Overview of ATAR Physics Requirements and Simulation/Analysis

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Outline:

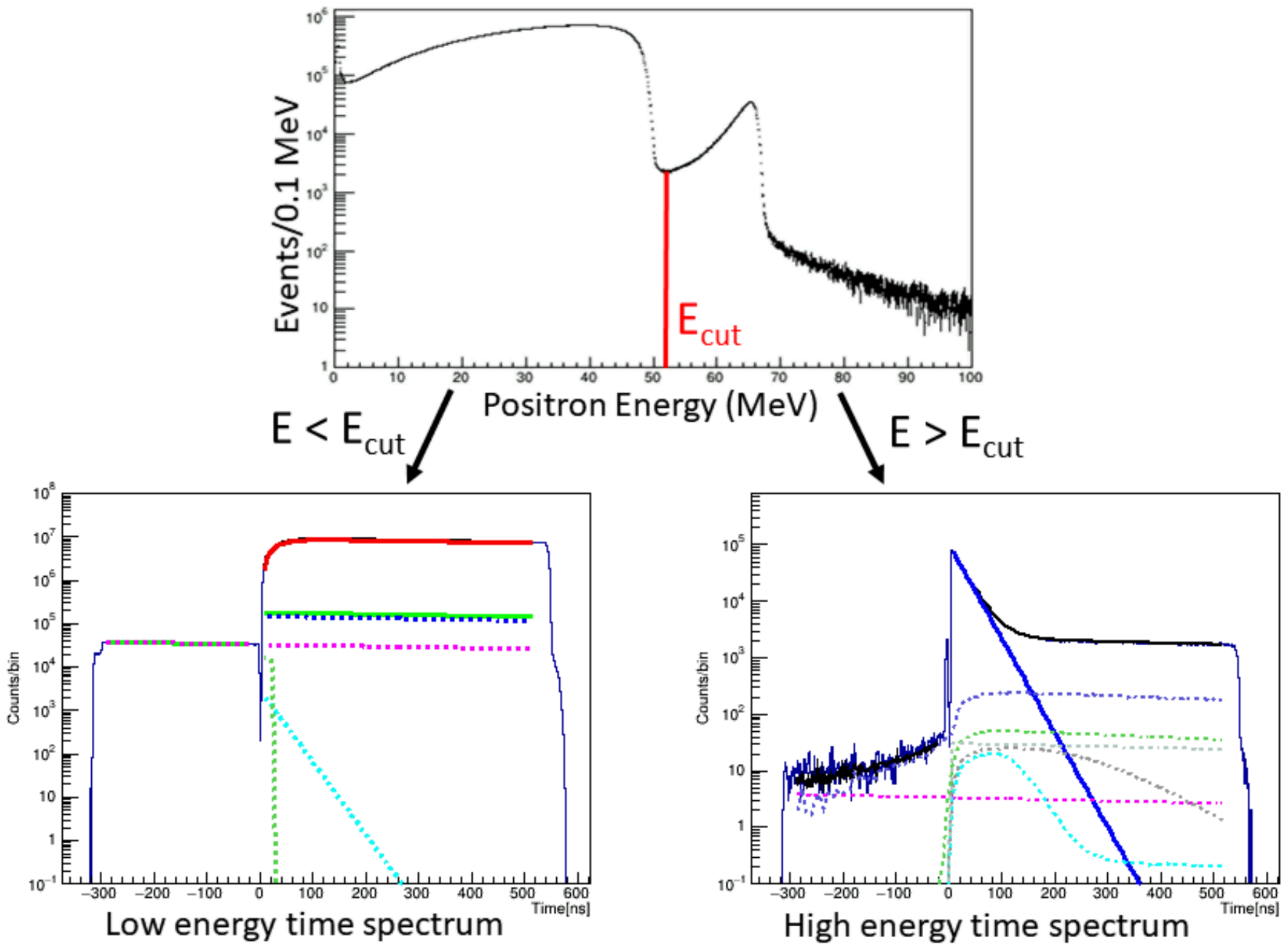
- Introduction to ATAR's role in $R_{e/\mu}$ measurement
- Factors affecting ATAR physics performance
- Challenges in ATAR R&D
- Simulation study plan to guide ATAR R&D

Thanks to everyone in ATAR Simulation Group for all the inputs
Bruce, Xin, Simone, Adam, Siddhant, Yousen, Doug

ATAR in PIONEER $R_{e/\mu}$ measurement

- PIONEER Phase I goals:
  - $R_{e/\mu}$ **measurement at the 0.01% level**
  - New physics search up to PeV scale

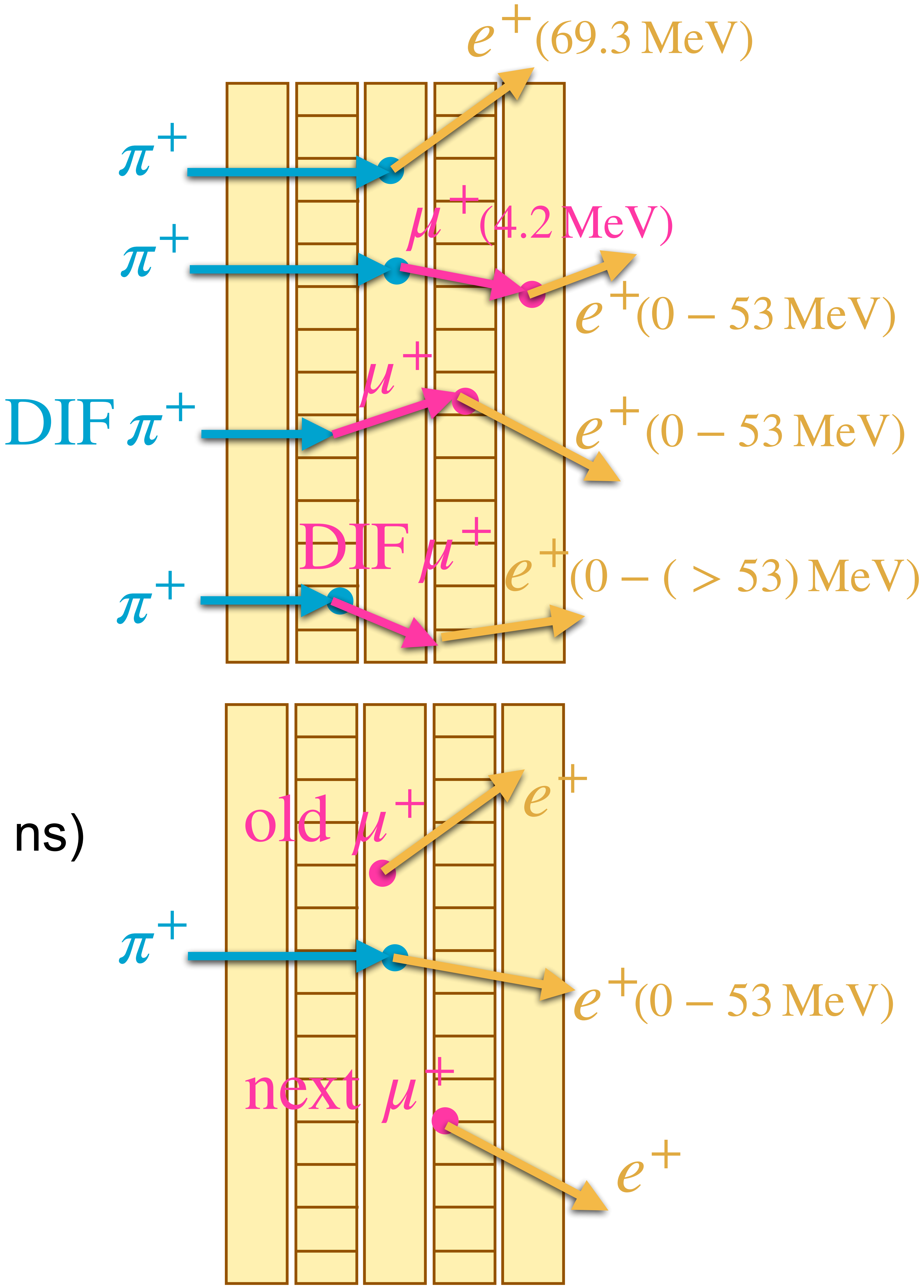
- The branching ratio for $\pi \rightarrow e\nu(\gamma)/\pi \rightarrow \mu\nu(\gamma)$ is extracted from the data by first dividing the energy spectrum into low energy and high energy and then fitting the time spectra simultaneously
- Two important keys to successful measurement:
  - Mitigation of significant contributions from **pileup**
    - Outgoing positron track matching the pion/muon stopping vertex
  - Suppression of **decay-in-flight (DIF) backgrounds**
    - π-e timing, dE/dx and track topology



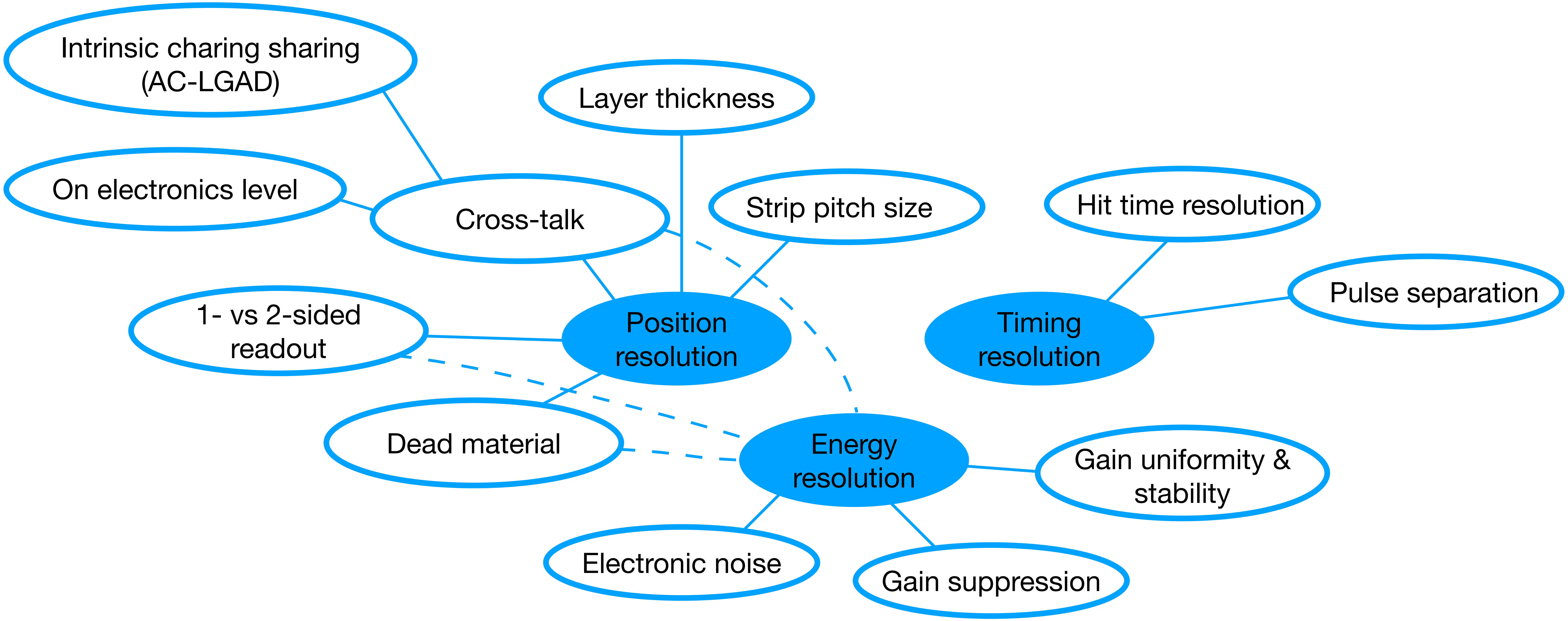
From PIENU

ATAR background suppression

- How to identify various backgrounds:
  - $\pi \to \mu \to e$
    - Positron time (muon lifetime 2.2 μs) → time resolution
    - 3 track pattern
    - 4.2 MeV muon → energy resolution & pulse separation
  - $\pi \xrightarrow{\text{DIF}} \mu \to e$
    - Positron time (muon lifetime 2.2 μs) → time resolution
    - dE/dx of (pion & muon) hits → energy resolution
    - Kink topology in ‘early’ hits → position resolution
  - $\pi \to \mu \xrightarrow{\text{DIF}} e$
    - muon signal after pion signal → pulse separation (pion lifetime 27 ns)
    - dE/dx of (muon & positron) hits → energy resolution
    - Kink topology in ‘delayed’ hits (muon travels up to 780 μm) → position resolution
  - Pileup
    - Pattern recognition → position resolution



Factors affecting ATAR performance



Electronic noise

- Level of electronics noise in the PiN option is crucial to the MIP identification
  - Require S/N ≳ 10:1, which corresponds to equivalent noise charge (ENC) ≲ 780 electrons
    - The (minimal) most probable value charge for a MIP track in a 120-um thick Si is about 7800 electrons
  - Level of electronics noise depends on the input capacitance and peaking time of electronics
  - The requirement for LGAD will be looser, i.e. shorter peaking time is possible

$$ENC \propto C_{\text{in}} \cdot \sqrt{\frac{1}{t_{\text{shaping}}}}$$

Optimal expectation:

– 6 e- /pF@ 1 us shaping @ room temperature

– **@ 20 pF, 20 ns shaping time gives us 850 electrons**

– At LXe temperature (~4 e/pF), ENC ~ 570

From Xin

@BNL, effort to construct a 'new' ASIC with short peaking time (~10 ns)

200 um pitch, 100 um width	N-type strip (2 cm)	P-type strip (2 cm)
Interstrip capacitance	0.1 fF/um → 4 pF	0.04 fF/um → 1.6 pF
Back capacitance	0.08 fF/um → 3.2 pF	0.08 fF/um → 3.2 pF
FLEX cable	50-60 pF/m → 2.5 – 3 pF	
Total	~ 10 pF	~ 8 pF

20 pF upper limit estimation includes system design, FLEX cable with ground plane

Minimizing input capacitance and increasing peaking time would improve S/N.
A balance between peaking time and S/N is needed.

Gain saturation/uniformity/stability

- LGAD gain suppression has been observed with large energy deposition
  - Caused by the field shielding effect from the gain electrons/hole pairs
- Gain saturation depends on
  - dE/dx
  - Incident angle of charge particle w.r.t gain layer
- Recently tested with CENPA test beam:
  - See presentation from Quentin (DocDB-202)

- Gain uniformity - how much would the uniformity of doping affect the energy resolution?
- Gain stability - how sensitive is the sensor to temperature changes?

Gain saturation would reduce the difference in dE/dx between π vs μ, as well as (μ & e vs e).
Gain uniformity and stability would affect energy resolution.
How much gain saturation and energy resolution level can we withstand?

Cross-talk in electronics

- Cross-talk between two adjacent channels can be estimated as

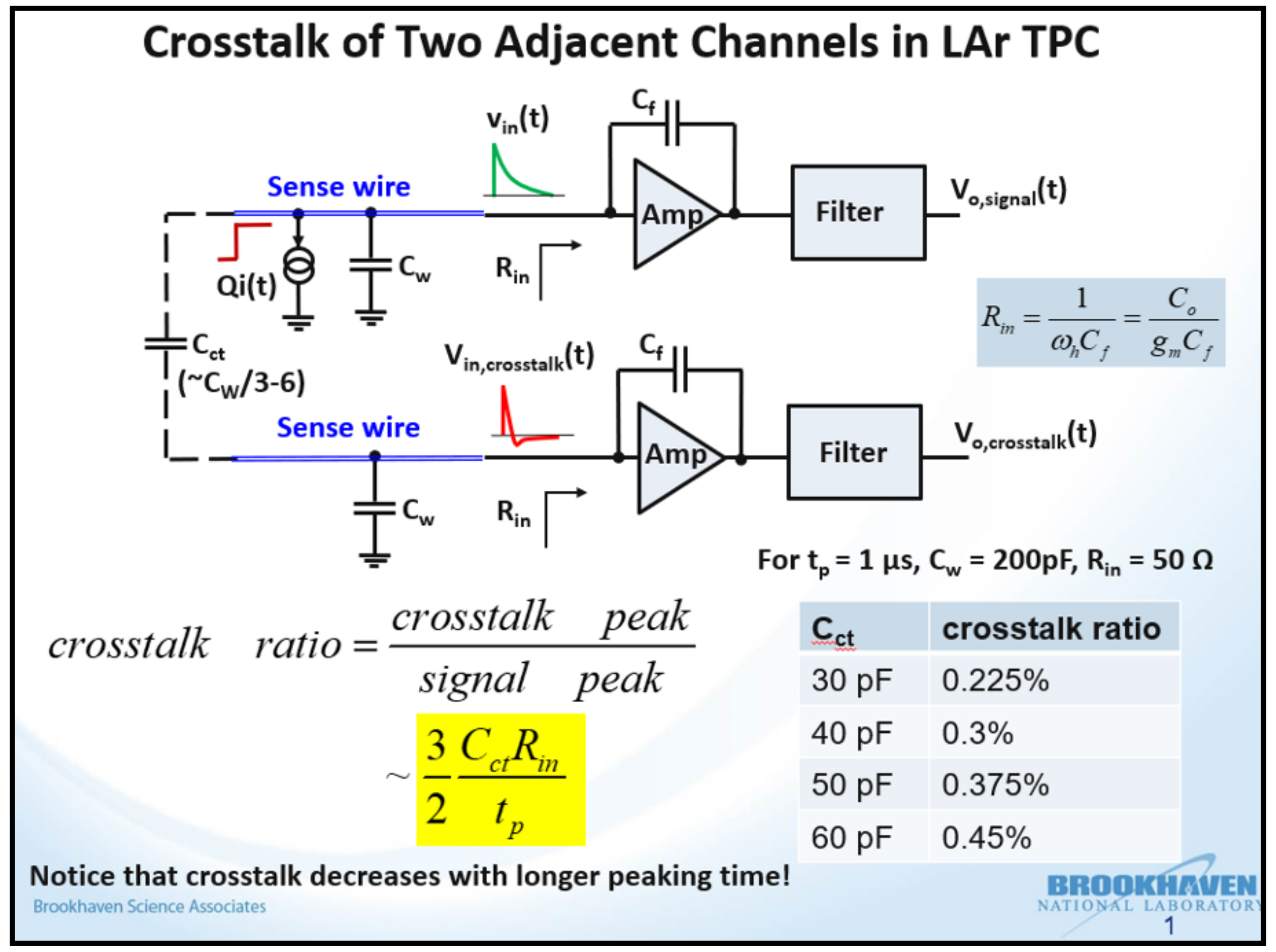
$$R = \frac{\text{cross-talk peak}}{\text{signal peak}} \sim \frac{3}{2}\frac{C_{ct}R_{in}}{t_p}$$

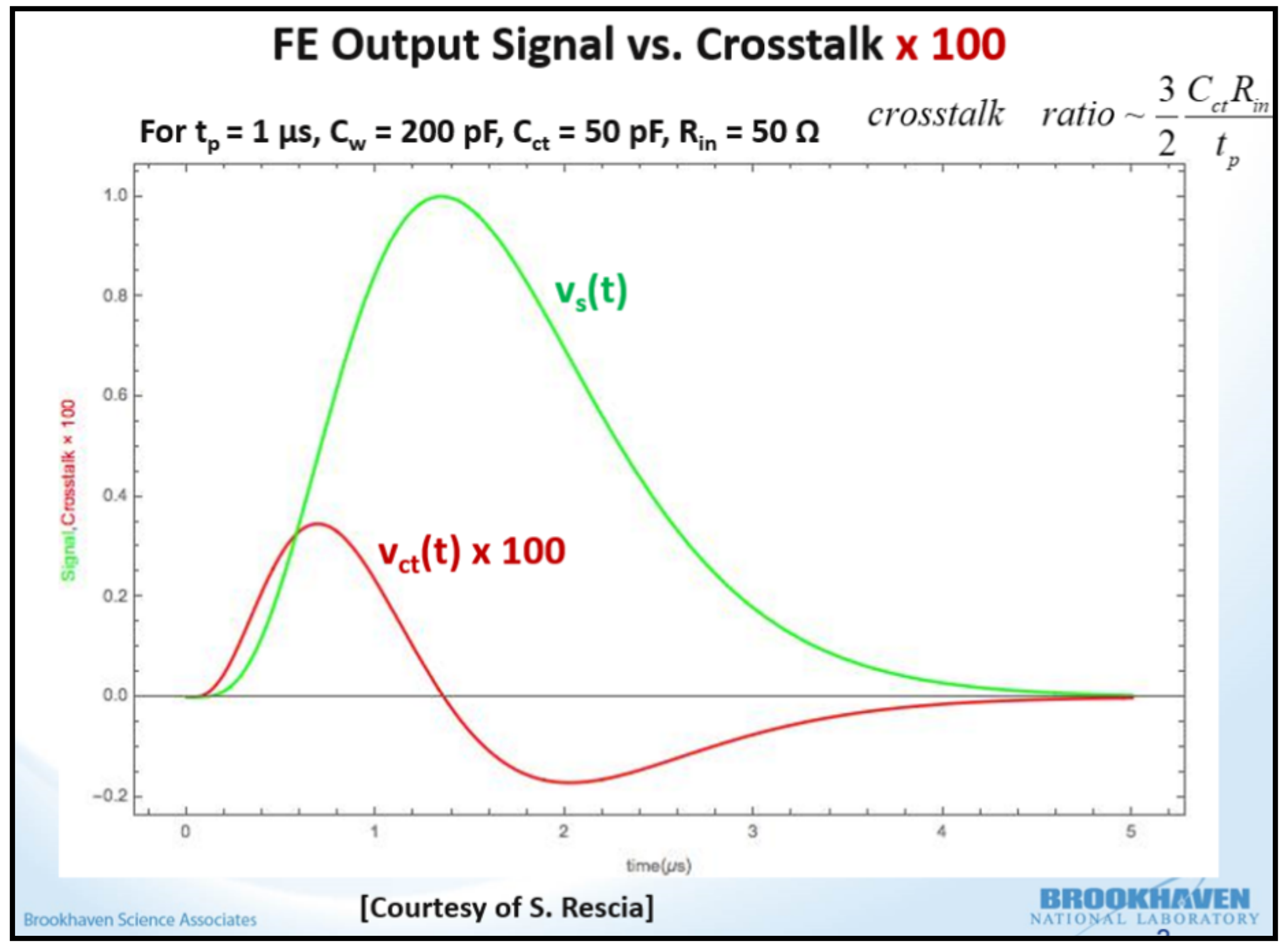
  - Cross-talk signal will have a shape similar to the derivative of the primary signal

- FAST electronics
  - Input impedance of 50 Ohm, shaping time ~1 ns, at 3 pF coupling capacitance
  - The cross talk ratio will be as large as 22.5%, with large distortion to the primary signal

- Hypothetical electronics for PiN
  - At 20 ns shaping time, the cross talk ratio will be ~1%

From Xin





Cross-talk could become an issue in dense tracking environment.
Can we handle cross-talk? How to simulate/calibrate/correct in reconstruction?

Two reference designs (single-sided readout)

LGAD (default)

- Intrinsic modest internal gain (10-50) → enhanced signal
- FAST2 readout electronics with O(1) ns peaking time
- Gain saturation, uniformity and stability
- > 40 μm of dead material between adjacent layers
- Dead materials: electrode, gain layer (~2 um), guard ring

- In the case of AC-LGAD:
  - Intrinsic charge sharing between strips
    - When there's NO neighbouring hit, charing sharing information can be used to obtain << the standard $\sqrt{12}$ detector precision. But questionable when there's multiple neighbouring hits.
- Alternative LGAD technologies:
  - Trench insulted LGAD
    - Very low inter-pad gap: 5-10 μm; No (detector-level) cross-talk

PiN

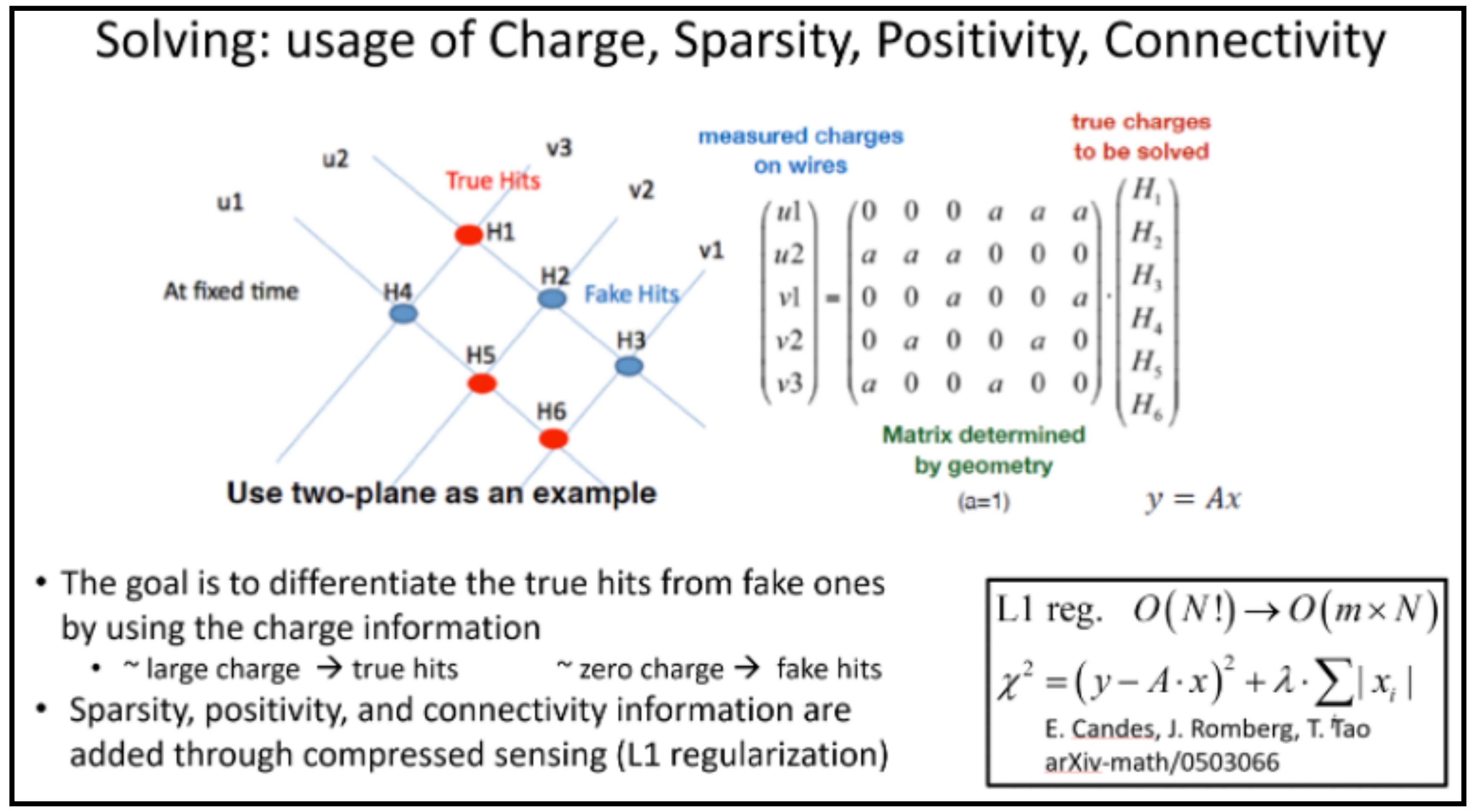
- No gain → challenge in identifying MIP signal
- New low-noise electronics with O(10) ns peaking time → pulse separation resolution
- Very linear in energy response to 1-100 MIP
  - Easier to calibrate (uniform, stable and topology independent)
- O(2) μm of dead material between adjacent layers
- Dead materials: electrode, guard ring

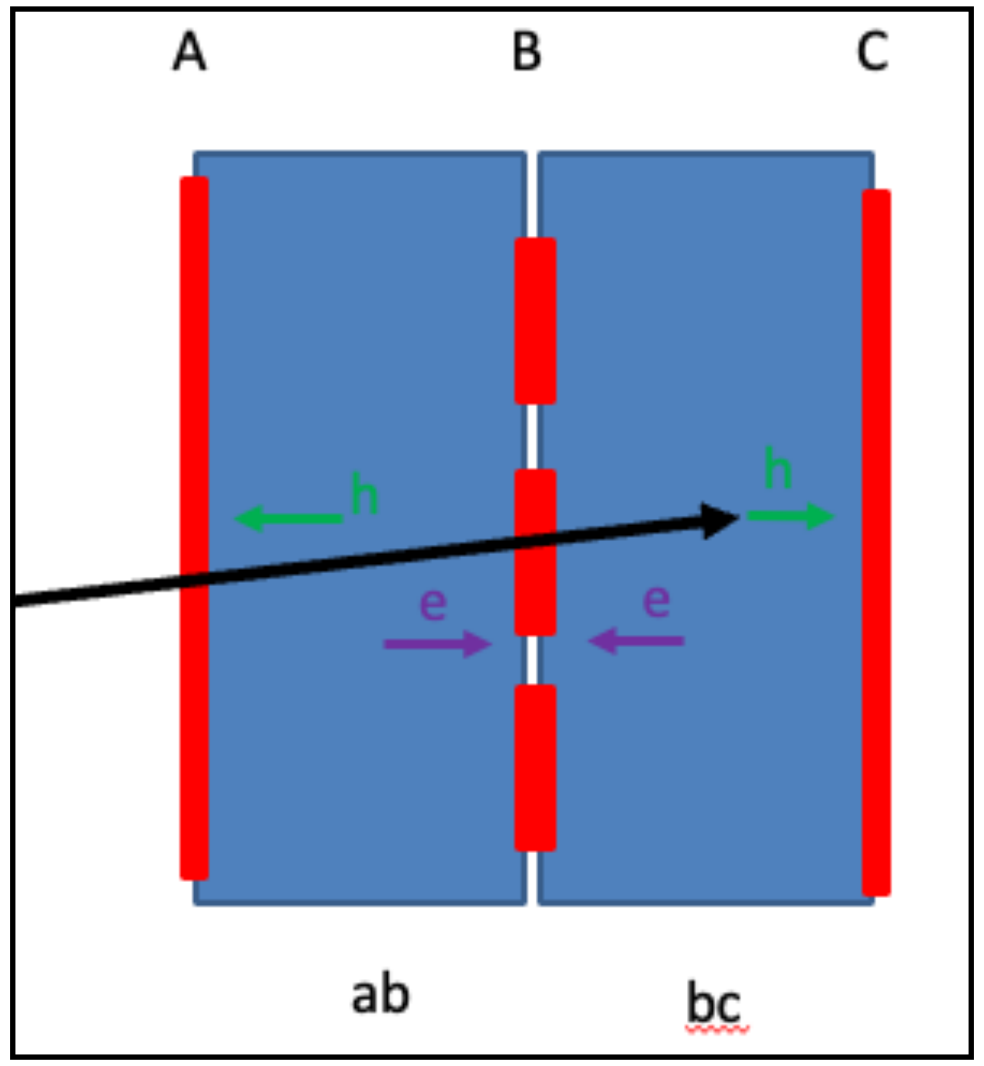
Comparison between single- and double-sided readout

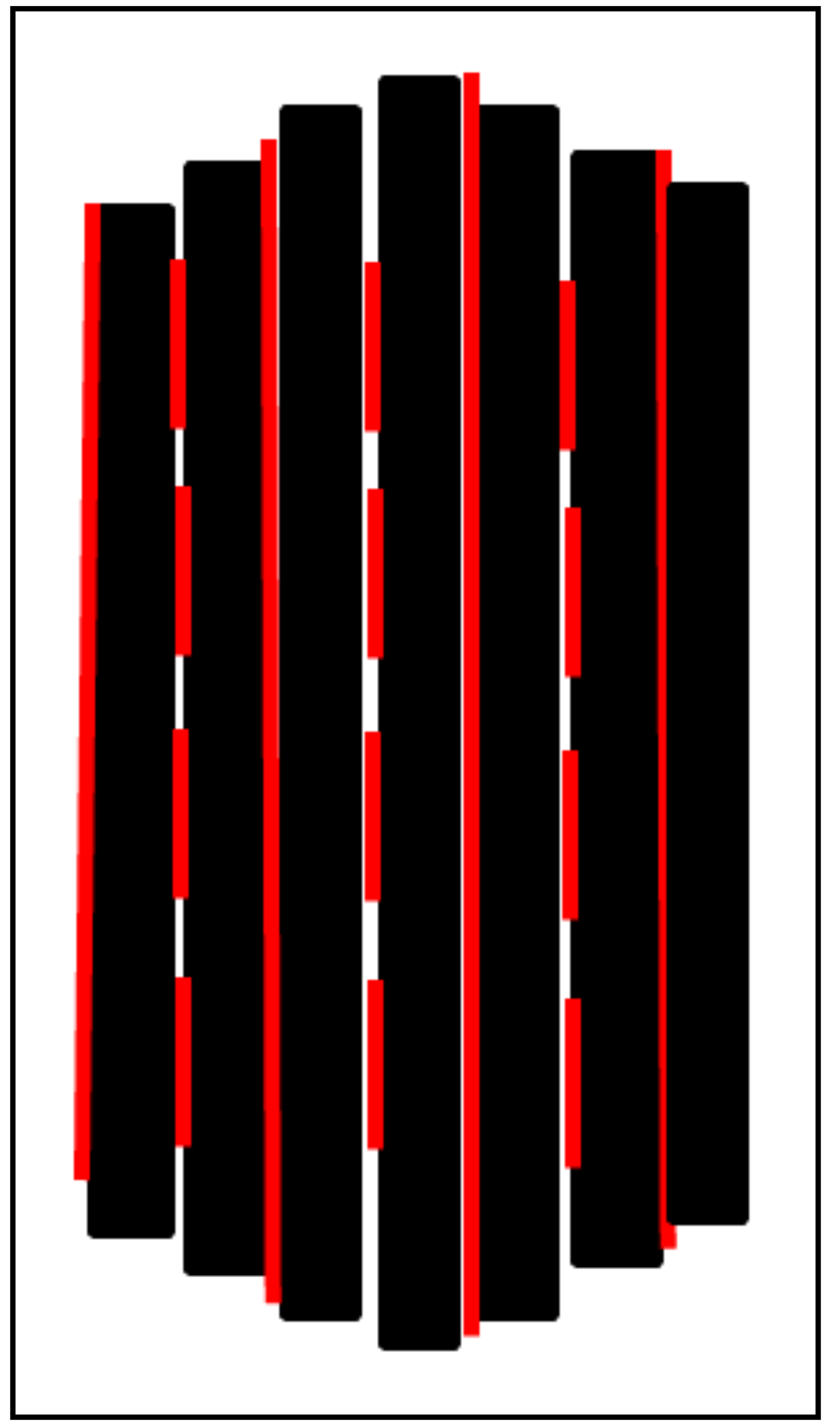
- In the double-sided readout design:
  - Like the default design, there will 48 layers (120 μm thickness) of ATAR strips, and 100 strips (200 μm pitch) per layer
  - But there will be readouts on BOTH sides, where the readouts will be oriented in orthogonal directions

- In the LGAD design, one side will be DC-LGAD, and the other side will be AC-LGAD.
  - 4800 x 2 channels in total
- In the PiN design, the readouts between adjacent layers will be shared.
  - 4900 channels in total

From Xin







R&D challenges

LGAD

- Demonstration of the control of the gain saturation
- Understanding LGAD gain suppression mechanism
- Demonstration of the control of cross-talk in AC-LGAD
- Demonstration of cable connection and support structure

PiN

- Demonstration of low-noise preamp electronics
- Demonstration of 120 μm layer fabrication
- Demonstration of double-sided fabrication with shared readout
- Demonstration of cable connection and support structure

Simulation study should be performed to identify critical requirements and guide the R&D efforts, if we want to know where we should put our resources on.

Simulation study plan

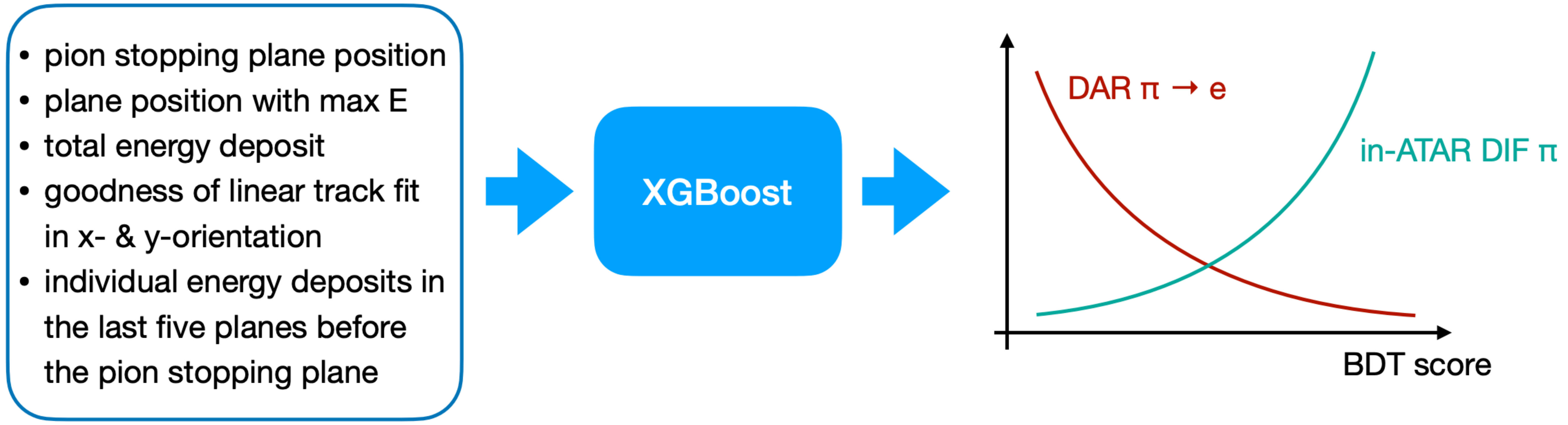
Ongoing effort of simulation study in the ATAR Simulation Group by Adam et al. to understand the physics requirement of ATAR.

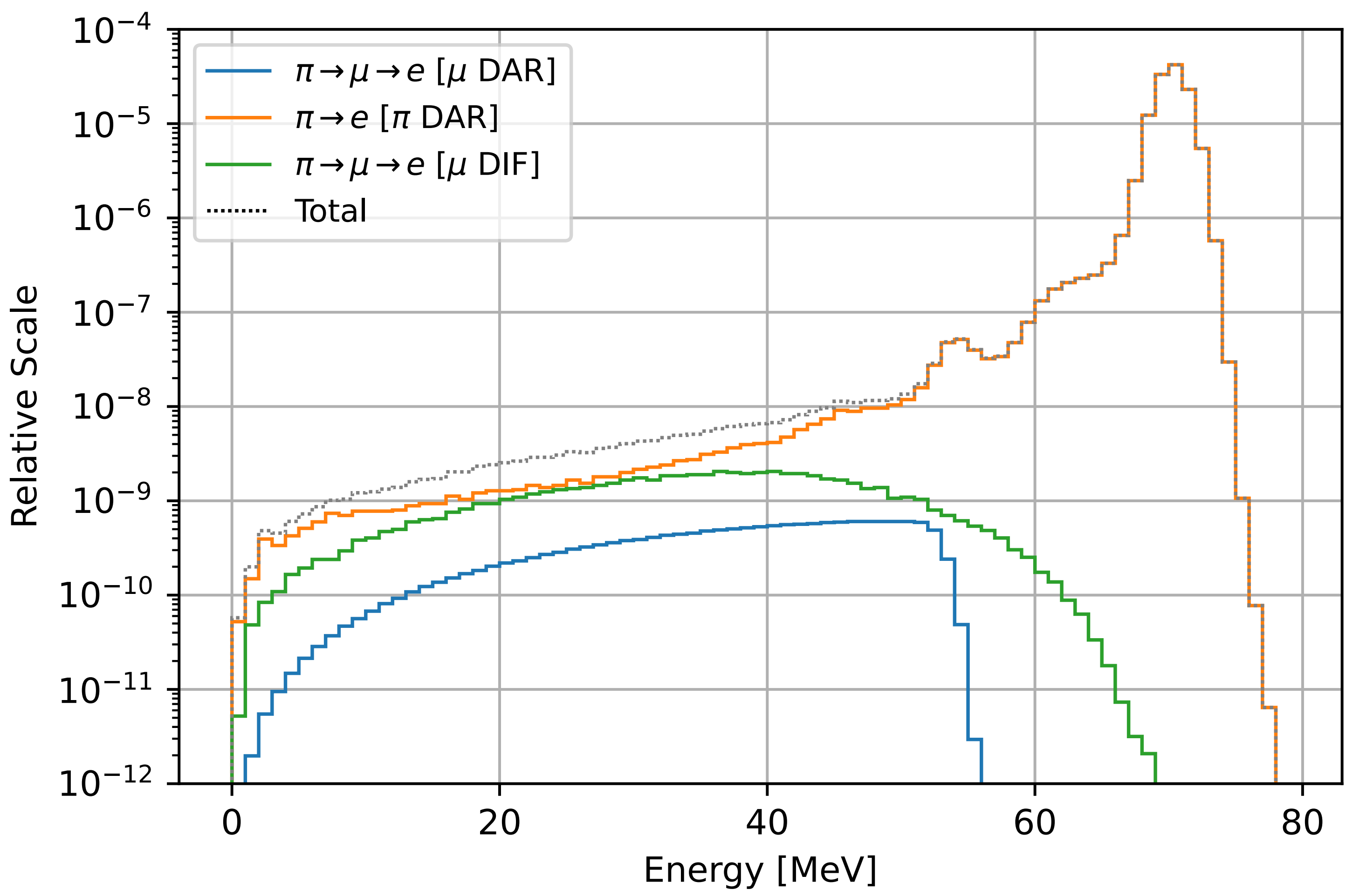
Short term plan

- Applying Vincent's DIF analysis (πDIF BDT classifier and cut-based μDIF suppression) and maybe also new improvements
  - Validate results from latest simulation by comparing results at some benchmark ATAR configuration
  - Perform ATAR performance study using simulation for various ATAR designs

Long(er) term plan

- Migrate the developed analysis code to the Fast Simulation Tool
  - Pileup study can then also be studied





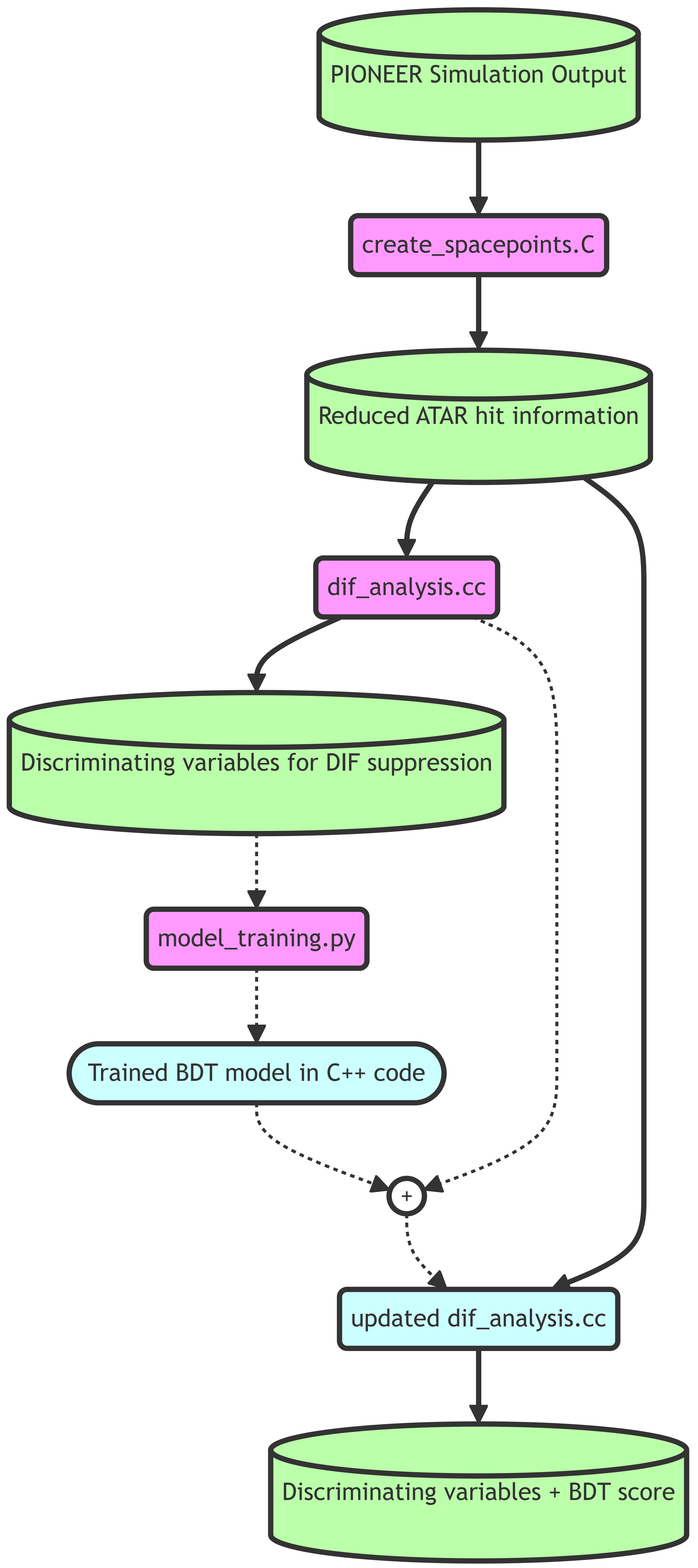
Simulation study plan

Analysis workflow has been developed to run on the raw simulation output, but this is NOT meant to divert from the Fast Simulation tool in the long term.

- Plan to join the effort and incorporate the needed tuneable features in the Fast Simulation tool, in preparation for studying the impact on pile-up suppression

Ordered list of items to be study:

1. Dead material
2. Energy resolution
3. Layer thickness
4. Position resolution, as one might expected from AC-LGAD if the charge sharing could be unfolded
   - To understand if there would be potential advantage from resolving the charge sharing
5. TI-LGAD
   - Geometry implemented by Adam; ready to be studied
6. Pulse separation resolution
7. Strip pitch size
8. Double-sided readout
9. Cross-talk
10. Hit time resolution



Summary & Outlook

- ATAR is a crucial sub-detector in PIONEER, in both pileup and DIF suppression
- Various factors that could be affecting the ATAR performance need to be studied
  - Like gain suppression, (detector level & electronics level) cross-talk, pulse separation, double-sided readout etc.
- Analysis workflow is ready. Bulk simulation production will be starting this week.
  - TI-LGAD geometry is now in place. Study could already be performed.
  - Double-sided readout geometry is also included (by Siddhant), but modification of the analysis code is needed.
  - Cross-talk study will require more effort, as dedicated reconstruction to resolve neighbouring hits is needed.