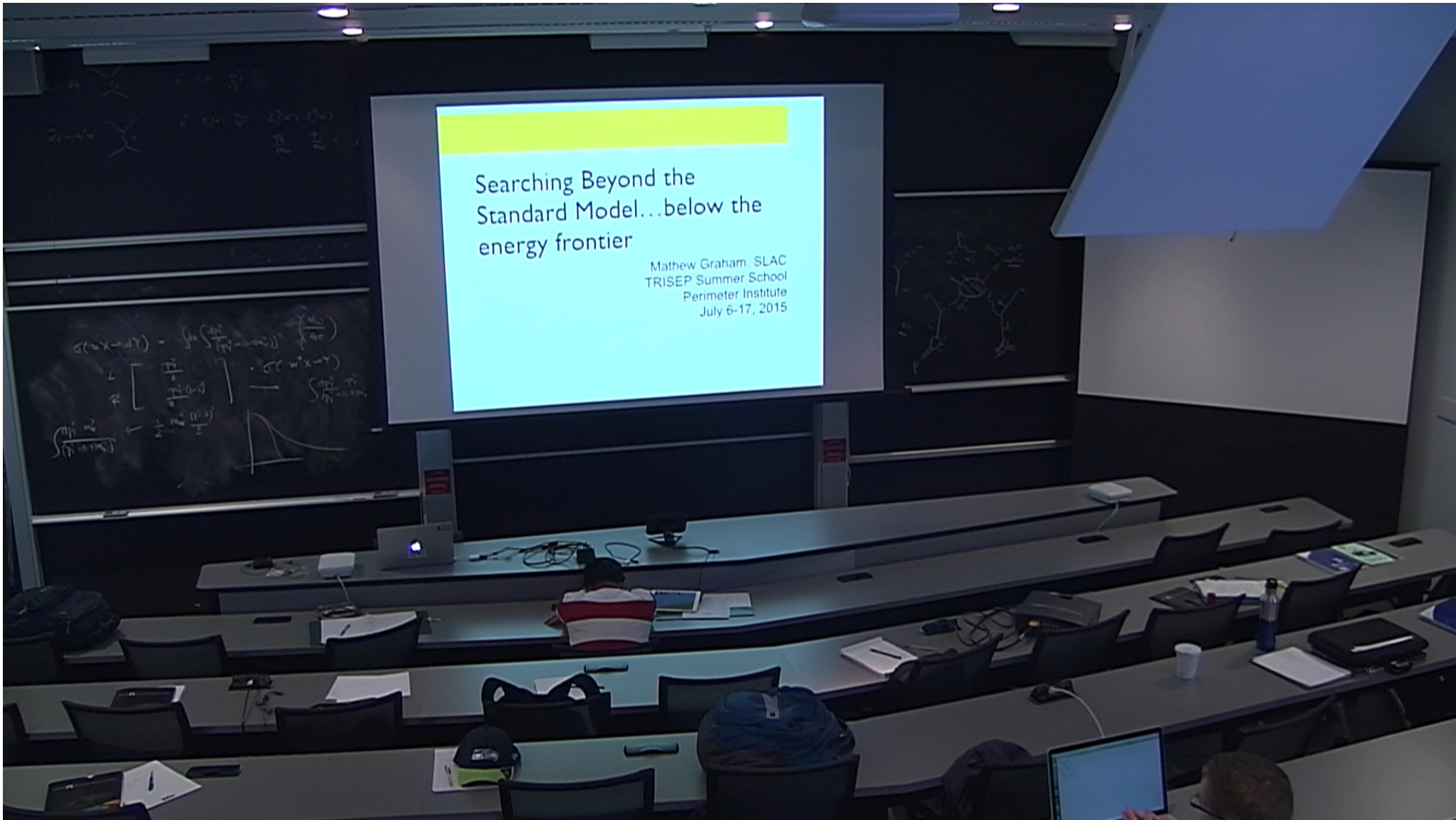


Title: Beyond the Standard Model – Experiment: Precision measurements

Date: Jul 08, 2015 10:15 AM

URL: <http://pirsa.org/15070023>

Abstract:



# Searching Beyond the Standard Model...below the energy frontier

Mathew Graham, SLAC  
TRISEP Summer School  
Perimeter Institute  
July 6-17, 2015

$$e^+ e^- \rightarrow W^+ W^-$$

$$\sigma = \epsilon_f(n) \frac{P_W}{P_f} \quad \Sigma_f^+(W^+) \cdot \Sigma_f^-(W^-)$$

$$\frac{T_1}{m_H} \quad \frac{T_2}{m_W} = ?$$

$$\sigma(uX \rightarrow dY) = \int d^2z \int \frac{d^2\vec{t}}{[P_t^2 + (1-z)m_W^2]^2} \left( \frac{\alpha_W}{4\pi} \right)$$

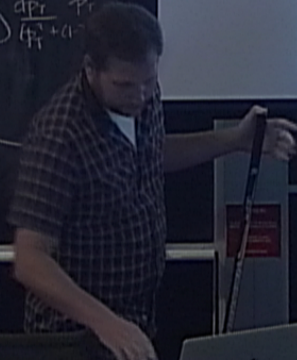
$$\left[ \frac{P_t^2}{z} \right] \rightarrow \sigma(W^+ X \rightarrow Y)$$

$$\left[ \frac{P_t^2 (1-z)}{z} \right]$$

$$\left[ \frac{d^2\vec{t}}{[P_t^2 + (1-z)m_W^2]} \right] \left[ \frac{1}{z} m_W^2 \frac{(1-z)^2}{z} \right]$$

# Searching Beyond the Standard Model...below the energy frontier

Mathew Graham, SLAC  
TRISEP Summer School  
Perimeter Institute  
July 6-17, 2015



# Not quite done...

No RH  $\nu$   
in the SM!



## Big Problems!

- ...strong CP problem...
- ...dark matter...
- ...CP of the universe...
- ...origin & nature of neutrino mass...

*minor issues...*

... "naturalness" & hierarchy (problems)...

# *How to look for new physics*

- Go to higher and higher energies!
  - directly produce new particles at scales unobtainable before!
  - has worked in the past...

# How do discover new physics @ low energies...

94

21 NOV 1974

02:10

**21 NOV 1974**

02:30

02:45

SCALE	UNIT	VALUE	UNIT	VALUE	UNIT	VALUE	UNIT	VALUE
1	TO TRIG	45374	80					
2	OR FLAG	20	81					
3	LV AGARD	20	82	EVENTS	948			
4	LV AGARD	20	83	PIPS/100	5322			
5	LIVETIME	4202	84	THRESHOLD	0			
6		0	85	CLUTTING	4854			
7		0	86		0			
8		0	87		0			
9		0	88		0			
10		0	89		0			
11		0	90		0			
12		0	91		0			
13		0	92		0			
14		0	93		0			
15		0	94		0			
16		0	95		0			
17		0	96		0			
18		0	97		0			
19		0	98		0			
20		0	99		0			
21		0	100		0			

INTEGRATED LUMINOSITY = 4100 24  
PIT2007

24

25

26

27

28

29

30

31

32

33

34

35

36

37

38

39

40

41

42

43

44

45

46

47

48

49

50

51

52

53

54

55

56

57

58

59

60

61

62

63

64

65

66

67

68

69

70

71

72

73

74

75

76

77

78

79

80

81

82

83

84

85

86

87

88

89

90

91

92

93

94

95

96

97

98

99

100

95

21 NOV 1974

03:20

**SON OF GLORY**

Chuck Madore, Alan Little, Bob Steg Jo it!

03:45

04:15

04:30

04:45

05:00

05:15

05:30

05:45

06:00

06:15

06:30

06:45

07:00

07:15

07:30

07:45

08:00

08:15

08:30

08:45

09:00

09:15

09:30

09:45

10:00

10:15

10:30

10:45

11:00

11:15

11:30

11:45

12:00

12:15

12:30

12:45

13:00

13:15

13:30

13:45

14:00

14:15

14:30

14:45

15:00

15:15

15:30

15:45

16:00

16:15

16:30

16:45

17:00

17:15

17:30

17:45

18:00

18:15

18:30

18:45

19:00

19:15

19:30

19:45

20:00

20:15

20:30

20:45

21:00

21:15

21:30

21:45

22:00

22:15

22:30

22:45

23:00

23:15

23:30

23:45

24:00

# How do discover new physics @ low energies...

The wand signals look OK for every chamber. All (11,12,13,14,16) have good 2nd hits. Zero wires are seeing the 1st hit. Trouble is to kill all 5 chambers I think must go out. Assuming 11,12,13,14,16 wands are what they need to be (111,112,113,114,116) at least 11 & 12 show no serious error problems.

**"2:30: We see a possibly significant bump..."**

now It is as if the 11 chambers are steadily increasing the rate and

02:30

WE SEE A POSSIBLY SIGNIFICANT BUMP AT 1.847 1.848 (nominal LOOKS ~ 6 HAD 3 HAD (steps are 2mu cm). STOP 2:30 TO 1.848

SP-17 DVL RUN 1523 1.85 GEV 3.9 KG CF-XXXXXXXX TL-2 A12  
 SCALERS

1	OS TRUE	45378	10		
2	OS FLSE	29	11		0 2
3	LU NO.SD	19229	12	EVENTS	968
4	LU NO.SU	26149	13	PIPE/100	58323
5	LIVETIME	42903	14		0
6		0	15	THYRTRON	968
7		0	16	CLOCKTIME	45584

$\vec{e} \rightarrow \vec{W}^+$

$\Sigma_0^+(W^+) \frac{P_W}{E}$

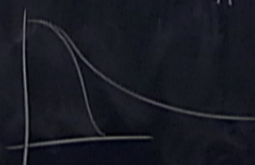
$\Sigma_0^+(W^+) \Sigma_0^+(W^+)$

$\frac{P_1}{m_W} \quad \frac{P_2}{m_W} = ?$

$\sigma(uX \rightarrow dY) = \int d^2 \int \frac{d^2 p_T^2}{(p_T^2 + (1-\tau)m_W^2)^2} \left( \frac{dW}{4\pi} \right)$

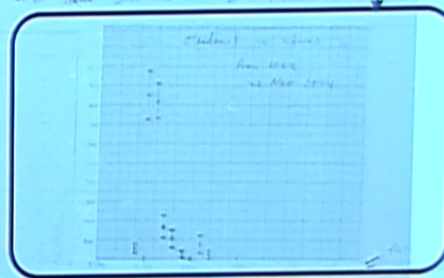
$\frac{1}{E} L \left[ \begin{array}{c} \frac{P_T^2}{z} \\ \frac{P_T^2(1-\tau)}{z} \end{array} \right] \rightarrow \sigma(W^+ X \rightarrow Y)$

$\frac{d^2 p_T^2}{(p_T^2 + (1-\tau)m_W^2)} \leftarrow \frac{1}{z} m_W^2 \frac{(1-\tau)^2}{z}$




## How do discover new physics @ low energies...

3:20 → **SON OF GLORY**  
 Check Problem, New Little, But Things Do it!

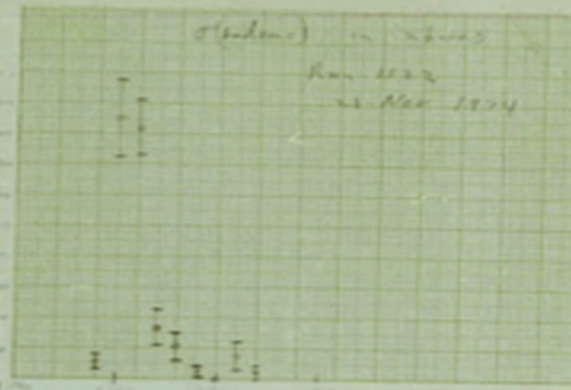




# How do discover new physics @ low energies...

3:20

03:20 SON OF GLORY  
Chuck Thomson, Allen Little, Bob Steg Jo it!



# *How to look for new physics*

- Go to higher and higher *energies*!
  - directly produce new particles at scales unobtainable before!
  - has worked in the past...
- Go to higher and higher *intensities*!
  - rare production modes
  - rare decay modes
  - precise measurements of SM predictions
- Look somewhere “*new*”\*\*\*!
  - neutrinos!
  - particle-astrophysics

\*\*\**neither of these are new, but definitely room for growth*

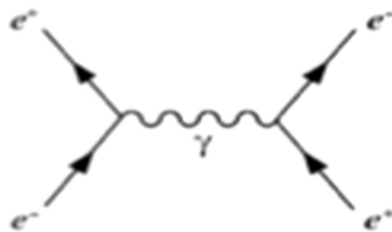
# *How to look for new physics*

- Go to higher and higher *energies*!
  - directly produce new particles at scales unobtainable before!
  - has worked in the past...
- Go to higher and higher *intensities*!
  - rare production modes
  - rare decay modes
  - precise measurements of SM predictions
- Look somewhere “*new*”\*\*\*!
  - neutrinos!
  - particle-astrophysics

\*\*\**neither of these are new, but definitely room for growth*

# Searching For BSM @ “low-energies”

- Low Energy != Low Scale
  - Loops are our friend!



...high mass scales of NP particles in the loops is not suppressed like they are @ tree level (direct production)  
Also! Typically don't have tree-level SM processes to compete against → lower background

# Searching For BSM @ “low-energies”

- Low Energy != Low Scale
  - Loops are our friend!
  - Rare or forbidden decays
    - Lepton flavor violation searches
  - precision measurements of well predicted parameters
    - muon  $g-2$
    - CKM unitarity triangle (& related measurements)
- Looking in new places — Neutrinos!
  - we haven't fully explored neutrino sector (it's hard)
  - mixing matrix still has many open questions
    - is it unitary? Are there more “neutrinos”
    - what's the CP phase...is it 0? Some other interesting number?
  - What's the deal with the neutrino mass(es)?
    - ordering of masses? SM-like or inverted
    - where does it come from?
- Direct production, but with very intense sources
  - A ton of experiments were done in the old days that looked for crazy things...now we have much more intense beams, better detectors & electronics. Some crazy things may be there!
    - Dark sector searches

# Searching For BSM @ “low-energies”

- Low Energy != Low Scale
  - Loops are our friend!
  - Rare or forbidden decays
    - Lepton flavor violation searches
  - precision measurements of well predicted parameters
    - muon  $g-2$
    - CKM unitarity triangle (& related measurements)
- Looking in new places — Neutrinos!
  - we haven't fully explored neutrino sector (it's hard)
  - mixing matrix still has many open questions
    - is it unitary? Are there more “neutrinos”
    - what's the CP phase...is it 0? Some other interesting number?
  - What's the deal with the neutrino mass(es)?
    - ordering of masses? SM-like or inverted
    - where does it come from?
- Direct production, but with very intense sources
  - A ton of experiments were done in the old days that looked for crazy things...now we have much more intense beams, better detectors & electronics. Some crazy things may be there!
    - Dark sector searches

**Today**

# “Theory”

$$|\mathcal{A}_{Tot}|^2 = |\mathcal{A}_{SM}|^2 + |\mathcal{A}_{NP}|^2 + 2\text{Re}(\mathcal{A}_{SM}\mathcal{A}_{NP}^*)$$

If SM  
is large

Tough...  $\mathcal{S} \sim \sqrt{\mathcal{L}} \times \frac{|\mathcal{A}_{NP}|^2}{|\mathcal{A}_{SM}|}$

$\mathcal{S}$  = Significance

$\mathcal{L}$  = Integrated Luminosity

# “Theory”

$$|\mathcal{A}_{Tot}|^2 = |\mathcal{A}_{SM}|^2 + |\mathcal{A}_{NP}|^2 + 2\text{Re}(\mathcal{A}_{SM}\mathcal{A}_{NP}^*)$$

If SM  
is large

Tough...  $\mathcal{S} \sim \sqrt{\mathcal{L}} \times \frac{|\mathcal{A}_{NP}|^2}{|\mathcal{A}_{SM}|}$

$\mathcal{S}$  = Significance

$\mathcal{L}$  = Integrated Luminosity



# “Theory”

$$|\mathcal{A}_{Tot}|^2 = |\mathcal{A}_{SM}|^2 + |\mathcal{A}_{NP}|^2 + 2\text{Re}(\mathcal{A}_{SM}\mathcal{A}_{NP}^*)$$

*If SM  
is (very)  
small*

Easy!  $\mathcal{S} \sim \mathcal{L} \times |\mathcal{A}_{NP}|^2$

$\mathcal{S}$  = Significance

$\mathcal{L}$  = Integrated Luminosity

# “Theory”

$$|\mathcal{A}_{Tot}|^2 = |\mathcal{A}_{SM}|^2 + |\mathcal{A}_{NP}|^2 + 2\text{Re}(\mathcal{A}_{SM}\mathcal{A}_{NP}^*)$$

*If SM  
is ~ NP*

Get tricky, measure the  
interference. Sensitive to  
 $\mathcal{A}_{NP}$  (not  $^2$ )...

$\mathcal{S}$  = Significance

$\mathcal{L}$  = Integrated Luminosity

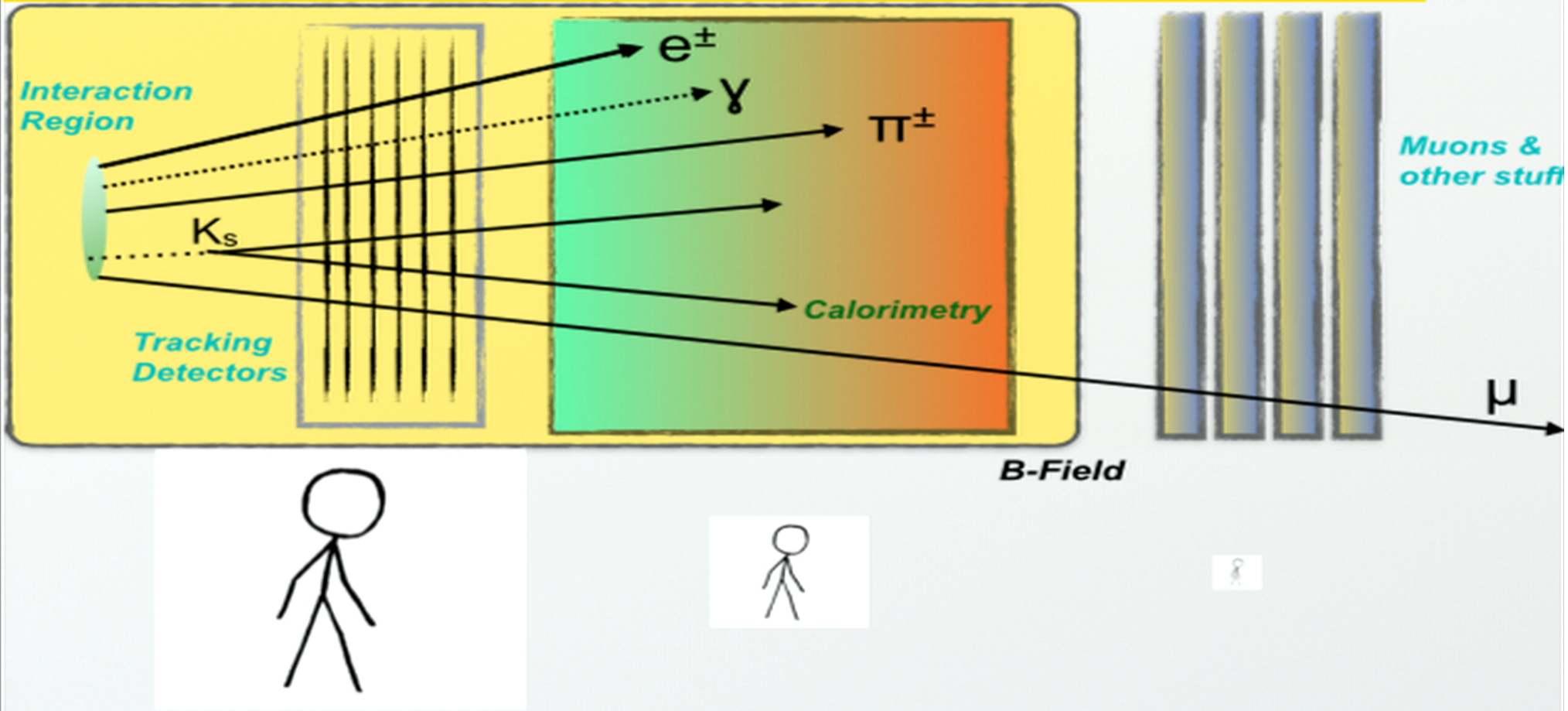
# ***BUT FIRST!***

...some words about detectors...



TRISEP 2015

# Every\* Particle Physics Detector



TRISEP 2015

17

\*may not be strictly true

$\vec{v} = \frac{1}{m} \vec{p}$

$\epsilon = \frac{1}{2} m v^2 = \frac{1}{2} \frac{p^2}{m}$

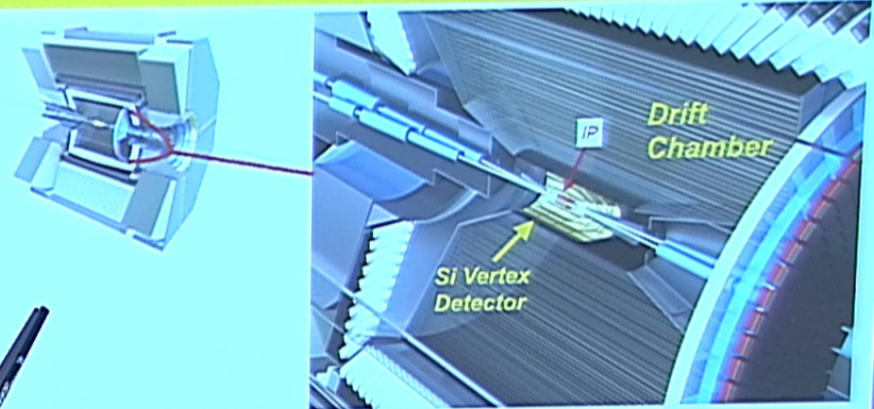
$\sigma(w^+ X \rightarrow dY) = \int dz \int \frac{d^2 p_T}{[p_T^2 + (1-z)m_w^2]^2} \left( \frac{q_w}{4\pi} \right)$

$\frac{1}{2} L \left[ \frac{P_T^2}{z} \right] \cdot \sigma(w^+ X \rightarrow Y)$

$\frac{1}{2} \frac{P_T^2 (1-z)^2}{z}$

$\frac{1}{2} \frac{m_w^2 (1-z)^2}{z}$

## The heart of the detector...

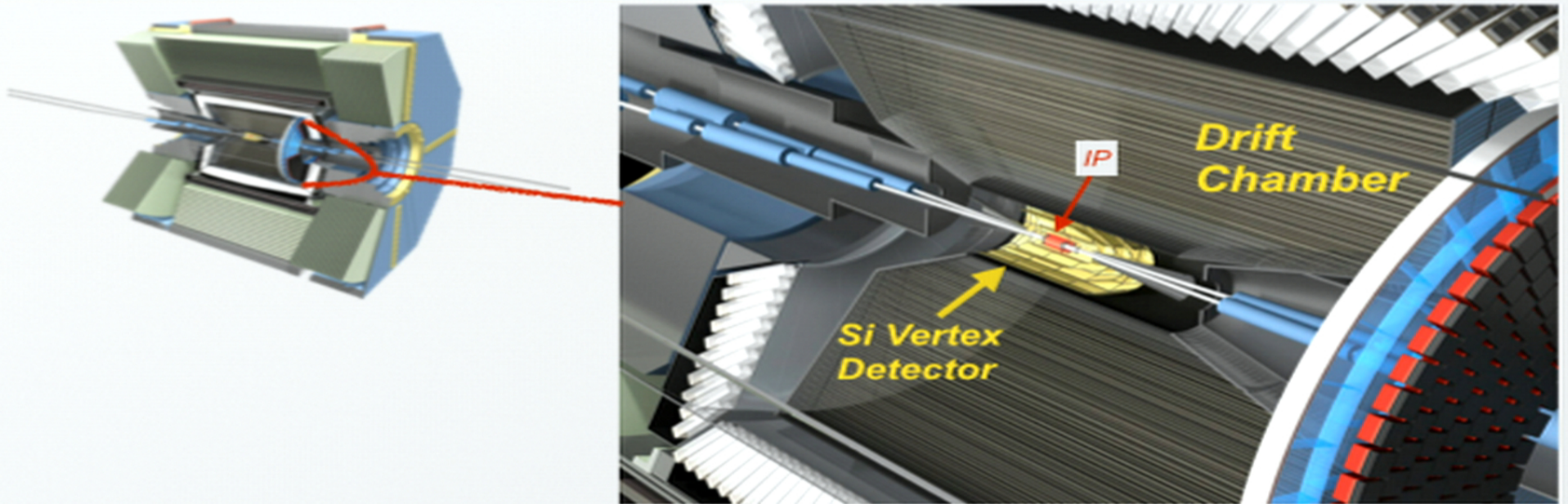


- Material budget is key for tracking detectors
  - ▶ lighter → less MS → better position & momentum resolution
  - ▶ Often Si-based (strips or pixels) for inner trackers; gas-based (straw tubes, drift chamber) for outer (cost-per-channel at issue)

TRISEP 2015

18

# The heart of the detector...

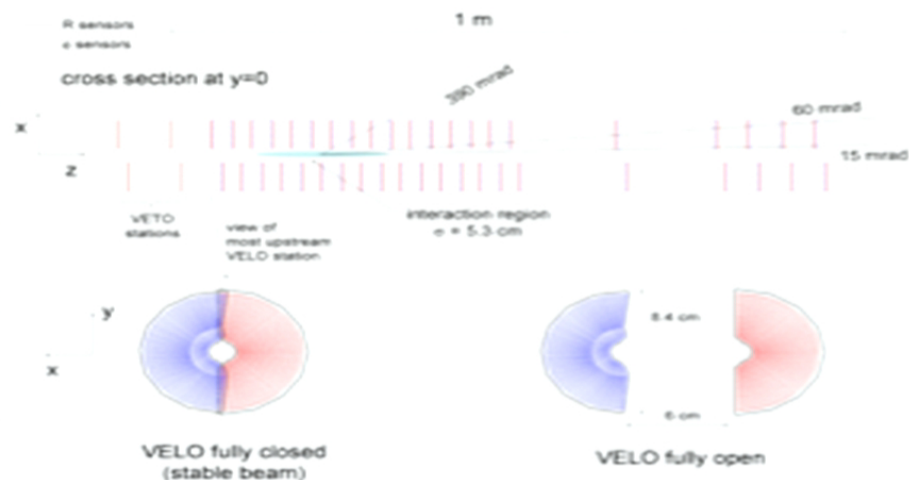


- ▶ Material budget is key for tracking detectors
  - ▶ lighter  $\Rightarrow$  less MS  $\Rightarrow$  better position & momentum resolution
- ▶ Often Si-based (strips or pixels) for inner trackers; gas-based (straw tubes, drift chamber) for outer (cost-per-channel at issue)

# A very cool thing.

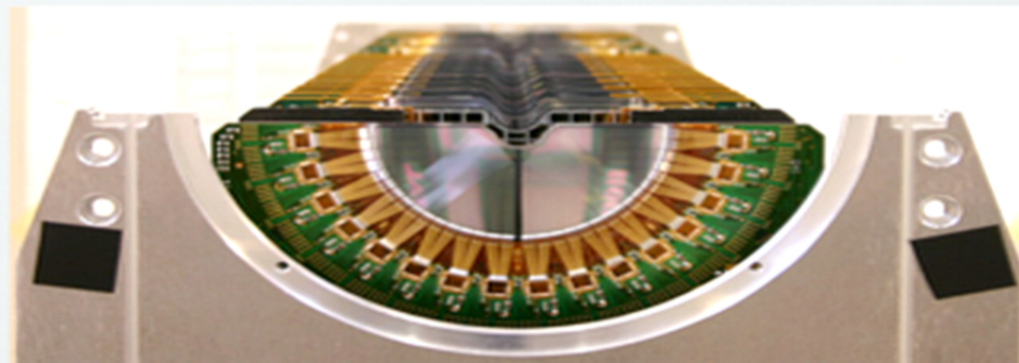
*The LHCb VELO is great example of a “vertex-tracker”...*

- ➔ encircles the LHC beam, aligned perpendicular to the beam direction
- ➔ designed to detect the B-meson decays slightly displaced from primary pp interaction

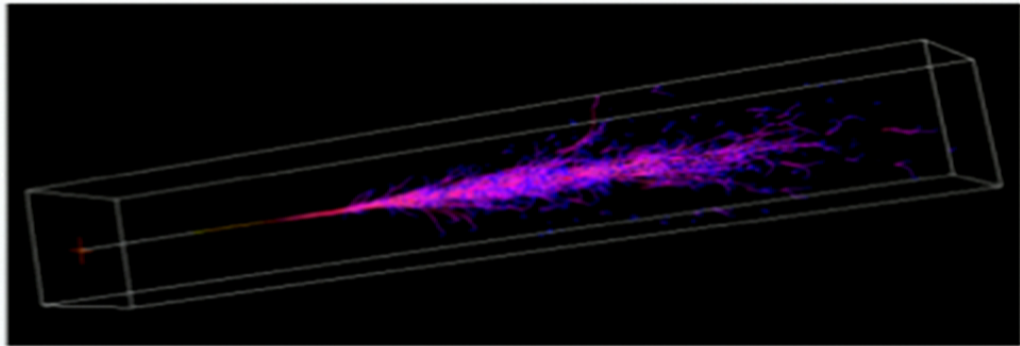
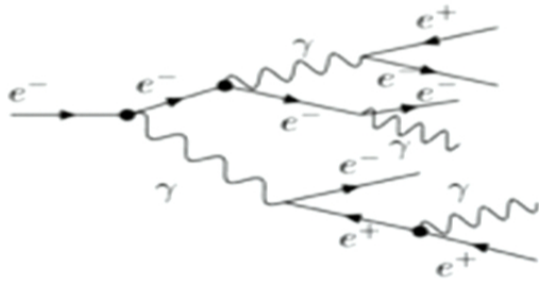


...retracts during beam tune and closes up for data taking

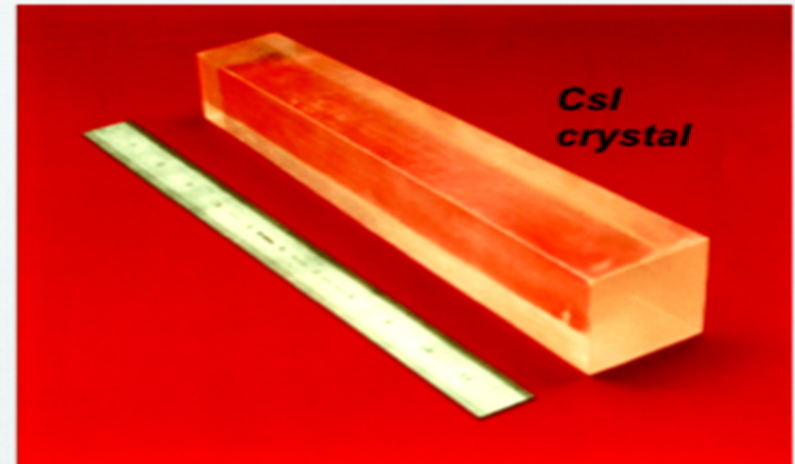
consists of pairs of radial-axial half-circle Si-strip layers



# (EM) Calorimetry



- ...opposite of trackers, put lots of material in the way...want to **cause** showers
  - high density, high Z materials
- Pb glass, PbW, CsI, LAr
- Measure the energy either from Cerenkov radiation/scintillation light (via PMTs or APDs) or from ionization charge (in LAr detectors);





# Two ECal Examples

BaBar Central Calorimeter

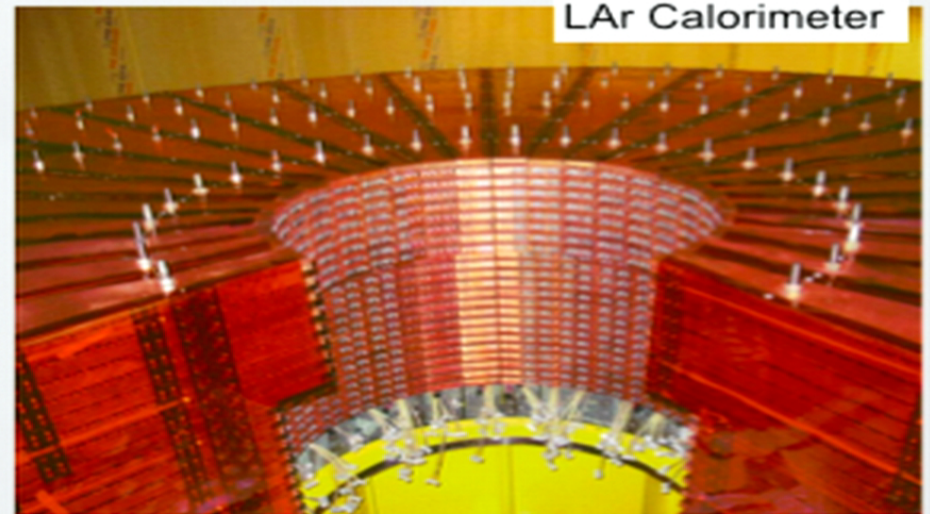


...also key for particle ID (photons! but also electrons/muons/pions).

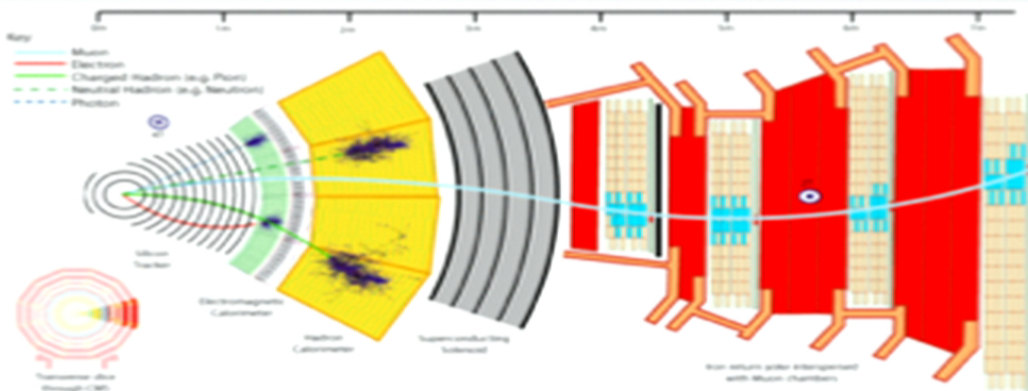
For hadron calorimetry, missing energy is a huge deal; need XCal systems to be ~hermetic.

Calorimeters tend to be **fast**, both the physics and the readout...trigger systems rely heavily on EM calorimetry

ATLAS Endcap LAr Calorimeter



# Muon ID

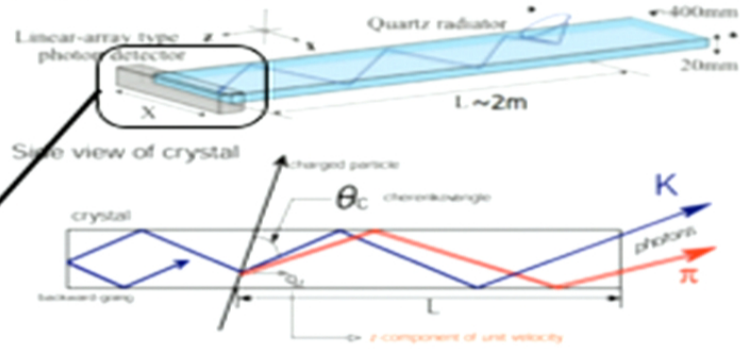


*“Muons are probably the most important particle in particle physics” — Matt Graham*

- easy to create, detect, identify, theoretically clean...
- muons pass through entire detector, just leaving MIP signals; Muon ID systems are the outermost system
- need to be cheap because they cover large area; sandwich detectors between iron is very common...if a particle gets all the way through it's a muon
  - scintillating paddles; Resistive Plate Chambers; streamer tubes...etc

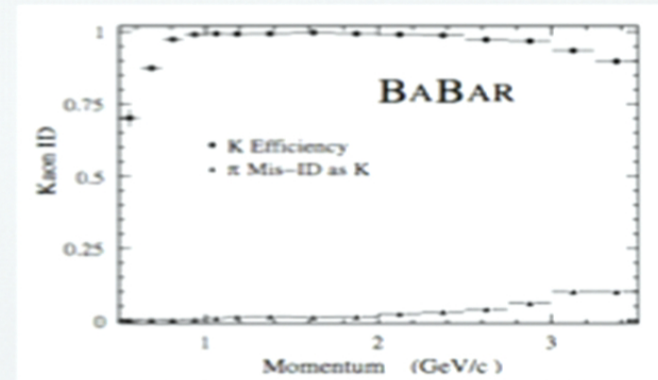
# Specialists...PID


BELLE-II TOP



Particularly at low-ish energies (GeV) it's important to decipher  $\pi/K$  (/p/d etc...);

for  $\pi/K$  separation at GeV, Cherenkov-based detectors are very powerful



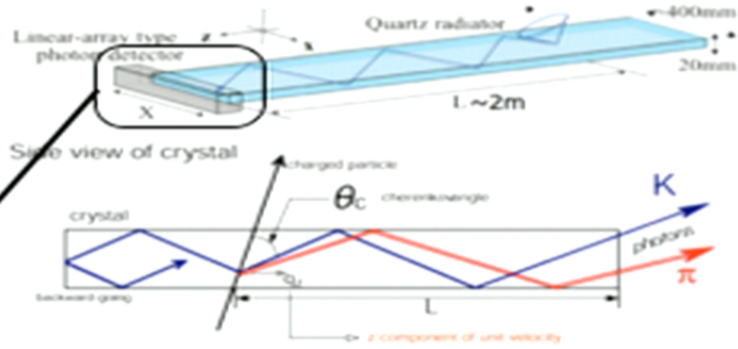


# Searching Beyond the Standard Model: Precision Measurements & Rare Decays

Mathew Graham, SLAC  
TRISEP Summer School  
Perimeter Institute  
July 6-17, 2015

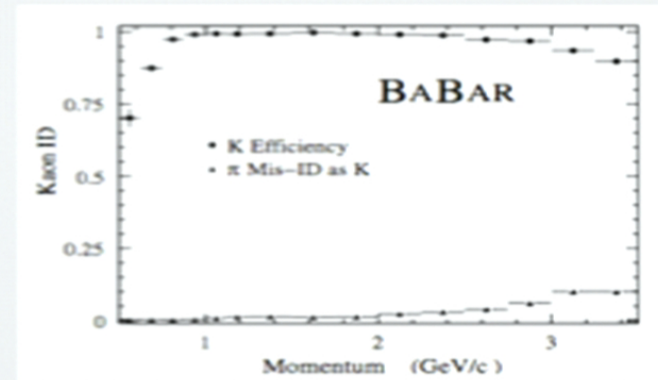
# Specialists...PID

BELLE-II TOP



Particularly at low-ish energies (GeV) it's important to decipher  $\pi/K$  (/p/d etc...);

for  $\pi/K$  separation at GeV, Cherenkov-based detectors are very powerful



# Searching Beyond the Standard Model: ~~Precision Measurements & Rare Decays~~

*Flavo(u)r*

Mathew Graham, SLAC  
TRISEP Summer School  
Perimeter Institute  
July 6-17, 2015

# This talk...intro: Flavor

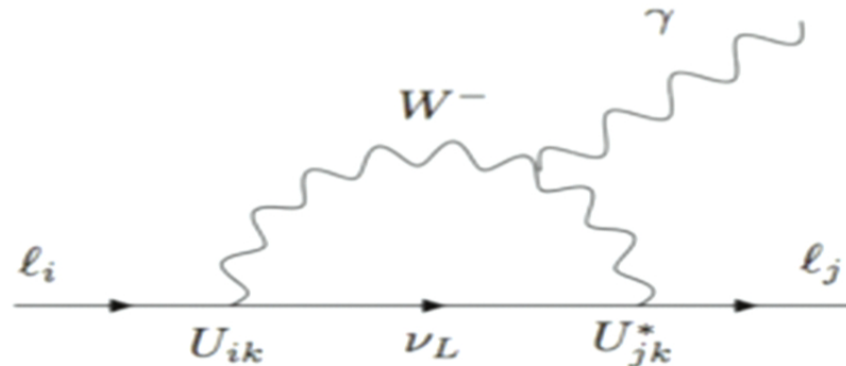
Three Generations of Matter (Fermions) spin  $\frac{1}{2}$

	I	II	III		
mass	2.4 MeV	1.27 GeV	171.2 GeV	0	0
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
name	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	
	Left Right	Left Right	Left Right	0	0
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon	
Quarks	Left Right	Left Right	Left Right	0	0
	0 eV	0 eV	0 eV	91.2 GeV	>114 GeV
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>Z<sup>0</sup></b> weak force	<b>H</b> Higgs boson
	Left Right	Left Right	Left Right	0	0
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV	spin 0
	-1	-1	-1	+1	
Leptons	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>W<sup>±</sup></b> weak force	
	Left Right	Left Right	Left Right		

Bosons (Forces) spin 1

- ▶ flavor, i.e. “u-ness”, “ $\mu$ -ness”, “ $\nu_\tau$ -ness” etc, is **not** conserved in the SM
- ▶ there is no mechanism for flavor-changing neutral currents **at tree-level** in the SM

# (Charged) Lepton-Flavor Violation

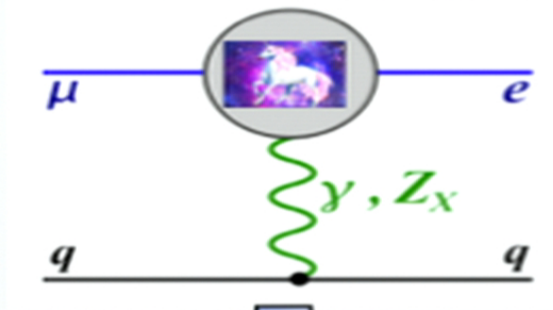


$$\text{Br}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{i1}^2}{M_W^2} \right|^2 < 10^{-54},$$

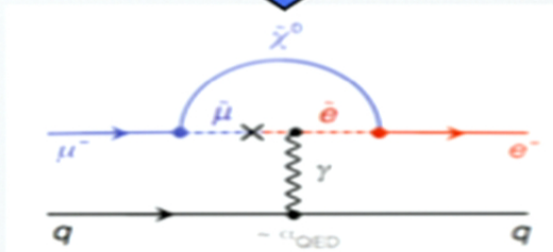
↓  
this is very, very small



# $\mu \rightarrow e X$



e.g.



Three ways to look for  $\mu \rightarrow e$ :

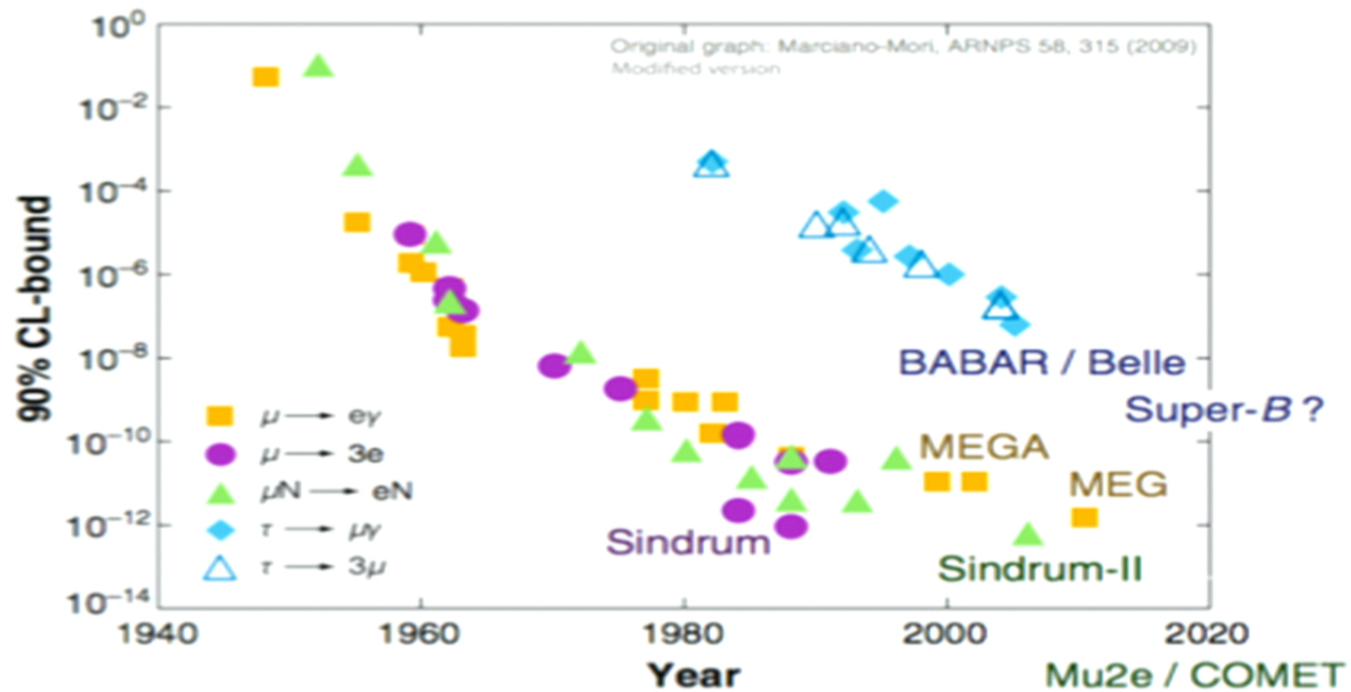
- ▶  $\mu^- \rightarrow e^- \gamma$
- ▶  $\mu^- \rightarrow e^- e^+ e^-$
- ▶  $\mu^- N \rightarrow e^- N$

These are **complimentary** probes sensitive to different **classes** of models

	$\mu \rightarrow 3e$	$\mu \rightarrow e \gamma$	$\mu \rightarrow e$ conversion
$O_{S,V}^{4\ell}$	✓	—	—
$O_D$	✓	✓	✓
$O_V^q$	—	—	✓
$O_S^q$	—	—	✓

Cirigliano@Beauty2014

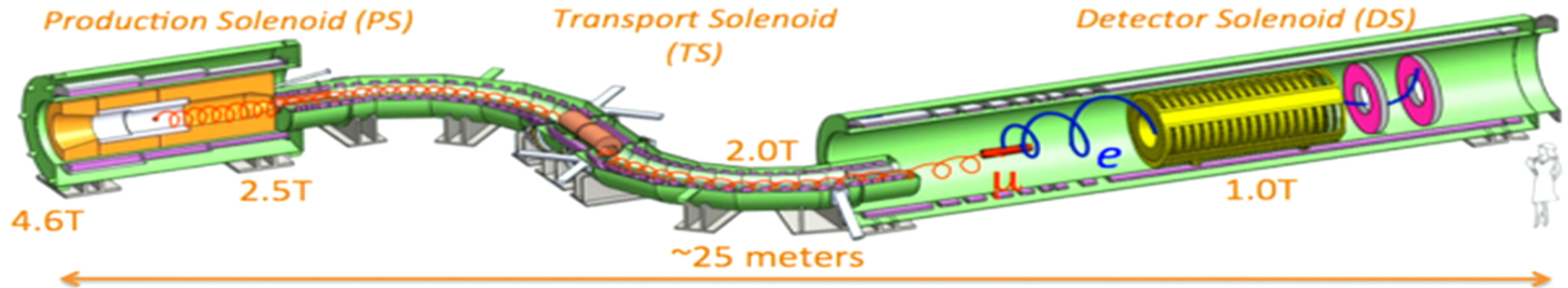
# So far, so nothing.



...current limits on  $\mu \rightarrow e$  probe up to  **$10^4$  TeV**

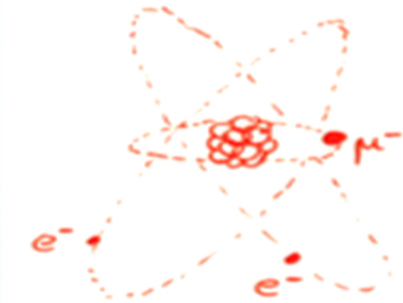
# The $\mu 2e$ Experiment @ FNAL

A System of superconducting solenoids and an intense muon beam



- ◆ 8 GeV Booster protons  $\rightarrow$  muons (and pions, neutrons, gammas ... )
- ◆ crazy, curvy beam line to get rid of any line-of-sight background
- ◆ muons steered into Al “stopping” target, where the magic happens

# Stopping muons



stopped muon replaces an electron in the Al atom...

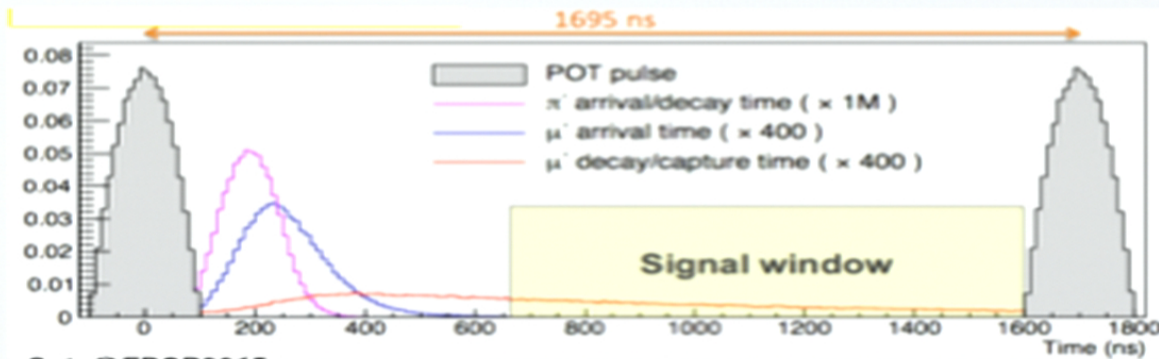
...most of the time, the muon either is "captured" (releasing  $\nu_\mu$ ) or decays in-orbit

primary background are "**DIO**" decays...but energy spectrum is different from signal



symmetry magazine

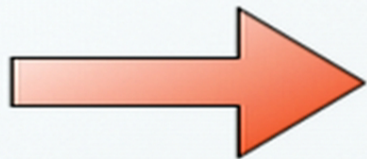
# $\mu 2e$ Signatures



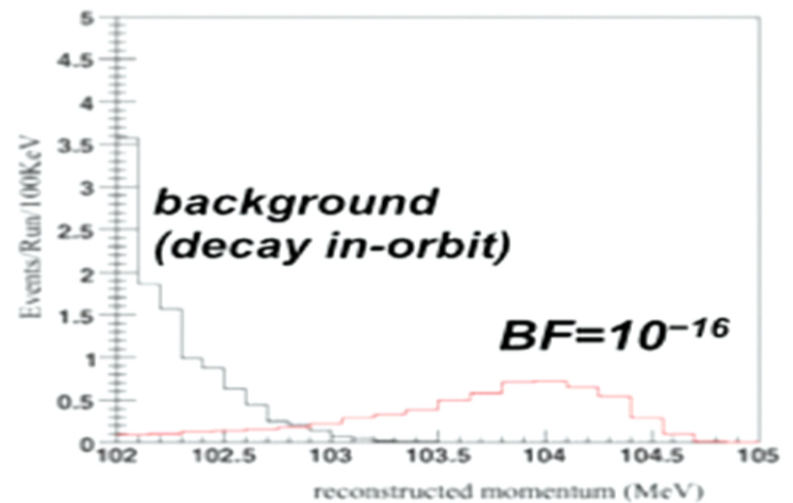
Sato@FPCP2015

1. pulsed beam  $\rightarrow$  wait until all is quite

2. measure energy of the electron;  $\mu \rightarrow e$  conversions peak at  $\sim m(\mu)$  while decays cut off before that



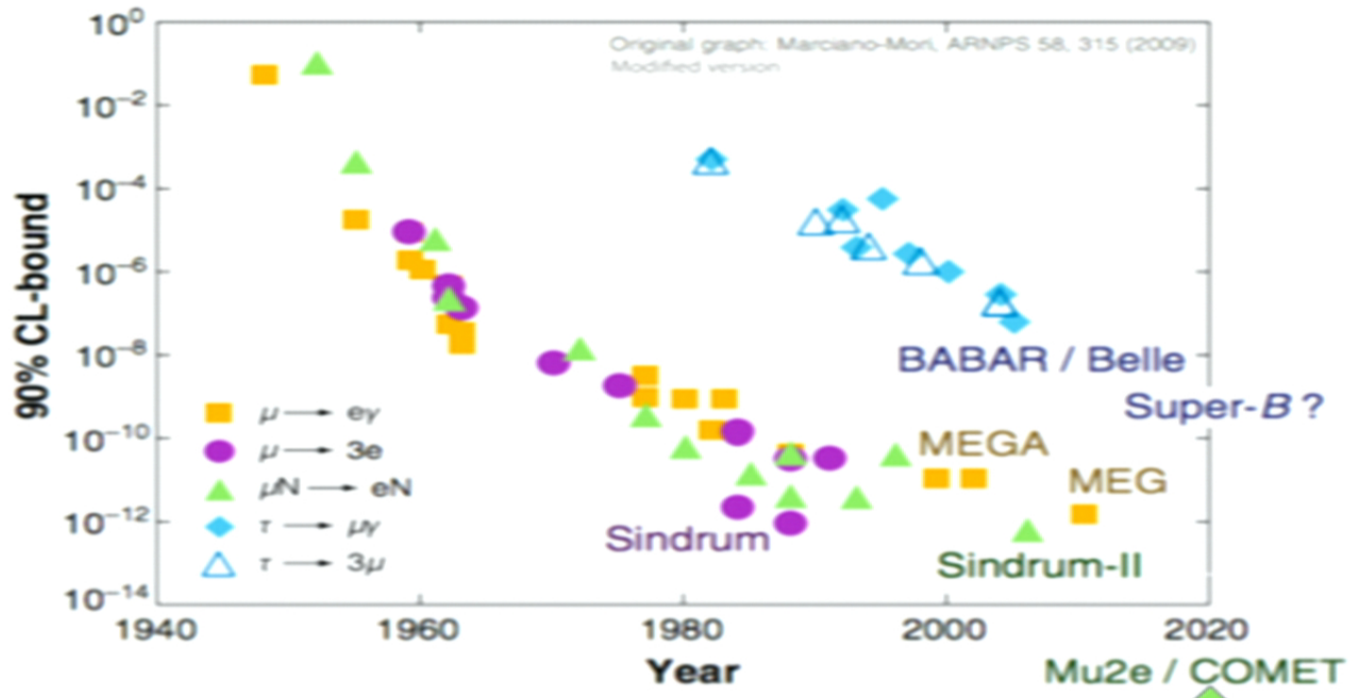
**Gives  $\sim$  background free signal region**



TRISEP 2015

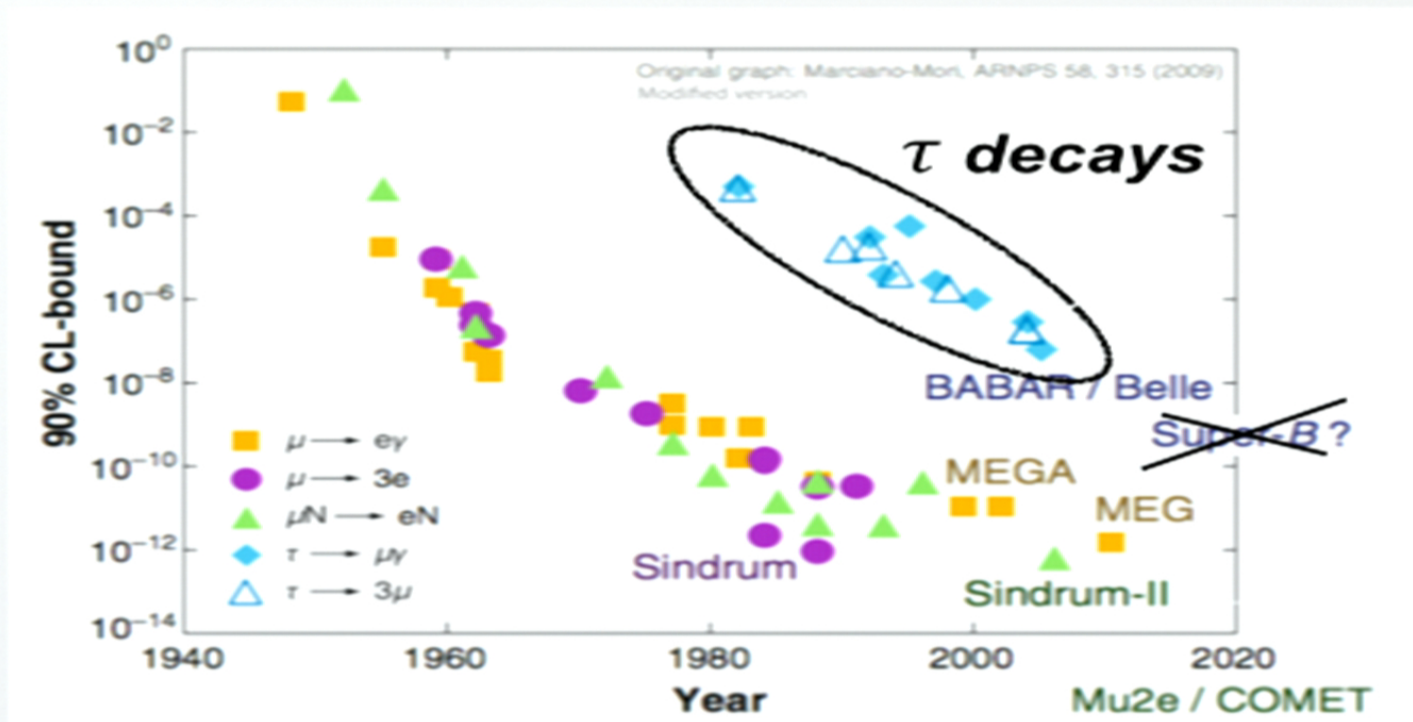
33

# $\mu 2e$ Sensitivity

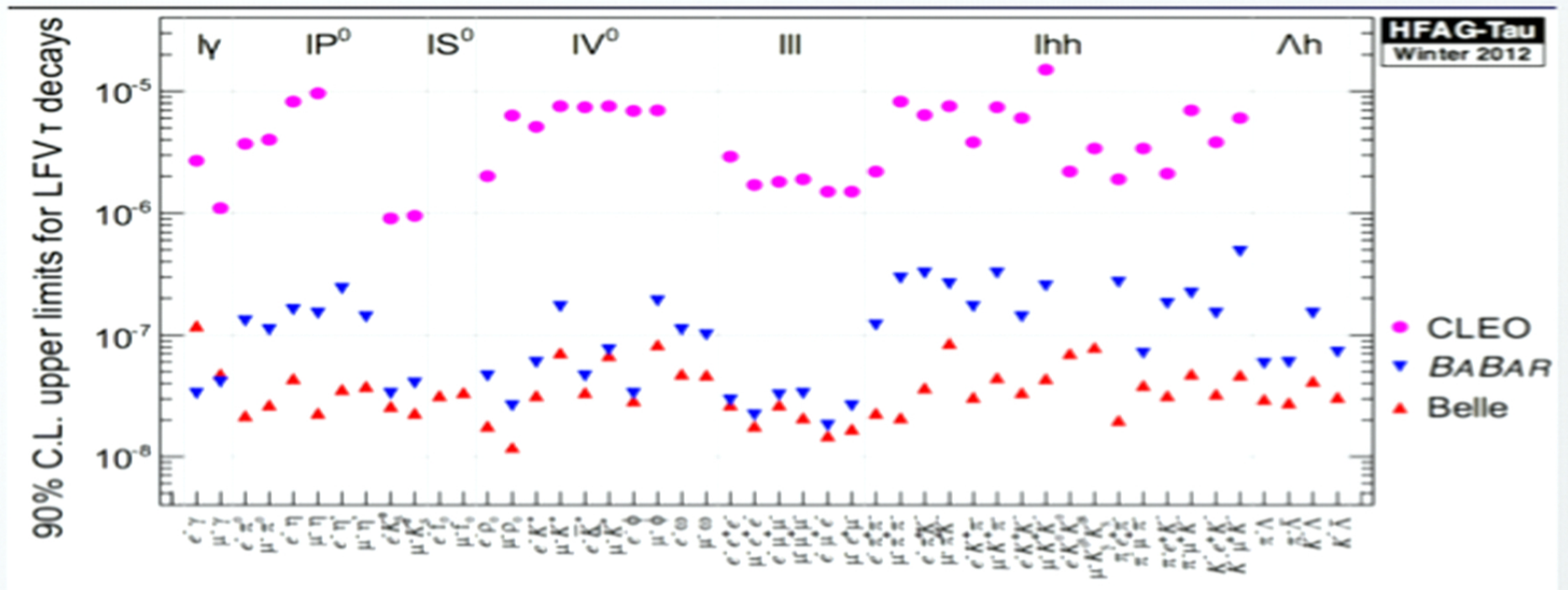


$\sim 6 \times 10^{-17}$

# Tau decays too...



# ...many, many tau decays



...these should go down by x10 by ~2025 (Belle-II)



## (C)LFV Recap

- Charged lepton flavor violating reactions are a great place to look for physics BSM...the first one we see will be a huge discovery
  - very clean theoretically AND experimentally...the limiting factor is how many muons or taus we can produce
  - can probe very high energy scales
  - good complementarity with the energy frontier
- Unfortunately, there's no indication that it's right around the corner
  - that's not a reason to not look...just keep digging!
- Upcoming experiments take a nice step forward:
  - $\mu 2e$  (FNAL)
  - COMET (J-PARC)
  - $\mu 3e$  (PSI)



# CKM Matrix & CP-Violation in the quark sector

$$V_{pq} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \propto \begin{pmatrix} \text{Magnitude} \\ \text{Phase} \end{pmatrix} \times \begin{pmatrix} \text{Phase} \end{pmatrix}$$

$$\approx \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda = \sin \theta_C = 0.22$$

Unitarity Conditions:

$$|V_{i1}|^2 + |V_{i2}|^2 + |V_{i3}|^2 = 1$$

$$V_{i1}V_{j1}^* + V_{i2}V_{j2}^* + V_{i3}V_{j3}^* = 0 \quad \text{"Unitarity Triangles"}$$

# THE Unitarity Triangle

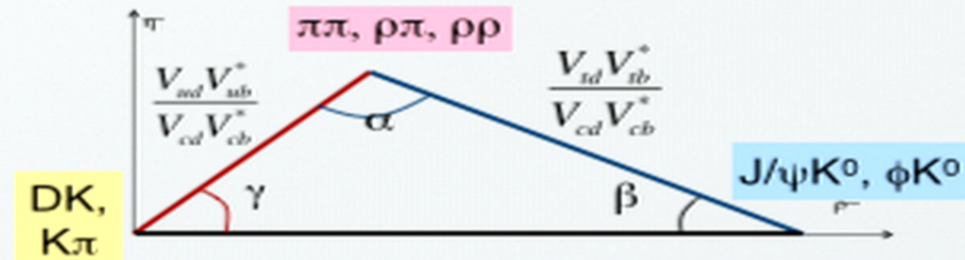
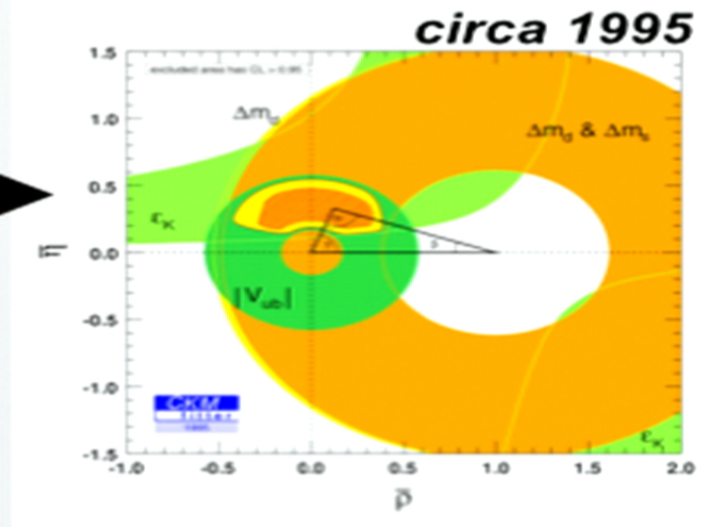
There are 6 triangle relations but most have very un-equal sides == large/small angles == small CPV effects

...EXCEPT!!!



THE UT = Column 1 (**d**) \* Column 3(**b**)

Unitarity condition:  $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$



One of the *main goals of B-Factories is to see if this triangle closes*...if it doesn't, it would be sign of **physics beyond the Standard Model!**

CKMfit Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184], updated results and plots available at: <http://ckmfit.in2p3.fr>