Measurement of the CP violating asymmetry in $B^0 \to \phi K_S^0$

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Belle II summer workshop

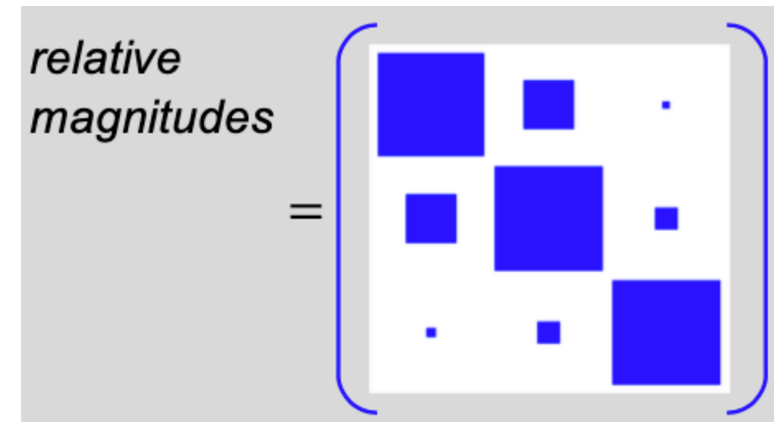
July 13, 2021

Recap: CKM matrix and CP violation

Review first day of workshop for more details

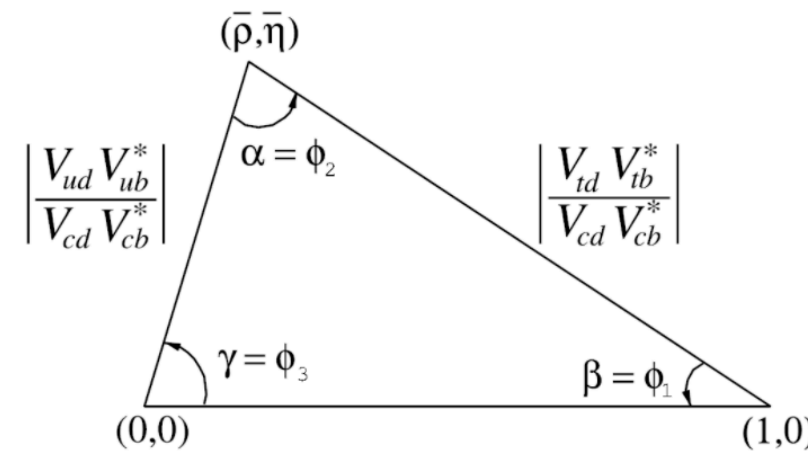
- Within Standard Model(SM)
  - CKM matrix:
    - Coupling strength among quarks

$$V_{\mathrm{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



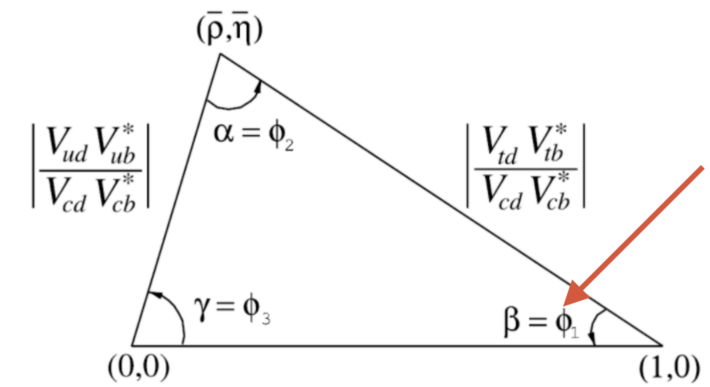
Credit: prof Soeren Prell's talk yesterday

    - One irreducible CP-violating phase factor
  - Unitary triangle:
    - Graphical representation of parameter relations

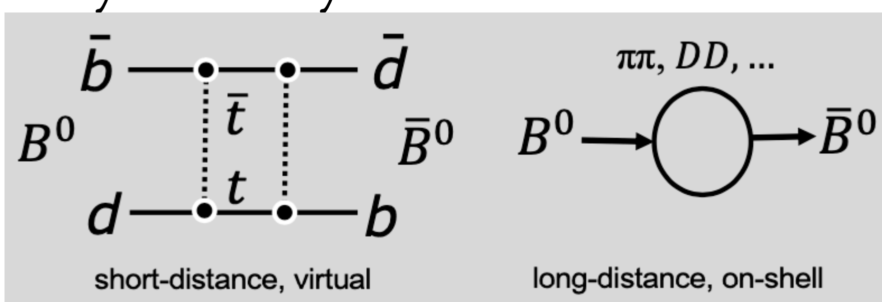


- CP-violation: fundamental asymmetry between matter vs antimatter
  - Phase factor from SM: magnitudes too small compared to observed
  - Search for contributions from New Physics(NP) beyond SM

CP violation and measurement of ϕ_1

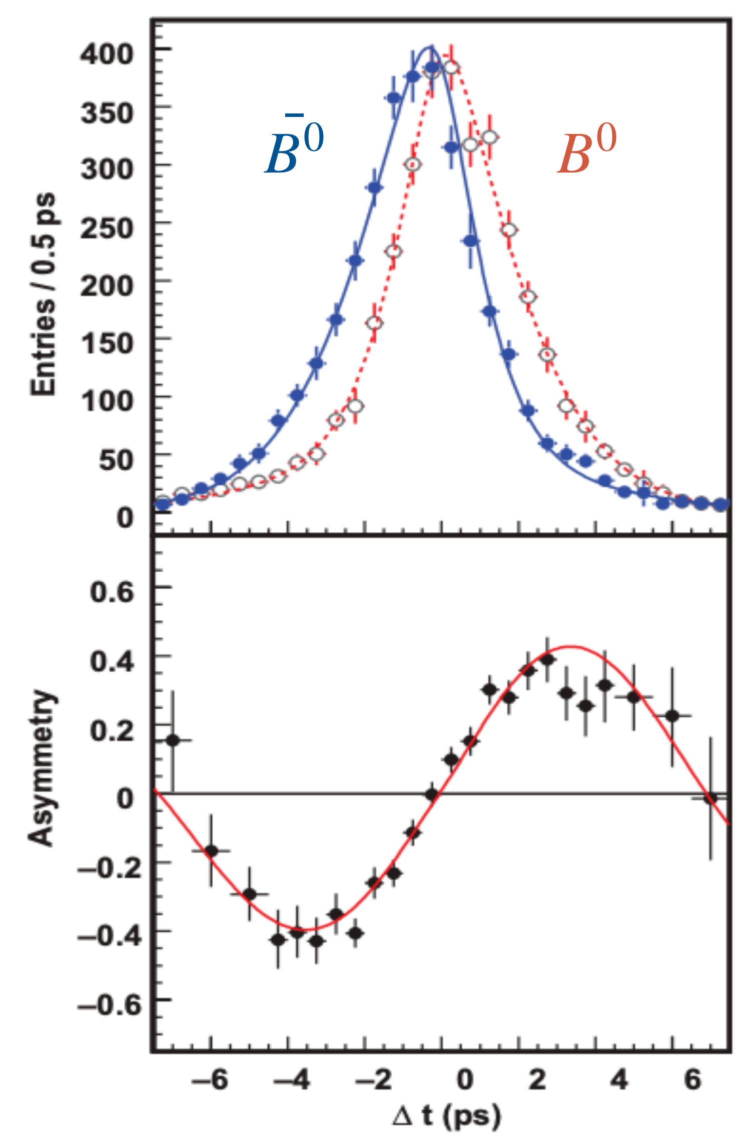


- CP violation manifests in:
  - **Mixing**: $B^0 \leftrightarrow \bar{B}^0$ oscillation
    - Asymmetry in the transition



Credit: prof Soeren Prell's talk yesterday

  - **Decay**: $B^0 \to \phi K_S^0$ vs $\bar{B}^0 \to \phi K_S^0$
    - Asymmetry in the decays
  - **Interference** between **mixing** and **decay**
    - Time-dependent CP asymmetry contains $\sin 2\phi_1$
      - Measure ϕ_1 through $A_{CP} = \dfrac{\Gamma_B(t) - \Gamma_{\bar{B}}(t)}{\Gamma_B(t) + \Gamma_{\bar{B}}(t)}$



Background-subtracted Δt distribution for B and $\bar{B}$ events and asymmetry for events with good quality tags. (Fig8 Physics achievements from the Belle Experiment")

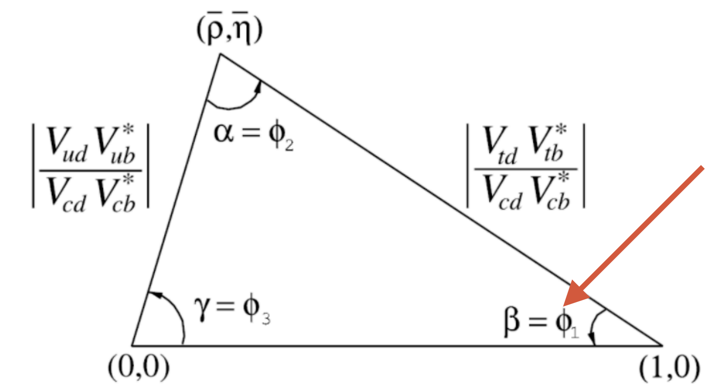
Credit: prof Soeren Prell's talk yesterday

$$A_{CP} = \frac{\Gamma(\bar{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\bar{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})} = -C_f \cos(\Delta M\, t) + S_f \sin(\Delta M\, t)$$

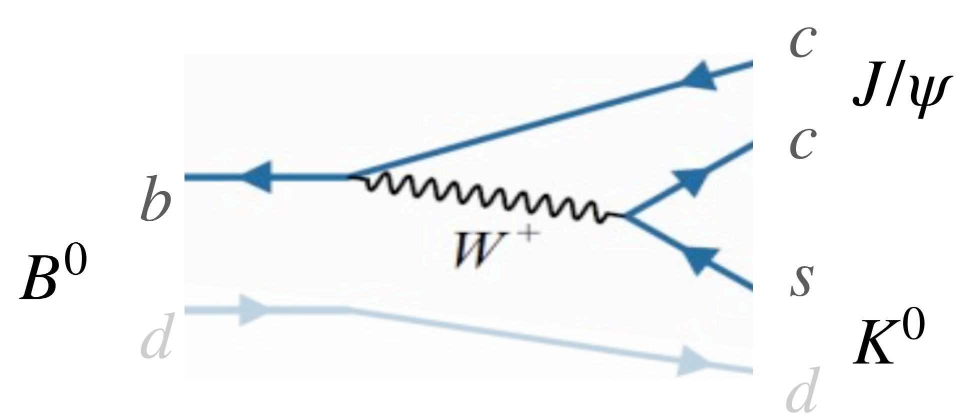
single weak amplitude: $|\lambda_{CP}| = 1$, $C_f = 0$, $S_f = -\mathrm{Im}\,\lambda_{CP}$

Decay channel of interest: $B^0 \to \phi K_S^0$

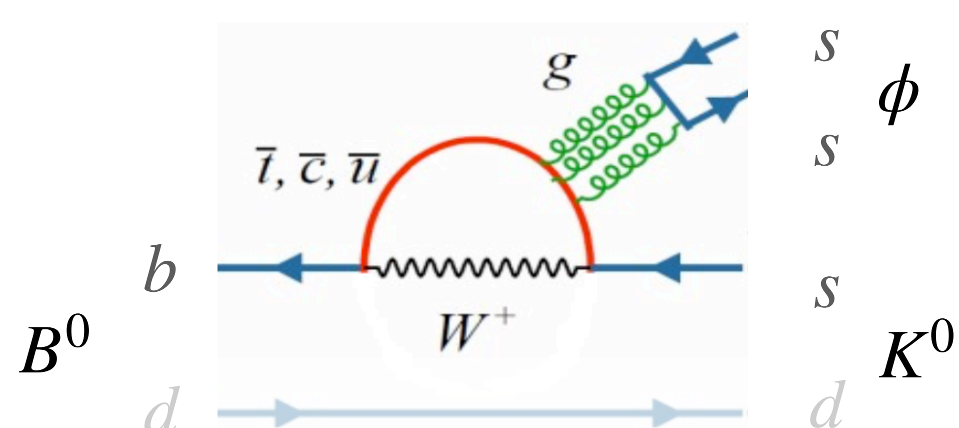
- Measure ϕ_1 through $A_{CP} = \dfrac{\Gamma_B(t) - \Gamma_{\bar{B}}(t)}{\Gamma_B(t) + \Gamma_{\bar{B}}(t)}$



- Tree level: golden mode $B^0 \to J/\psi K^0$
  - Most precise measurement of ϕ_1
  - Free from New Physics
  - Penguin pollution can be constrained by other channels

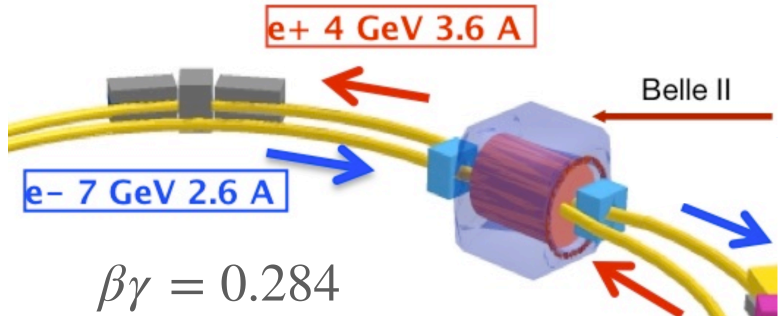


- Penguin loop: this channel $B^0 \to \phi K_S^0$
  - Suppressed in Standard Model
  - Can be modified by New Physics models

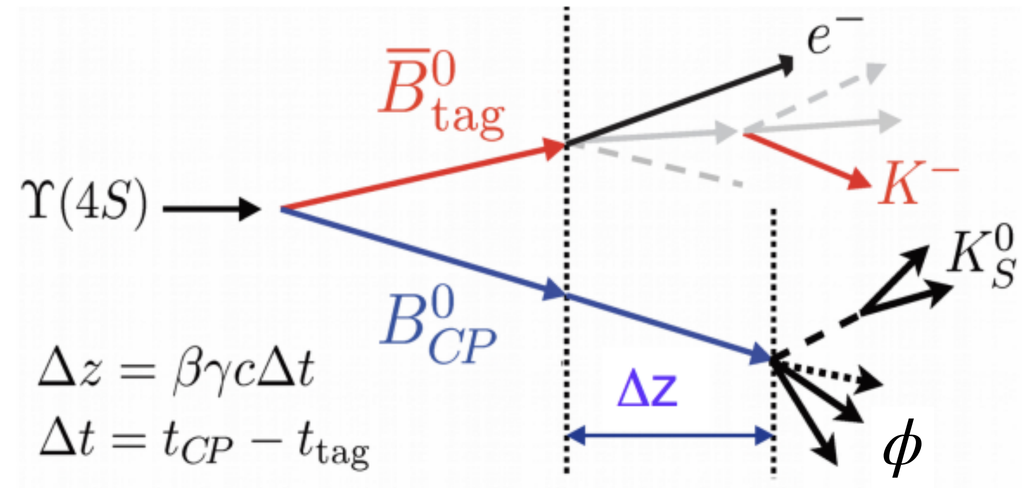


Roadmap: CPV measurement of $B^0 \to \phi K_S^0$

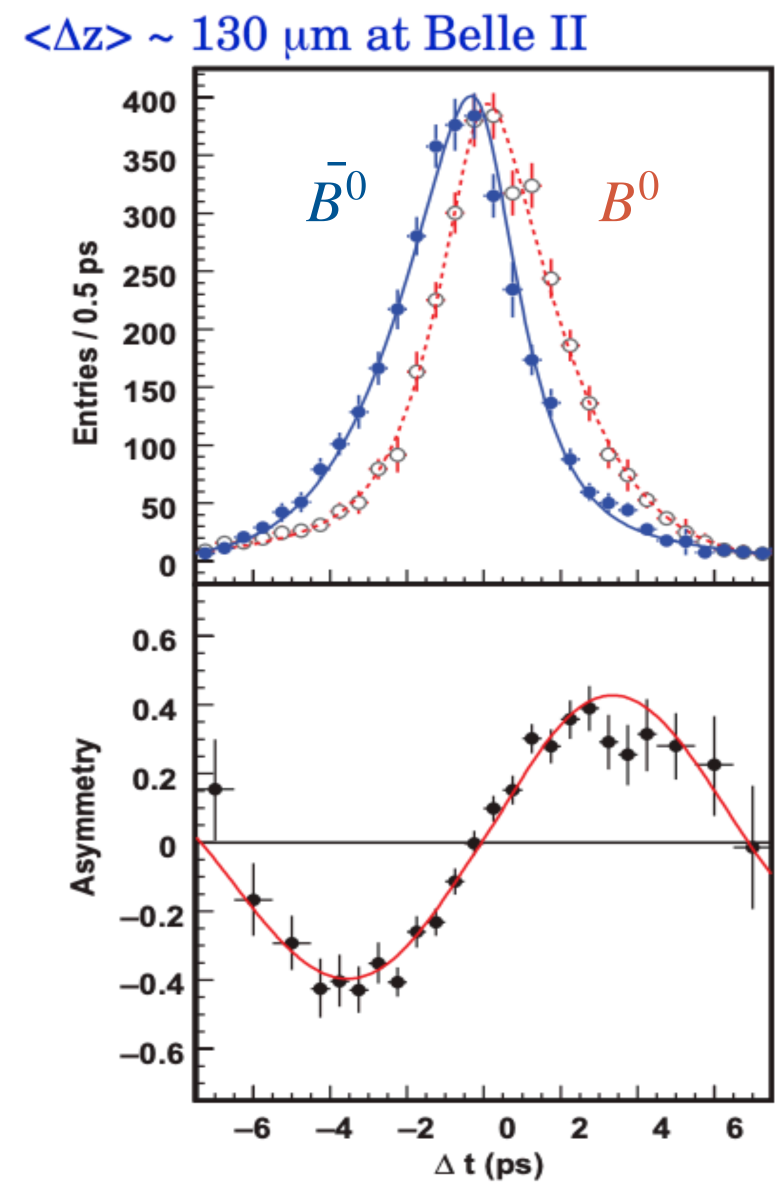
- Principle:



  - $e^+e^- \to \Upsilon(4S)$: moves in lab frame
  - $\Upsilon(4S) \to B^0\bar{B}^0$: one side decays first
    - Example shows tag side decays first

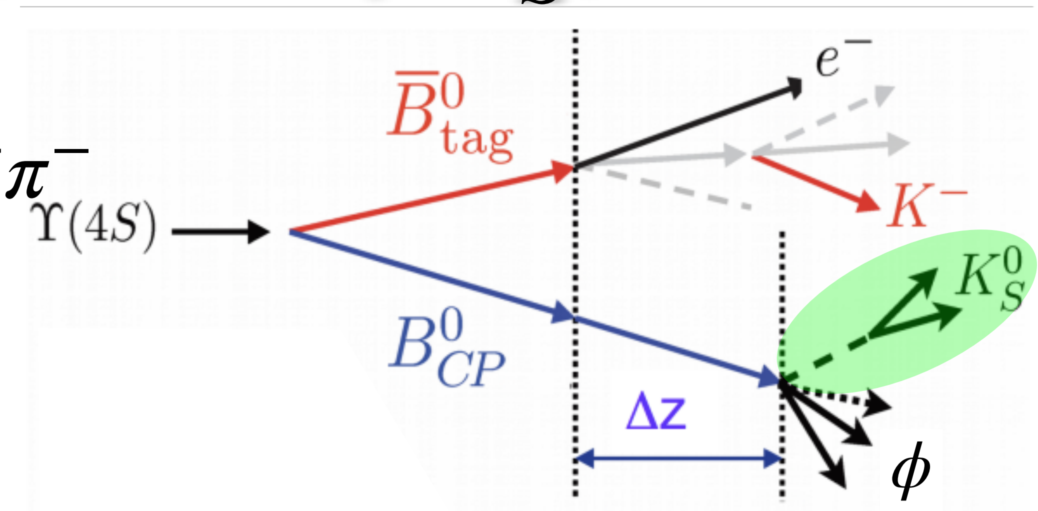


- First stage:
  - Reconstruct CP side decay
- Second stage:
  - Obtain vertex positions on CP and tag sides
- Third stage:
  - Obtain Δt distribution with flavor tagging

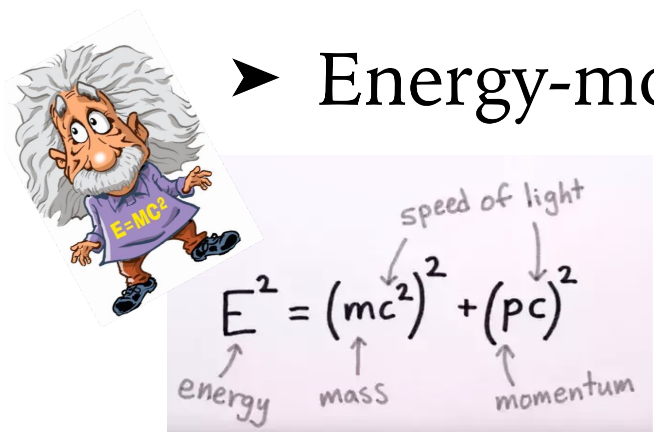


Background-subtracted Δt distribution for B and $\bar{B}$ events and asymmetry for events with good quality tags. (Fig8 Physics achievements from the Belle Experiment")

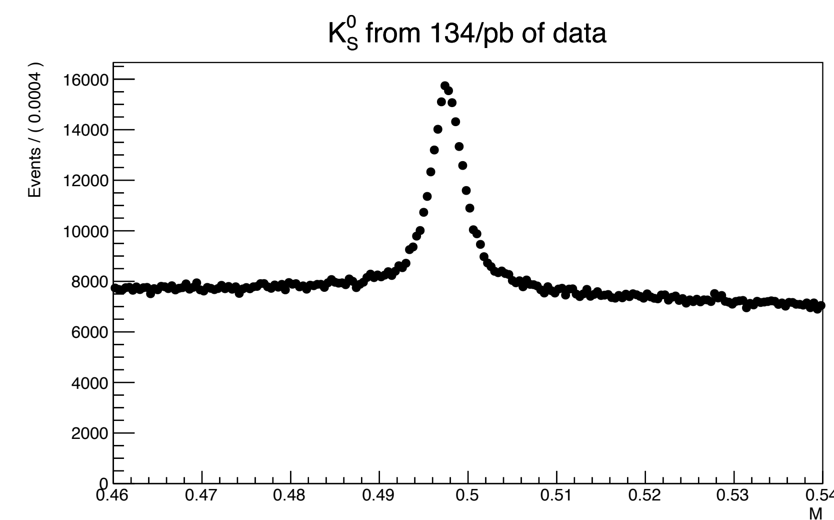
Reconstruct CP side ($B^0 \to \phi K^0_S$)



- Daughter decays: $\phi \to K^+K^-$ and $K^0_S \to \pi^+\pi^-$
- Forming K^0_S candidates:
  - Directly detected tracks from π^+ and π^-
  - Converge 2 tracks back to a decay vertex
  - Energy-momentum conservation



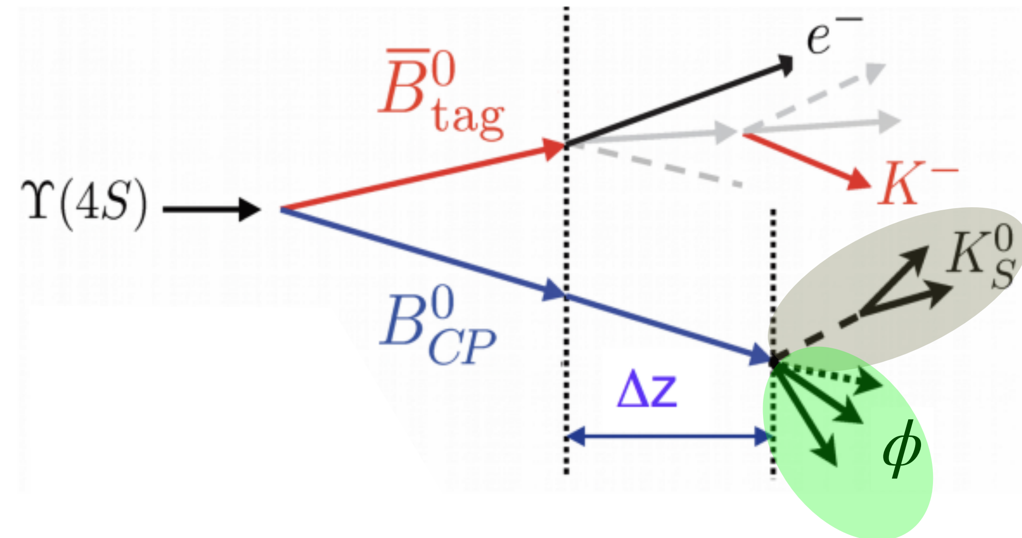
    - $(E_{K^0_S}, \overrightarrow{p_{K^0_S}}) = (E_{\pi_1}, \overrightarrow{p_{\pi_1}}) + (E_{\pi_2}, \overrightarrow{p_{\pi_2}})$
    - $m_{reco} = \sqrt{E^2 - (\overrightarrow{p})^2}$

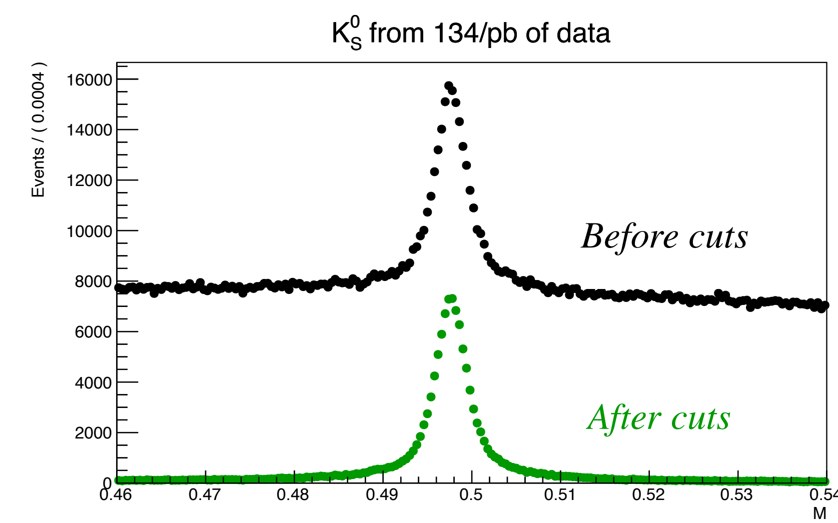


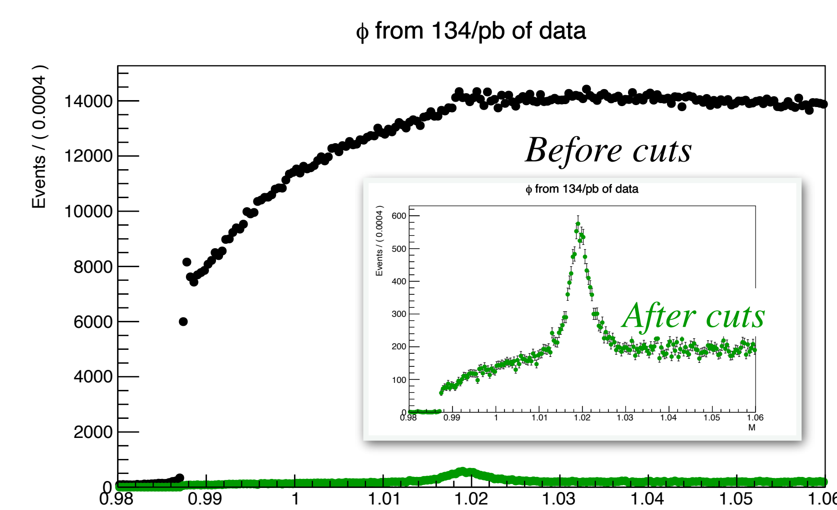
- Expected: invariant mass $m_{K^0_S}$
  - Double-Gaussian functions: finite resolution of detectors
  - Combinatorial backgrounds: results of wrong track combinations

Selection cuts on daughters

- Objective: keep signal & reject background
  - Cuts: put requirements on candidates
- Figure of merit $S/\sqrt{S+B}$
  - Optimize on MC files
  - Final selections:
    - $K_S^0 \to \pi^+\pi^-$ cuts:
      - chiProb of vertex fitting > 0, kinematic updates on daughters
      - “goodBelleKshort”
    - $\phi \to K^+K^-$ cuts:
      - chiProb of vertex fitting > 0, kinematic updates on daughters
      - Tracks: ‘kaonID>0.05 and nCDCHits>0 and inCDCAcceptance’
    - (More details on cuts in backup)

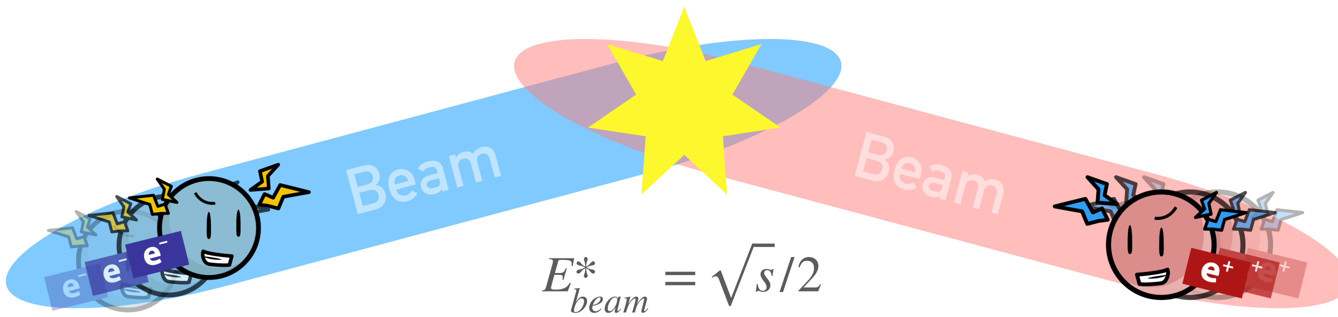




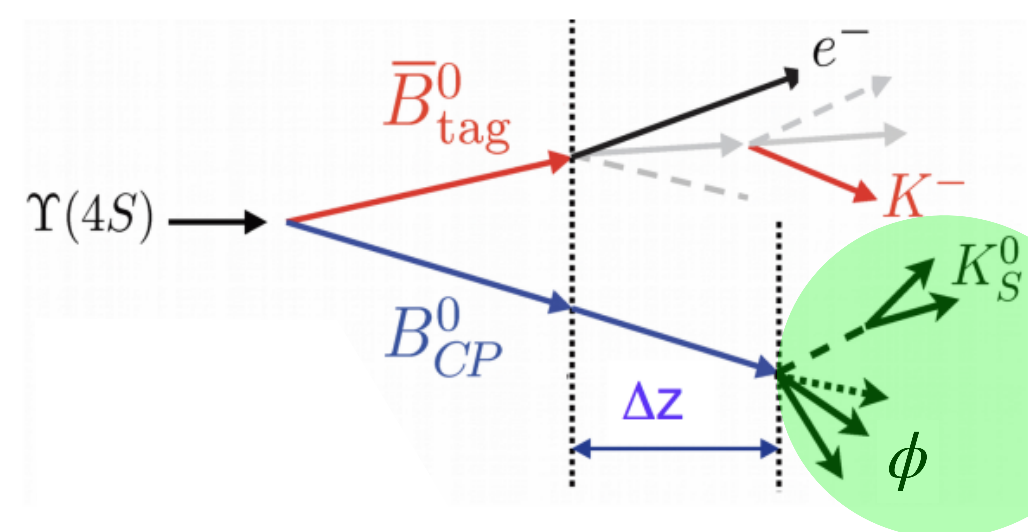


B^0 candidate reconstruction

- Reconstruct $B^0 \to \phi K_S^0$:



e+e- cartoon: HiggsTan



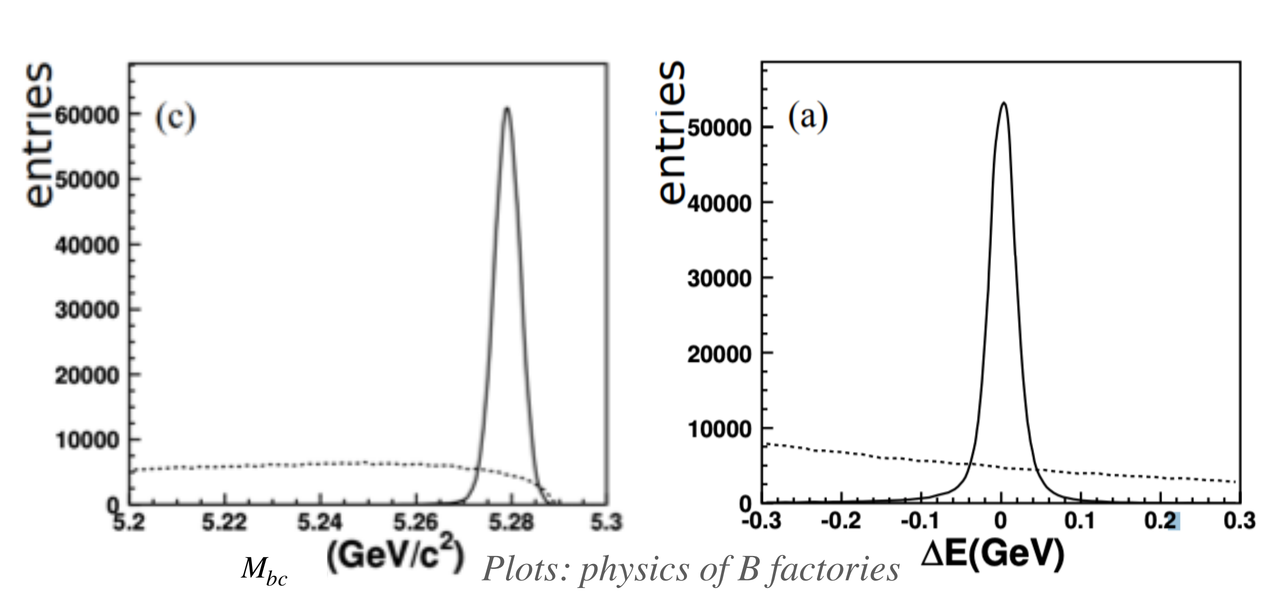
- Kinematic constrains in B-factories:
  - e^+e^- beam 4-momentum very well-measured
- Variables to reconstruct:
  - Beam-energy constrained mass

Similar to $m_{reco} = \sqrt{E^2 - (\vec{p})^2}$; also p_B^* could be larger than E^*_{beam} to weed out wrong candidates.

$$M_{bc} = \sqrt{{E^*_{beam}}^2 - {p_B^*}^2}$$

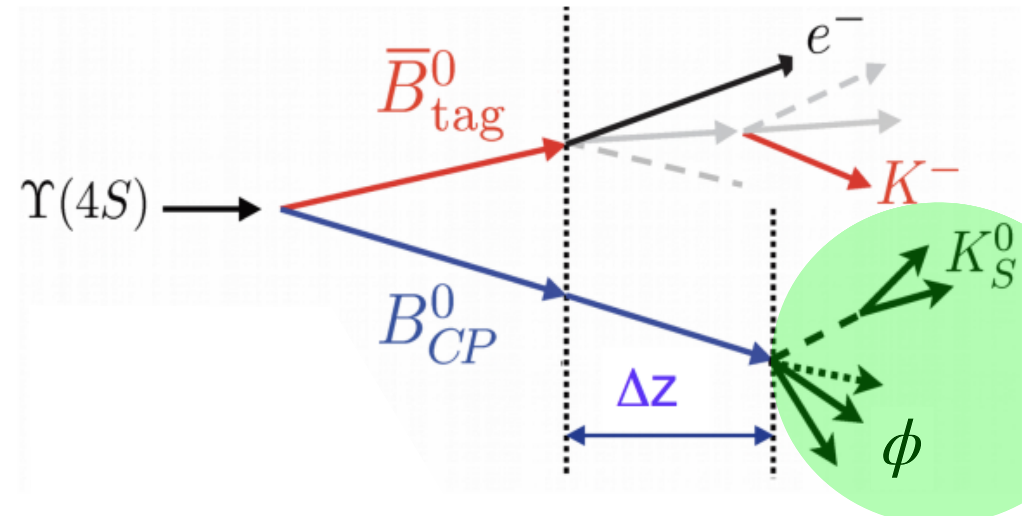
  - Energy difference

$$\Delta E = E_B^* - E^*_{beam}$$

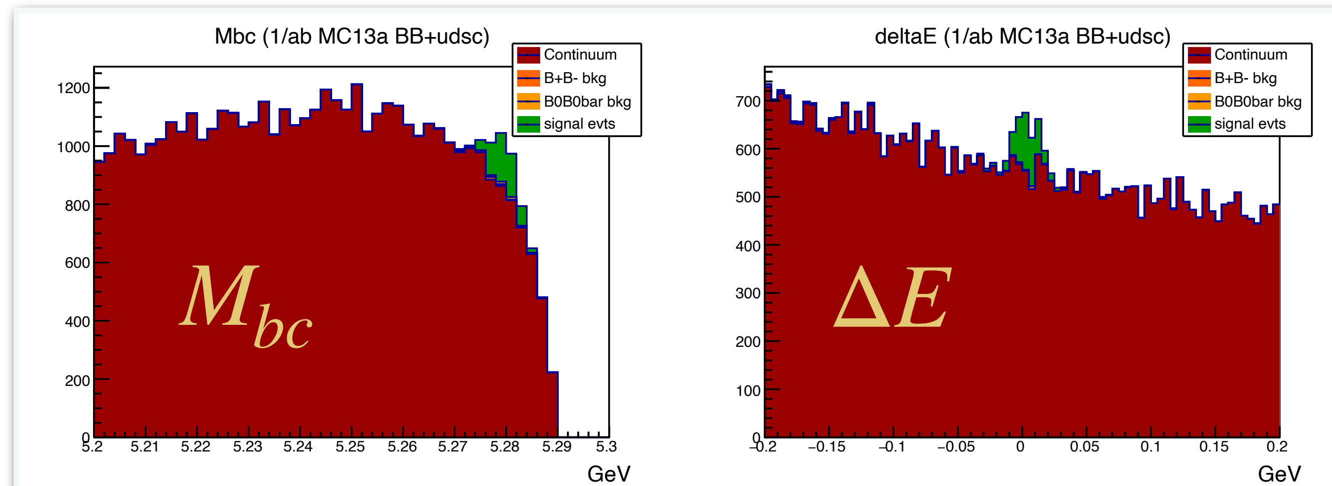


Plots: physics of B factories

B^0 candidate reconstruction



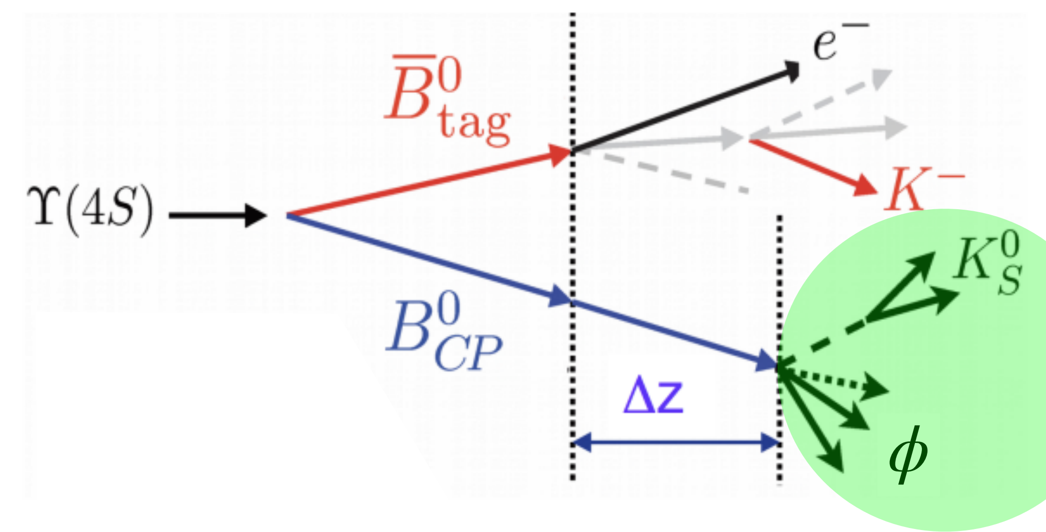
- MC sample: 1/ab of BBbar and qqbar
- Preselection:
  - Vertex fit, chiProb>0, no daughter kinematics update
- In addition to cuts on ϕ and K^0_S
  - 3σ(tail) mass window on ϕ and K^0_S
  - $5.2 < M_{bc} < 5.3$, $|\Delta E| < 0.2$
    - Single candidate: multiplicity<1.004
    - Best candidate based on chiProb



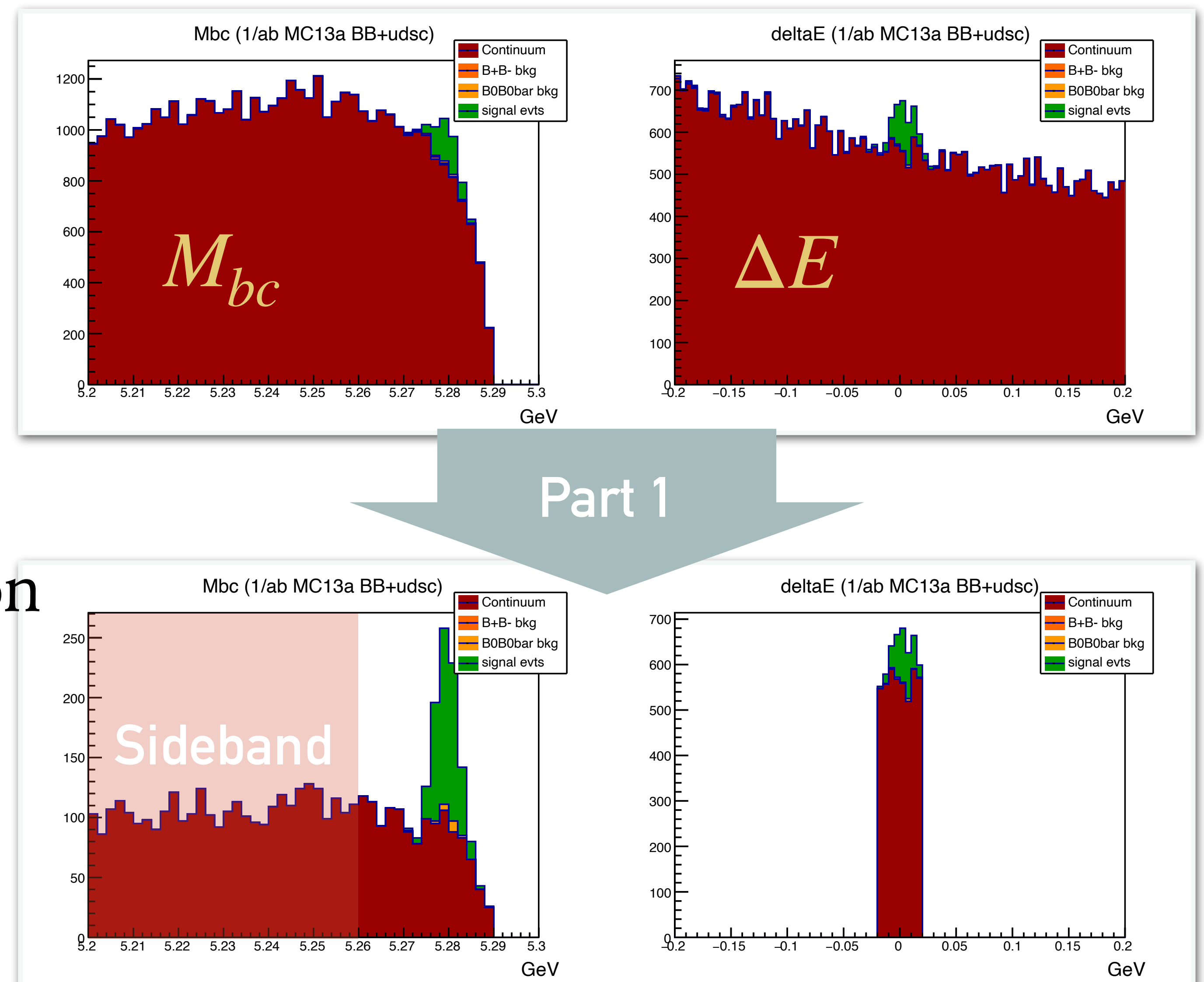
Signal and background components MC13a (1/ab)

- Signal and background components
  - Signal: visible peak
  - Background: dominated by qqbar("continuum")

B^0 selection cuts



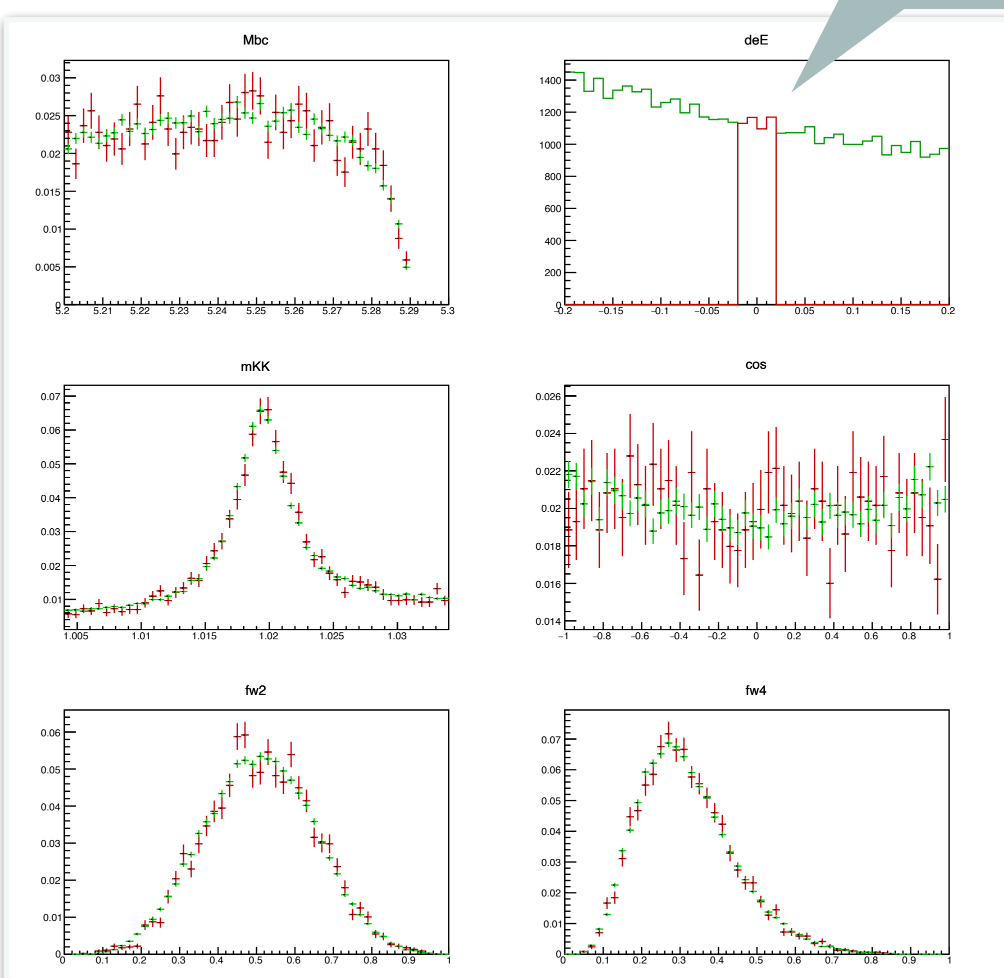
- Bkg dominated by continuum
  - Part 1: Tighten $|\Delta E| < 0.02$
  - Part 2: continuum suppression

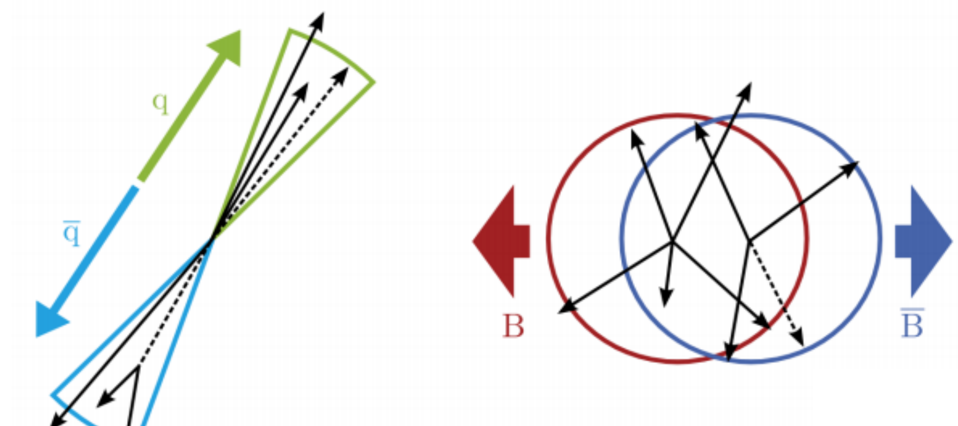


"Fancy" B^0 selection cuts

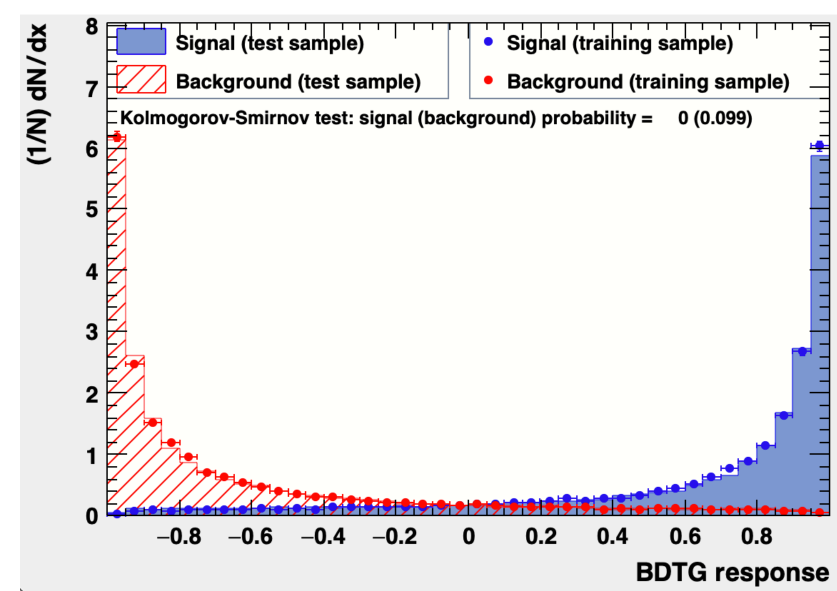
- ➤ Continuum suppression with BDT
- ➤ Training samples
  - ➤ Signal MC
  - ➤ Continuum with $|\Delta E| < 0.2$
    - ➤ To increase statistics

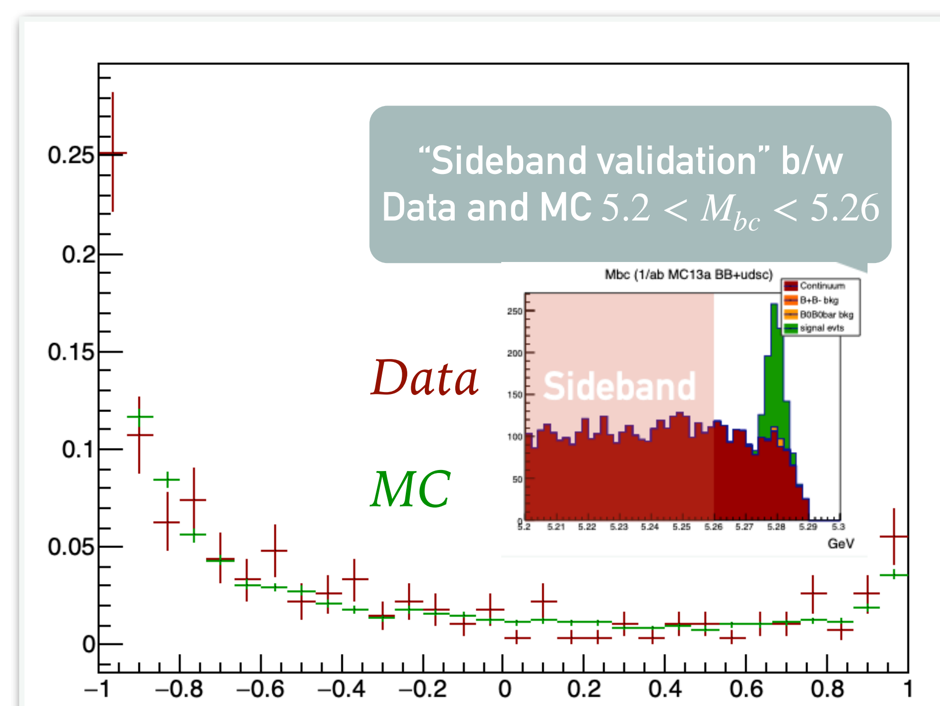
Validation of var distr





Comprehensive introduction: https://indico.belle2.org/event/5/sessions/10/attachments/85/122/Continuum_suppression_lecture_V2.pdf





"Fancy" B^0 selection cuts

- Continuum suppression with BDT
- Training samples
  - Signal MC
  - Continuum with $|\Delta E| < 0.2$
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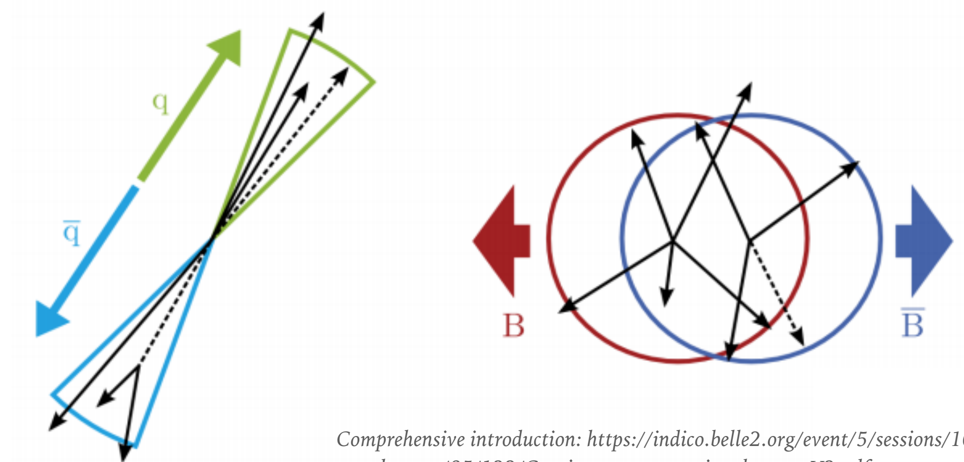

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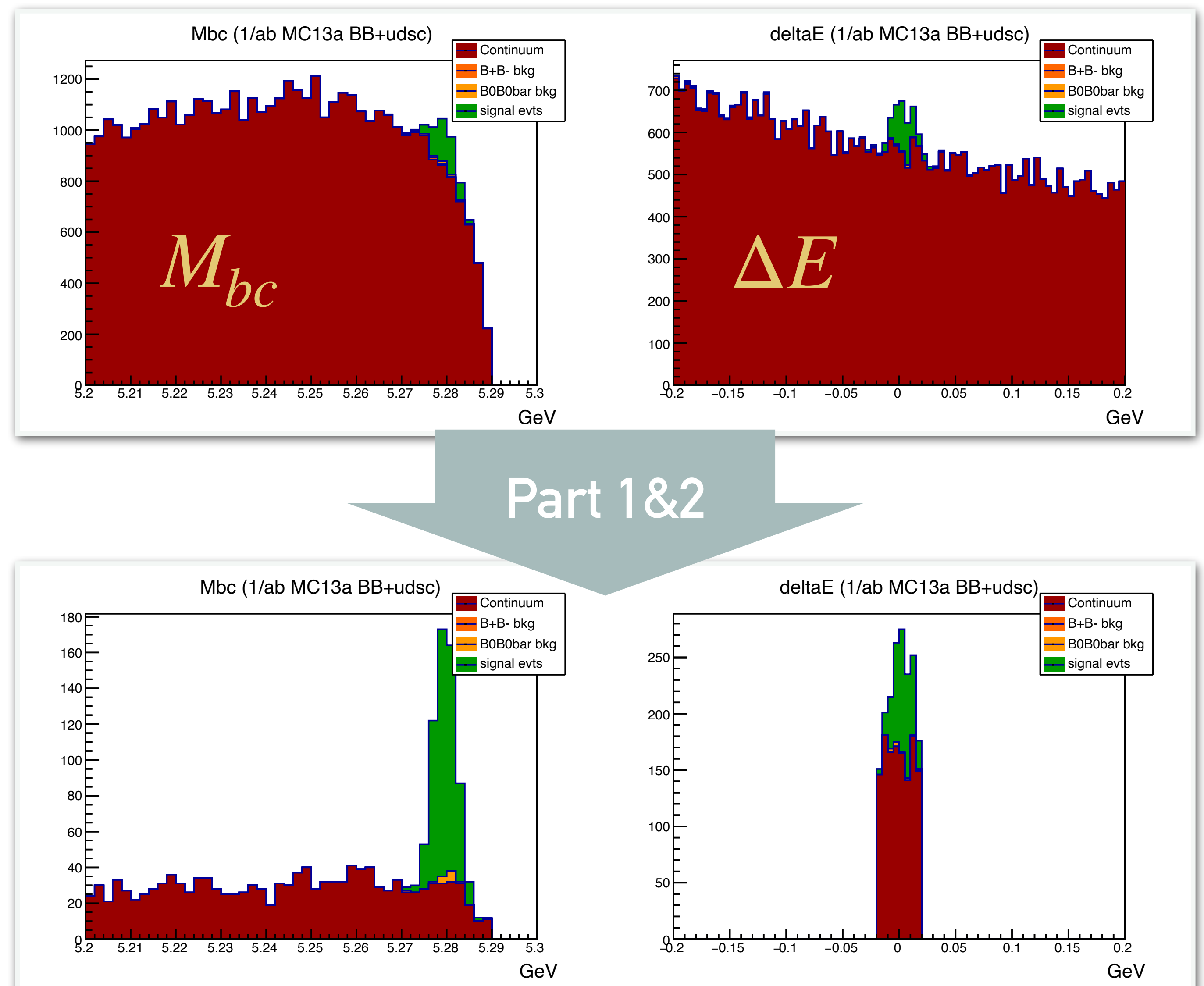
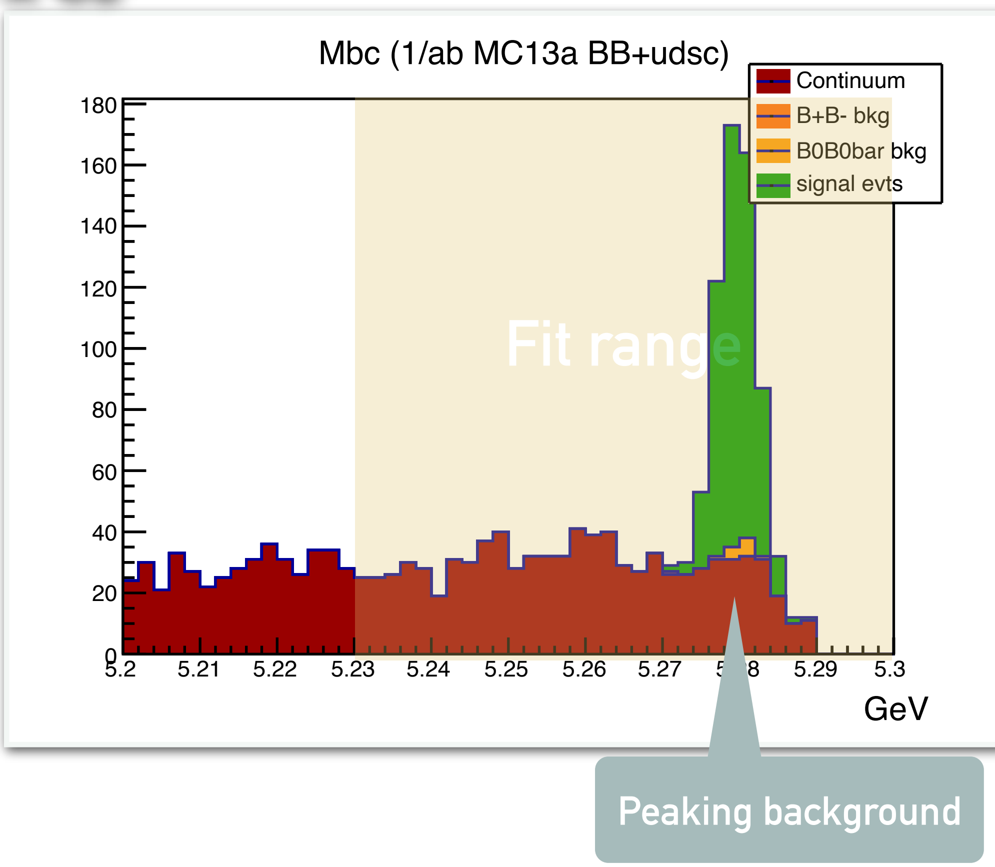
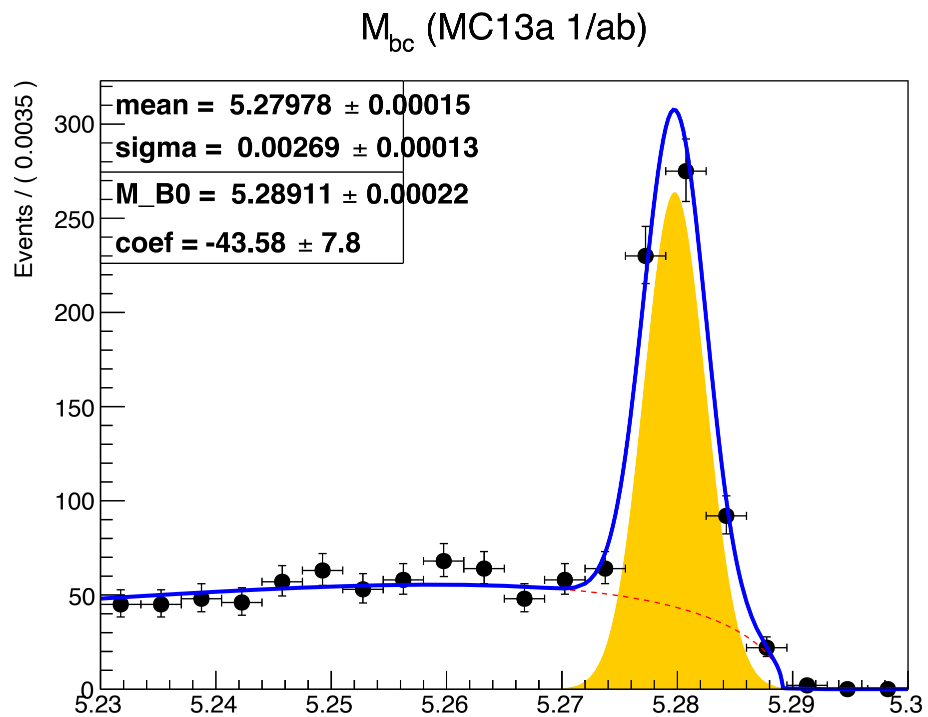


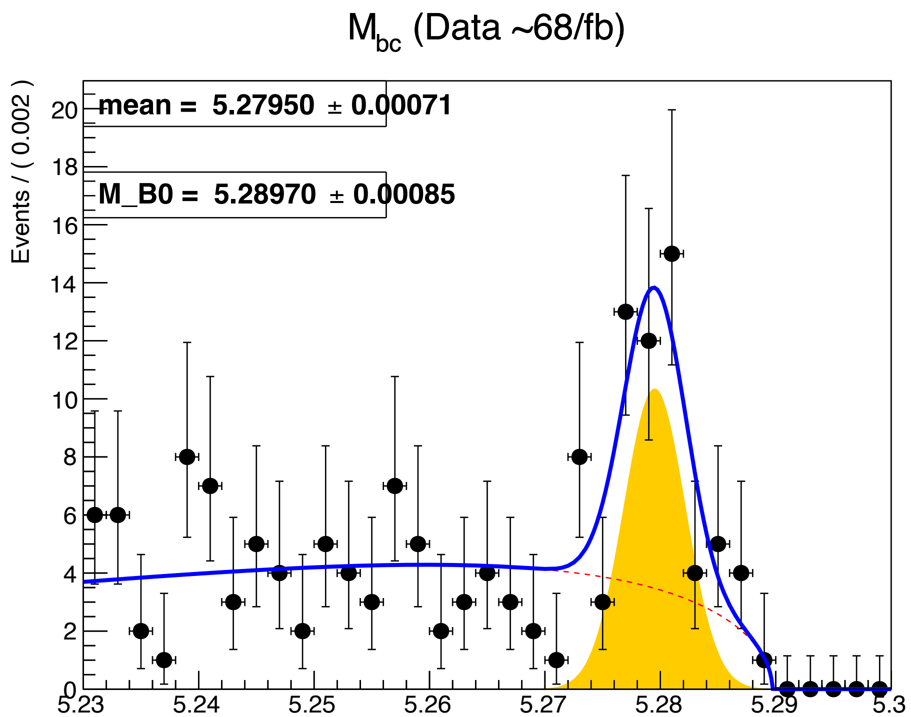
Fitting yield

- Eventually will move to multi-variable fit
- This fit: M_{bc} only
  - Fix signal resolution to MC
  - Fix Argus shape to MC





~1/14

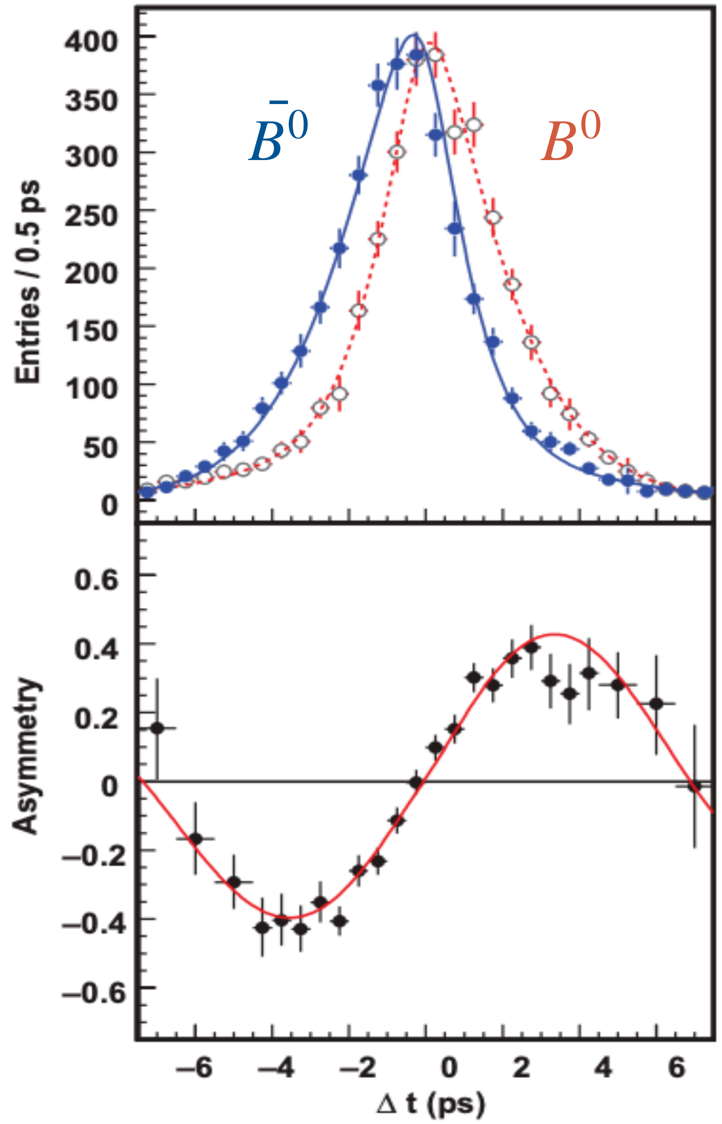



```
RooRealVar::nsig = 509.478 +/- 28.9847  L(0 - 300000)
35bins
```

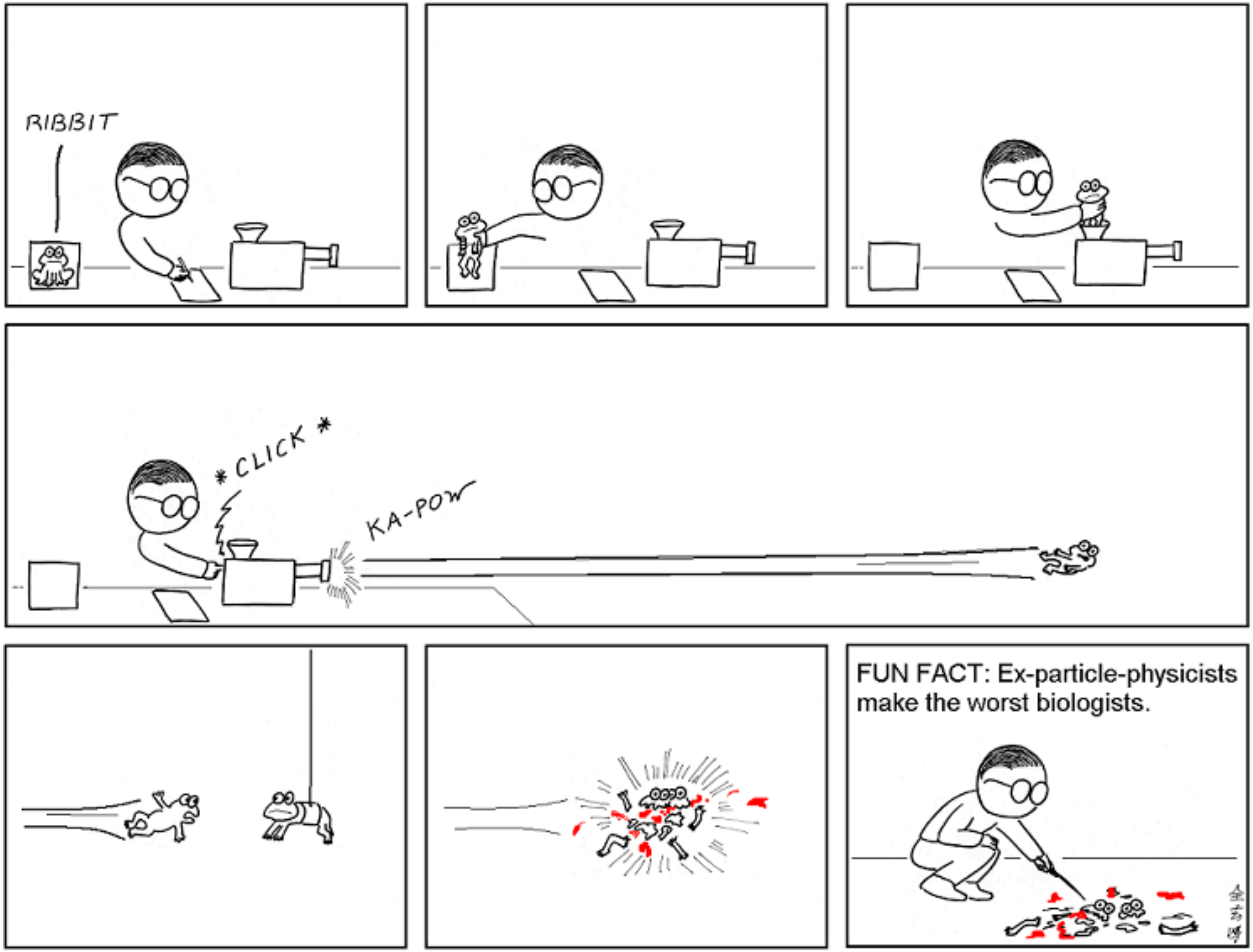
```
RooRealVar::nsig = 34.9189 +/- 7.6694  L(0 - 300000)
20bins
```

Future steps

- Address peaking background
- Fit to multiple variables
  - M_{bc}, ΔE, BDT response, Δt…
- Measurement of ϕ_1



Thank you for your attention!



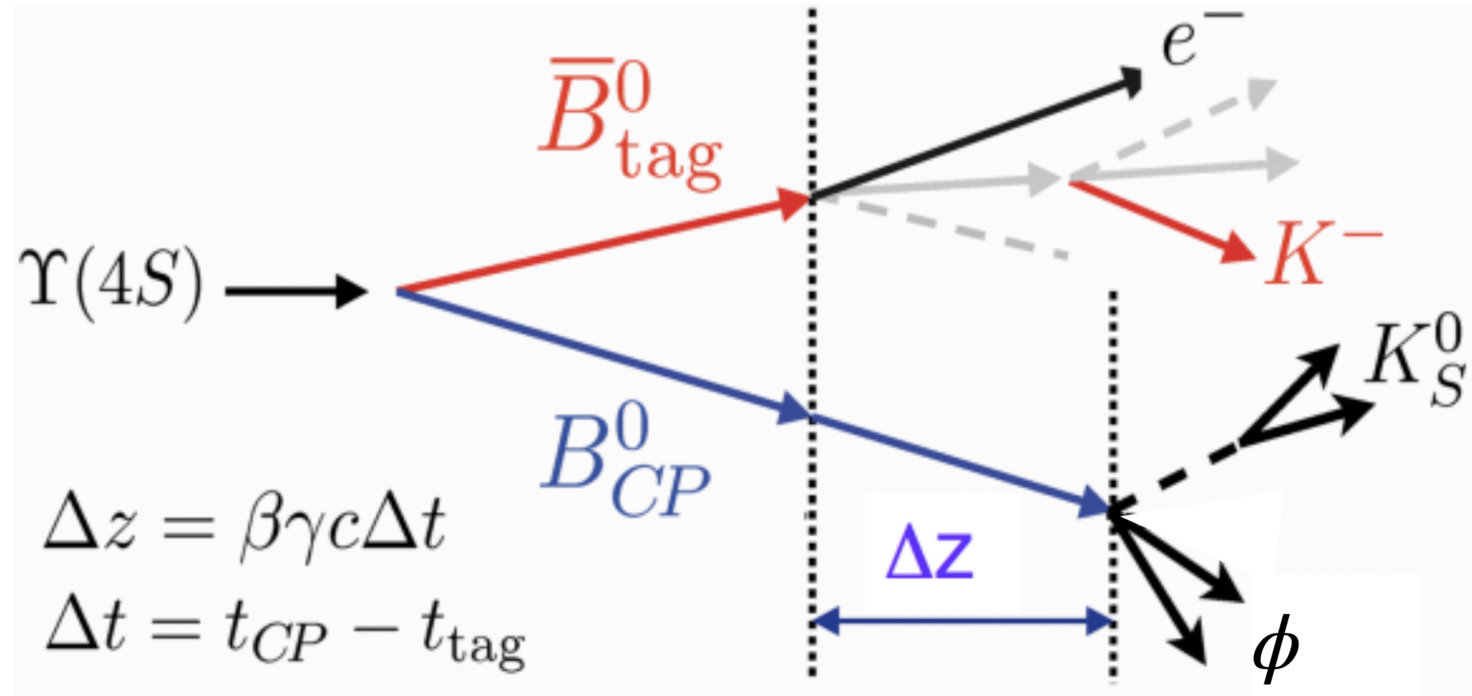
Backup slides to follow…

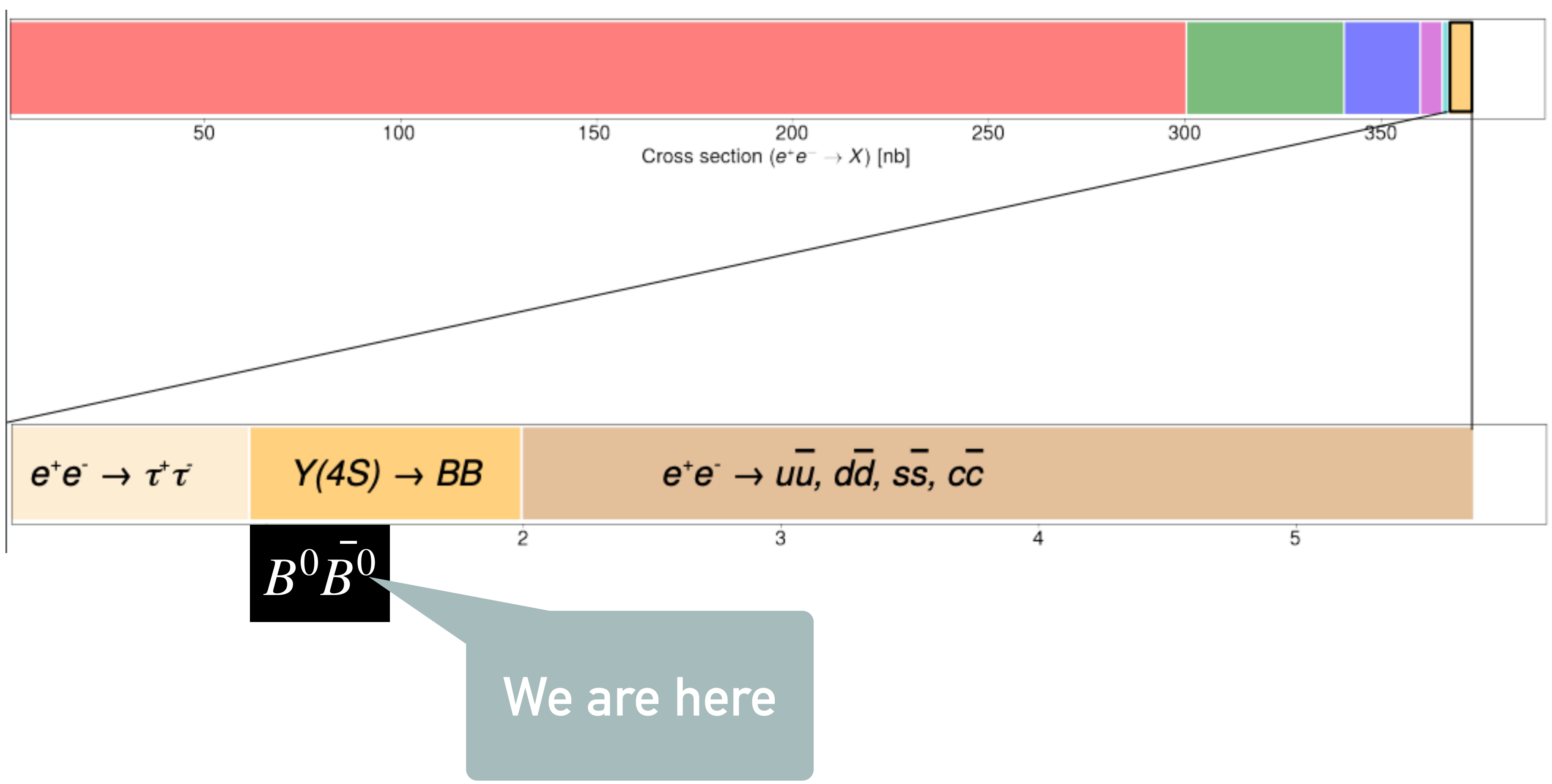
Outline of this talk

- Principle of measurement
  - Review of CKM matrix and CP violation
  - Measurement of ϕ_1 in Unitary Triangle
- Reconstructions and selections
  - Daughter particles ϕ and K_S^0
  - $B^0 \to \phi K_S^0$ candidates
- BDT training and variable validation
  - Widen ΔE for larger training sample
  - Sideband validation between MC and data
- Future plans

The making of $B^0 \to \phi K^0_S$

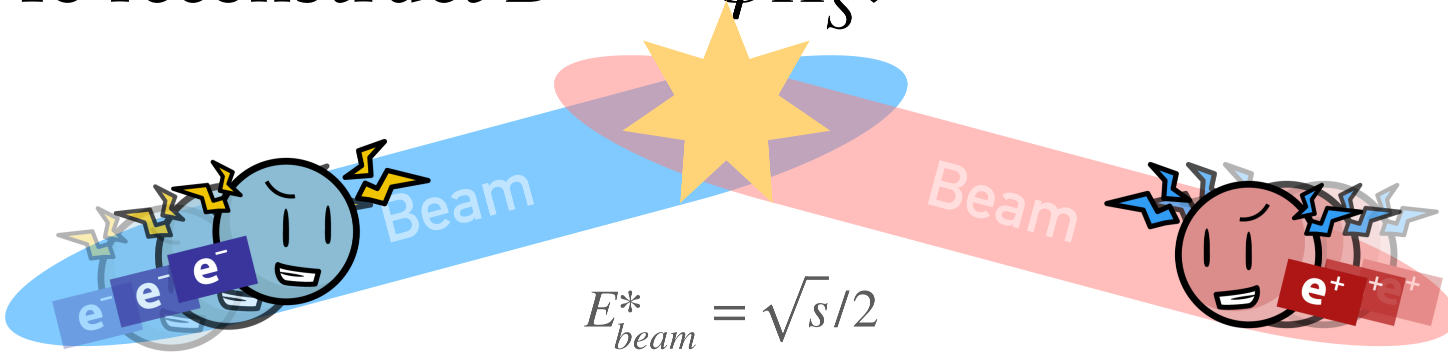
- $e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0$
  - Asymmetric energy:
  - Moves in the lab frame
  - One side decays first
  - (Example shows tag side first)

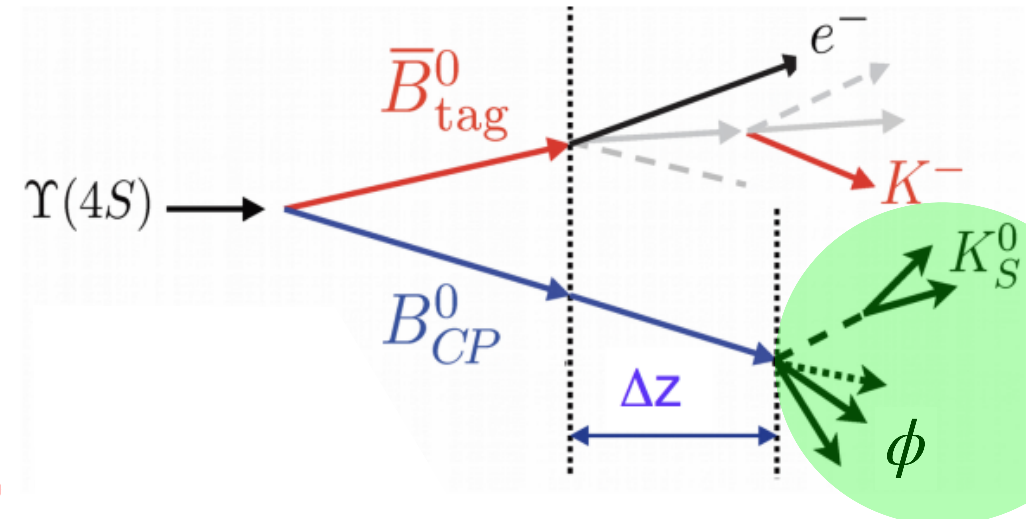




B0 candidate reconstruction

- To reconstruct $B^0 \to \phi K_S^0$:





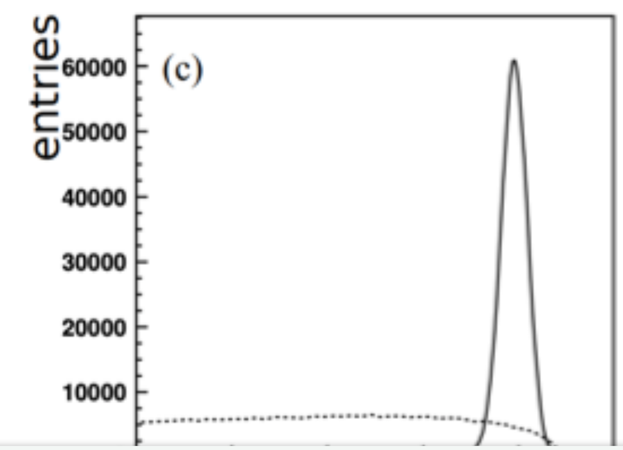
e+e- cartoon: HiggsTan

- In B-factories: e^+e^- beam 4-momentum very well-measured
- Variables to reconstruct:
  - Beam-energy constrained mass

$$M_{bc} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$$

  - Energy difference

$$\Delta E = E^*_B - E^*_{beam}$$




```
// Mbc and deltaE

    double particleMbc(const Particle* part)
    {
      PCmsLabTransform T;
      TLorentzVector vec = T.rotateLabToCms() * part->get4Vector();
      double E = T.getCMSEnergy() / 2;
      double m2 = E * E - vec.Vect().Mag2();
      double mbc = m2 >= 0 ? sqrt(m2) : std::numeric_limits<double>::quiet_NaN();
      return mbc;
    }

    double particleDeltaE(const Particle* part)
    {
      PCmsLabTransform T;
      TLorentzVector vec = T.rotateLabToCms() * part->get4Vector();
      return vec.E() - T.getCMSEnergy() / 2;
    }
```

Physics of B factories

Phi and Kshort cuts on SigMC

- ϕ: where $\mu \pm 3\sigma$ window = (1.004,1.034)GeV

Require p≥1.8	Rel eff (acc)	Abs eff (acc)
numMatched	$\frac{N_{this\ and\ all\ cuts\ above}}{N_{all\ cuts\ above}}$	$\frac{N_{this\ and\ all\ cuts\ above}}{N_{all\ generated}}$
pre-vtx	85.9%	85.9%
Other ana cuts	74.8%	64.2%
3sigma window	90.5%	58.1%

- K_S^0: where $\mu \pm 3\sigma$ window = (0.483,0.513)GeV

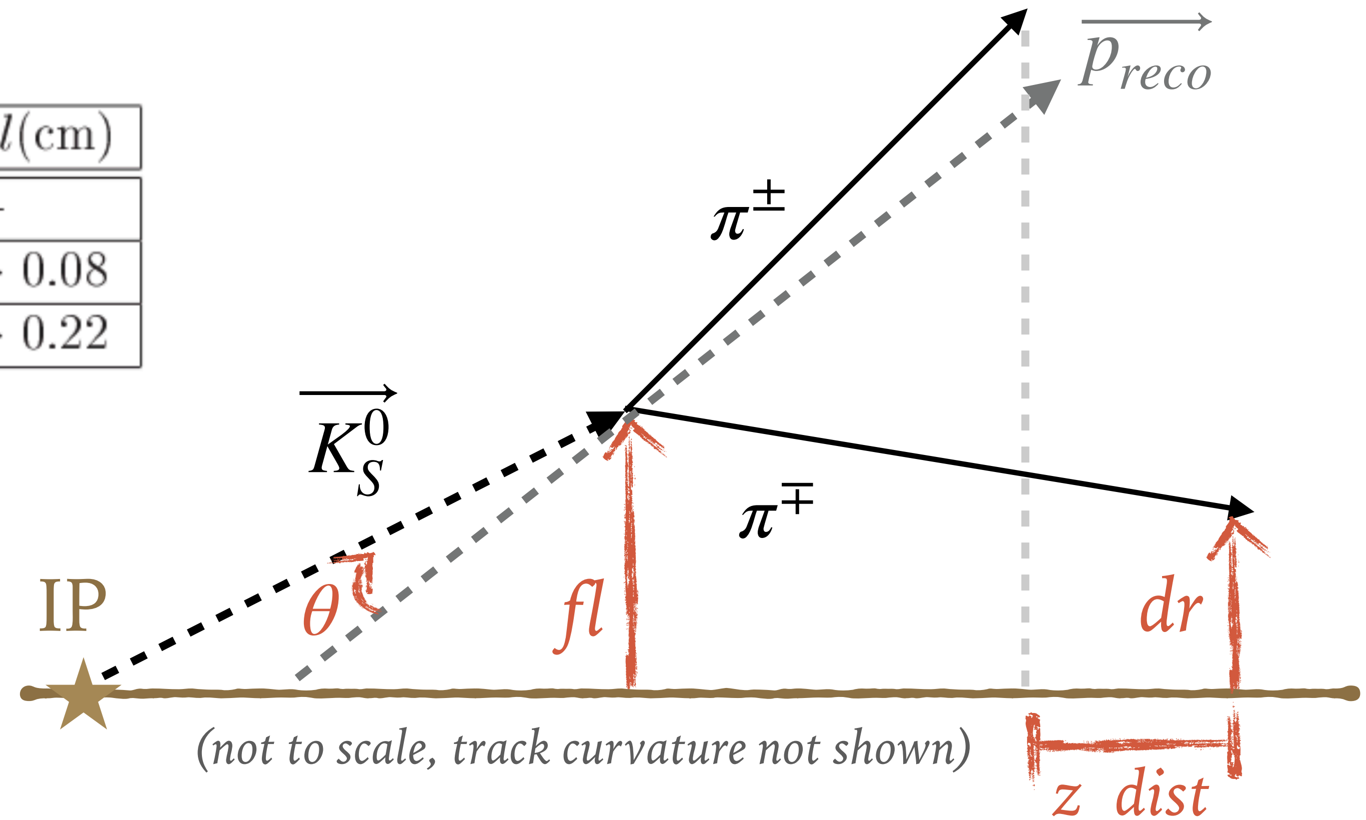
Require p≥1.8	Rel eff (acc)	Abs eff (acc)
numMatched	$\frac{N_{this\ and\ all\ cuts\ above}}{N_{all\ cuts\ above}}$	$\frac{N_{this\ and\ all\ cuts\ above}}{N_{all\ generated}}$
pre-vtx	75.6%	75.6%
Other ana cuts	89.6%	67.8%
3sigma window	98.3%	66.6%

- Signal MC events with B0 candidates

	Rel eff (acc)	Abs eff (acc)	Abs eff (ind)
numEvts with candidates	$\frac{N_{this\ and\ all\ cuts\ above}}{N_{all\ cuts\ above}}$	$\frac{N_{this\ and\ all\ cuts\ above}}{N_{all\ generated}}$	$\frac{N_{this\ cut\ alone}}{N_{all\ generated}}$
phi_ana_cuts	67.4%	67.4%	67.4%
phi_3sigma	88.0%	59.3%	90.4%
Ks_ana_cuts	78.7%	46.7%	74.0%
Ks_3sigma	97.1%	45.3%	87.7%

goodBelleKshorts

Momentum(Gev)	dr(cm)	$d\phi$(rad.)	z_dist(cm)	fl(cm)
< 0.5	> 0.05	< 0.3	< 0.8	$-$
$0.5 - 1.5$	> 0.03	< 0.1	< 1.8	> 0.08
> 1.5	> 0.02	< 0.03	< 2.4	> 0.22




```
double p = particleP(KS);
double fl = particleDRho(KS);
double dphi = acos(((particleDX(KS) * particlePx(KS)) + (particleDY(KS) * particlePy(KS))) / (fl * sqrt(particlePx(KS) * particlePx(
                    KS) + particlePy(KS) * particlePy(KS))));
double dr = std::min(abs(trackD0(d0)), abs(trackD0(d1)));
double zdist = v0DaughterZ0Diff(KS);

bool low = p < 0.5 && abs(zdist) < 0.8 && dr > 0.05 && dphi < 0.3;
bool mid = p < 1.5 && p > 0.5 && abs(zdist) < 1.8 && dr > 0.03 && dphi < 0.1 && fl > .08;
bool high = p > 1.5 && abs(zdist) < 2.4 && dr > 0.02 && dphi < 0.03 && fl > .22;
```

https://stash.desy.de/projects/B2/repos/software/browse/analysis/variables/src/BelleVariables.cc?at=refs%2Ftags%2Frelease-04-02-07#44

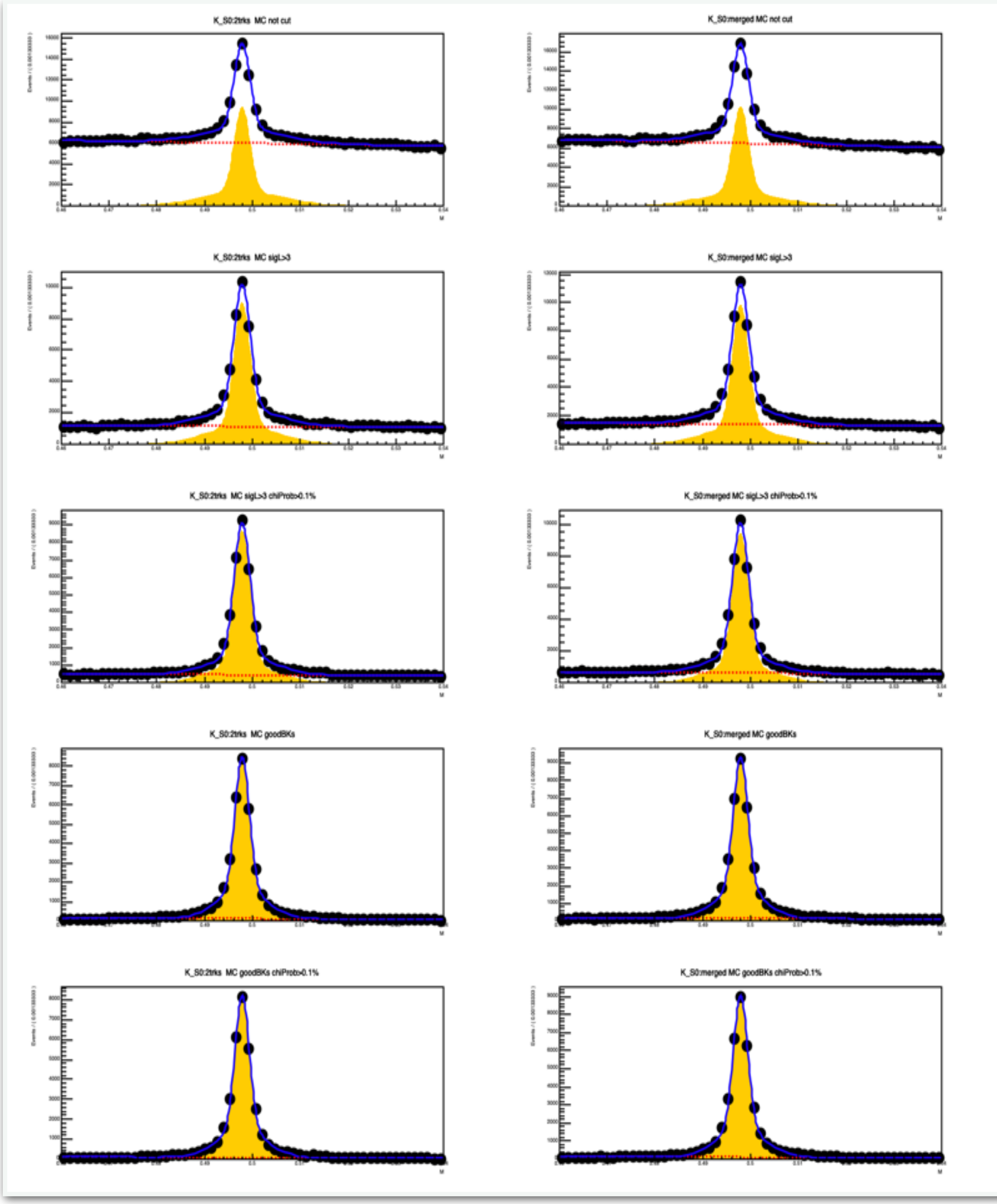
Decay vertex vector (particleDX, particleDY, particleDZ) defined in:
https://stash.desy.de/projects/B2/repos/software/browse/analysis/variables/include/VertexVariables.h#117

Momentum vector (particlePX, particlePY, particlePZ) defined in:
https://stash.desy.de/projects/B2/repos/software/browse/analysis/variables/src/Variables.cc#76

Performance in $\pm 3\sigma$ region

Significance = S/sqrt(S+B) Purity = S/(S+B)	KS:2trk	KS:merged
No cut	123 0.44	128 0.44
SigLxy > 3	162 0.80	167 0.78
SigLxy>3 confL>0.1%	167 0.90	173 0.89
goodBelleKs	168 0.97	(Default) 175 0.97
goodBelleKs confL>0.1%	164 0.98	172 0.97

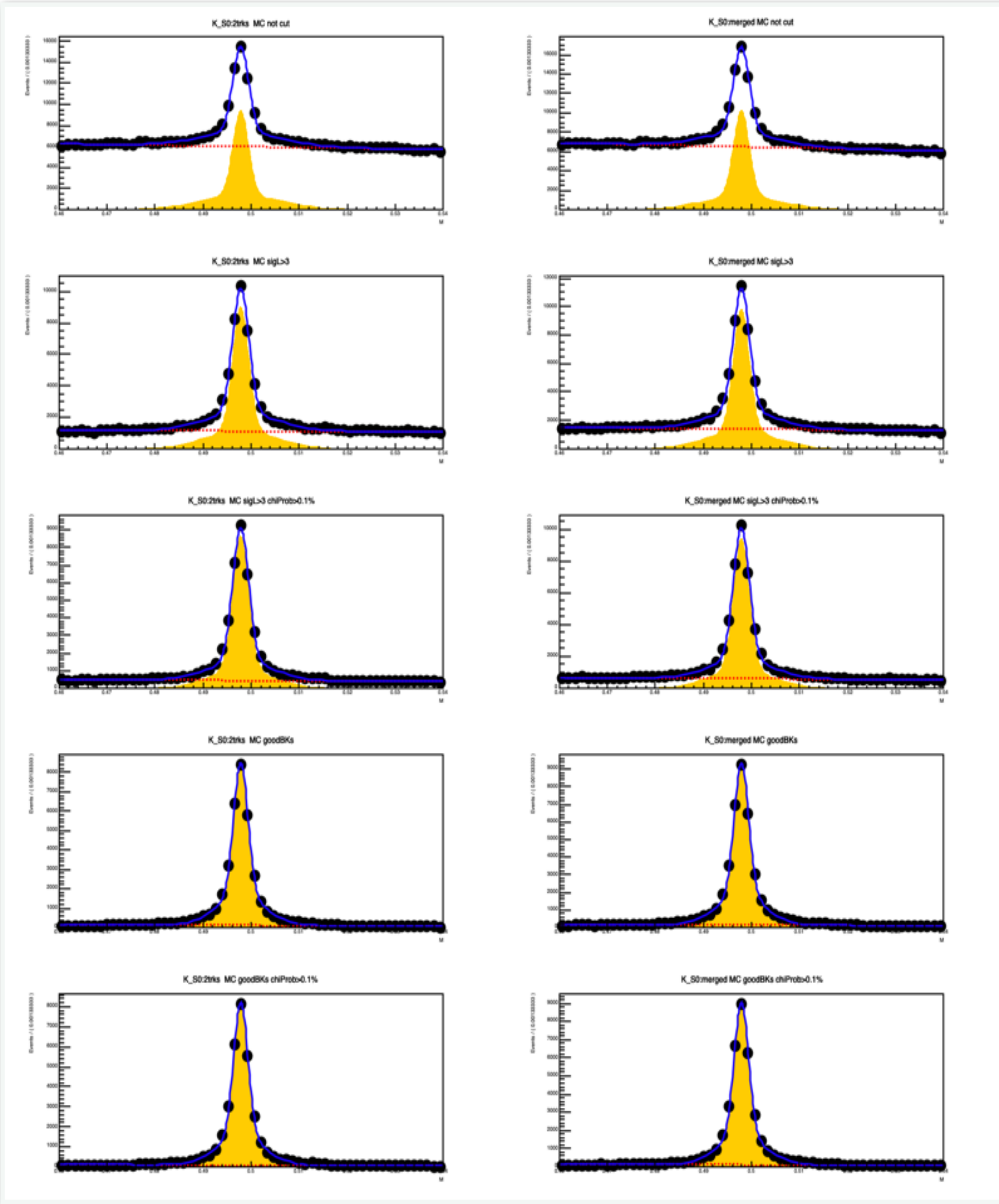
- Combo 200k MC13a unskimmed mDST
  - Estimated integrated luminosity 42 pb^{-1}
  - “mixed”, “charged”, “uubar”, “ddbar”, “ssbar”, “ccbar”



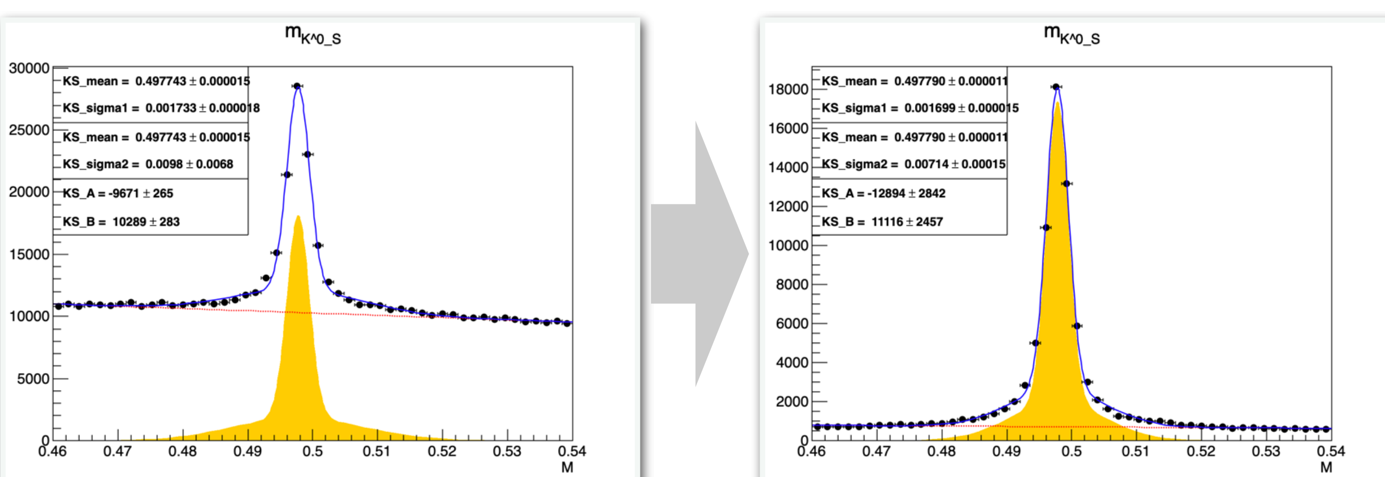
Performance in $\pm 3\sigma$ region

- ➤ Combo 200k MC13a unskimmed mDST
  - ➤ Estimated integrated luminosity 42 pb^{-1}
  - ➤ "mixed", "charged", "uubar", "ddbar", "ssbar", "ccbar"

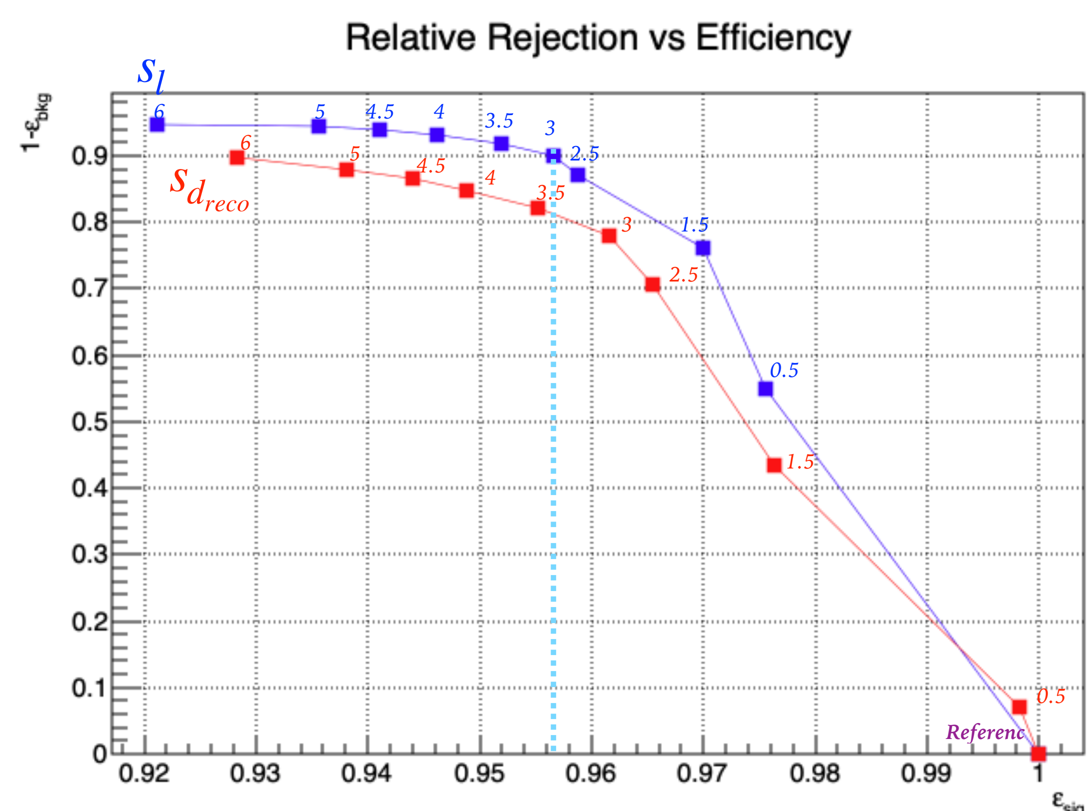
Total signal (fitted) Total Background (fitted)	KS:2trk	KS:merged
No cut	34,241 (92.4%) 43,214 (92.4%)	37,049 (ref) 46,762 (ref)
SigLxy > 3	32,738 (88.4%) 8,195 (17.5%)	35,774 (96.5%) 10,082 (21.6%)
SigLxy>3 confL>0.1%	30,755 (83.0%) 3,197 (6.8%)	33,712 (91.0%) 4,341 (9.3%)
goodBelleKs	28,849 (77.9%) 809 (1.7%)	(Default) 31,763 (85.7%) 1,044 (2.2%)
goodBelleKs confL>0.1%	27,607 (74.5%) 633 (1.4%)	30,426 (82.1%) 836 (1.8%)



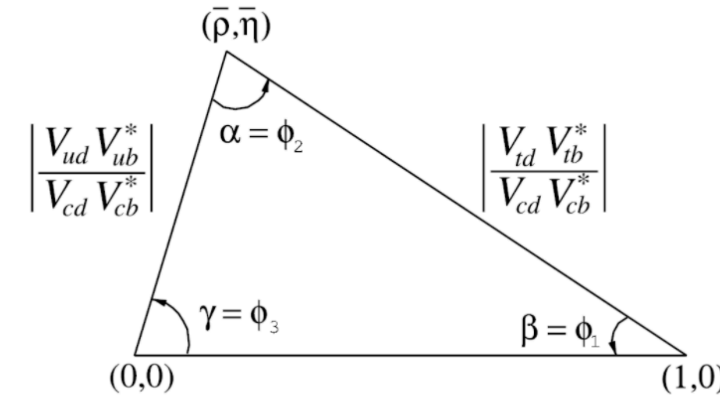
Total signal (fitted) Total Background (fitted)	KS:2trk	KS:merged	Significance = S/sqrt(S+B) Purity = S/(S+B)	KS:2trk	KS:merged
No cut	34,241 (92.4%)	37,049 (ref)		123	128
	43,214 (92.4%)	46,762 (ref)		0.44	0.44
SigLxy > 3	32,738 (88.4%)	35,774 (96.5%)		162	167
	8,195 (17.5%)	10,082 (21.6%)		0.80	0.78
SigLxy>3 confL>0.1%	30,755 (83.0%)	33,712 (91.0%)		167	173
	3,197 (6.8%)	4,341 (9.3%)		0.90	0.89
goodBelleKs	28,849 (77.9%)	31,763 (85.7%)		168	175
	809 (1.7%)	1,044 (2.2%)		0.97	0.97
goodBelleKs confL>0.1%	27,607 (74.5%)	30,426 (82.1%)		164	172
	633 (1.4%)	836 (1.8%)		0.98	0.97



Example shows SigLxy> 3 and confL>0.1%

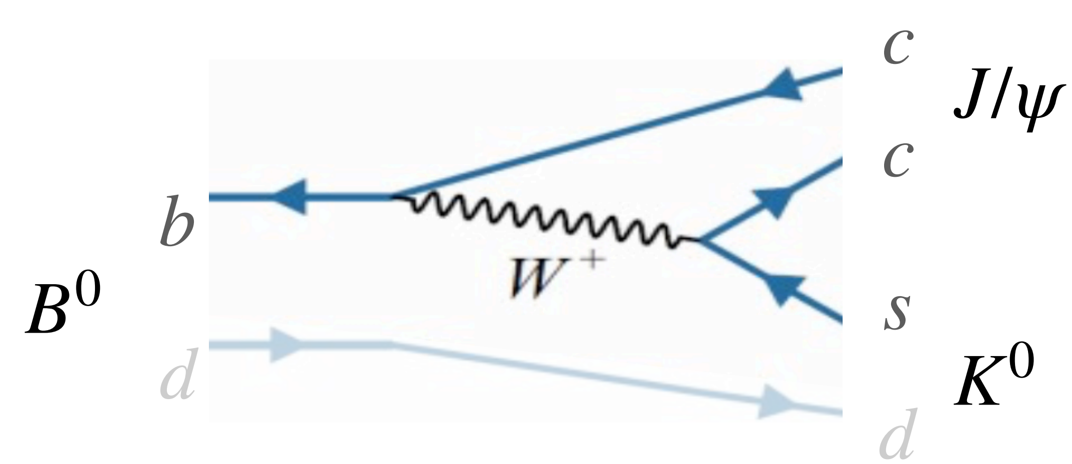


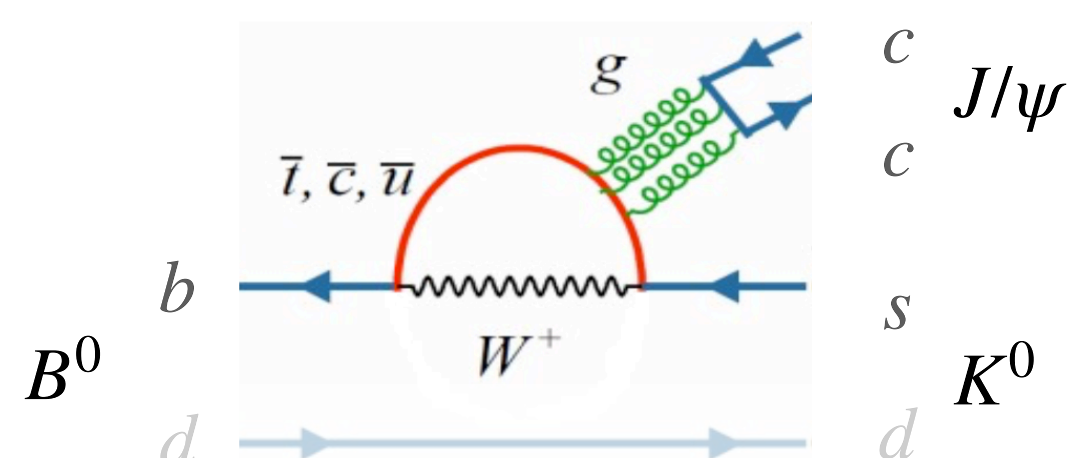
Golden mode for ϕ_1



- ϕ_1 most precisely by $B^0 \to J/\psi K^0$ via $b \to c\bar{c}s$
- Interference between mixing and decay: $A_{CP} = \dfrac{\Gamma_B(t) - \Gamma_{\bar{B}}(t)}{\Gamma_B(t) + \Gamma_{\bar{B}}(t)}$
  - Tree level:
    - $A = 0;\ S = -\sin 2\phi_1$ in absence of loop
    - Free from New Physics
  - Penguin loop:
    - Suppressed in Standard Model
    - Can be modified by New Physics models
    - Contains "Penguin pollution"

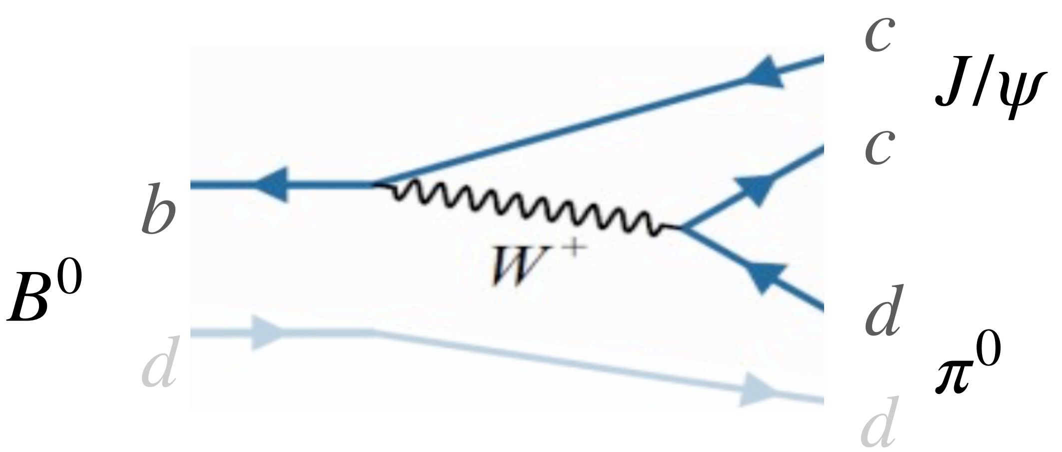
$$S_{J/\psi K^0_S} \equiv \sin\phi_d + \Delta S_{J/\psi K^0_S} \equiv \sin(\phi_d + \delta\phi_{J/\psi K^0_S})$$

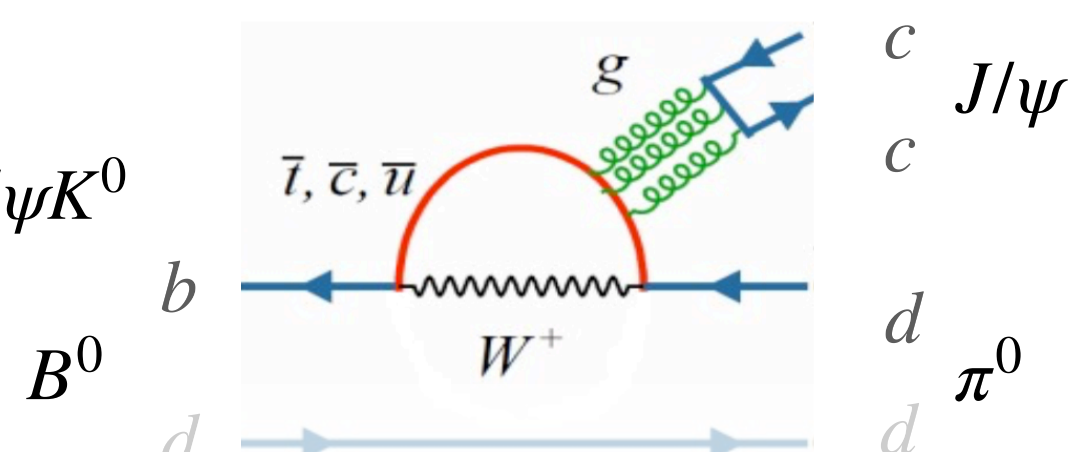




The channel $B \to J/\psi\pi^0$

- ϕ_1 most precisely by $B^0 \to J/\psi K^0$ via $b \to c\bar{c}s$
- $B \to J/\psi\pi^0$ proceeds via $b \to c\bar{c}d$: Cabbibo suppressed
  - Tree level: also color suppressed
    - $A = 0;\ S = -\sin 2\phi_1$ in absence of loop
    - Same weak phase as $b \to c\bar{c}s$
  - Penguin loop:
    - (Highly) suppressed in Standard Model
    - Can be modified by New Physics models
    - Shift values of A and S
    - Constrain "penguin pollution" for $B^0 \to J/\psi K^0$





Variables used in BDTG

foxWolframR1 foxWolframR2 foxWolframR3 foxWolframR4

harmonicMomentThrust1 harmonicMomentThrust2 harmonicMomentThrust3 harmonicMomentThrust4

cleoConeThrust0 cleoConeThrust1 cleoConeThrust2 cleoConeThrust3 cleoConeThrust4 cleoConeThrust5 cleoConeThrust6 cleoConeThrust7 cleoConeThrust8

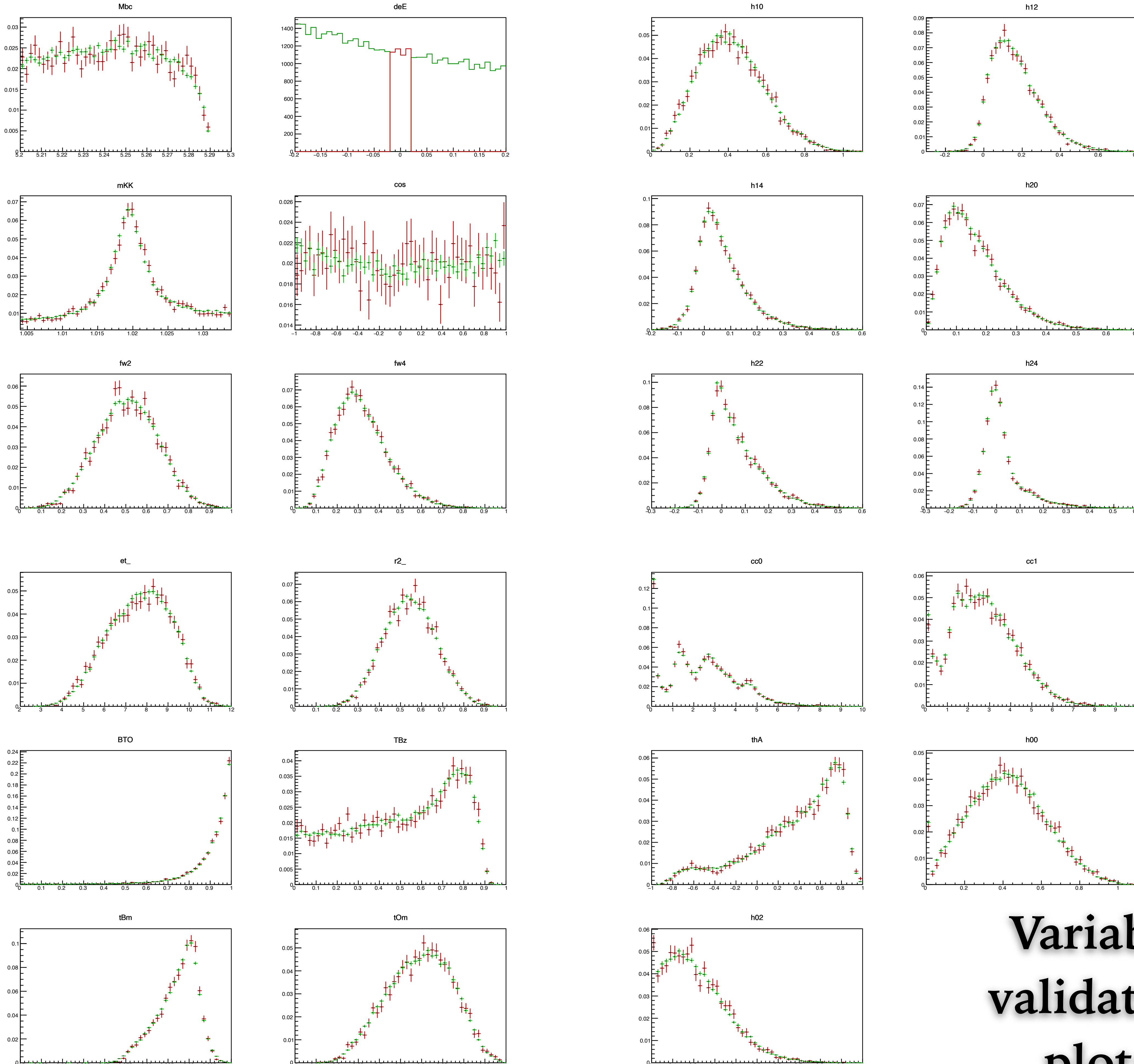
thrustAxisCosTheta

KSFWVariables(hso00) KSFWVariables(hso02) KSFWVariables(hso04) KSFWVariables(hso10) KSFWVariables(hso12) KSFWVariables(hso14) KSFWVariables(hso20) KSFWVariables(hso22) KSFWVariables(hso24)

KSFWVariables(hoo1) KSFWVariables(hoo2) KSFWVariables(hoo3) KSFWVariables(hoo4) KSFWVariables(et) KSFWVariables(mm2)

M(phi) cosineHelicityAngle(phi) [To suppress non-resonant K+K-K0]

No significant improvement by including some other variables



Variable validation plots