TSD Intro

Michael Hedges

TSD Topical Group meeting

01/18/2024

Outline

Mu2e

Instrumentation with quantum dots

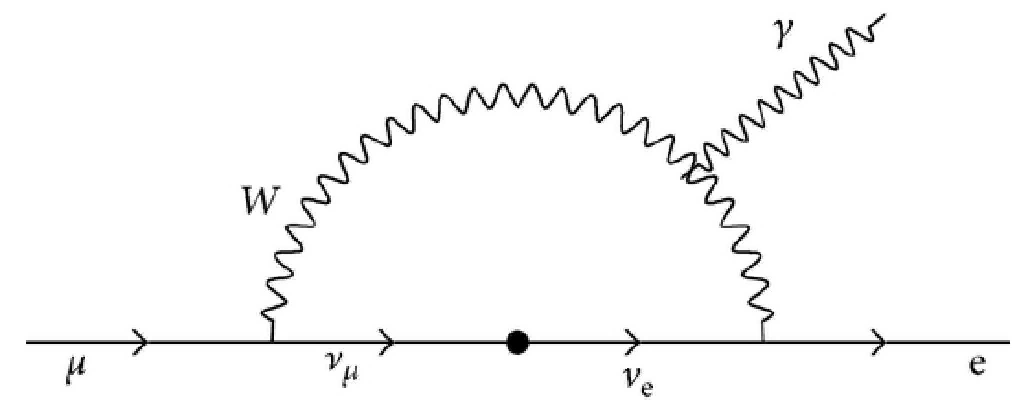
Belle II analysis

Charged Lepton Flavor Violation

Charged leptons are only fermions without observation of flavor violation

- Quarks mix (CKM)
- Neutrinos oscillate

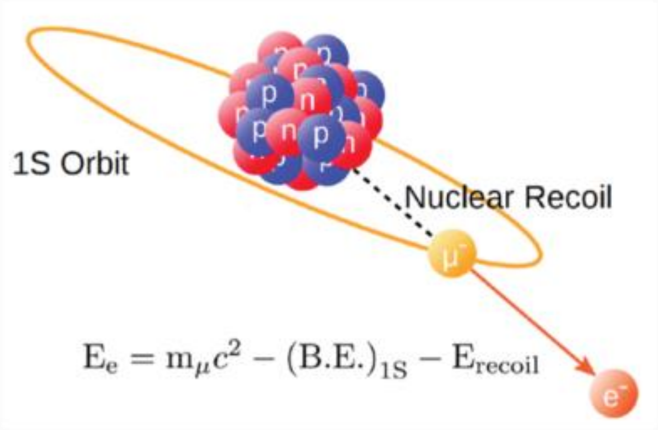
CLFV is required in νSM, but ludicrously suppressed



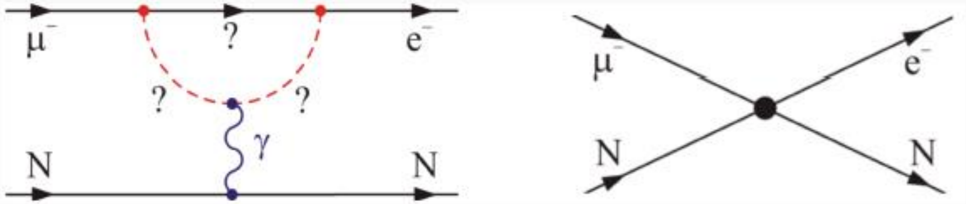
$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{k=2,3} U^*_{\mu k} U_{ek} \left(\frac{\Delta m^2_{1k}}{M^2_W}\right)^2 \right|^2 < 10^{-54}$$

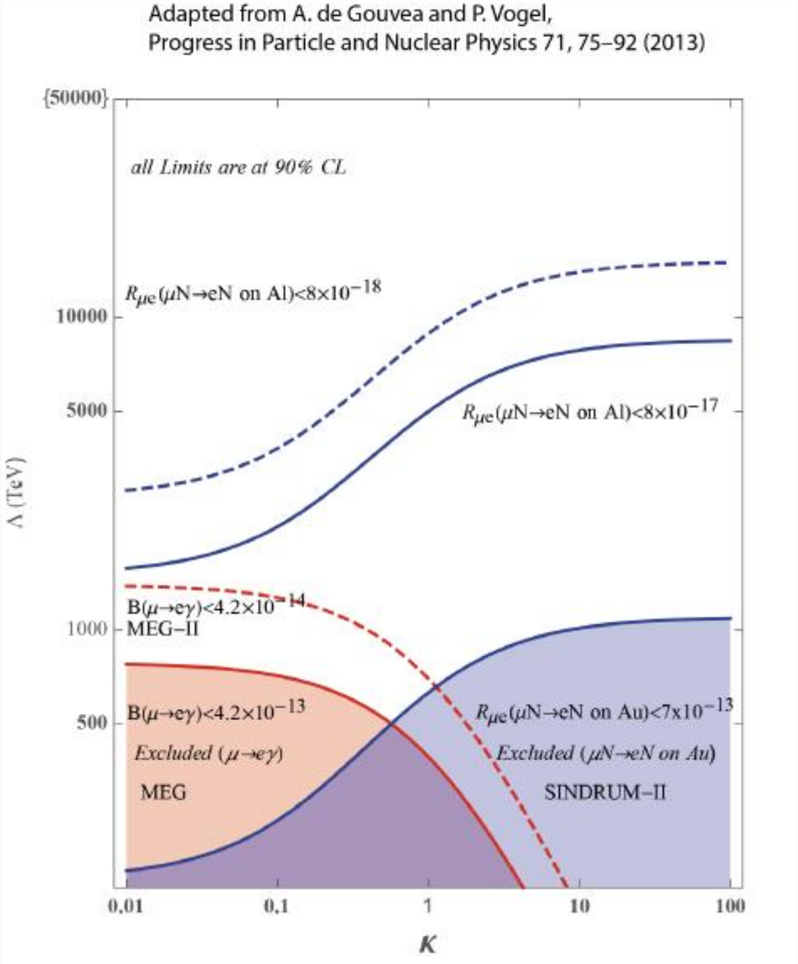
Any experimental observation would unambiguously indicate New Physics

CLFV: μ→e conversion



- Monoenergetic ~105 MeV/c conversion-electron (CE)
- Sensitive to Λ-scales $\mathcal{O}(10^3)$ TeV





$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

Challenge 1: μ- beam from FNAL protons

High-level proton beam parameters

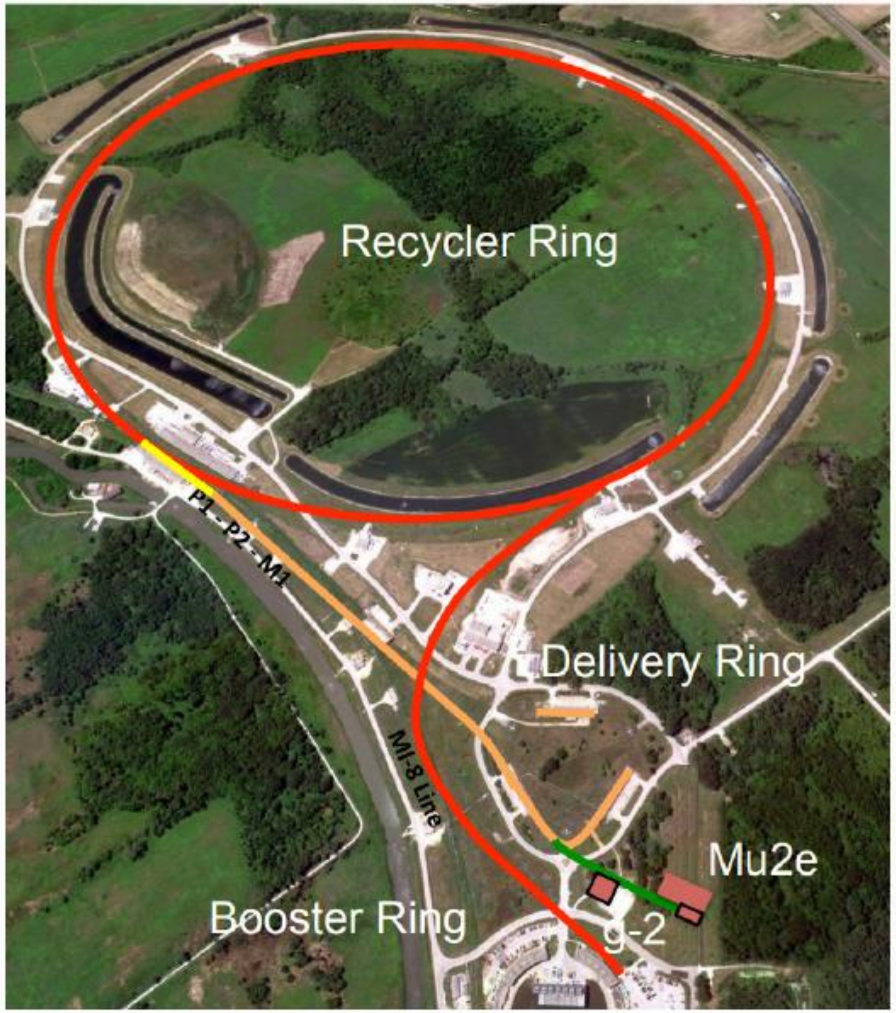
Linac: 400 MeV

Booster: 8 GeV

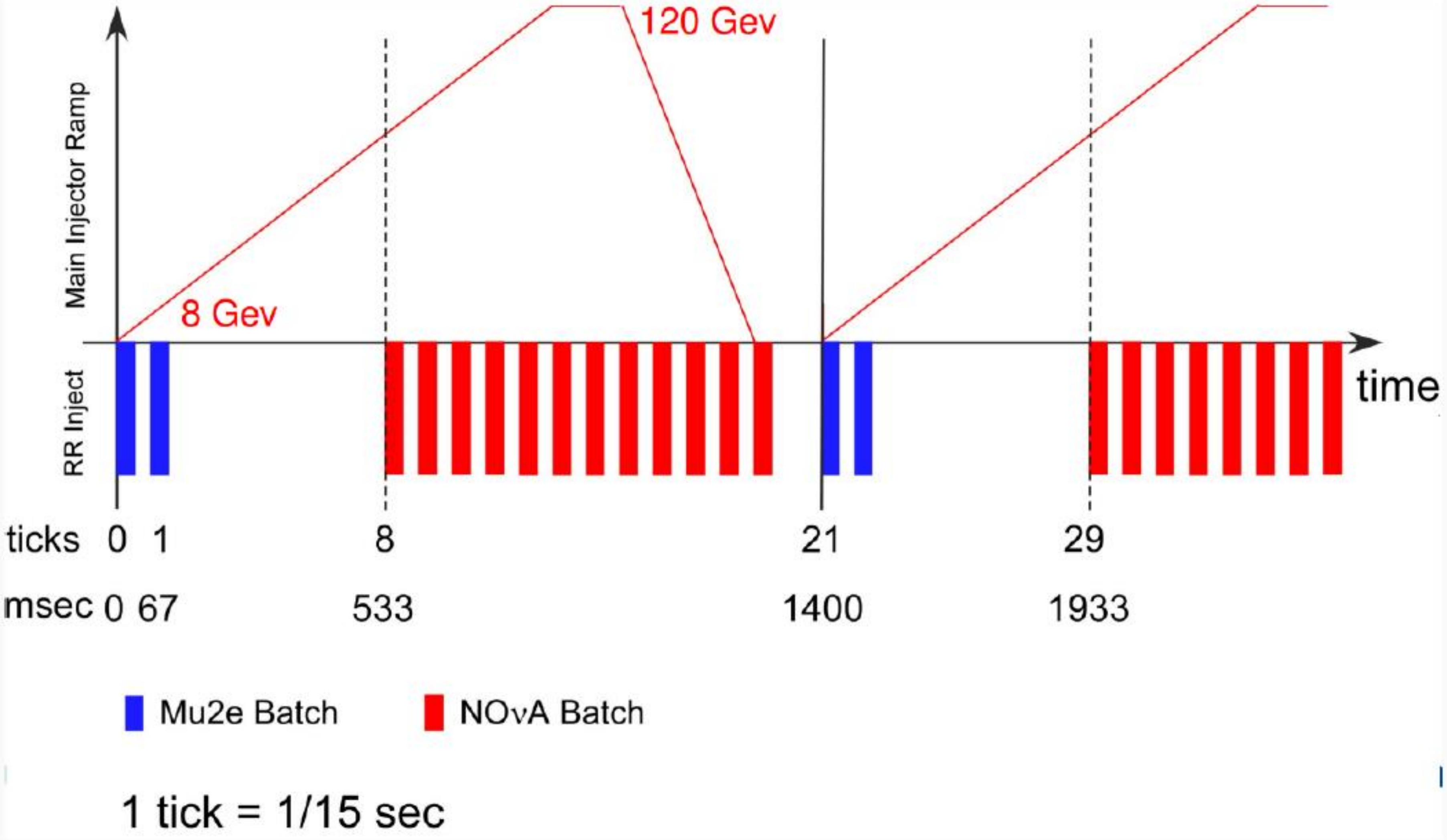
Recycler rebunches

Slow-extraction in Delivery Ring

Beam to Mu2e



FNAL neutrino needs drive 8 GeV protons

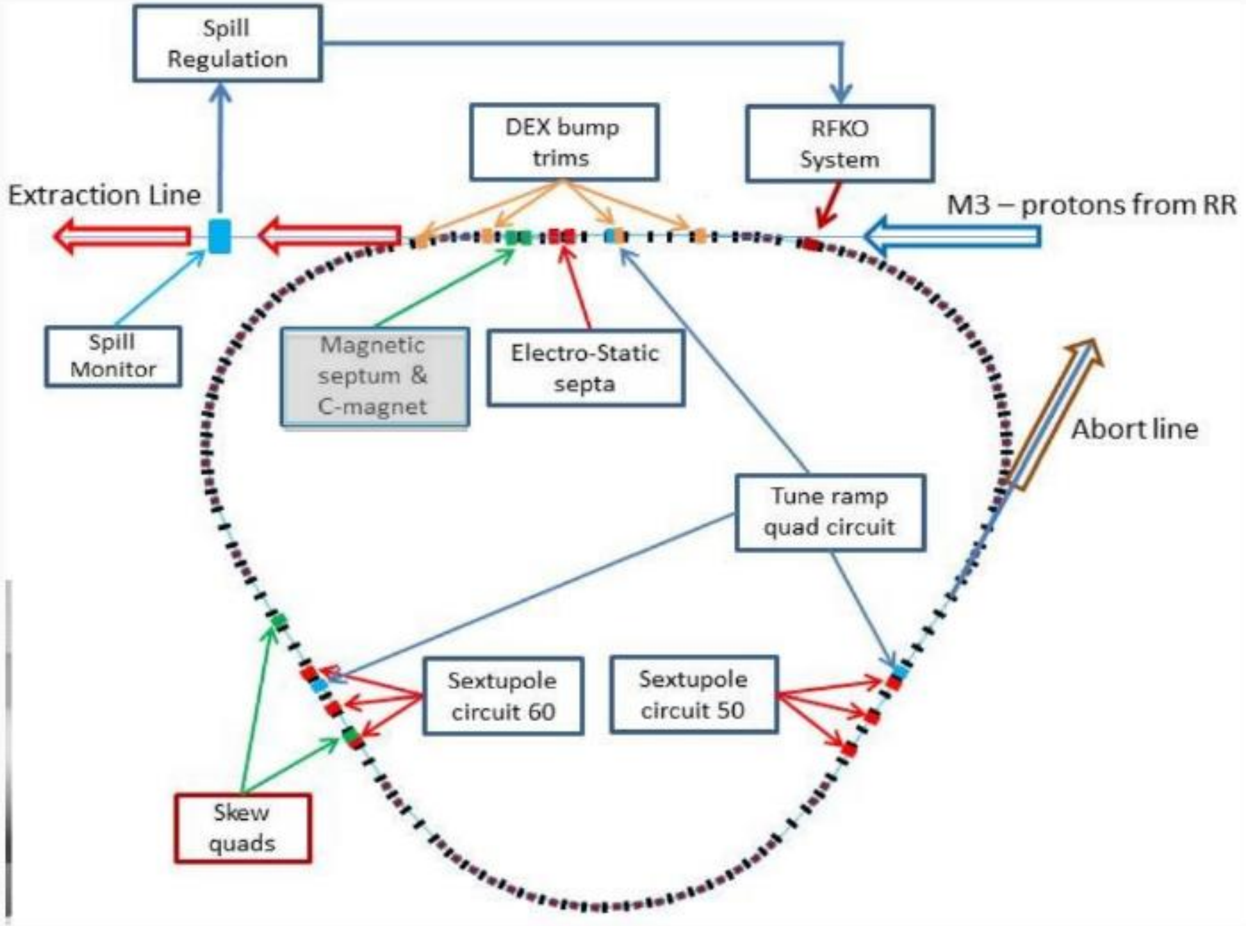


Resonant extraction in Delivery Ring

Take-home: Inject instability, "scrape" off small piece of spill every revolution

Mu2e target will see:

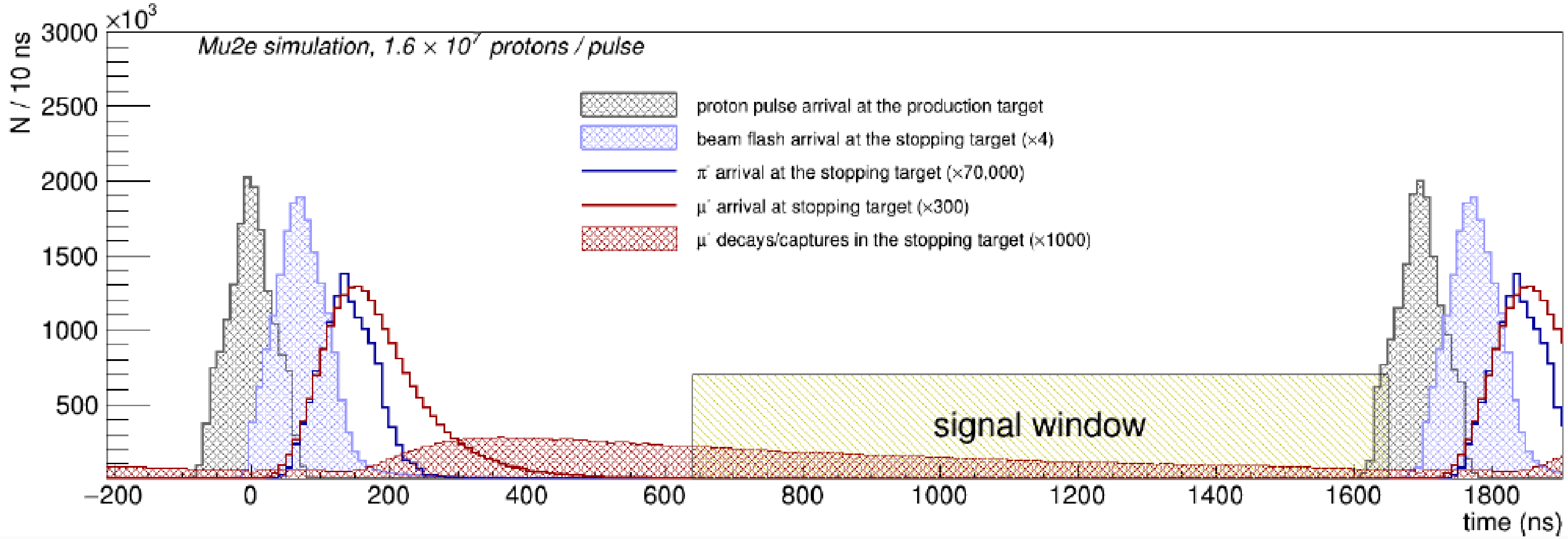
- $\sim 4 \times 10^7$ protons @ 8 GeV
- ~ 1 mm gaussian beam radius
- 250 ns pulses
- 1.7 μs pulse period
- At 2.5 MHz



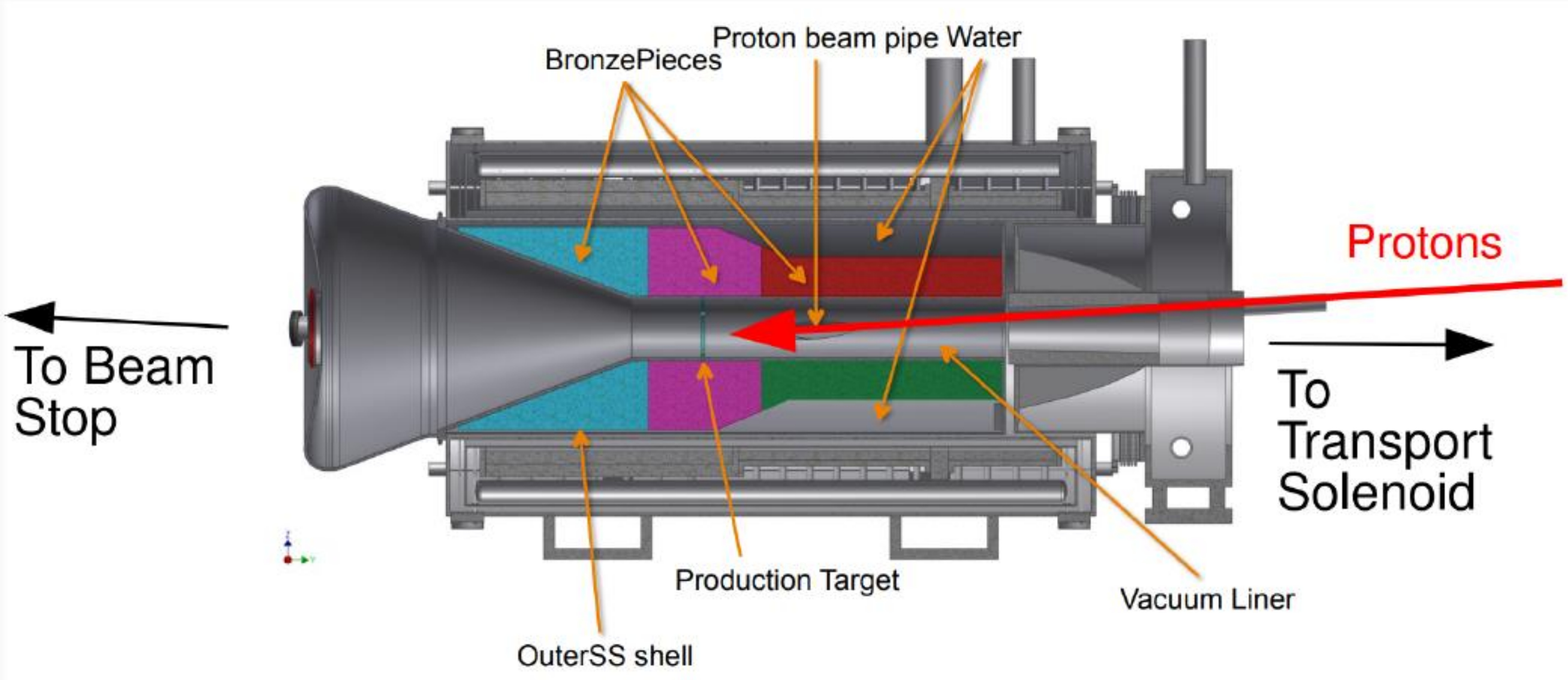
Challenge 2: Ideal Mu2e conditions

Mu2e needs:

- High yield of *stoppable* muons $\Rightarrow$ low momentum μ^- beam
- Minimal beam-induced backgrounds (i.e. radiative pion capture)
- Low radiation environment



Solution: Production Solenoid (PS)



Compact, high-Z pion-production target in high B-field
with backwards extraction

Production Target

LaO_2-doped Tungsten, core EDMed from single rod

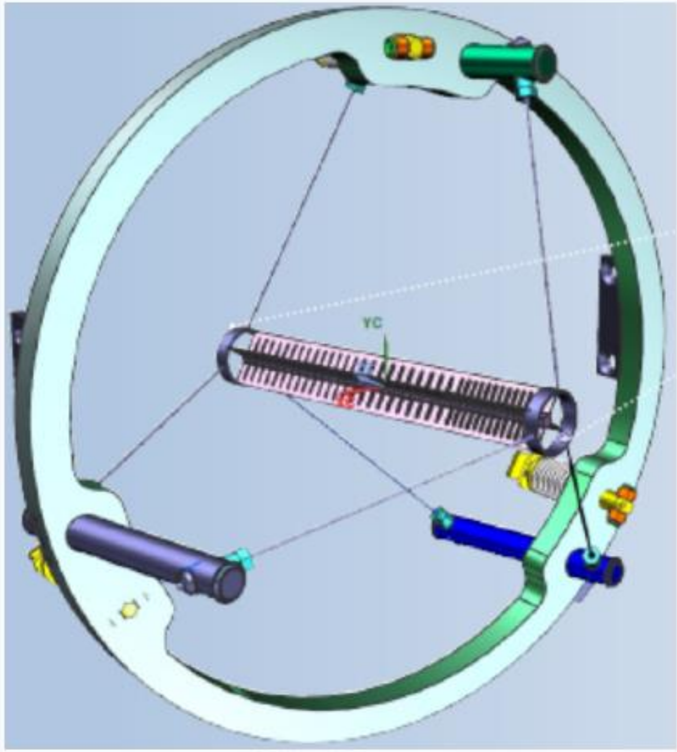
Longitudinally segmented cylinder
⇒ stress management

Longitudinal fins
⇒ thermal and structural management

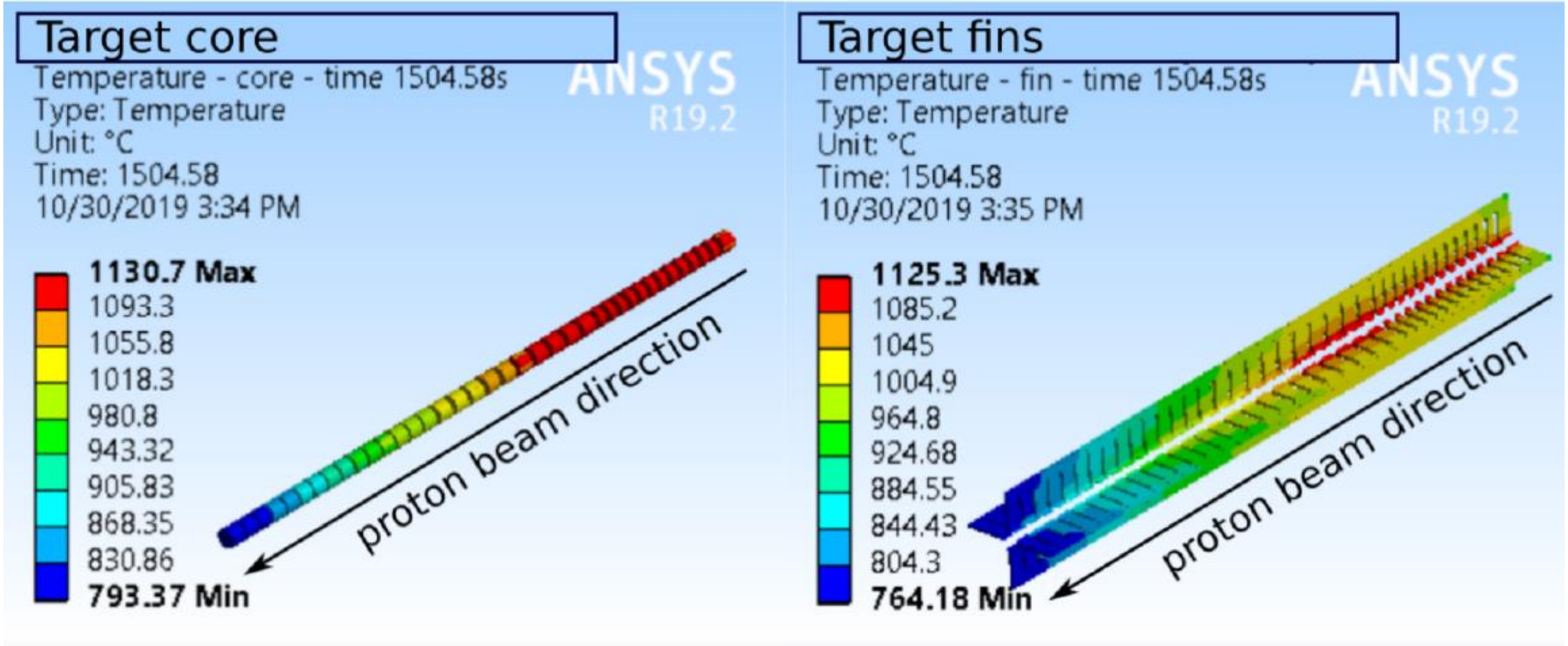
1mm tungsten spokes

~700 W power absorbtion ⇒ ~1500 K

- Radiatively cooled



Expect target lifetime of ~1 year: ⇒ replace during summer shutdowns

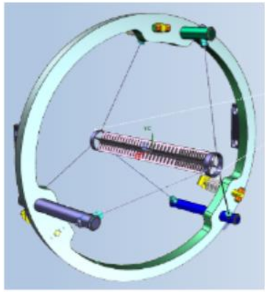

Target core
Temperature - core - time 1504.58s
Type: Temperature
Unit: °C
Time: 1504.58
10/30/2019 3:34 PM
ANSYS
R19.2
1130.7 Max
1093.3
1055.8
1018.3
980.8
943.32
905.83
868.35
830.86
793.37 Min
proton beam direction
Target fins
Temperature - fin - time 1504.58s
Type: Temperature
Unit: °C
Time: 1504.58
10/30/2019 3:35 PM
ANSYS
R19.2
1125.3 Max
1085.2
1045
1004.9
964.8
924.68
884.55
844.43
804.3
764.18 Min
proton beam direction

(ever growing) task list

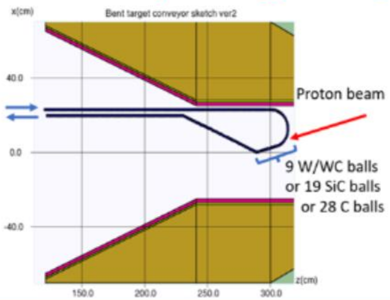
- Repeat thermal and stress analyses with Geant4 (instead of G4Beamline) and varying beam/target conditions and geometries
- Plan and conduct AP0 target test
- Target health monitoring during Mu2e Operations (currently none)
- Pulse-by-pulse intensity measurements during Mu2e Operations (one conditional, investigate additional)
- Investigate compact, high-Z targets and beam-intercept devices for future muon beams
- Bring in university partners to help with all of this

Long term vision

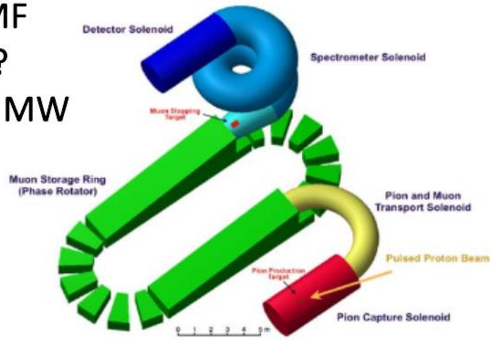
Mu2e
Tungsten, 6.3 mm x 220 mm
8 kW beam in 4.5 T



Mu2e-II
R = 1 cm W/WC spheres
100 kW



AMF
???
~1 MW

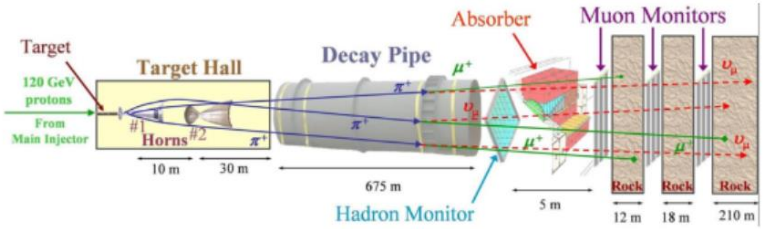


Compact, high-power targets and accompanying beam-intercept devices inside extraction solenoid

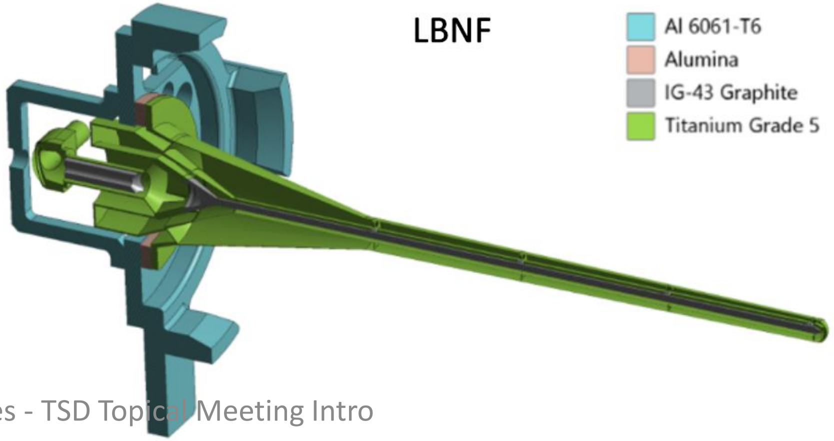
Muon collider
??????????????????????
Multi-MW in 20 T!!!

Short → Near → Long

NuMI



LBNF



Four Grand Challenges encompass this Instrumentation revolution

- **Advancing HEP detectors to new regimes of sensitivity**: *To make the unmeasurable measurable will require the development of sensors with exquisite sensitivity with the ability to distinguish signal from noise…. Research will be needed to develop these sensors with maximal coupling to the quanta to be sensed and push their sensitivities to ultimate limits.*

- **Using Integration to enable scalability for HEP sensors**: *Future HEP detectors for certain classes of experiments will require massive increases in scalability to search for and study rare phenomena ... A key enabler of scalability is integration of many functions on, and extraction of multidimensional information from, these innovative sensors.*

- **Building next-generation HEP detectors with novel materials & advanced techniques**: *Future HEP detectors will have requirements beyond what is possible with the materials and techniques which we know. This requires identifying novel materials … that provide new properties or capabilities and adapting them & exploiting advanced techniques for design & manufacturing.*

- **Mastering extreme environments and data rates in HEP experiments**: *Future HEP detectors will involve extreme environments and exponential increases in data rates to explore elusive phenomena. ... To do so requires the intimate integration of intelligent computing with sensor technology.*

28

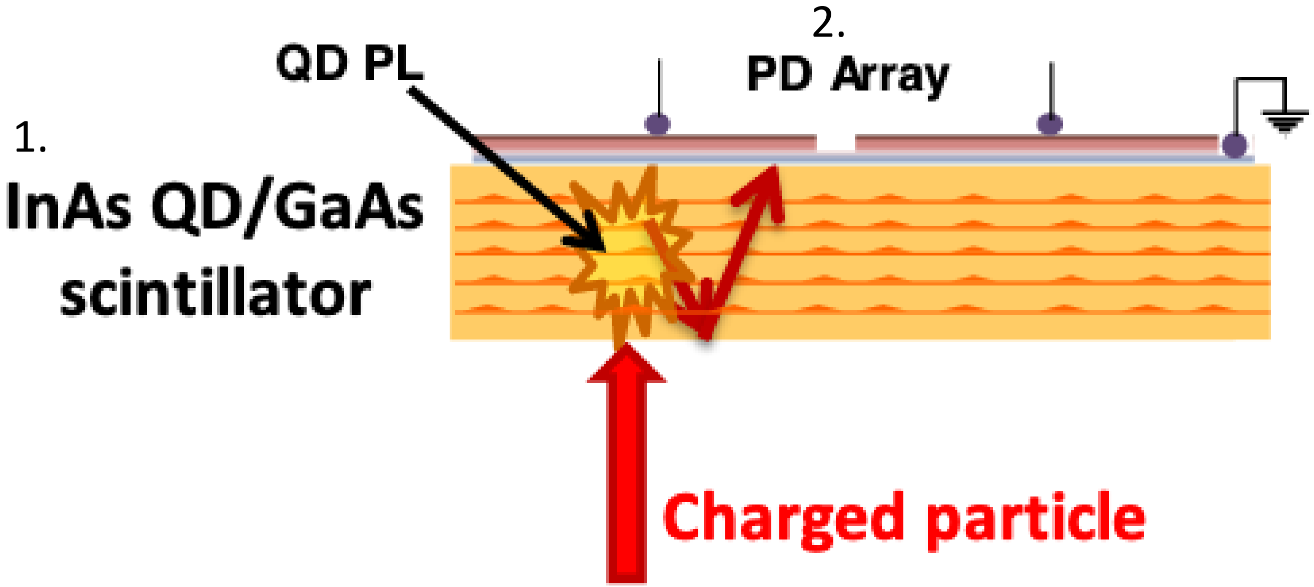
Beyond semiconductors

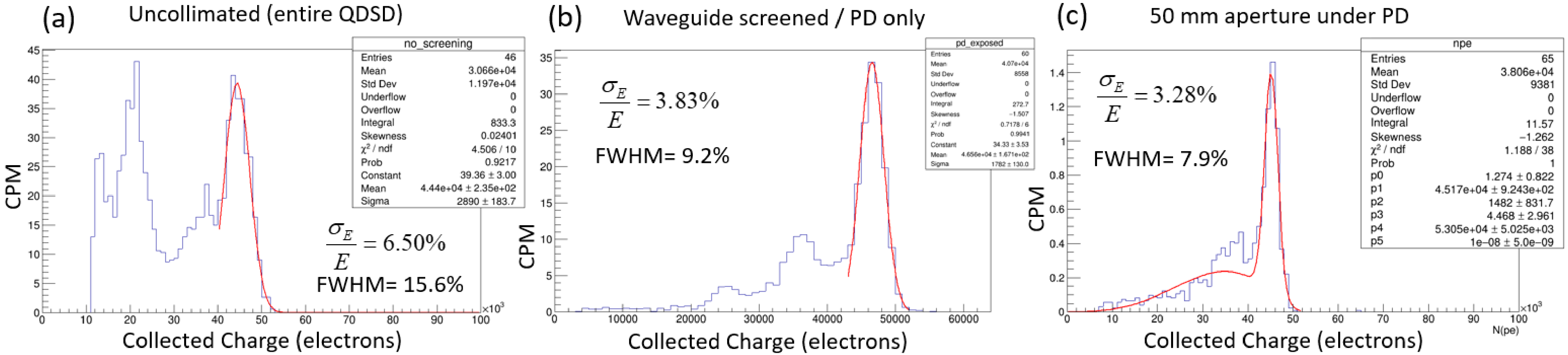
Is it possible to transition from a charge-drift paradigm to light collection for fast-timing, radiation-hard, and particle tracking applications?

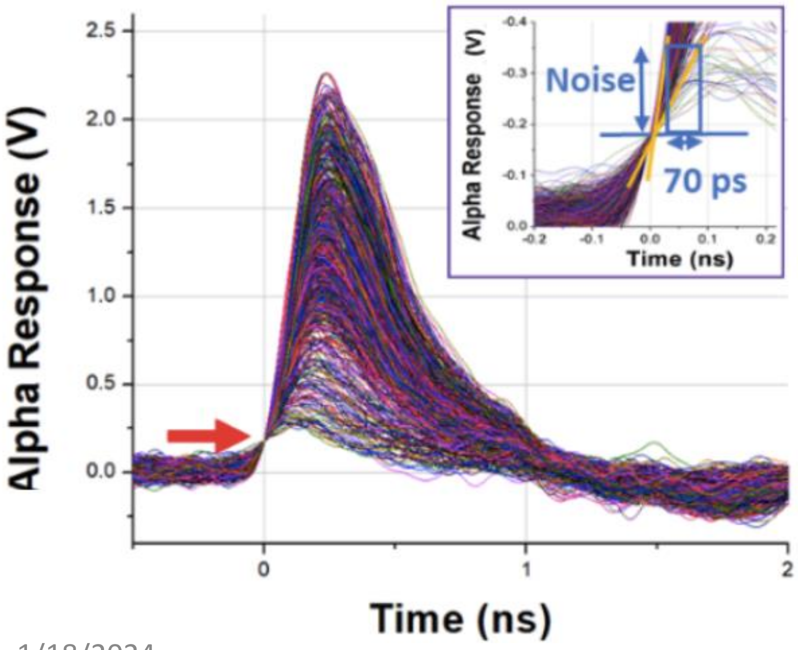
- Thin detector (small X_0)
- Fast light emission (< 1 ns)
- High light-yield
- Integrated photodetector
- Low power
- Radiation hard

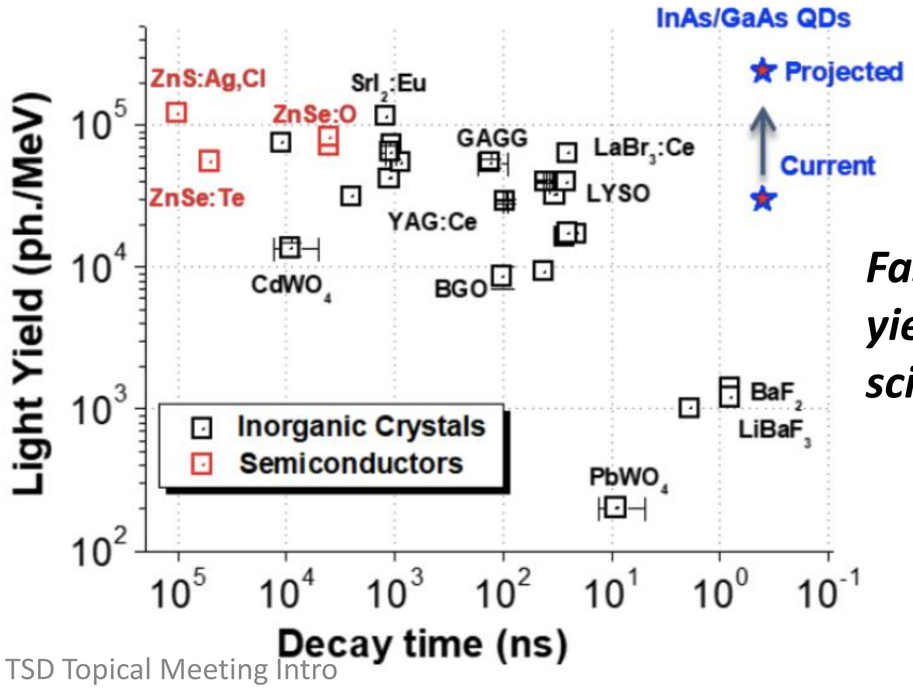
InAs quantum dots embedded in GaAs

1. Quantum Dot Scintillator
    - Total thickness of ~20 um
    - e-/h pairs in GaAs
    - QDs absorb e- (~few ps)
    - QDs emit photons (~1 ns)
    - 1.1 eV emitted photons (IR)
        - Low self-absorption
2. Photosensor(s)
    - Physically integrated
    - ~1 um thick photodiode



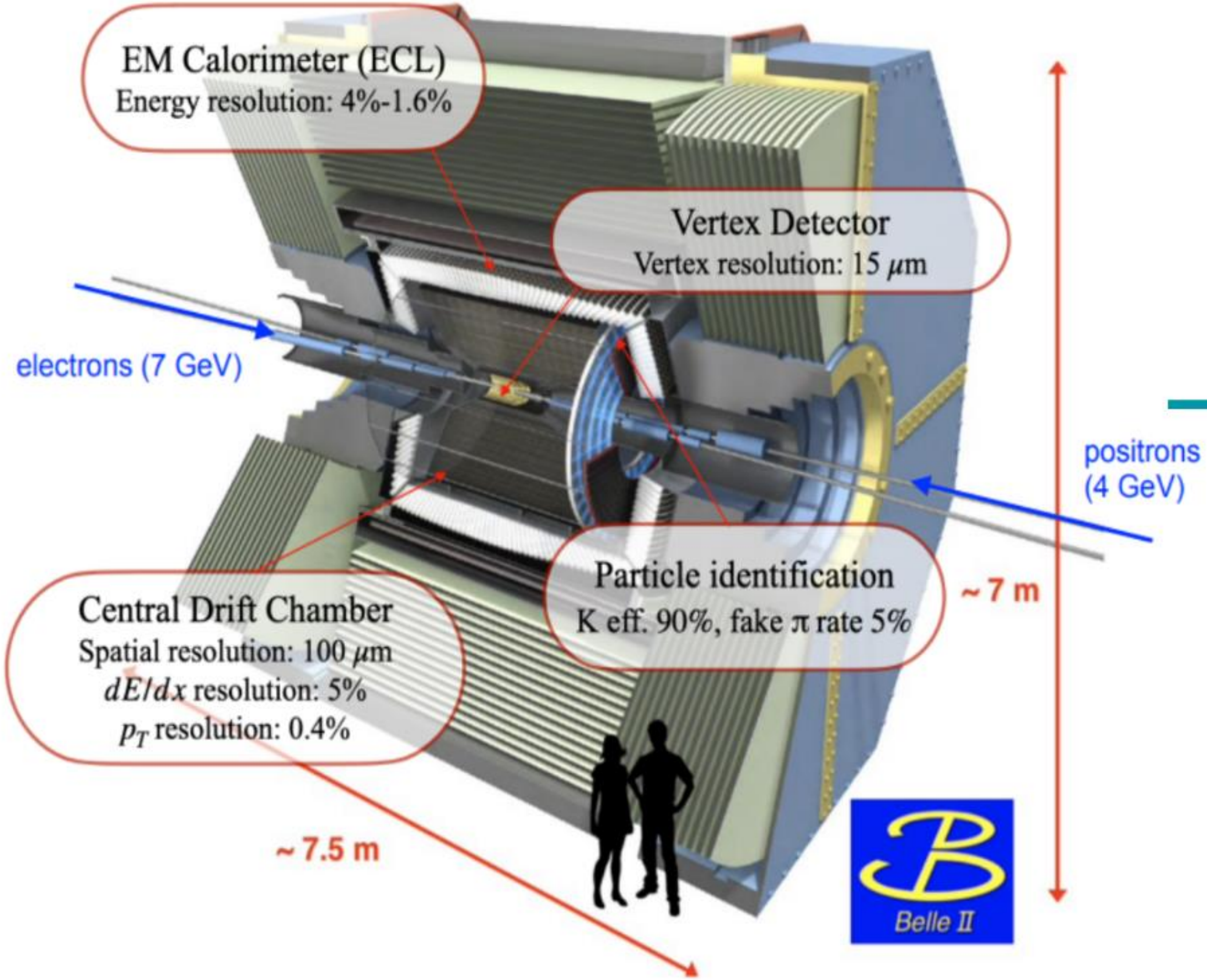




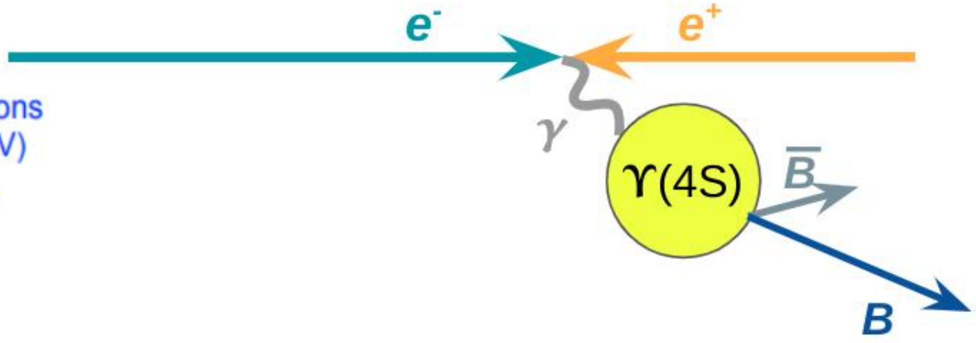


Fastest, highest light-yield of any known scintillator!

Belle II

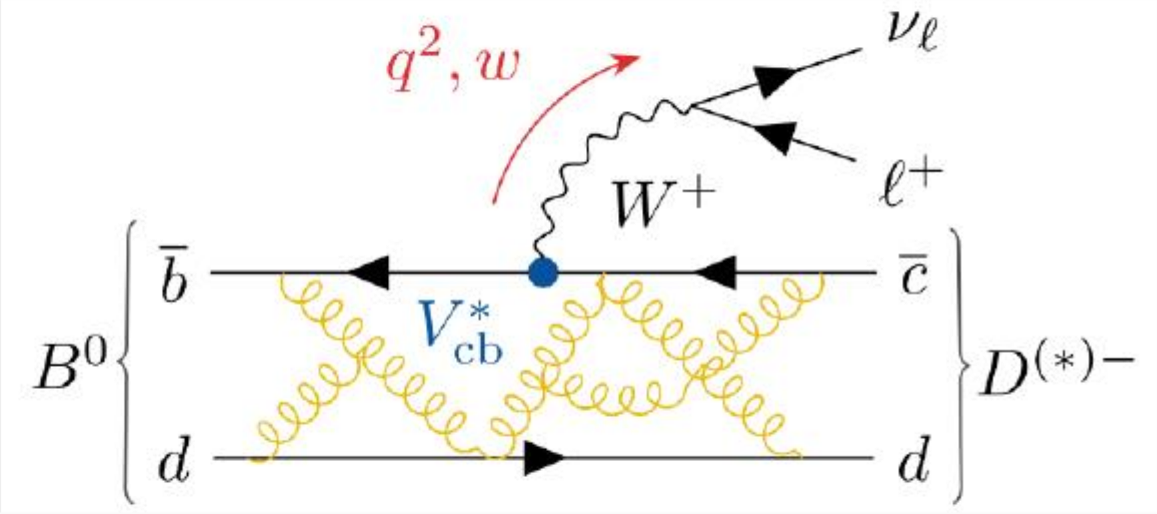


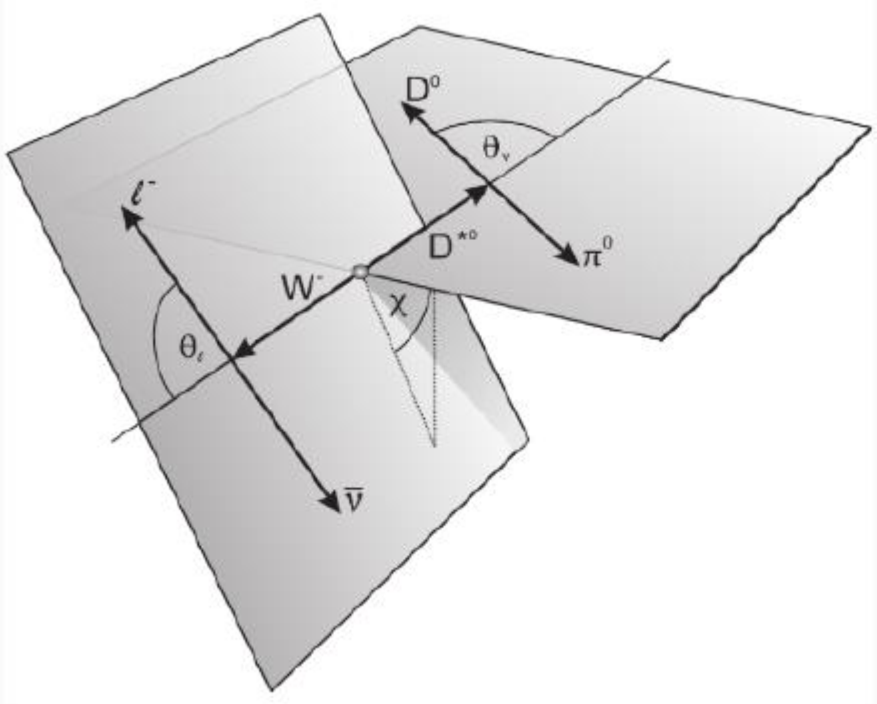
EM Calorimeter (ECL)
Energy resolution: 4%-1.6%
Vertex Detector
Vertex resolution: 15 μm
electrons (7 GeV)
positrons
(4 GeV)
Particle identification
K eff. 90%, fake π rate 5%
Central Drift Chamber
Spatial resolution: 100 μm
dE/dx resolution: 5%
p_T resolution: 0.4%
~ 7 m
~ 7.5 m
Belle II



e^-
e^+
γ
$\Upsilon(4S)$
$\overline{B}$
B

$B^0 \rightarrow D^{(*)-} l^+ \nu$

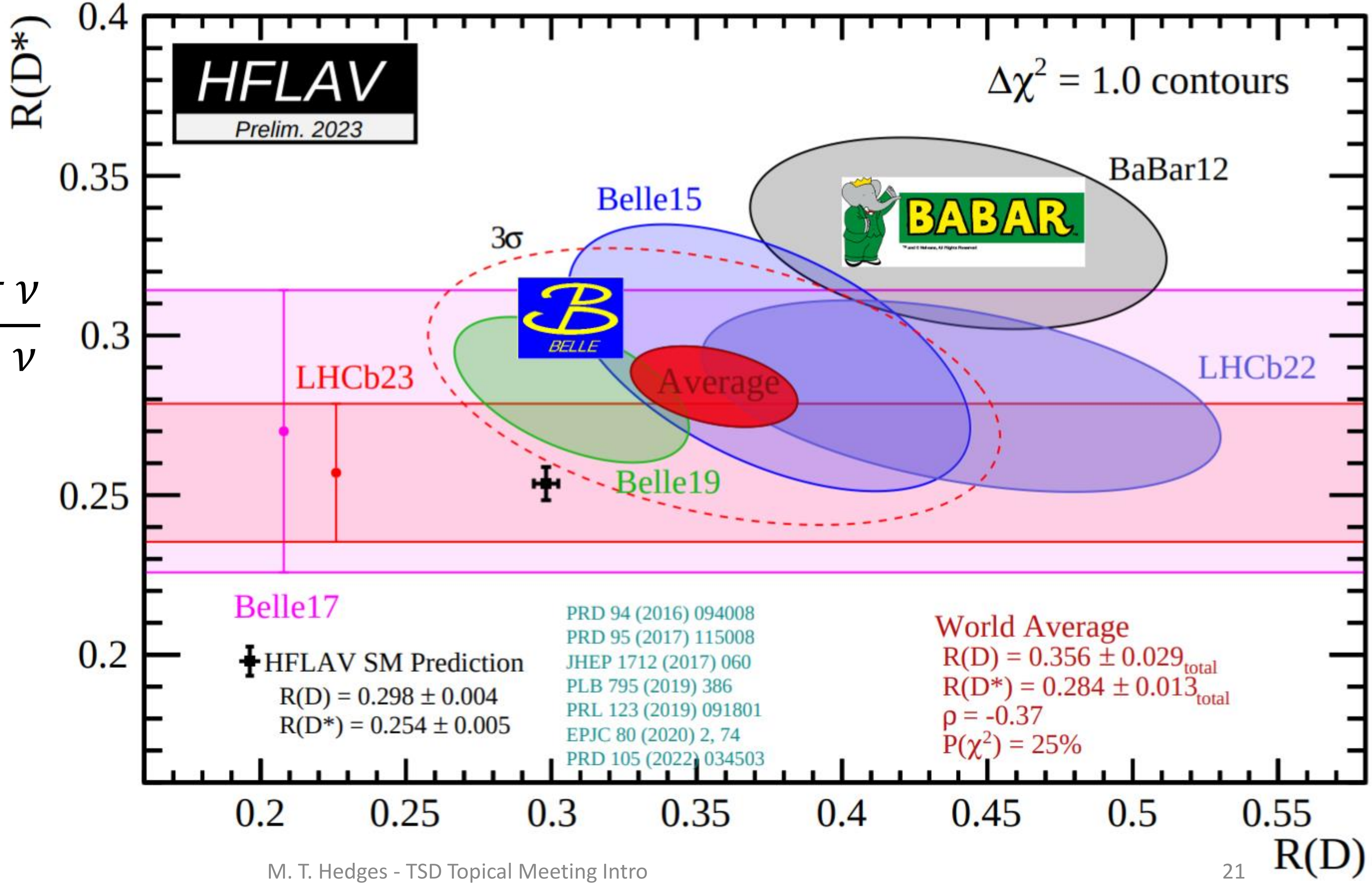




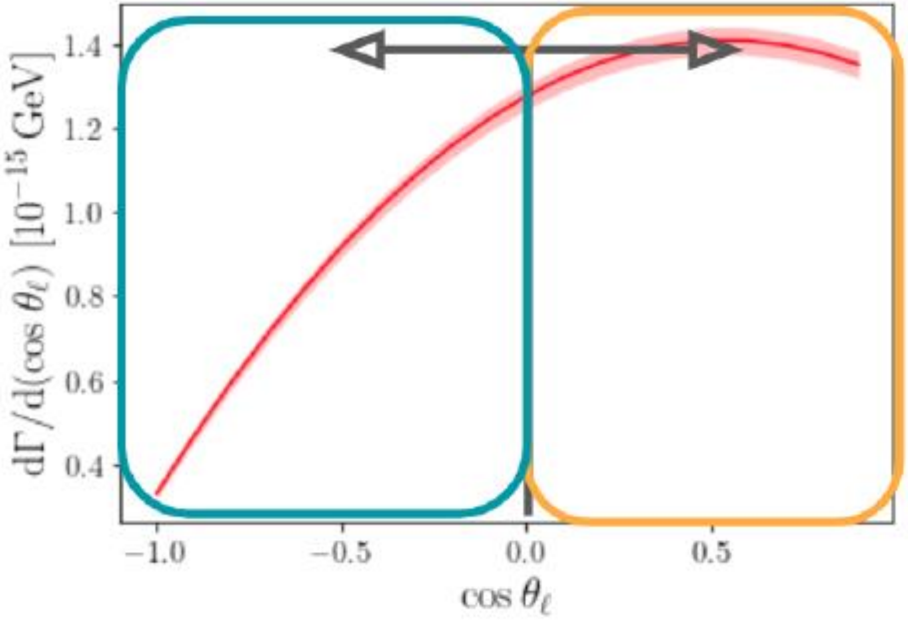
Who cares...?

$$R\left(D^{(*)}\right) = \frac{B \rightarrow D^{(*)}\,\tau\,\nu}{B \rightarrow D^{(*)}\,l\,\nu}$$

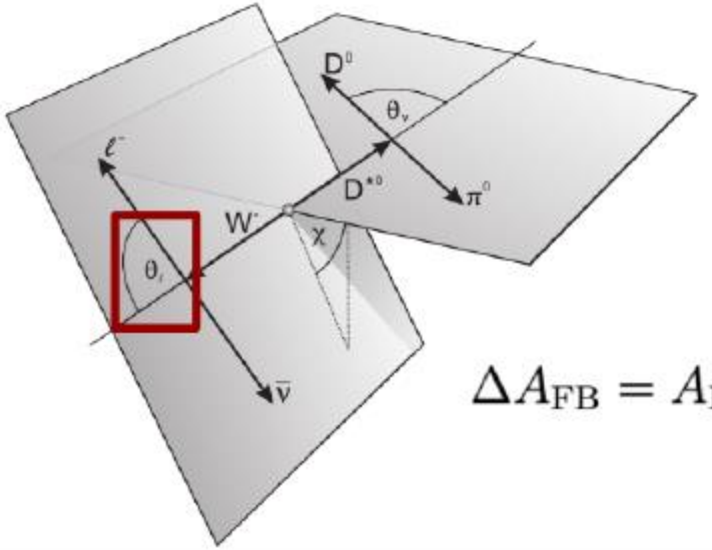
NB: $l = \{e, \mu\}$



Lepton Universality outside of decay rates

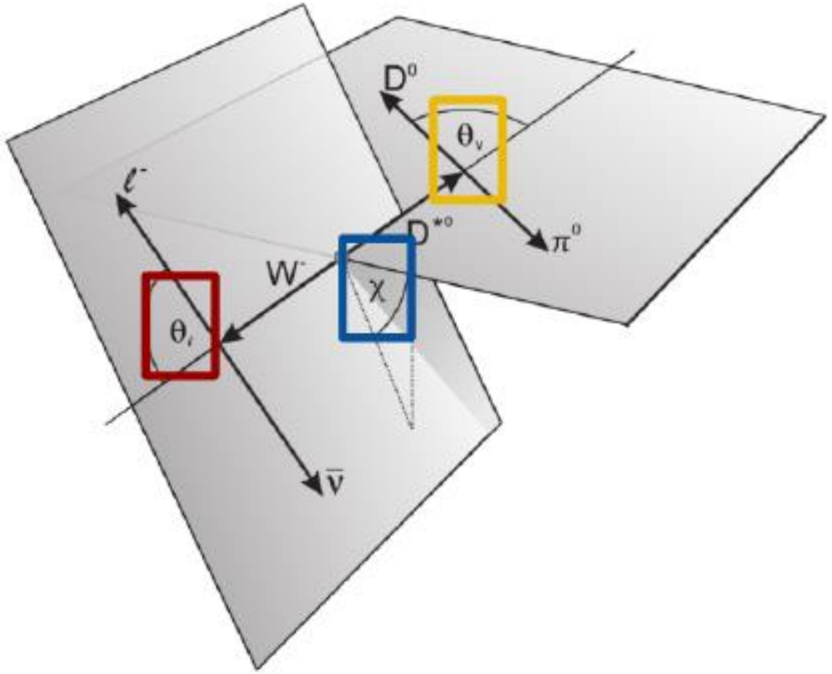


$$A_{\mathrm{FB}} = \frac{\int_0^1 \mathrm{d}\cos\theta_\ell \frac{\mathrm{d}\Gamma(\bar{B}\to D^*\ell\bar{\nu})}{\mathrm{d}\cos\theta_\ell} - \int_{-1}^0 \mathrm{d}\cos\theta_\ell \frac{\mathrm{d}\Gamma(\bar{B}\to D^*\ell\bar{\nu})}{\mathrm{d}\cos\theta_\ell}}{\int_{-1}^1 \mathrm{d}\cos\theta_\ell \frac{\mathrm{d}\Gamma(\bar{B}\to D^*\ell\bar{\nu})}{\mathrm{d}\cos\theta_\ell}}$$



$$\Delta A_{\mathrm{FB}} = A_{\mathrm{FB}}(m_\ell = m_\mu) - A_{\mathrm{FB}}(m_\ell = m_e)$$

Δ-all the things!



$$A_{FB}(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_\ell \, \frac{d^2\Gamma}{d\cos\theta_\ell dq^2},$$

$$S_3(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^{\pi/4} - \int_{\pi/4}^{\pi/2} - \int_{\pi/2}^{3\pi/4} + \int_{3\pi/4}^{\pi} + \int_{\pi}^{5\pi/4} - \int_{5\pi/4}^{3\pi/2} - \int_{3\pi/2}^{7\pi/4} + \int_{7\pi/4}^{2\pi}\right] d\chi \, \frac{d^2\Gamma}{dq^2 d\chi},$$

$$S_5(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^{\pi/2} - \int_{\pi/2}^{\pi} - \int_{\pi}^{3\pi/2} + \int_{3\pi/2}^{2\pi}\right] d\chi \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta^* \, \frac{d^3\Gamma}{dq^2 d\cos\theta^* d\chi},$$

$$S_7(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^{\pi} - \int_{\pi}^{2\pi}\right] d\chi \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta^* \, \frac{d^3\Gamma}{dq^2 d\cos\theta^* d\chi}.$$

$$\mathcal{A}(q^2) = \frac{N^+ - N^-}{N^+ + N^-}.$$

$$\Delta\mathcal{A}(q^2) = \mathcal{A}^\mu(q^2) - \mathcal{A}^e(q^2).$$

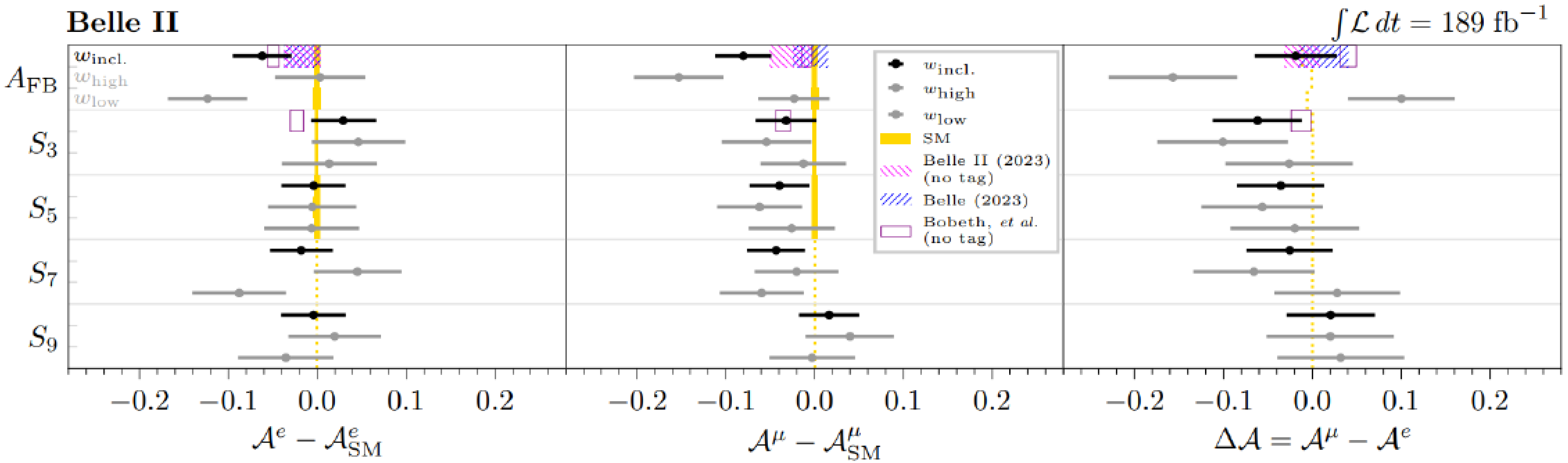


Figure 2: Observed asymmetries and their differences (points with error bars), one-standard-deviation bands from the Belle [16] and Belle II [17] measurements (hatched boxes), calculations from Ref. [9] based on a previous measurement from Belle [10](empty boxes), and standard-model expectations (solid boxes). The standard-model expectation is drawn with a dashed line when its uncertainty is too small to display.