Search of $\tau \to \eta\pi\nu$ in the Belle (II) Experiment

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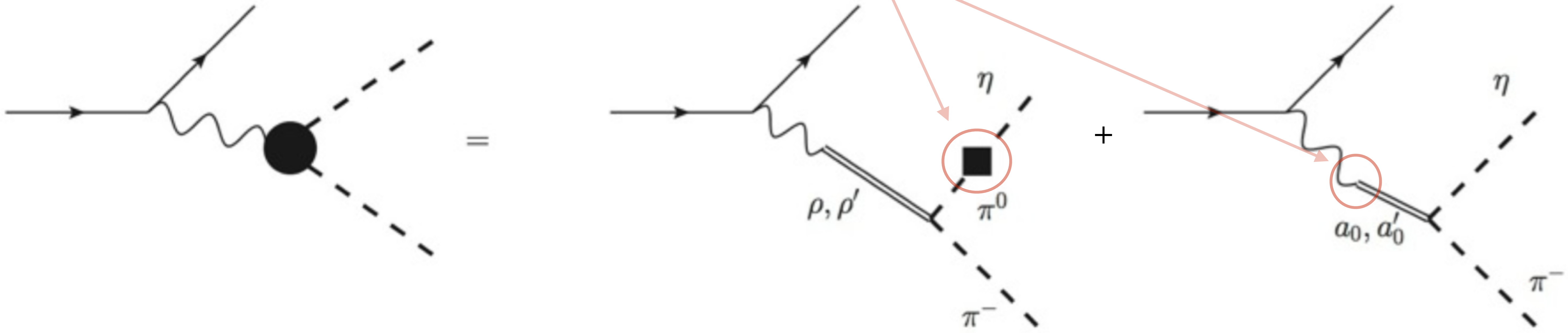
Motivation: QCD models

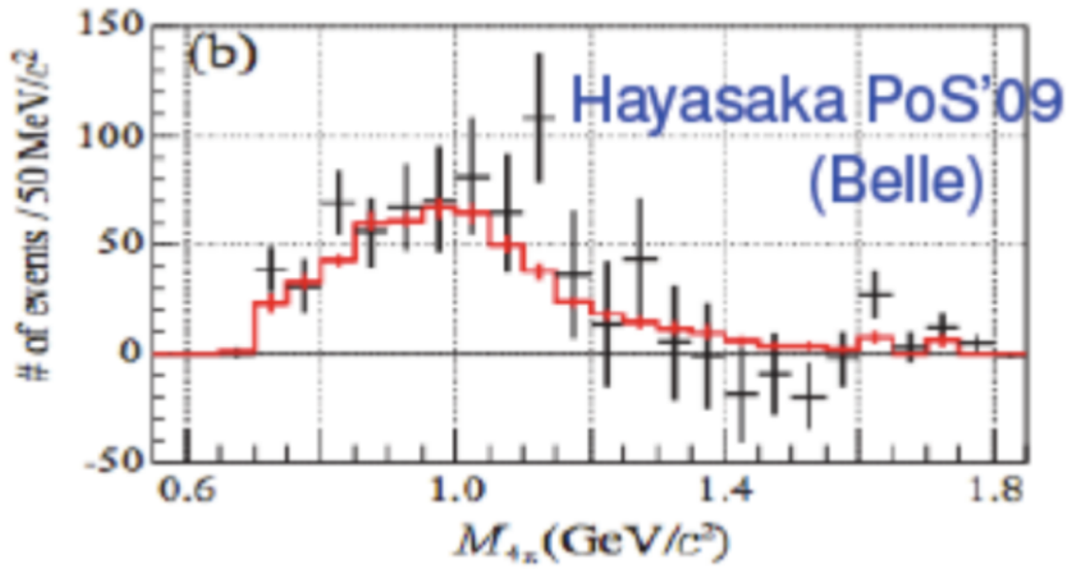
- $\tau^- \to \eta\pi^-\nu_\tau$ in the SM: isospin violation

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



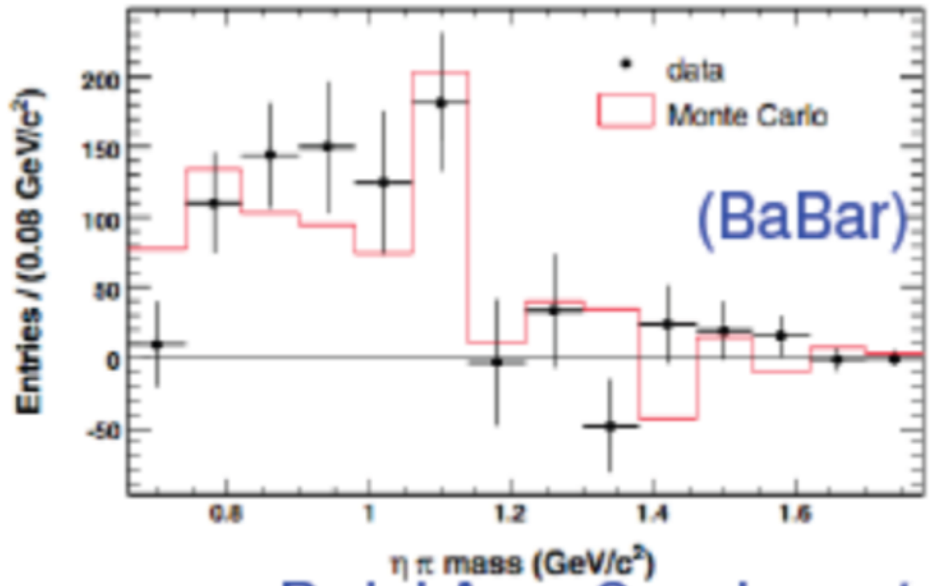
- Previous results: Strong background contributions, mostly from other τ decays.

670 fb^{-1}



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

470 fb^{-1}



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

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

SM predictions[1]: BR($\tau \to \eta\pi\nu$) ~ 10^{-5}

BR_V (x10^5)	BR_S (x10^5)	BR_{V+S} (x10^5)	Model
0.36	1.0	1.36	MDM, 1 resonance
[0.2, 0.6]	[0.2, 2.3]	[0.4, 2.9]	MDM, 1 and 2 resonances
0.44	0.04	0.48	Nambu-Jona-Lasinio
0.13	0.20	0.33	Analiticity, Unitarity
0.26	1.41	1.67	3 coupled channels

We have the capability of testing QCD models

[1]Escribano, R. et. al. (2016). Phys. Rev. D **94**, 034008.

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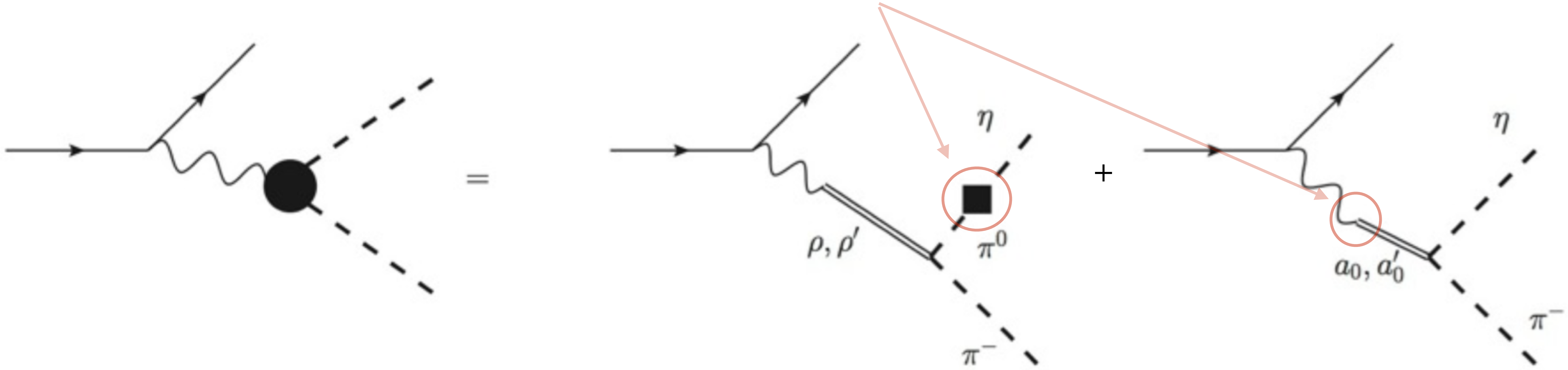
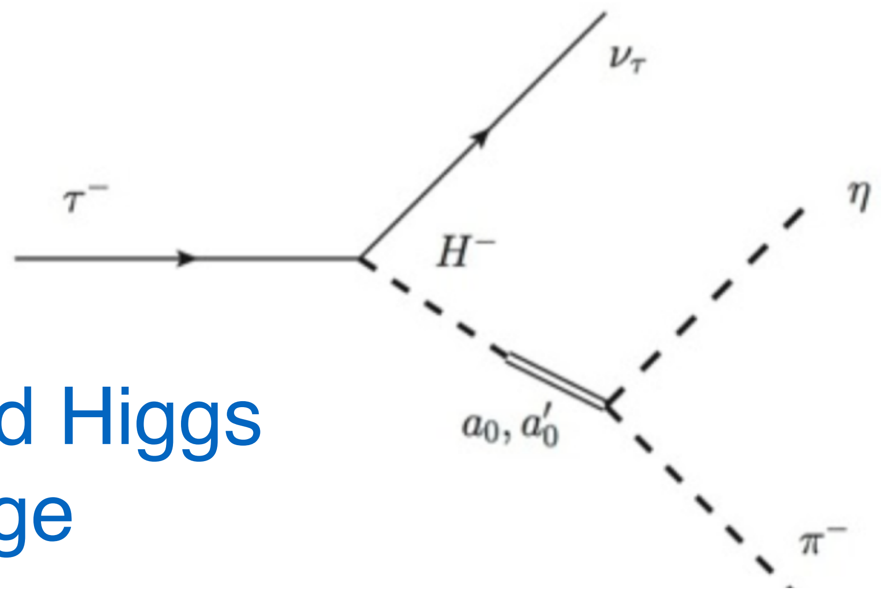
Motivation: scalar and tensor interactions

- $\tau^- \to \eta\pi^-\nu_\tau$ in the SM: isospin violation

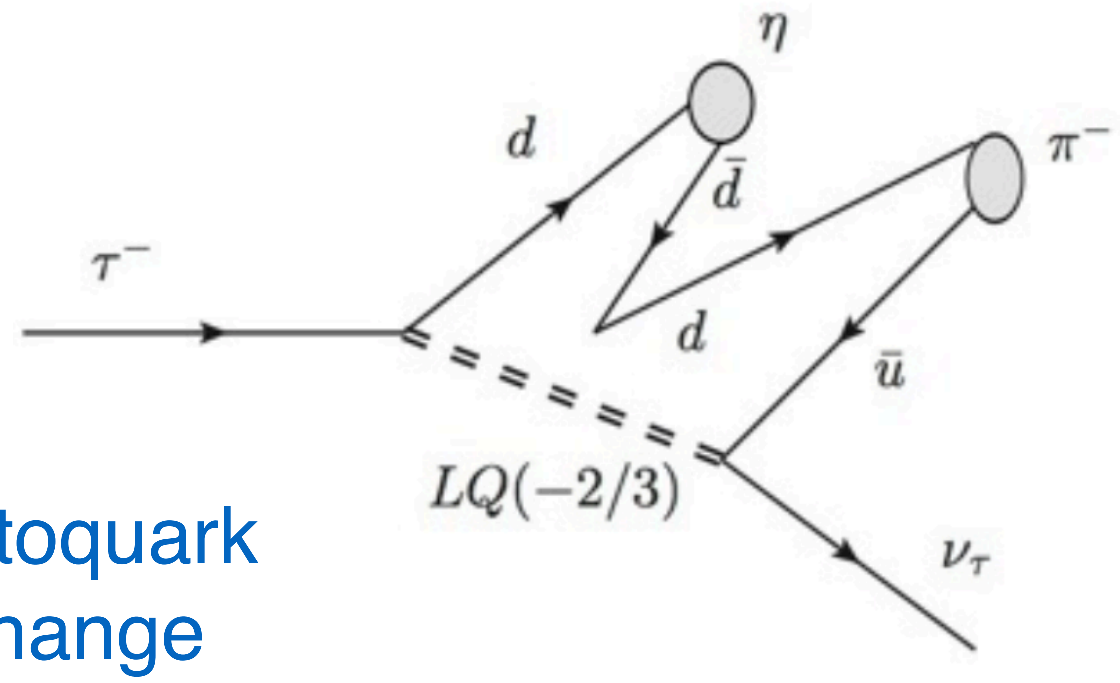


- The corresponding suppression of the SM contribution can make new physics (NP) visible.

Charged Higgs exchange



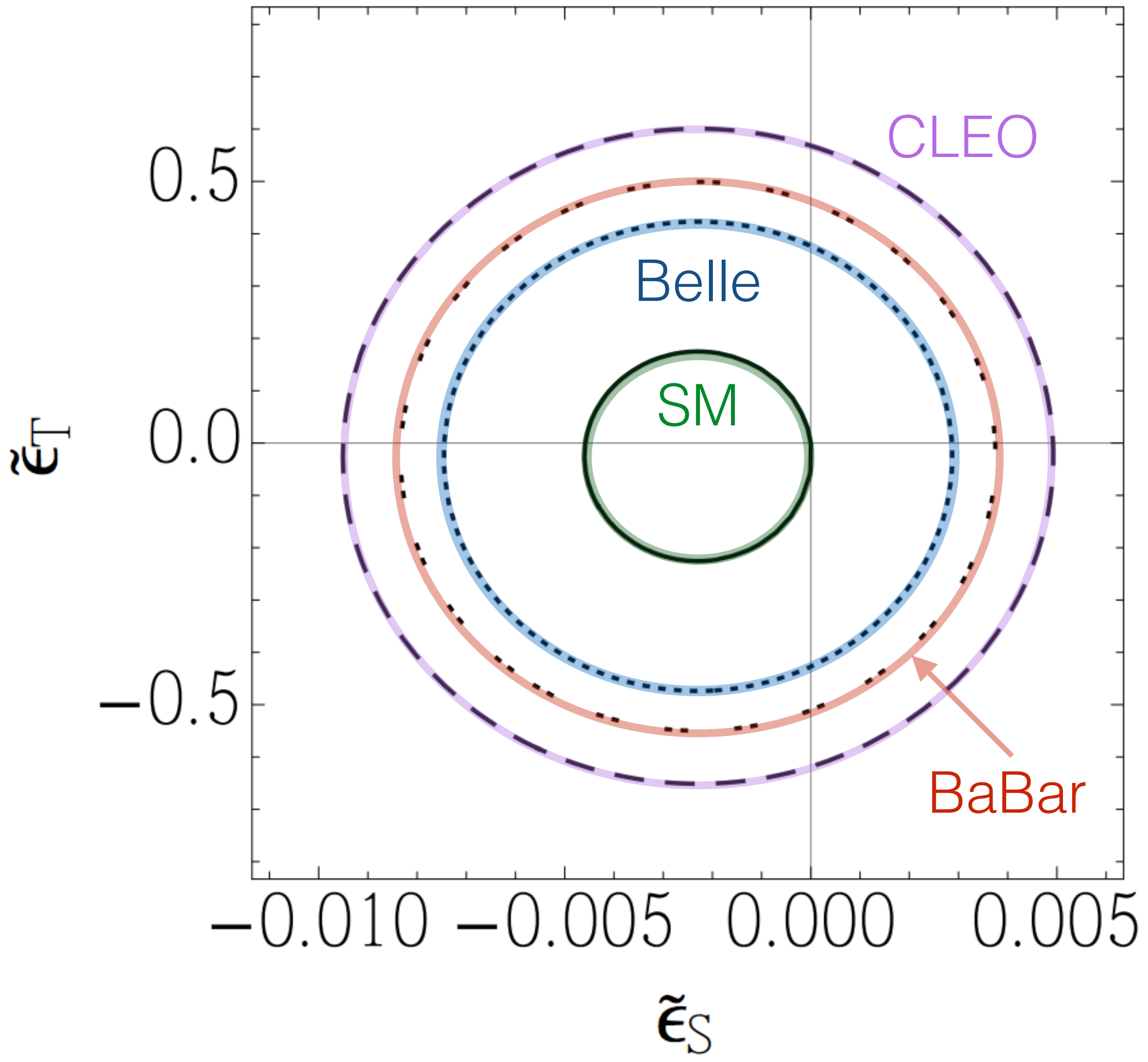
Leptoquark exchange



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

- Constraints on scalar and tensor couplings can be obtained from upper limits on BRs.[2]

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

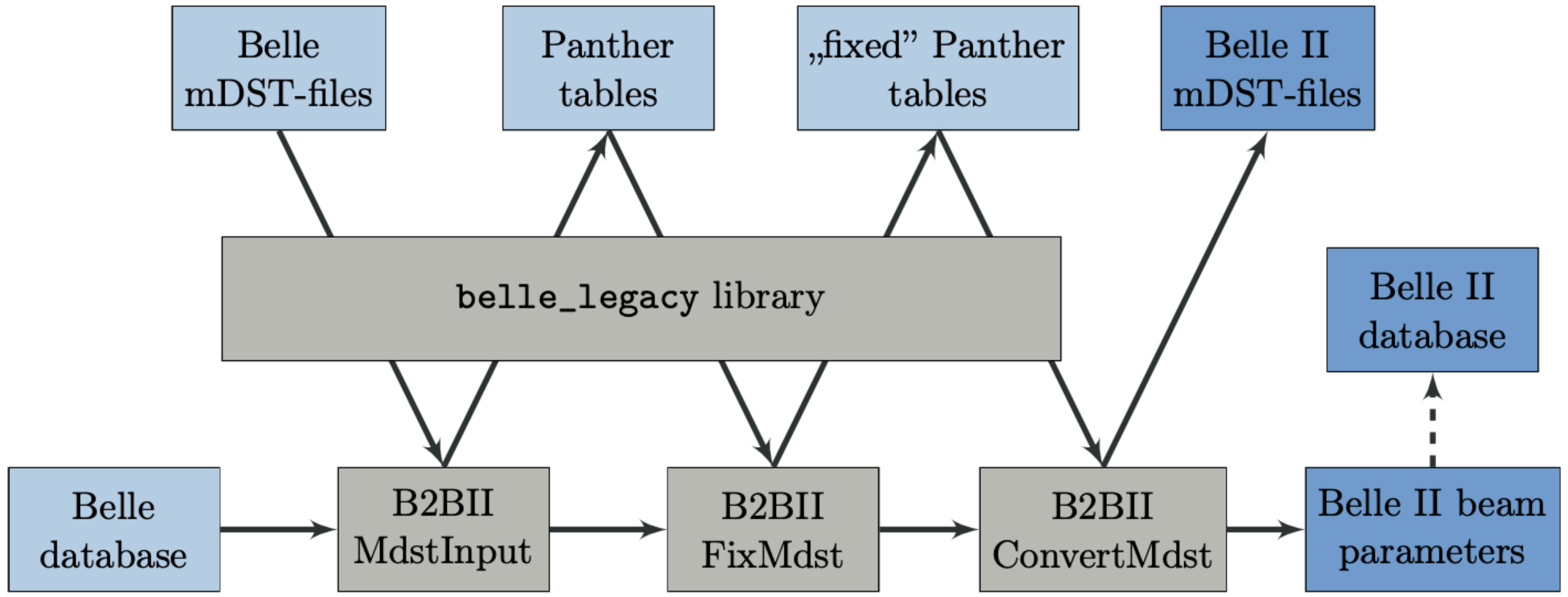


[2] E. A. Garcés, MHV, G. López Castro, P. Roig; JHEP, 2017(12), 27.

$\tau \to \eta\pi\nu$ reconstruction in Belle using B2BII

- η mesons can be reconstructed from $\gamma\gamma$ (1-prong) or $\pi^+\pi^-\pi^0$ (3-prong). In this work, the 1-prong topology is used.
- For the processing of the mdst samples, **Basf2 with B2BII is used.**
  - B2BII converts the Belle mDST data, which contains mostly detector independent objects like tracks and calorimeter clusters, into the new mDST format used by BASF2.
  - Update to release-05-00–00 (includes new features related hadron skim and trigger tables).

- Samples
  - Data, Υ(4S), Υ(5S), and continuum:
    - Exp 7 - Exp 71, **915 fb^{-1}**. HadronBJ + Tau skims
  - Signal MC sample:
    - $\tau \to (a^0 \to \eta\pi)\nu$, with a^0 width of 100 MeV (~18M).
  - Generic MC samples
    - Tau pair (10 streams for SVD2, 2 streams for SVD1).
    - Charm + uds MC samples (6 streams).
    - Two photon (10 streams for SVD2, 2 streams for SVD1)
    - Bhabha (Exp 31 - 35, 5 streams).



Gelb, Moritz, et al. Computing and Software for Big Science 2.1 (2018): 9.

$\tau \rightarrow \eta\pi\nu$ reconstruction in Belle using B2BII

- Selection cuts classified with 13 indexes.
- Good charged track, Belle acceptance
- Good gamma: **only barrel**
- Tag side:
  - $N_\gamma \leq 1$, $M_{tag} < 1.8$ GeV/c^2
  - Leptonic tag: e-ID > 0.1 or μ-ID > 0.1
    Hadronic tag: π-ID > 0.8, e-ID < 0.9 and μ-ID < 0.9
- Signal side:
  - $N_\gamma = 2$, $M_{sig} < 1.8$ GeV/c^2
  - π-ID > 0.8, e-ID < 0.9 and μ-ID < 0.9
- Event Kinematics:
  - $-0.6235 < \cos(\theta_{miss}) < 0.8332$, $p_{miss} > 1.0$ GeV
  - 3.0 GeV < visible E_{cms} < 9.0 GeV
  - 1.0 GeV/c^2 < M_{miss} < 7.4 GeV/c^2,
  - $V_{thrust} > 0.8$
- **PID scale factors applied (lepton and K ID).**

Description	index	Selection criteria
Charged tracks	1	$dr \leq 1.0$ cm; $dz \leq 5.0$ cm,
	2	$p_t > 0.06$ GeV/c for $-0.6235 < \cos\theta_{\rm trk} < 0.8332$,
		$p_t > 0.1$ GeV/c for $-0.8660 < \cos\theta_{\rm trk} < -0.6235$ or $0.8332 < \cos\theta_{\rm trk} < 0.9563$,
Photons	3	$E_\gamma > 0.1$ GeV; $-0.6235 < \cos\theta_\gamma < 0.8332$,
Tag side	4	$N_\gamma^{\rm tag} \leq 1$, $M_{\rm tag} < 1.8$ GeV/c^2,
	5	$e-{\rm ID_{tag}} > 0.1$ or $\mu-{\rm ID_{tag}} > 0.1$ (leptonic tag)
		or $\pi-{\rm ID_{tag}} > 0.8$, $e{\rm ID_{tag}} < 0.9$, and $\mu{\rm ID_{tag}} < 0.9$ (hadronic tag),
Signal side	6	$N_\gamma^{\rm sig} = 2$, $M_{\rm tag} < 1.8$ GeV/c^2,
	7	$0.4 < M_{\gamma\gamma} < 0.8$ GeV/c^2,
	8	$\pi-{\rm ID_{sig}} > 0.8$, $e{\rm ID_{sig}} < 0.9$, and $\mu{\rm ID_{sig}} < 0.9$
Event kinematics	9	$P_{\rm missing} > 1.0$ GeV/c, $-0.8660 < \cos\theta_{\rm missing} < 0.9563$
	10	$V_{\rm thrust} > 0.8$,
	11	$3.0 < E_{\rm visible} < 9.0$ GeV,
	12	$1.0 < M_{\rm missing} < 7.4$ GeV/c^2,
π^0 veto in signal side	13	$E_\gamma > 0.05$ GeV; $-0.8660 < \cos\theta_\gamma < 0.9563$, $0.105 < M_{\gamma\gamma} < 0.165$ GeV/c^2

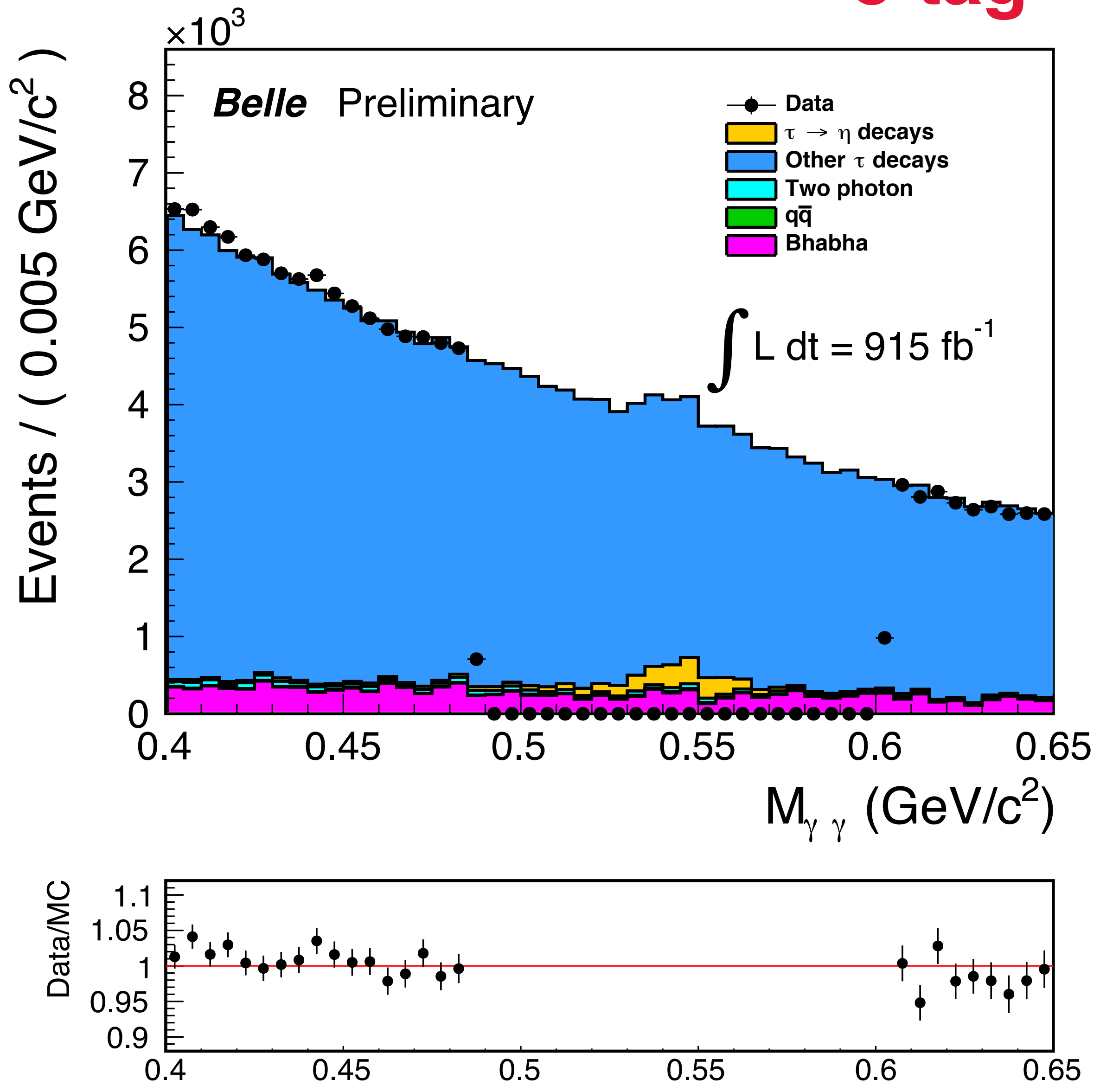
Cut	Data	$\tau \to \eta + X$	Other $\tau\tau$	$q\bar{q}$	two-photon	Bhabha	All bkg (MC)	$\epsilon_{\rm sig}$
1-9	935,286	20,710	1,439,267	31,929	23,369	89,936	1,605,211	3.85%
10	912,084	20,517	1,416,455	25,590	15,453	89,153	1,567,169	3.82%
11	870,660	20,141	1,381,067	22,884	11,894	40,608	1,476,593	3.77%
12	845,572	20,029	1,354,940	22,245	11,052	21,977	1,430,244	3.72%
13	420,627	11,701	661,043	10,200	7,977	17,618	708,541	3.29%

$\eta \to \gamma\gamma$ distributions in 1-1 prong

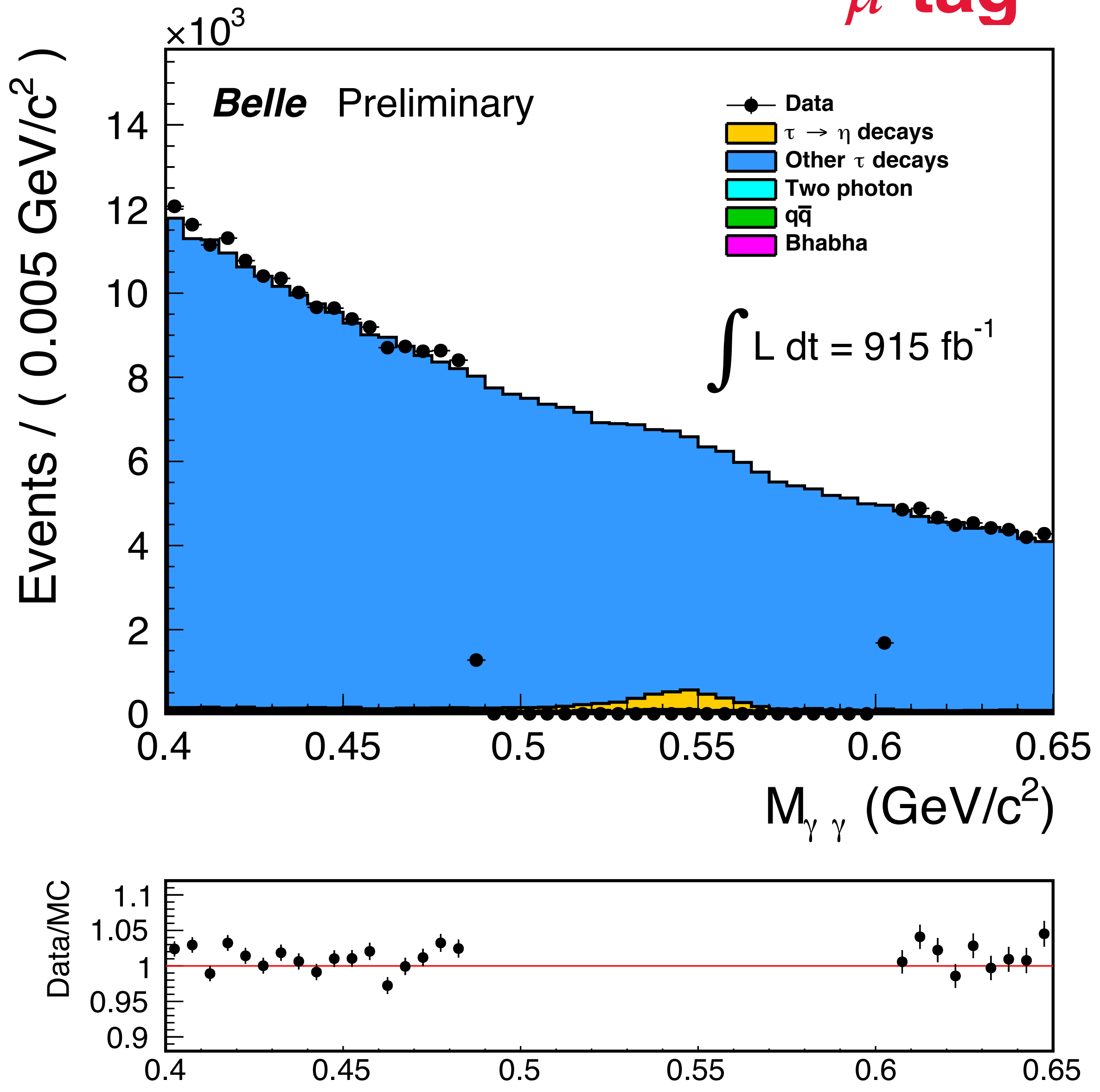
- **Strategy**: extract the number of $\tau \to \eta\pi\nu$ candidates from a fit in the η peak.
- Cuts 1-13 applied on MC and sidebands data. Datasets from Υ(4S), Υ(5S) and off-resonance included.
- MC scaled to the data luminosity.

- Overall agreement between data and MC.
- Strong background contributions, as expected.
- It is known that some resonances are not well described on *qq* MC samples.

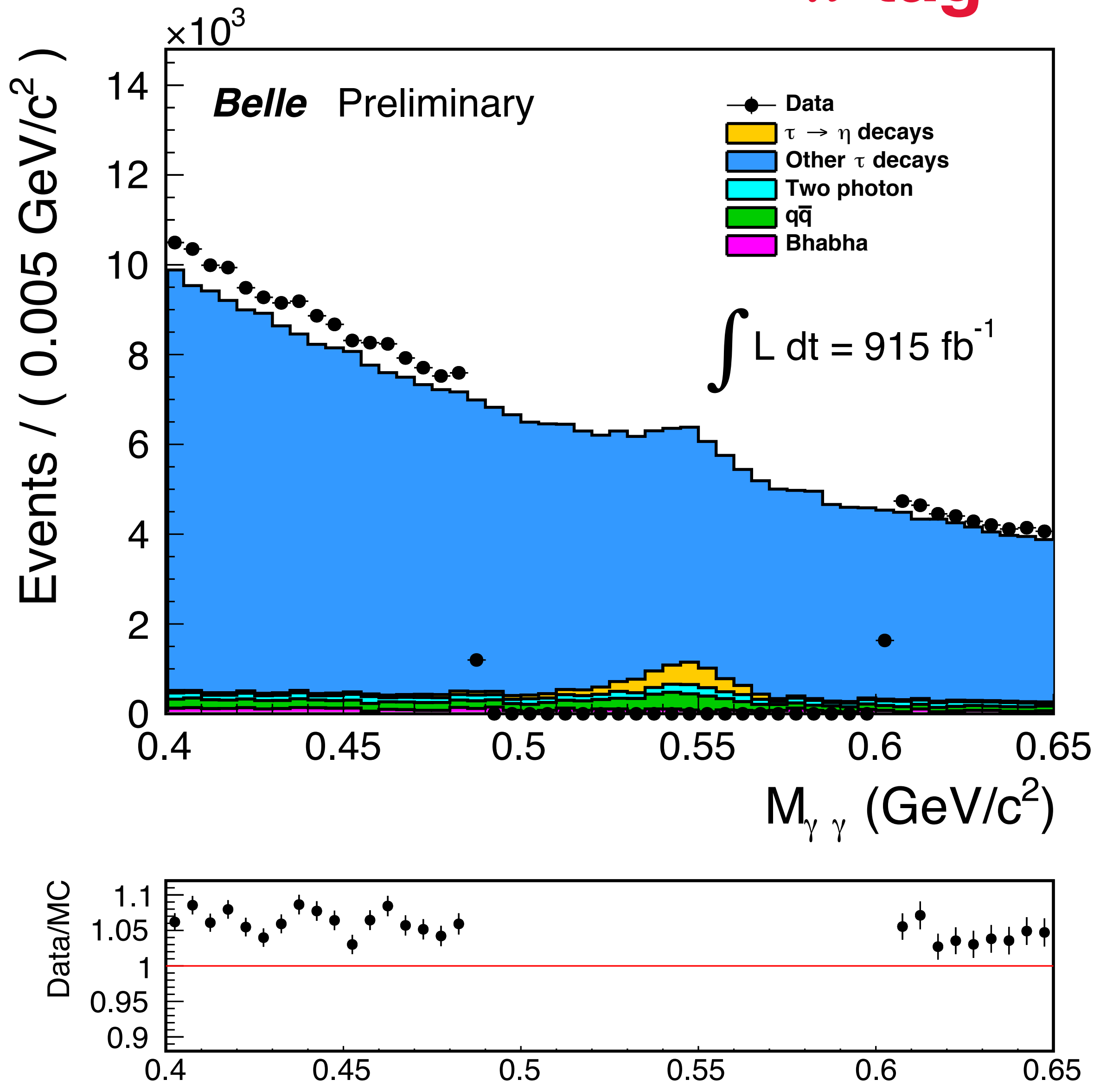
e-tag



μ-tag



π-tag



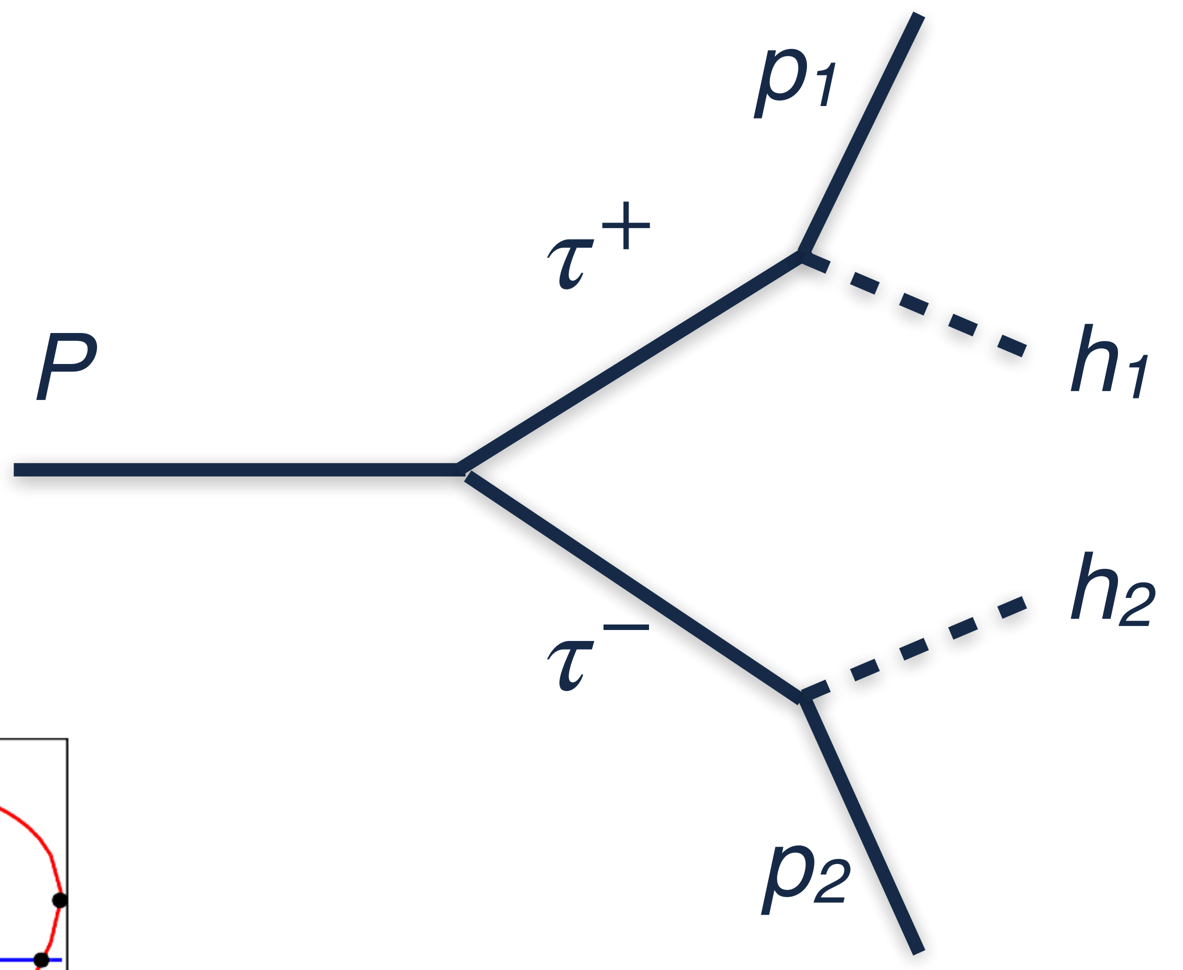
Kinematic Suppression

- Given the kinematics of the whole event, it is possible to find kinematic limits (regions in the phase space with physical meaning)[1].
- Three four-vectors are known: P, p_1 and p_2.
- μ_1 and μ_2 represents the missing invariant mass of the signal/tag side.
- The solution for the system of equations is

$$P = p_{\tau 1} + p_{\tau 2} = p_1 + h_1 + p_2 + h_2$$

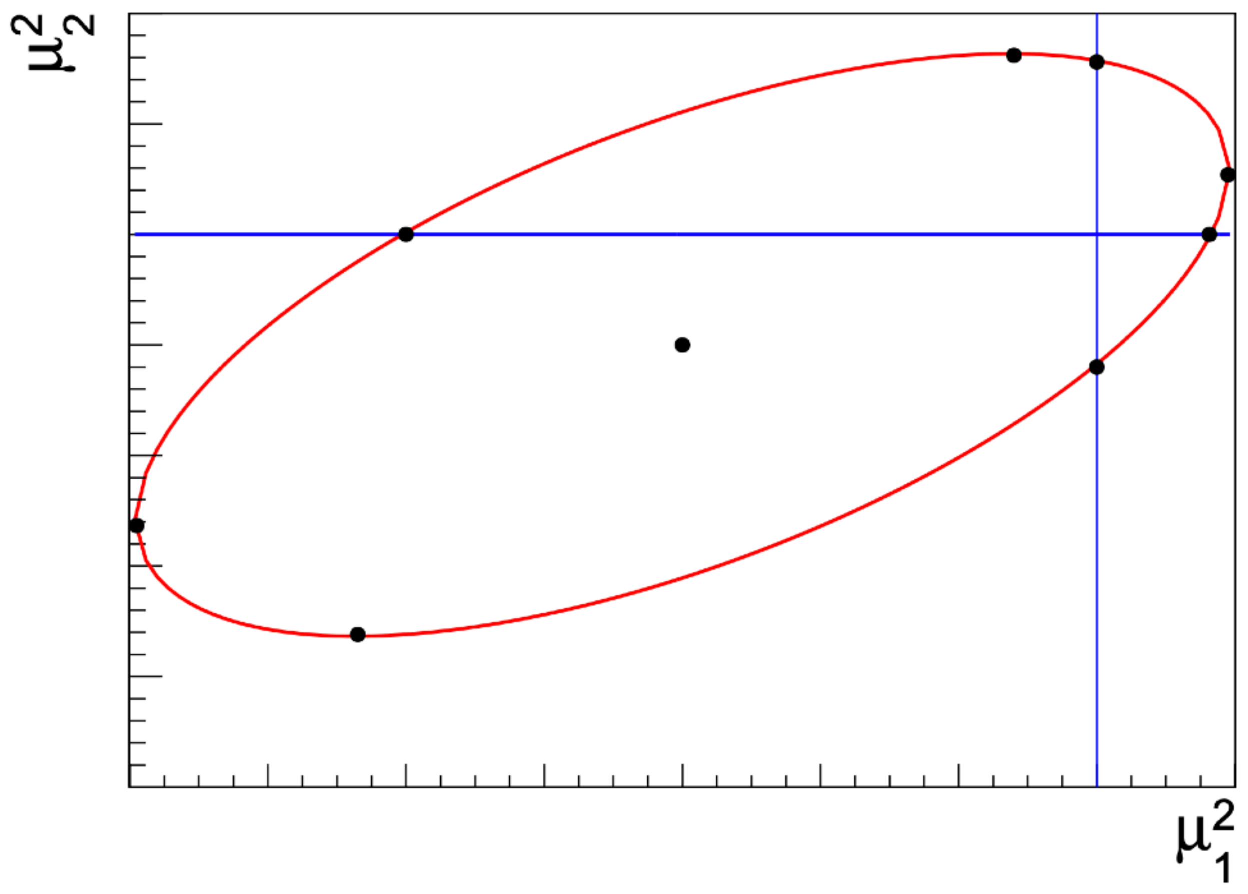
$$(p_1 + h_1)^2 = m_\tau^2,\ (p_2 + h_2)^2 = m_\tau^2$$

$$(p_{\tau 1} - p_1)^2 = \mu_1^2,\ (p_{\tau 2} - p_2)^2 = \mu_2^2$$



$$\left(-P^2 g_{\nu\sigma} + P_\nu P_\sigma\right)\left[\left(m_\tau^2 - \mu_1^2 + m_1^2 - Pp_1\right) p_2^\nu + \left(m_\tau^2 - \mu_2^2 + m_2^2 - Pp_2\right) p_1^\nu\right] \times \left[\left(m_\tau^2 - \mu_1^2 + m_1^2 - Pp_1\right) p_2^\sigma + \left(m_\tau^2 - \mu_2^2 + m_2^2 - Pp_2\right) p_1^\sigma\right] = \left(4m_\tau^2 - P^2\right) \epsilon^{\alpha\beta\gamma\rho} \epsilon_{\alpha_1\beta_1\gamma_1\rho} P_\alpha p_{1\beta} p_{2\gamma} P^{\alpha_1} p_1^{\beta_1} p_2^{\gamma_1}$$

- This represents an ellipse in the space (μ_1^2, μ_2^2).
- **For $\mu_2^2 \geq 0$, max(μ_1^2) must be ≥ 0 if events are reconstructed correctly.**
- Wrong reconstruction, radiative effects or missing particles destroy the kinematics of the event.



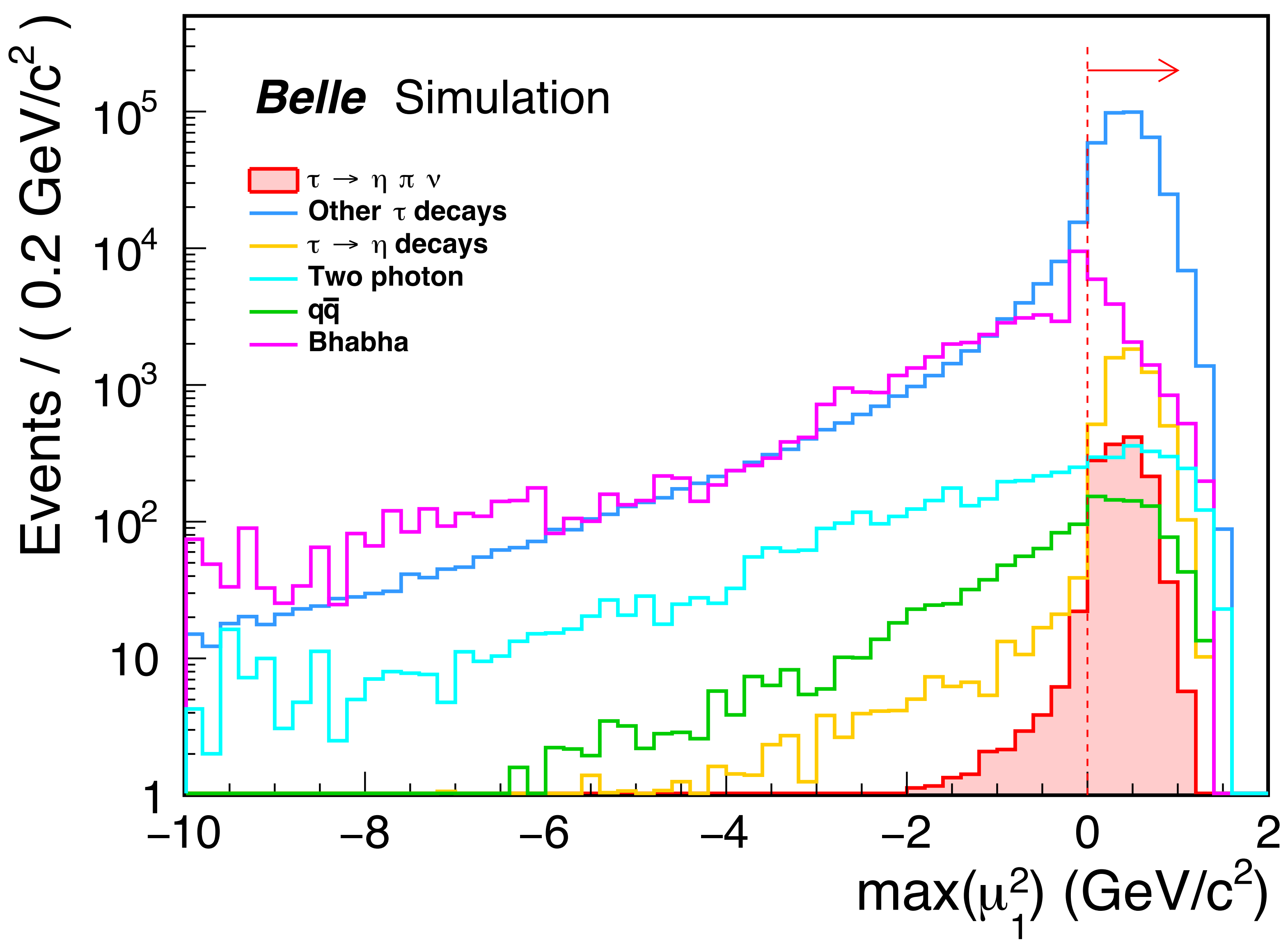
[1] A. Bobrov, Study of the $\tau \to hhh\nu$ decays, BGM Nov 2020.

Kinematic Suppression

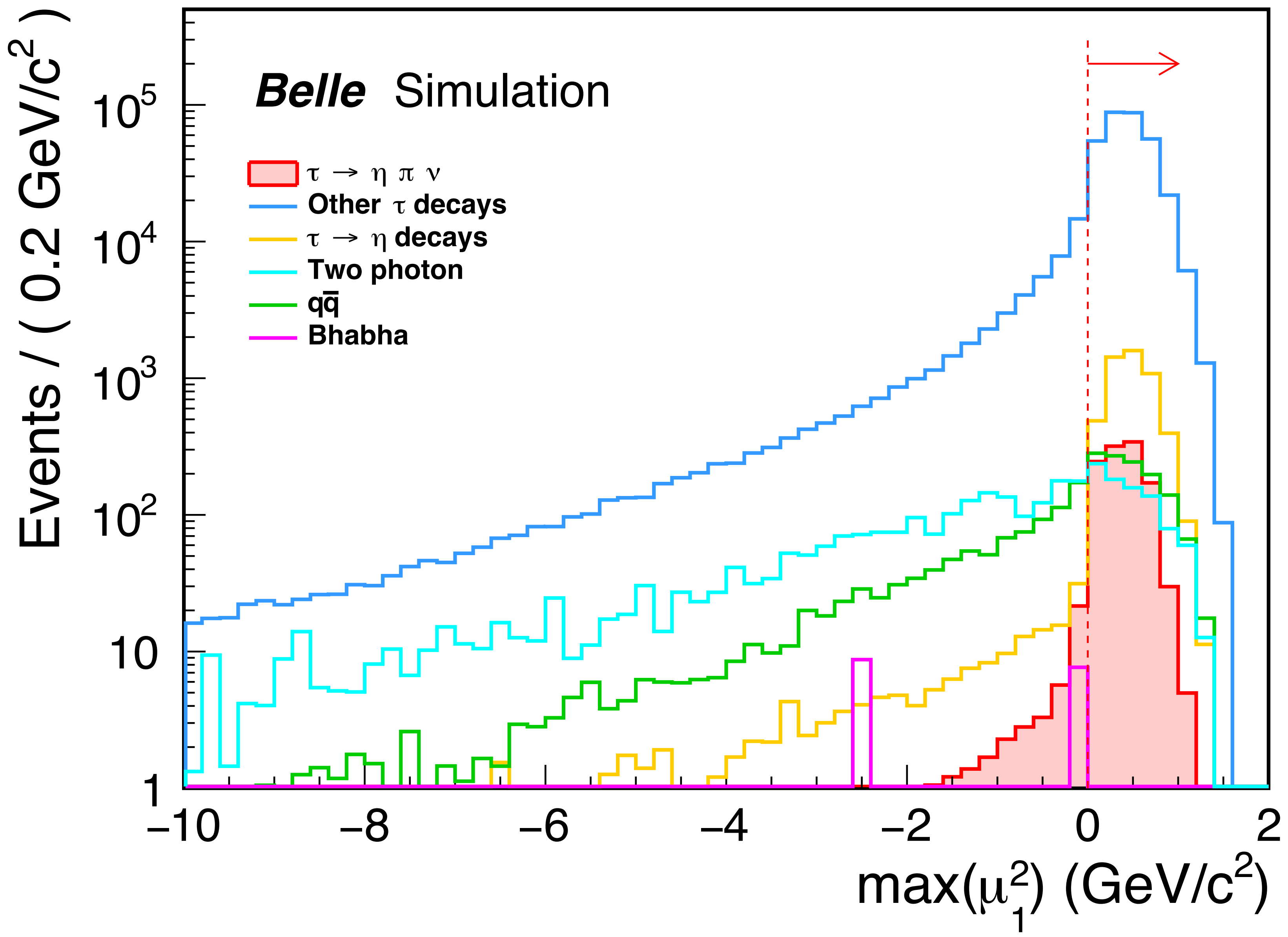
- For $\mu_2^2 \geq 0$, $\max(\mu_1^2)$ must be ≥ 0 if events are reconstructed correctly.
- A cut of $\max(\mu_1^2) \geq 0$ is applied to remove non-physical events (missing detectable particle, wrong mass hypothesis, etc).

Signal vs bkg, assuming BR($\tau \to \eta\pi\nu$) = 5x10^{-5}

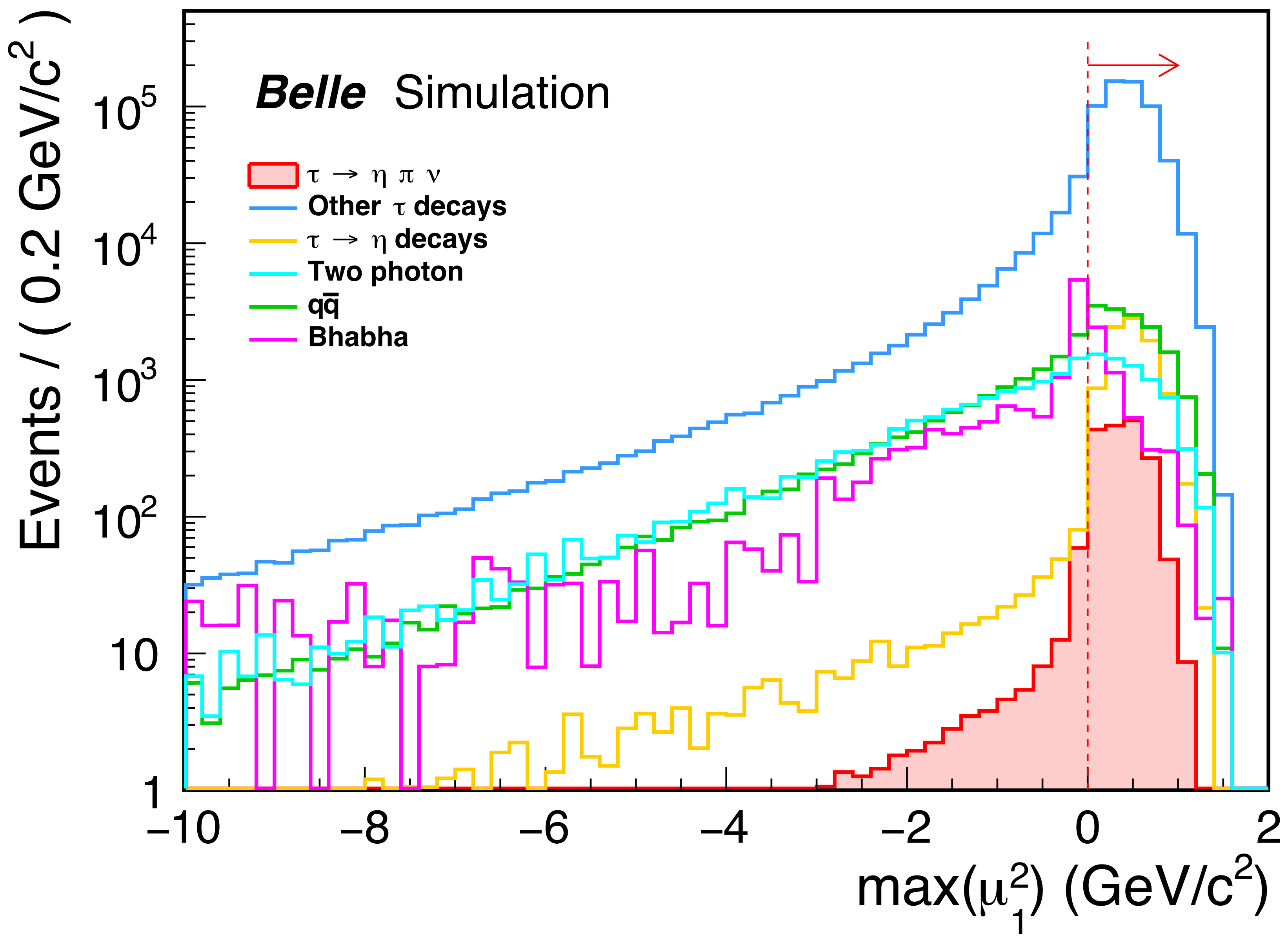
e-tag



μ-tag



π-tag



FastBDT training

- To select $\tau \to \eta + X$ events, a BDT with 4 variables is trained using a gradient boost.
- As **signal**, samples of $\tau \to \eta$ from generic tau decays + signal MC are used.
- As **background**, non $\tau \to \eta$ decays from tau pair MC, qqbar and BBar.
- **Splitting samples** for training and testing in **50%** each.

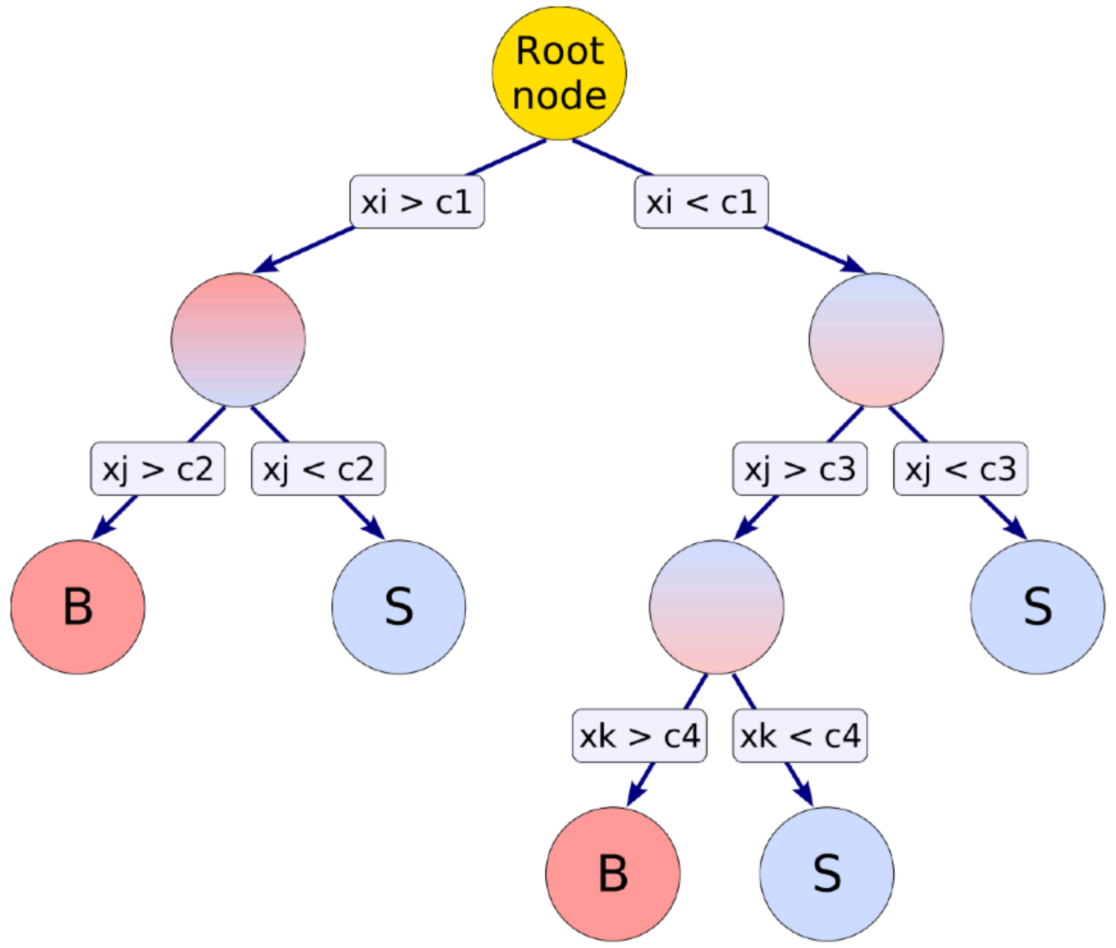
- **Main issue**: poorly model of $\tau \to \eta + X$ decays in the generator.

Variables in training:

- A(γ's) = $|E_{\gamma_1} - E_{\gamma_2}|/(E_{\gamma_1} + E_{\gamma_2})$
- $\angle(\gamma_1, \gamma_2)$
- $\theta(\gamma)$'s

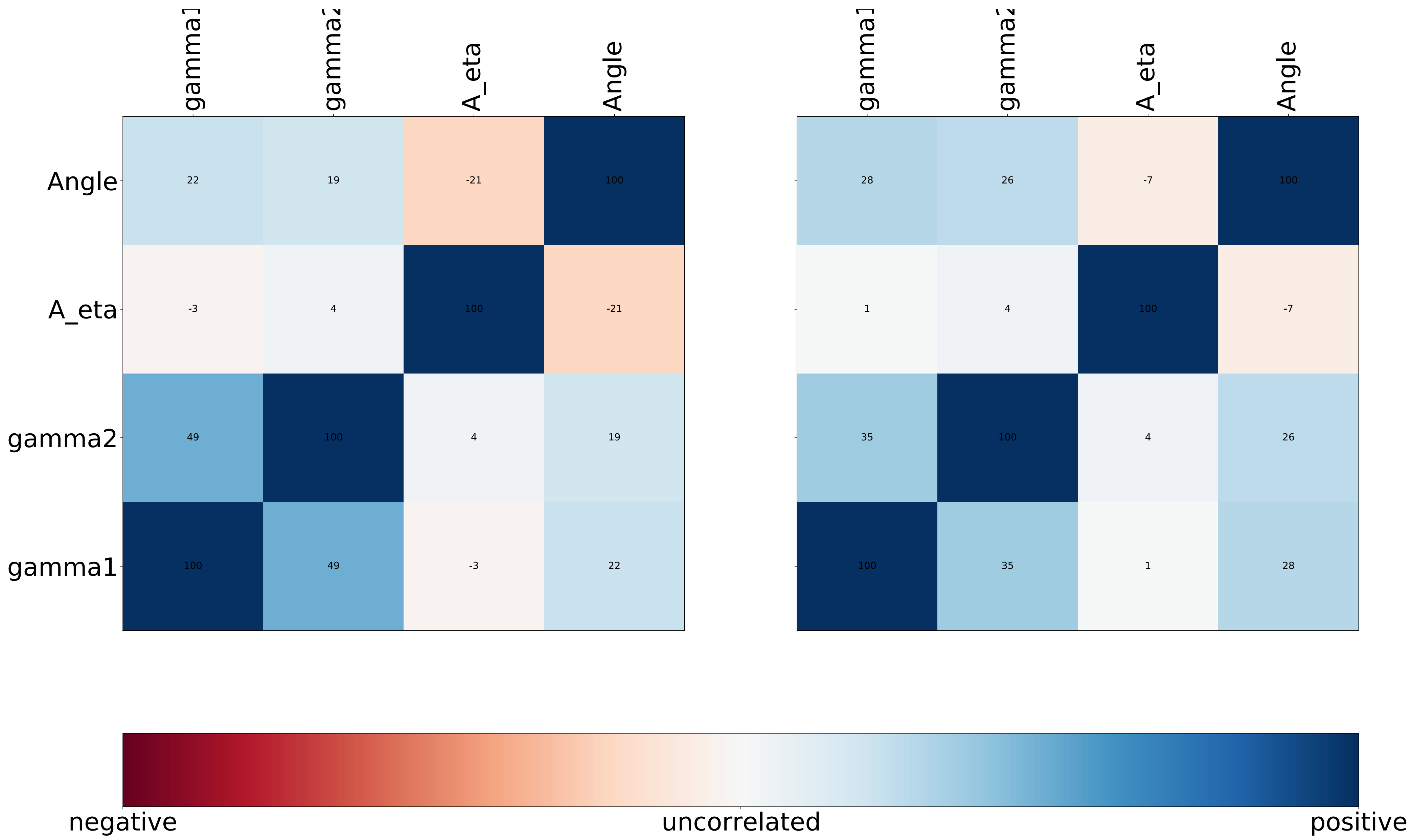
Selected to avoid any dependency to the dynamics of the $\tau \to \eta + X$ decays.

- A Random Forest is an ensemble method that combines different trees.
- Final output is determined by the majority vote of all the trees.



$$bdt = \frac{\sum_i w_i N_i}{\sum_i w_i}; \quad N_i = 0 \text{ or } 1$$

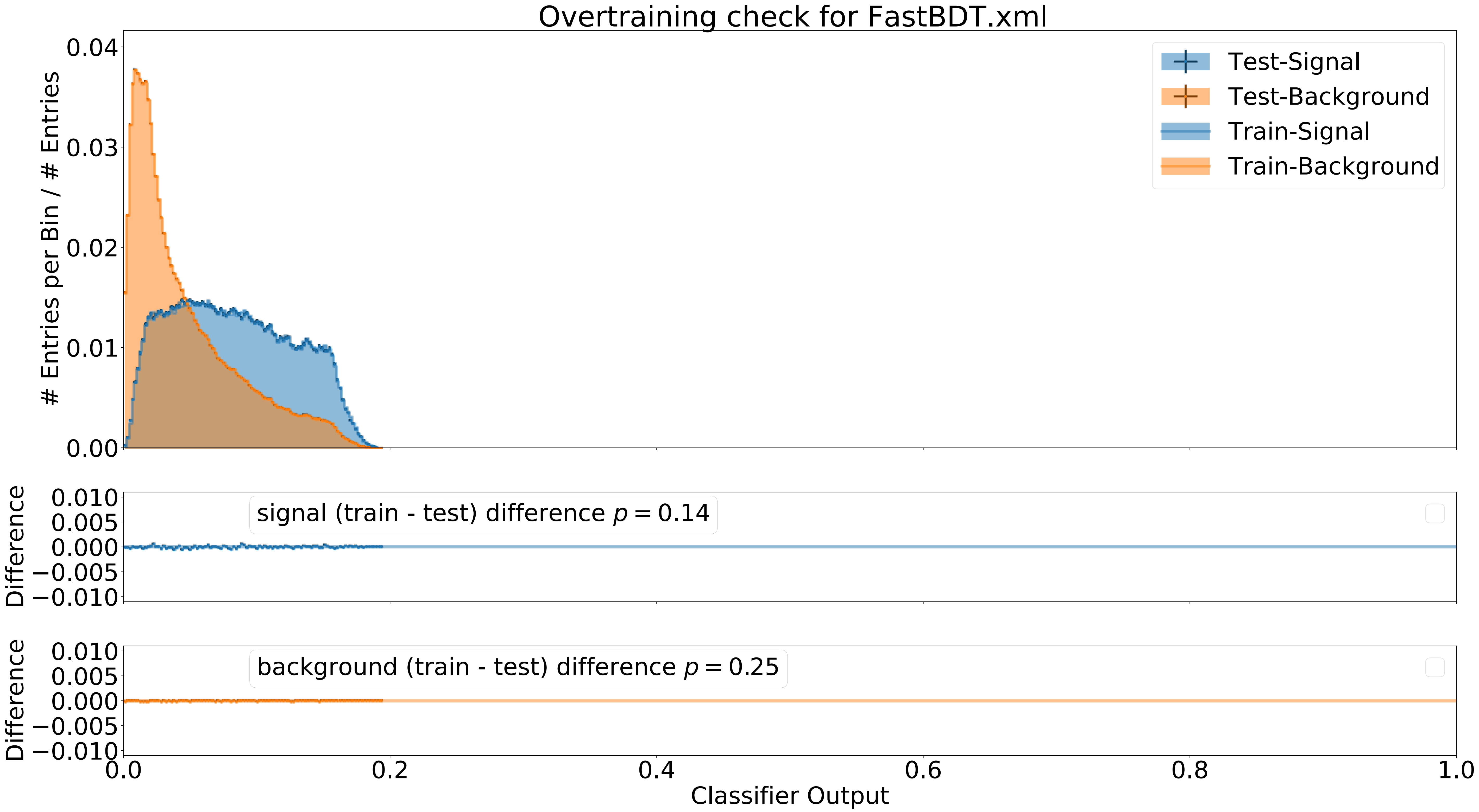
Correlation of variables



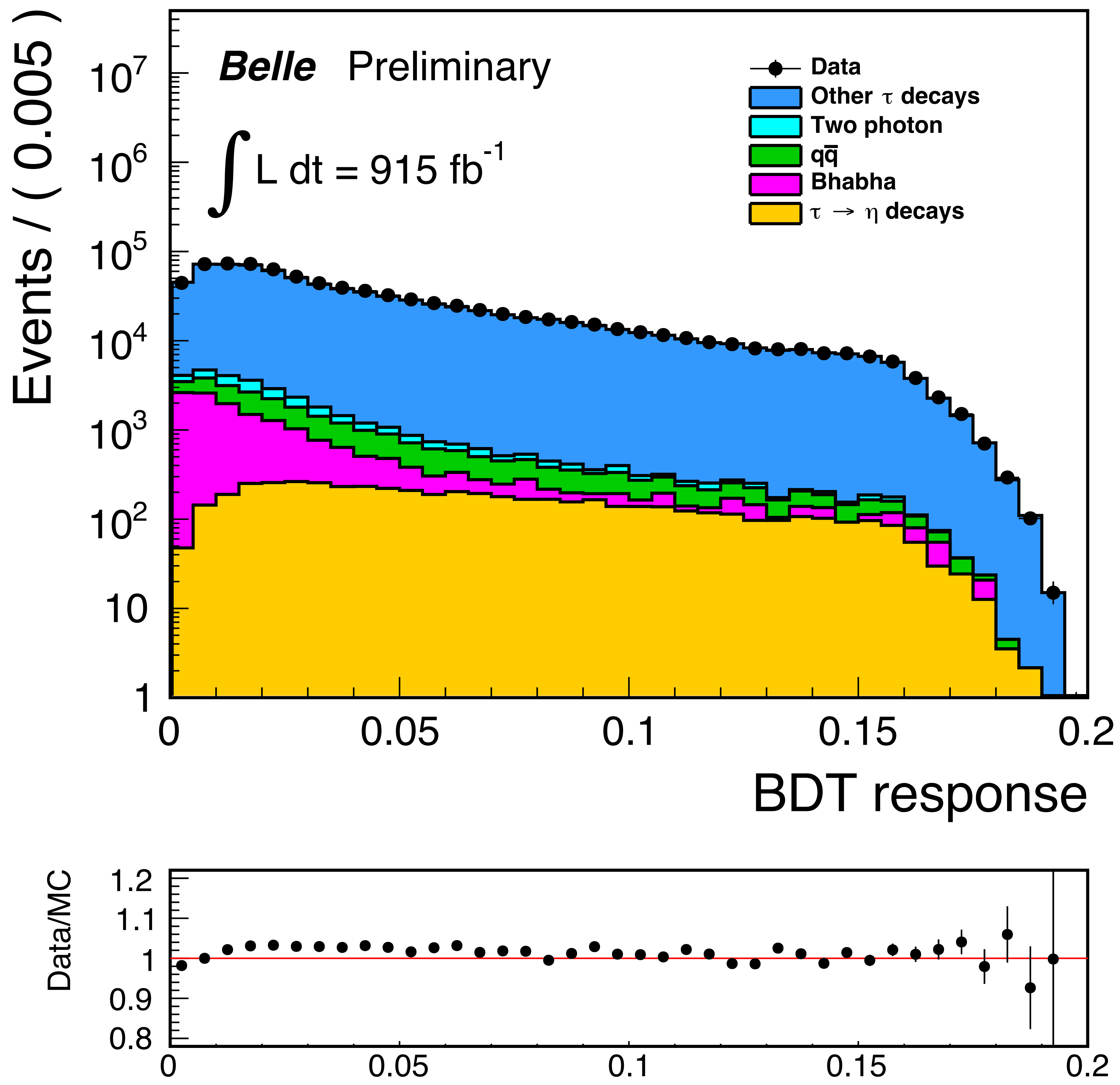
FastBDT response

- N_{trees} = 500, N_{layers} = 3.
- Overtraining check is OK.
- Agreement between data and MC in the BDT response.

Training vs test MC

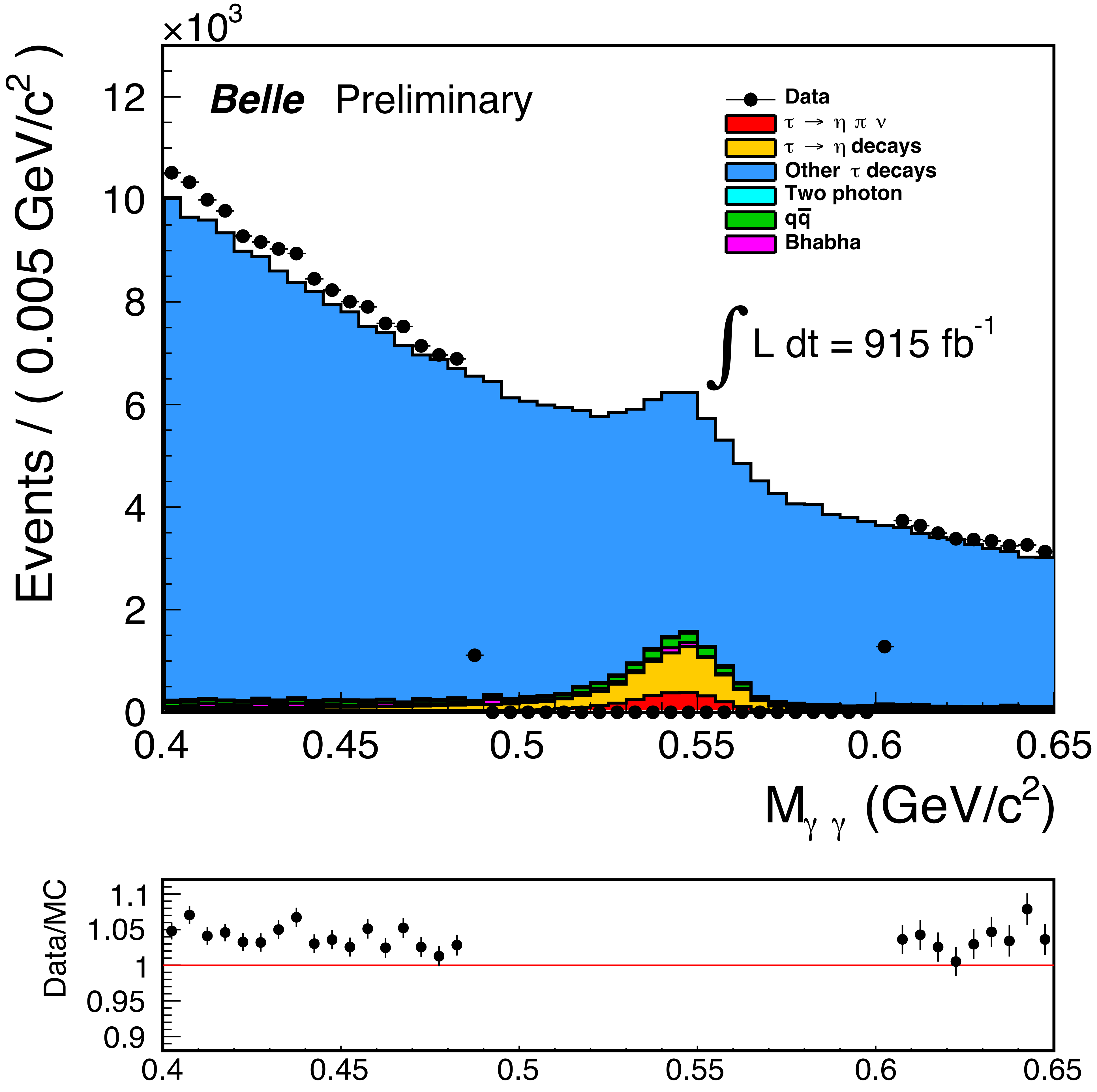


Data vs MC, sidebands:



$\eta \to \gamma\gamma$ mass distribution with BDT and kin suppression

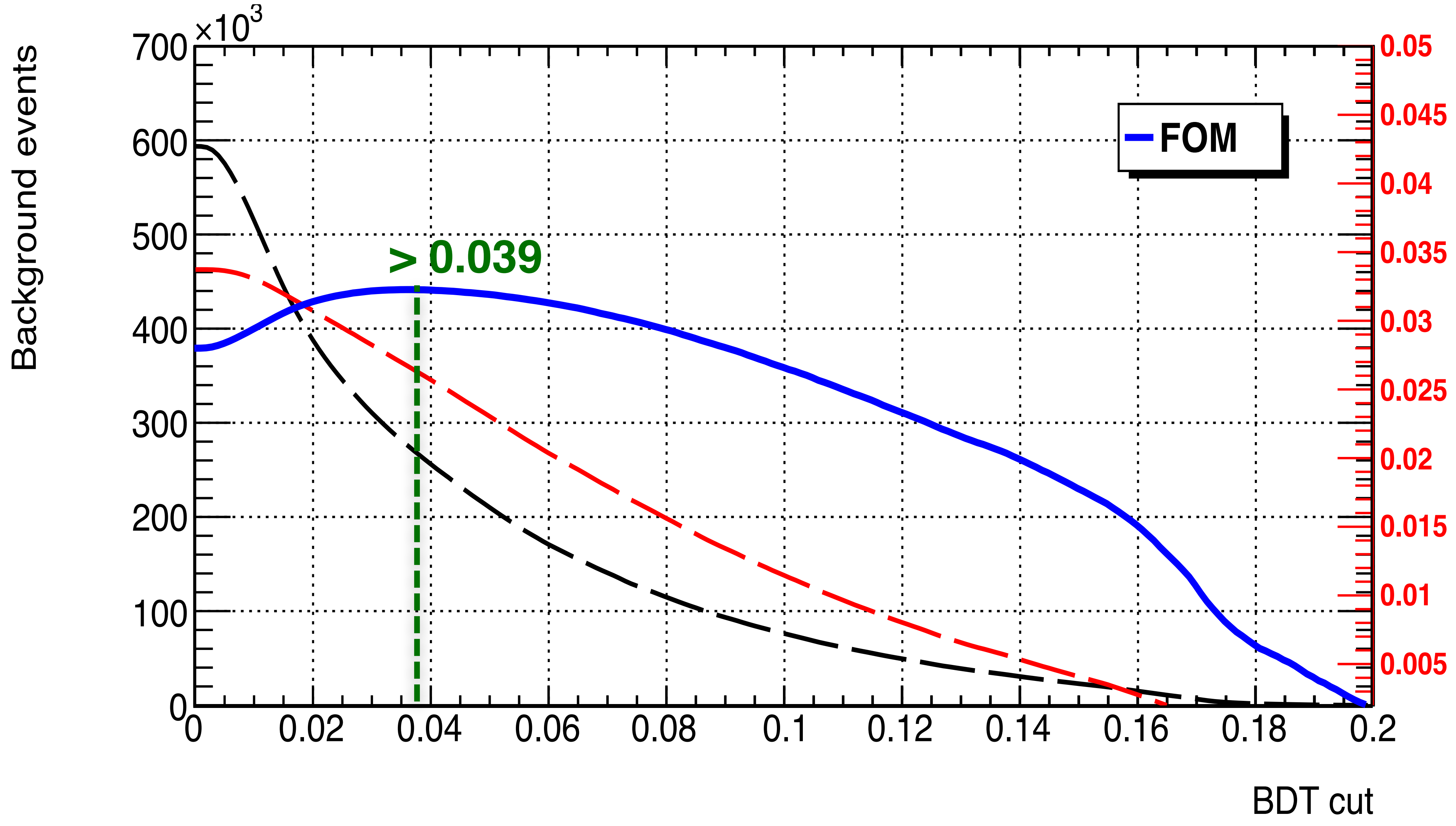
Assuming BR($\tau \to \eta\pi\nu$) = 5x10^{-5}



- The BDT has been optimized using a Punzi FOM

$$FOM = \frac{\epsilon_{\rm sig}}{a/2 + \sqrt{N_{\rm bkg}}}$$

Optimization of BDT response



Systematic Uncertainties

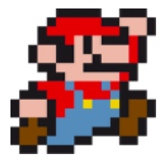
- Systematic uncertainties are under study.
- PID syst uncertainties will come from official data (link).
- Peaking backgrounds estimated using MC.
- Unblind analysis in control channels
  $\tau^- \to \eta\pi^-\pi^0\nu_\tau$,
  $\tau^- \to \eta K^-\nu_\tau$
  for SVD2, Υ(4S) data.

Previous studies

From MC/sidebands

Control channels
$\tau^- \to \eta K^-\nu_\tau$
$\tau^- \to \eta\pi^-\pi^0\nu_\tau$

Source	**Uncertainty (%)**
Luminosity	1.4
Cross Section	0.3
η detection efficiency	2.0
Tracking efficiency	0.7
Signal efficiency due to MC stat	?
π/K - ID	?
Lepton - ID	?
Peaking background $\tau\tau$	?
Peaking background qq	?
π^0 veto	?
BDT	?
Kinematic suppresion	?



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Prospects for Belle II

- What we have learnt from Belle:
  - Kinematic suppression and FastBDT are working as tools for discriminating non $\tau \to \eta$ bkg events.
  - Peaking backgrounds are the most complicated to account or remove
    $\tau^- \to \eta\pi^-\pi^0\nu_\tau$,
    $\tau^- \to \eta K^-\nu_\tau$,
    $\tau^- \to \eta K^*\nu_\tau$.
  - Generation of $\tau^- \to \eta + X$ is performed with a generic model for weak decays (phase space, multiplied by a factor from the expected shape of the momentum spectrum of the weak decay). This poorly models the distribution in MC.

- Understanding of $\tau^- \to \eta + X$ backgrounds is a good first step in **Belle II**.
  - In particular, we need the unfolded invariant mass distributions $\eta\pi^-\pi^0$, ηK, etc.
  - Then, models for generation can be implemented in Tauola.

- Additionally, study of $q\bar{q}$ peaking contributions below the η mass region is required in Belle II
  - Can be performed using an enriched qq selection (see backup for details).

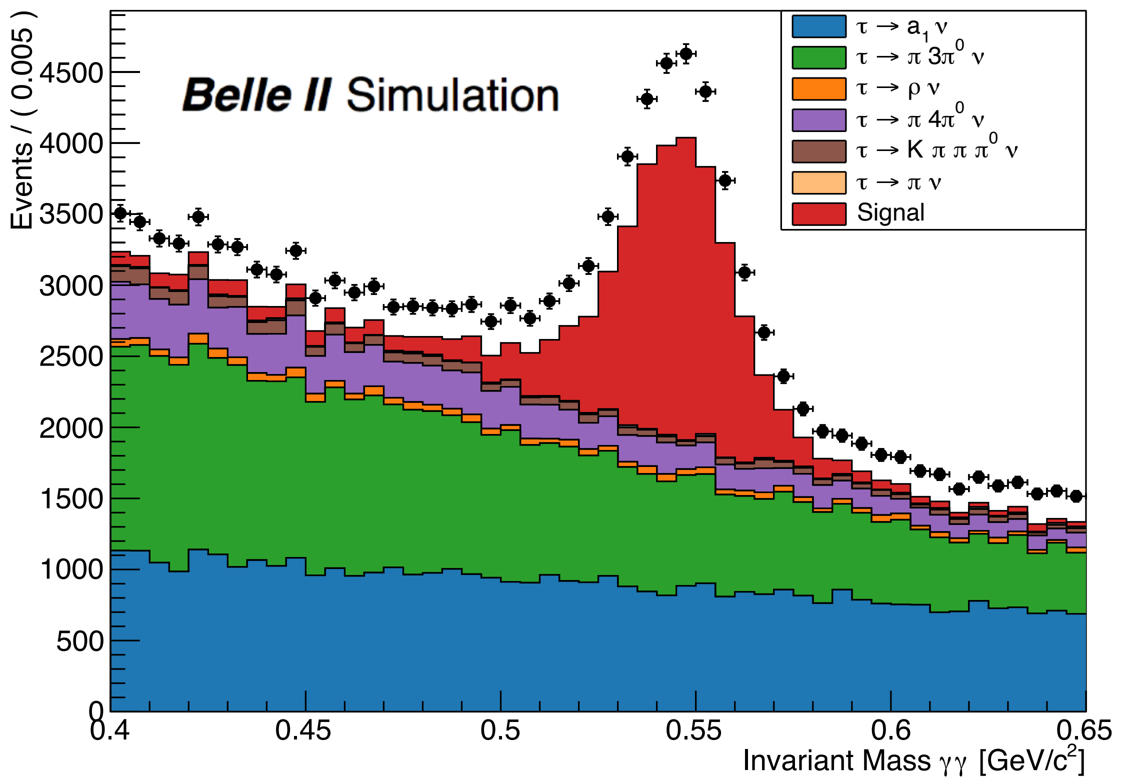
$\tau \to \eta\pi\pi^0\nu$ in Belle II

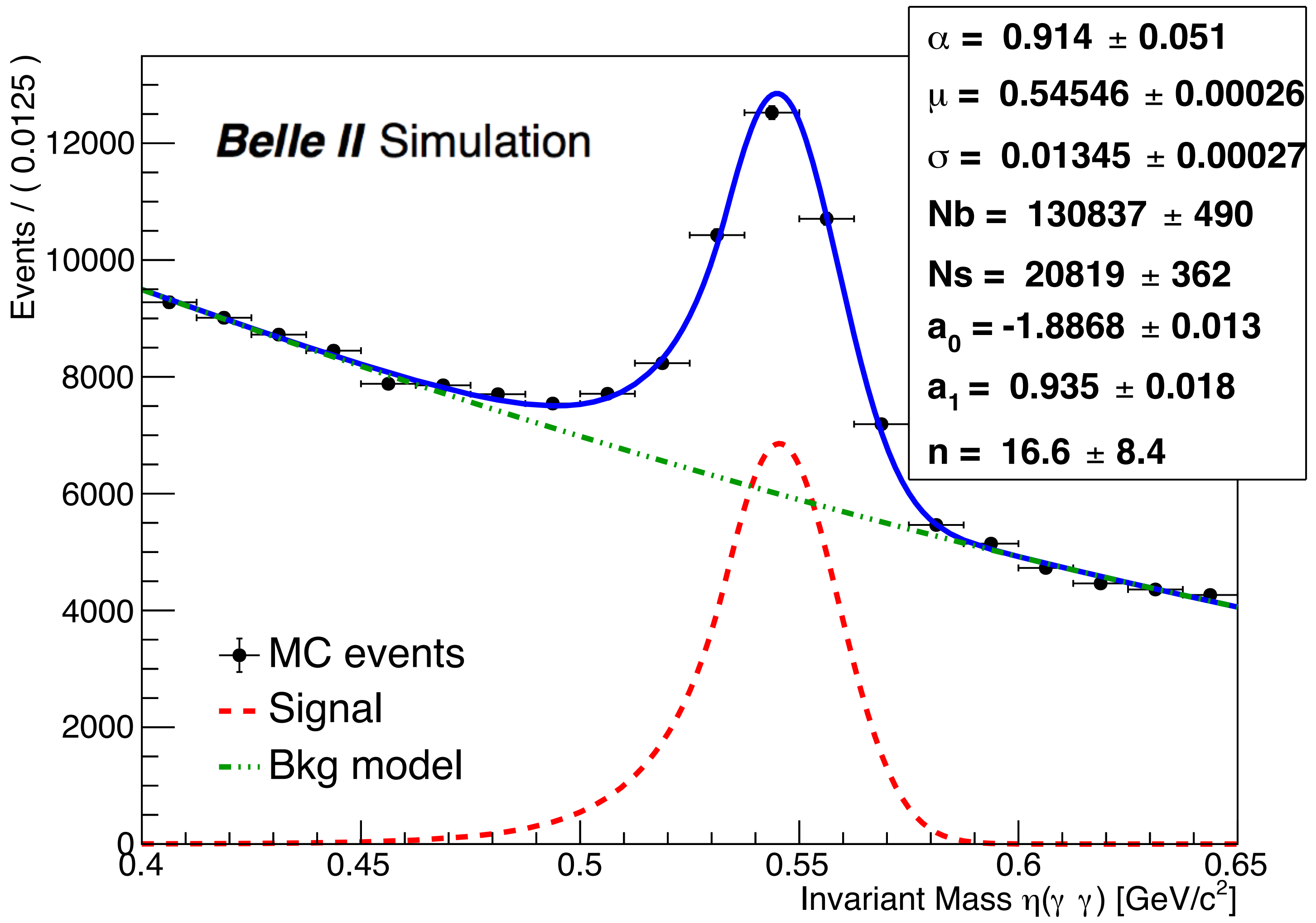
- $\tau \to \eta\pi\pi^0\nu$ **is the decay from** τ **to** η **with the highest Branching Ratio.**
- It is also our main peaking background in the measurement of $\tau \to \eta\pi\nu$.
- The PDG reports:

  BR(τ —> $\eta\pi\pi^0\nu$) = (1.39 ± 0.07) x10^{-3}
- Proper modeling of the decay in the simulation is critical for the precise measurement of $\tau \to \eta\pi\nu$.
- The measurement of the BR and invariant mass distributions will provide the input required to implement the decay model[1] in Tauola.

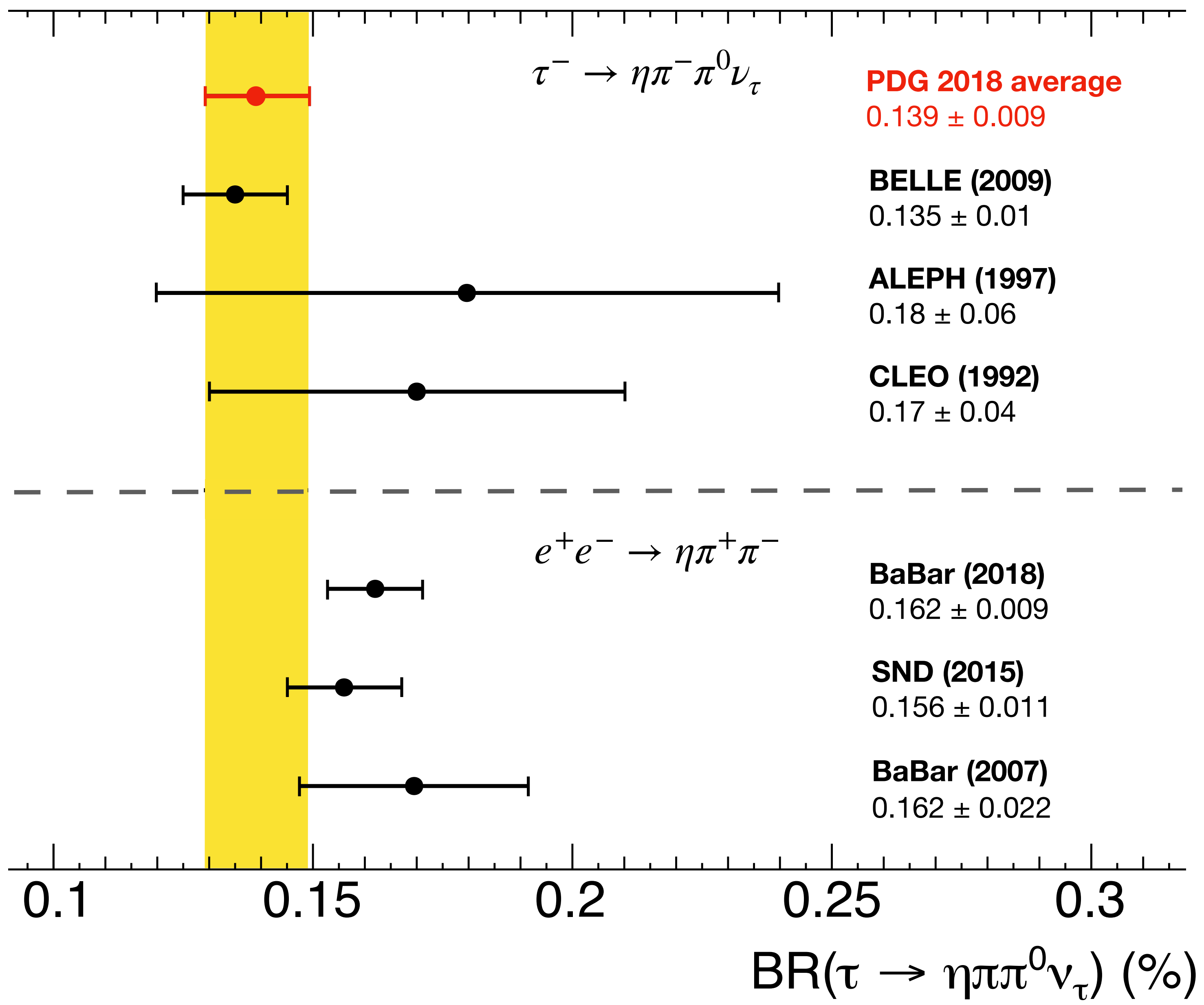
[1]D. Gómez Dumm and P. Roig, Phys. Rev. D **86**, 076009 (2012)

Belle II @ 2 ab^{-1}:



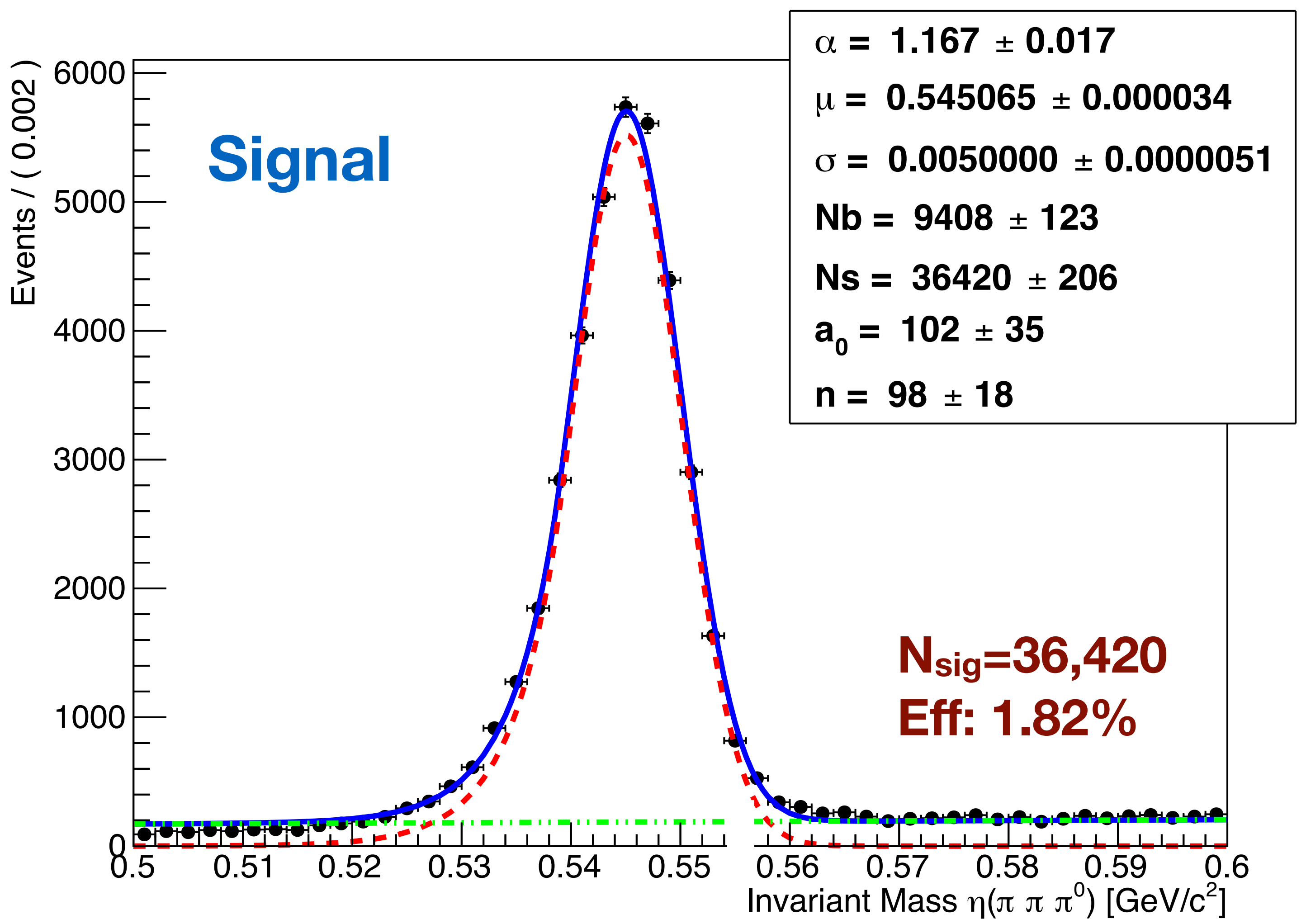


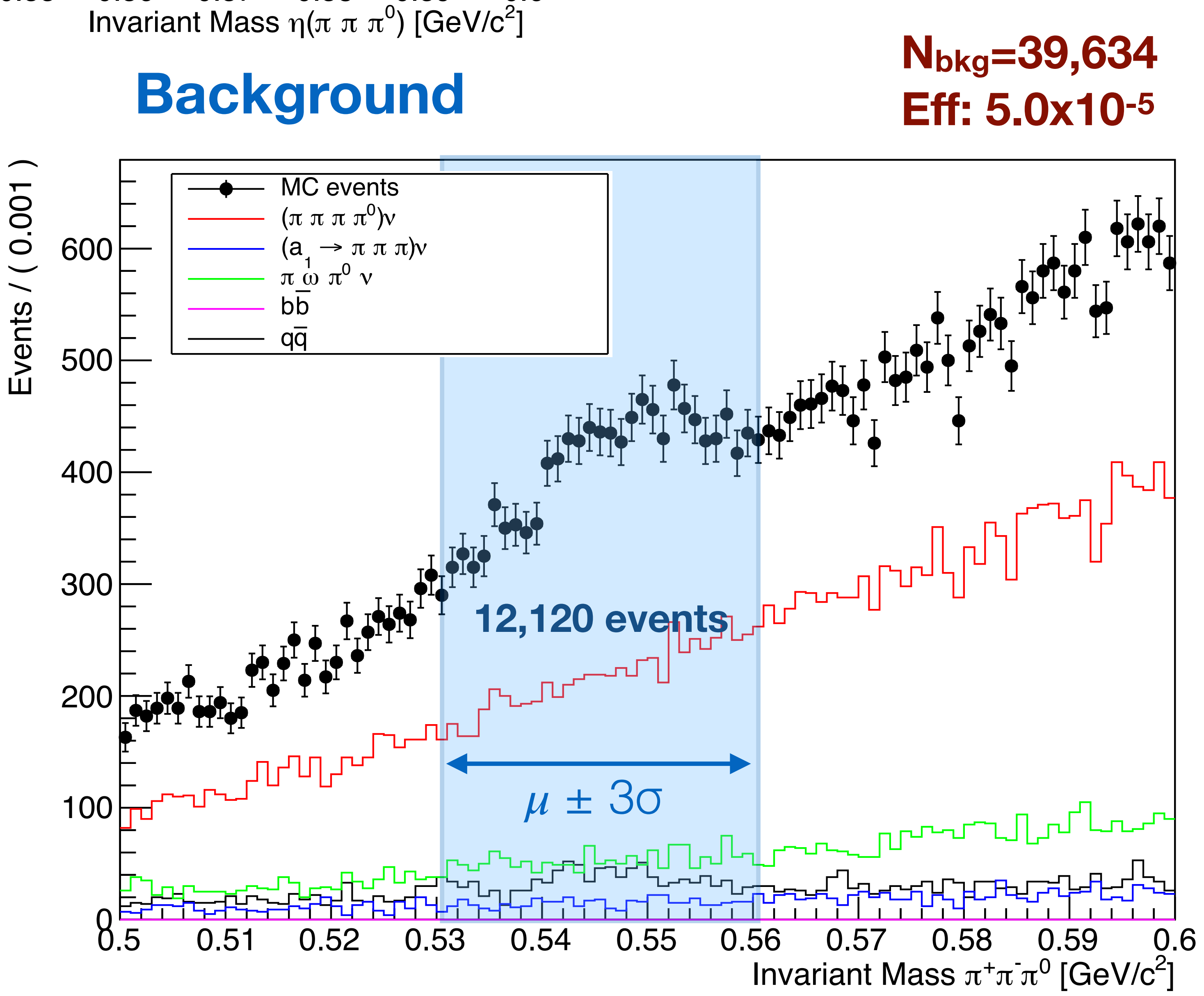
- In the limit of the SU(2) isospin symmetry, is a good cross-check of consistency with $\sigma(e^+e^- \to \eta\pi^+\pi^-)$:

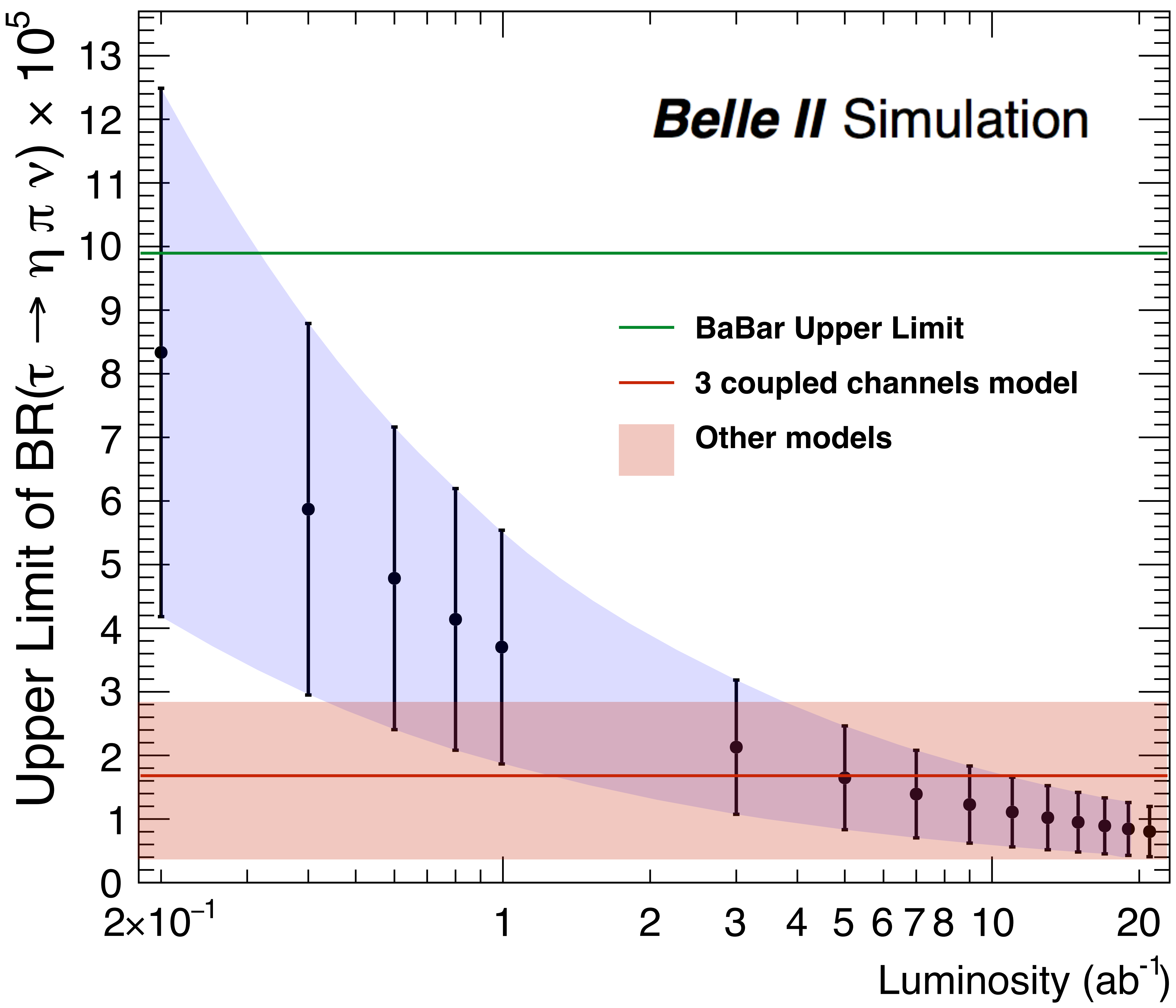


[1] MHV, PhD Thesis, DOI: 10.2172/1495350

Sensitivity of $\tau \to \eta\pi\nu$ @ Belle II







[1] MHV, PhD Thesis, DOI: 10.2172/1495350

Summary

- Our main goal is the BR measurement (or improvement of the upper limit) for the decay $\tau \to \eta\pi\nu$.
    - Powerful channel in the searches of new physics. Constrains in a scalar coupling are the strongest to the date.
- Blind analysis using B2BII from basf2 release-05-00 presented.
    - Kinematic suppression and FastBDT are working as tools for discriminating non $\tau \to \eta$ bkg events.
    - Upper limit in the BR expected to be lower than the reported by BaBar.
- Study of systematic uncertainties on going.
    - We will use control samples $\tau^- \to \eta K^- \nu_\tau$ and $\tau^- \to \eta\pi^-\pi^0\nu_\tau$ for estimation of the syst associated to π^0-veto, kin suppresion and BDT.
- In Belle II, first steps are being taken towards the rediscovery of $\tau^- \to \eta + X$ decays.
- We are aiming to the measurement of kinematic distributions required for the implementation of models in Tauola.

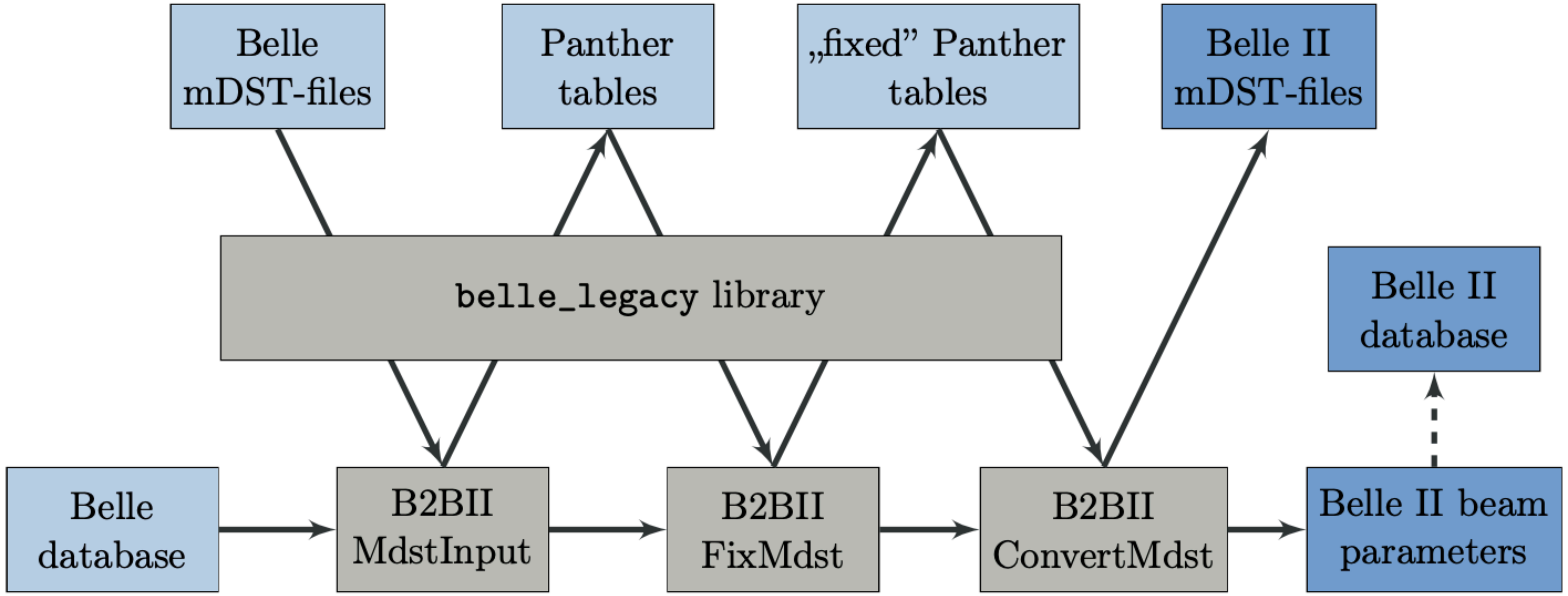
Thank you

Backup

B2BII: Conversion from Belle to Belle II

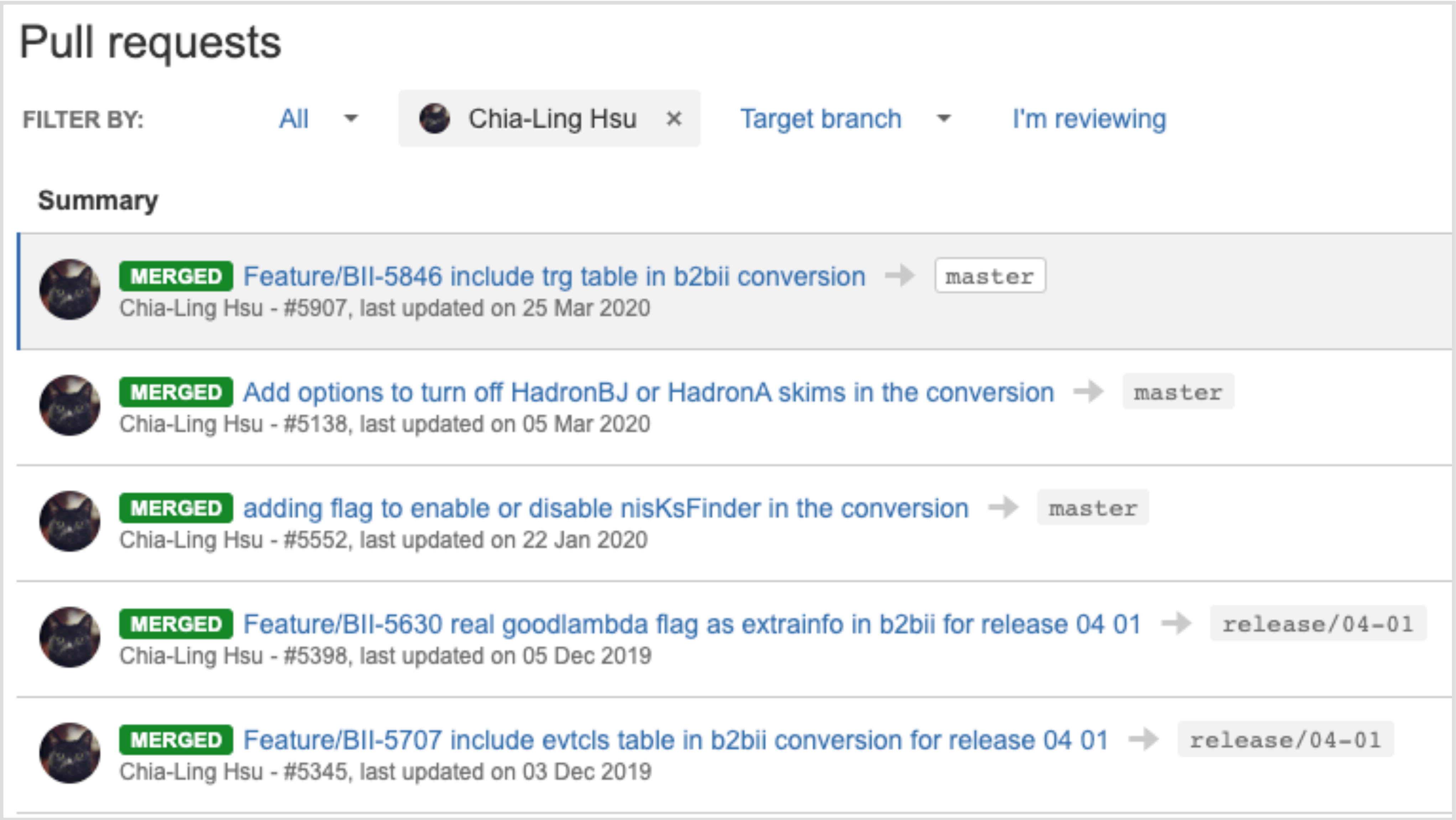
- At Belle, the raw data coming from the detector was calibrated, reconstructed and stored on tape using PANTHER data summary tape (DST) files.
- After each experiment the calibration constants were recomputed by detector experts, and stored in the Belle Conditions Database.
- The data of the completed experiment was reprocessed and stored in a compact form called mDST files.
- The mDST files were handled by the Belle analysis framework BASF.

- B2BII converts the Belle mDST data, which contains mostly detector independent objects like tracks and calorimeter clusters, into the new mDST format used by BASF2:



New features in B2BII

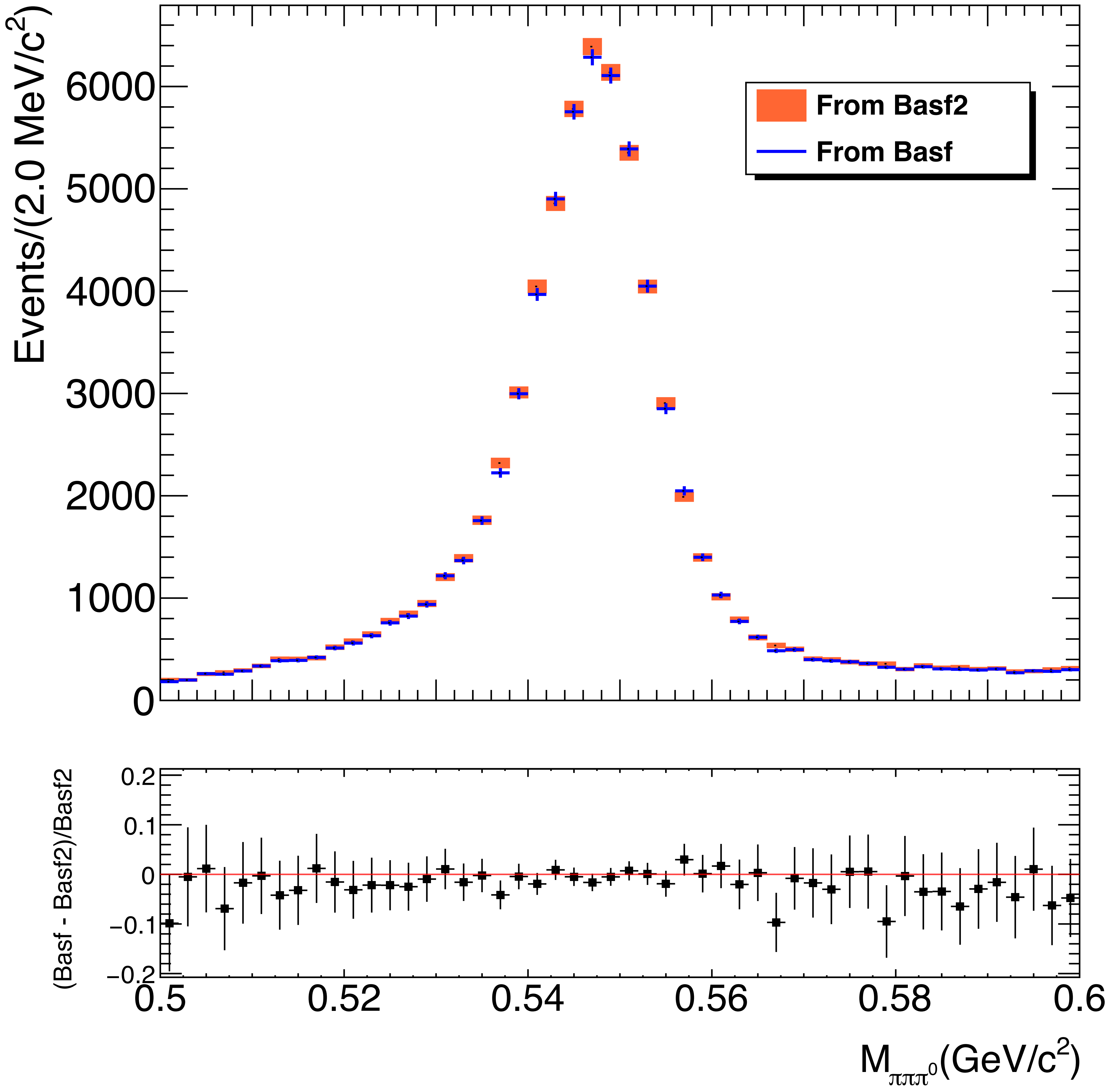
- Evtcts tables conversion (pull request 5345)
- Disabling nisKsFinder (pull request 5552)
- Option to turn off HadronBJ and HadronA skims (pull request 5138)
- Include trigger table in conversion (pull request 5907)



- All available in release-05.

Basf vs Basf2 in 3-prong

- Hayasaka-san's student, Ogawa-san, is currently studying 3-prong reconstruction with Basf.
- in order to compare the output and validate B2BII in τ decays, I got a sample using:
  - same MC signal
  - same selection criteria as him.
- Result is statistically compatible.



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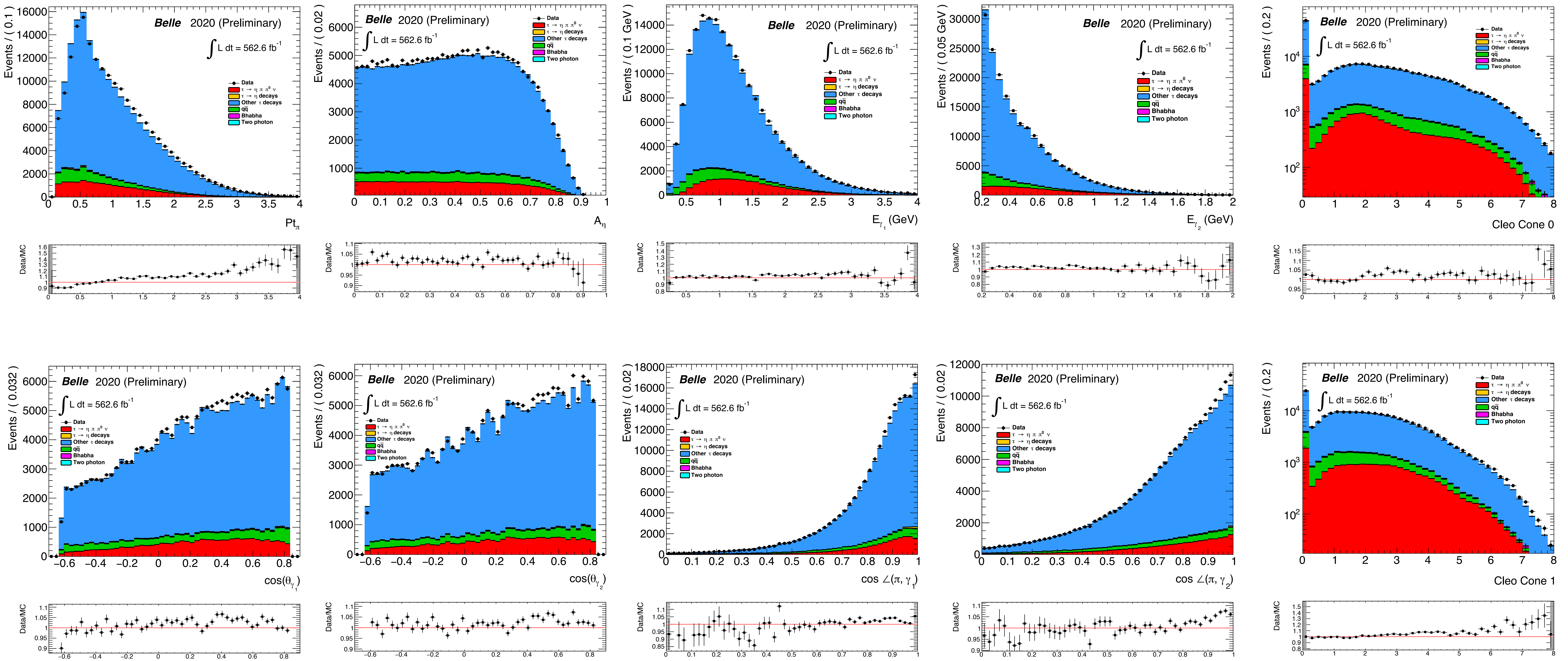
Variables, data vs MC



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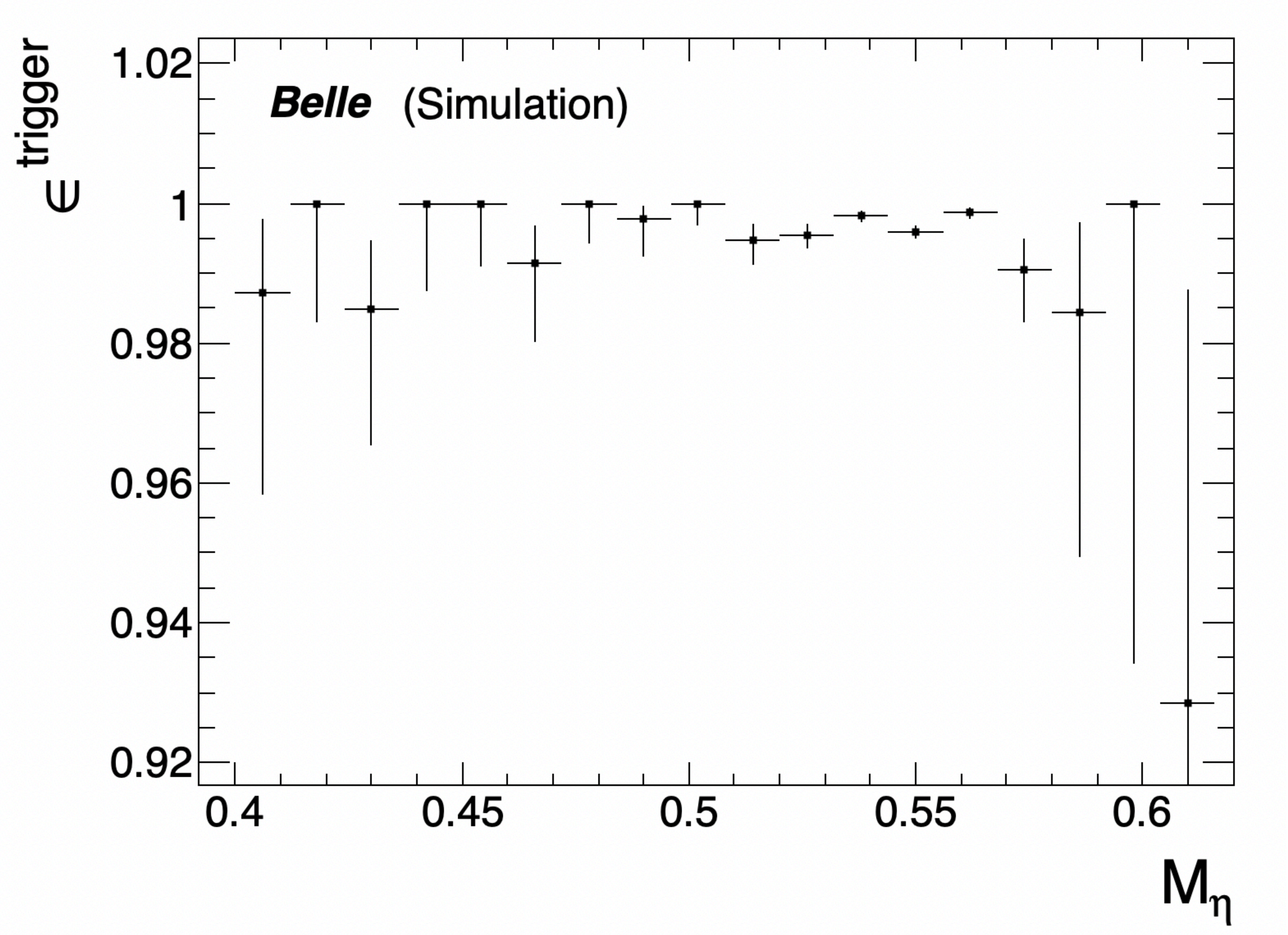
Trigger efficiency

- Tau signal sample include **TSim** simulation.
- Using B2BII conversion of trigger tables ([pull request 5907]), it is possible the study of trigger distributions.
- Using RecTRG_summary3 table, with final(0) and final(1) flags.
  - https://belle.kek.jp/group/tautp/tauphys/tsim/tsim.html

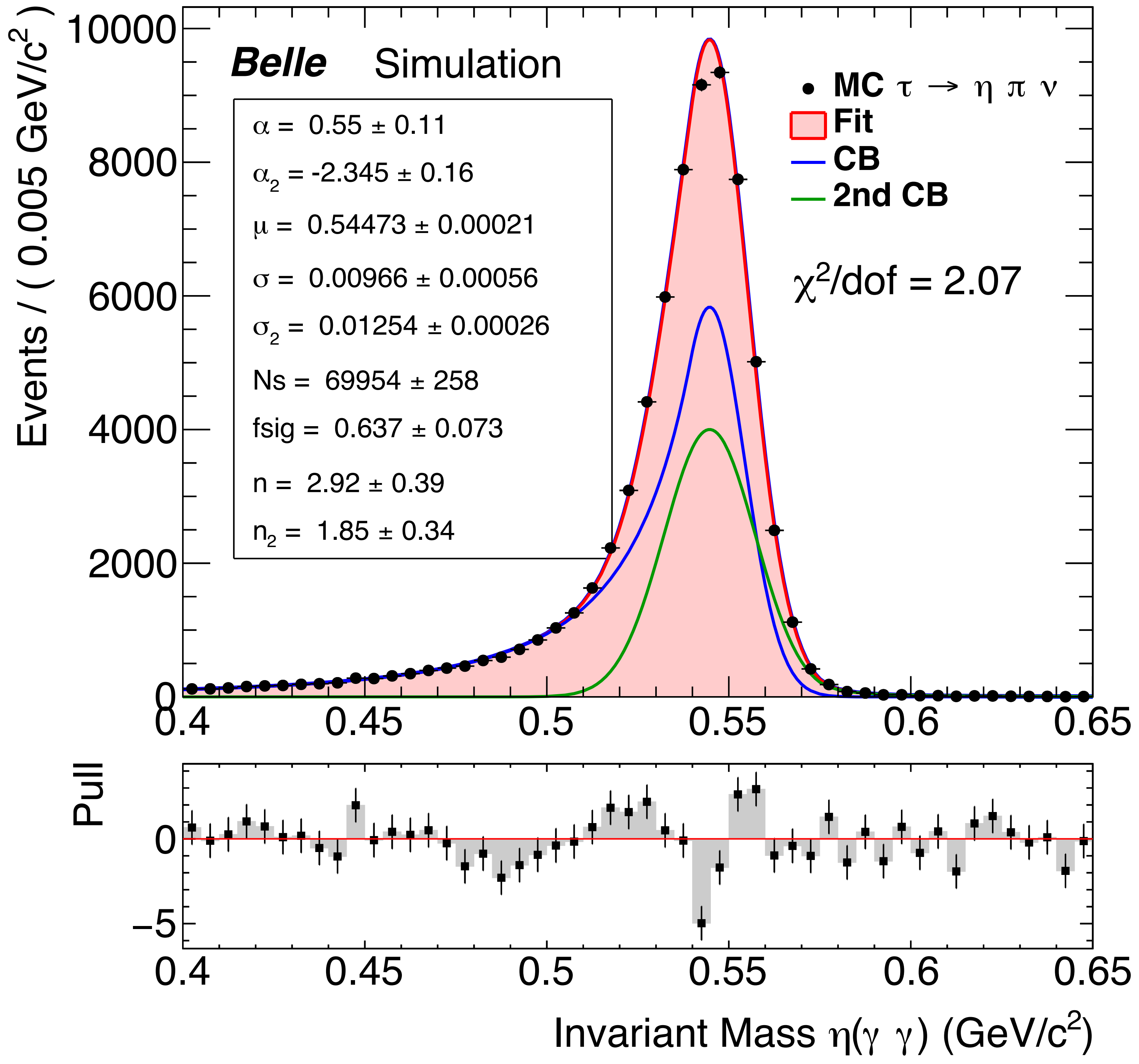
Trigger efficiency of signal: 99.5 %



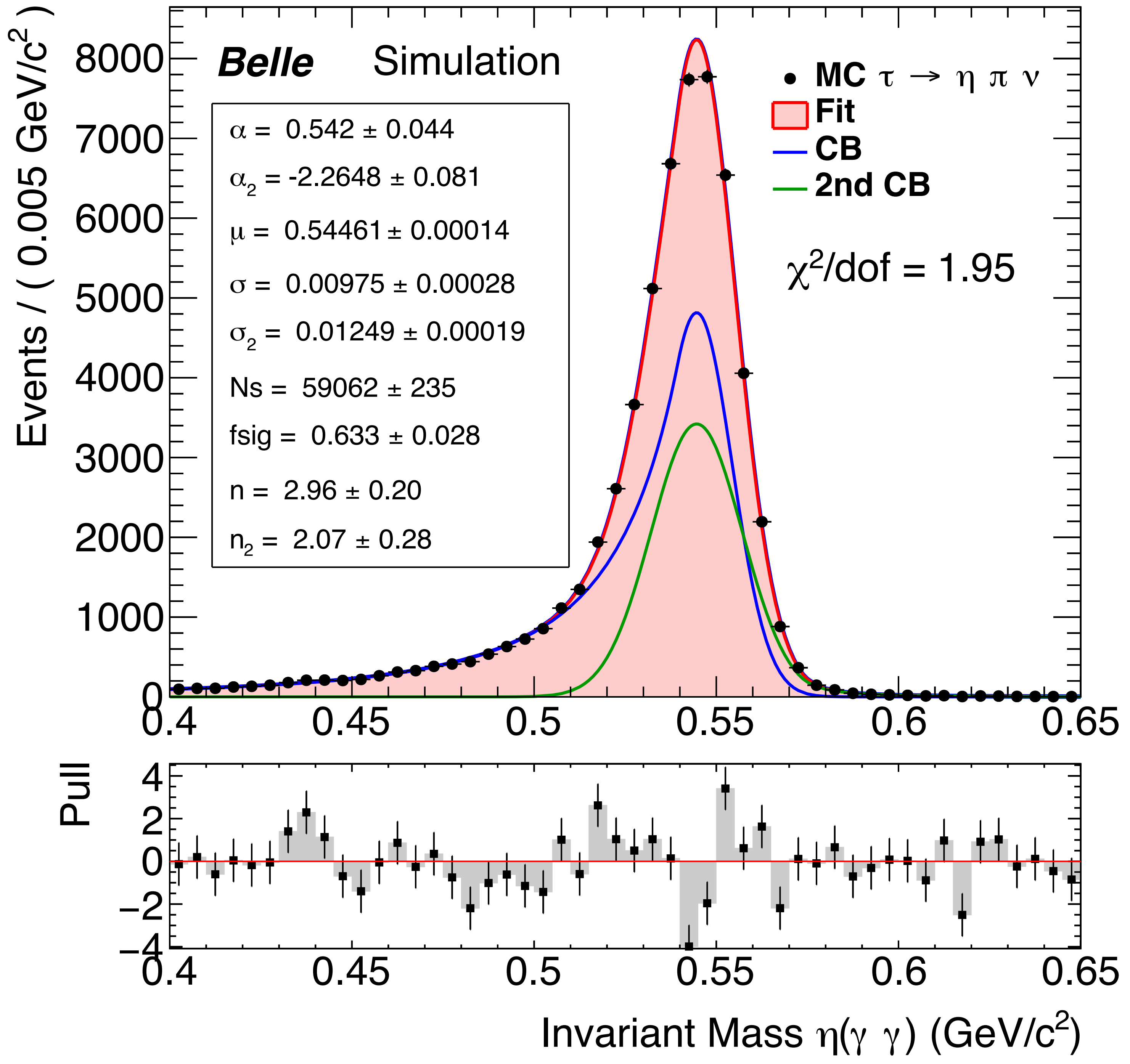
Signal Efficiency

- Signal efficiency determined by the generated signal MC samples after the selection criteria.
    - $\tau \rightarrow (a^0 \rightarrow \eta\pi)\nu$, with a^0 width of 100 MeV (~18M)
- Signal shape modeled with two Crystal-Ball functions.

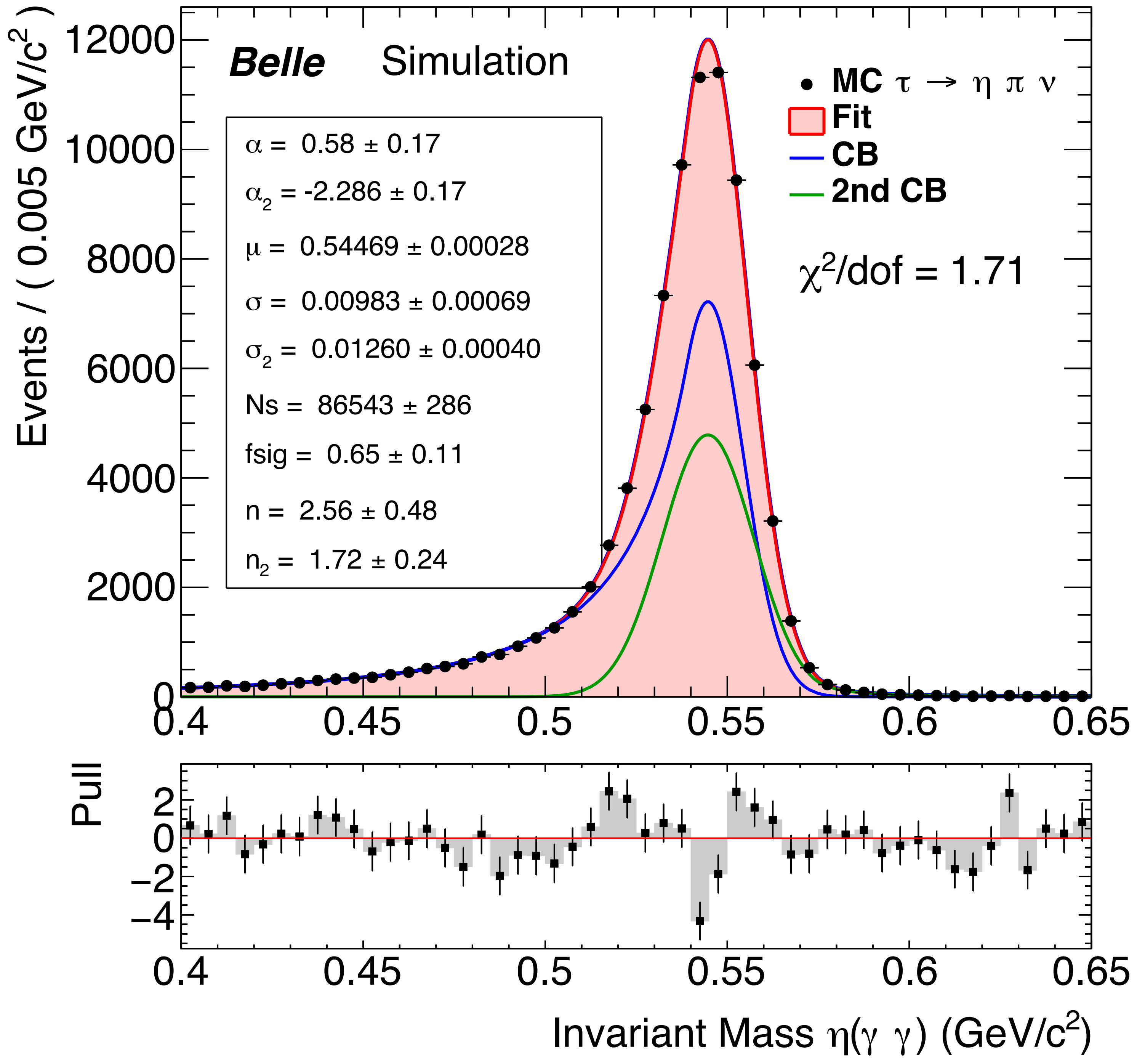
e-tag
eff: (0.771 ± 0.003)%



μ-tag
eff: (0.651 ± 0.003)%



π-tag
eff: (0.953 ± 0.003)%

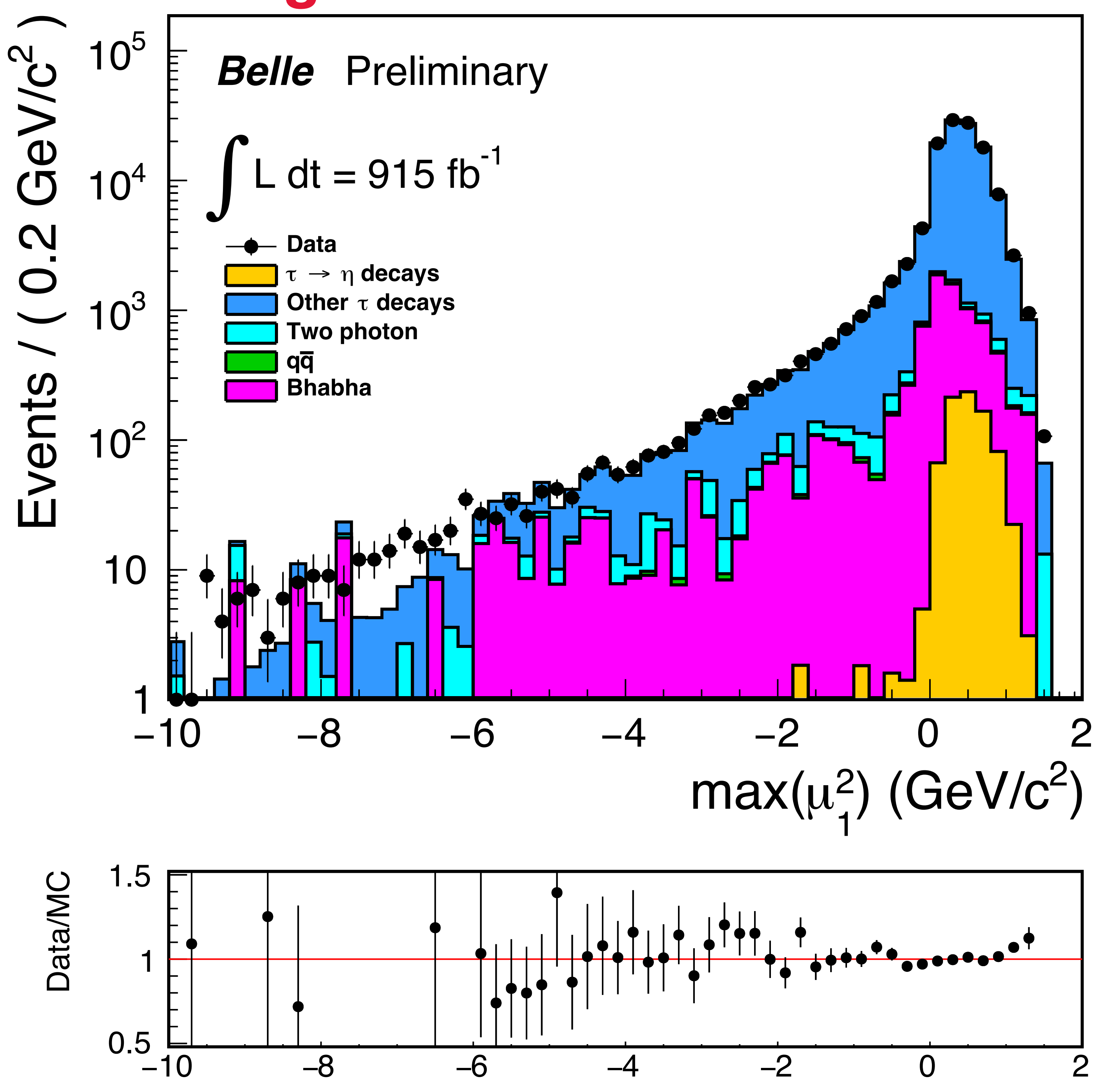


Kinematic Suppression

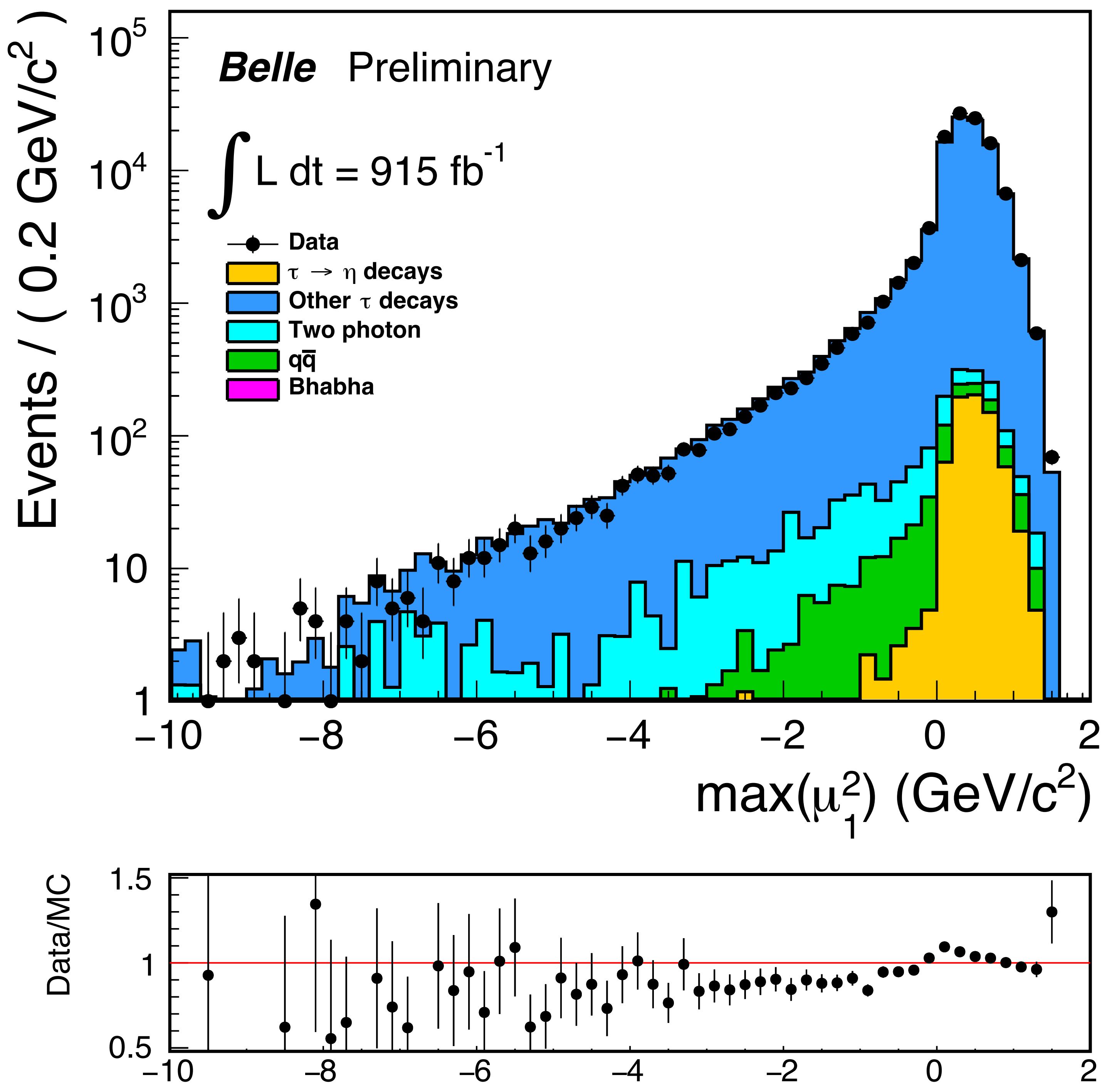
- For $\mu_2^2 \geq 0$, max(μ_1^2) must be $\geq$ 0 if events are reconstructed correctly.
- A cut of max(μ_1^2) $\geq$ 0 is applied to remove non-physical events (missing detectable particle, wrong mass hypothesis, etc).

Data vs MC, sidebands region

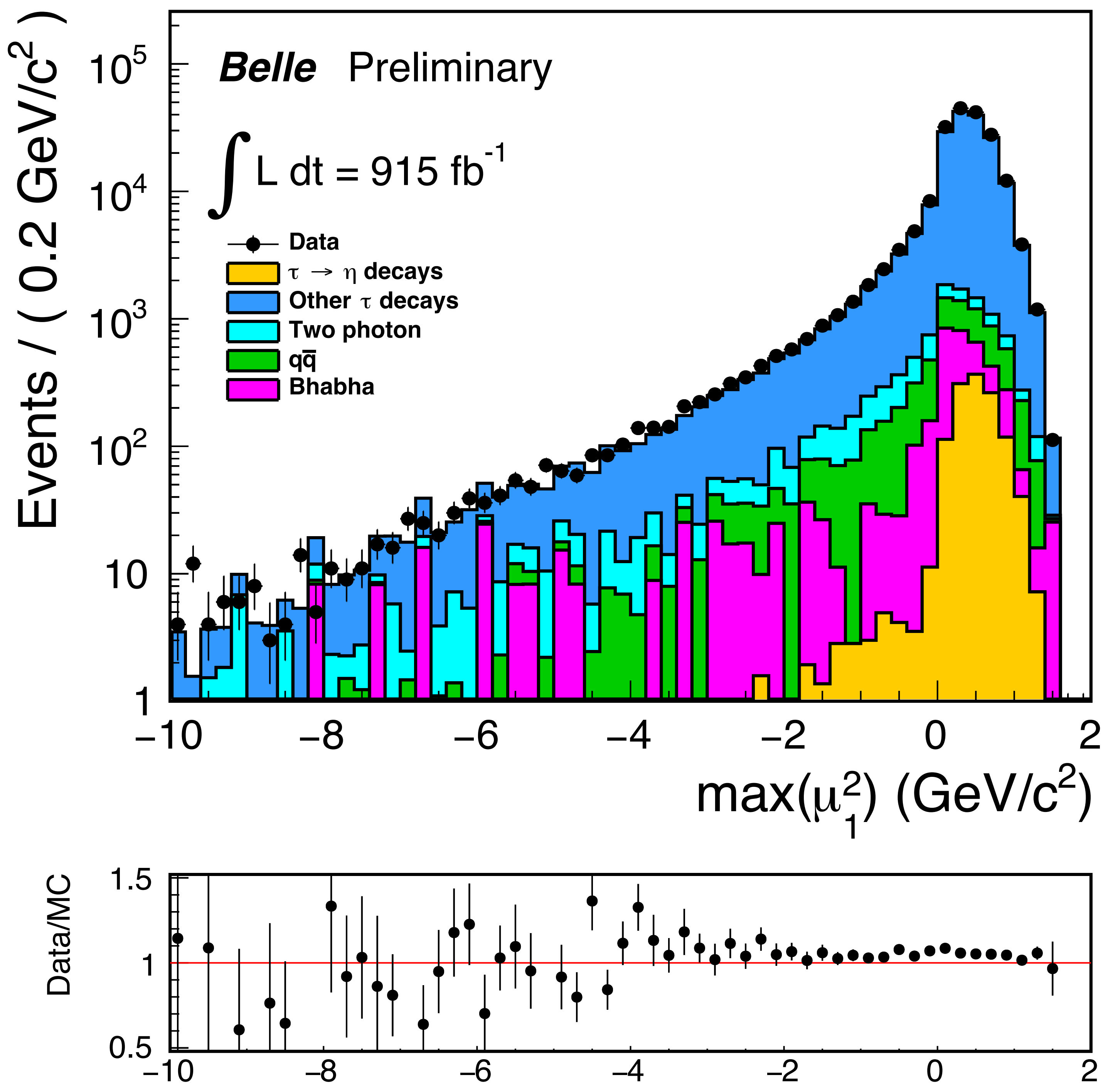
e-tag



μ-tag

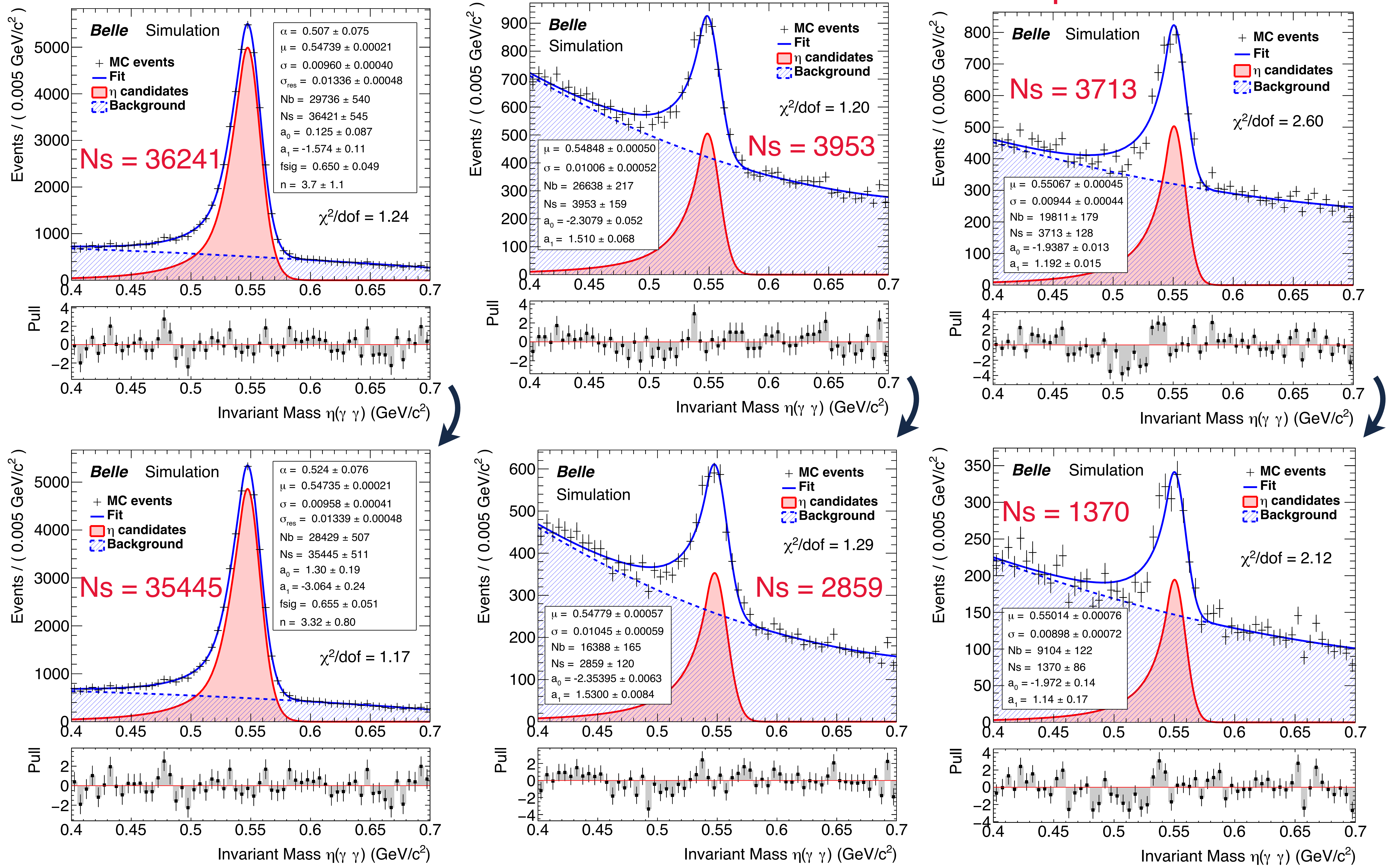


π-tag



Peaking backgrounds with kin suppression (max(μ_1^2) > 0)

$\tau \to \eta + X\,\nu$ 5 streams | qqbar 2 streams | Two photon 5 streams



- Upper figures: no kinematic suppresion.
- Lower figures: with kinematic suppresion.

Relative Efficiency:

- $\epsilon_{\tau\tau} = 0.97$
- $\epsilon_{q\bar{q}} = 0.72$
- $\epsilon_{eeqq} = 0.37$

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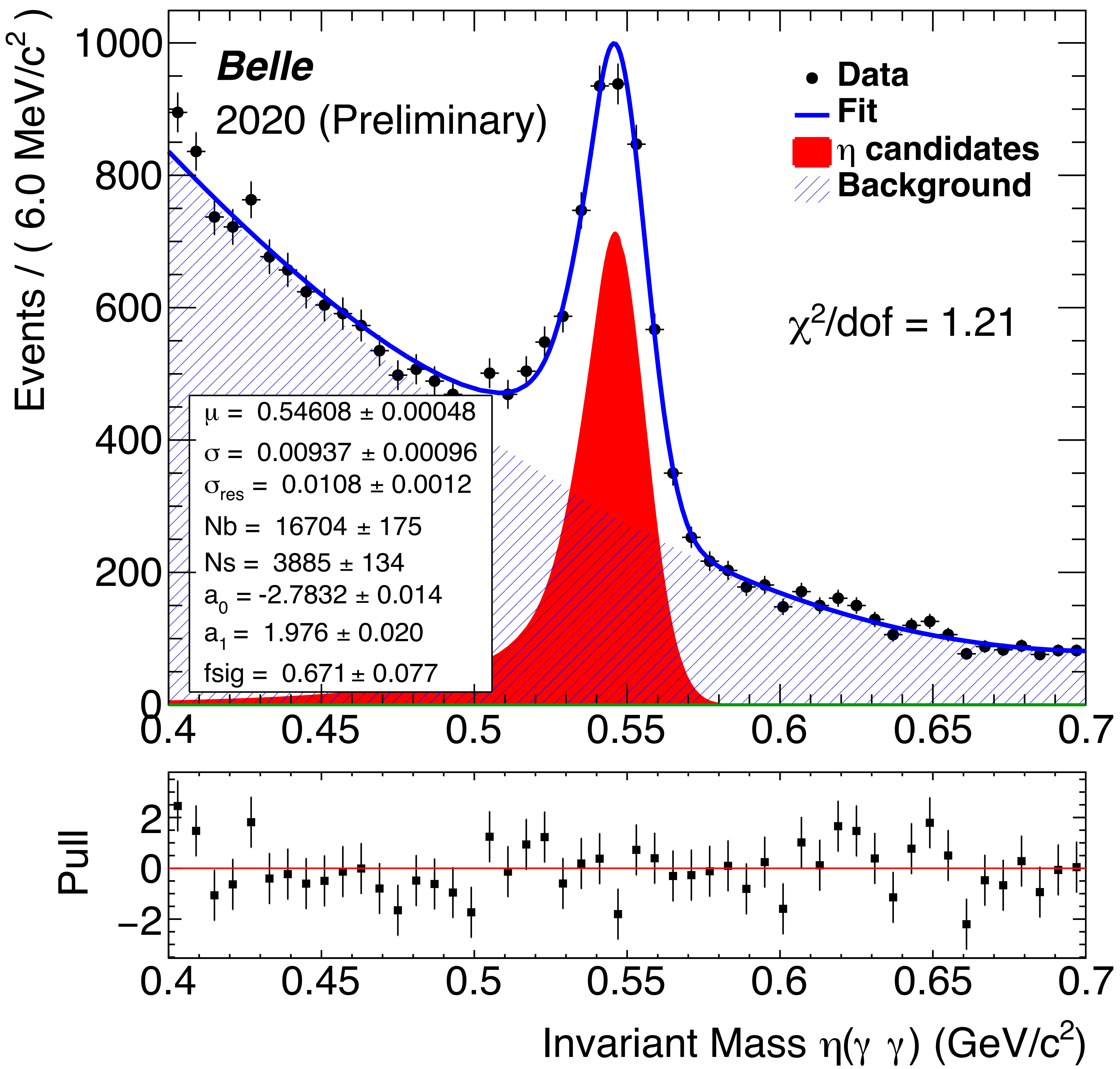
BR estimation on data w/FBDT in control sample $\tau \rightarrow \eta\pi\pi^0\nu$

Control sample $\tau \rightarrow \eta\pi\pi^0\nu$:



To validate the response of the BDT, **an aggressive cut of BDT response > 0.15** is used in the BR measurement of the control sample $\tau \rightarrow \eta\pi\pi^0\nu$.

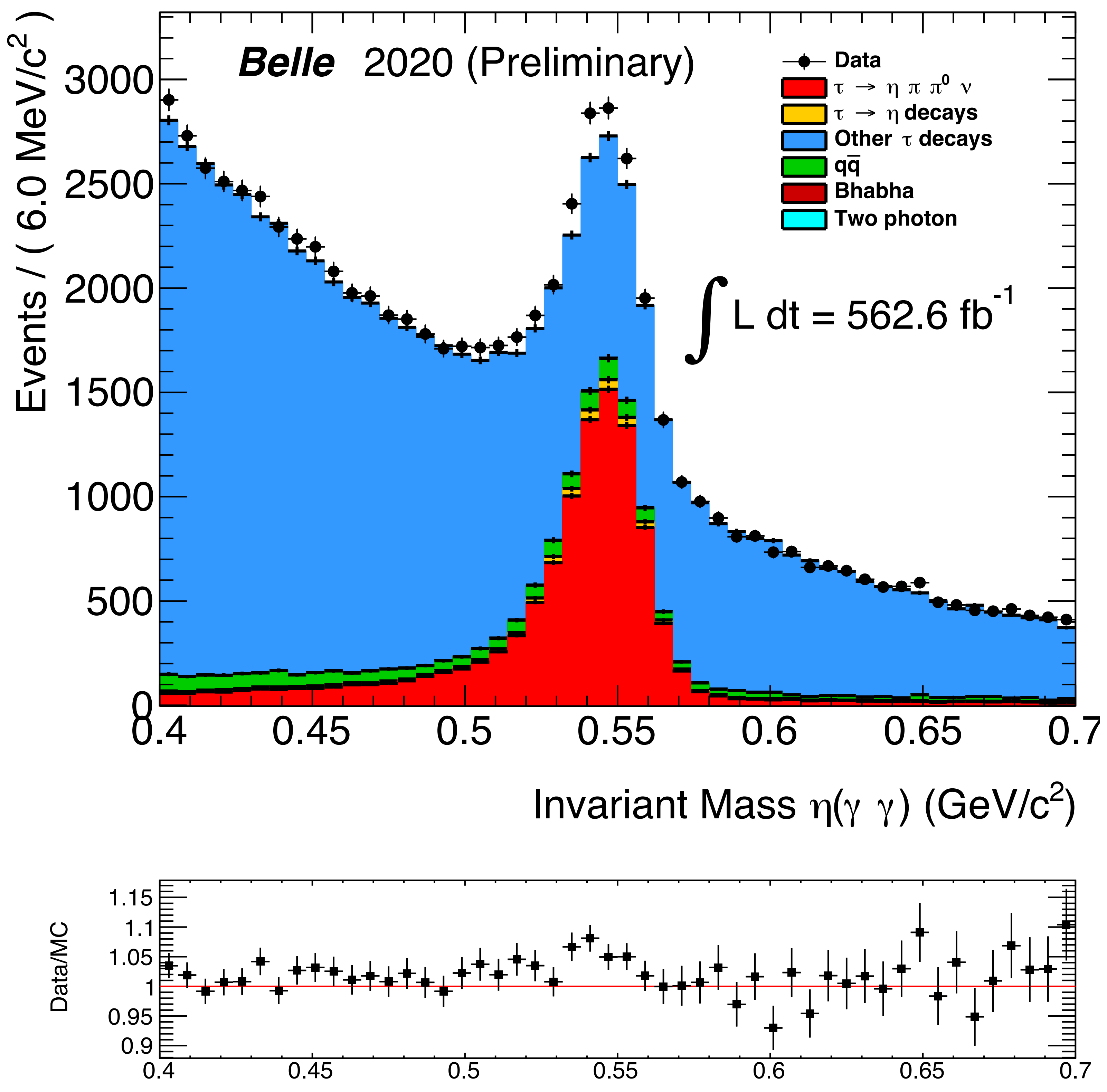
$$N_s = 2 \cdot L \cdot \sigma(ee \rightarrow \tau\tau) \cdot BR(\tau \rightarrow \eta\pi\pi^0\nu) \cdot BR(\eta \rightarrow \gamma\gamma) \cdot \epsilon$$

- Efficiency from MC:
  (0.501 +/- 0.002)%
- Yield in fit:
  Ns = 3885 ± 134
- Peaking bkg: 202 ± 16 → Nsig = 3683 ± 377
- **Measured (stat only):**
  $BR(\tau \rightarrow \eta\pi\pi^0\nu) = (1.43 \pm 0.14) \times 10^{-3}$
- Without BDT and kin suppresion:
  $BR(\tau \rightarrow \eta\pi\pi^0\nu) = (1.41 \pm 0.03) \times 10^{-3}$

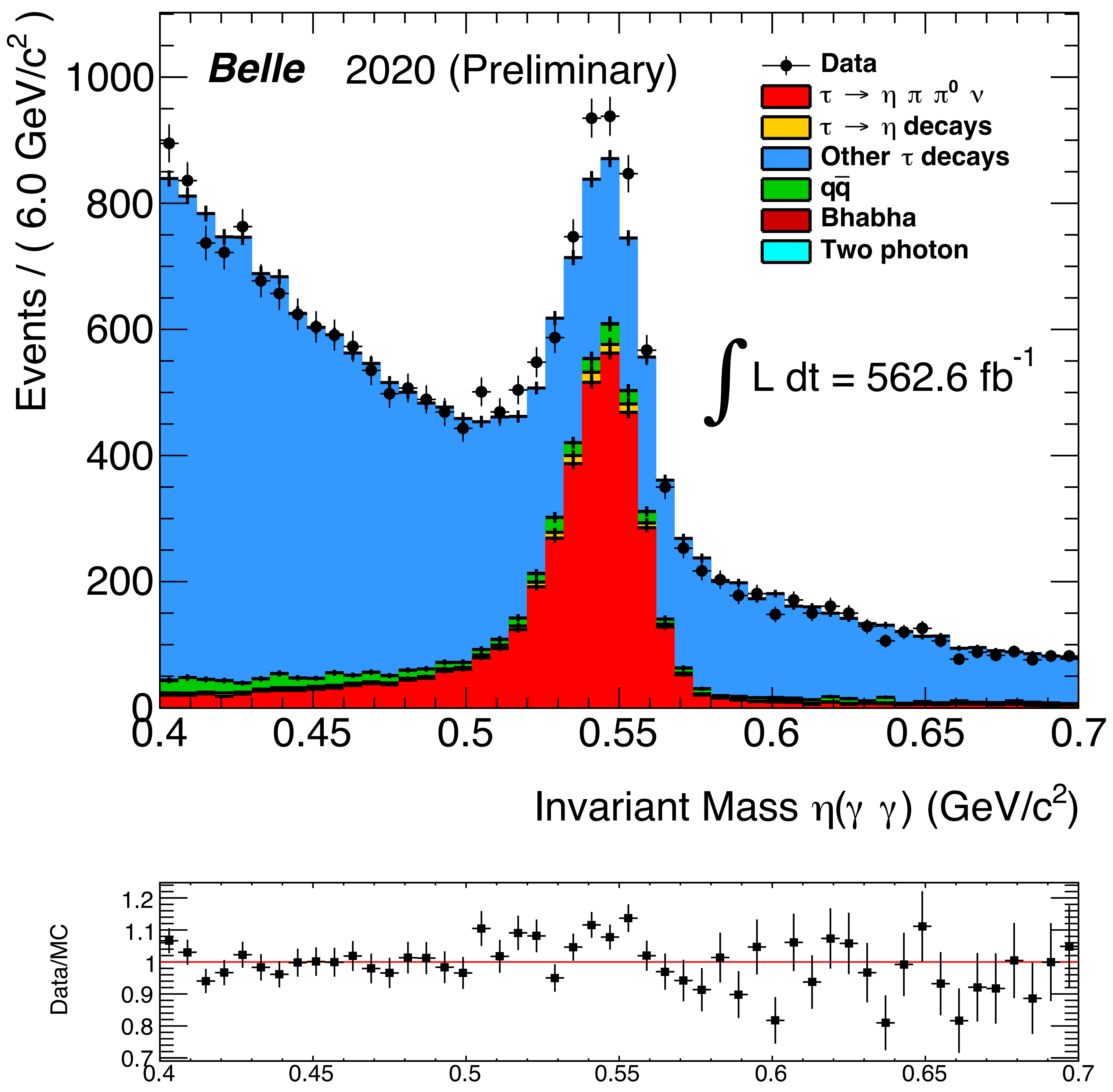
$\eta \rightarrow \gamma\gamma$ mass distribution in control sample

- To validate the response of the BDT in data, control channel $\tau \rightarrow \eta\pi\pi^0\nu$ is evaluated.
-

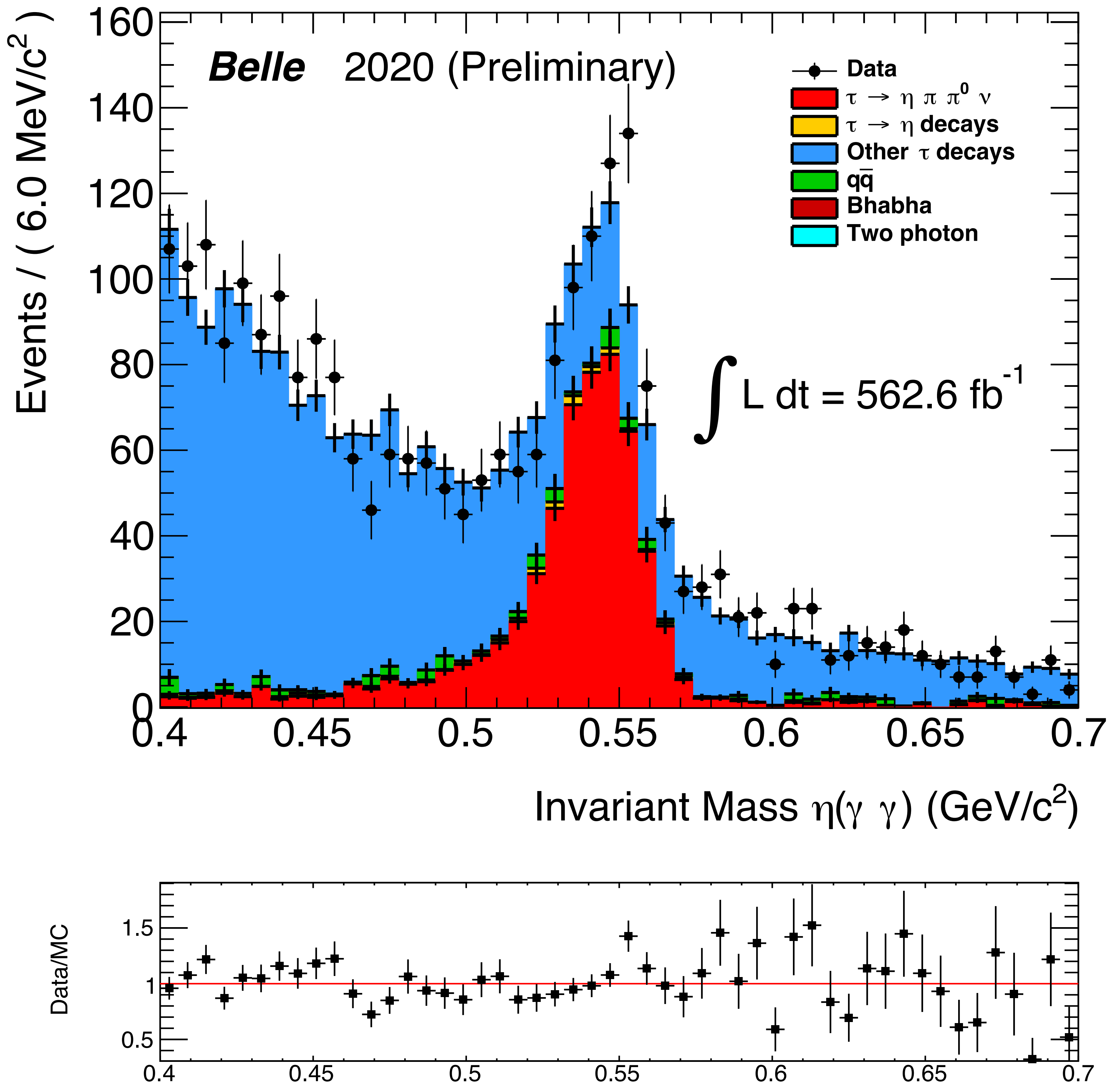
BDT response > 0.1



BDT response > 0.15



BDT response > 0.2

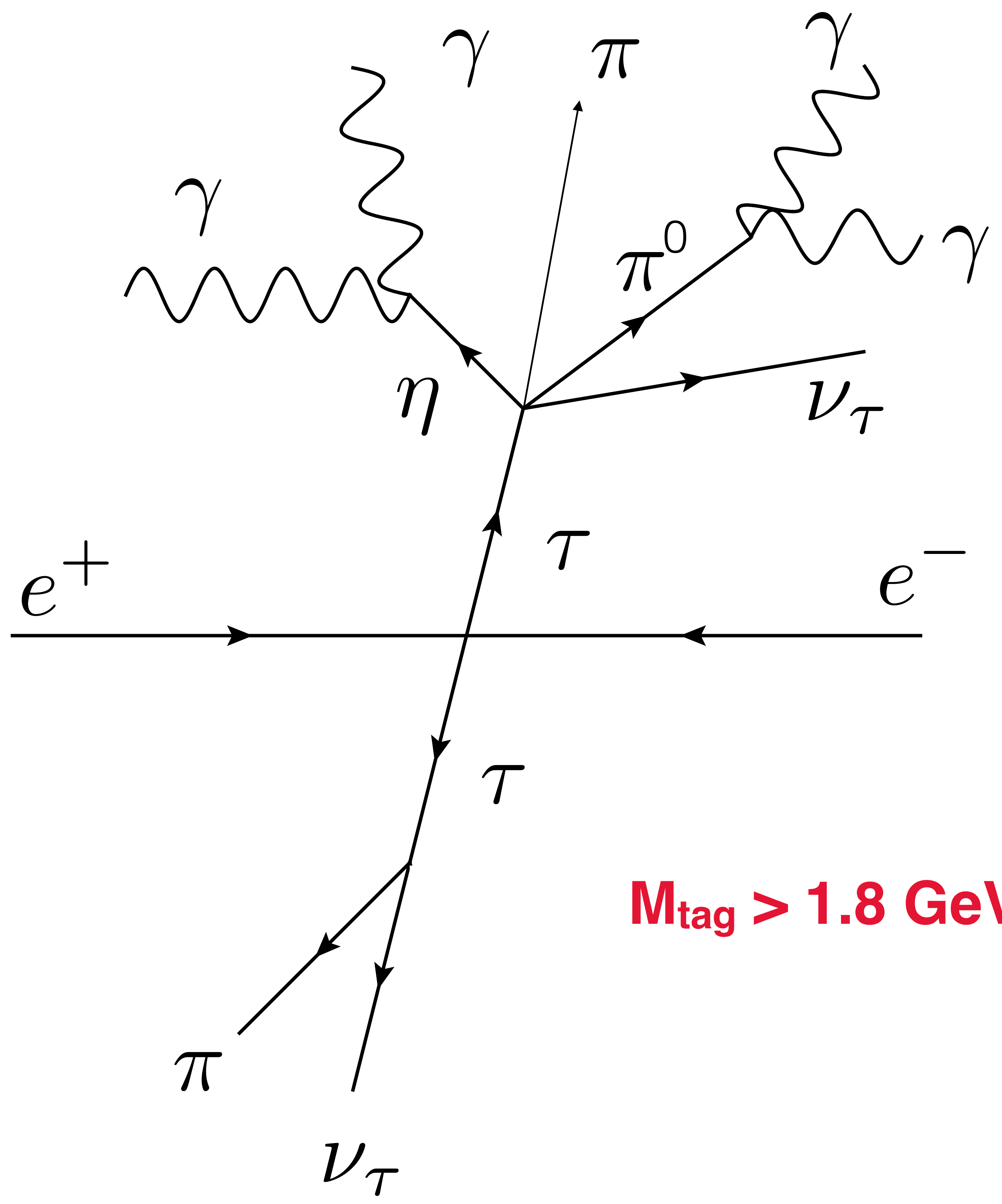


$\tau\to\eta\pi\nu$ with enriched qq selection

- It is known that some resonances are not well described on the q$\bar{q}$ MC samples.

- To evaluate the yield between data and MC in the τ side-band region, we use a qq enriched sample with the same selection cuts, except:

- Signal side:
  - **M_{sig} unrestricted**
- Tag side:
  - **M_{tag} > 1.8 GeV/c^2**
  - **π-ID > 0.9 e-ID < 0.9 and μ-ID < 0.9**
  - **Ngammas >= 0**

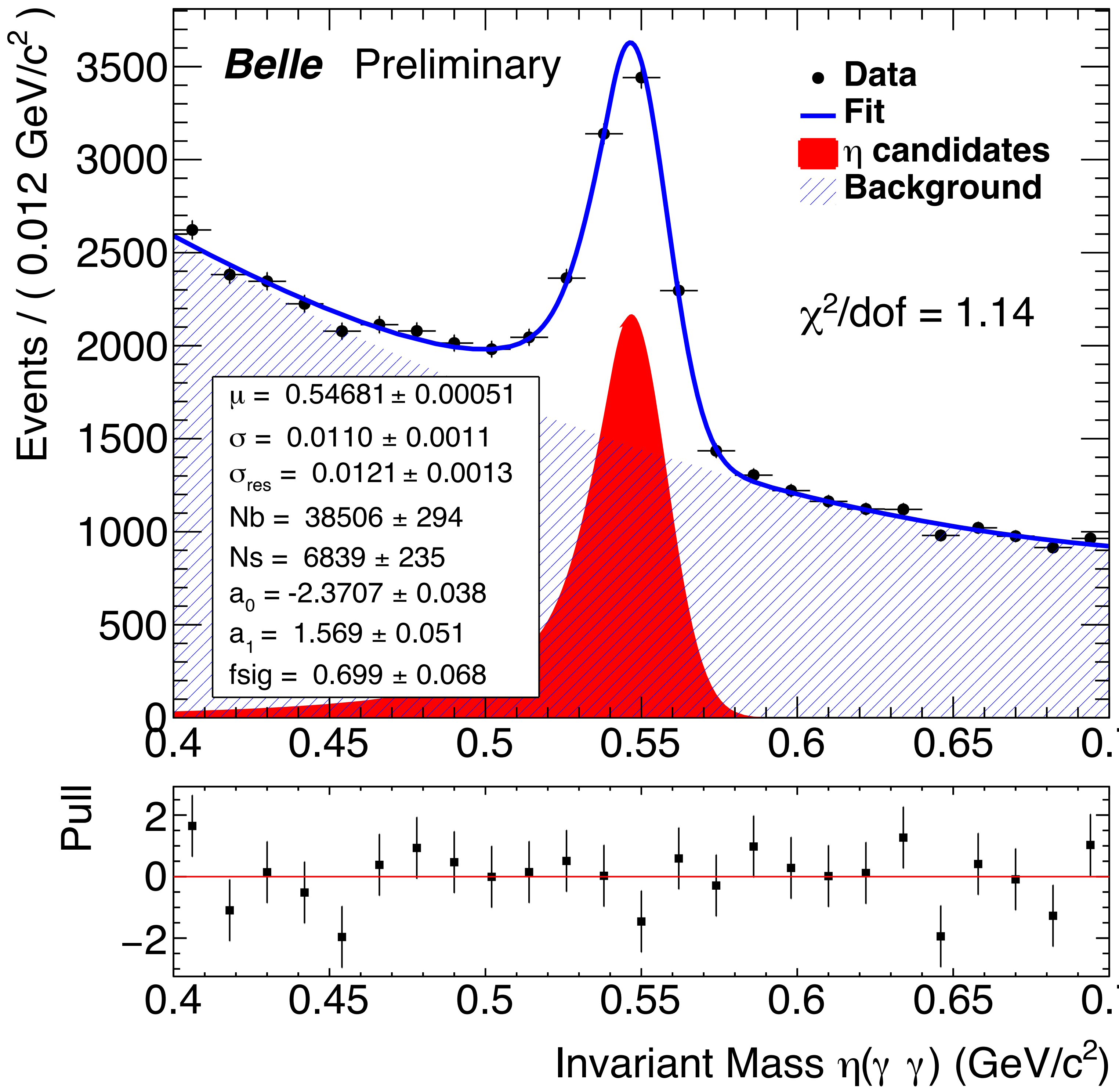


M_{tag} > 1.8 GeV/c^2

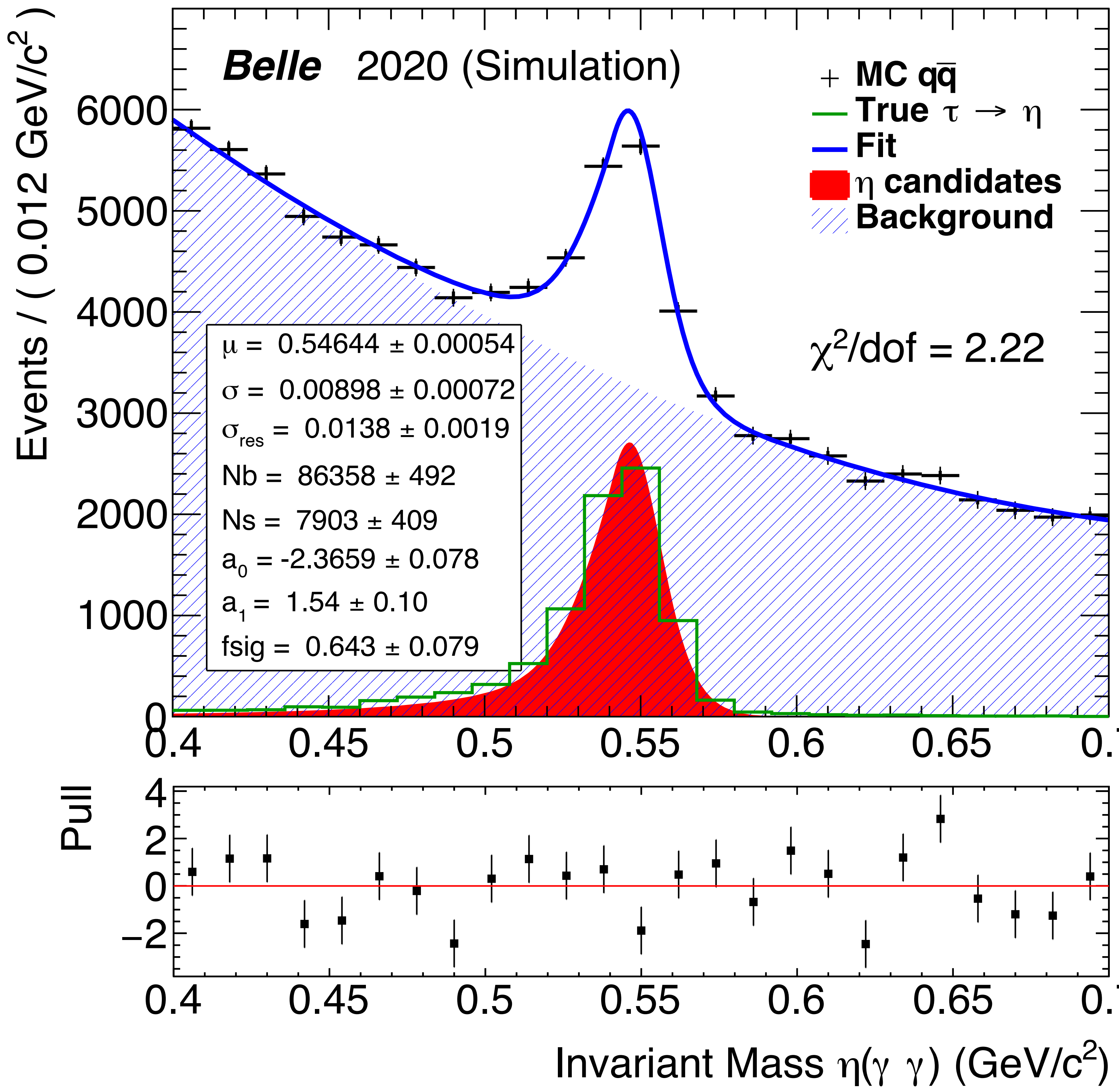
$\tau \to \eta \pi \nu$ with enriched qq selection

- Comparing data vs MC in with an qq enriched sample (PID scale factor applied as weight).
- Orthogonal to signal sample.

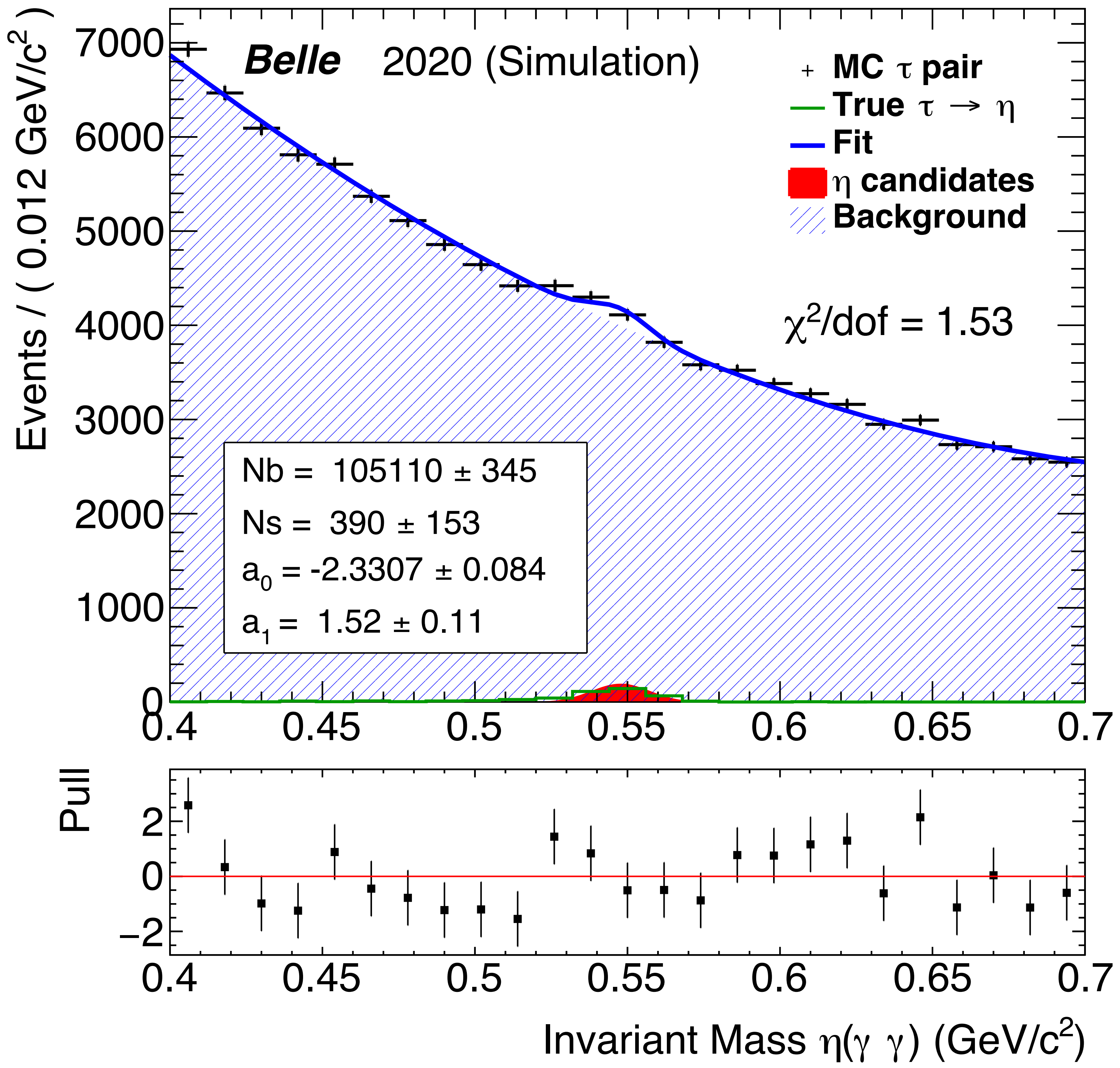
Data
Ns = 6839 ± 235, Nb = 38506 ± 294



qqbar (6 streams)
Ns = 7903 ± 409, Nb = 86358 ± 492

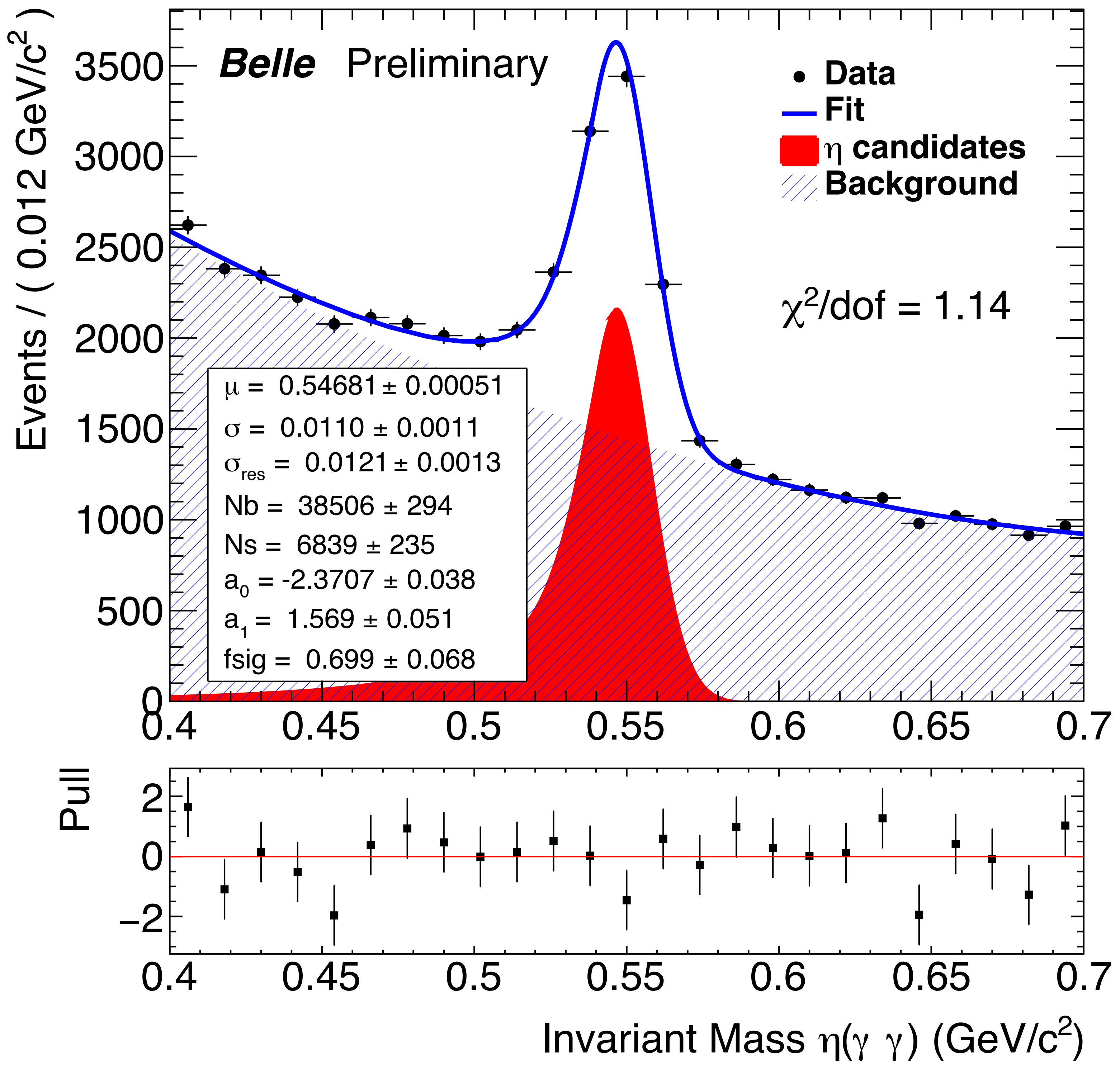


Tau pair (10 streams)
Ns = 390 ± 153, Nb = 105110 ± 345



$\tau \to \eta\pi\nu$ with enriched qq selection

- Comparing data vs MC in with an qq enriched sample (PID scale factor applied as weight).
- Orthogonal to signal sample.



Data
Ns = 6839 ± 235, Nb = 38506 ± 294

qqbar (6 streams)
Ns = 7903 ± 409, Nb = 86358 ± 492

Tau pair (10 streams)
Ns = 390 ± 153, Nb = 105110 ± 345

Correction factor (f_{qq}):

$$f_{q\bar{q}} = \frac{N^{data} - N^{MC}_{\tau\tau}}{N^{MC}_{q\bar{q}}}$$

For η candidates:

$$f_{q\bar{q}} = \frac{6839 \pm 235 - 39 \pm 15}{1317 \pm 68} = 5.16 \pm 0.19$$

(Belle Note 1080: 5.51 ± 0.34)