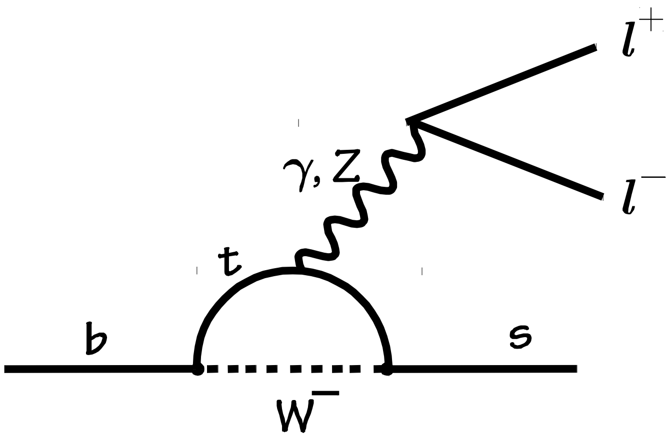
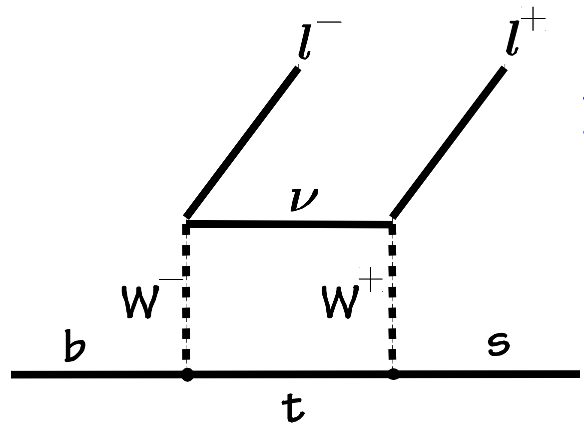
Beautiful paths to probe physics beyond the standard model of particles





K. Trabelsi

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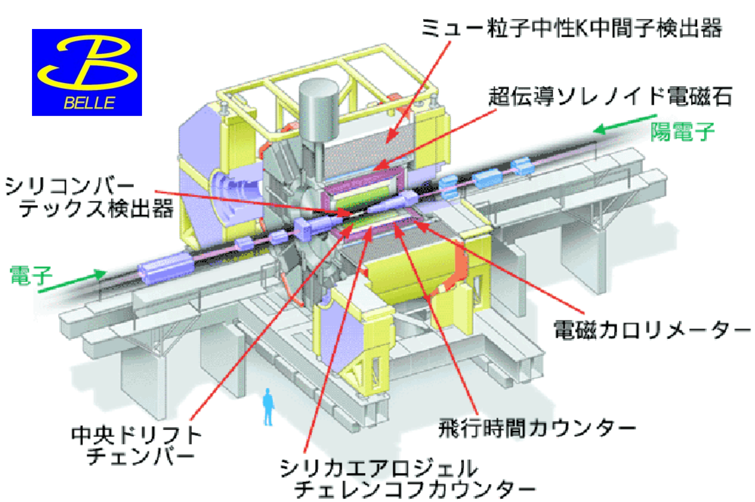
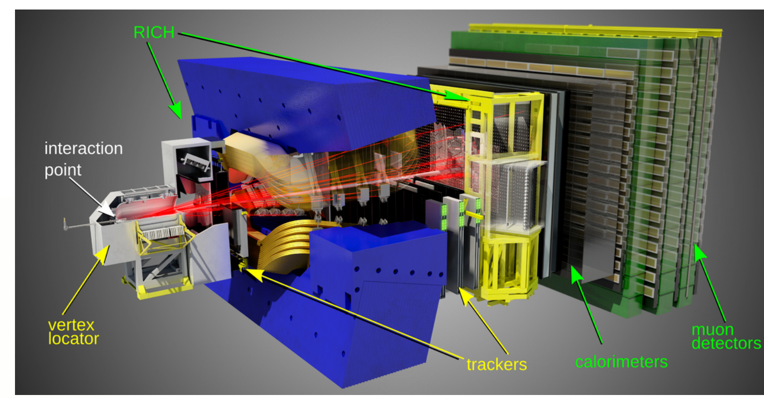
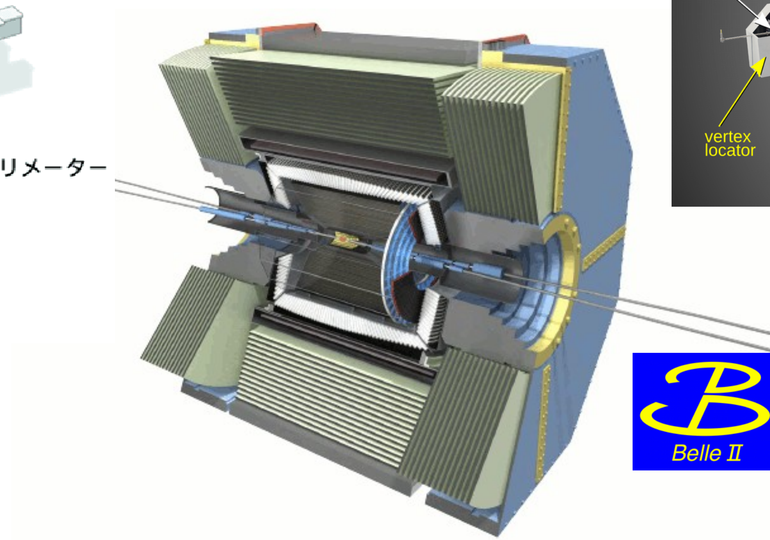
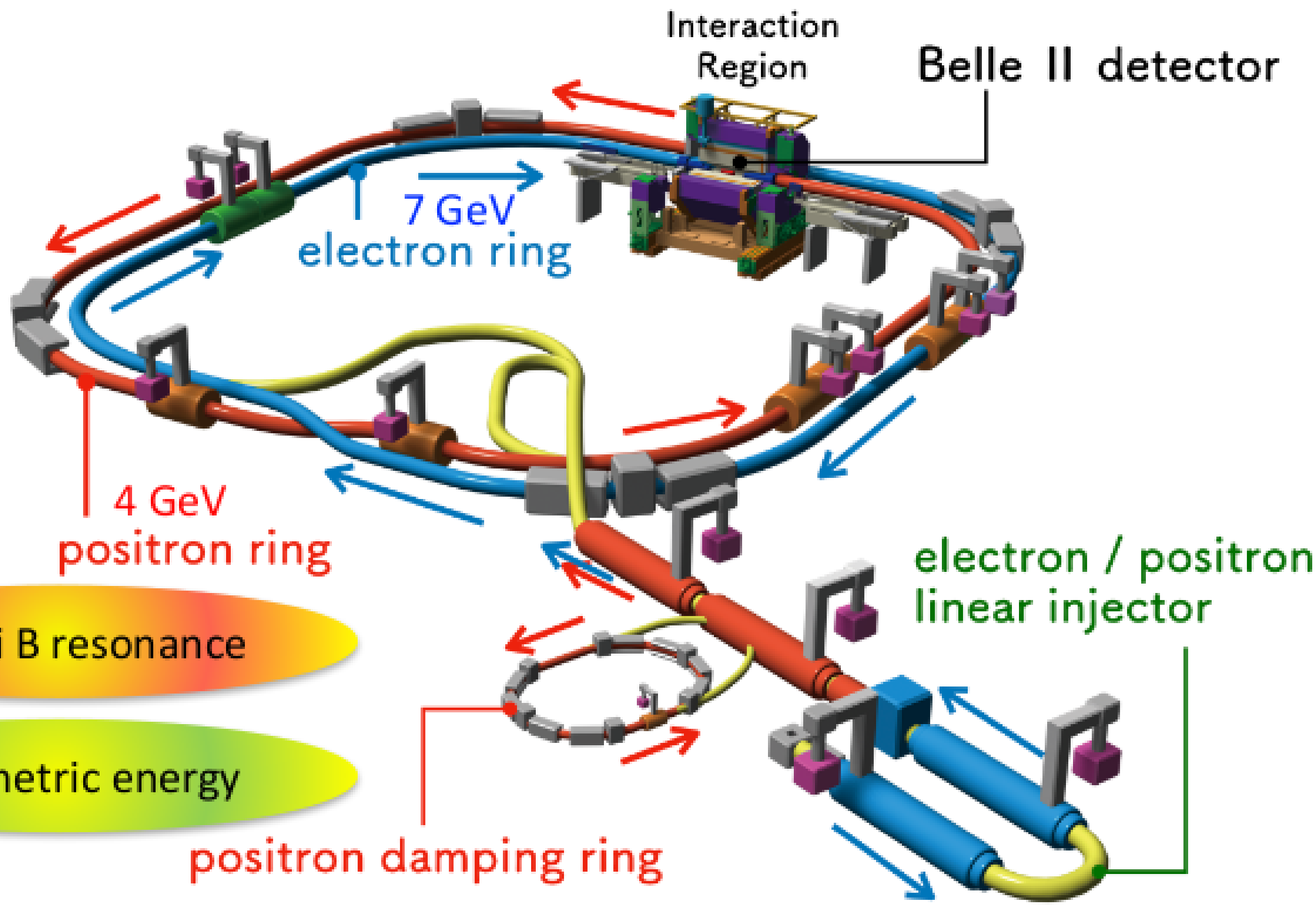






Jennifer school, July 22nd 2020

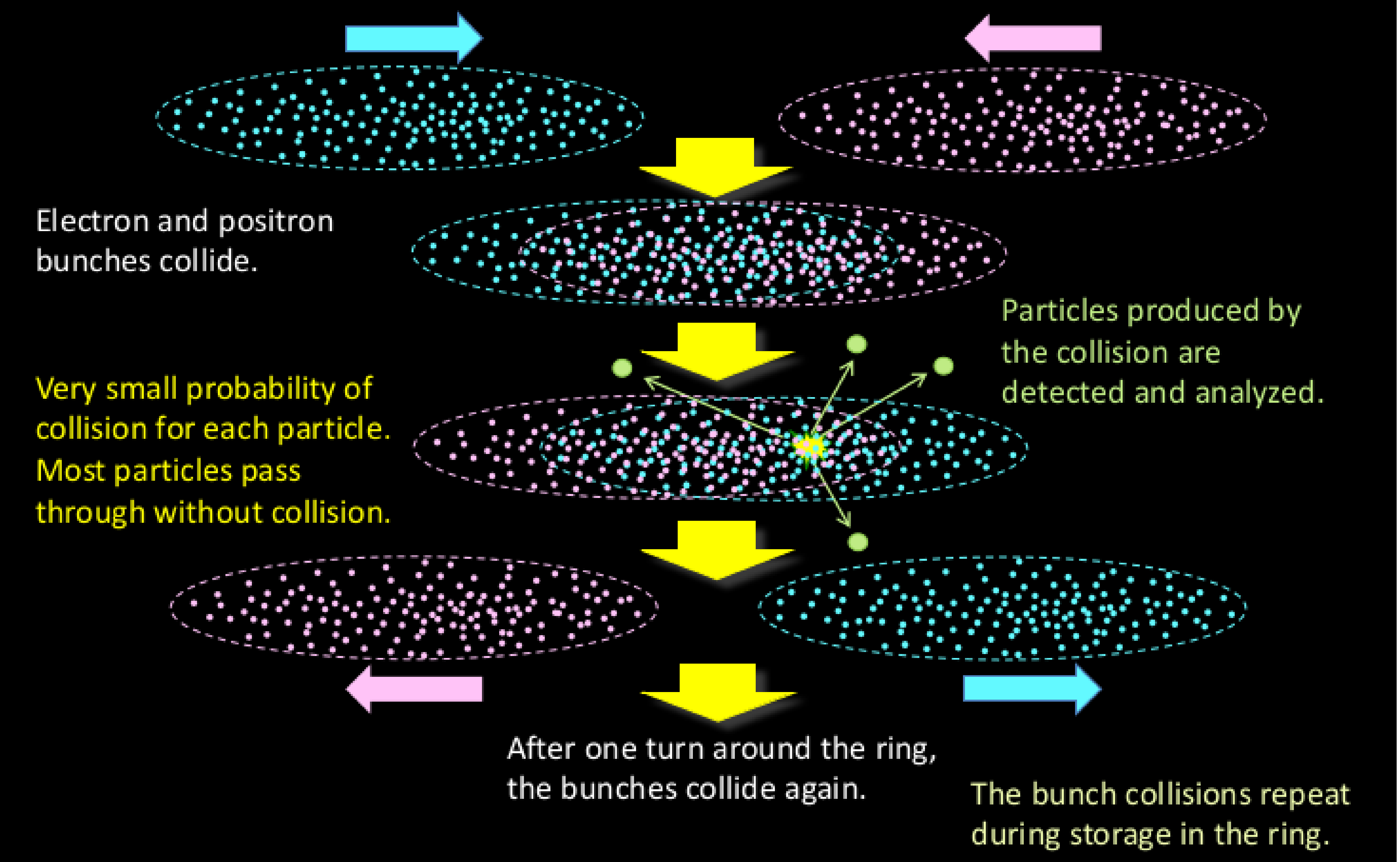
SuperKEKB accelerator complex



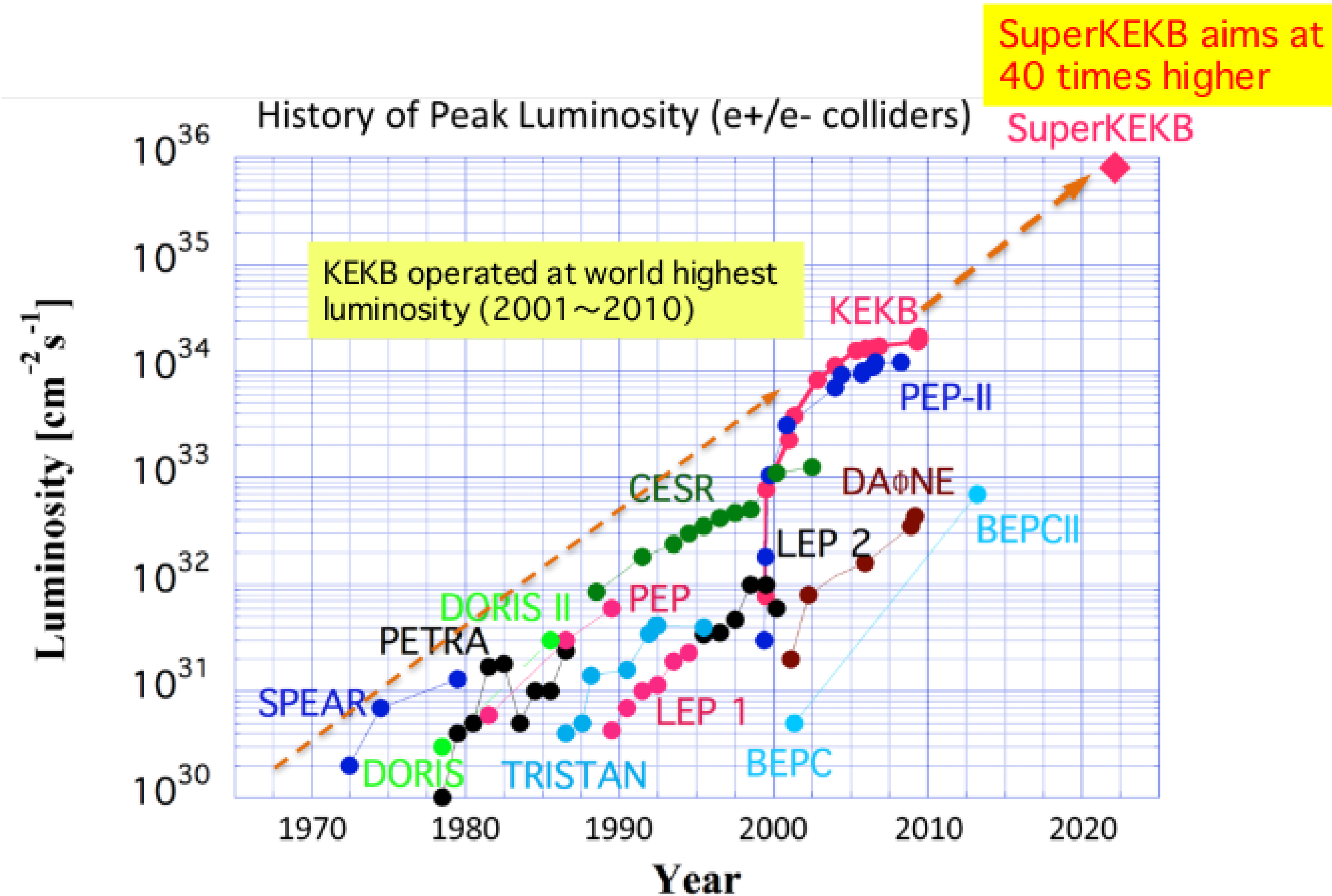
B - anti B resonance

asymmetric energy

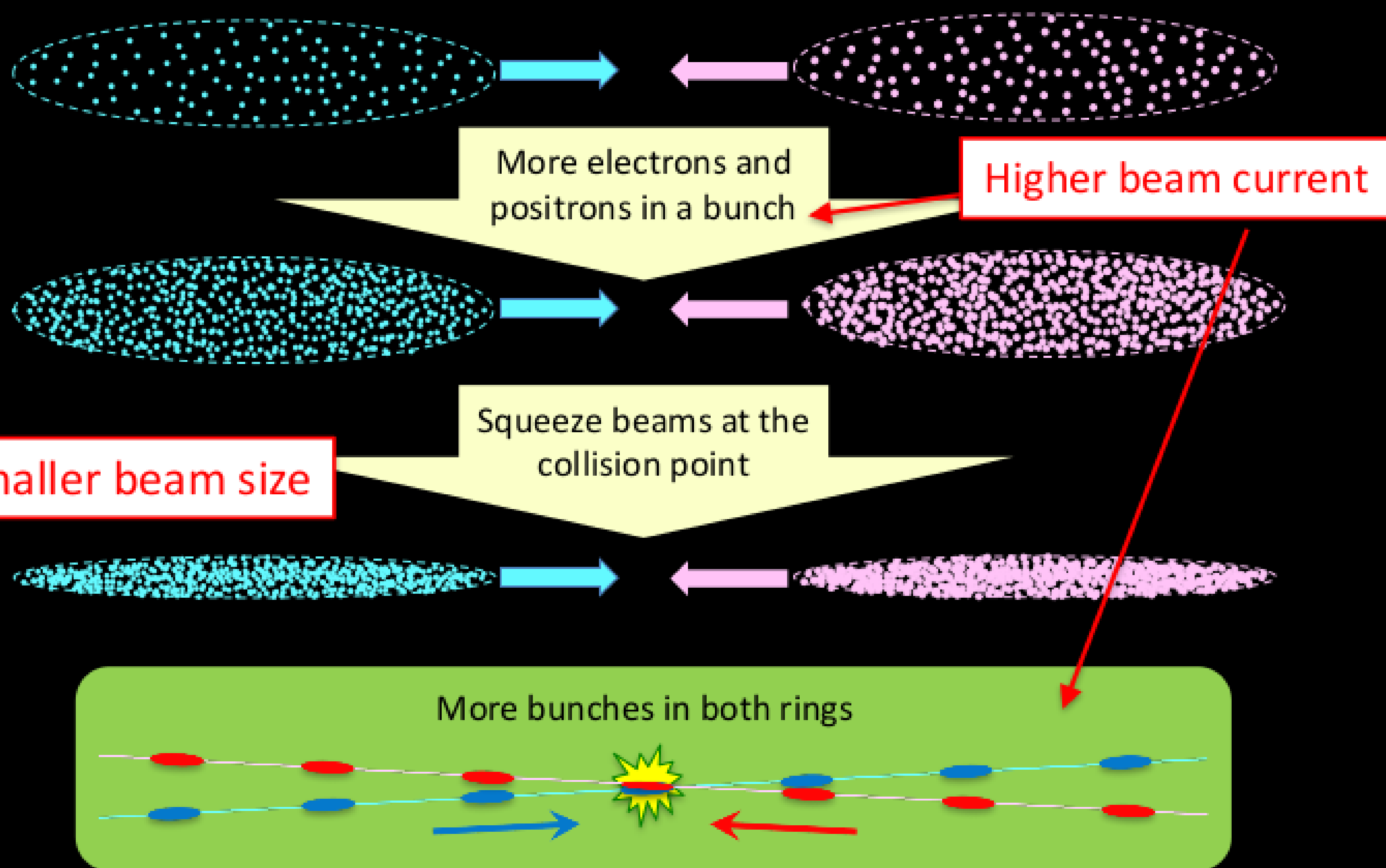
Beam collision



Luminosity frontier of e^+e^- colliders



Higher and higher luminosity



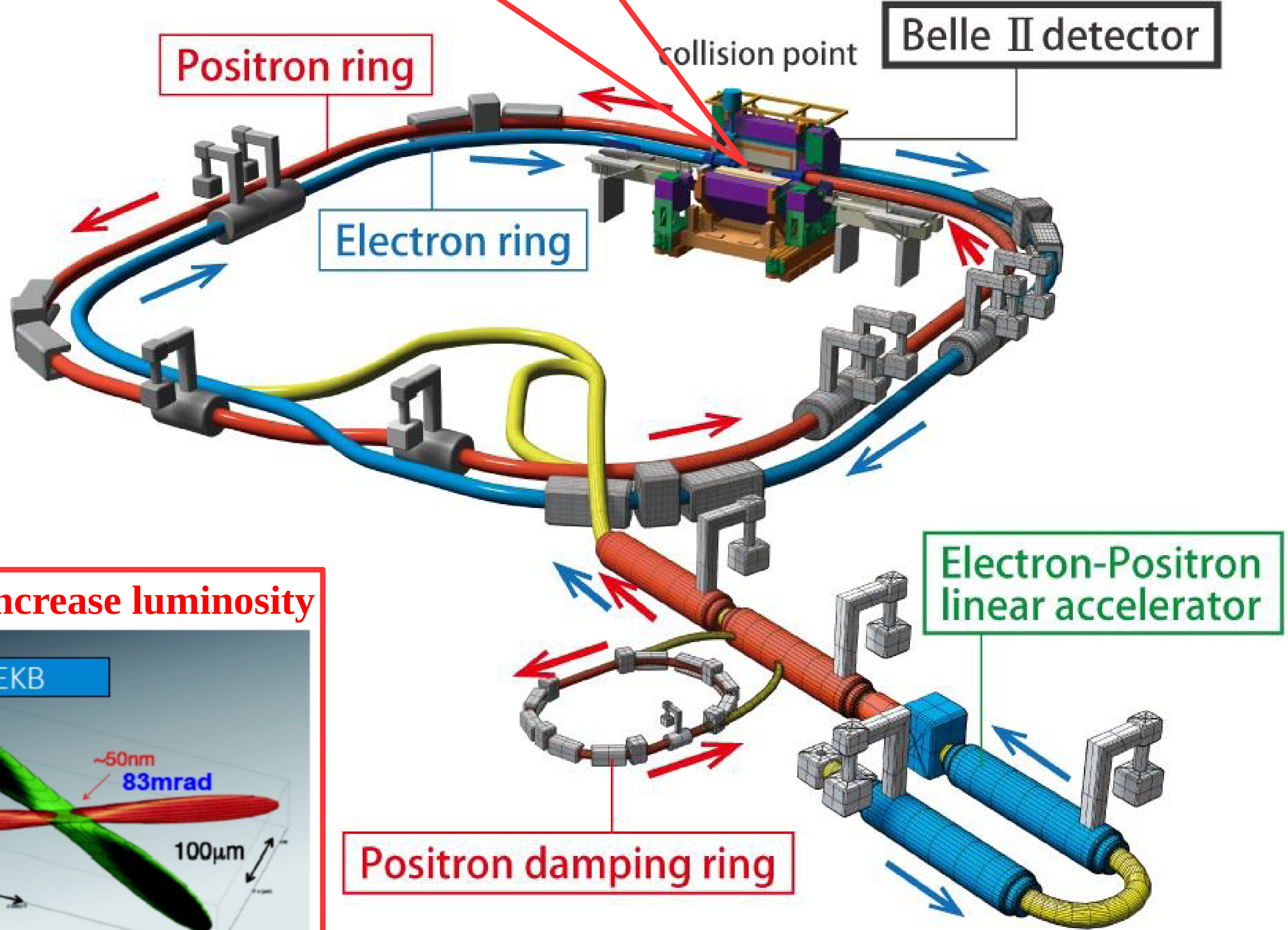
SuperKEKB, the first new collider in particle physics since the LHC in 2008 (electron-positron $(e^+ e^-)$ rather than proton-proton (p-p))

Phase 1
Background, Optics commissioning
Feb - June **2016**
Brand new 3km positron ring

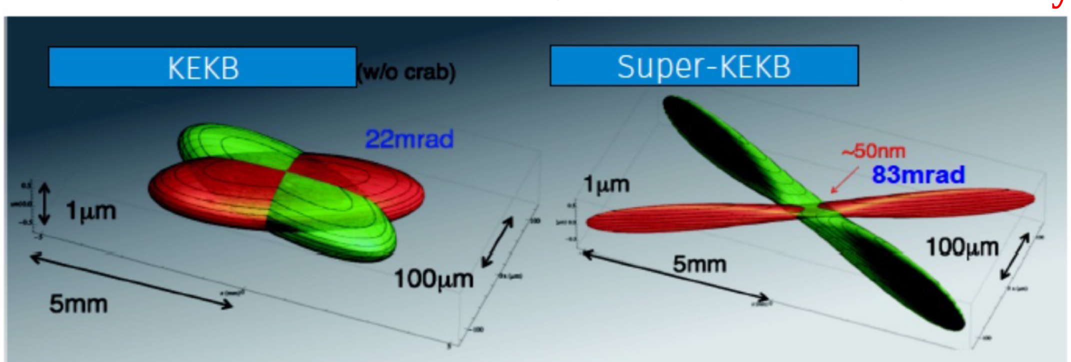
Phase 2: Pilot run
Superconducting Final Focus
add positron damping ring
First Collisions $(0.5\ \mathrm{fb}^{-1})$
April 27 - July 17, **2018**

Phase 3: Physics run
Since April, **2019**

Squeeze strongly at IP



Nano-beams and more beam current to increase luminosity



	E (GeV) LER/HER	β*y (mm) LER/HER	β*x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm⁻²s⁻¹)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10³⁴
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10³⁴

factor 20 factor 2-3

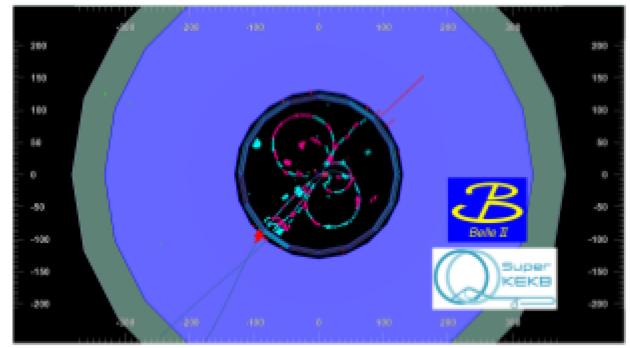
⇒ to reach $\sim 6\times10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

⇒ cumulate 50 ab^{-1} by ~2030

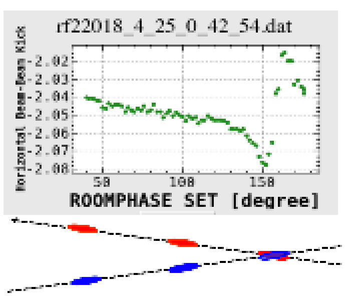
First collision

Apr. 26, 2018

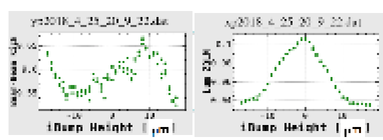
Belle II control room



First hadronic event observed by Belle II

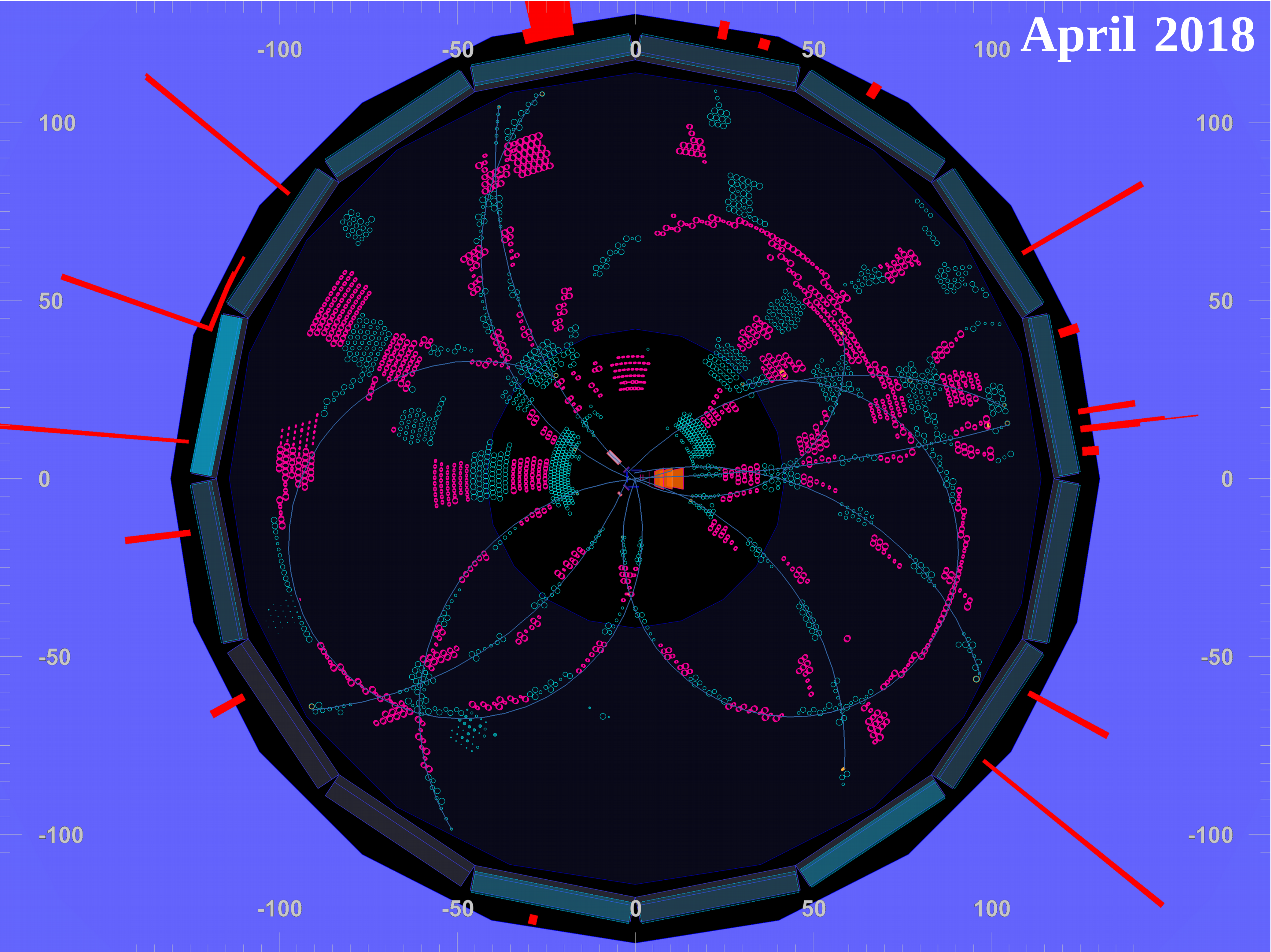


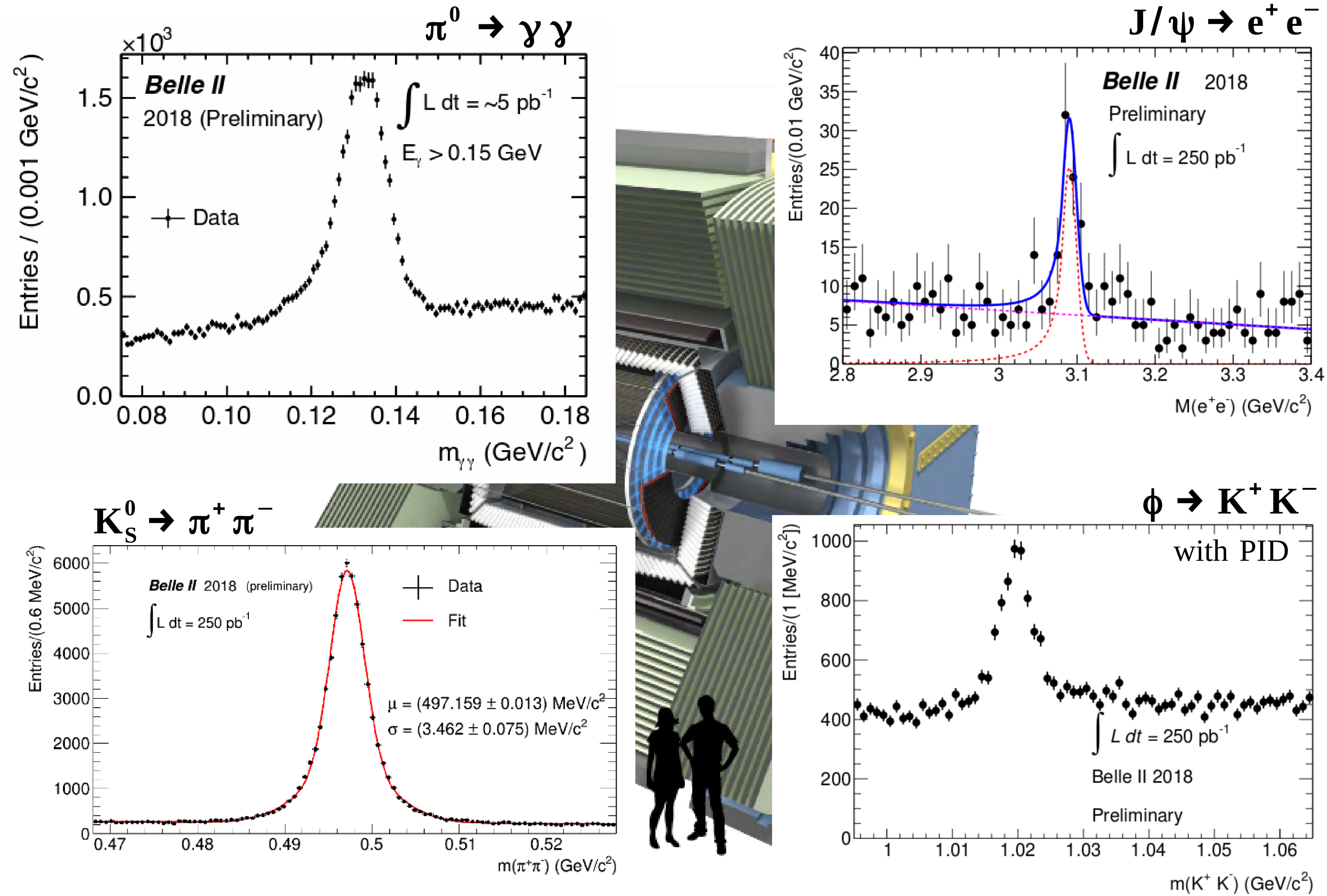
Horizontal beam-beam kick



Vertical beam-beam kick

SuperKEKB control room


April 2018
-100
-50
0
50
100
50
-50

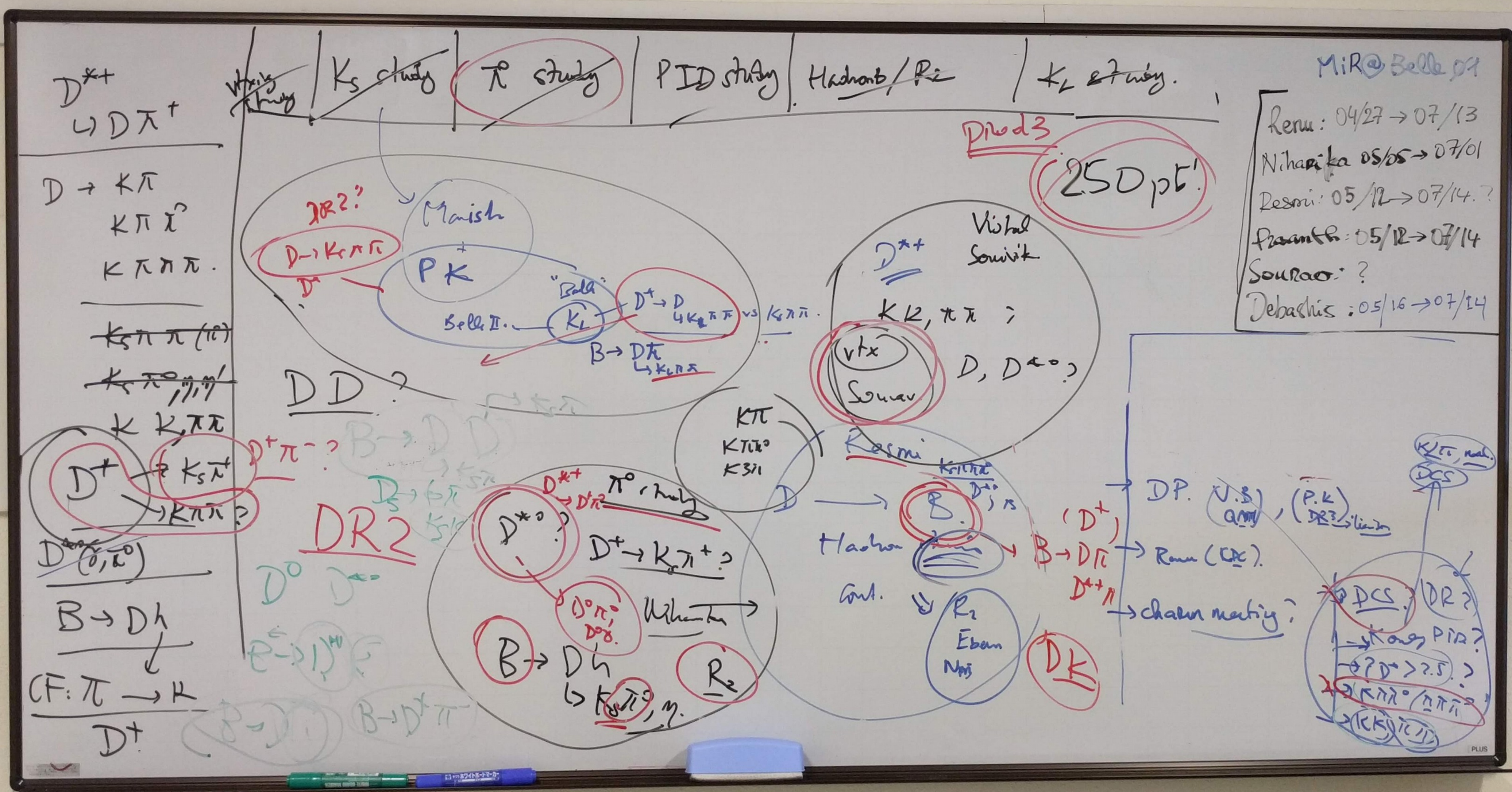


π0 → γγ
×10^3
Belle II
2018 (Preliminary)
∫L dt = ~5 pb-1
Eγ > 0.15 GeV
Data
Entries / (0.001 GeV/c2)
mγγ (GeV/c2)
J/ψ → e+e−
Belle II 2018
Preliminary
∫L dt = 250 pb-1
Entries/(0.01 GeV/c2)
M(e+e-) (GeV/c2)
K0S → π+π−
Belle II 2018 (preliminary)
∫L dt = 250 pb-1
Data
Fit
μ = (497.159 ± 0.013) MeV/c2
σ = (3.462 ± 0.075) MeV/c2
Entries/(0.6 MeV/c2)
m(π+π-) (GeV/c2)
ϕ → K+K−
with PID
∫L dt = 250 pb-1
Belle II 2018
Preliminary
Entries/(1 [MeV/c2])
m(K+ K-) (GeV/c2)

charm and beauty re-discoveries ...

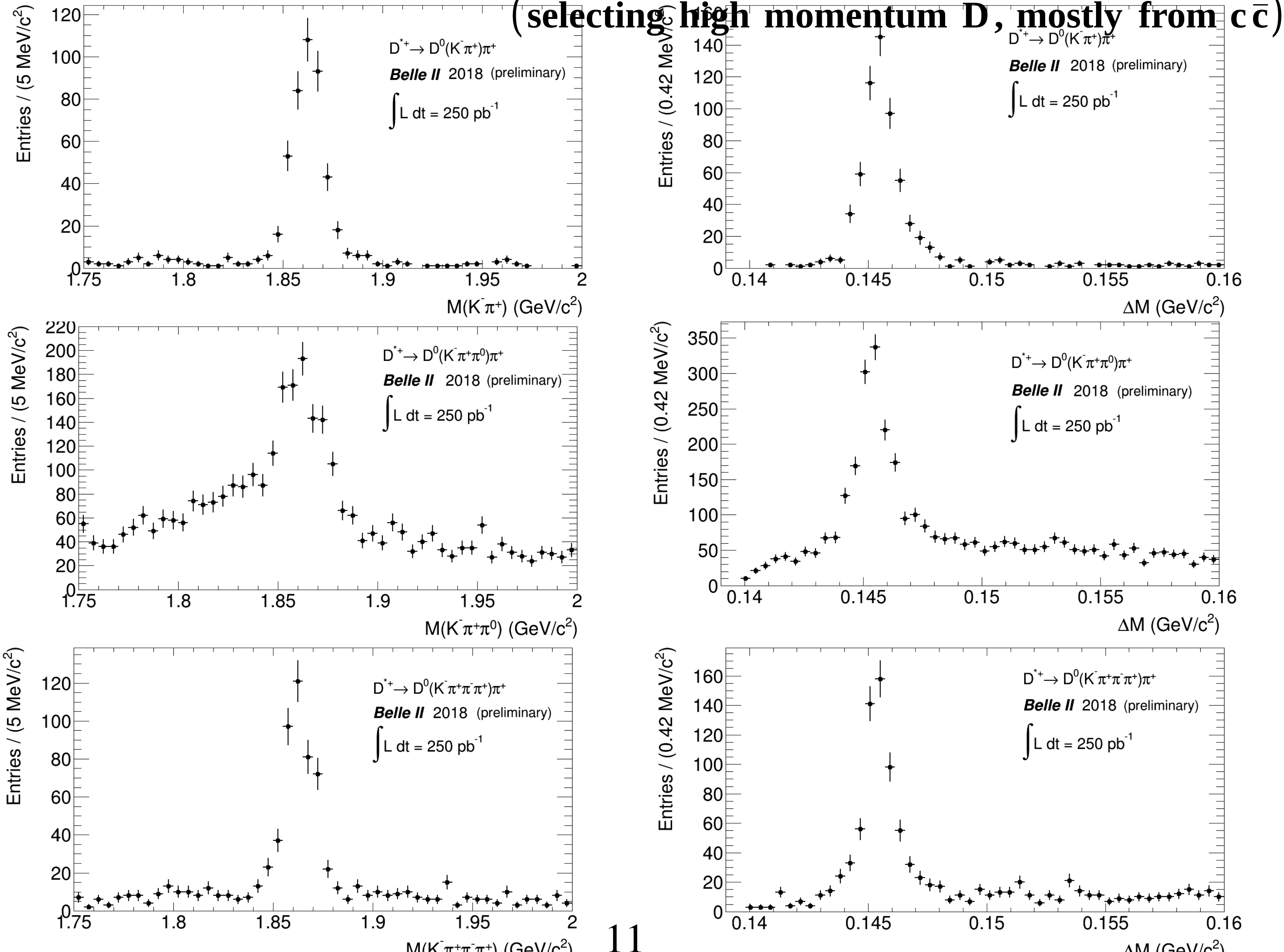
... using less than 1 fb^{-1}

(spring - summer 2018)

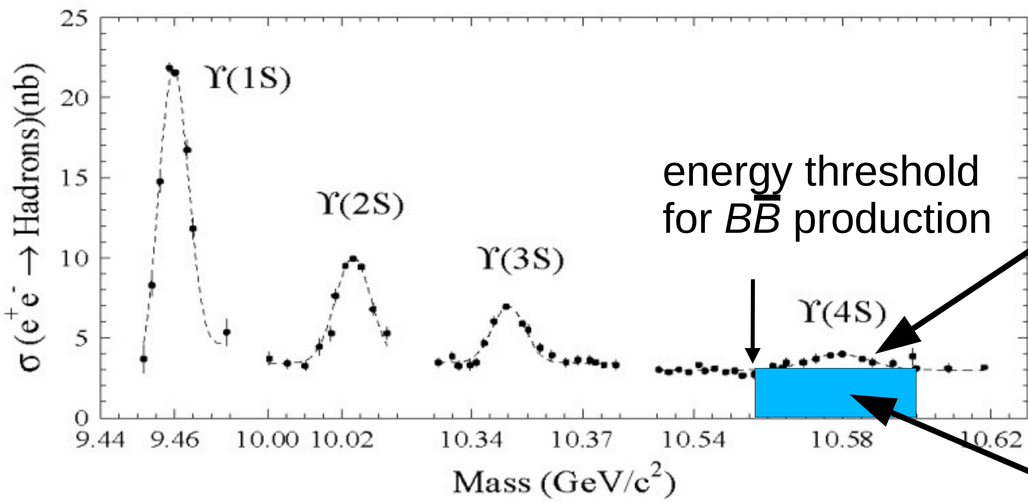


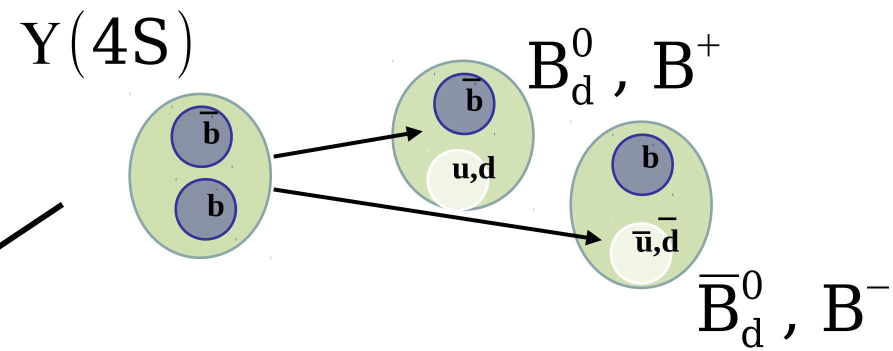
Rediscovering charm: $D^{*+} \to D\pi^+$, $D \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$

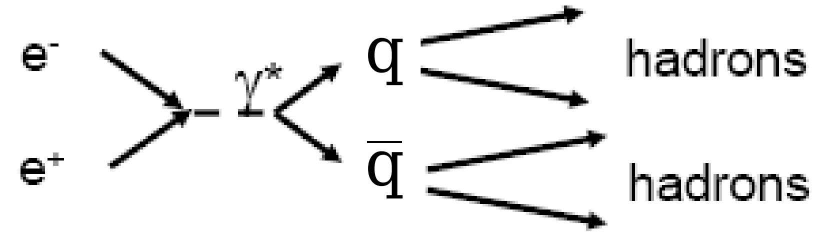
(selecting high momentum D, mostly from $c\bar{c}$)



At a B-factory …

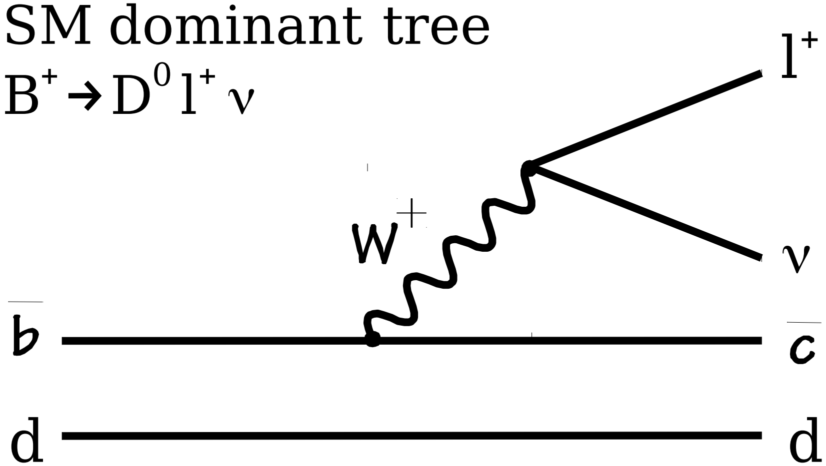


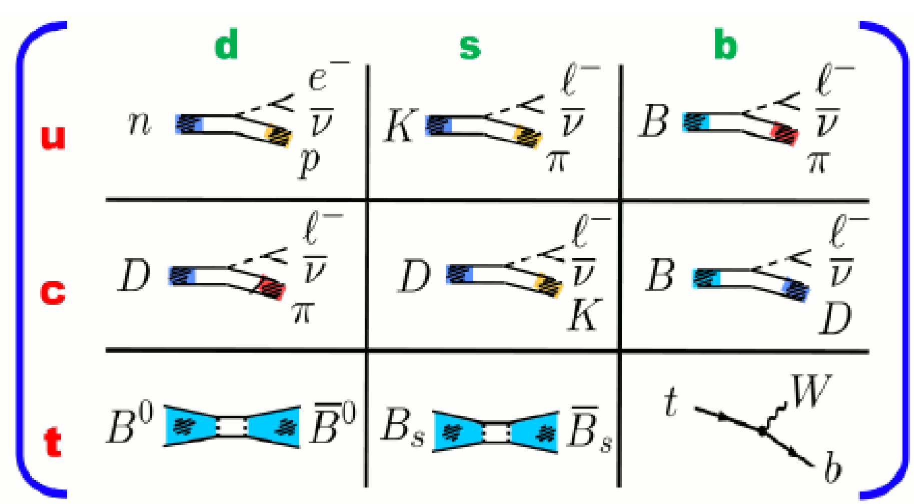




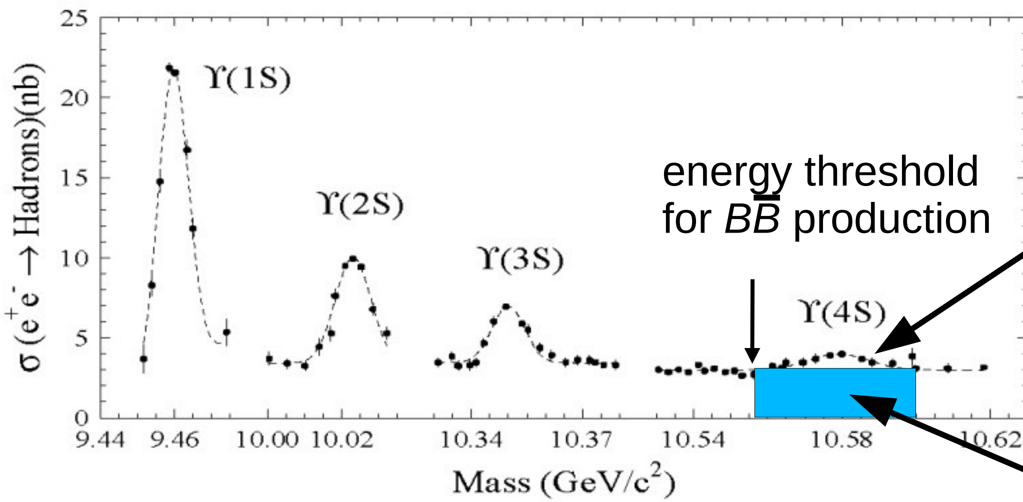
SM dominant tree

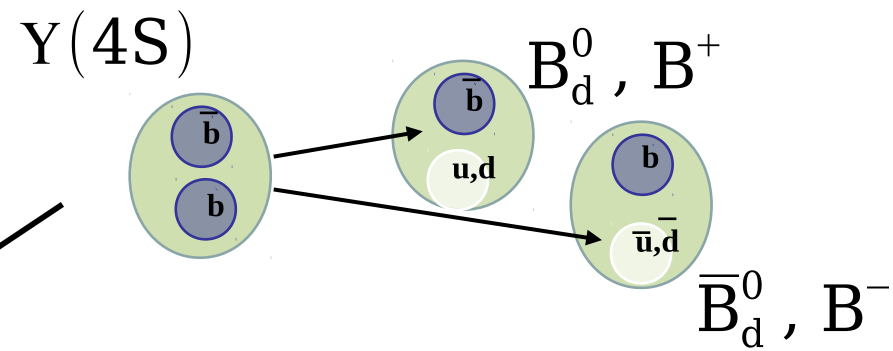
$B^+ \to D^0 l^+ \nu$

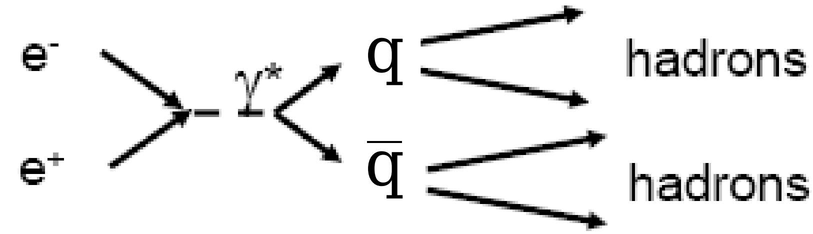




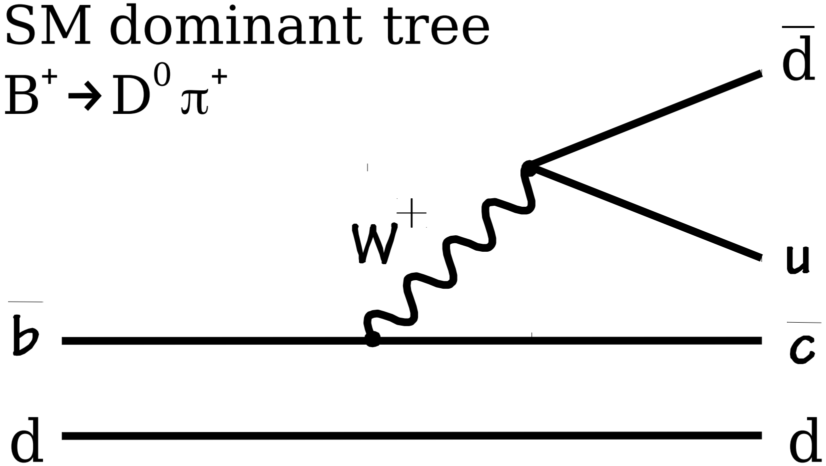
At a B-factory …





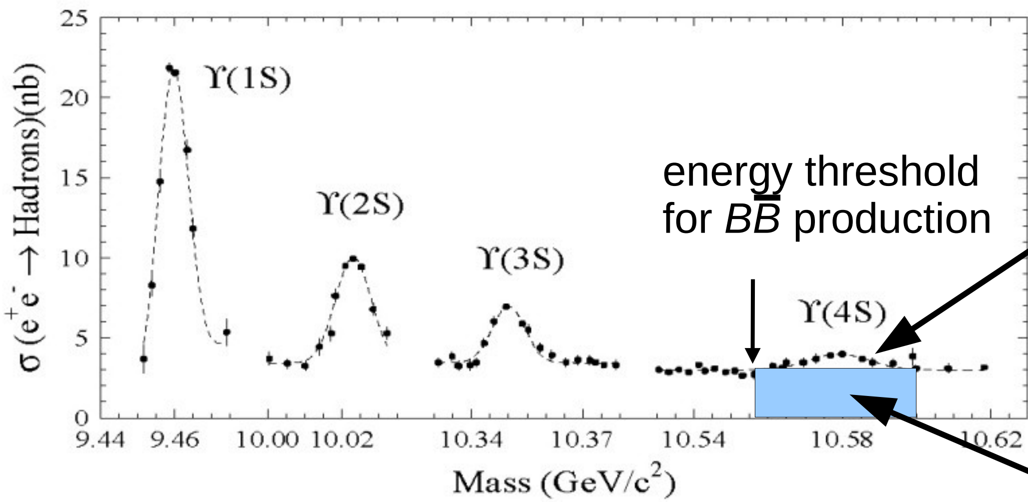


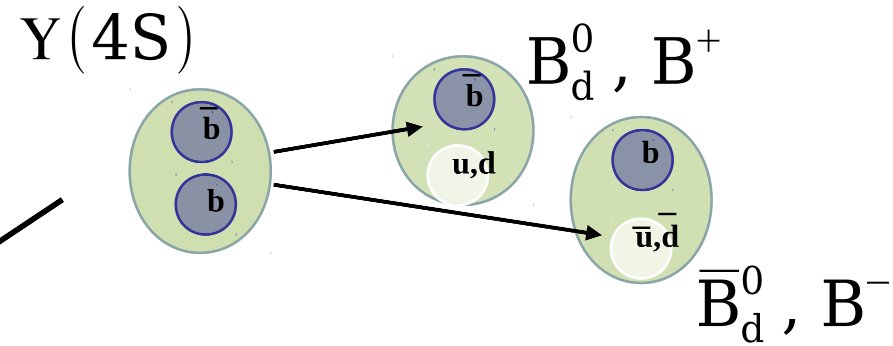
SM dominant tree
$B^+ \to D^0 \pi^+$

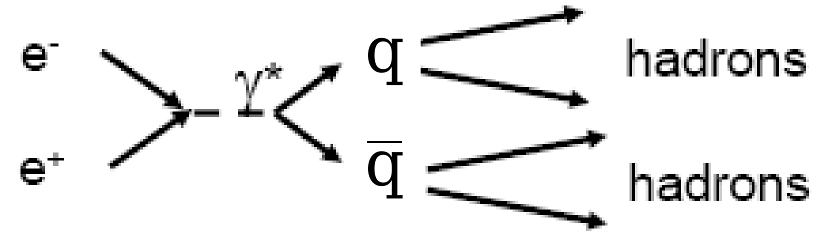


How many B candidates can I reconstruct with $1\ \mathrm{fb}^{-1}$?
$1\ \mathrm{fb}^{-1} \to 1 \times 10^6$ B produced
but $\mathrm{BF}(B \to D^0 \pi^-) = 5 \times 10^{-3}$
and $\mathrm{BF}(D \to K^- \pi^+) = 3.8\%$
and reconstruction efficiency $\sim 10\%$…
signal yield ~ 10 events !!

Reconstruct a B candidate…







Energy difference:

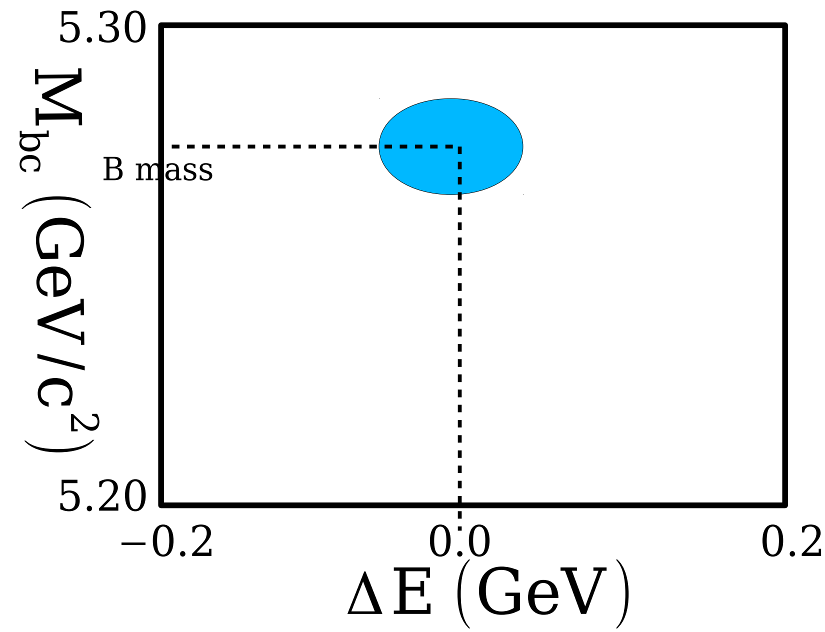
$$\Delta E = E_B^* - E_{beam}$$

(resolution ~ 10 MeV)

Beam-energy-constrained mass:

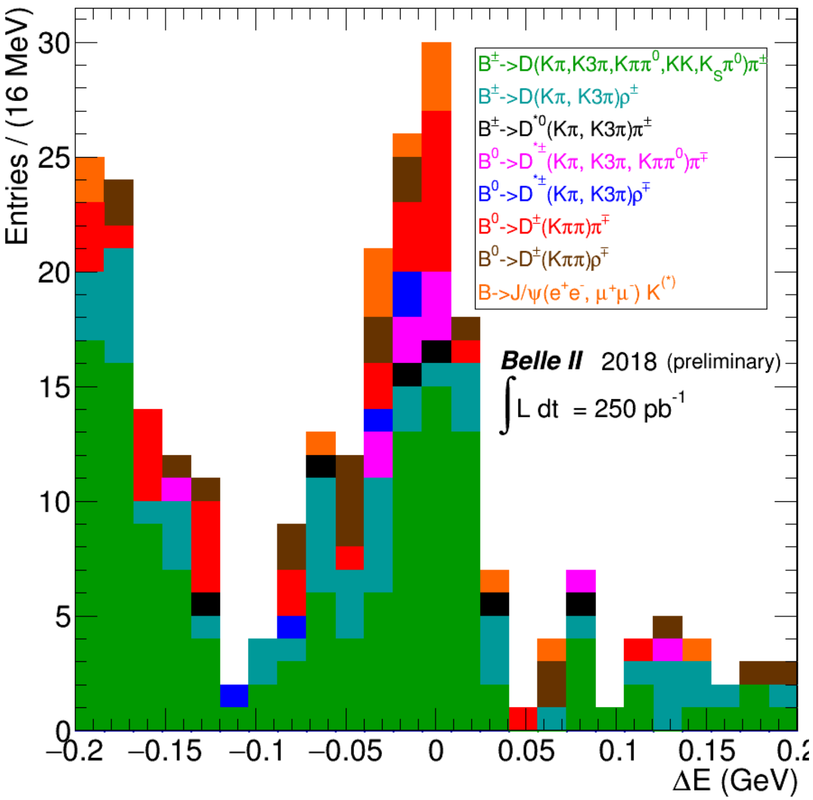
$$M_{bc} = \sqrt{(E_{beam}/c^2)^2 - (p_B^*/c)^2}$$

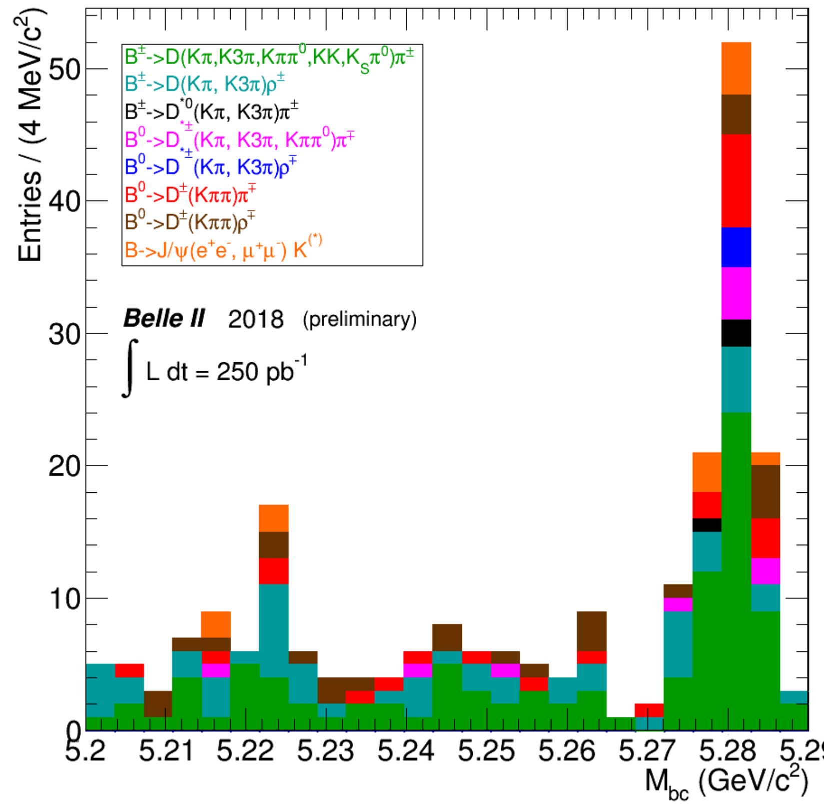
(resolution ~ 2.5 MeV)



Rediscovering beauty: $B \to D^{(*)}h$ + $B \to J/\psi K^{(*)}$

with very limited statistics ($< 1\ \mathrm{fb}^{-1}$), Belle II can rediscover the B meson





Candidates in signal box
($M_{bc} > 5.27$ GeV/c^2,
$|\Delta E| < 0.050$ GeV)

Mode	yield
$B^\pm \to D\pi^\pm$	51
$B^\pm \to D\rho^\pm$	16
$B^\pm \to D^*\pi^\pm$	3
$B^0 \to D^{*\pm}\pi^\mp$	7
$B^0 \to D^{*\pm}\rho^\mp$	3
$B^0 \to D^\pm\pi^\mp$	13
$B^0 \to D^\pm\rho^\mp$	8
$B \to J/\psi K^{(*)}$	8

~ 100 evts

Show capacity for charm physics in $e^+e^- \to c\bar{c}$

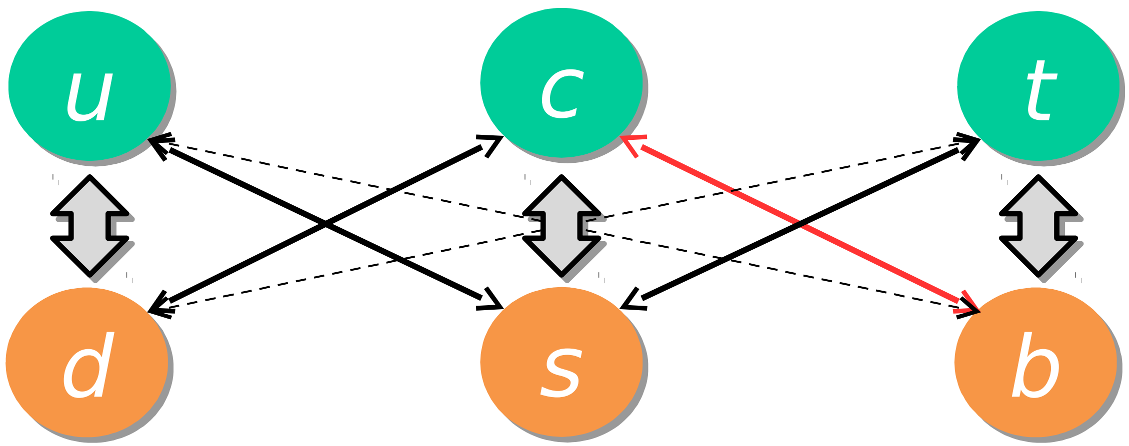
- D^0, D^+, D^*
- Cabibbo favoured and suppressed modes

that is for dominant decays....
...we are looking for rare decays

...for B-physics

- hadronic modes from $b \to c$
- semileptonic decay modes from $b \to c$

But you said ''rare B decays''...



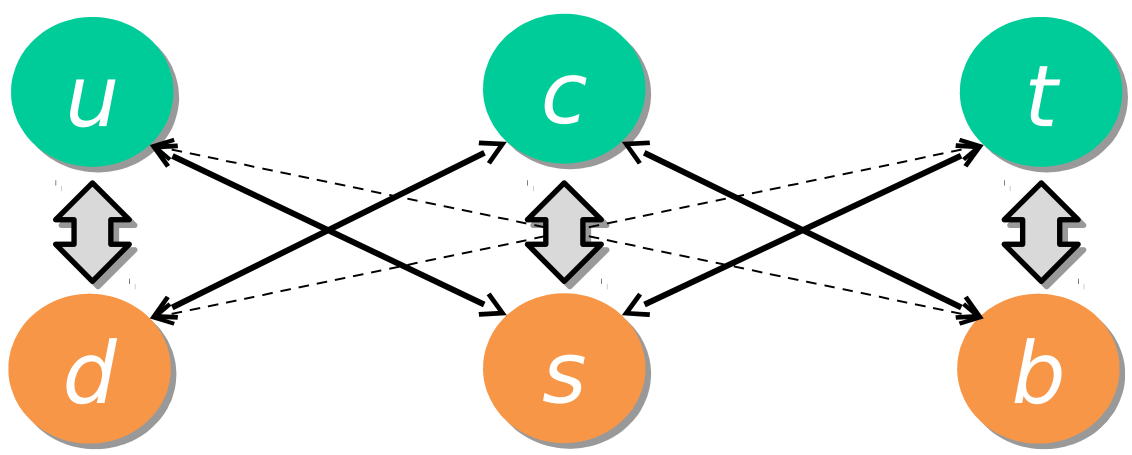
What are rare decays ?

Dominant decays: Not rare

Phase space suppressed decays: Not that rare

Cabibbo-suppressed decays: Some call them rare

$B(\mathrm{D}^0 \rightarrow \mathrm{K}^- \pi^+)$ versus $B(\mathrm{D}^0 \rightarrow \pi^- \pi^+)$ $B(\mathrm{b} \rightarrow \mathrm{c}\, l^+ \nu)$ versus $B(\mathrm{b} \rightarrow \mathrm{u}\, l^+ \nu)$



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$$\frac{B\left(D^0 \to K^- \pi^+\right)}{B\left(D^0 \to \pi^- \pi^+\right)} = 28 \qquad \frac{B\left(b \to c\, l^+ \nu\right)}{B\left(b \to u\, l^+ \nu\right)} = 135$$

What are rare decays ?

Dominant decays: Not rare

Phase space suppressed decays: Not that rare

Cabibbo-suppressed decays: Some call them rare

Colour-suppressed decays: Not really rare

$$\mathcal{B}(B^0 \to D^- \pi^+) = (3.5 \pm 0.9)\, 10^{-3},$$
$$\mathcal{B}(B^0 \to \overline{D}^0 \pi^0) = (2.9 \pm 0.3)\, 10^{-4},$$

while they are both $b \to c\,W$ and $W \to u\,\overline{d}$ transitions.

What are rare decays ?

Dominant decays: Not rare

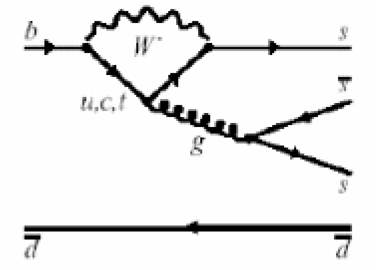
Phase space suppressed decays: Not that rare

Cabibbo-suppressed decays: Some call them rare

Colour-suppressed decays: Not really rare

Hadronic FCNC decays: Not the topic of our lecture

- For instance $B \to \phi K_S^0$, or $B \to K_S^0 K \pi$...



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Dominant decays: Not rare

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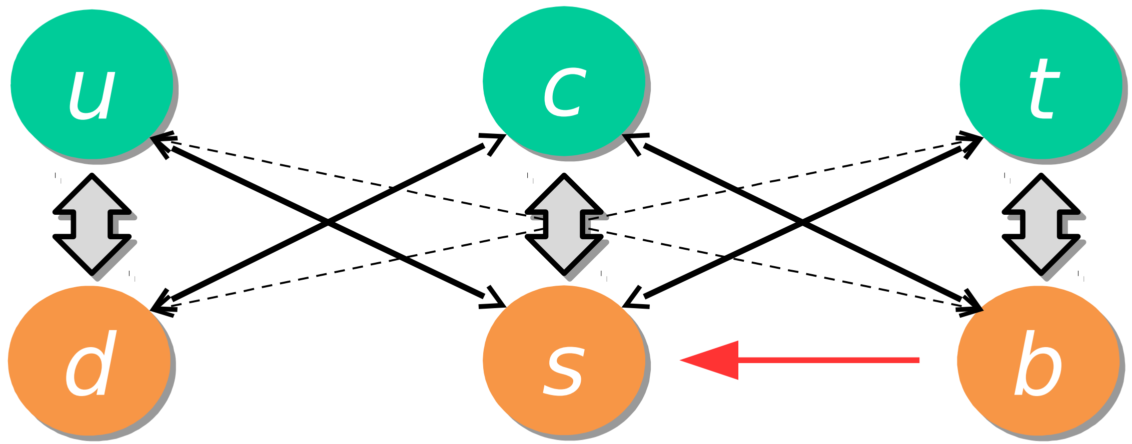
Hadronic FCNC decays: Not the topic of our lecture

- For instance $B \to \phi K^0_S$, or $B \to K^0_S K \pi$...
- Or $B^0 \to \phi K^0_S$, or the penguin contribution to $B \to J/\psi K^0_S$

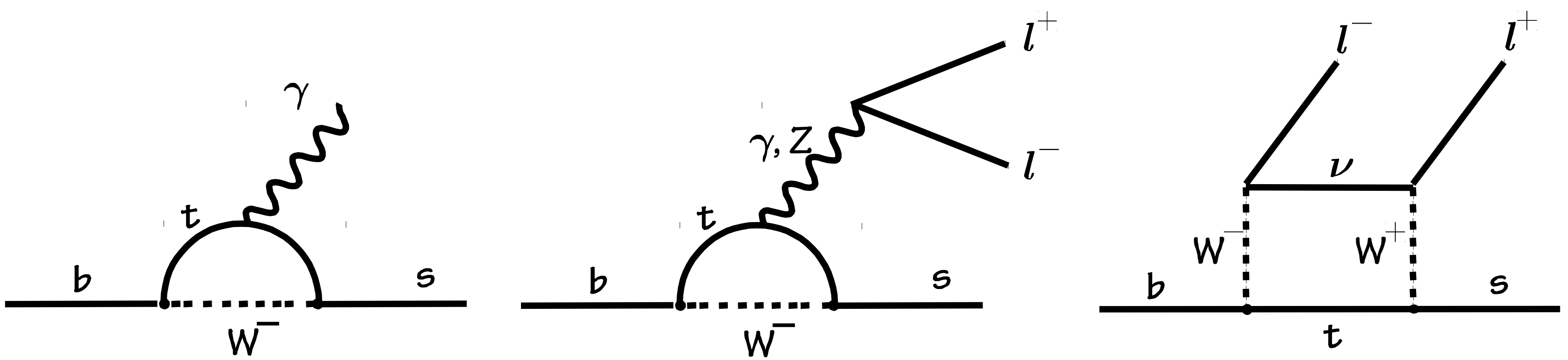
Electroweak FCNC penguins: That's rare !

- $b \to s \gamma$
- $b \to s l l$
- And friends...

Rare B decays



- FCNC: Flavour Changing Neutral Current
- FCNC are strongly suppressed in the SM: only loops + GIM mechanism



Motivations for NP

SM, are we done ?

No. Open questions

D. Tonelli

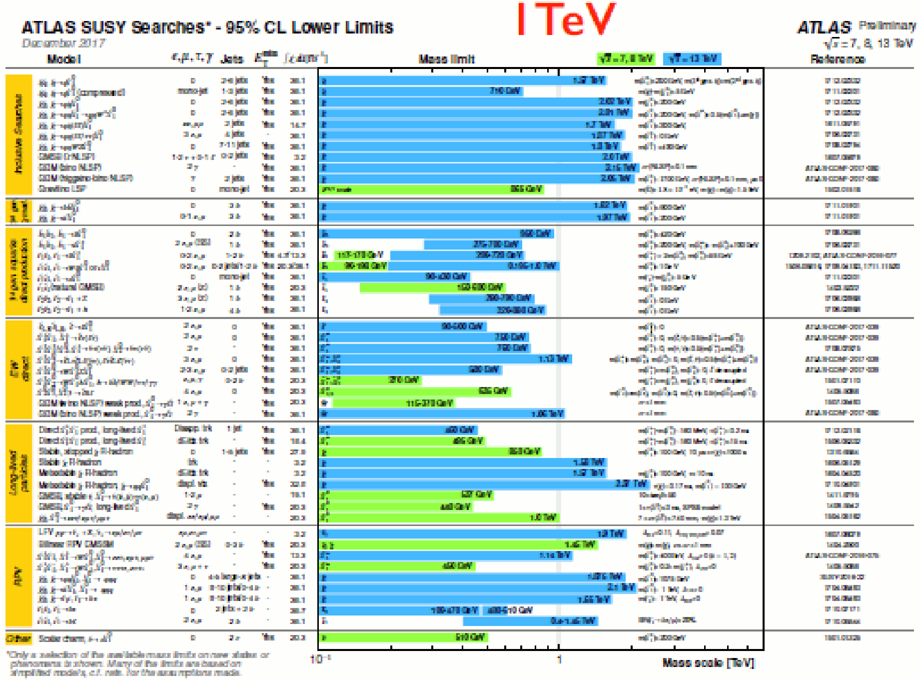
These and many other questions fuel the strong and wide-spread prejudice that the SM is completed at high-energy by new particles and interactions

How do you we search for new particles ?

Direct vs Indirect Searches

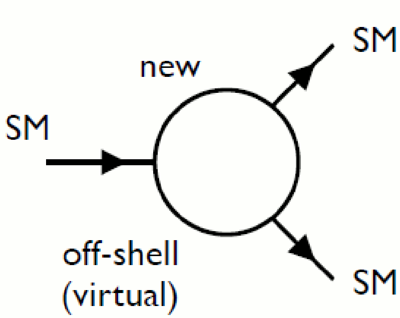
complementarity with LHC

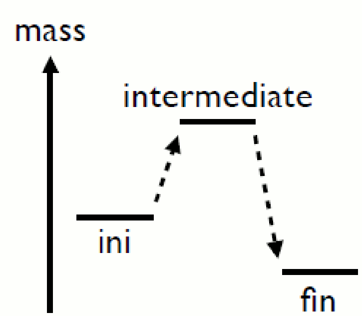
1 TeV



> ~100GeV (1TeV), if interaction is weak (strong)

New particle via quantum effects

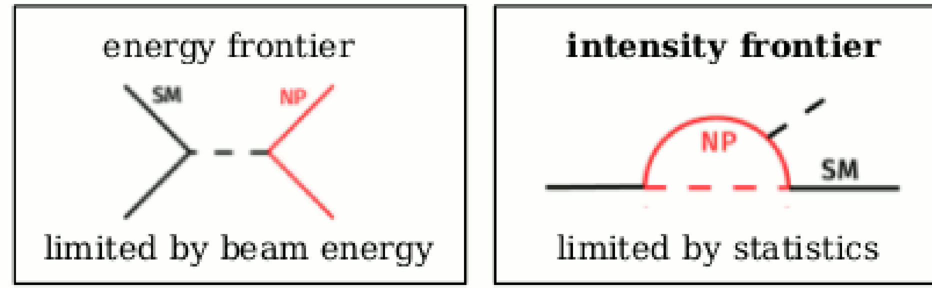




No sharp cutoff for energy scale (cf. LHC search)

— suppressed by $(E/\Lambda)^n$

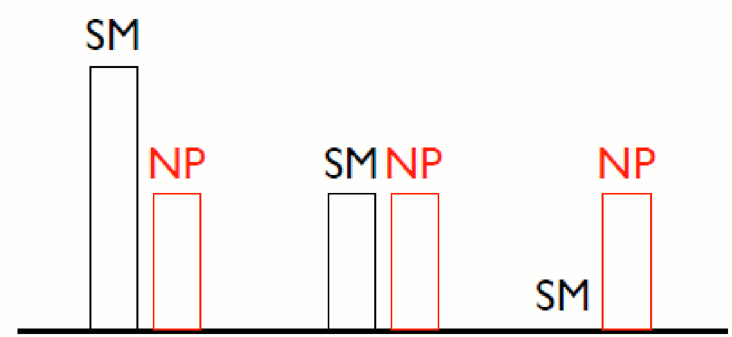
Why flavor physics ?



→ **NP beyond the direct reach of the LHC**

Three classes of SM processes (M.Endo)

$$\mathcal{O}_{\rm obs} = \mathcal{O}_{\rm SM} + \mathcal{O}_{\rm NP}$$

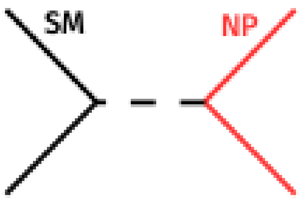


SM tree	loop	forbidden
extremely precise	precision	good but…

Rare B decays

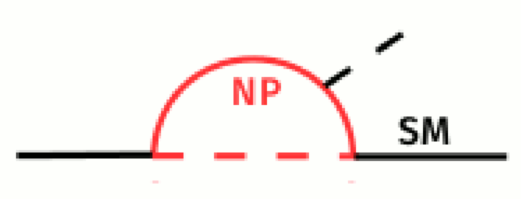
- FCNC are strongly suppressed in the SM: only loops + GIM mechanism
- Any new particle generating new diagrams can change the amplitudes

energy frontier



limited by beam energy

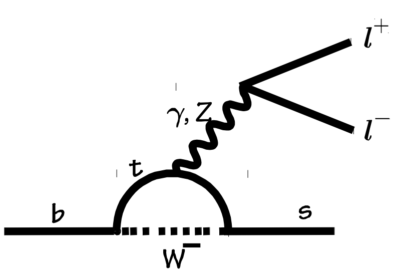
intensity frontier

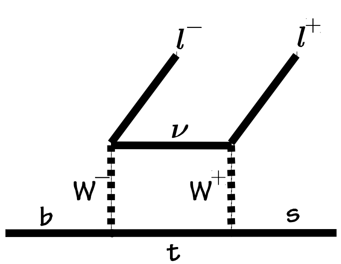


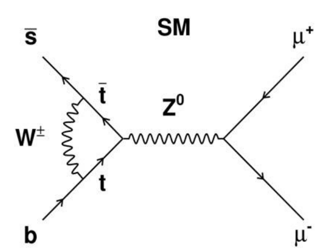
limited by statistics

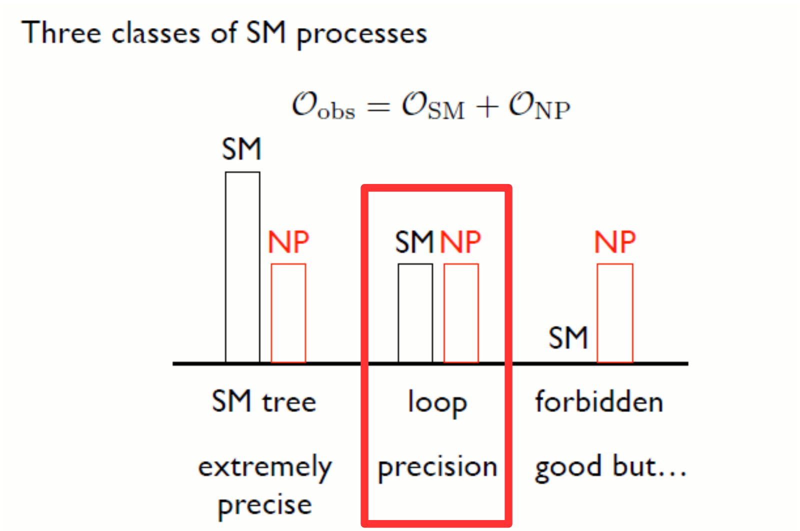
→ **NP beyond the <u>direct</u> reach of the LHC**

New particles can for example contribute to loop or tree level diagrams **by enhancing/suppressing decay rates, introducing new sources of CP violation or modifying the angular distribution of the final-state particles**









Why rare decays ?

We want to find new physics indirectly !

No new physics at tree level: we would have noticed ?

Interference of tree interactions and new physics: this is what CP violation does

Interference of loop induced decays and new physics:

- Only allowed in loops
- Could be SM Z and W, or anything else that is heavy

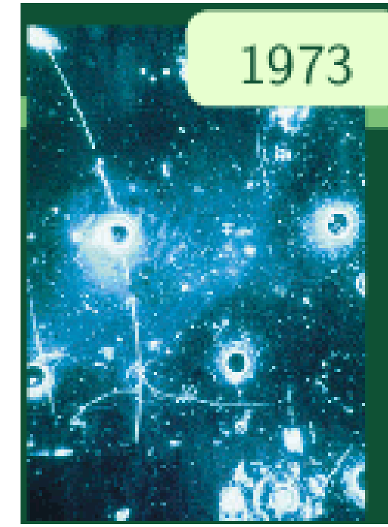
Experimental aspects:

- You want to measure a 50% effect on a rare decay, not a 1% effect on the neutron lifetime. That's very hard.

  $\Rightarrow$ Statistic versus systematic error

Theoretical **clean**: There are many rare decays that are theoretically clean. This is needed as in the end you will compare a measured effect to an SM prediction.

Indirect searches

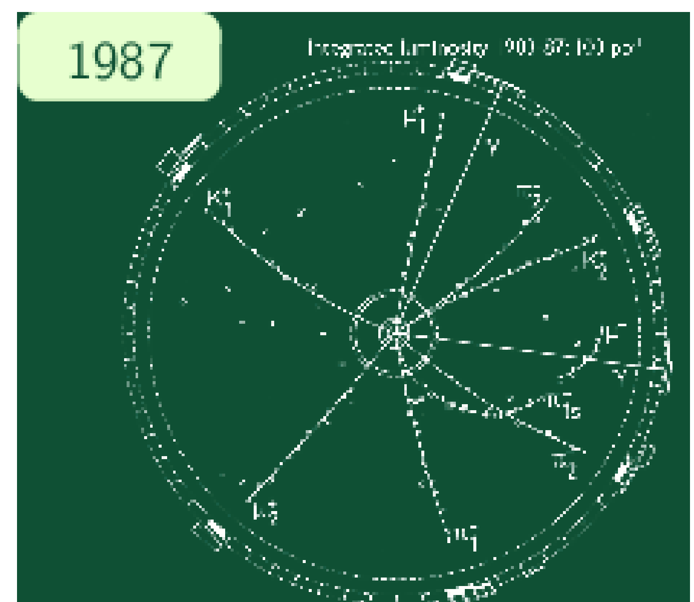


Sensitive to New Physics effects

- When was the Z discovered ?
  - 1973 from $N\nu \rightarrow N\nu$?
  - 1983 at SpS ?
- c quark postulated by GIM , third family by KM

Estimate masses

- t quark from $B\overline{B}$ mixing



Get phases of couplings

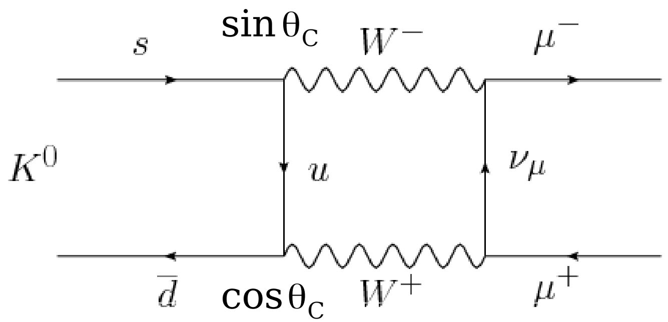
  - Half of new parameters
- Needed for a full understanding

Look in lepton and **flavour** sectors

→ CP asymmetry in the Universe

Illustration of indirect search: $K_L^0 \to \mu\mu$

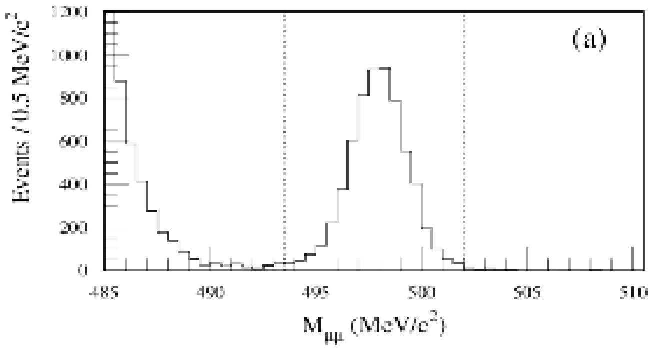
$K_L \to \mu^+\mu^-$ decay can be generated by the box diagram:



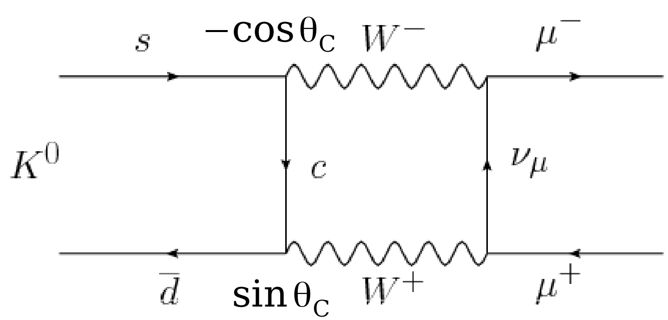
$K_L^0 \to \mu\mu$ was not observed though expected

Now BF is measured to be $(6.84 \pm 0.11)10^{-9}$

[Ambrose et al, 2000]



in a renormalisable gauge theory, is expected to give a branching ratio of $\mathbf{g^4 \sim \alpha^2 \sim 10^{-4}}$, with α the fine structure constant.



GIM observed that, with a fourth quark, there is a second diagram, with c replacing u. In the limit of exact flavour symmetry, the two diagrams cancel.

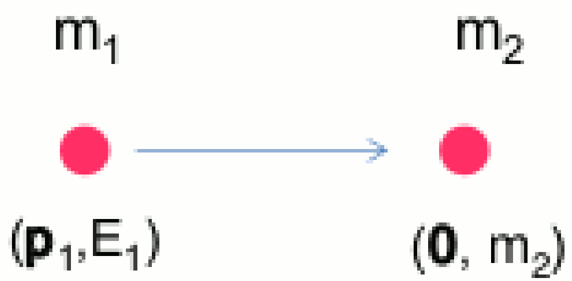
[Glashow, Iliopoulos and Maiani, 1970]

The breaking of flavour symmetry induces a mass difference between the quarks, so the sum of the two diagrams is of order $g^4(m_c^2 - m_u^2)/m_W^2 \sim \alpha^2 m_c^2/m_W^2$.

With the measured charm quark mass $m_c \sim 1.27$ GeV, the predicted rates are in agreement with observation.

$\Rightarrow$ but no experimental evidence of a fourth quark...

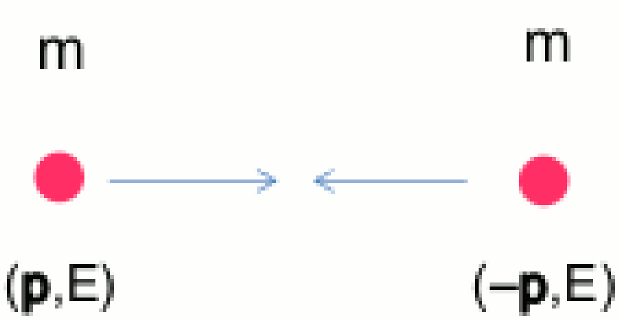
Proton beam
Fixed target experiment



$\sqrt{s}$ = 25 GeV >> 3 GeV

- In proton collision, other particles (than J/ψ) are also produced.

Electron beam
Collider experiment



$\sqrt{s}$ = 3 GeV

- CM energy is efficiently used to produce J/ψ .

Proton beam
Fixed target experiment

m_1 m_2

$(\mathbf{p}_1, E_1)$ $(\mathbf{0}, m_2)$

$m_1 = 0.938$ GeV
~ 1 GeV : proton
$m_2 \sim 9$ GeV : Beryllium
$E_1 = 30$ GeV

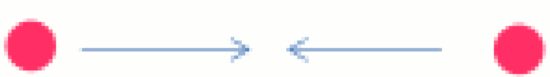
CM energy
(center-of-mass)

$$\sqrt{s} = \sqrt{(E_1 + m_2)^2 - |\vec{p_1}|^2}$$
$$= \sqrt{2E_1 m_2 + m_1^2 + m_2^2}$$

= 25 GeV >> 3 GeV

Electron beam
Collider experiment

m m



$(\mathbf{p}, E)$ $(-\mathbf{p}, E)$

m = 0.511 keV

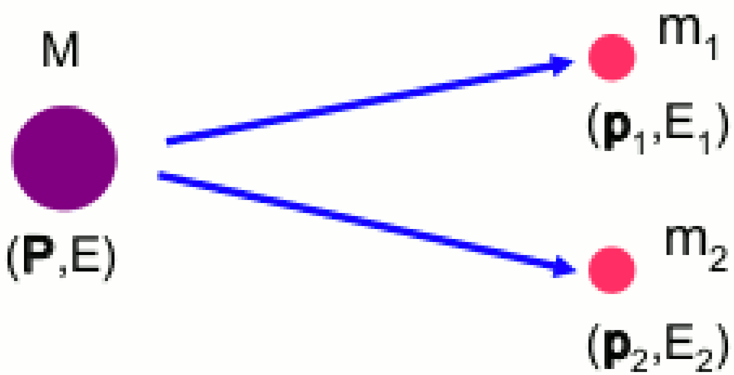
E = 1.5 GeV

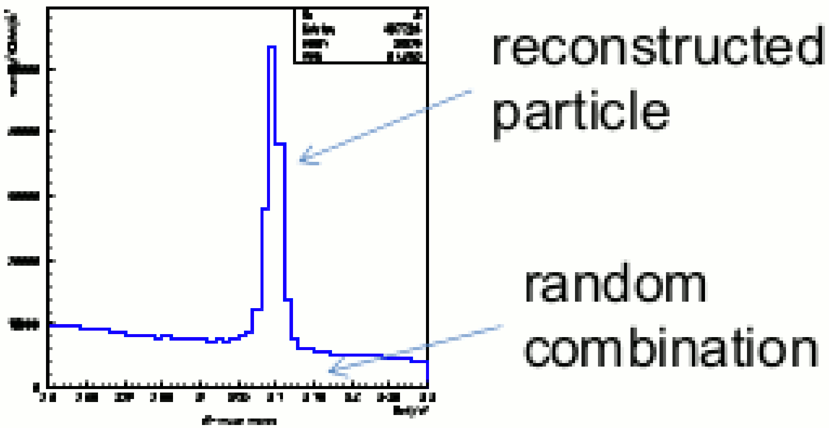
CM energy $\sqrt{s} =$ 2E = 3 GeV

How to detect particles

Most short-lived particles generated by the collision (, in which we are interested), decay inside the detector, but we can reconstruct them if we know the 4-momentum of decay products.

Simple case: 2-body decay.





energy and momentum conservation

$$E = E_1 + E_2$$

$$\mathbf{P} = \mathbf{p}_1 + \mathbf{p}_2$$

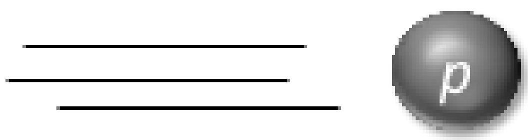
$$M^2 = E^2 - |\mathbf{P}|^2 = (E_1+E_2)^2 - |\mathbf{p}_1+\mathbf{p}_2|^2$$

In reality, there are many particles in a final state; we don't know which is the correct combination.

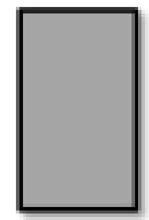
J/ψ (1974)

Experiment carried out by S. Ting group at Brookhaven National Laboratory

– fixed target experiment:

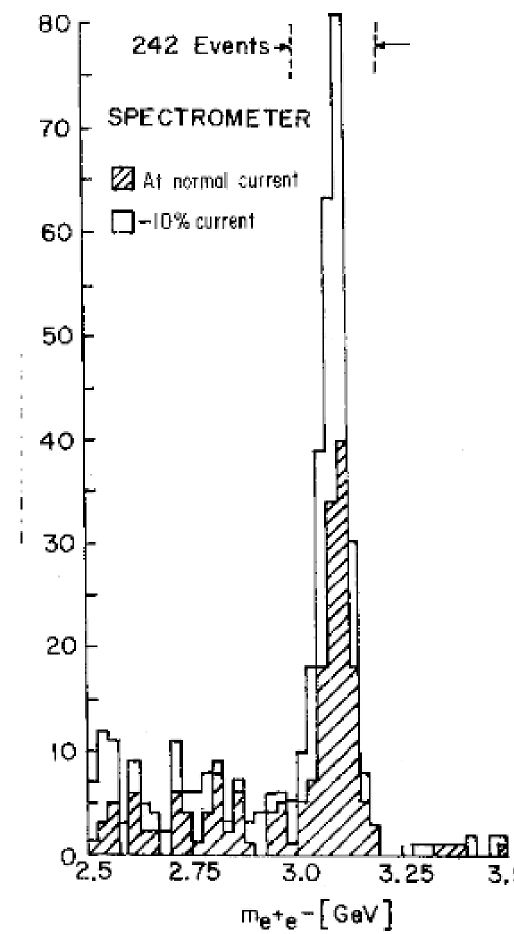


Energetic proton accelerated by an accelerator



Beryllium target

$$p + \text{Be} \rightarrow (e^+ + e^-) + x \quad (x \ldots \text{anything})$$



– particle found at 3.0 GeV/c^2

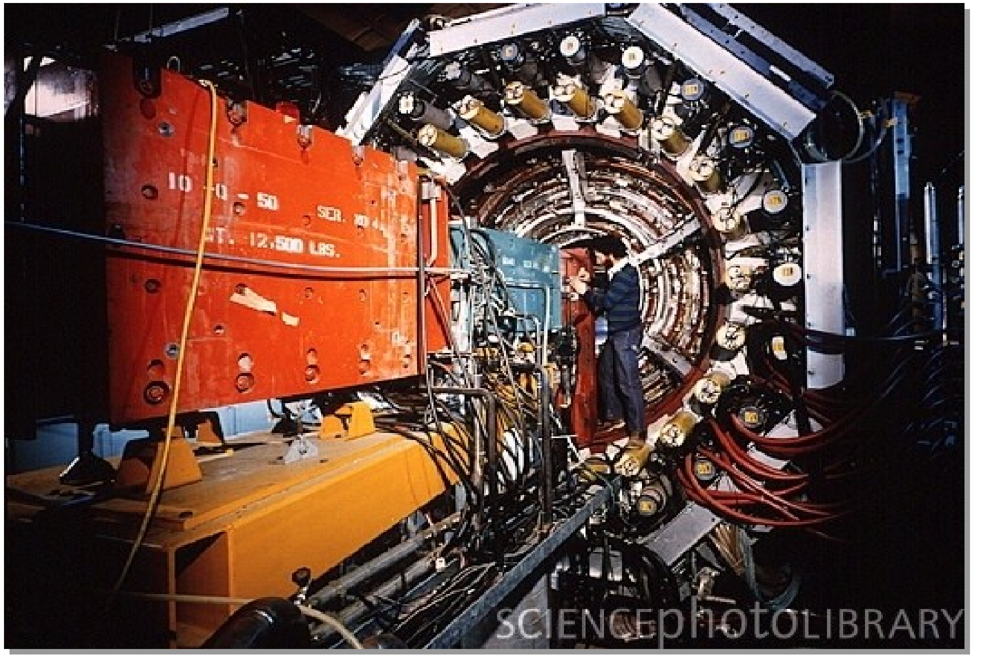
– They coined name of ''J'' to the particle

J/ψ (1974)

Experiment carried out by B. Richter group

– $e^+ e^-$ collider experiment

Contrarily to the S. Ting's group, B. Richter's group tried to find out a new particle by scanning the $e^+ e^-$ collision energy from 2.4 GeV by 0.2 GeV step



MARK-I detector at SLAC

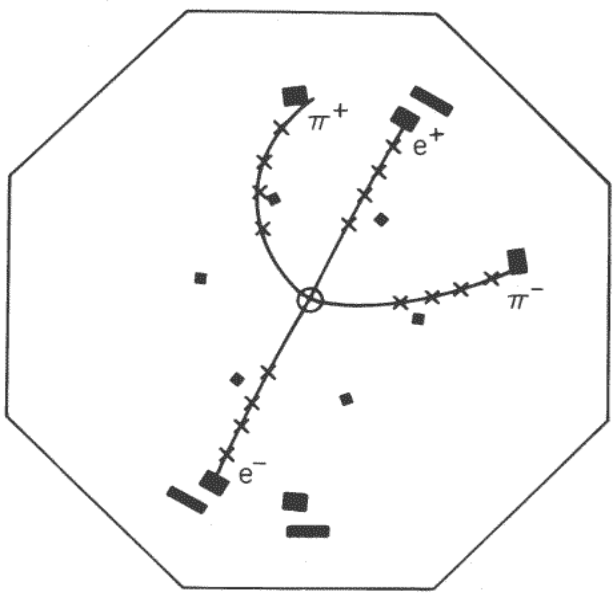
J/ψ (1974)

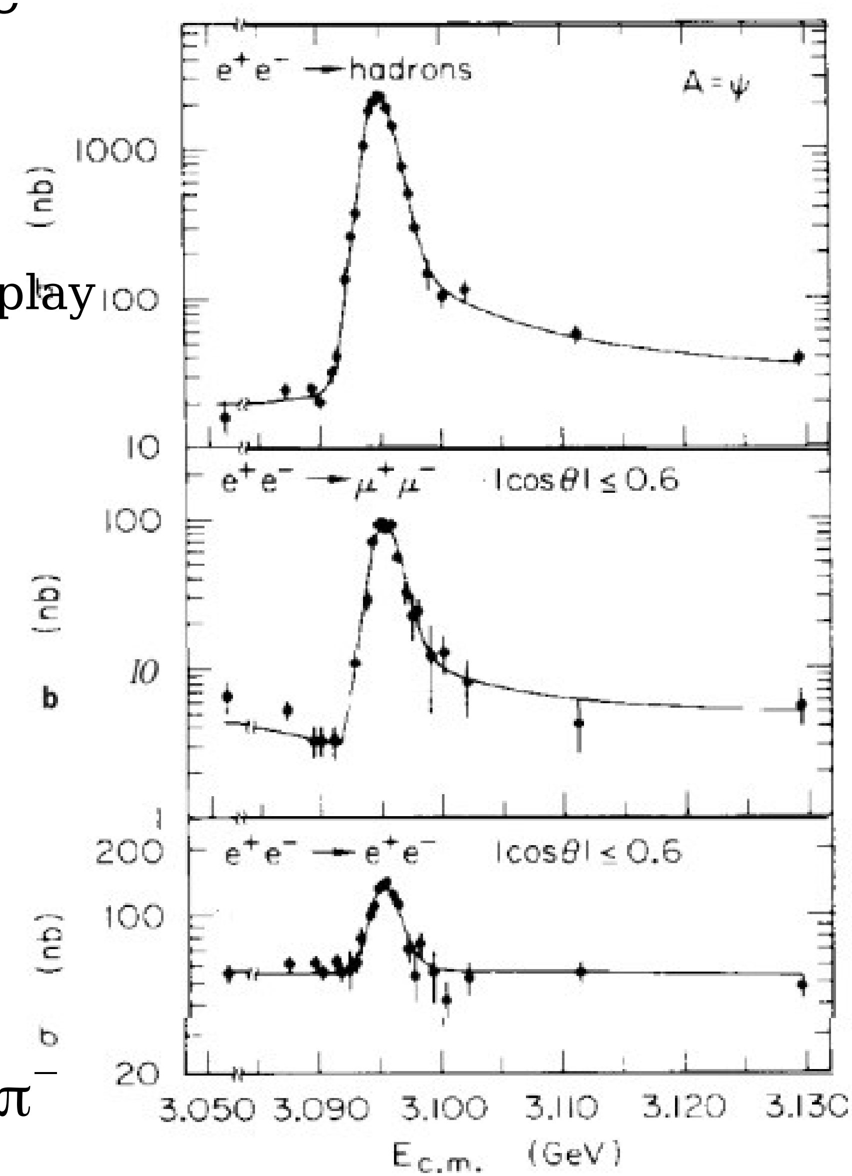
Experiment carried out by B. Richter group

– They observed a bump at 3 GeV/c^2

– Event display

The particle name was taken from its event display



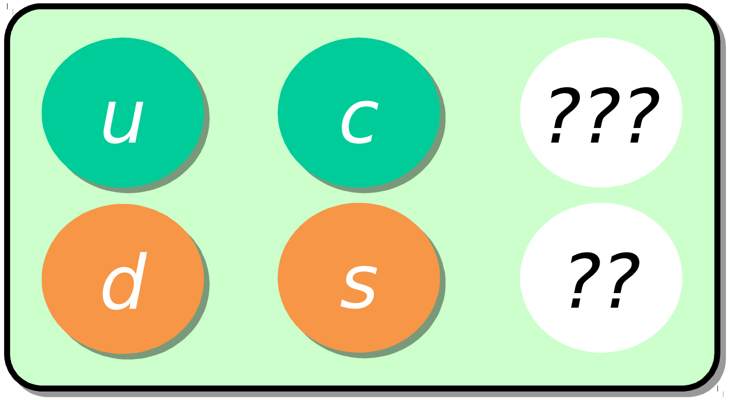


$$e^+ + e^- \rightarrow (e^+ + e^-) + \pi^+ + \pi^-$$

J/ψ (1974)

Discovery of the 4th quark

Finally, the J/ψ particles were identified as $c\bar{c}$ mesons



Two names for the same particle

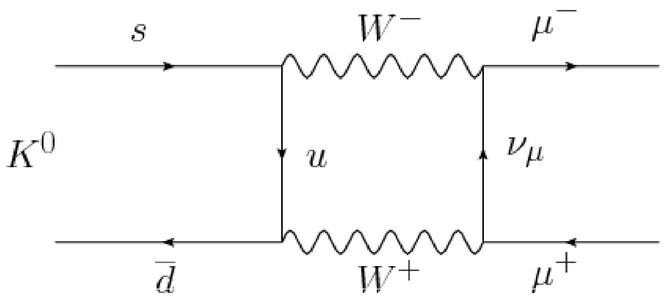
As both groups published the discoveries of J and ψ on the same day (11th Nov 1974), the particle was given 2 names: J/ψ

November revolution

⇒ Nobel Prize 1976 rewarded Richter and Ting

indirect search: $K_L^0 \to \mu\mu$

$K_L \to \mu^+\mu^-$ decay can be generated by the box diagram:



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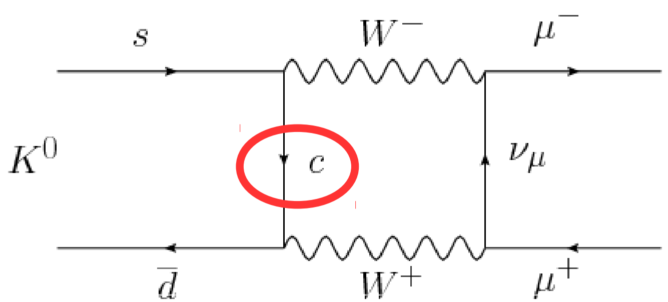

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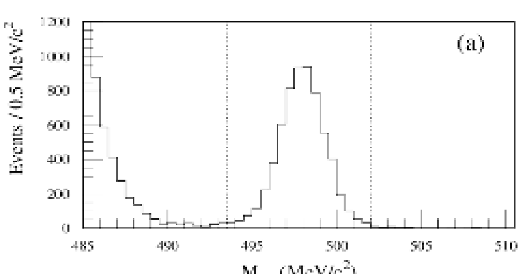
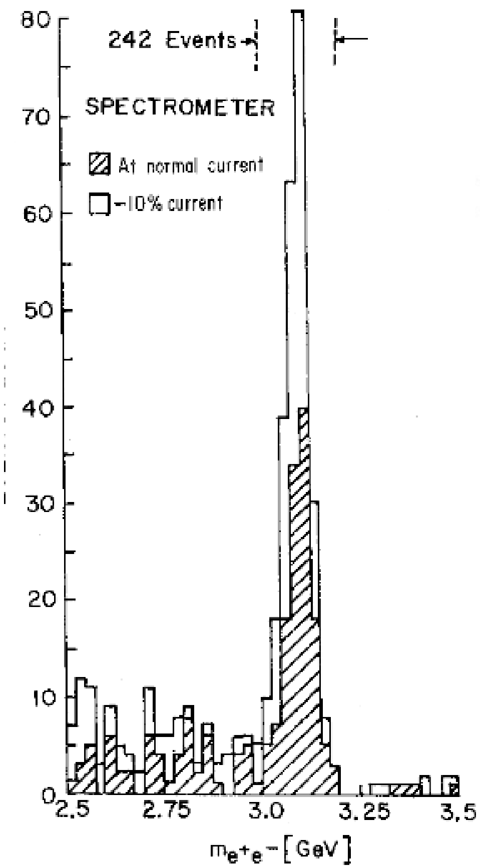


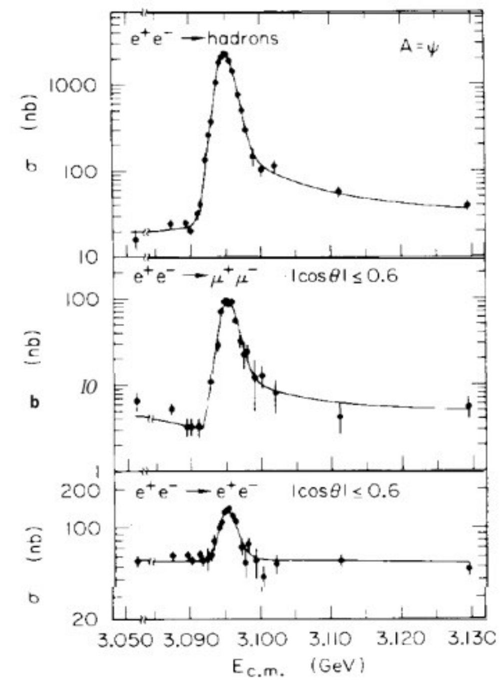
[Ambrose et al, 2000]

direct search: $J/\psi \to ee$

→ c quark eventually observed in 1974 [Ting], [Richter]

J/ψ





With the measured charm quark mass $m_c \sim 1.27$ GeV, the predicted rates are in agreement with observation.

W and Z bosons discoveries

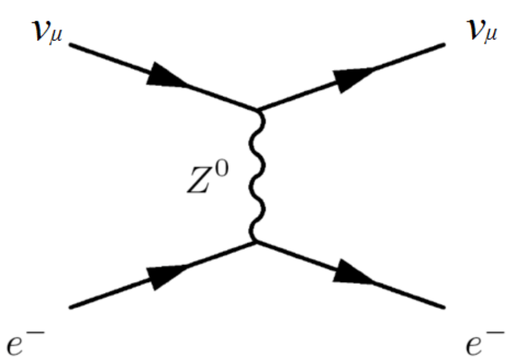
The weak force is essentially as strong as the electromagnetic force, but it appears weak because its influence is limited by the large mass of the Z and W bosons. Their mass limits the range of the weak force to about 10^{-18} meters, and it vanishes altogether beyond the radius of a single proton.

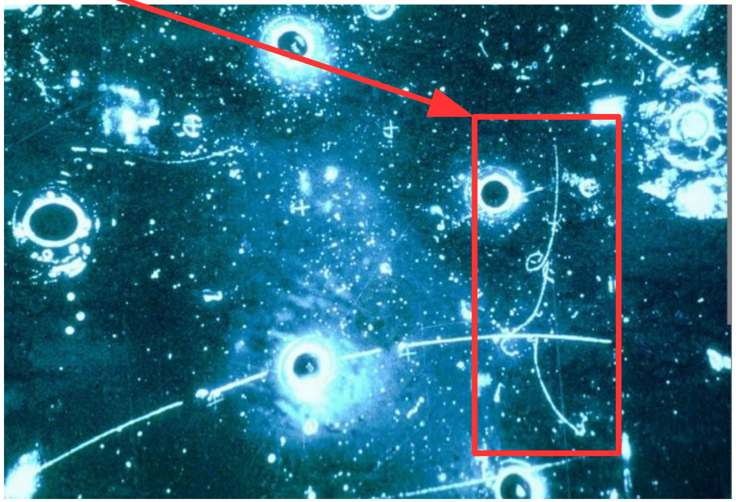
Sheldon Glashow, Abdus Salam and Steven Weinberg developed in the 1960s the theory in its present form, when they proposed that the weak and electromagnetic forces are actually different manifestations of one electroweak force.

First, in 1973, came the observation of neutral current interactions as predicted by electroweak theory at Gargamelle bubble chamber (Andre Lagarrigue et al)

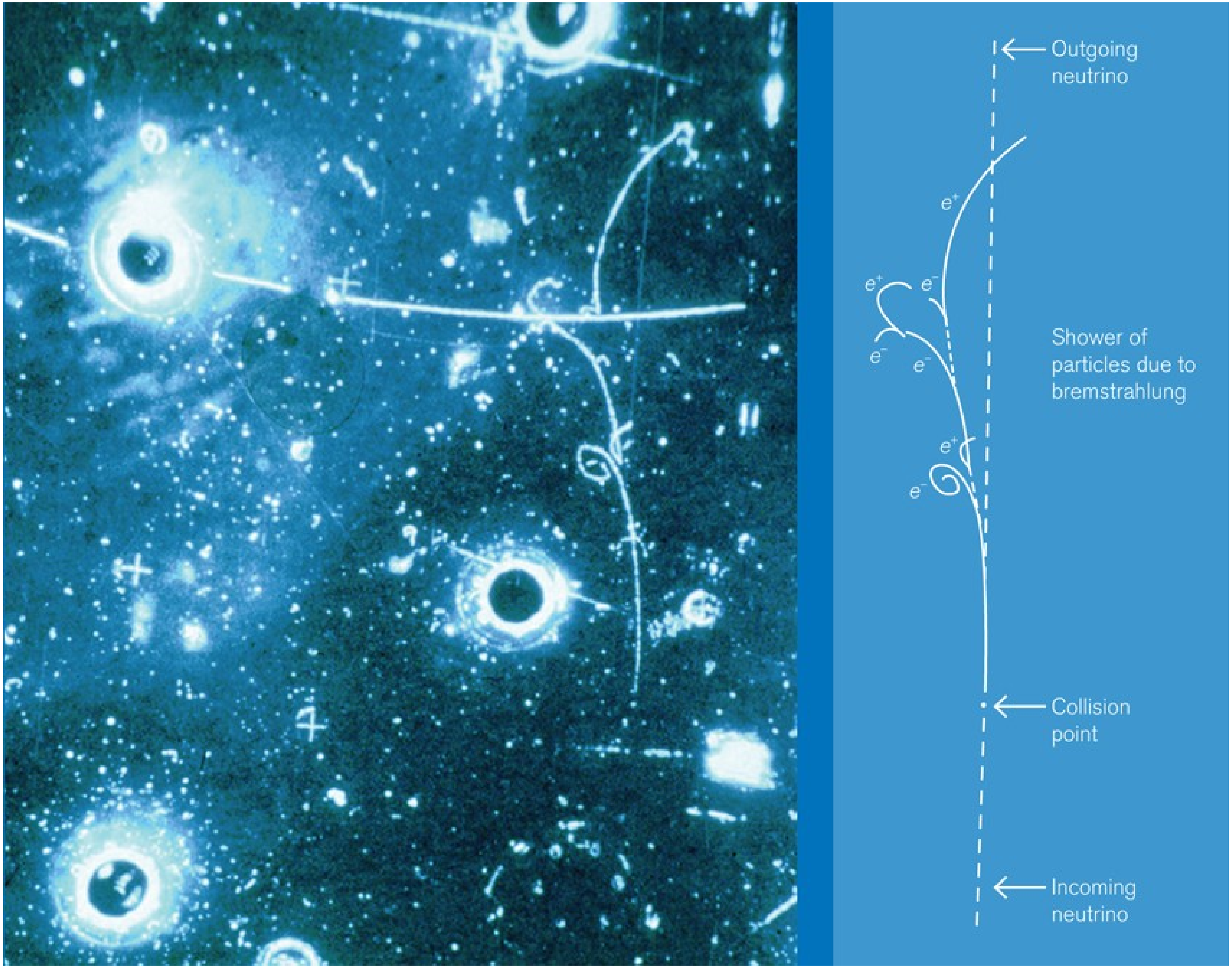
Neutrinos are particles that interact only via the weak interaction, and when the physicists shot neutrinos through the bubble chamber they were able to **detect evidence of the weak neutral current, and hence indirect evidence for the Z boson.**

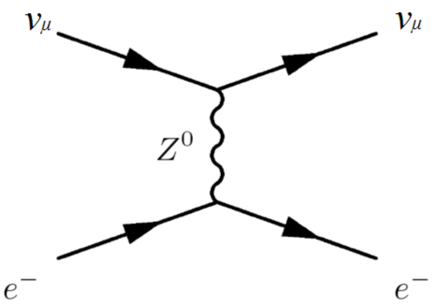
neutrino beam



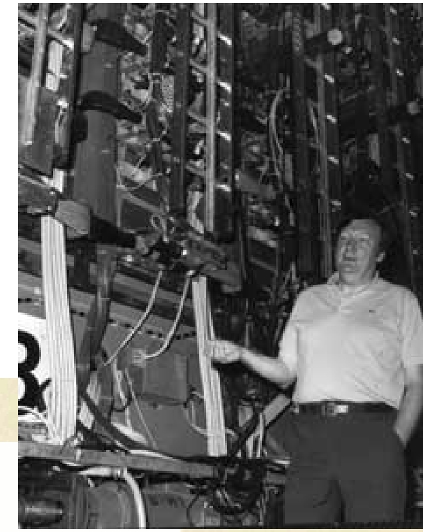


W and Z bosons discoveries



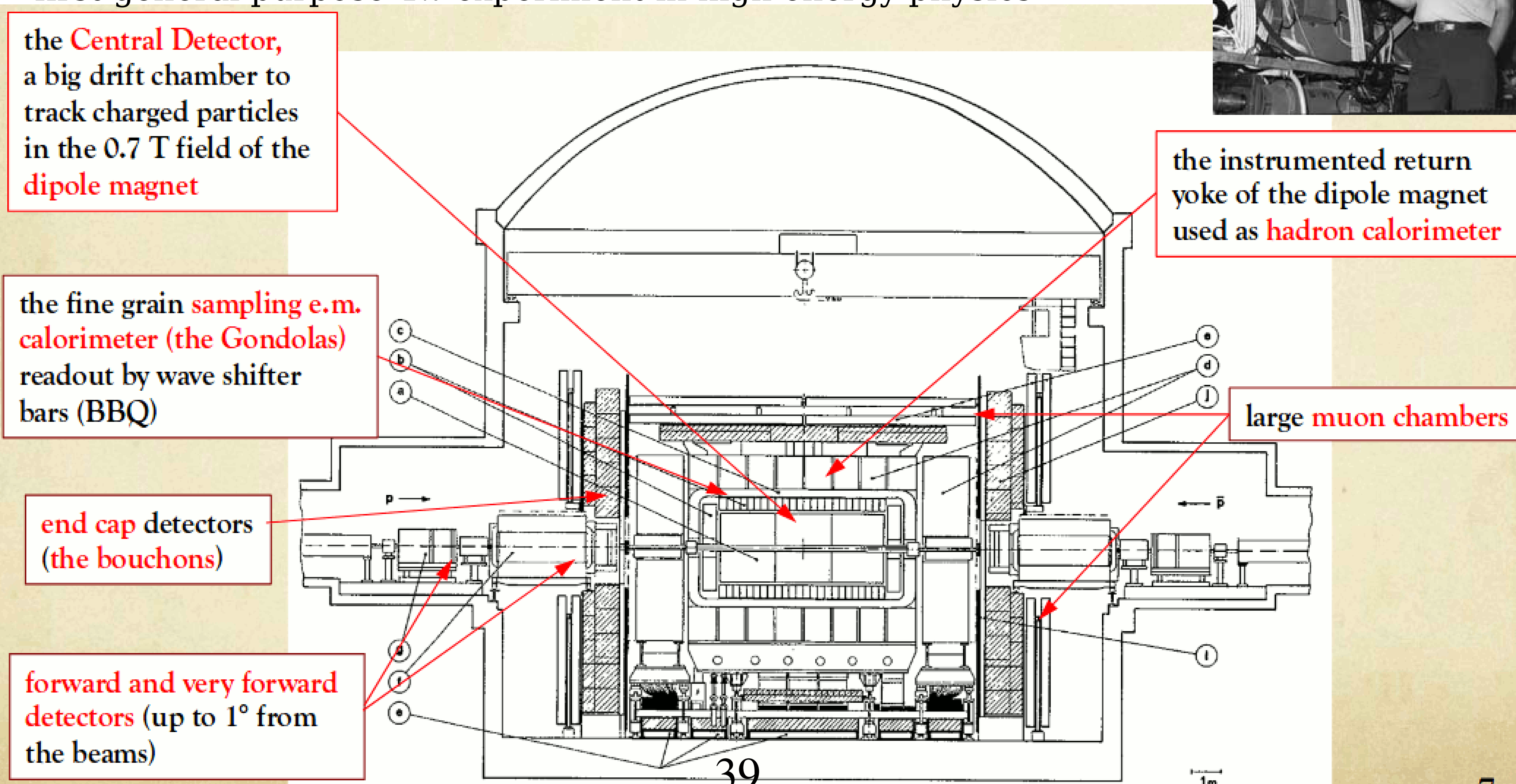


W and Z bosons discoveries

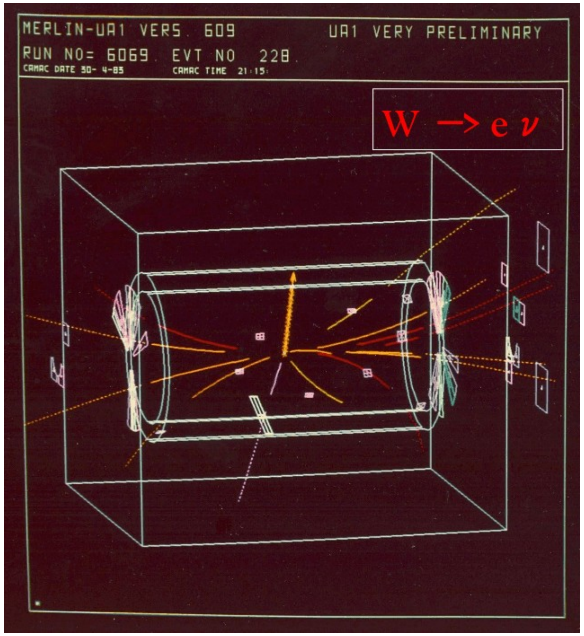


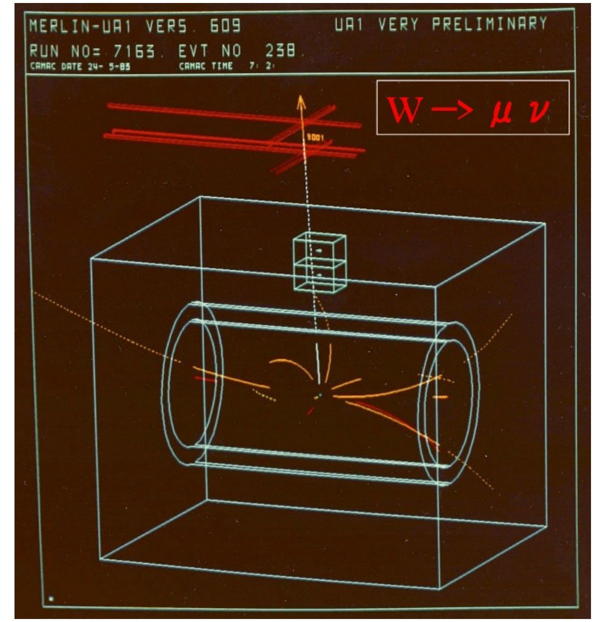
Super Proton Synchrotron, proton-antiproton collider, where unambiguous signals of W bosons were seen in January 1983 during a series of experiments made possible by Carlo Rubbia and Simon van der Meer. Experiments are UA1 and UA2.

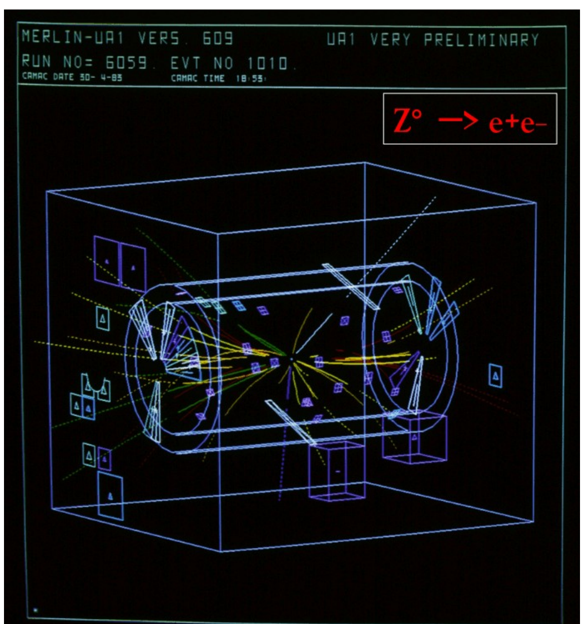
270 GeV per beam, enough energy to produce W and Z particles
first general purpose 4π experiment in high energy physics

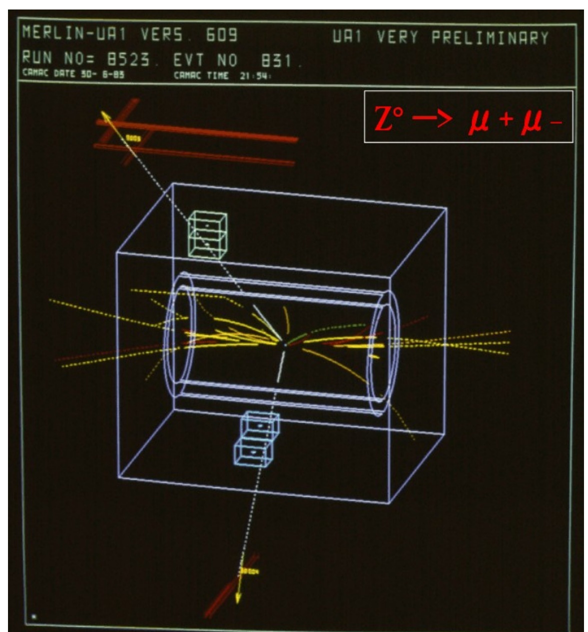


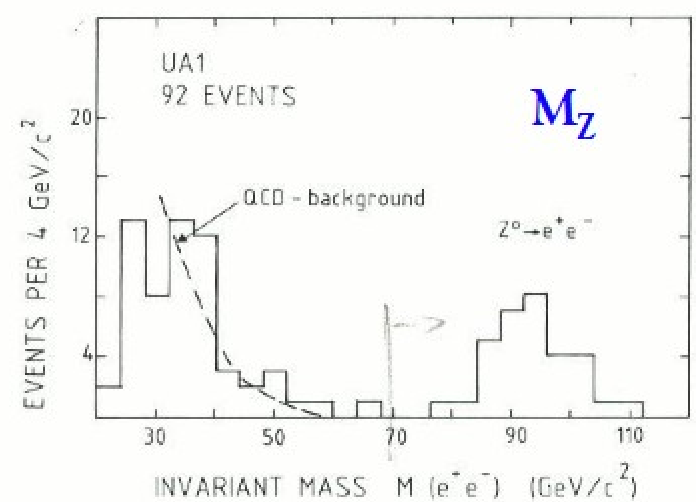
W and Z bosons discoveries











Rubbia and van der Meer were promptly awarded the 1984 Nobel Prize in Physics.