Radiative/Electroweak B Decays at SuperKEKB

Follow-up of BNM-I and summary for write-up

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December 19th, 2006, BNM2006II

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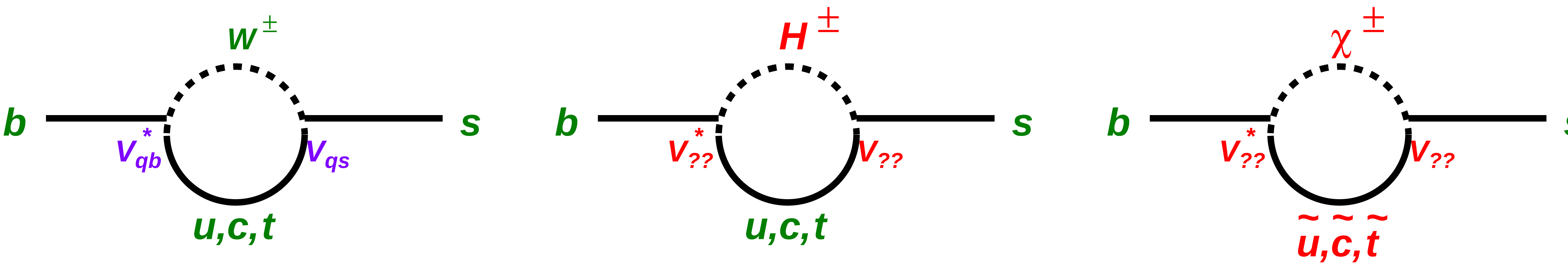
Experimental status

- $b \to s\gamma$ processes
  - Full- and semi- inclusive $B \to X_s\gamma$ BF and A_{CP}
  - $B \to K^*\gamma$ BF, A_{CP}, isospin asymmetry
  - Higher resonances: $B \to K_2^*(1430)\gamma$, $B \to K_1(1270)\gamma$
  - Three-body decays: $B \to K\phi\gamma$, $B \to K\eta\gamma$, $B \to \Lambda\bar{p}\gamma$
  - Time-dependent CPV: $B \to K_S^0\pi^0\gamma$
- $b \to s\ell^+\ell^-$ processes
  - Exclusive $B \to K\ell^+\ell^-$, $B \to K^*\ell^+\ell^-$
  - Semi-inclusive $B \to X_s\ell^+\ell^-$
  - First $A_{FB}(B \to K^*\ell^+\ell^-)$
- $b \to d\gamma$ processes
  - Combined $B \to (\rho,\omega)\gamma$ observed $\Rightarrow |V_{td}/V_{ts}|$

Many observables that are sensitive to new physics

Precision Physics with Radiative/EW B decays



No order one deviation found, and probably not in future
i.e., need precision measurements

- Revival of $\mathcal{B}(B \to X_s\gamma)$ to identify new physics
  NNLO calculation $\Leftrightarrow$ Precision measurement below 5% error
- Hope to measure $\mathcal{B}(B \to X_d\gamma)$ for $|V_{td}|$
  $\Rightarrow$ Once we have a 5σ measurement, $\delta|V_{td}| \sim 10\%$
- For exclusive modes, "ratios/asymmetries" are keys
  $\Rightarrow$ Most have been already measured, with limited statistics
  $\Rightarrow$ Sensitive to new physics since theory errors are reduced
  $\Rightarrow$ Direct and time-dep. CPV, A_{FB}, isospin asymmetry, ...

What was new at BNM-I

- New study of semi-inclusive $b \to d\gamma$ study
  - Second try on estimating inclusive $b \to d\gamma$ sensitivity
  - More realistic MC sample and cuts
  - 7.5σ signal with 5 ab^{-1}
- Photon polarization measurement of $B \to K^*\gamma$
  - First try to use $\gamma \to e^+e^-$ conversion to measure photon polarization
  - Very clear signal can be reconstructed
  - 3σ modulation could be found if $A_R \sim A_L$ with 5 ab^{-1}

After a more detailed studies, we found these are too optimistic. . .

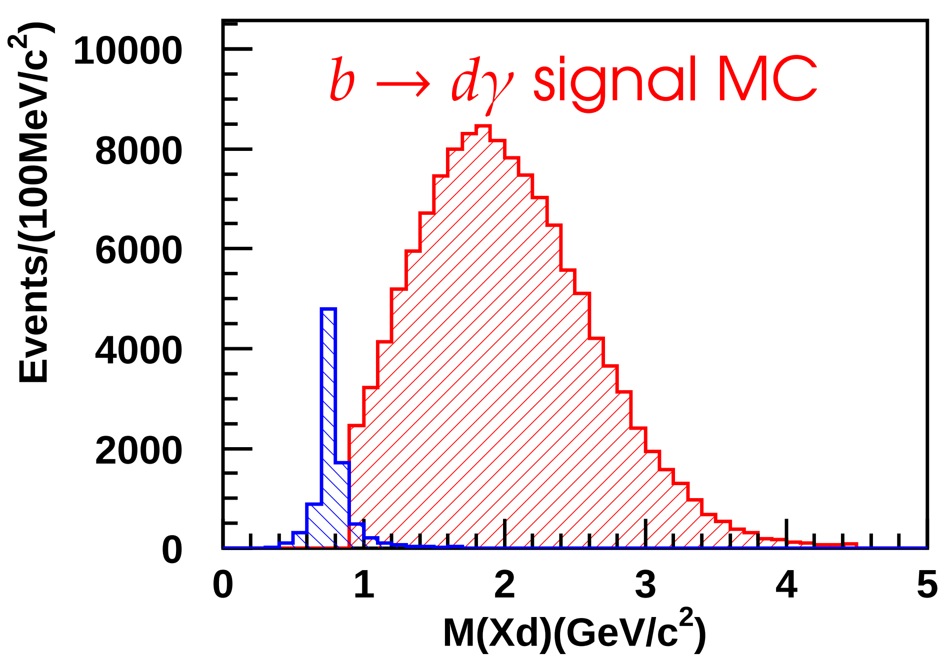
$B \to X_d\gamma$ branching fraction

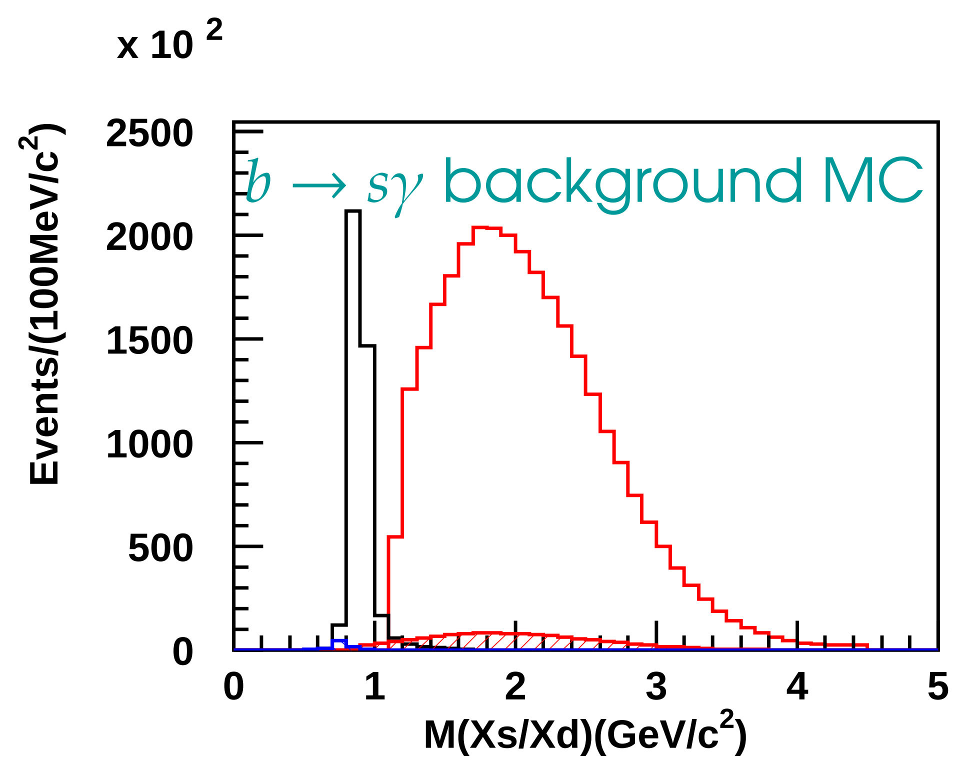
Inclusive $B \to X_d\gamma$

- No form-factors from BF ratio to $|V_{td}/V_{ts}|$

$$\left|\frac{V_{td}}{V_{ts}}\right|^2 \propto \left[\frac{\mathcal{B}(B \to X_d\gamma)}{\mathcal{B}(B \to X_s\gamma)} + \text{corr.}\right]$$

- Small theory error (corr. for annihilation diagram, etc.)
- BF$\sim 1.5 \times 10^{-5}$, but experimentally challenging:

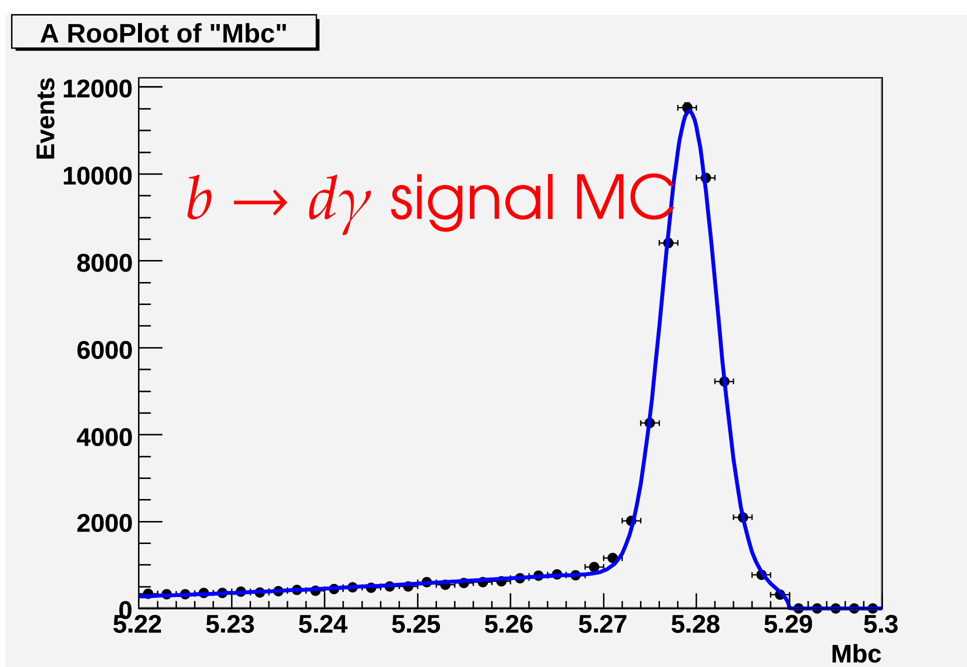


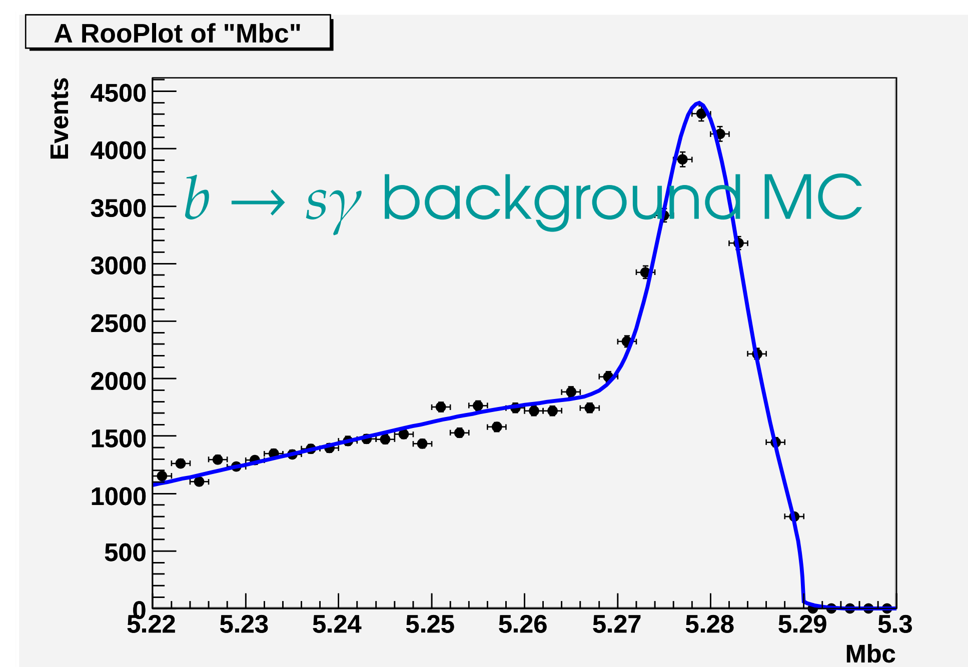


At BNM-I, EvtGen $M(X_d)$ spectrum didn't look correct (shifted towards lower), and $B \to (\rho, \omega)\gamma$ region was double counted (making efficiency too high).

MC cut tuning

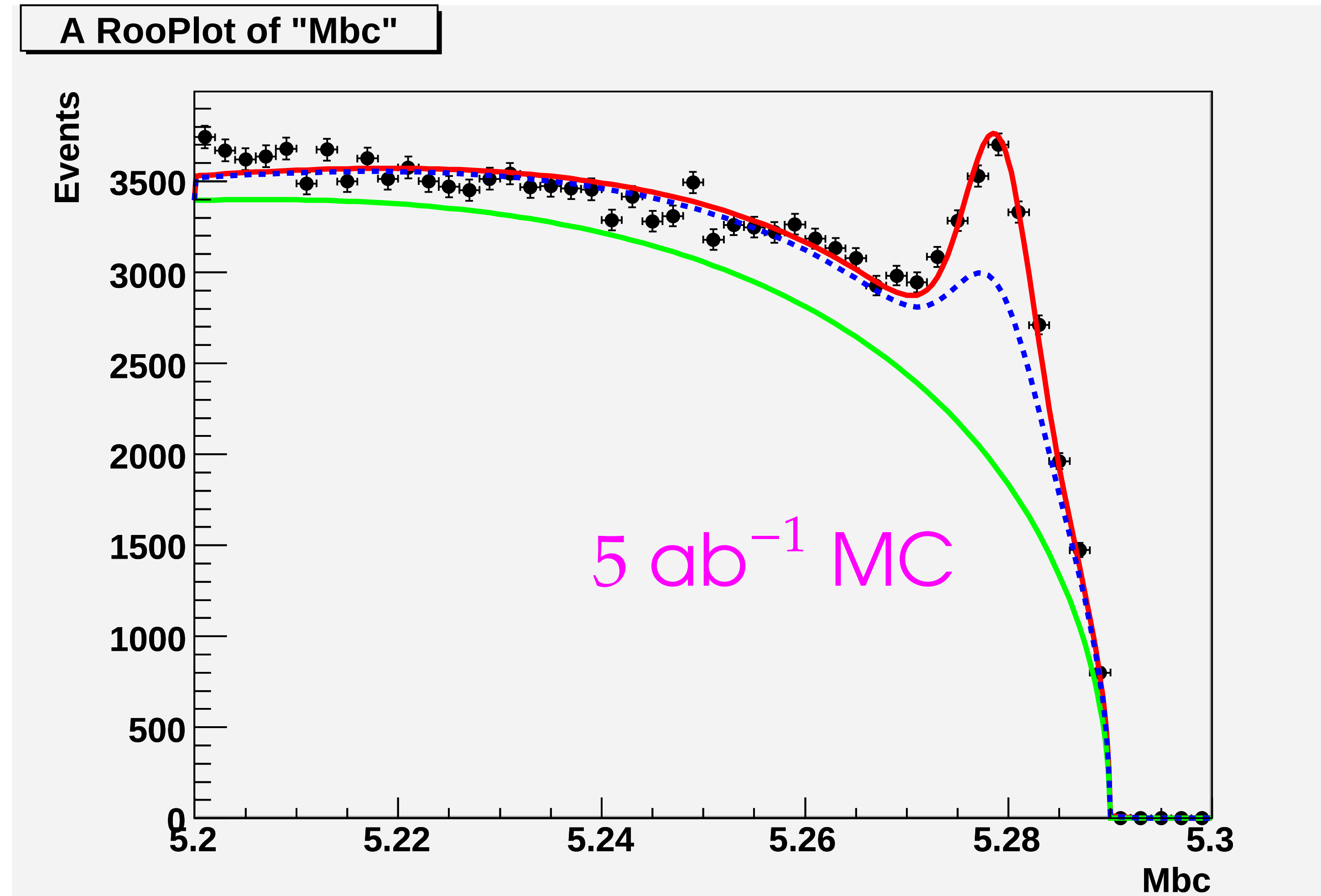
- 1st try at Hawaii Joint SuperB WS ('05 Apr.), 2nd try at BNM-I
- More realistic MC samples and cuts
  - Continuum suppression from $B \to \rho\gamma$ analysis
  - 2–4 π (up to 1 π^0) final state for $M(X_d) < 2.0$ GeV
  - New K_S^0 veto $\Rightarrow$ reduces peaking $b \to s\gamma$ background
  - $b \to c$ backgrounds are now included, but no charmless ($B \to \pi^0 X$, etc) yet





$B \to X_d\gamma$ at 5 ab^{-1}

- Efficiency 2.9%
- A fit result:
  $\Rightarrow Y = 4249 \pm 224 \pm 888$
- $b \to s\gamma$ component
  $\pm 20\%$ uncertainty
- Error sources:
  Stat.: 5%
  Fit.: 21%
  Model: 10% (not in Y)
  Total: 24%



$B \to X_d\gamma$ seems to be possible with 5 ab^{-1}!

(still challenging, systematic error could be quite different in reality)

$B \to X_d\gamma$ worries and hopes

Worries...

- $B \to \pi^0 X$ could be a dangerous peaking background (to be studied)
- $M(X_d)$ spectrum is assumed to be the same as $M(X_s)$. No theory calculation to my knowledge

Hopes!

- $B \to K^*\gamma$ is a huge background over wide $M(X_d)$, may be suppressed by $M(\text{“}K\text{''}\pi)$ cut
- Current PID is assumed in this study — a better PID device should kill $b \to s\gamma$ more effectively, and fake rate error (the dominant part of fitting error) should be reduced

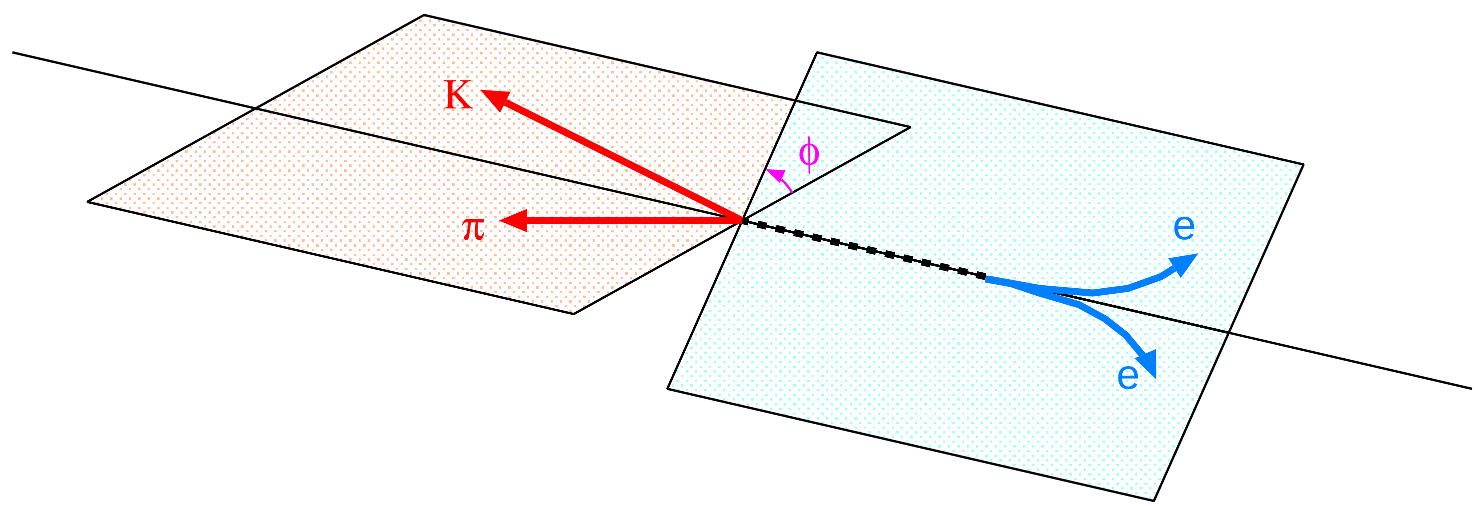
Either Hopes or Worries...

- Fitting error is not really well studied. Could be different?
- No more bug in the analysis?

Photon helicity measurements from γ-conversion

Photon helicity measurements from γ-conversion

- $B \to K^*\gamma$ with $\gamma \to e^+e^-$ in the detector could be used to measure the left- and non-SM right-handed components (A_L and A_R) (Grossman-Pirjol JHEP 0006,029(2000))



- If $A_R \neq 0$, phi modulation in the form:

$$1 + \xi(E_e, q^2)\frac{|A_R||A_L|}{|A_R|^2 + |A_L|^2}[\cos(2\phi + \delta)],$$

$\left[\begin{array}{c} \xi\text{: efficiency factor} \\ \text{average } \xi \sim 0.3 \end{array} \right]$

- Similar modulation in $\gamma^* \to e^+e^-$ and $B \to K^*e^+e^-$ interference (CS.Kim-YG.Kim-CD.Lu-Morozumi PRD62,034013(2000))

Easy analysis?

- Even if conversion rate is low ($\sim 3\%$), $\mathcal{B}(B \to K^*\gamma)$ is relatively large $\Rightarrow$ **$\sim$ 100 events per 500 $\mathbf{fb^{-1}}$**
- **Signal is very clean** because the dominant background is also suppressed with the same conversion rate
- **Standard reconstruction techniques** to find the events, then calculate ϕ distribution
- **Assumption 1:** efficiency factor ξ is reasonably large
- **Assumption 2:** ϕ is easy to measure, θ is not needed

These two assumptions (at BNM-I) seem to be too optimistic

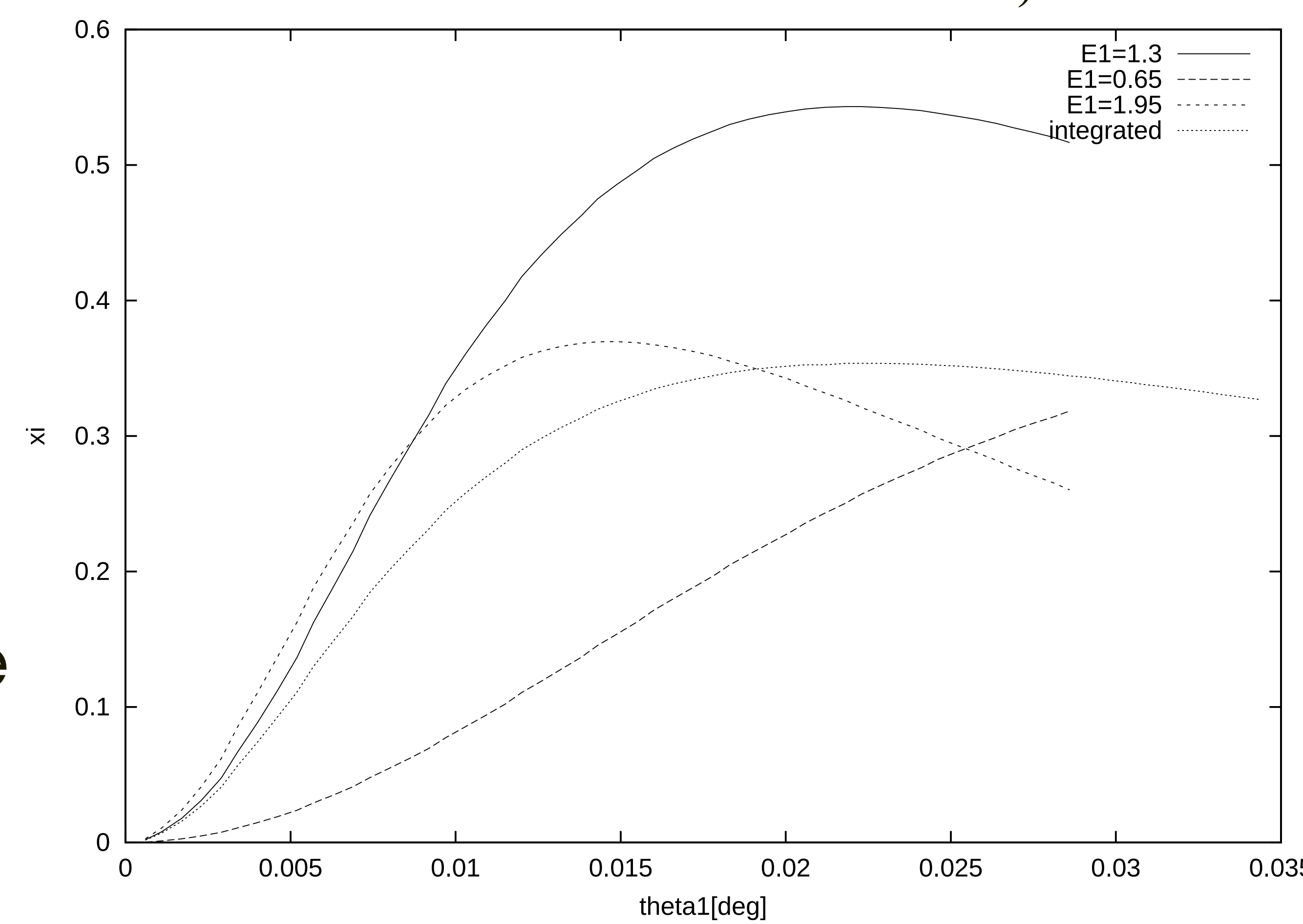
Efficiency factor

$$\frac{d\sigma}{dE_1 d\Omega_1 d\Omega_2} = \frac{Z^2e^6}{16\pi^3} \times \left\{ \frac{(k^2 - 4{E_2}^2)(\vec{e}\cdot\vec{p}_1)(\vec{e}^*\cdot\vec{p}_1)}{(E_1 - |\vec{p}_1|\cos\theta_1)^2} + \frac{(k^2 - 4{E_1}^2)(\vec{e}\cdot\vec{p}_2)(\vec{e}^*\cdot\vec{p}_2)}{(E_2 - |\vec{p}_2|\cos\theta_2)^2} \right.$$

$$- \frac{k^2 + 4E_1E_2}{(E_1 - |\vec{p}_1|\cos\theta_1)(E_2 - |\vec{p}_2|\cos\theta_2)} \times [(\vec{e}\cdot\vec{p}_1)(\vec{e}^*\cdot\vec{p}_2) + (\vec{e}^*\cdot\vec{p}_1)(\vec{e}\cdot\vec{p}_2)]$$

$$\left. E_\gamma^2 \frac{|\vec{p}_1|^2 \sin^2\theta_1 + |\vec{p}_2|^2 \sin 2\theta_2 + 2|\vec{p}_1||\vec{p}_2| \sin\theta_1 \sin\theta_2 \cos(\phi_1 - \phi_2)}{(E_1 - |\vec{p}_1|\cos\theta_1)(E_2 - |\vec{p}_2|\cos\theta_2)} \right\}$$

- Typically $\xi \sim 0.3$(?)
  (figure from Grossman-Pirjol)
- But $\xi = 0.103$ if e^+ and e^- are in the same plane and integrated over E and θ (PR78,623 (1950))
- Sensitivity should improve if we know E and θ



Signal reconstruction

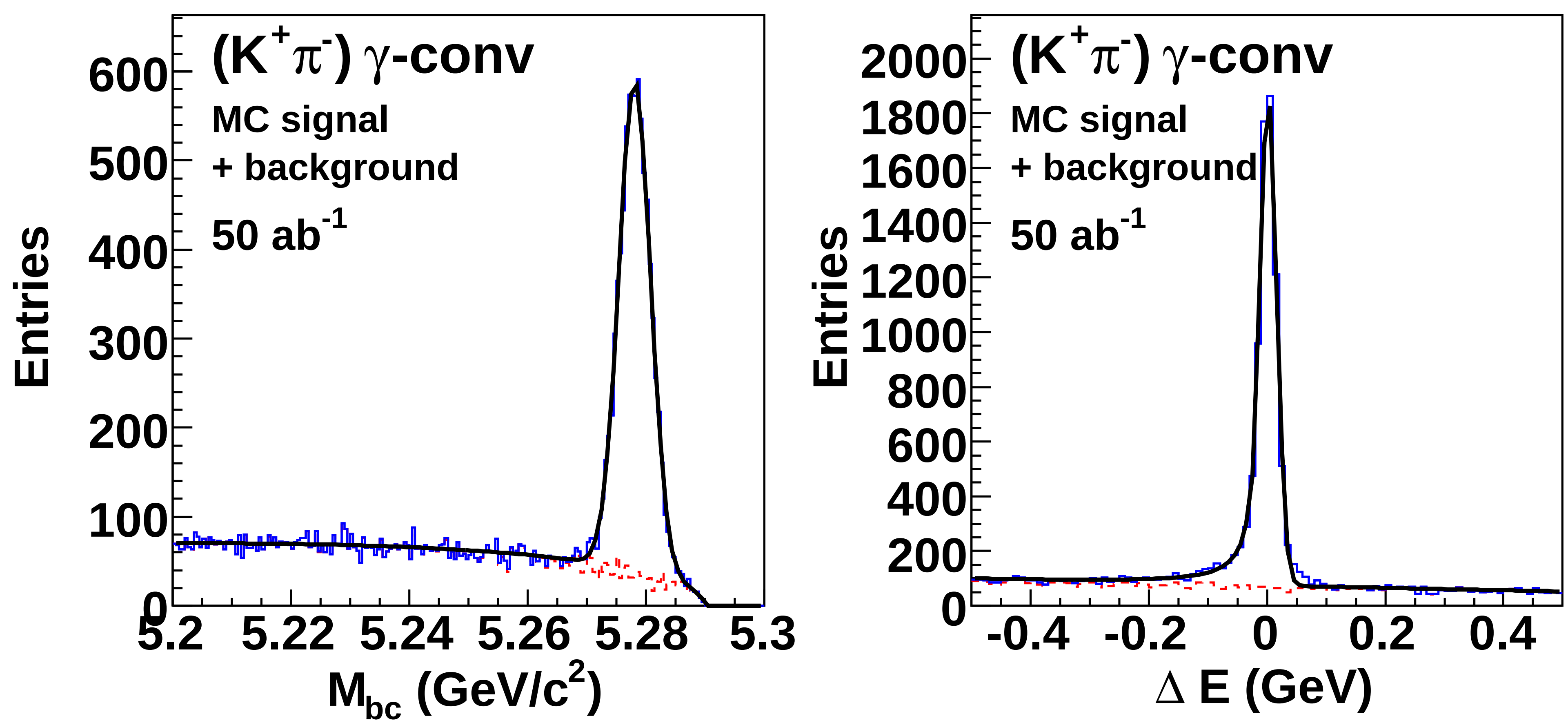
- Almost fully-optimized selection criteria

both eid>0.9 — $LR(\text{mod.FW}, \cos\theta_B, \Delta z) > 0.8$

π^0/η-likelihood veto — $5.270 < M_{bc} < 5.286$ GeV

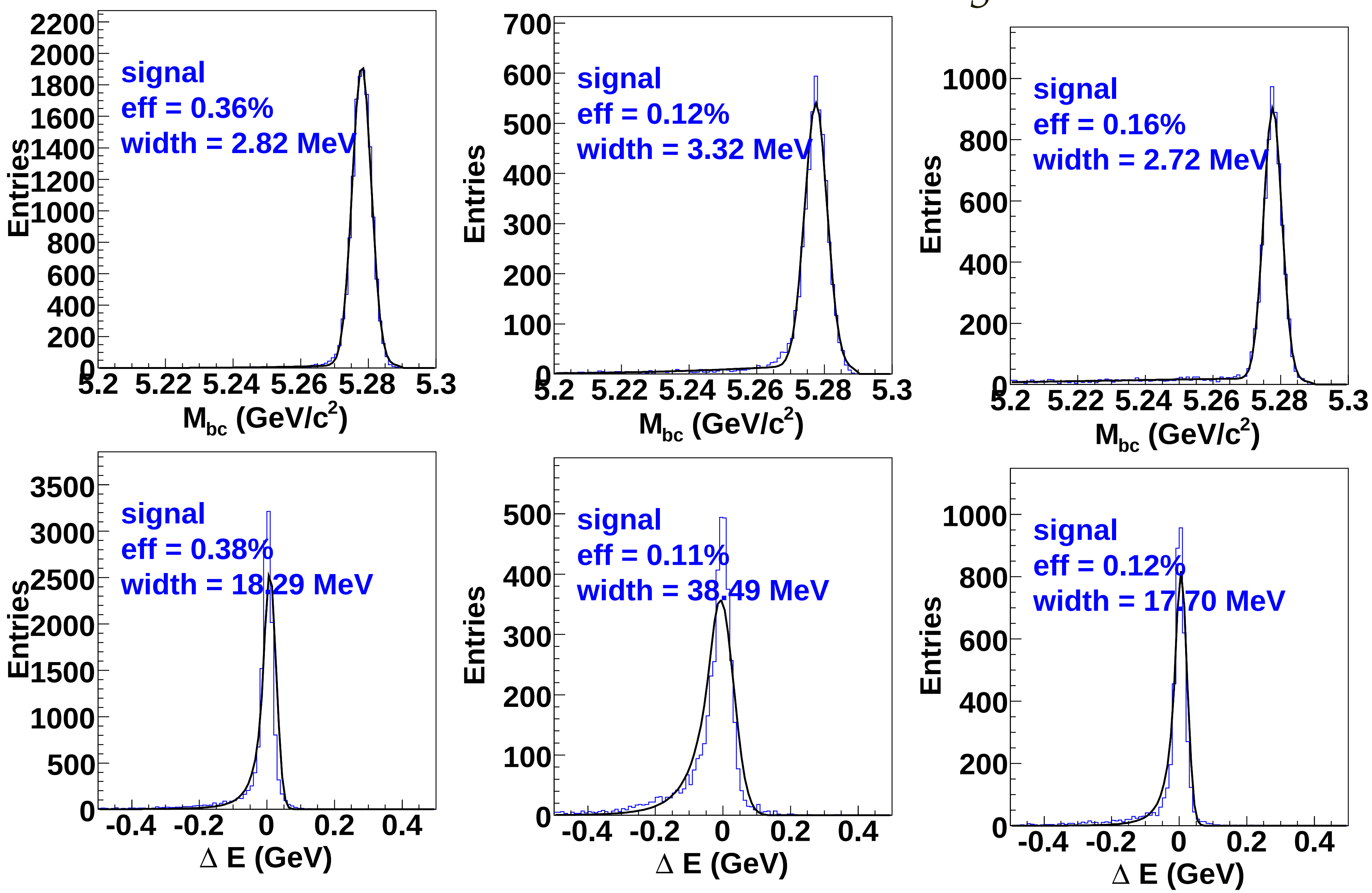
$|M(K\pi) - M(K^*)| < 75$ MeV — $-0.1 < \Delta E < 0.08$ GeV

kid>0.6 for K else π (or K_S^0 cut / π^0 cut for $K^{*+}\gamma$)



M_{bc}, ΔE and efficiency

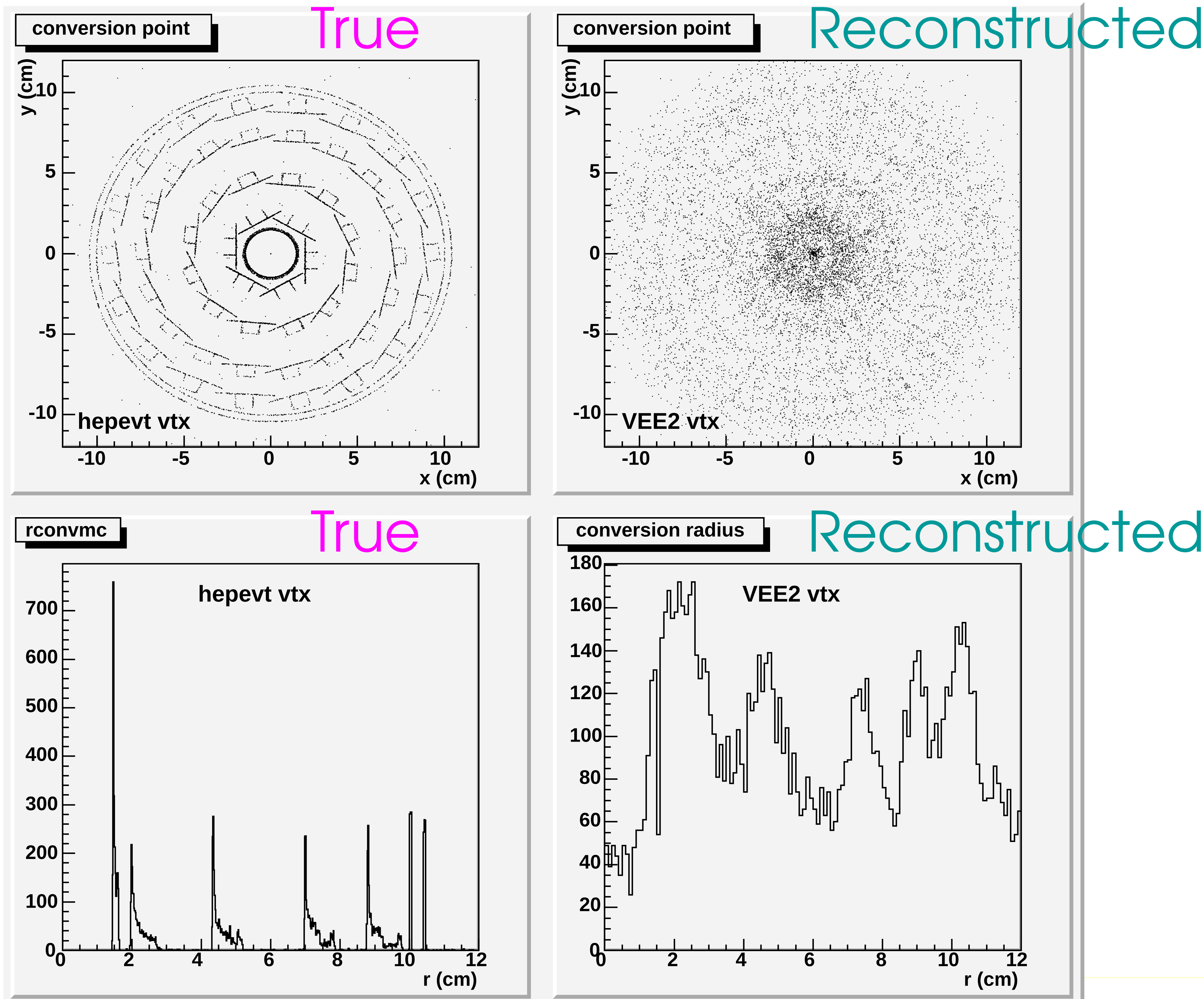
$(K^+\pi^-)(e^+e^-)$ $(K^+\pi^0)(e^+e^-)$ $(K^0_S\pi^+)(e^+e^-)$



- Efficiency sum $\sim$ 0.64%, $\mathcal{B}(B \to K^*\gamma) = 4 \times 10^{-5}$
  $\Rightarrow$ 128 event for 500 M $B\overline{B}$

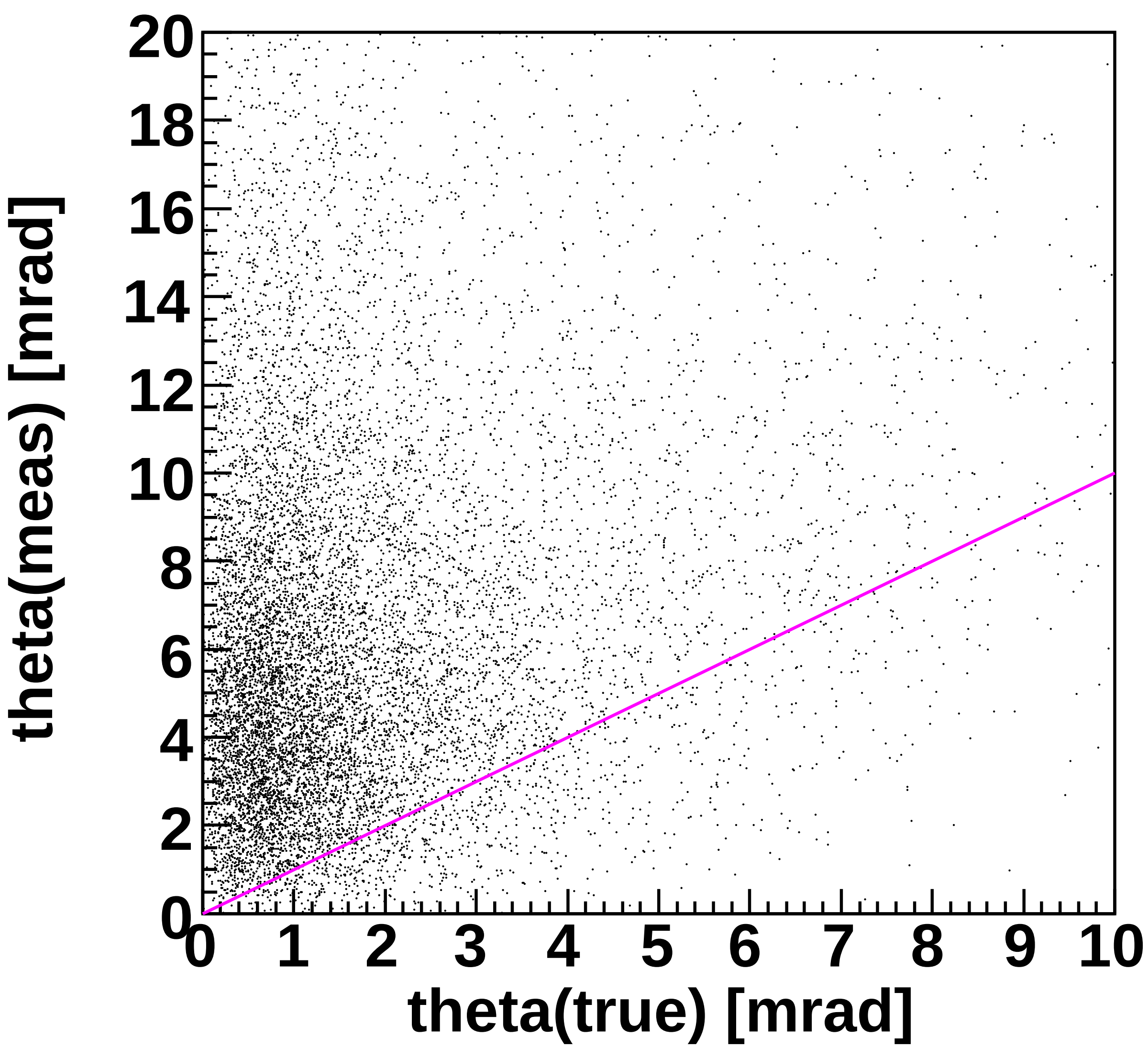
Caution: analysis is still under construction, everything is not necessarily consistent.

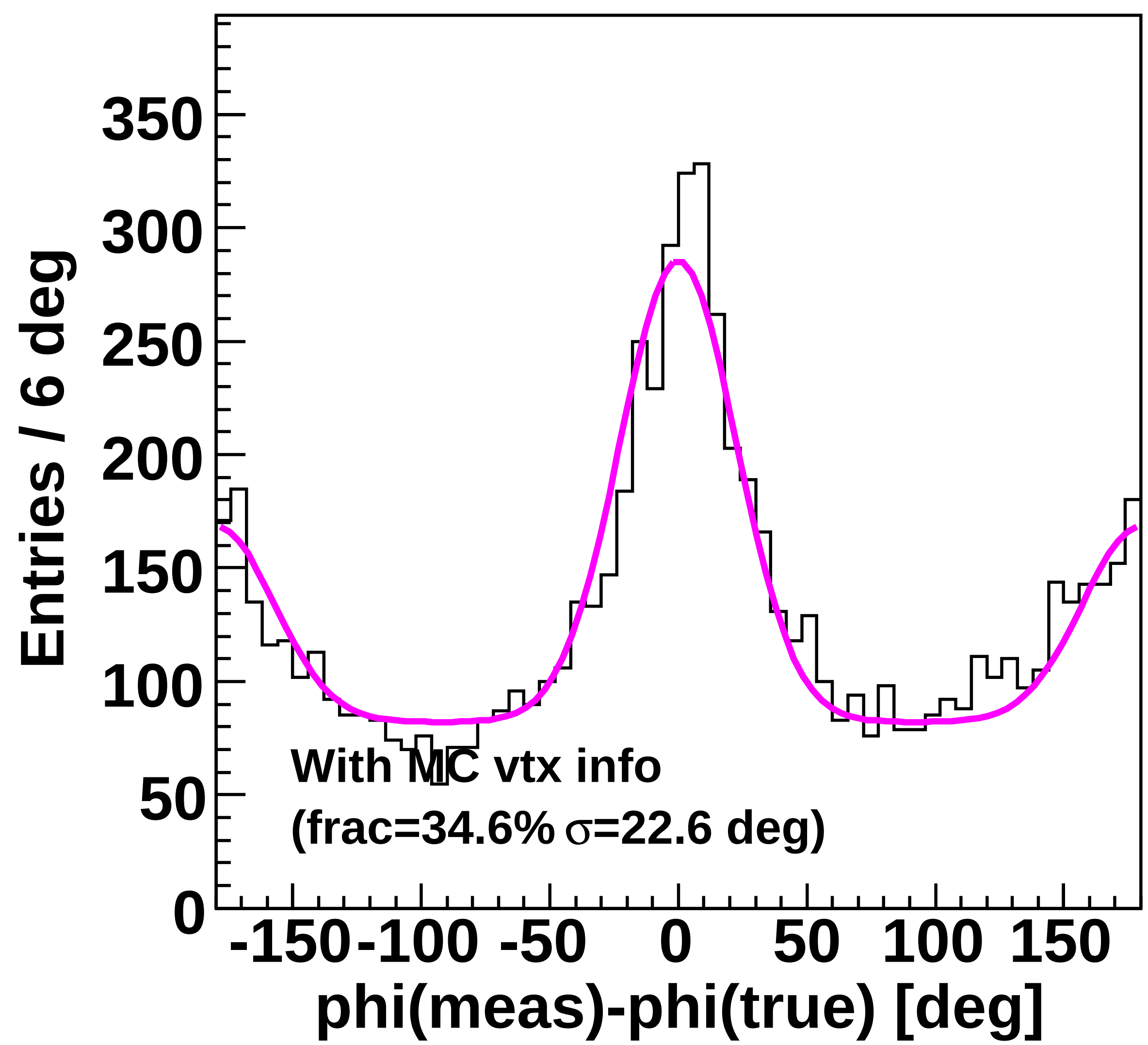
Conversion in $r-\phi$ plane (SVD2)



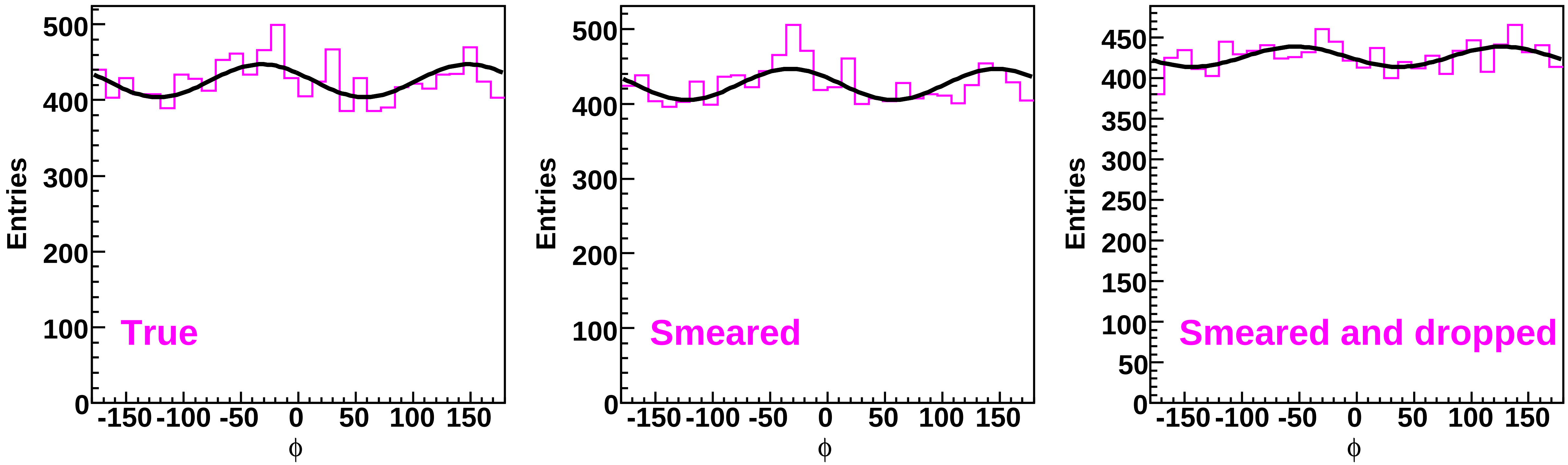
Angular resolution

- Theta is not measured at all
- Phi could be measured to some extent





Toy MC ($50\ \mathrm{ab}^{-1}$)



- For $A_R \sim A_L$, $|A_R||A_L|/(|A_R|^2 + |A_L|^2) = 0.5$
  $\Rightarrow$ 5% modulation after integrating E and θ ($\xi = 0.103$)
- Perfect detector with no background, $\sim 4\sigma$ effect (LEFT)
- If ϕ resolution $\sigma = 23°$, still $\sim 4\sigma$ effect (RIGHT)
- If effective ϕ efficiency $\epsilon_\phi = 35\%$, drops to 2σ effect (RIGHT)
  (note that $\epsilon_\phi = 35\%$ is achieved only if conversion point is 100% correctly reconstructed)

Photon conversion hopes and worries

Hopes!

- SuperB vertex detector will have more layers (by factor 2?)
  $\Rightarrow$ higher conversion rate
- Angular resolution should be much better with dedicated a track reconstruction code
- If opening angle is measured, full fit on (E, θ, ϕ)

Worries...

- Totally based on GEANT. Is it correctly modeled?
- How to calibrate MC?
  No good control sample (polarized photon) within Belle
  (Spring-8 polarized photon beam may be usable for a beam test)

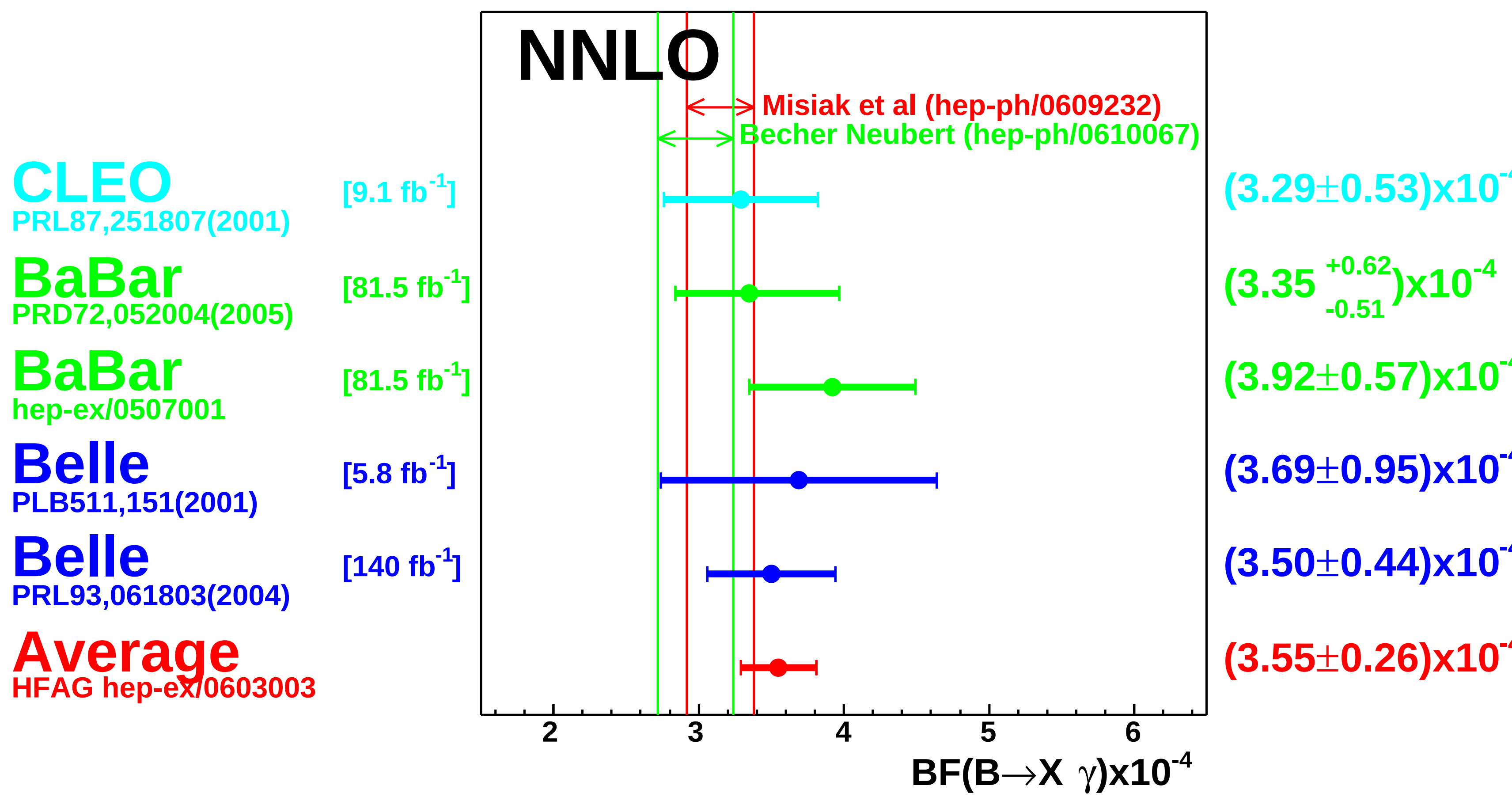
$B \to X_s\gamma$ branching fraction

$B \to X_s\gamma$ branching fraction

Average branching fraction for $E_\gamma > 1.6$ GeV

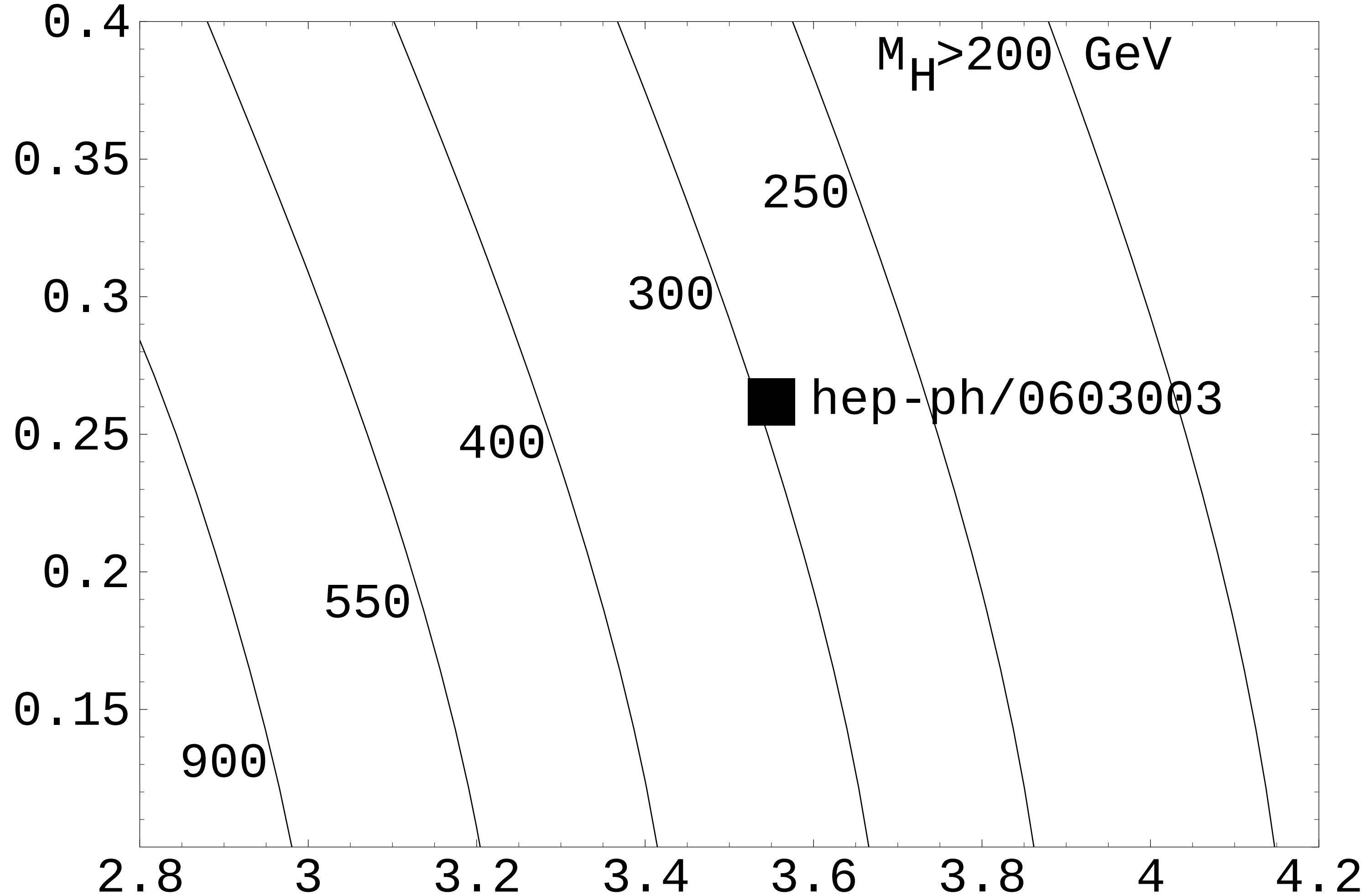
(Heavy Flavor Averaging Group (HFAG), hep-ex/0603003)

$$\mathcal{B}(B \to X_s\gamma;\ E_\gamma > 1.6\ \text{GeV}) = (355 \pm 24_{(\text{stat+sys})}\ {}^{+9}_{-10}{}_{(\text{shape})} \pm 3_{(d\gamma)}) \times 10^{-6}$$



- Tension between measurement and NNLO calculation?

Charged Higgs limit



- Lower limit on type-II charged Higgs mass for any $\tan\beta$
  (Misiak et al, hep-ph/0609232)
- $M(H^+) > 295$ GeV (95% CL), or $M(H^+) \sim 650$ GeV(?)
- Need to decrease the experimental error!
- Room for other new physics

$B \to X_s\gamma$ hopes and worries

Hopes

- E_γ cut could be lowered to 1.6 GeV before SuperB, or further down with SuperB
- All NNLO calculations converges with a small error ($\sim 5\%$) or less, and agree with the fraction above E_γ cut (Neubert, Gardi, . . .)

Either Hopes or Worries. . .

- Theorists (Misiak et al) finds no other large corrections to push up the prediction high again
- No way to get a 3σ effect, no matter how well measured? Any tension could be an input to a bigger NP fit

Worries. . .

- Hadronic background — anti-n, K_L^0, . . .

Two more methods

$B \to X_s\gamma$ with photon conversion

- Conversion fraction $\sim 3\% \Rightarrow 10$ event / fb^{-1}
- Same fraction of continuum and $B \to \pi^0 X$
- No anti-n and K_L^0, but should be easier
- Excellent E_γ resolution (though in $\Upsilon(4S)$ frame. . .)
- Absolute conversion fraction is not known precisely — calibrate with $B \to K^*\gamma$

Full-reconstruct tagged $B \to X_s\gamma$

- Tag-efficiency $\sim 0.3\% \Rightarrow 1$ event / fb^{-1}
- Clean signal, other cut efficiency should be high
- Much less affected by continuum, same fraction of $B \to \pi^0 X$
- Still anti-n and K_L^0, but should be easier

Additions and Summary

(more materials in backup slides)

Additions from LoI and BNM-I (1)

- $A_{FB}(B \to K^*\ell^+\ell^-)$ and Wilson Coefficients
  - Today: first measurement, $A_9 A_{10} < 0$
  - $\delta A_9 \sim 0.11$, $\delta A_{10} \sim 0.13$ at 5 ab^{-1}, $\delta A_9 \sim \delta A_{10} \sim 0.04$ at 50 ab^{-1}
- Branching fraction and A_{FB} for $B \to X_s\ell^+\ell^-$
  - Today: $\mathcal{B}(B \to X_s\ell^+\ell^-) = (4.5 \pm 1.0) \times 10^{-6}$
  - not so easy to scale
- $R_K = \Gamma(B \to K\mu^+\mu^-)/\Gamma(B \to Ke^+e^-)$
  - Today: $R_K = 1.48 \pm 0.32$, $R_{K^*} = 1.15 \pm 0.31$ (HFAG ~ 0.5 ab^{-1})
  - SM: $R_K = 1$, $R_{K^*} = 0.75$
  - $\delta R_K \sim 0.07$ at 5 ab^{-1}, $\delta R_K \sim 0.02$ at 50 ab^{-1}

Additions from LoI and BNM-I (2)

- $A_{CP}(B \to X_s\gamma)$
  - SM expectation: $A_{CP} = (0.42\,^{+0.17}_{-0.12})\%$
  - Today: $Acp(B \to X_s\gamma) = 0.004 \pm 0.037$ (HFAG ~ 0.35 ab^{-1})
  - $\delta A_{CP} \sim 1\%$ at 5 ab^{-1}, $\delta A_{CP} \sim 0.5\%$ at 50 ab^{-1}
- $A_{CP}(B \to K^0_S\pi^0\gamma)$
  - Today: $\mathcal{S} = -0.10 \pm 0.31 \pm 0.7$, $\mathcal{A} = -0.20 \pm 0.20 \pm 0.06$
  - $\delta\mathcal{S} = 0.1$ at 5 ab^{-1}, $\delta\mathcal{S} = 0.03$ at 50 ab^{-1}
- $\mathcal{B}(B \to \rho^0\gamma)$
  - Today: $\mathcal{B}(B \to \rho\gamma) = (0.91\,^{+0.19}_{-0.18}) \times 10^{-6}$
  - 10% error at 5 ab^{-1}, 5% error at 50 ab^{-1}
  - For V_{td}/V_{ts}, need significant improvement from Lattice
- $A_{CP}(B \to \rho^0\gamma)$
  - $\delta\mathcal{S} = 0.4$ at 5 ab^{-1}, $\delta\mathcal{S} = 0.15$ at 50 ab^{-1}

More to be studied (never-ending list...)

- $B \to K^* e^+ e^-$ at very low q^2
  — sensitive to photon polarization (Grossman, CSKim)
- $B \to (\pi, \rho)\ell^+\ell^-$
  — sensitive to $|V_{td}/V_{ts}|$
- $B \to X_{(s+d)}\gamma$ direct CPV
  — extremely small SM CPV (Hurth)
- Triple products using $B \to K_1(1400)\gamma$
  — search for right handed current (Gronau)
- Triple products using $B \to K\phi\gamma$
  — null test for vast range of new physics (Soni)
- Isospin asymmetry in $B \to X_s\gamma$
  — test of scale dependece for photon energy cut (Neubert)
- Isospin asymmetry for $B \to (\rho, \omega)\gamma$
  — test of QCDF/pQCD predictions and eventually Lattice?

Summary

Rich physics program from radiative and electroweak decays

- $\mathcal{B}(b \to s\gamma)$, still the place to search for deviation from SM
  - Slight tension between NNLO and data $\Rightarrow$ room for NP
  - Rooms to improve measurements (some needs SuperB)
- Right-handed amplitude if exists from
  - Time-dependent CPV in $b \to s\gamma$
  - Photon polarization from conversion
- Reliable $|V_{td}/V_{ts}|$ from inclusive $b \to d\gamma$
  - Small theory error, competitive to Δm_s measurements
  - Not relying on Lattice QCD at all
- And more...
  - A_{FB}, R_K, direct CPV, isospin violation, ...

Backup Slides

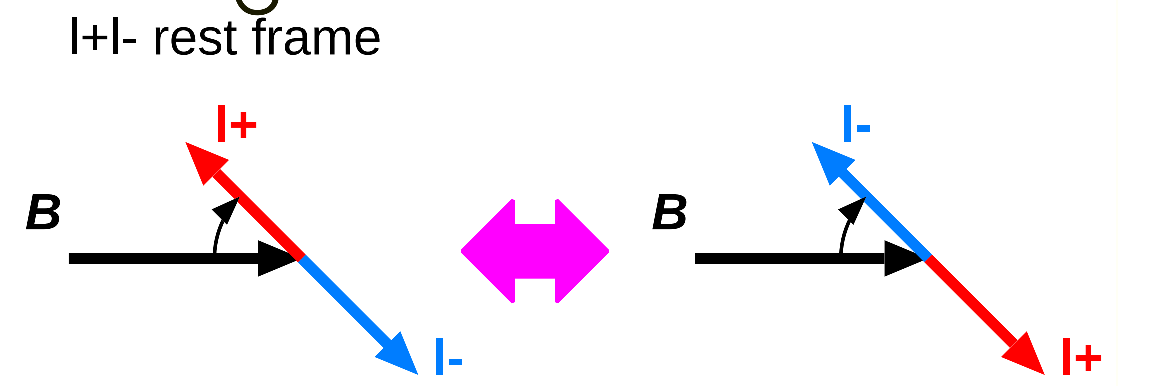
EW / radiative B decays at SuperKEKB

- Statistics dominated studies
  - Forward-backward asymmetry in $B \to K^* \ell^+ \ell^-$
  - $R_K = \Gamma(B \to K\mu^+\mu^-)/\Gamma(B \to Ke^+e^-)$
  - Time-dependent CPV in $B \to K^*\gamma$, $B \to \rho\gamma$ and more
  - $A_{CP}(B \to X_s\gamma)$
  - Photon helicity measurement from photon conversion
- Technically challenging studies
  - Improving $\mathcal{B}(B \to X_s\gamma)$
  - Improving $\mathcal{B}(B \to X_s\ell^+\ell^-)$
  - Inclusive $\mathcal{B}(B \to X_d\gamma)$ measurement
  - Photon helicity measurement from $B \to K_1(1400)\gamma$

(red colored items = new or updated studies in this talk)

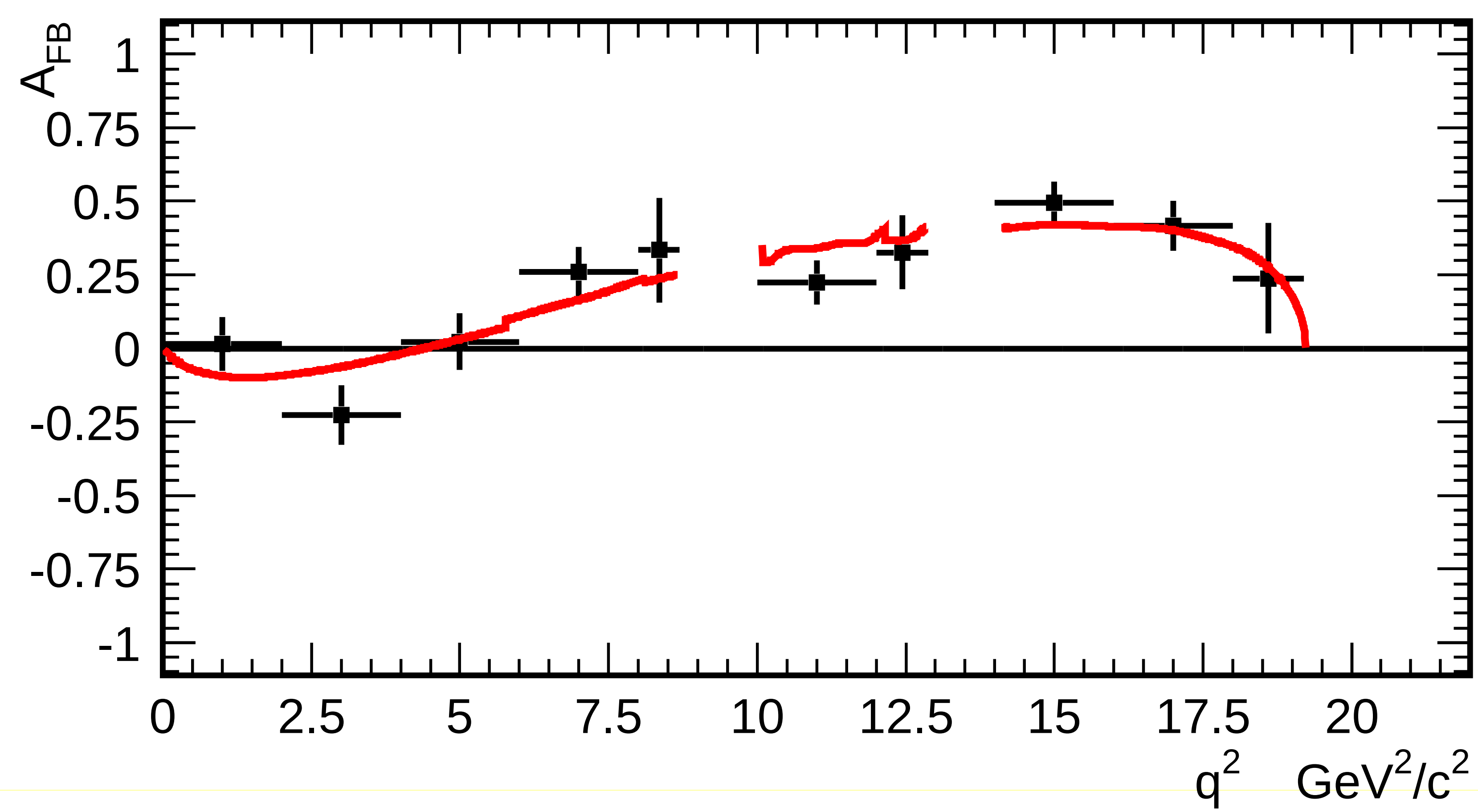
$A_{FB}(B \to K^*\ell^+\ell^-)$ from HL6 workshop

- Sensitive to C_9 and C_{10} Wilson coefficients
- Full (q^2, θ) fit with SM q^2 dist with leading coefficients only (A_9 and A_{10})



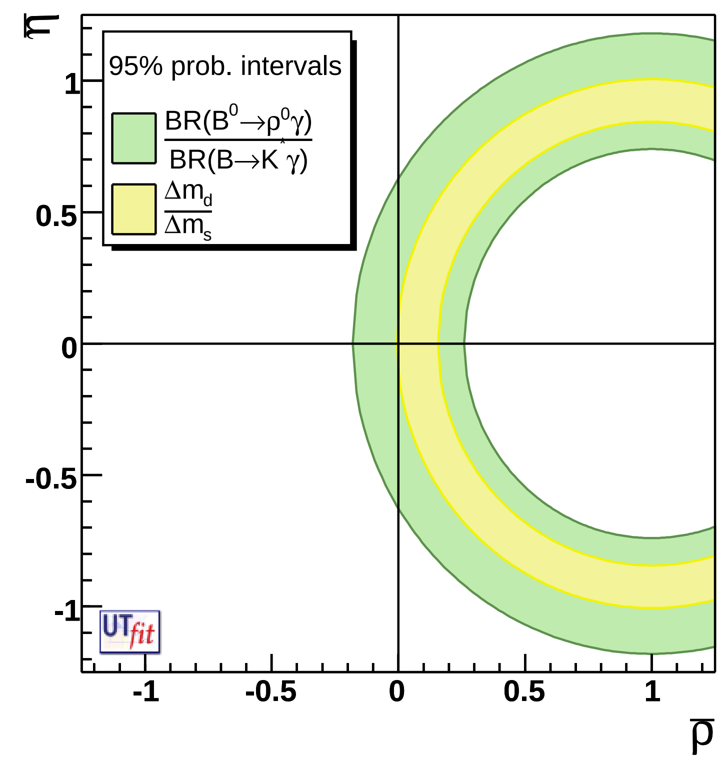
- $\delta A_9/A_9 \sim 11\%$
  $\delta A_{10}/A_{10} \sim 13\%$ at 5 ab^{-1}

(i.e., $\delta A_9/A_9 \sim \delta A_{10}/A_{10} \sim 4\%$ at 50 ab^{-1})



Exclusive $\overline{B}^0 \to \rho^0\gamma$

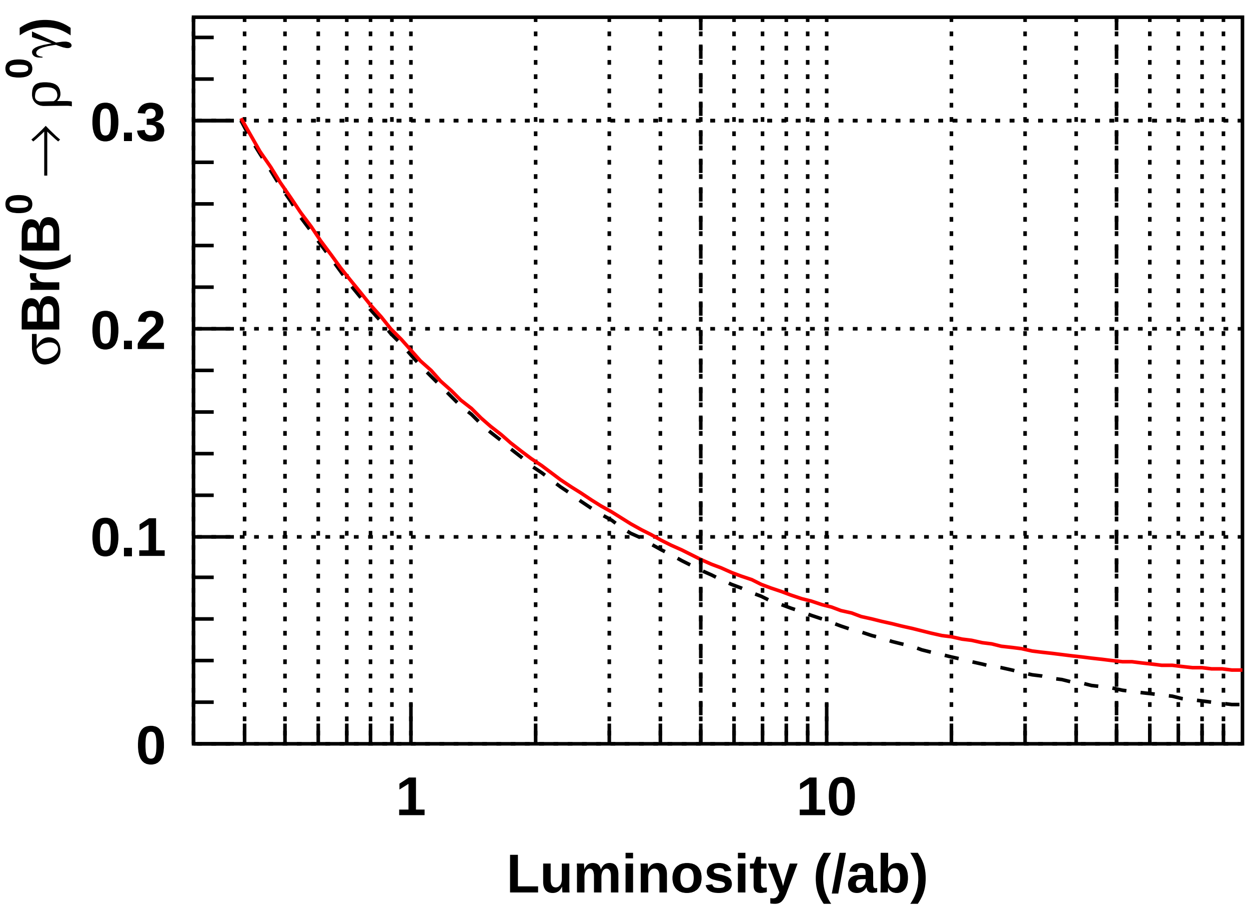
- $|V_{td}/V_{ts}|$ from $b \to d\gamma$: not very competitive with Tevatron B_s mixing, but still the second best measurement
- Belle/Babar have reported $|V_{td}/V_{ts}|$ using combined $B \to (\rho, \omega)\gamma$, but,
  - $B^+ \to \rho^+\gamma$ should be dropped because of annihilation diagram
  - $B \to \omega\gamma$ should be dropped because of less knowledge
- And still the theory error would be 20–30% in BF



$$\frac{\mathcal{B}(\overline{B}^0 \to \rho^0\gamma)}{\mathcal{B}(B^0 \to K^{*0}\gamma)} = \frac{1}{2}\left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{(1-m_\rho^2/m_B^2)^3}{(1-m_{K^*}^2/m_B^2)^3}\zeta^2[1+\Delta R]$$

Future sensitivity on $\overline{B}^0 \to \rho^0\gamma$

- If we scale the Belle result with fixed 3% systematic error, $\mathcal{B}(\overline{B}^0 \to \rho^0\gamma) = (1.25\,^{+0.37}_{-0.33}\,^{+0.07}_{-0.06}) \times 10^{-6}$, Error will drop quickly below the level of theory error (i.e., no more improvements on $|V_{td}/V_{ts}|$ soon)



- $|V_{td}/V_{ts}|$ has to be measured through inclusive $b \to d\gamma$ (!)
- $\overline{B}^0 \to \rho^0\gamma$ and $B \to \omega\gamma$ are useful for time-dep. CPV
- $B^+ \to \rho^+\gamma$ is useful for direct CPV

Time-dependent CPV in radiative decays

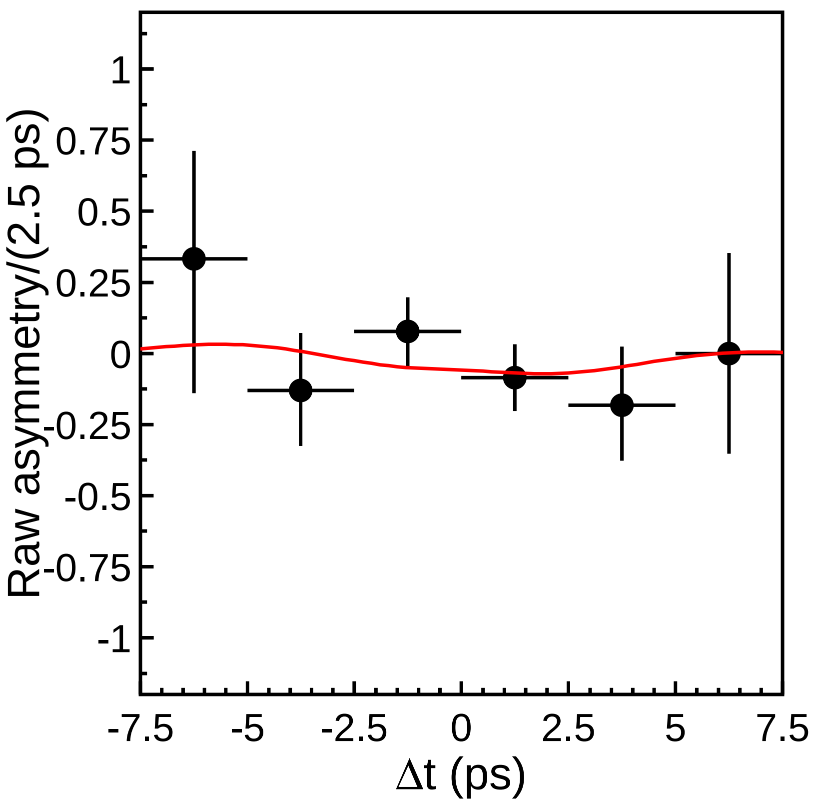
- Time-dependent CPV for radiative decays with CP eigenstate or $P^0Q^0\gamma$

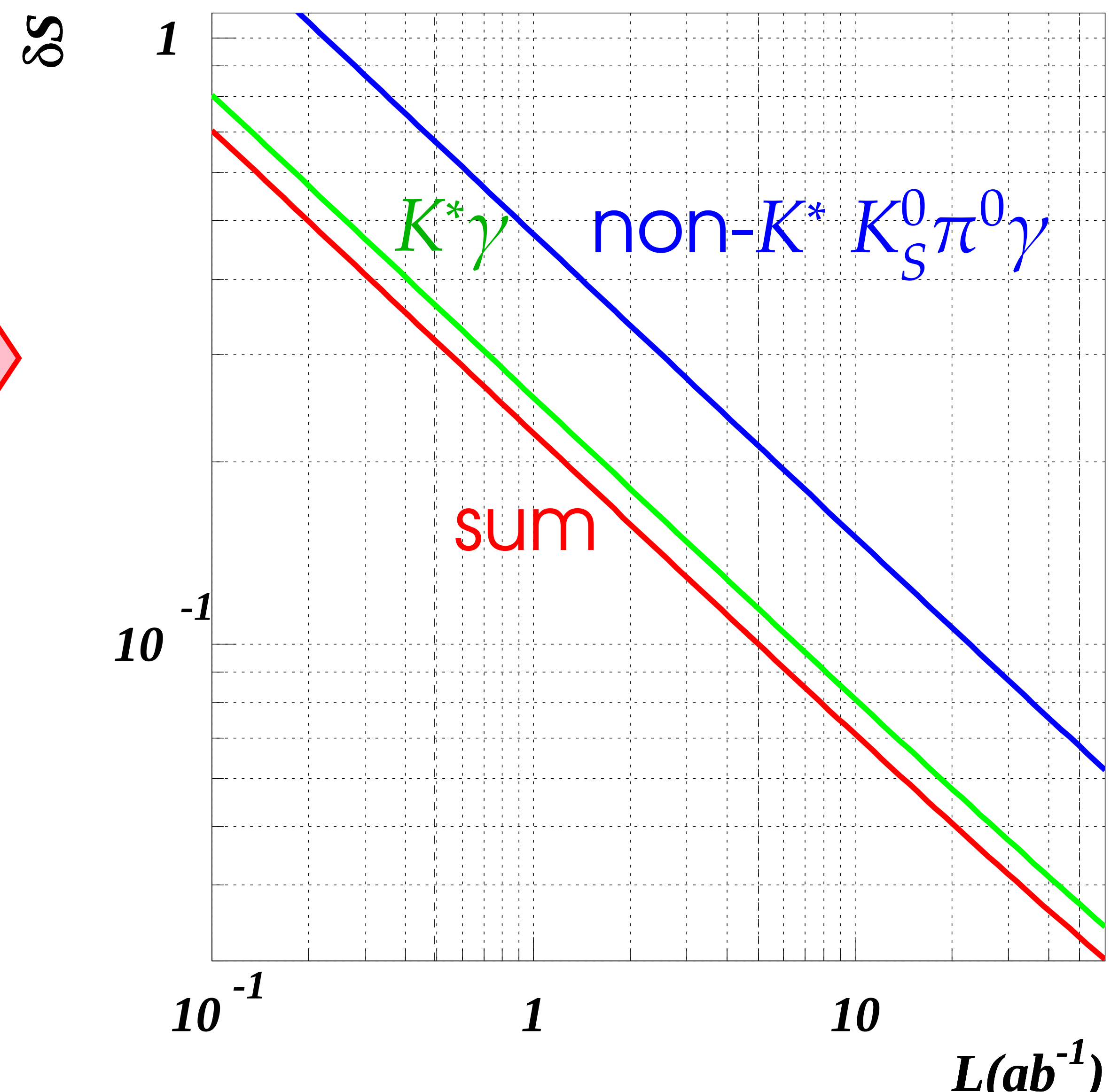
$$A_{CP}(\Delta t) = \frac{\Gamma(B^0(t) \to K_S^0\pi^0\gamma) - \Gamma(\overline{B}^0(t) \to K_S^0\pi^0\gamma)}{\Gamma(B^0(t) \to K_S^0\pi^0\gamma) + \Gamma(\overline{B}^0(t) \to K_S^0\pi^0\gamma)} = S \sin \Delta m \Delta t + A \cos \Delta m \Delta t$$

- Due to left handed photon of SM $b \to s\gamma$, S is small
  At largest $|S| \sim 0.10 \Rightarrow$ any large S term due to non-SM right handed photon such as left-right symmetric model
- $B \to K_S^0\pi^0\gamma$, $B \to K_S^0\eta(\to \gamma\gamma)\gamma, \ldots$
  - K_S^0 vertex reconstruction technique established
- $B \to K_S^0\phi\gamma$, $B \to K_S^0\eta(\to \pi^+\pi^-\pi^0)\gamma$, $B \to K_S^0\eta'\gamma$, $B \to K_S^0\rho^0\gamma, \ldots$
  - Standard vertexing, but rates are very low
- $B \to \rho^0\gamma$, $B \to \omega\gamma$
  - CPV would be large and may not be easy to interpret, but interesting to see it

$B \to K_S^0\pi^0\gamma$ TCPV at SuperKEKB

- Extrapolation of 0.5 ab^{-1} errors





$S_{K_S^0\pi^0\gamma} = -0.10 \pm 0.31 \pm 0.07$

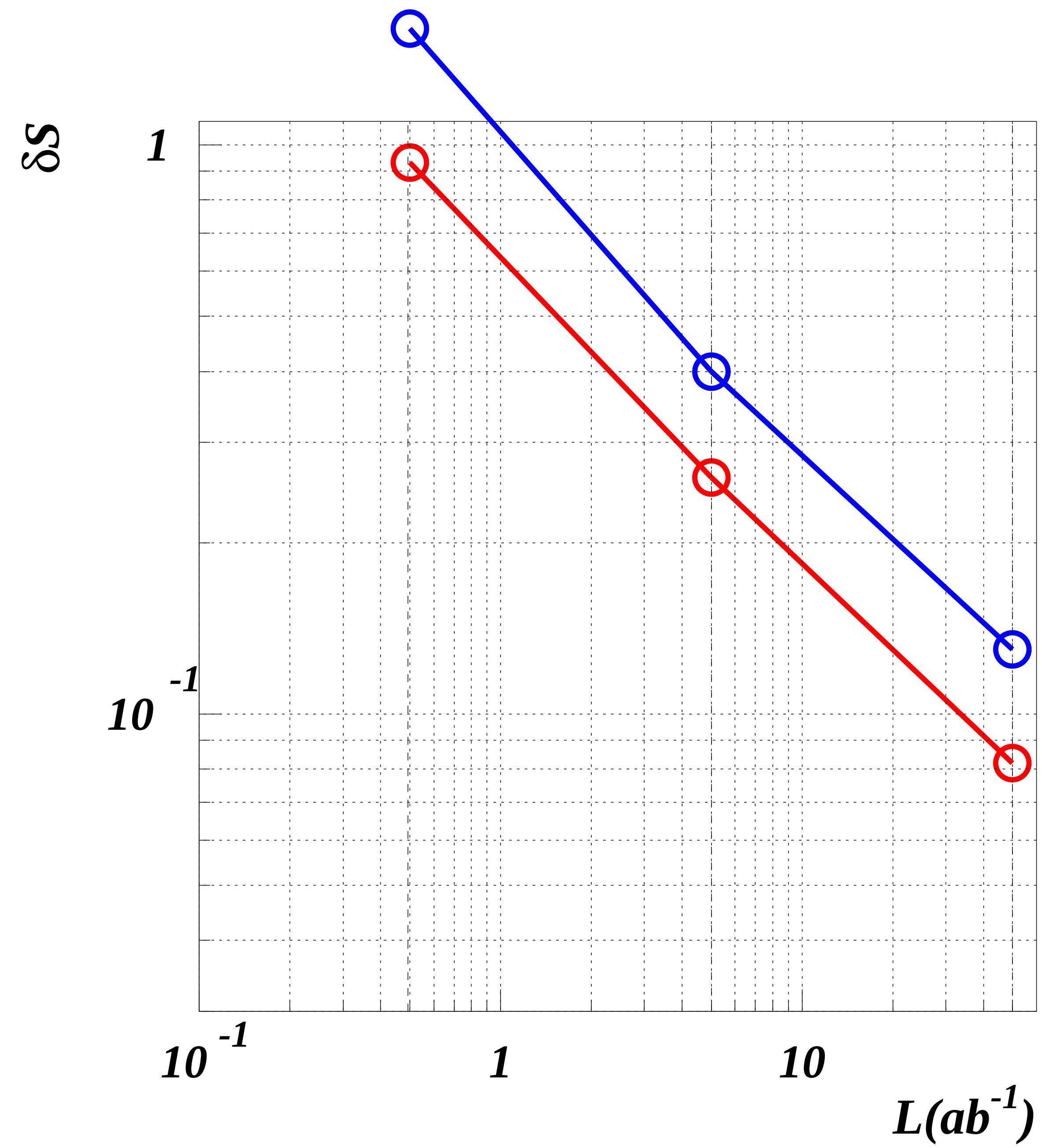
$A_{K_S^0\pi^0\gamma} = -0.20 \pm 0.20 \pm 0.06$

(hep-ex/0608017 535M $B\overline{B}$)

> 10 ab^{-1} is needed to be sensitive to 10% CPV

$B \to \rho^0\gamma$ TCPV at SuperKEKB

- Toy MC study based on Belle's and SM-like $\overline{B}^0 \to \rho^0\gamma$ rate



- Vertexing efficiency
  $\sim 87\%$ (a la ϕK_S^0)
- All background PDF
  $B \to K^*\gamma$, $X_s\gamma$, $\rho\pi^0$, other B decays, continuum
- Background Δt PDF from $K_S^0\pi^0\gamma$ analysis

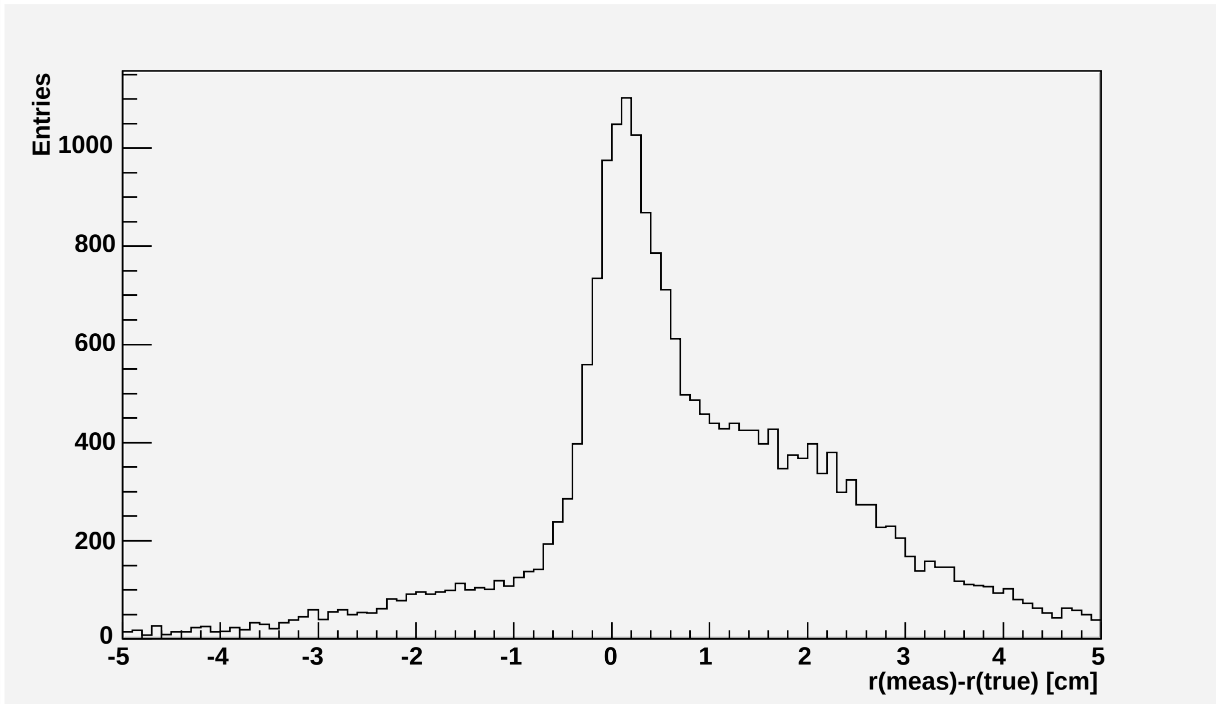
Need 50 ab^{-1} for $\sim 10\%$ error

For a better angular resolution

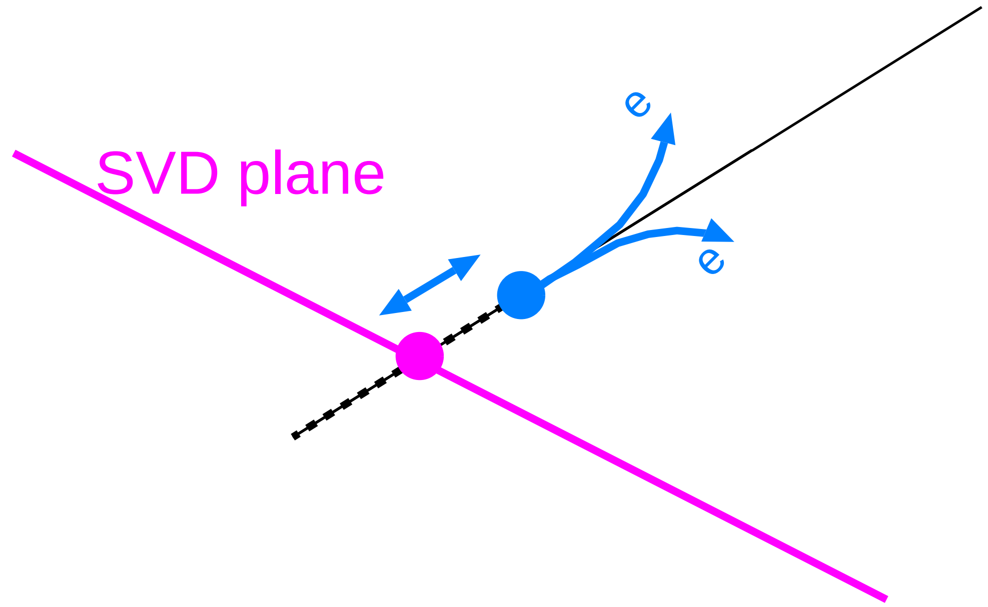
- Track fit has to be redone with
  - constraints of the conversion point to be on SVD
  - proper handling of overlapping SVD cluster for two tracks
- No such a code is available yet
  - At least SVD hit info is needed, current MDST_xxx is not enough
  - Size of SVD hit info will be small if limited to the SVD hits for conversion tracks
  - Ishino-san and I will work on it to at least include SVD hit info in MDST_xxx — hopefully before grand reprocess

Reconstructed vs true conversion point

- Reconstructed conversion vertex tends to be more outside
- Direction precisely measured, but radius is not
  Could be wrong by a few cm!
- Should be improved by using geometry knowledge

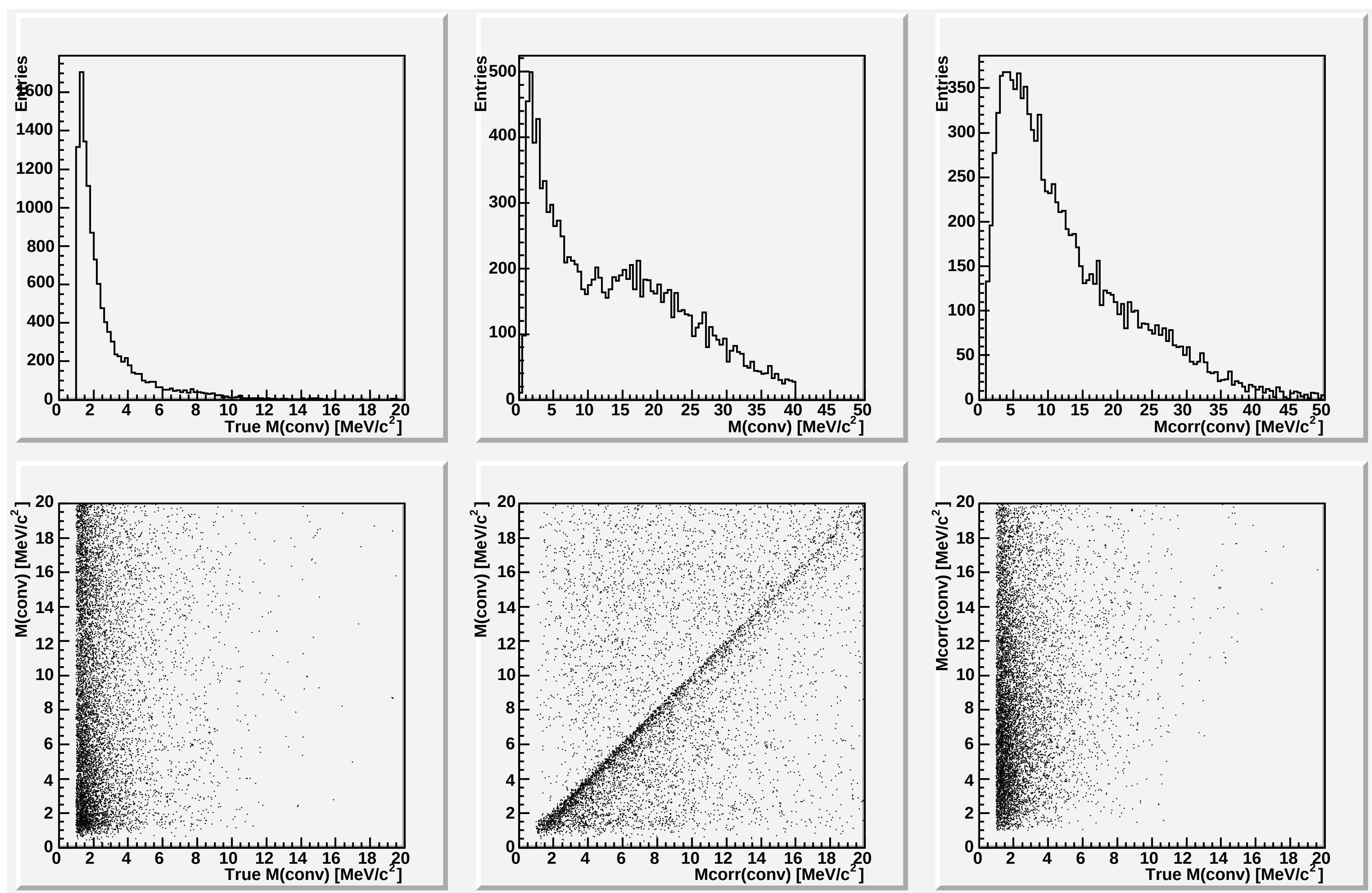


Recon – true radius in cm



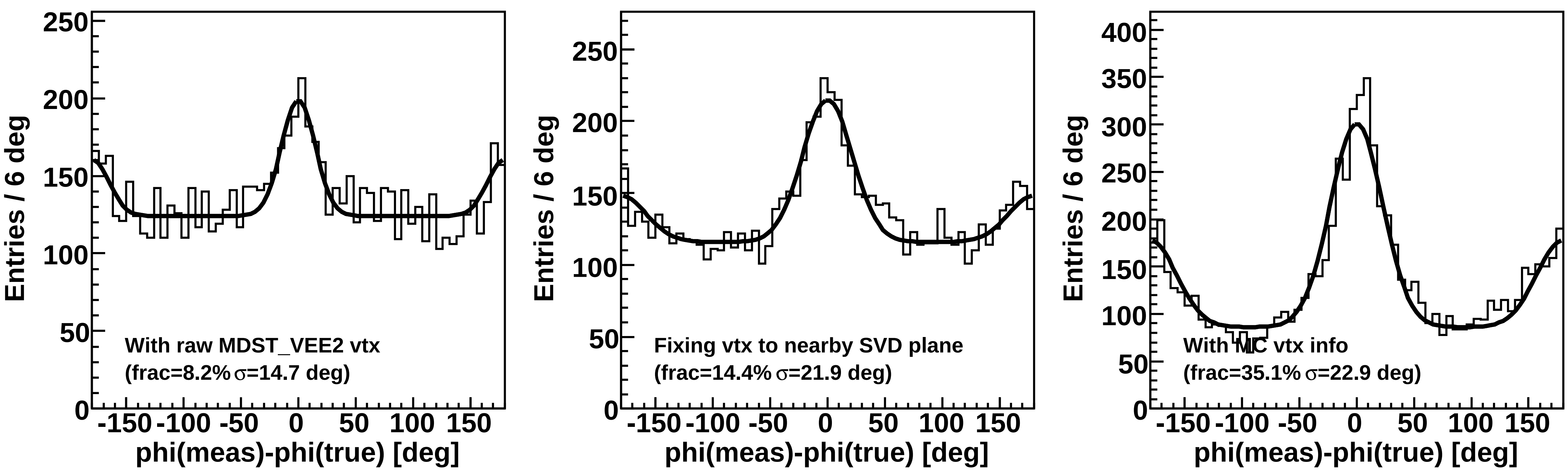
$m(e^+e^-)$ resolution

- No correlation in true vs measured $m(e^+e^-)$ (LEFT-BOTTOM) even after moving pivot to SVD plane (RIGHT-BOTTOM) $\Rightarrow$ i.e, no sensitivity to θ_i, θ_j

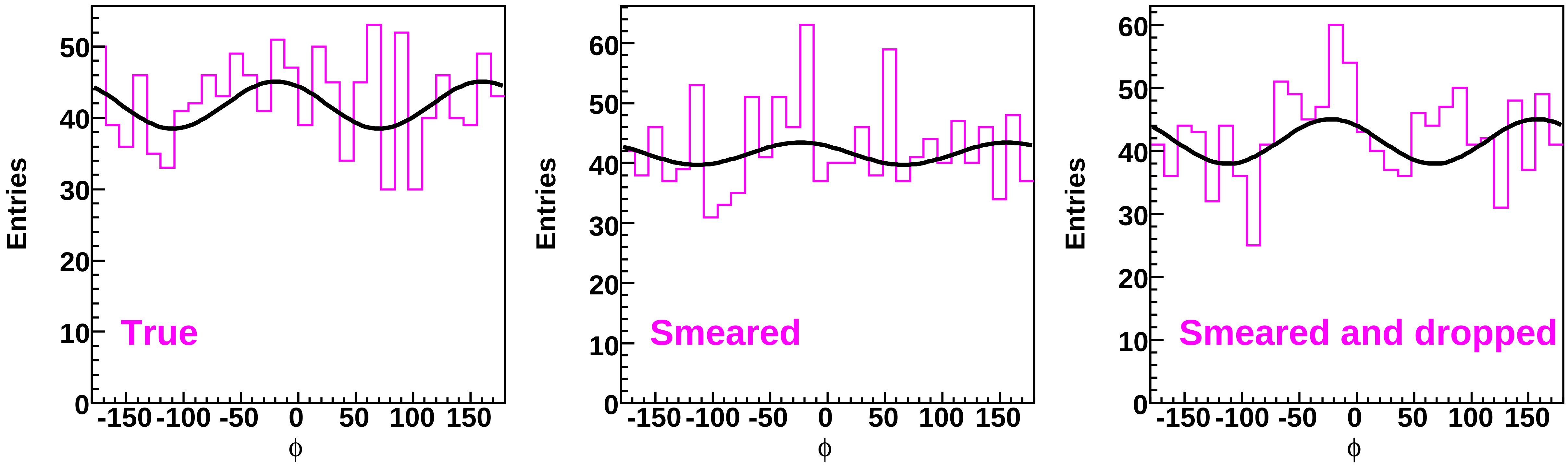


ϕ resolution

- True ϕ_{ee} from GEANT vs reconstructed ϕ_{ee}
  - (LEFT) ϕ_{ee} in MDST_VEE2_DAUGHTERS is very distorted
  - (CENTER) Pivot moved to nearby SVD plane $\Rightarrow$ better!
  - (RIGHT) Pivot moved to true vertex (ideal) $\Rightarrow$ ~1/3 of events
- Room for improvement: e.g., using fit χ^2 or SVD hit info



Toy MC ($5\ \mathrm{ab}^{-1}$)



- Similar toy MC for $A_R \sim A_L$
- Even with a perfect detector, $\sim 2\sigma$ effect (LEFT)
- Statistical fluctuation can easily mimic the modulation
  This sample (RIGHT) should not have visible effect
- Need to improve effective efficiency factor ξ with θ measurement