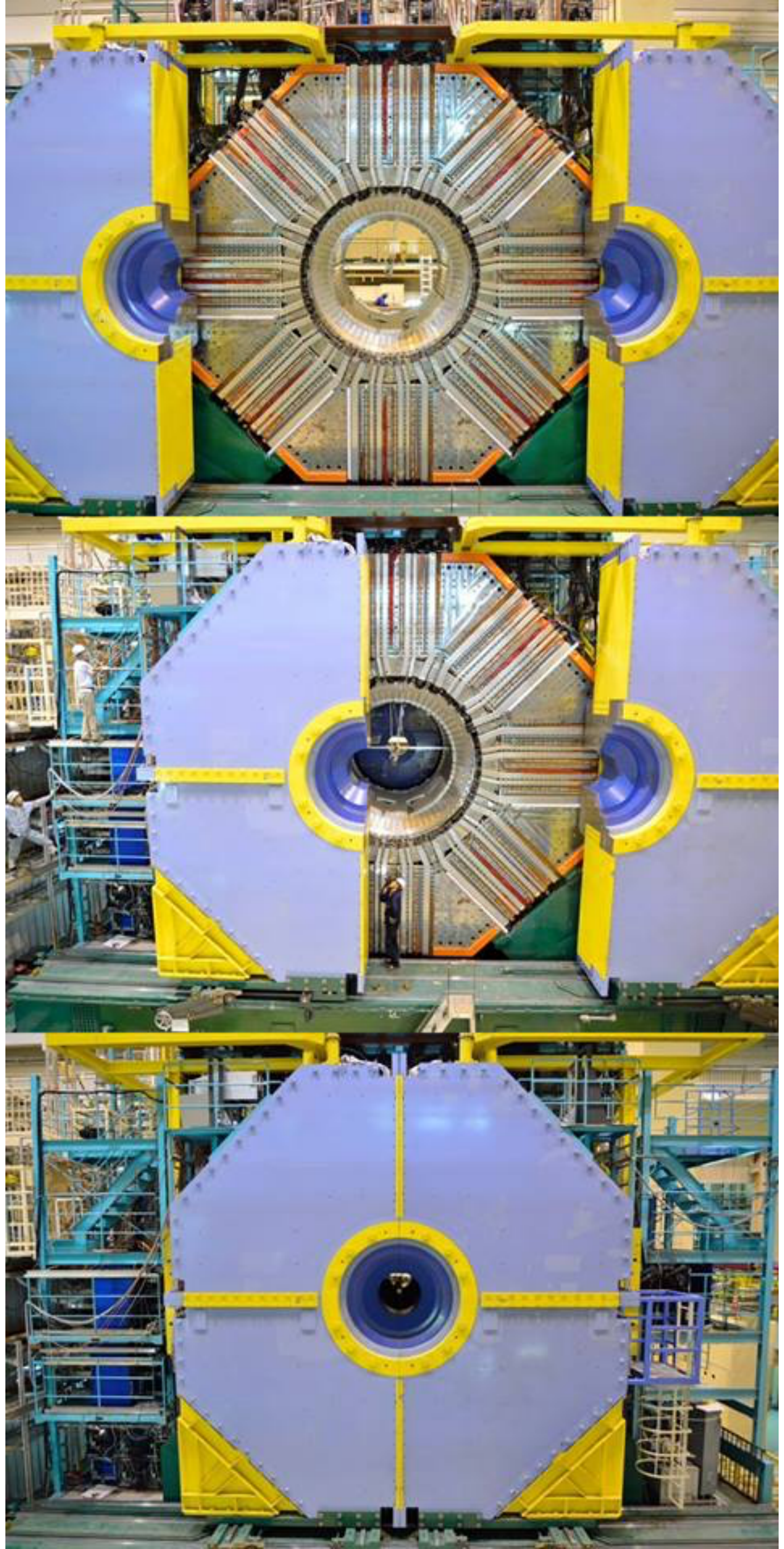


$B \to D^{(*)} l \nu$

Belle, Babar, Belle II

Phillip Urquijo, Eiasha Waheed

MITP

April 2018

Recent (past 2 years) & upcoming measurements

- $B \to D\, l\, \nu$
  - Hadron tagged, Belle (2016 PRD)
- $B \to D^*\, l\, \nu$
  - Hadron tagged, Belle (2017 preliminary)
- $B \to D^{**}\, l\, \nu$
  - $B \to D(^*)\pi\pi\, l\, \nu$, Hadron tagged, Babar (2016 PRL)
  - $B \to D^{(*)}\pi\, l\, \nu$, Hadron tagged, Belle (2018 submitted to PRD)
- Expected from B-factories
  - $B \to D^*\, l\, \nu$ full differentials (untagged), more tests for new physics in e/μ channels.
  - + many more studies from Belle II

$|V_{cb}|$ and Form Factors

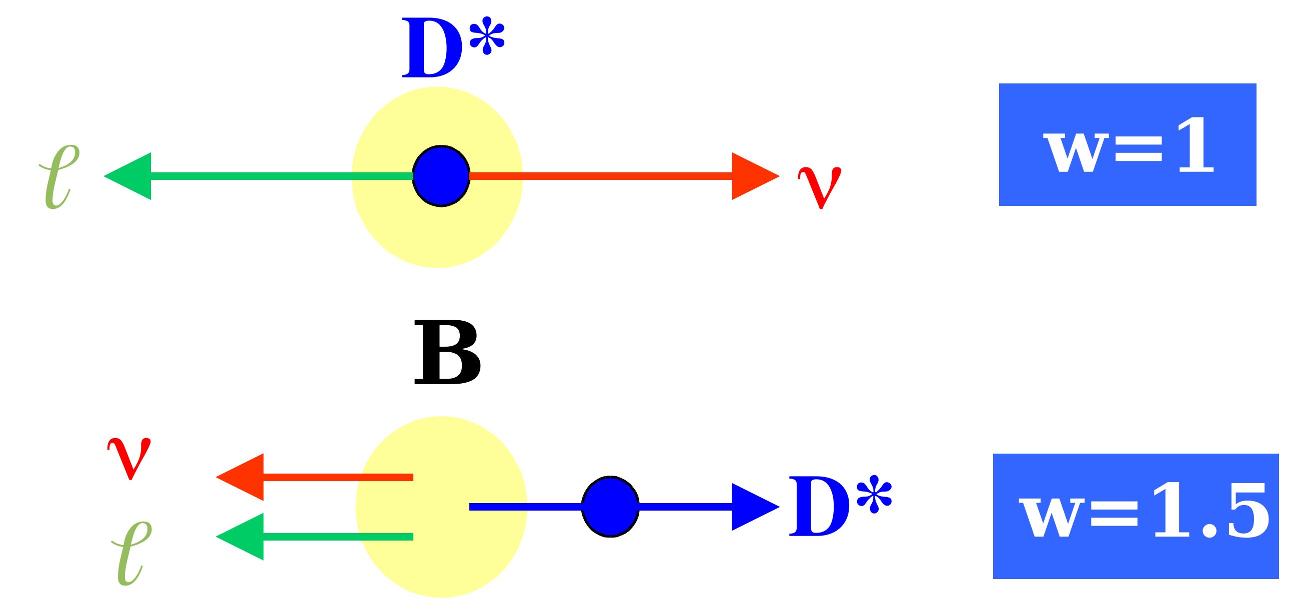
$$\frac{d\Gamma}{dw}(B \to D\ell\nu) \sim (\text{Phase Space})|V_{cb}|^2 G(w)^2$$

$$\frac{d\Gamma}{dw}(B \to D^*\ell\nu) \sim (\text{Phase Space})|V_{cb}|^2 F(w)^2 \sum_{i=+,0,-} |H_i(w)|^2$$

$$w = \frac{m_B^2 + m_D^2 - q^2}{2m_B m_d}$$

Normalisation: $\xi(w=1)=1$

(heavy quark limit)



BGL, Boyd, Grinstein, Lebed Phys.Rev.Lett 74, 4603 (1995)

$$F_i(w) = \frac{p_i(w)}{B_i(z)\phi_i(z)} \sum_{n=0}^{N} a_n^{(i)} z^n \qquad z = (\sqrt{w+1} - \sqrt{2})/(\sqrt{w+1} + \sqrt{2})$$

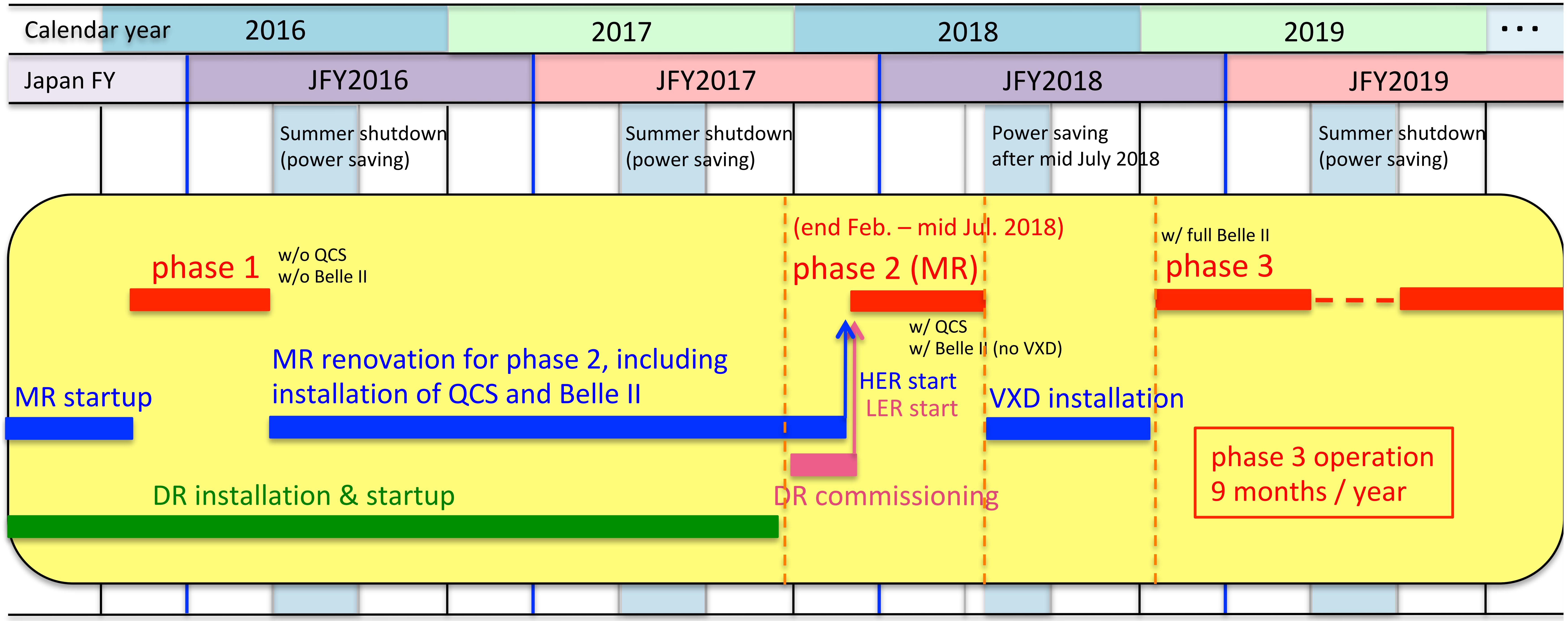
Coefficient a^i_n free parameters: Unitarity bounds the sum of $a^i_n{}^2$.

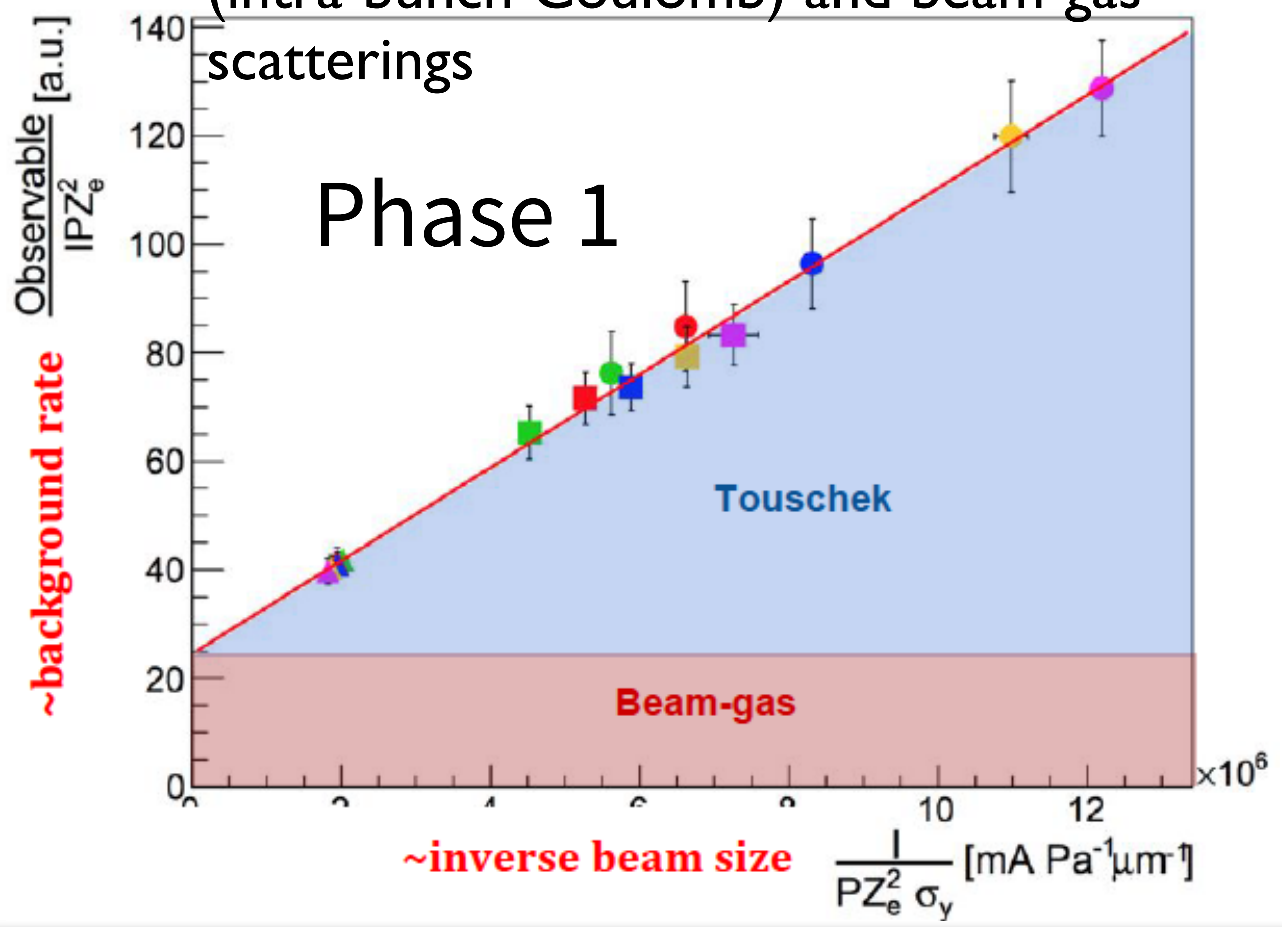
CLN, Caprini, Lellouch, Neubert Nucl.Phys.B530, 153 (1998)

$$G(w) = G(1)[1 - 8\rho^2 z + (51\rho^2 - 10)z^2 - (252\rho^2 - 84)z^3]$$

Use HQET to reduce number of free parameters.

Belle II General Status and Timeline

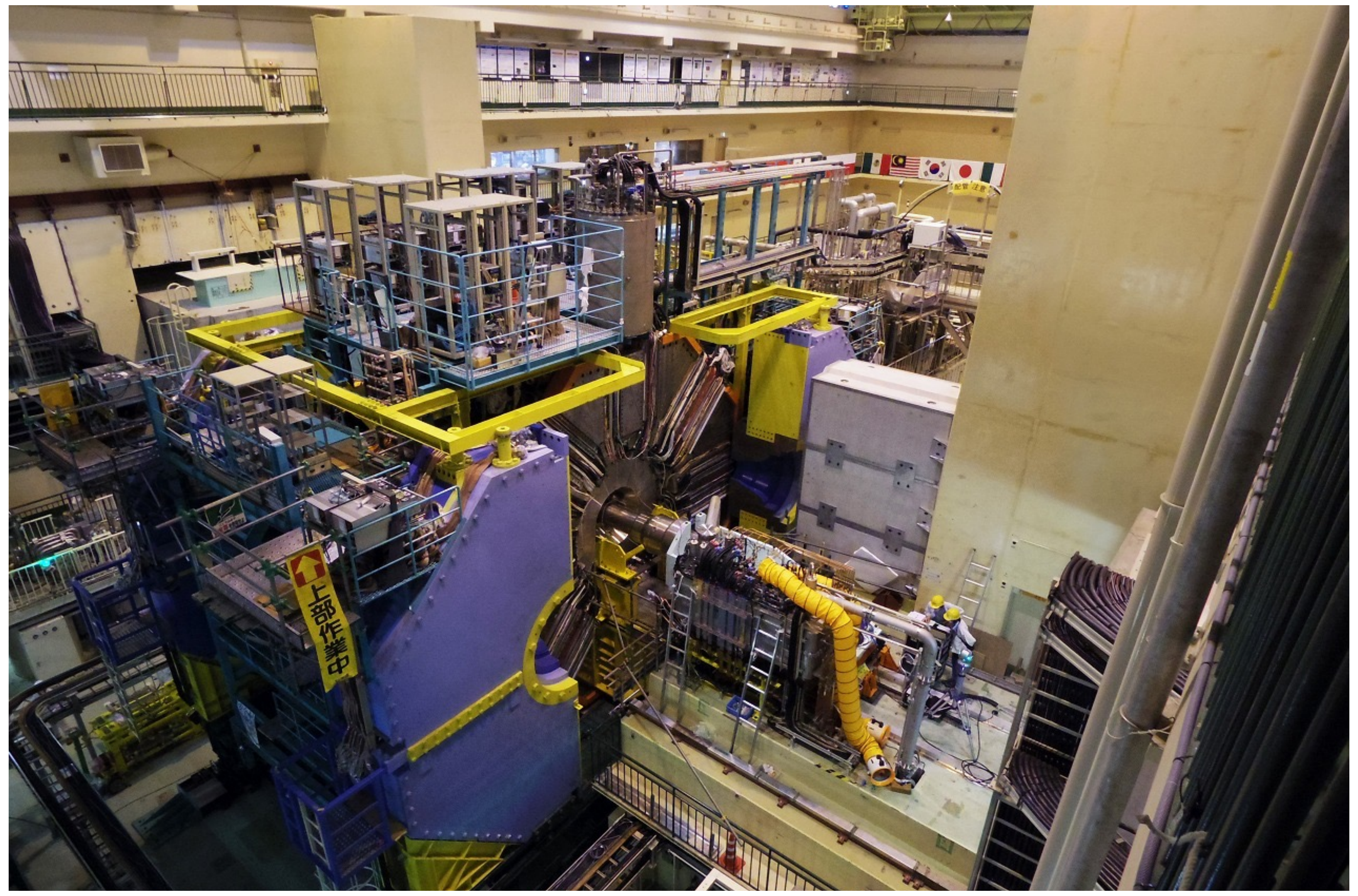




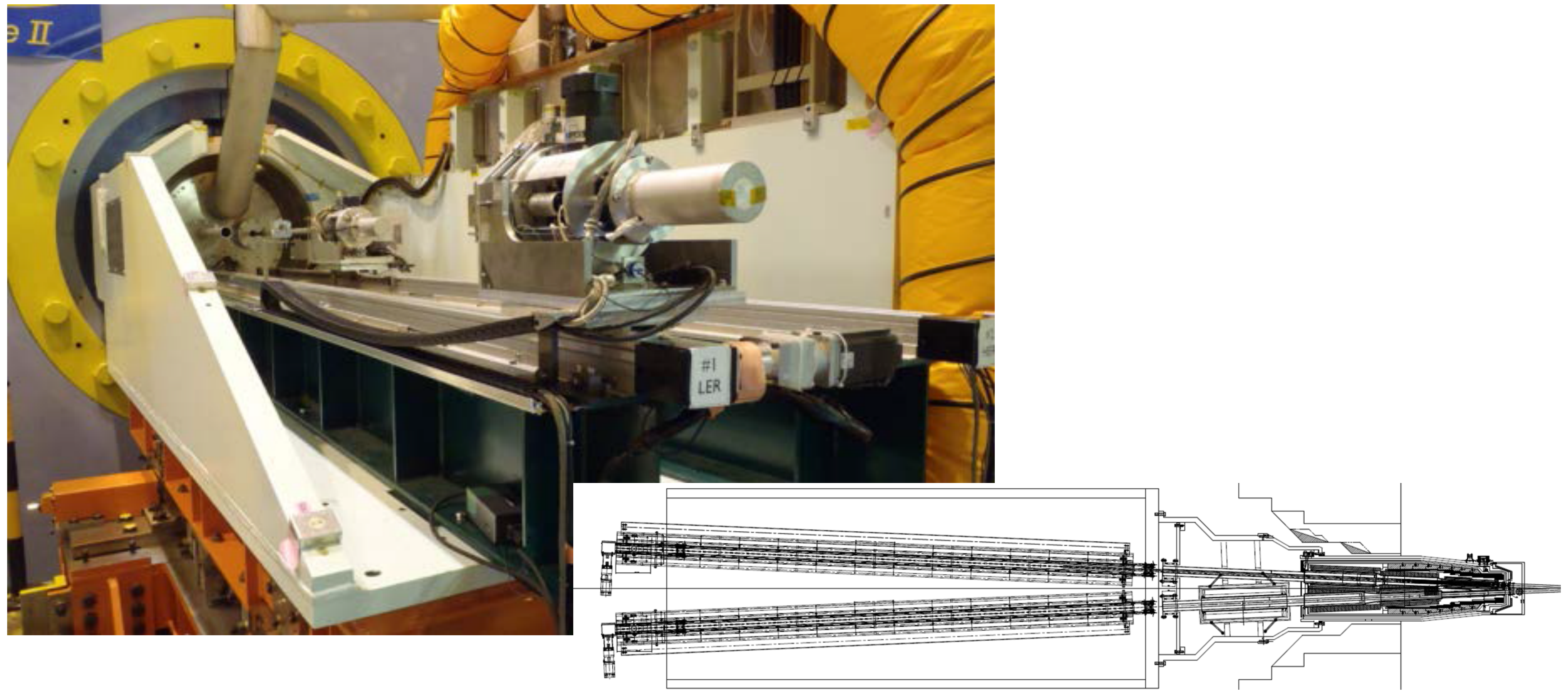
- Phase 2 (w/final focusing Q, w/Belle II, w/ partial Si configuration & background monitors)
- Verification of nano-beam scheme
  - Target L> 10^{34} cm-2s-1
- Understand beam background and its luminosity scaling - particularly in VXD volume.

Detector installation activities

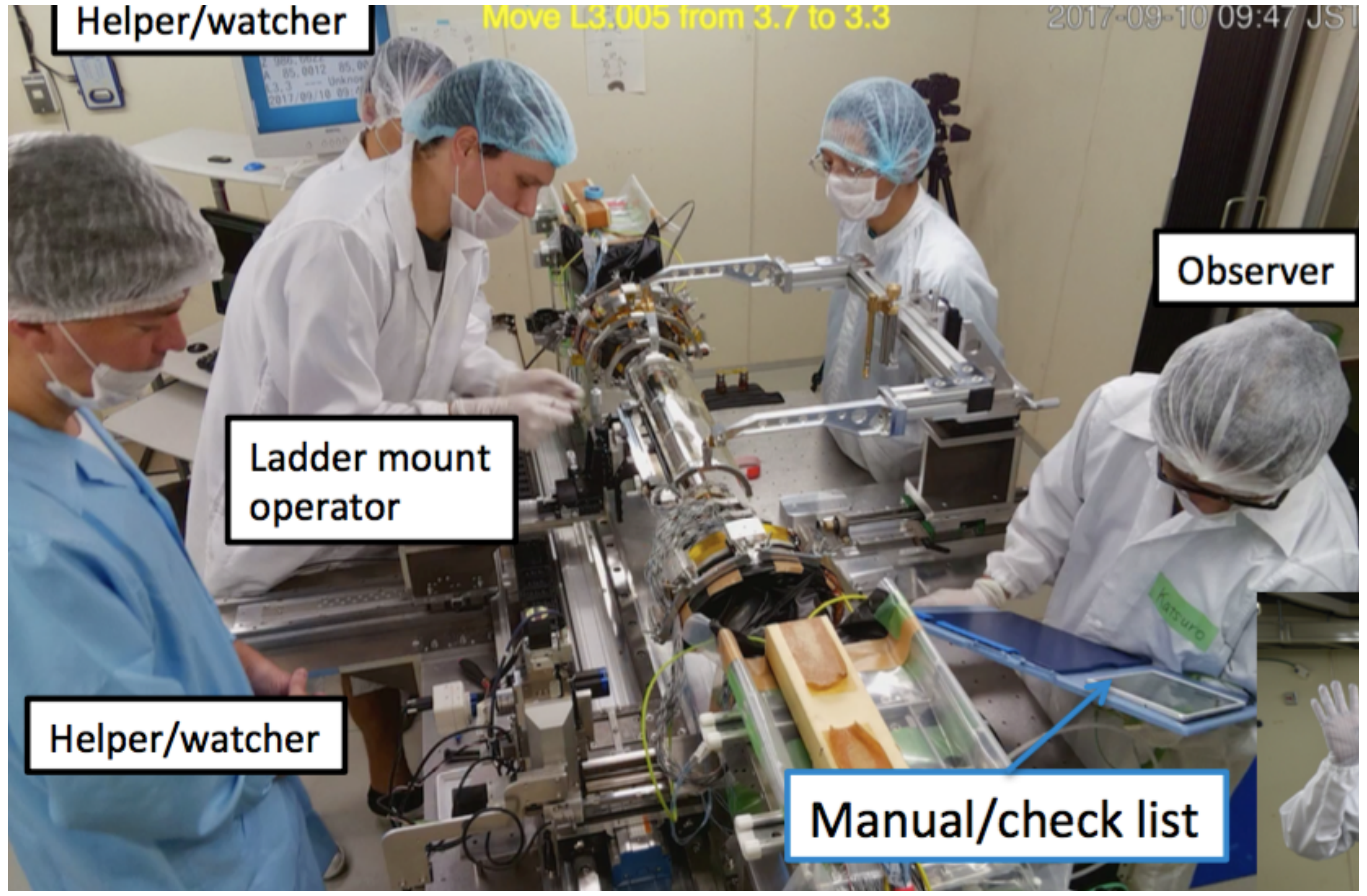
Belle II Roll-in



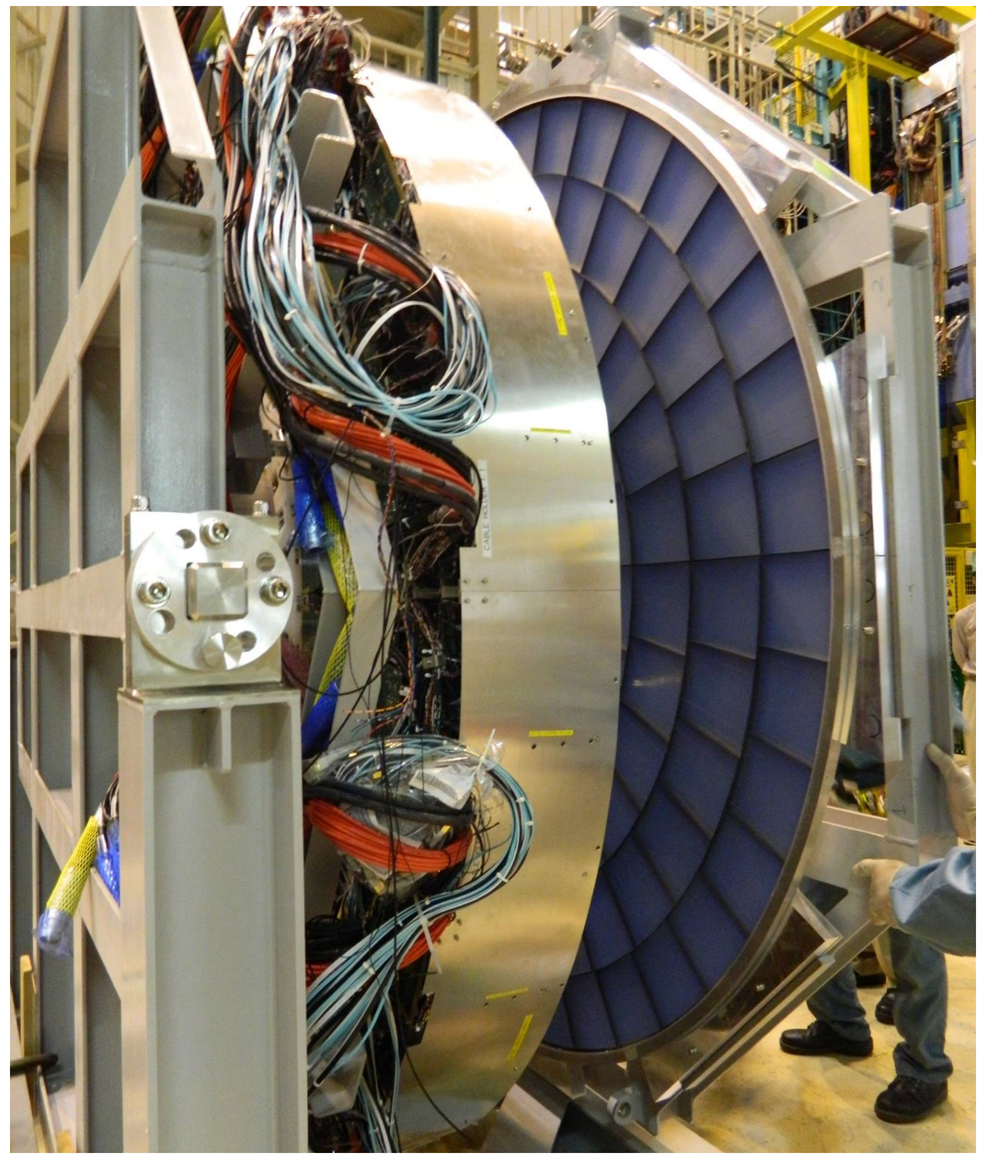
QCS solenoid



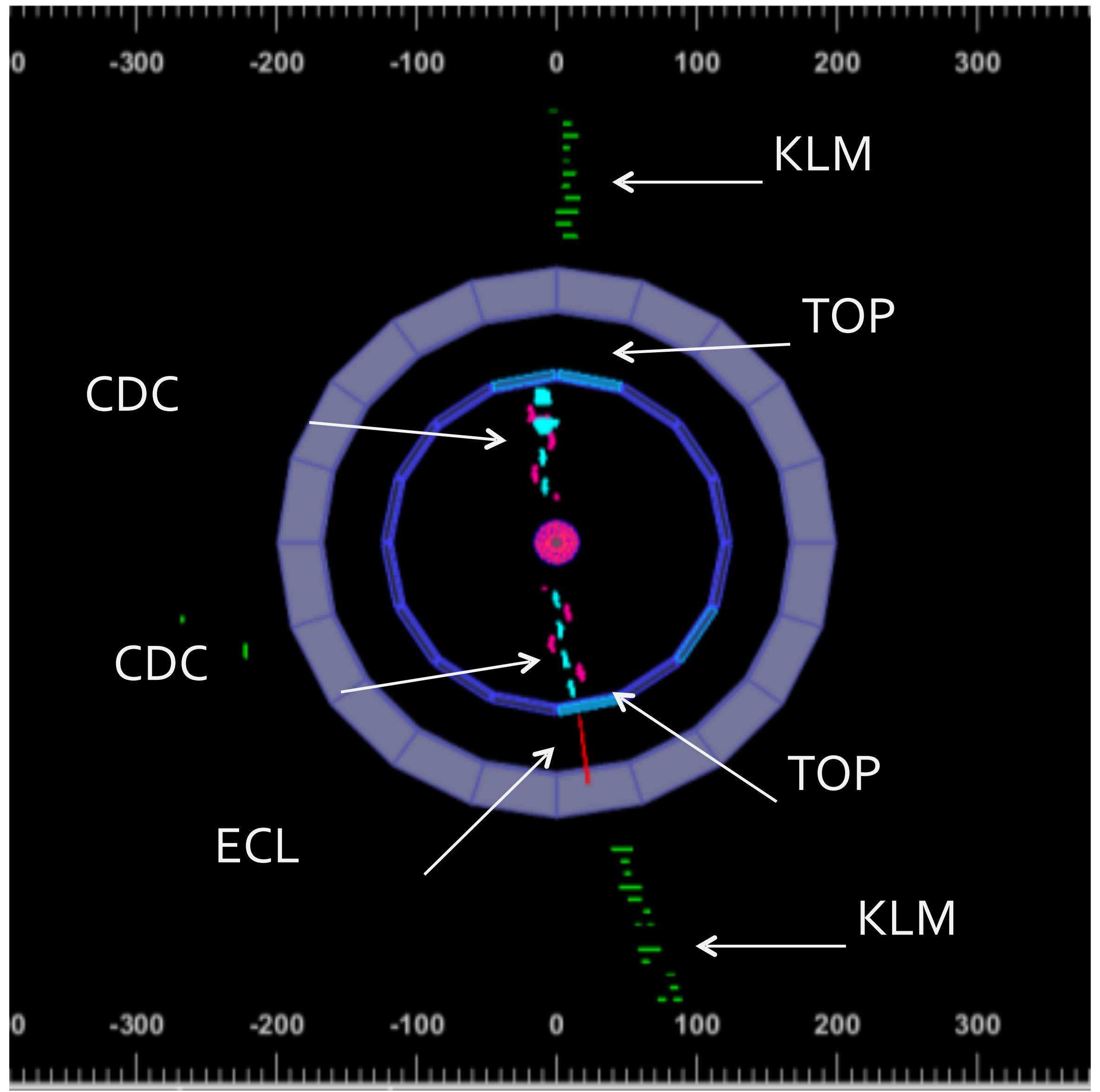
SVD Ladder mount



ARICH installation



Readout integration: cosmic



Start of Phase II

Control room, 14/2/2018

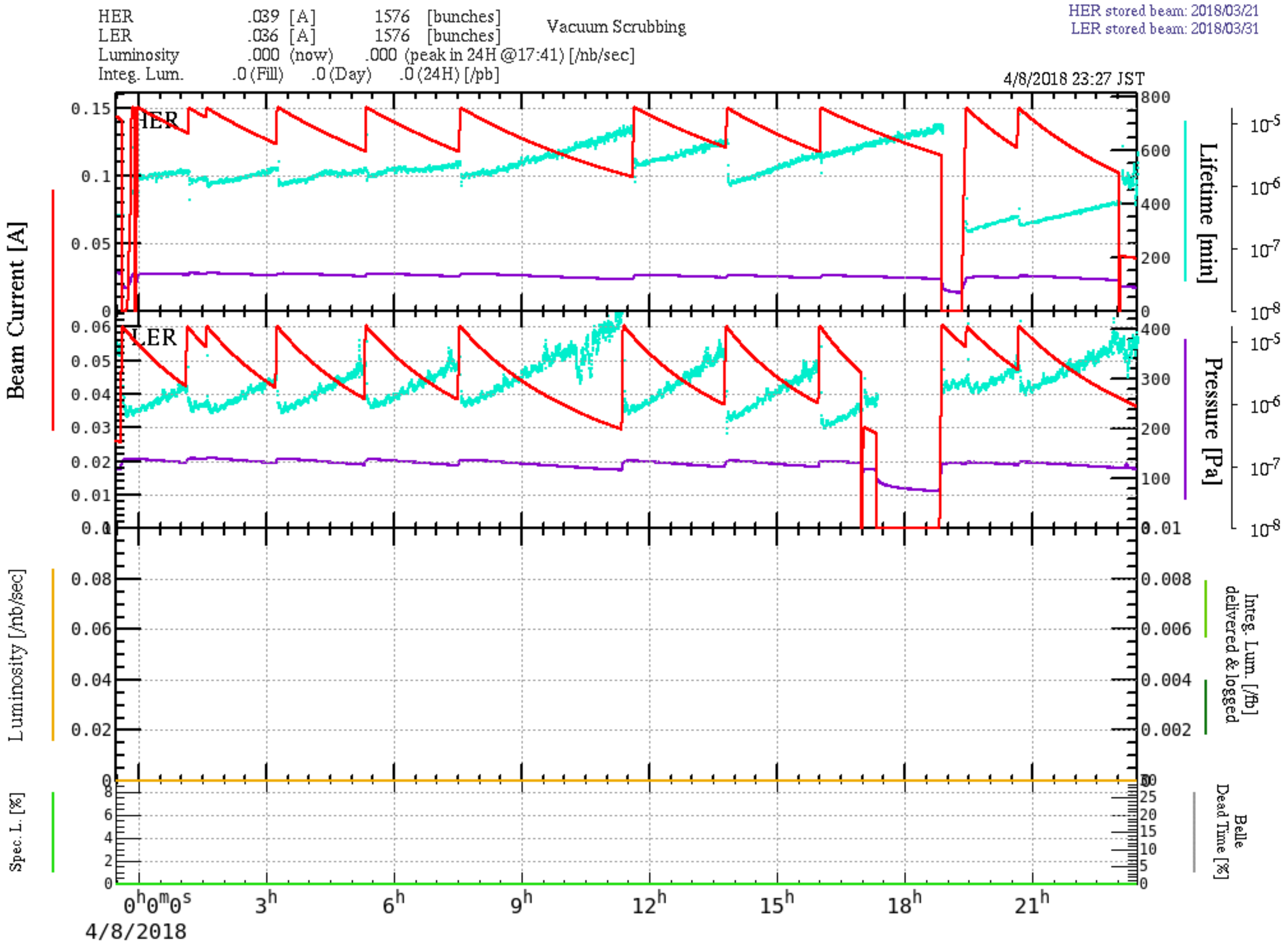

Cosmic rays, 10/02/2018
SVD, PXD
CDC
TOP
Zoom
SVD hits

LER and HER current: 8 April 2018

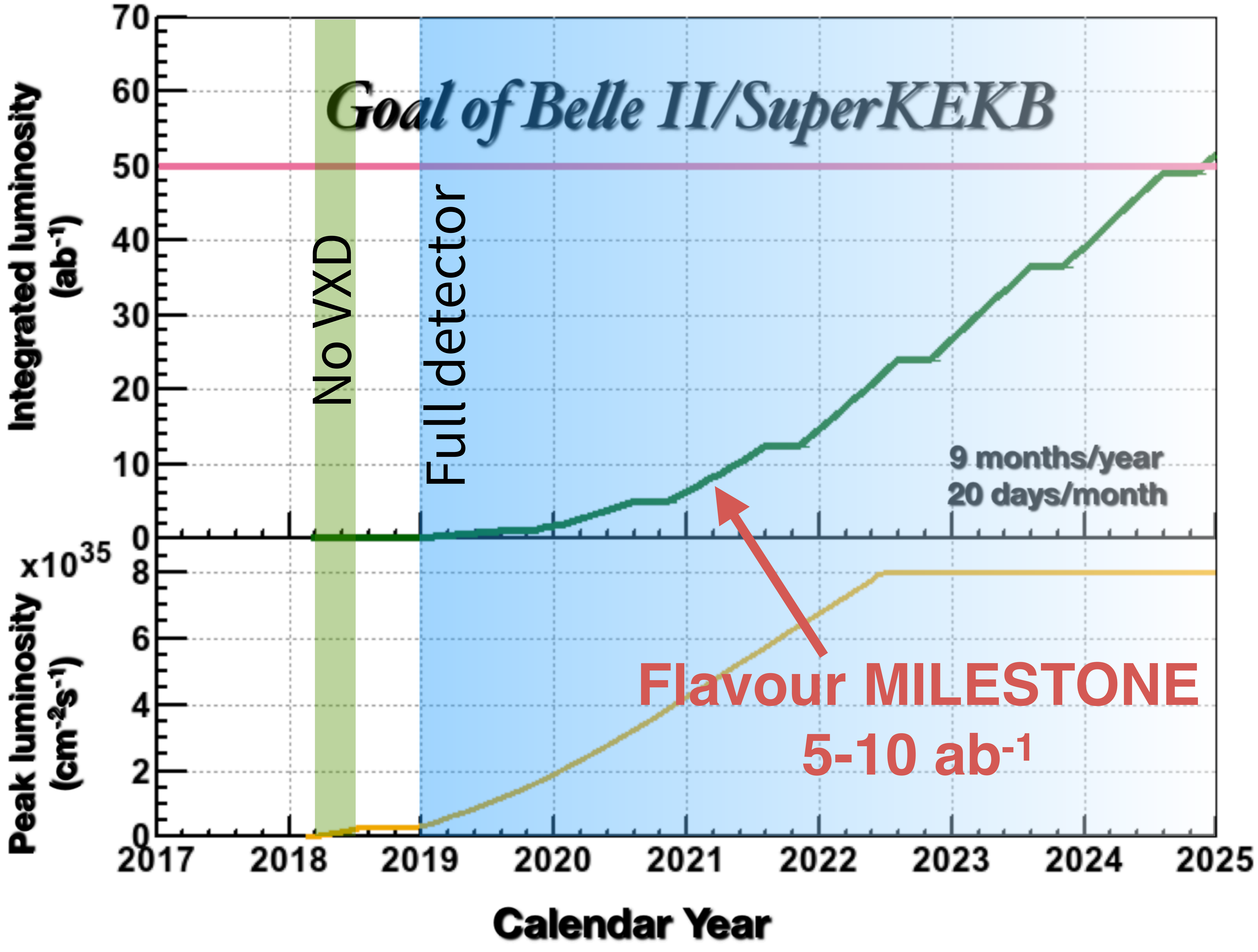
HER

LER

http://www-linac.kek.jp/skekb/snapshot/ring.html



SuperKEKB / Belle II Luminosity projections



Phase 2:
Peak luminosity reaches
1 x 10^{34} cm^{-2}s^{-1} (Belle)
20 fb^{-1} for physics near Y(4S)

Feb 2018: Global cosmic ray runs.

March 2018: First beams.

April 2018: First collisions

July 2018: End of commissioning run.

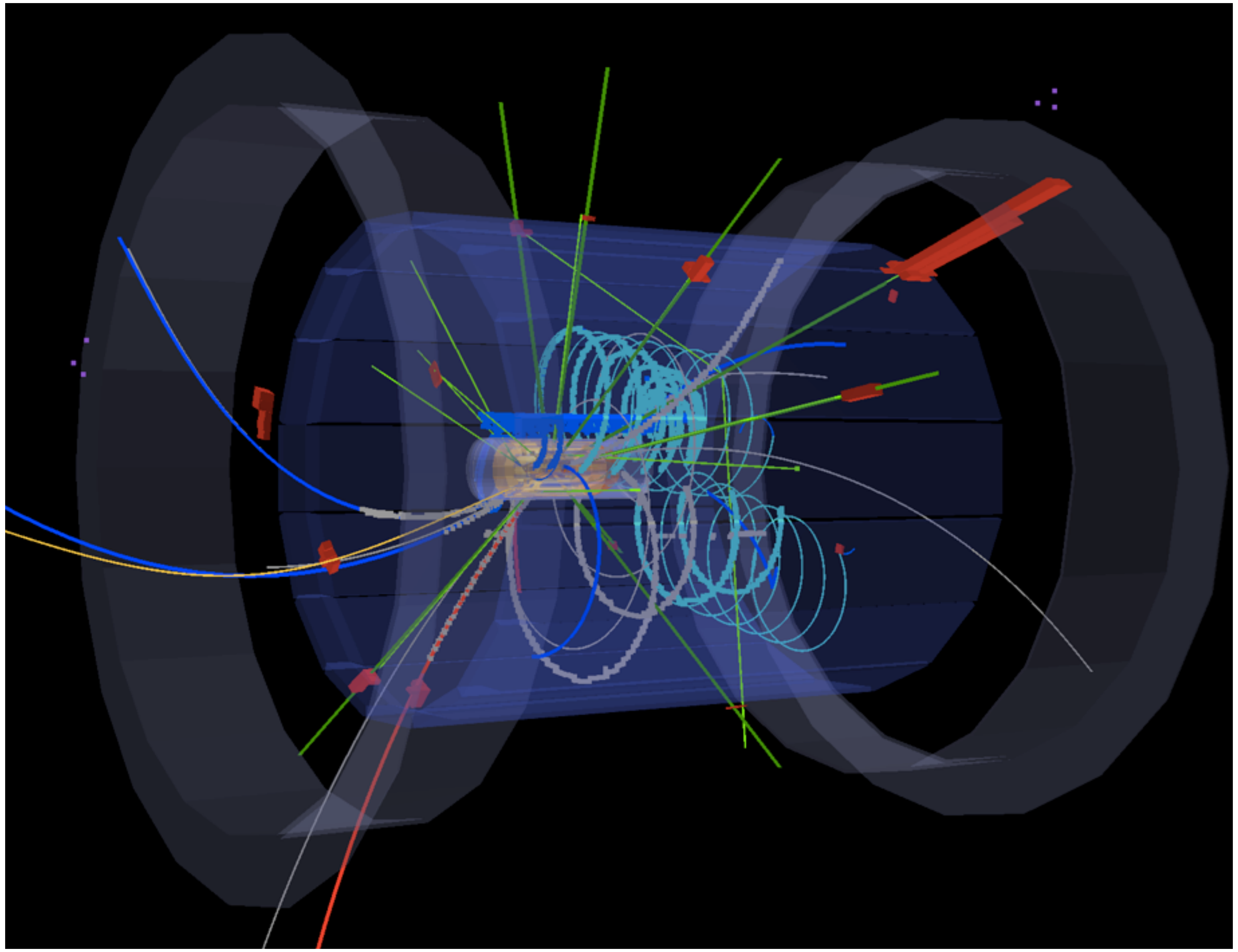
Phase 3:
50 ab^{-1} by 2025
50x Belle, 100x Babar

Early 2019: "**Phase 3**"

All 2018 dates are tentative

Analysis requirements

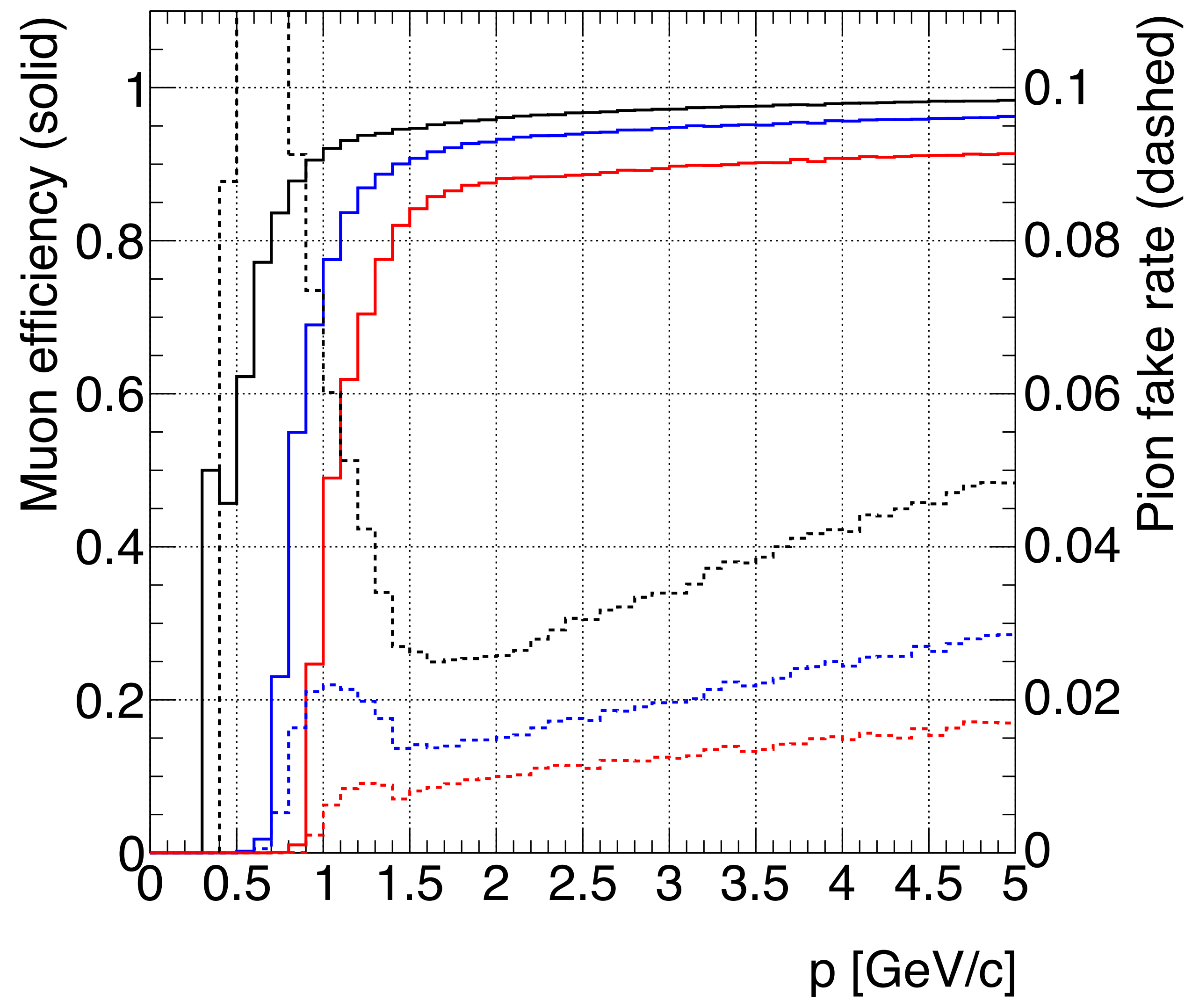
- **Reconstruction**
  - Low p_T tracking for D*
  - Curling track rejection for excess track veto
  - e/μ ID, particularly < 1 GeV leptons from τ
  - γ clusters for E_{ECL}
  - Beam background mitigation
  - π^0 selection for D and D*-π^0_{slow}
- **Analysis**
  - B tagging methods
  - Vertex fitting (B, D … τ maybe)
  - MVA's used in all recent signal analyses
- *I discuss current reconstruction performance, new algorithms under development and naive projections.*

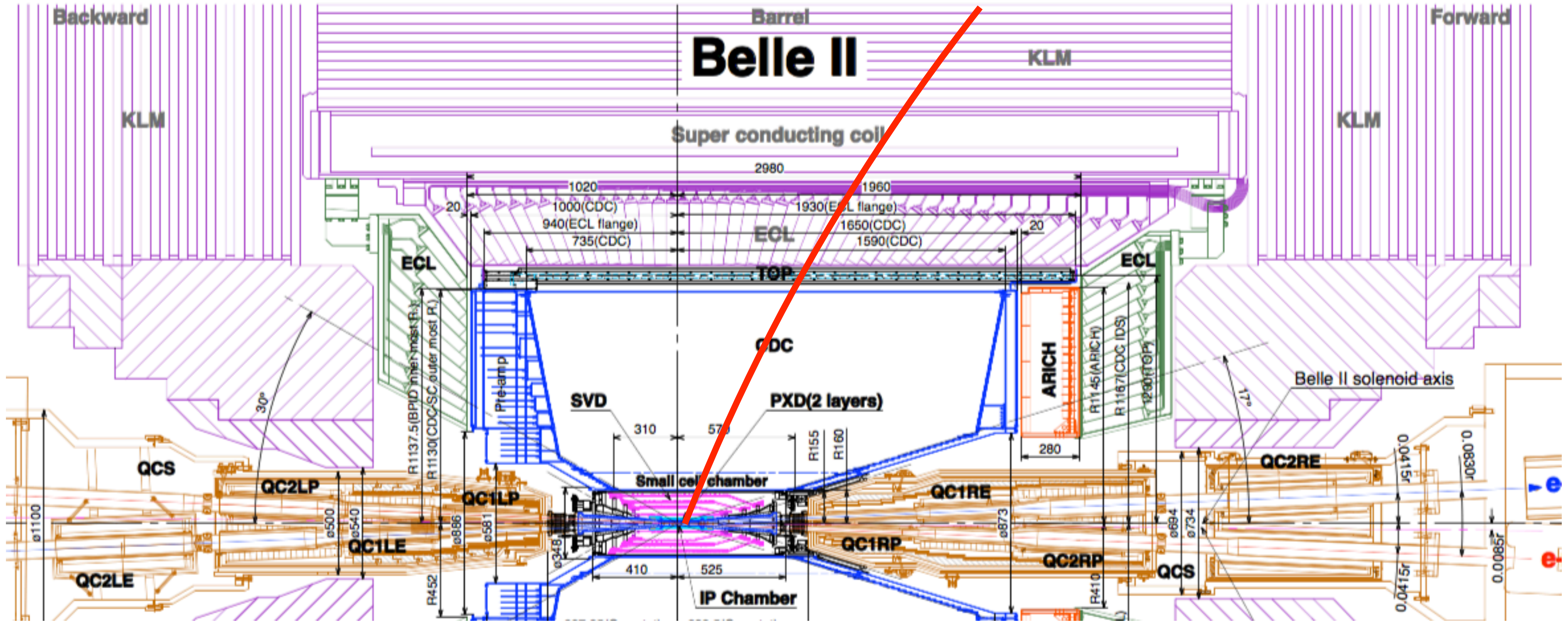


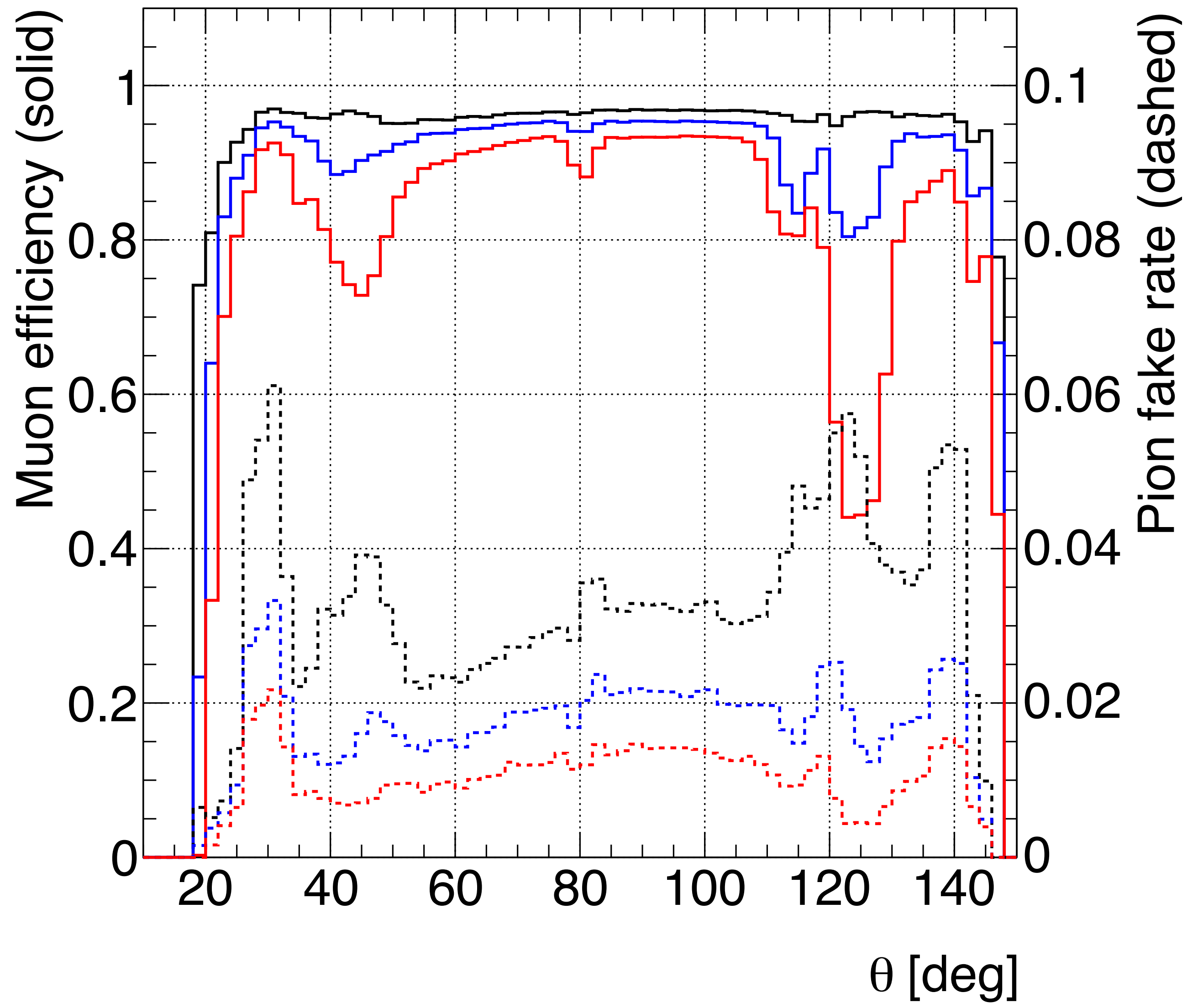
Muon identification

- Muons are the easiest to identify
  - Little to **no radiation** (heavy)
  - **Stable** within particle detectors
  - No strong interactions in absorber material
  - In B-factories, need p > 700 MeV/c to reach muon detectors
- ECL not used for μID at Belle → to be used in Belle II.

μID

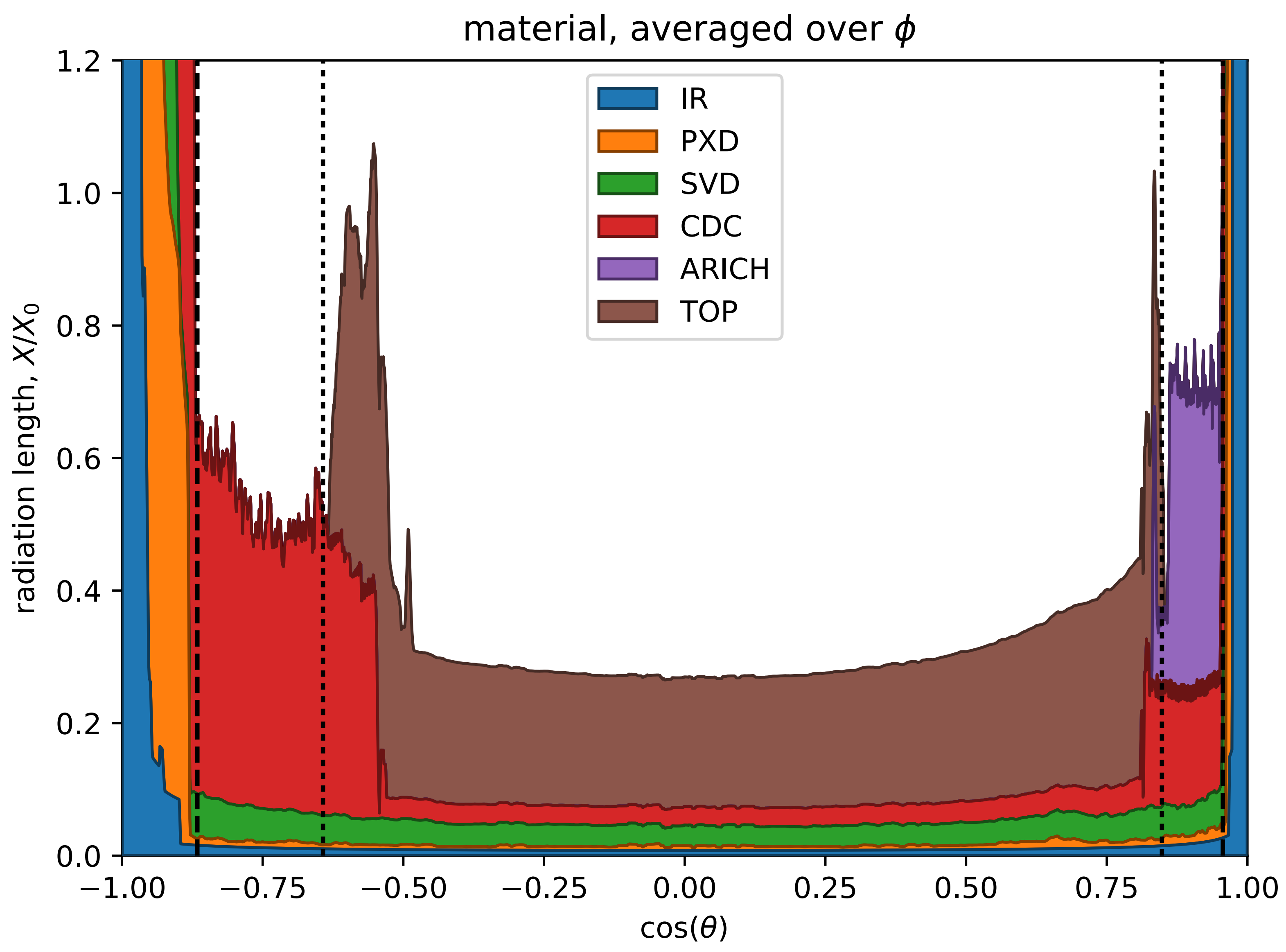


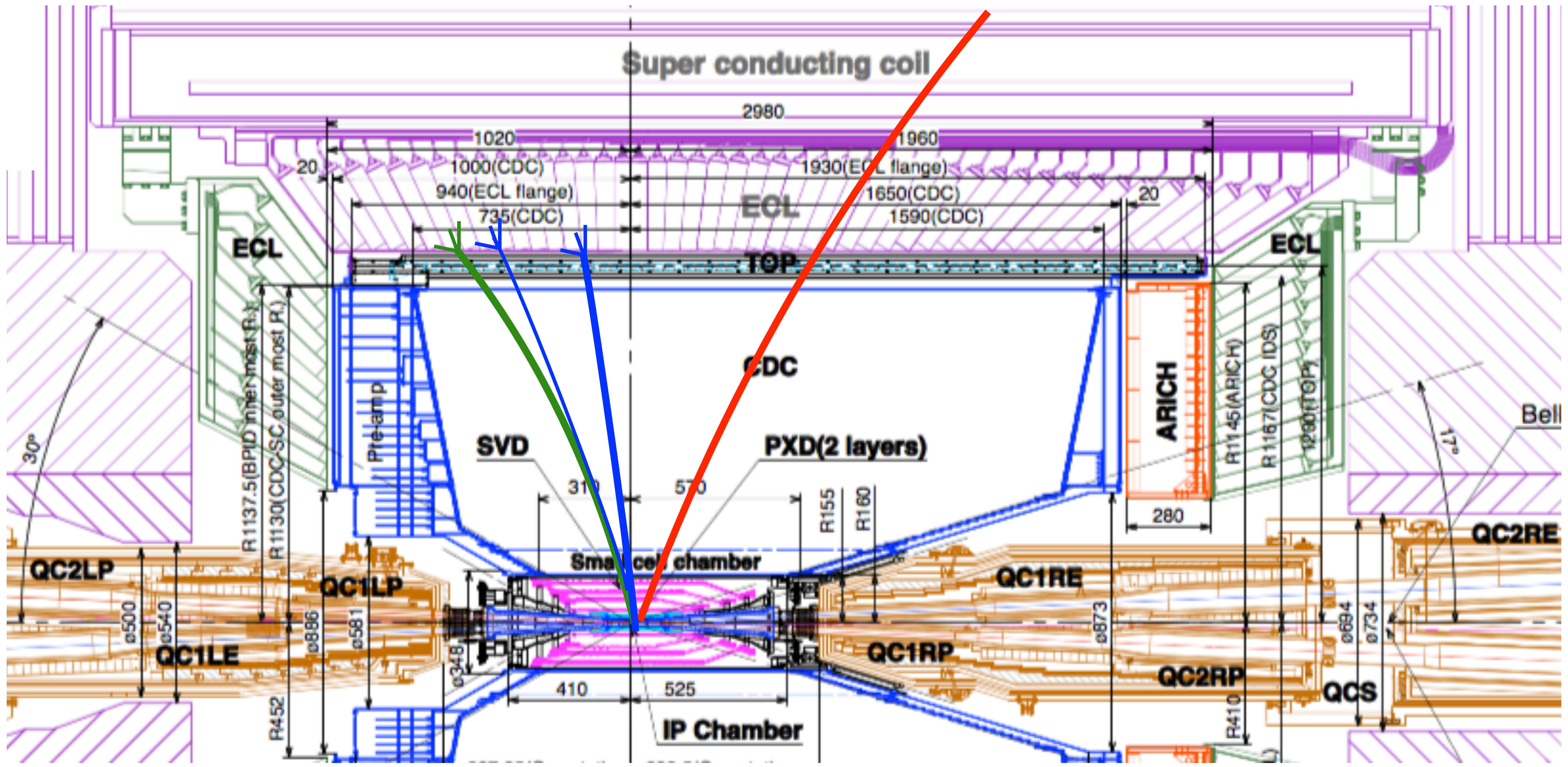


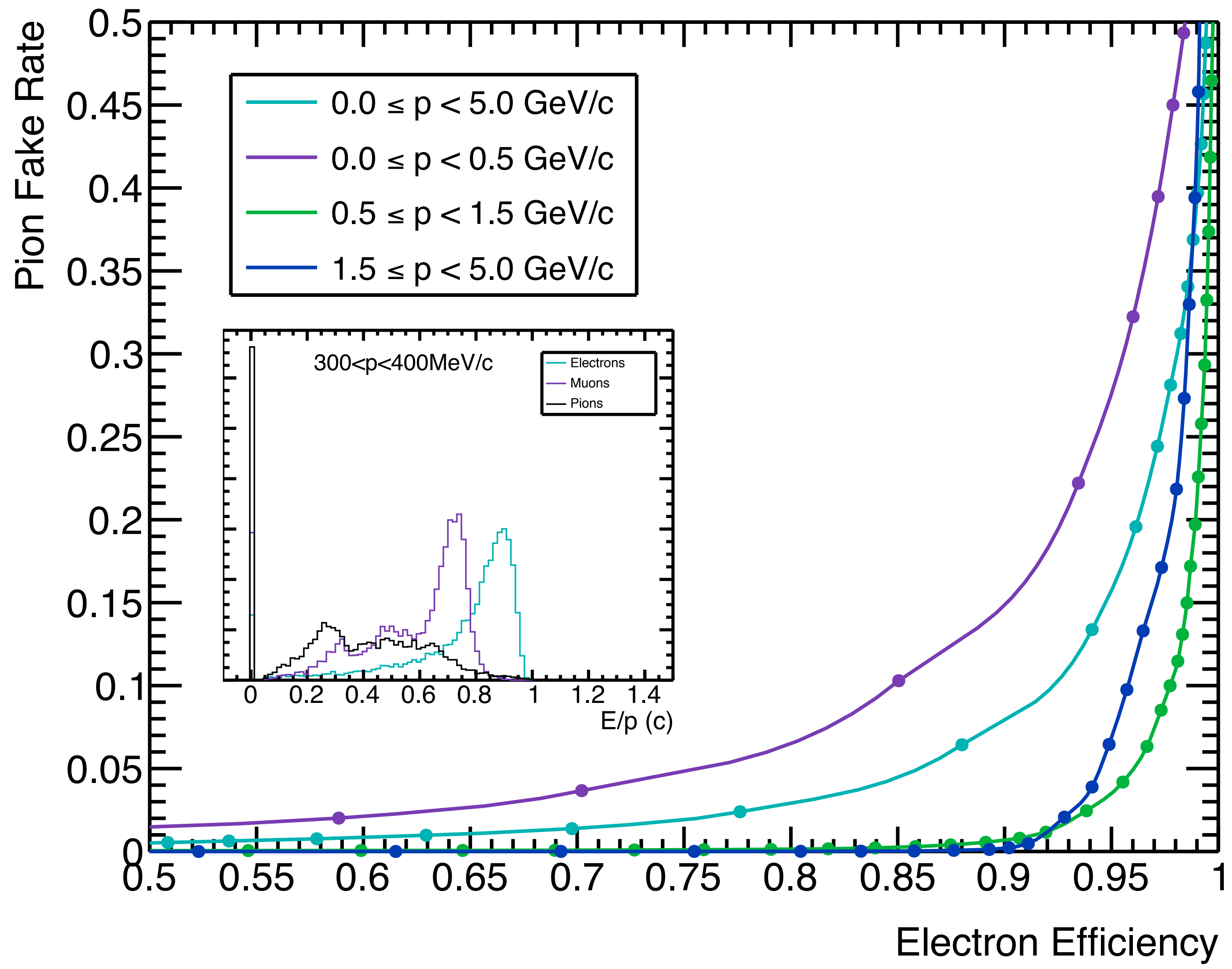


Electron identification

- Electrons are light: **Final state radiation**
  - **Bremsstrahlung** in material is likely
    - Measure too low momentum, Too low energy in calorimeter
    - **Bremsstrahlung recovery** partial fixes this
- Belle: dE/dx + ECL + ACC + TOF used for e.
- Belle II: TOP, ARICH, dE/dx, ECL-shower depth & Zernike moments → **development for low momentum in progress.**







Beam background (MC 2017)

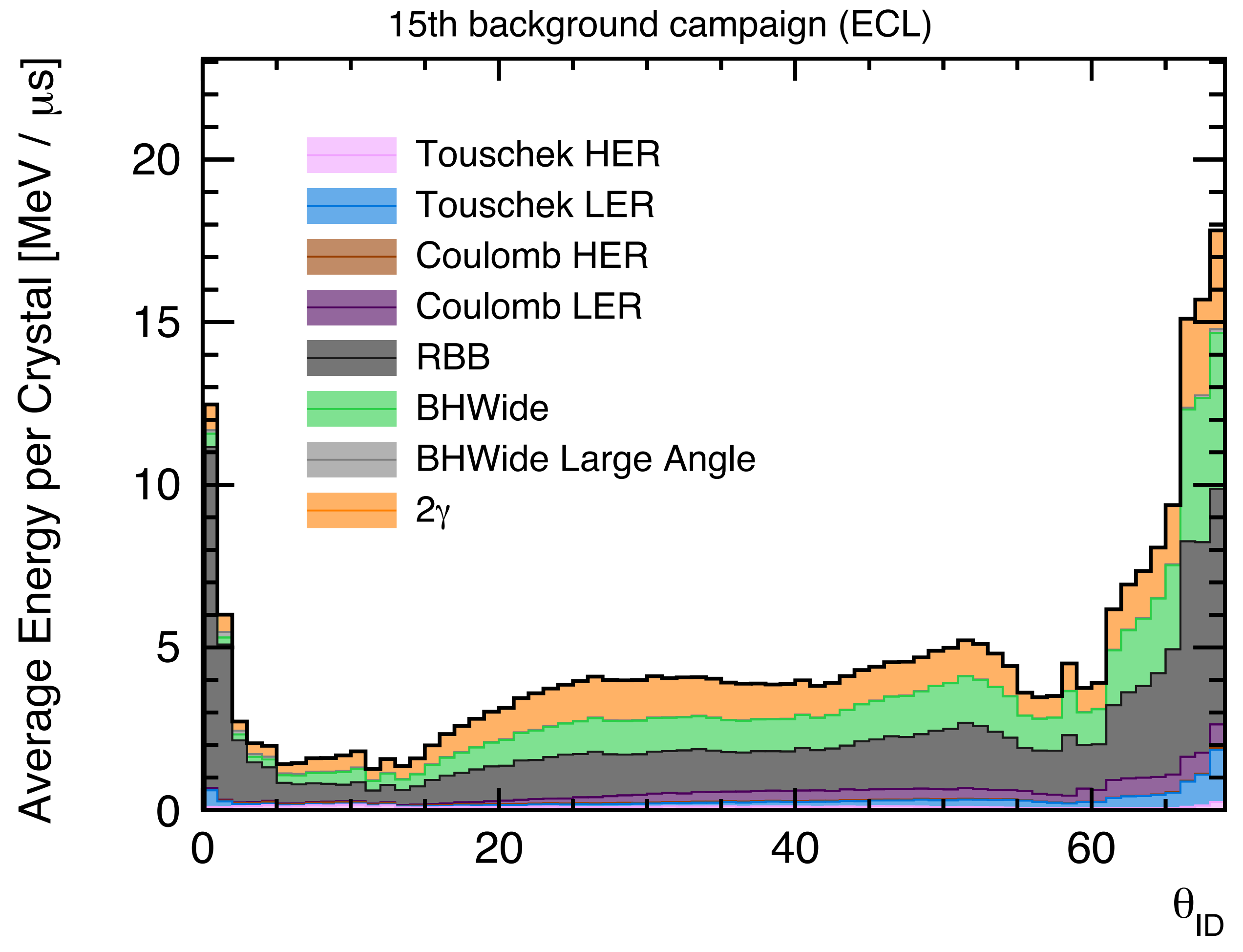
- Increases occupancy in inner Si layers - can degrade tracking.
- Increases off-time energy deposition in the calorimeter.

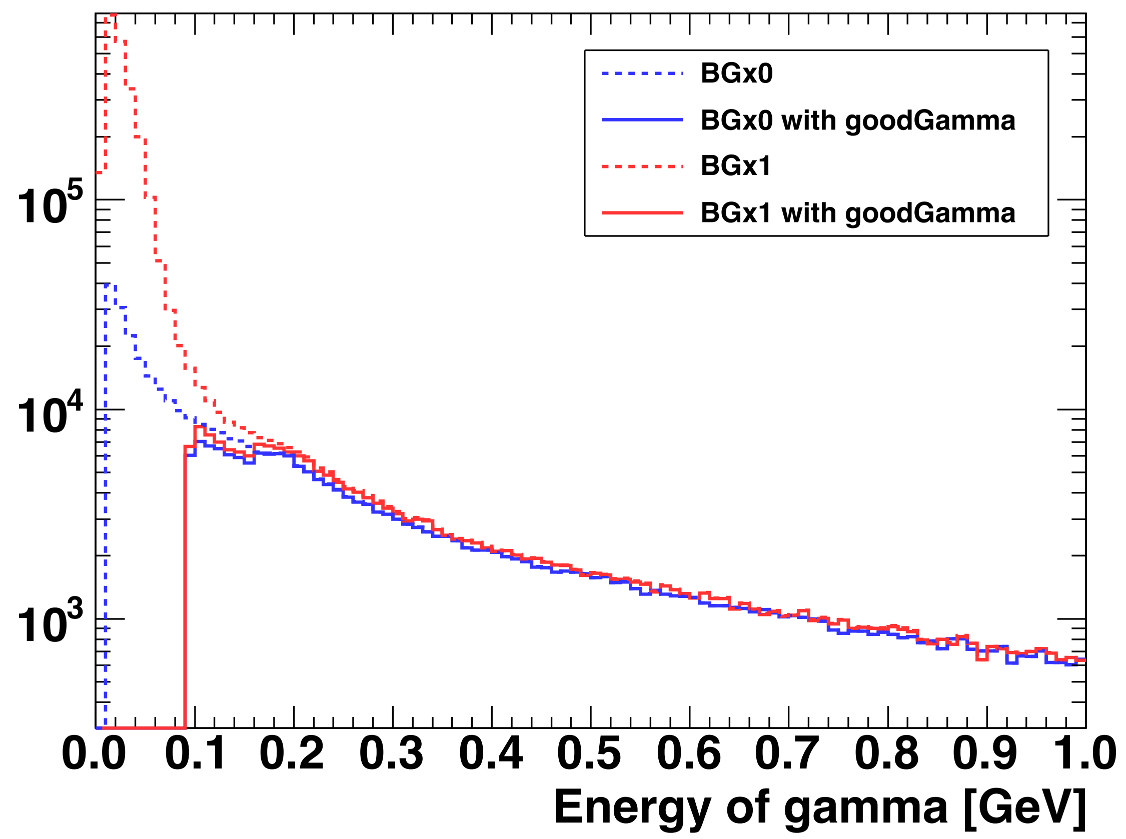
Processes

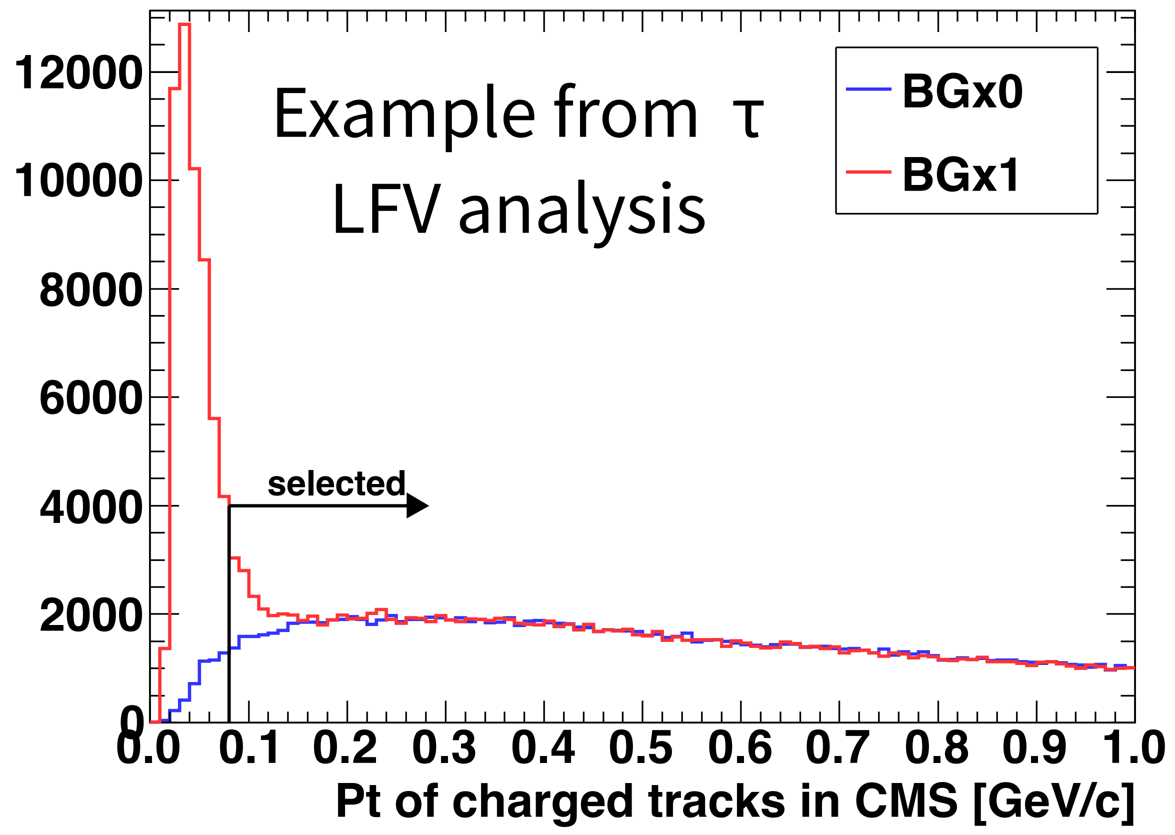
type	source	rate [MHz]
radiative Bhabha	HER	1320
radiative Bhabha	LER	1294
radiative Bhabha (wide angle)	HER	40
radiative Bhabha (wide angle)	LER	85
Touschek scattering	HER	31
Touschek scattering	LER	83
beam-gas interactions	HER	1
beam-gas interactions	LER	156
two-photon QED	-	206

Occupancy

component	background	generic $B\overline{B}$
PXD	10000 (580)	23
SVD	284 (134)	108
CDC	654	810
TOP	150	205
ARICH	191	188
ECL	3470	510
BKLM	484	33
EKLM	142	34



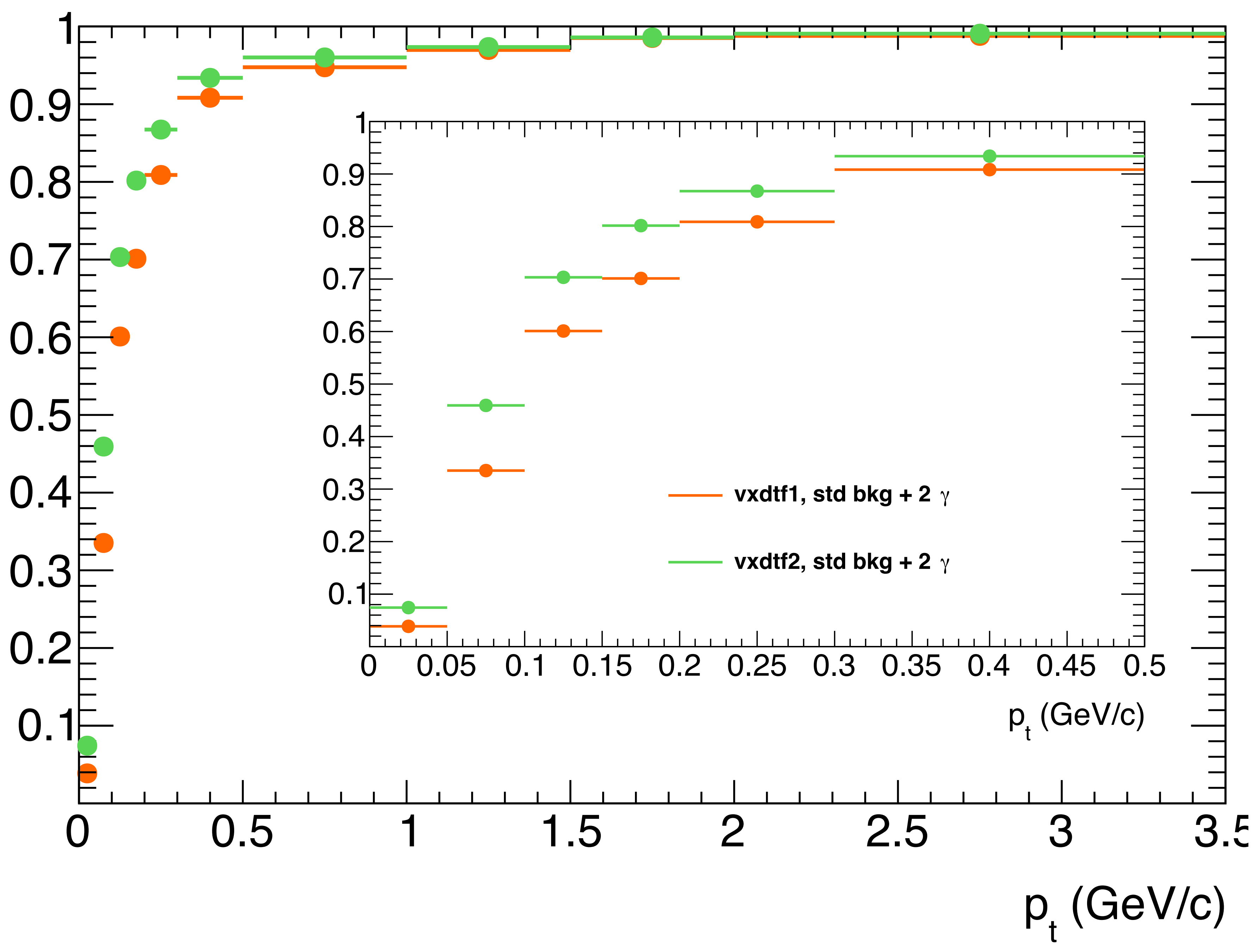




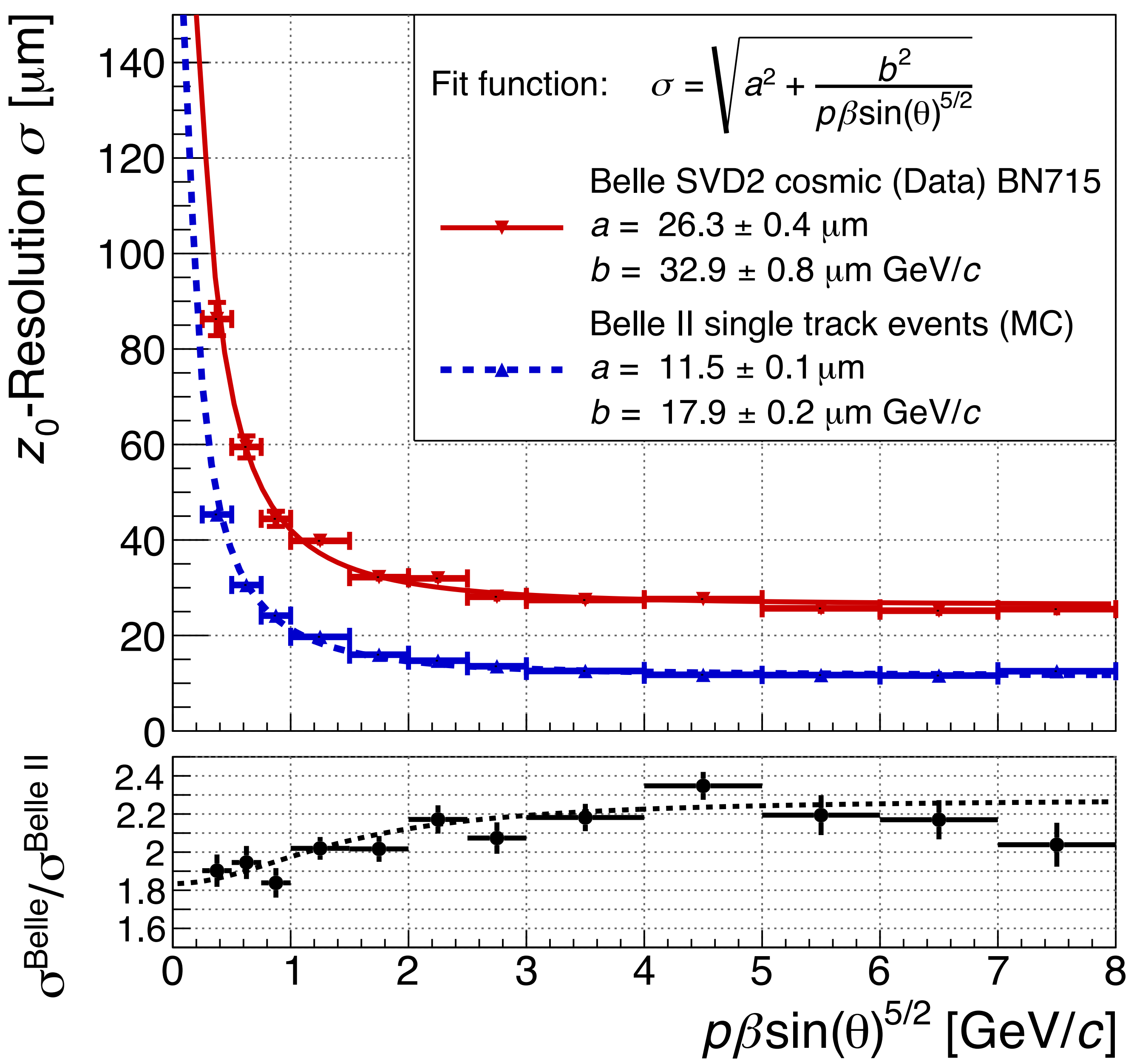
Track reconstruction

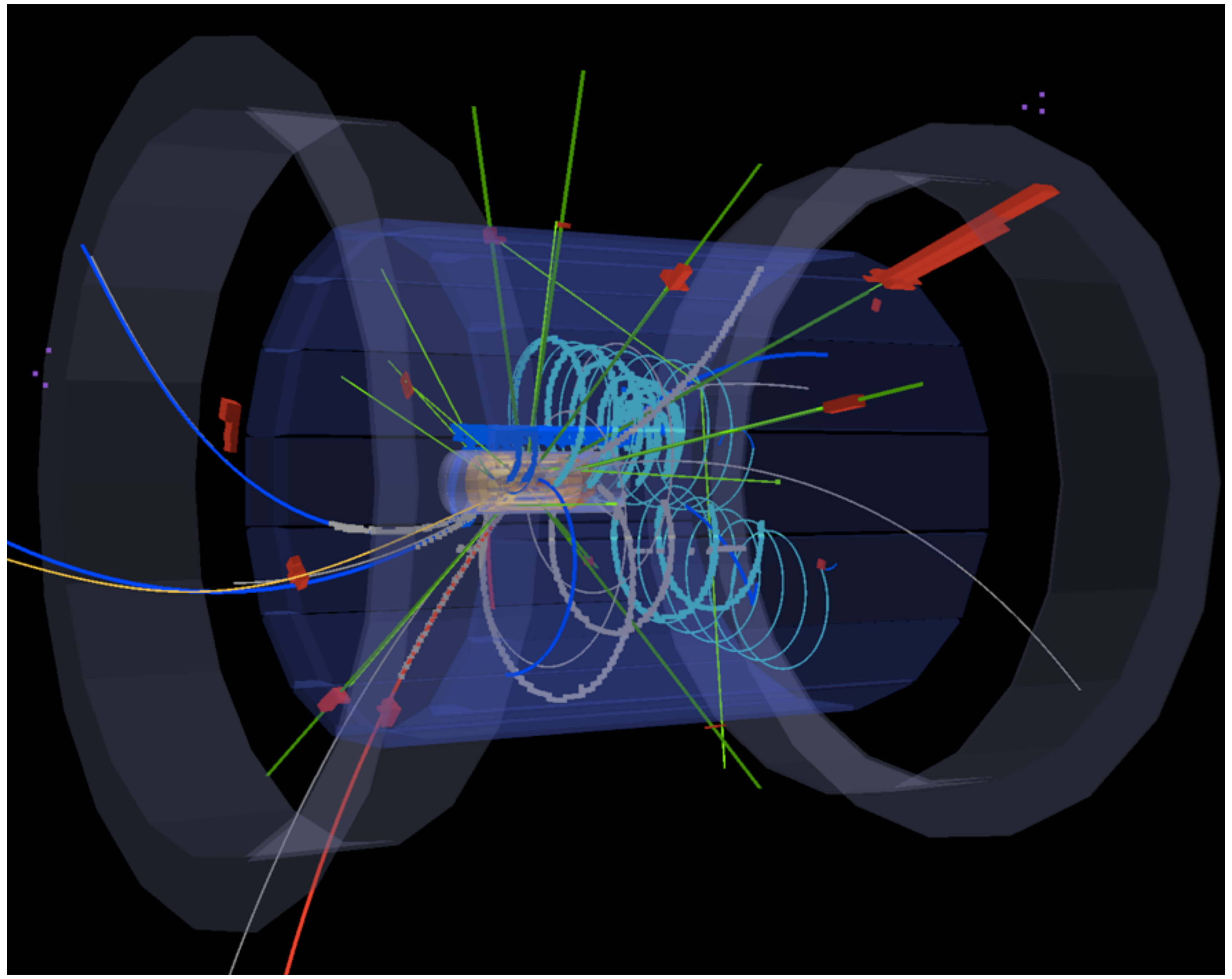
- Impact parameters: σ_{d0} Belle II ~ 0.5 x σ_{d0} Babar
- Vertex: σ_z Belle II ~ 0.5 x σ_z Belle
- Mass: σ_M Belle II ~ 0.7 x σ_M Belle
- Novel silicon—dedicated tracking. Good for D* efficiencies <$p_{\pi\text{-slow}}$> ~ 100 MeV.

Track efficiency



IP resolution



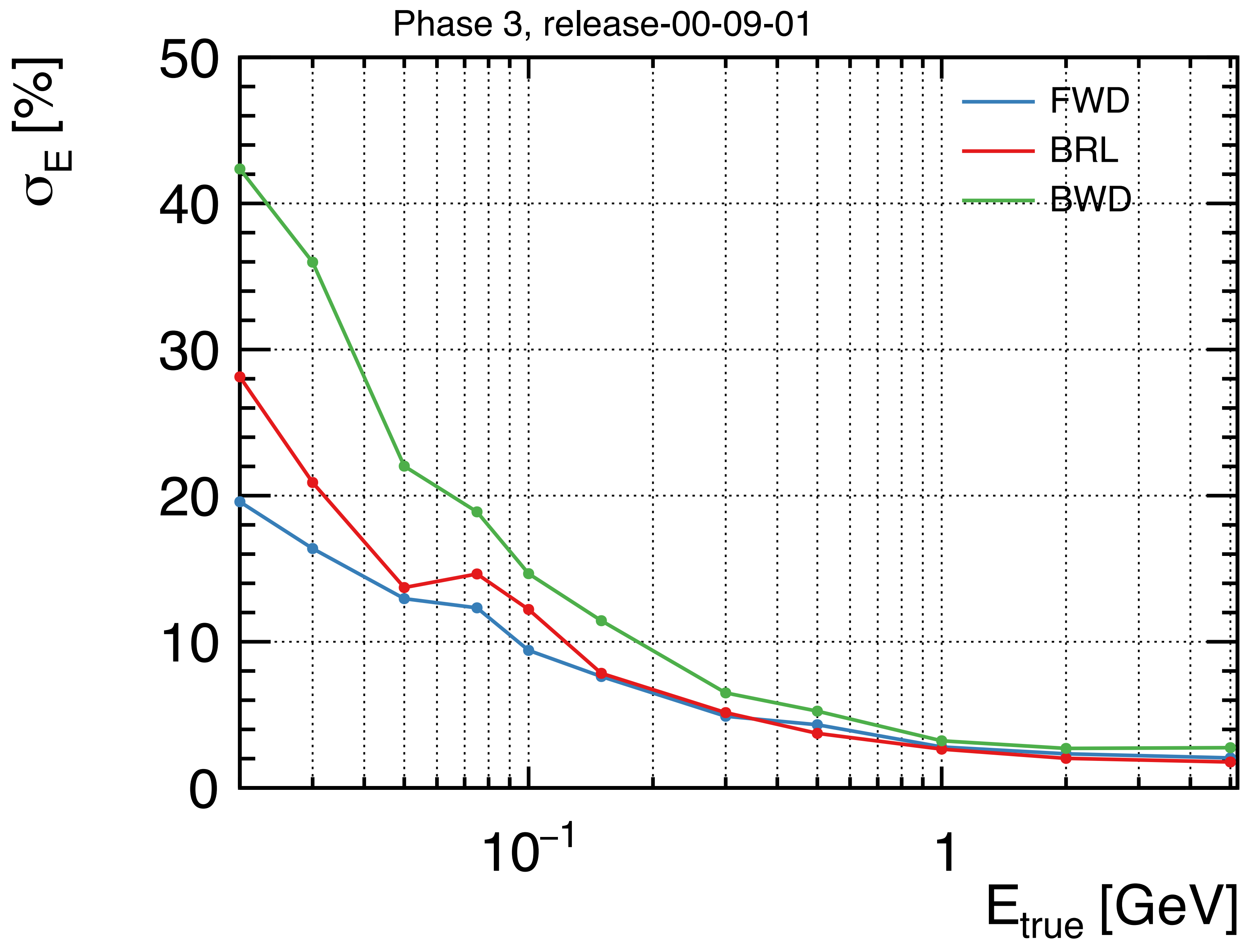


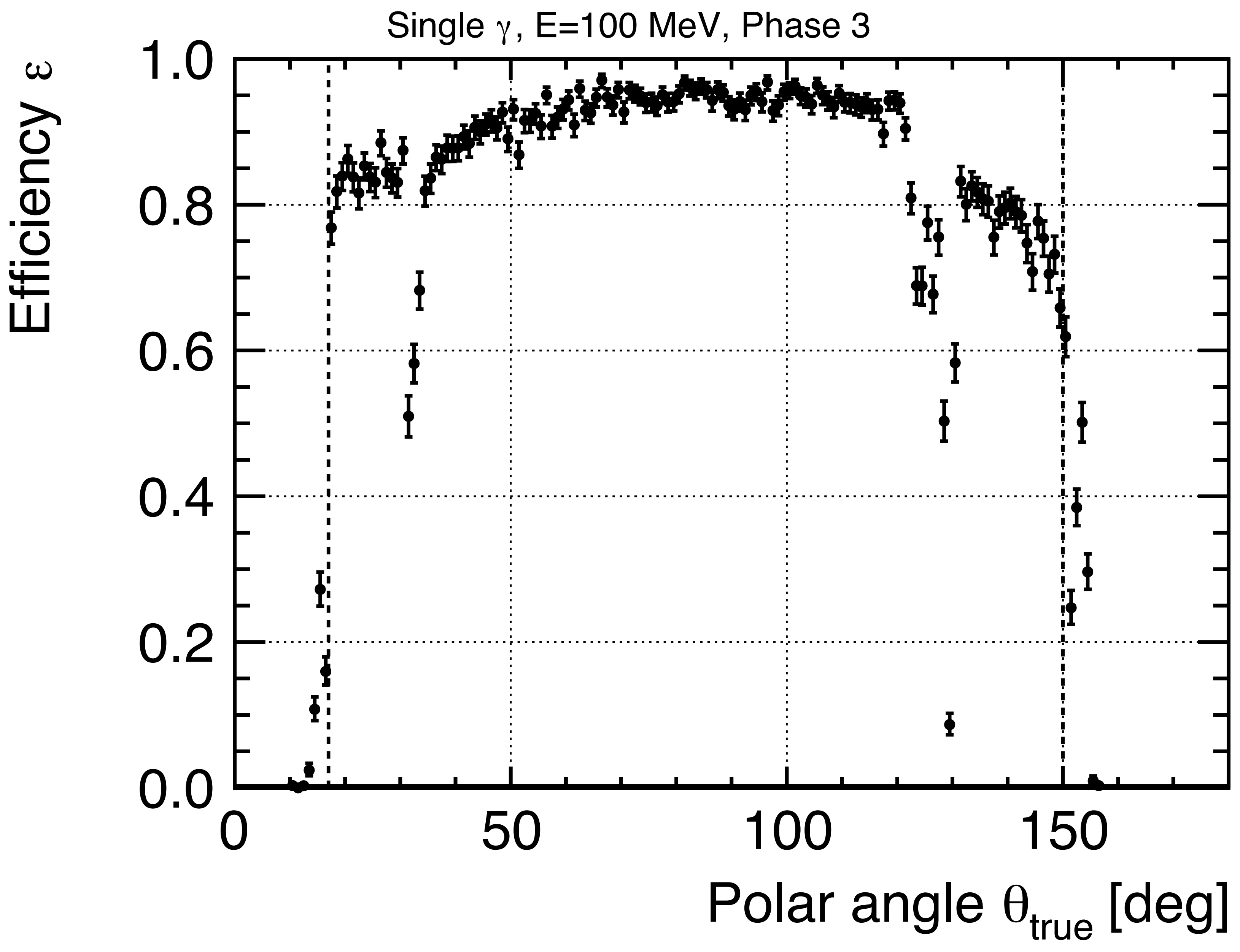
Photons reconstruction

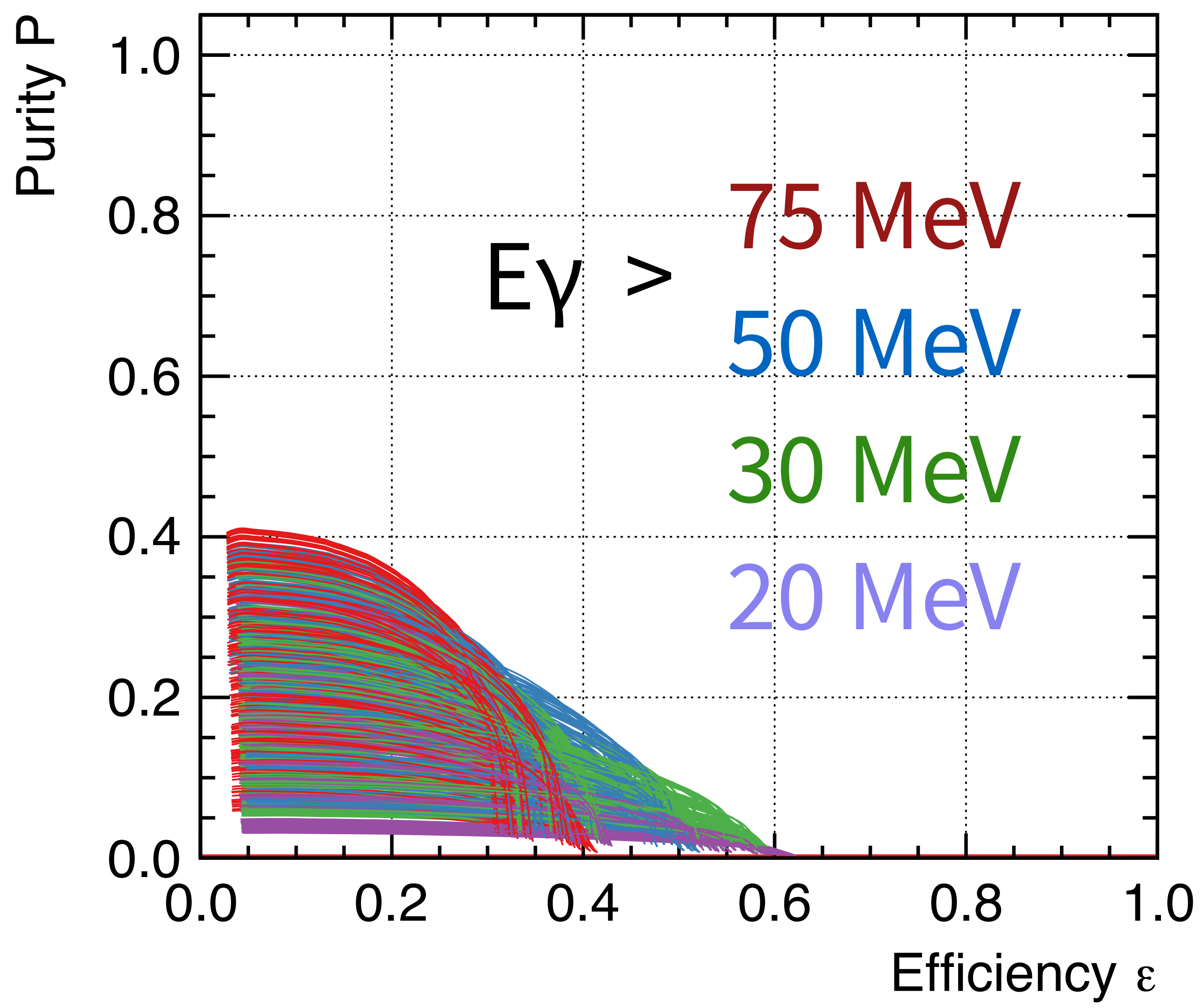
- Beam background mitigated with wave form sampling, timing.

ECL resolution

Photon and π^0 efficiencies



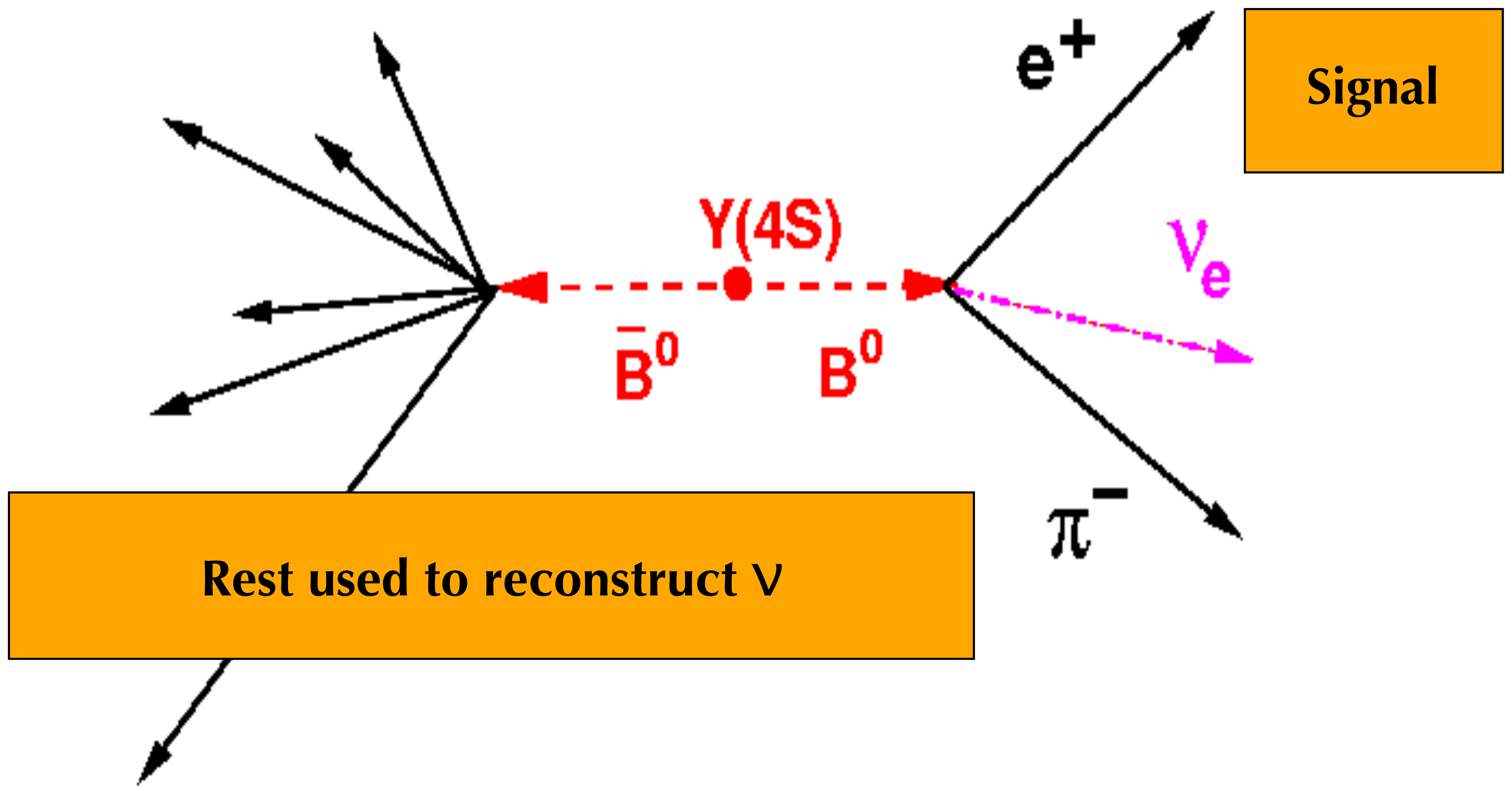




B-factory Approaches to Measuring $B \rightarrow X l \nu$

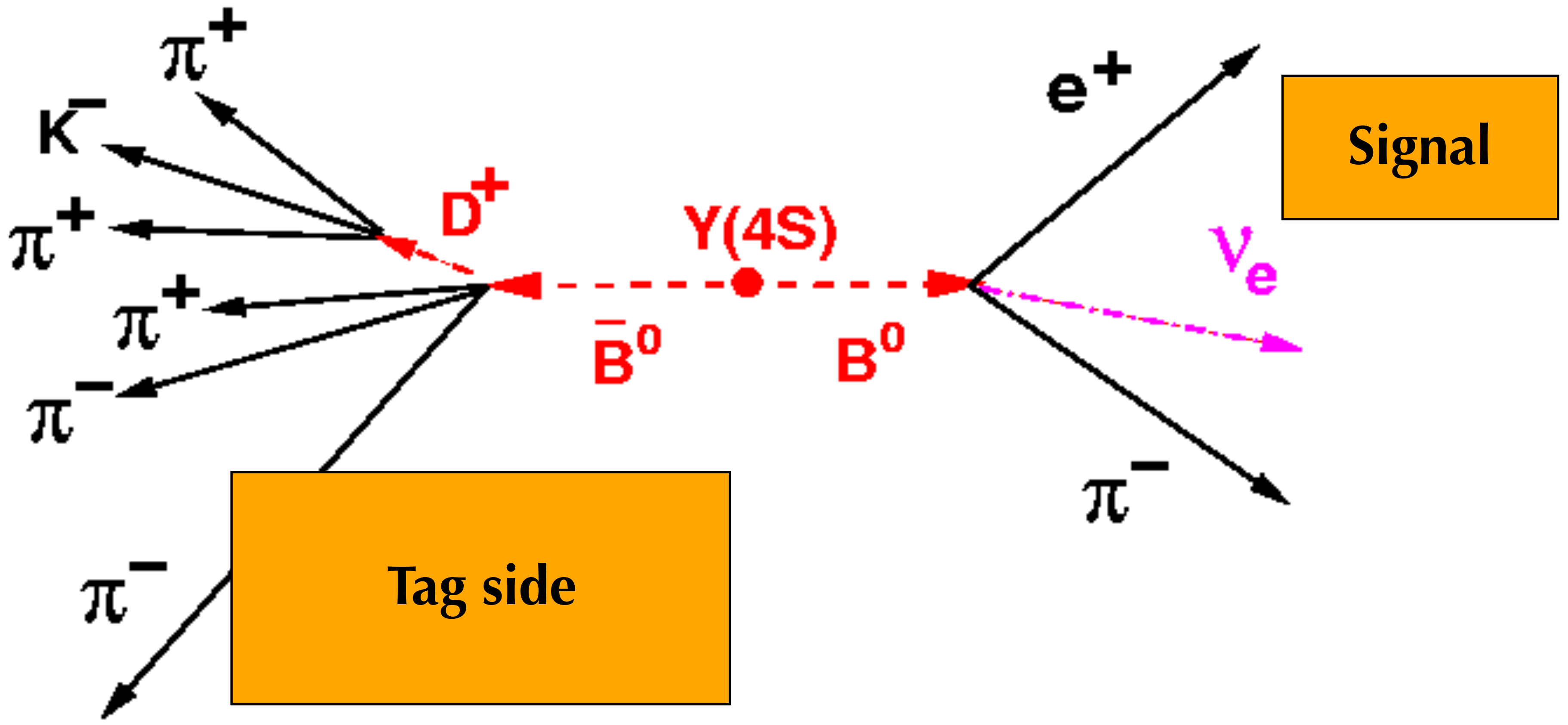
Untagged

initial 4-momentum known
missing 4-momentum = ν
Reconstruct $B \rightarrow X_q \, l \, \nu$
Use other side to constrain B flight direction.

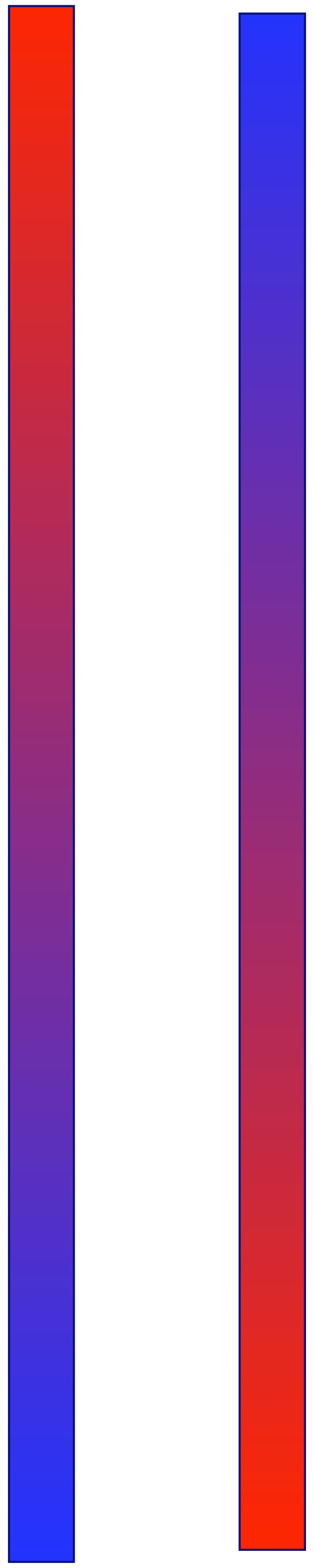


Fully Reconstructed Tag

One B reconstructed completely in a known $b \rightarrow c$ mode without ν.
"B-meson Beam"



Eff.	Purity
High	Low



Low	High

B-factory Approaches to Measuring B → X lν

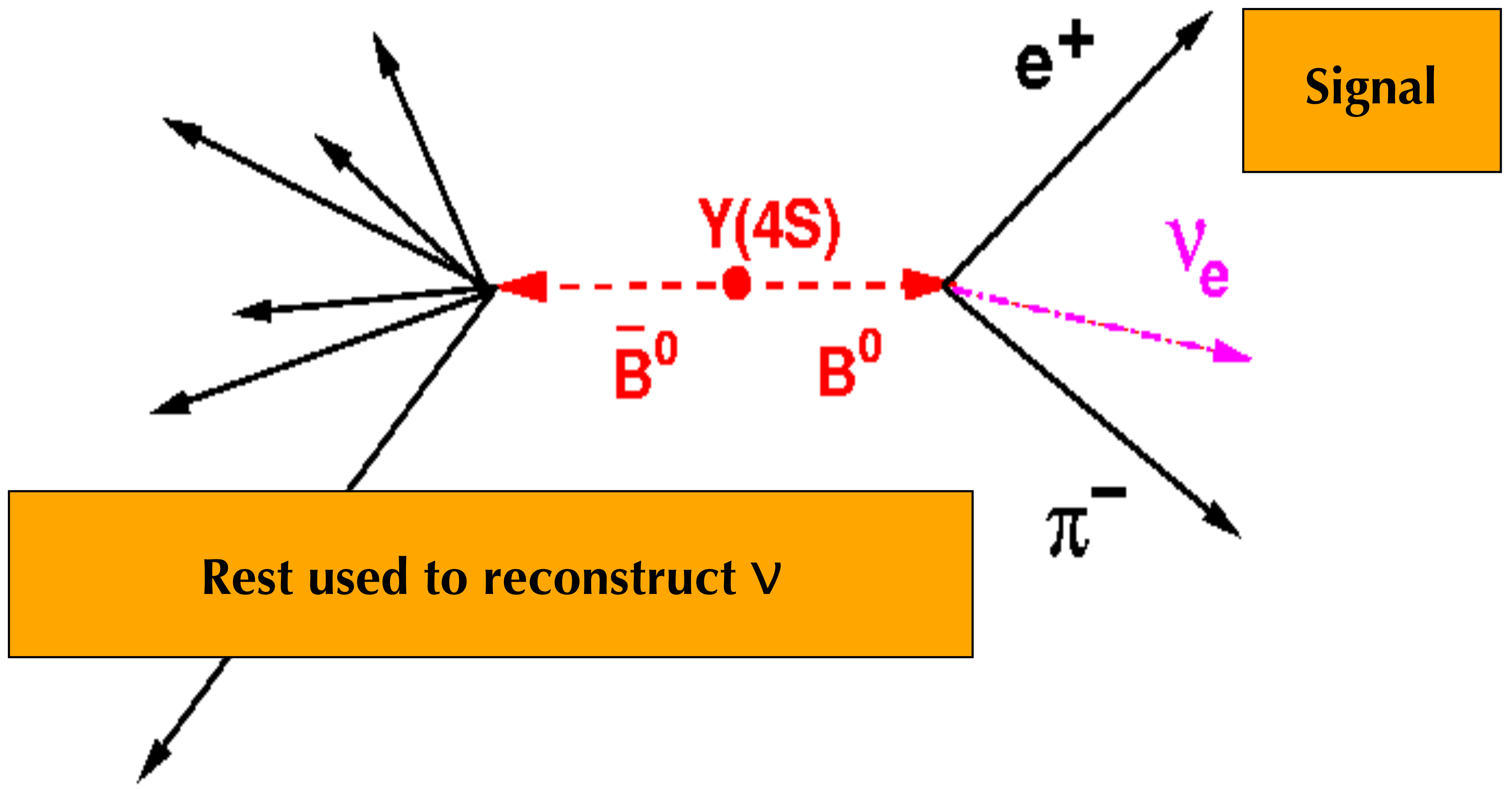
Untagged

initial 4-momentum known

missing 4-momentum = ν

Reconstruct B → X_q l ν

Use other side to constrain B flight direction.

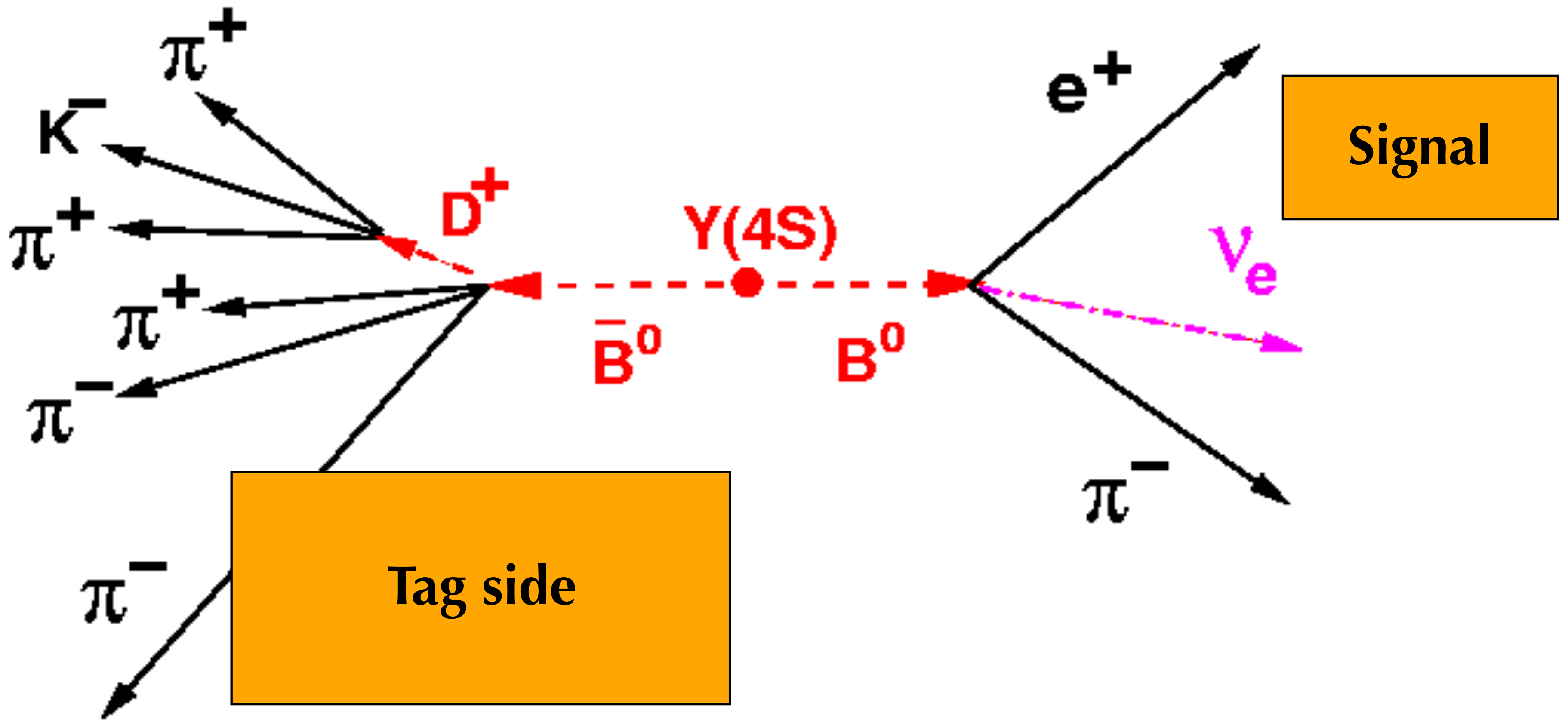


Fully Reconstructed Tag

One B reconstructed completely in a known b → c mode without ν.

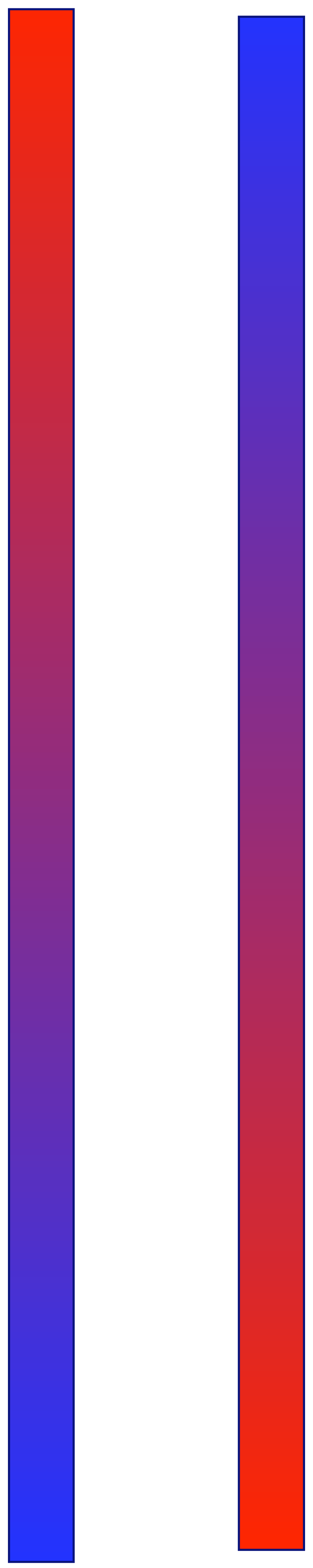
"B-meson Beam"

$$\left(p_{e^+e^-} - p^B_{\text{tag}} - p^{D^*} - p_\ell\right)^2 = (p_\nu)^2 = m^2_{\text{miss}} \backsim 0$$



Eff. **Purity**

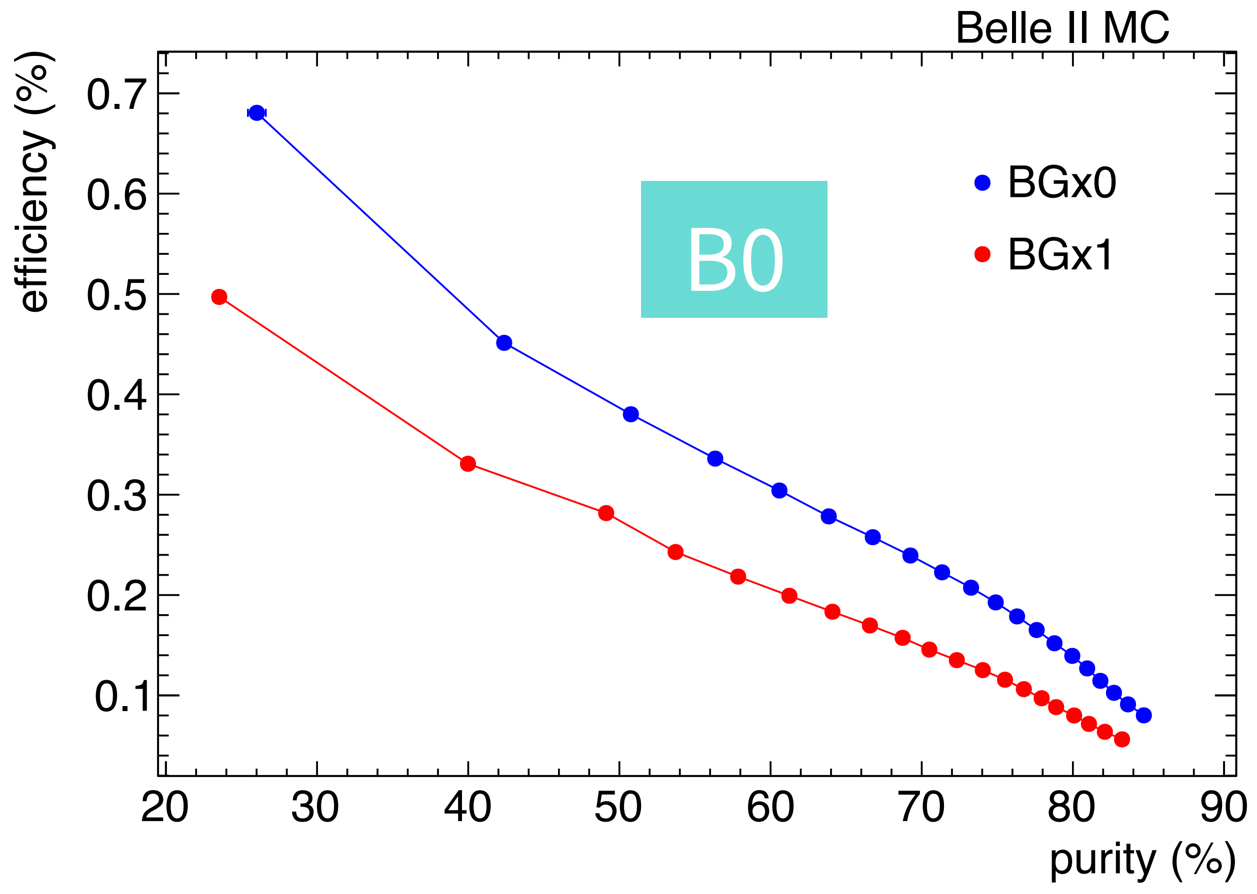
High Low

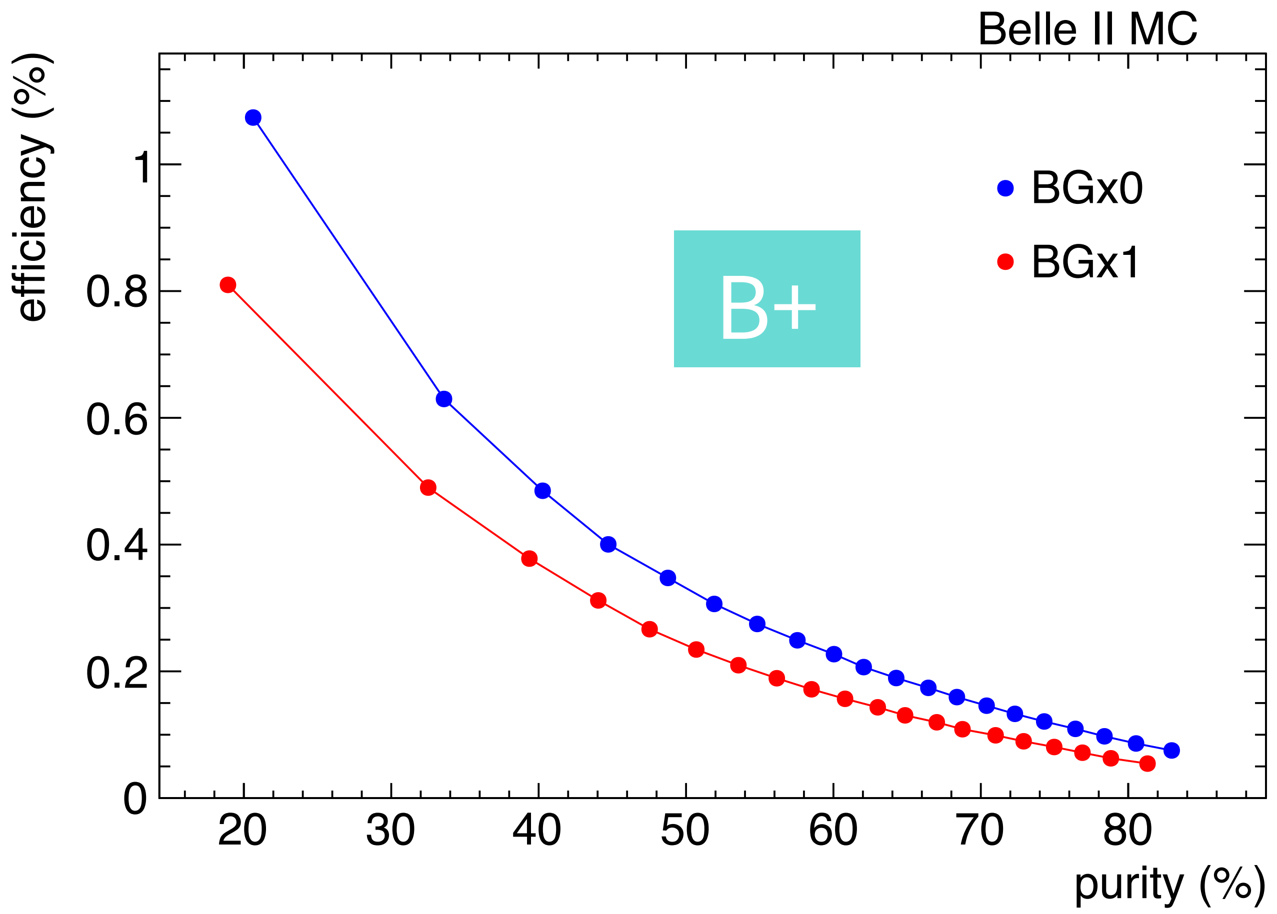


Low High

Hadronic tagging

Tag algorithm date	MVA	Efficiency	Purity
Belle v1 (2004)	Cut-based (Vcb)	-	-
Belle v3 (2007)	Cut-based	0.1	0.25
Belle NB (2011)	**Neurobayes**	**0.2**	**0.25**
Belle II FEI (2016)	FastBDT	0.5	0.25





B^+ modes	B^0 modes	D^+,D^{*+},D_s^+ modes	D^0,D^{*0} modes
$B^+ \to \bar{D}^0\pi^+$	$B^0 \to D^-\pi^+$	$D^+ \to K^-\pi^+\pi^+$	$D^0 \to K^-\pi^+$
$B^+ \to \bar{D}^0\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0$	$D^+ \to K^-\pi^+\pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0$
$B^+ \to \bar{D}^0\pi^+\pi^0\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-$	$D^+ \to K^-K^+\pi^+$	$D^0 \to K^-\pi^+\pi^+\pi^-$
$B^+ \to \bar{D}^0\pi^+\pi^+\pi^-$	$B^0 \to D_s^+D^-$	$D^+ \to K^-K^+\pi^+\pi^0$	$D^0 \to \pi^-\pi^+$
$B^+ \to D_s^+\bar{D}^0$	$B^0 \to D^{*-}\pi^+$	$D^+ \to K_S^0\pi^+$	$D^0 \to \pi^-\pi^+\pi^0$
$B^+ \to \bar{D}^{*0}\pi^+$	$B^0 \to D^{*-}\pi^+\pi^0$	$D^+ \to K_S^0\pi^+\pi^0$	$D^0 \to K_S^0\pi^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^0$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-$	$D^+ \to K_S^0\pi^+\pi^+\pi^-$	$D^0 \to K_S^0\pi^+\pi^-$
$B^+ \to \bar{D}^{*0}\pi^+\pi^+\pi^-$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-\pi^0$	$D^{*+} \to D^0\pi^+$	$D^0 \to K_S^0\pi^+\pi^-\pi^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D_s^{*+}D^-$	$D^{*+} \to D^+\pi^0$	$D^0 \to K^-K^+$
$B^+ \to D_s^{*+}\bar{D}^0$	$B^0 \to D_s^+D^{*-}$	$D_s^+ \to K^+K_S^0$	$D^0 \to K^-K^+K_S^0$
$B^+ \to D_s^+\bar{D}^{*0}$	$B^0 \to D_s^{*+}D^{*-}$	$D_s^+ \to K^+\pi^+\pi^-$	$D^{*0} \to D^0\pi^0$
$B^+ \to \bar{D}^0K^+$	$B^0 \to J/\psi K_S^0$	$D_s^+ \to K^+K^-\pi^+$	$D^{*0} \to D^0\gamma$
$B^+ \to D^-\pi^+\pi^+$	$B^0 \to J/\psi K^+\pi^+$	$D_s^+ \to K^+K^-\pi^+\pi^0$	
$B^+ \to J/\psi K^+$	$B^0 \to J/\psi K_S^0\pi^+\pi^-$	$D_s^+ \to K^+K_S^0\pi^+\pi^-$	
$B^+ \to J/\psi K^+\pi^+\pi^-$		$D_s^+ \to K^-K_S^0\pi^+\pi^+$	
$B^+ \to J/\psi K^+\pi^0$		$D_s^+ \to K^+K^-\pi^+\pi^+\pi^-$	
$B^+ \to J/\psi K_S^0\pi^+$		$D_s^+ \to \pi^+\pi^+\pi^-$	
		$D_s^{*+} \to D_s^+\pi^0$	

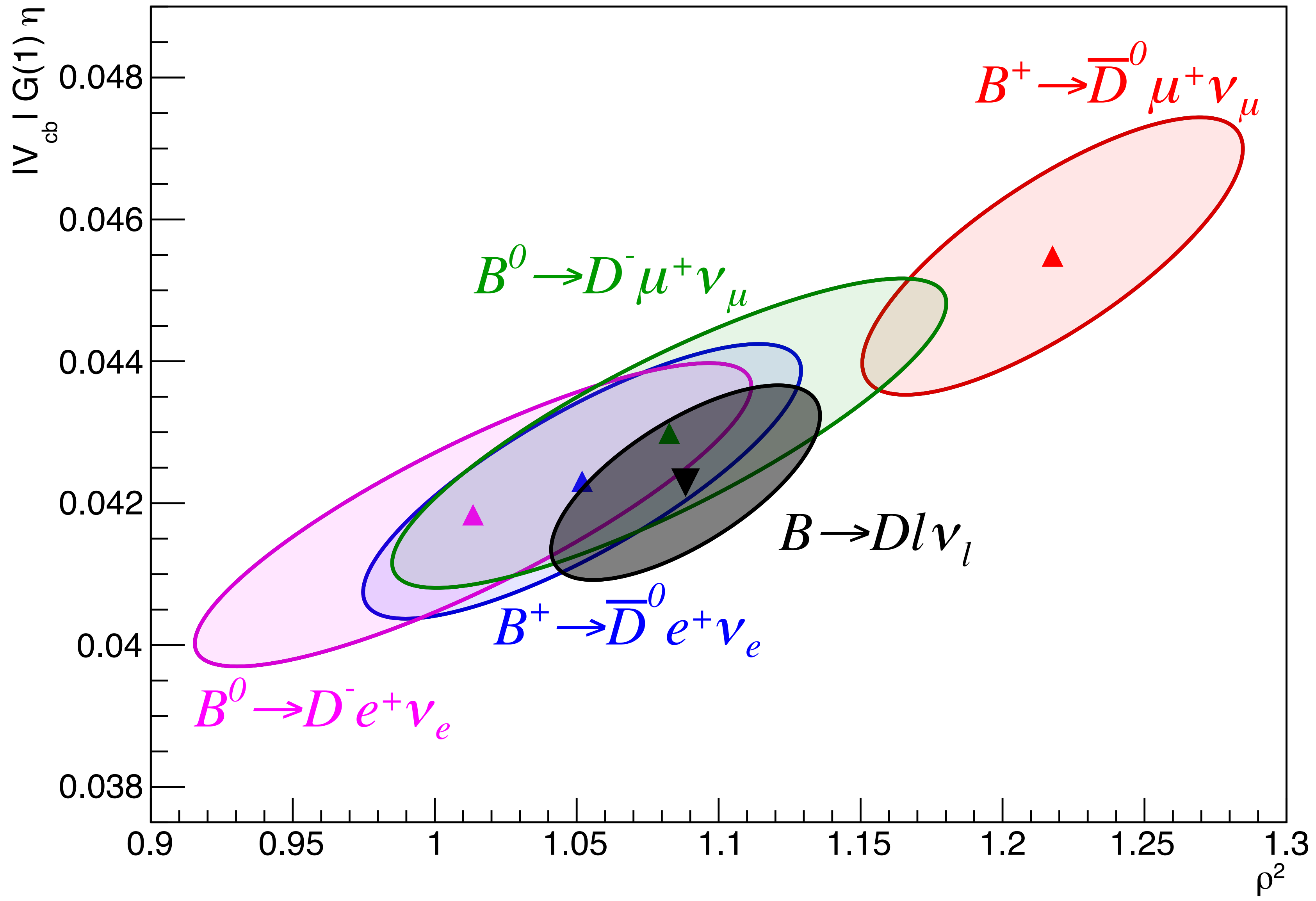
$B^+ \to D^-\pi^+\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0\pi^0$	$D^+ \to \pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0\pi^0$
$B^+ \to \bar{D}^0\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-\pi^0$	$D^+ \to \pi^+\pi^+\pi^-$	$D^0 \to K^-\pi^+\pi^+\pi^-\pi^0$
$B^+ \to \bar{D}^0D^+$	$B^0 \to \bar{D}^0\pi^+\pi^-$	$D^+ \to \pi^+\pi^+\pi^-\pi^0$	$D^0 \to \pi^-\pi^+\pi^+\pi^-$
$B^+ \to \bar{D}^0D^+K_S^0$	$B^0 \to D^-D^0K^+$	$D^+ \to K^+K_S^0K_S^0$	$D^0 \to \pi^-\pi^+\pi^0\pi^0$
$B^+ \to \bar{D}^{*0}D^+K_S^0$	$B^0 \to D^-D^{*0}K^+$	$D^{*+} \to D^+\gamma$	$D^0 \to K^-K^+\pi^0$
$B^+ \to \bar{D}^0D^{*+}K_S^0$	$B^0 \to D^{*-}D^0K^+$	$D_s^+ \to K_S^0\pi^+$	
$B^+ \to \bar{D}^{*0}D^{*+}K_S^0$	$B^0 \to D^{*-}D^{*0}K^+$	$D_s^+ \to K_S^0\pi^+\pi^0$	
$B^+ \to \bar{D}^0D^0K^+$	$B^0 \to D^-D^+K_S^0$	$D_s^{*+} \to D_s^+\pi^0$	
$B^+ \to \bar{D}^{*0}D^0K^+$	$B^0 \to D^{*-}D^+K_S^0$		
$B^+ \to \bar{D}^0D^{*0}K^+$	$B^0 \to D^-D^{*+}K_S^0$		
$B^+ \to \bar{D}^{*0}D^{*0}K^+$	$B^0 \to D^{*-}D^{*+}K_S^0$		
$B^+ \to \bar{D}^{*0}\pi^+\pi^0\pi^0$	$B^0 \to D^{*-}\pi^+\pi^0\pi^0$		

- Below line: not used in Belle NB tag.

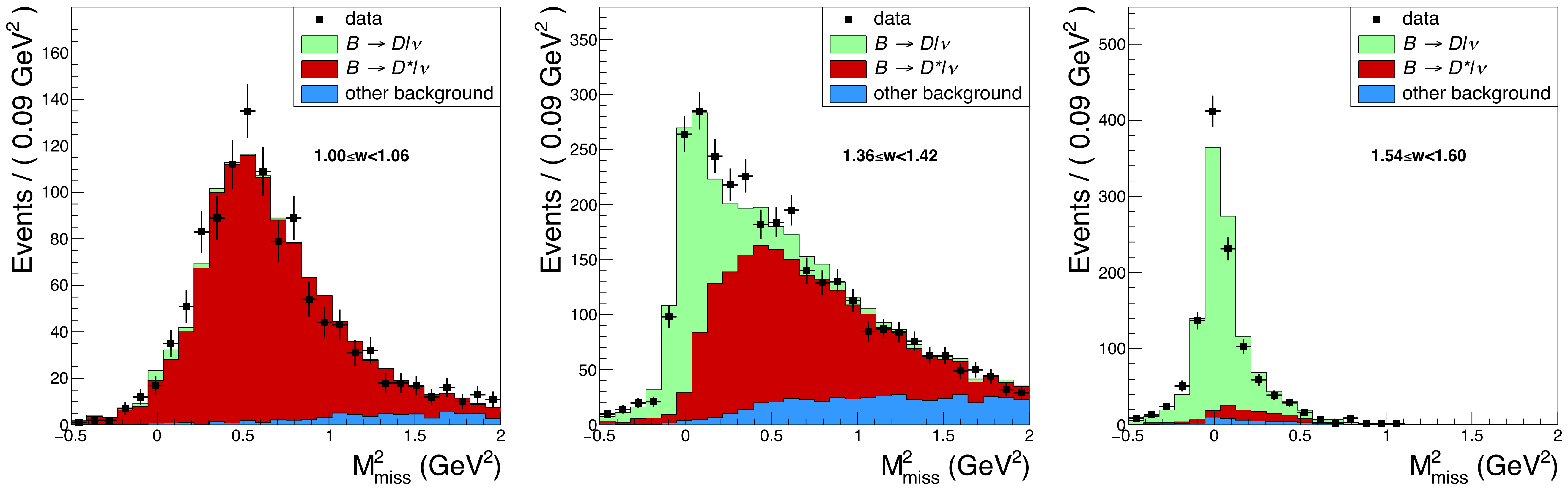
$B \to D\,l\,\nu$

Belle PRD 93, 032006 (2016)

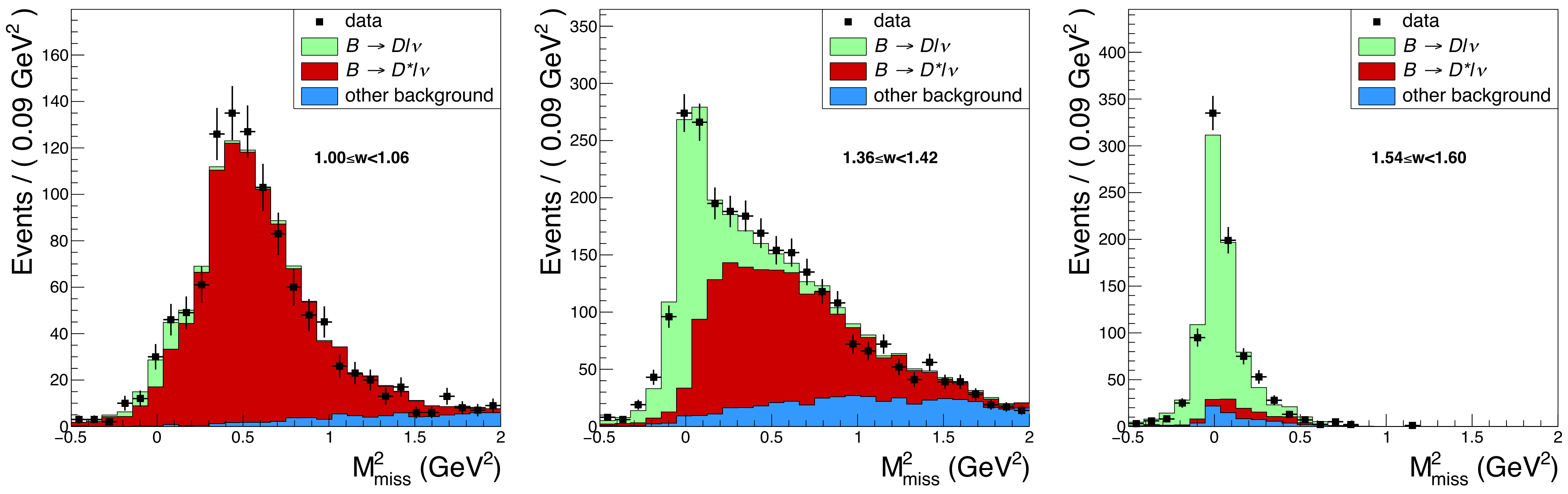
- Use both $B \to D^0 l\nu$ and $B \to D^+ l\nu$
- Signal extract in 10 bins of w from M_{miss}^2
- Fit ~17000 signal events
- Largest background $B \to D^* l\nu$
- Use B tagging: calibration with $B \to X l \nu$
- First BGL analysis of $b \to c l \nu$



B→ D e ν

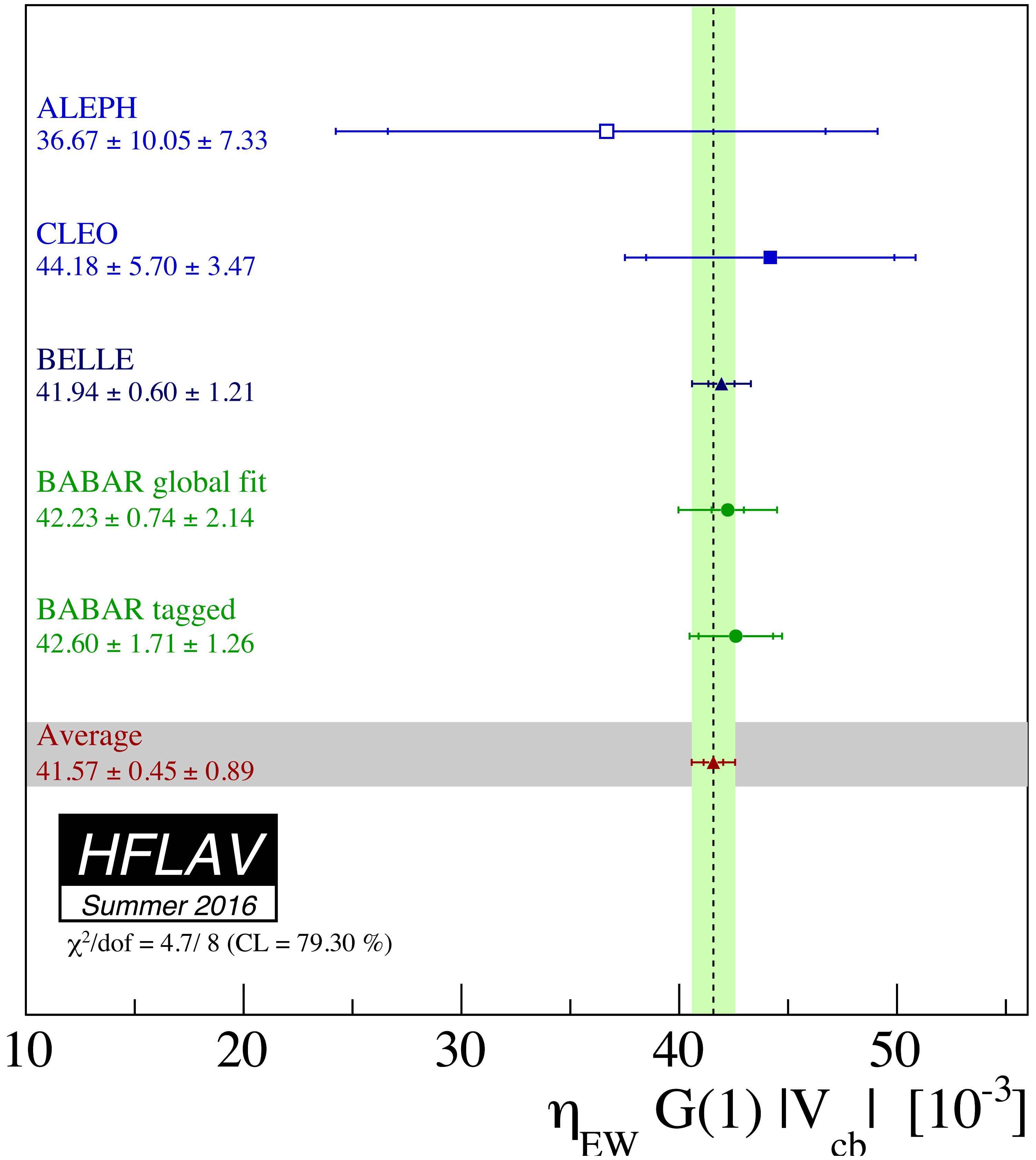


B→ D μ ν

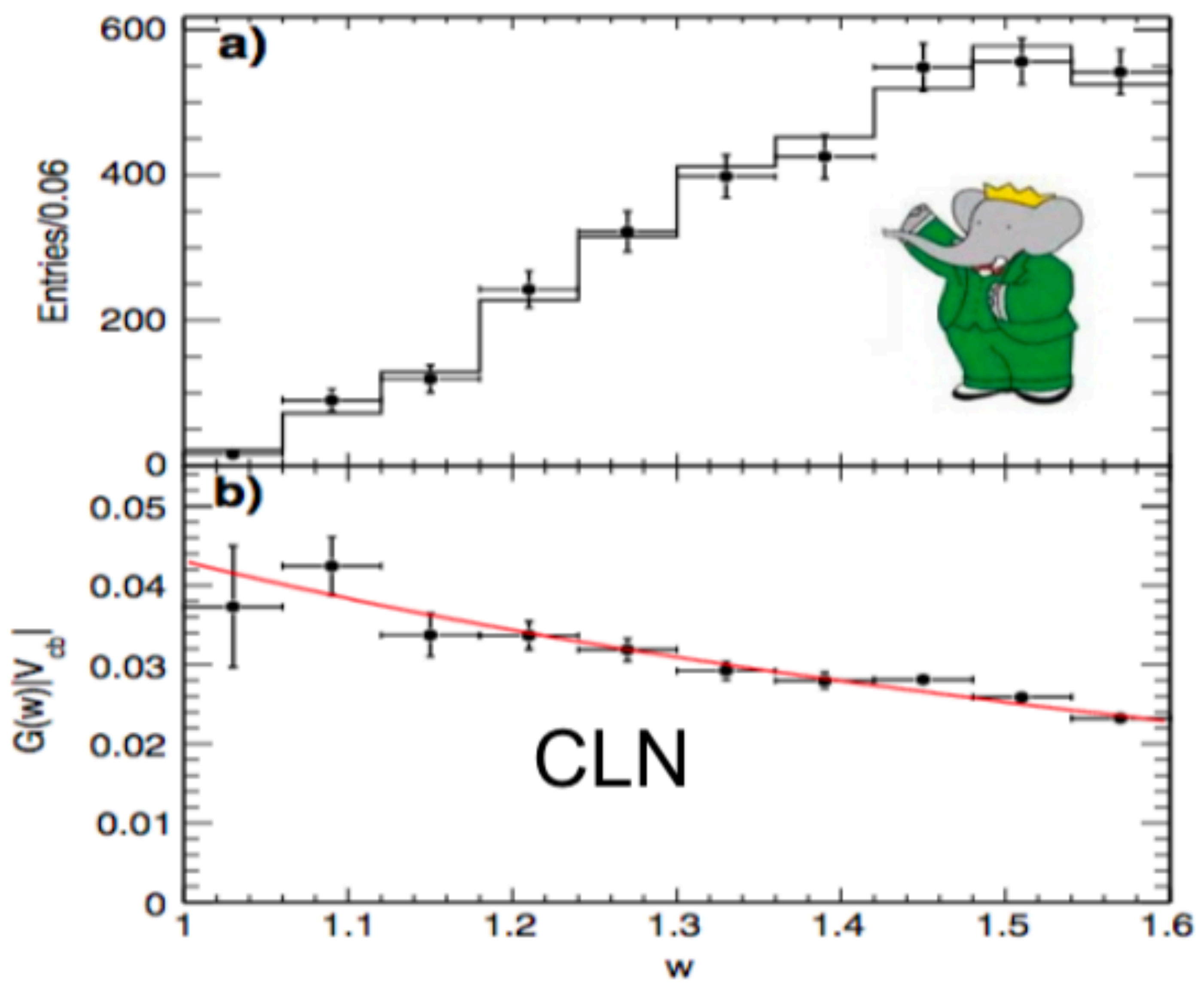


next-to-w=1 recoil bin is highly stat limited

B → D l ν



Babar PRL 104:011802(2010)



Belle PRD 93, 032006 (2016)

	$N=2$	$N=3$	$N=4$
$a_{+,0}$	0.0127 ± 0.0001	0.0126 ± 0.0001	0.0126 ± 0.0001
$a_{+,1}$	-0.091 ± 0.002	-0.094 ± 0.003	-0.094 ± 0.003
$a_{+,2}$	0.34 ± 0.03	0.34 ± 0.04	0.34 ± 0.04
$a_{+,3}$	–	-0.1 ± 0.6	-0.1 ± 0.6
$a_{+,4}$	–	–	0.0 ± 1.0
$a_{0,0}$	0.0115 ± 0.0001	0.0115 ± 0.0001	0.0115 ± 0.0001
$a_{0,1}$	-0.058 ± 0.002	-0.057 ± 0.002	-0.057 ± 0.002
$a_{0,2}$	0.22 ± 0.02	0.12 ± 0.04	0.12 ± 0.04
$a_{0,3}$	–	0.4 ± 0.7	0.4 ± 0.7
$a_{0,4}$	–	–	0.0 ± 1.0
$\eta_{\mathrm{EW}}\|V_{cb}\|$	40.01 ± 1.08	41.10 ± 1.14	41.10 ± 1.14
χ^2/n_{df}	24.7/16	11.4/16	11.3/16
Prob.	0.075	0.787	0.787

- Consistent results between the existing measurements.
- **Challenge is that a lot of information comes from w=1 but d Γ/dw → 0 at this point**
- Belle Unfolded spectrum fitted with the Lattice from FNAL & HPQCD points to extract |Vcb| and the form factor shape

$B \to D\, l\, \nu$ Systematics and LFU

- Tag correction dominates - use only the cleaner modes at Belle II, e.g. lower multiplicity, fewer modes with γ or K_S.
- Despite overall stat error, low recoil bin is highly stat limited
- Ratio not explicitly measured in Belle. Errors should cancel. $R_{\mu/e}$ stat±6%, sys±1% (estimated).
- In Belle II: $R_{\mu/e}$ stat±<1%, sys±<1%. = total±1%

Sample	Signal yield	$\mathcal{B}$ [%]
$B^0 \to D^- e^+ \nu_e$	$2848 \pm 72 \pm 17$	$2.44 \pm 0.06 \pm 0.12$
$B^0 \to D^- \mu^+ \nu_\mu$	$2302 \pm 63 \pm 13$	$2.39 \pm 0.06 \pm 0.11$
$B^+ \to \bar{D}^0 e^+ \nu_e$	$6456 \pm 126 \pm 66$	$2.57 \pm 0.05 \pm 0.13$
$B^+ \to \bar{D}^0 \mu^+ \nu_\mu$	$5386 \pm 110 \pm 51$	$2.58 \pm 0.05 \pm 0.13$
$B^0 \to D^- \ell^+ \nu_\ell$	$5150 \pm 95 \pm 29$	$2.39 \pm 0.04 \pm 0.11$
$B^+ \to \bar{D}^0 \ell^+ \nu_\ell$	$11843 \pm 167 \pm 120$	$2.54 \pm 0.04 \pm 0.13$
$B \to D \ell \nu_\ell$	$16992 \pm 192 \pm 142$	$2.31 \pm 0.03 \pm 0.11$

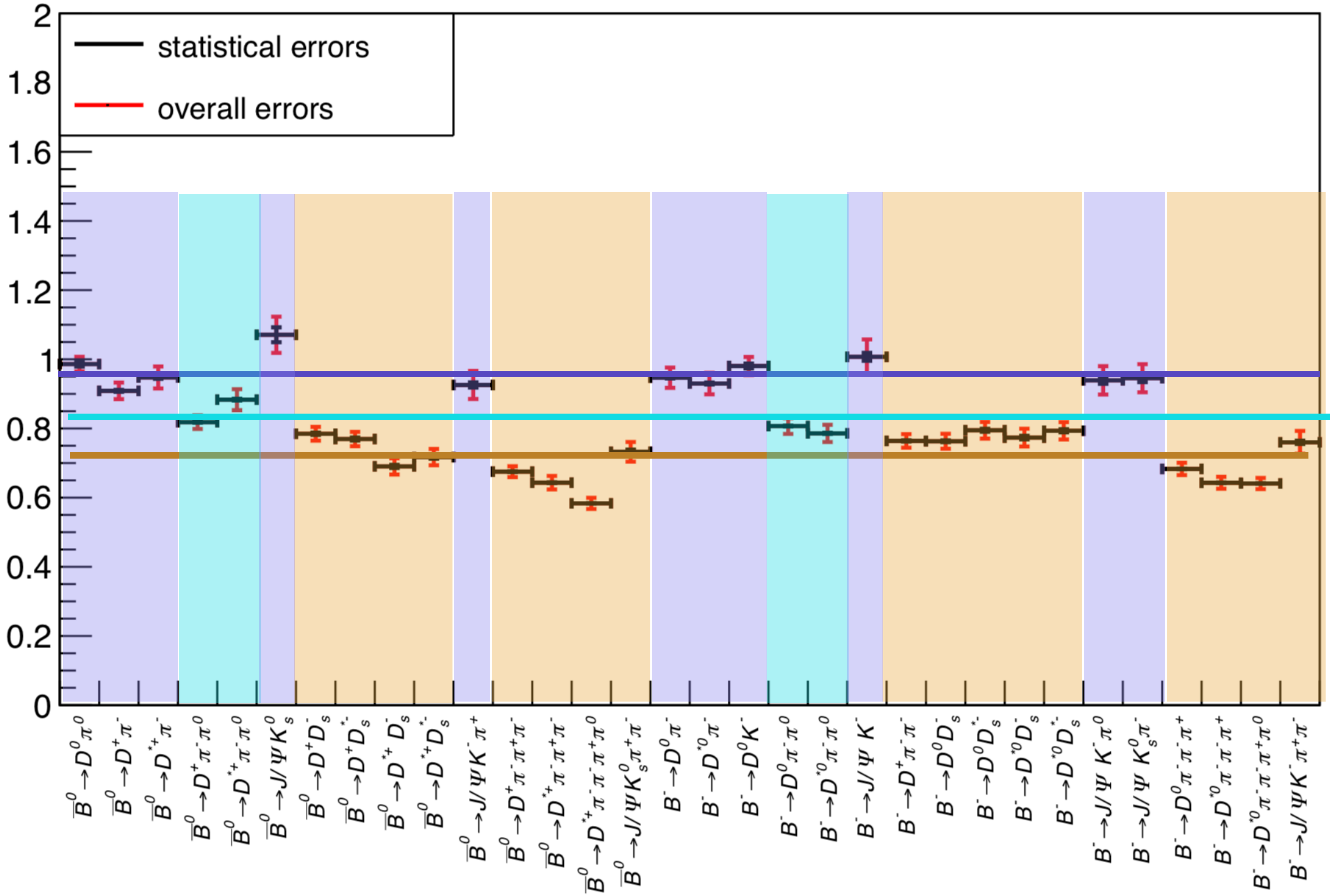
Tag Method	tagged
Br [10^{-2}]	2.31
Errors	%
Track	1.6
$B \to D^{**} l\nu$, FF	0.7
$B \to D^{**} l\nu$, Bfs	0.8
$D^{(*)}$ Bfs	1.8
PDFs	0.5
particle ID	1.0
Tag calibration	**3.3**
Luminosity	1.4
τ_B	0.2
π^0 efficiency	0.6
Total	4.6
Stat	1.3

Tag mode calibration Data/MC $B_{sig} \rightarrow X\, l\, \nu$ @ Belle

Cleaner modes

Moderately clean

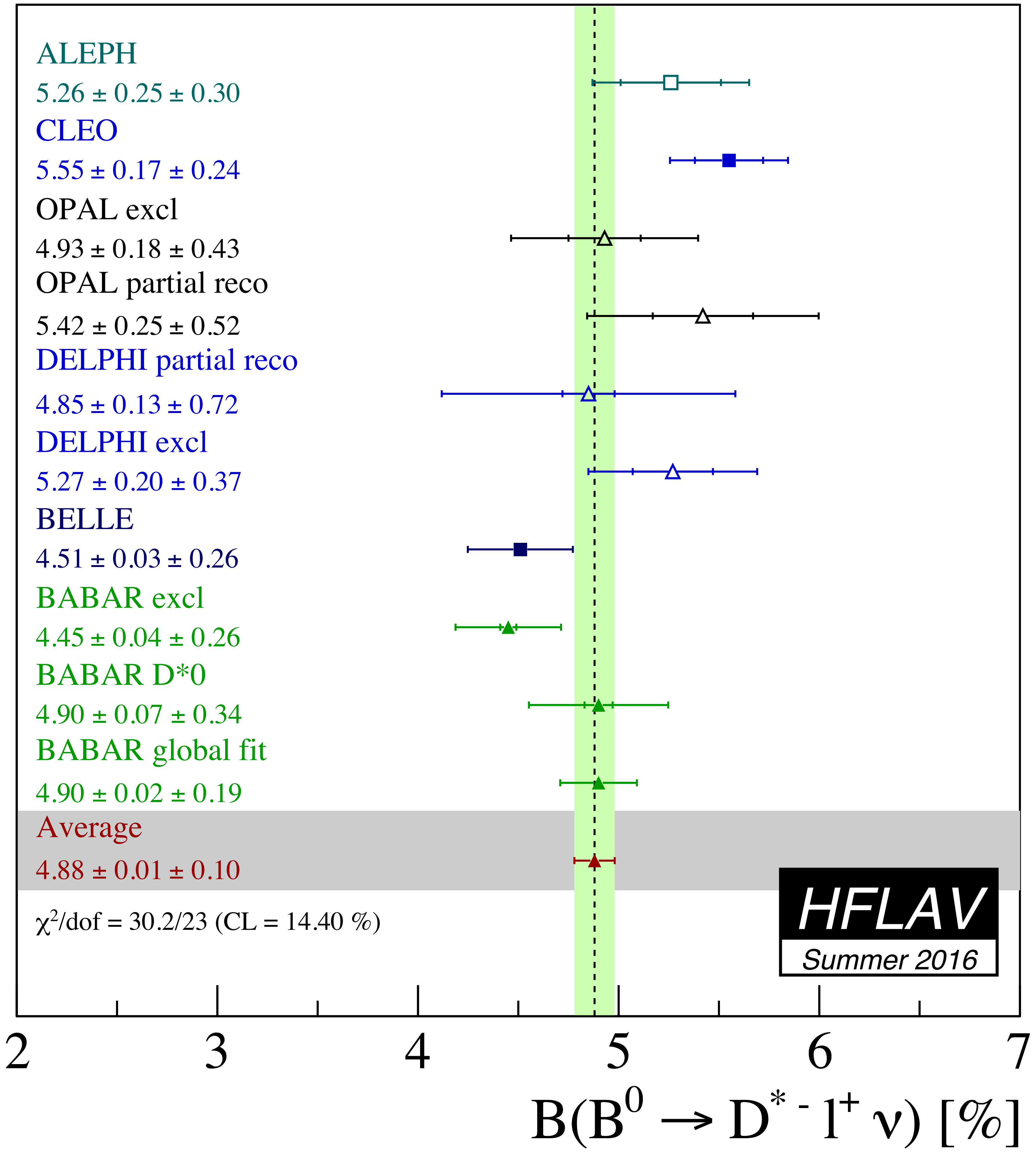
High multiplicity, lower purity modes



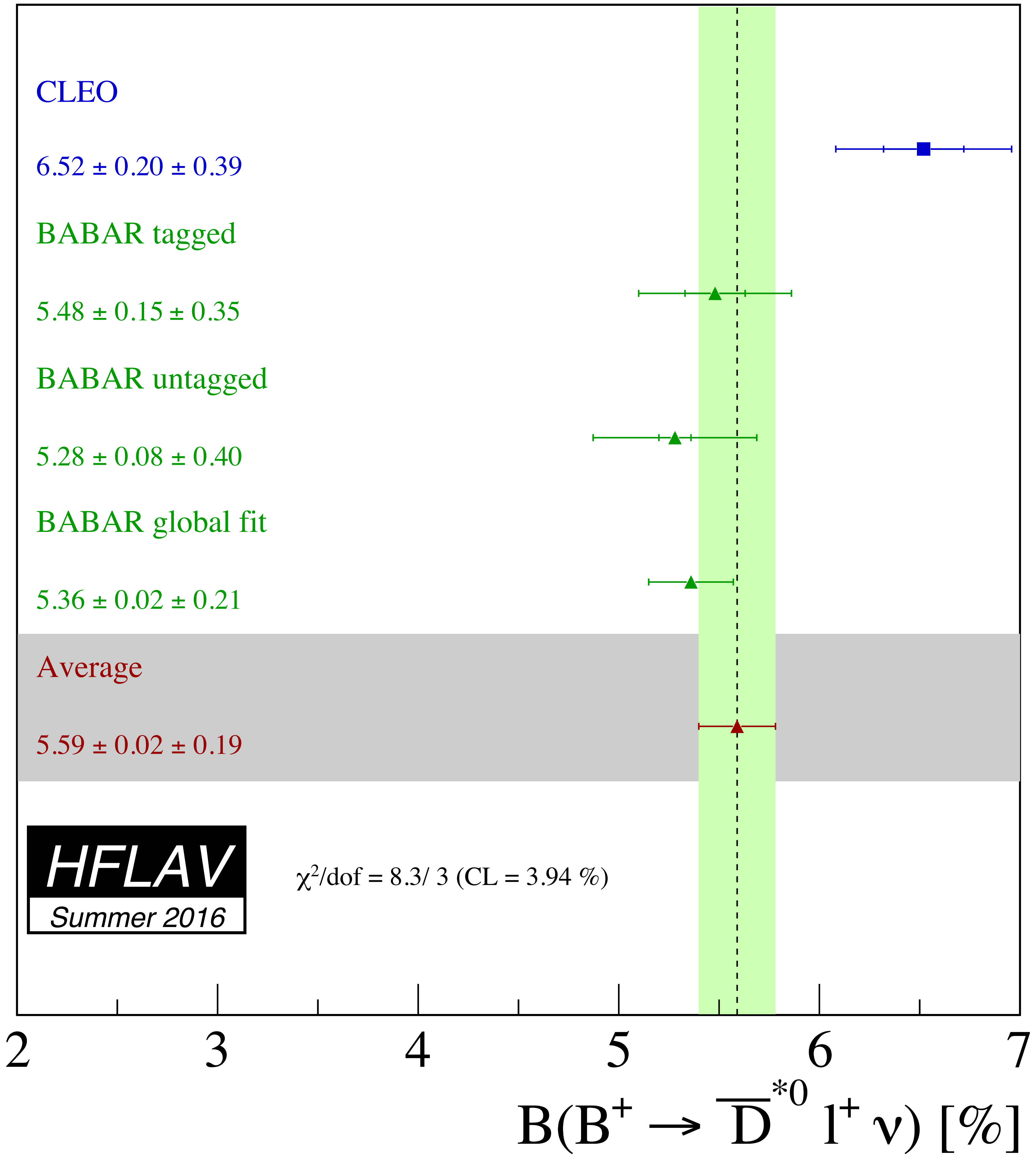
$B \to D^* l \nu$ status

- Reasonable consistency among Belle and Babar

B+ and B0 (isospin constraint)



B+

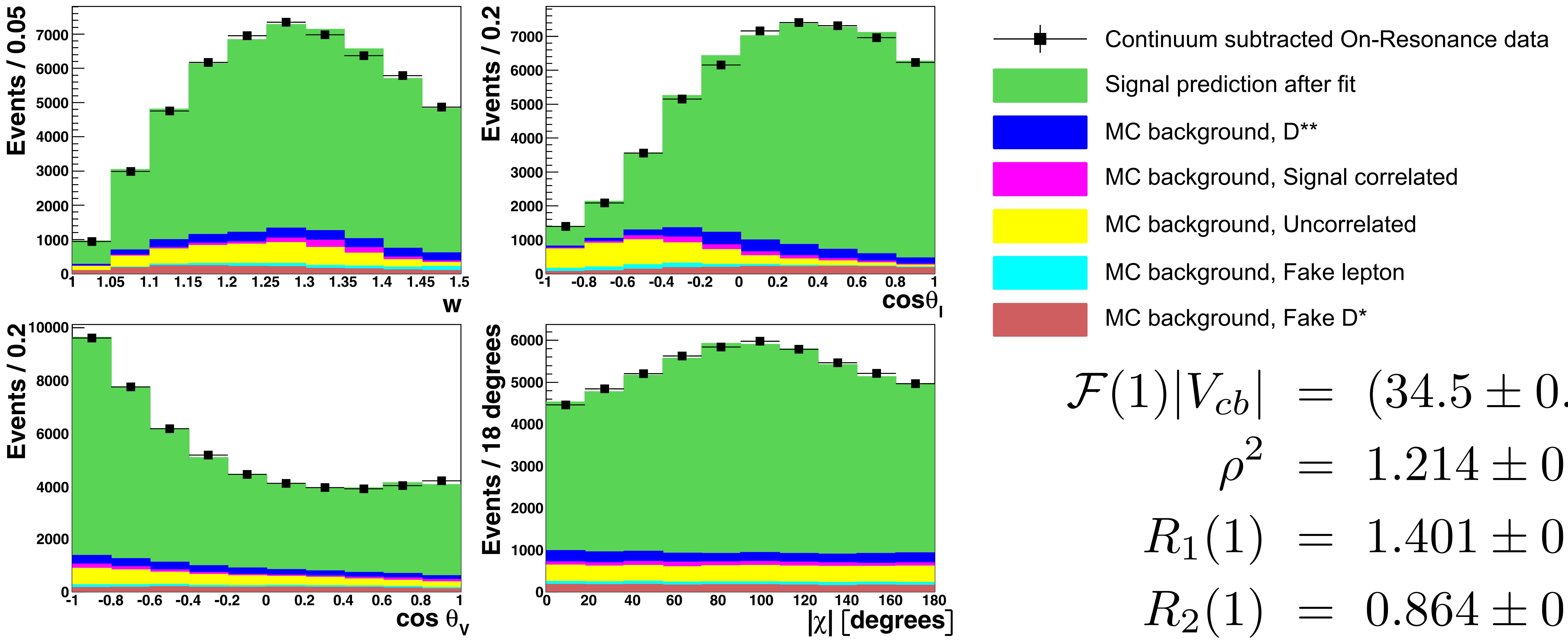


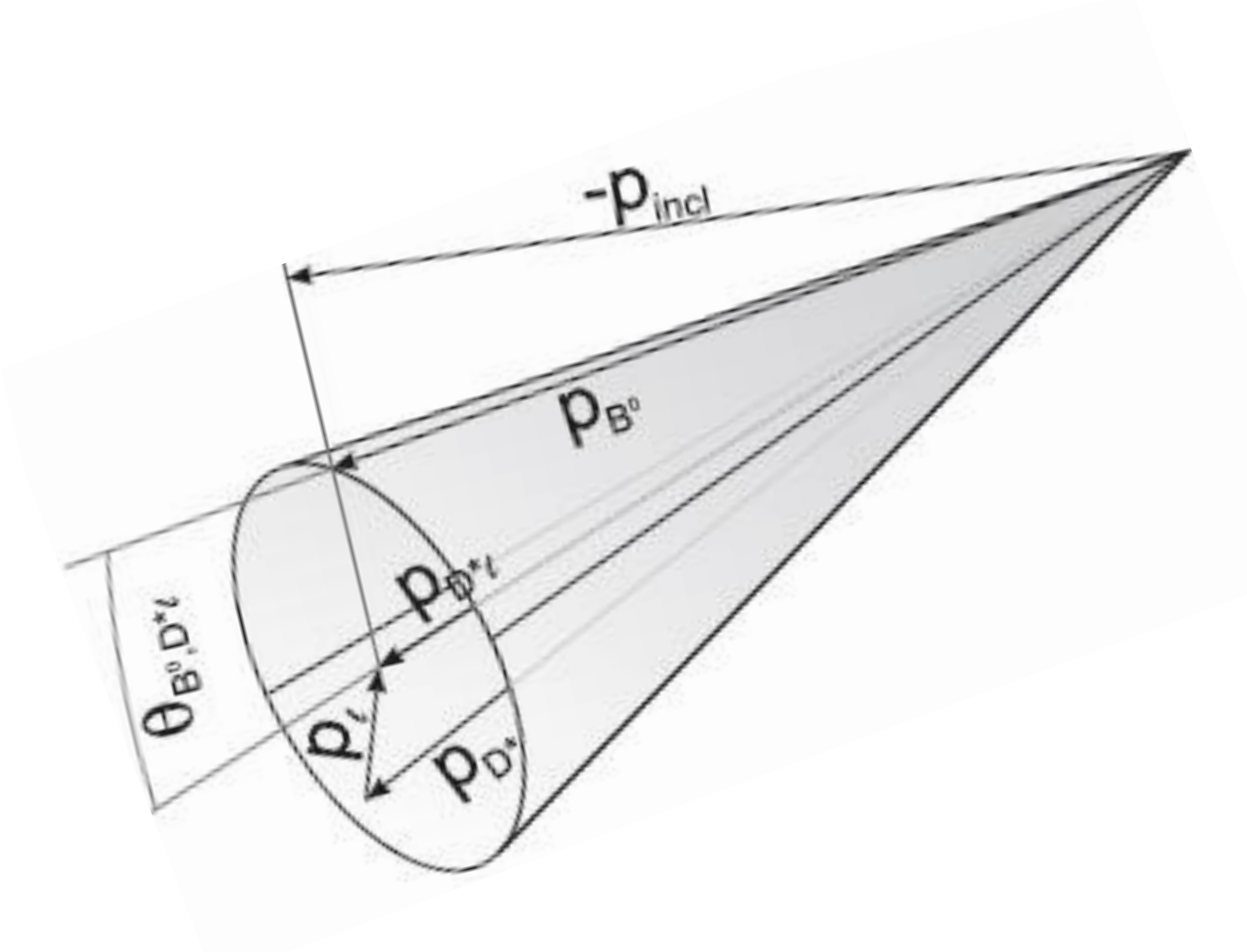
$B \to D^* l \nu$ untagged

Belle PRD 82, 112007 (2010)

- **$B^0 \to D^{*-} l\nu$ ($D^{*-} \to D^0\pi^-$, $D^0 \to K\pi$)** both **e and μ** modes (120k signal events)
- Conservation of momentum: p_B is on a cone around (D^*l) axis making an opening angle $\cos\theta_{B,D^*l}$.
    - Take the sum of momenta of non-signal side of the decay, p_{incl}
- Fit 1D projections in w, cos θl , cos θV, χ (P-value of CLN fit = 47%)

Not unfolded



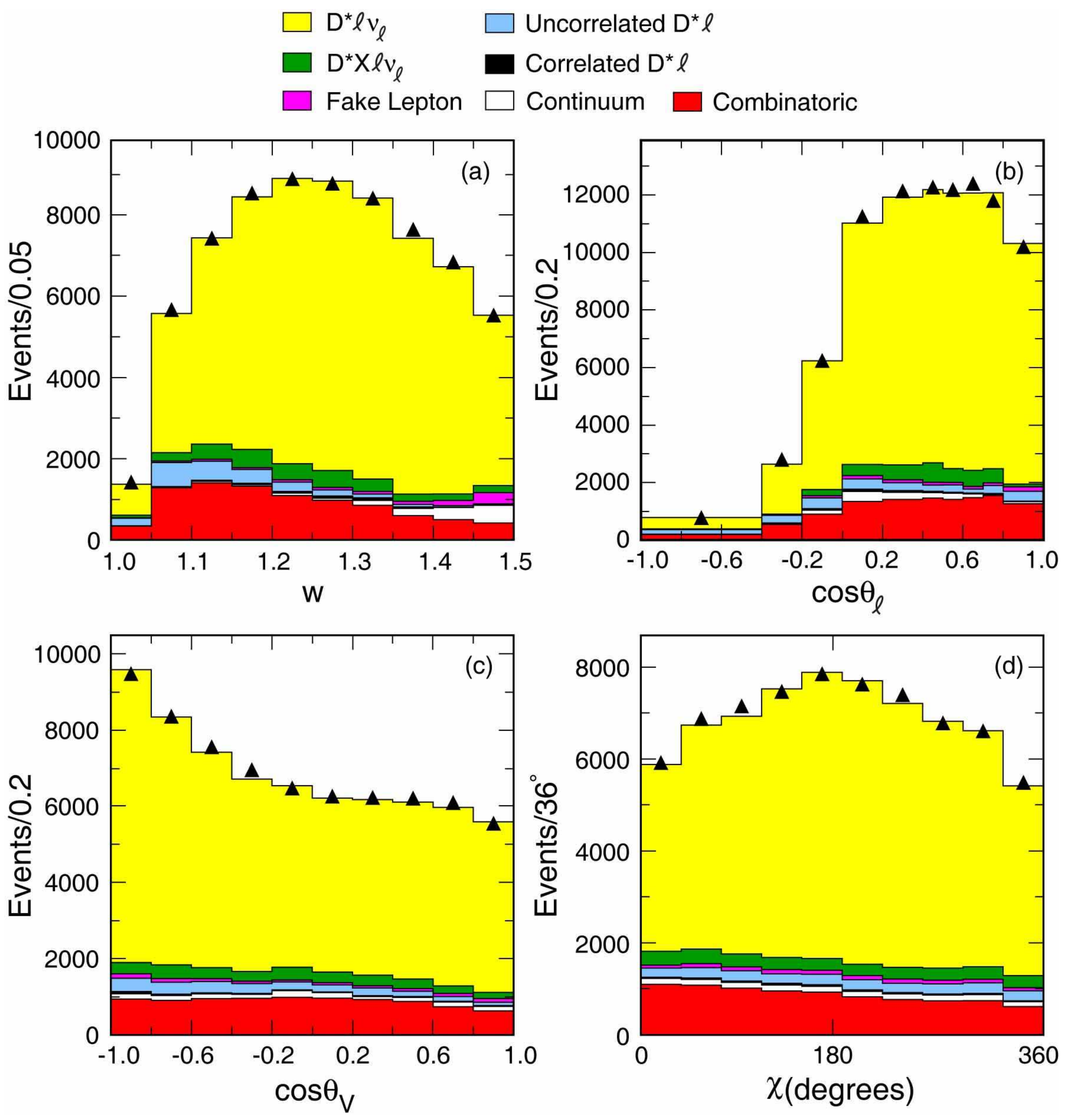


$$\begin{aligned}\mathcal{F}(1)|V_{cb}| &= (34.5 \pm 0.2 \pm 1.0) \times 10^{-3}, \\ \rho^2 &= 1.214 \pm 0.034 \pm 0.009, \\ R_1(1) &= 1.401 \pm 0.034 \pm 0.018, \\ R_2(1) &= 0.864 \pm 0.024 \pm 0.008,\end{aligned}$$

$B \to D^* l \nu$

Babar PRD 77:032002,2008

- Based on 79 fb^{-1}
  Find 52.8 K signal events
- $B^0 \to D^{*-} l\nu$ ($D^{*-} \to D^0\pi$, $D^0 \to \{K\pi, K3\pi, K\pi\pi^0\}$)
- Fit projections, accounting for bin-bin correlations directly from data
- CLN analysis only.



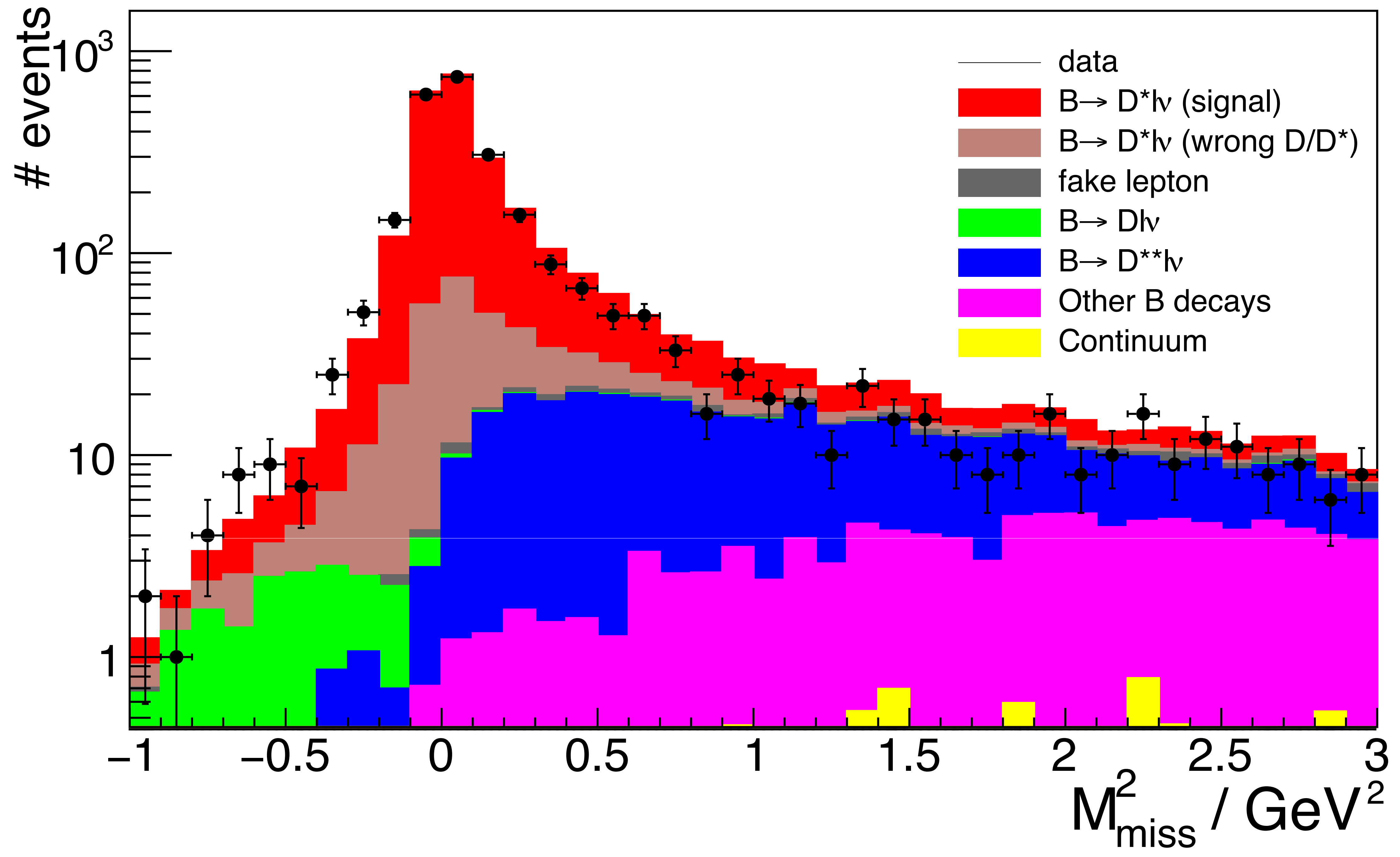
Subsample	ρ^2	$R_1(1)$	$R_2(1)$	$\mathcal{F}(1)\|V_{cb}\| \times 10^3$	χ^2/d.o.f.
$K\pi\, e$	0.971 ± 0.163	1.166 ± 0.182	0.977 ± 0.107	$34.76 \pm 0.61 \pm 0.61$	23.9/24
$K\pi\, \mu$	1.013 ± 0.175	1.193 ± 0.206	0.922 ± 0.123	$34.55 \pm 0.66 \pm 0.65$	37.9/24
$K\pi\pi\pi\, e$	1.581 ± 0.151	2.043 ± 0.384	0.405 ± 0.232	$33.30 \pm 1.27 \pm 0.96$	15.6/24
$K\pi\pi\pi\, \mu$	1.146 ± 0.258	1.156 ± 0.351	0.946 ± 0.197	$34.14 \pm 1.10 \pm 0.98$	28.0/24
$K\pi\pi^0\, e$	1.042 ± 0.165	1.217 ± 0.206	0.926 ± 0.118	$34.86 \pm 0.64 \pm 1.46$	26.9/24
$K\pi\pi^0\, \mu$	1.170 ± 0.155	1.439 ± 0.228	0.838 ± 0.131	$34.38 \pm 0.74 \pm 1.46$	24.8/24

$B \to D^* l \nu$ tagged

Belle arXiv:1702.01521

- Hadronic tag, tag calibration with $B \to X l \nu$
- Signal from un-binned maximum likelihood fit to M^2_{miss}
  - Yields extracted in 4x10 bins
  - Spectrum unfolded for later analysis in BGL parameterisation - first unfolded spectrum.

ℓ	ν^{sig}	ν^{sig}_{MC}	$\epsilon_{reco}\epsilon_{tag}$
$e+\mu$	2374 ± 53	2310.1	3.19×10^{-5}
e	1306 ± 40	1248.8	3.45×10^{-5}
μ	1066 ± 34	1061.3	2.93×10^{-5}



$$\mathcal{B}(\bar{B}^0 \to D^{*+} e^- \bar{\nu}_e) = (5.04 \pm 0.15 \pm 0.23) \times 10^{-2}$$

$$\mathcal{B}(\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu) = (4.84 \pm 0.15 \pm 0.22) \times 10^{-2}$$

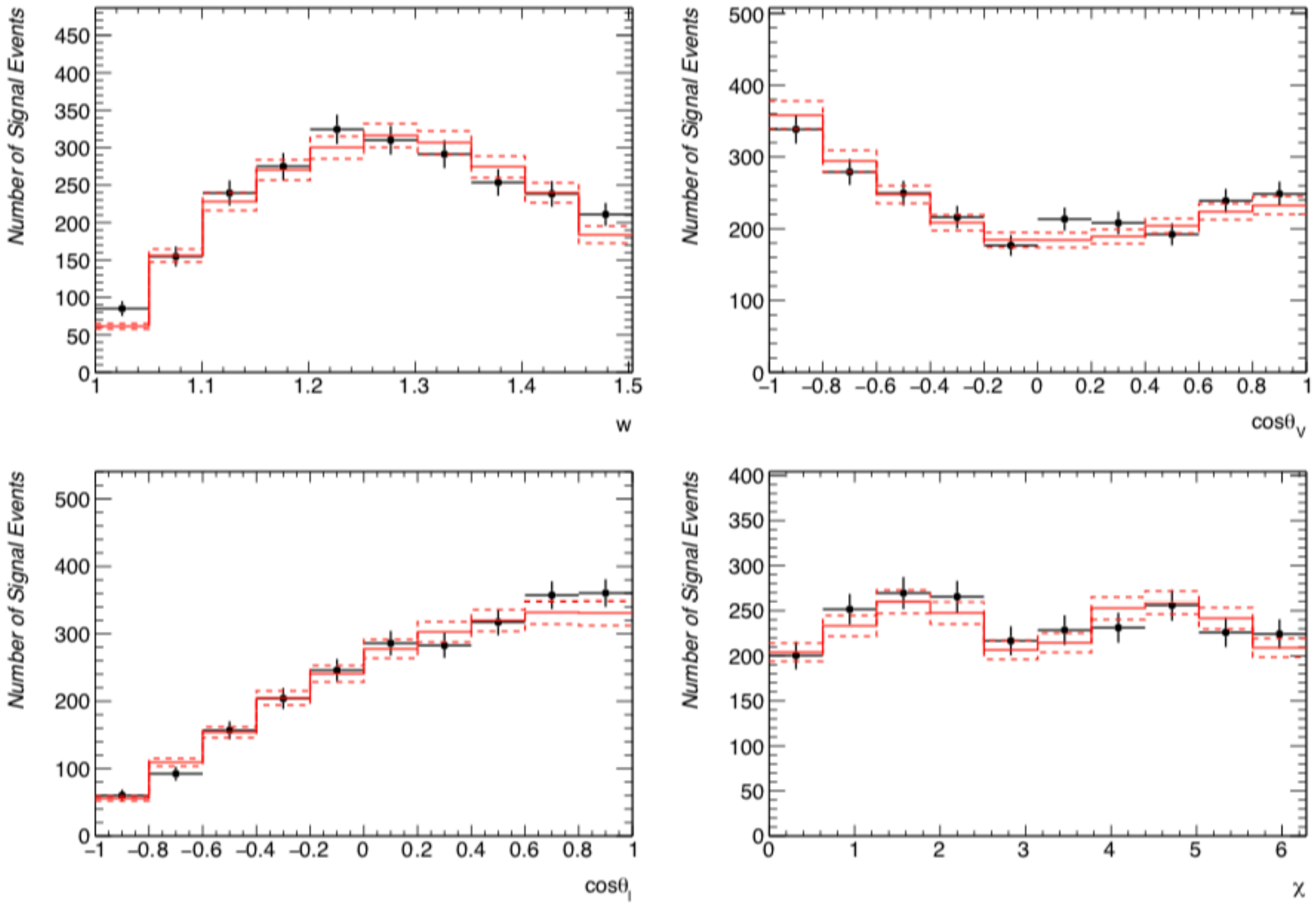
$$R_{e\mu} = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+} e^- \bar{\nu}_e)}{\mathcal{B}(\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu)} = 1.04 \pm 0.05 \pm 0.01$$

Model independent measurements

Bigi et al., arXiv:1703.06124

- BGL expansion. More reliable B → D(*) l ν differentials & errors for |Vcb| and for background modelling in B → D(*) τ ν.

Unfolded



$$H_0(w) = \mathcal{F}_1(w)/\sqrt{q^2},$$
$$H_\pm(w) = f(w) \mp m_B m_{D^*}\sqrt{w^2-1}\,g(w).$$

$$f(z) = \frac{1}{P_{1+}(z)\phi_f(z)}\sum_{n=0}^{N} a_n^f z^n\,,$$
$$\mathcal{F}_1(z) = \frac{1}{P_{1+}(z)\phi_{\mathcal{F}_1}(z)}\sum_{n=0}^{N} a_n^{\mathcal{F}_1} z^n\,,$$
$$g(z) = \frac{1}{P_{1-}(z)\phi_g(z)}\sum_{n=0}^{N} a_n^g z^n.$$

BGL Fit:	Data + lattice	Data + lattice + LCSR
χ^2/dof	27.9/32	31.4/35
$\lvert V_{cb}\rvert$	$0.0417\,(^{+20}_{-21})$	$0.0404\,(^{+16}_{-17})$
a_0^f	0.01223(18)	0.01224(18)
a_1^f	$-0.054\,(^{+58}_{-43})$	$-0.052\,(^{+27}_{-15})$
a_2^f	$0.2\,(^{+7}_{-12})$	$1.0\,(^{+0}_{-5})$
$a_1^{\mathcal{F}_1}$	$-0.0100\,(^{+61}_{-56})$	$-0.0070\,(^{+54}_{-52})$
$a_2^{\mathcal{F}_1}$	0.12 (10)	$0.089\,(^{+96}_{-100})$
a_0^g	$0.012\,(^{+11}_{-8})$	$0.0289\,(^{+57}_{-37})$
a_1^g	$0.7\,(^{+3}_{-4})$	$0.08\,(^{+8}_{-22})$
a_2^g	$0.8\,(^{+2}_{-17})$	$-1.0\,(^{+20}_{-0})$

CLN Fit:	Data + lattice	Data + lattice + LCSR
χ^2/dof	34.3/36	34.8/39
$\lvert V_{cb}\rvert$	0.0382 (15)	0.0382 (14)
$\rho^2_{D^*}$	$1.17\,(^{+15}_{-16})$	1.16 (14)
$R_1(1)$	$1.391\,(^{+92}_{-88})$	1.372 (36)
$R_2(1)$	$0.913\,(^{+73}_{-80})$	$0.916\,(^{+65}_{-70})$
$h_{A_1}(1)$	0.906 (13)	0.906 (13)

Comparison of approaches @ Υ(4S)

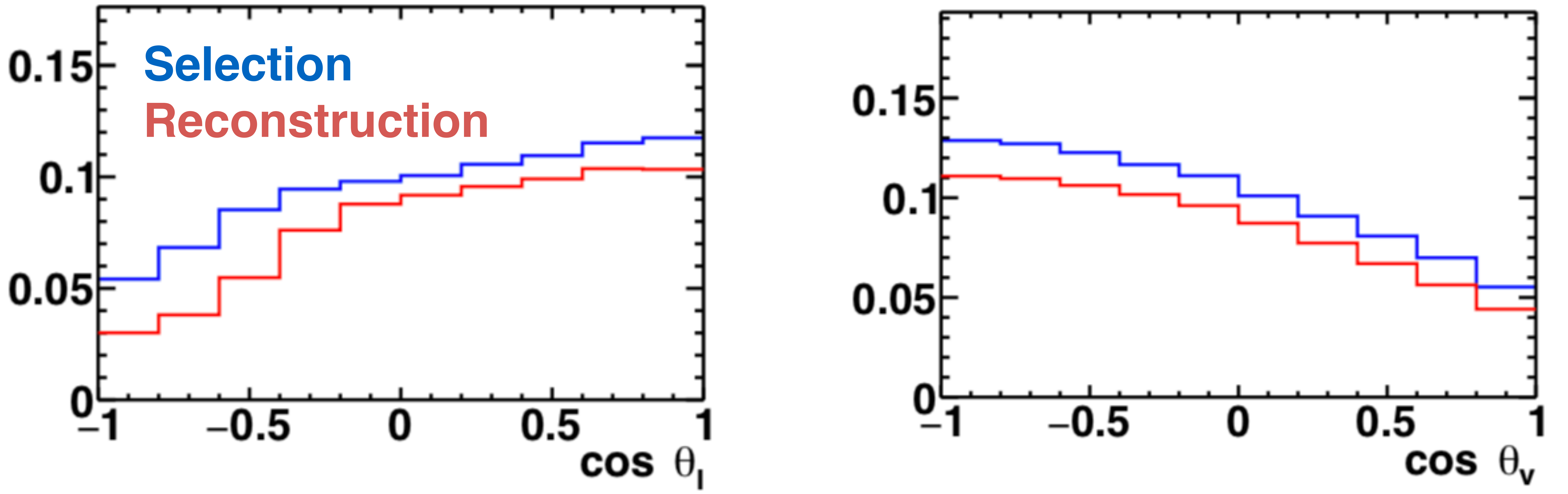
- Untagged measurement predates tracking update in Belle: $\Delta\varepsilon_{track}$ reduced by 3.
- Errors on tracking, PID, π^0 efficiencies are data driven.
  - Slow pion Tracking in Belle II ~2x efficiency < 100 MeV
- Br needs better measure of N_{BB}, f_{+0} — limited by precision of integrated luminosity measurement.
- Tag calibration error can be improved by choosing cleaner tags in larger data sets. *But we still need control modes!*
- Most errors cancel in **LFUV** measurement.
  - Belle tagged: stat±5%, sys±1%
  - Belle untagged (estimated - reanalysis in progress): stat±1%, sys±1%
  - Belle II total ±< 1%.

Tag Method	untagged	tagged
Br [10^{-2}]	**4.58**	**4.95**
Errors	%	%
Track	4.50	1.6
Slow track	1.29	0.1
eID	2.18	0.2 (in tag)
μID		0.1 (in tag)
fake leptons	0.07	<0.1
$B \to D^{**} l\nu$, FF	0.24	<0.1
$B \to D^{**} l\nu$, Bfs	0.57	0.2
$D^{(*)}$ Bfs	1.48	0.5
PDFs	0.22	0.9
Tag calibration	0.00	3.6
N_{BB}	1.38	1.4
f_{+0}	1.35	1.1
τ_B	0.59	0
π^0 efficiency	0.00	0.5
Total	**5.8**	**4.5**
Stat	**0.7**	**2.2**

More model independent

- Any substantial modifications to the signal shape (CLN → BGL, or NP) will affect acceptance.
- 4D differentials, not 4 x 1D are preferable if feasible to measure. Any changes to the generated spectra should minimally affect the signal efficiency in the 4D case.
- If we analyse in 4D, we need to understand background in 4D.
- Tagged analysis ~**3k events/ab**, untagged analysis **~ 170k/ab**

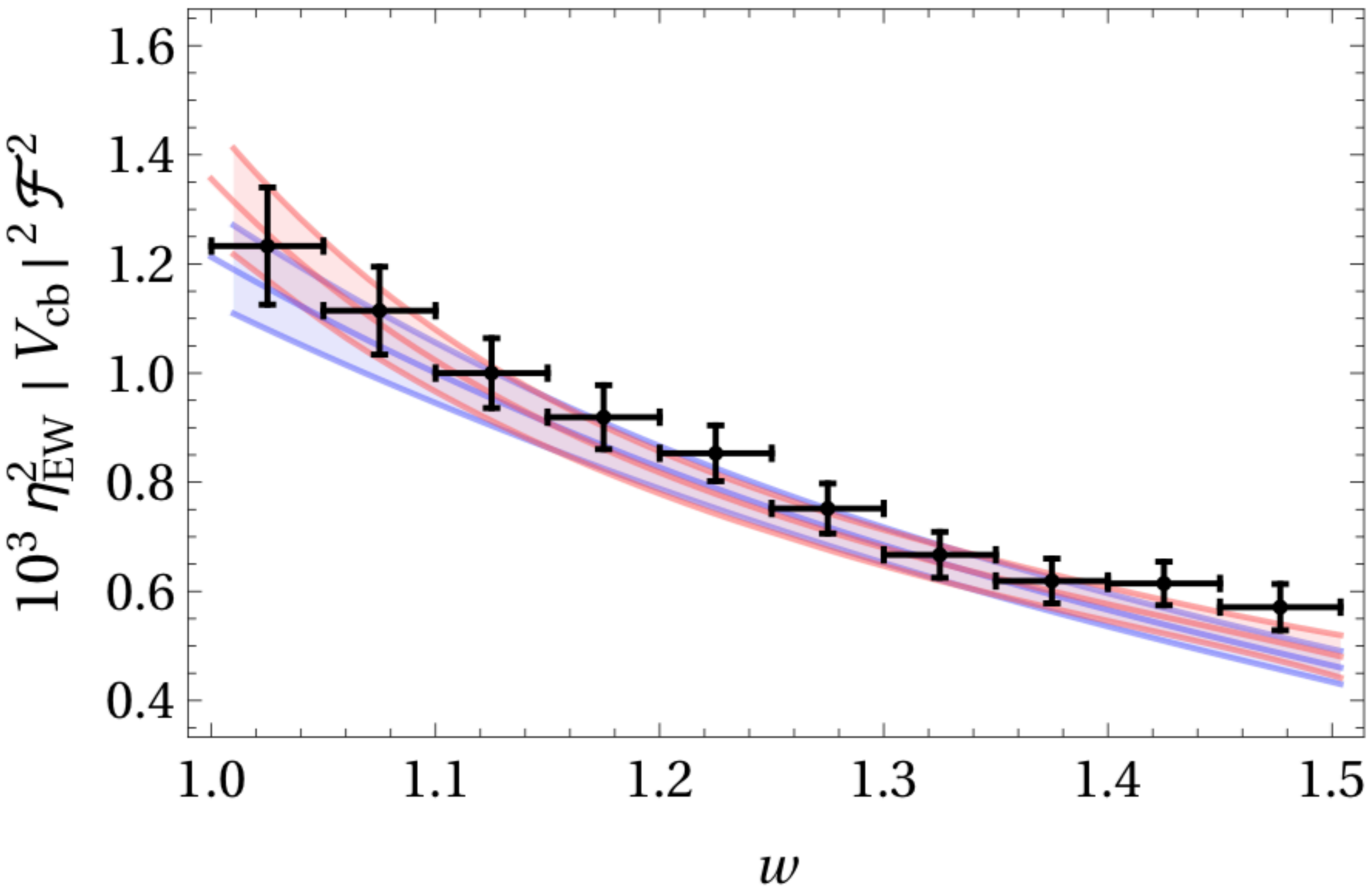
Efficiency (untagged analysis)

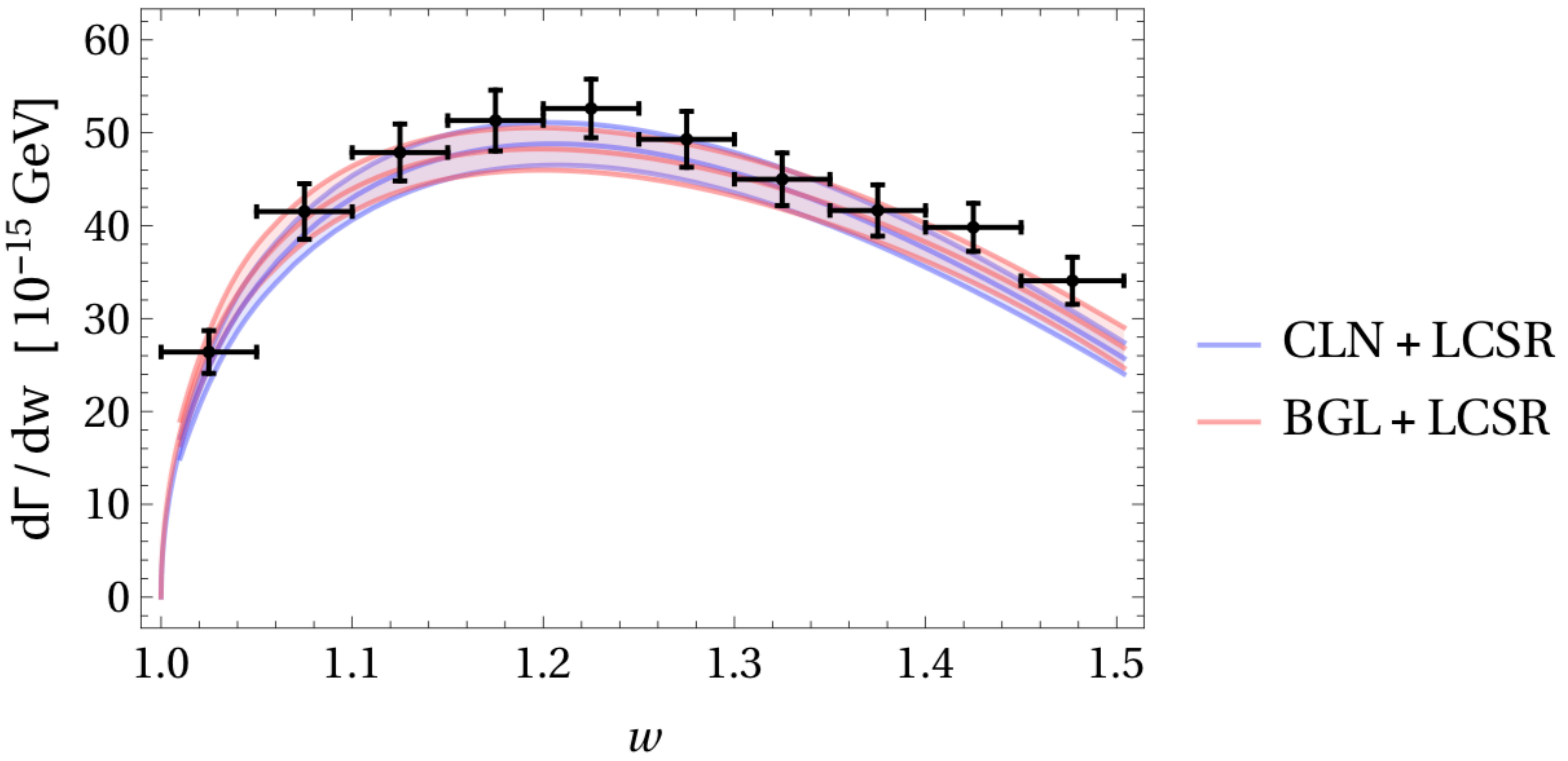


Low efficiency where lepton or πslow has relatively low momentum

Kinematic endpoint

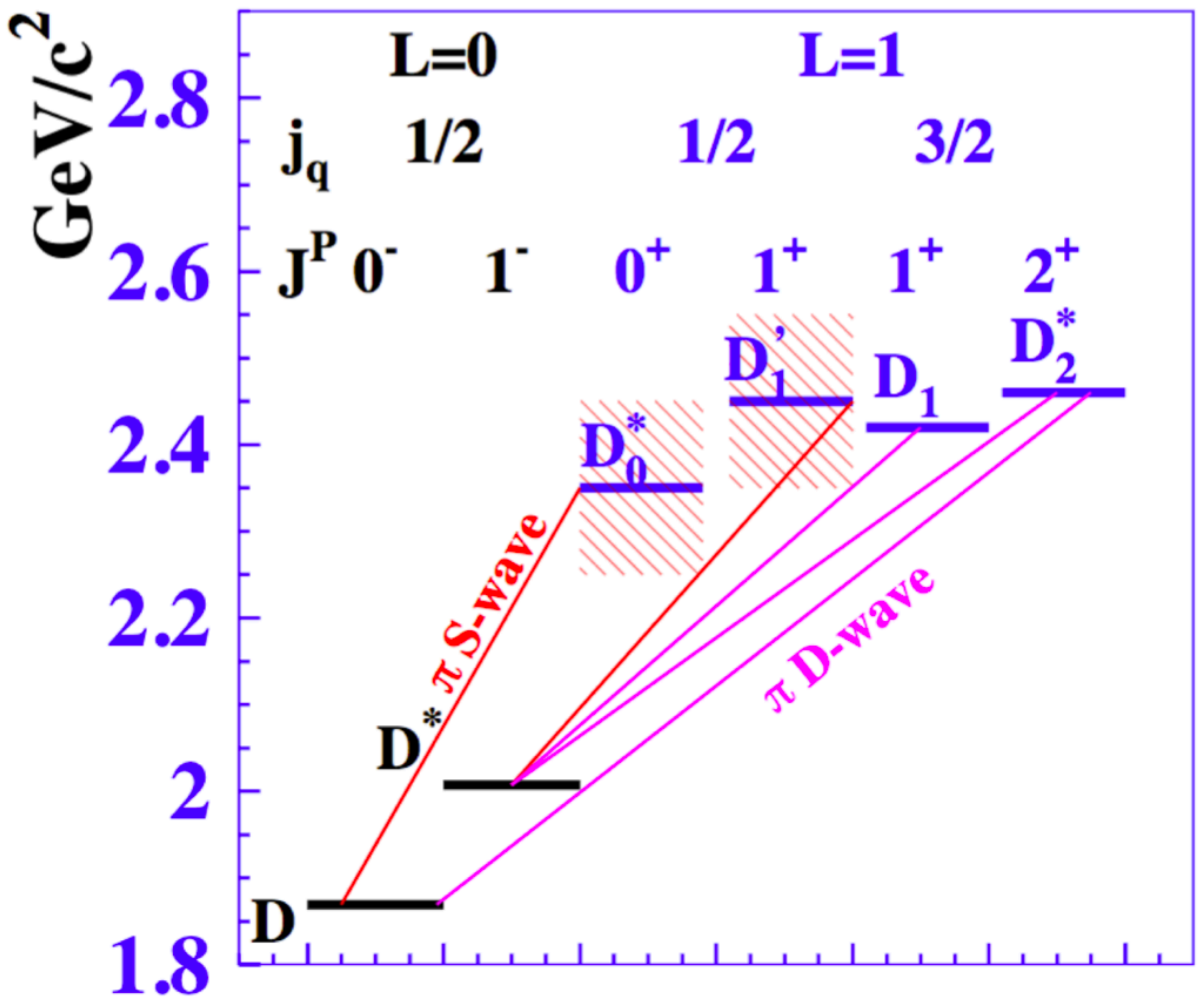
- BGL - CLN difference most striking at low recoil - high q^2.
- We should study this carefully for B→D*, B→D at the lepton endpoint.





B → D** l ν

- No absolute Br of exclusive B → D** l ν decay modes.
  - D** branching ratios need complementary information from hadronic B decays.
  - Unmeasured D** → modes, for saturation of B → X l ν
  - B → D(*)nπ l ν + B → D(*)η l ν etc. No attempts at neutral modes, or modes with π0.
- Scarce information on B →D** l ν differentials - statistics limited.



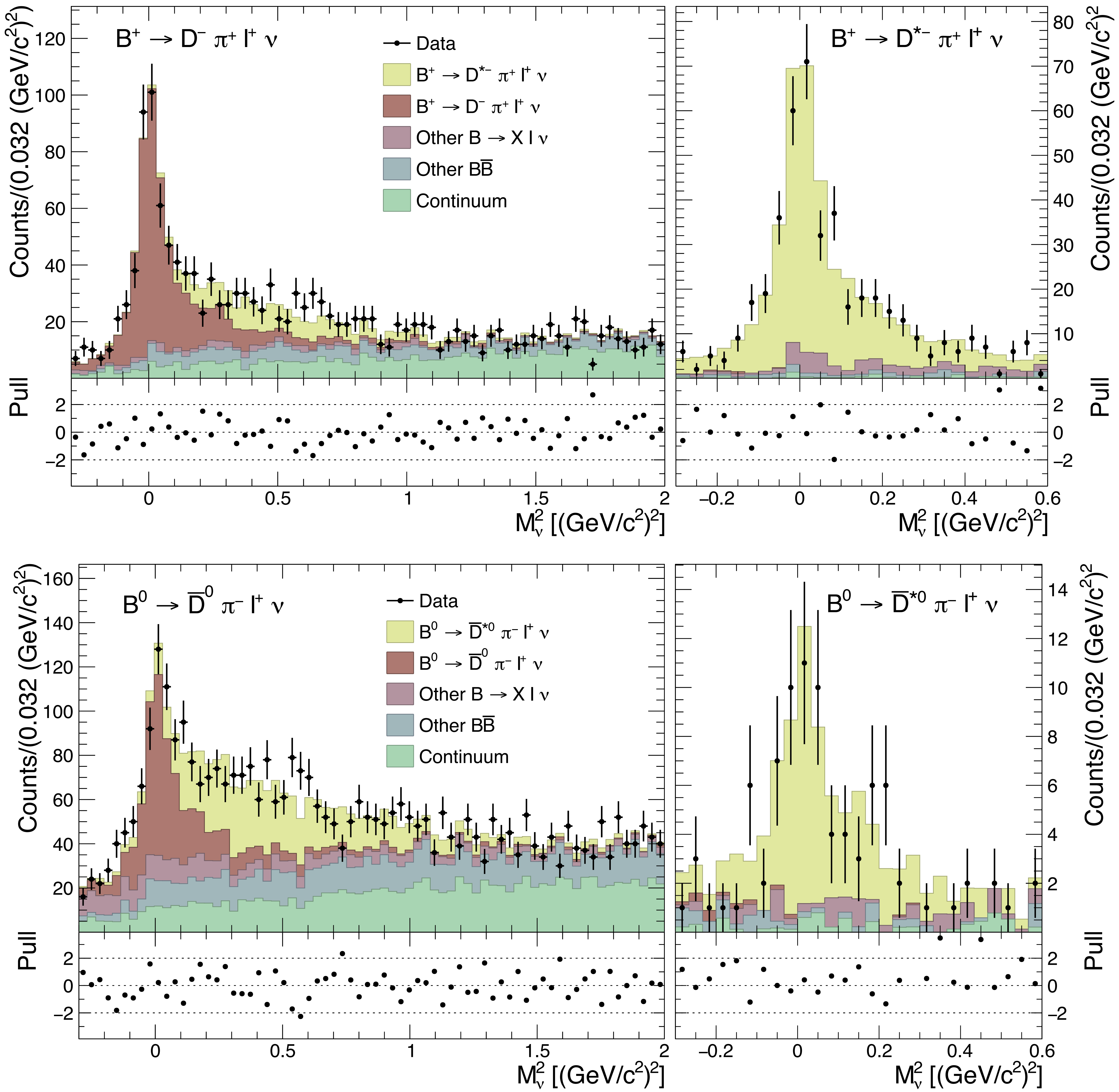
D		J	Observed	Possible
D_0^*	1P	1/2	Dπ	Dη
D_1^*	1P	1/2	D*π	Dππ, Dη
D_1	1P	3/2	D*π, Dππ	D_0*π, D_0*ρ, D_0*f_0
D_2^*	1P	3/2	D*π, Dπ	Dππ
D’	2S			D(ρ,ππ), D*(η,π)
D’*	2S			D*(ρ,ππ), D(η,π)

$B \to D^{(*)} \pi\, l\, \nu$ (NEW)

Belle, arXiv:1803.06444

- Hadron tag
- $B^+ \to D^{(*)} \pi^0\, l\, \nu$ (1.4k signal)
- $B^+ \to D^{(*)} \pi^+\, l\, \nu$ (1.1k signal)
- Binned fit to $m^2_{miss/\nu}$ to D and D* simultaneously (B^+, B^0 separately)

  - $\mathcal{B}(B^+ \to D^-\pi^+\ell^+\nu) = [4.55 \pm 0.27\ (\text{stat.}) \pm 0.39\ (\text{syst.})] \times 10^{-3}$,
  - $\mathcal{B}(B^0 \to \bar{D}^0\pi^-\ell^+\nu) = [4.05 \pm 0.36\ (\text{stat.}) \pm 0.41\ (\text{syst.})] \times 10^{-3}$,
  - $\mathcal{B}(B^+ \to D^{*-}\pi^+\ell^+\nu) = [6.03 \pm 0.43\ (\text{stat.}) \pm 0.38\ (\text{syst.})] \times 10^{-3}$,
  - $\mathcal{B}(B^0 \to \bar{D}^{*0}\pi^-\ell^+\nu) = [6.46 \pm 0.53\ (\text{stat.}) \pm 0.52\ (\text{syst.})] \times 10^{-3}$.

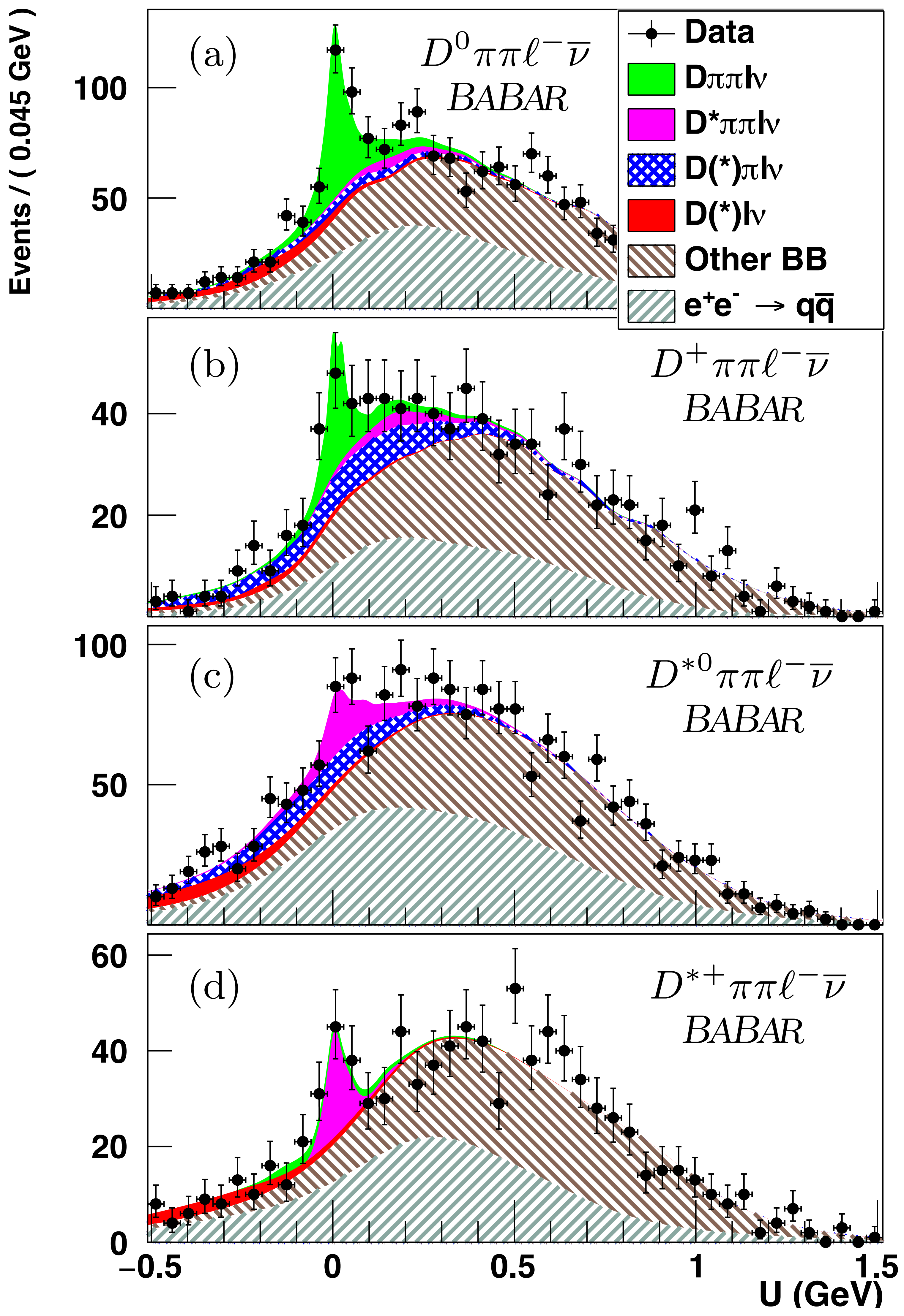


$B \to D^{(*)} \pi\pi \, l \, \nu$

Babar PRL 116, 041801 (2016)

- Gap between inclusive B → Xc lν sum of known exclusive decays
- Good candidates: B → D(*)ππ(X)lν (could also be B → D(*)ηlν)
- Hadronic tag, normalise to B → D(*) l ν
- Unbinned ML fit
- Closes exclusive-inclusive gap to about 1% (10% of SL rate).

$$U \equiv E_{\text{miss}} - |\vec{p}_{\text{miss}}|c$$



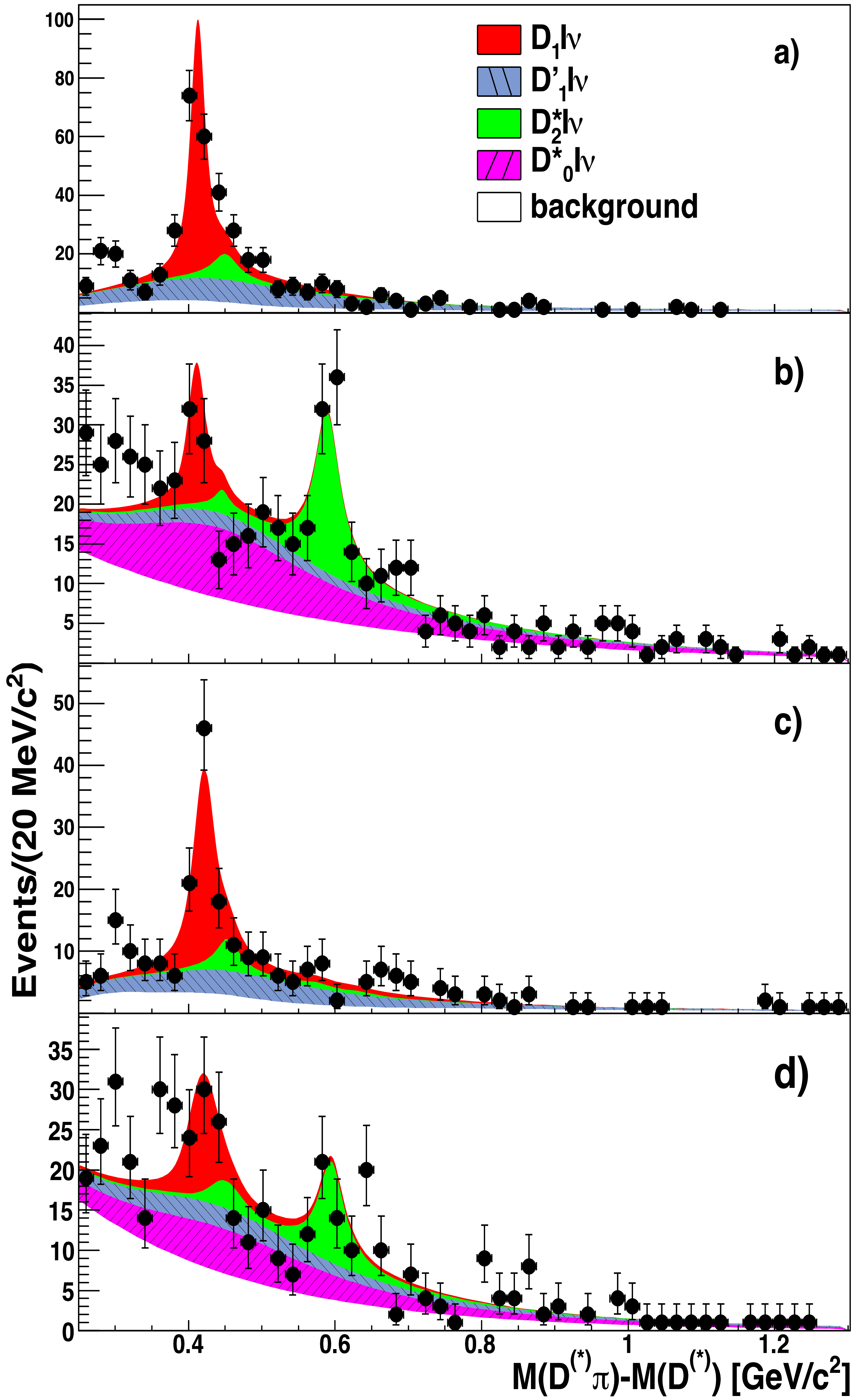
Channel	$R^{(*)}_{\pi^+\pi^-} \times 10^3$	$\mathcal{B} \times 10^5$
$D^0\pi^+\pi^-\ell^-\bar{\nu}$	$71 \pm 13 \pm 8$	$161 \pm 30 \pm 18 \pm 8$
$D^+\pi^+\pi^-\ell^-\bar{\nu}$	$58 \pm 18 \pm 12$	$127 \pm 39 \pm 26 \pm 7$
$D^{*0}\pi^+\pi^-\ell^-\bar{\nu}$	$14 \pm 7 \pm 4$	$80 \pm 40 \pm 23 \pm 3$
$D^{*+}\pi^+\pi^-\ell^-\bar{\nu}$	$28 \pm 8 \pm 6$	$138 \pm 39 \pm 30 \pm 3$
$D\pi^+\pi^-\ell^-\bar{\nu}$	$67 \pm 10 \pm 8$	$152 \pm 23 \pm 18 \pm 7$
$D^*\pi^+\pi^-\ell^-\bar{\nu}$	$19 \pm 5 \pm 4$	$108 \pm 28 \pm 23 \pm 4$

B → D** l ν

Babar PRL 101:261802 (2008)

- Reconstruct B → D(*)π±lv in events tagged with hadronic B decays
- Simultaneous fit to M(D(*)π) or M(D(*)π) -M(D(*)), including cross- feeds
- Background yield constrained from fit to B_{tag} mass. Shapes checked on wrong-sign data combinations
- Large rate for broad states!

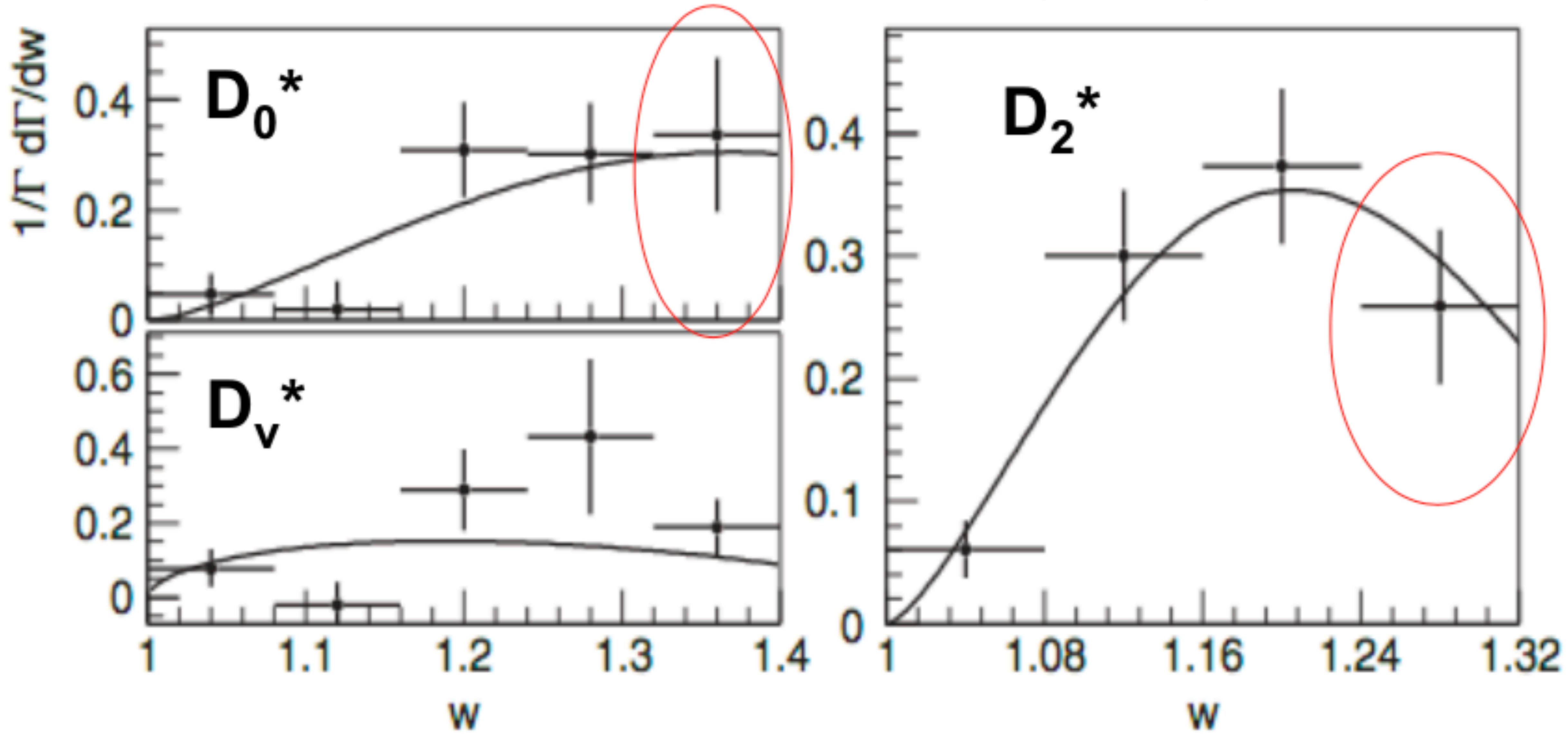
Decay Mode	Yield	$\epsilon_{\text{sig}}(\times 10^{-4})$	$\mathcal{B}\ (\overline{B} \to D^{**}\ell^-\bar{\nu}_\ell\ ) \times \mathcal{B}(D^{**} \to D^{(*)}\pi^\pm)$ %
$B^- \to D_1^0\ell^-\bar{\nu}_\ell$	165 ± 18	1.24	$0.29 \pm 0.03 \pm 0.03$
$B^- \to D_2^{*0}\ell^-\bar{\nu}_\ell$	97 ± 16	1.44	$0.15 \pm 0.02 \pm 0.01$
$B^- \to D_1^{\prime 0}\ell^-\bar{\nu}_\ell$	142 ± 21	1.13	$0.27 \pm 0.04 \pm 0.05$
$B^- \to D_0^{*0}\ell^-\bar{\nu}_\ell$	137 ± 26	1.15	$0.26 \pm 0.05 \pm 0.04$
$\overline{B}^0 \to D_1^+\ell^-\bar{\nu}_\ell$	88 ± 14	0.70	$0.27 \pm 0.04 \pm 0.03$
$\overline{B}^0 \to D_2^{*+}\ell^-\bar{\nu}_\ell$	29 ± 13	0.91	$0.07 \pm 0.03 \pm 0.01$ (< 0.11 @90% CL)
$\overline{B}^0 \to D_1^{\prime +}\ell^-\bar{\nu}_\ell$	86 ± 18	0.60	$0.31 \pm 0.07 \pm 0.05$
$\overline{B}^0 \to D_0^{*+}\ell^-\bar{\nu}_\ell$	142 ± 26	0.70	$0.44 \pm 0.08 \pm 0.06$



$B \to D^{**} l \nu$ exclusive measurements

Babar PRL 101:261802 (2008)
Babar PRL 103:051803 (2009)
Belle PRD 77:091503 (2008)

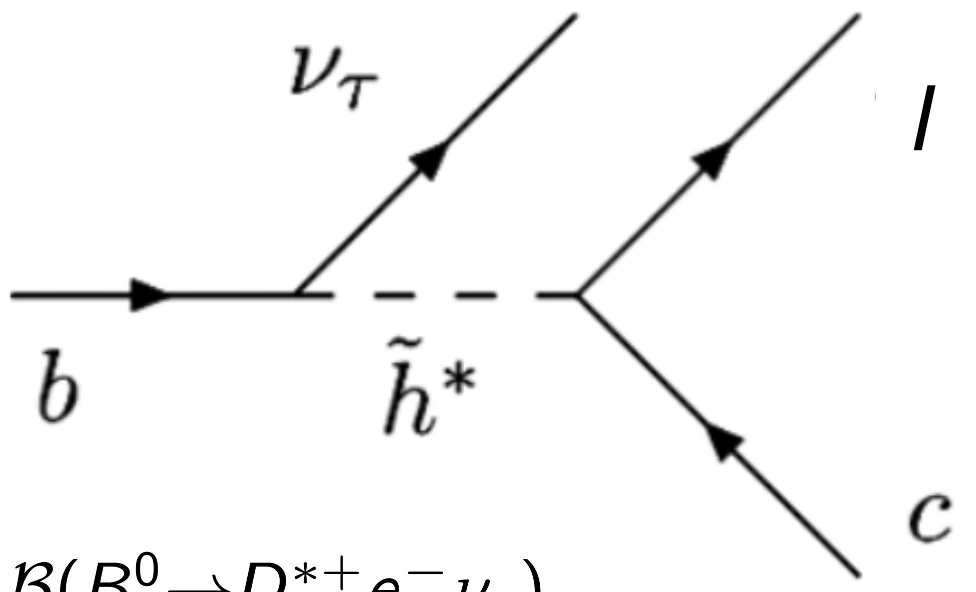
- $B \to D^{(*)} \pi l \nu$ - ultimately want to measure form factors
- Normalised with $D l \nu$ or $X l \nu$
- Strong model dependence in systematics - particularly broad J=1/2 modes.
- **Highly stats limited** (modelling errors can be overcome by measuring differentials)



	Belle tagged J=3/2 & 1/2	Babar tagged J=3/2 & 1/2
N_{BB} [10^6]	657	460
Error	%	%
Tracking		1.8-2.4
Particle ID	2	1.2-1.6
π^0 & γ Eff.		0.2-4.8
MC stats.	in stat.	-
Comb.&Cont.	-	0.2-10.4
Helicity corr.		**4.5-13.8**
Signal model	**12-22**	
PDFs		**0.2-8.7**
N_{BB}	-	-
D(*) Bfs	10	3-4.5
Norm		4-6
Bkg	6	-
total sys	**14-25**	**5.5-17**
total stat	**14-40**	**10-20**

Future measurements of B → D(*) l ν

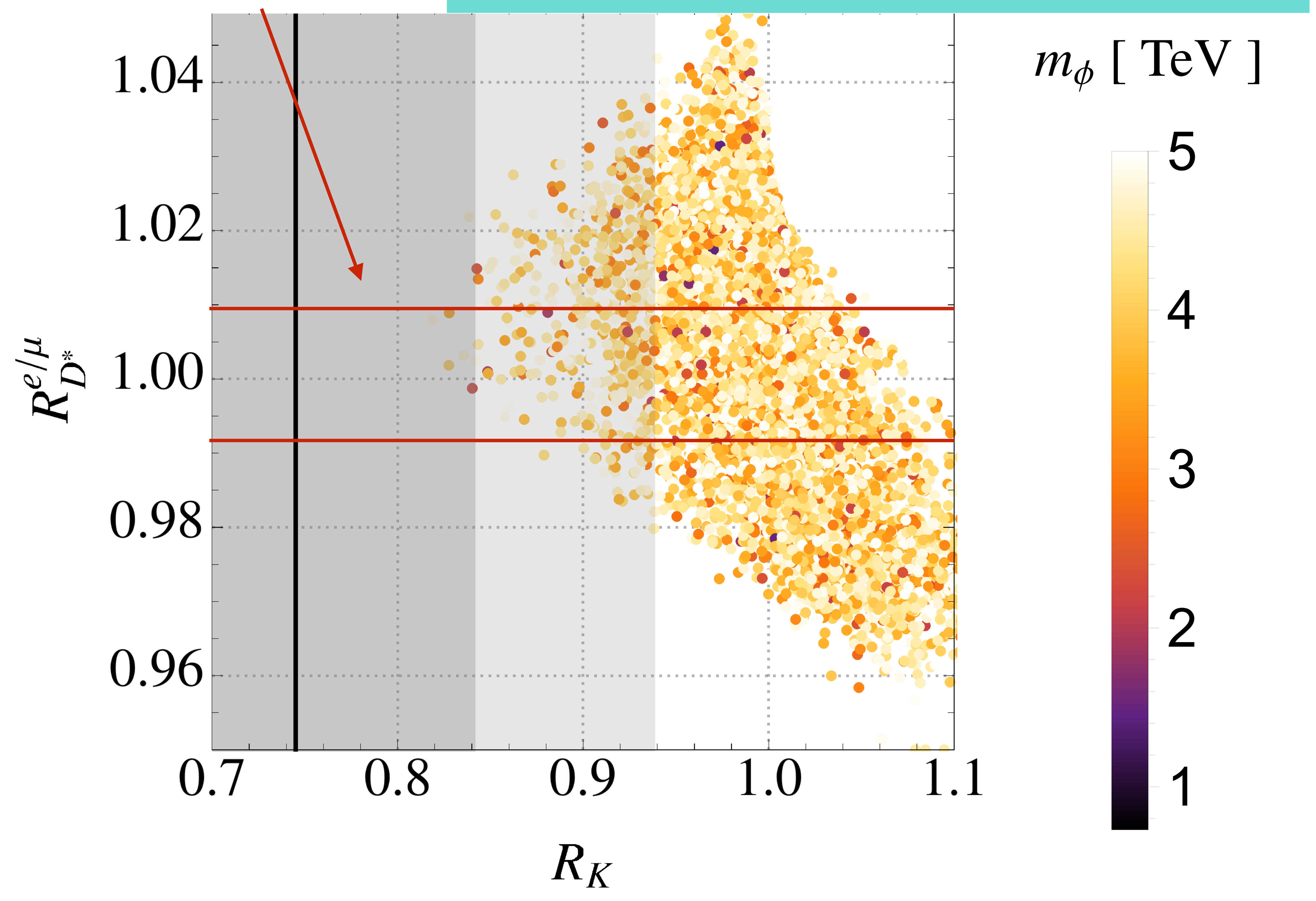
- Direct measurements with BGL in 4x1D and 4D.
  - 4-dimension binning: What binning is best? Can we model background in 4D? Method of moments?
- *Forward* folding Vs. unfolding.
- Model independent + NP fits (particularly V_R), accounting for modified acceptance and PDFs.
- Studies of B → D* l ν and B → D l ν near the kinematic endpoint. Can the BGL-CLN differences have an impact on inclusive $|V_{ub}|$, B→ X τ ν studies?
- Differential measurements of B → D** l ν (resonant).
- Precise e/μ LFUV tests.
- More tests of B+ vs. B0 (different EM corrections)



$$\mathcal{R}_{e/u} = \frac{\mathcal{B}(B^0 \to D^{*+} e^- \nu_e)}{\mathcal{B}(B^0 \to D^{*+} \mu^- \nu_\mu)}$$

Belle II expectation

Cai, et al. JHEP 1710 (2017) 047



Belle II considerations

- Systematics dominated analyses.
- **Reconstruction**
  - Tracking - trade off between efficiency and purity. We can choose cleaner tracks! Systematics due to small differences between data/MC.
  - eID, μID errors extracted from studies of $ee \to \mu\mu(\gamma)$, $ee \to ee(\gamma)$, $J/\psi \to l^+l^-$. Data driven, therefore can be improved with more data.
- **Normalisation**
  - Tag uncertainties due to low purity modes (dominant) and due to tag calibration modes. We can use cleaner tagging.
  - NBB and f+0 must be remeasured at Belle II. Dominated by luminosity errors - due to trigger stability & can be studied with extra triggers.
- **Background**
  - Better vertex fitting, neutral reconstruction should better mitigate background.

$B \to D^* l \nu$

Tag Method	untagged	tagged
Br [10^{-2}]	**4.58**	**4.95**
Errors	%	%
Track	4.50	1.6
Slow track	1.29	0.1
eID	2.18	0.2 (in tag)
μID		0.1 (in tag)
fake leptons	0.07	<0.1
$B \to D^{**} l \nu$, FF	0.24	<0.1
$B \to D^{**} l \nu$, Bfs	0.57	0.2
$D^{(*)}$ Bfs	1.48	0.5
PDFs	0.22	0.9
Tag calibration	0.00	3.6
N_{BB}	1.38	1.4
f_{+0}	1.35	1.1
τ_B	0.59	0
π^0 efficiency	0.00	0.5
Total	**5.8**	**4.5**
Stat	**0.7**	**2.2**

Naive Belle II projections

- $B \to D^* l \nu$,
  - $|V_{cb}|$ Experiment Error : 3% → 1%
  - $R_{e/\mu}$: 5% → 1%
- $B \to D l \nu$,
  - $|V_{cb}|$ Experiment Error 3% → 1%
  - $R_{e/\mu}$: (6% approx.) → 1%
- $B \to D^{**} l \nu$
  - Exclusive modes never done comprehensively at B-factories. A long way to go to eliminate this as bias on $B \to D(^*) \tau \nu$.

Summary

- Recent results:
  - B→D* l ν (Belle preliminary 2017), B→D l ν (Belle 2016)
  - B→ D(*) π l ν (Belle New 2018), B→D(*) π π l ν (Babar 2016)
- Experiments working on more model independent data preparation - particularly B→ D* l ν.

- Belle II will have a challenge in improving precision,
  - Focus for Vcb will be on improved systematic errors from particle reconstruction and tagging.
  - B→D** l ν will clearly benefit from >> 1 ab^{-1}.

Backup

Belle II Upgrades

Central beam pipe: decreased diameter from 3cm to 2cm (Beryllium)

Vertexing: new 2 layers of pixels, upgraded 4 double-sided layers of silicon strips

Tracking: drift chamber with smaller cells, longer lever arm, faster electronics

PID: new time-of-flight (barrel) and proximity focusing aerogel (endcap) Cherenkov detectors

EM calorimetry: upgrade of electronics and processing with legacy CsI(Tl) crystals

K_L and μ: scintillators replace RPCs (endcap and inner two layers of barrel)