Recent highlights from Belle

Youngjoon Kwon
Yonsei University

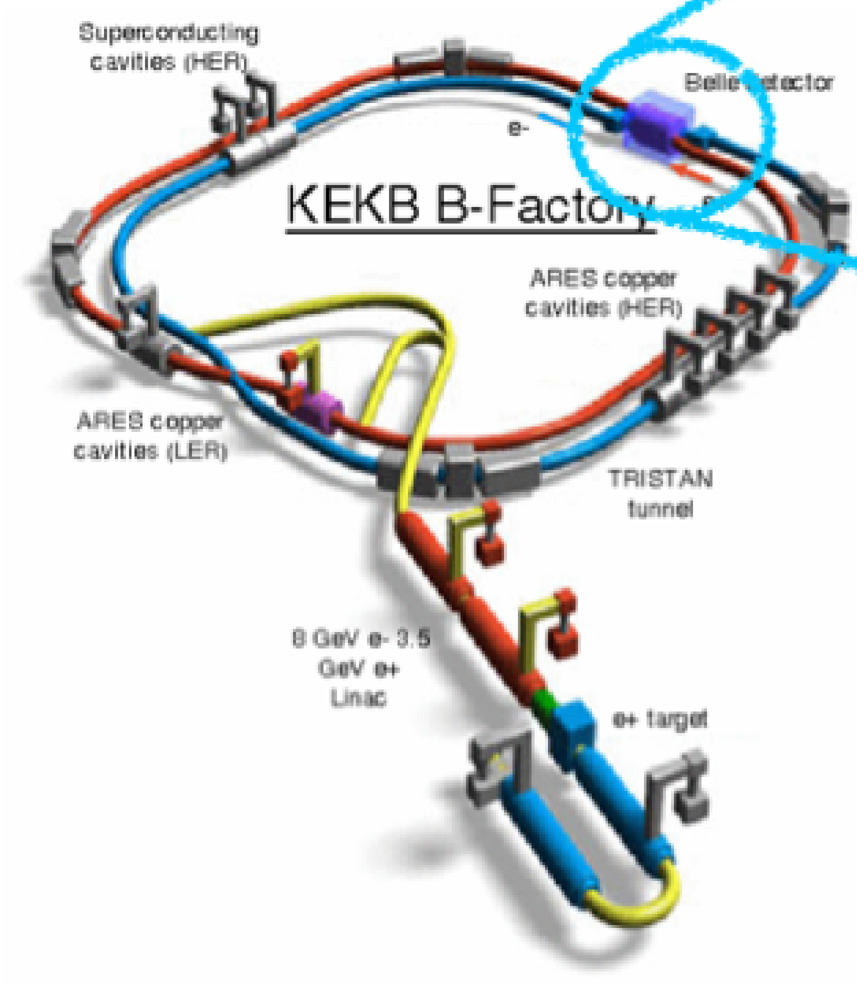
June 4-6, 2015,   BRL 2015, Wonju

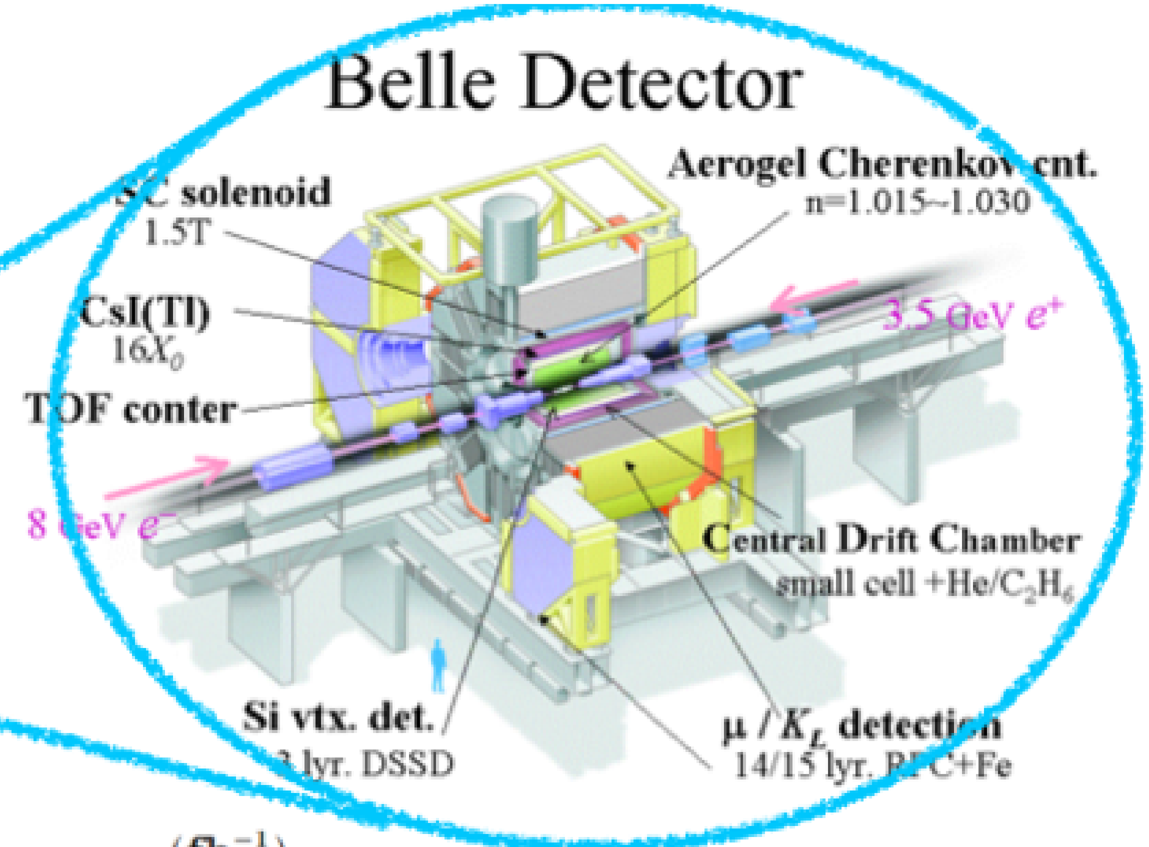
Outline

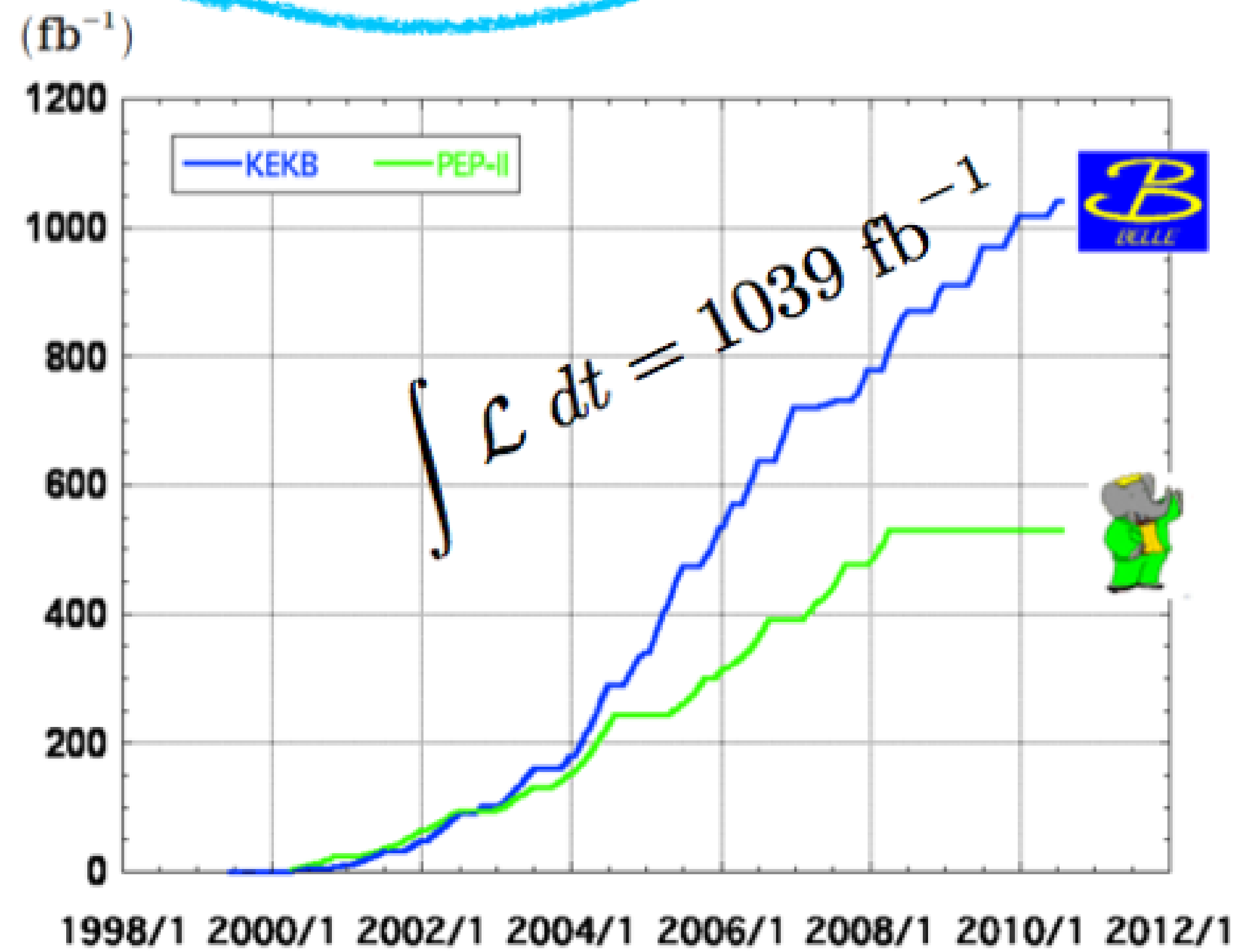
1) Intro. — the Belle experiment
2) Search for dark sector from Belle
3) Recent Belle highlights
   - $B \rightarrow D^{(*)} \tau\nu$
   - $B^+ \rightarrow \tau^+ \nu$, semileptonic
4) Summary

18 countries
80 institues
356 members

$$\mathcal{L}_{\text{peak}} = 21.1\ \text{nb}^{-1}\text{s}^{-1}$$







> 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}

$$e^- \xrightarrow{\textbf{8 GeV}} (\star) \xleftarrow{\textbf{3.5 GeV}} e^+$$

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

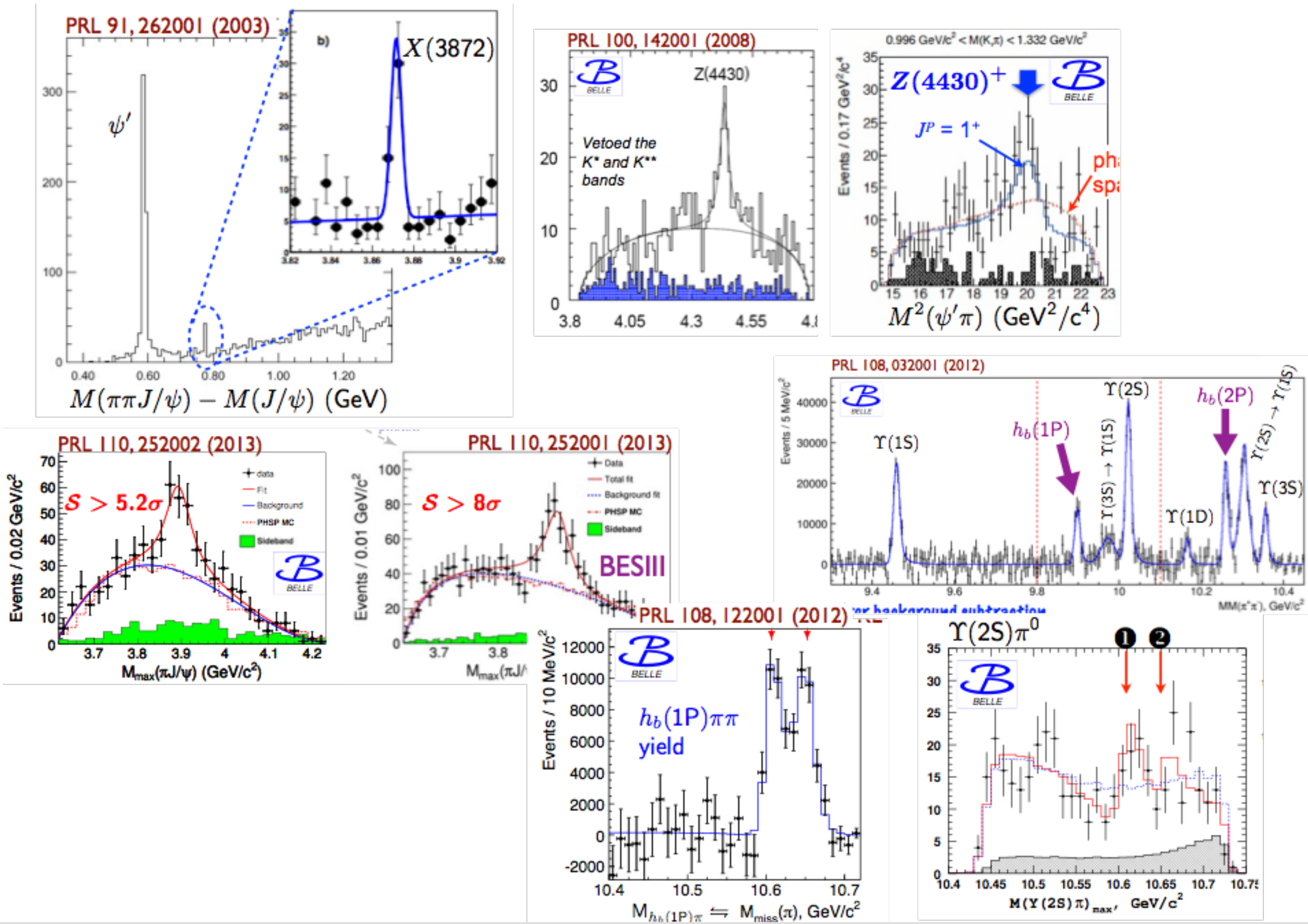
Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

CPV is due to an irreducible phase in the unitary quark mixing matrix in 3 generations

- Critical role of the *B*-factories in the verification of the KM hypothesis was recognized and cited by the Nobel Foundation
- A single irreducible phase in the weak int. matrix accounts for most of the *CP* violation observed in the *K*'s and in the *B*'s
- *CP*-violating effects in the B sector are $\mathcal{O}(1)$ rather than $\mathcal{O}(10^{-3})$ as in the K^0 system.

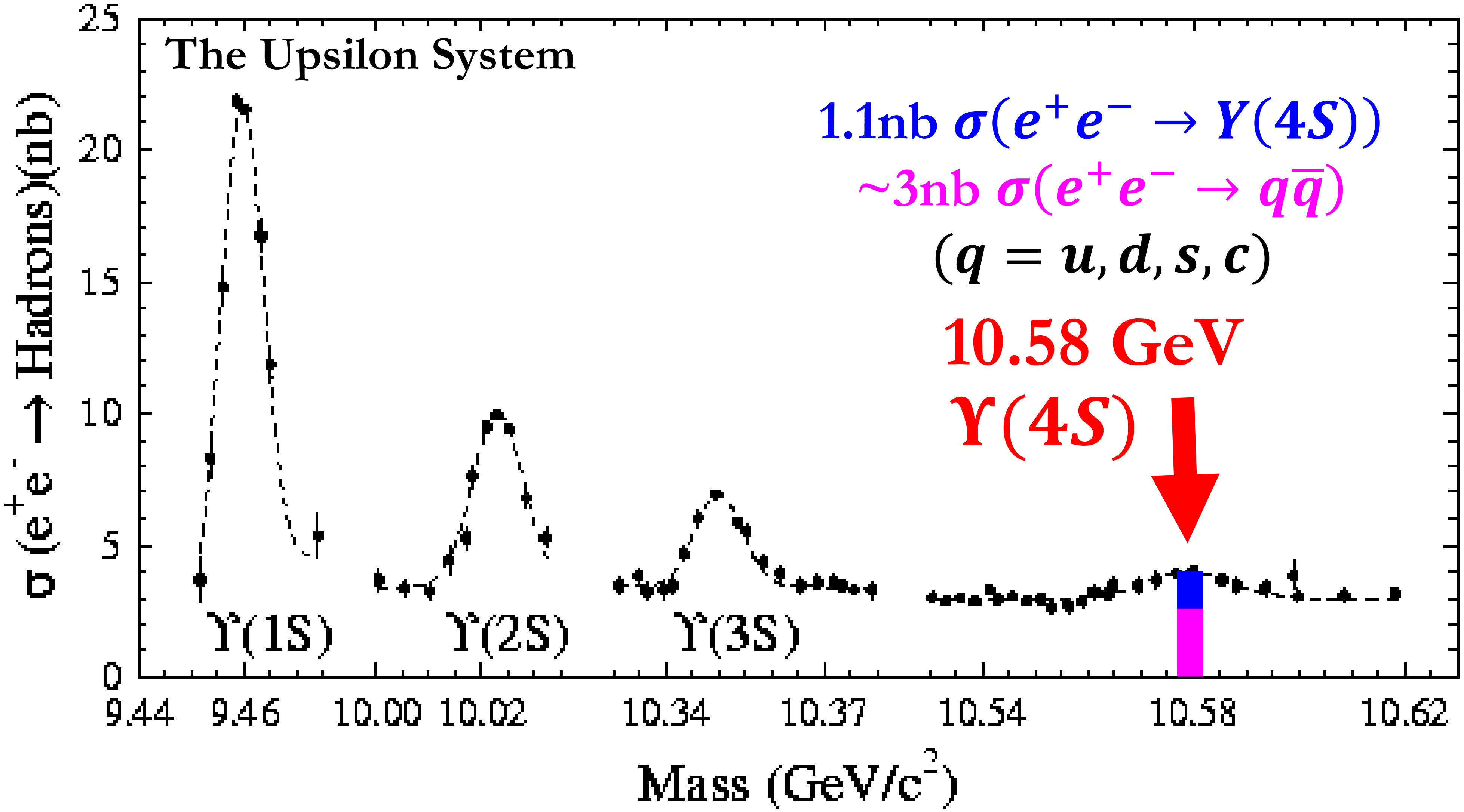


PRL 91, 262001 (2003)
X(3872)
ψ′
M(ππJ/ψ) − M(J/ψ) (GeV)
PRL 100, 142001 (2008)
Z(4430)
Vetoed the K* and K** bands
0.996 GeV/c² < M(K,π) < 1.332 GeV/c²
Z(4430)+
J^P = 1+
M²(ψ′π) (GeV²/c⁴)
PRL 108, 032001 (2012)
Υ(1S)
h_b(1P)
Υ(2S)
h_b(2P)
Υ(1D)
Υ(3S)
PRL 110, 252002 (2013)
S > 5.2σ
Events / 0.02 GeV/c²
M_max(πJ/ψ) (GeV/c²)
PRL 110, 252001 (2013)
S > 8σ
BESIII
Events / 0.01 GeV/c²
PRL 108, 122001 (2012)
h_b(1P)ππ yield
Events / 10 MeV/c²
Υ(2S)π⁰
M(Υ(2S)π)_max, GeV/c²
BELLE

A tale of two B-factories?

- making B's at hadron colliders (e.g. LHCb)
  - huge number of B mesons are produced, but
  - no info. on p_B^μ, unless you actually reconstruct the B meson
    $\Rightarrow$ will be of little use for modes with invisible particle(s)
- making B's at e^+e^- colliders with $\sqrt{s} = m(\Upsilon(4S))$
  - a moderate number of B mesons are produced
  - $E_B = \sqrt{s}/2 \sim 5.29$ GeV ; $|\vec{p}_B| \sim 0.35$ GeV/c
  - but.. direction of $\vec{p}_B$?

$e^+e^- \to \Upsilon(4S)$ as a B-factory

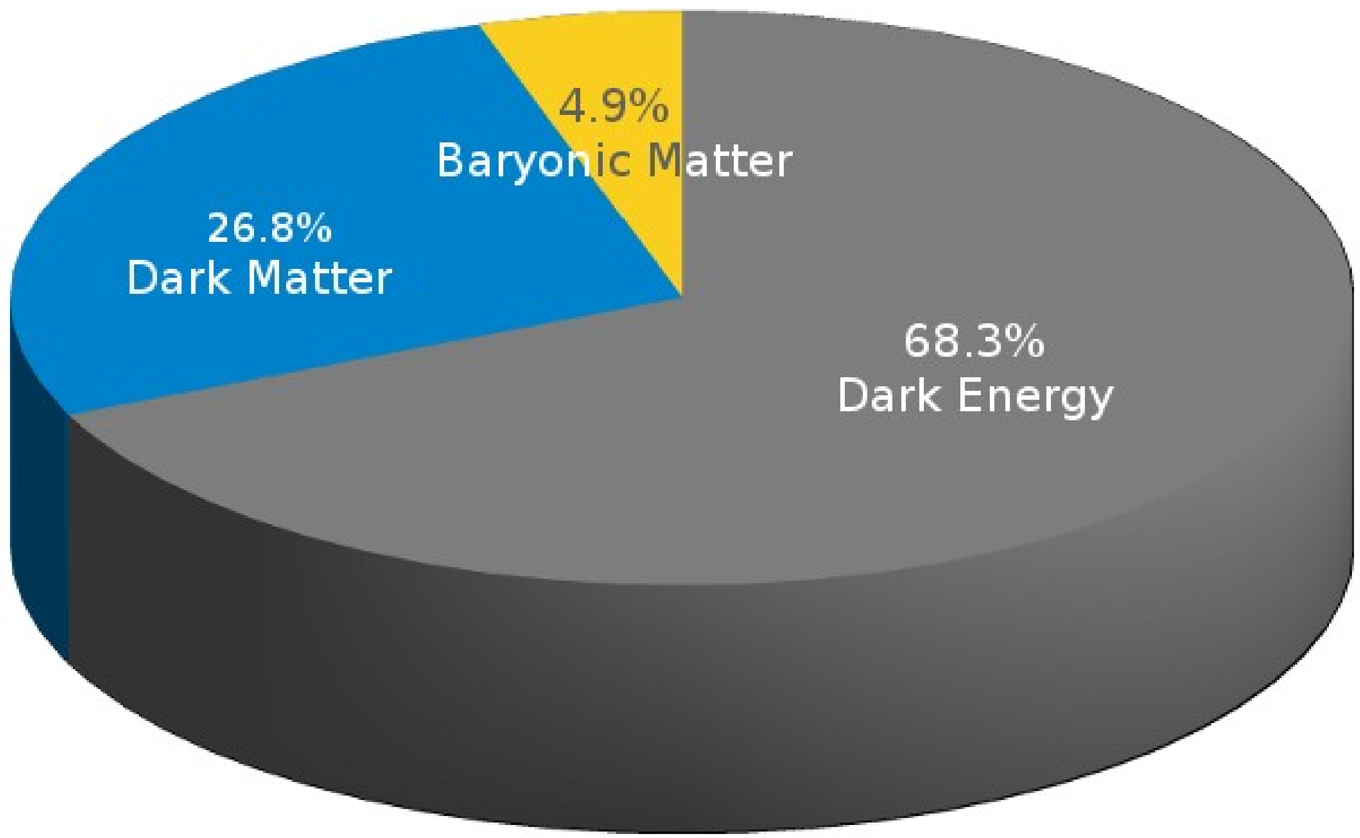


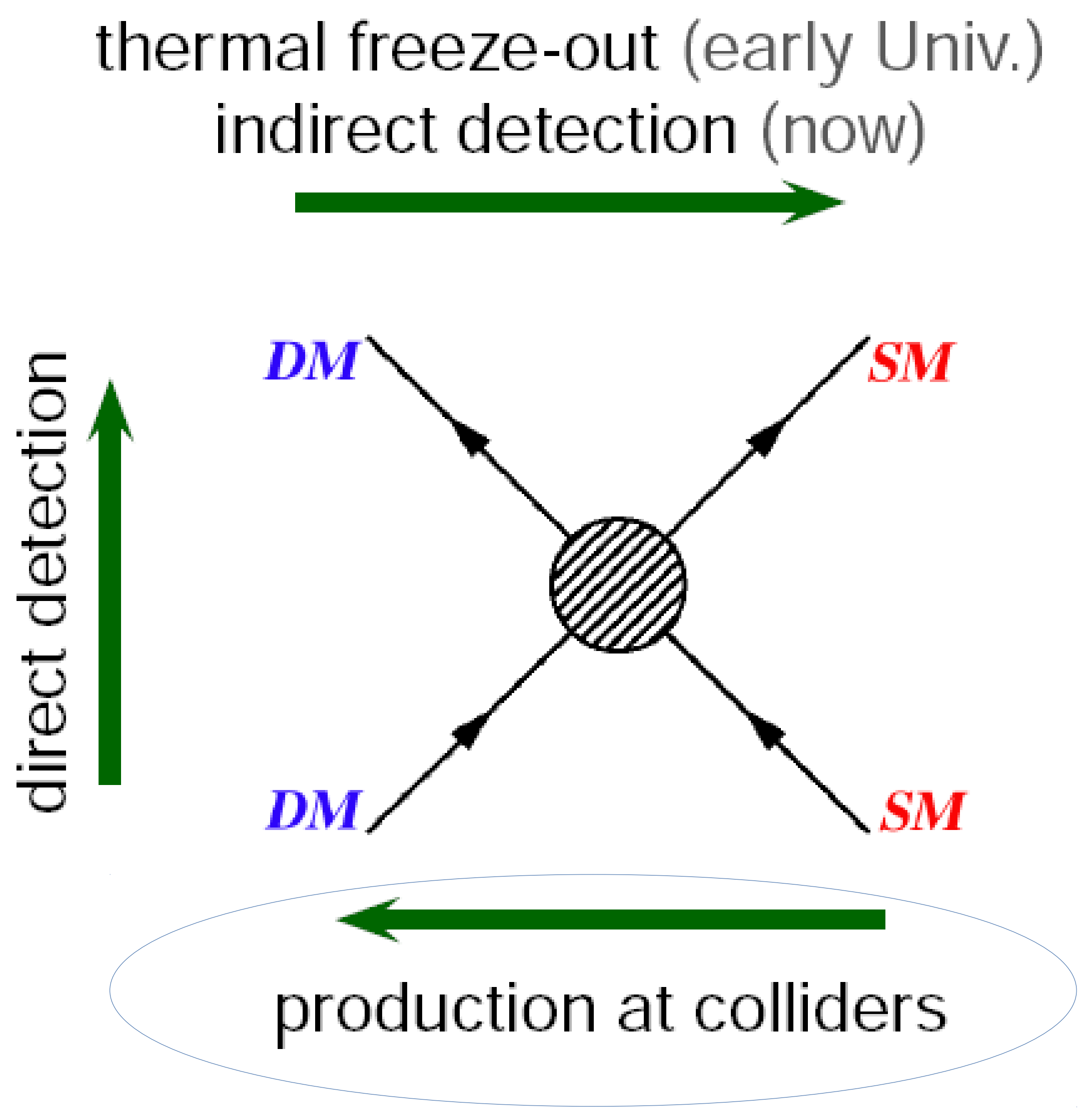
- $\mathcal{B}(\Upsilon(4S) \to B\bar{B}) > 96\%$, with $p_B^{CM} \sim 0.35$ GeV/c
- nothing else but $B\bar{B}$ in the final state

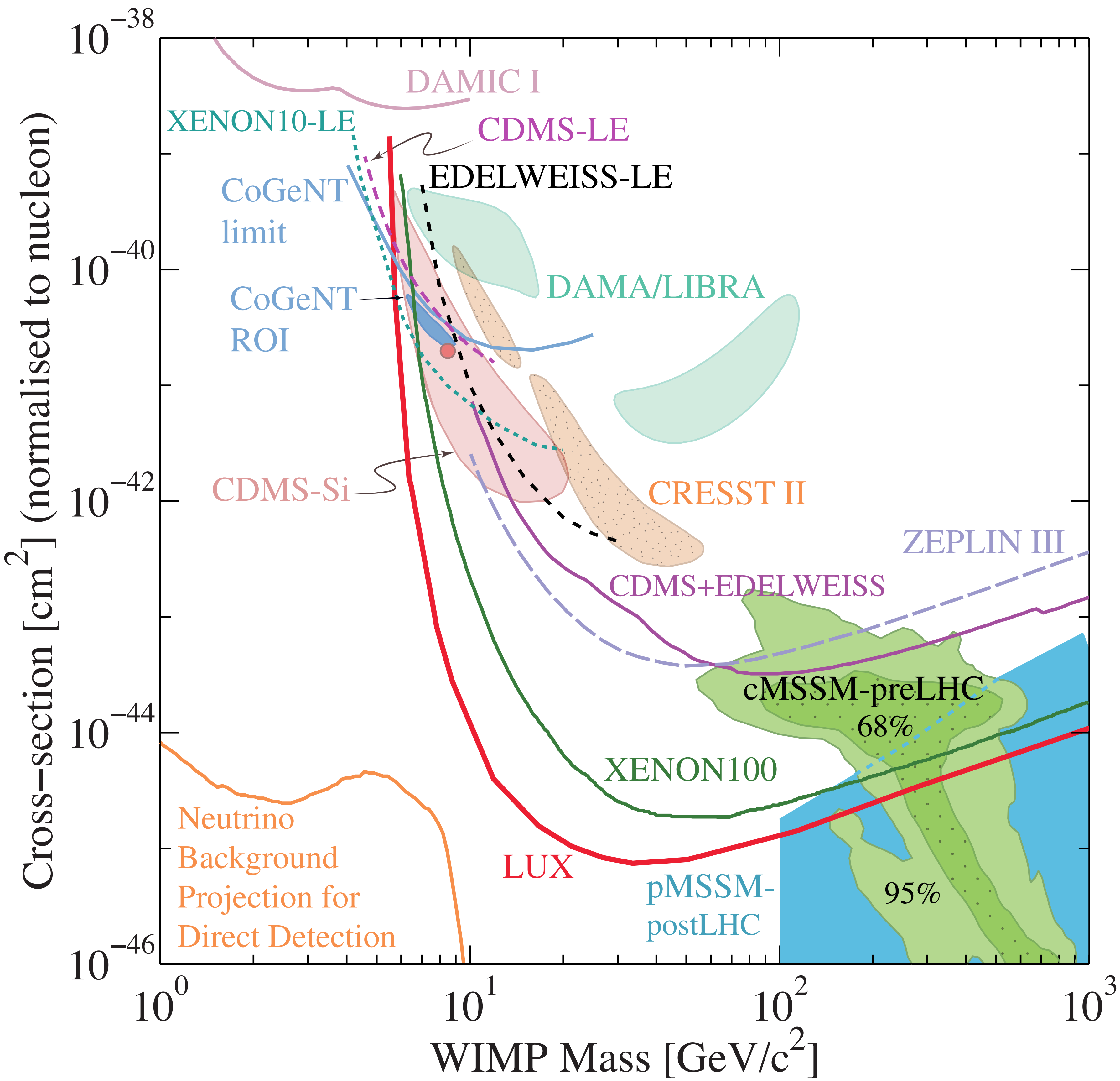
  $\therefore$ if we know $(E, \vec{p})$ of one B, the other B is also constrained

Search for dark sector at Belle

Age of En'dark'enment?



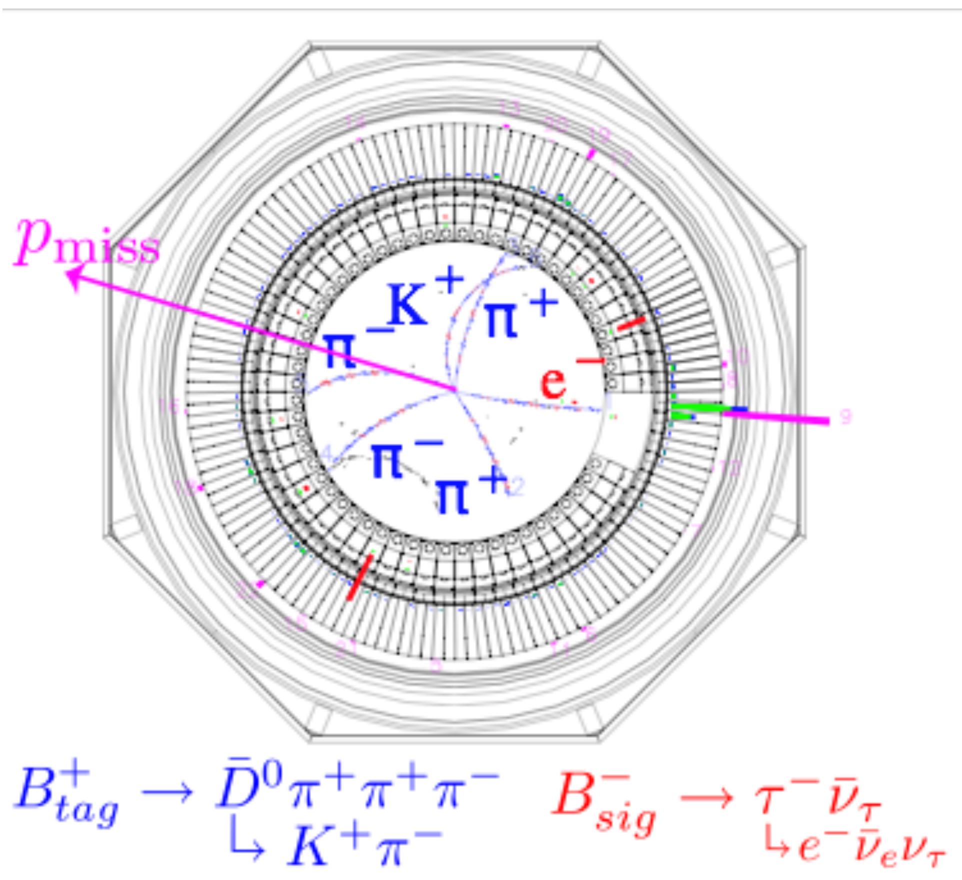


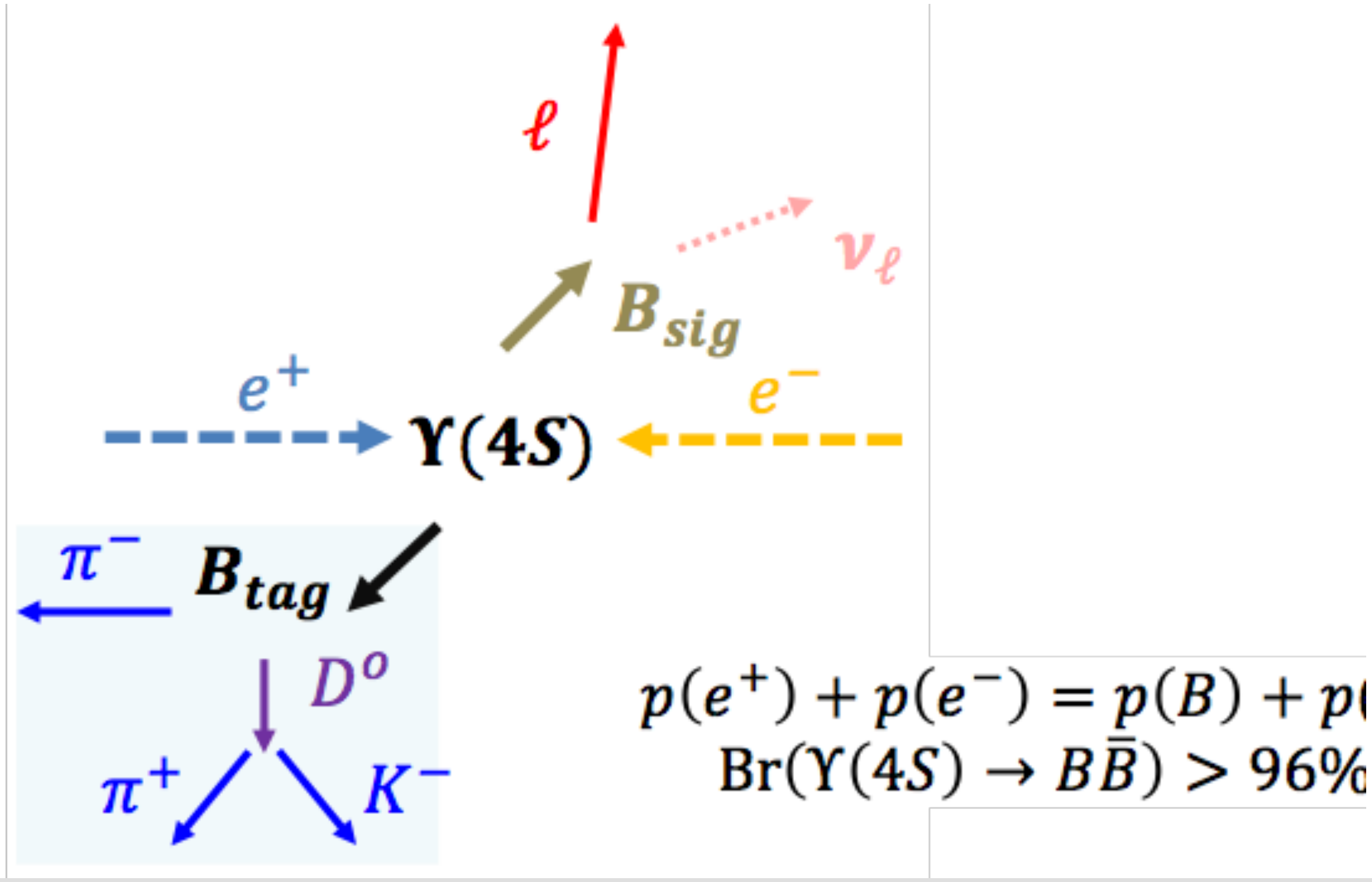


Direct WIMP searches are, in general, not very sensitive for WIMP mass $\lesssim 10$ GeV/c^2

Studying invisibles @ Belle

- (Ex) $B \to X_u \ell^+ \nu_\ell$, $B^+ \to \tau^+ \nu_\tau$ and other exotic kinds (e.g. $B^0 \to \nu\bar{\nu}$)
- hadronic tagging method
  - * full reconstruction of B_{tag} in $\Upsilon(4S) \to B_{\text{sig}} B_{\text{tag}}$
    $\Rightarrow$ constrain the charge, flavor, & $(E, \vec{p})$ of B_{sig}
    $\Rightarrow$ resulting in very high-purity, but with low-efficiency ($\sim \mathcal{O}(0.1\%)$)
  - * need an algorithm for improved full-reconstruction of B mesons





How to improve full-recon. B

stage	particles
1	tracks, K_S, γ, π^0
2	$D^{\pm}_{(s)}$, D^0 and J/ψ
3	$D^{*\pm}_{(s)}$ and D^{*0}
4	$B^{\pm}$ and B^0

- adding more B tag modes – will increase the signal, but
  - background will increase drastically (esp. with high-multiplicity decays)
- intermediate cuts – best to avoid, for max. effi'cy, but
  - need cuts after each stage, due to limited computing resources (time, storage)

Neurobayes M. Feindt, *et al.*, NIM A 654, 432 (2011)

- multivariate analysis S/W using a **neural** network
- The output of the network can be interpreted as **Bayesian** probability
- provides a well-discriminating variable for intermediate cuts, *whose behaviors are under control*

NeuroBayes in the real world

History of NeuroBayes

<phi-t>®
Physics Information Technologies

1993-2003 M.F. & co-workers: experience with NN in DELPHI, development of many packages: ELEPHANT, MAMMOTH, BSAURUS etc.
1999 Invention of NeuroBayes algorithm
1997-now extensive use of NeuroBayes in CDF II
2000-2002 NeuroBayes®- specialisation for economy at the University of Karlsruhe, supported by BMBF
2002: Phi-T GmbH founded, industrial projects, further developments
2008: Foundation of sub-company Phi-T products & services, 2. office in Hamburg
2008-now: extensive use of NeuroBayes in Belle
2010: LHCb decides to use NeuroBayes massively to optimise reconstruction code

Phi-T owns exclusive rights for NeuroBayes®
Staff (currently ≈40) almost all physicists (mainly from HEP)
Continuous further development of NeuroBayes®

<phi-t> PRODUCTS & SERVICES

Michael Feindt NeuroBayes Classifications for CMS CMS MVA Workshop, Dec. 13, 2010

<phi-t> customers & projects

Very successful projects for: among others
- BGV and VKB car insurances
- Lupus Alpha Asset Management
- Otto Versand (mail order business)
- Thyssen Krupp (steel industry)
- AXA and Central health insurances
- dm drogerie markt (drugstore chain)
- Libri (book wholesale)
- ..... expanding

Badisch gut versichert. BGV central dm OTTO BAUR AXA heine Schwab Libri SportScheck axel springer ThyssenKrupp Steel la

➢ Medicine and Pharma research
  e.g. effects and undesirable effects of drugs
  early tumor recognition
➢ Banks
  e.g. Credit-Scoring (Basel II), Finance time series prediction, valuation of derivates, risk minimised trading strategies, client valuation
➢ Insurances
  e.g. risk and cost prediction for individual clients, probability of contract cancellation, fraud recognition, justice in tariffs
➢ Trading chain stores: turnover prognosis

Necessary prerequisite:
Historic or simulated data must be available.

from M. Feindt talk on NeuroBayes and phi-t

NeuroBaeyes full-recon. B

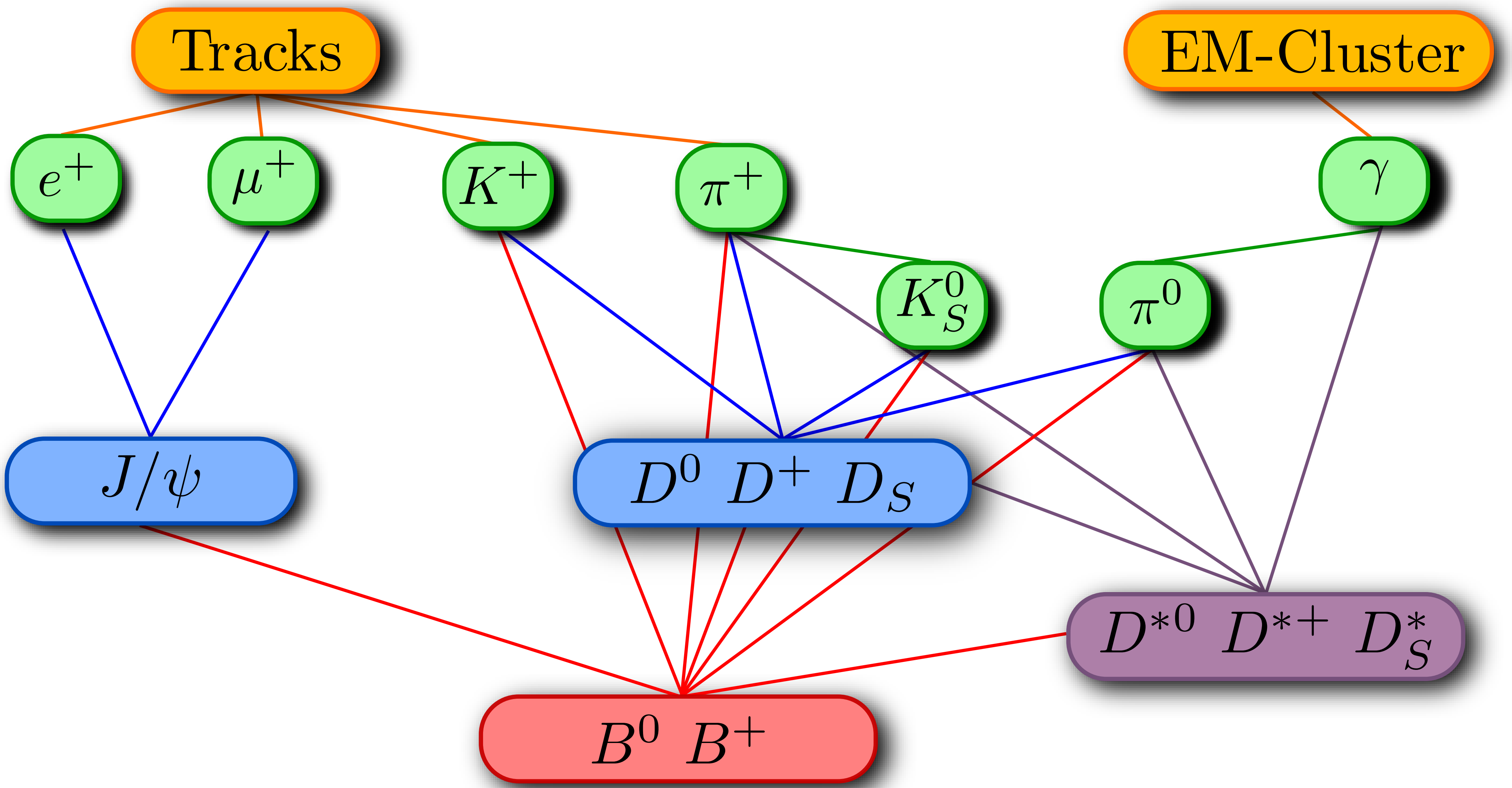
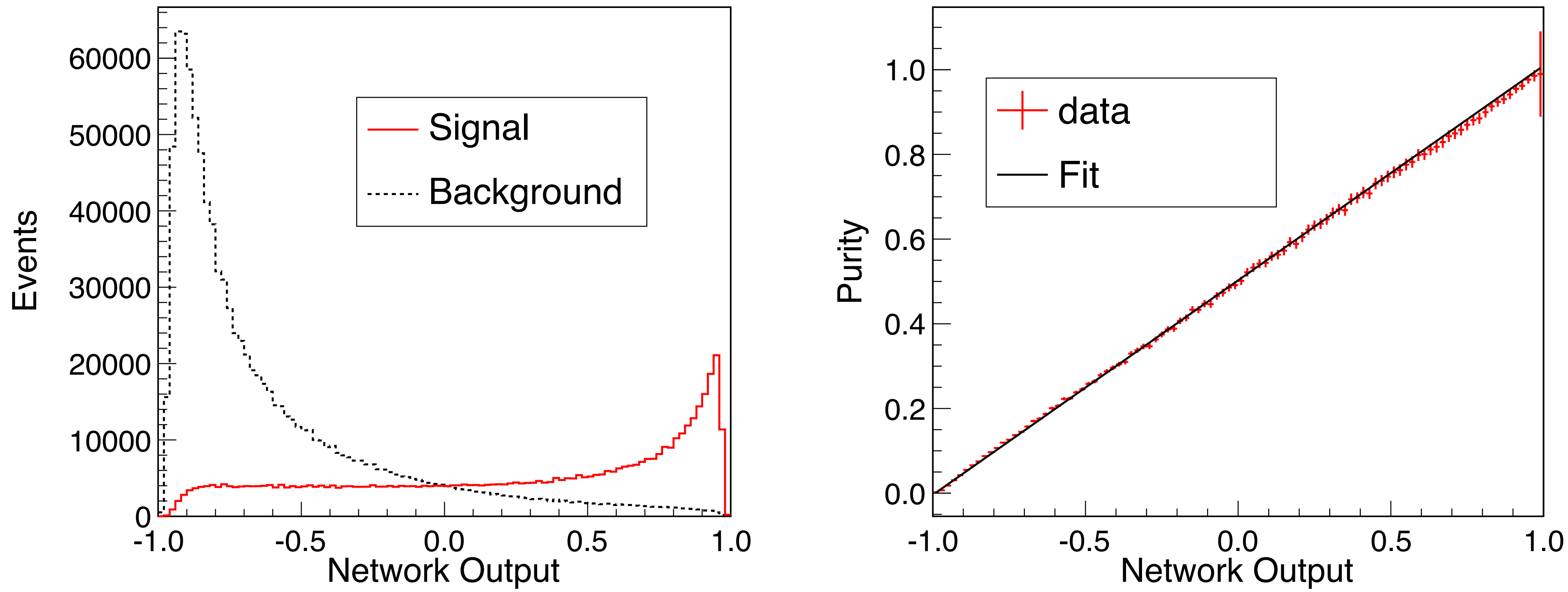


Figure 3: The 4 stages of the full reconstruction

NeuroBaeyes full-recon. *B*



(a) (b)

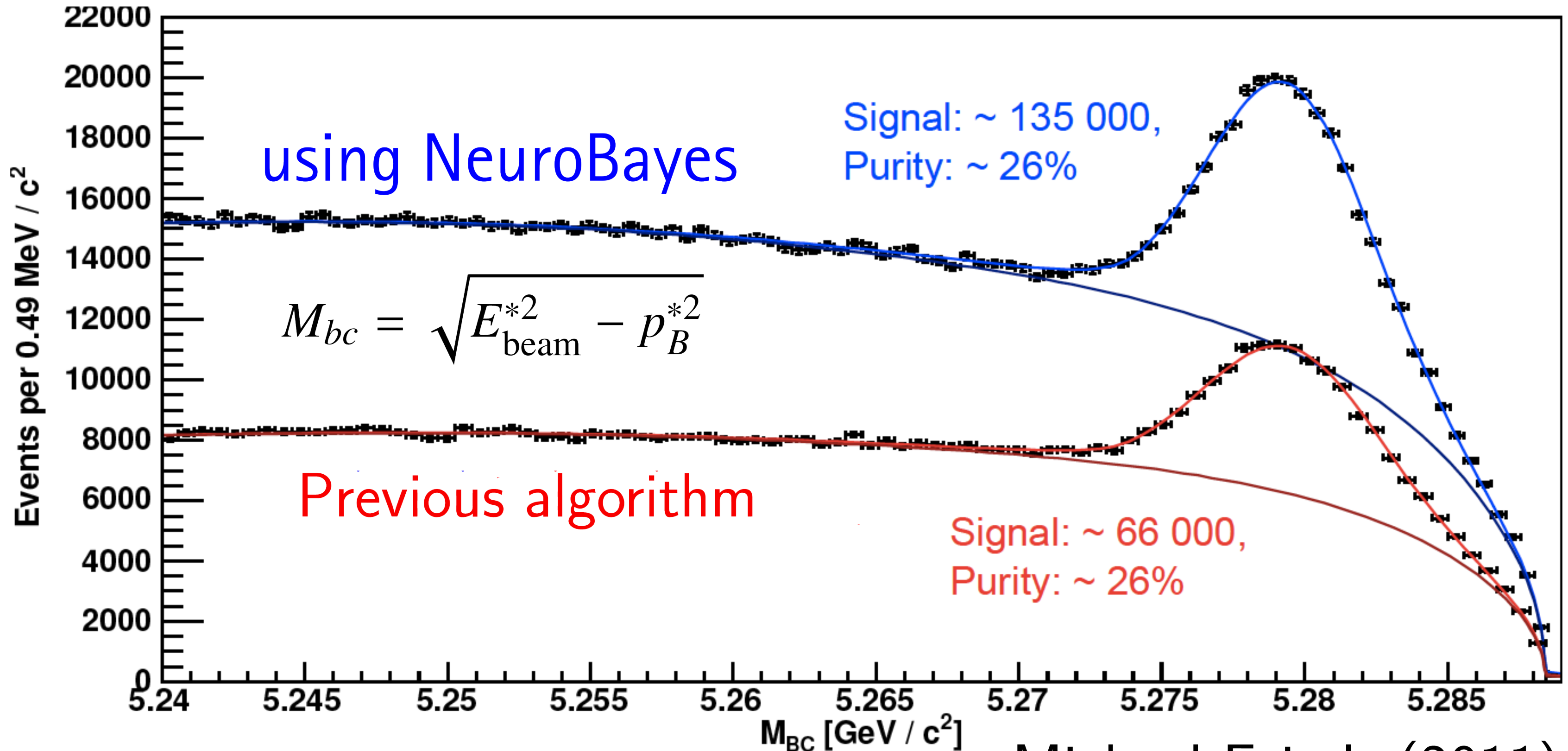
Figure 2: (a): The distribution of the NeuroBayes output for signal (red) and background (black) for an exemplary classification task of π^0 candidates. (b): The purity, obtained from the network output distributions shown in Fig. (a), is a linear function of the NeuroBayes output.

The network output (O_{NB}) is linearly related to the Bayesian probability of a reconstructed candidate to be true

NeuroBayes – *the performance*

- hadronic tagging method
  - * full reconstruction of $B_{\rm tag}$ in $\Upsilon(4S) \to B_{\rm sig}B_{\rm tag}$
  - * NeuroBayes algorithm — M. Feindt, *et al.*, NIM A 654, 432 (2011)

    - much improved performace by adding more $B_{\rm tag}$ and D modes



Michael Feindt (2011)

* $\times(2 \sim 3)$ statistical gain over previous hadron-tagged analyses!

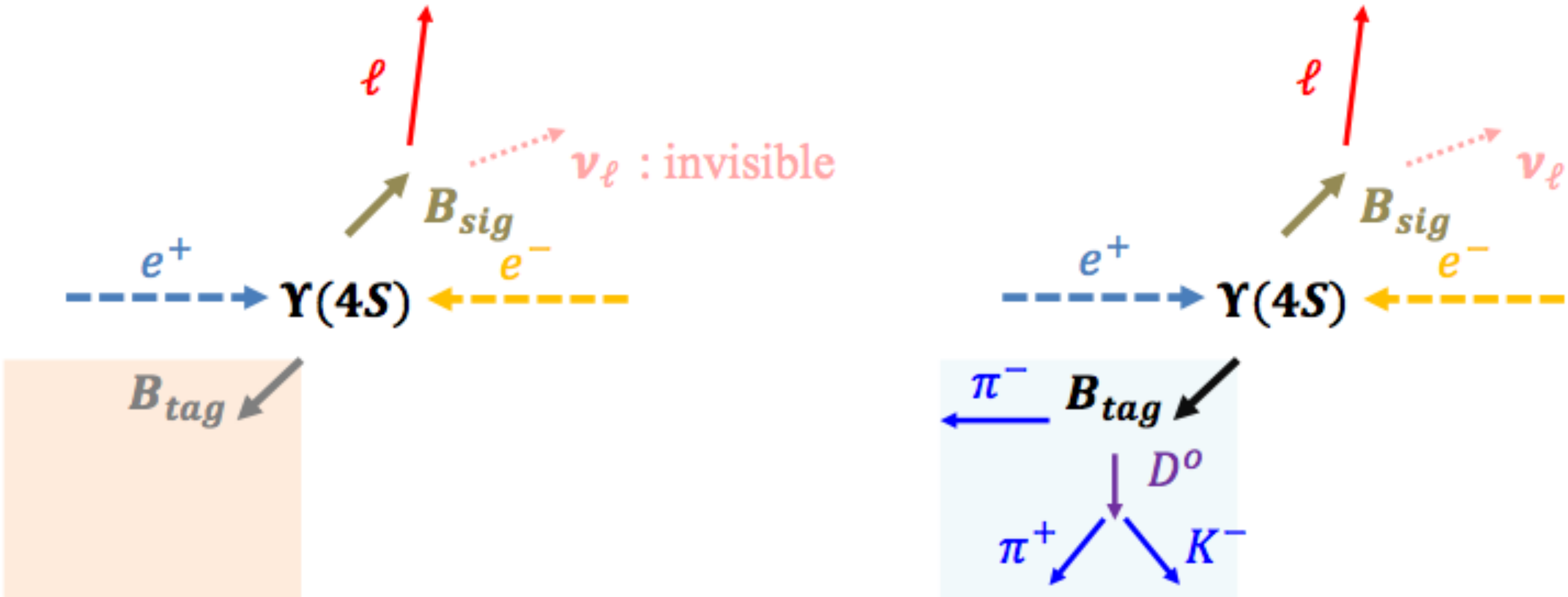
Search for $B^+ \to \ell^+ \nu_\ell$

- (experimental) very clean
  - just a charged lepton and nothing else
- (theoretical) suppressed
  - helicity suppression: $\mathcal{B} \propto m_\ell^2$

$$\Gamma(B^+ \to e^+\nu) \ll \Gamma(B^+ \to \mu^+\nu) \ll \Gamma(B^+ \to \tau^+\nu)$$

Two methods for $B^+ \to \ell^+ \nu_\ell$

untagged (*no use of full-recon.*) **vs. tagged**



<Untagged Reconstruction>

<Hadronic Tag. Reconstruction>

Pros: Higher efficiency due to no prior reconstruction.

Cons: Many combinatorial backgrounds and worse B_{tag} related variable resolution.

Efficiency

Purity

Pros: The best knowledge on kinematics in B_{sig} results in high purity.

Cons: Lower efficiency due to prior reconstruction.

$\Gamma(e^+\nu_e)/\Gamma_{total}$ Γ_{27}/Γ

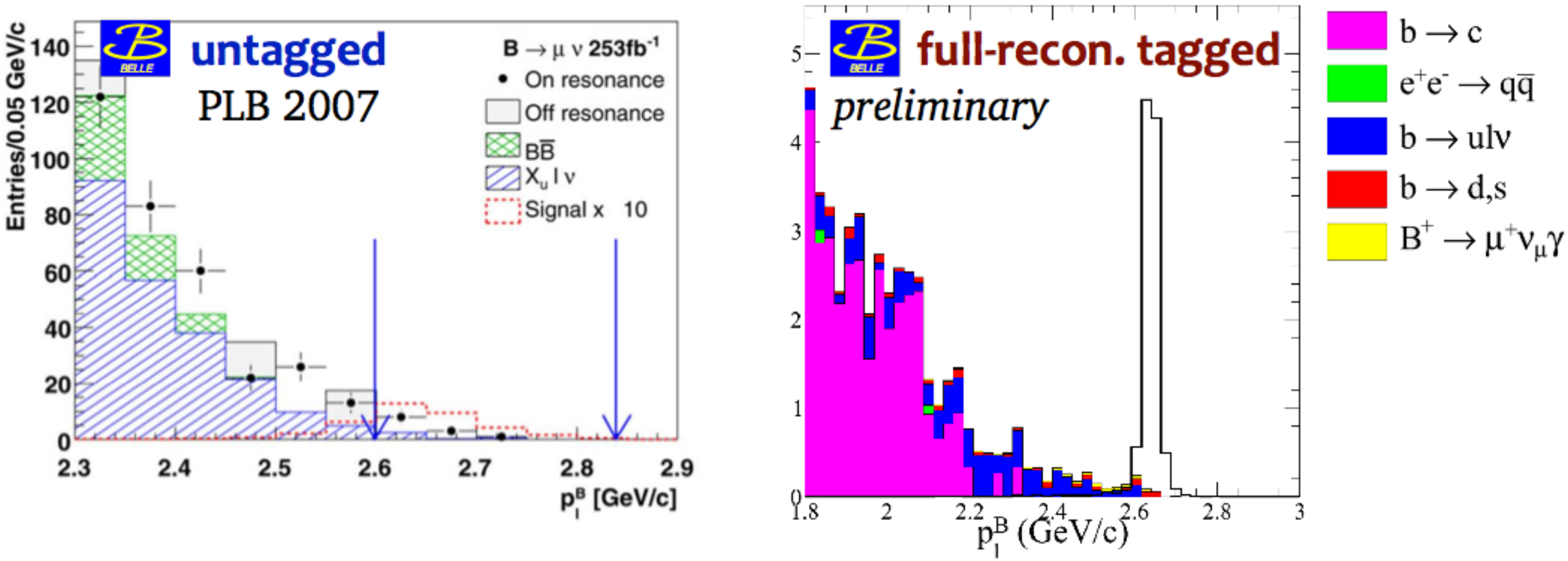
VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	COMMENT	
< 0.98	90	[1] SATOYAMA	07	BELL	$e^+e^- \to \Upsilon(4S)$	untagged
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 8	90	[1] AUBERT	10E	BABR	$e^+e^- \to \Upsilon(4S)$	
< 1.9	90	[1] AUBERT	09V	BABR	$e^+e^- \to \Upsilon(4S)$	untagged
< 5.2	90	[1] AUBERT	08AD	BABR	$e^+e^- \to \Upsilon(4S)$	*full-recon.*

$\Gamma(\mu^+\nu_\mu)/\Gamma_{total}$ Γ_{28}/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	COMMENT	
< 1.0	90	[1] AUBERT	09V	BABR	$e^+e^- \to \Upsilon(4S)$	untagged
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<11	90	[1] AUBERT	10E	BABR	$e^+e^- \to \Upsilon(4S)$	
< 5.6	90	[1] AUBERT	08AD	BABR	$e^+e^- \to \Upsilon(4S)$	*full-recon.*
< 1.7	90	[1] SATOYAMA	07	BELL	$e^+e^- \to \Upsilon(4S)$	untagged

Why then bother with 'tagged' for $B^+ \to \ell^+ \nu_\ell$?

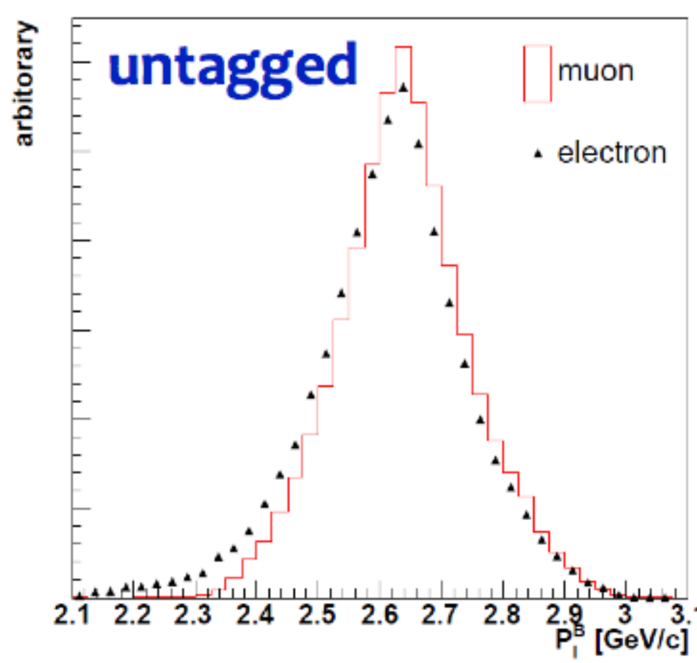
- The signal lepton candidate's momentum in B_{sig} rest frame. -



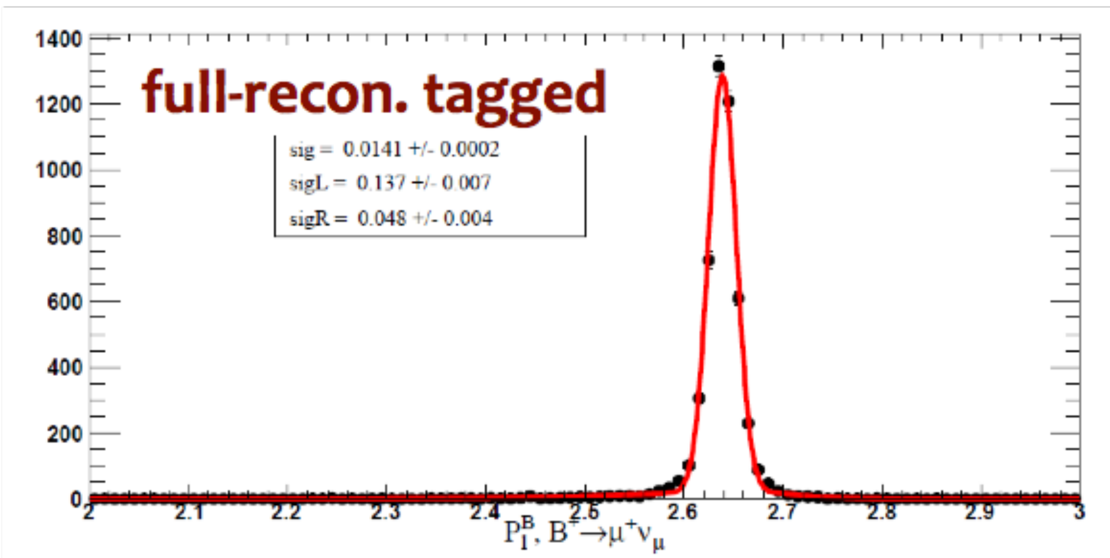
- an order-of-magnitude better resolution of p_ℓ^B with the full-recon. tagging
- But, does it make a case for 'full-recon-tagged' analysis of $B^+ \to \ell^+ \nu_\ell$?

Why then bother with 'tagged' for $B^+ \to \ell^+\nu_\ell$?

- Note: $\mathcal{B}_{SM}(B^+ \to e^+\nu_e) \sim 10^{-11}$ and $\mathcal{B}_{SM}(B^+ \to \mu^+\nu_\mu) \sim 3 \times 10^{-7}$
  $\Rightarrow$ Any signal for $B^+ \to e^+\nu_e$ at the Belle sensitivity is way beyond the SM
- In that case, are we *sure* what we see is *really* $B^+ \to e^+\nu_e$?
- What about $B^0 \to e^+\tau^-$? How about $B^+ \to e^+X^0$ where X^0 is any exotic neutral particle that just behaves like a neutrino?



$\epsilon_{sig} = 2.18\%$
$N_{bkg} = 7.4 \pm 1.0$



$\epsilon_{sig} = 0.104\%$
$N_{bkg} = 0.26^{+0.10}_{-0.08}$

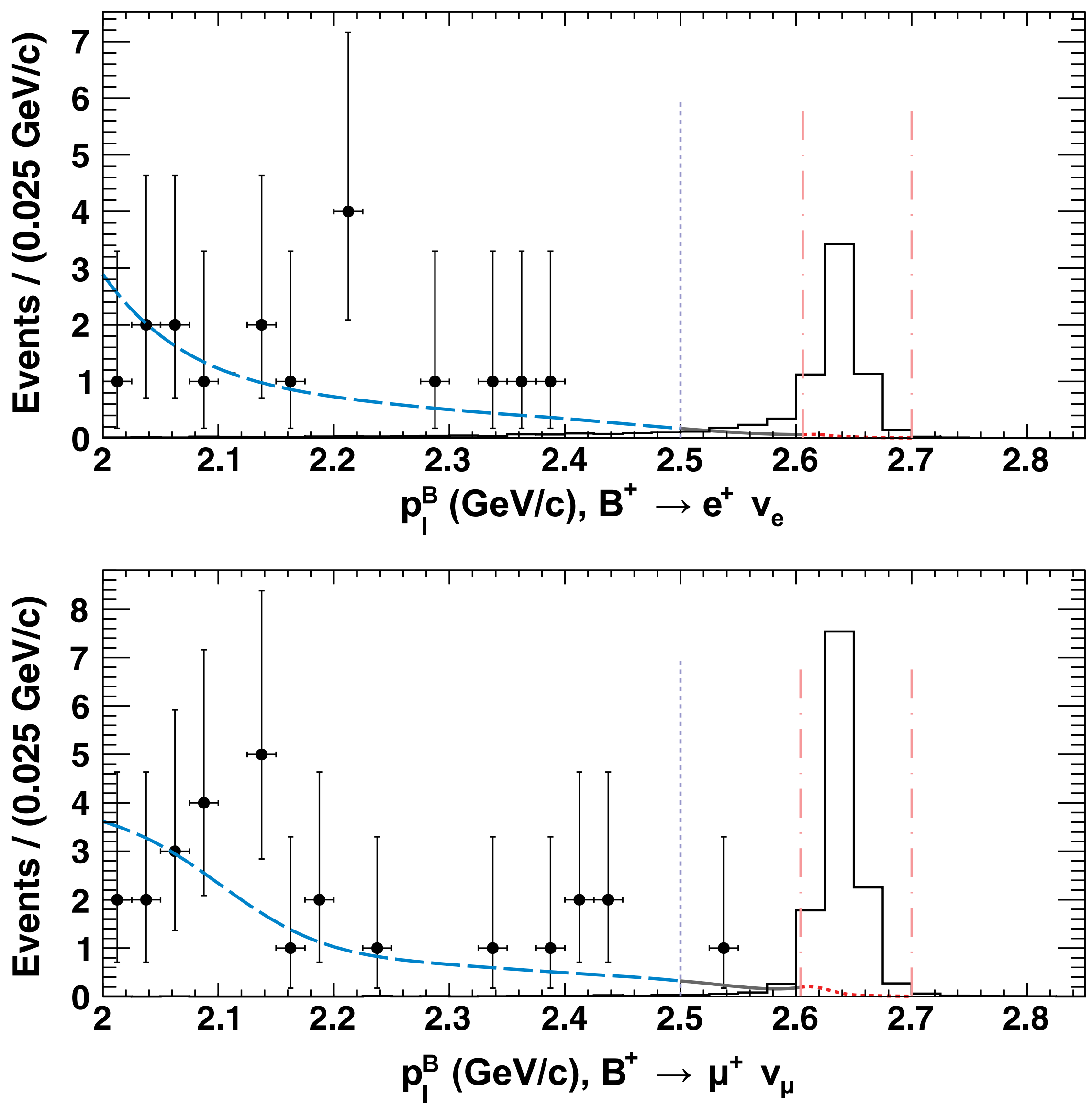
- With full-recon., p_ℓ^B resolution is sharp enough to discern many such cases

$B^+ \to \ell^+ \nu_\ell$ results

PHYSICAL REVIEW D **91,** 052016 (2015)

Search for $B^+ \to e^+\nu_e$ and $B^+ \to \mu^+\nu_\mu$ decays using hadronic tagging

Y. Yook,[70] Y.-J. Kwon,[70] A. Abdesselam,[58] I. Adachi,[12] S. Al Said,[58,27] K. Arinstein,[4] D. M. Asner,[49] V. Aulchenko,[4]



Mode	ϵ_s [%]	N_{obs}	$N_{\text{exp}}^{\text{bkg}}$
$B^+ \to e^+\nu_e$	0.086 ± 0.007	0	0.10 ± 0.04
$B^+ \to \mu^+\nu_\mu$	0.102 ± 0.008	0	$0.26^{+0.09}_{-0.08}$

collected by the Belle experiment. We find no evidence of $B^+ \to e^+\nu_e$ and $B^+ \to \mu^+\nu_\mu$ processes. We set the upper limits of the branching fraction at $\mathcal{B}(B^+ \to e^+\nu_e) < 3.5 \times 10^{-6}$ and $\mathcal{B}(B^+ \to \mu^+\nu_\mu) < 2.7 \times 10^{-6}$ at 90% C.L., which are by far the most stringent limits obtained with the hadronic tagging method. Given the low background level demonstrated in this search, we expect more stringent constraints on the new physics models to be set by Belle II [27], the next generation B factory experiment.

“Heavy ν” searches at Belle

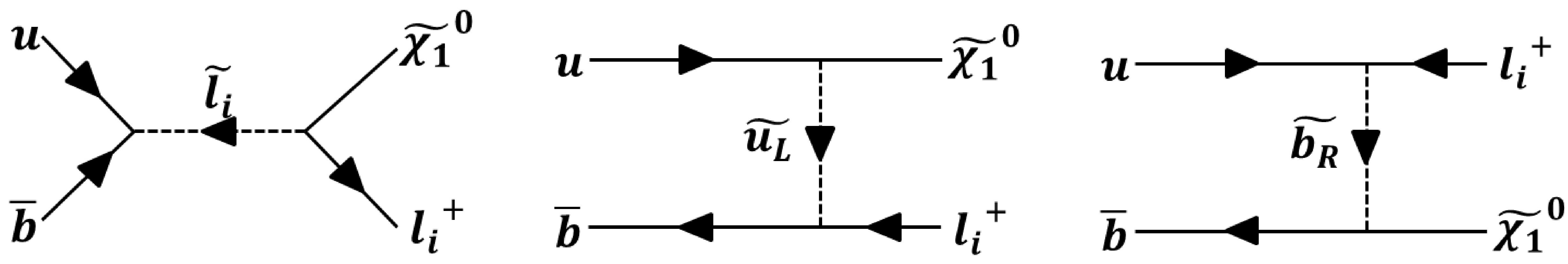
- $B^+ \to \ell^+ X^0$: search for massive neutral invisible particle X^0
- $B \to (X)\ell\nu_{\rm h}$: search for heavy neutrino $\nu_{\rm h}$ *(not with full-recon.)*

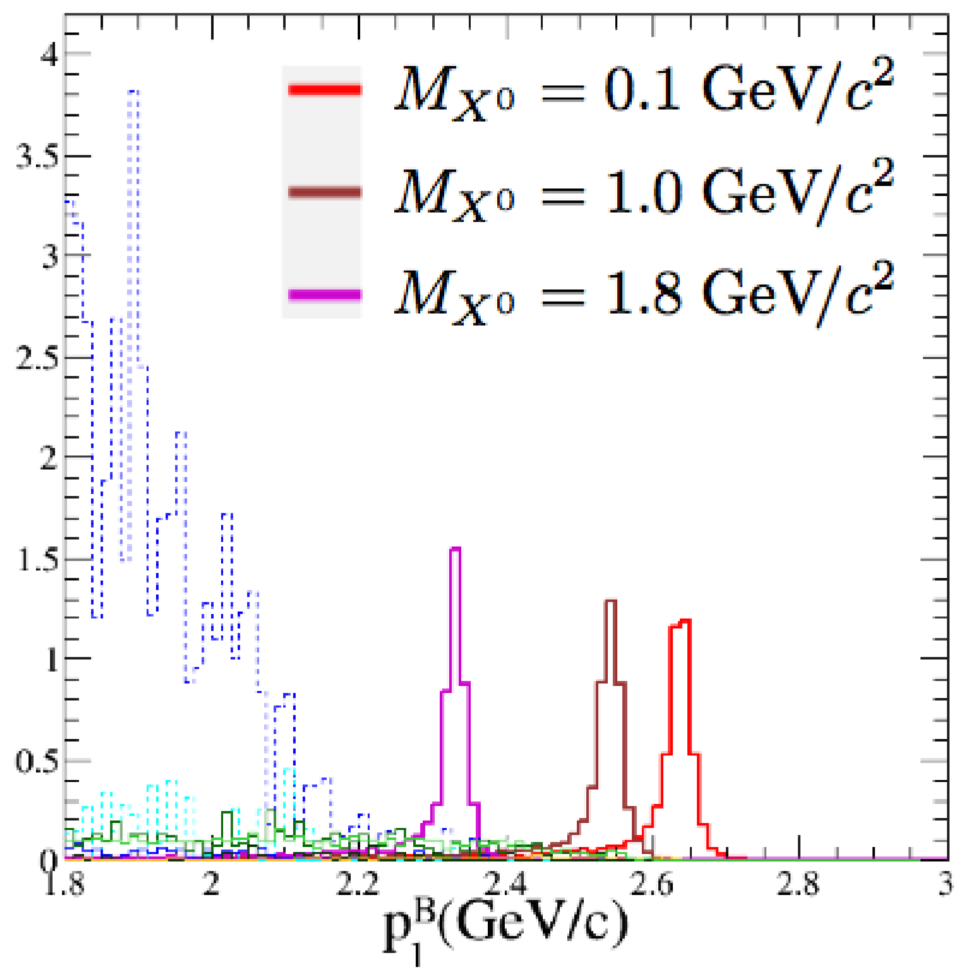
Why heavy ν?

- Within the minimal SM, $\exists$ no place for ν_R.
- With ν oscillations, we need ν_R for $m_\nu \neq 0$. But, in what capacity do we have it?
- Heavy neutrinos ("ν_h") appear in many BSM hypotheses.
  - The ν_h's might even be of Majorana type.

- So, why not go search for it?

$B^+ \to \ell^+ X^0$



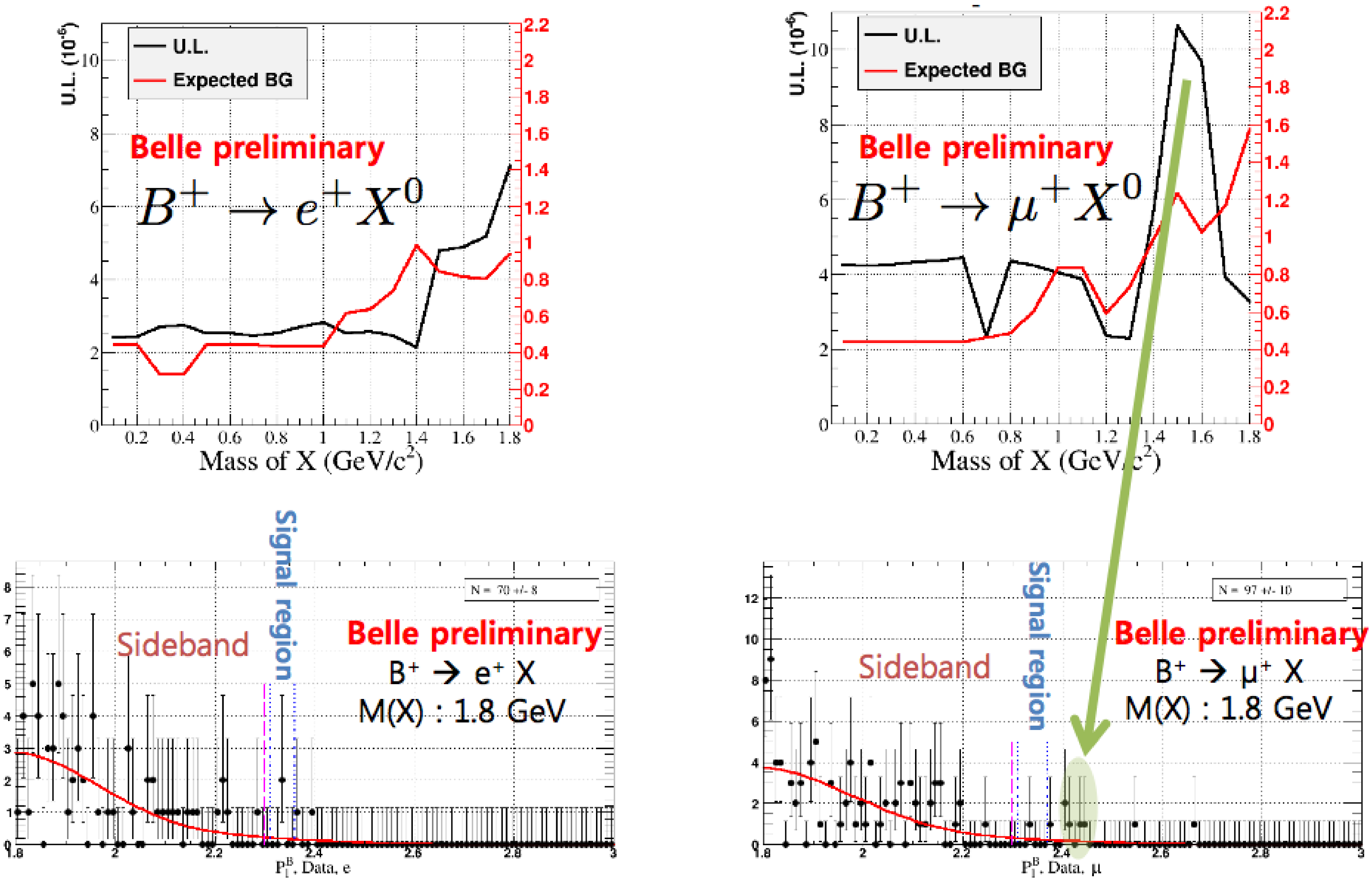


- Search for massive neutral invisible fermion "X^0"

  It can be a heavy neutrino, or an LSP in RPV models, or whatever

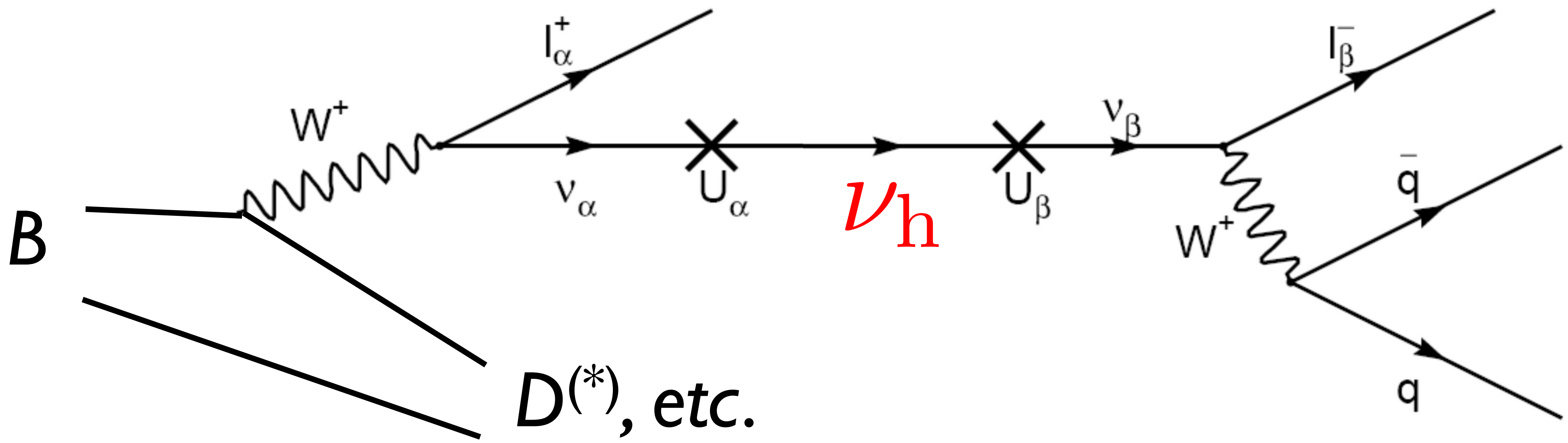
- Experimentally, very similar signature to $B^+ \to \ell^+ \nu_\ell$
- But, p_ℓ^B gives a handle on M_X

$B^+ \to \ell^+ X^0$ Results



Heavy ν search

- Search for $B \to (X)\ell_2^{\pm}\nu_{\rm h}$ with $\nu_{\rm h} \to \ell_1^{\pm}\pi^{\mp}$.
  If $\nu_{\rm h}$ is of Dirac type, $\nu_{\rm h} \to \ell_1^{-}\pi^{+}$.

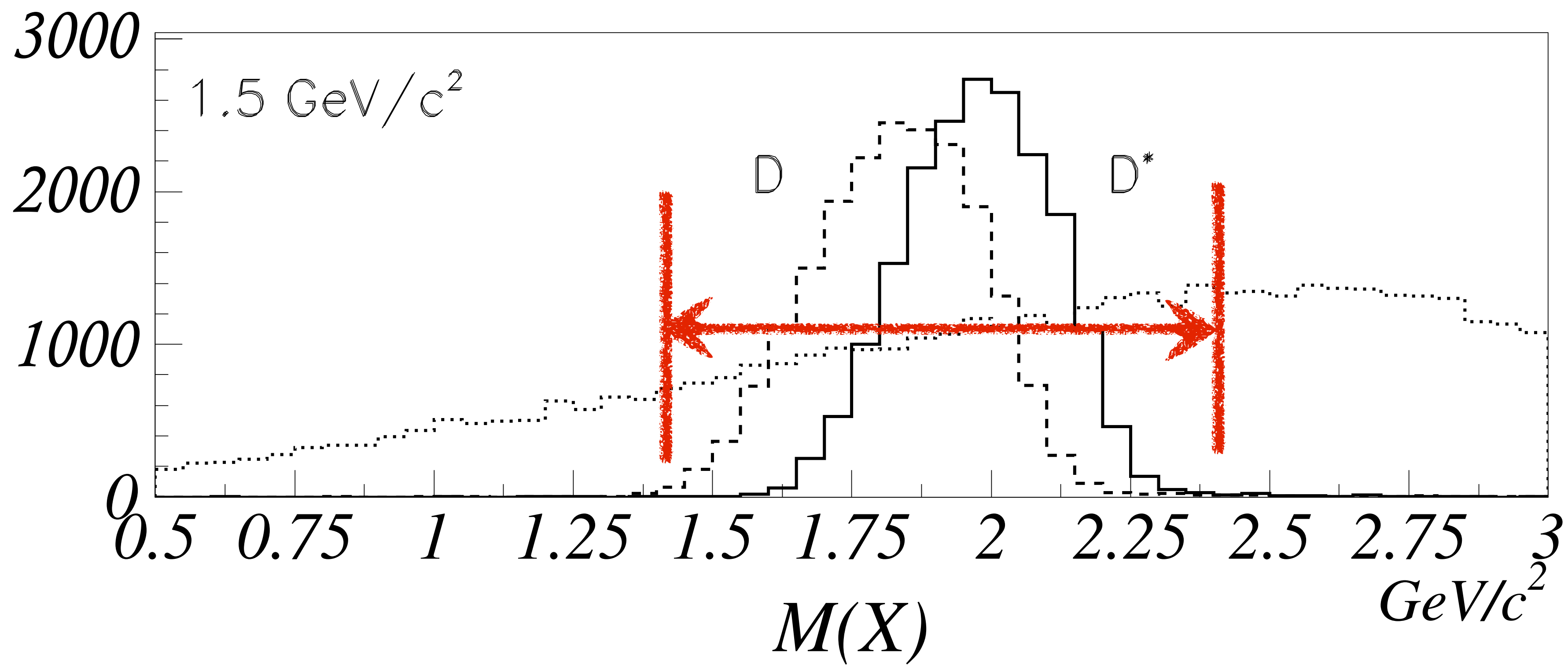


- Main features
  - * $\nu_{\rm h}$ interacts only via mixing with $\nu_{\rm L}$
  - * Long flight distance
    $c\tau \simeq 20$ m for $M(\nu_{\rm h}) = 1$ GeV$/c^2$ and $|U_e|^2 = |U_\mu|^2 = 10^{-4}$

Heavy ν search

- Separately for large and small $M(\nu_\mathrm{h})$
  - * "small" $M(\nu_\mathrm{h}) < 2.0$ GeV/c^2: $X = D,\ D^*$ only

    $D^{(*)}$ is identified by "missing mass": $M_X^2 \equiv (E_\mathrm{CM} - E_{\ell_1\ell_2\pi})^2 - P_{\ell_1\ell_2\pi}^2 - P_B^2$
  - * "large" $M(\nu_\mathrm{h}) \geq 2.0$ GeV/c^2: $X = D^{(*)}$, light meson, "nothing"

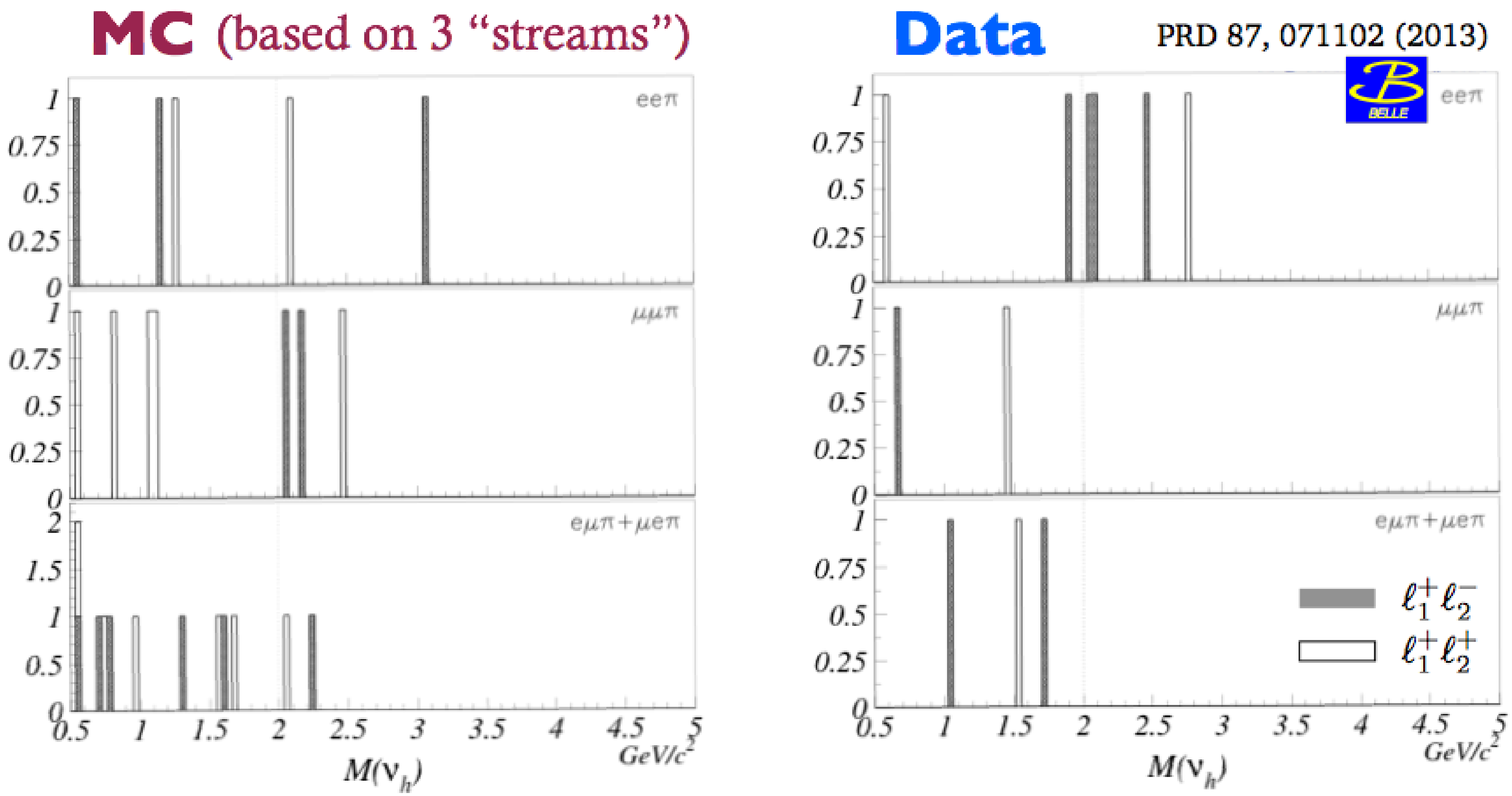


Heavy ν search

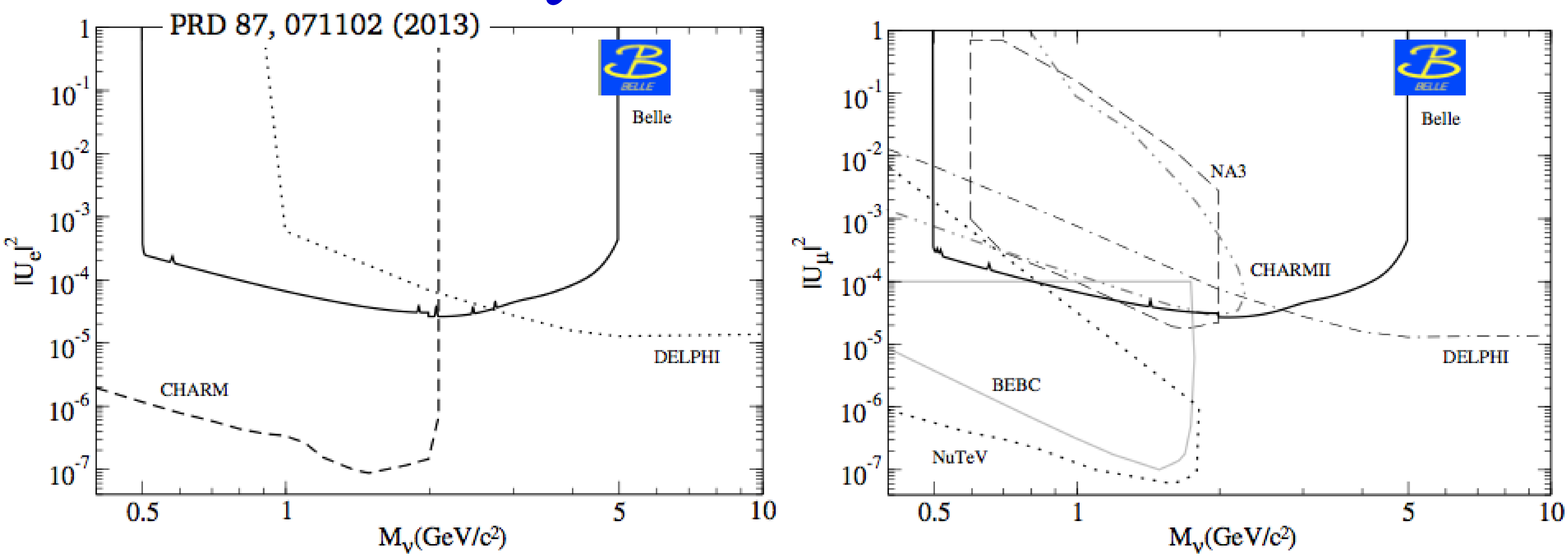
- Separately for large and small $M(\nu_{\rm h})$
  - "small" $M(\nu_{\rm h}) < 2.0$ GeV/c^2: $X = D,\ D^*$ only
    $D^{(*)}$ is identified by "missing mass": $M_X^2 \equiv (E_{\rm CM} - E_{\ell_1\ell_2\pi})^2 - P_{\ell_1\ell_2\pi}^2 - P_B^2$
  - "large" $M(\nu_{\rm h}) \geq 2.0$ GeV/c^2: $X = D^{(*)}$, light meson, "nothing"
- Main background
  - QED: suppressed by $N(\text{track}) \geq 5$
  - "V" decays from K_S^0, γ, Λ suppressed by strict lepton ID and kinematic cuts
  - Long flight distance of $\nu_{\rm h}$ is exploited by vertex distance cuts
    For vertices close to IP: $dr > 0.09$ cm, $d\phi < 0.03$, $z_{\rm dist} < 0.4$ cm
    For other vertices: $dr > 5$ cm, $d\phi < 0.15$, $z_{\rm dist} < 2$ cm
- After all cuts,
  - background: reduced by a factor of $\sim 10^6$
  - efficiency: $(3 \sim 10)\%$, depending on $M(\nu_{\rm h}),\ M_X,\ R$, etc.

Heavy ν search *Results*

mode	MC expected	Data
$ee\pi$	1.7 ± 0.7	6 ± 2.4
$\mu\mu\pi$	2.3 ± 0.9	2 ± 1.4
$e\mu\pi + \mu e\pi$	4.0 ± 1.2	3 ± 1.7



Heavy ν search *Results*



- Upper limits on $\nu_h - \nu_\ell$ mixing ($|U_\ell|^2$) are obtained, in the range $0.5 < M(\nu_h) < 5$ GeV/c^2.

  Maximum sensitivity is reached at $M(\nu_h) \sim 2$ GeV/c^2.

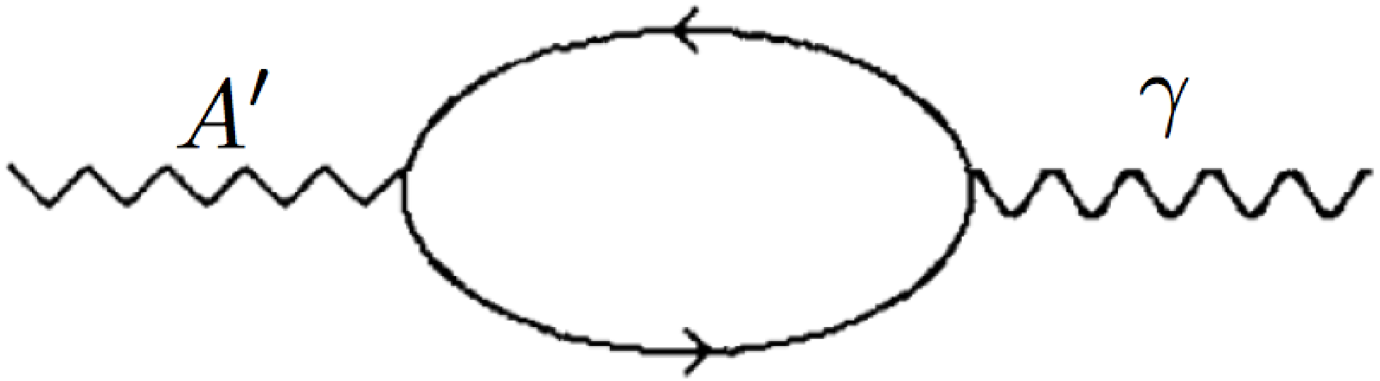
- Upper limit for product branching fraction (for $M(\nu_h) = 2$ GeV/c^2):

  $\mathcal{B}(B \to \ell_2 \nu_h(X)) \times \mathcal{B}(\nu_h \to \ell_1 \pi) < 7.2 \times 10^{-7}$ for $\ell = e,\ \mu$.

Dark photon search at Belle

Dark photon & kinetic mixing – a window to dark sector

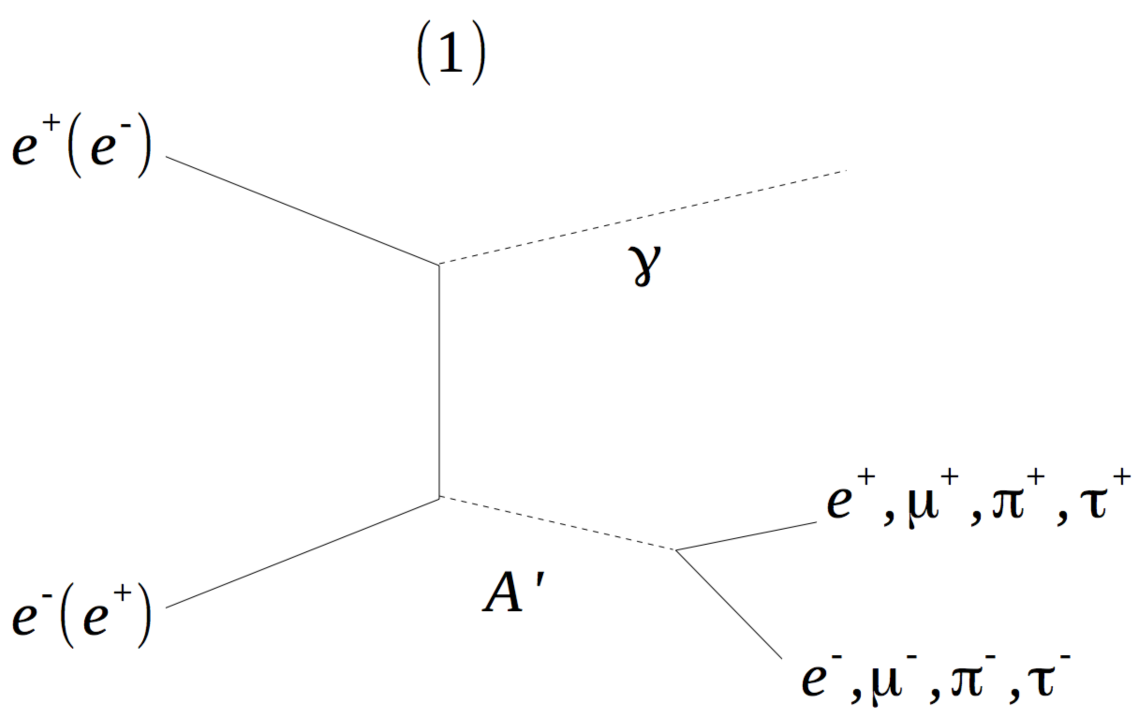
- Dark photon, first proposed in P. Fayet, PL B**95**, 285 (1980)
- (Holdom, 1986) A boson A' belonging to an additional $U(1)'$ would mix kinetically with γ

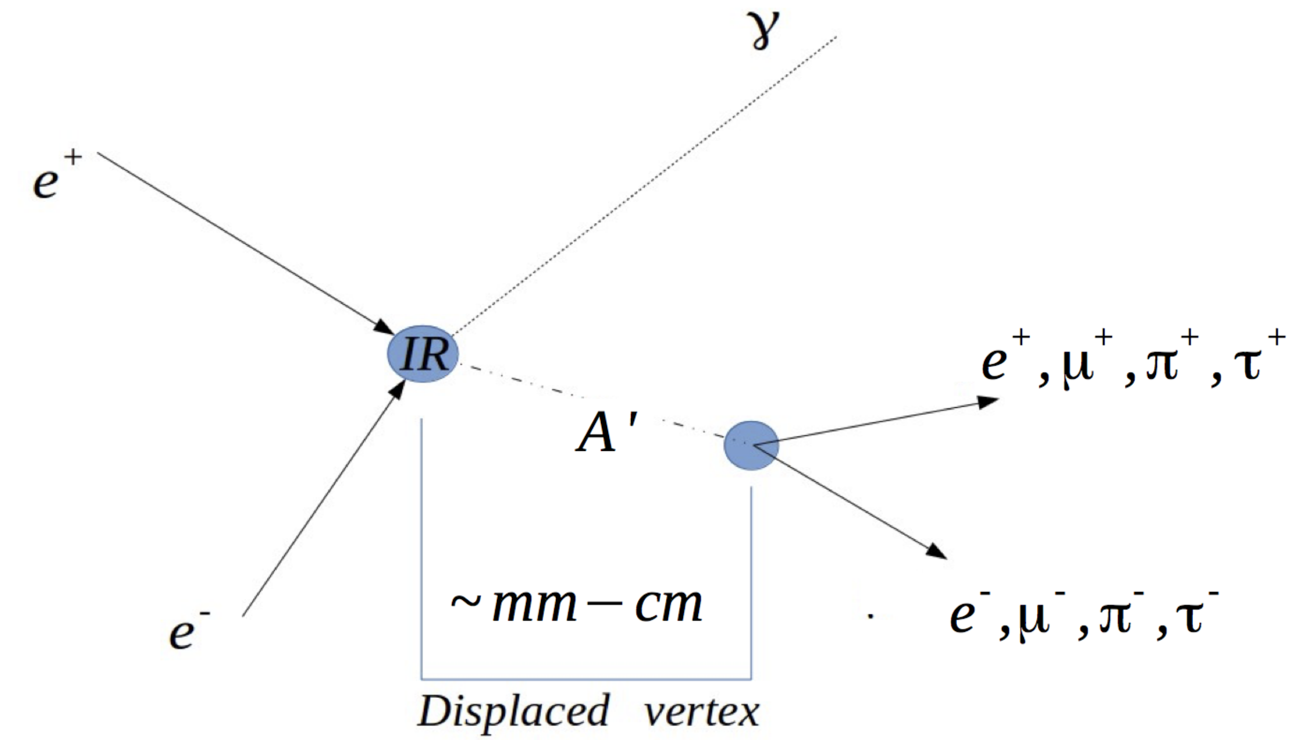


  - in general, one can express kinetic mixing as $(1/2)\epsilon\, F_{\mu\nu}F'^{\mu\nu}$
  - ϵ, the strength of the kinetic mixing, is supposed to be small, $(10^{-5} \sim 10^{-2})$.

- For A' to acquire mass, an extended Higgs sector is required to break this $U(1)'$

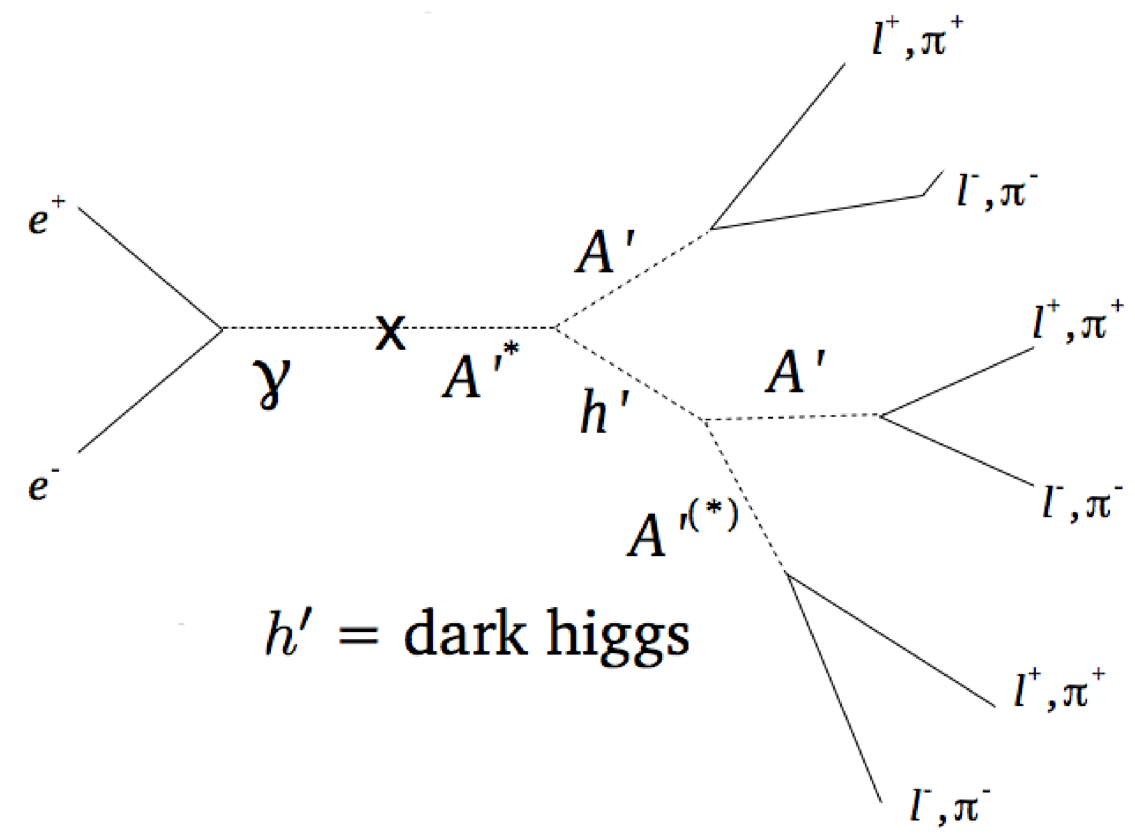
Dark photon search at e^+e^- B-factory





- low-multiplicty final state
- $A' \to \ell^+\ell^-$ or $\pi^+\pi^-$ with prompt or displaced vertex
- also study invisible final state, e.g. $e^+e^- \to \gamma A'(\to \chi\bar{\chi})$
  $\Leftarrow$ need special single-γ trigger (BaBar did; Belle did not)

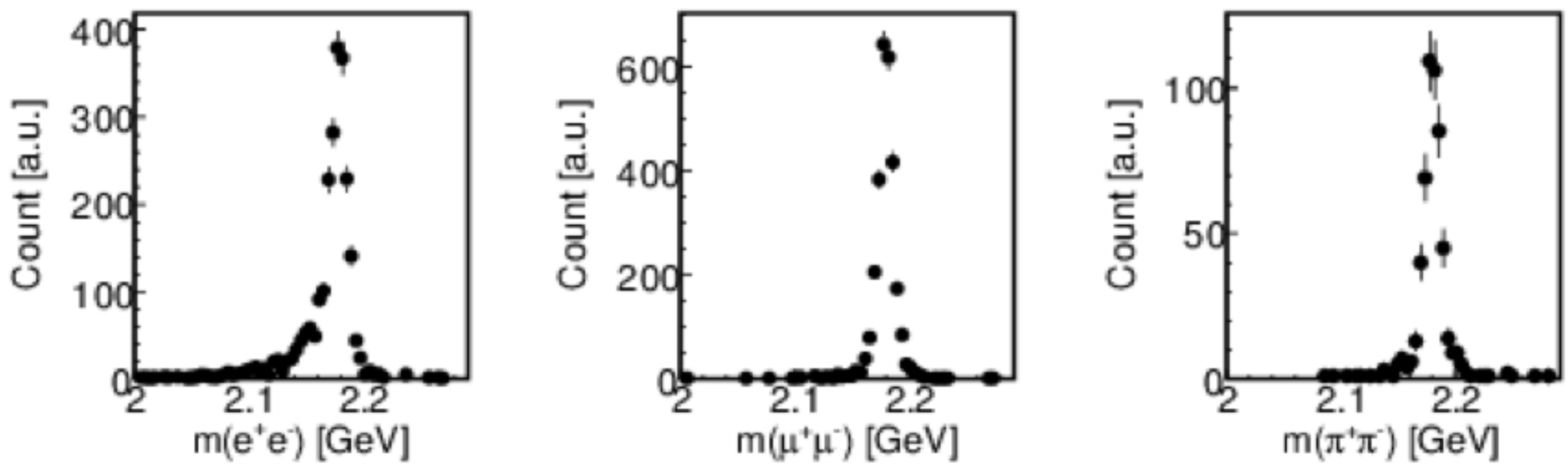
Dark photon search via Higgs-strahlung



- Search mode depends on $M_{h'}$ and $M_{A'}$
- In this talk, only $M_{h'} > 2M_{A'}$ is considered $\Rightarrow h' \to A'A'$ is used
  - 'exclusive': 3 charged-track pairs, each with the same invariant mass
  - 'inclusive': 2 charged-track pair, each with the same invariant mass, and missing $(E, \vec{p})$

Event selection

- 3 (at least 2) lepton/hadron pairs (e^+e^-, $\mu^+\mu^-$, or $\pi^+\pi^-$)
  - 10 exclusive channels: $3e^+3e^-$, $3\mu^+3\mu^-$, $2e^+2e^-\mu^+\mu^-$, $2\mu^+2\mu^-e^+e^-$, $3\pi^+3\pi^-$, $2\pi^+2\pi^-e^+e^-$, $2\pi^+2\pi^-\mu^+\mu^-$ $2e^+2e^-\pi^+\pi^-$, $2\mu^+2\mu^-\pi^+\pi^-$, $e^+e^-\mu^+\mu^-\pi^+\pi^-$
  - 3 inclusive channels for $m_A > 1.1$ GeV/c^2:$2e^+2e^-X$, $2\mu^+2\mu^-X$, $e^+e^-\mu^+\mu^-X$
- impact parameters and χ^2 of vertex fit requirements
- consistent with $(E, \vec{p})$ conservation
- mass of each $\ell^+\ell^-$, $\pi^+\pi^-$ pair be consistent with $M_{A'}$

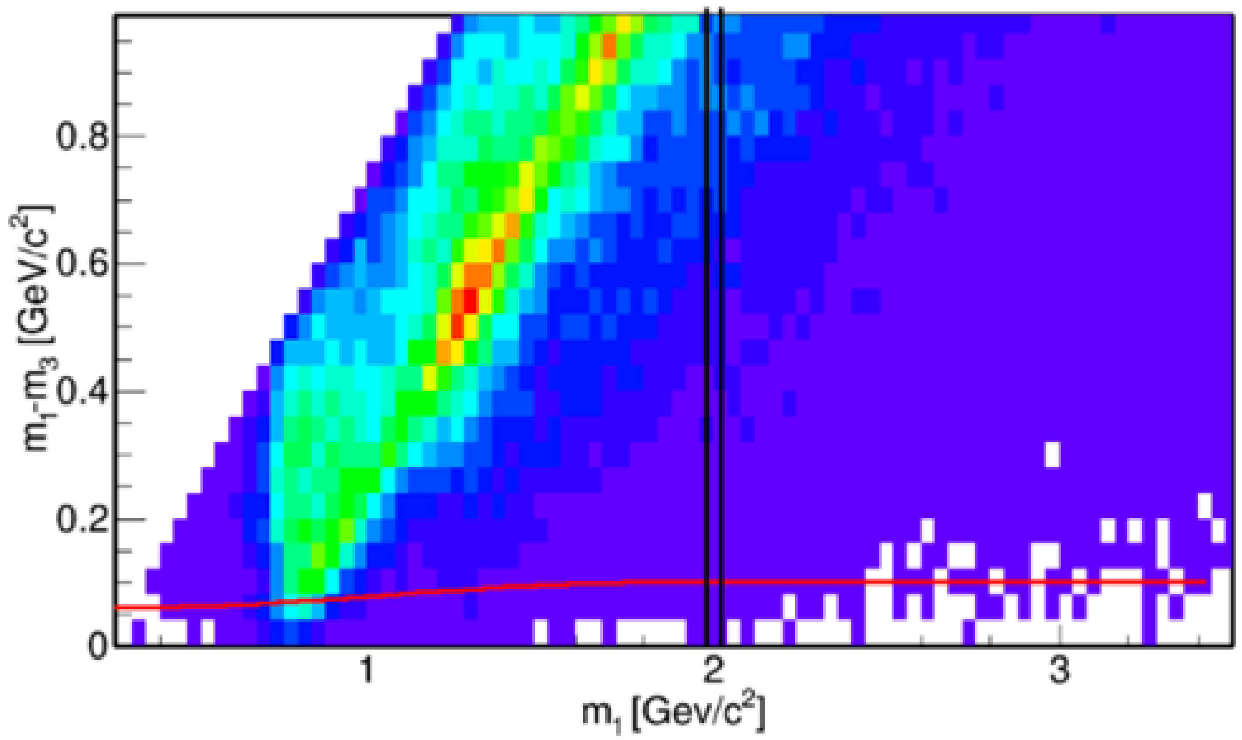


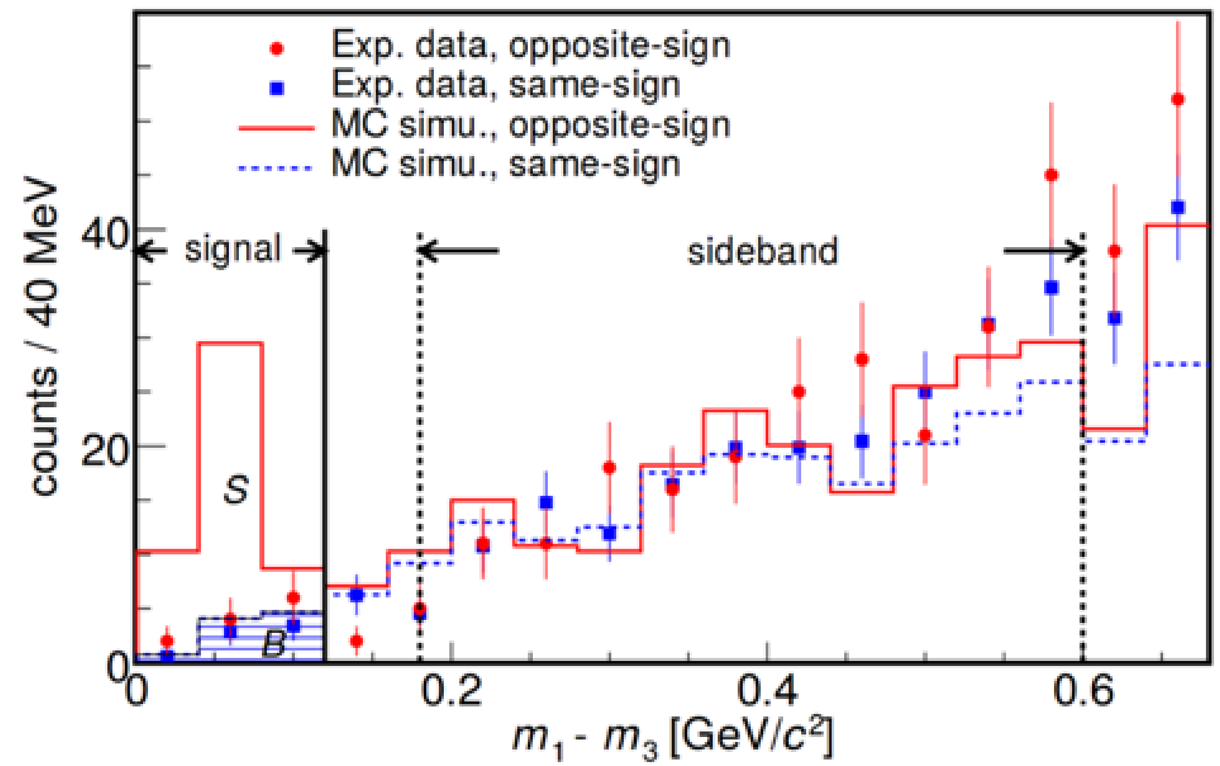
signal MC for $M_{h'} = 5$ GeV$/c^2$, $M_{A'} = 2.19$ GeV$/c^2$

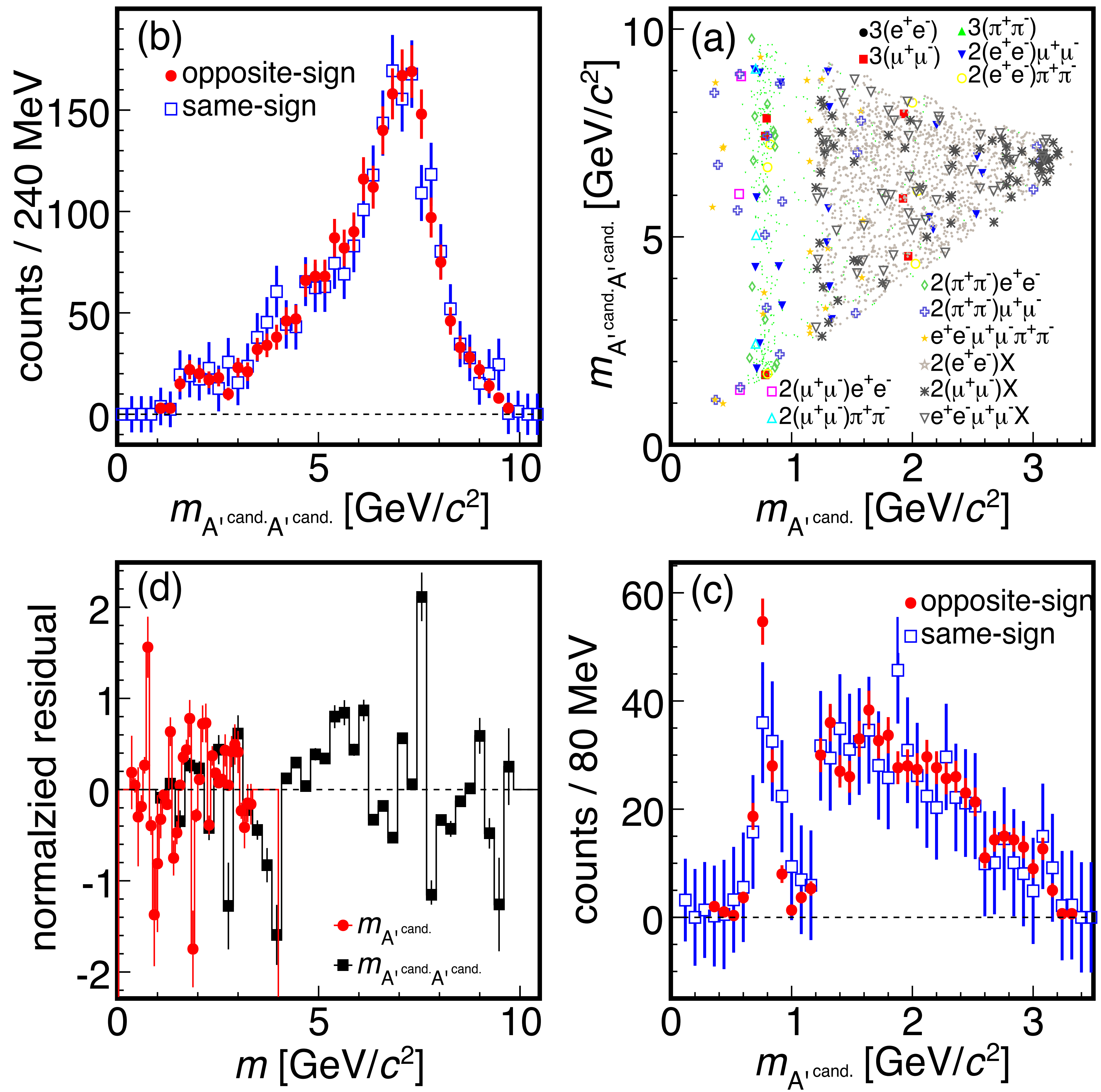
Background

- estimated using "same-sign" pairs from $e^+e^- \to (\ell^+\ell^+)(\ell^+\ell^-)(\ell^-\ell^-)$
- Sort the pairs by invariant mass, $m_1 > m_2 > m_3$
  then plot $m_1 - m_3$ vs. m_1
- For each $M_{\ell^+\ell^-}$ region, scale same-sign yield to $\ell^+\ell^-$ in the side-band, then extrapolate into the $M_{\ell^+\ell^-}$ signal region.

for 6π mode, with $m_1 = 2$ GeV$/c^2$







(b)
opposite-sign
same-sign
counts / 240 MeV
$m_{A'^{cand.}A'^{cand.}}$ [GeV/c^2]
(a)
3(e+e-)
3(π+π-)
3(μ+μ-)
2(e+e-)μ+μ-
2(e+e-)π+π-
2(π+π-)e+e-
2(π+π-)μ+μ-
e+e-μ+μ-π+π-
2(e+e-)X
2(μ+μ-)X
e+e-μ+μ-X
2(μ+μ-)e+e-
2(μ+μ-)π+π-
$m_{A'^{cand.}A'^{cand.}}$ [GeV/c^2]
$m_{A'^{cand.}}$ [GeV/c^2]
(d)
normalzied residual
$m_{A'^{cand.}}$
$m_{A'^{cand.}A'^{cand.}}$
m [GeV/c^2]
(c)
opposite-sign
same-sign
counts / 80 MeV
$m_{A'^{cand.}}$ [GeV/c^2]

Results – Limits on $\mathcal{B} \times \sigma_{\rm Born}$

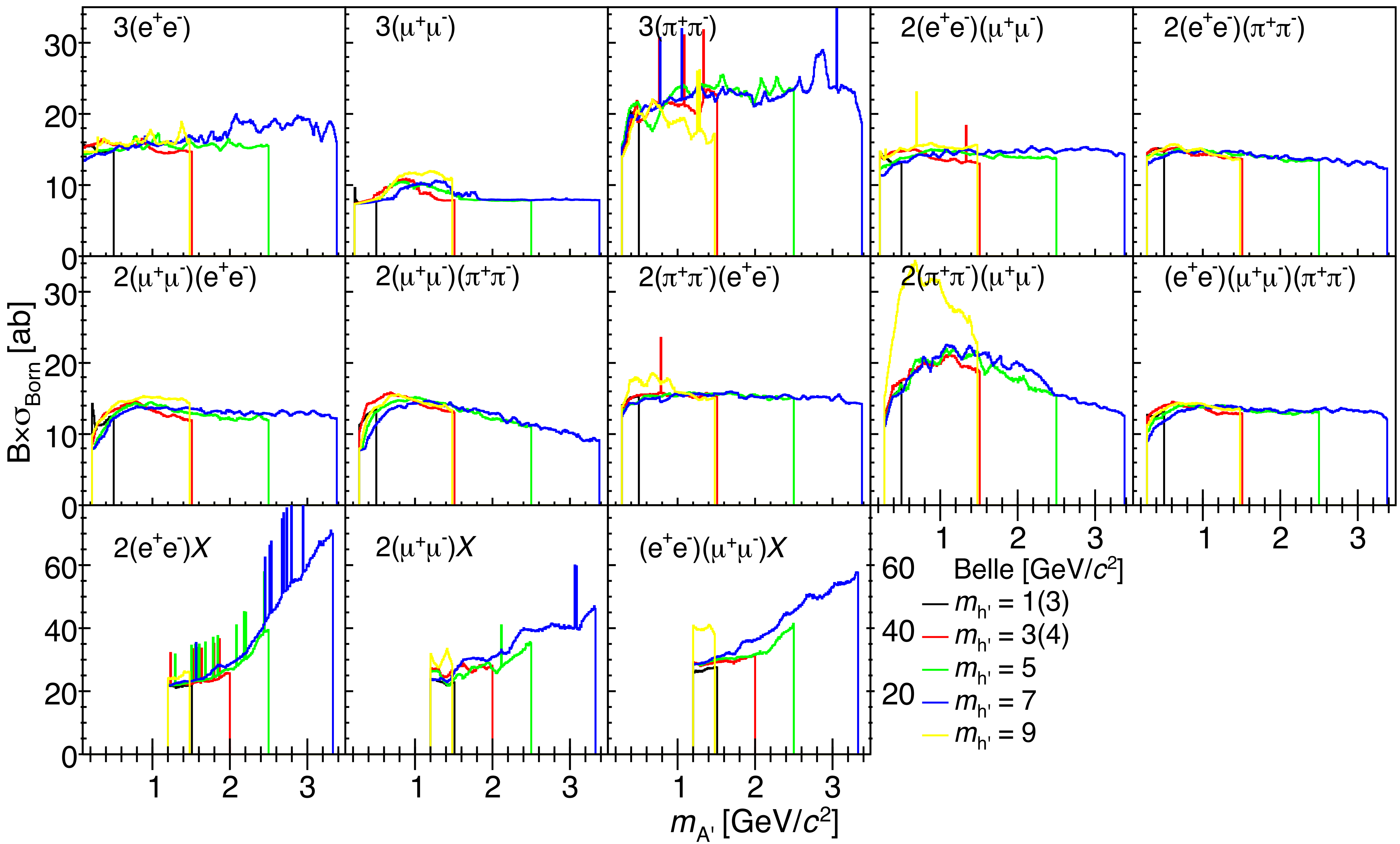
$$N_{\rm obs} = \sigma_{\rm Born}\ (1+\delta)|1-\Pi(s)|^2\ \mathcal{L}\ \mathcal{B}\ \epsilon + N_{\rm bkg}$$

- $(1+\delta)$ from E.A. Kuraev and V.S. Fadin, Sov. J. Nucl. Phys. 41, 466 (1985)
- $|1-\Pi(s)|^2$ from S. Actis *et al.*, Eur. Phys. J. C 66, 585 (2010) and F. Ignatov, http://cmd.inp.nsk.su/~ignatov/vpl/.

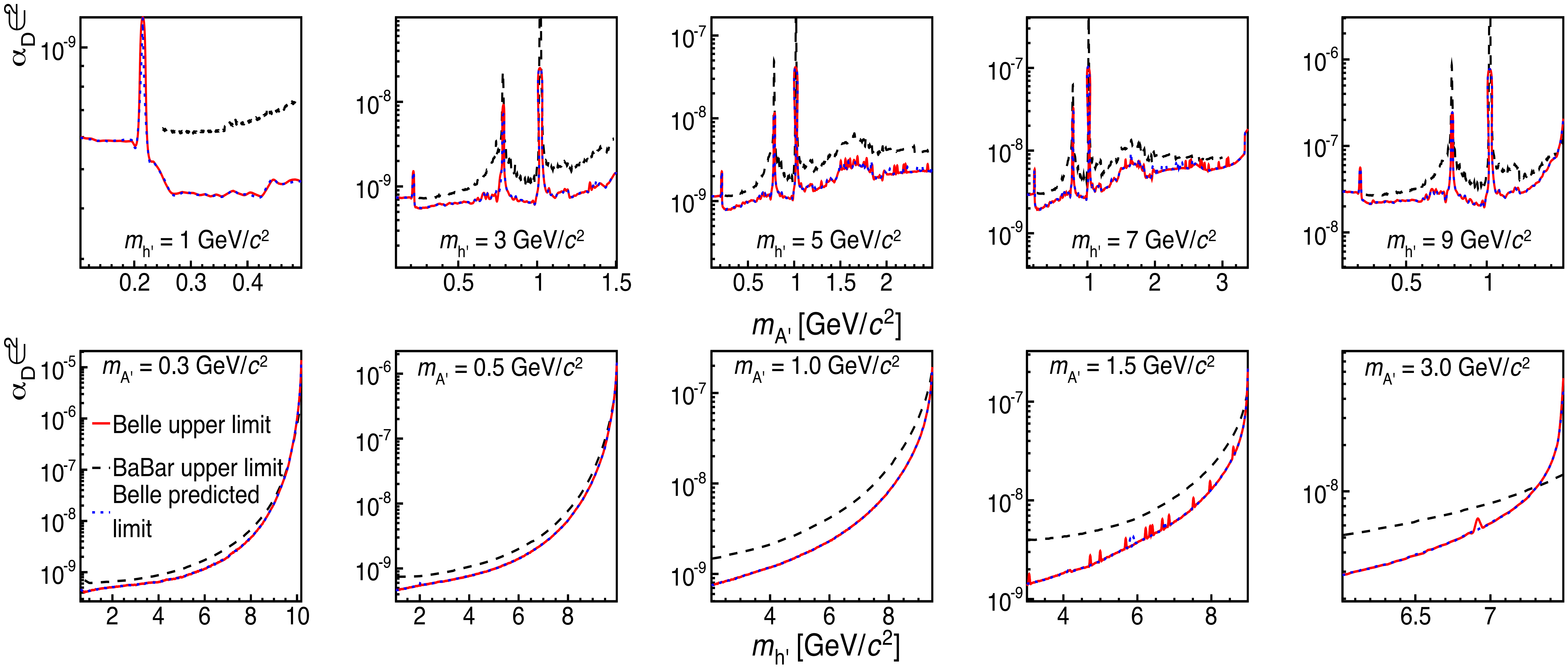
- Limits are obtined from Bayesian method, using Markov Chain Monte Carlo[1]
  - * logarithmic prior for $\sigma_{\rm Born}$
  - * gaussian prior for other parameters

[1] A. Caldwell, D. Kollar, K. Kröninger, BAT -The Bayesian Analysis Toolkit, Comp. Phys. Comm. 180, 2197 (2009).

Results – Limits on $\mathcal{B} \times \sigma_{\text{Born}}$



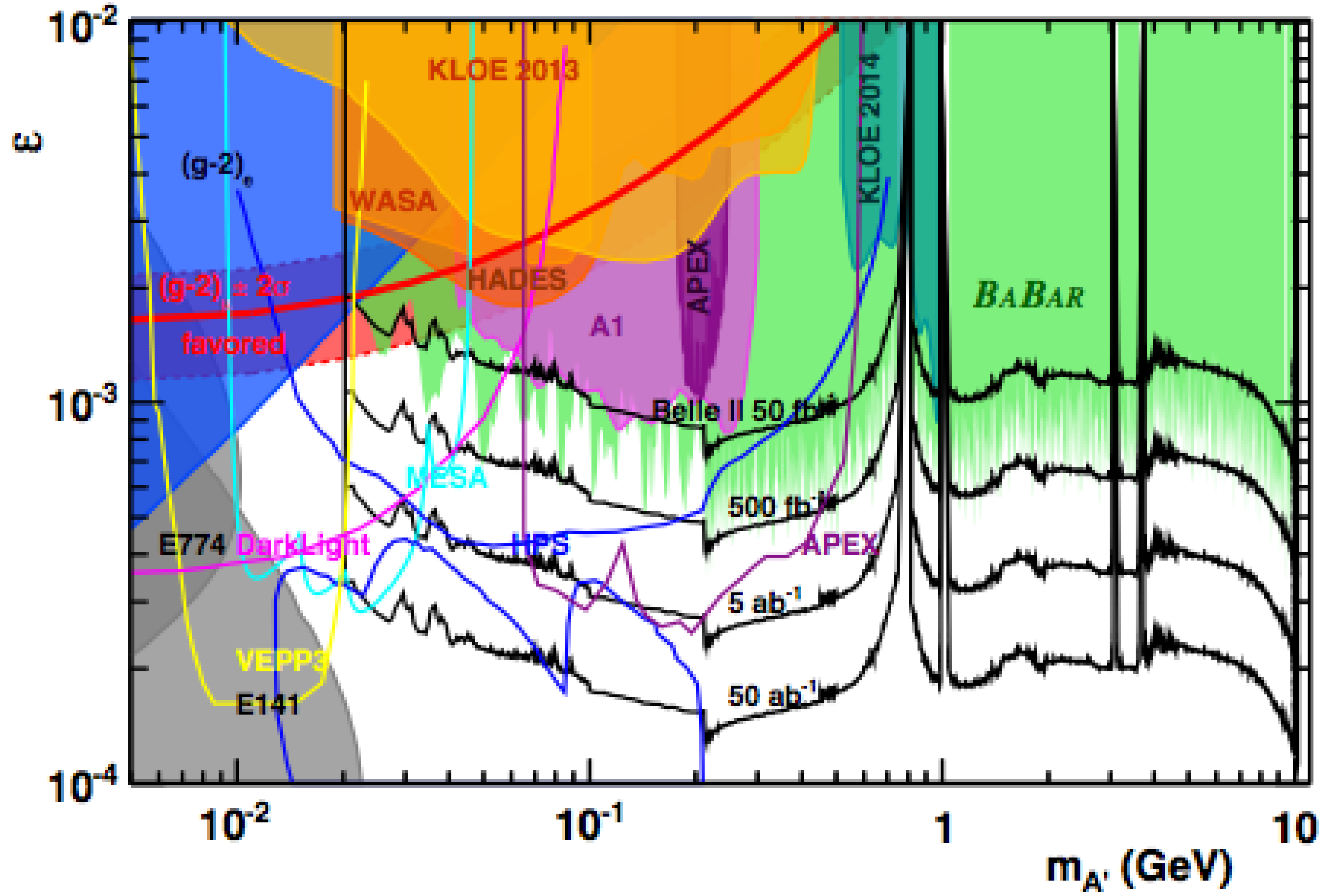
Limits on kinetic mixing parameters



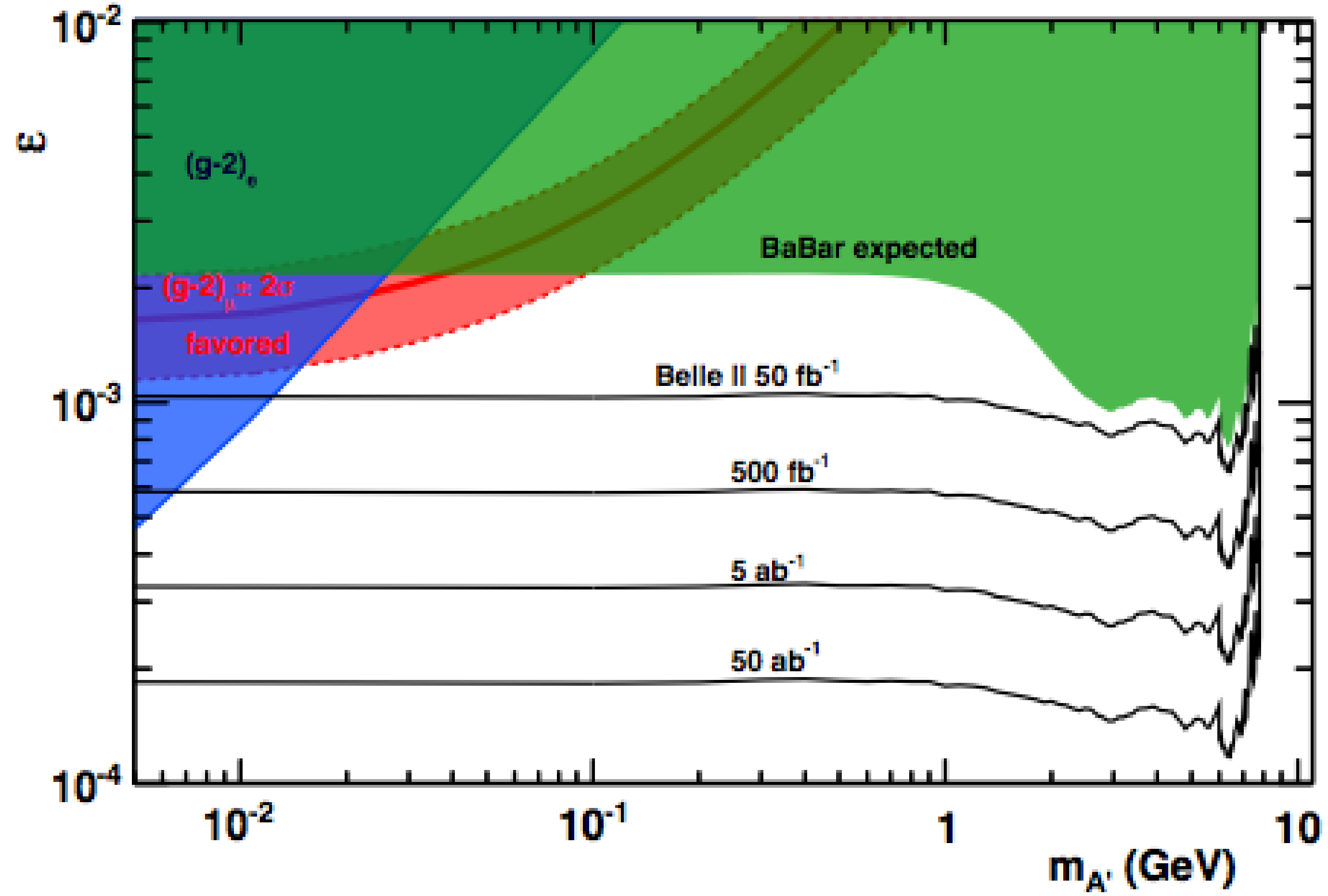
- $\epsilon \lesssim 8 \times 10^{-4}$ for $\alpha_D = 1/137$, $M_{h'} < 8$ GeV/c^2, $M_{A'} < 1$ GeV/c^2
- first limits (by any experiment) on $3(\pi^+\pi^-)$ and $2(e^+e^-)X$
- For Belle II, the improvement will be nearly linear (almost background-free for many modes)

Prospects with Belle II

$e^+e^- \to \gamma\, A'(\to \ell^+\ell^-)$



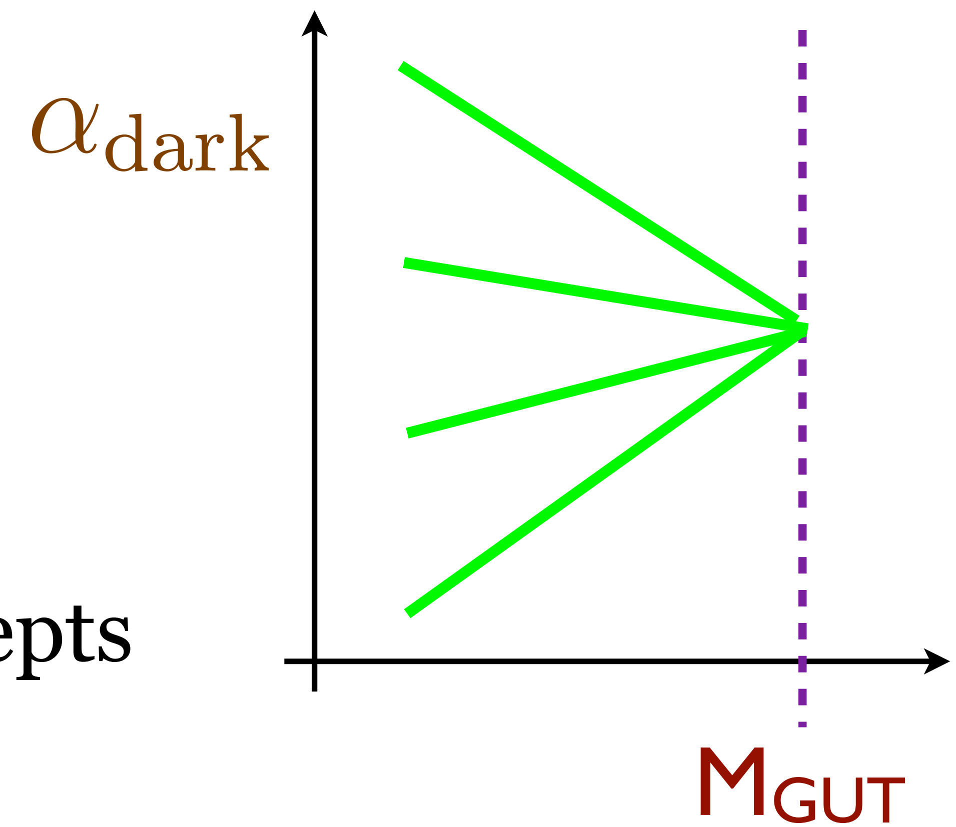
$e^+e^- \to \gamma\, A'(\to \chi\bar{\chi})$



Epilogue

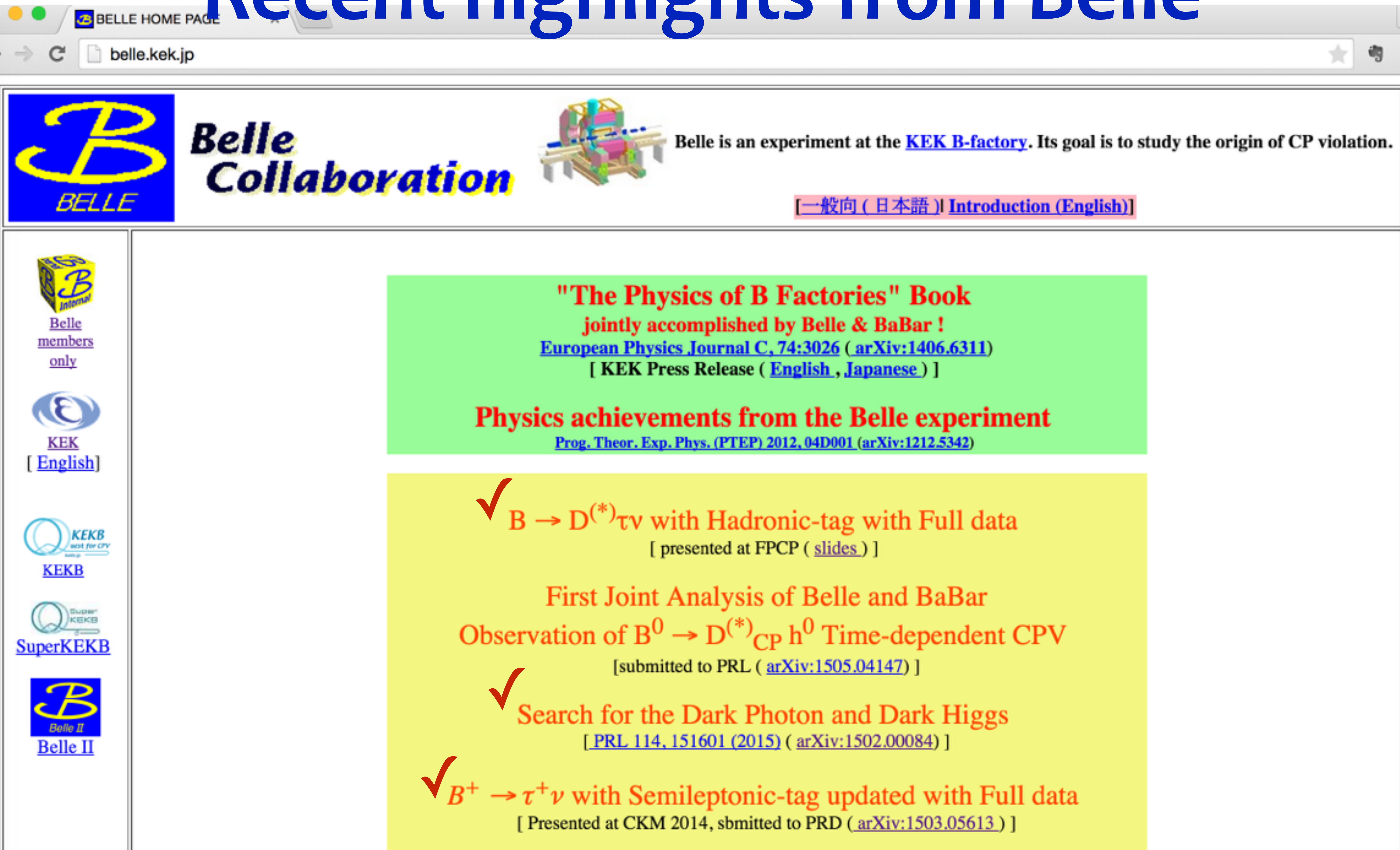
adapted from N.Arkani-Hamed talk @ DF 2009

- Two methods of probing the dark sector
  - direct detection of DM
  - use high-L / low-E collider



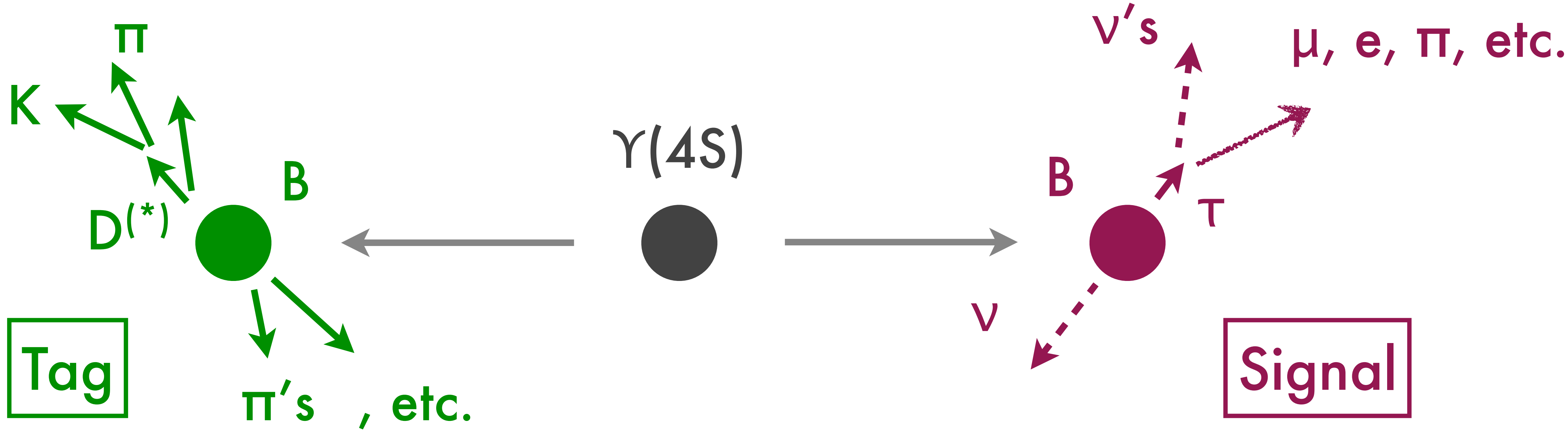
- If such a sector is discovered,
  - it could allow us to study the core concepts which we care about, *at low-E* !
  - e.g. probe SUSY & SUSY-breaking in the DS!
    - analogy: Galilei's discovery of "solar system" in Jupiter & its moons

Recent highlights from Belle



- $\mathcal{B}(B^+ \to \tau^+ \nu)$ semi-leptonic tag
- $\mathcal{B}(B \to D^{(*)} \tau^+ \nu)$

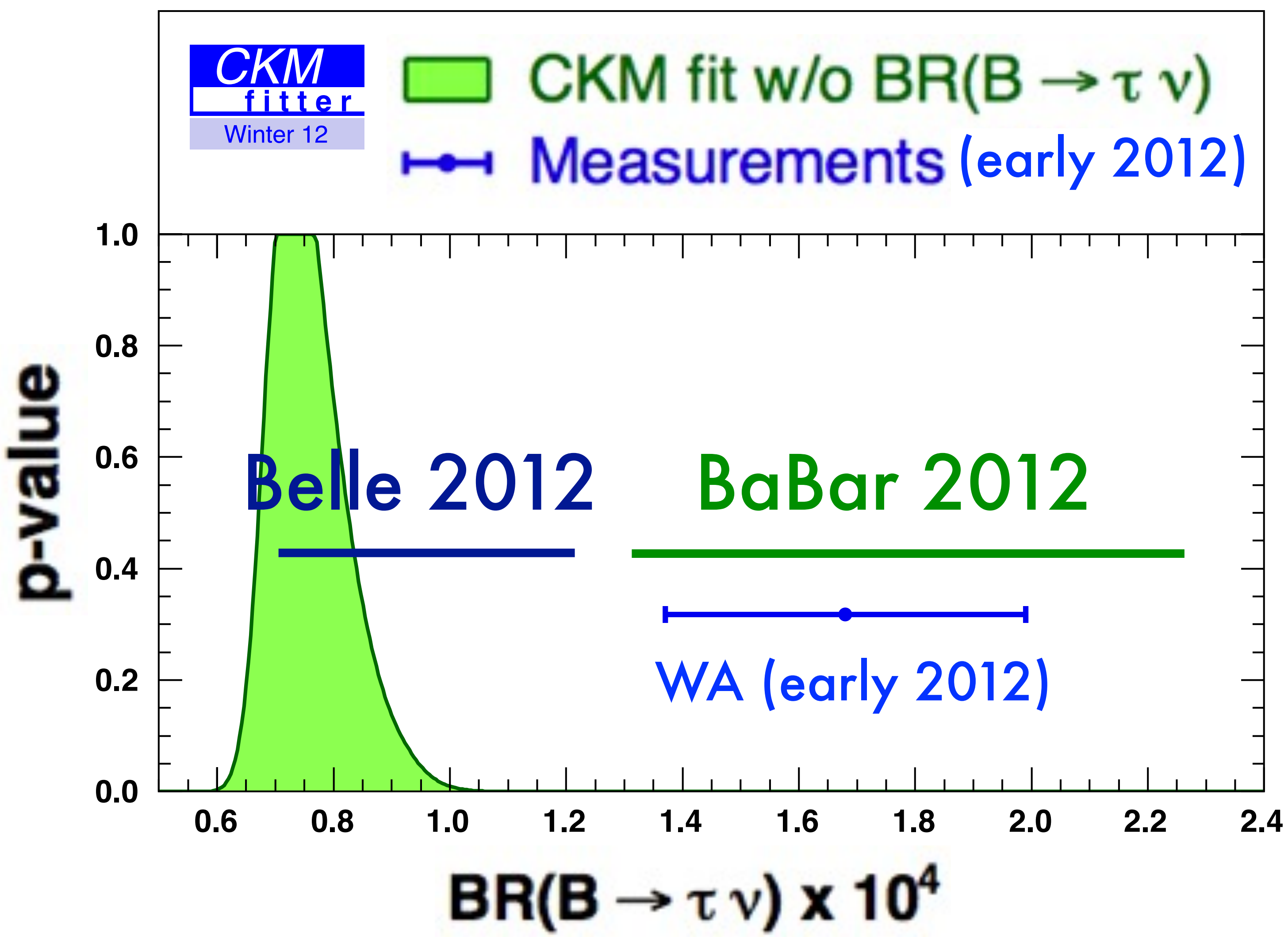
$B^+ \to \tau^+\nu_\tau$ analysis by tagging

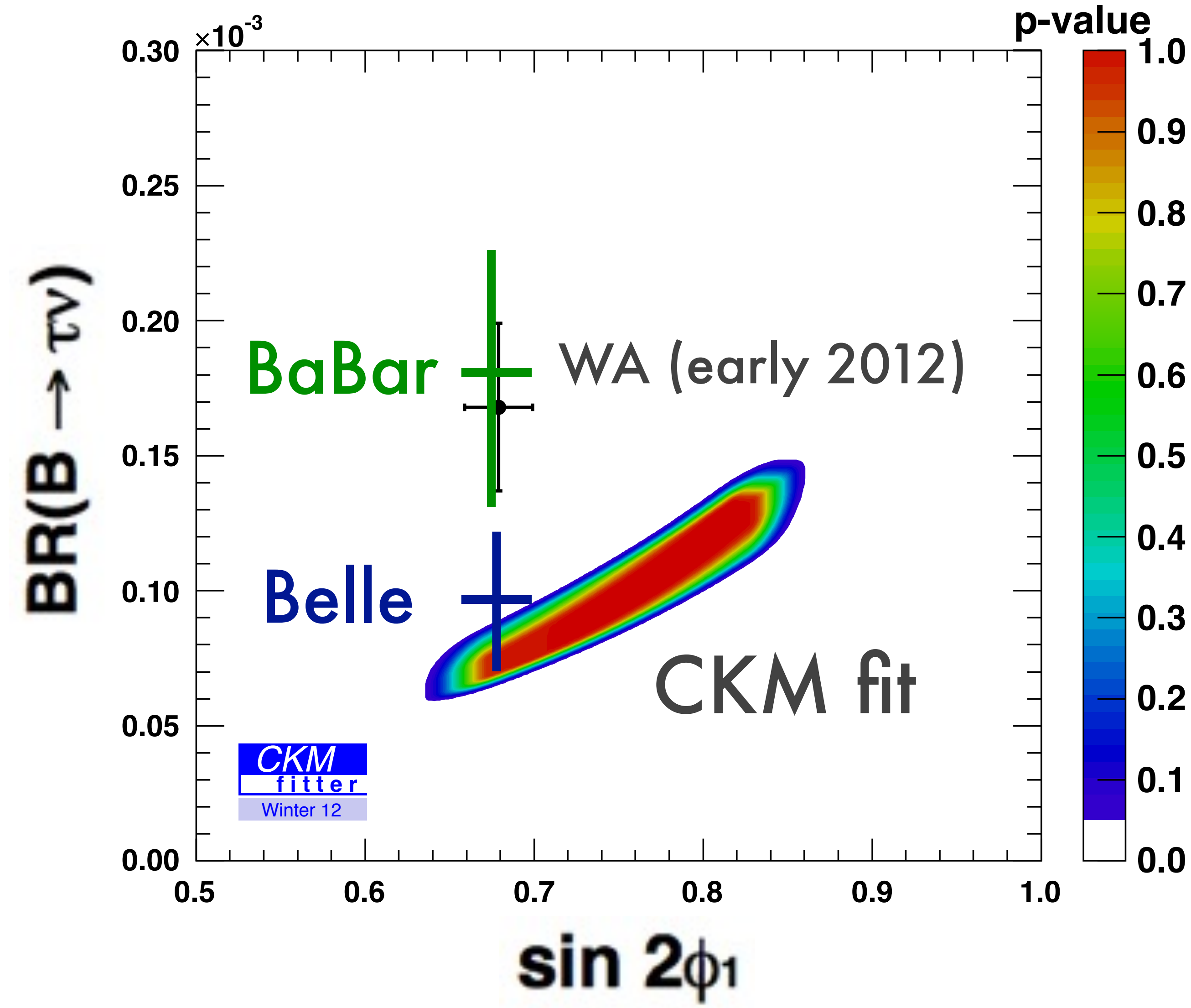


- Exploit the reaction process $e^+e^- \to \Upsilon(4S) \to B\overline{B}$
  * two B's and nothing else in the final state
  * hence, tight constraints on the signal B ("B_{sig}"), by measuring the other B ("B_{tag}")

- Two different methods of tagging
  * hadronic tag: use fully-reconstructed hadronic B_{tag} decays
  * semileptonic tag: use $B \to D^{(*)}\ell^+\nu_\ell$

    missing one ν_ℓ, but clean and plentiful enough to compensate for it

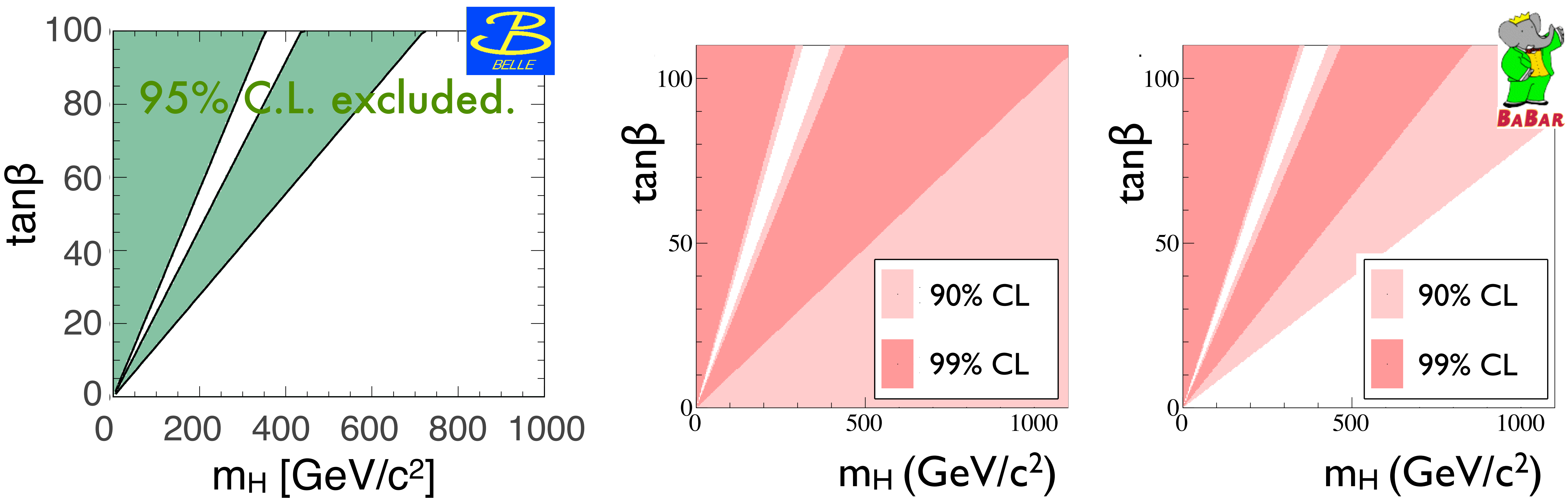

CKM fitter
Winter 12
CKM fit w/o BR(B → τ ν)
Measurements (early 2012)
Belle 2012
BaBar 2012
WA (early 2012)
p-value
BR(B → τ ν) x 10^4


×10^-3
p-value
BaBar
WA (early 2012)
Belle
CKM fit
CKM fitter
Winter 12
BR(B → τν)
sin 2φ1

$B^+ \to \tau^+\nu_\tau$ constraints on charged Higgs

- Assuming 2-Higgs doublet model (type II),

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \mathcal{B}_{\rm SM}(B^+ \to \tau^+\nu_\tau) \times \left[1 - (m_B^2/m_H^2)\tan^2\beta\right]^2$$



V_{ub} from excl.+incl. b→ulν

V_{ub} from exclusive b→ulν

V_{ub} from inclusive b→ulν

Update of B → τν with Semileptonic Tag

NEW

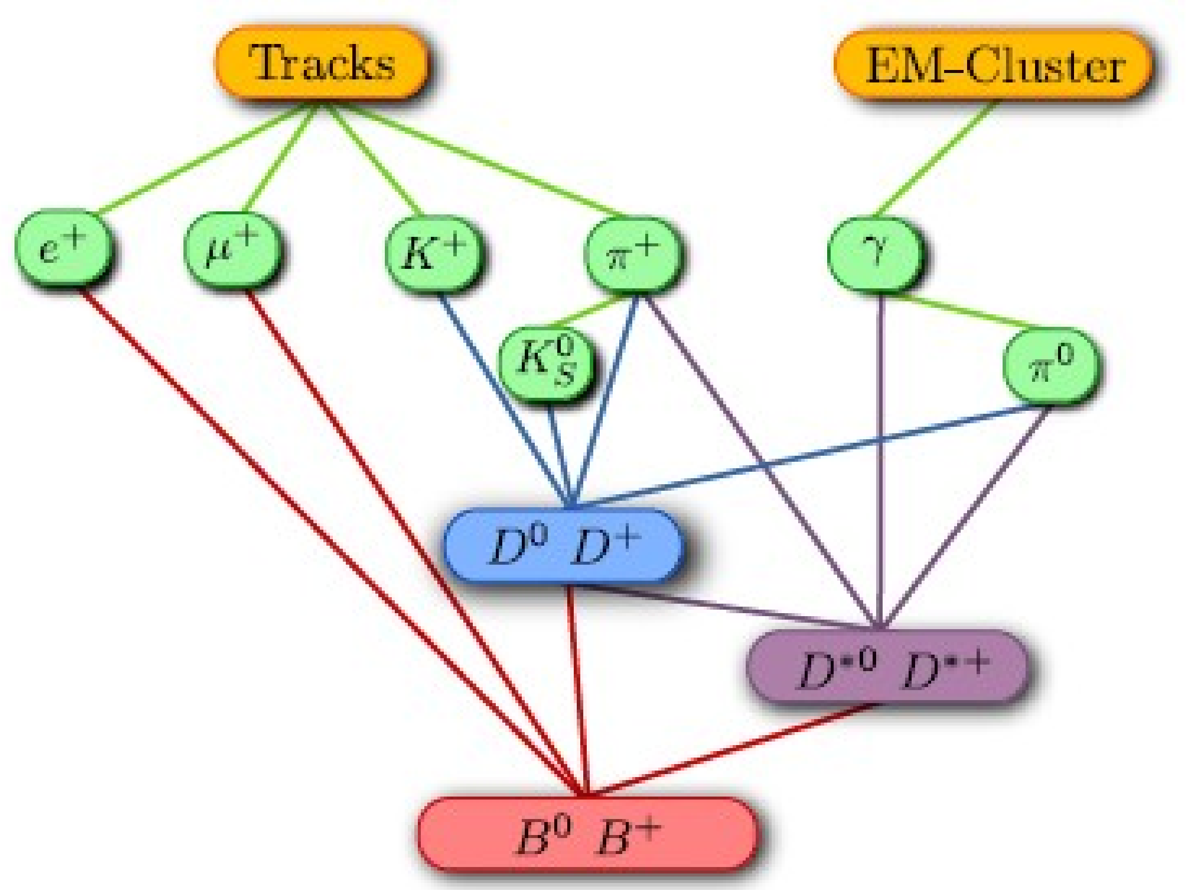
- Improvements compared to previous analysis (PRD 82, 071101 (2010), 657M B$\bar{B}$)
- ✔ Full Belle dataset (772M B$\bar{B}$)
- ✔ Reprocessed data
- ✔ Additional tau decay channel
- ✔ Improved semi-leptonic tag
- ✔ Reoptimized selection
- ✔ Data-driven continuum background estimation
- ✔ 2D fit for signal extraction

Efficiencies [10^{-4}] of reconstructed $\tau \to X\nu$ decay modes

Final State	e^+	μ^+	π^+	$\pi^+\pi^0$
e^+	6.6 ± 0.1	0.1 ± 0.0	0.2 ± 0.0	0.1 ± 0.0
μ^+	0.1 ± 0.0	4.7 ± 0.1	0.6 ± 0.0	0.2 ± 0.0
π^+	0	0.1 ± 0.0	1.6 ± 0.0	0.5 ± 0.0
$\pi^+\pi^0$	0	0.1 ± 0.0	1.4 ± 0.0	4.9 ± 0.1
$\pi^+\pi^0\pi^0$	0	0	0.2 ± 0.0	1.3 ± 0.0
Other	0	0	0.1 ± 0.0	0.2 ± 0.0
All	6.8 ± 0.1	5.1 ± 0.1	4.0 ± 0.0	7.2 ± 0.1
Total	23.1 ± 0.1			

Improved Semileptonic Tag

- Hierarchical system similar to new hadronic tag
- ➔ Multivariate classifiers (NeuroBayes)
- ➔ More D^0 decay channels

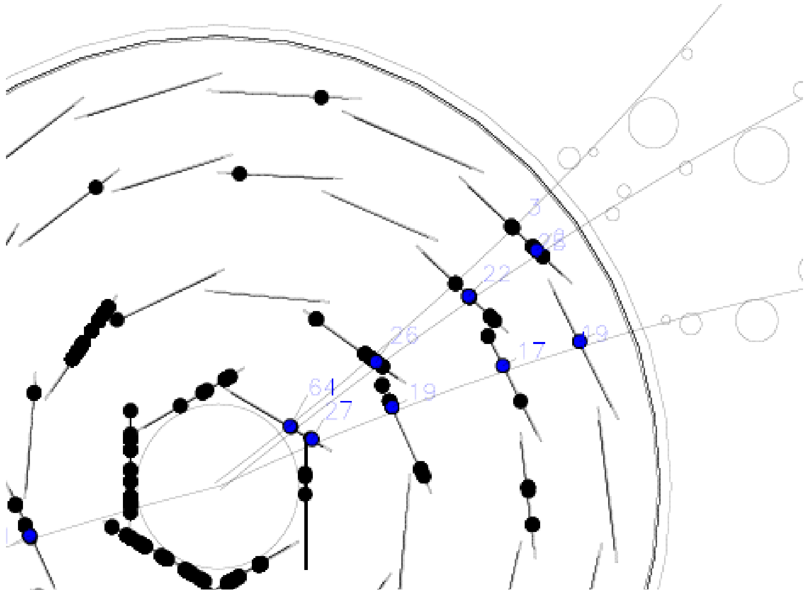


Decay Channel	Branching Fraction (%)
$D^0 \to K^- \pi^+ \pi^0$	13.9 ± 0.5
$D^0 \to K^- \pi^+ \pi^+ \pi^-$	8.1 ± 0.2
$D^0 \to K_S^0\ \pi^+ \pi^- \pi^0$	5.2 ± 0.6
$D^0 \to K^- \pi^+$	3.9 ± 0.1
$D^0 \to K_S^0\ \pi^+ \pi^-$	2.8 ± 0.2
$D^0 \to \pi^+ \pi^- \pi^0$	1.4 ± 0.1
$D^0 \to K_S^0\ \pi^0$	1.2 ± 0.1
$D^0 \to K_S^0\ K^+ K^-$	0.5 ± 0.03
$D^0 \to K^+ K^-$	0.4 ± 0.01
$D^0 \to \pi^+ \pi^-$	0.1 ± 0.003
Sum	37.5 ± 0.85

Reoptimized Selection

$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E_{\mathrm{beam}}E_{D^{(*)}\ell} - m_B^2 - m_{D^{(*)}\ell}^2}{2p_B^* p_{D^{(*)}\ell}^*}$$

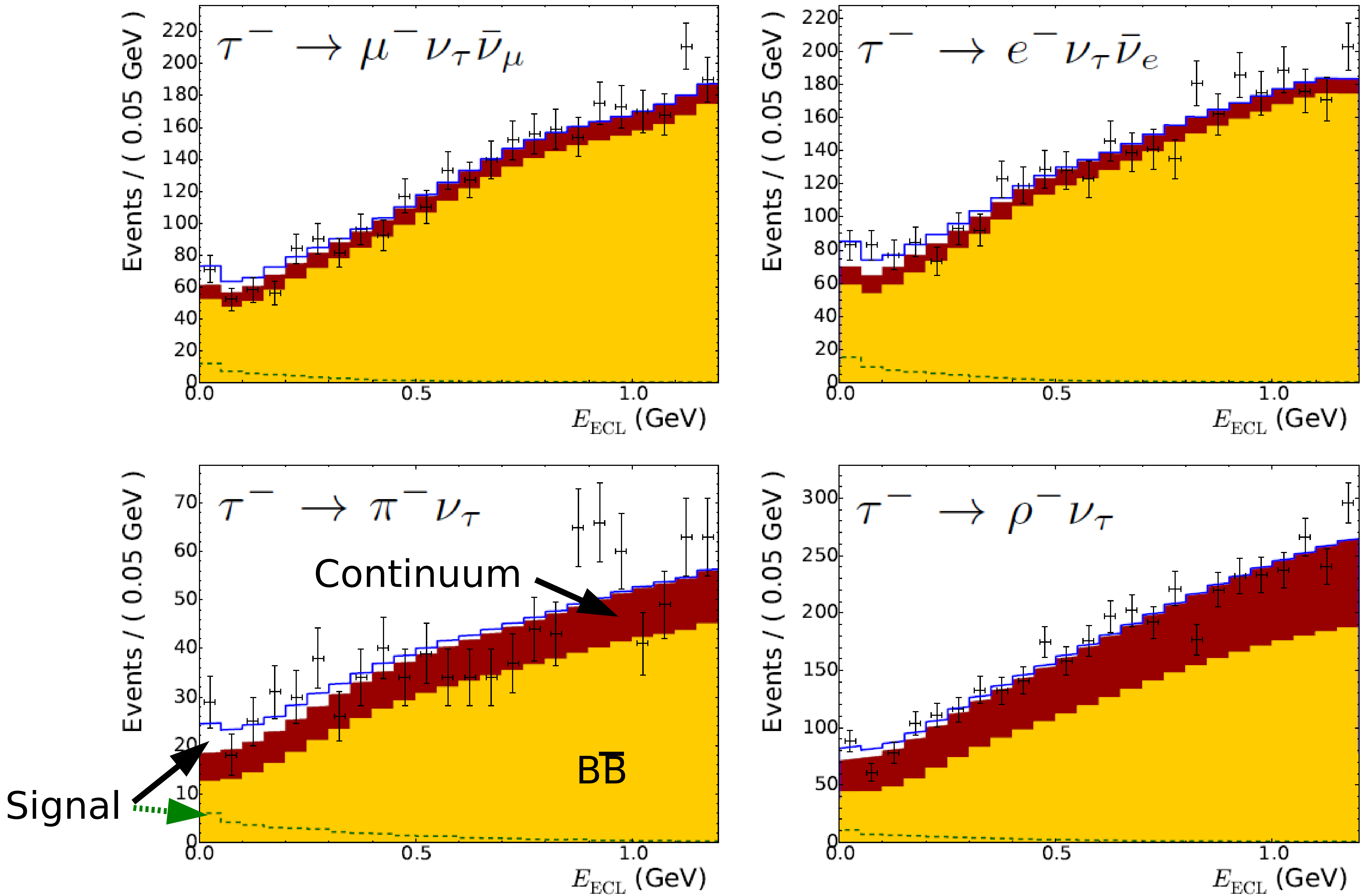
- Selection on momenta, impact parameters, tag quality, K/π PID, ρ mass, and $\cos\theta_{B,D(*)\ell}$ chosen to maximize signal significance
- Events with additional tracks or π^0 not from $B_{sig/tag}$ rejected
  - ➔ Selection of tracks for veto optimized
- Large continuum background for hadronic tau decays
  - ➔ Multivariate continuum suppression algorithm using 27 event shape variables
- Background from conversions in electron channel
  - ➔ Rejection of candidates with low track pair mass



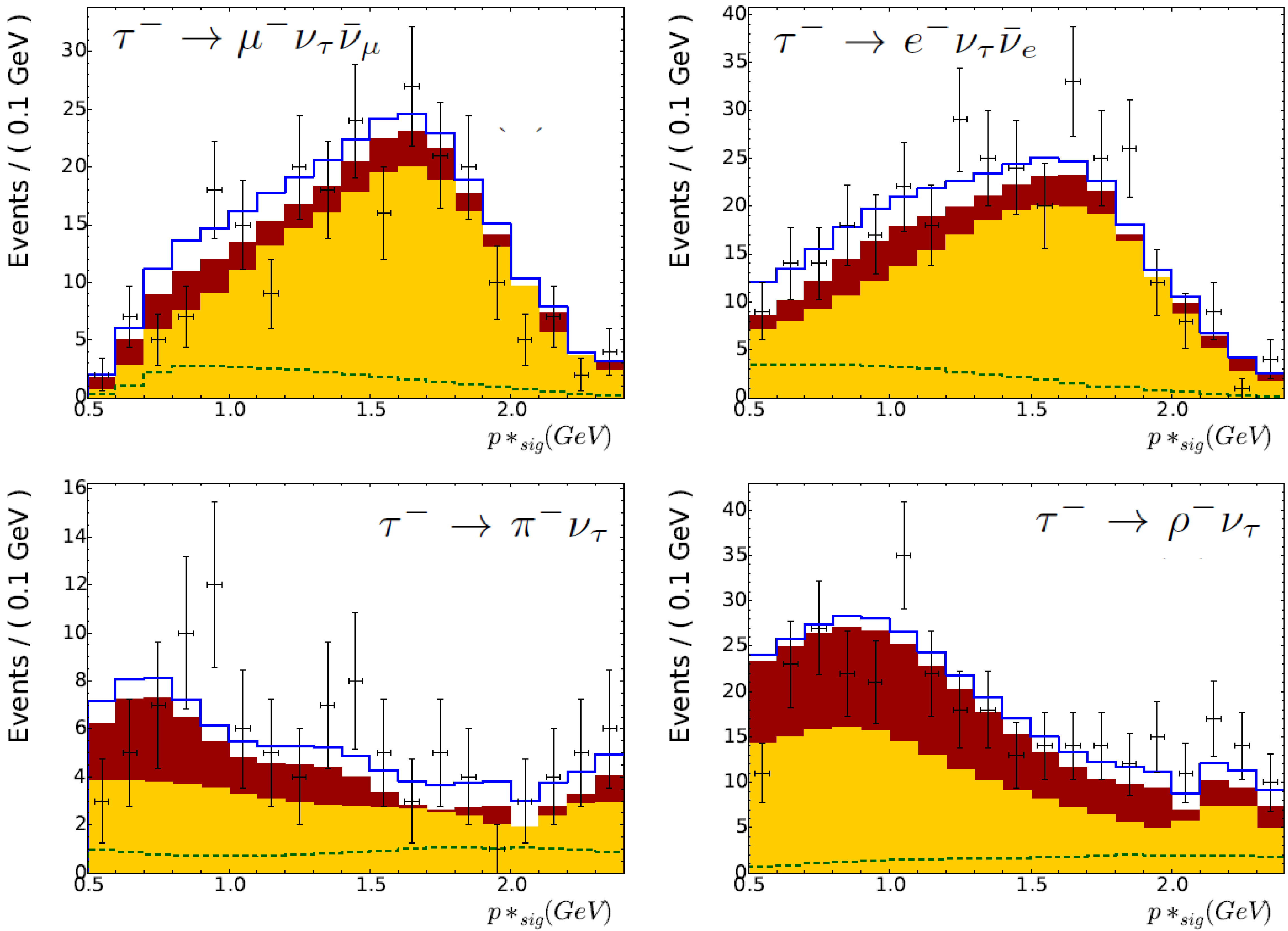
$B^+ \to \tau^+\nu$ signal extraction

- 2D binned max. likelihood fit of
  - $E_{\rm ECL}$: extra energy in the calorimeter not from $B_{\rm sig}$ nor $B_{\rm tag}$
  - $p^*_{\rm sig}$: momentum in CM of τ daughter particle(s)
- Fit functions: product of 1D PDF's, except for τ signal in hadronic modes (2D histogram)
- Signal and $B\bar{B}$ background shapes from MC
- Continuum background shapes from off-resonance data
- Relative size of continuum and $B\bar{B}$ is fixed
- Fit parameters
  - signal BF
  - background normalization for each τ mode

E_{ECL} fit projections



p^*_{sig} fit projections in E_{ECL} signal region

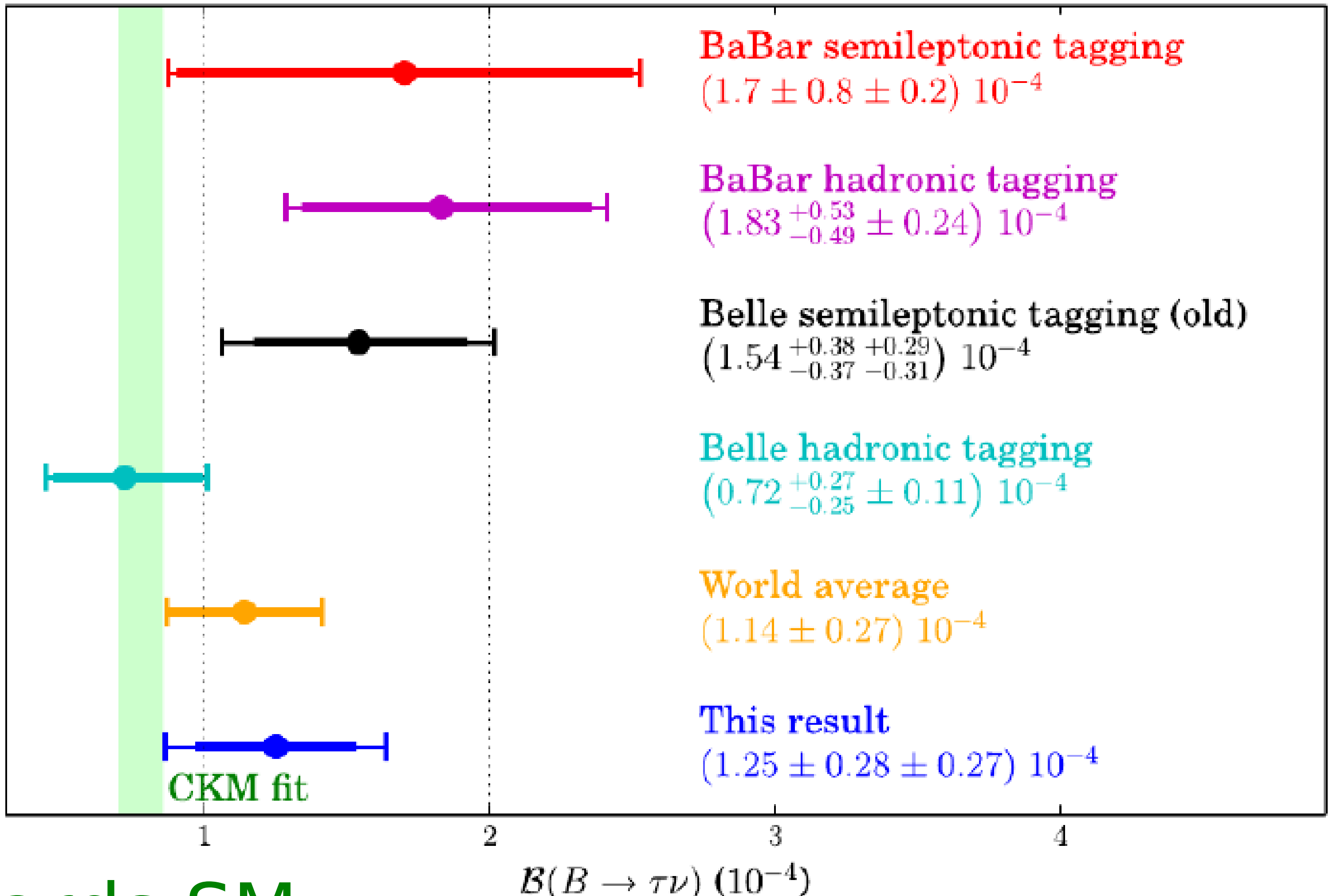


Results

- $\mathcal{B}(B \to \tau\nu) = [1.25 \pm 0.28\ (\text{stat}) \pm 0.27\ (\text{syst})] \times 10^{-4}$
- Signal significance of 3.4σ including systematics

Decay Mode	N_{sig}	$\mathcal{B}(10^{-4})$
$\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$	13±21	0.34±0.55
$\tau^- \to e^- \nu_\tau \bar{\nu}_e$	47±25	0.90±0.47
$\tau^- \to \pi^- \nu_\tau$	57±21	1.82±0.68
$\tau^- \to \rho^- \nu_\tau$	119±33	2.16±0.60
Combined	222±50	1.25±0.28

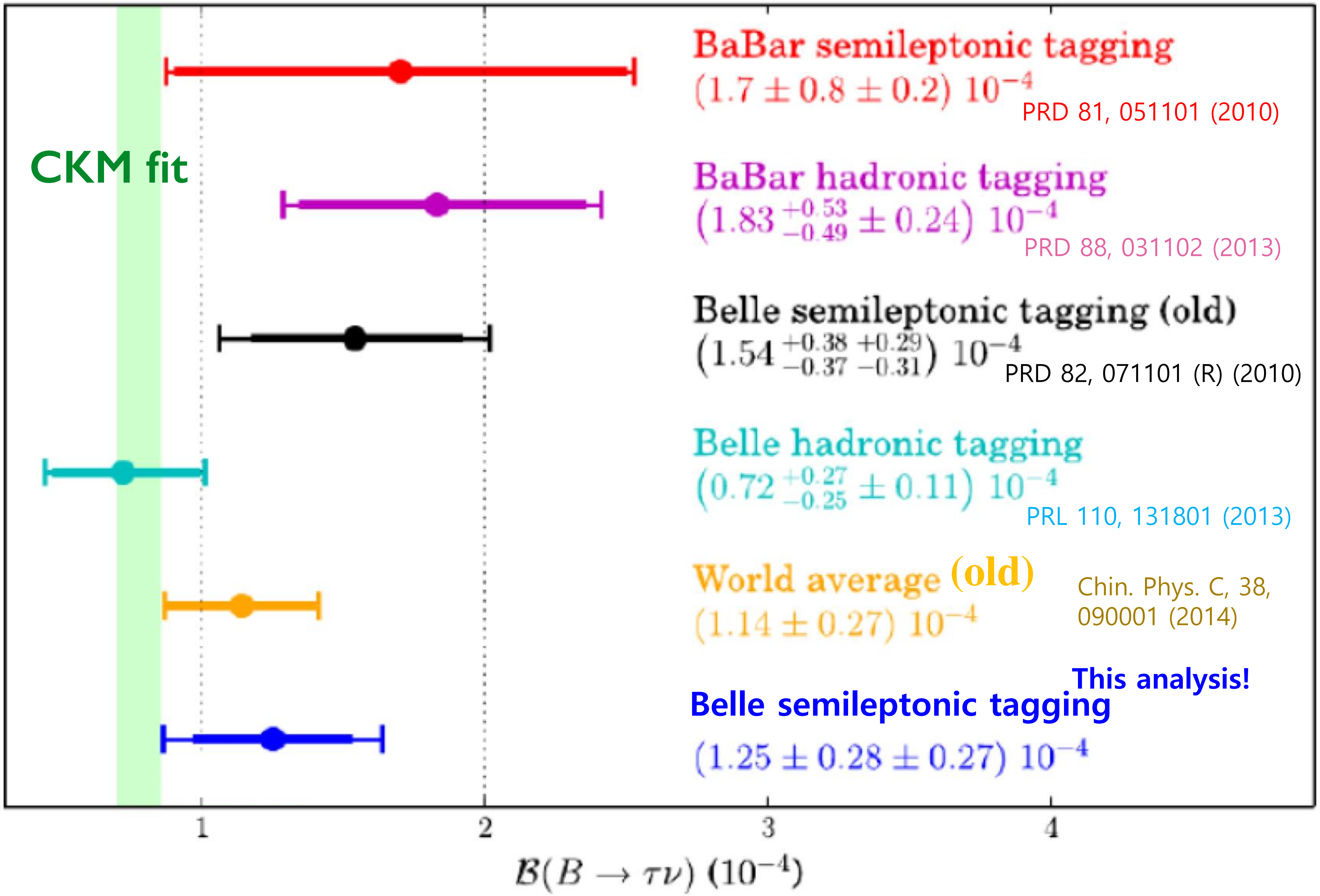
statistical errors only



- Consistent results among tau channels

→ Central value shifted towards SM

- Combination with Belle hadronic tag result in progress



$$B.F._{Belle}(B \to \tau\nu) = [0.91 \pm 0.19(stat.) \pm 0.11(syst.)] \times 10^{-4}$$

The new world average not available yet.

$$\mathcal{B}(B \to \overline{D}^{(*)} \tau^+ \nu)$$

Hot off the press, just presented a week ago!

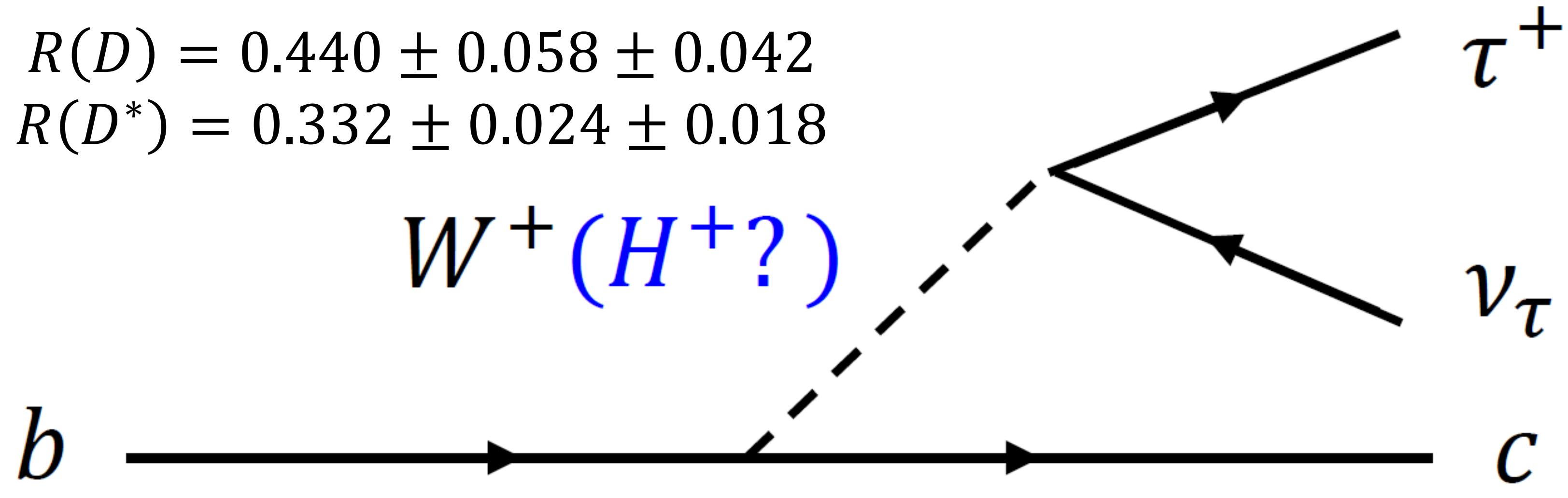
by T. Kuhr (LMU, Munich) @ FPCP 2015

The slides shown today are made by Mr. Youngmin Yook (Yonsei) for Blois 2015 presentation this week.

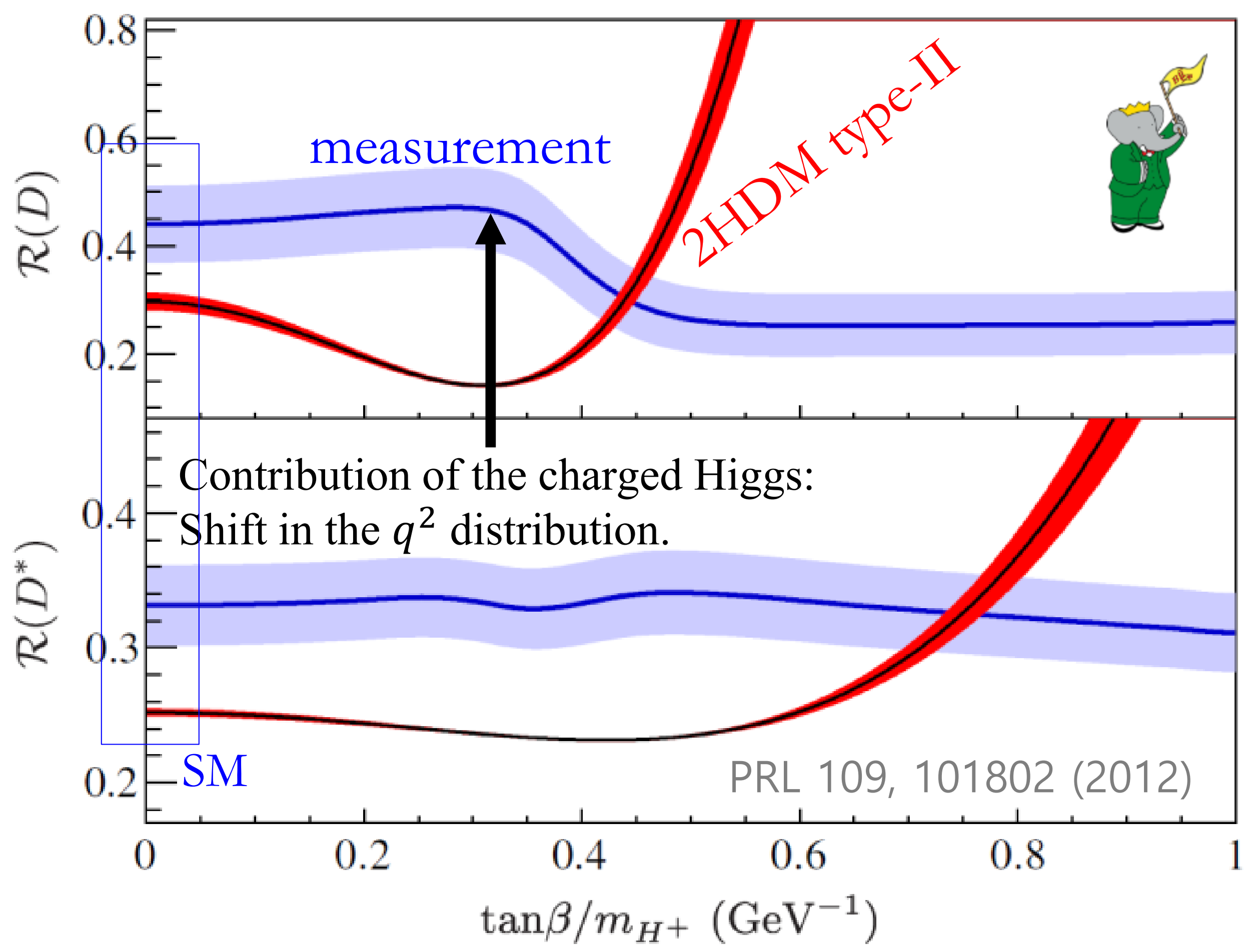
Physics Motivations

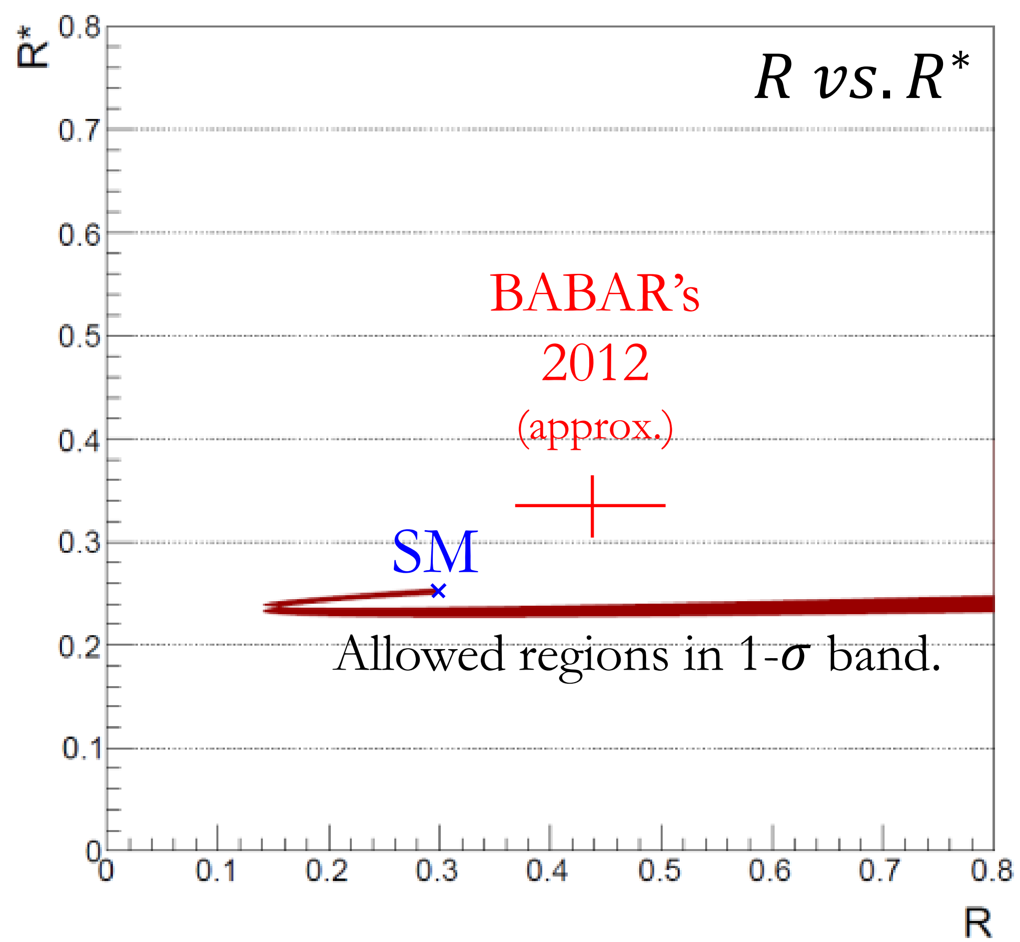
A little bit more in the case of 2HDM type-II

$R(D) = 0.440 \pm 0.058 \pm 0.042$
$R(D^*) = 0.332 \pm 0.024 \pm 0.018$



$R(R^*)$ each matches for
$tan\beta/m_{H^+} = 0.44 \pm 0.02\ (0.75 \pm 0.04)\ GeV^{-1}$





2HDM type-II
at the verge?

$B \to D^{(*)}\tau\nu$ Hadronic tagging

A new hadronic tagging analysis from Belle

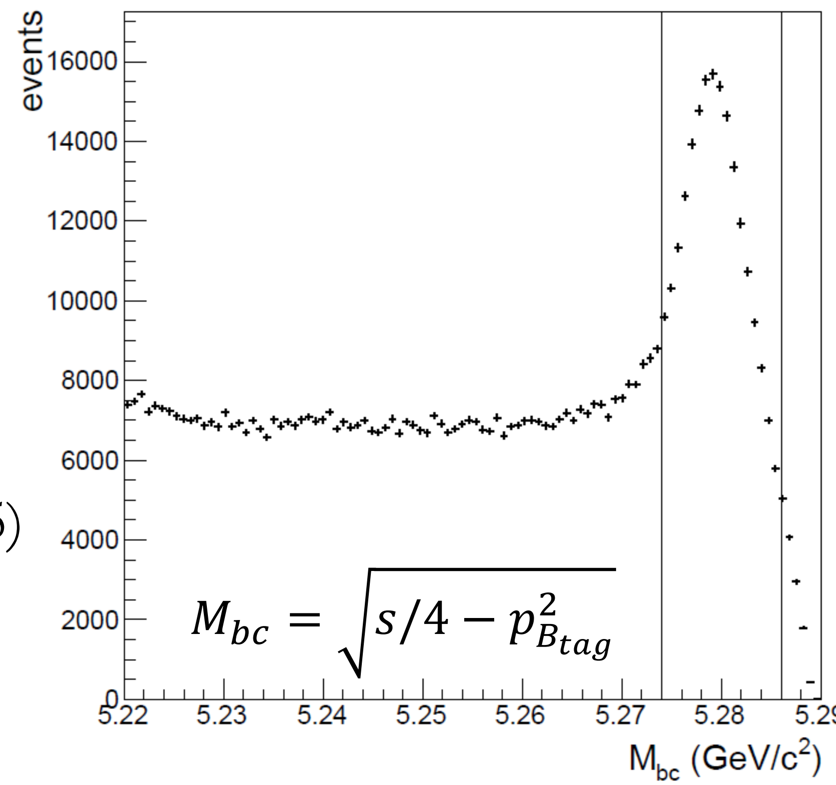
B_{tag} side

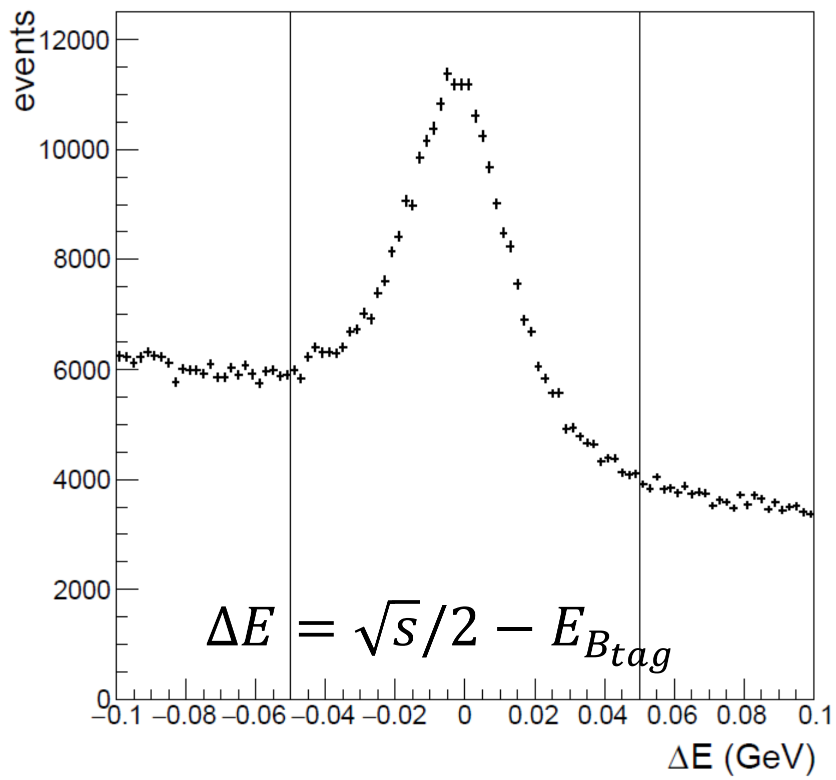
NIMS A654: 432 (2011)

- A hadronic tagging analysis
- B_{tag} quality control @ purity of 85%
- Efficiency correction done in:

  Well-tagged → $D^{(*)}\ell\nu$ control sample

  Wrong-tagged → M_{bc} sideband of (5.23-5.25)





before the selections are applied

B_{sig} side

Interested in leptonic τ decays: same final state as $B \to D^{(*)}\ell\nu$

The 4 "$D^{(*)}\ell$" final state channels reconstructed in:

$D^+[K^-\pi^+\pi^+, K^0_S\pi^+, K^0_S\pi^+\pi^0, K^0_S(3\pi)^+]$

$D^0[K^-\pi^+, K^-(3\pi)^+, K^-\pi^+\pi^0, K^0_S\pi^0]$

$D^{*+}[D^0\pi^+, D^+\pi^0]$ / $D^{*0}[D^0\pi^0, D^0\gamma]$

$B \to D^{(*)}\tau\nu$ Hadronic tagging

Signal selection and M^2_{miss} disribution

- Kinematical cuts to remove backgrounds from continuum and $b \to u\ell\nu$ processes
- Interested in $-0.2 < M^2_{miss} < 8.0\ GeV^2/c^4$

$$M^2_{miss} = \left(P_{beam} - P_{B_{tag}} - P_{D^{(*)}} - P_{\ell}\right)^2$$

Fit strategy

Perform simultaneous extended ML fit for all 4 reconstruction channels with 12 free parameters:

- 4 from $D^{(*)}\ell\nu$ signal / channel
- 2 from $D\ell\nu$ channel's $D^*\ell$ cross-feeds in $D\ell$ channels
- 4 from $D^{**}\ell\nu$ BG / channel
- 2 left are $R(D)$ & $R(D^*)$ assuming isospin symmetry

Validated with pseudo experiments, no bias in fit nor M^2_{miss} splitting.

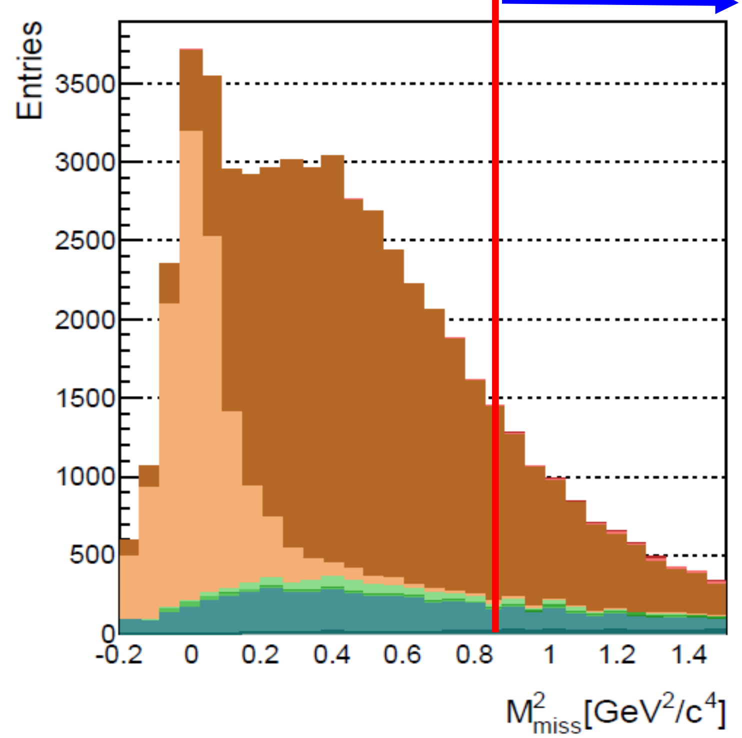
$D^{**}\ell\nu$ background MC validated with data sample w/ an additional π^0 from fits to M^2_{miss} & $o_{NB,trafo}$'s input variables.

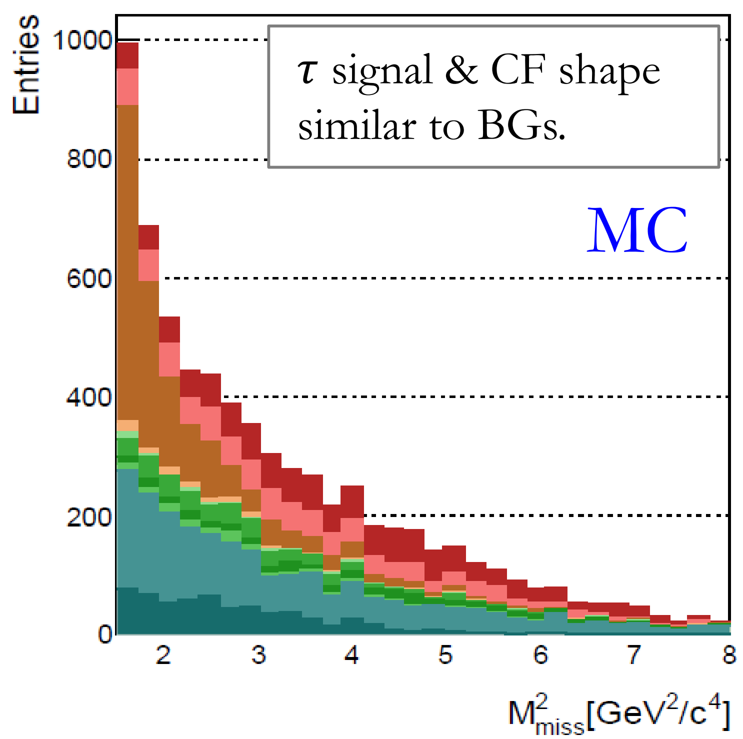
Fit in M^2_{miss}

$M_{miss} = 0.85\ GeV^2/c^4$ line

$D^{(*)}\ell\nu$ enhanced region

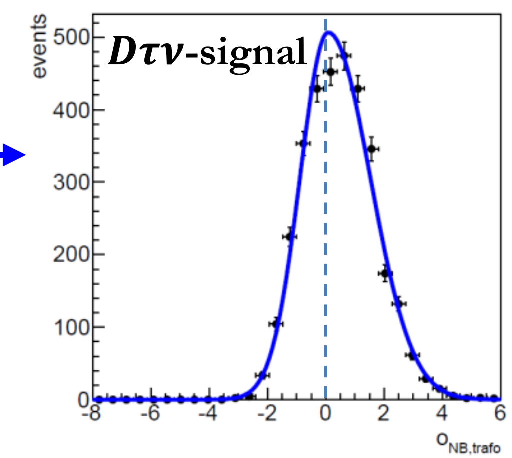
$D^{(*)}\tau\nu$ enhanced region

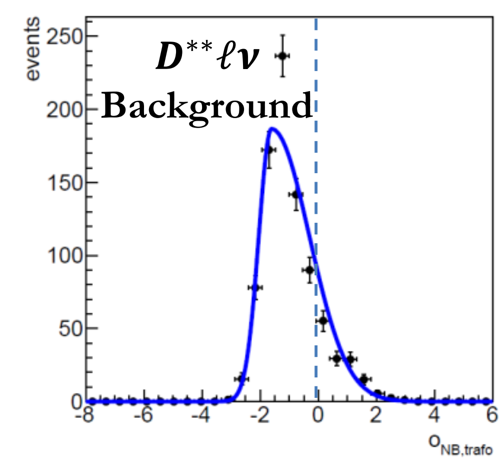




Fit in a NN output

$o_{NB,trafo}$



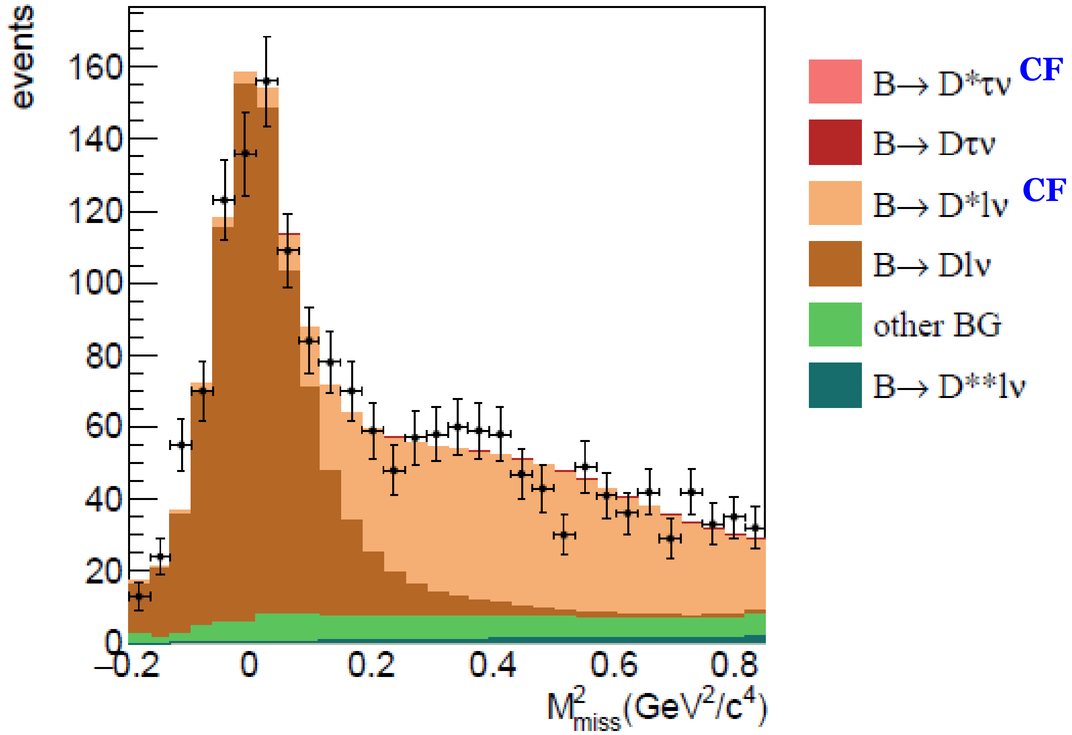


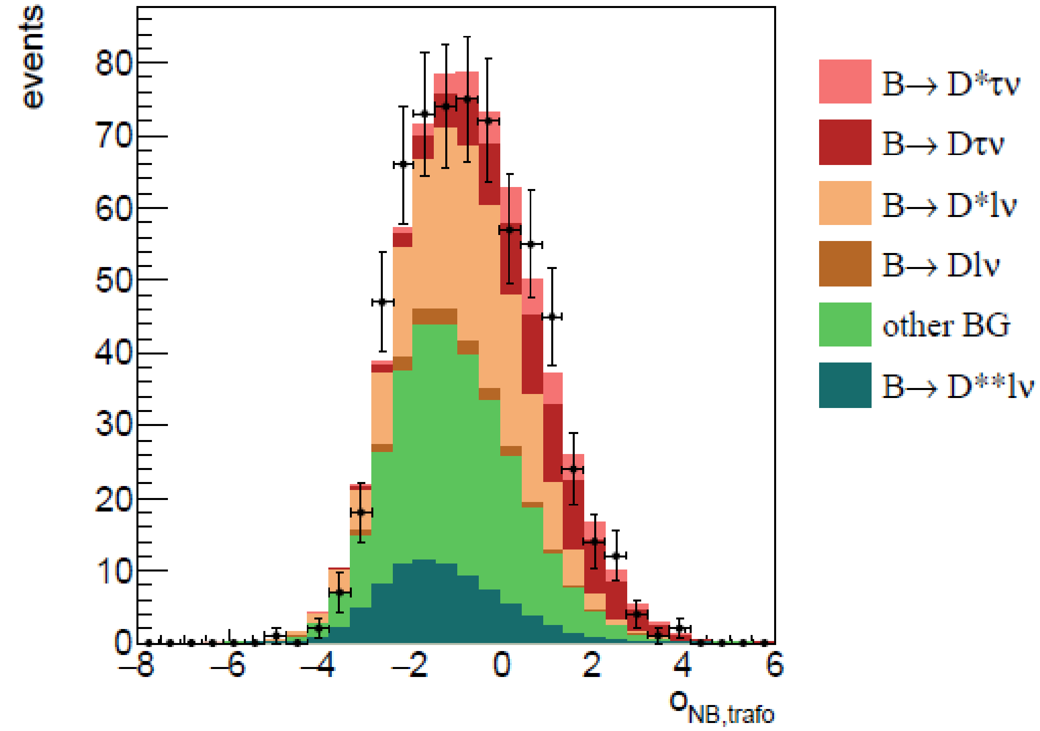
$B \to D^{(*)}\tau\nu$ Hadronic tagging

Fits

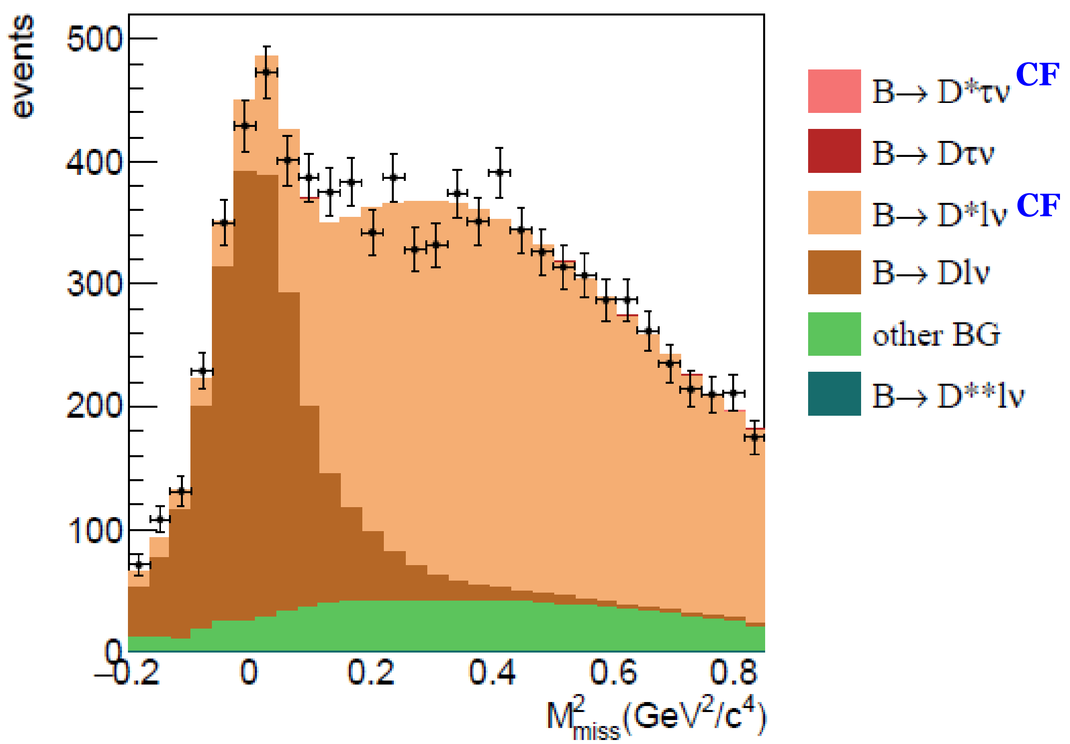
Cross-Feeds: Included in the $D^*\ell$ modes calculation / Small MC yield – broad M^2_{miss} backgrounds fixed to MC

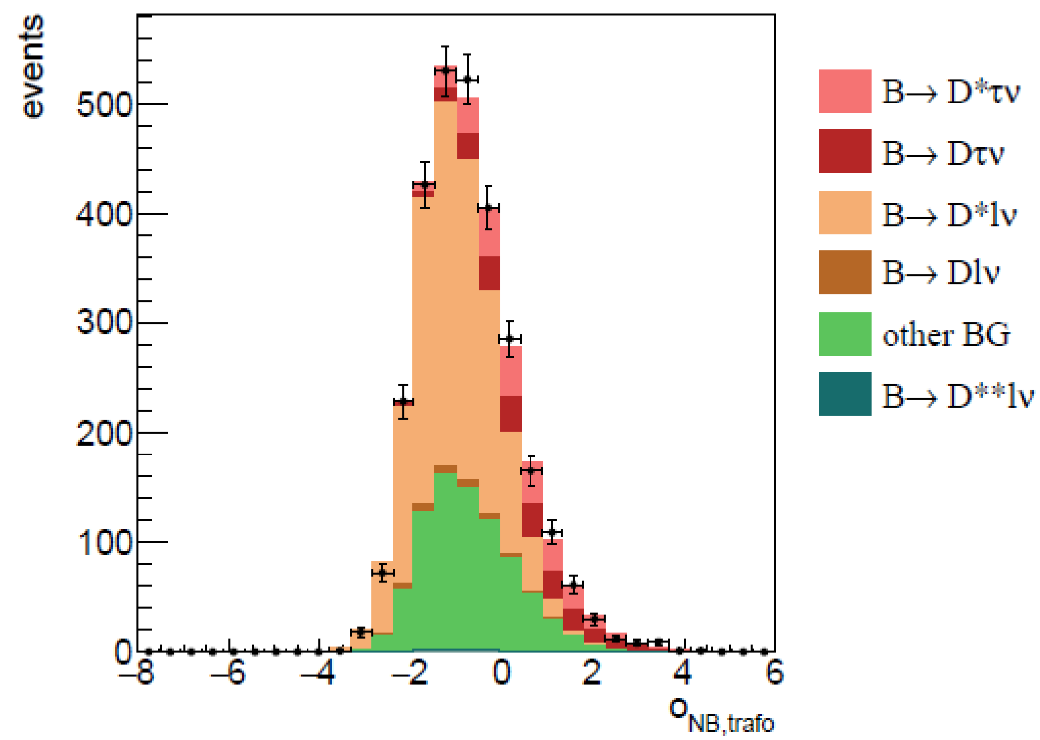
$D^+\ell$





$D^0\ell$





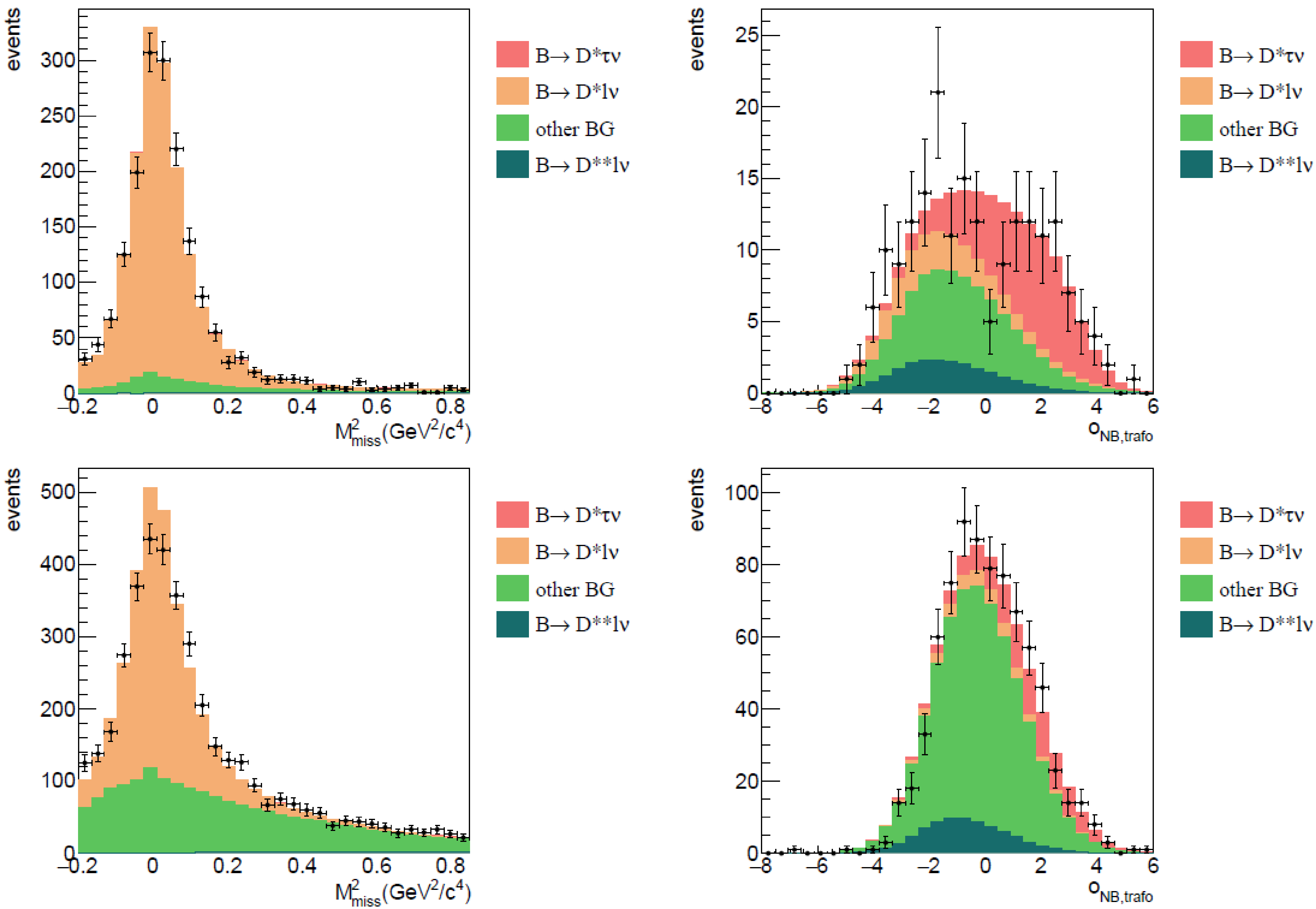
***$D\ell\nu$* enhanced region** ***$D\tau\nu$* enhanced region**

$B \to D^{(*)}\tau\nu$ Hadronic tagging

Fits

$D^{*+}\ell$

$D^{*0}\ell$



***Dℓν* enhanced region**

***Dτν* enhanced region**

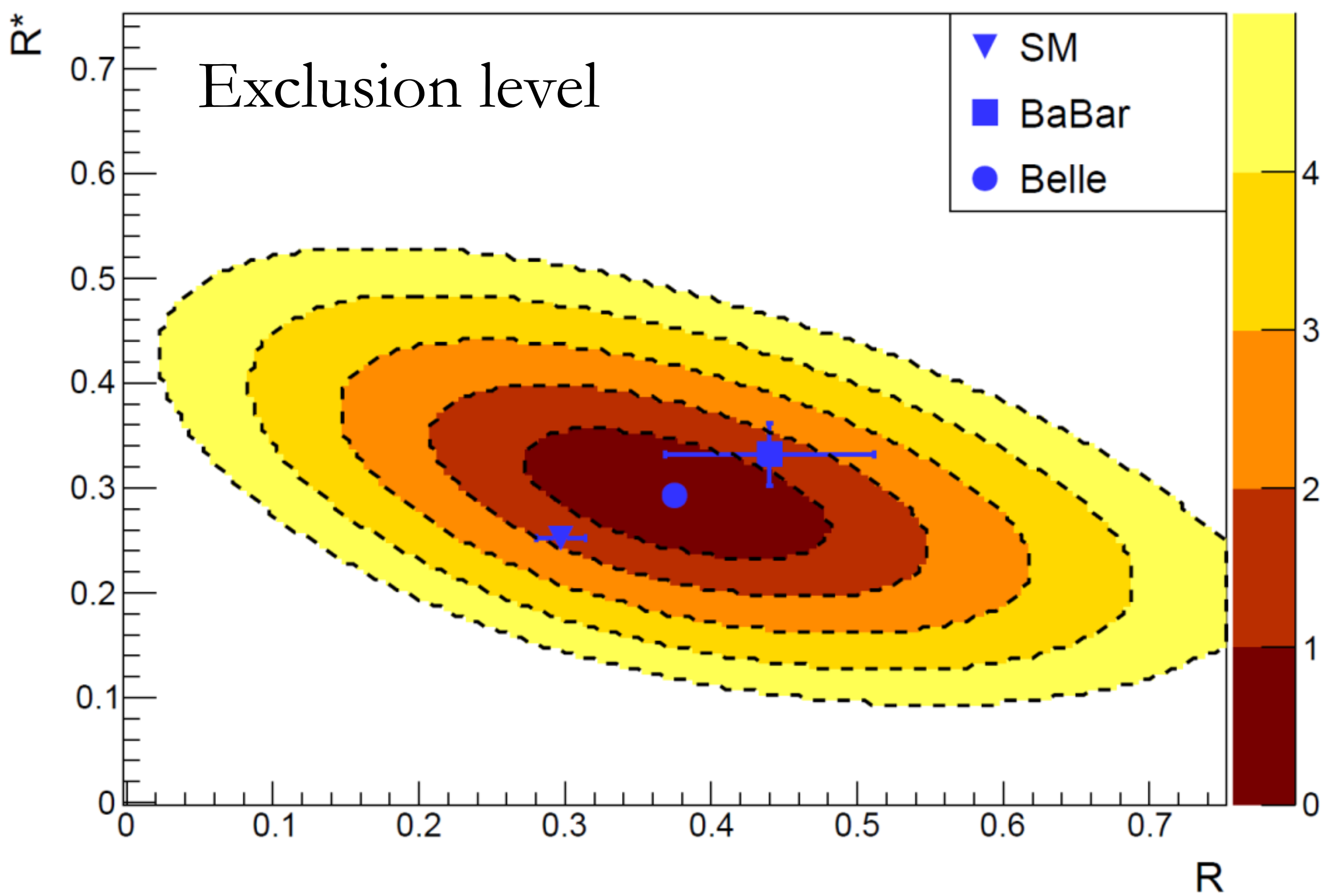
$B \to D^{(*)}\tau\nu$ Hadronic tagging

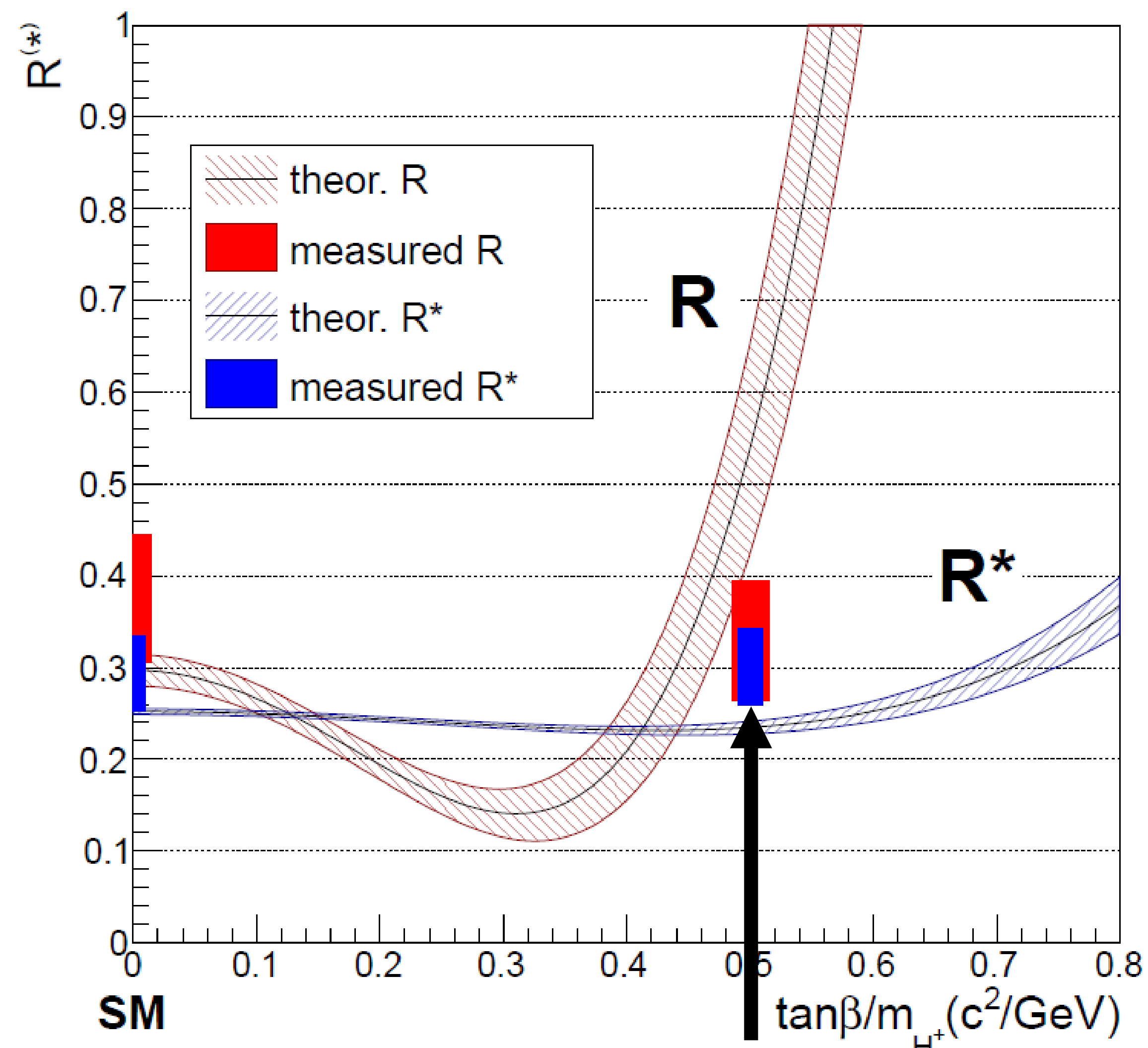
$R_{SM}(D) \sim 0.296(16)$
$R_{SM}(D^*) \sim 0.252(3)$

RESULTS

$$R(D) = 0.376^{+0.064}_{-0.063}(stat) \pm 0.026(syst)$$
$$R(D^*) = 0.283^{+0.039}_{-0.037}(stat) \pm 0.015(syst)$$

Major systematic uncertainty sources from lack of understanding the D^{**} BG's and factors (f, g) used in the fit.





Repeated with $tan\beta / m_{H^+} = 0.5$

The new measurement from Belle lies within the SM and BaBar result while is yet compatible with the 2HDM.

Closing

- Belle has a potential to explore low-mass dark sector, esp. below ~O(GeV). The first results are in.
- Searches for heavy neutrino(s) have been made.
- A new result on B -> $D^{(*)}$ $\tau\nu$ is released. The results (R, R*) lie between SM and BaBar.
  - (Note) LHCb also has shown their own B -> D* $\tau\nu$.