintillation, attachment and outgassing studies.

C. Synergies:

- Large-volume tracking TPCs (**separate R&Ds but encourage synergies**!)
- High spatial sampling and spatial resolution (tracking detectors).
- Optical and negative-ion simulations.
- Neutron and very-low-energy X-ray detection with directional information.

IV. TPCs for Rare Events (feedback to the process)

WG2-applications
(TPC survey)

<u>clear groups / work packages</u>

1. Negative ion TPCs (gas mixtures, structures, electronics, simulation)*
2. Optical readout (gas mixtures, scintillation studies, structures, sensors, simulation)
3. Charge readout at the physical limit (down to single-electron counting, Fano energy resolution, Penning mixtures….)
4. Dual-phase readouts (overlap with DRD2)
5. High performing TPCs for specific scientific goals (low-threshold / high sampling / high energy resolution / optimization for pressure far from atmospheric conditions)
6. Radiopurity (structures, gases, materials, methods)
7. New gas mixtures and eco-gases.

*note: a **lot** of interest in negative ion TPCs but the use case and capabilities of the groups not fully clear.