Trigger and Data Acquisition (DAQ) Systems at Belle II Experiment

Chunhua LI

Liaoning Normal University

IHEP, Beijing

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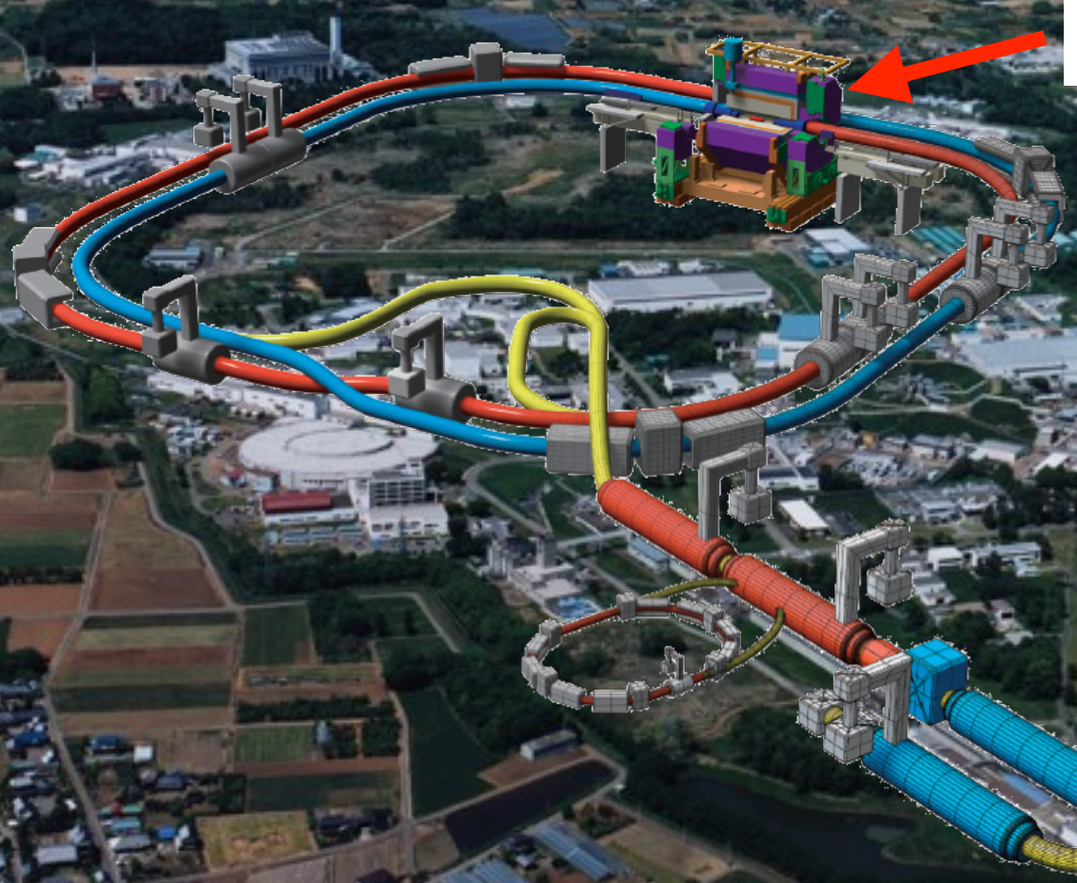
SuperKEKB

An asymmetric electron-positron collider

e^+~ 4GeV e^-~ 7GeV

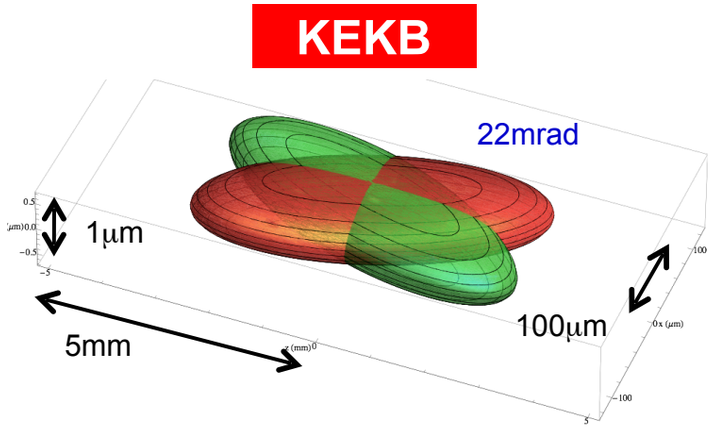
~3km circumference

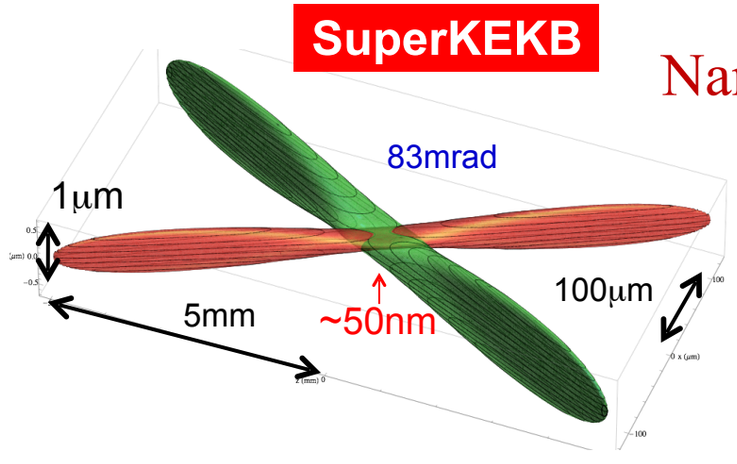


Belle II detector

@KEK, Tsukuba
One hour away from Tokyo

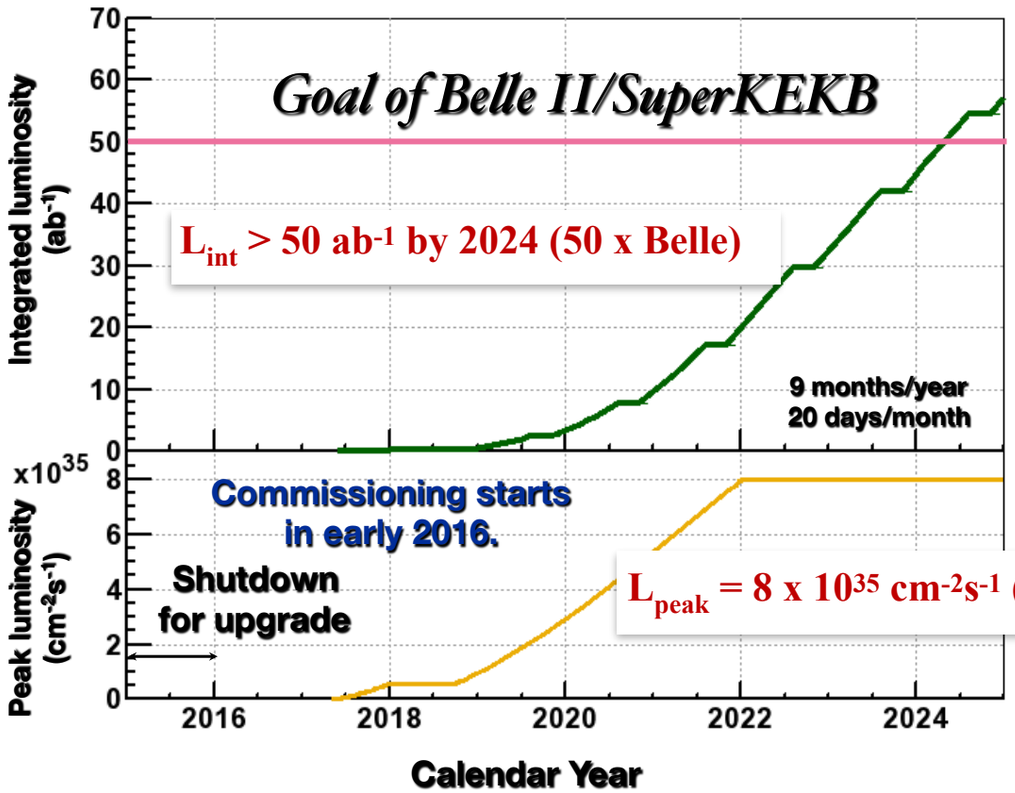
SuperKEKB

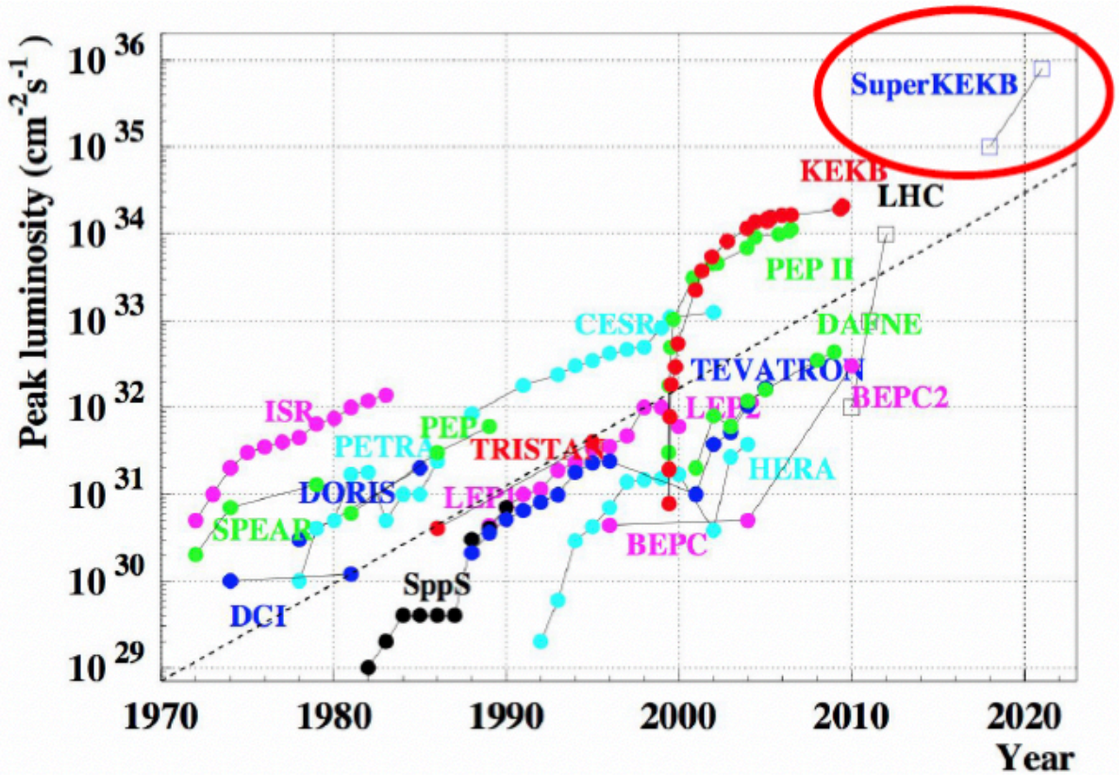




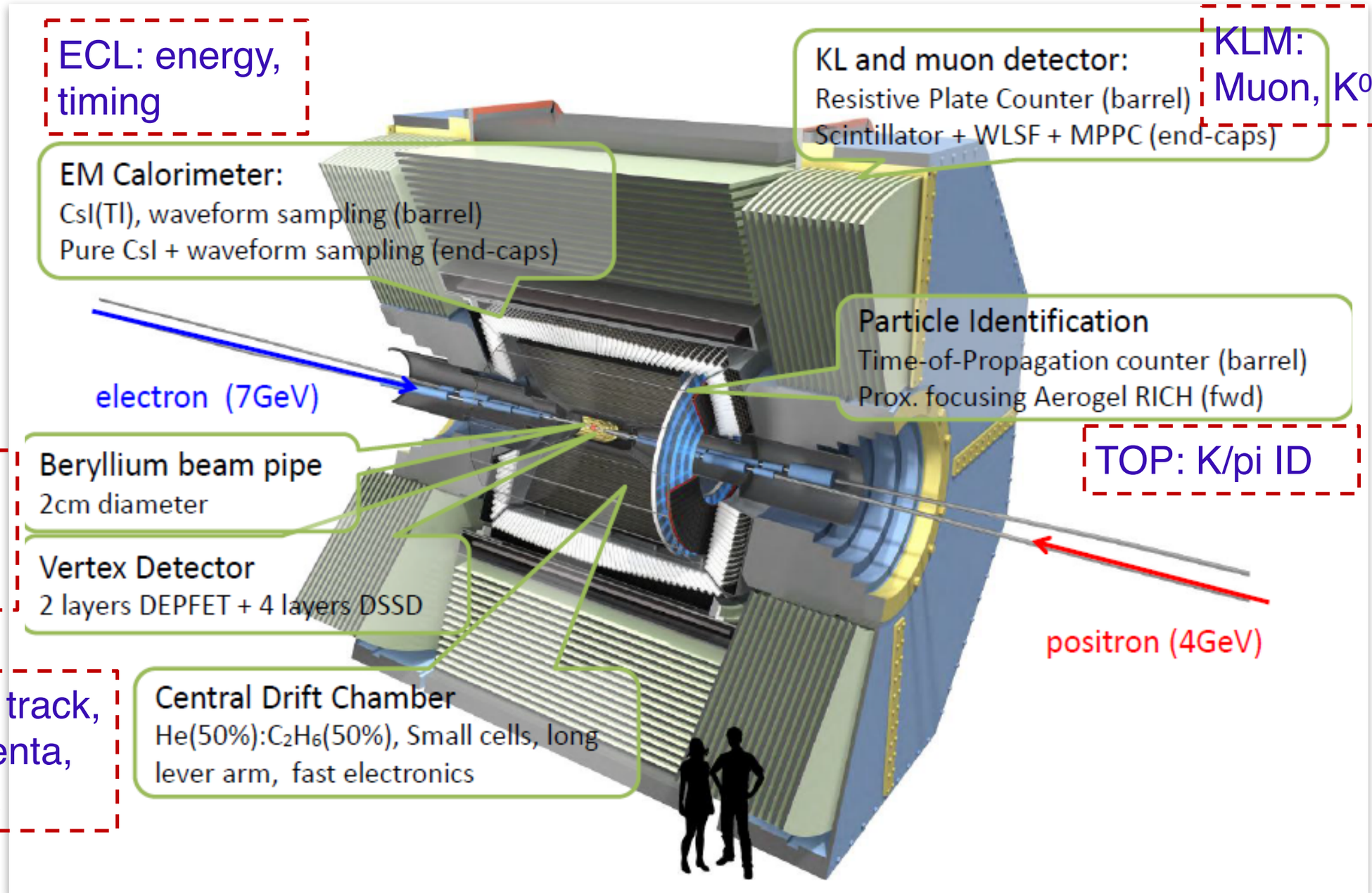
Nano-Beam Scheme

SuperKEKB Luminosity Project





Belle II Detector



Belle II Collaboration

722 Colleagues
104 Institutions
24 Countries/regions

Awaiting for the First Collision

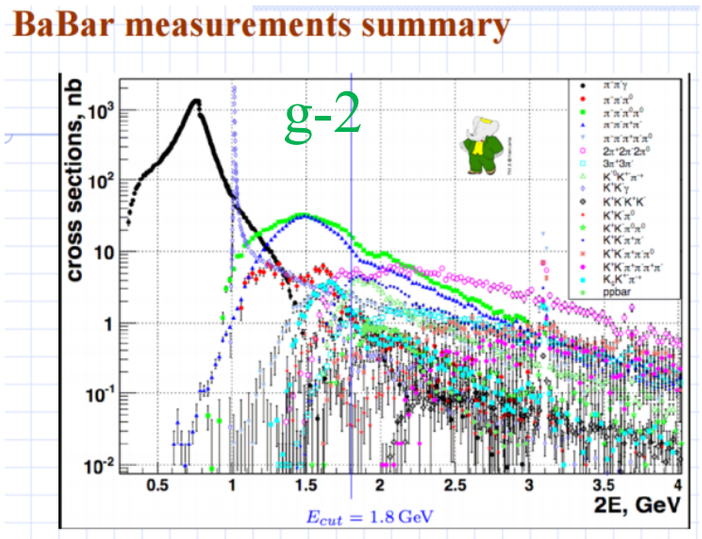
Live broadcast of SuperKEKB/Belle II first collision started on 12:00, April 20, 2018 on Niconico

http://live.nicovideo.jp/gate/lv312372695

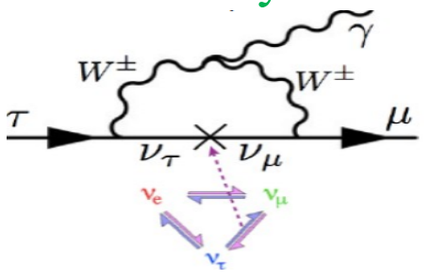
First collision will happen in the next few days!

Trigger and DAQ Challenges

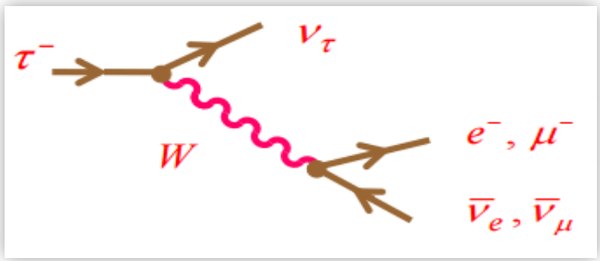
- High Luminosity, High background
  - Peaking luminosity at SuperKEKB : ***$8x10^{35}$ $cm^{-2}s^{-1}$ (40 x KEKB)***
  - Total physics trigger rate ~15kHz@$8x10^{35}$ $cm^{-2}s^{-1}$
  - Large beam-related, QED backgrounds
  - Huge data flow from pixel detector (~1MB/event)
- Physics processes triggers
  - Y(4S)+continuum: almost 100% efficiency
  - Low multiplicity processes challenge trigger



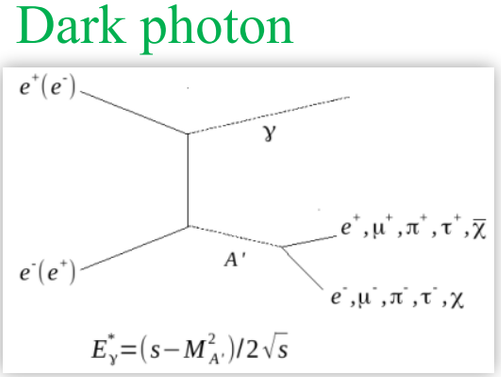
LFV tau decay



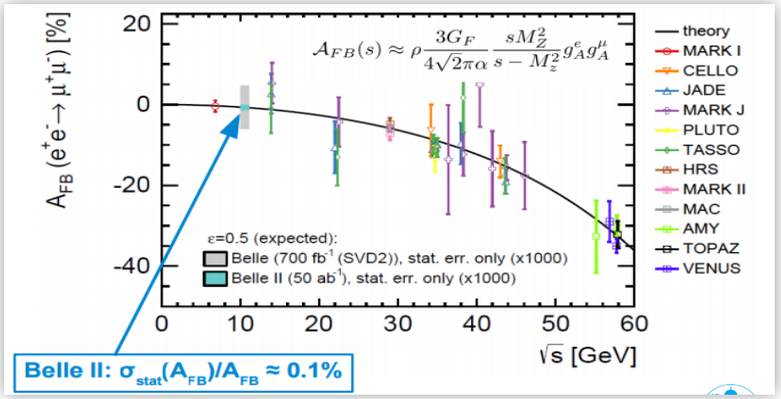
Leptonic tau decay



Dark photon



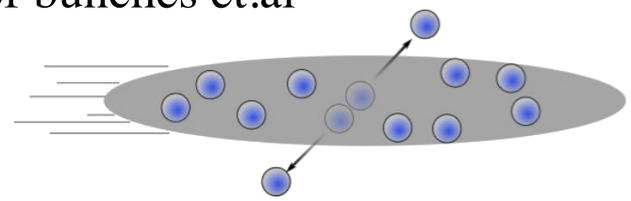
Precision electroweak tests



Belle II Beam Background

- Due to the low final state particle multiplicity of dark matter processes, background from beams become a major challenge.
- Total background is significantly higher than Belle

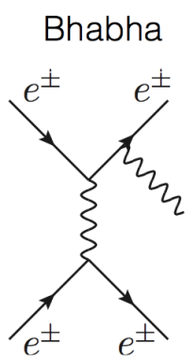
- **Touschek effect**
  - Intra bunch scattering
  - Rate ∝ the inverse beam size, number of bunches et.al
  - Suppressed with movable collimators



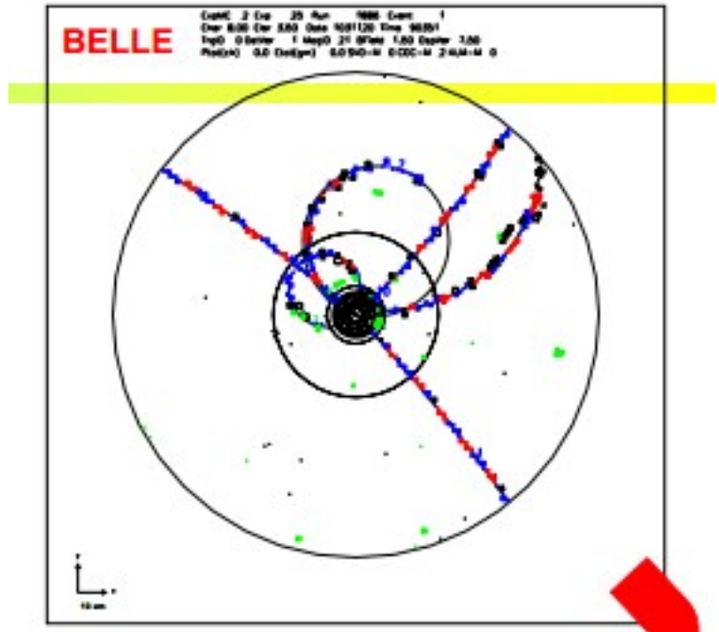
- **Beam gas**
  - Coulomb and bremsstrahlung scattering by the residual gas atoms
  - Rate ∝ the vacuum level and the beam current

- **Synchrotron radiation**
  - Rate ∝ the beam energy squared and magnetic field squared

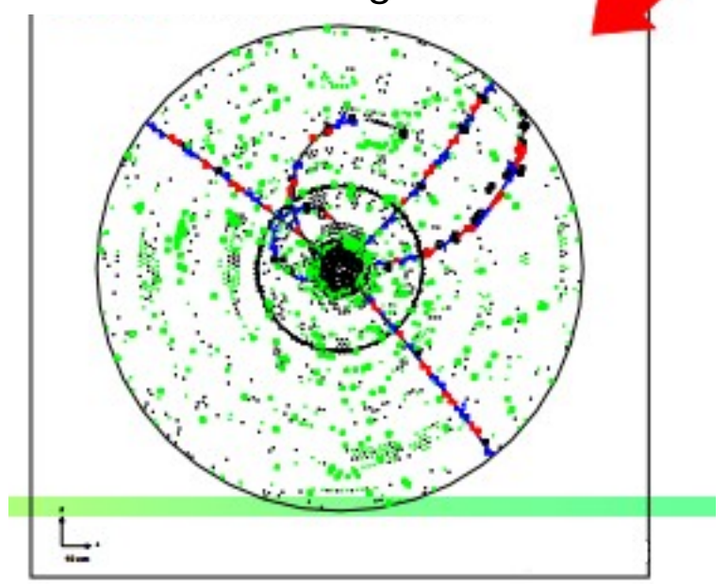
- **Physical backgrounds**
  - Bhabha ee→(γ)ee
  - Two photon: ee→eeee
  - Rate ∝ luminosity



Dominant when luminosity is high



Estimate ~20xBelle bkg at Belle II



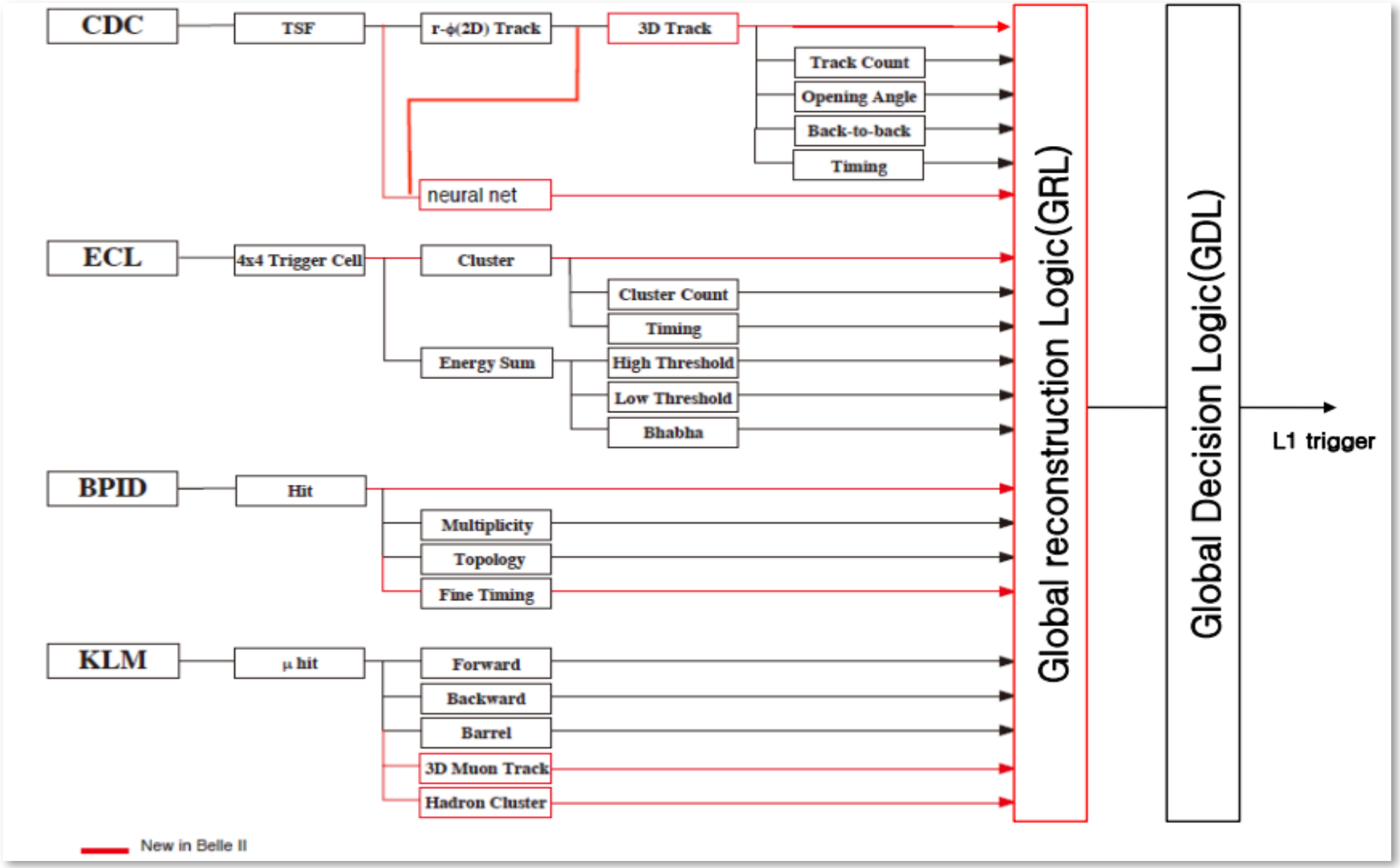
Trigger

Scheme: Hardware trigger + Software trigger

- Level 1 (L1): hardware based
- High Level Trigger (HLT): software based, a component of DAQ

L1 Trigger Scheme

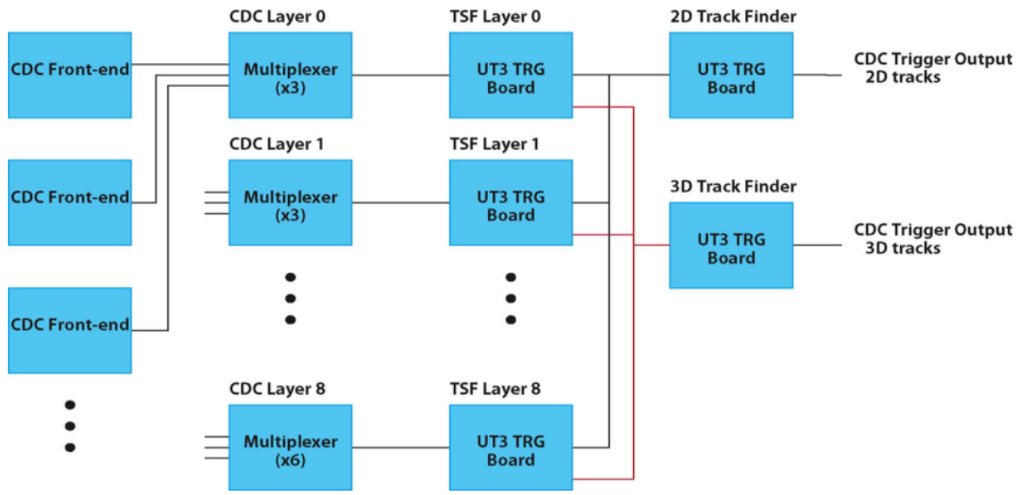
Sub-Detector Triggers + Global Decision Logic (GDL)



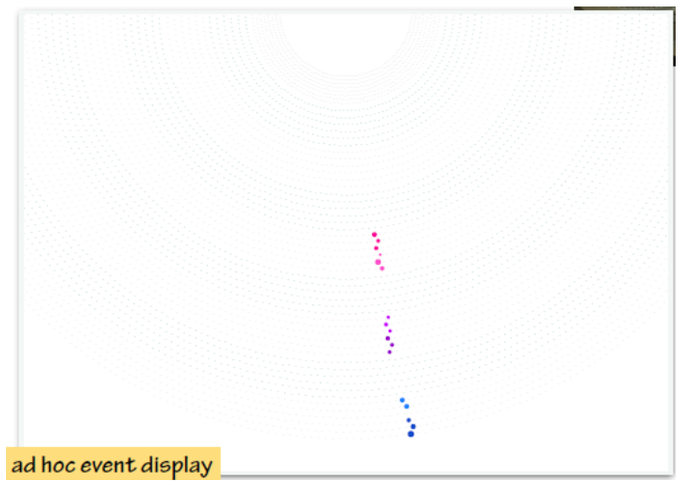
Trigger Rate < 30 kHz

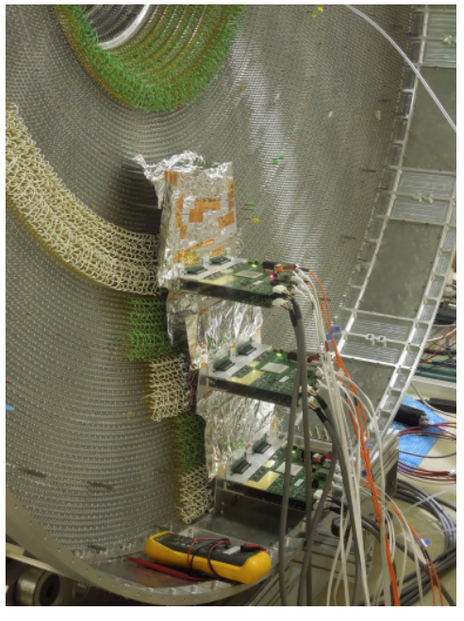
CDC Trigger

- Track segment finder (TSF)
  - Realized using one universal trigger board (UT3)
  - 9 UT3 boards in total
- 2D Track Finder
  - Aiming at charged track with Pt>0.3 GeV
  - Using conformal transformation to detect circle
- 3D Track
  - Measurement of the axial coordinate of a track
  - Neuro network
  - 3D finder



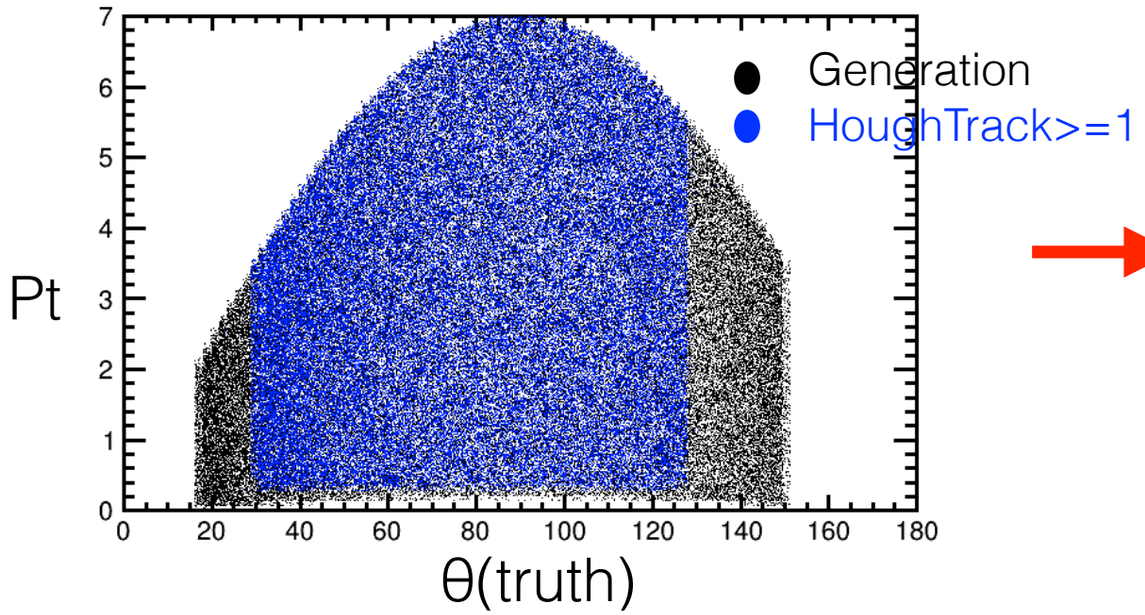
Event Display

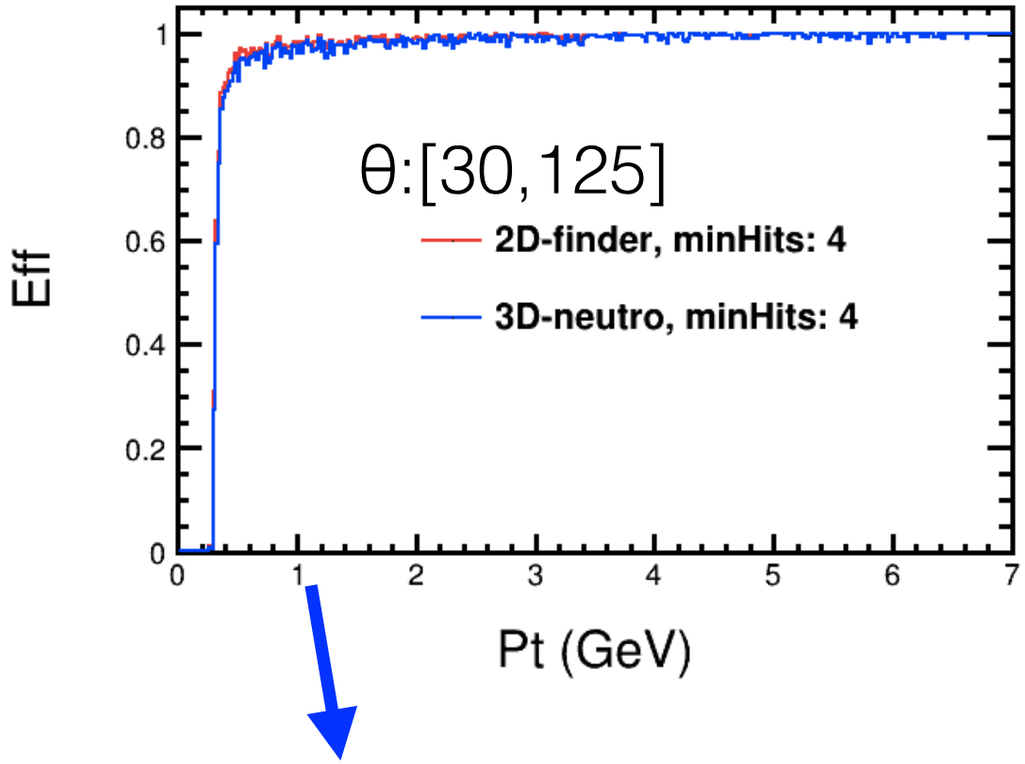


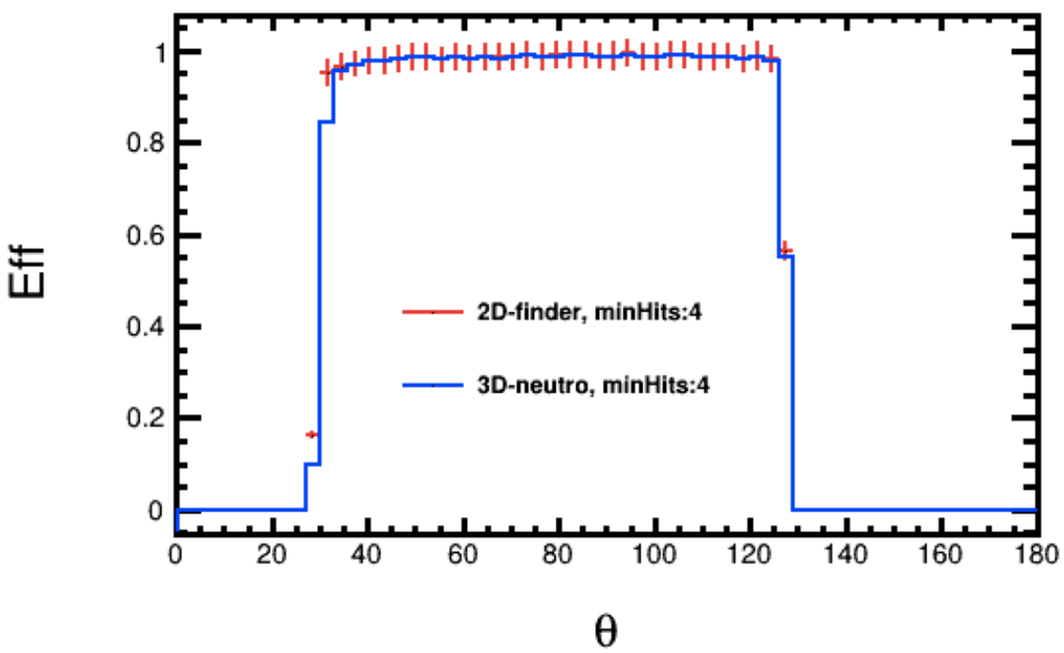


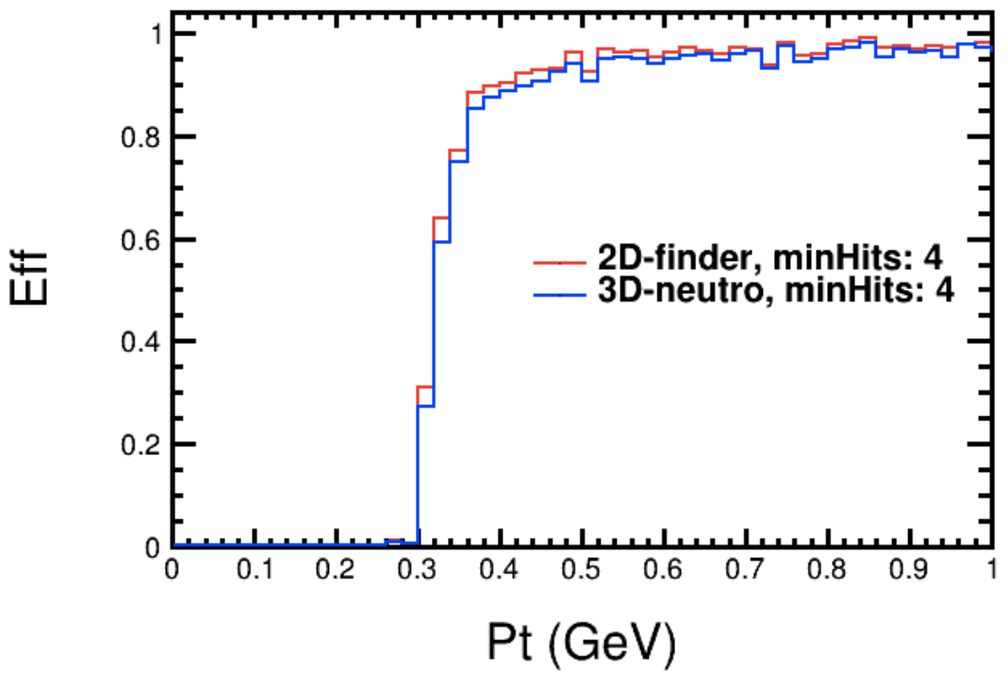
Study based on TSIM

Tracking Efficiency

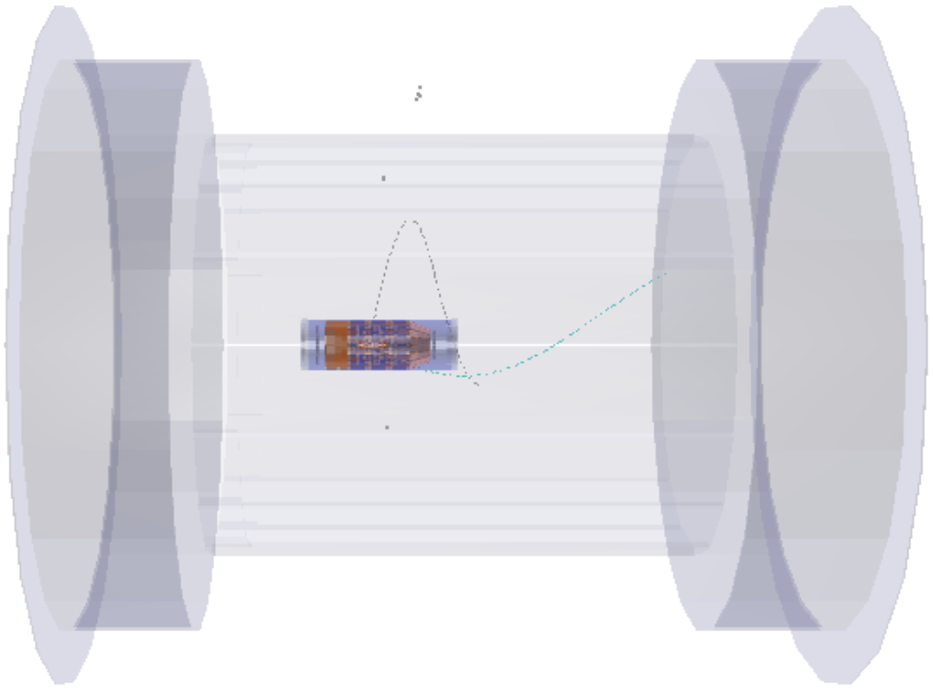


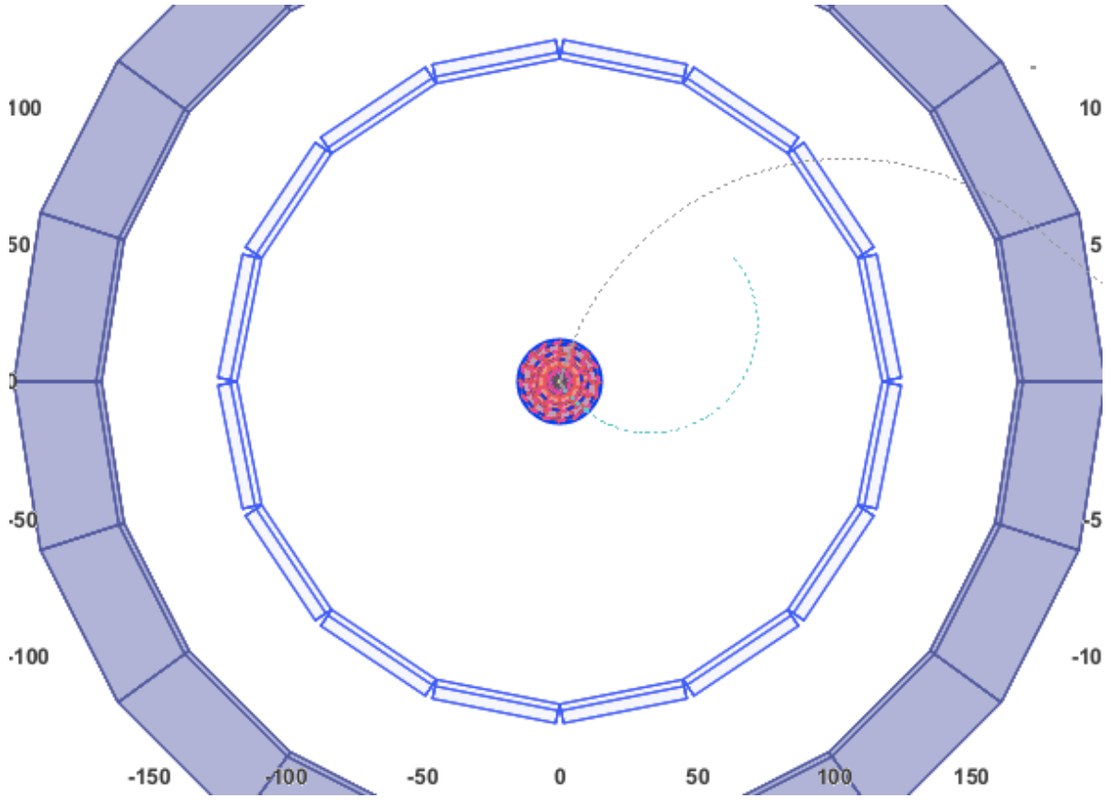




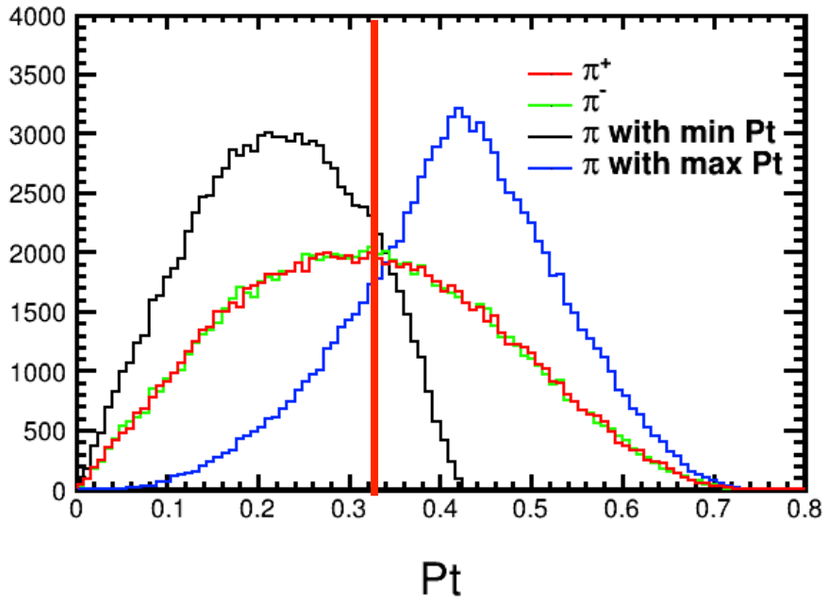


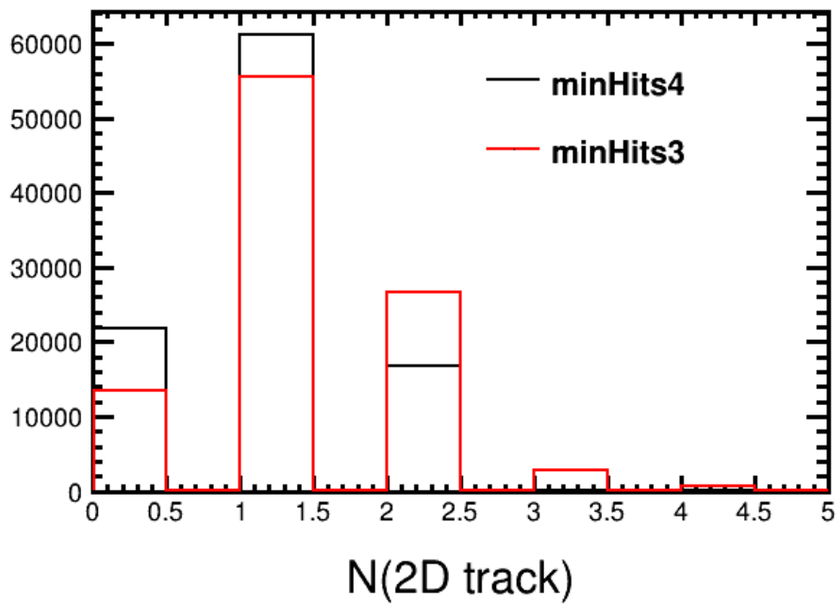
$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S), \Upsilon(1S) \to$ Invisible



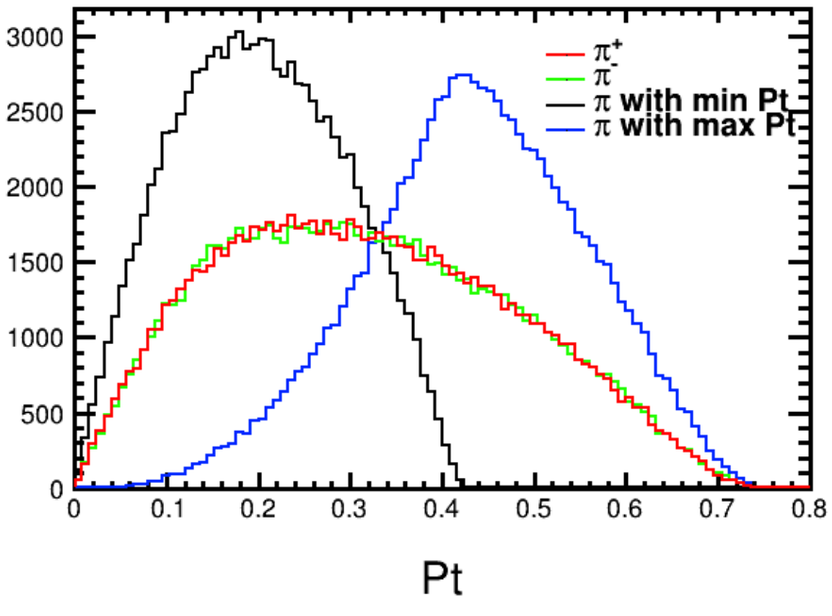


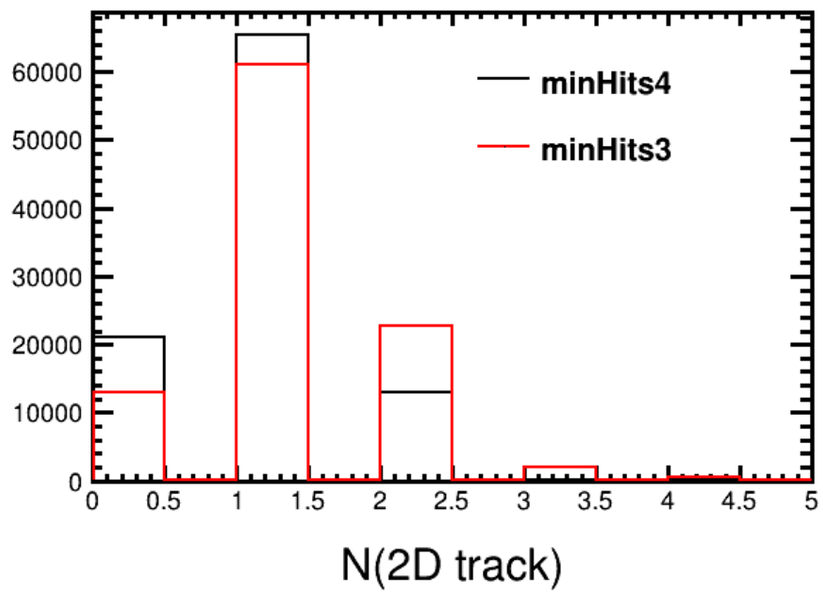
$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S), \Upsilon(1S) \to$ Invisible





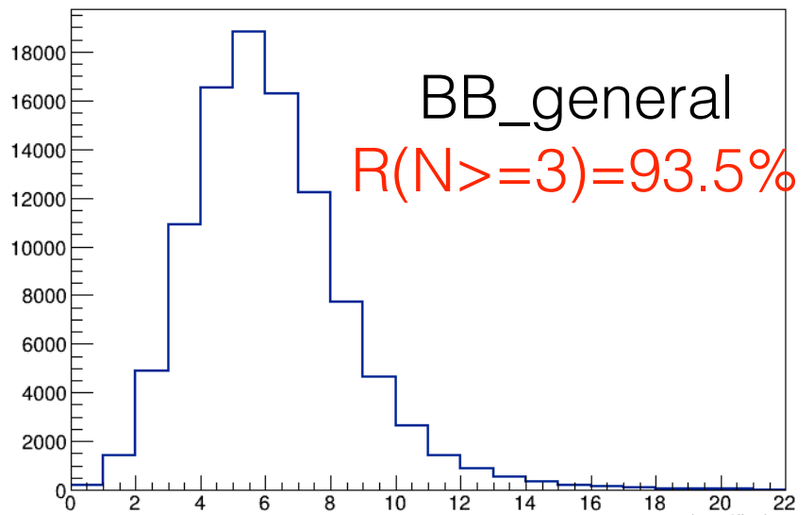
$\Upsilon(4S) \to \gamma_{\rm ISR}\Upsilon(3S), \Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S), \Upsilon(1S) \to$ Invisible

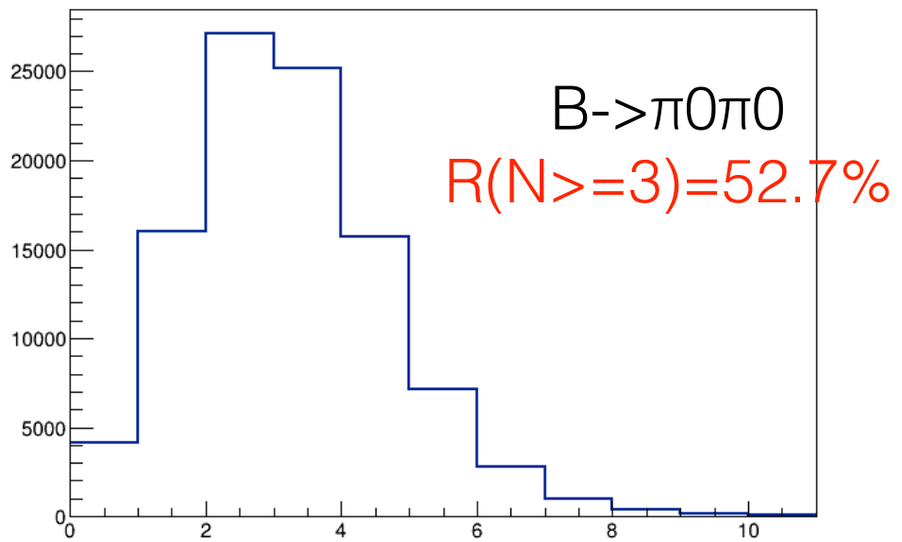




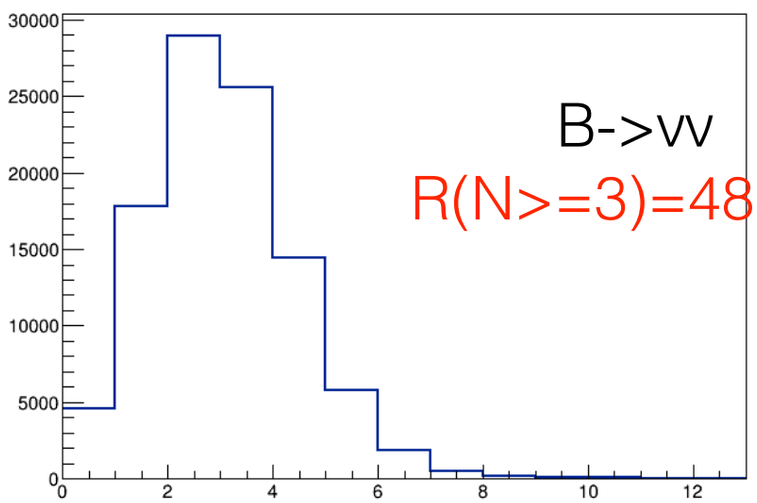
Study based on TSIM

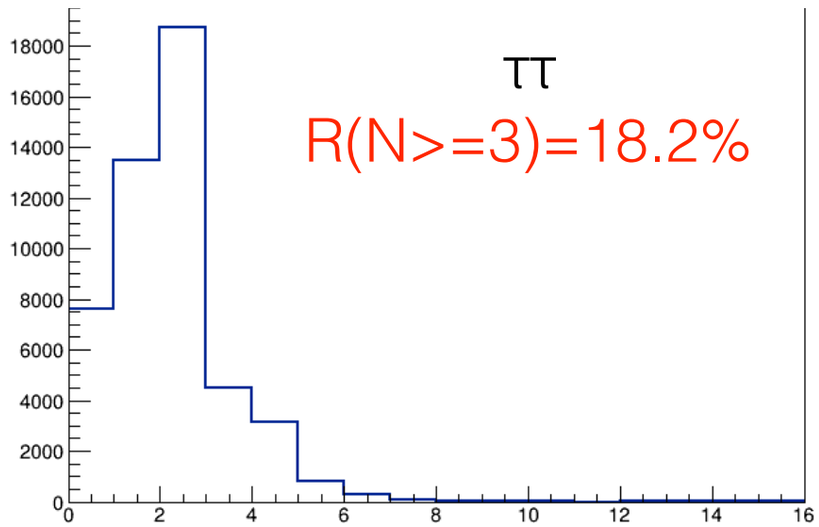
$N_{trk}>=3$





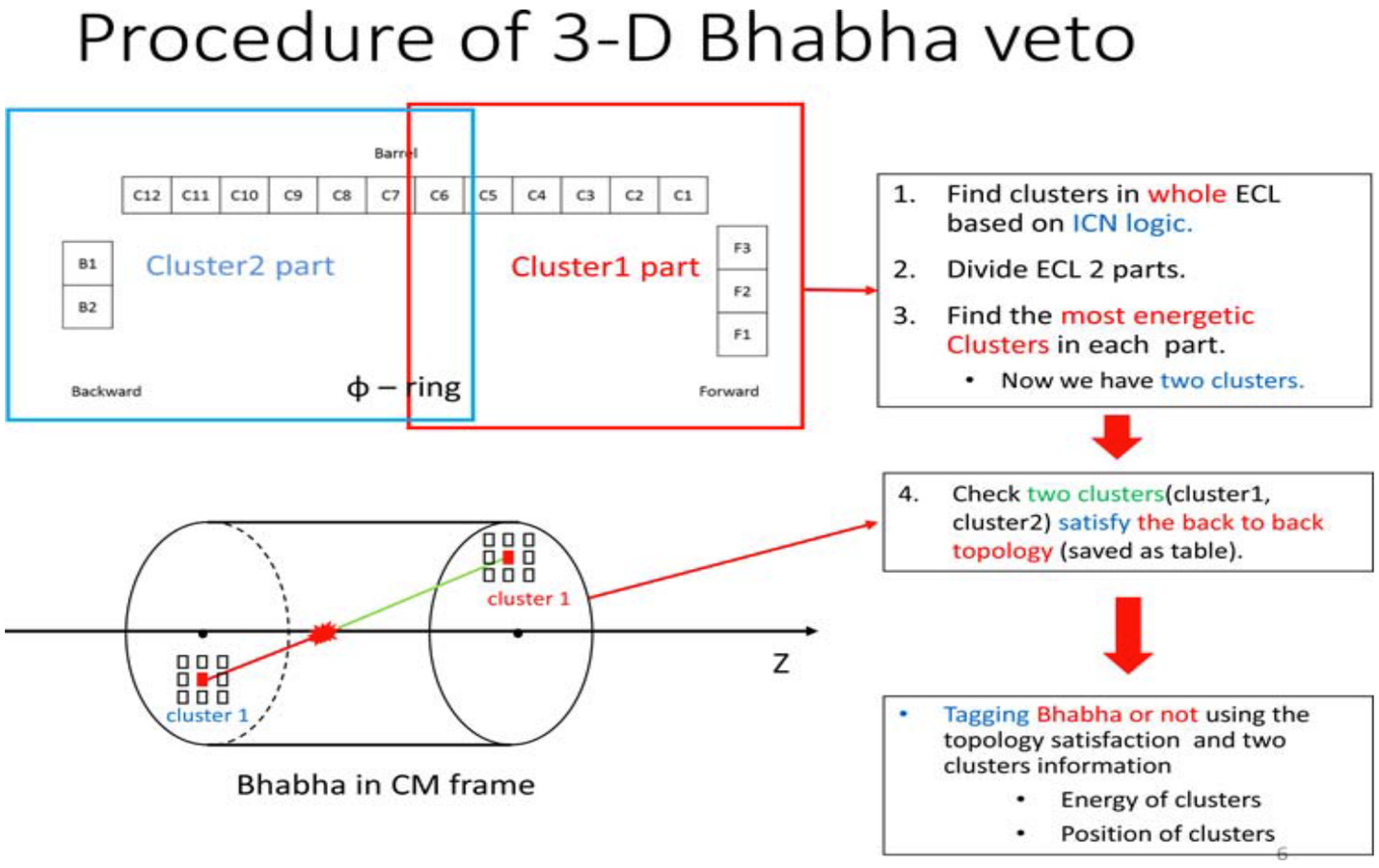
Ntrk (2D_trackfinder)





ECL Trigger

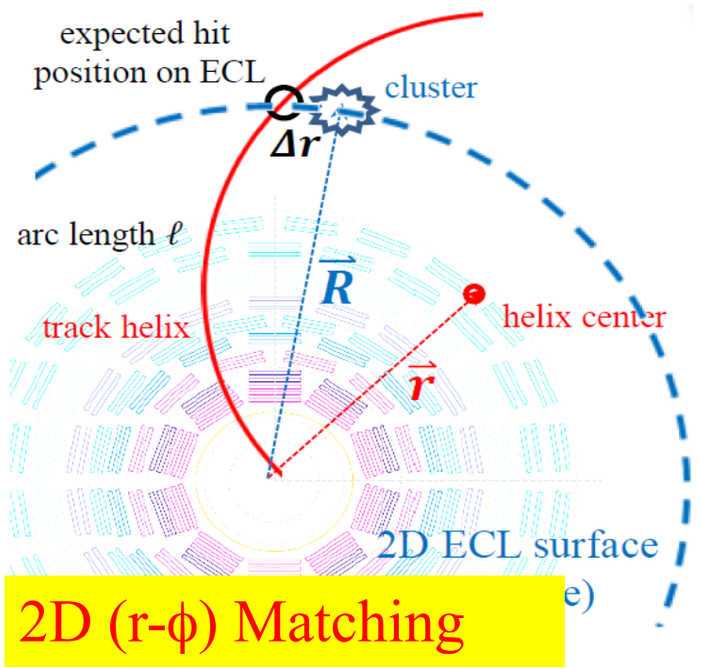
- Upgrade Bhabha logic at Belle II
  - 3D Bhabha Veto Logic
  - Use r-θ–ϕ (3-D) information
  - Keep efficiencies of ττ and low multiplicity

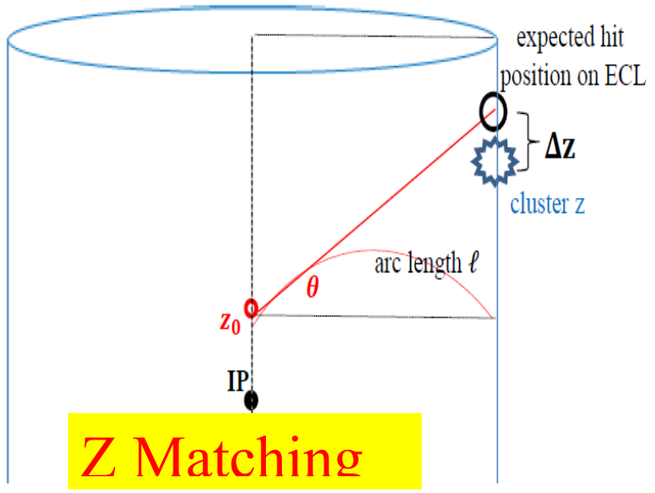


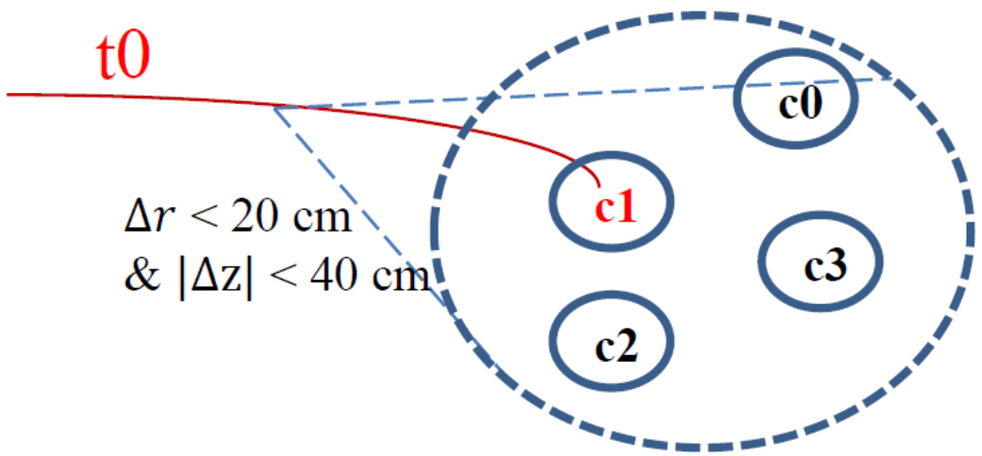
GRL

- CDC track and ECL cluster matching *(new at Belle II)*

- Match in r-ϕ and Z directions
- Δr, Δz: the deviations between cluster position and expected hit position in r-f and Z directions, respectively.







- Δr, Δz selections
- Match track t0 to the cluster c1 with the smallest Δr in its (Δr, Δz) region
- The rest are neutral clusters
- Electron ID with E/P

Study based on TSIM

Proposed L1 Trigger Menu (Phase II)

$L = 4 \times 10^{34}\ cm^{-2}/s = 40\ nb^{-1}/s = 5\%$ of nominal

			e+e-	0.5 deg	
			122760	nb	
Bit	Description	Prescale	% Selected	exclusive	Rate
0	3 or more 3D tracks	1	0.0047	0.0040	228
1	2 3D tracks, ≥1 within 25 cm, not a trkBhabha	1	0.0213	0.0170	1046
2	2 3D tracks, not a trkBhabha	20	0.0022	0.0010	106
3	2 3D tracks, trkBhabha	1	0.0087	0.0000	425
4	1 track, <25cm, clust same hemi, no 2 GeV clust	1	0.0037	0.0030	182
5	1 track, <25cm, clust opp hemi, no 2 GeV clust	1	0.0120	0.0090	587
6	≥3 clusters inc. ≥1 300 MeV, not an eclBhabha	1	0.0271	0.0140	1331
7	2 GeV E* in [4,14], not a trkBhabha	1	0.0041	0.0010	199
8	2 GeV E* in [4,14], trkBhabha	1	0.0084	0.0000	412
9	2 GeV E* in 2,3,15 or 16, not a trkBhabha or eclBhabha	1	0.0067	0.0030	327
10	2 GeV E* in 2,3,15 or 16, trkBhabha or eclBhabha	1	0.0239	0.0210	1171
11	2 GeV E* in 1 or 17, not a trkBhabha or eclBhabha	10	0.0048	0.0040	236
12	2 GeV E* in 1 or 17, trkBhabha or eclBhabha	10	0.0023	0.0010	110
13	exactly 1 E*>1 GeV and 1 E>300 MeV, in [4,15]	1	0.0042	0.0030	204
14	exactly 1 E*>1 GeV and 1 E>300 MeV, in 2,3 or 16	1	0.0068	0.0050	331
15	clusters back-to-back in phi, both >250 MeV, no 2 GeV	1	0.0034	0.0020	167
16	clusters back-to-back in phi, 1 <250 MeV, no 2 GeV	1	0.0281	0.0110	1380
17	clusters back-to-back in 3D, no 2 GeV	1	0.0257	0.0110	1260
	Percentage selected by at least 1 trigger		0.1499	0.1090	7358
	Cross section (nb)		184	134	
	Rate, phase2 backgrounds, luminosity (nb-1/s) =	40	7358		

Study based on TSIM

Proposed L1 Trigger Menu (Phase II)

$L = 4 \times 10^{34}$ cm^{-2}/s … 5% of nominal

			e+e-	0.5 deg	
Bit	Description			ive	Rate
0	3 or more 3D tracks			0	228
1	2 3D tracks, ≥1 within 25 cm, not a trkBhabha			0	1046
2	2 3D tracks, not a trkBhabha			10	106
3	2 3D tracks, trkBhabha			0.0000	425
4	1 track, <25cm, clust same hemi, no 2 GeV clust	1		0.0030	182
5	1 track, <25cm, clust opp hemi, no 2 GeV clust				587
6	≥3 clusters inc. ≥1 300 MeV, not an eclBhabha				11
7	2 GeV E* in [4,14], not a trkBhabha				
8	2 GeV E* in [4,14], trkBhabha				
9	2 GeV E* in 2,3,15 or 16, not a trkBhabha or eclBhabha				27
10	2 GeV E* in 2,3,15 or 16, trkBhabha or eclBhabha				1171
11	2 GeV E* in 1 or 17, not a trkBhabha or eclBhabha	10		0.0040	236
12	2 GeV E* in 1 or 17, trkBhabha or eclBhabha	10			110
13	exactly 1 E*>1 GeV and 1 E>300 MeV, in [4,15]				
14	exactly 1 E*>1 GeV and 1 E>300 MeV, in 2,3 or 16				
15	clusters back-to-back in phi, both >250 MeV, no 2 GeV				
16	clusters back-to-back in phi, 1 <250 MeV, no 2 GeV				
17	clusters back-to-back in 3D, no 2 GeV				
	Percentage selected by at least 1 trigger				7358
	Cross section (nb)		184	134	
	Rate, phase2 backgrounds, luminosity (nb-1/s) =	40	7358		

Hadronic events

Two-track events, ττ, γππ, Y(1S) inv. decay et.al

w/ a large cluster events ττ, γππ, dark photon, et.al

Back-to-back clusters ττ, γππ, dark photon

Study based on TSIM

Proposed L1 Trigger Menu (Phase II)

$L = 4 \times 10^{34}$ cm^{-2}/s … 5% of nominal

			e+e-	0.5 deg	
Bit	Description			ive	Rate
0	3 or more 3D tracks			0	228
1	2 3D tracks, >1 within 25 cm, not a trkBhabha			0	1046
				10	106
				0.0000	425
			1	0.0030	182
					587
					1
9	2 GeV E* in 2,3,15 or 16, not a trkBhabha or eclBhabha				27
10	2 GeV E* in 2,3,15 or 16, trkBhabha or eclBhabha				1171
11	2 GeV E* in 1 or 17, not a trkBhabha or eclBhabha		10	0.0040	236
12	2 GeV E* in 1 or 17, trkBhabha or eclBhabha		10		110
13	exactly 1 E*>1 GeV and 1 E>300 MeV, in [4,15]				
14	exactly 1 E*>1 GeV and 1 E>300 MeV, in 2,3 or 16				
		eV			
	Percentage selected by at least 1 trigger				7358
	Cross section (nb)		184	134	
	Rate, phase2 backgrounds, luminosity (nb-1/s) =	40	7358		

Hadronic events

Two-track events, ττ, γππ, Y(1S) inv. decay et.al

w/ a large cluster events ττ, γππ, dark photon, et.al

Back-to-back clusters ττ, γππ, dark photon

Some trigger lines are designed for
- Detector performance study
- Trigger efficiency
- Calibration
- Luminosity measurement

Tighten some trigger lines once the trigger and DAQ system can not undertake the rate.

Study based on TSIM

Proposed L1 Trigger Menu (2020)

$L = 2 \times 10^{35}\ cm^{-2}/s = 200\ nb^{-1}/s = 25\%$ nominal

			e+e-	0.5 deg	
			122760	nb	
Bit	Description	Prescale	% Selected	exclusive	Rate
0	3 or more 3D tracks	1	0.0047	0.0040	1142
1	2 3D tracks, ≥1 within 10 cm, not a trkBhabha	1	0.0057	0.0040	1387
2	2 3D tracks, not a trkBhabha	20	0.0022	0.0020	528
			.0044	0.0010	1068
			.0012	0.0000	295
			.0042	0.0030	1019
			.0152	0.0110	3720
7	2 GeV E* in [4,14], not a trkBhabha	1	0.0041	0.0010	994
8	2 GeV E* in [4,14], trkBhabha	2	0.0042	0.0010	1031
9	2 GeV E* in 2,3,15 or 16, not a trkBhabha or eclB	1	0.0067	0.0030	1633
10	2 GeV E* in 2,3,15 or 16, trkBhabha or eclBhabha	1	0.0239	0.0220	5856
11	2 GeV E* in 1 or 17, not a trkBhabha or eclBhabha	20	0.0024	0.0020	589
12	2 GeV E* in 1 or 17, trkBhabha or eclBhabha	20	0.0012	0.0000	282
13	exactly 1 E*>1 GeV and 1 E>300 MeV, in [4,15]	1	0.0042	0.0030	1019
14	exactly 1 E*>1 GeV and 1 E>300 MeV, in 2,3 or 16	5	0.0014	0.0010	331
15	clusters back-to-back in phi, both >250 MeV, no 2	1	0.0034	0.0030	835
16	clust back-to-back in phi, <250 MeV, no 2 GeV, no	3	0.0062	0.0050	1522
17	clusters back-to-back in 3D, no 2 GeV	5	0.0052	0.0040	1264
	Percentage selected by at least 1 trigger		0.0842	0.0700	20661
	Cross section (nb)		103	86	
	Rate, phase2 backgrounds, luminosity (nb-1/s) =	200	20661		

Similar to Phase II
- Tighten some logics
- Further pre-scale some lines

Study based on TSIM

Efficiency

$L = 2 \times 10^{35}\ cm^{-2}/s = 200\ nb^{-1}/s = 25\%$ nominal

Sample	Note	Generated sigma nb	Percentage selected	Accepted sigma nb	Rate Hz 200 nb-1/sec	Fiducial efficiency %	Barrel efficiency %
Bhabha	0.5 & 5 deg	122760	0.080	97.6	19519	86.9	80.7
gamma gamma		25.2	12.3	3.1	619	97.0	100.0
e e e e		1693	0.15	2.5	498		
e e mu mu		67.8	1.8	1.2	238		
tau tau		0.919	85.5	0.8	157	88.9	96.1
mu mu		1.115	63.4	0.7	141	84.5	99.5
BB		1.05	100.0	1.0	210		
u u-bar		1.61	88.4	1.4	285		
d d-bar		0.4	88.1	0.4	70		
s s-bar		0.38	93.8	0.4	71		
c c-bar		1.3	99.5	1.3	259		
2gamma production of ALP	0.2 GeV					6.3	
	0.5 GeV					46.0	
	2 GeV					97.3	
	10 GeV					99.1	100.0
2gamma production of pi0	no tag					1.1	0.0
	1 tag						
ALP--> invisible	9.3 GeV					72.1	92.9
ALP --> gamma gamma	0.2 GeV					99.1	100.0
	0.5 GeV					99.3	
	3 GeV					99.6	
	9.3 GeV					99.6	
a' --> e e	0.5 GeV					98.0	99.9
a' --> invisible	0.5 GeV					83.5	99.9
	9.3 GeV					58.9	94.0
gamma pi+pi-	0.5 GeV					91.6	99.9
tau --> e gamma						99.1	99.7
tau --> mu gamma						96.2	99.0
Y3S --> pi pi Y1S						29.1	40.1
TOTAL					22068		

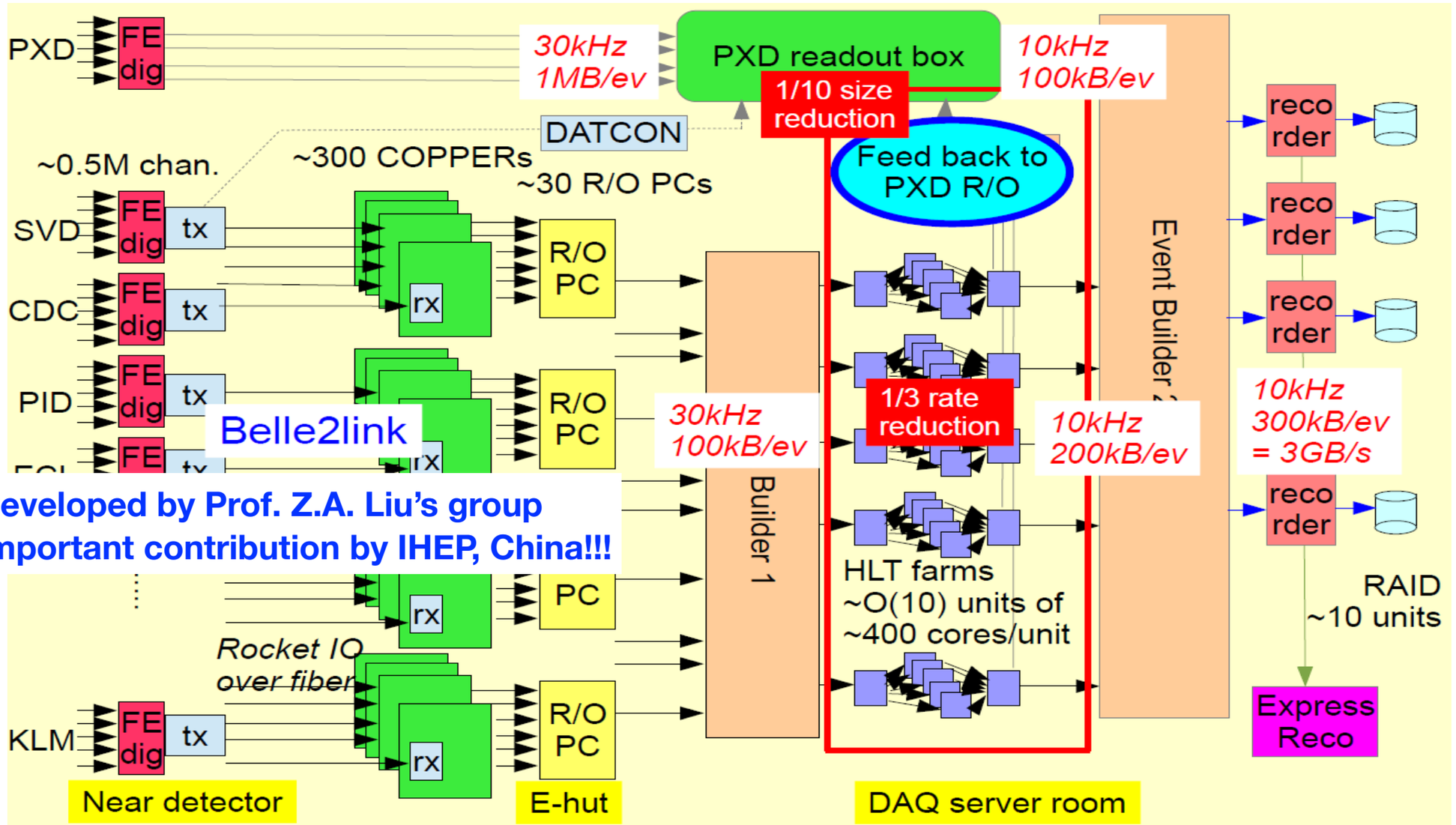
DAQ

Components:

- Unified data link (Belle2Link)
- Common pipeline platform for electronics readout (COPPER)
- Merge data pieces from all detectors (Event builder I)
- High level trigger (HLT): software based

HLT in Belle II DAQ

- Parallel processing: Multi-core, Multi-node
- ~10 HLT units, 20 nodes x 16 cores per unit
- Input: 100kB/event, 3kHz/unit, Output: 200kB/event, 1kHz/unit



Developed by Prof. Z.A. Liu's group
Important contribution by IHEP, China!!!

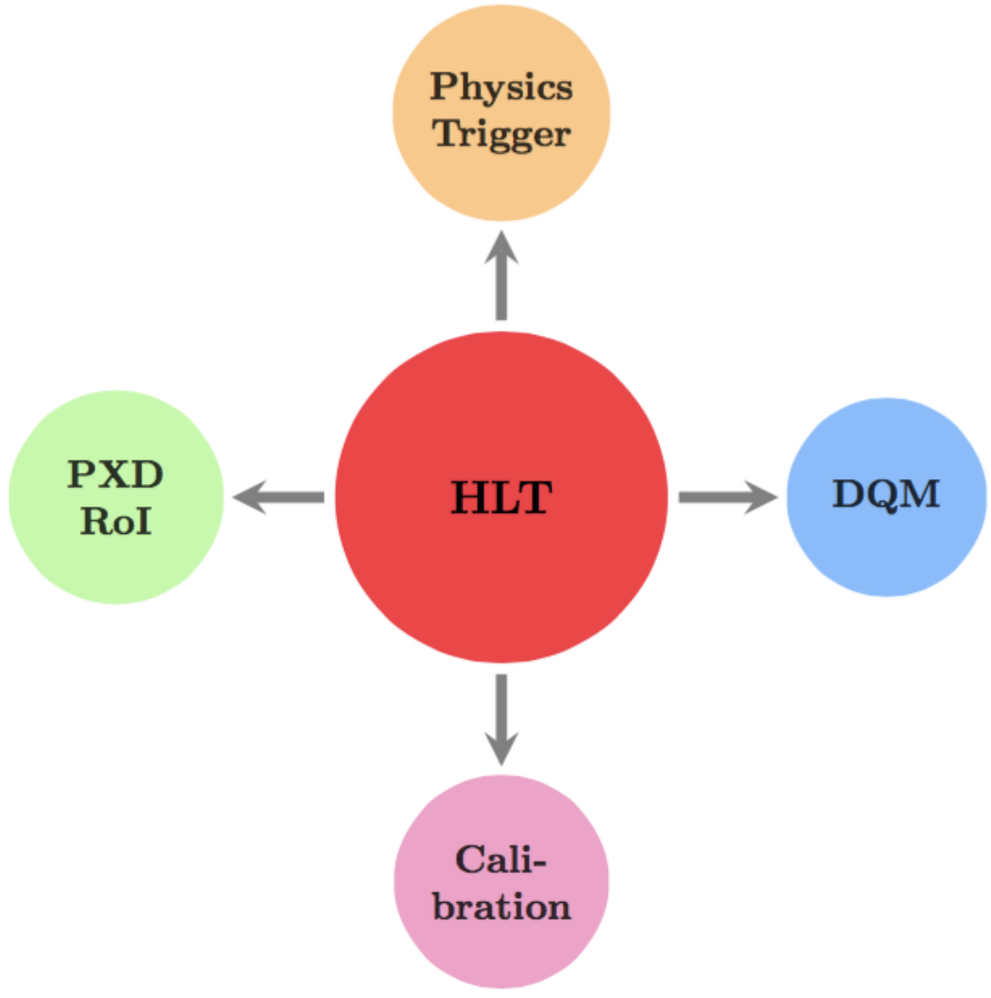
HLT

- Physics Trigger: suppress event rates from 30 kHz to 10 kHz

- PXD RoI: provide HLT trigger result and tracking information of SVD and CDC to calculate Region of Interest of PXD.

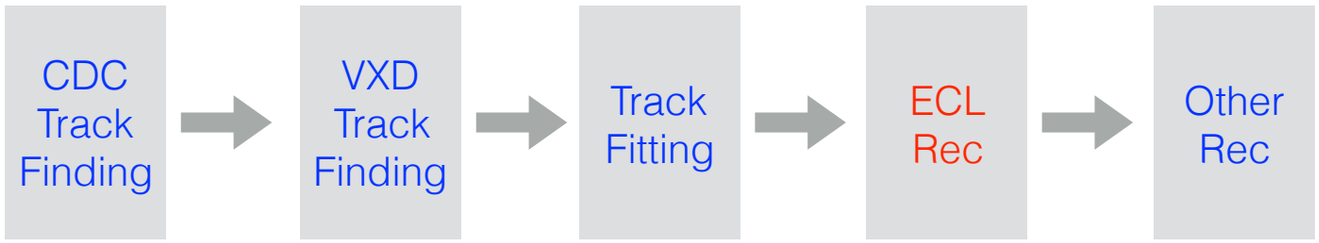
- Calibration: Flag samples for the calibration of detectors

- DQM: Information from Reconstruction for data quality monitoring

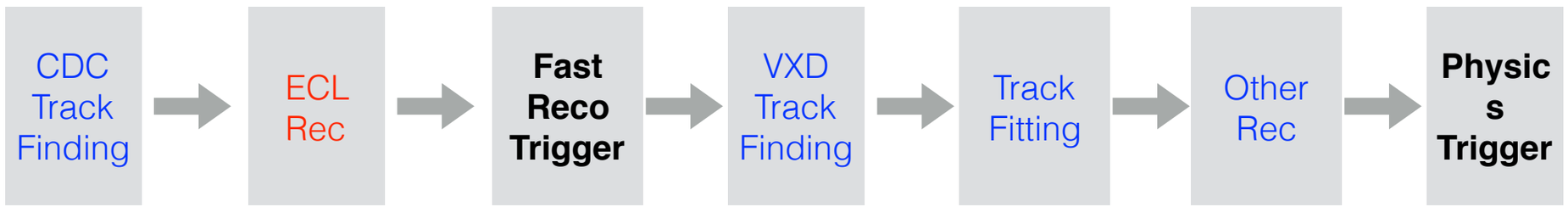


HLT Software

Standard Offline Reconstruction



HLT Standard Reconstruction and Trigger



HLT Commissioning

Realistic strategy of HLT commissioning in Phase 2

1. At the beginning of Phase 2, HLT is operated without any processing. All the events are pass-through to Storage
   * An intensive debugginig of “FastReco(=CDC+ECL recon)” and “Level3” is supposed to be done offline.
   * Also RoI generation is supposed to be debugged.

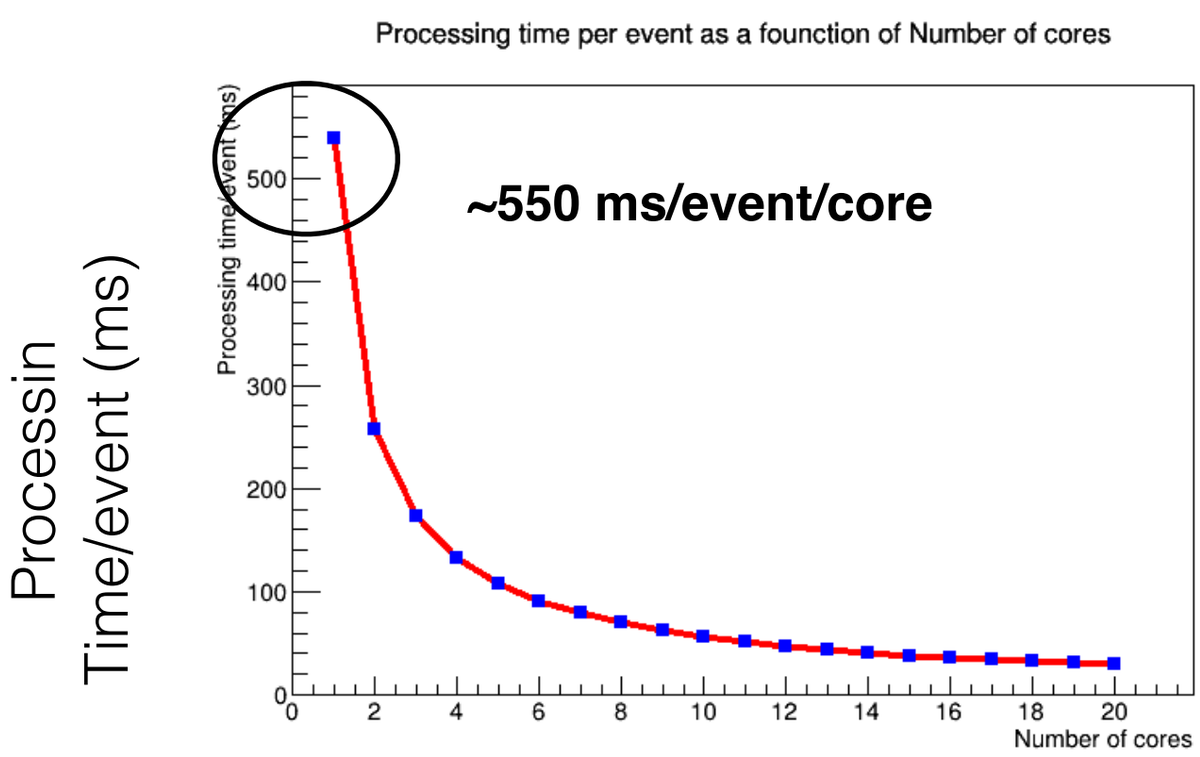
2. After FastReco(Level3) is proven to be stable, we will implement FastReco(Level3) in HLT.
   * The software trigger by FastReco only may be turned on in case the trigger rate is too high.
   * Debugging of full HLT script is done offline.

3. Then the full HLT script is implemented.
   * FastReco trigger is turned on.
   * But final software trigger is not turned on during Phase 2.

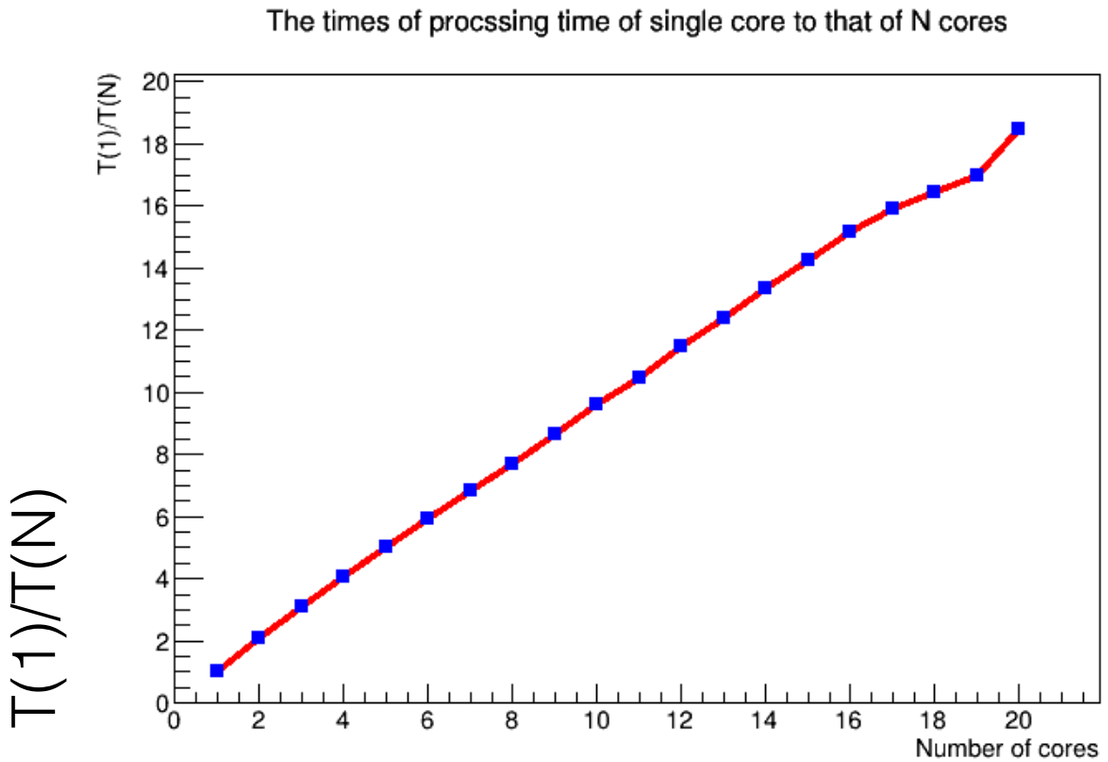
Software performance on HLT

Test

- 20 cores (node 1, hlt03)
- ~2000 BB events

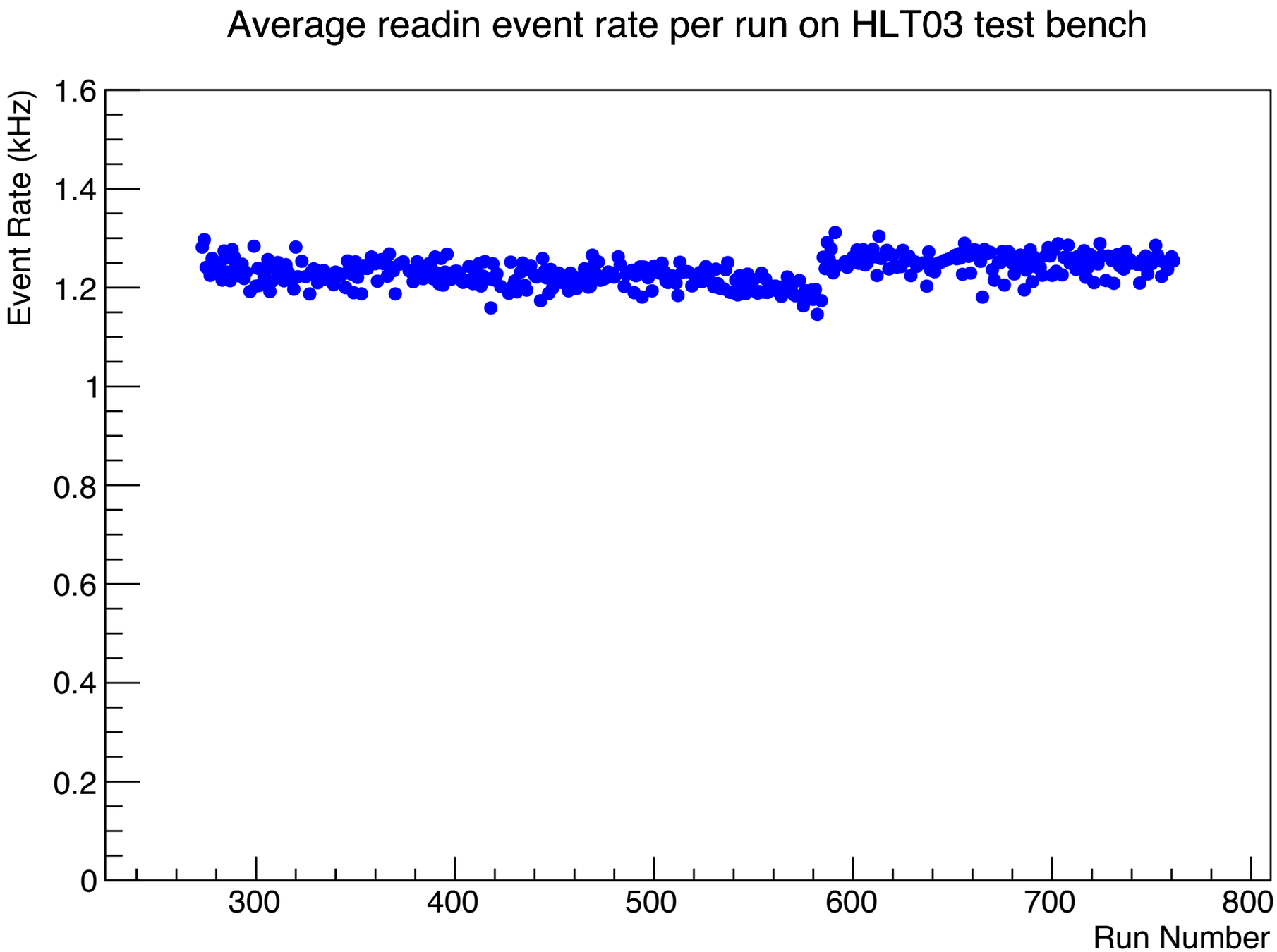


Number of cores



Number of cores

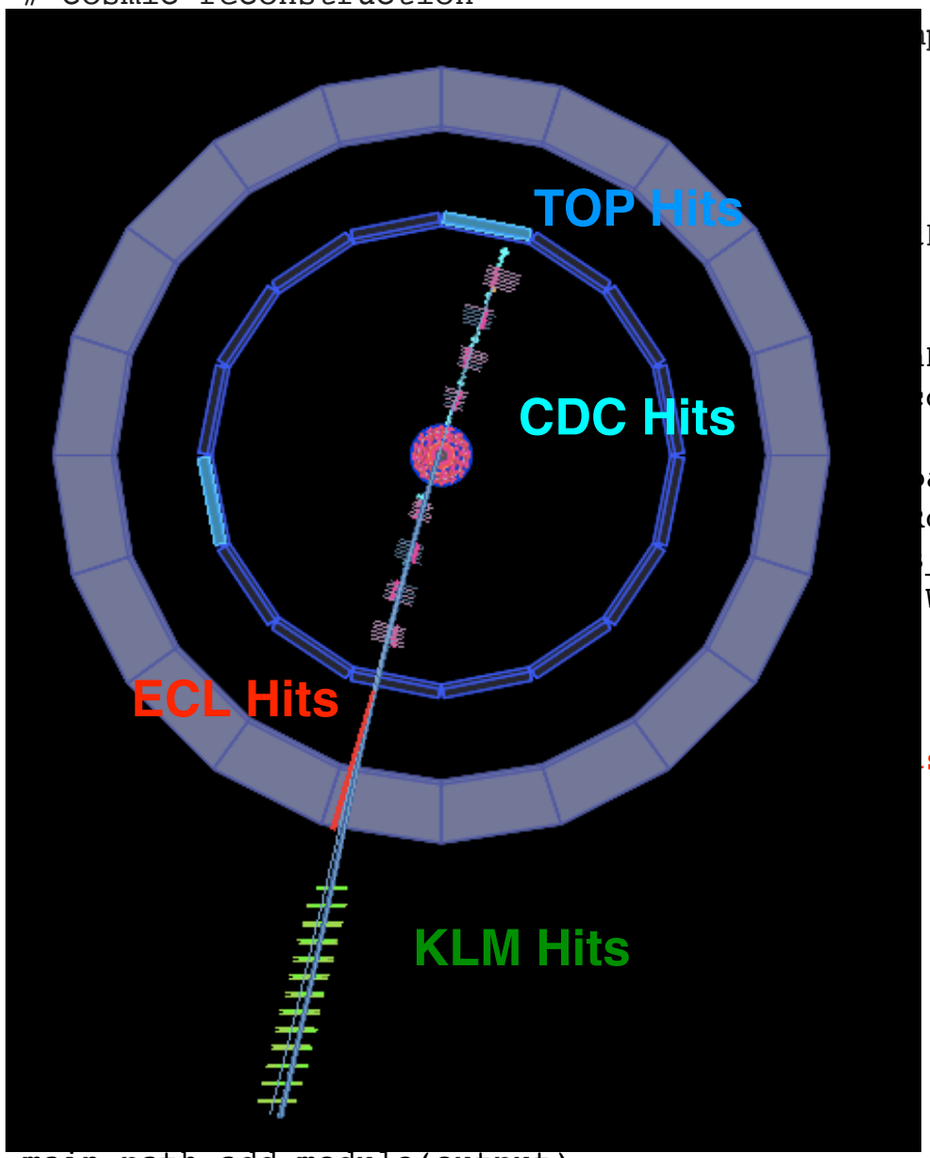
Trigger Rate

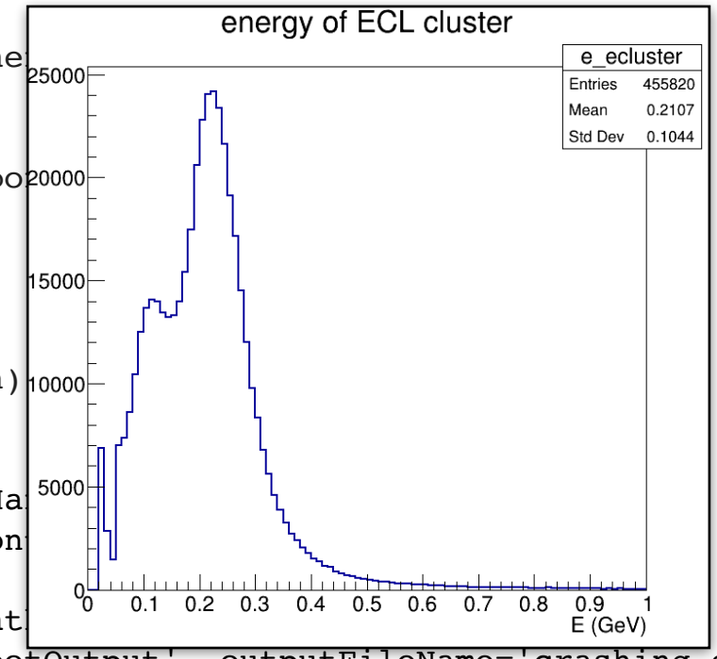


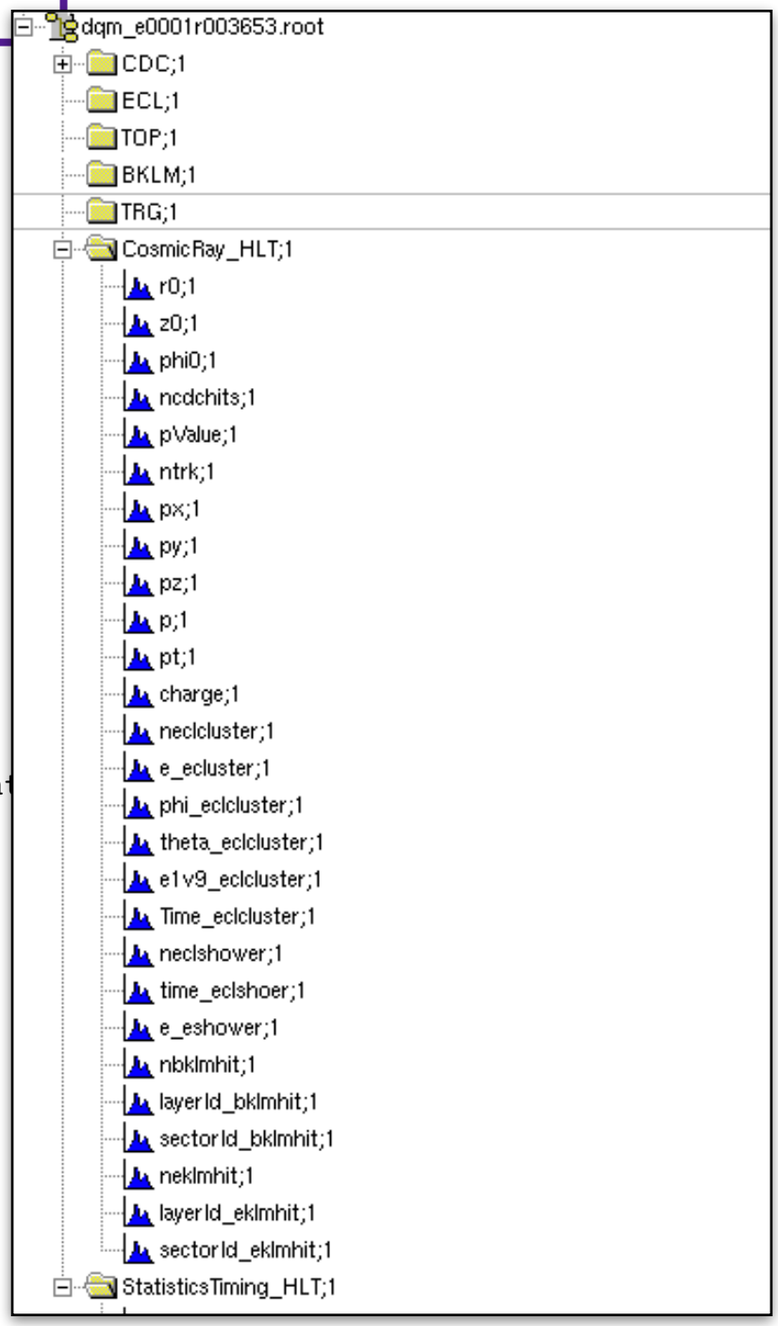
Cosmic Ray Data Taking

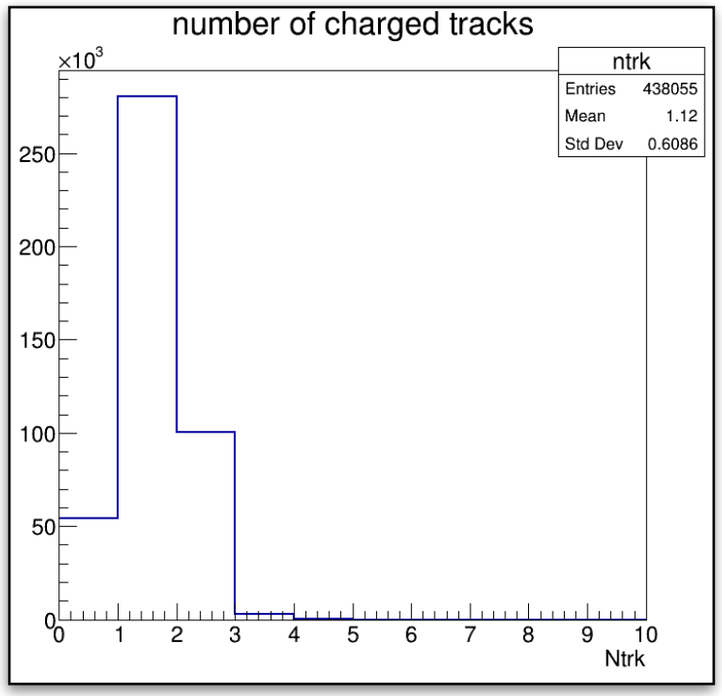
DQM of sub-detectors and HLT

```
# HistoManager for real HLT
histoman = basf2.register_module('DqmHistoManager')
histoman.param("Port", int(argvs[3]))
histoman.param("Port", 9991)
histoman.param("DumpInterval", 180)
histoman.param("WriteInterval", 180)

main_path.add_module(histoman)

# Raw data unpackers
add_unpackers(crashsafe_path, components=compone

# cosmic reconstruction
```







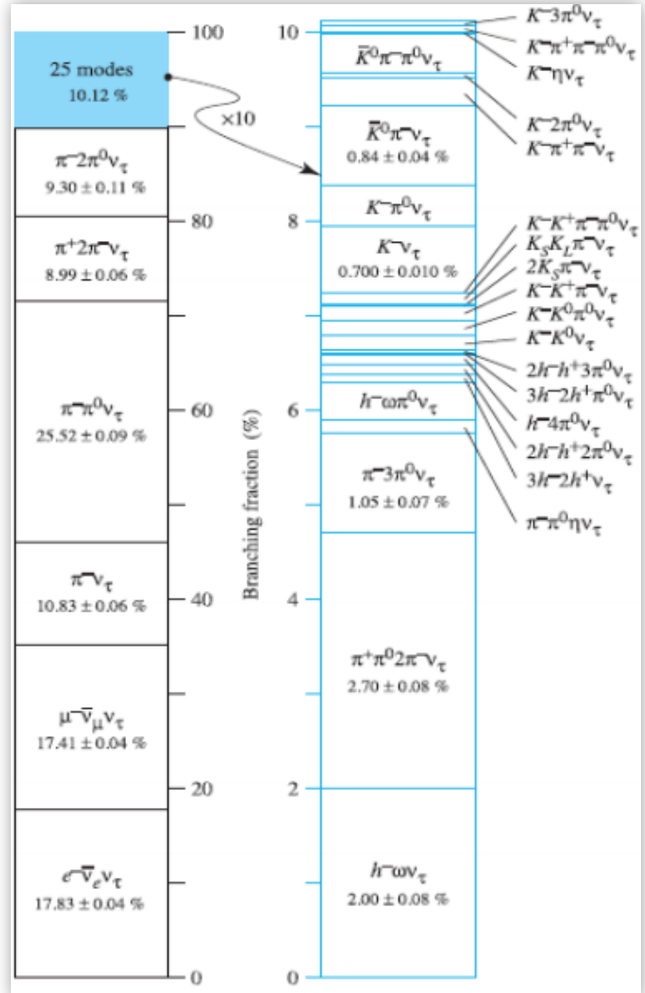



```
main_path.add_module(output)

##########
# Other utilities
##########
progress = basf2.register_module('Progress')
```

Physics Prospects

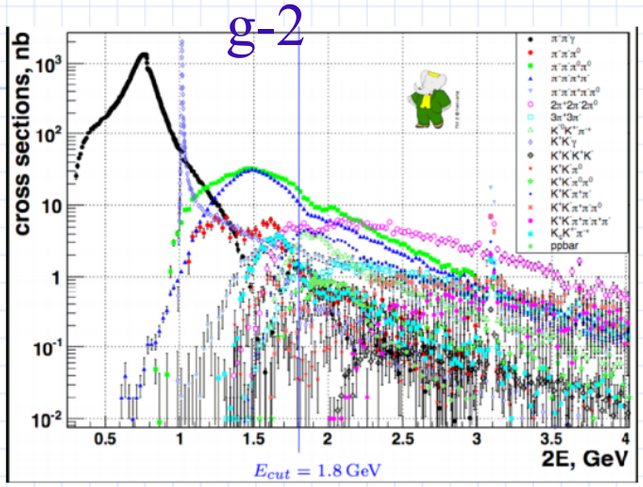
- There is still space for new physics contributions
- Open questions, e.g.
  - New CPV phases?
  - Sources of LFV beyond the SM?
  - Multiple Higgs bosons, dark sectors?
  - Discrepancies between experimental results and SM predictions (e.g enhancements in semi-tauonic decays)?

Tau decay

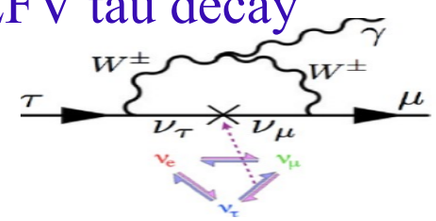


BaBar measurements summary

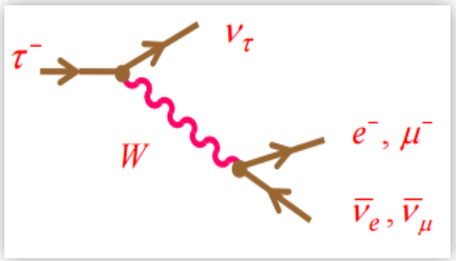
g-2



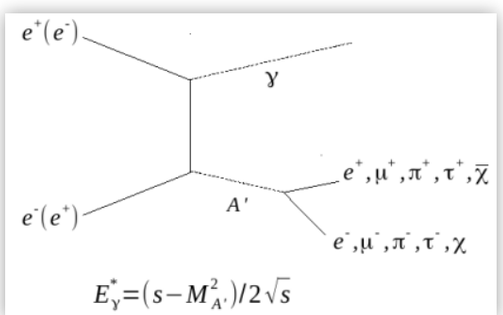
LFV tau decay



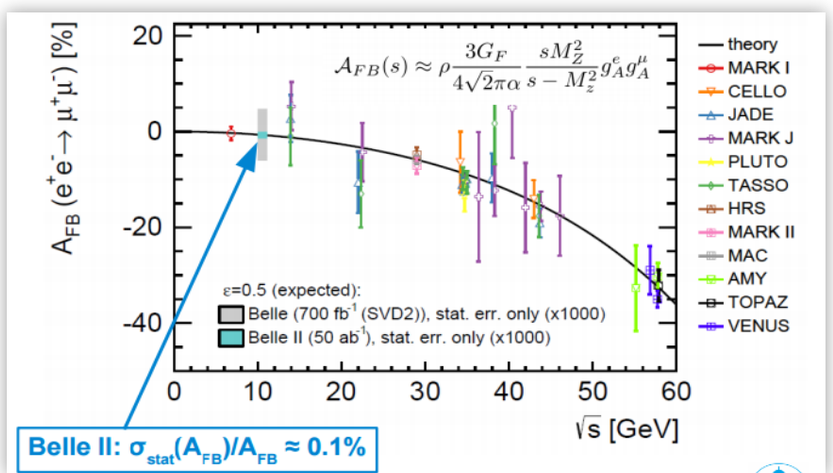
Leptonic tau decay



Dark Photon

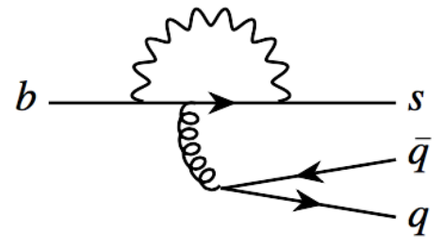


Precision Electroweak tests



Penguin b→s decays

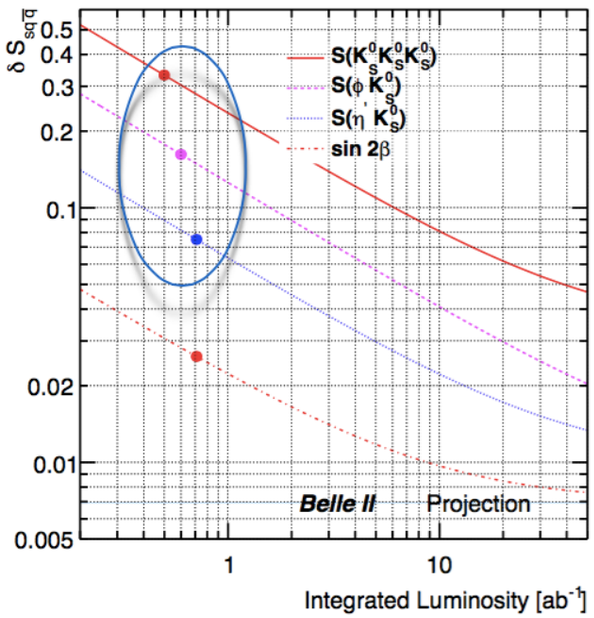
- Precision measurements of sin(2β) is important for the search of new sources of CPV
- b→s transition via penguin diagram
- sensitive to possible new heavy particle contributions



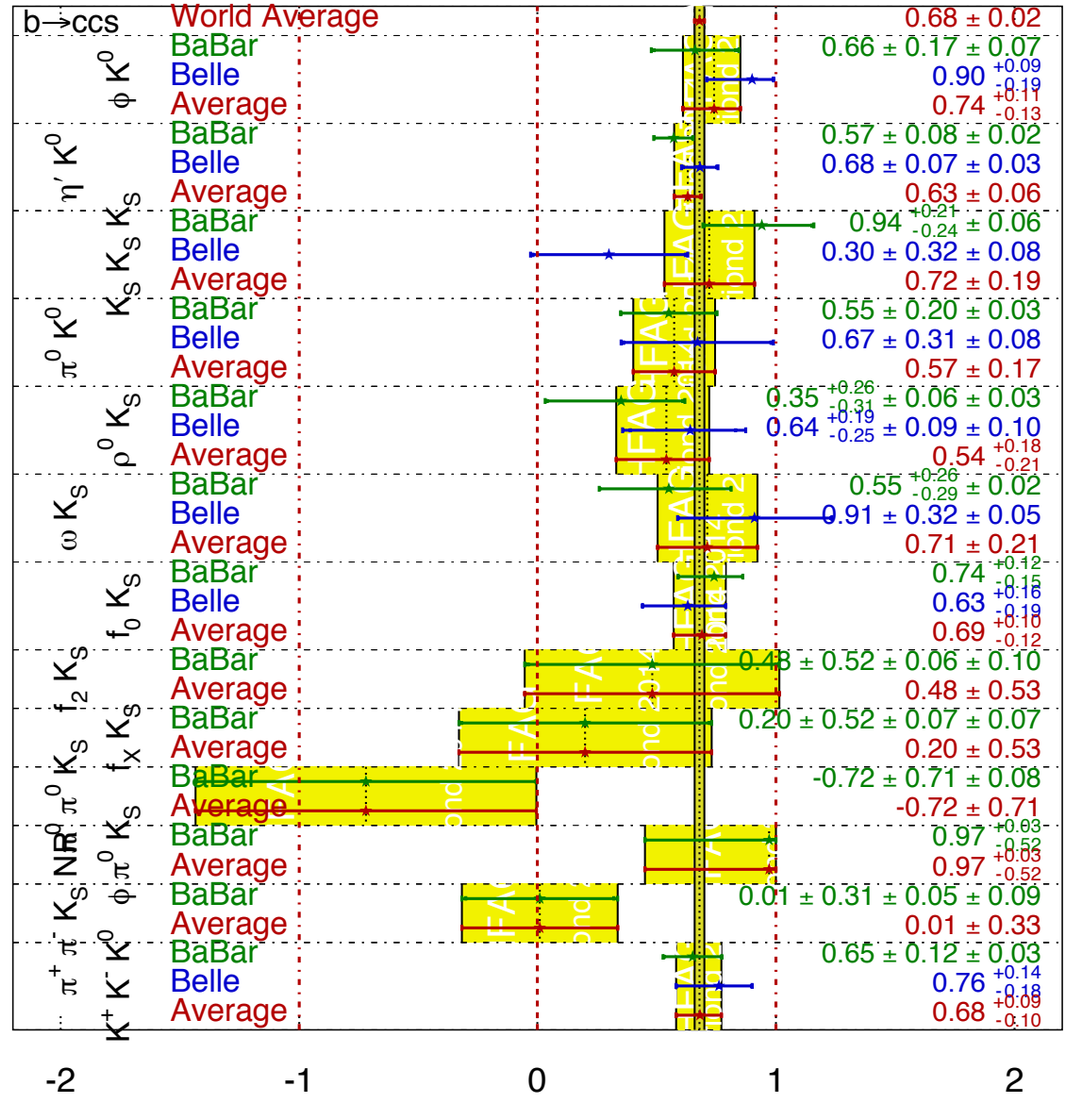
$$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$$

HFAG Moriond 2014 PRELIMINARY

- Belle II



sin(2β)	σ(stat)@ Belle	σ(stat)@Belle II 50 ab^{-1}
B→ΦK^0	0.09	0.018
B→η'K^0	0.07	0.011
B→KsKsKs	0.32	0.033



EWP: $B \to K^{(*)} \nu\nu$

- SM: penguin + box digram

  $B_{SM}(B^+ \to K^+\nu\nu) = (4.0\pm0.5)\times10^{-6}$

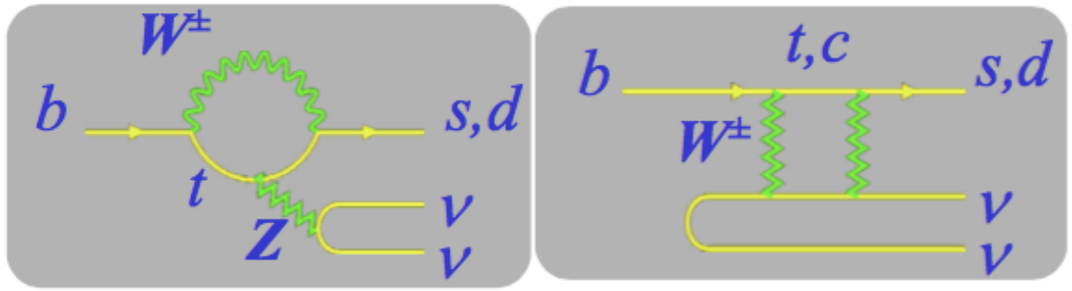
  $B_{SM}(B^0 \to K^{*0}\nu\nu) = (9.2\pm1.0)\times10^{-6}$

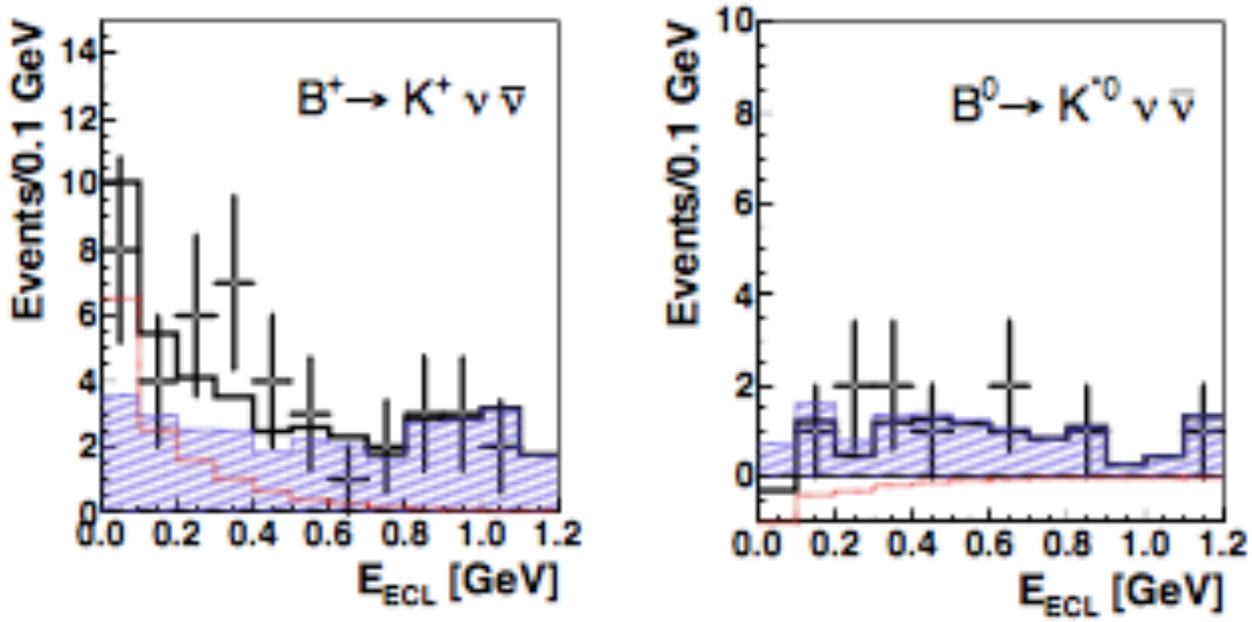
  arXiv: 1409.4557

- Belle:

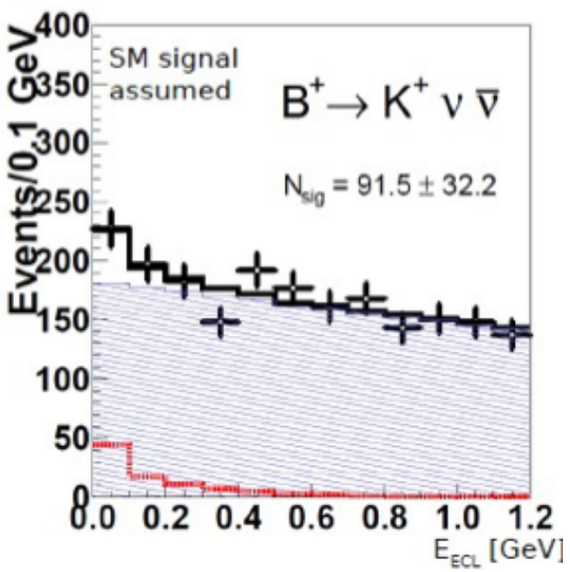
  $B(B^+ \to K^+\nu\nu) < 5.5\times10^{-5}$,
  Nsig=13.3+7.4-6.6, 2.0σ

  $B(B^0 \to K^{*0}\nu\nu) < 5.5\times10^{-5}$





Belle, PRD 87, 111103(R) (2013)

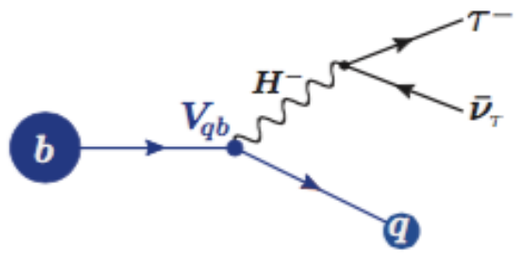


Belle II:
Nsig~91.5±32.2@50 ab^{-1}

Semi-leptonic B decays

Semi-tauonic decay modes are highly sensitive to new physics

$B \to D^{(*)} \tau\nu$: WA is ~4σ from the SM!



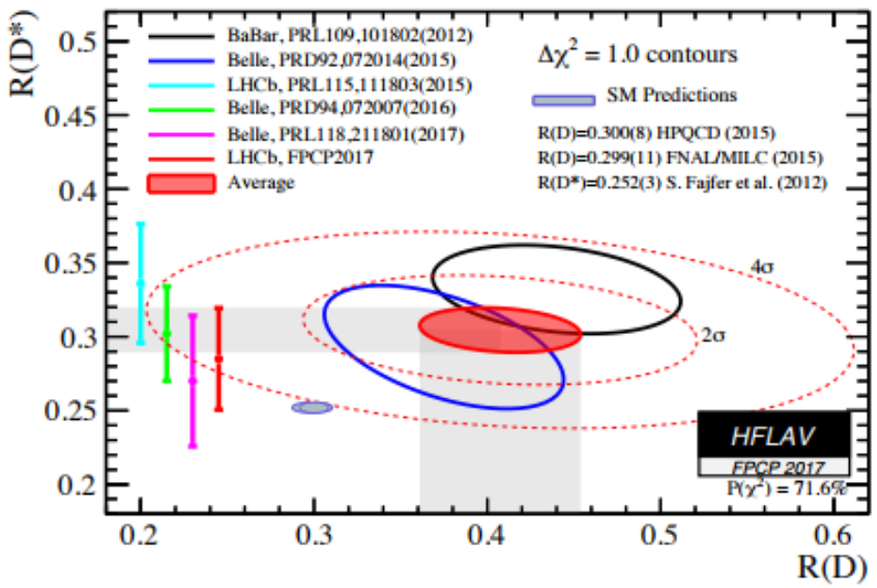
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\,\tau\,\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\,\ell\,\bar{\nu}_\ell)}$$

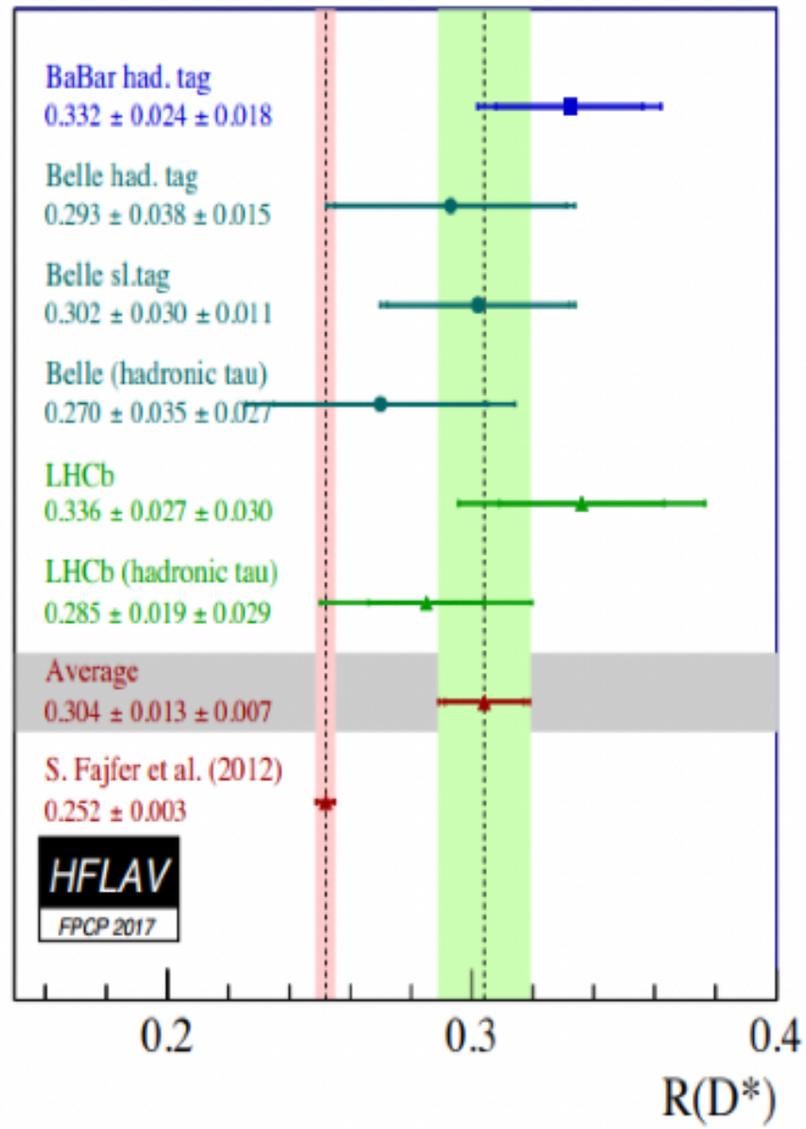
$R(D)$

Error	stat.	tot.
B-Factories	13%	16.2%
Belle II 5/ab	3.8%	5.6%
Belle II 50/ab	1.2%	**3.4%**

$R(D^*)$

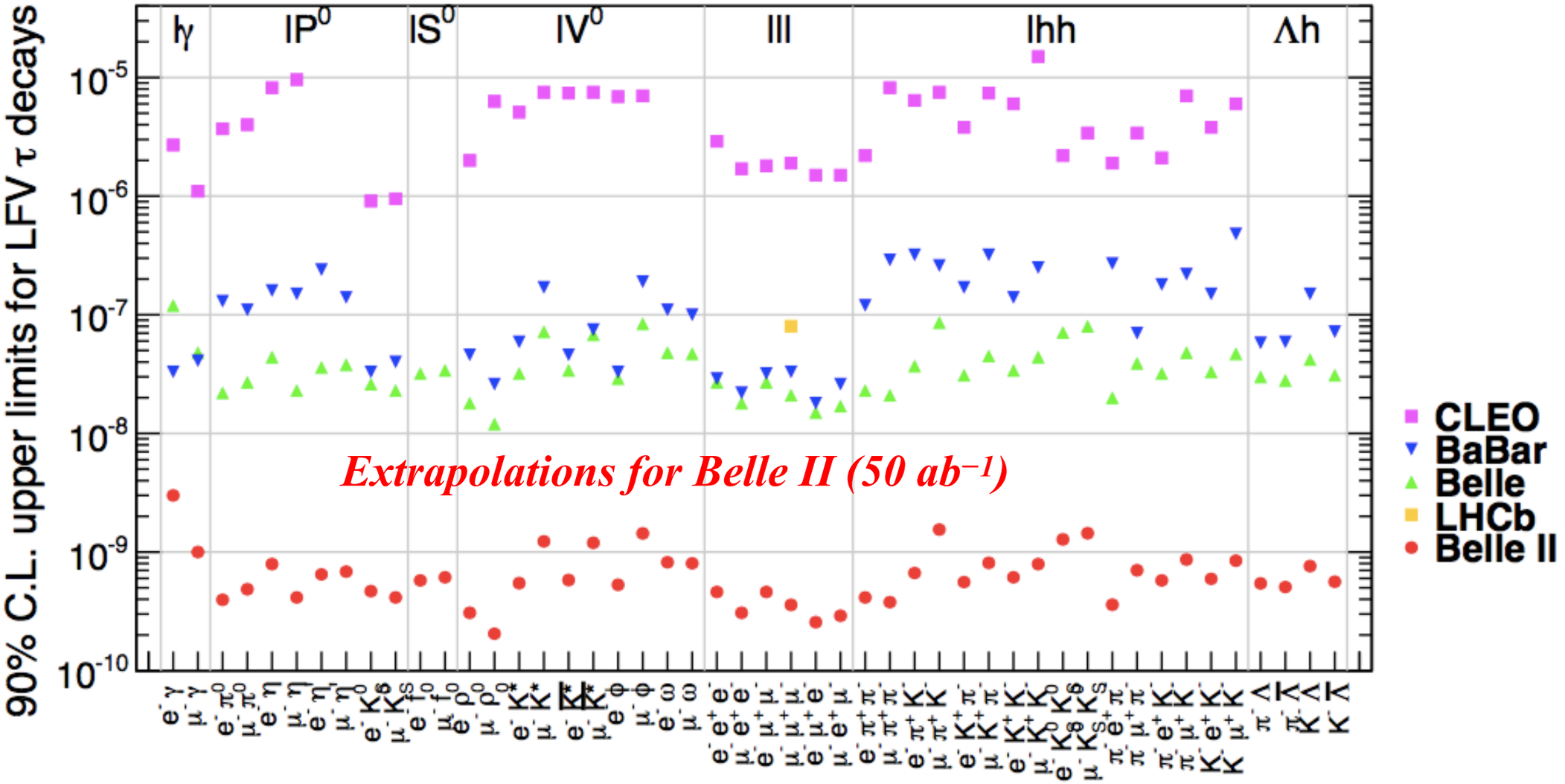
Error	stat.	tot.
B-Factories	7.1%	9.0%
Belle II 5/ab	2.1%	3.2%
Belle II 50/ab	0.7%	**2.1%**





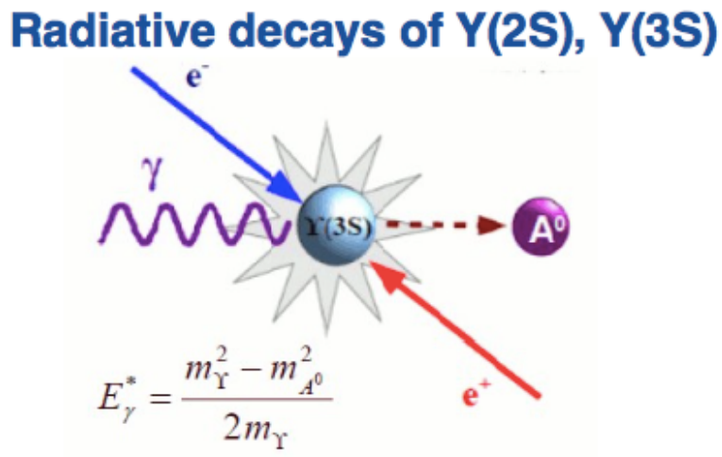
LFV τ decays

- Lepton Flavour Violation is highly suppressed in the SM (e.g. Br(τ→μγ) ~10^{-40}), LFV τ decays are clean probes for New Physics effects
- Belle II : Sensitivity for LFV decay rates is at least one order higher than Belle

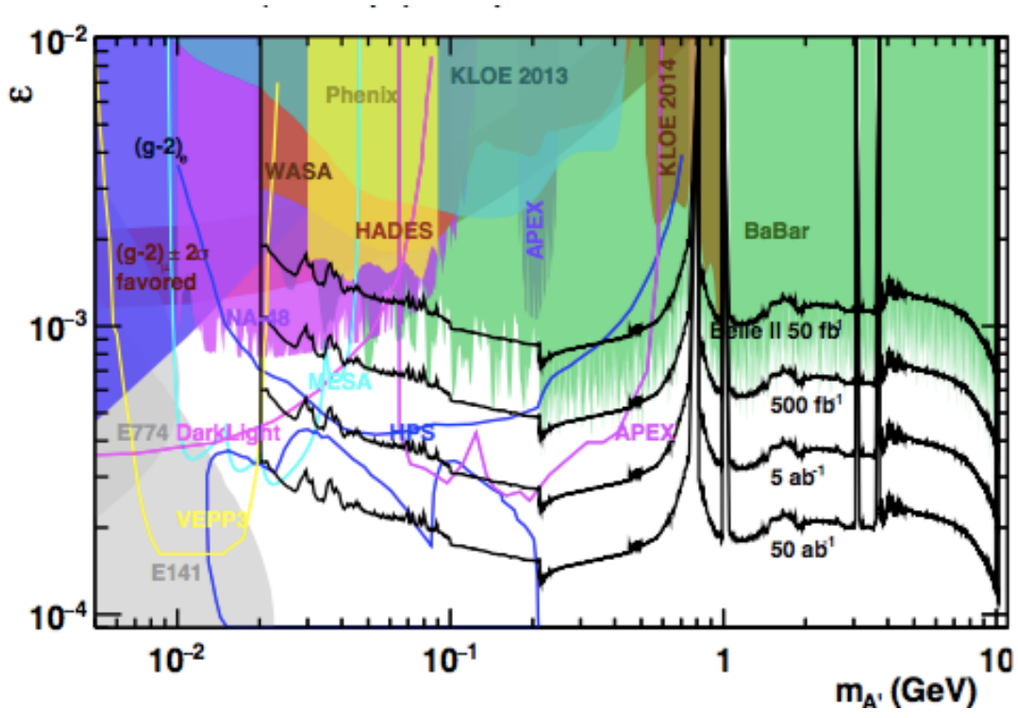


Dark Sector

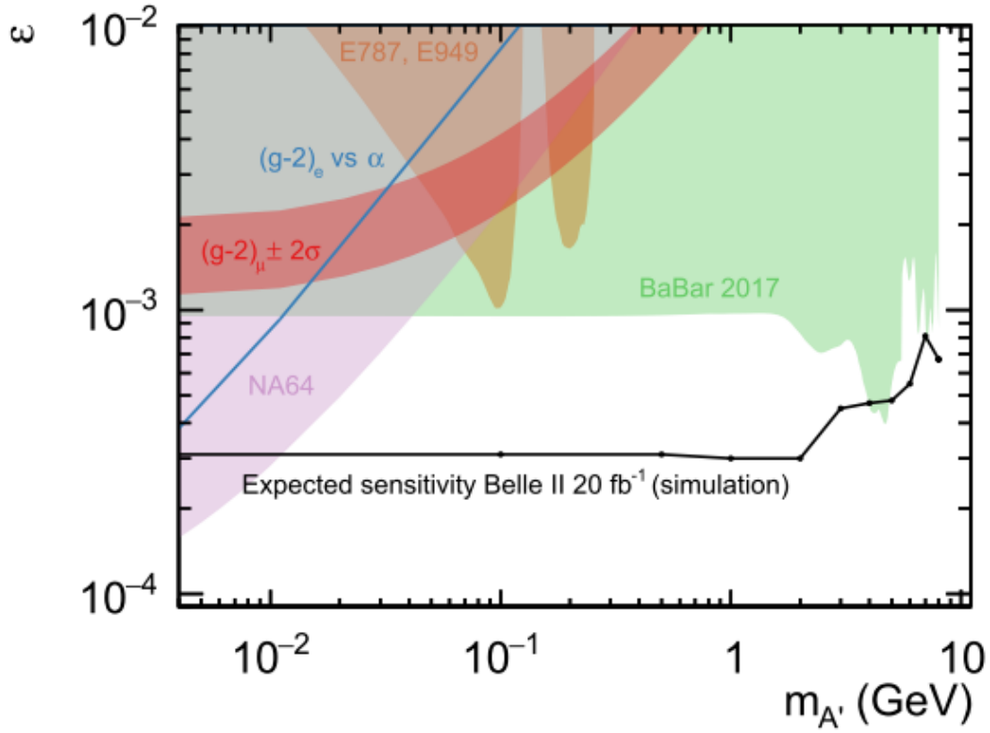
- Dark photon A’, motivated be in MeV-GeV mass
- Probe leptonicaly decaying dark photons through mixing
- probe sub-GeV dark matter in invisible decays



A’ →ee/μμ

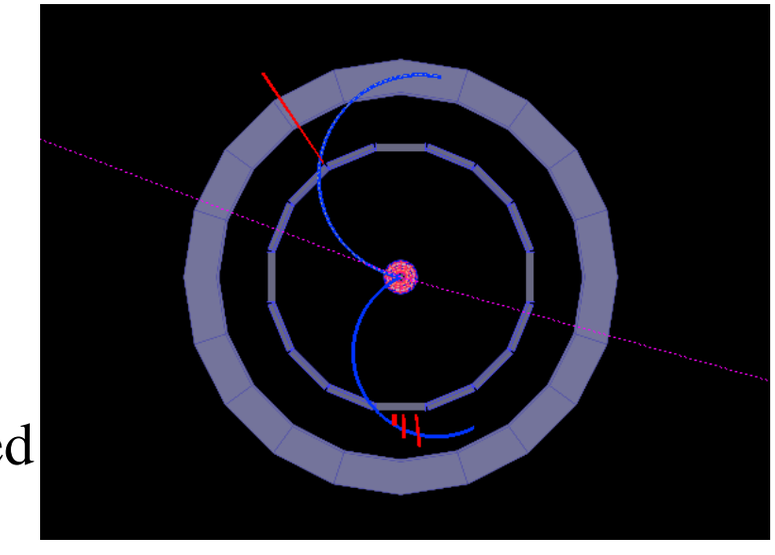


A’ →invisible



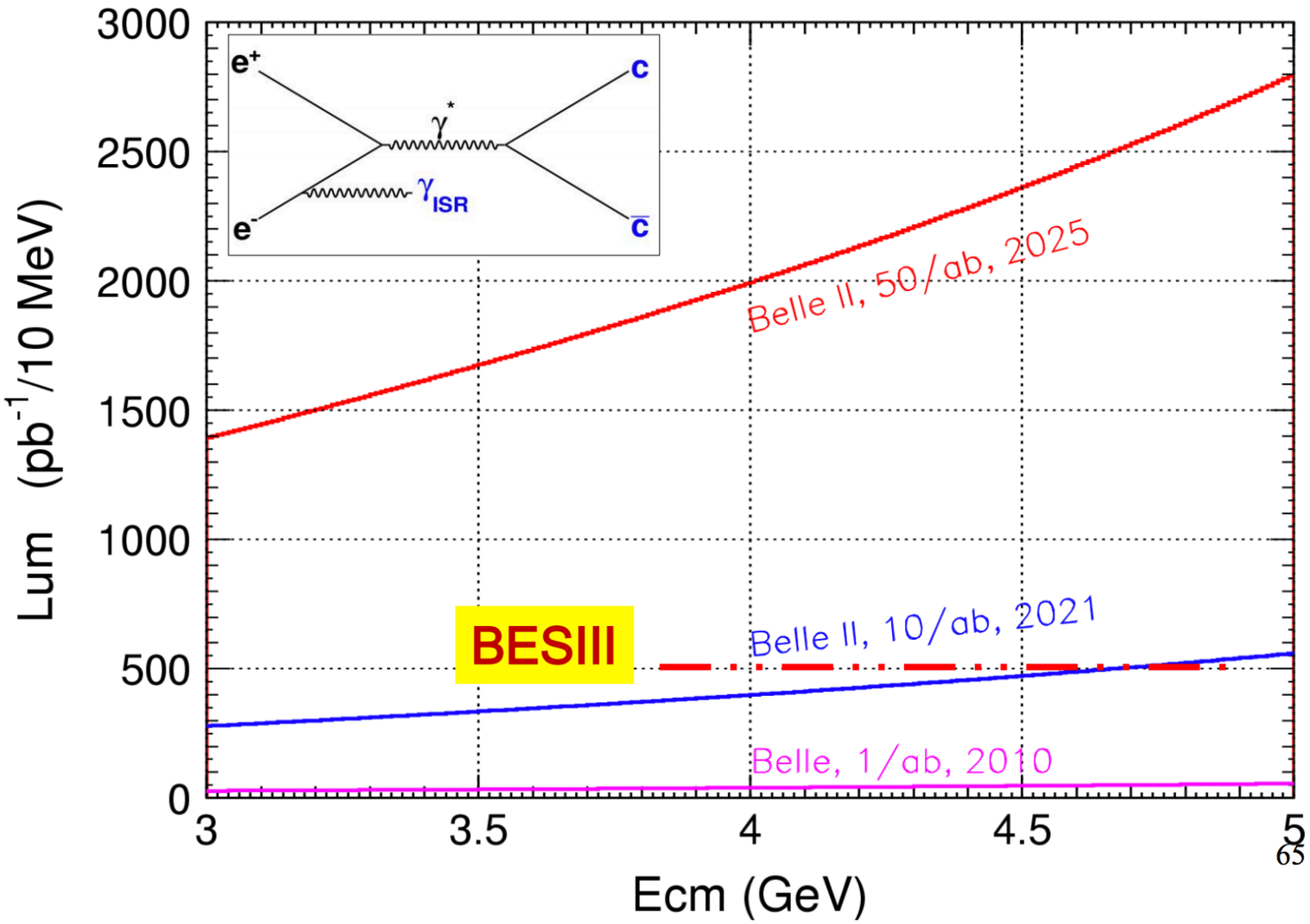
Search for dark matter in Y(1S) invisible decays

- Y(1S) invisible decay
  - In SM, B(Y(1S) → νν) ≈ 10^{-5} (PLB 441(1998) 419-424)
  - If low mass dark matter less than b quark mass exist, Y(1S) →invisible is enhanced
  - B<3x10^{-4} at 90% C.L. by Babar: PRL 103(2009) 251801, other measurements by Belle: PRL 98(2007) 132001, CLEO: (PRD 75(2007) 031104)
- Production at Belle II
  - e^+e^- → Υ(2,3S) → $\pi^+\pi^-$Υ(1S), Υ(1S)→invisible
  - Two slow charged π in the final state
- Dedicated trigger
  - Trigger with low threshold of transverse momentum is needed
  - Study is in progress
- Main backgrounds
  - Two photon process e^+e^- → e^+e^- X, where e^+e^- are out of detector, and X= $\pi^+\pi^-/\mu^+\mu^-$,



Charmonium(-like) states

- B decay, two photons collision, double charmonium production, initial state radiation



From Prof. C.Z.Yuan, 2018年粲偶素及类粲偶素物理研讨会
https://indico.ihep.ac.cn/event/7627/session/1/contribution/0/material/slides/0.pdf

Summary

- The trigger system have been improved significantly compared to Belle
  - 3D tracking.
  - 3D ecl Bhabha logics.
  - GRL, match between CDC-Track and ECL-Cluster.
  - Abundant trigger menu.
- DAQ
  - Large readout bandwidth, 3GB/s.
  - New scheme of software trigger at Belle II, powerful trigger capability.
  - HLT operation is smooth during cosmic ray test.
- First collision of Belle II is coming, many puzzles are expected to be solved at Belle II.

LNNU experimental particle physics group

- Location
  - LNNU is located in DALIAN, Liaoning province
- Job opportunity
  - There is a strong theoretical particle physics group in LNNU with 6 faculties.
  - We are building the experimental group. 2 faculty positions for BESIII/Belle II projects are opening, please contact to me if you are interested in.