Sensitivity study of $\tau \to \eta\pi\nu$ at the Belle II experiment

Michel Hernández Villanueva,

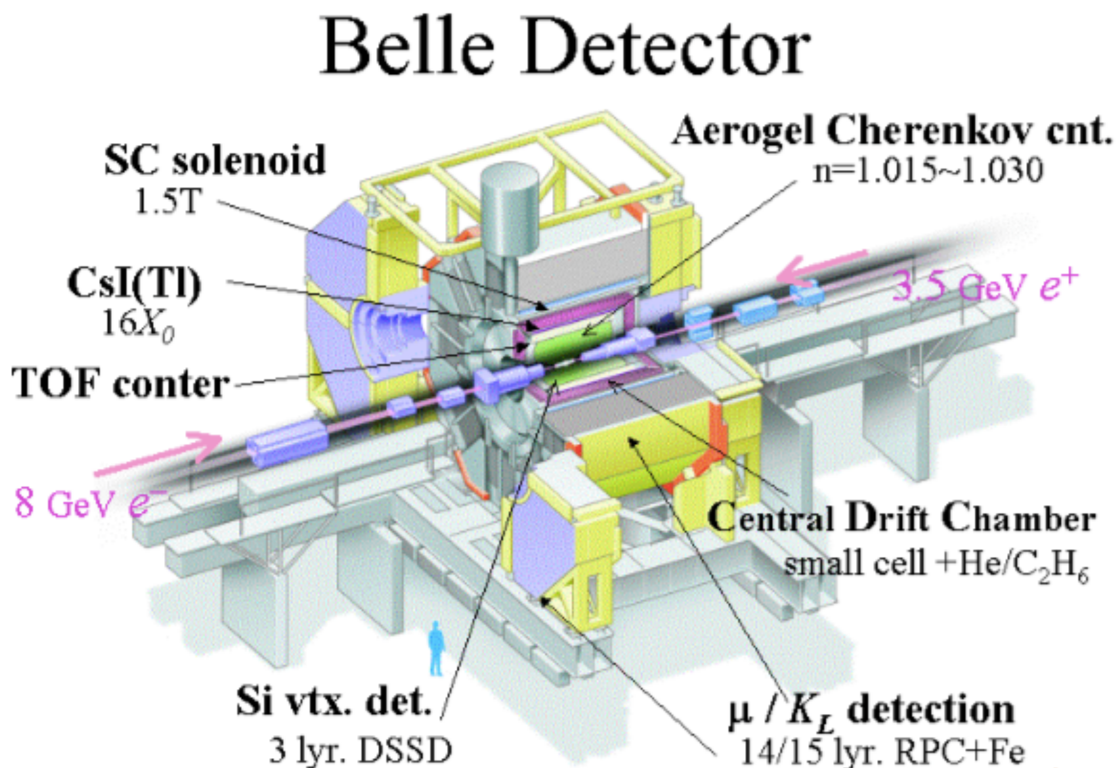
Cinvestav Group
Mexico City

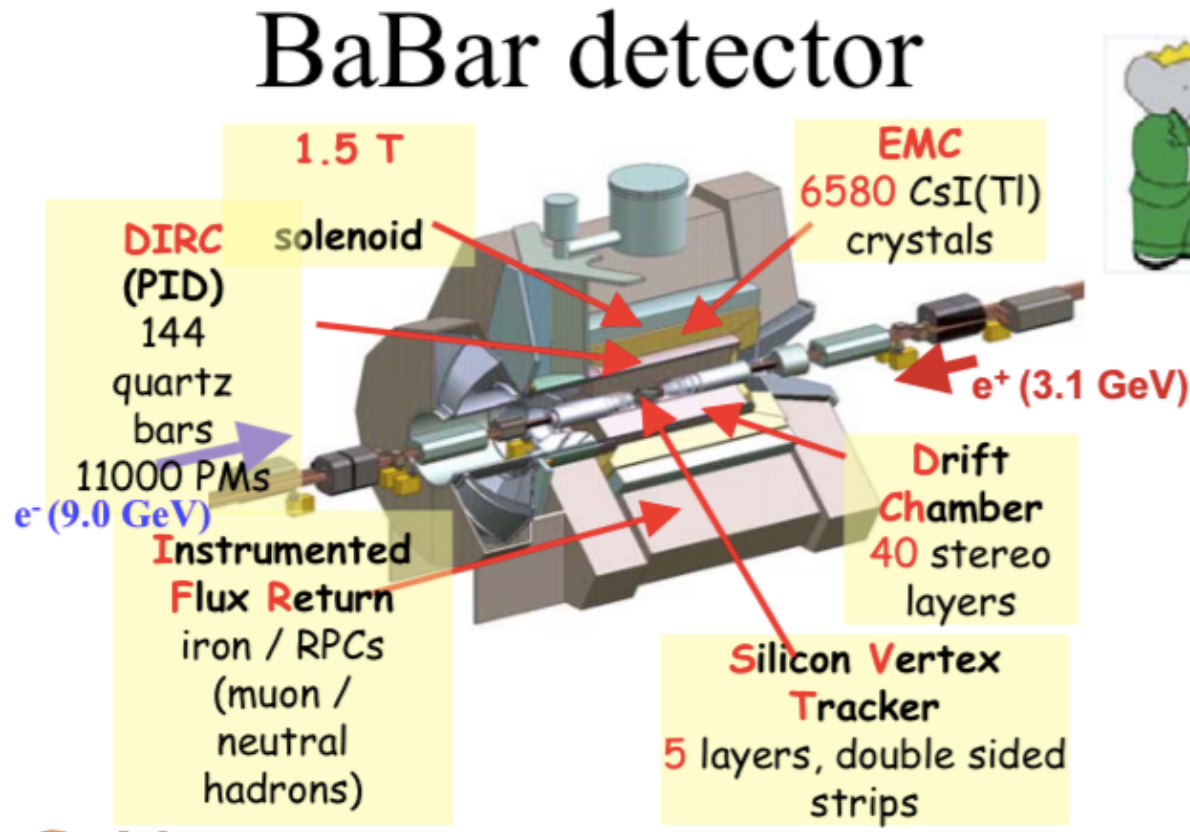
28 Sep 2017

Outline

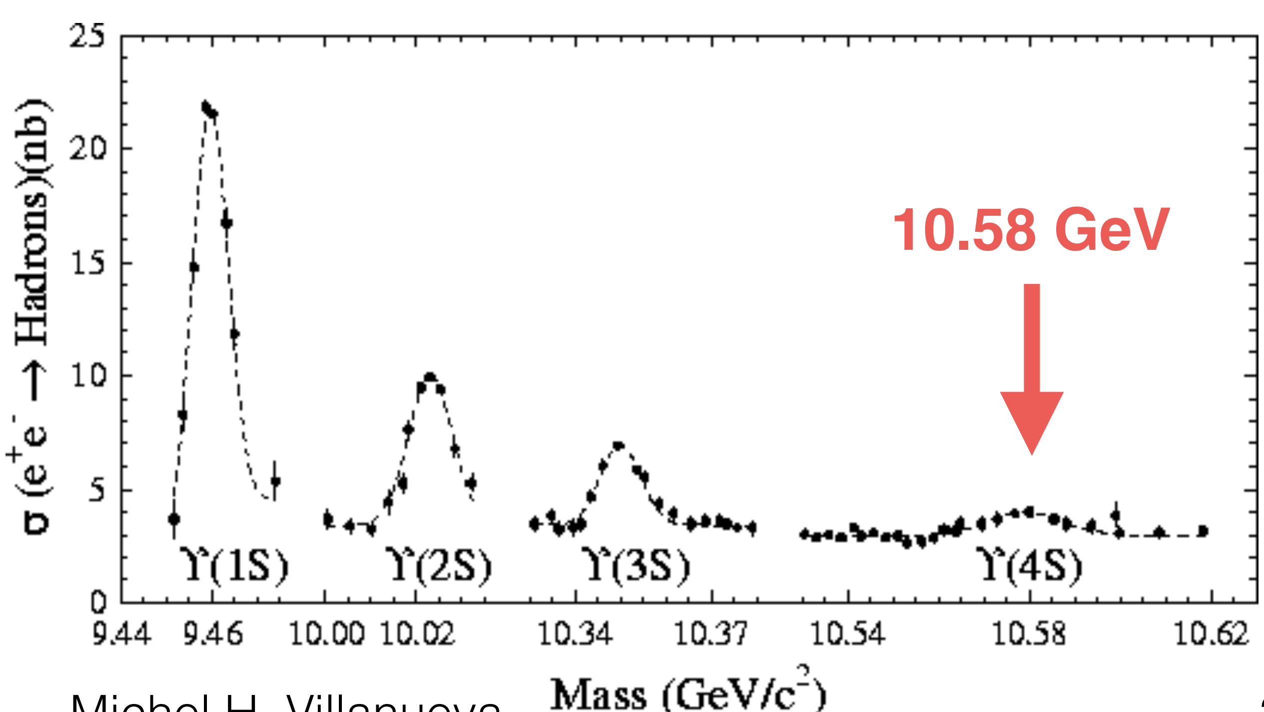
- B-factories and τ physics.
- Second class currents
- $\tau \to \eta\pi\nu$ decay
- Outlook.

B Factories





$\sqrt{s}$=10.58 GeV

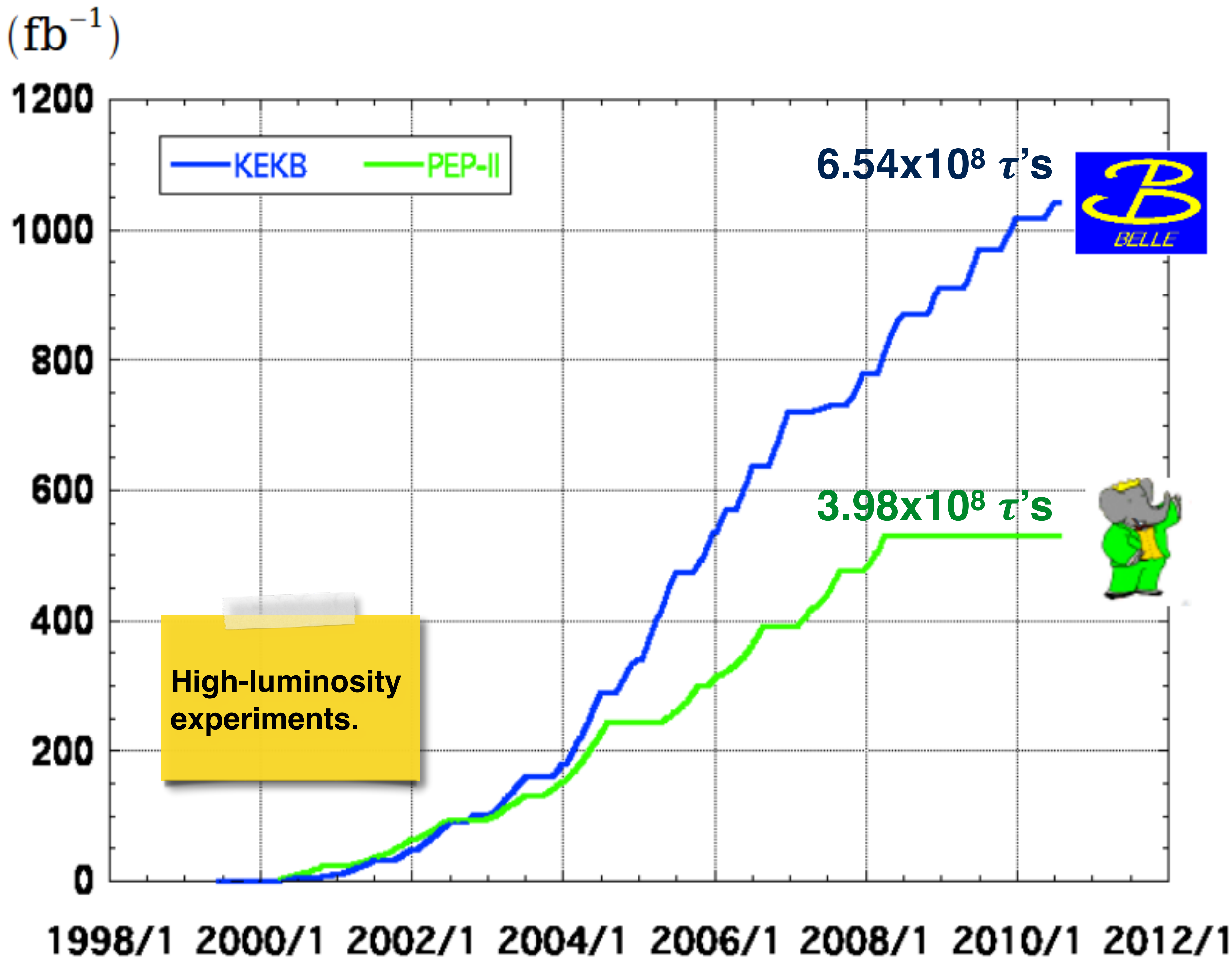


- B-Factory
  $BR(\Upsilon(4S) \to B\bar{B}) > 96\%$

- $\boldsymbol{\tau}$ factory too!
  $\sigma(e^+e^- \longrightarrow \Upsilon(4s)) = 1.05$ nb
  $\sigma(e^+e^- \longrightarrow \tau\,\tau) = 0.92$ nb

Cinvestav

Integrated Luminosity of B factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

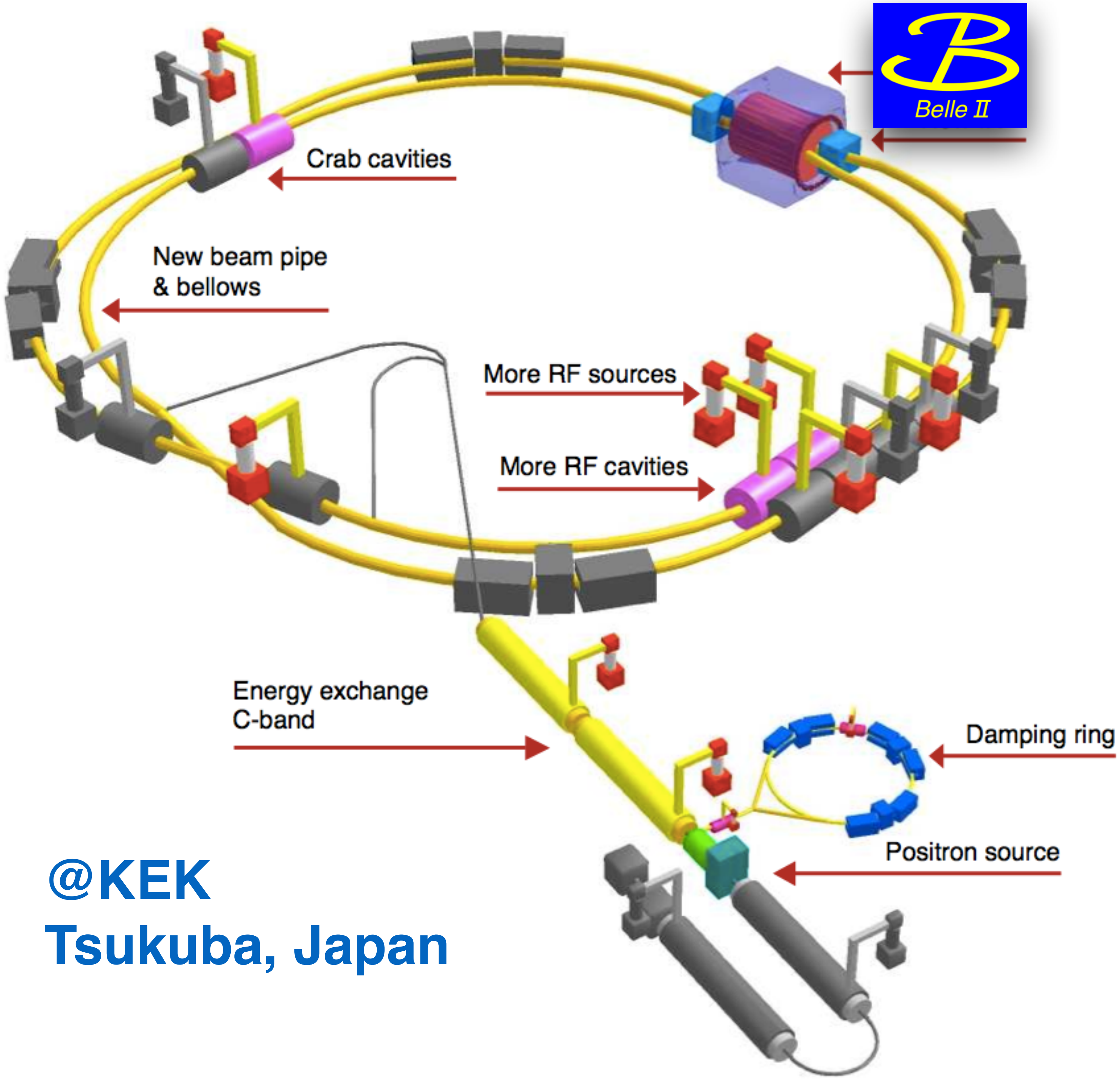
$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

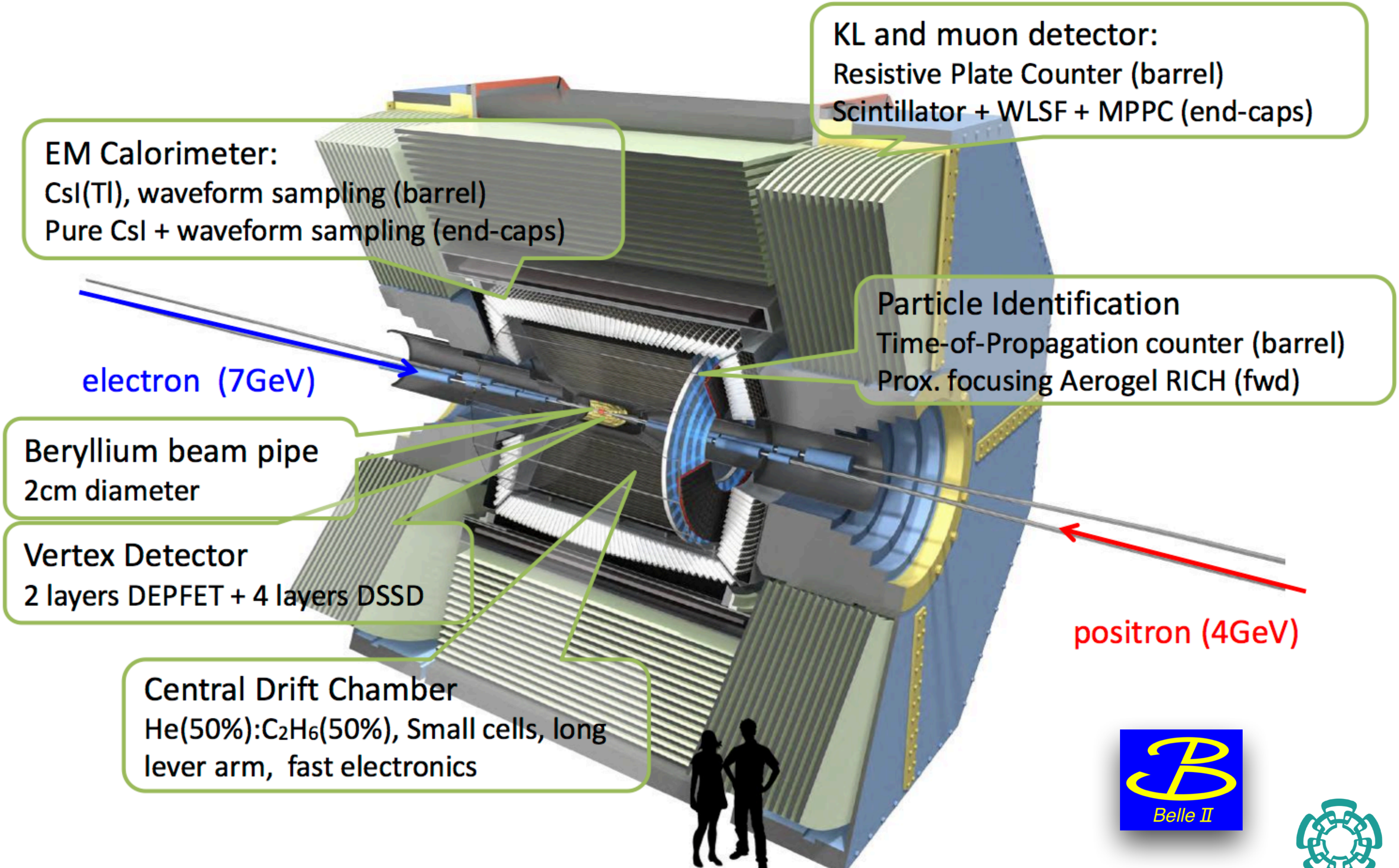
SuperKEKB



- Super B-Factory
  (And τ factory too!)
- Integrated luminosity expected: **50 ab^{-1}**
  (4.6x10^{10} τ pairs)
- Full physics program starts: late 2018

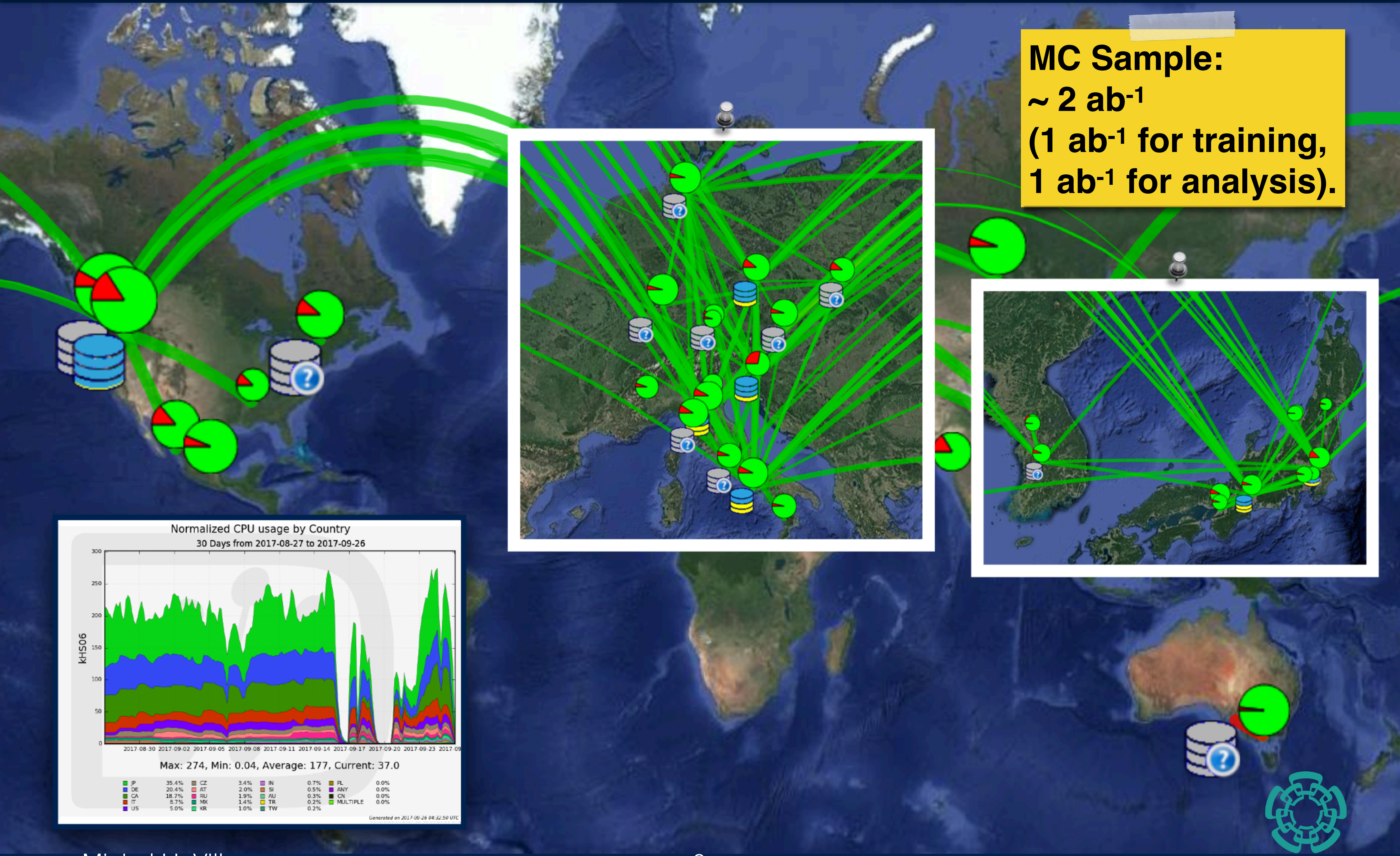
@KEK
Tsukuba, Japan

Belle II Detector



Belle II MC samples

MC Sample:
~ 2 ab^{-1}
(1 ab^{-1} for training,
1 ab^{-1} for analysis).



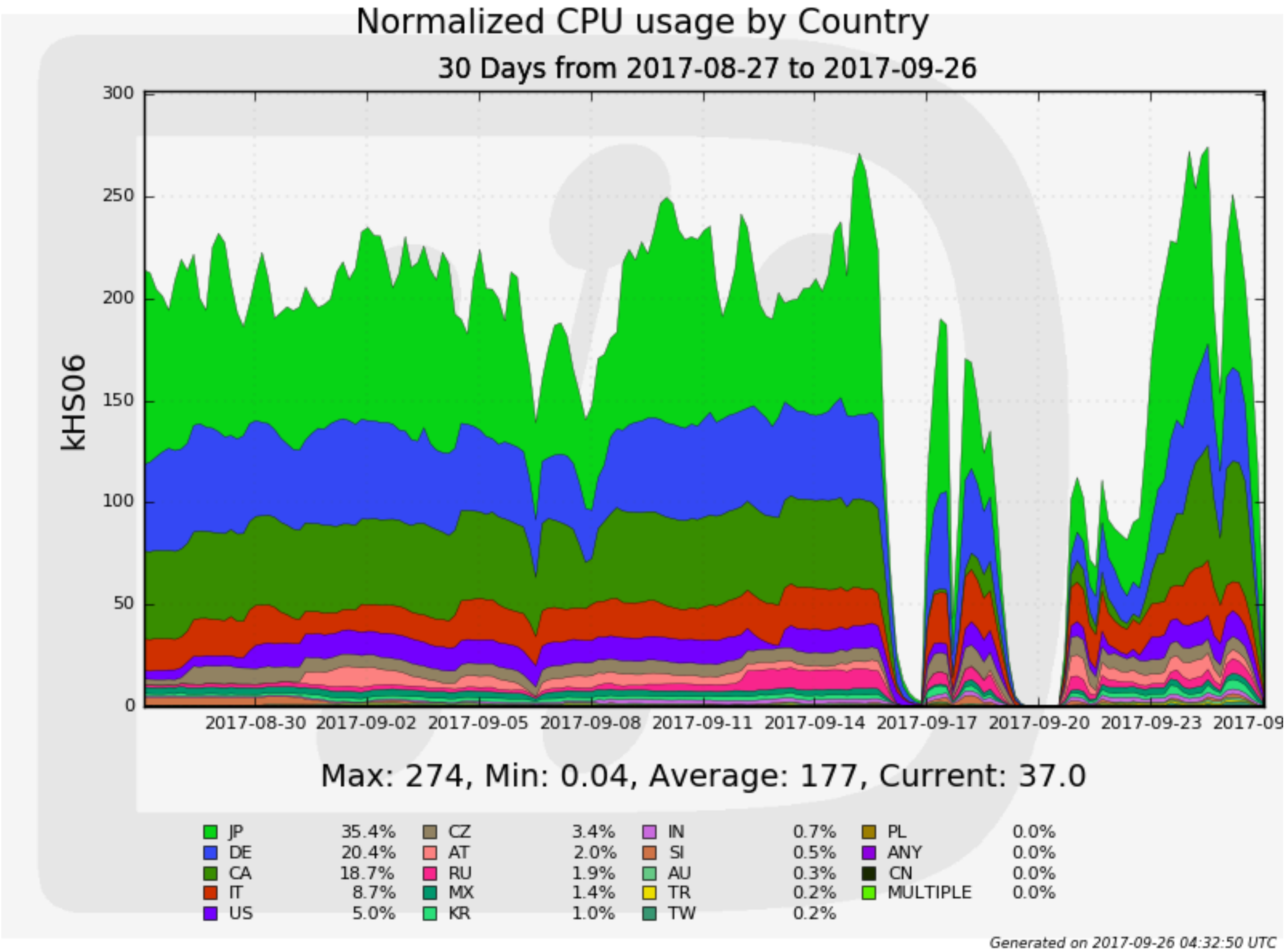
Cinvestav

Mexican Contribution

- 504 cores
  3.7 KHS06

  70 TB storage

~1.4% CPU usage of the grid

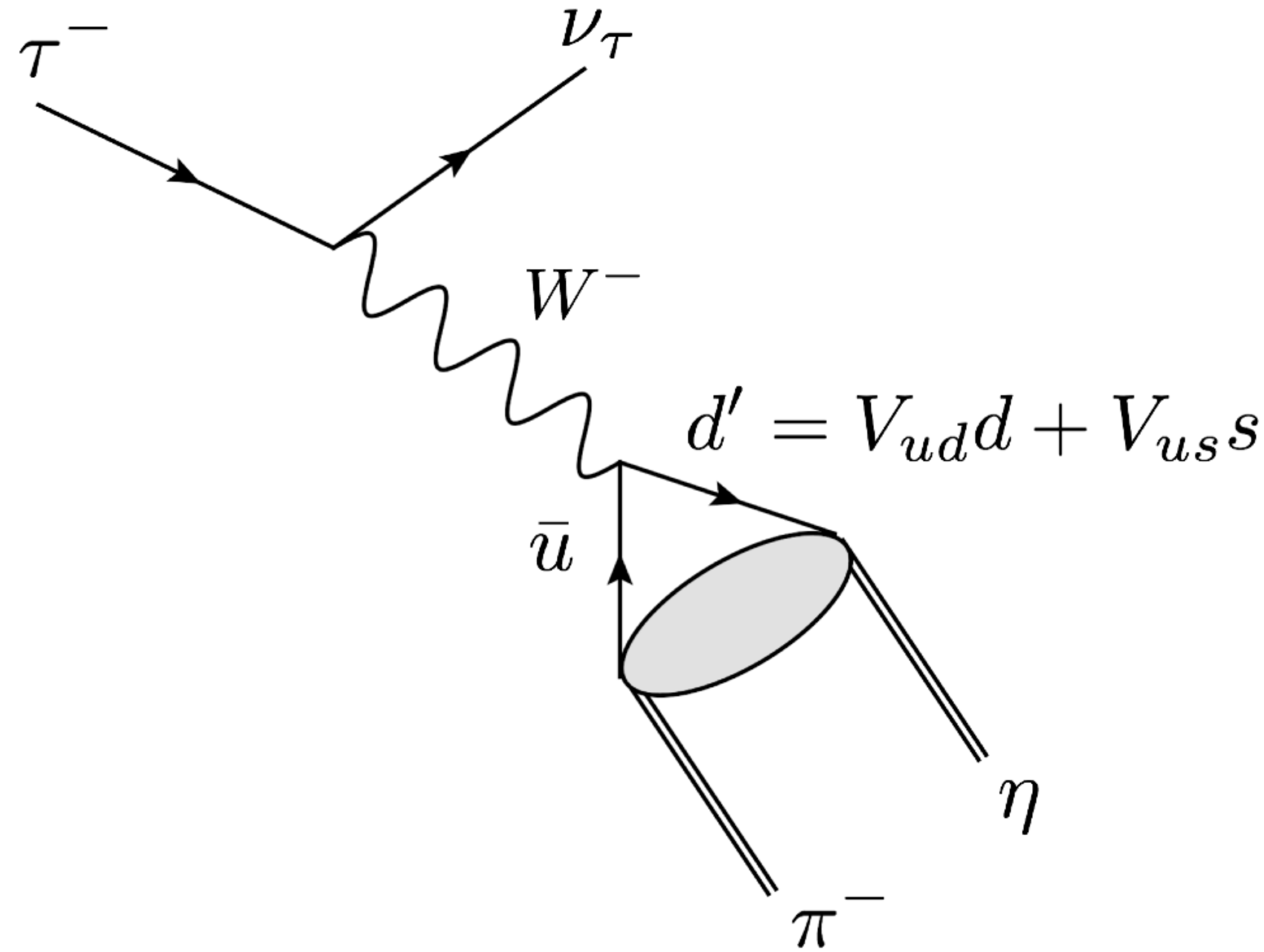


The $\tau \to \eta\pi\nu$ decay

- In this work, we are studying the feasibility to measure the decay

  $\tau \to \eta\pi\nu$,

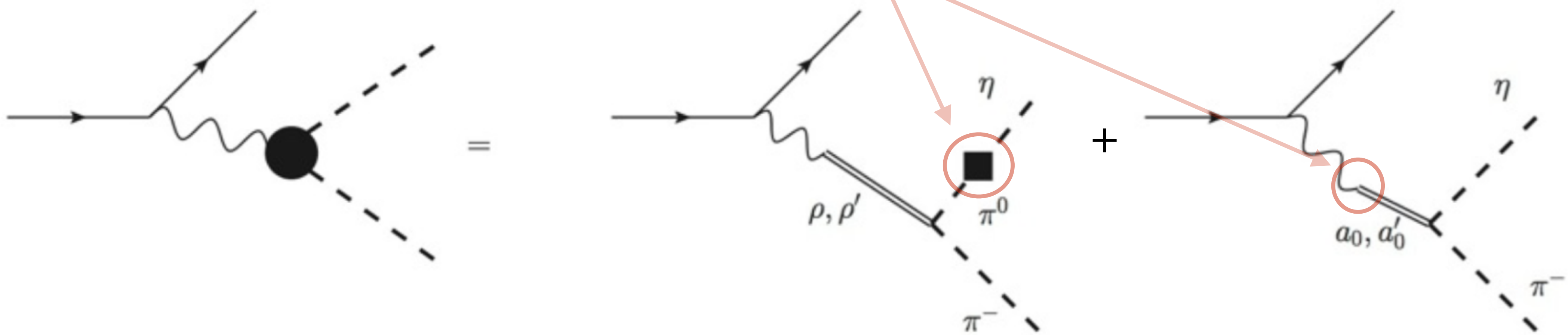
  in order to get information related at:
  - Second class currents.
  - Scalar and tensorial currents.



Disadvantage:
We cannot detect ν

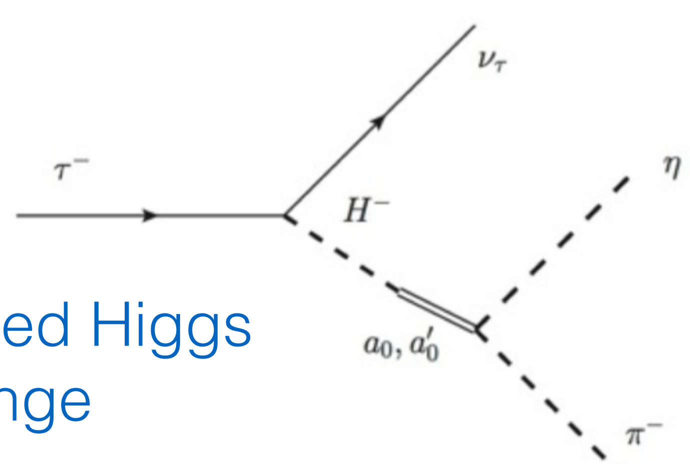
The $\tau \to \eta\pi\nu$ decay

- Mechanisms in the SM: isospin violation[1]

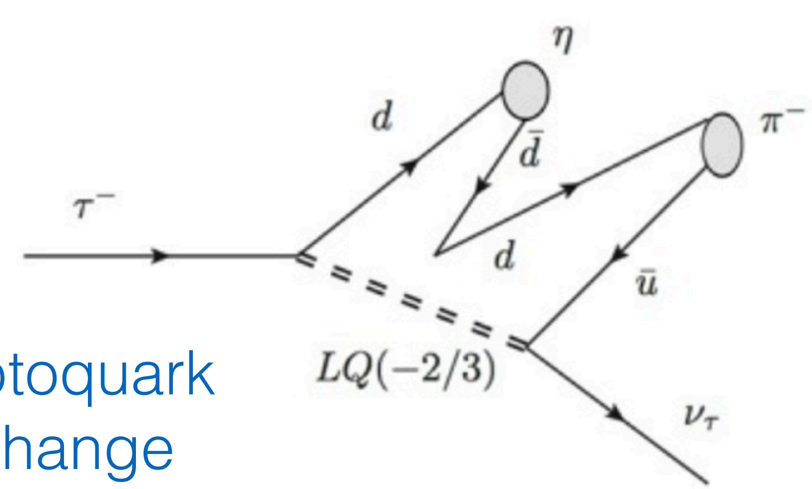


$$\epsilon_{\eta\pi} = \frac{\langle \pi^0 | H | \eta \rangle}{m_\eta^2 - m_{\pi^0}^2} = \frac{\sqrt{3}}{4} \frac{m_d - m_u}{m_s - \bar{m}} \sim 1.5 \times 10^{-2}$$

- The corresponding suppression of the SM contribution can make new physics visible.



Charged Higgs exchange



Leptoquark exchange

[1] R. Escribano, S. Gonzalez, P. Roig; Phys.Rev. D94 (2016) no.3, 034008

Some recent theoretical predictions

Ref	$BR_V (\times 10^5)$	$BR_S (\times 10^5)$	$BR_{V+S} (\times 10^5)$	Model
[8]	0.36	1.0	1.36	MDM, 1 resonance
[9]	[0.2, 0.6]	[0.2, 2.3]	[0.4, 2.9]	MDM, 1 and 2 resonances
[10]	0.44	0.04	0.48	Nambu-Jona-Lasinio
[11]	0.13	0.20	0.33	Analiticity, Unitarity
[12]	0.26	1.41	1.67	3 coupled channels

Largest difference comes from scalar form factor.

[8] S. Nussinov + A. Soffer, PRD78, (2008)

[9] N. Paver + Riazuddin, PRD82, (2010)

[10] M. Volkov D. Kostunin, PRD82, (2012)

[11] S. Descotes-Genon+B. Moussallam, EJPC74, (2014)

[12] R. Escribano, S. Gonzalez, P. Roig; Phys.Rev. D94 (2016) no.3, 034008

- $BR(\tau \to \eta \pi \nu) \sim 10^{-5}$ ← Accesible at Belle II luminosity.

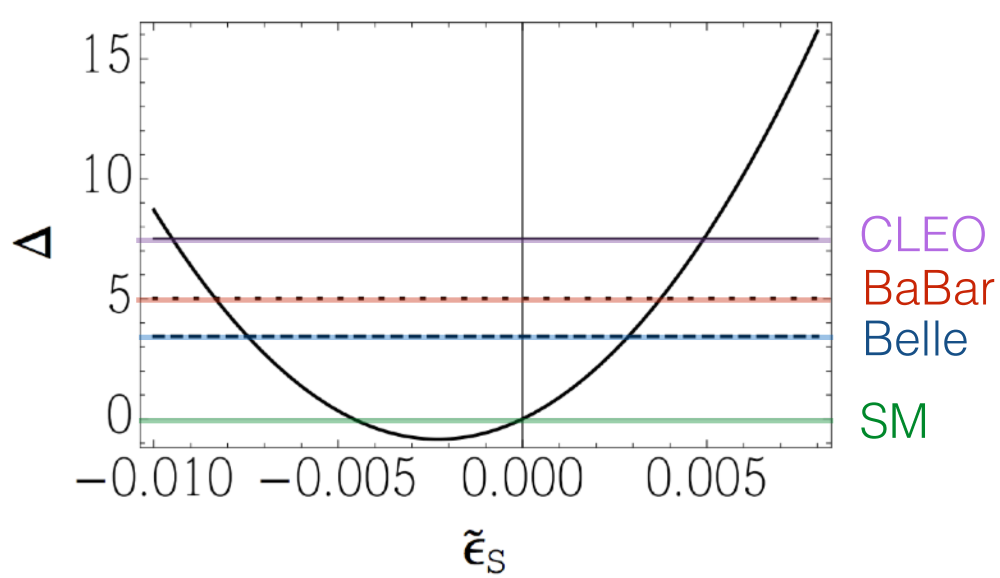
The $\tau \to \eta\pi\nu$ decay

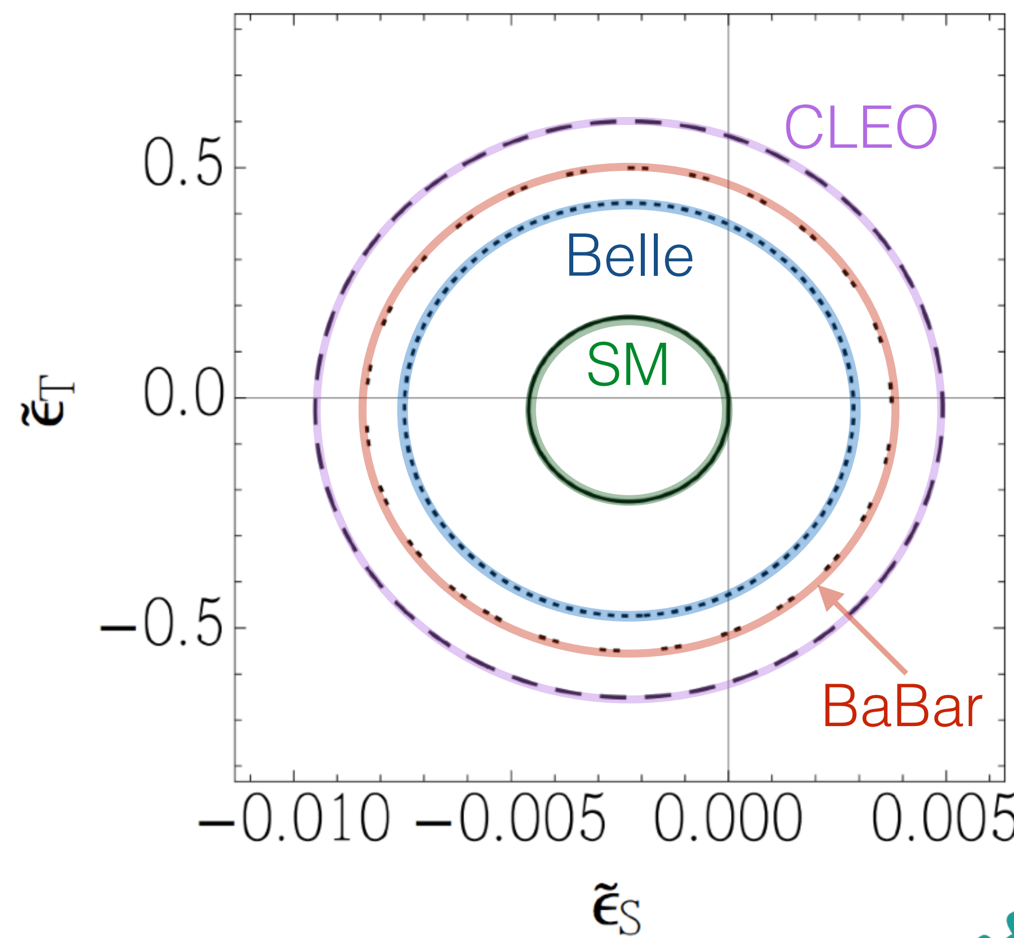
- NP contributions (scalar and tensorial currents) can be studied in the framework of an effective field theory [1]

$$\mathcal{M} = \mathcal{M}_V + \mathcal{M}_S + \mathcal{M}_T$$
$$= \frac{G_F V_{ud}\sqrt{S_{EW}}}{\sqrt{2}}(1+\epsilon_L+\epsilon_R)\left[L_\mu H^\mu + \tilde{\epsilon}_S L H + 2\tilde{\epsilon}_T L_{\mu\nu} H^{\mu\nu}\right],$$

- Constraints on scalar and tensor couplings can be obtained from experimental upper limits on branching fractions.

$$\Delta \equiv \frac{\Gamma - \Gamma^0}{\Gamma^0}$$

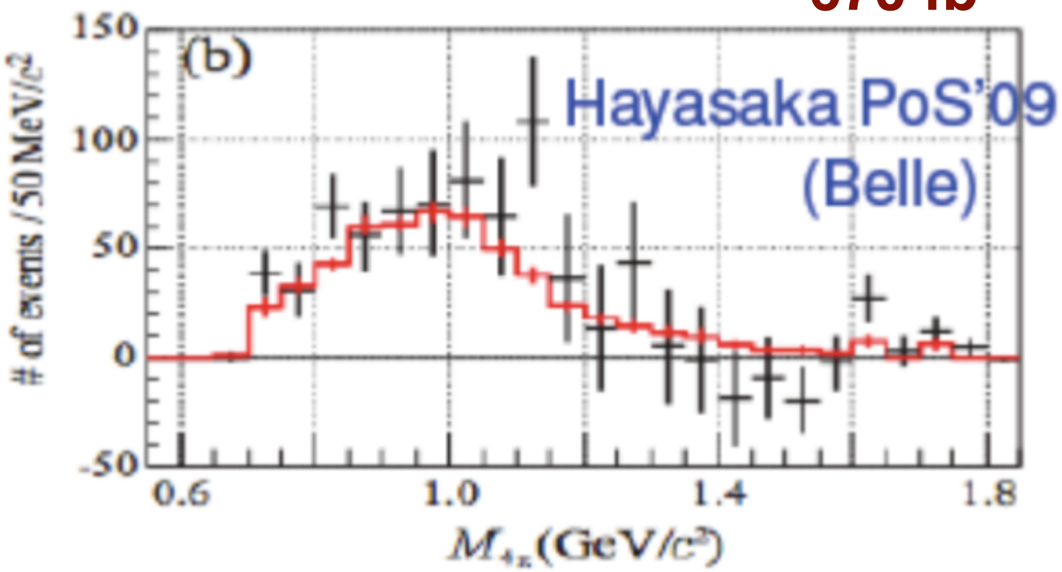




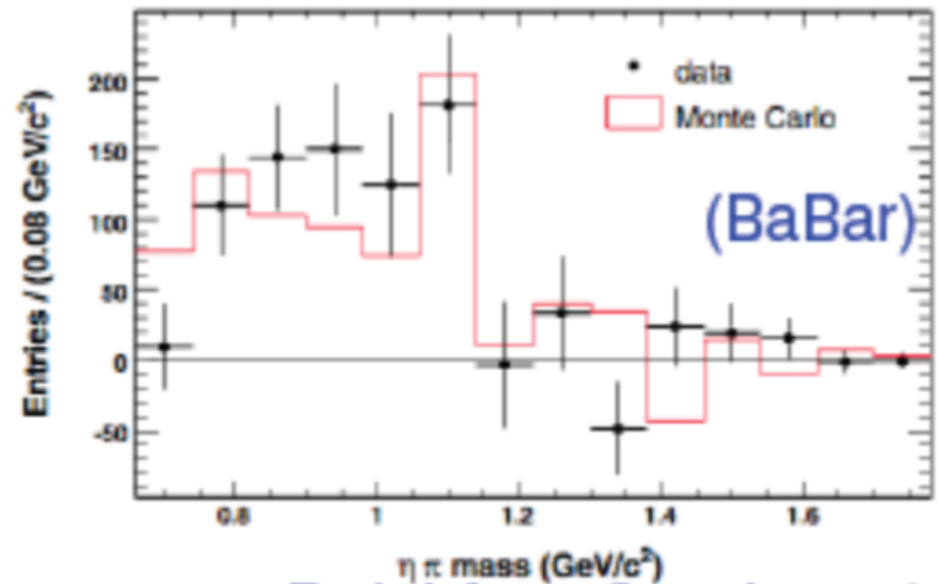
[1] E. A. Garcés, MHV, G. López Castro, P. Roig; arXiv:1708.07802

Previous Results

670 fb^{-1}



470 fb^{-1}



P. del Amo Sanchez *et.al*
(PRD 83 032002 '11)

$BR_{exp}^{Belle} < 7.3 \cdot 10^{-5}$ $90\% CL$

$BR_{exp}^{BaBar} < 9.9 \cdot 10^{-5}$ $95\% CL$

- This decay mode should have already been discovered if there were no strong background.
- Control of the background is essential.

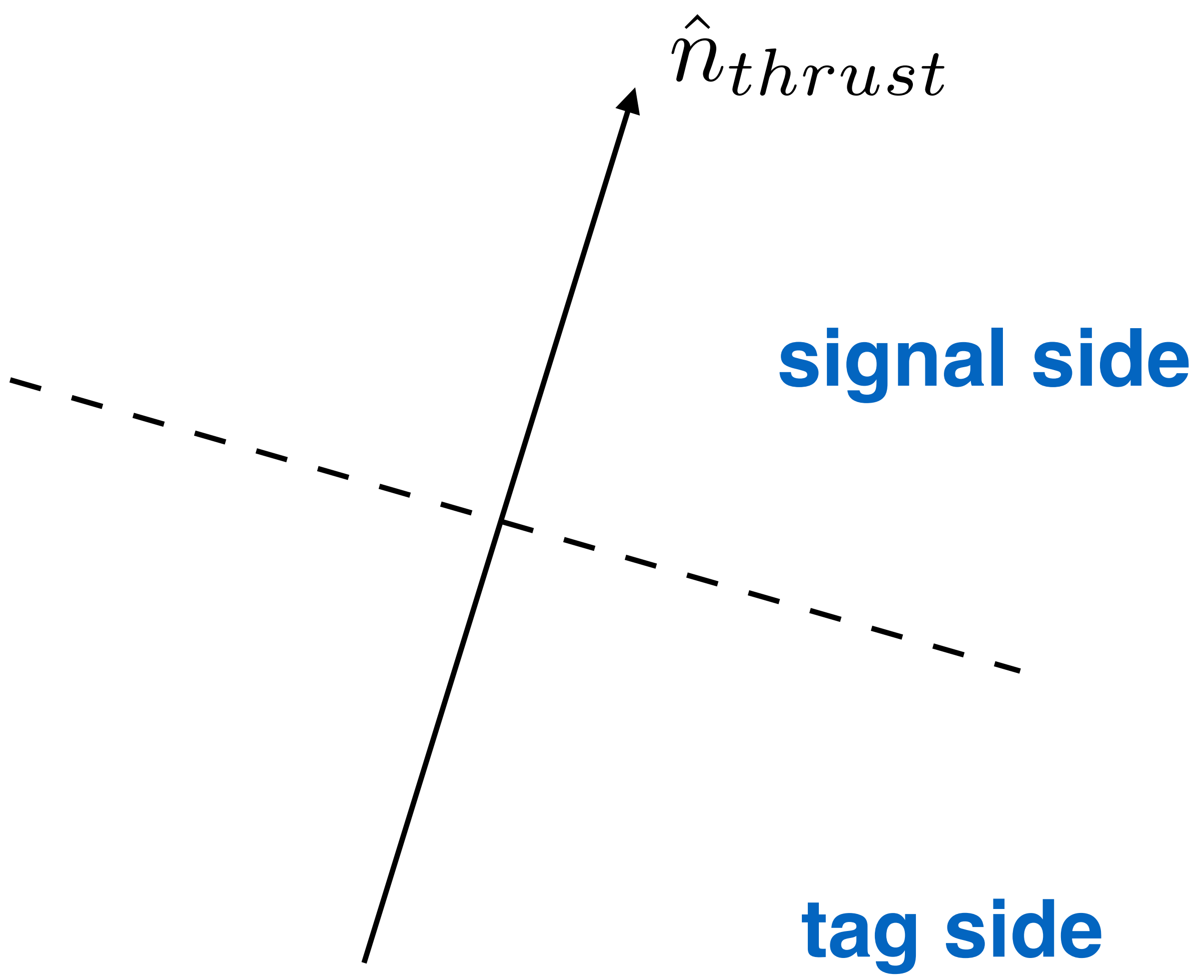
Cinvestav

Thrust axis

- Thrust axis: $\hat{n}_{thrust}$ such that V_{thrust} is maximum.

$$V_{thrust} = \frac{\sum_i |\vec{p_i}^{\,cm} \cdot \hat{n}_{thrust}|}{\sum_i |\vec{p_i}^{\,cm}|}$$

The thrust axis define a plane which splits the space in two.



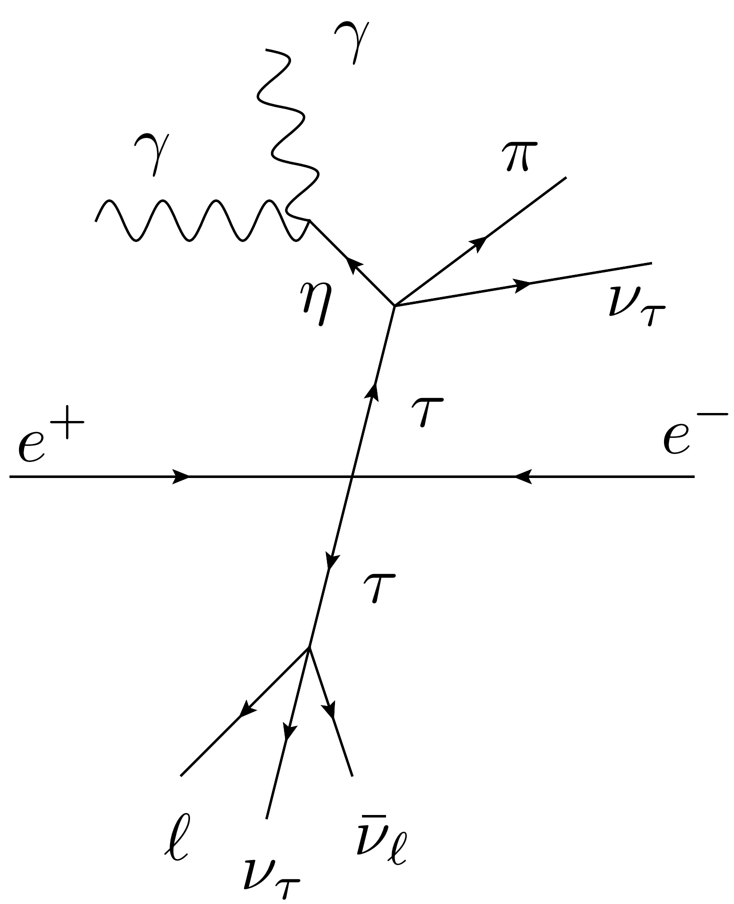
2 ways to reconstruct η

- Thrust axis: $\hat{n}_{thrust}$ such that V_{thrust} is maximum.

$$V_{thrust} = \frac{\sum_i |\vec{p_i}^{\,cm} \cdot \hat{n}_{thrust}|}{\sum_i |\vec{p_i}^{\,cm}|}$$

1-prong

BR(η —> $\gamma\gamma$) = 39.41%

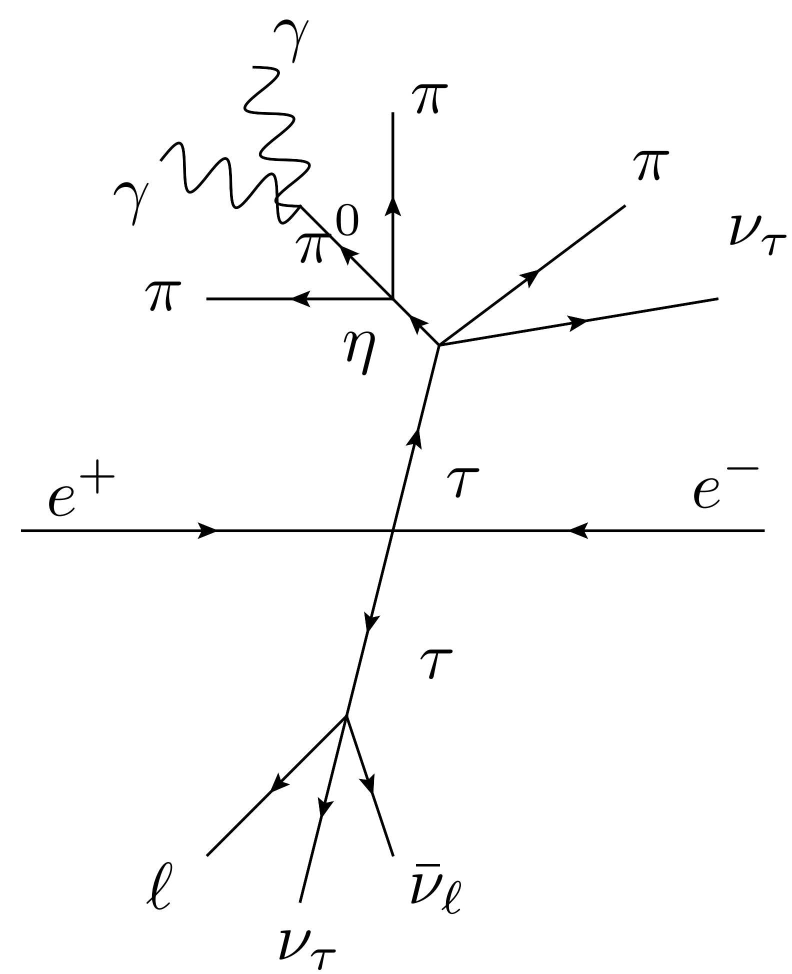


Signal side

Tag side

3-prong

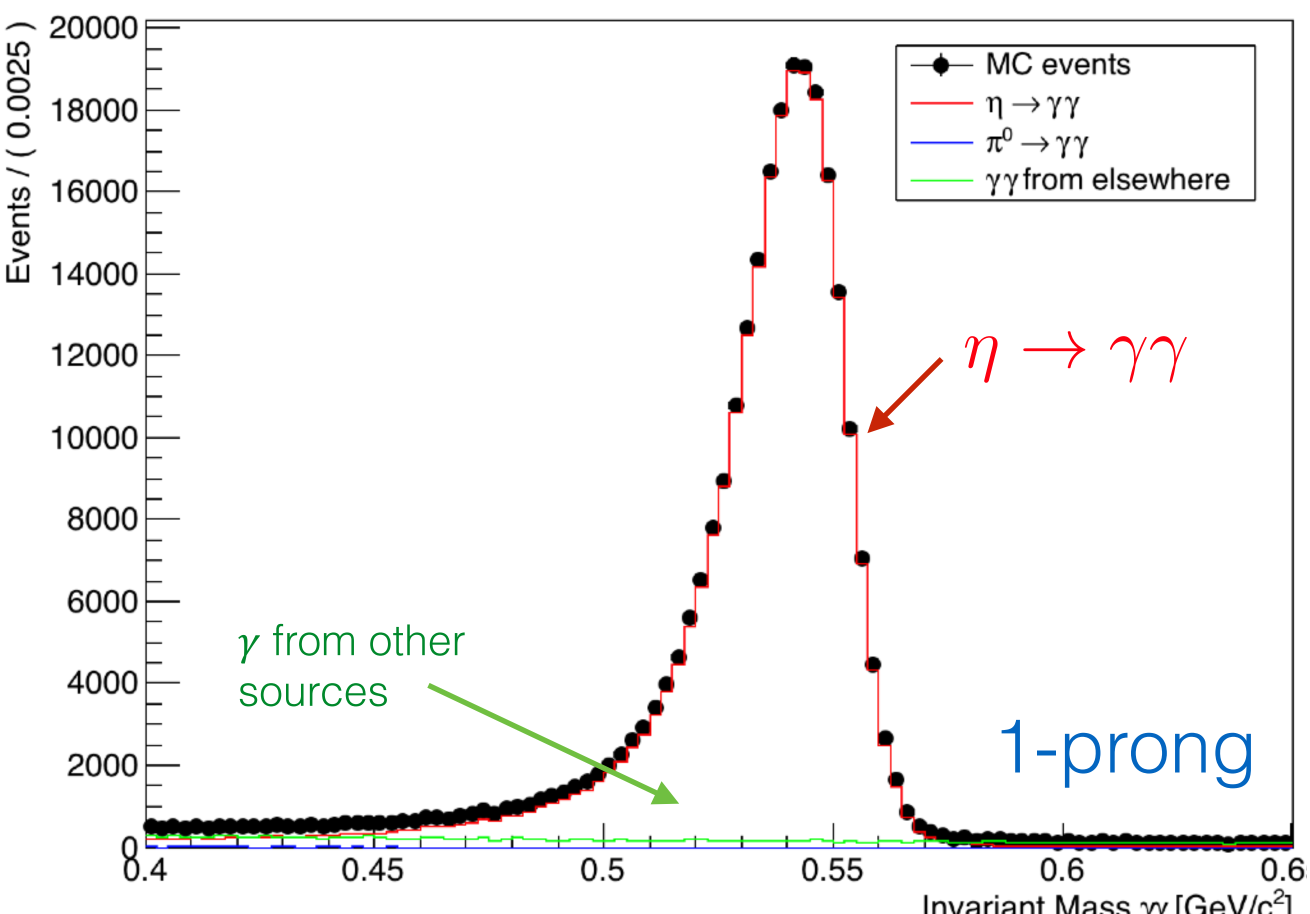
BR(η —> $\pi\pi\pi^0$) = 22.92%



$\tau \to \eta \pi \nu$ signal events

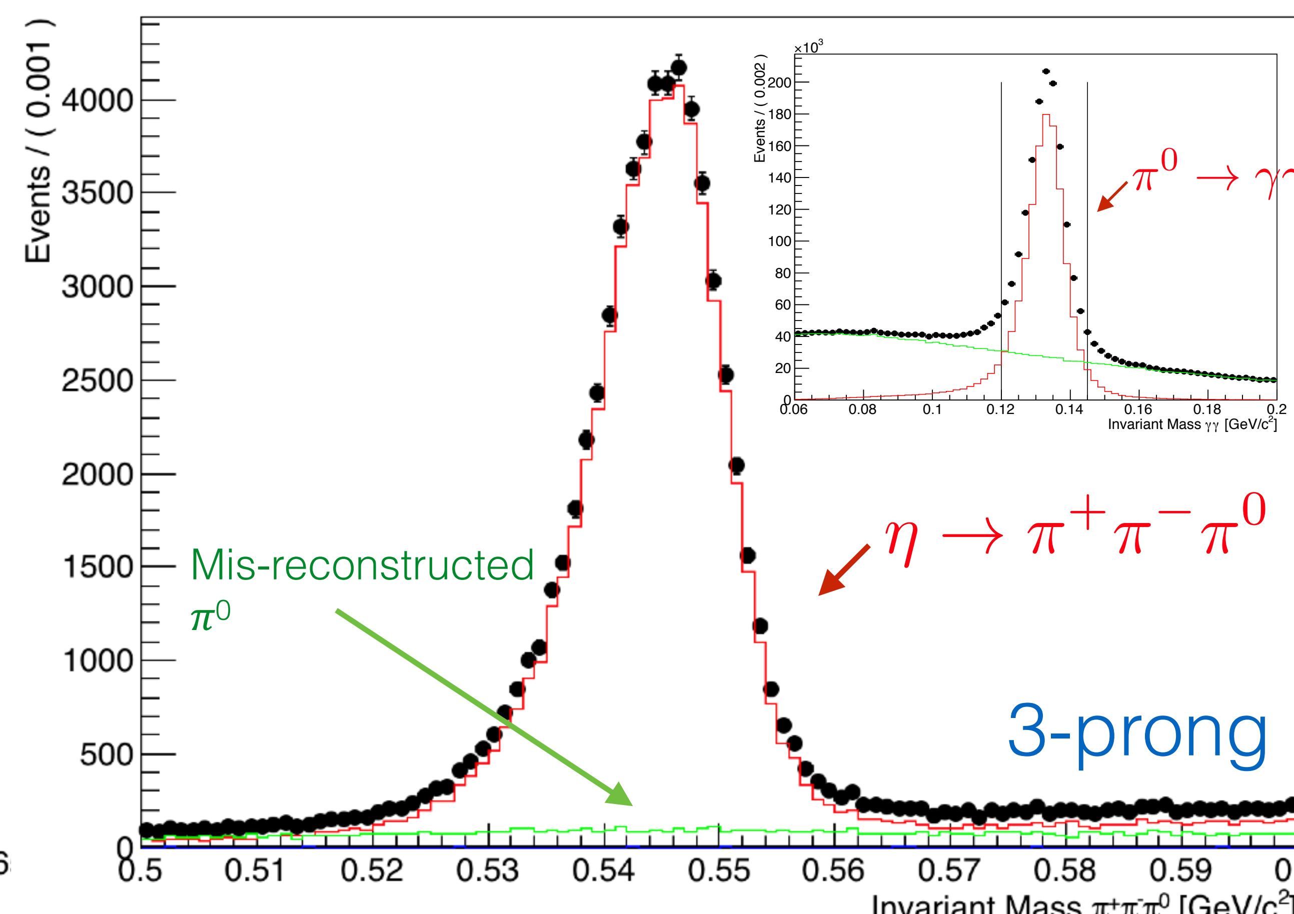
- Selection criteria :tag + 1 or 3 charged + 2 or 3 γ.
- Signal events generated: 4M**.**
  (2M for training and 2M for sensitivity study).

Eff: 13.56%



BR(η —> $\gamma\gamma$) = 39.41%

Eff: 3.70%



BR(η —> $\pi\pi\pi^0$) = 22.92%

Cinvestav

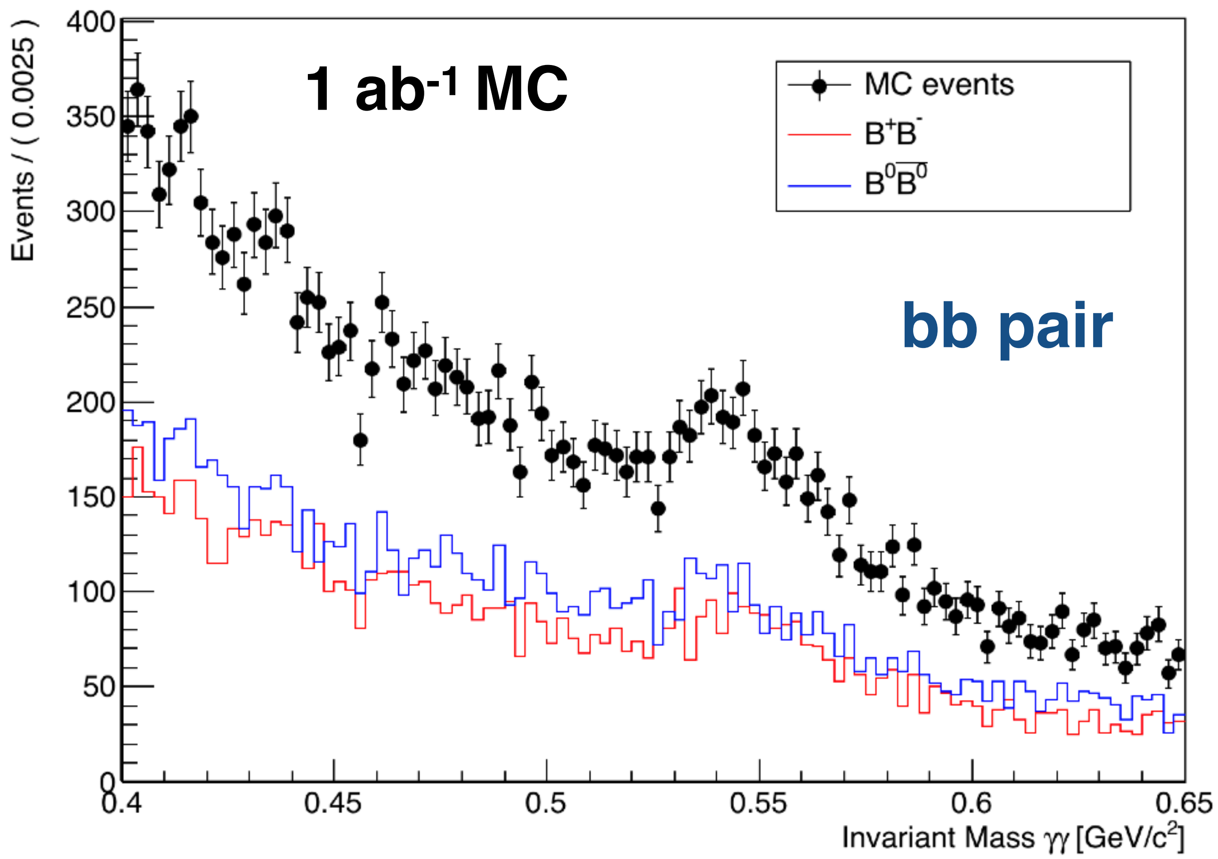
$\tau \to \eta \pi \nu$ bkg events

1-prong

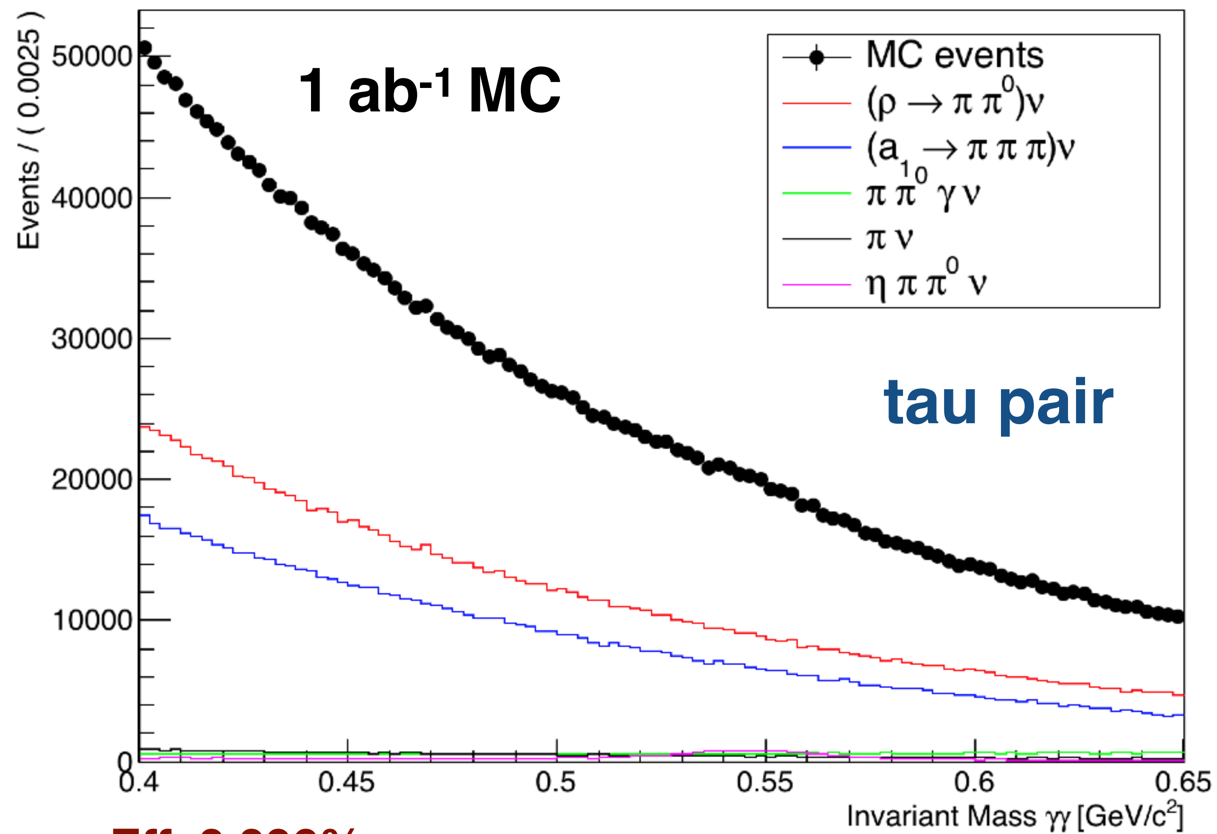
- Background sources:
  - $\tau\tau$ pair
  - bb pair
  - qq pair

π^0 veto applied.

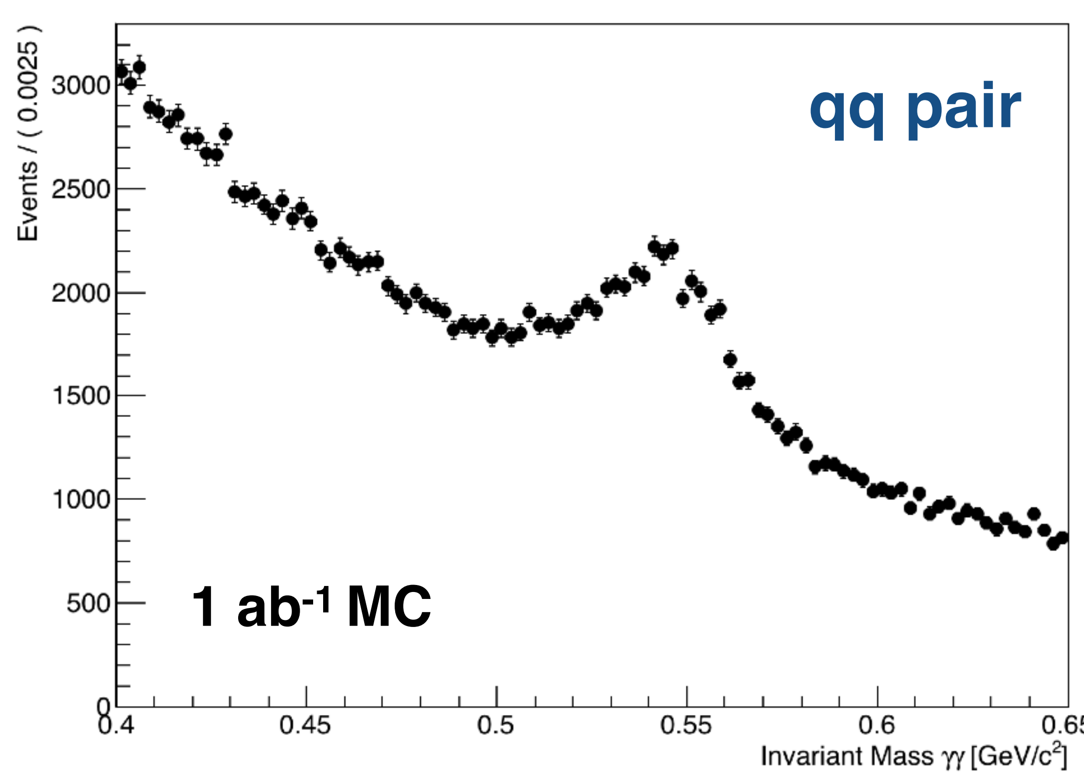
Eff: 0.002%



Eff: 0.34%



Eff: 0.006%



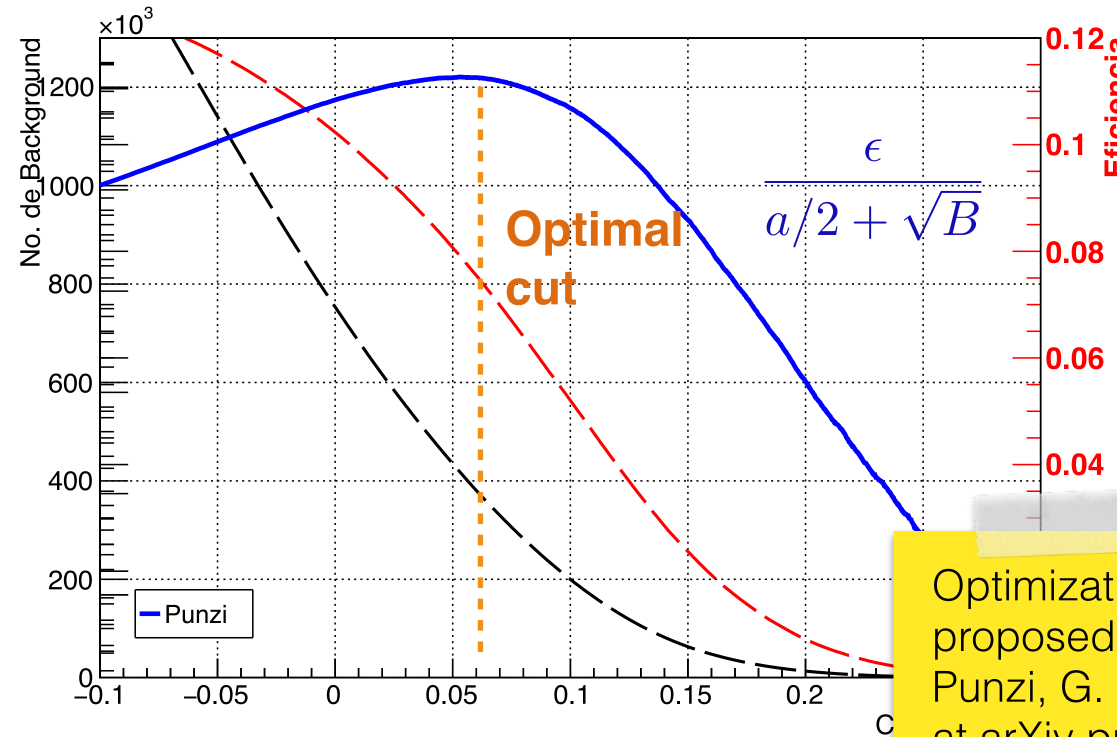
Michel H. Villanueva

Cinvestav

BDT variables (1-prong)

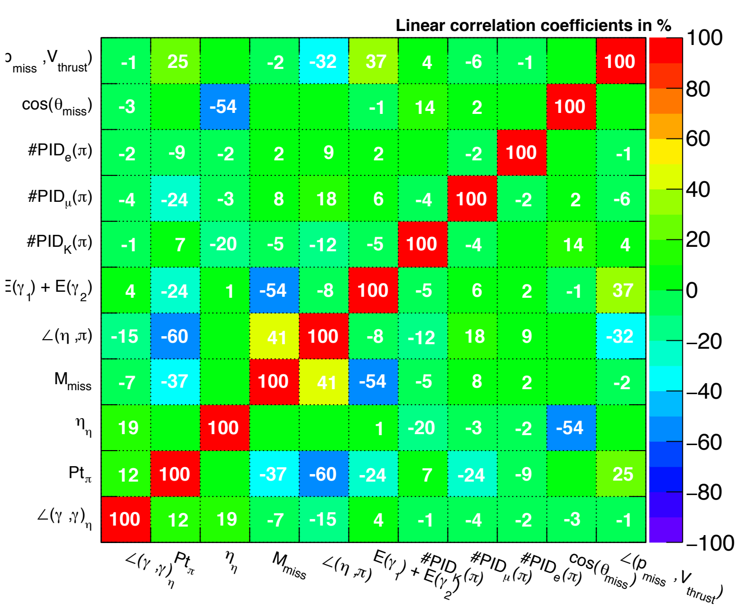
TMVA used for this test.

- $\angle(\eta,\pi)$
- $\angle(p_{miss}, V_{thrust})$
- M_{miss}
- $P_t(\pi)$
- $\eta(\eta)$
- $\angle(\gamma,\gamma)_\eta$
- $\cos(\theta_{miss})$
- $PID_e(\pi)$
- $PID_\mu(\pi)$
- $PID_K(\pi)$
- $E(\gamma)$

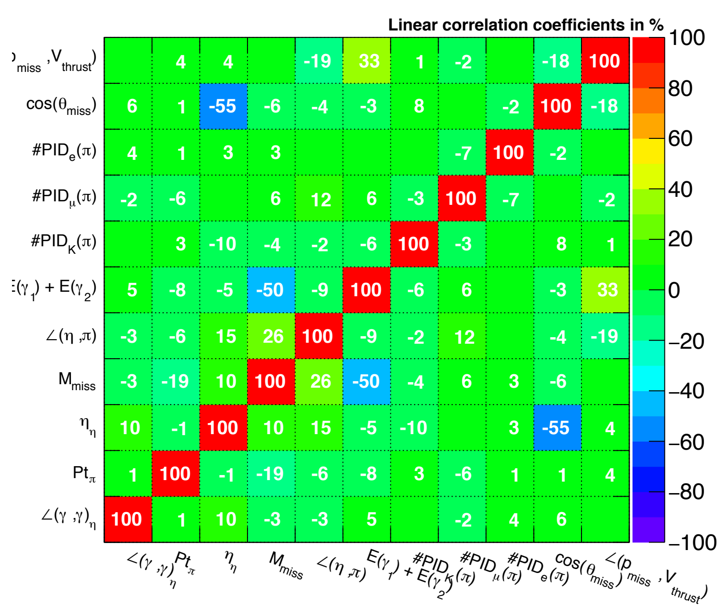


Optimization proposed by Punzi, G. at arXiv preprint physics/0308063

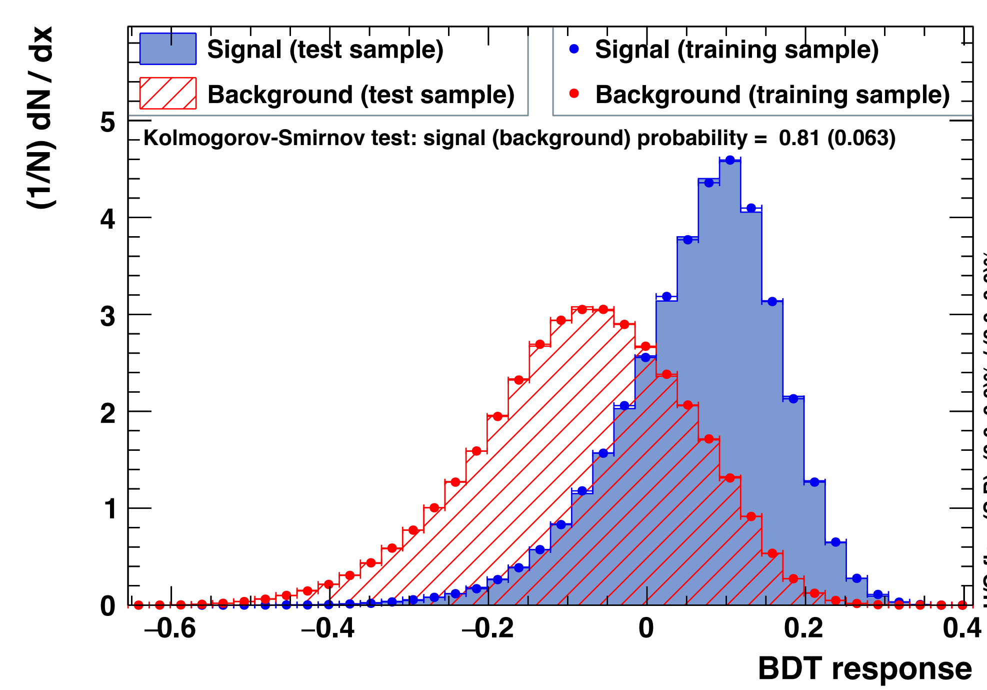
Correlation Matrix (signal)



Correlation Matrix (background)



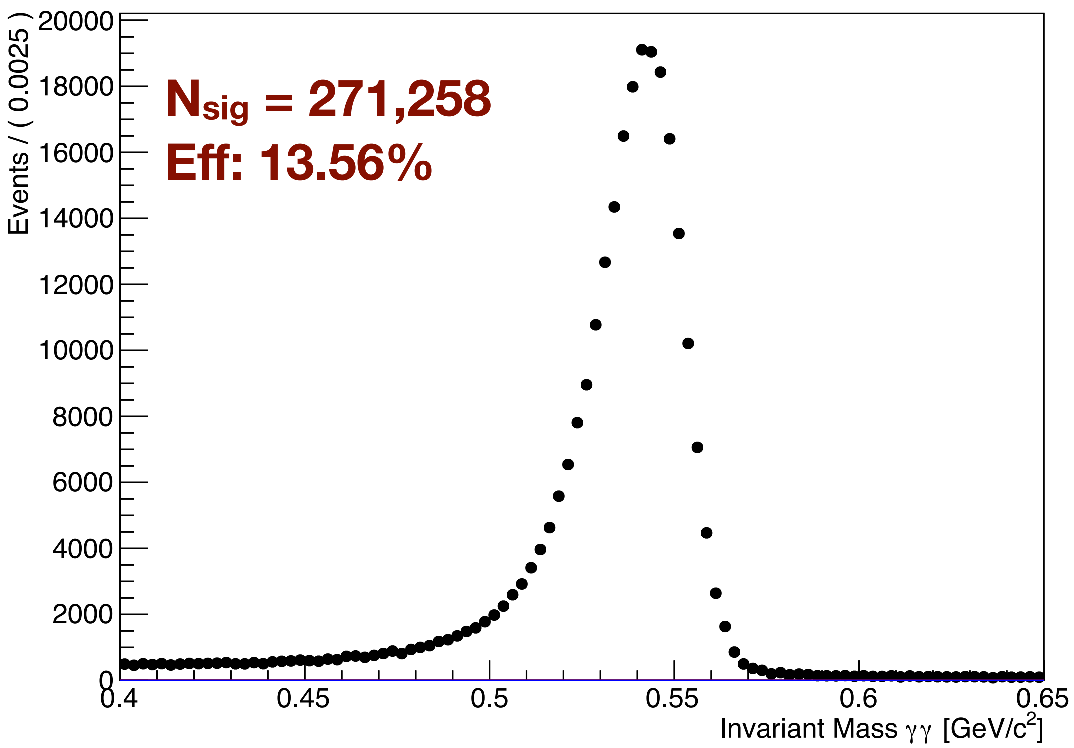
TMVA overtraining check for classifier: BDT

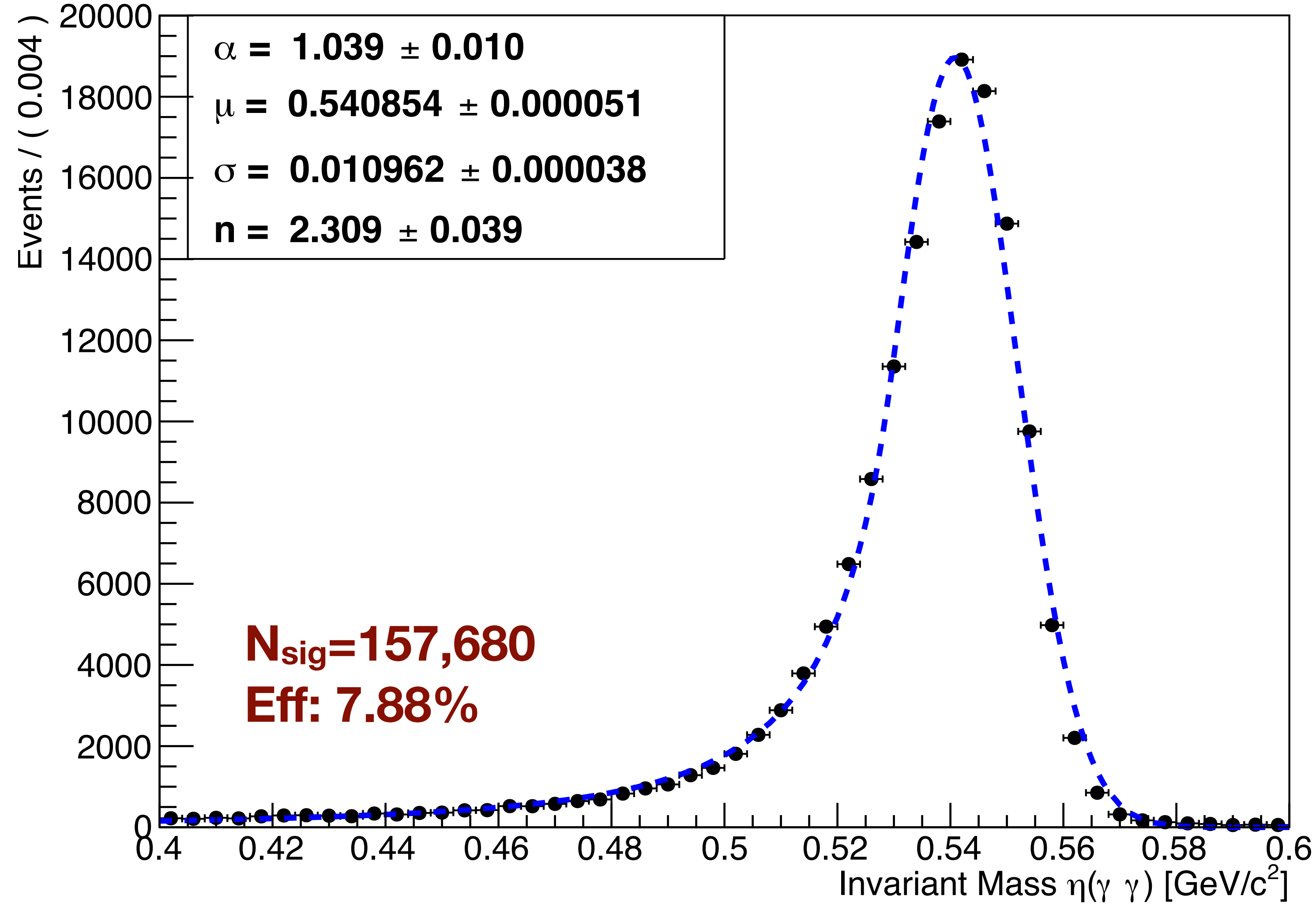


Optimal BDT cut

Signal
1-prong

$Eff_{cut} = 41.87\%$

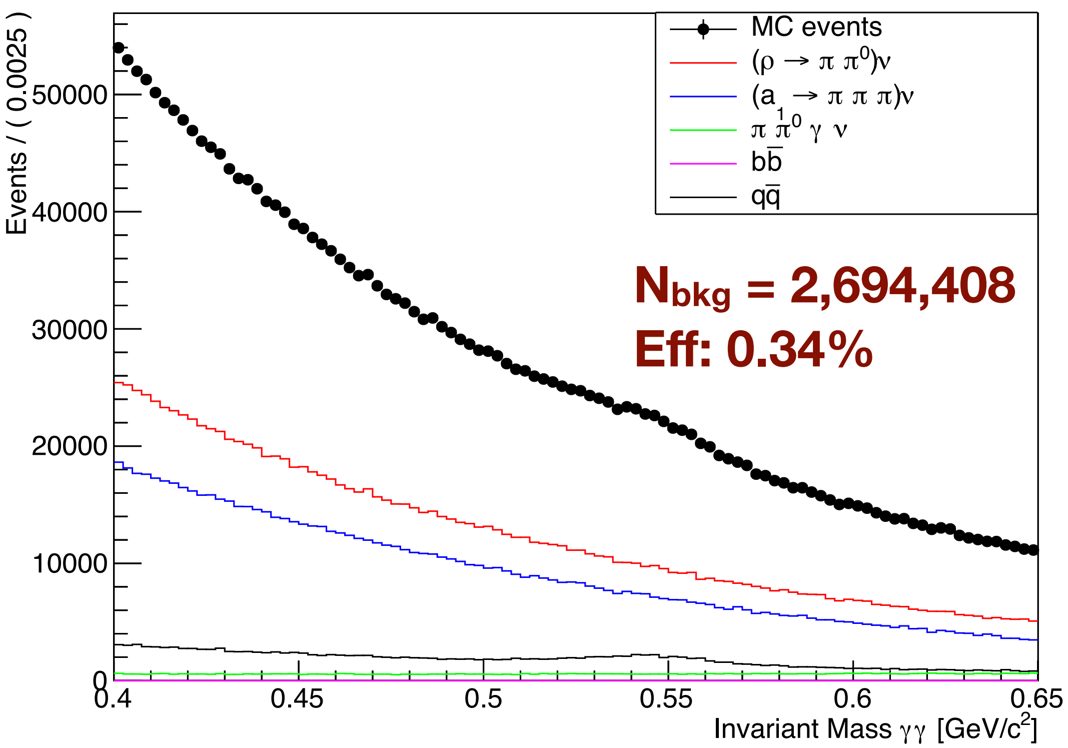




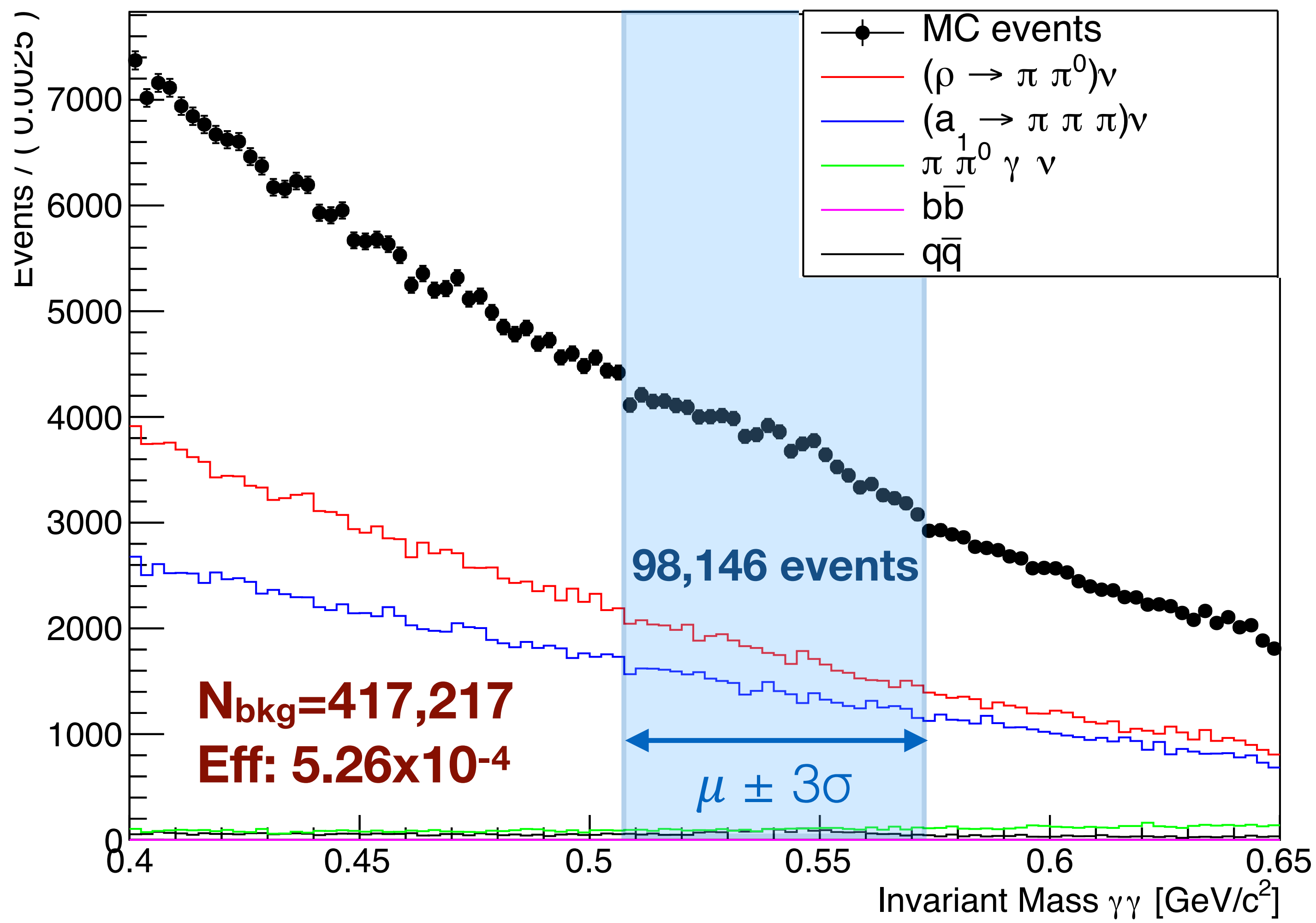
Cinvestav

Optimal BDT cut

Background 1-prong



$Eff_{cut} = 84.51\%$



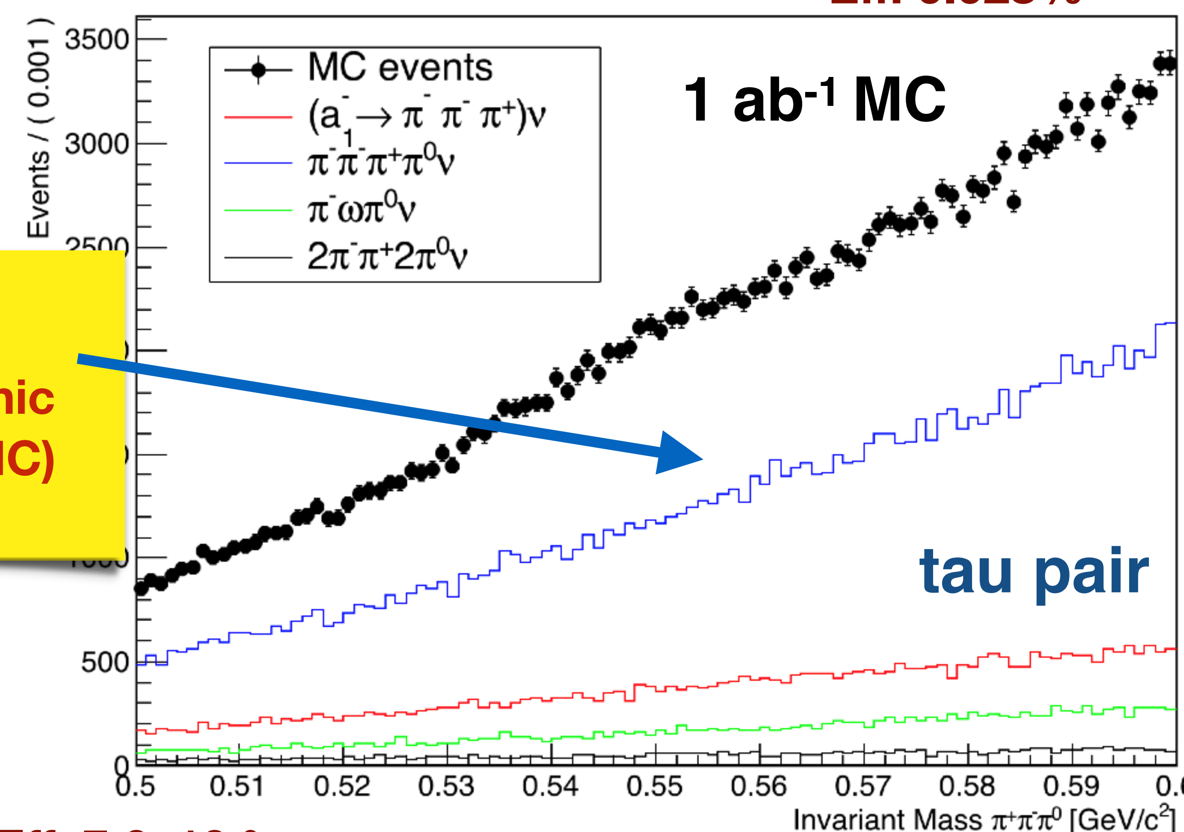
$\tau \rightarrow \eta \pi \nu$ bkg events

3-prong

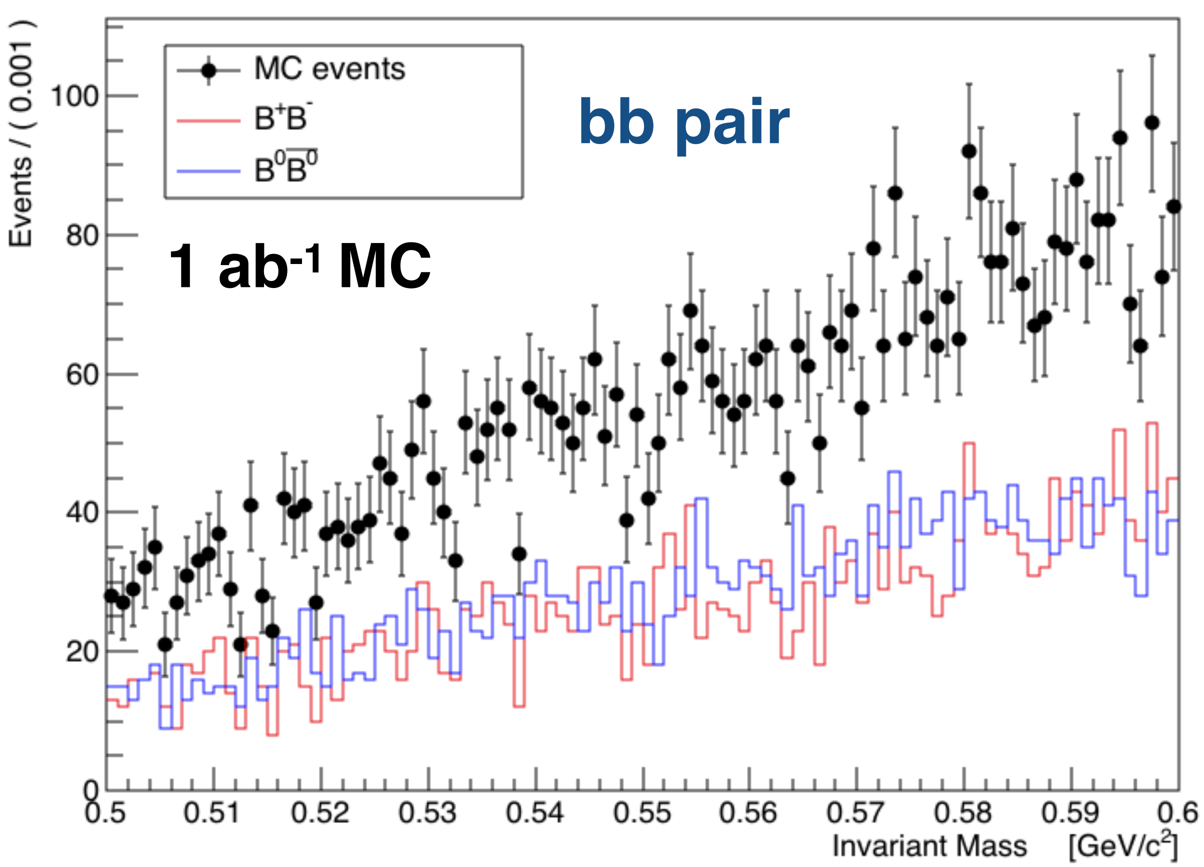
- Background sources:
  - $\tau\tau$ pair
  - bb pair
  - qq pair

3ππ⁰ is the mayor issue.
(This depends of the hadronic input in the generation of MC)

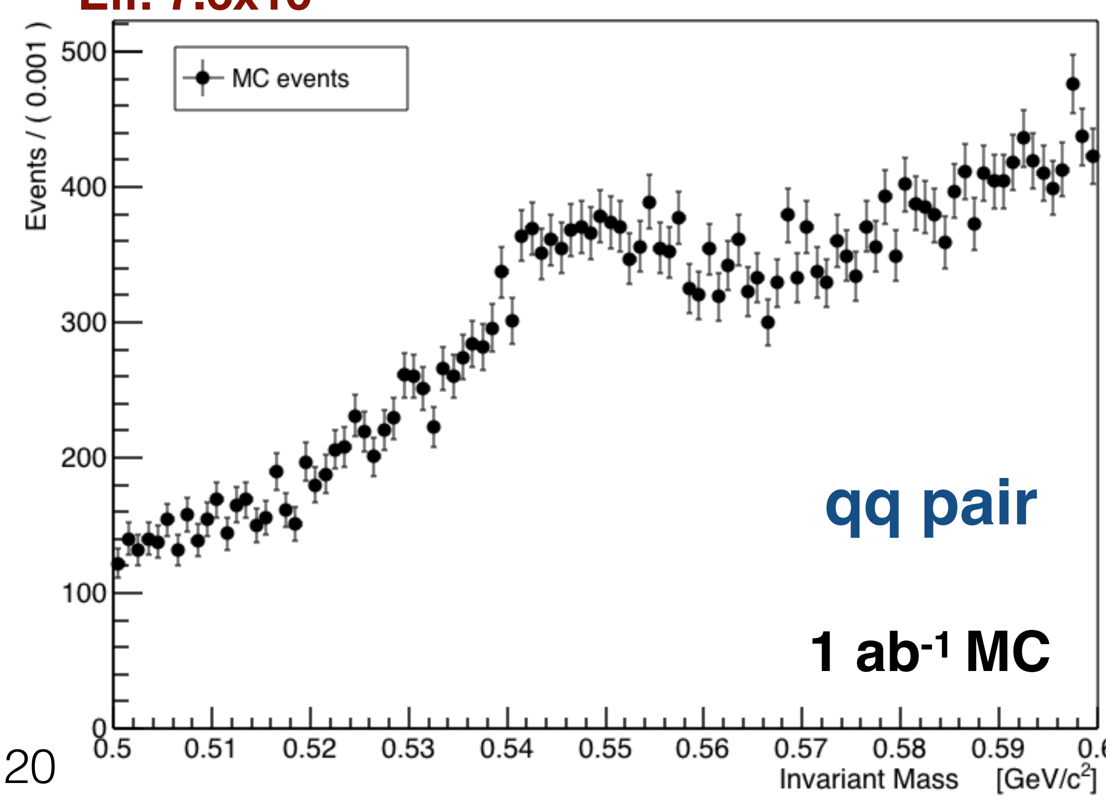
Eff: 0.028%



Eff: 5.6x10⁻⁶

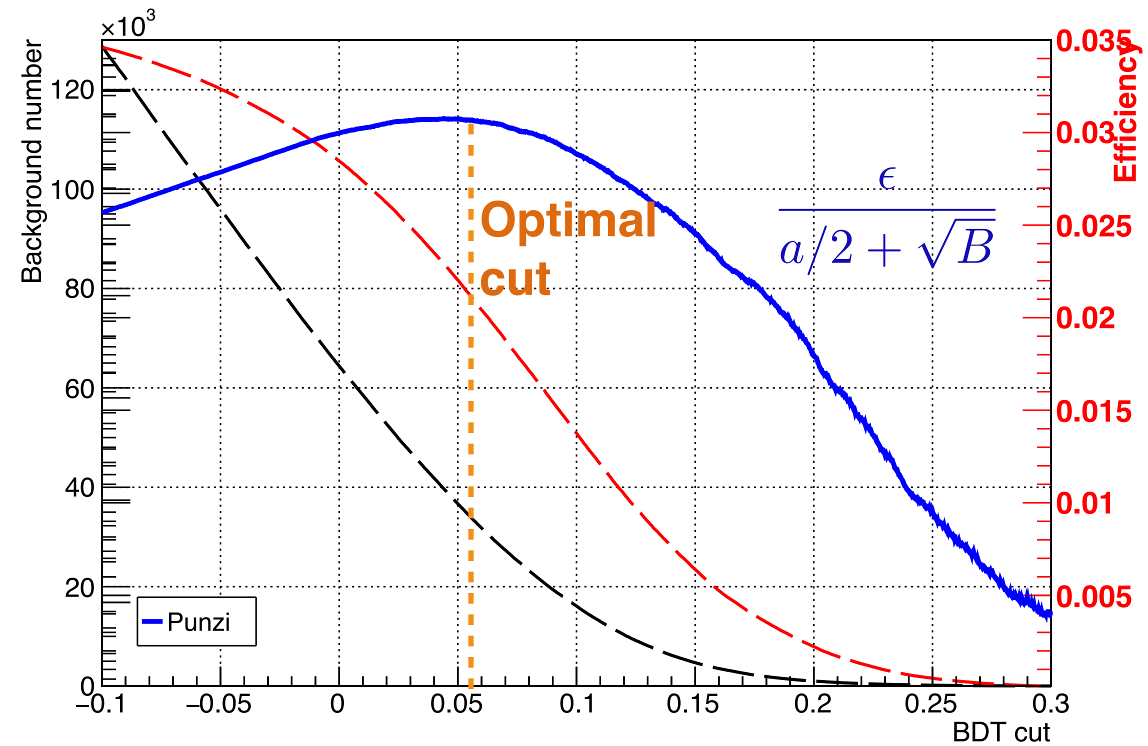


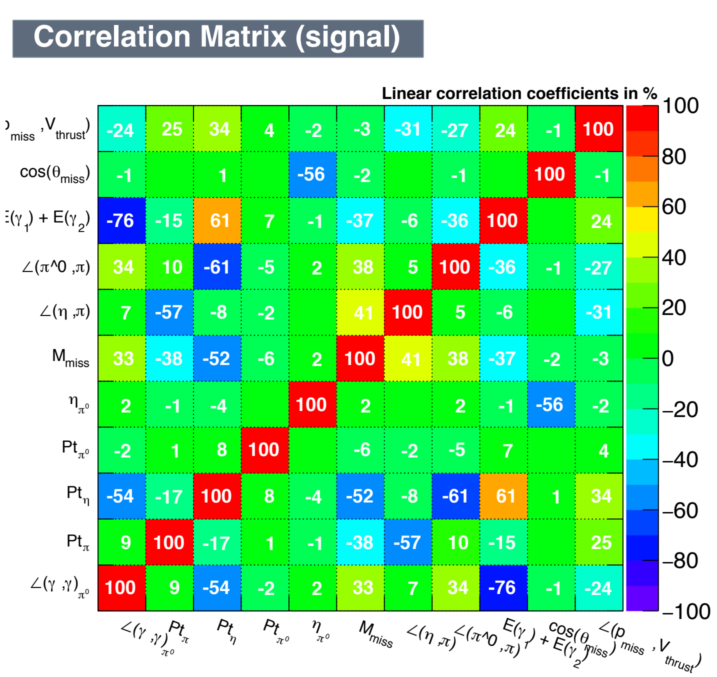
Eff: 7.6x10⁻⁶

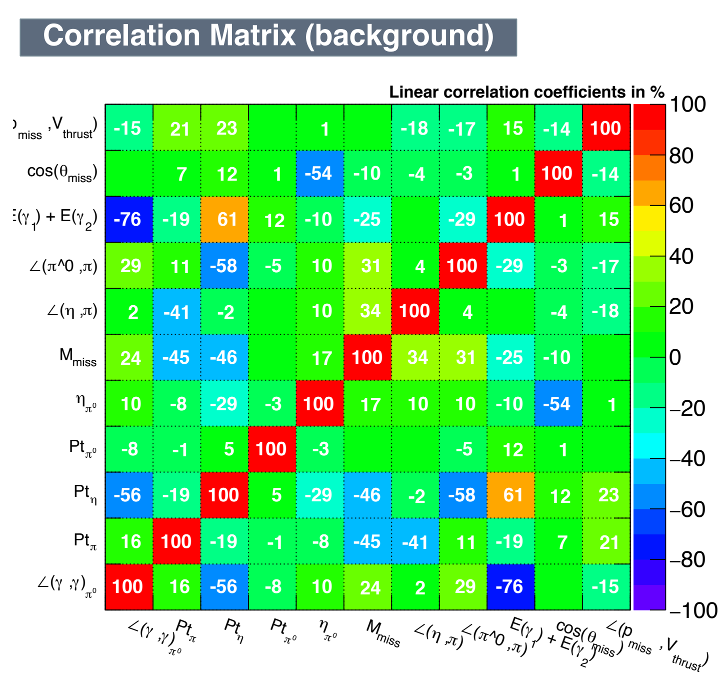


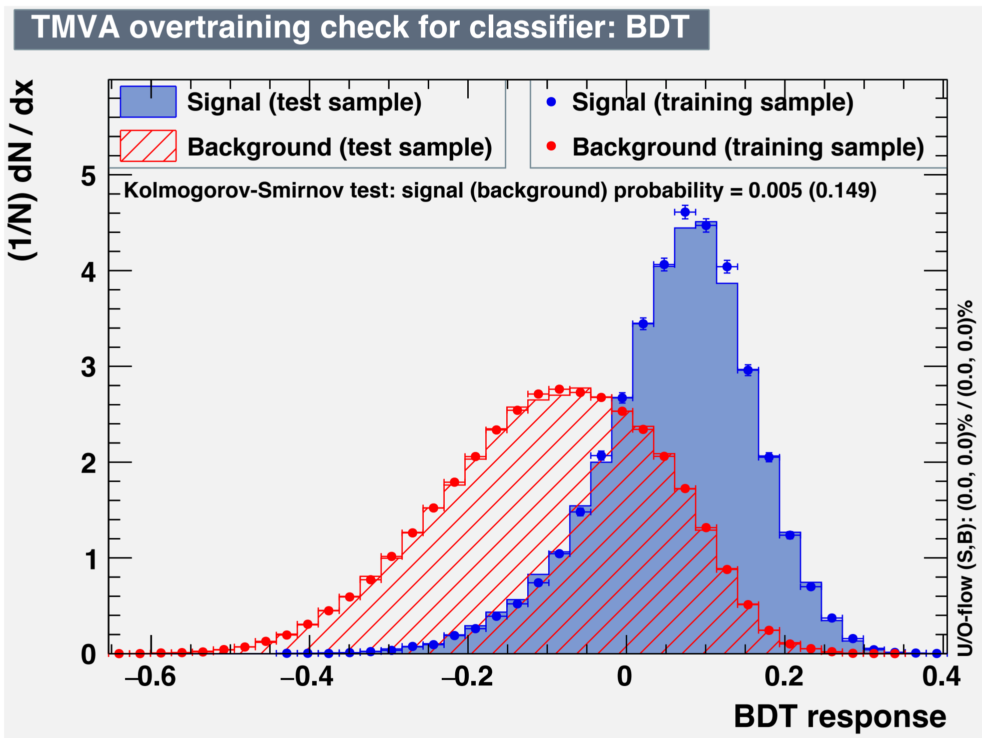
BDT variables (3-prong)

- $\angle(\eta,\pi)$
- $\angle(p_{miss}, V_{thrust})$
- $\angle(\pi, \pi^0)$
- $\angle(\gamma, \gamma)_{\pi 0}$
- M_{miss}
- $P_t(\pi)$
- $P_t(\eta)$
- $P_t(\pi^0)$
- $\eta(\pi^0)$
- $E(\gamma)$







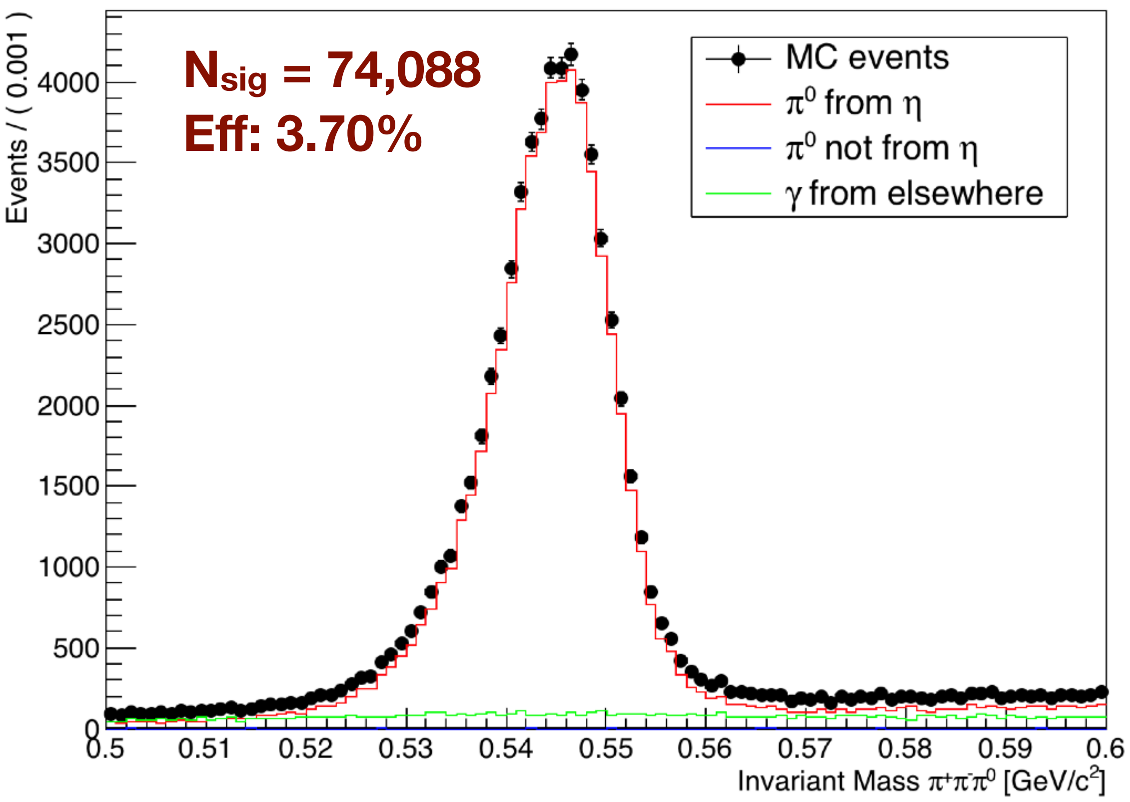


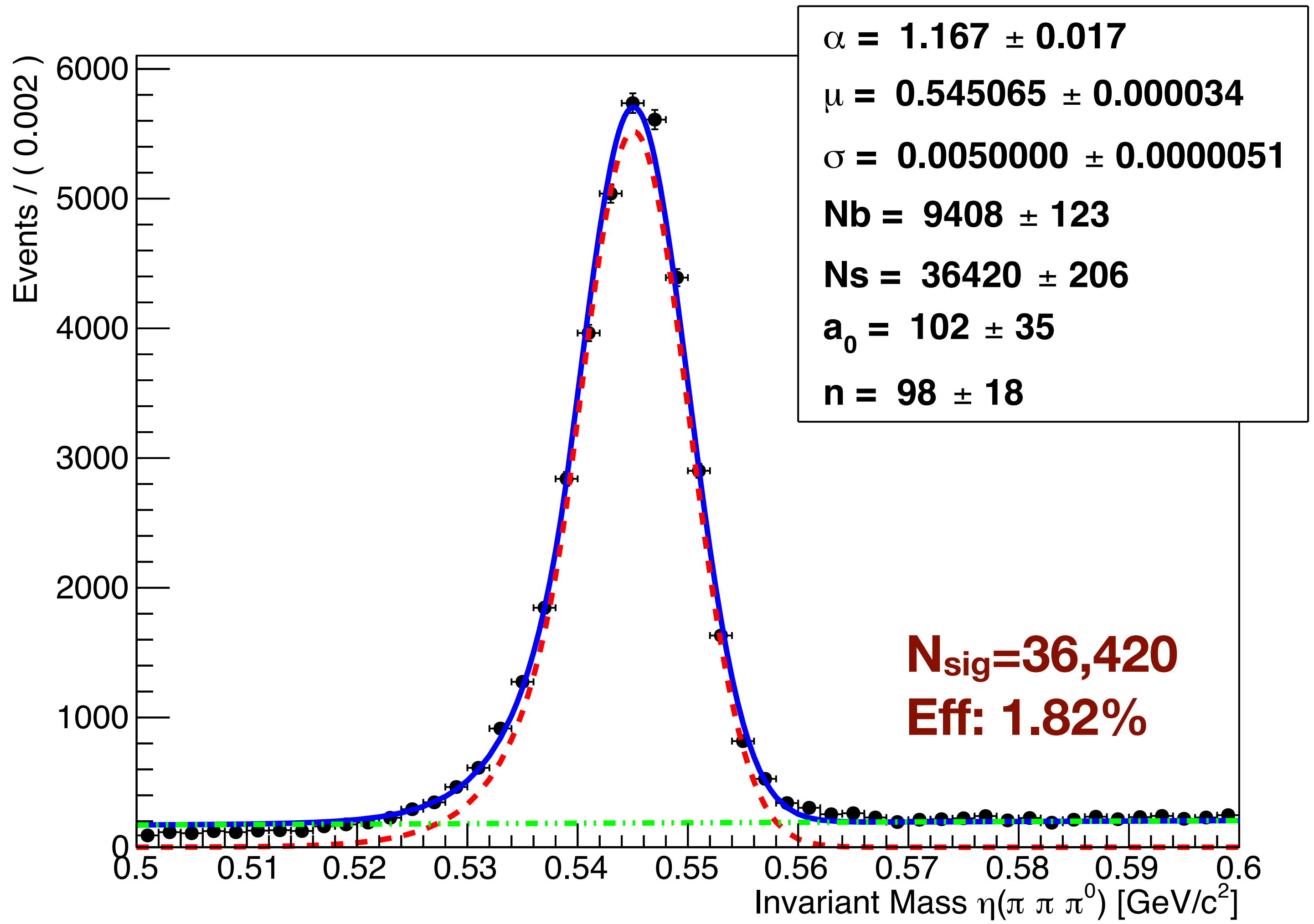
Cinvestav

Optimal BDT cut

Signal 3-prong

$Eff_{cut} = 38.14\%$

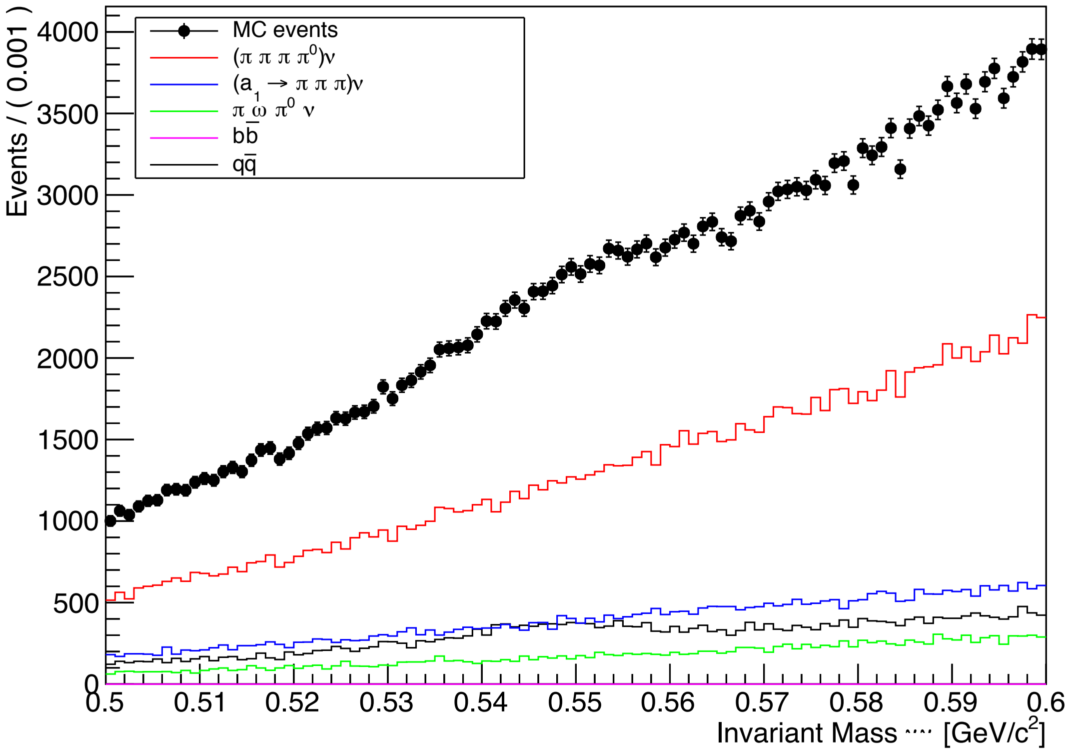




Cinvestav

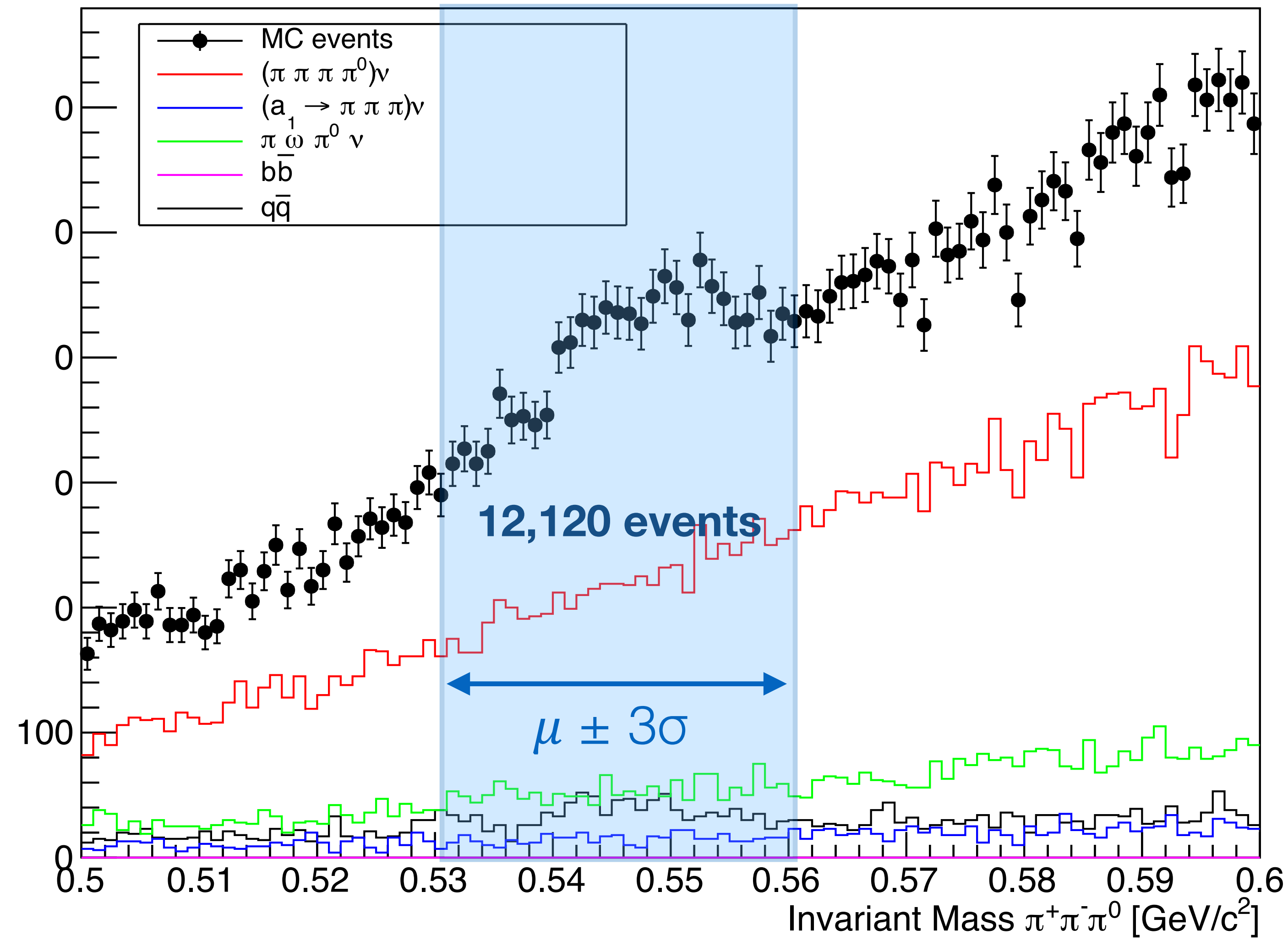
Optimal BDT cut

Background
3-prong



N_{bkg} = 240,438
Eff: 3.03x10^{-4}

Eff_{cut} = 83.52%



N_{bkg}=39,634
Eff: 5.0x10^{-5}

Estimation @ 1 ab^{-1}

- BR($\tau \rightarrow \eta\pi\nu$) ~ 10^{-5}

$$N_{sig} = \epsilon \cdot \sigma_{\tau\tau} \cdot BR(\tau \to \ell\nu\bar{\nu}) \cdot L \cdot BR(\tau \to \eta\pi\nu)$$

1-prong

In the mass window of η:

- N_{bkg} = 98,146

$$\frac{N_{sig}}{\sqrt{N_{bkg}}} \simeq 0.786$$

3-prong

In the mass window of η:

- N_{bkg} = 12,120

$$\frac{N_{sig}}{\sqrt{N_{bkg}}} \simeq 0.516$$

Estimation @ 50 ab^{-1}

- $BR(\tau\rightarrow\eta\pi\nu) \sim 10^{-5}$

$$N_{sig} = \epsilon \cdot \sigma_{\tau\tau} \cdot BR(\tau \rightarrow \ell\nu\bar{\nu}) \cdot L \cdot BR(\tau \rightarrow \eta\pi\nu)$$

1-prong

In the mass window of η:

- $N_{bkg} \simeq 4.9\text{x}10^{6}$

$$\frac{N_{sig}}{\sqrt{N_{bkg}}} \simeq 5.56$$

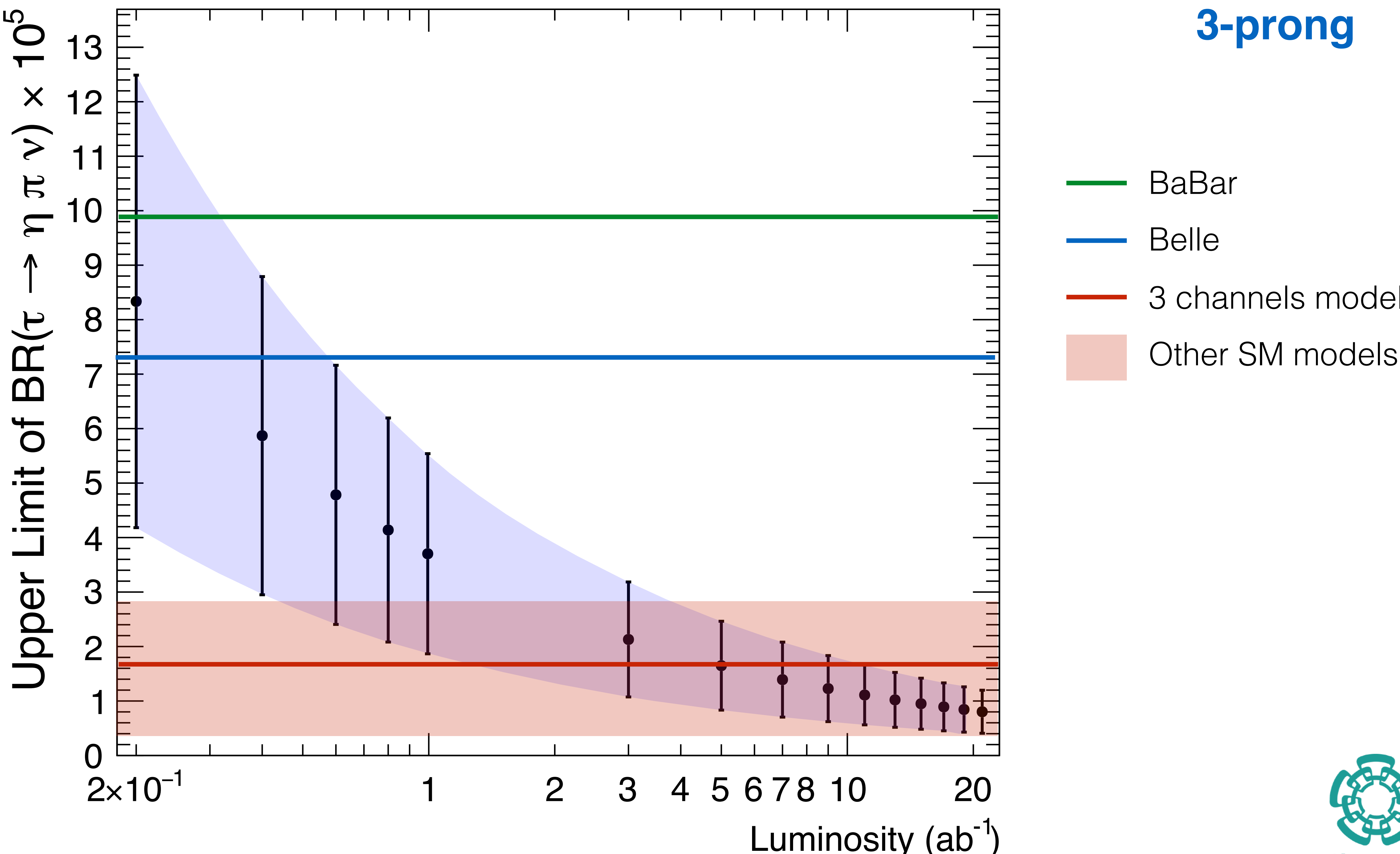
3-prong

In the mass window of η:

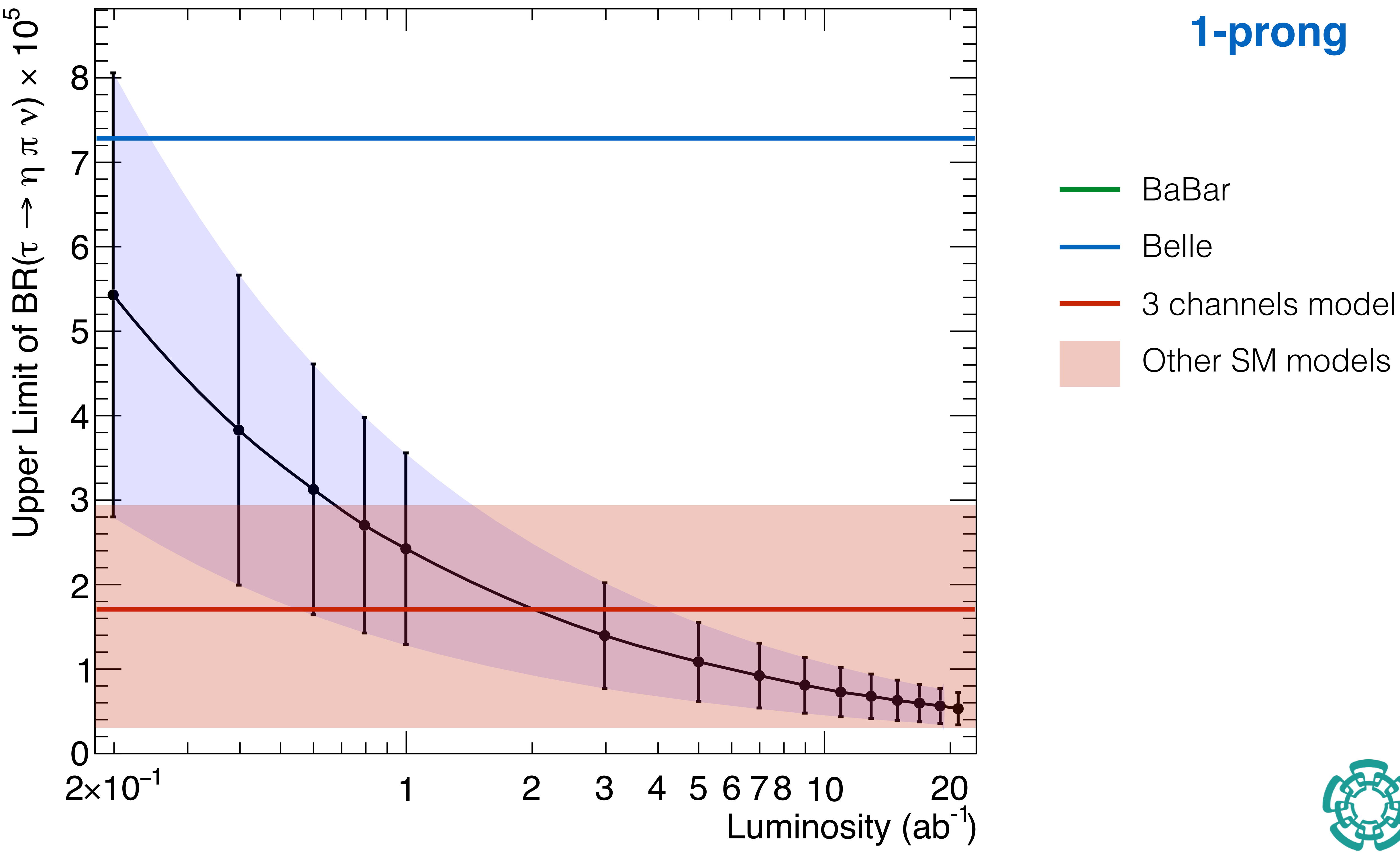
- $N_{bkg} \simeq 6.06\text{x}10^{5}$

$$\frac{N_{sig}}{\sqrt{N_{bkg}}} \simeq 3.65$$

Estimated Upper Limits



Estimated Upper Limits



Summary

- SuperKEKB will produce a sample of τ pairs 50 times larger than previous B-factories. τ physics is now considered “precision physics”.
- BR measurement (or upper limit), invariant mass of $\eta\pi$, and Dalitz plots will be very important to disentangle models.
- Better selection of variables or more MVA techniques have to be tested.
- Some extra contributions to the background has to be studied.
- The comparison of channels generated, with the data obtained in the beginning of the experiment, is important to control the bkg.

Thank you

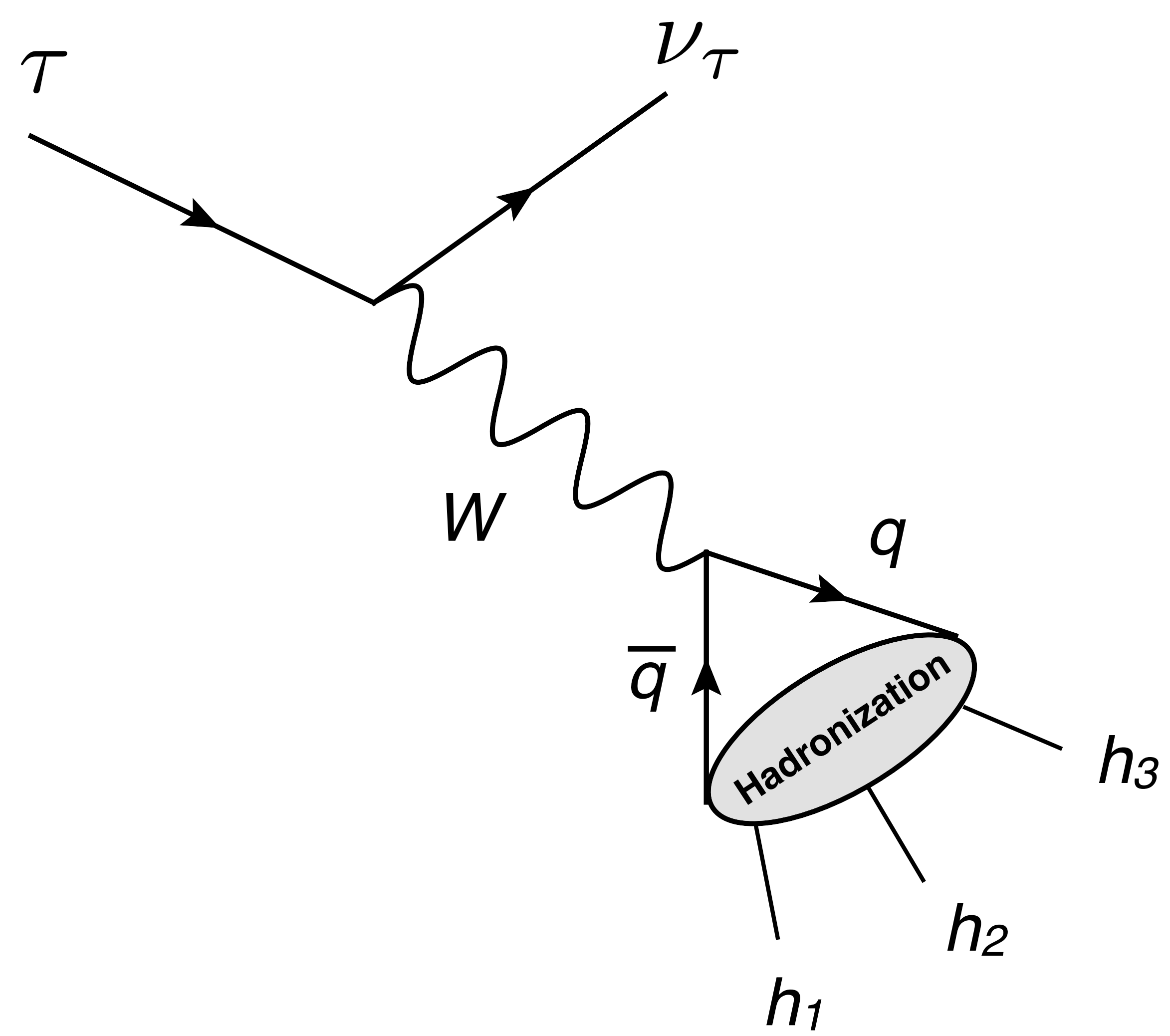
Backup

Semileptonic decays of τ lepton

- The τ lepton is the only lepton massive enough to decay into hadrons.

- Semileptonic decay channels $\tau \to H\, \nu_\tau$ allow a clean theoretical analysis of the hadronization, determination of SM parameters and properties of weak currents[1]:
  - α_s
  - CKM parameters
  - CPV
  - LNV and LFV
  - SM and NP interactions
  - etc.

- **B-factories** provide a large dataset of τ leptons to precision studies.



> 200 hadronic channels

Disadvantage:
We cannot detect ν

[1]Pich, A. *Progress in Particle and Nuclear Physics*, *75*, 41-85 (2014).

Cinvestav

Hadronic Currents

- V-A currents can be classified by their transformation proprieties under *G*-parity [1].

$$G = Ce^{i\pi I_2}$$

- First-class currents:

Standard Model

$$GV_\mu G^{-1} = +V_\mu$$
$$GA_\mu G^{-1} = -A_\mu$$

$$J^{PG} = 0^{++}, 0^{--}, 1^{-+}, 1^{+-}, \ldots$$

- Second-class currents (SCC):

New physics

$$GSG^{-1} = -S$$
$$GA'_\mu G^{-1} = +A'_\mu$$

$$J^{PG} = 0^{+-}, 0^{-+}, 1^{++}, 1^{--}, \ldots$$

[1] S. Weinberg. *Physical Review*, *112*(4), 1375 (1958).

Second-class currents

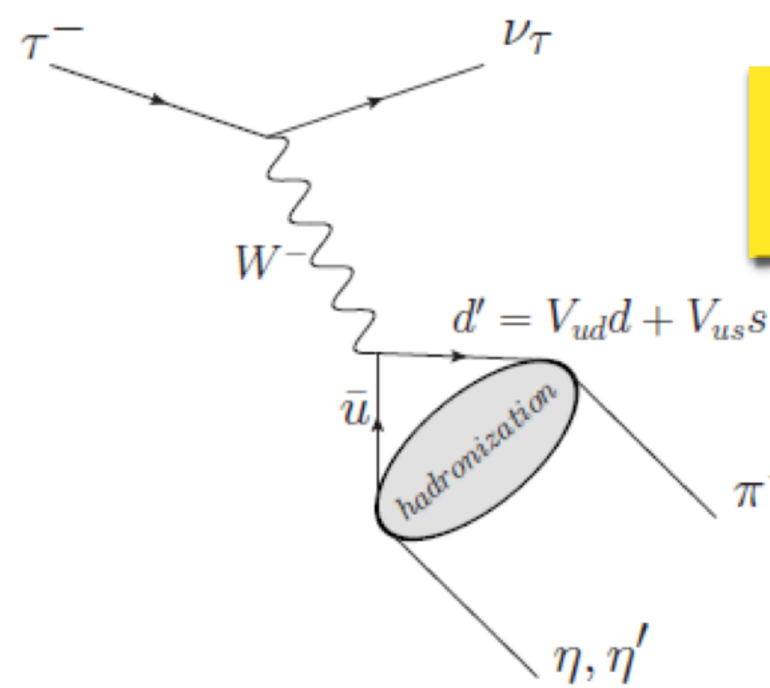
- SCC are isospin violating processes, suppressed by isospin symmetry.

$$\not{G} \sim S\not{U}(2) \sim \frac{m_d - m_u}{\Lambda}$$

- Unsuccessful searches of SCC in nuclear Physics.

- Another possibility: Search in tau decays[1]

$$\tau^- \to \eta\pi^-\nu_\tau$$



$$G|\bar{d}\gamma^\mu u\rangle = +|\bar{d}\gamma^\mu u\rangle$$

$$G|\pi\rangle = -|\pi\rangle$$
$$G|\eta\rangle = +|\eta\rangle$$

[1]Leroy, C., & Pestieau, J. (1978). Physics Letters B, 72(3), 398-399.

G-parity

- G-parity is defined by[1] $G = Ce^{i\pi I_2}$

- Is a good symmetry of the strong interactions

$$[H_{str}, I_i] = 0; \quad [H_{str}, C] = 0$$

Convenient to analyze process where the initial or final state contains only mesons

$$G|\pi\rangle = -|\pi\rangle$$
$$G|\eta\rangle = +|\eta\rangle$$
$$G|\rho\rangle = +|\rho\rangle \qquad \rho \to \pi\pi, 4\pi; \quad \not\to 3\pi, \eta\pi$$
$$G|\omega\rangle = -|\omega\rangle \qquad \omega \to 3\pi, \rho\pi; \quad \not\to 2\pi, 4\pi$$
$$G|a_0\rangle = -|a_0\rangle \qquad a_0 \to \eta\pi; \quad \not\to 2\pi$$

- However, G-Parity is not exact. $[H_{tot}, I_i] \neq 0;$

[1]T. D. Lee, and Chen Ning Yang. *Il Nuovo Cimento* 3.4 (1956): 749-753.

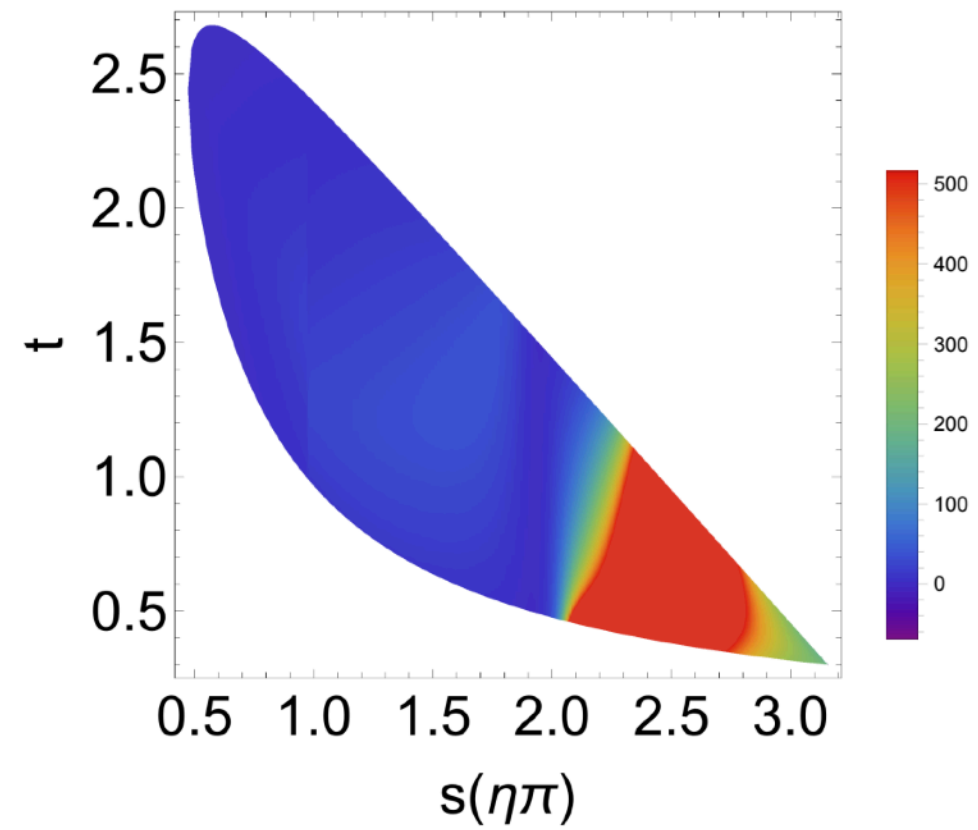
The $\tau \to \eta\pi\nu$ decay

- NP contributions (scalar and tensorial currents) can be studied in the framework of an effective field theory [1]

$$\begin{aligned} \mathcal{M} &= \mathcal{M}_V + \mathcal{M}_S + \mathcal{M}_T \\ &= \frac{G_F V_{ud} \sqrt{S_{EW}}}{\sqrt{2}} (1 + \epsilon_L + \epsilon_R) \left[L_\mu H^\mu + \tilde{\epsilon}_S L H + 2\tilde{\epsilon}_T L_{\mu\nu} H^{\mu\nu} \right], \end{aligned}$$

- New Physics effects can appear in the distribution of Dalitz plots, with a large enhancement expected towards large values of the hadronic invariant mass[1].

$$R(\tilde{\epsilon}_S, \tilde{\epsilon}_T) = \frac{\overline{|\mathcal{M}|^2}}{\overline{|\mathcal{M}|^2_{00}}}$$

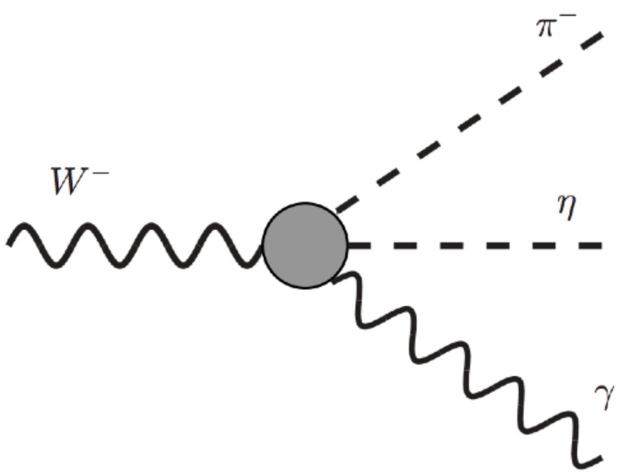


Ratio between the squared amplitude of EFT with ϵ_T = 0.3 and squared amplitude of SM.

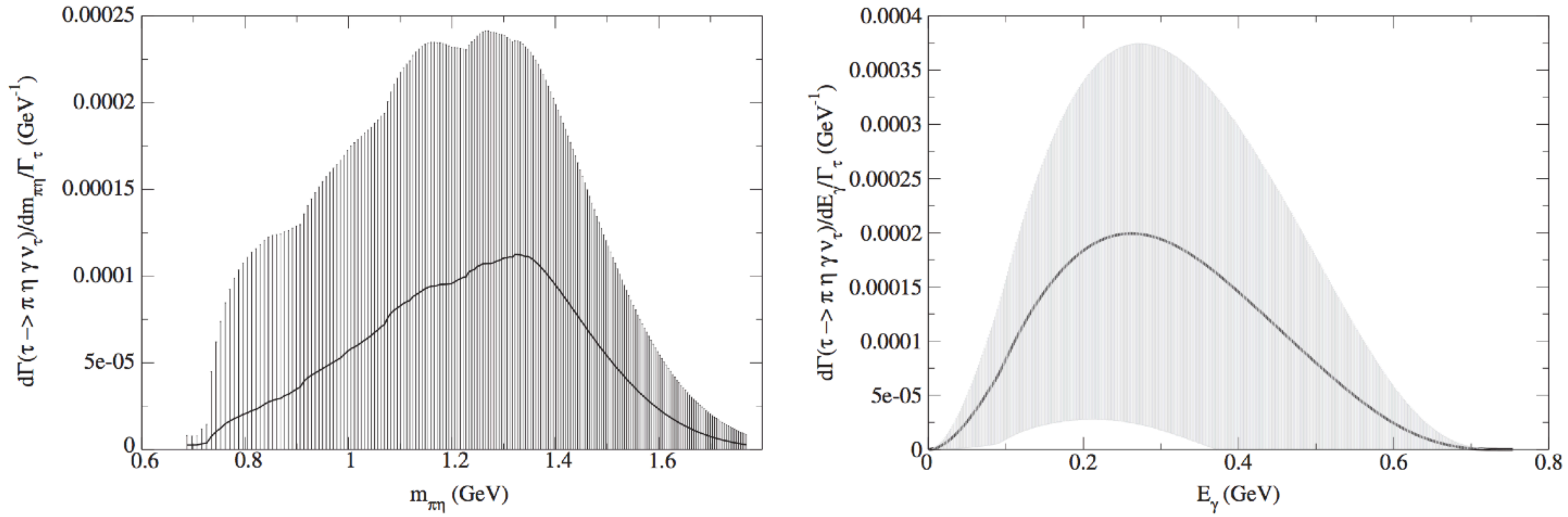
[1] E. A. Garcés, MHV, G. López Castro, P. Roig; arXiv:1708.07802

A new bkg source[1]

- $\tau^- \rightarrow \eta\pi^-\nu_\tau\gamma$



- BR ~ 10^{-5} !
  (Not suppressed by G-parity, unlike the channel without photon.)



(a) Normalized spectrum (corresponding to the data in Fig. 14) in the invariant mass of the $\eta\pi^-$ system is plotted.

(b) For the same points as in (a), the normalized spectrum in E_γ is drawn.

FIG. 15. Normalized spectra of the $\tau^- \rightarrow \eta\pi^-\nu_\tau\gamma$ decays according to $R\chi L$.

- Veto of photons with Eγ > 100 MeV should get rid of this background.

[1]A. Guevara, G. López-Castro, P. Roig (2016). Phys.Rev. D95 no.5, 054015 (2017)

Cinvestav

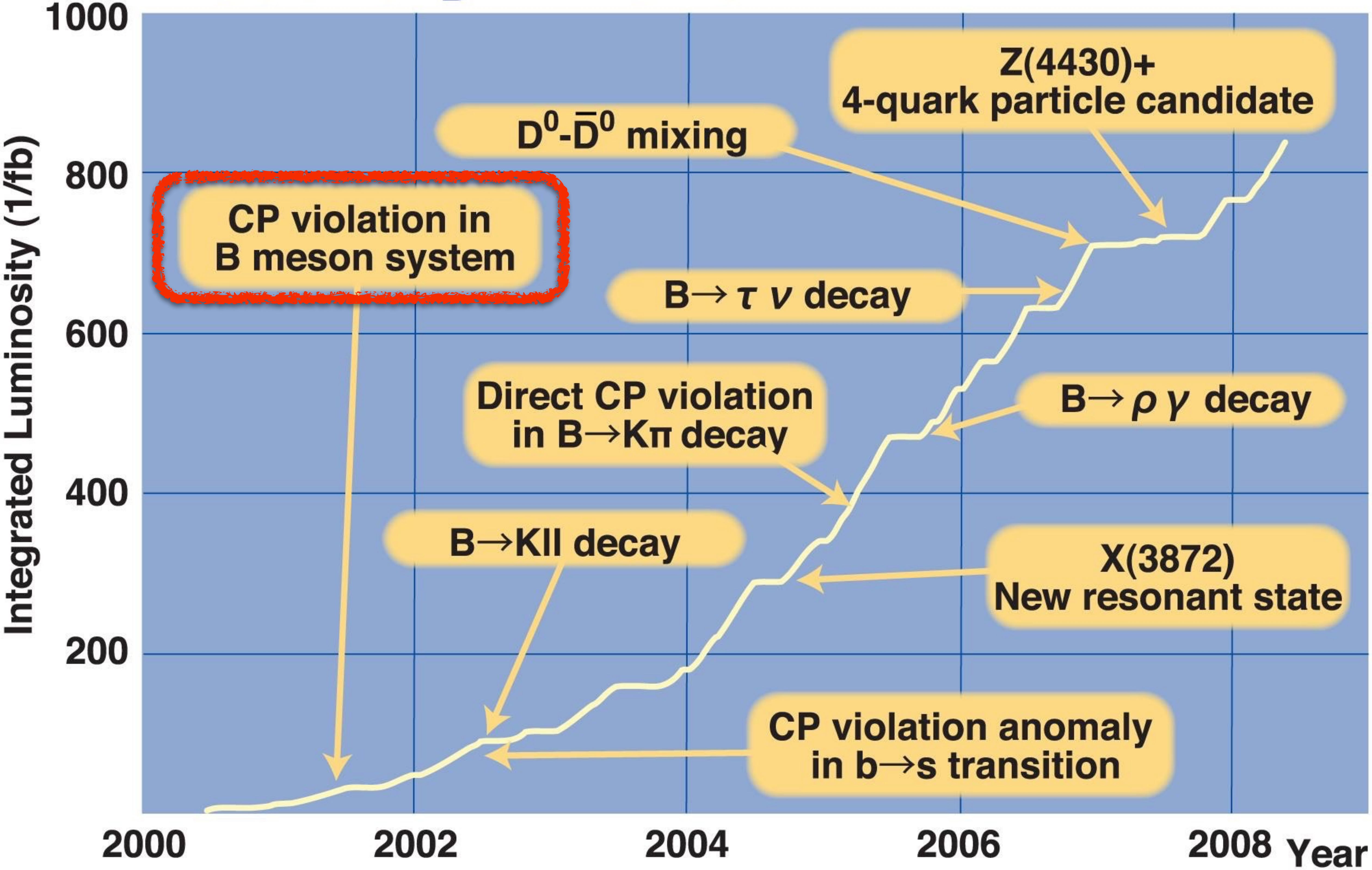
B-Factories

	PEP-II	KEKB	SuperKEKB
Detector	BaBar	Belle	Belle II
Año de inicio	1999	1999	2016
Fin de operaciones	2008	2010	-
Energía del haz (GeV)	e-: 9.0 e+: 3.1	e-: 8.0 e+: 3.5	e-: 7.0 e+: 4.0
Luminosidad max	550 fb^{-1}	1 ab^{-1}	50 ab^{-1}

Michel H. Villanueva

Cinvestav

Discovery in Belle



- Hadronic matrix element: 2 form factors

$$H_\mu(p_0, p_-) \equiv \langle \eta\pi|\bar{d}\gamma_\mu u|0\rangle = f_+(t)\left((p_0 - p_-)_\mu - \frac{\Delta^2}{t}q_\mu\right) + f_0(t)\frac{\Delta^2}{t}q_\mu$$

$$t = (p_- + p_0)^2$$

- Invariant mass distribution

$$\frac{d\Gamma}{dt} = \frac{G_F^2|V_{ud}|^2}{768\pi^3 m_\tau^3} \times \frac{(m_\tau^2 - t)^2}{t^3}\lambda^{1/2}(t, m_\eta^2, m_\pi^2)I(t)$$

$$I(t) = |f_+(t)|^2(m_\tau^2 + 2t)\lambda(t, m_\eta^2, m_\pi^2) + 3|f_0(t)|^2\Delta^4 m_\tau^2$$

Spin-1 (V) ↖ Spin-0 (S) ↗

spin of ηπ system in its rest frame

- Form factors

$$f_+(0) = f_0(0) \qquad (m_\eta + m_\pi)^2 \leq t \leq m_\tau^2$$

- MDM: Meson dominance models.
- Sum of Breit-Wigner formulae
- Chiral theory, etc.

$$f_+^{\mathrm{I}}(t) = \frac{\sqrt{2}\epsilon_{\eta\pi}}{1+\beta_\rho}\left[\mathrm{BW}_\rho(t) + \beta_\rho \mathrm{BW}_{\rho'}(t)\right]$$

$$f_0^{\mathrm{I}}(t) = \frac{\sqrt{2}\epsilon_{\eta\pi}}{1+\beta_a}\left[\mathrm{BW}_{a_0}(t) + \beta_a \mathrm{BW}_{a_0'}(t)\right]$$

$$\mathrm{BW}_X(t) = m_X^2/(m_X^2 - t - i m_X \Gamma_X(t))$$

$$f_+^{\mathrm{II}}(t) = \sqrt{2}\epsilon_{\eta\pi}\left[1 + \frac{f_\rho g_{\rho\pi\pi}}{m_\rho^2}\left(\widetilde{\mathrm{BW}}_\rho(t) + \beta_\rho \widetilde{\mathrm{BW}}_{\rho'}(t)\right)\right]$$

$$f_0^{\mathrm{II}}(t) = \sqrt{2}\epsilon_{\eta\pi}\left[1 + \frac{f_{a_0} g_{a_0\eta\pi}}{m_\eta^2 - m_\pi^2}\left(\widetilde{\mathrm{BW}}_{a_0}(t) + \beta_a \widetilde{\mathrm{BW}}_{a_0'}(t)\right)\right]$$

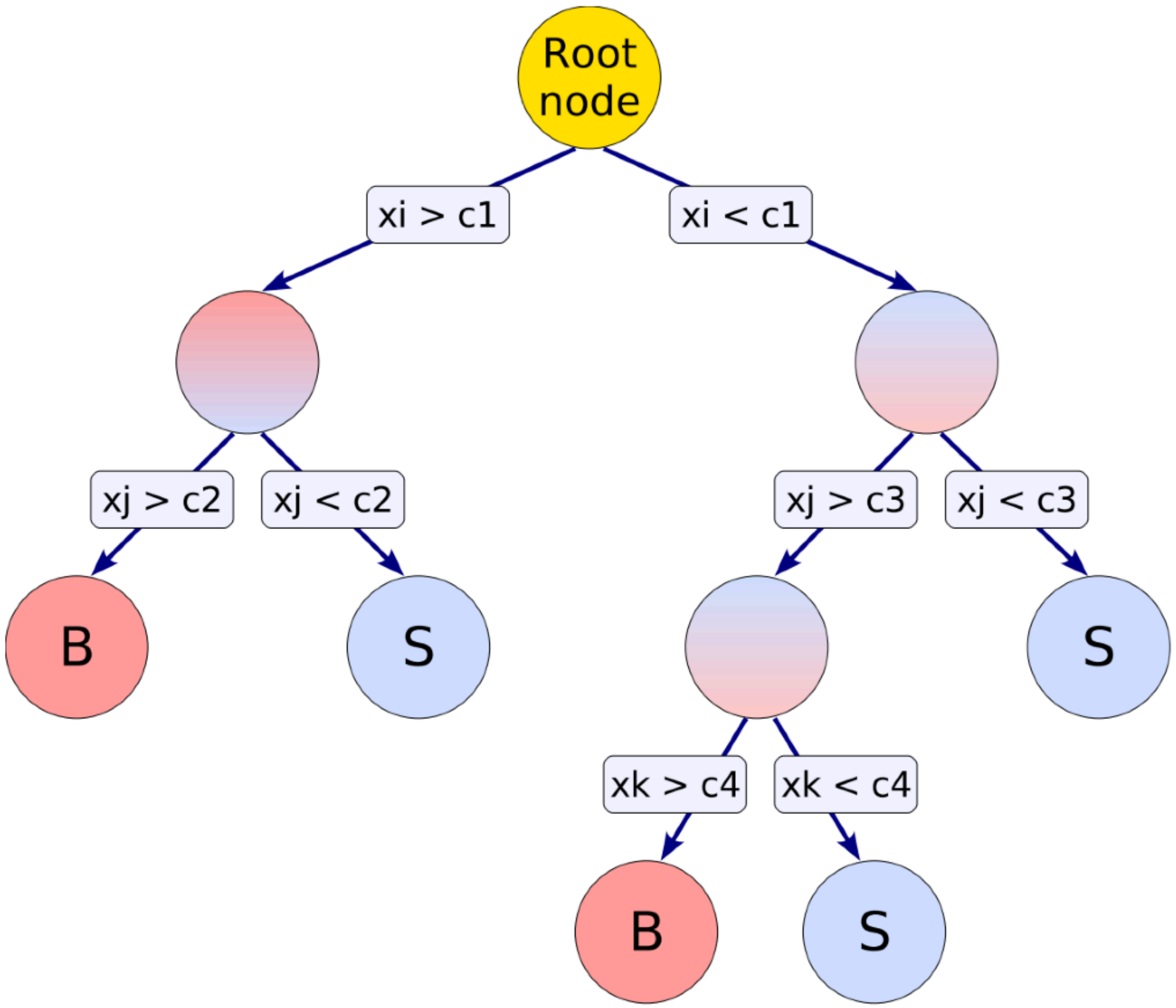
$$\widetilde{\mathrm{BW}}_X(t) = t/(m_X^2 - t - i m_X \Gamma_X(t))$$

TinyDST

- For tau physics study, roughly TinyDST (tdst) is designed[1].
- Events having:
  - Less than 6 charged tracks with $|dr|<0.5$ cm, $|dz|<3.0$ cm, $p_t>0.1$ GeV/c and $-0.8660<\cos\theta<0.9535$.
  - Less than 10 photons with $E_\gamma>50$ MeV and $-0.8660<\cos\theta<0.9535$.
- Thrust vector information contained.
- To squeeze the size, one lepton is required.
  - In SM precise measurement, to avoid qq BG, usually, leptonic decay is required for tag tau (tau with non-signal decay).
- 50MBytes for 200k events. (In original mdst, 50MBytes for 20k events.)

Boosted Decision Trees

- What is a Decision Tree?
  - Consecutive set of questions (**nodes**).
  - Two possible answers per node.
  - Final verdict (**leaf**) is reached after a defined maximum of nodes.



- Advantages
  - Easy to understand.
  - Fast training.

- Disadvantages
  - Single tree not strong (that's why we use **Random Forests**).

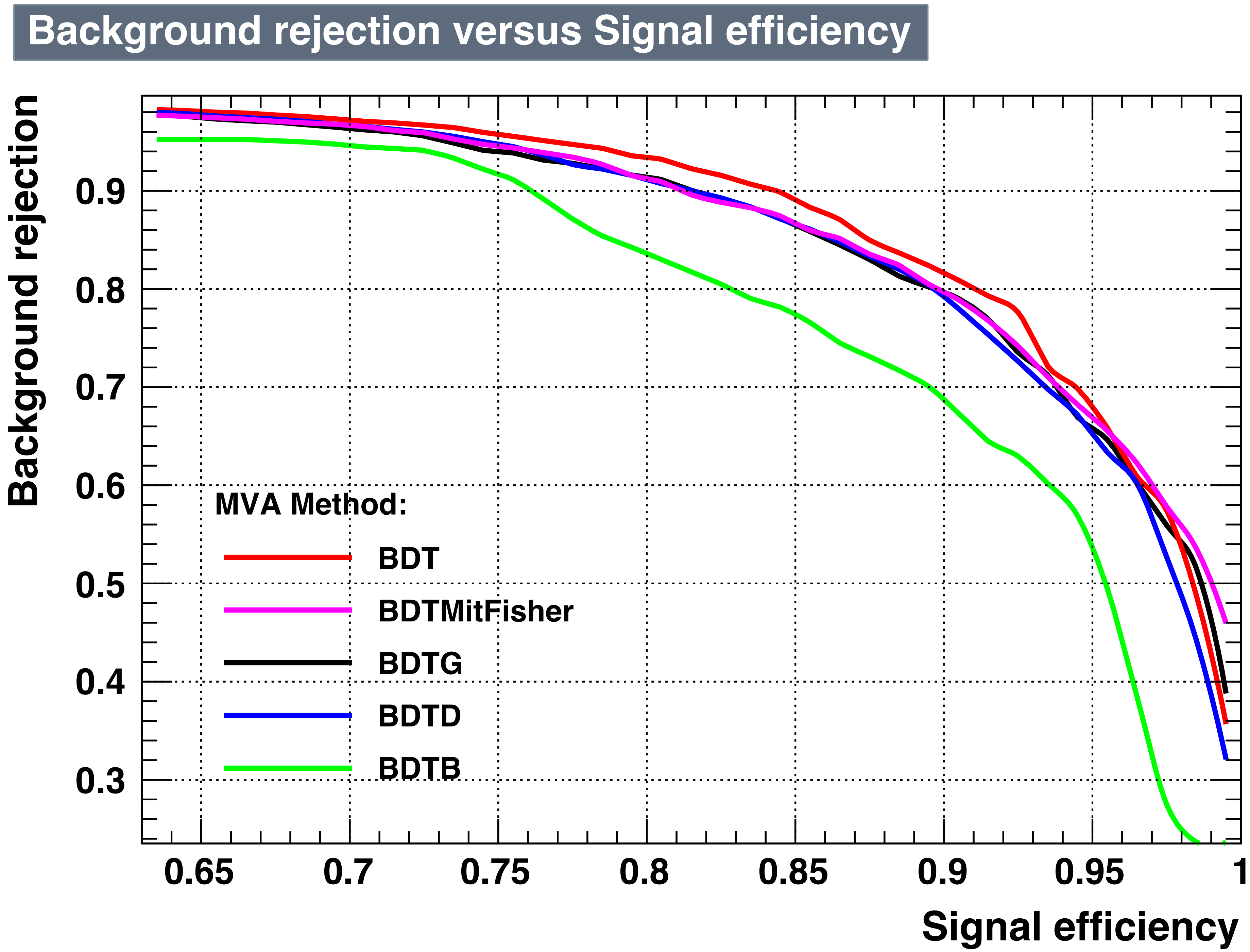
Boosted Decision Trees

- Random Forest is an ensemble method that combines different trees.
- Final output is determined by the majority vote of all the trees.
- Boosting:
  - Misclassified events are weighted higher so that future learners concentrate on these.

The score of an event is a weighted average of the scores the event receives from each tree in the forest.

$$bdt = \frac{\sum_i w_i N_i}{\sum_i w_i}; \quad N_i = \text{-1 or 1}$$

BDT tests



Background rejection versus Signal efficiency
Background rejection
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
Signal efficiency
MVA Method:
BDT
BDTMitFisher
BDTG
BDTD
BDTB