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Accelerator Frontier Outlook on Dark Sector Searches

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Accelerator-based Dark Sector Searches Agora

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Talk Structure

Intense Proton Rings
- LANL PSR
- ORNL SNS
- FNAL Proposed PAR
- FNAL Proposed RCS
- ESS Proposed ESSnuSB AR

Proton Slow-spill
- FNAL Main Injector, PIP-II Linac

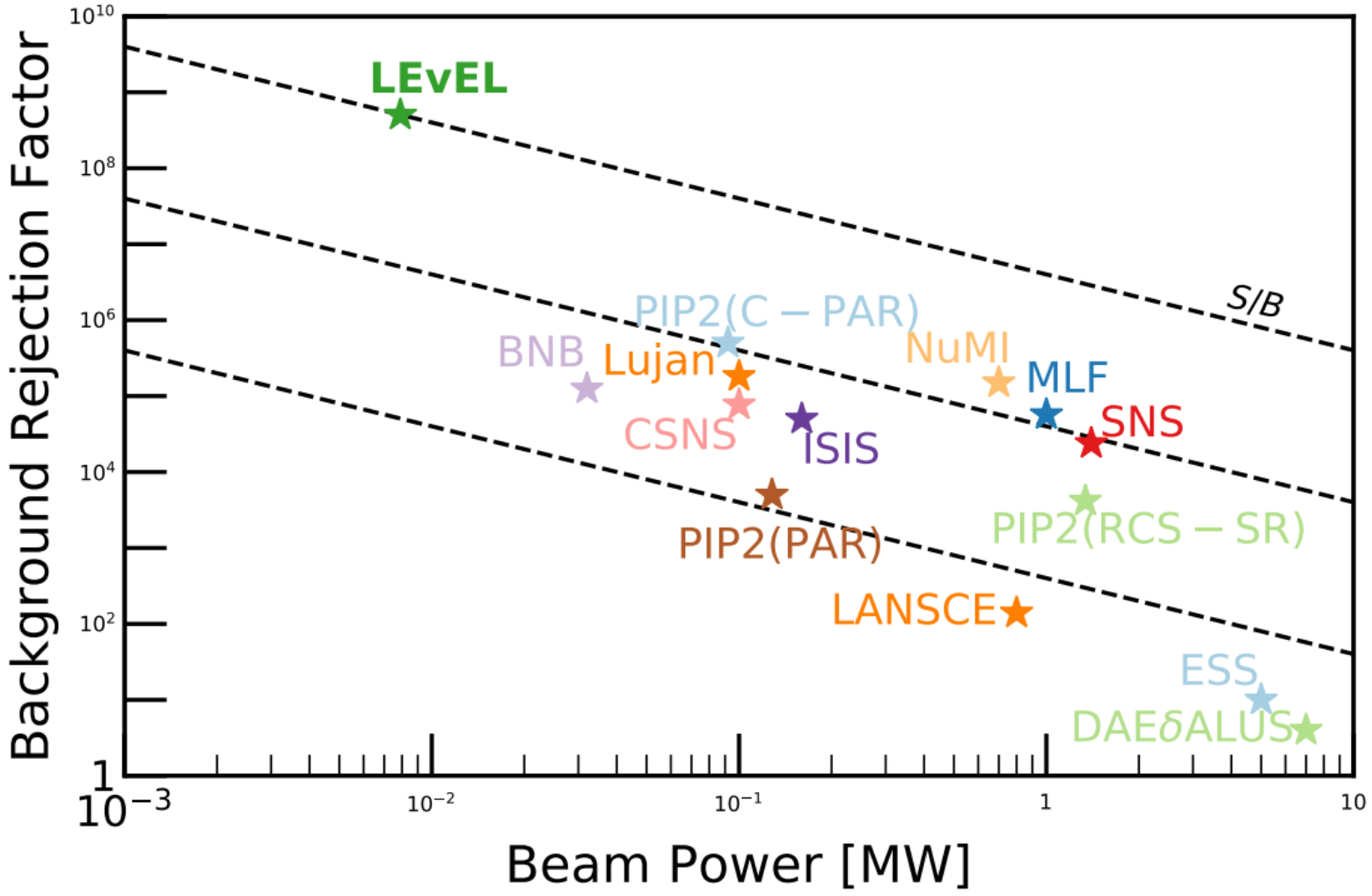
Colliders
- CERN LHC
- KEK Belle II

Electron Searches
- SLAC LCLS-II
- JLAB CEBAF HPS

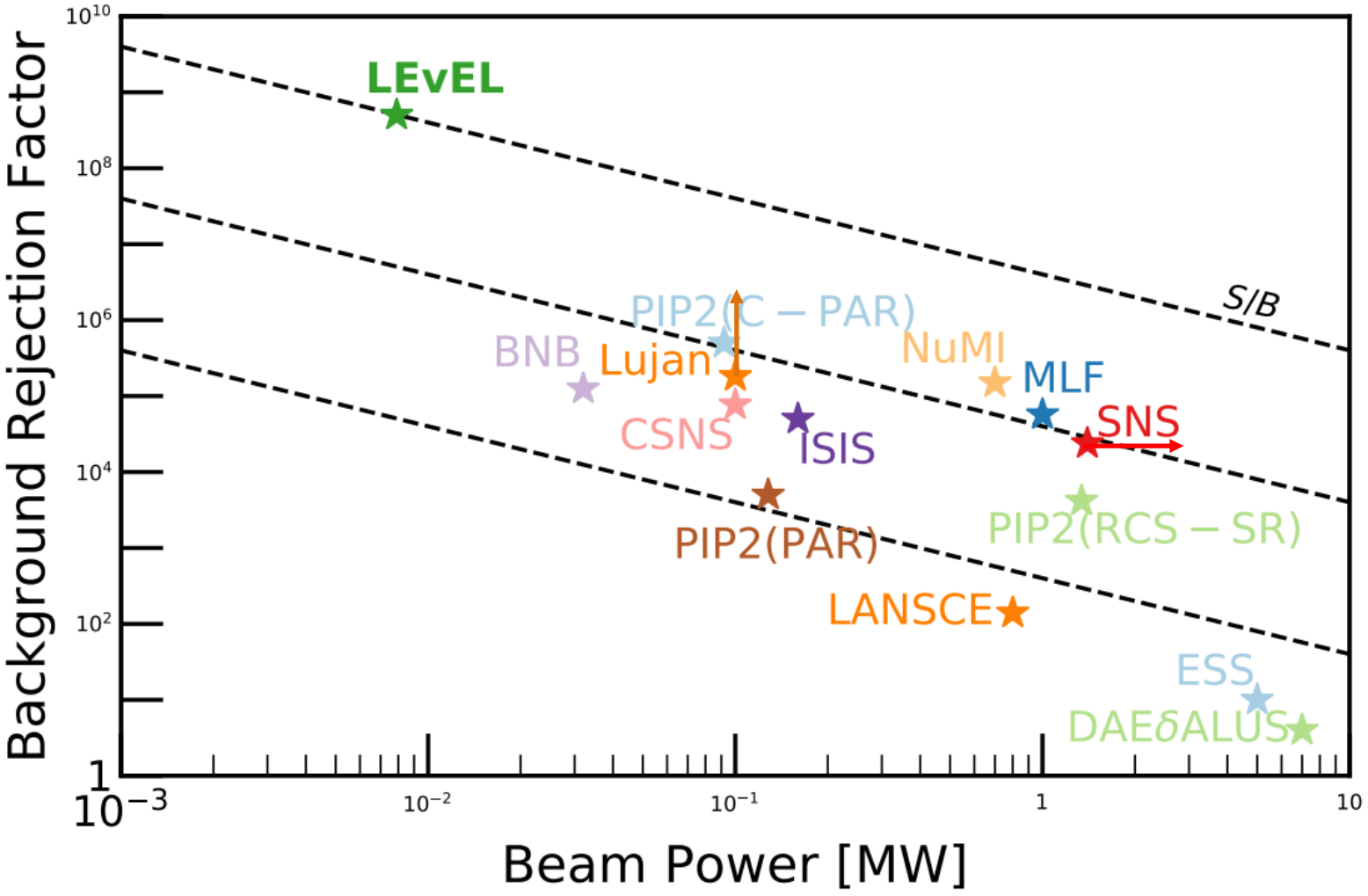
Proton Source Comparison

Facility	Energy	Intensity	Rep. rate	Pulse-length	Power
LANL PSR	0.8 GeV	40 e12	20 Hz	$\leq$300 ns	0.1 MW
SNS	1.0 GeV	155 e12	60 Hz	750 ns	1.4 MW
SNS FTS (**$\sim$2023**)	1.3 GeV	210 e12	$^{3}/_{4} \times$ 60 Hz	750 ns	2.0 MW
SNS STS (**$\sim$2030**)	1.3 GeV	224 e12	15 Hz	750 ns	0.7 MW
Proposed $\sim$2029-2032					
FNAL PAR	0.8 GeV	8 e12	100 Hz	2000 ns	0.1 MW
FNAL C-PAR	1.2 GeV	4.8 e12	100 Hz	20 ns	0.09 MW
Proposed $\sim$2036-2042					
FNAL RCS-AR	2.0 GeV	34 e12	120 Hz	2000 ns	1.3 MW
FNAL SBN-BD v1	8.0 GeV	26 e12	$^{6}/_{12} \times$ 10 Hz	2000 ns	0.17 MW
FNAL SBN-BD v2	8.0 GeV	37 e12	$^{23}/_{28} \times$ 20 Hz	2000 ns	0.75 MW
ESSnuSB AR	2.5 GeV	220 e12	4 $\times$ 14 Hz	1200 ns	5.0 MW

Proton Source Quality Chart



Proton Source Quality Chart



LANL PSR

Upgrade of PSR Snowmass white paper,
for Coherent CAPTAIN Mills (CCM) experiment.

LANL PSR Capabilities
- **40e12** protons in **300ns** pulses every **20Hz** (**100kW** at **0.8 GeV**).

PSR with Short-Pulse Upgrade
- Aims for sub-100ns pulses, possible **30ns** pulses.
- Synergy with PSR neutron resonance experiments.
- Pulse stacking with 2nd harmonic cavities to flatten RF-wave.
- Manage impedances and electron-cloud instabilities with ferrites, transverse and longitudinal feedback systems.

ORNL SNS

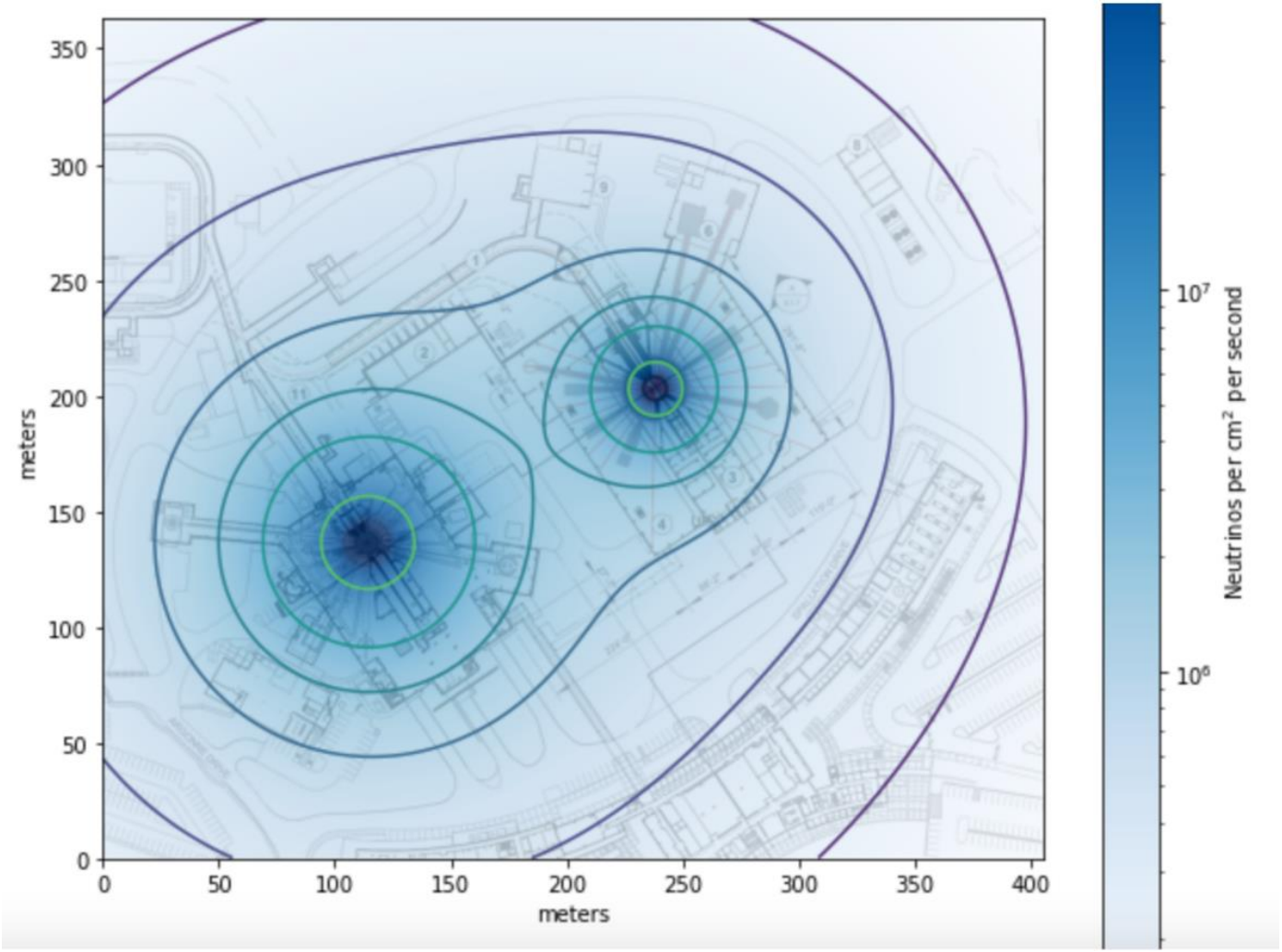
SNS Proton Power Upgrade (PPU) CDR.
COHERENT Snowmass white paper.
SNS Capabilities
- **155e12** protons in **750ns** pulses every **60Hz** (**1.4 MW** at **0.97 GeV**).

SNS with Proton Power Upgrade (PPU) ~2023

- First Target Station (FTS) ~2023: thermal n from liquid-Hg target
210e12 protons in **750ns** pulses every **3/4x60Hz** (**2.0 MW** at **1.3 GeV**).

- Second Target Station (STS) ~2030: cold n from rotating-W target
224e12 protons in **750ns** pulses every **15Hz** (**0.7 MW** at **1.3 GeV**).

FTS vs STS Locations (neutrinos)



Fermilab PIP-II Outlook

Fermilab Proton Improvement Plan II (PIP-II) Upgrade CDR.
PIP2 Beam Dump (PIP2BD) Snowmass white paper.

PIP-II Linac Capabilities ~2029
- **2mA CW-capable** at **0.8 GeV** (94-99% of **1.6MW** unsubscribed)

(Proposed) PIP-II Accumulator Ring (PAR)
- - 0.8 GeV, 474m ring to facilitate injection into the Booster and to host PIP2-BD experimental program.
- PIP2-BD: 8e12 protons in **2000ns** pulses every **100Hz** (**0.1 MW** at **0.8 GeV**).
- With pulse compression: ~4e12 protons in **500ns** pulses every **100Hz** (**0.05 MW** at **0.8 GeV**).
- see **Pellico et al.** Snowmass white paper for preliminary ring design.

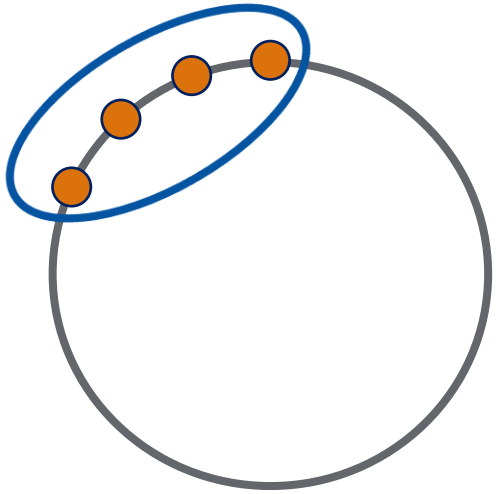
Fermilab PIP-II Outlook

PIP2 Beam Dump (PIP2BD) Snowmass white paper.

… or (Proposed) Compact PAR (C-PAR)
- 100m ring, better optimized for experimental program.
- Would (likely) not help with Booster injection.
- Sited to be compatible with a 1.2 GeV injection.
- Compact ring capable of high rep. rate compatible with requirements for a proposed PRISM-like CFLV. See Prebys et al. and Aoki et al..
- **PIP2-BD mode: 4.8e12** protons in **20ns** pulses every **100Hz** (**0.09 MW** at **1.2 GeV**).
- **CLFV mode: 0.9e12** protons in **20ns** pulses every **800Hz** (**0.14 MW** at **1.2 GeV**).

C-PAR Pulse Schemes

PIP2-BD mode:

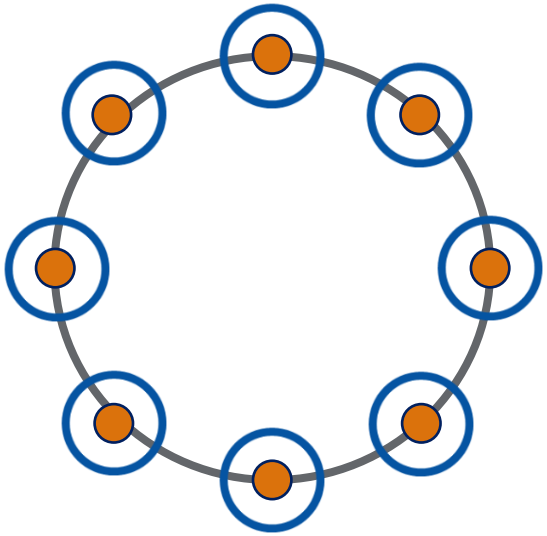


4-bunch merge and 100 Hz extraction

Four 1.2e12 bunches consecutive RF buckets

100 Hz fill

CLFV mode:



800 Hz single-bunch extraction

Eight 0.9e12 bunches every other RF bucket

100 Hz fill

Fermilab RCS (Proposed)

2.4 MW RCS upgrade white papers, summary of two versions 1 2.

(Proposed) 2.4 MW RCS Upgrade for DUNE/LBNF ~2038
- A ~2 GeV upgrade of PIP-II Linac.
- New ~550m rapid-cycling synchrotron (RCS) to replace Booster ring and provide 26-37e12 protons every 10-20 Hz at 8 GeV.

Possible Accumulator Ring & Experimental Program
- A **2 GeV** ~550m AR is required by some RCS upgrade scenarios and may be beneficial for other RCS scenarios.
- If H- laser-stripping technology can be developed, this AR could operate a high-power experimental program simultaneously.
- **DM mode: ~34e12** protons in **2000ns** pulses every ~**120Hz** (**1.3 MW**).

8-GeV Dark Sector Searches
- The 2.4 MW RCS upgrade would provide **170-750 kW** at **8 GeV**.
- The dominant factor in beam power is the RCS ramp rate.
- **SBN-BD white paper Toups et al.**

ESS nuSB Accumulator Ring (Proposed)

ESSnuSB Snowmass white paper.
ESS Status & Comissioning paper N. Milas et al.

ESS Linac ~2026:
62.5 mA for **2.86ms** every **14Hz** (**2.0 MW** at **0.8 GeV**).
ESS Linac at Full Power:
62.5 mA for **2.86ms** every **14Hz** (**5.0 MW** at **2.0 GeV**).

(Proposed) ESSnuSB Accumulator Ring ~2037
- Upgrade to 2.5 GeV & 10MW, with 14 Hz H- interleaved with 14 Hz p+.
- ESSnuSB AR is 380m ring which extracts four 1.2us pulses separated by 0.9ms every 72ms, dividing the pulses across four neutrino targets/horns.
- ESSnuSB: 220e12 protons in **1.2us** pulses every **4x14Hz**
(**5.0 MW** at **2.5 GeV**).

ESSnuSB white paper discusses subsequent a **2ns** proton compressor ring, to serve as a proton driver for a **future muon collider** program.

Proton Dark Matter Searches

Common Themes in Intense Proton Facilities

- High power **H- injection**, foils -> lasers.
- **Intense space-charge** - compact, GeV-scale, large aperture rings.
- **Pulse compression schemes**, longitudinal manipulation.
- Kickers with **high rep. rate** extraction, **fast rise time**.
- Service to **multiple experimental** programs.

FNAL is deciding on it's future experimental program

FNAL Slow Spill Protons

DarkQuest Snowmass white paper.

Main Injector Slow Spill
- **8e12** protons at **120 GeV**, over **six seconds**, **once a minute**.
- Limited by particle loss rates during 2nd-order resonant extraction.

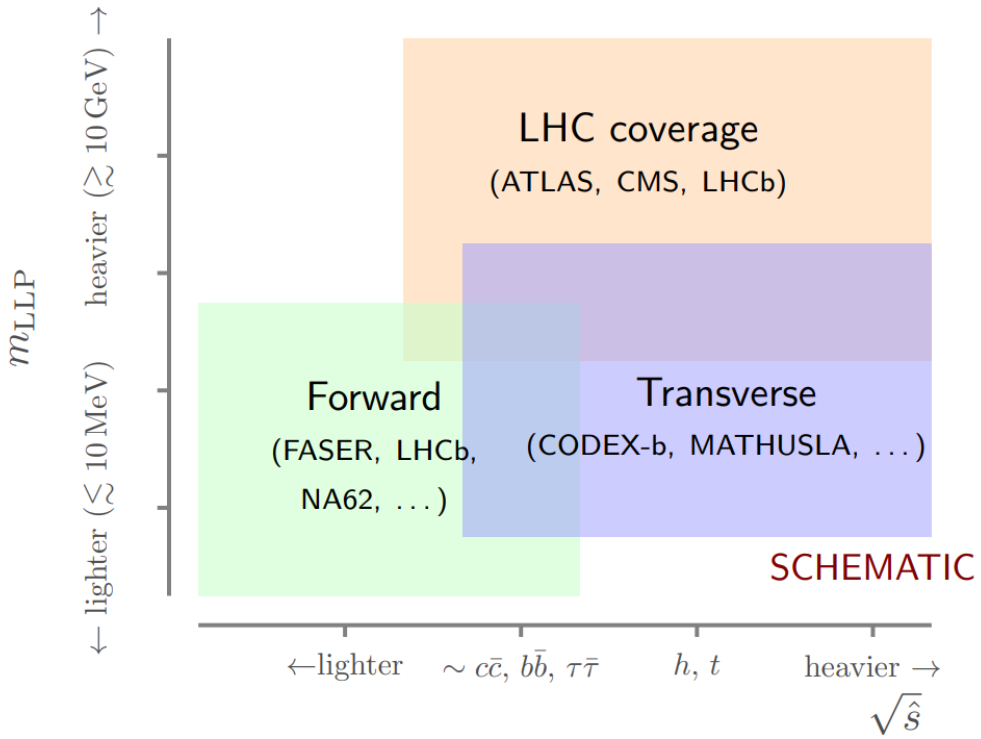
REDTOP paper Gatto et al.

PIP-II Linac Capabilities ~2029
- **2mA CW-capable** at **0.8 GeV**
- REDTOP Run-II, tagged η

Upgraded PIP-II Linac Capabilities ~2038
- **2mA CW-capable** at **2.0 GeV**
- REDTOP Run-III, tagged η’

CERN LHC

Forward Facility at HL-LHC Snowmass white paper.
CODEX-b Snowmass white paper.
LHC-b Dark Sector Snowmass white paper.



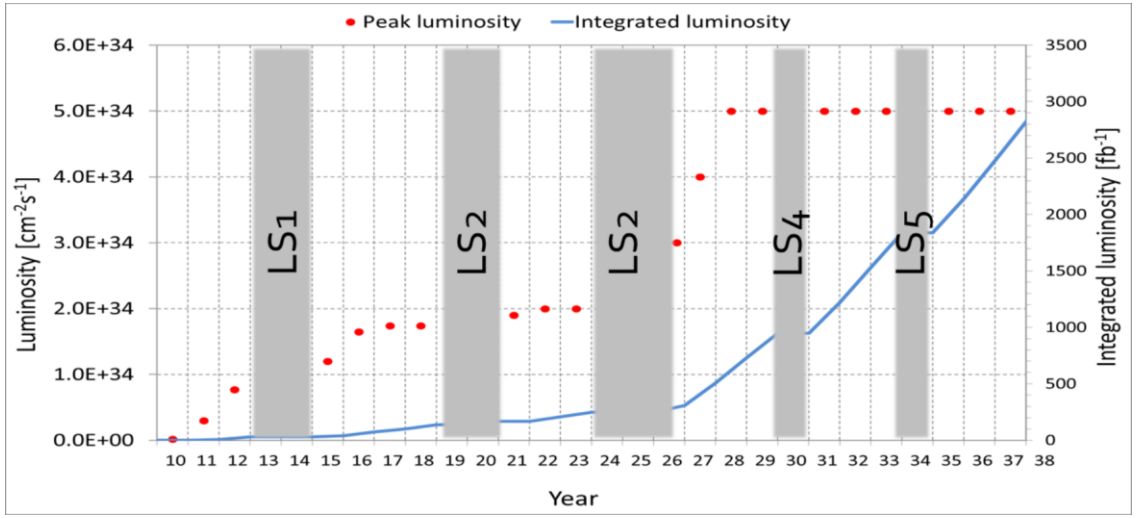
LEvEL at LHC Beam Dump, K. Kelly et al.

CERN LHC

Forward Facility at HL-LHC Snowmass white paper.
CODEX-b Snowmass white paper.
LHC-b Dark Sector Snowmass white paper.

LHC capabilities
- **2.06e34 $cm^{-2}s^{-1}$** instantaneous luminosity circular p^+ p^+ collider.
- **13 TeV** center of mass energy (6.5+6.5 Gev) symmetric collision.
- also supports ion-ion collisions.

HL-LHC:
- crab cavities
- Nb3Sn quads
- bunch spacing
- detector upgrades
- **B. Schmidt**



FCC Snowmass white paper

KEK Belle II

Belle-II GAZELLE Snowmass white paper.

Belle II Capabilities

- **2.4e34 $cm^{-2}s^{-1}$** instantaneous luminosity circular e^+ e^- collider.
- **10.58 GeV** center of mass energy (4+7 Gev) asymmetric collision.

Proposed Polarization Upgrade Snowmass white paper.

JLAB CEBAF HPS & APEX

HPS Snowmass white paper.
Physics with CEBAF paper J. Arrington et al.

LERF Capabilities
- Up to **135pC** at **74.85 MHz CW**, **0.17 GeV** electrons, up to **~1.7 MW**.
DarkLight experiment

CEBAF Capabilities
- Up to **1.3pC** at **249.5 MHz CW**, **1-11 GeV** electrons, up to **1 MW**.
    - up to 85% polarization.
- APEX experiment in Hall A.
- HPS experiment in Hall B.

HPS:

Run	Energy (GeV)	Target (% X_0 W)	Beam Time Used	$\int \mathcal{L}$ pb^{-1}
2015	1.056	0.125	9.5 days	1.17
2016	2.30	0.125	5.5 days	10.75
2019	4.55	0.25/0.625	30 days	122
2021	3.74	0.625	28 days	168

Experiments need runtime, looking at target & detector improvements.

SLAC LCLS-II

LDMX Snowmass white paper.

LCLS-II capabilities
Cu Linac (now): 180pC at **120 Hz**, **15 GeV** electrons.
SC Linac (comissioning): 100pC at **1 MHz**, **4 GeV** electrons.
- LDMX at SLAC LCLS-II SC Linac or JLAB CEBAF.

LCLS-II-HE
- Extend SC Linac to provide **8 GeV** electrons

(PEP-II / BaBar no longer operational.)

Final Thoughts

Common Themes in Proton Facilities

- High power **H- injection**, foils -> lasers.
- **Intense space-charge** - compact, GeV-scale, large aperture rings.
- **Pulse compression schemes**, longitudinal manipulation.
- Kickers with **high rep. rate** extraction, **fast rise time**.
- Service to **multiple experimental** programs.

Slow-extraction, Electron Machines & Colliders

- Experiment **beamtime** and **real estate**.
- **Accelerator performance.** Rep. rate, luminosity, energy, polarization.
- Design of Dark Sector **targets** and **detectors.**

Consider also future colliders such as FCC and ILC.