The Search For Light Dark Matter

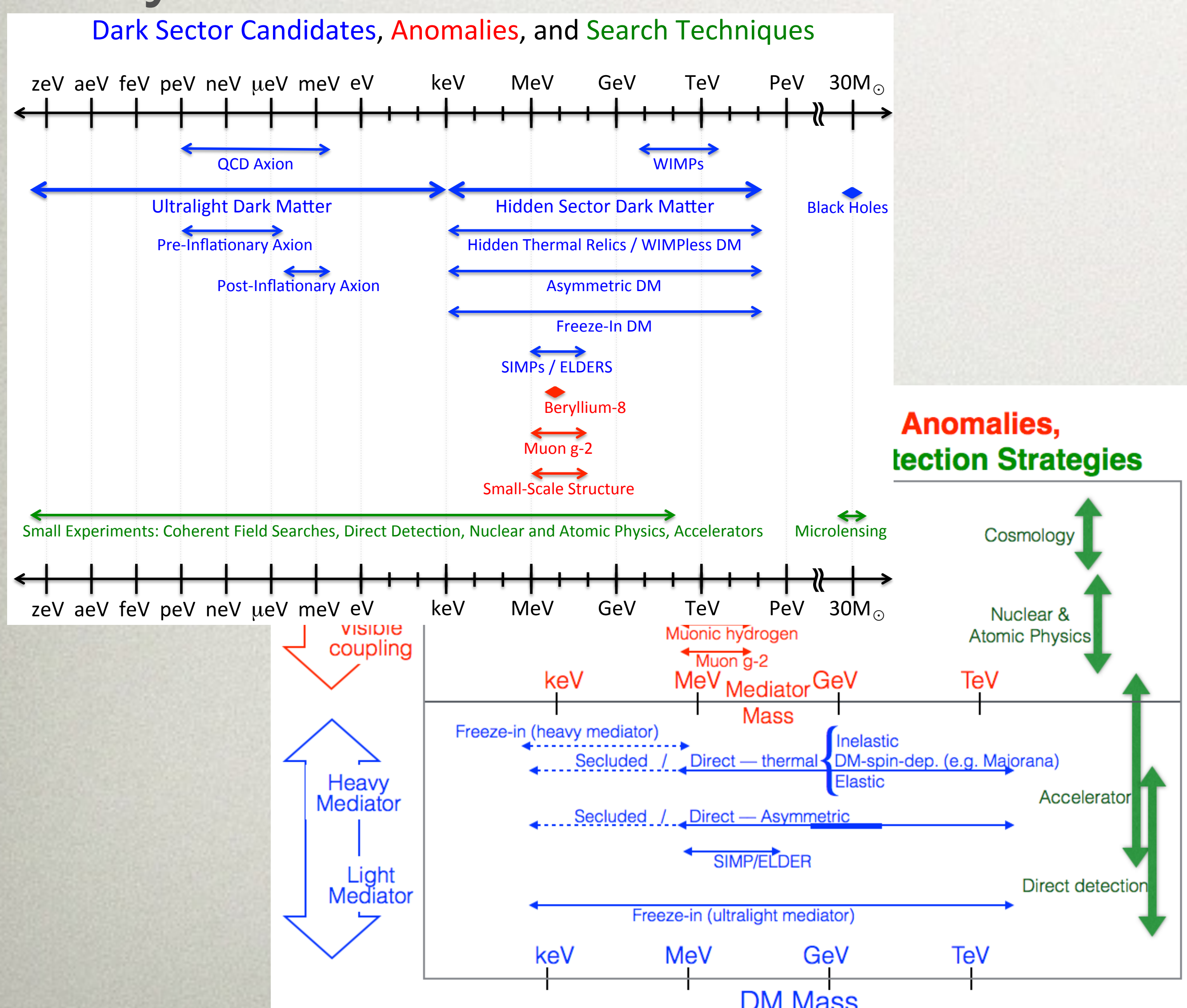
Philip Schuster (SLAC)

HPS Collaboration Meeting
October 26, 2017

A New Frontier

Over the last few years, a strong science case for moving beyond WIMPs has been established

Workshop and Community Report:
arXiv: 1707.04591
Light hidden-sector dark matter
a key area of focus



arXiv:1707.04591v1 [hep-ph] 14 Jul 2017

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

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First Steps Beyond WIMPs

Thermal origin is a simple and compelling idea for the origin of dark matter

Vicinity of the weak-scale remains well-motivated

No need to toss out all of the nice and simple features of WIMPs

- **Thermal Origin**
- **Standard Model-like Mass**
- **Standard Model forces**

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First Steps Beyond WIMPs

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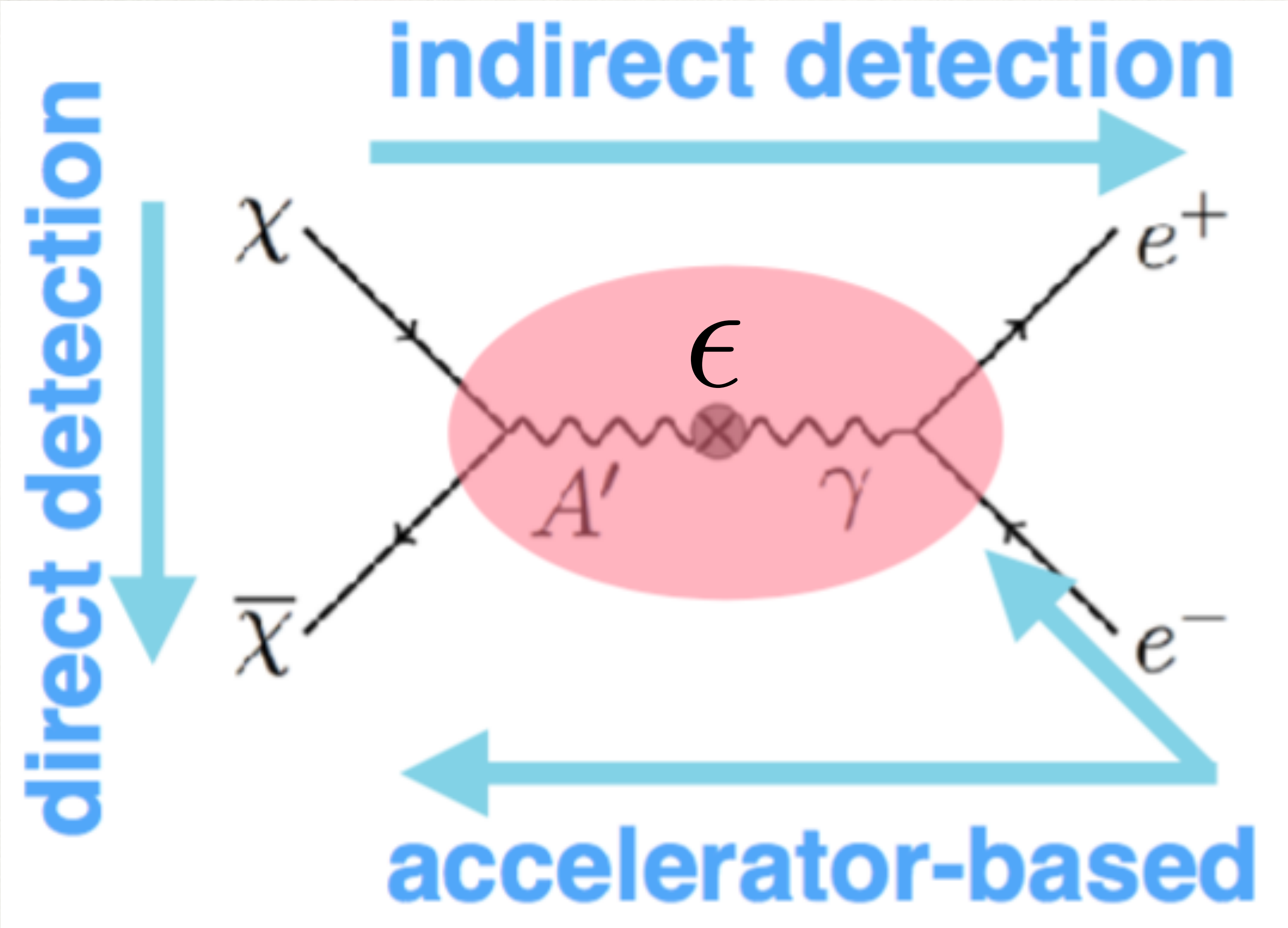
"WIMP-like" dark matter, just not charged under SU(2) weak. Interacts via some other mediator — hidden (or dark) sector dark matter!

WIMP & Thermal LDM Experimental Effort: Phenomenology Similarities



+ other modes

Experimental strategies similar to WIMP program, but new challenges and opportunities arise from the lower mass scales

Thermal LDM Models

Low-energy phenomenology depends on

- DM spin (fermion or scalar)
- Mass structure ($U(1)_D$–preserving, $U(1)_D$–breaking, or both)

charged, elastic *axially coupled elastic* *inelastic*

Particle Type **Dark Matter Current** **Different Low-Energy Phenomenology!**

Model	Mass terms	J_D^μ	scattering $\sigma \propto$	Annilhilation $\sigma v \propto$	CMB-viable?
Fermion DM – Direct Annihilation					
Majorana	$\not{U}(1)_D$	$\bar{\Psi}\gamma^\mu\gamma_5\Psi$	v^2	p-wave $\propto v^2$	Y
Dirac	$U(1)_D$-inv.	$\bar{\Psi}\gamma^\mu\Psi$	1	s-wave $\propto v^0$	N
Pseudo-Dirac	$U(1)_D$-inv. & $\not{U}(1)_D$	$\bar{\Psi}_L\gamma^\mu\Psi_H$	kin. forbidden [a]	kin. forbidden	Y
Scalar DM – Direct Annihilation					
Complex	$U(1)_D$-inv.	$\phi^*\partial^\mu\phi - \phi\partial^\mu\phi^*$	1	p-wave $\propto v^2$	Y
Pseudo-complex	$U(1)_D$-inv. & $\not{U}(1)_D$	$\phi_L\partial^\mu\phi_H - \phi_H\partial^\mu\phi_L$	kin. forbidden	kin. forbidden [b]	Y

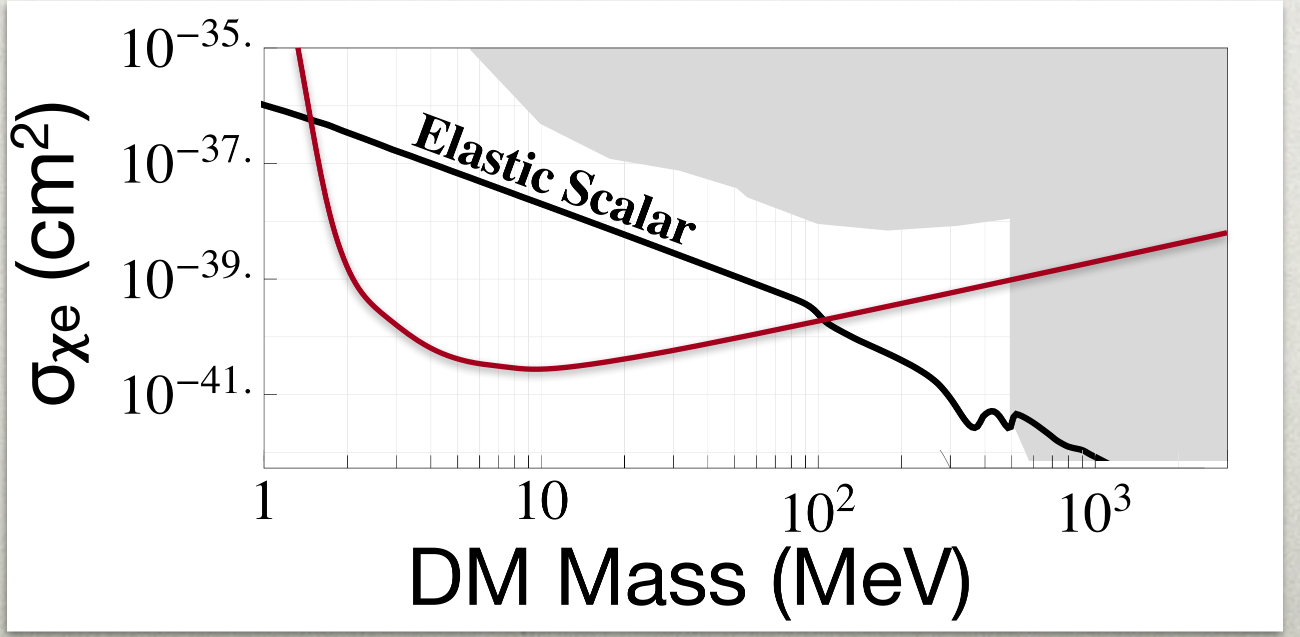
Like neutralino WIMP

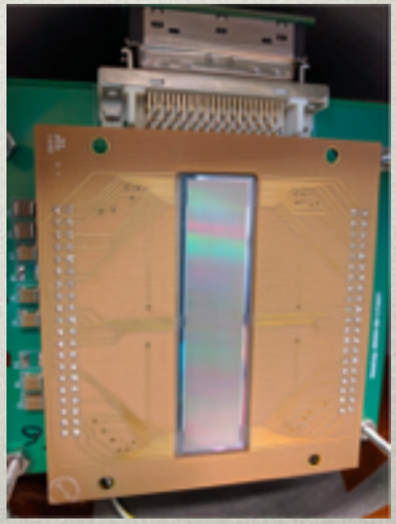
Like sneutrino or Dirac neutrino WIMP

Dark-Matter-Electron Scattering

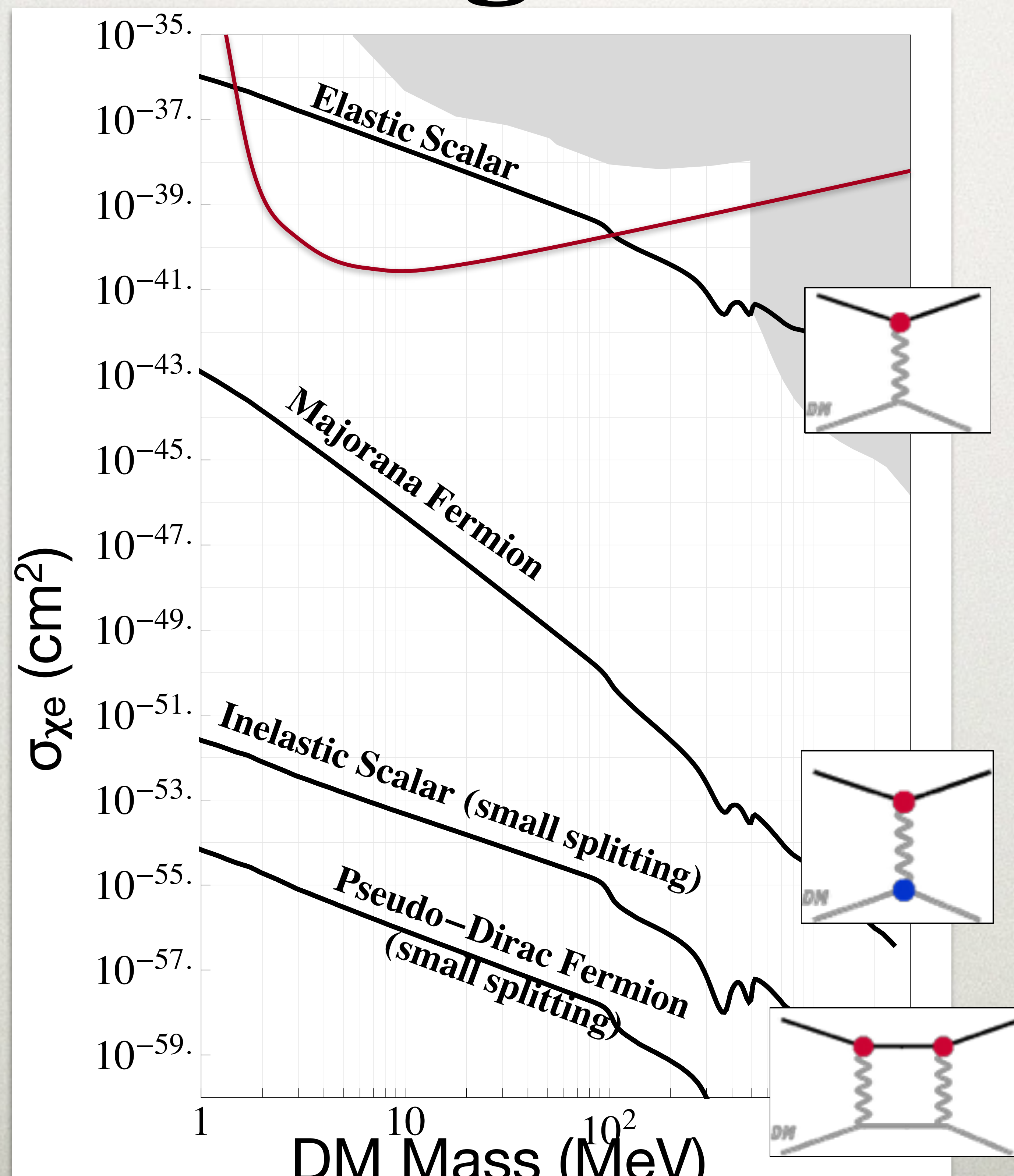
New dedicated experiments aim to see electron recoils at **lower** energy than typical backgrounds (radiogenic, etc)

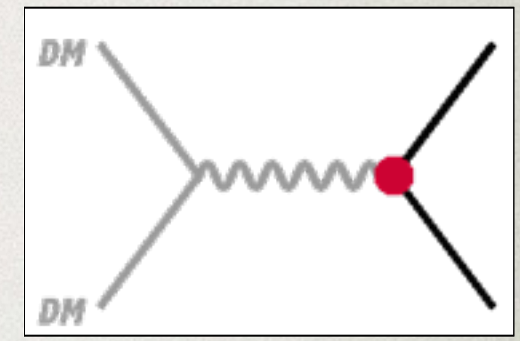
e.g. SENSEI:
1–100g detector made from low-noise skipper CCDs





Dark-Matter-Electron Scattering: Limitations





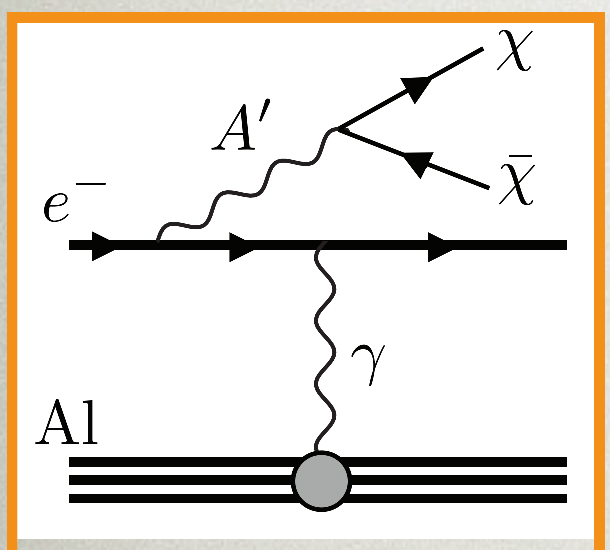
Dark matter halo is non-relativistic! (10^{-3} *c*) ⇒

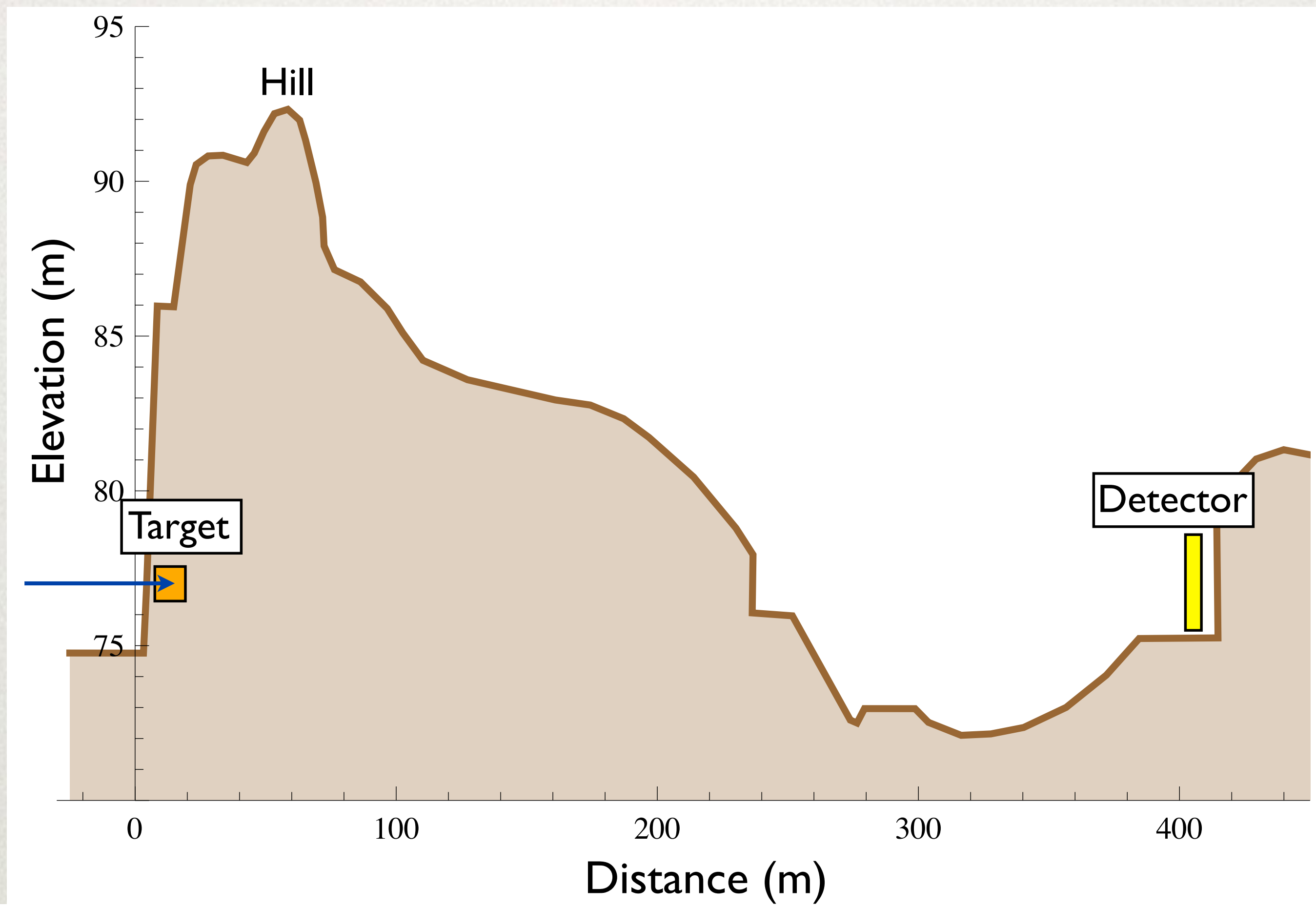
Xsec predictions spread over tens of decades, much like for WIMPs!

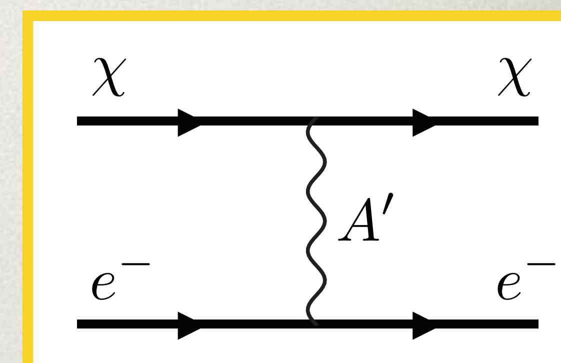
- Small DM-SM coupling
- Velocity-suppression

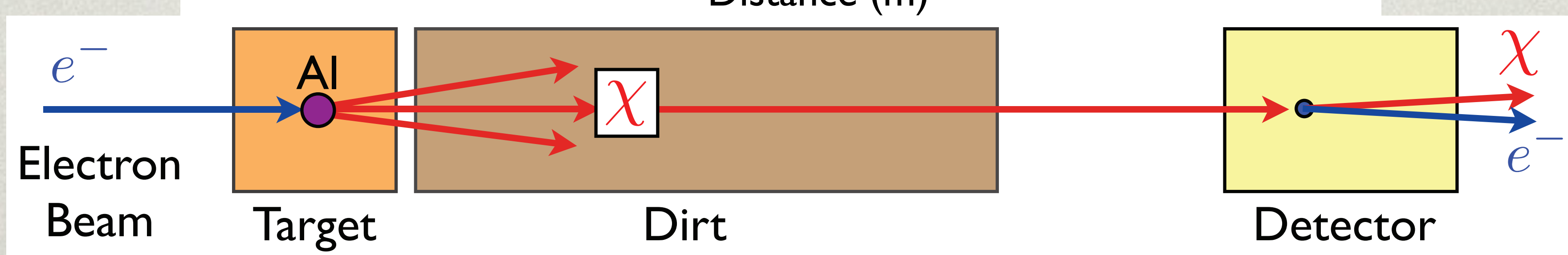
Dark-Matter Production I

- **Remedy:** make relativistic dark matter! In fact, there are already powerful constraints on such production from experiments >30 years ago



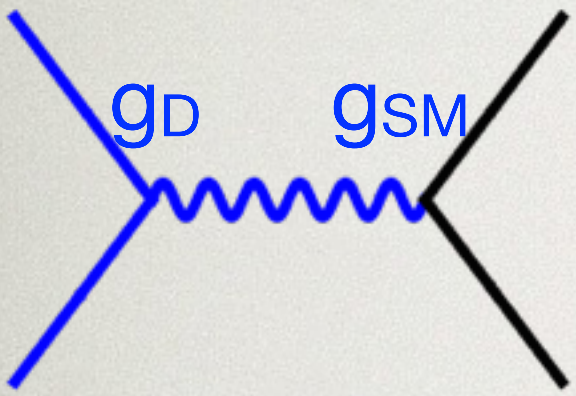






- Similarly, accelerator neutrino experiments are also Dark Matter factories

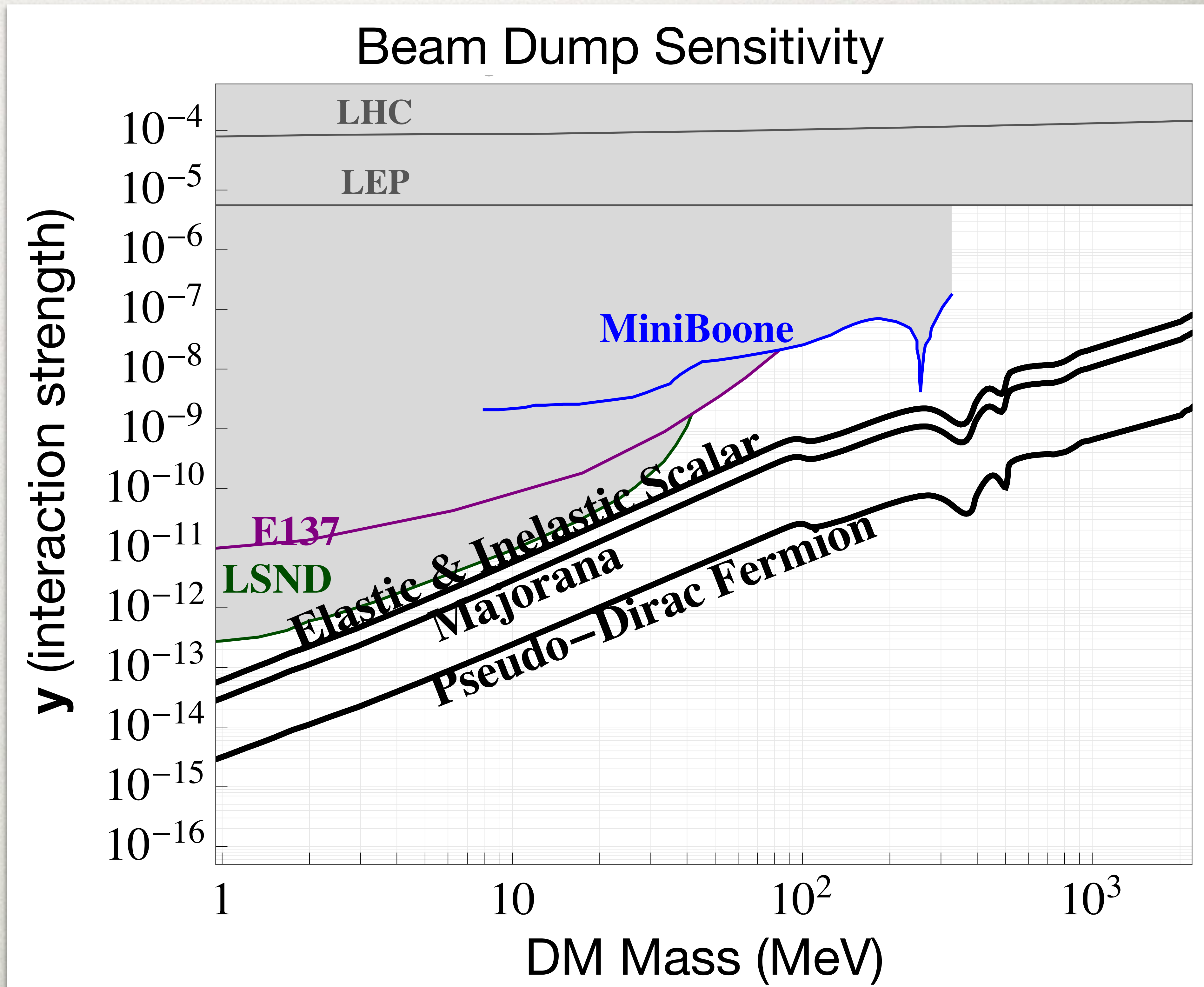
Dark-Matter Production I



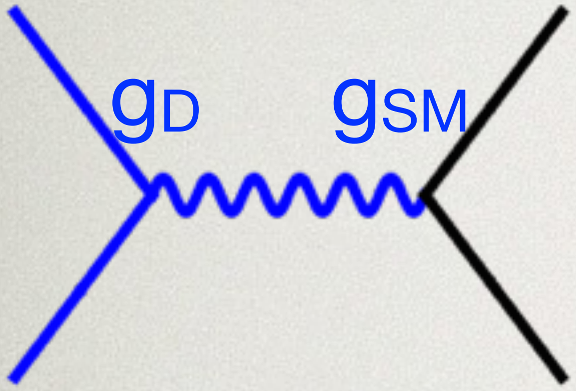
$\sigma \sim$
$g_{SM}^2\, g_D^2\;\; m_{DM}^2 / \, m_{Med}^4$
$\equiv y/m_{DM}^2$

Production $\propto g_{SM}^2$ – infer **worst-case y** sensitivity from physical upper limits on g_D and m_{DM}/m_{Med}

Detection $\propto$ another **y**



Dark-Matter Production I



$\sigma \sim g_{SM}^2\, g_D^2\, m_{DM}^2 / m_{Med}^4 \equiv y / m_{DM}^2$

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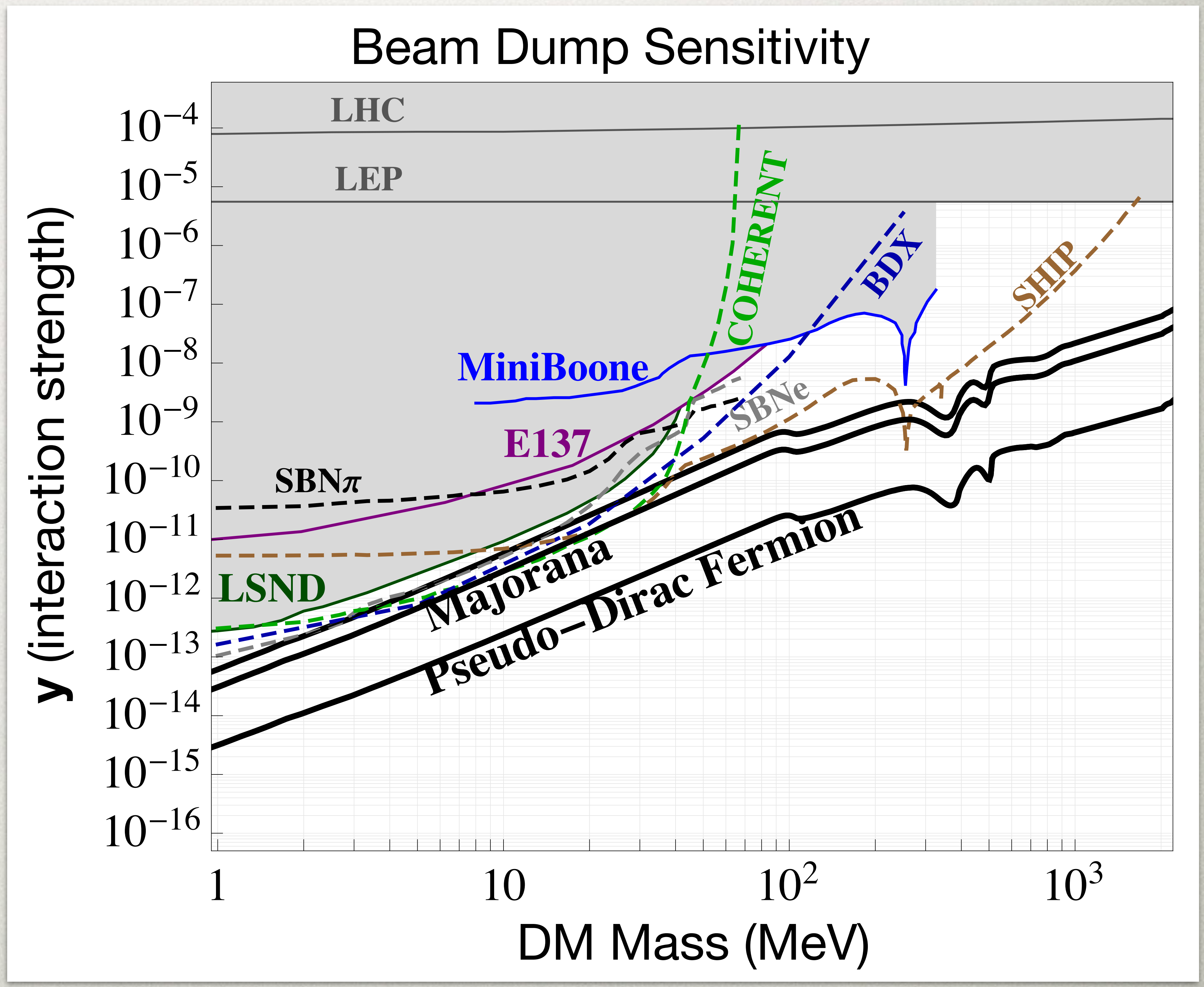

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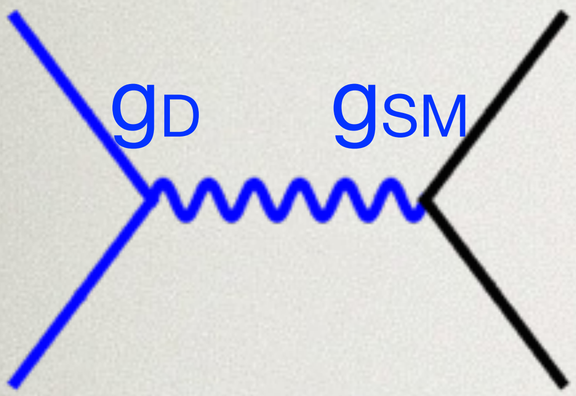

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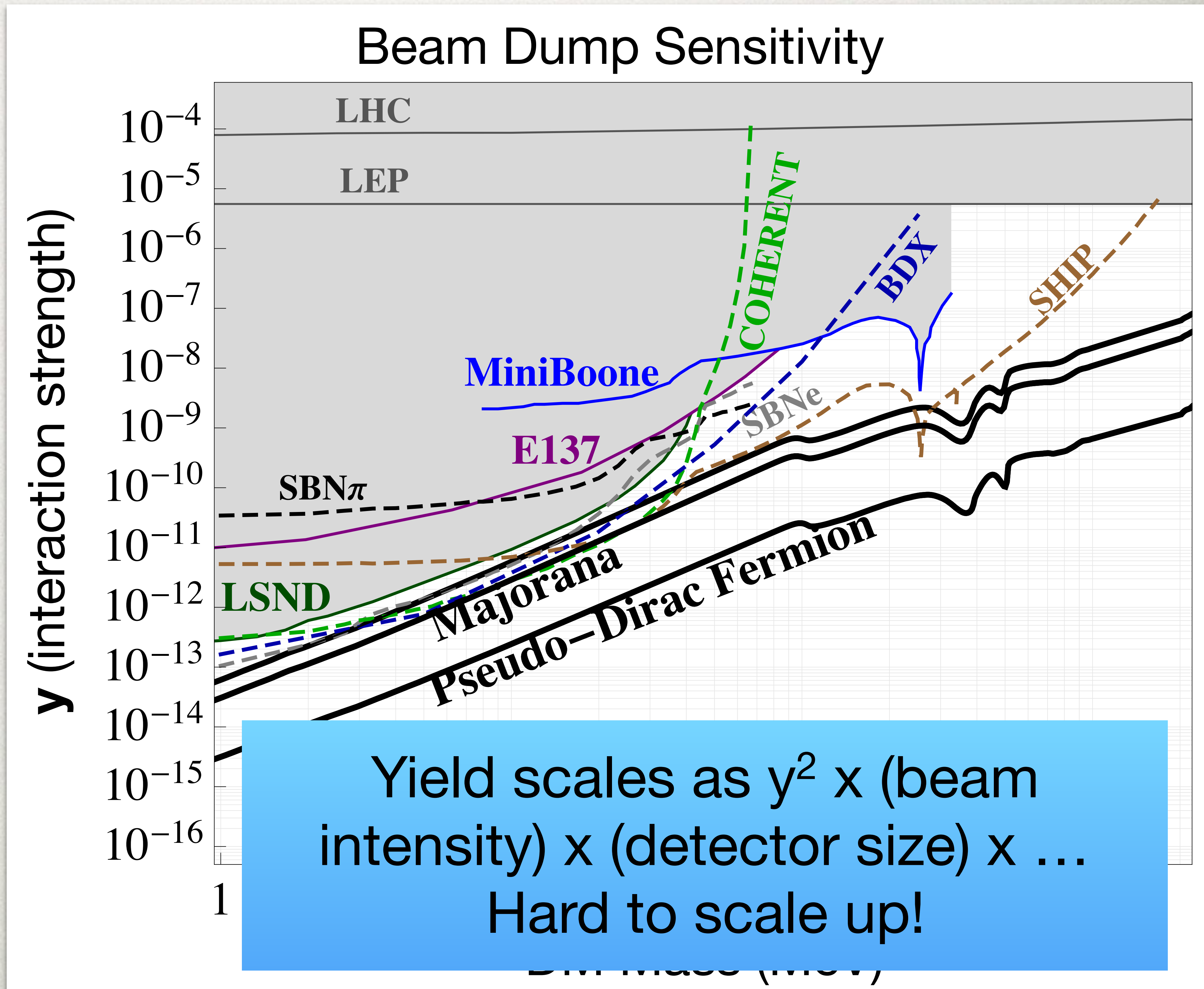
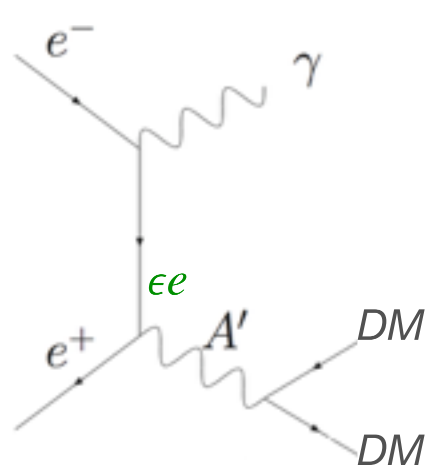


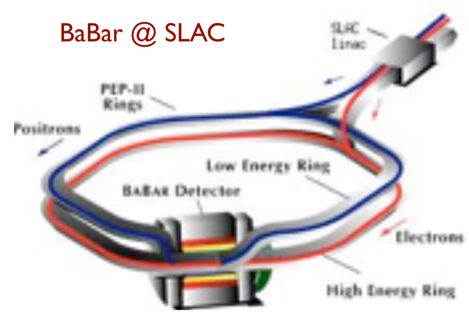
Yield scales as y^2 x (beam intensity) x (detector size) x … Hard to scale up!

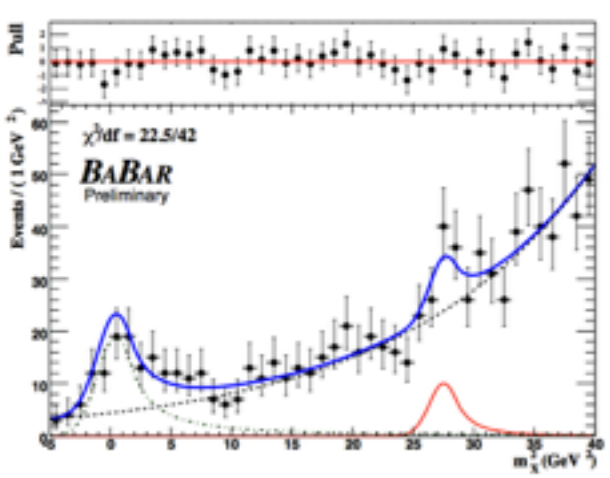
Dark-Matter Production II

- To beat this scaling, must detect dark matter production via **kinematics** of visible final states
  - gives signal yield∝y; low irreducible background

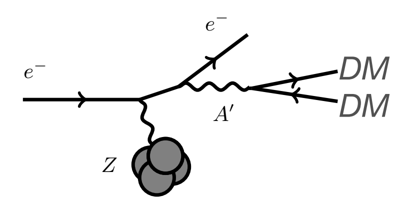
Missing Mass (e^+e^- colliders)
= full kinematic reconstruction

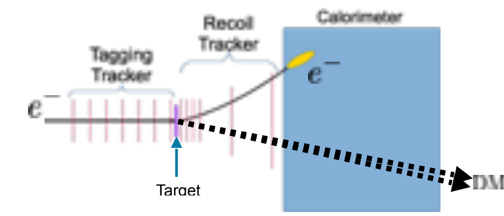


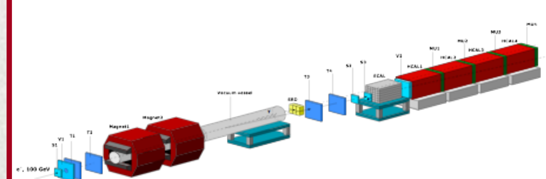


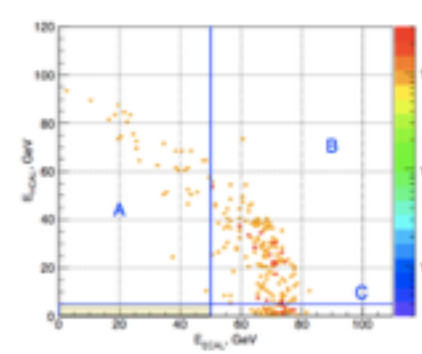


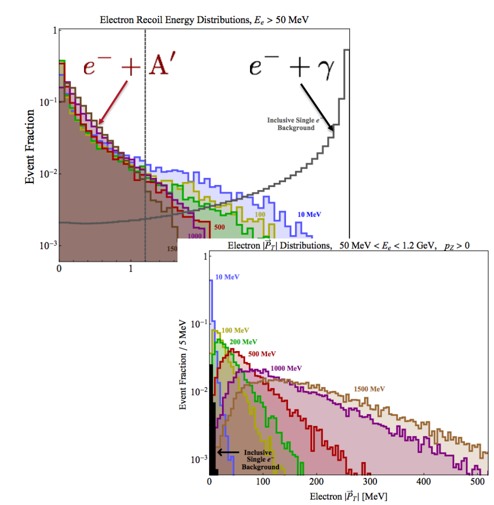
Missing Energy/Momentum
(e^- fixed target)
= partial kinematic reconstruction









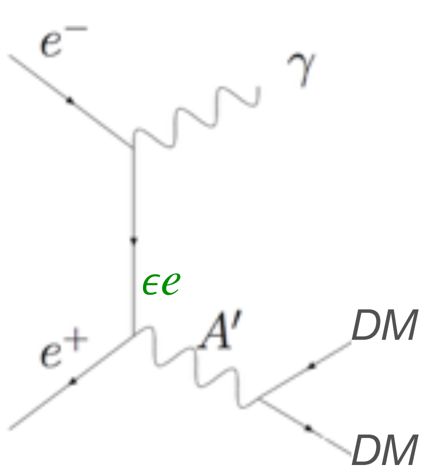


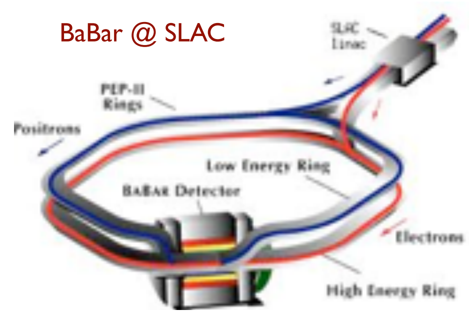
lower mass

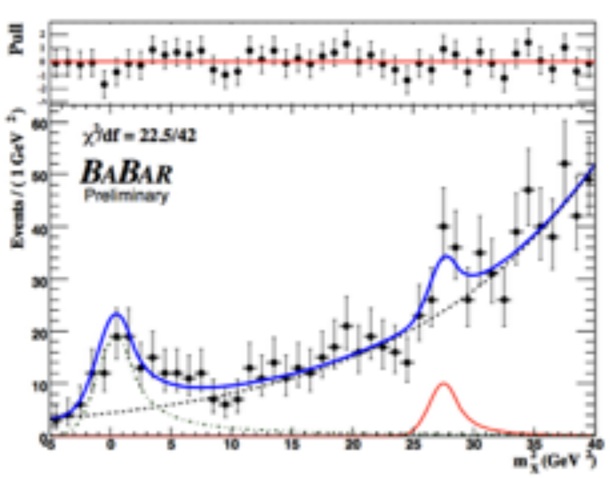
Dark-Matter Production II

- To beat this scaling, must detect dark matter production via **kinematics** of visible final states
  - gives signal yield$\propto$y; low irreducible background

Missing Mass (e^+e^- colliders)
= full kinematic reconstruction





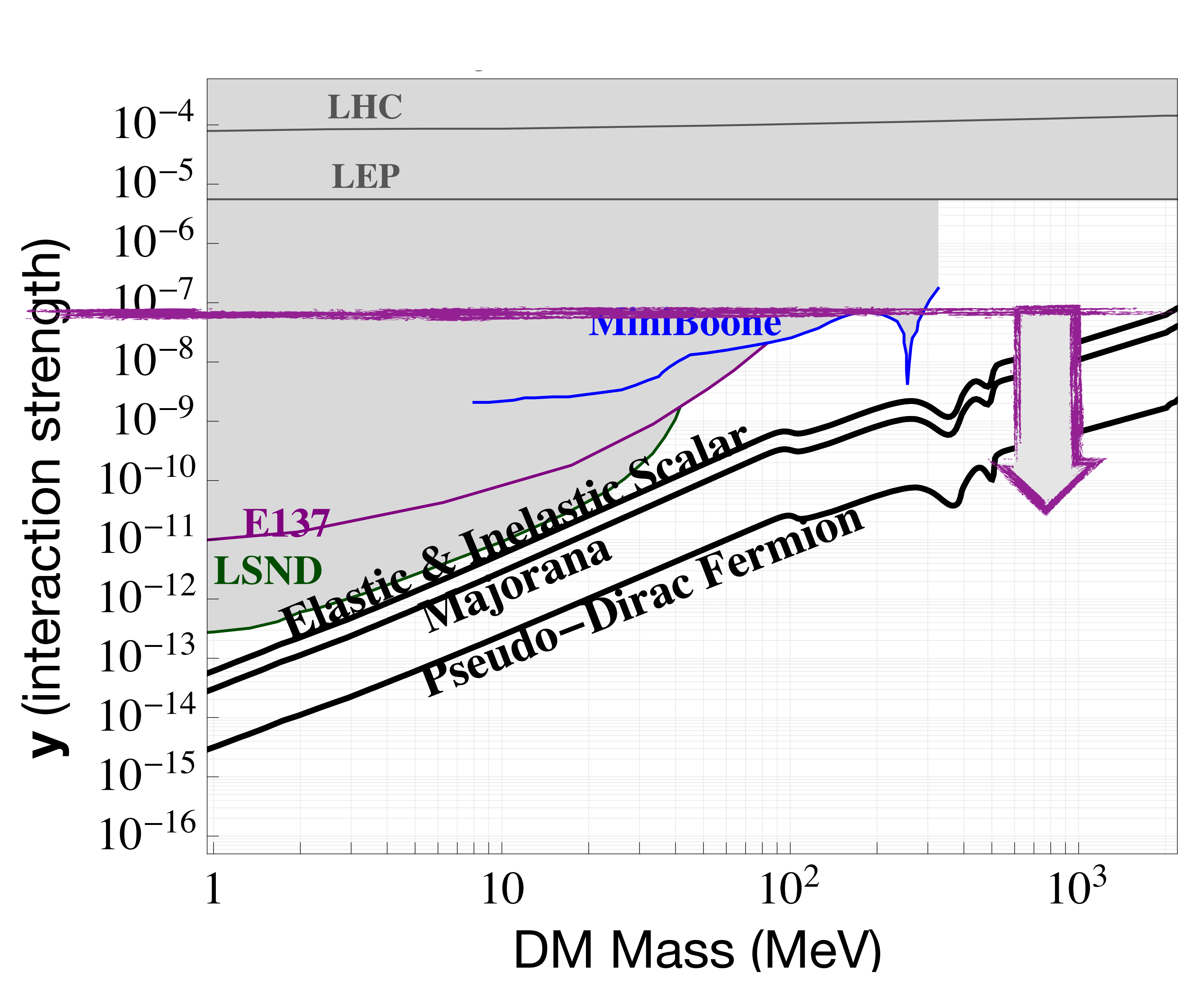


Dark-Matter Production II

- To beat this scaling, must detect dark matter production via **kinematics** of visible final states

Colliders:

Rate ~ **y**$\mathscr{L}$ /E_{CM}^2



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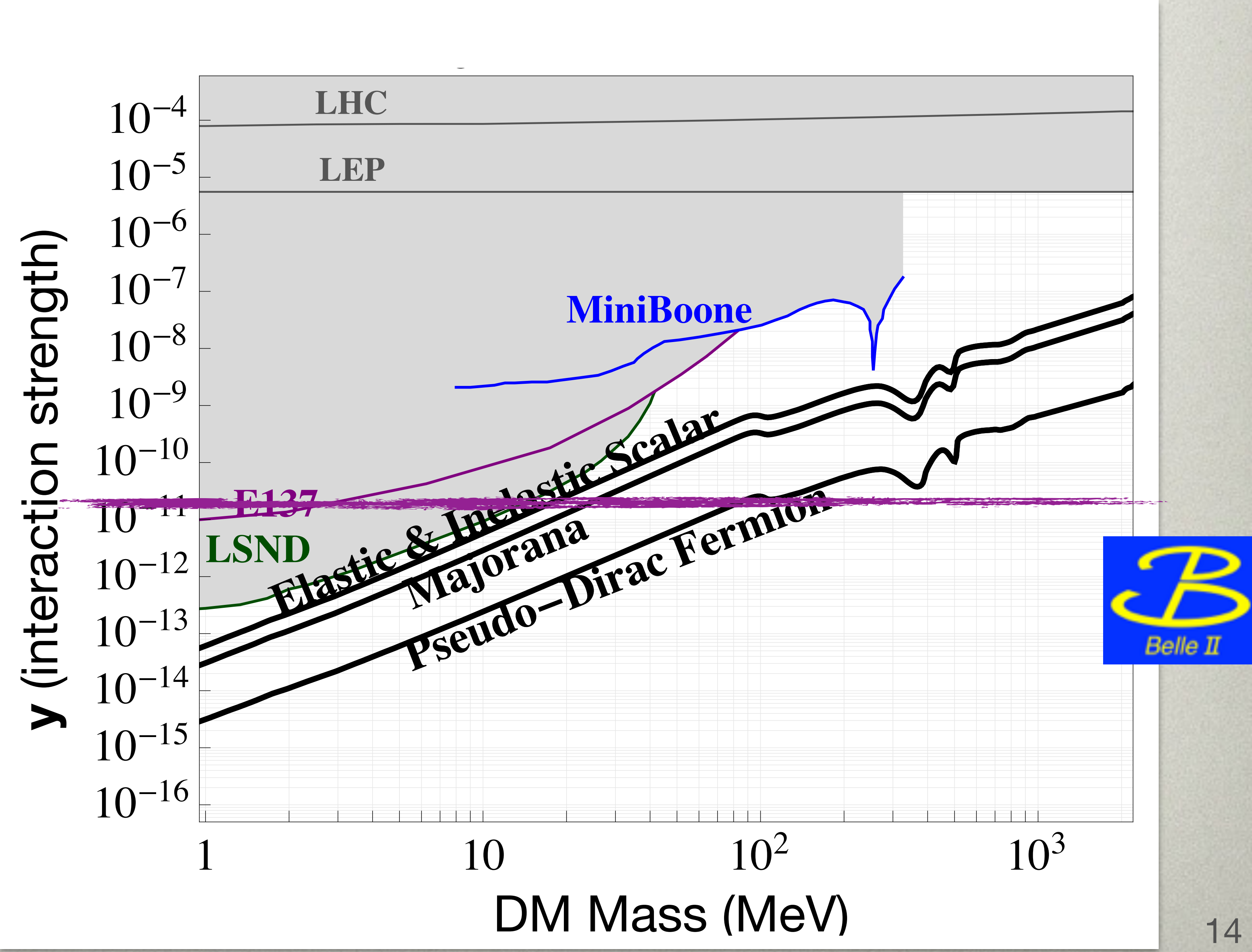

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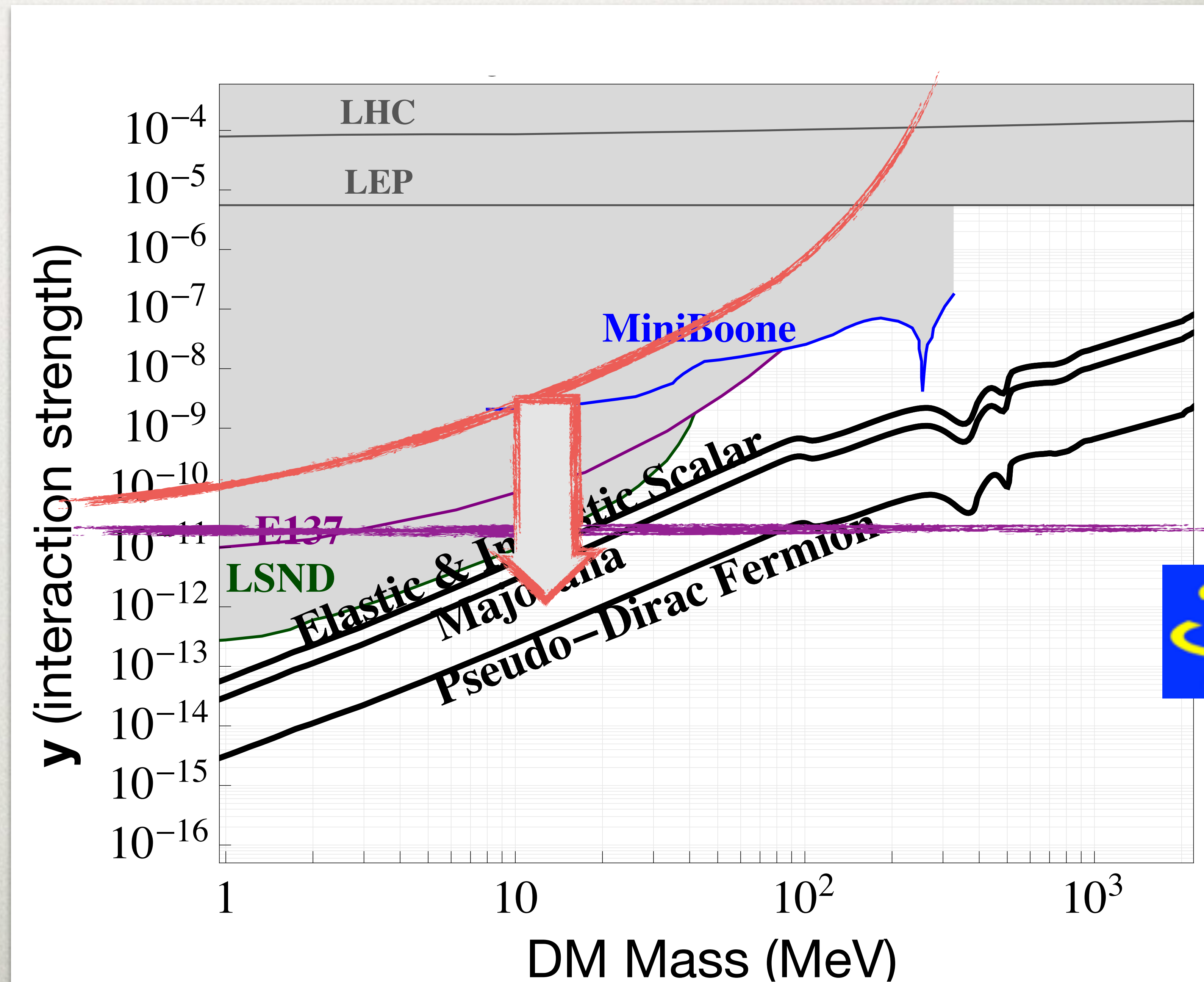
Colliders:

Rate ~ $\mathbf{y}\mathscr{L}/E_{CM}^2$

Fixed target:

Rate ~ $\mathbf{y\ N_e m_e^2/m_{DM}^2}$ (add'l form factor penalty @ high masses)



Belle II

Dark-Matter Production II

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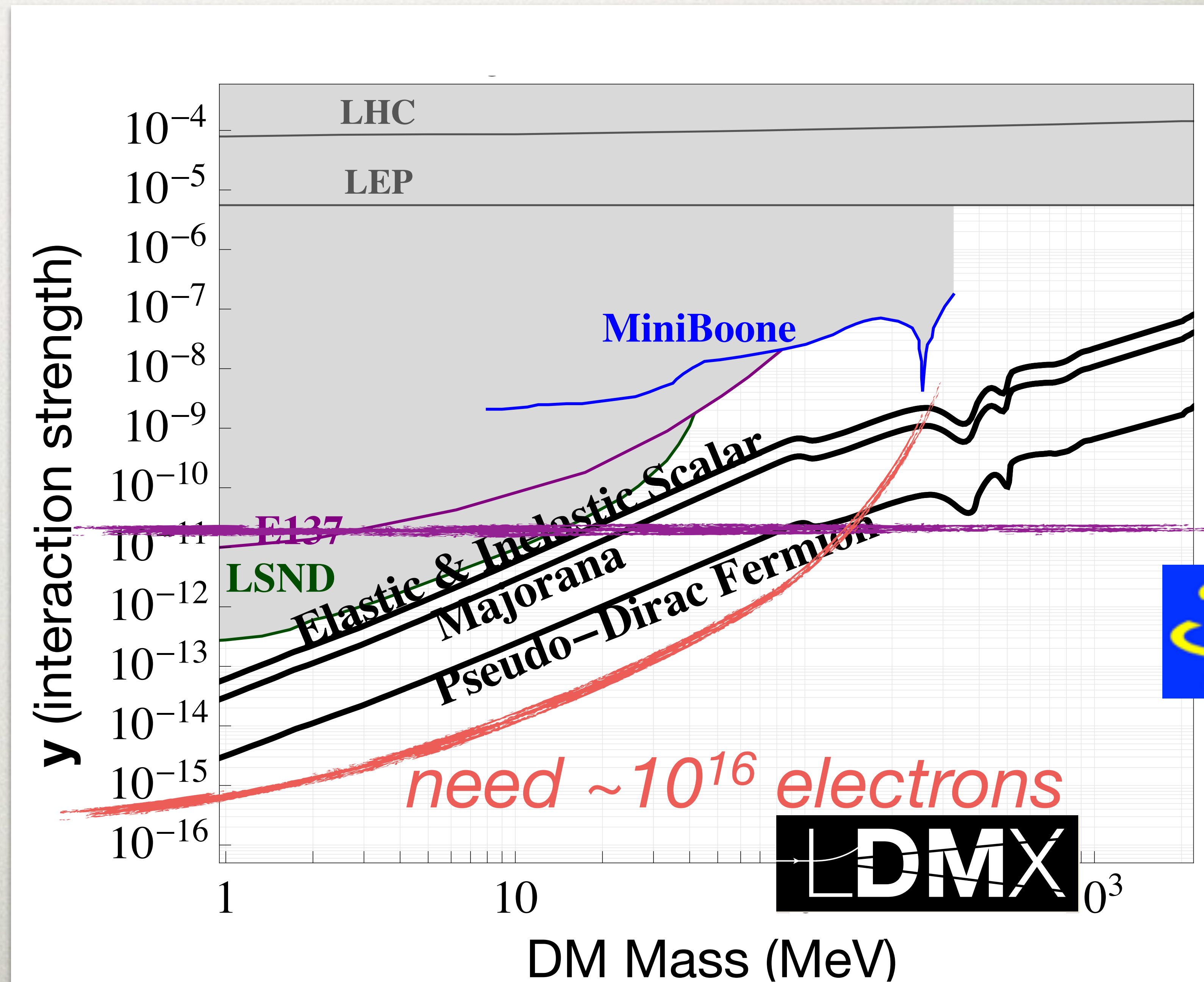
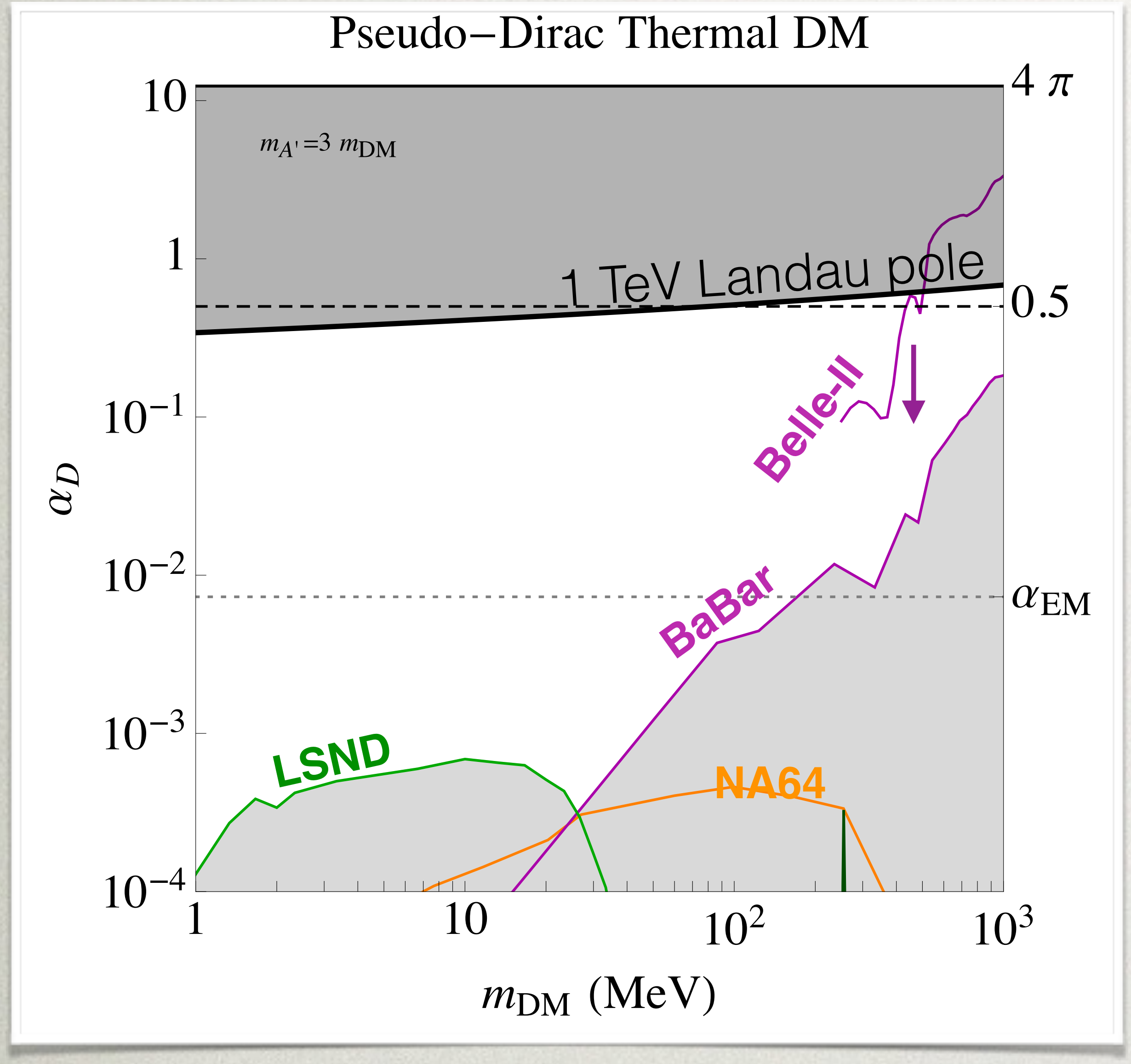
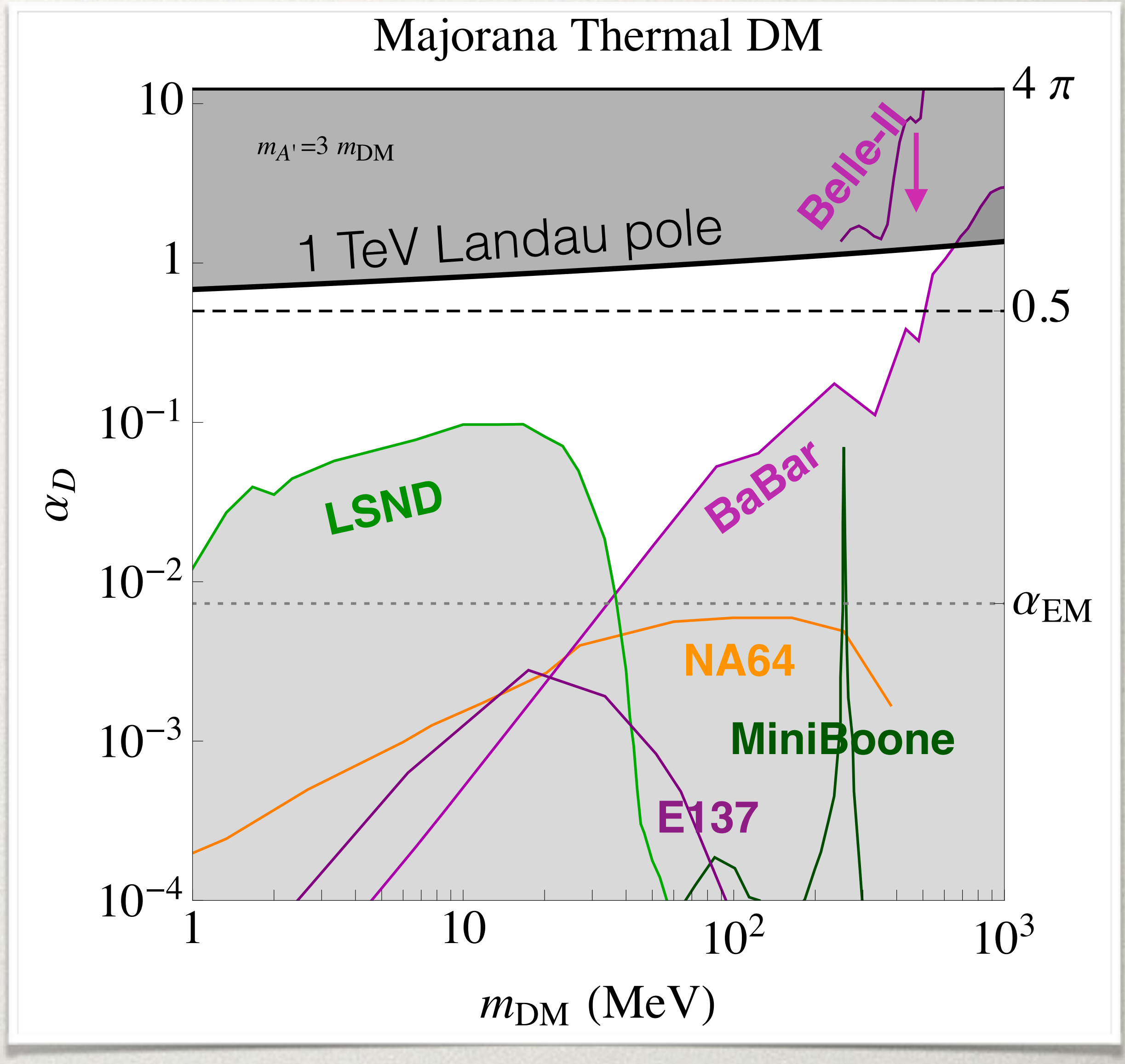


Belle II

Accelerator Experiments Have Cornered Thermal LDM

Assuming thermal abundance to fix ϵ



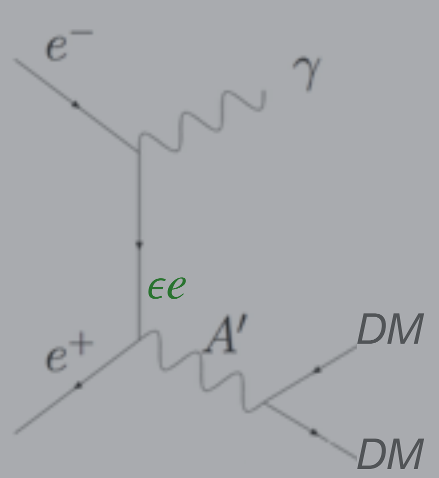


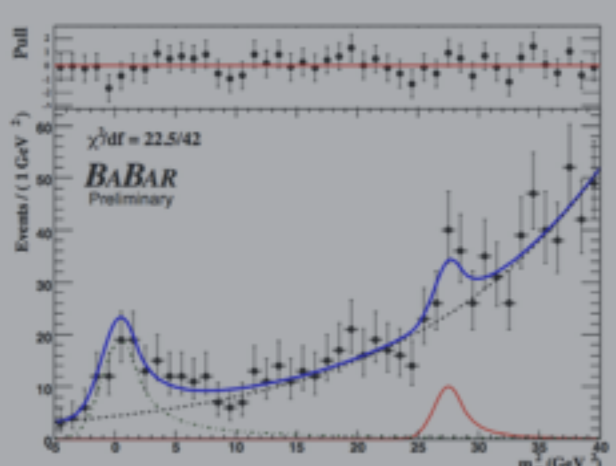
Remaining 1-3 orders of magnitude represent some of the best motivated parameter space. An amazing opportunity!

Dark-Matter Production II

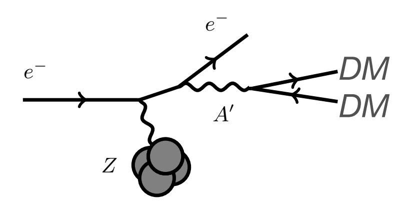
- To beat this scaling, must detect dark matter production via kinematics of visible final states
  - need signal yield∝y and low background

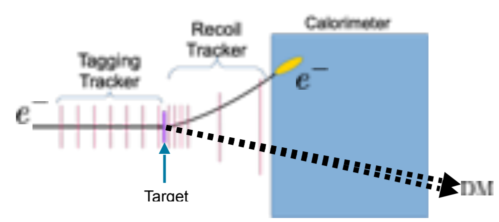
Missing Mass (e^+e^- colliders)
= full kinematic reconstruction

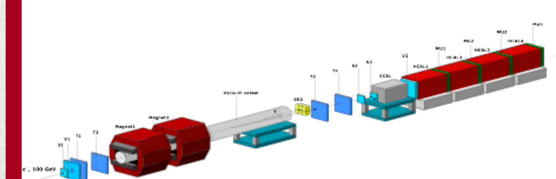


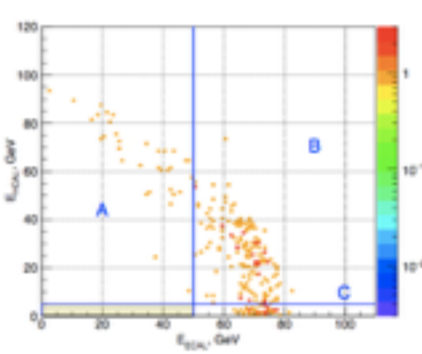


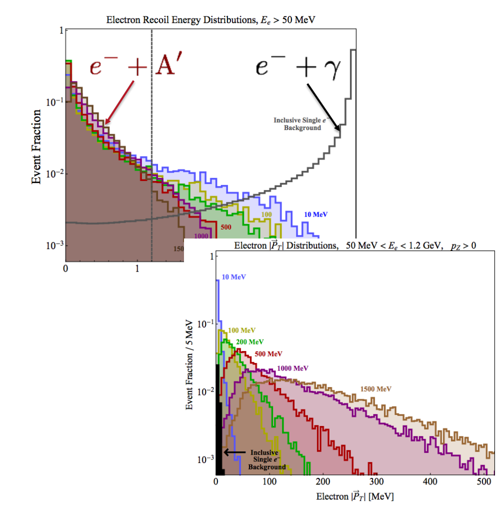
Missing Energy/Momentum
(e^- fixed target)
= partial kinematic reconstruction







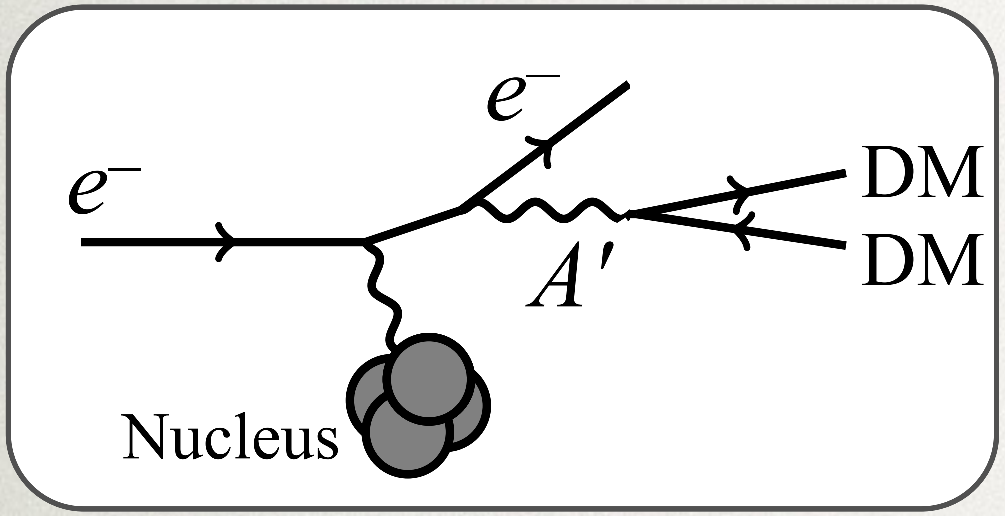




~0.1 – 10 GeV Dark Matter

MeV–GeV Dark Matter

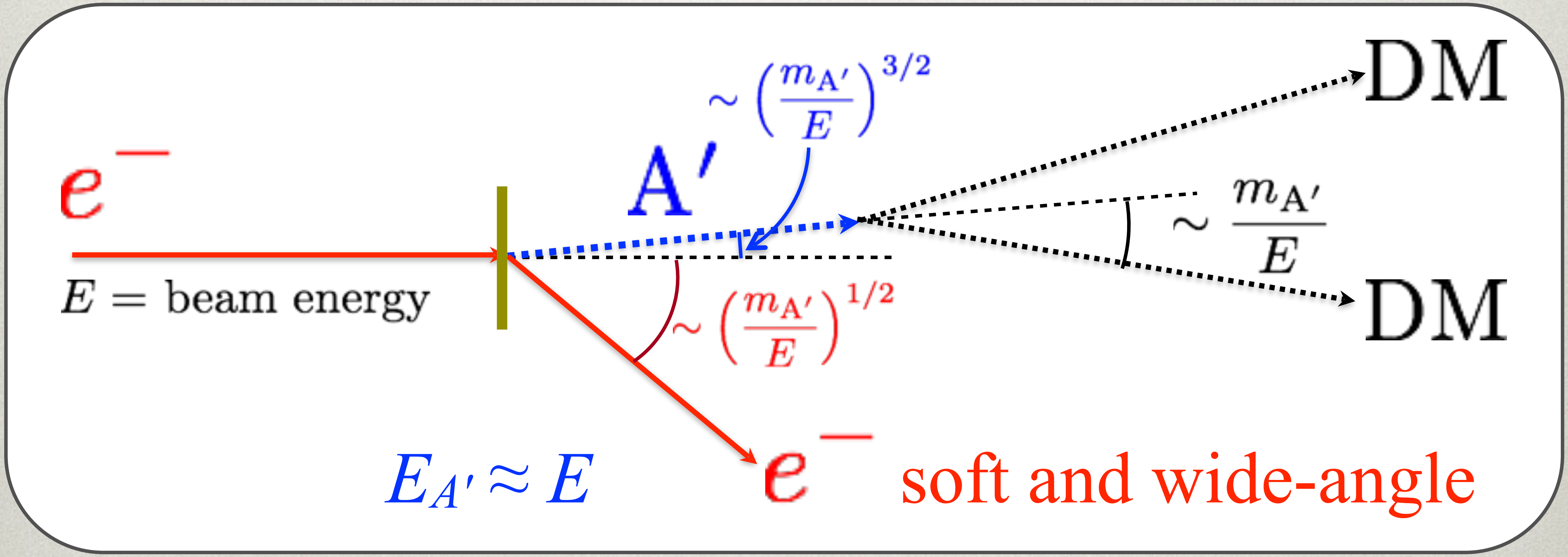
Kinematics of New-Particle Production in Electron Beams



Low-energy nucleus typically not measurable

$E(A') \approx E_{beam}$ $\quad$ $E(e) \ll E_{beam}$

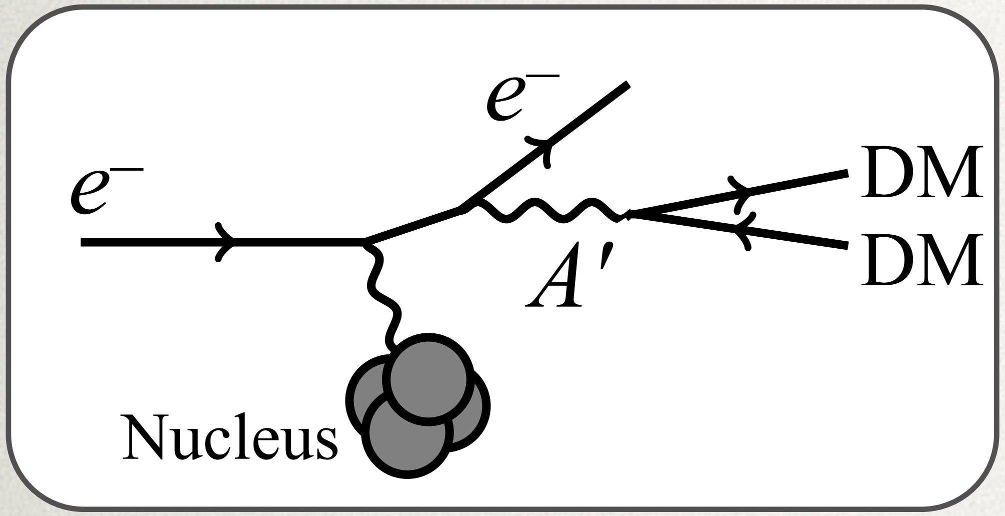
$p_T(A') \sim p_T(e) \sim m_{A'}$



Most of beam energy carried away by invisible particles

Recoil electron kinematics opposite of typical bremsstrahlung

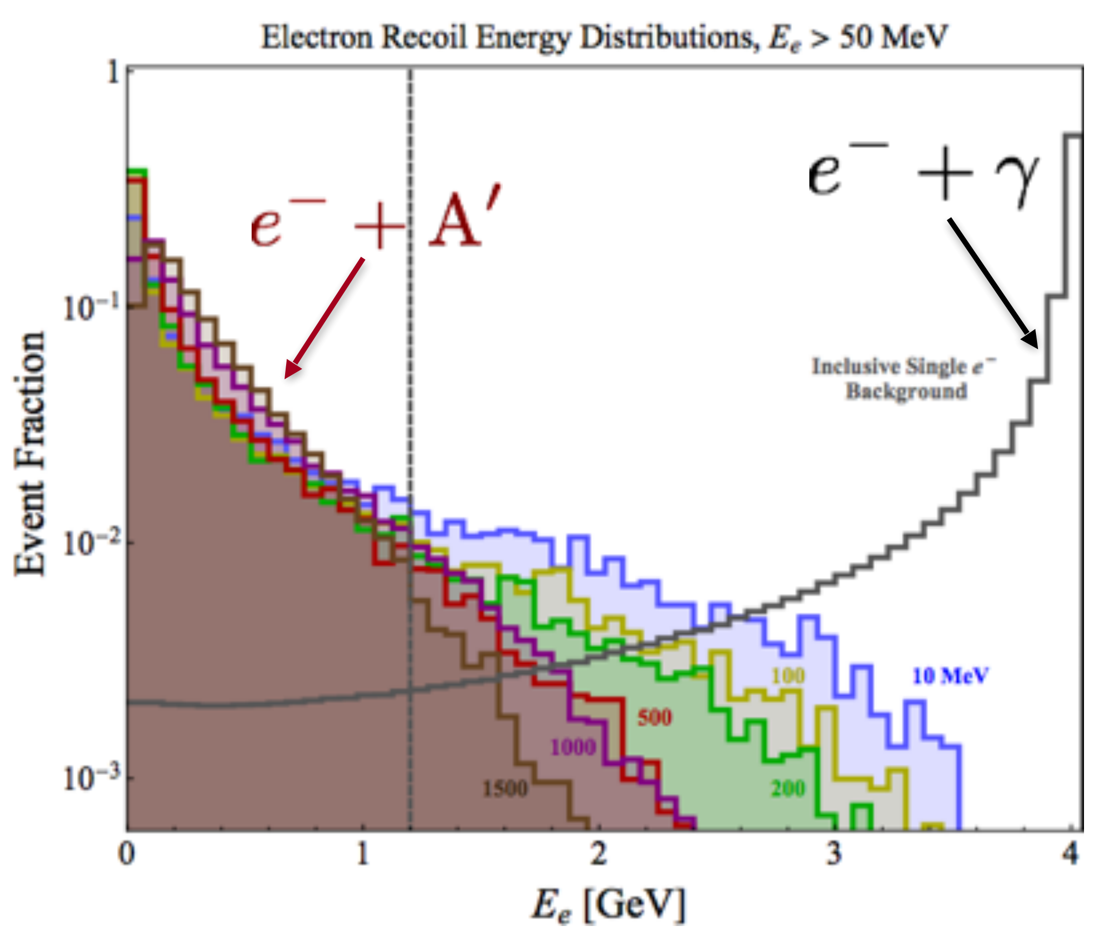
Kinematics of New-Particle Production in Electron Beams



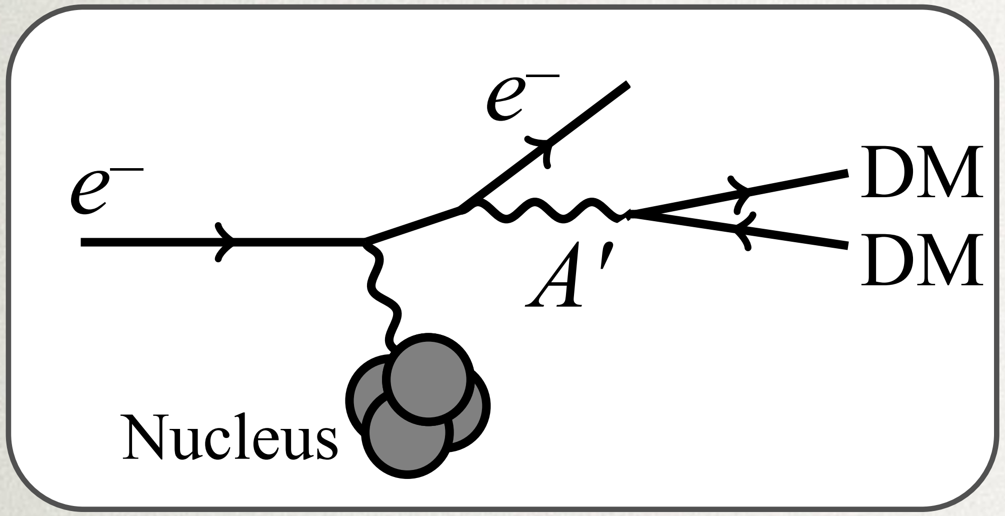
$E(A') \approx E_{beam} \quad E(e) \ll E_{beam}$

$p_T(A') \sim p_T(e) \sim m_{A'}$

recoil distributions, 4 GeV e^- on 10% X_0 target



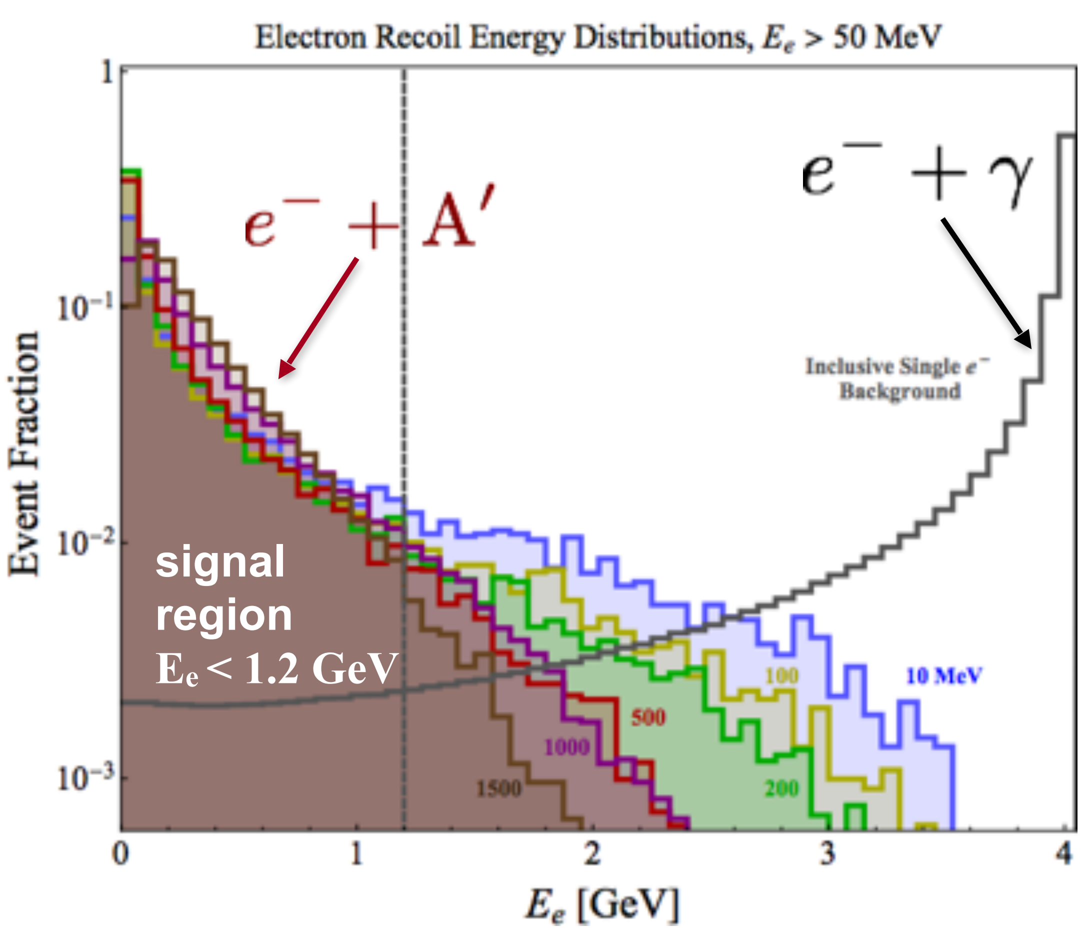
Kinematics of New-Particle Production in Electron Beams



$E(A') \approx E_{beam} \quad E(e) \ll E_{beam}$

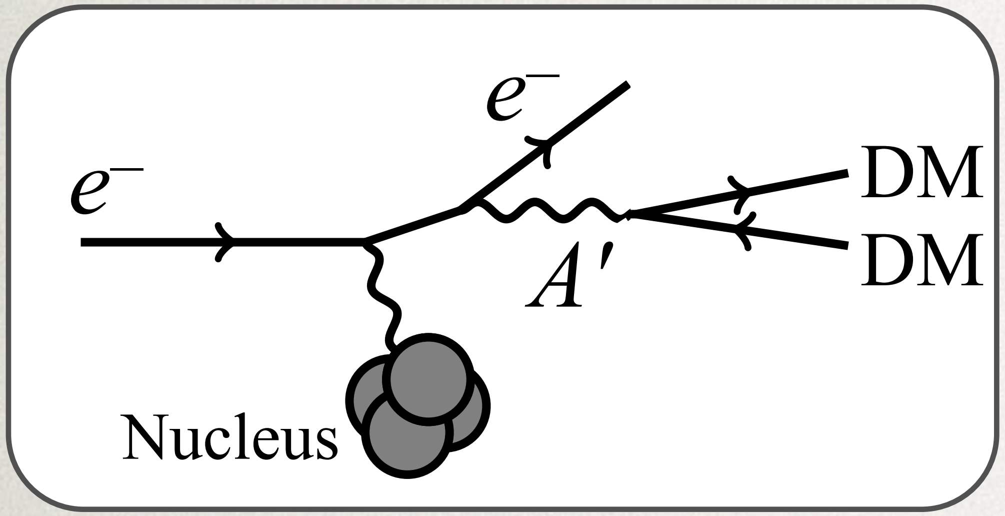
$p_T(A') \sim p_T(e) \sim m_{A'}$

recoil distributions, 4 GeV e^- on 10% X_0 target



Recoil energy → *high-efficiency signal region with ~30x background rejection*

Kinematics of New-Particle Production in Electron Beams



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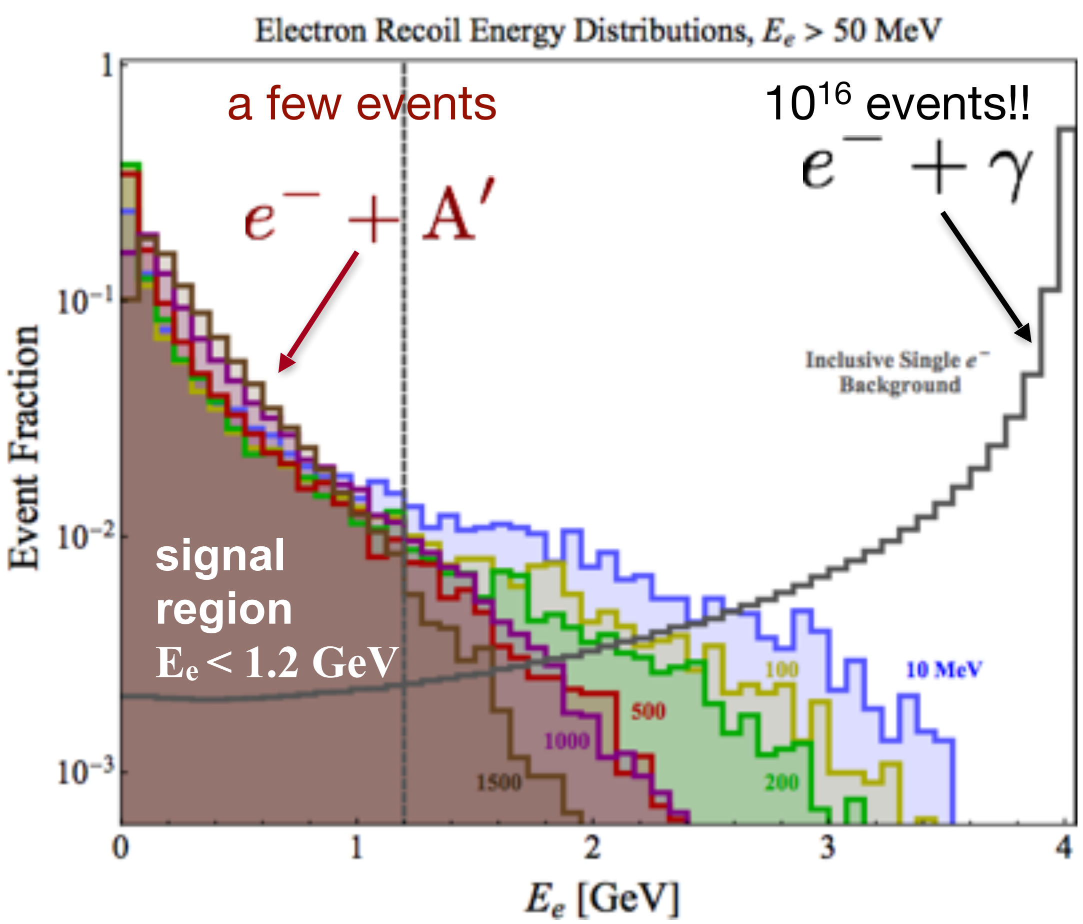

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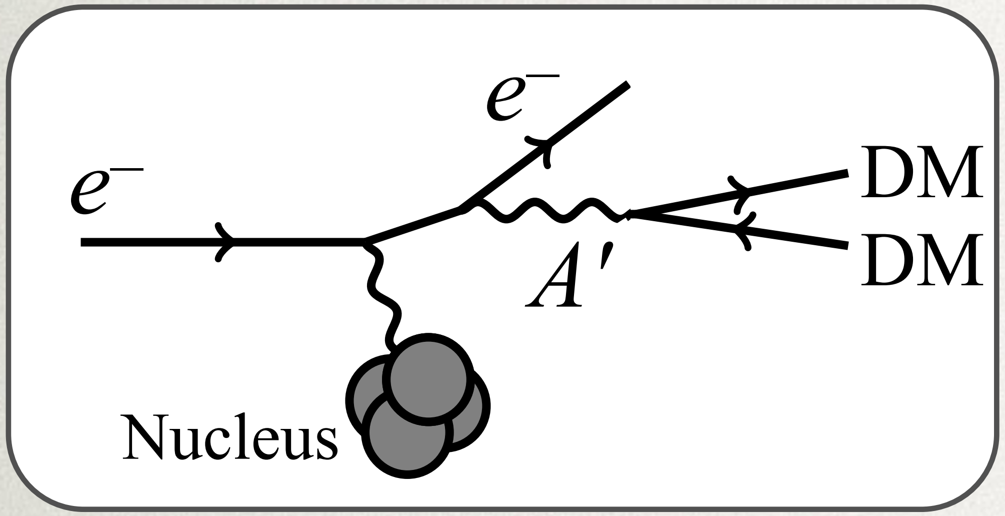
Kinematics of New-Particle Production in Electron Beams



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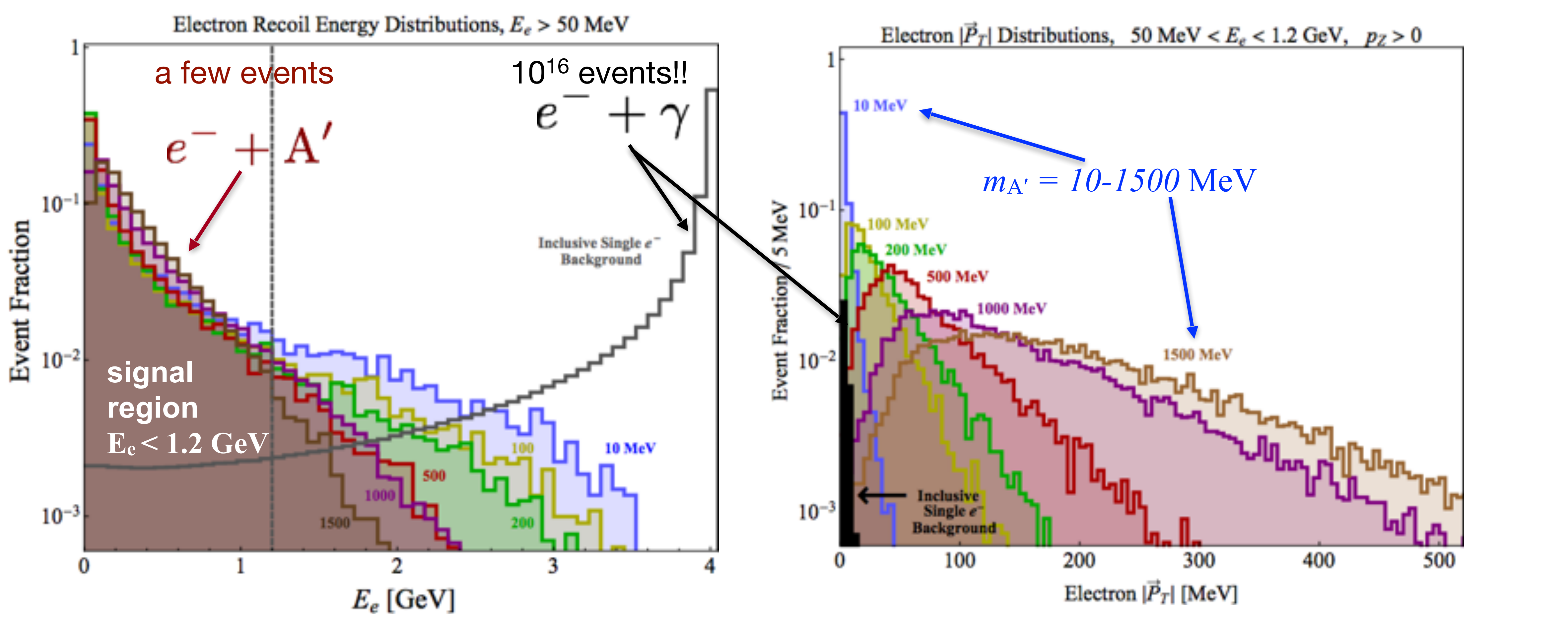
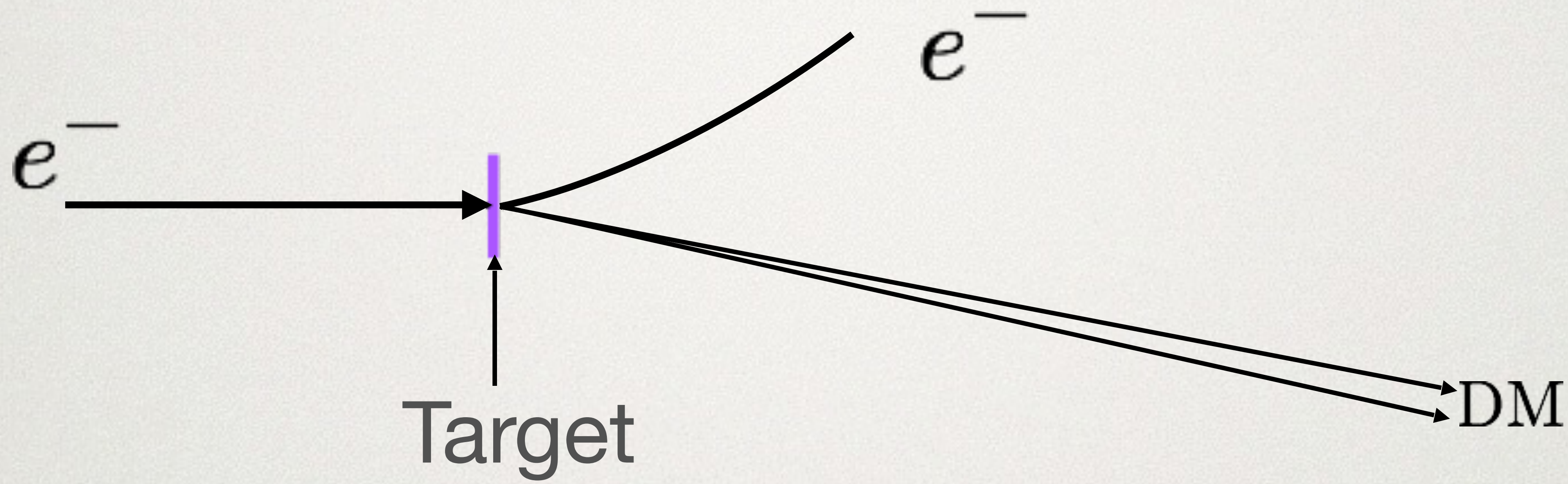
recoil distributions, 4 GeV e^- on 10% X_0 target – NOT TO SCALE



How to Identify These Events?



✦ Electron beam impinging on target

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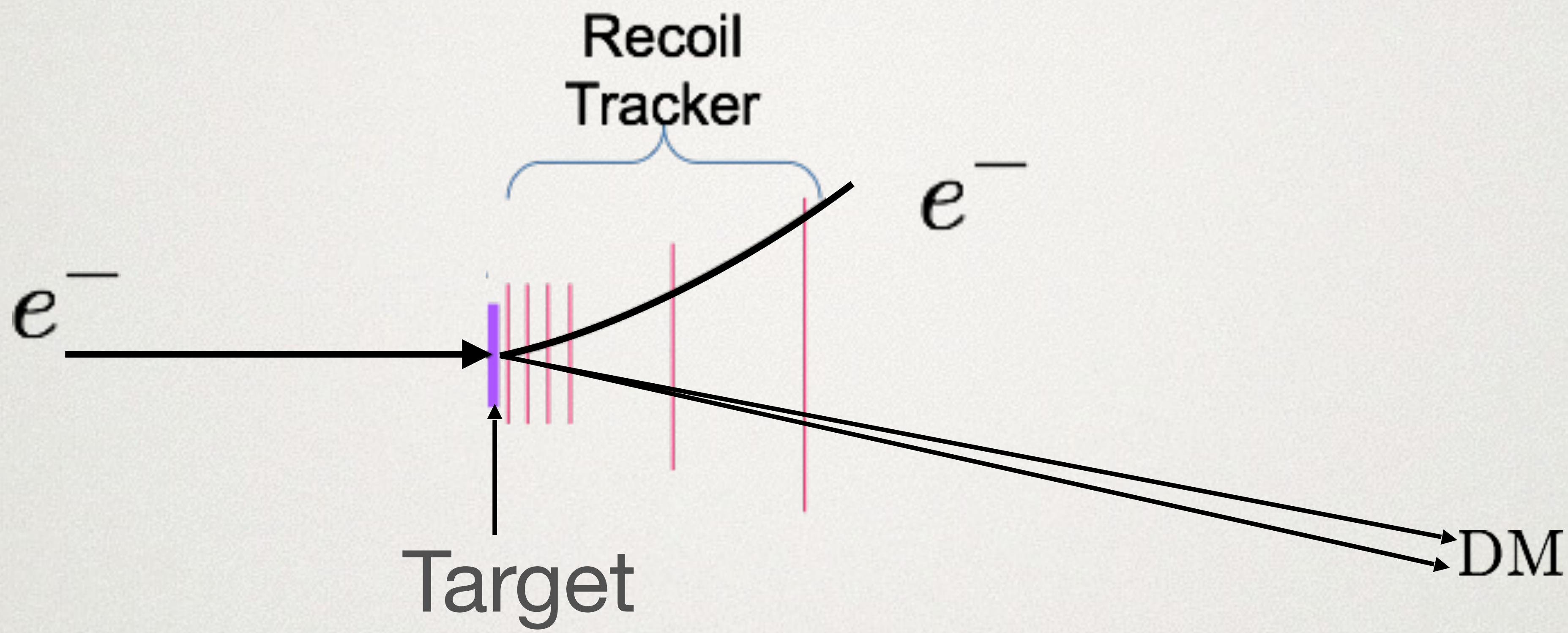

- ✦ Electron beam impinging on target
- ✦ Measure recoiling low-energy-fraction electron & its p_T
  - Forward tracking in (small) B-field

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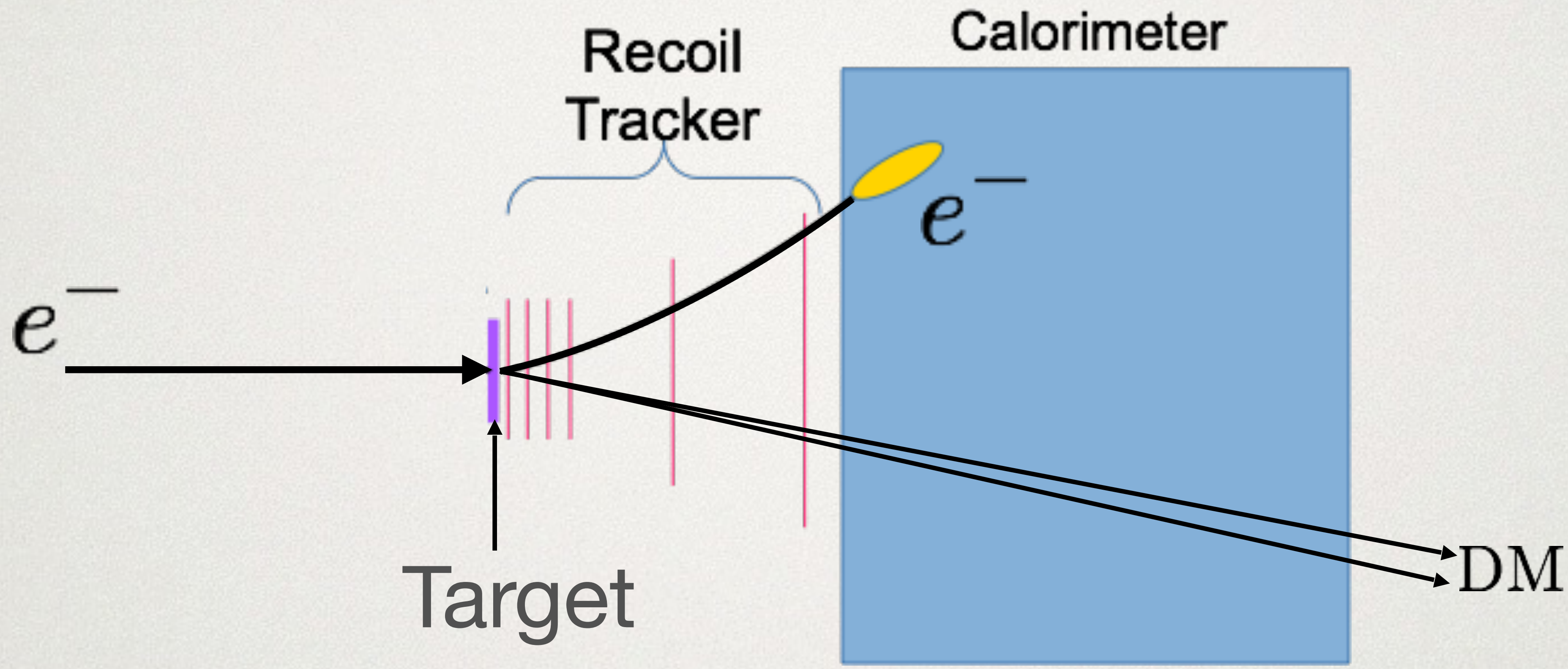
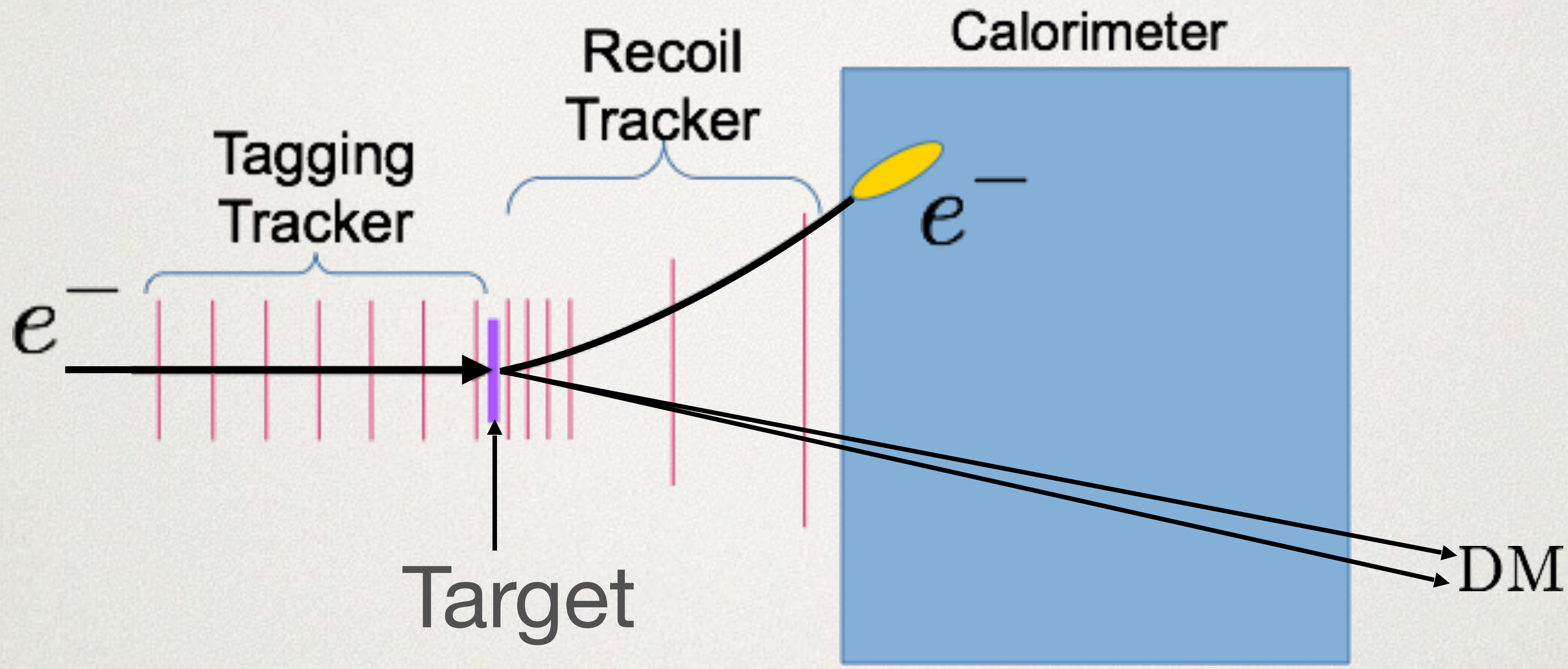


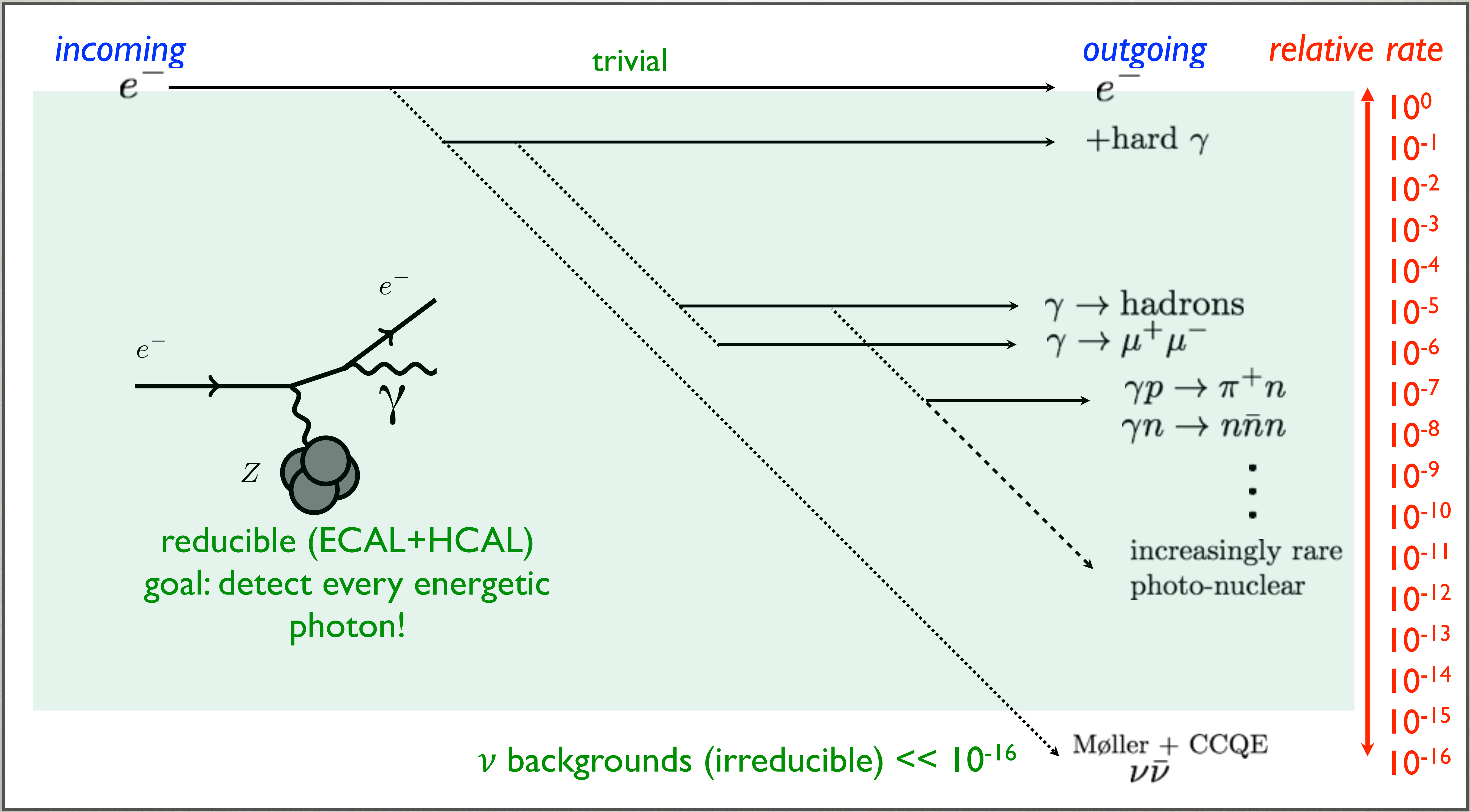
- ✦ Electron beam impinging on target ~one at a time
- ✦ Measure recoiling low-energy-fraction electron & its p_T
  - Forward tracking in (small) B-field
- ✦ Reject events with visible particles carrying remaining energy
  - Deep, highly segmented calorimeter

How to Identify These Events?



- ✦ Electron beam impinging on target
- ✦ Measure recoiling low-energy-fraction electron & its p_T
  - Forward tracking in (small) B-field
- ✦ Reject events with visible particles carrying remaining energy
  - Deep, highly segmented calorimeter
- ✦ Positively identify high-energy incident electron
  - (High-B-field) tracking upstream of target

Backgrounds!



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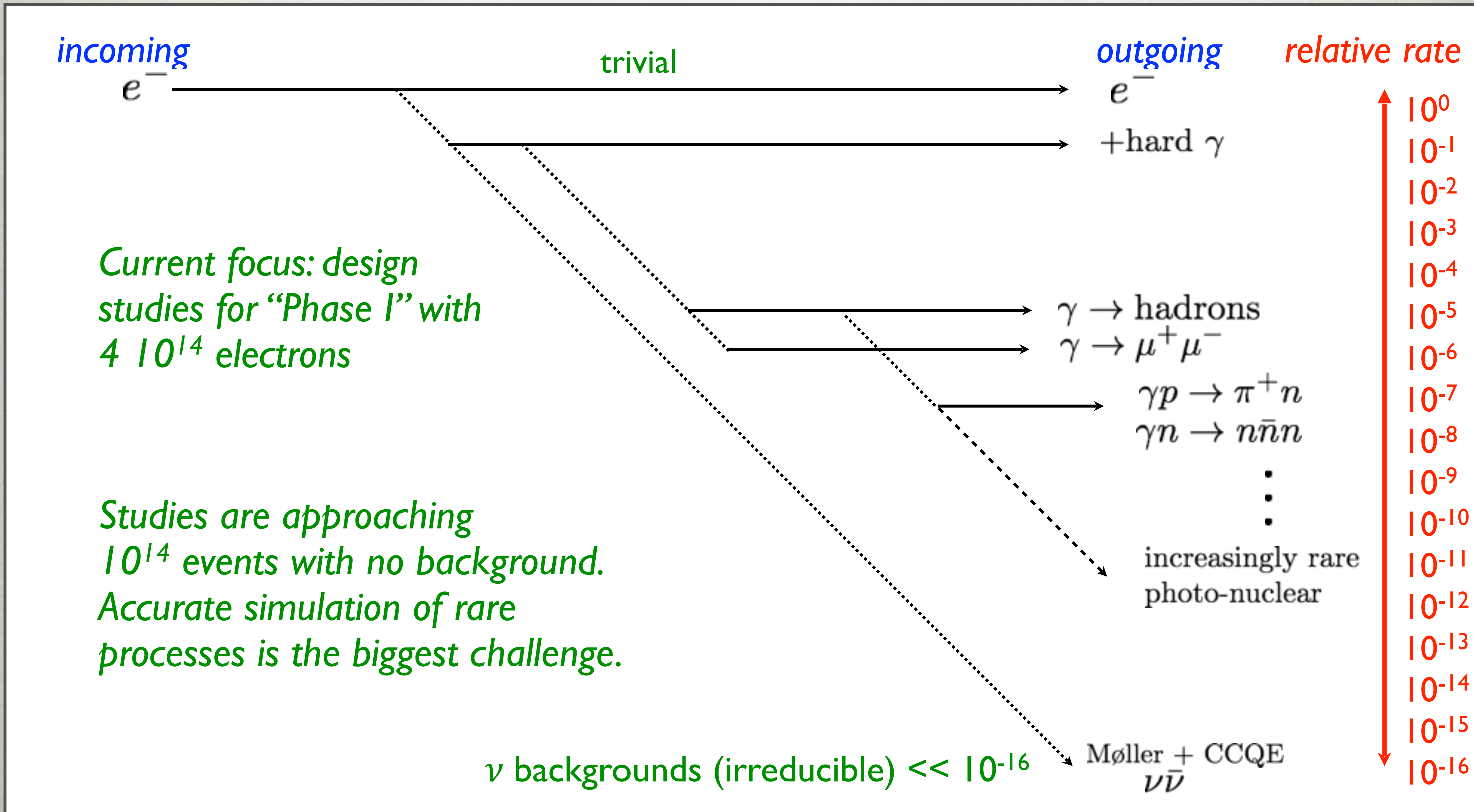

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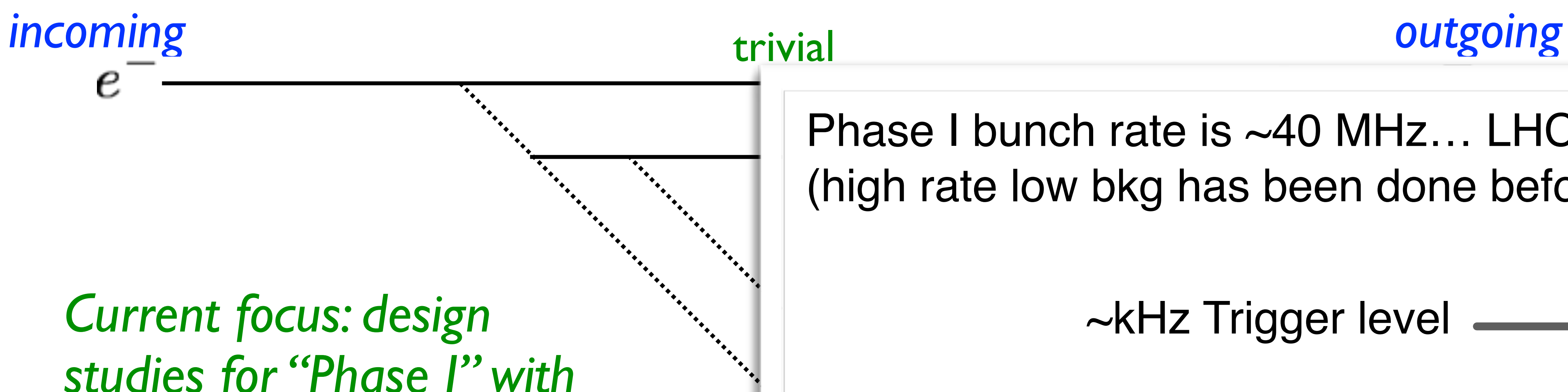


Current focus: design studies for "Phase I" with 4 10^{14} electrons

Studies are approaching 10^{14} events with no background. Accurate simulation of rare processes is the biggest challenge.

ν backgr

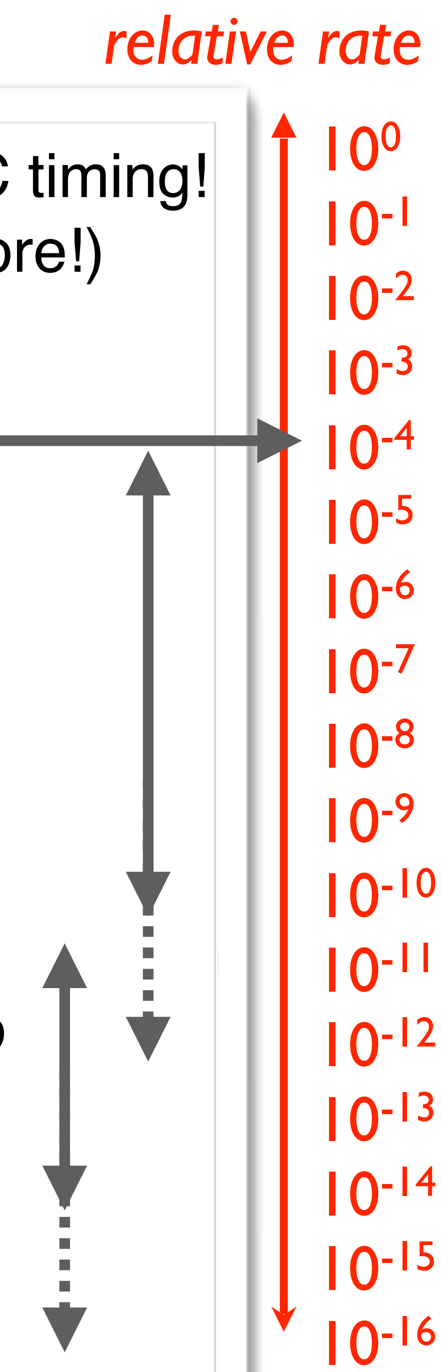
Phase I bunch rate is ~40 MHz… LHC timing!
(high rate low bkg has been done before!)

~kHz Trigger level

ECAL only veto

ECAL+HCAL veto

In reserve:
~10-1000 (mass dependent) rejection from recoil momentum tracking



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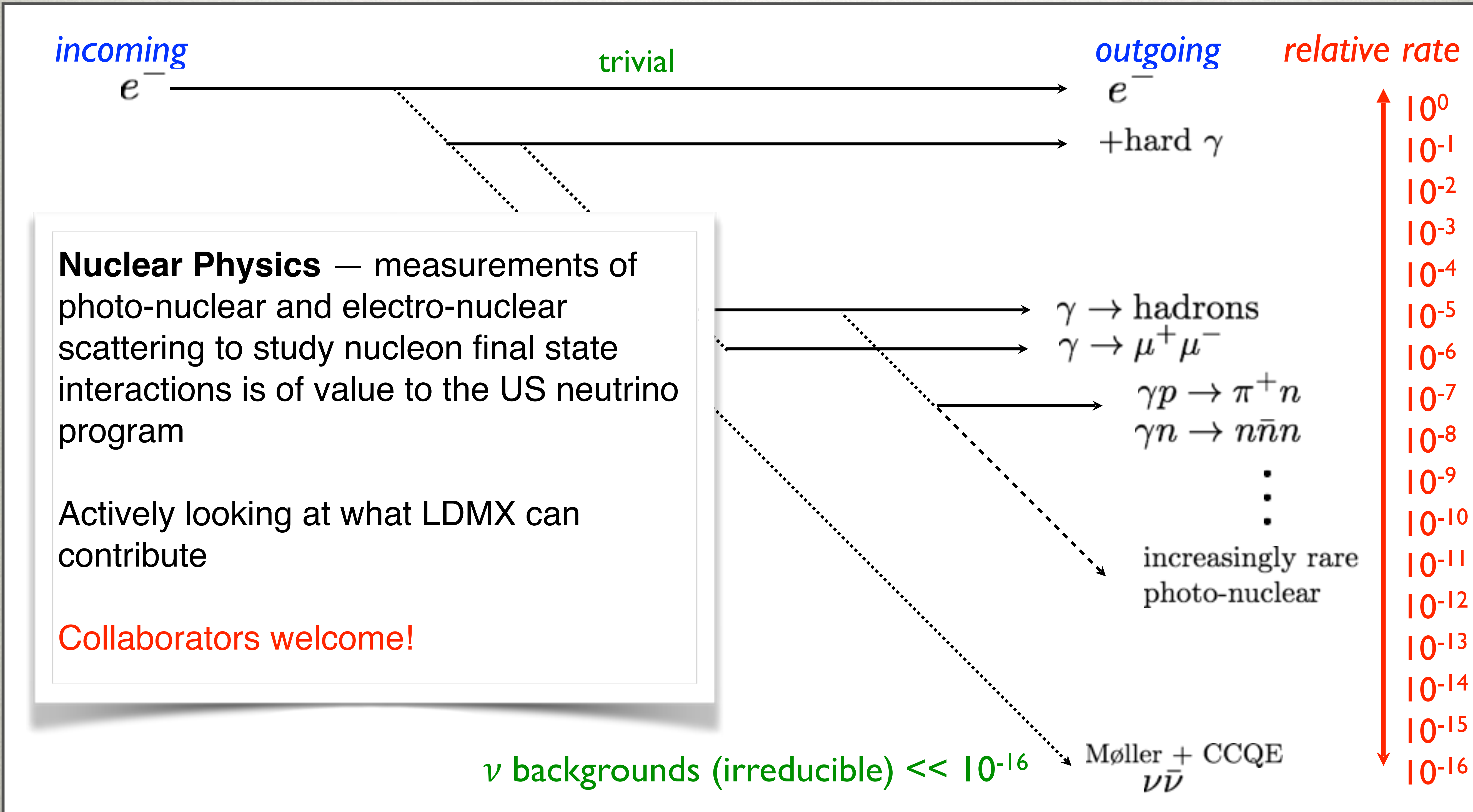


Nuclear Physics — measurements of photo-nuclear and electro-nuclear scattering to study nucleon final state interactions is of value to the US neutrino program

Actively looking at what LDMX can contribute

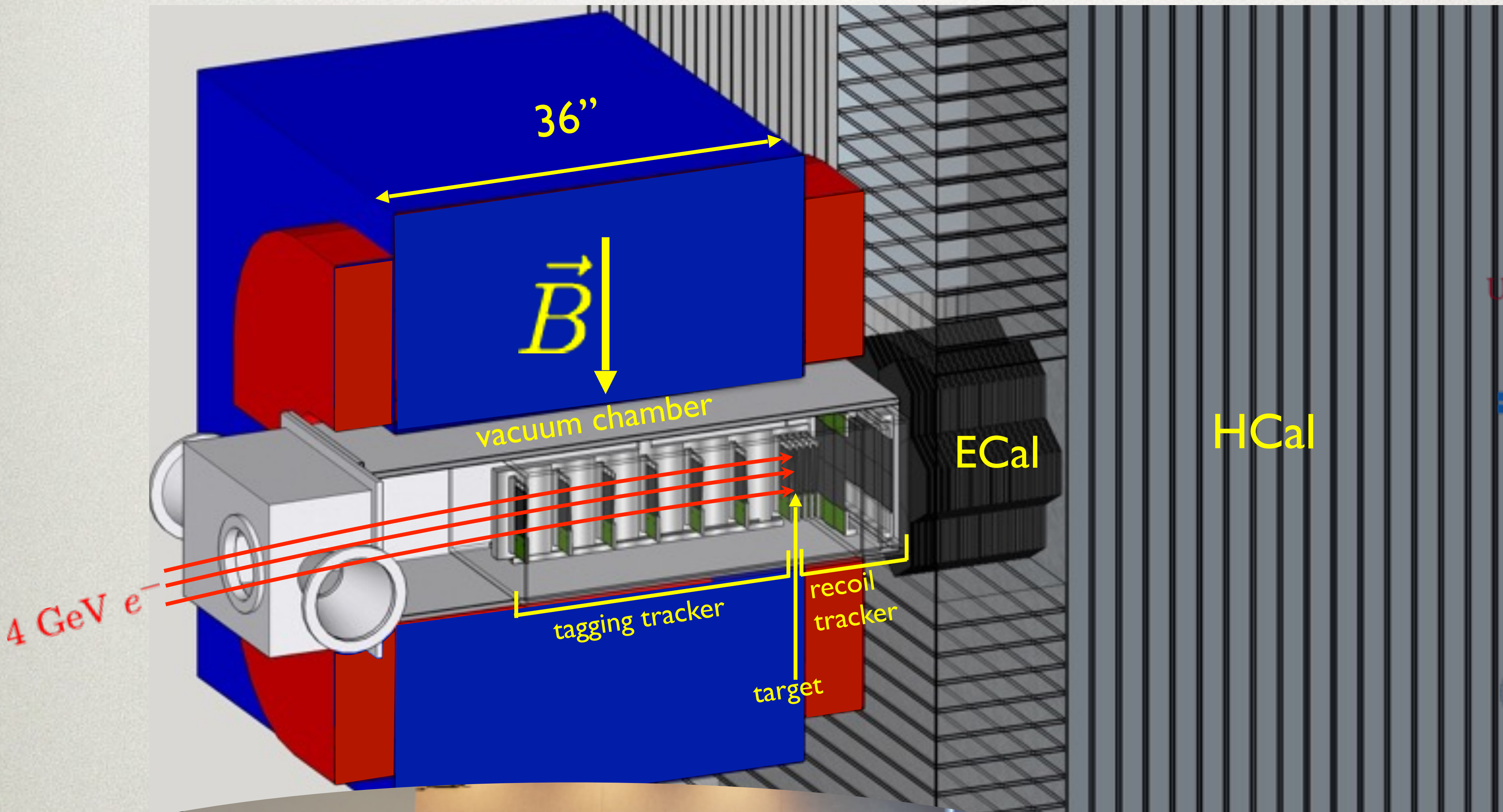
Collaborators welcome!

LDMX

Light Dark Matter eXperiment

Phase I Detector Concept and Collaboration

SLAC NATIONAL ACCELERATOR LABORATORY



UCSB

UNIVERSITY OF MINNESOTA

Fermilab

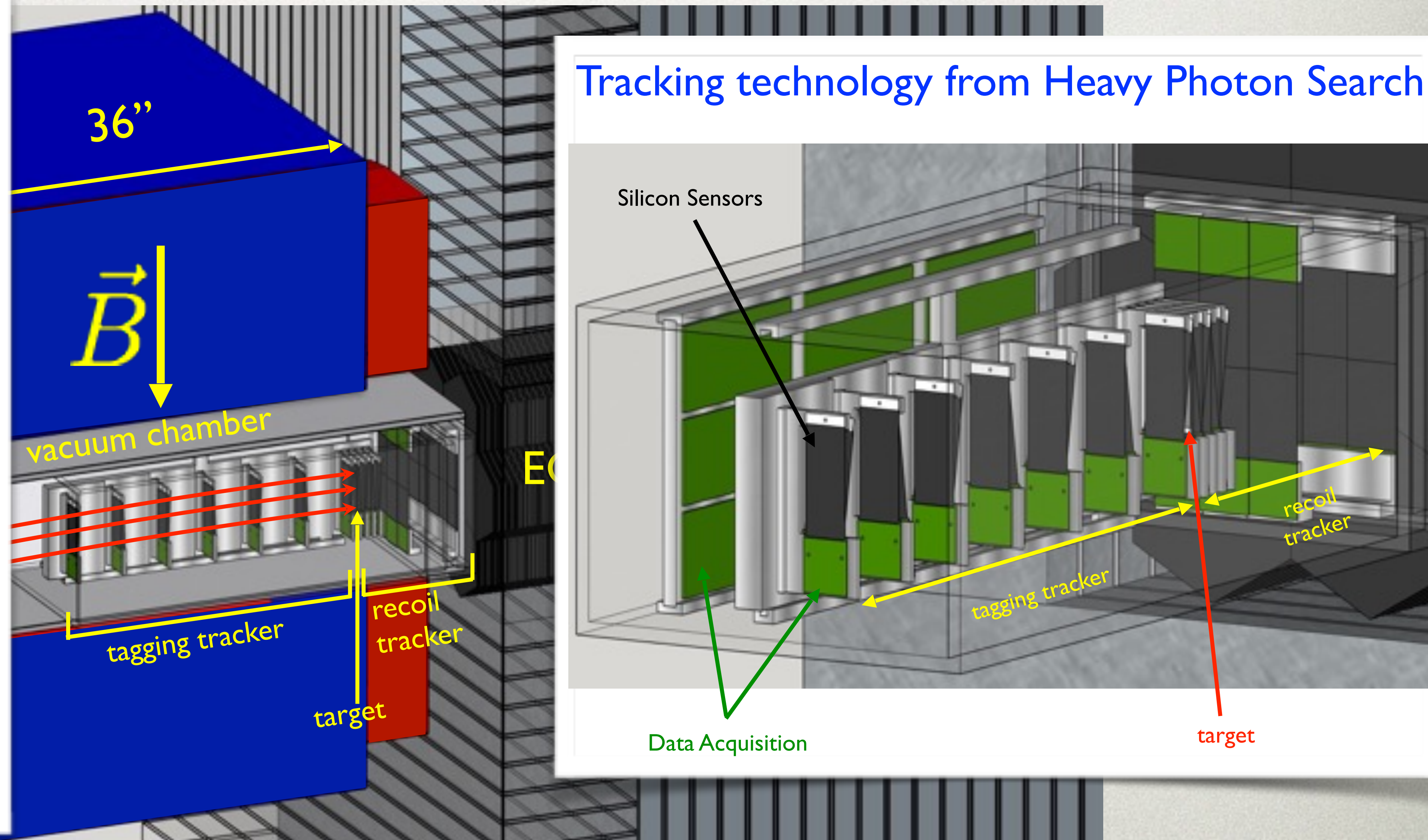
Caltech

UC SANTA CRUZ

LUND UNIVERSITY

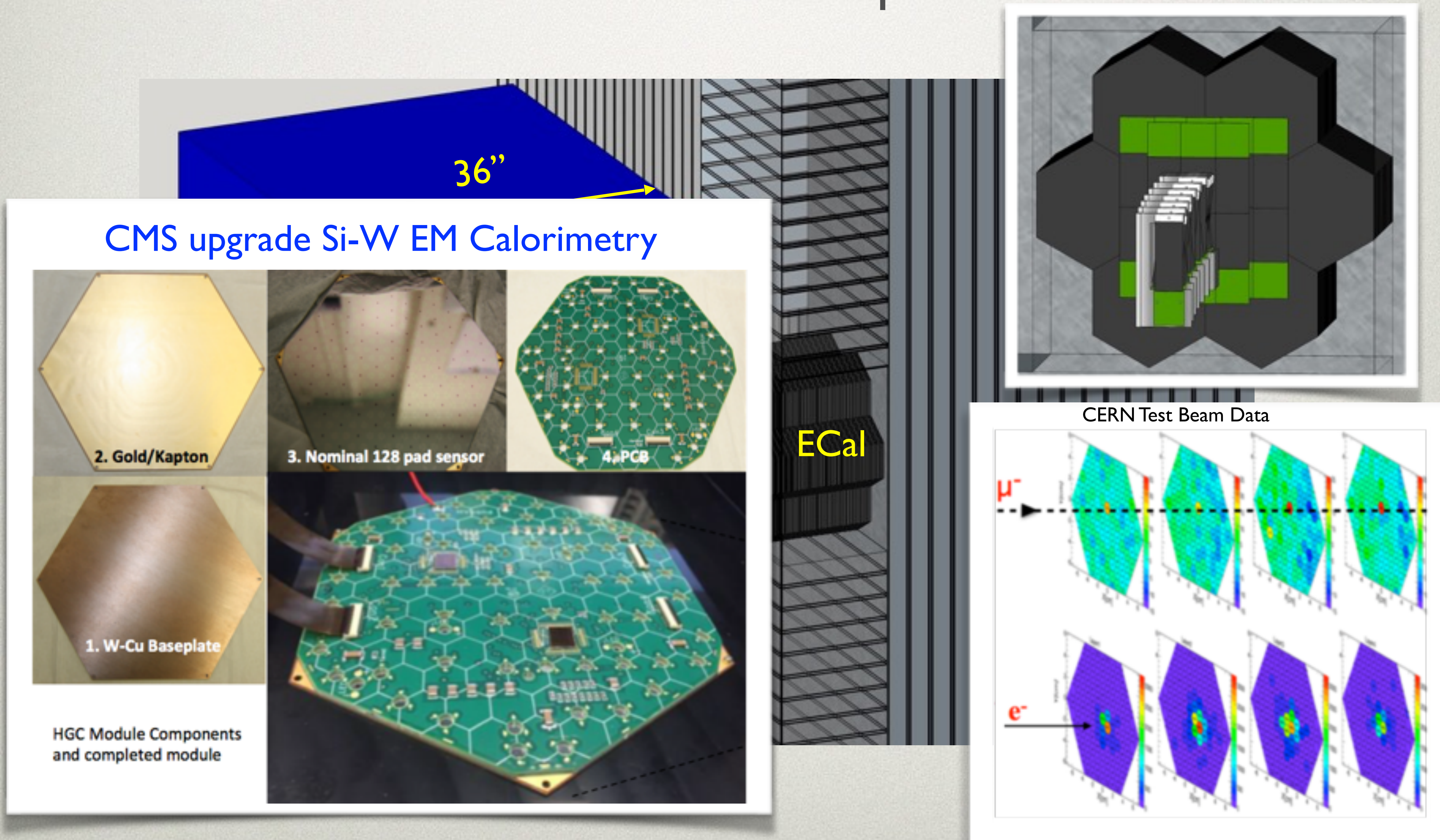
LDMX Light Dark Matter eXperiment

Phase I Detector Concept and Collaboration



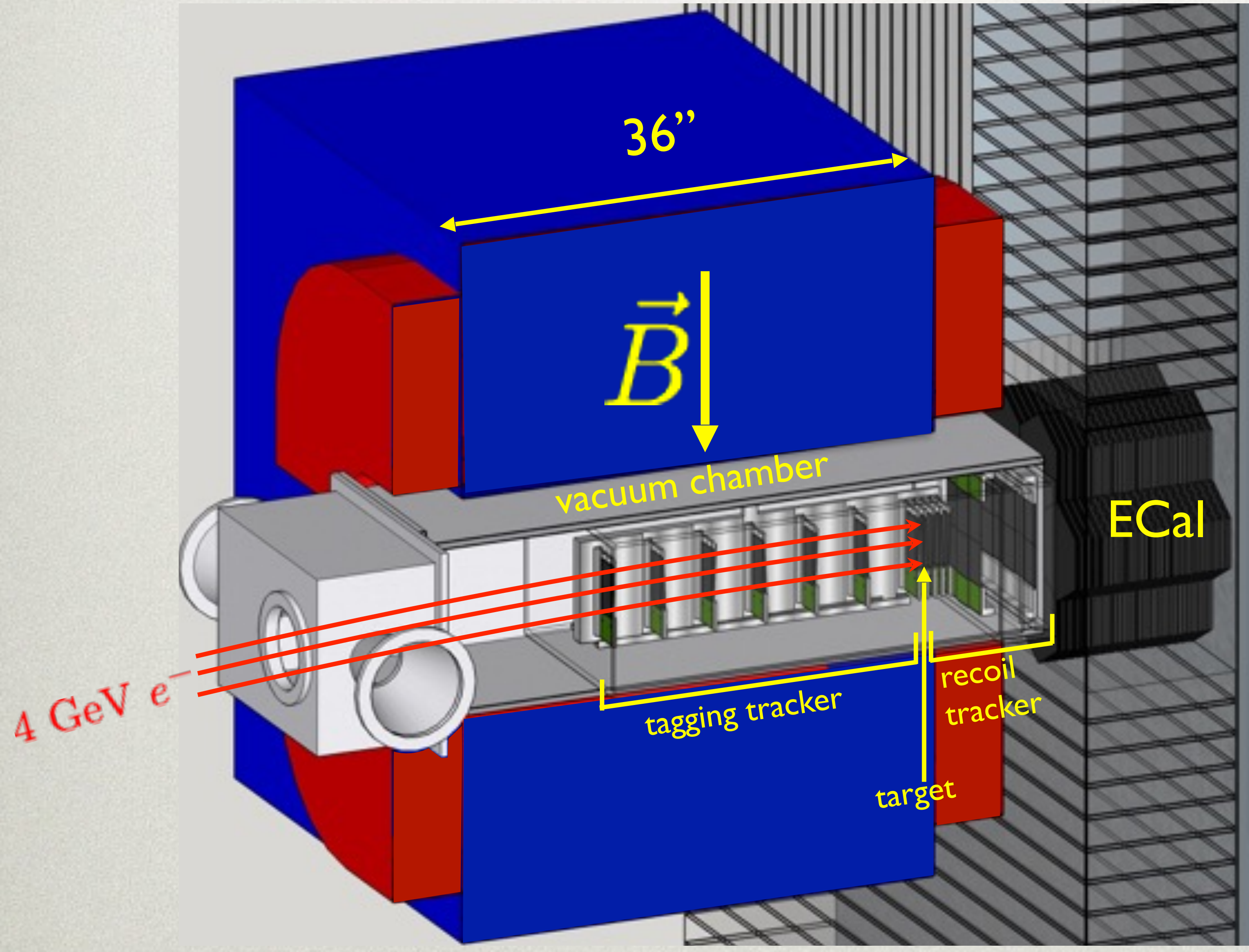
LDMX Light Dark Matter eXperiment

Phase I Detector Concept and Collaboration

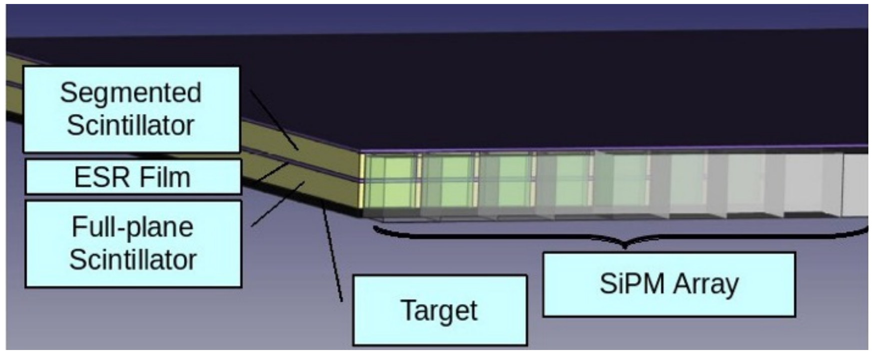


Light Dark Matter eXperiment

Phase I Detector Concept and Collaboration

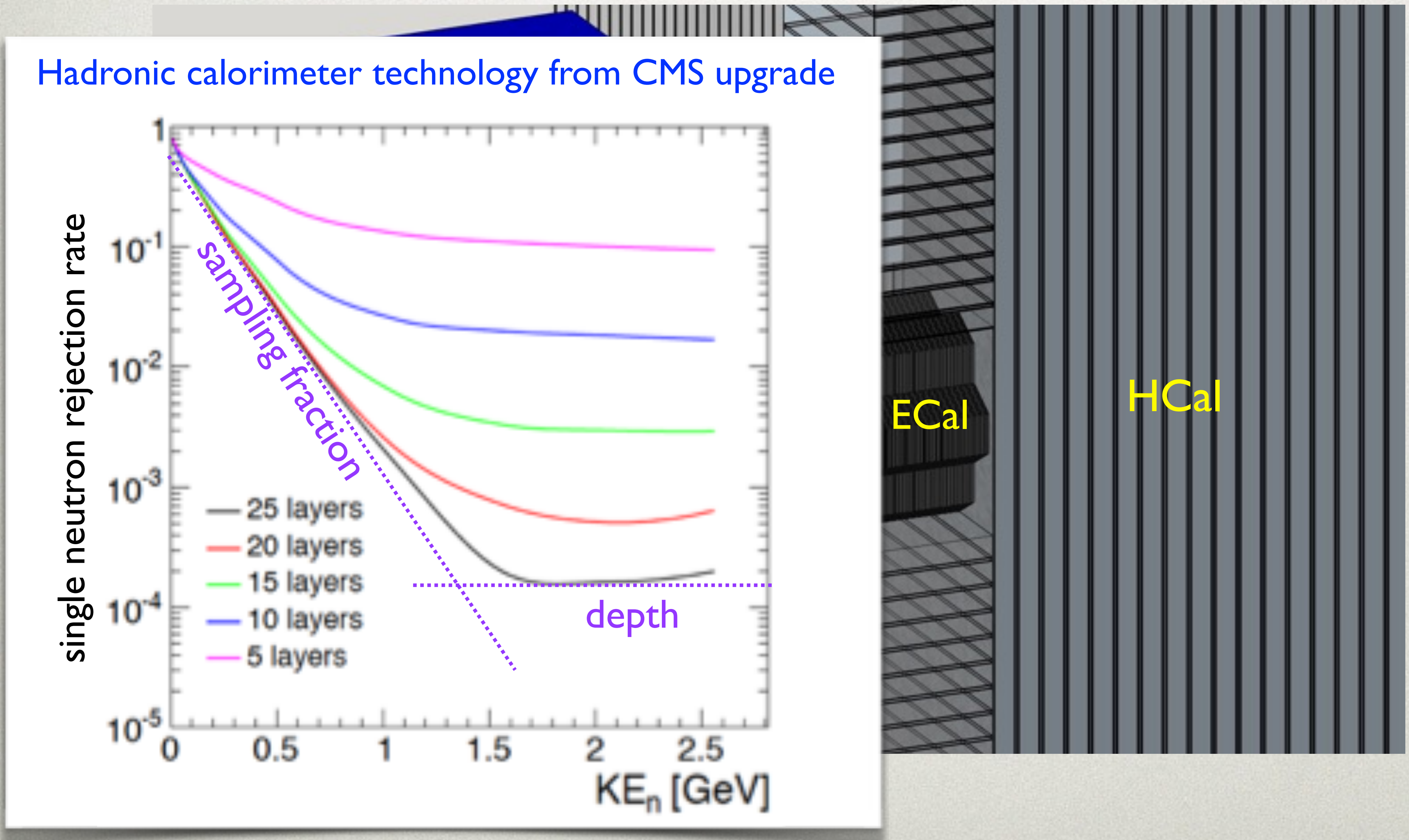


Trigger: Low energy deposition in ECAL + hits in scintillator pad near target



Light Dark Matter eXperiment

Phase I Detector Concept and Collaboration



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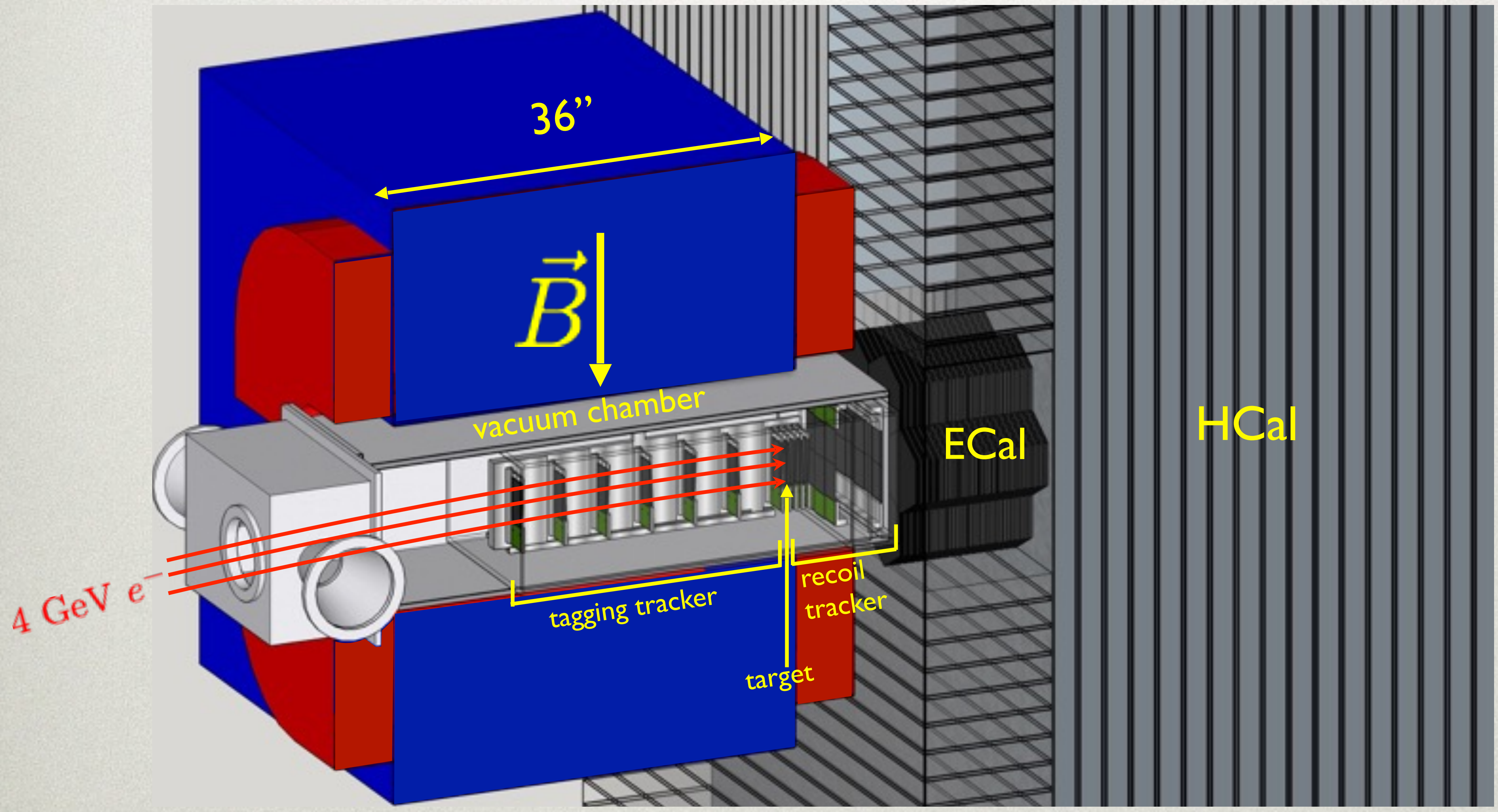
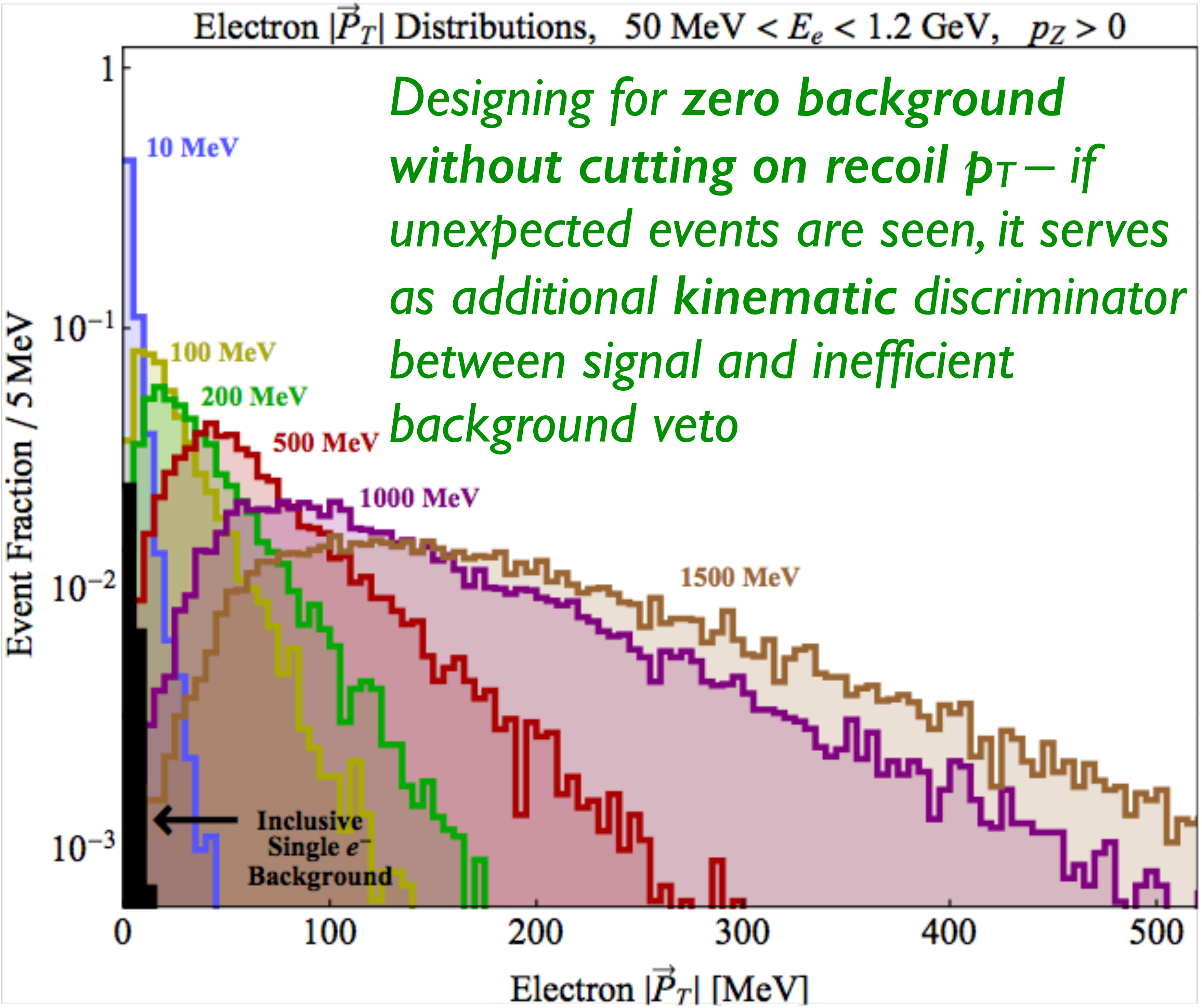


Phase II may require more granularity and faster detectors (for pileup mitigation) + new trigger

Backgrounds!



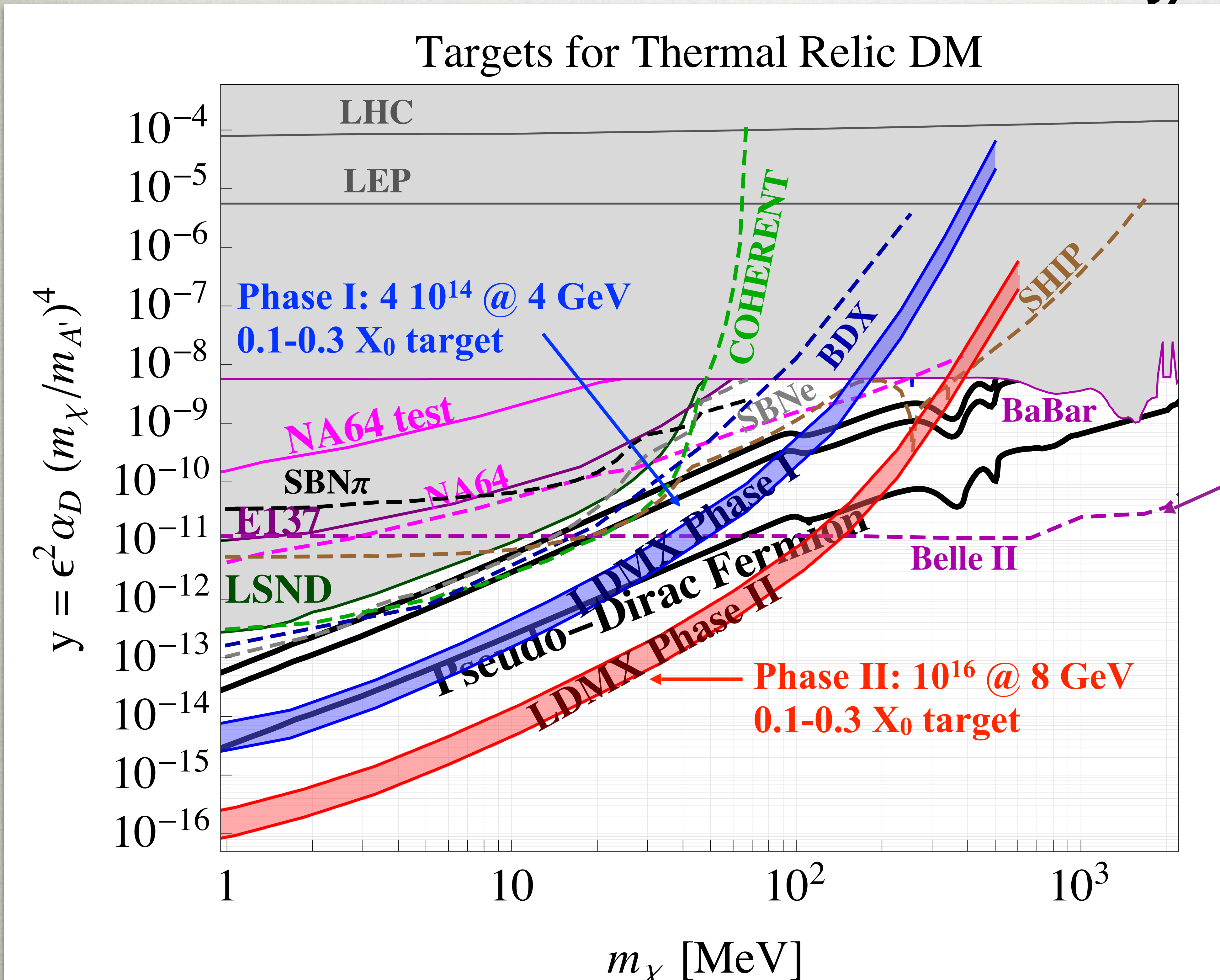
Designing for ***zero background without cutting on recoil p_T*** *– if unexpected events are seen, it serves as additional* ***kinematic*** *discriminator between signal and inefficient background veto*

outgoing	*relative rate*
e^-	10^0
+hard γ	10^{-1}
$\gamma \to$ hadrons $\gamma \to \mu^+\mu^-$ $\gamma p \to \pi^+ n$ $\gamma n \to n\bar{n}n$ ⋮	
increasingly rare photo-nuclear	
Møller + CCQE $\nu\bar{\nu}$	10^{-16}

10^0, 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7}, 10^{-8}, 10^{-9}, 10^{-10}, 10^{-11}, 10^{-12}, 10^{-13}, 10^{-14}, 10^{-15}, 10^{-16}

ν backgrounds (irreducible) << 10^{-16}

LDMX Sensitivity

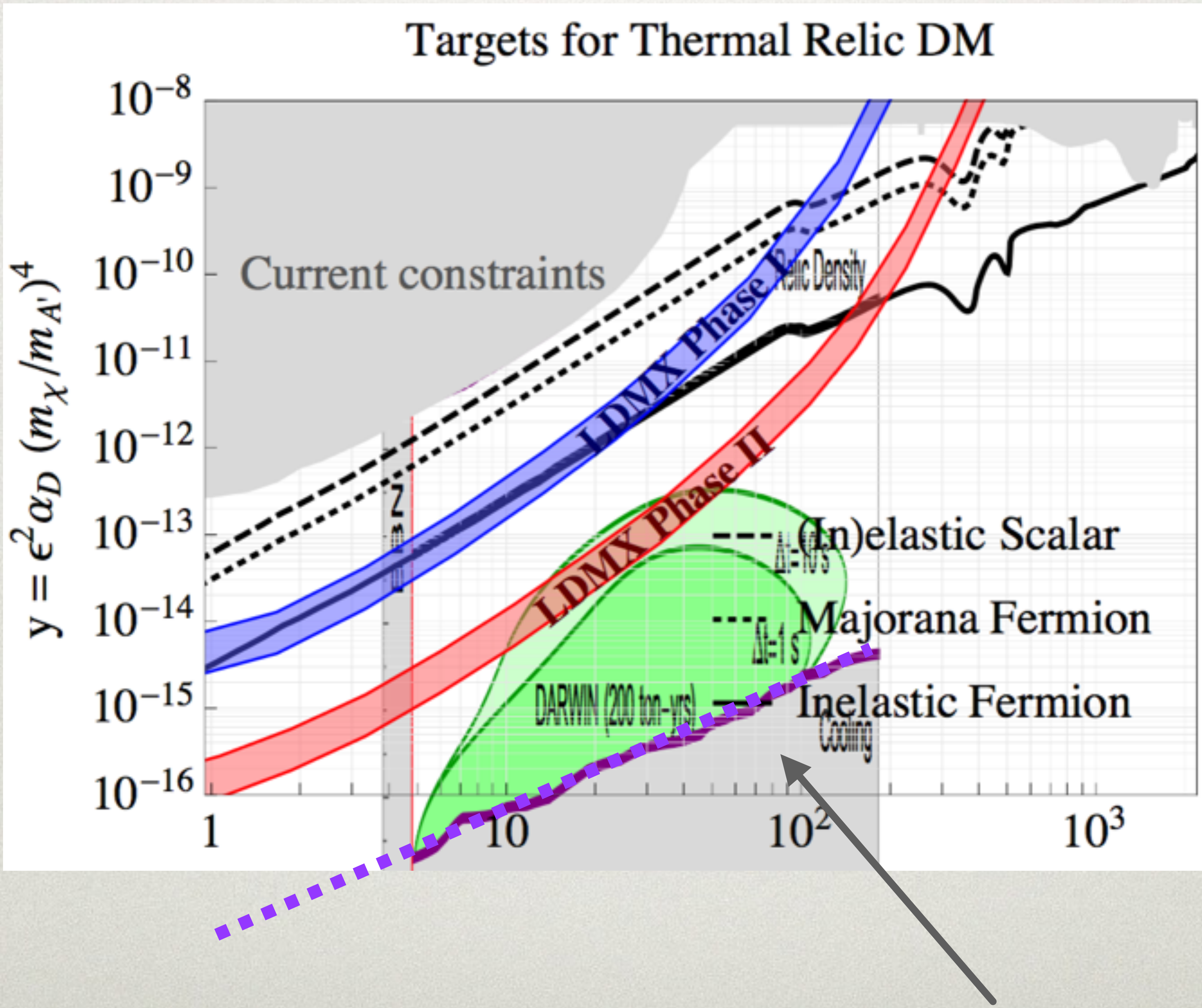


Belle II missing mass search – complementary high-mass sensitivity

Unique potential to reach all thermal DM milestones at masses below ~100 MeV

Overlapping with Supernovae constraints at very small coupling

See upcoming paper by Stanford and Berkeley groups. Contact Peter Graham



Light DM production increases supernovae cooling —> Upper bound on coupling

Overlapping with Supernovae constraints at very small coupling

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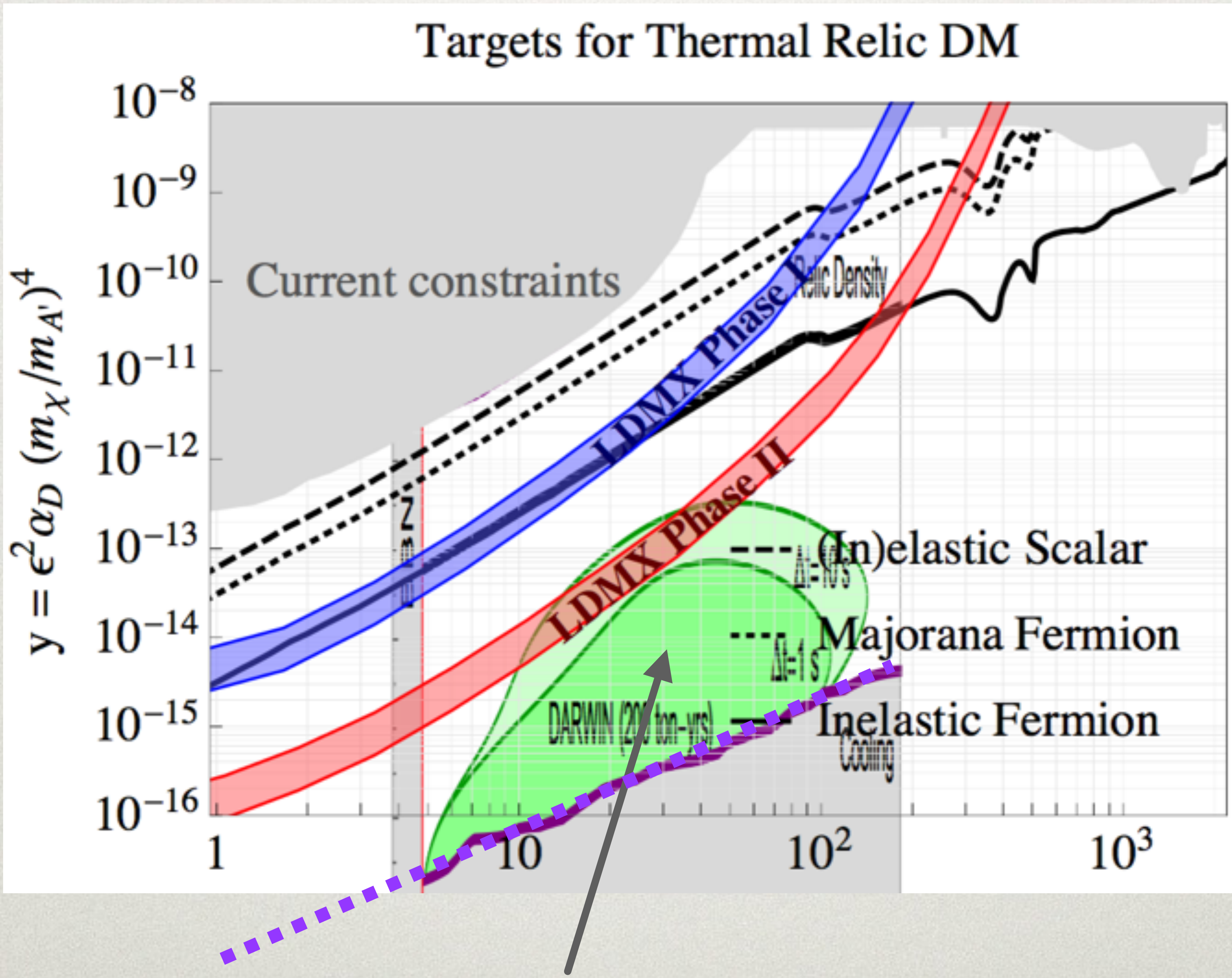


Sub-dominant halo of semi-relativistic light DM produced in SN explosions. Future (large-scale) nuclear target direct detection experiments will have sensitivity.

Conclusions

Accelerator experiments are at the forefront of light DM (and dark sectors more generally) exploration

Excellent discovery opportunities!

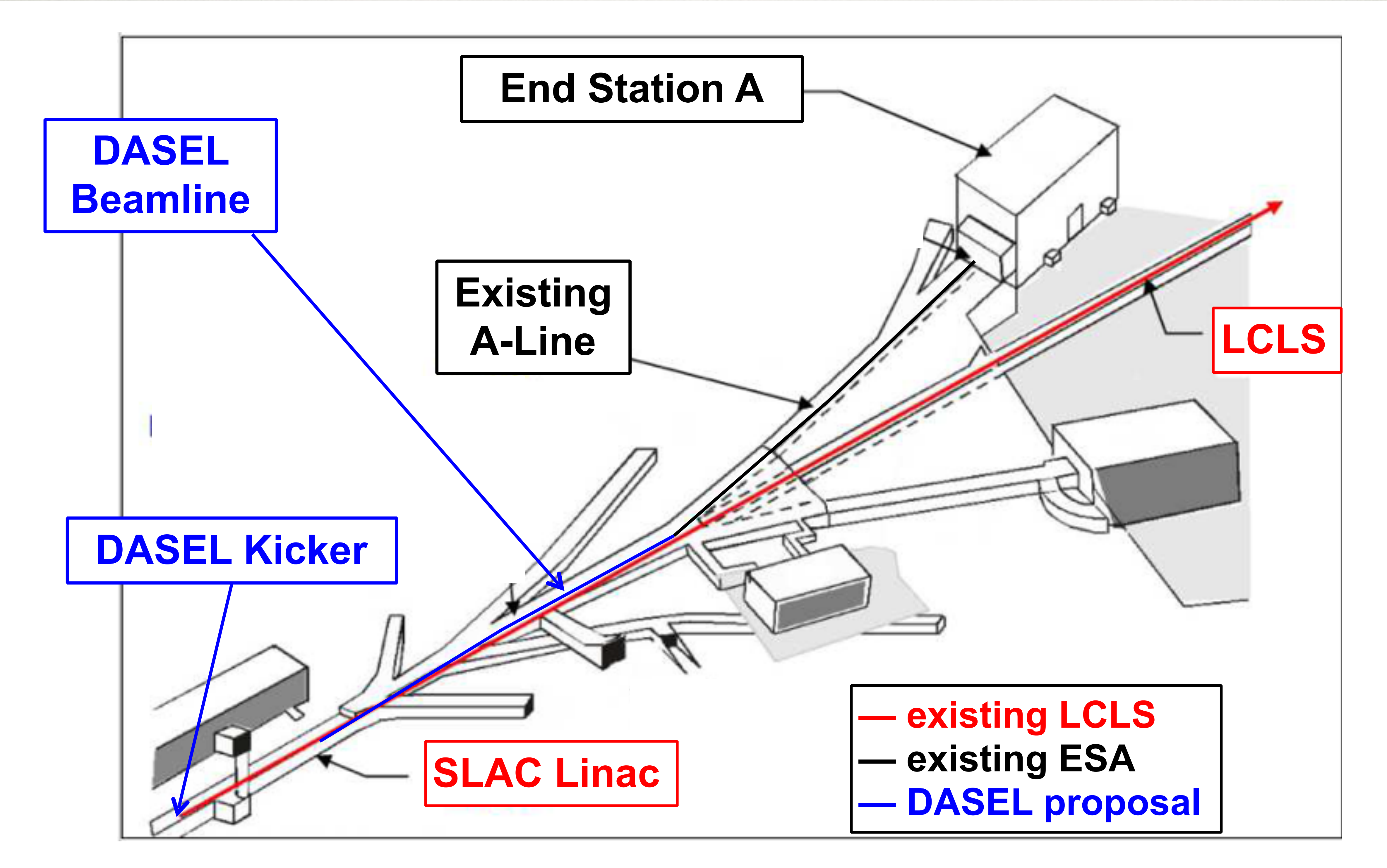
Powerful lessons about dark matter (sectors) can be derived from high sensitivity measurements of missing momentum in electron-nuclear scattering

$\longrightarrow$ LDMX

Backup

DASEL Beamline @ SLAC

Low-current but "continuous" multi-GeV beam needed for LDMX can be delivered parasitically!



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