Improved study of $\overline{B} \to D^{(*)}\tau\bar{\nu}$ with vertexing at Belle II

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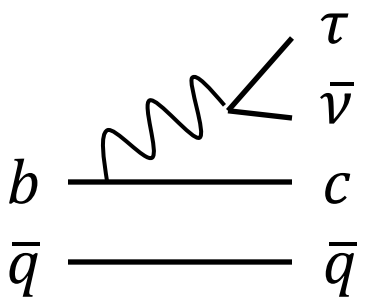
$\bar{B} \to D^{(*)}\tau\bar{\nu}$ introduction

- Largest cross section for τ production in B decays
- Sensitive to new physics that couples more strongly to heavy fermions (e.g., charged Higgs)
- Important physics at LHCb and Belle II



- In addition, $R(D^{(*)}) \equiv \frac{Br(B\to D^{(*)}\tau\nu)}{Br(B\to D^{(*)}\ell\nu)}$ are currently 3.8σ from SM prediction

- An important background is $\bar{B} \to D^{**}\ell\bar{\nu}$

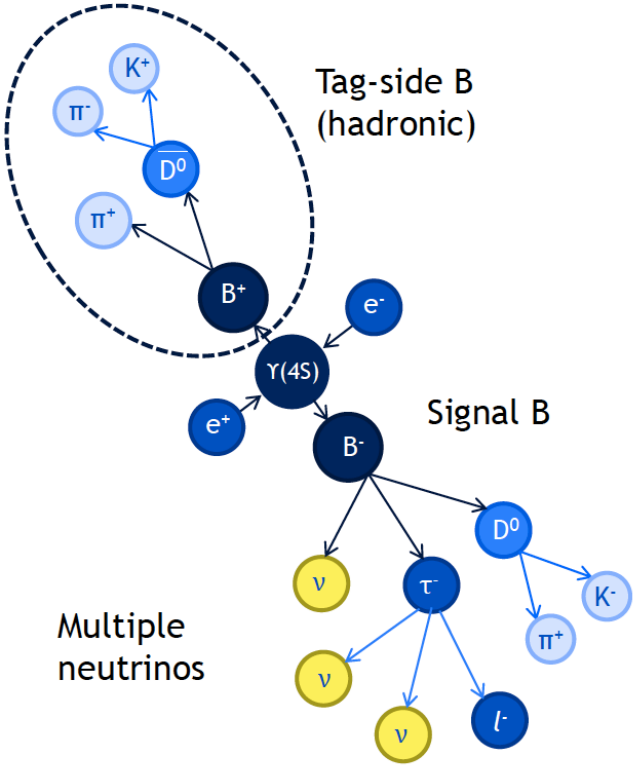
$$D^{**} \to D^{(*)} + \text{pions}$$

Excited charm state

Unobserved

- Most of this talk focuses on addressing the $\bar{B} \to D^{**}\ell\bar{\nu}$ background at Belle II using precise vertexing.

Hadronic recoil-B reconstruction in $e^+e^- \to \bar{B}B$ events



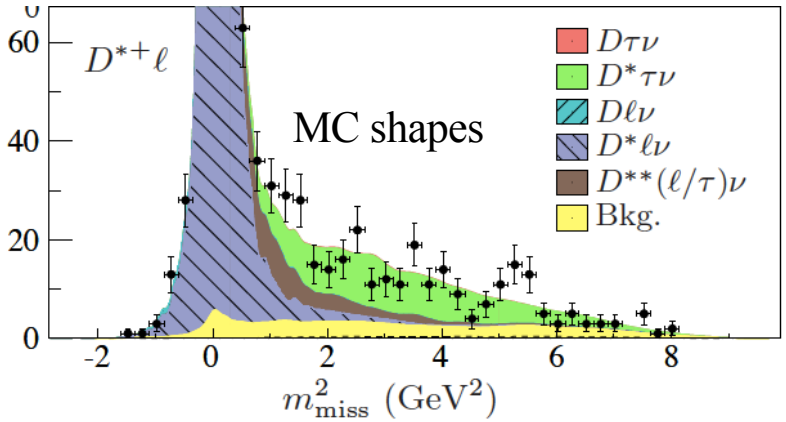
- Reconstructing the event in full is very useful in missing energy studies to constrain the event and reduce backgrounds
- Multiple channels for tag-side B are used to increase efficiency
- Hadronic full reconstruction expected to be used for:
  - Semi-leptonic and semi-tauonic modes for $R(D^{(*)})$
  - $B \to \tau\nu$ decays
- These studies will use Belle II's new algorithm

$$m^2_{miss} = \left(p_{ee} - p_{tag} - p_D - p_\ell\right)^2$$

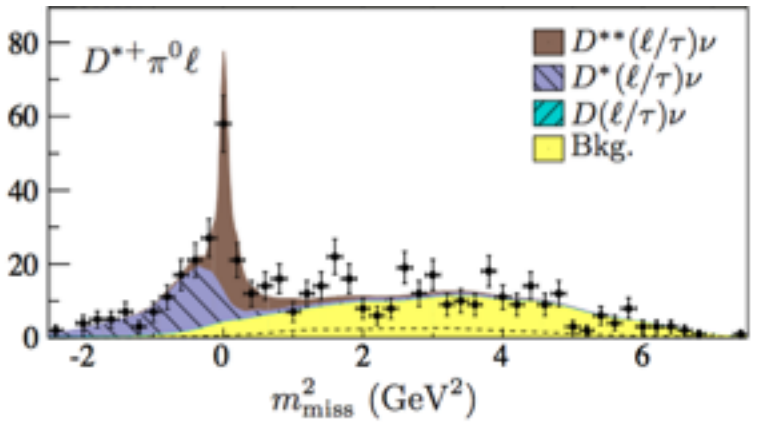
is the main signal-background discriminator

m^2_{miss} and $\bar{B} \to D^{**}\ell\bar{\nu}$ background

E.g.,1 mode in BABAR analysis[1]:



Simultaneous fit to $\bar{B} \to D^{**}\ell\bar{\nu} + \pi^0$ candidate:



→ D** systematic (%)	$R(D)$	$R(D^*)$
• Relative efficiencies	5.0	2.0
• $Br\left(D^{**} \to D^{(*)}\pi^0/\pi^{\pm}\right)$	0.7	0.5
• $Br\left(D^{**} \to D^{(*)}\pi\pi\right)$	2.1	2.6
• $Br(\bar{B} \to D^{**}\ell\bar{\nu})$	0.8	0.3
• $Br(\bar{B} \to D^{**}\tau\bar{\nu})$	1.8	1.7

- $\sim 1.3 - 3.3\%$ error in Belle [2] & LHCb [3] analyses with $\tau \to \ell\nu\bar{\nu}$

- At Belle II, 2% will already be a large error with 5 ab^{-1}

[1] arXiv:1205.5442, arXiv:1303.0571
[2] arXiv:1507.03233 , arXiv:1607.07923
[3] arXiv:1506.08614

What we know about D^{**} states

State	~Width (MeV)	J^P	Seen/allowed decays
$D_0^*(2400)$	270	0^+	$D\pi, D\eta$
$D_1(2420)$	27	1^+	$D^*\pi, D\pi\pi, D^*\pi\pi$
$D_1'(2430)$	380	1^+	$D^*\pi, D^*\eta, D^{(*)}\pi\pi$
$D_2^*(2460)$	50	2^+	$D^{(*)}\pi, D^{(*)}\pi\pi, D^{(*)}\eta$
$D(2550)$	130	0^-	$D^*\pi$
$D(2600)$	90	$?^?$	$D^{(*)}\pi$
$D^*(2640)$	< 15	$?^?$	$D^*\pi\pi$
$D(2750)$	65	$?^?$	$D^{(*)}\pi$

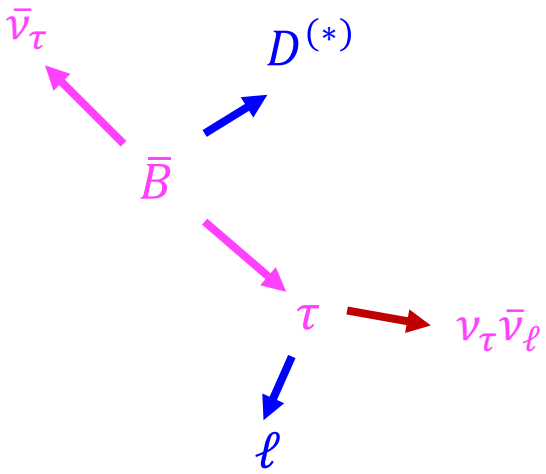
- Exclusive $\bar{B} \to D^{**}\ell\bar{\nu}$ decays observed only for the 4 lightest resonances
- Additional resonances?
- Nonresonant $\bar{B} \to D^{**}\ell\bar{\nu}$ decays
- Additional $D^{(*)}(n\pi)$decays?

Assumptions affect the m_{miss}^2 shape in the fit

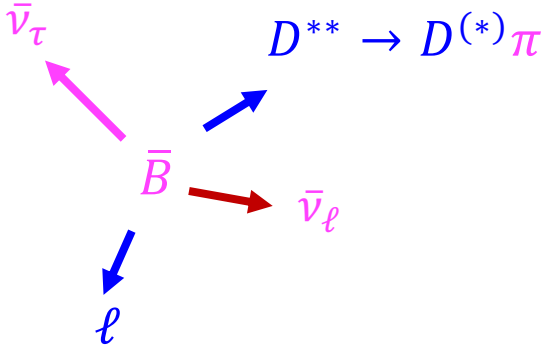
Need a model-independent handle on $\bar{B} \to D^{**}\ell\bar{\nu}$ background in $\bar{B} \to D^{(*)}\tau\bar{\nu}$

Distance between B vertex & lepton

Signal:

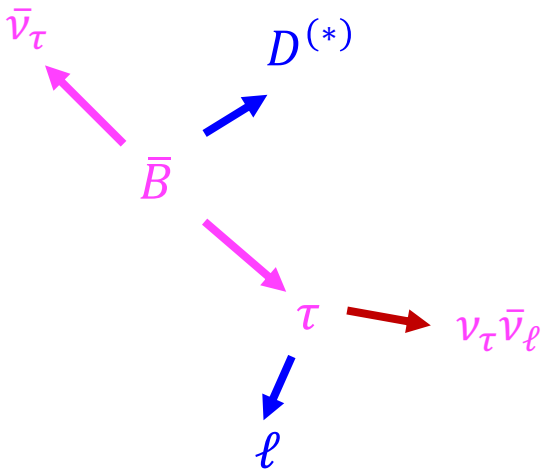


Background:

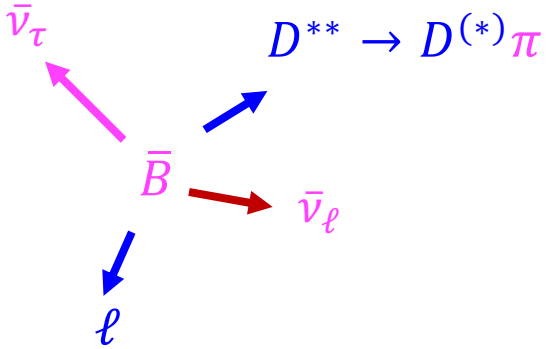


Distance between B vertex & lepton

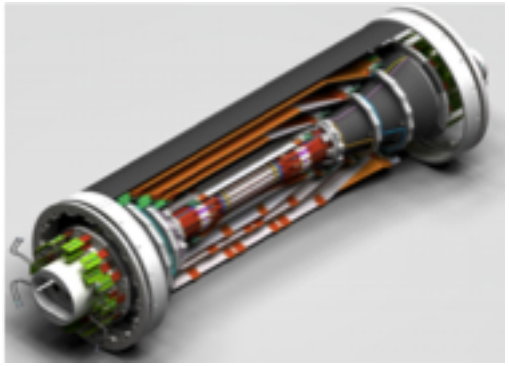
Signal:



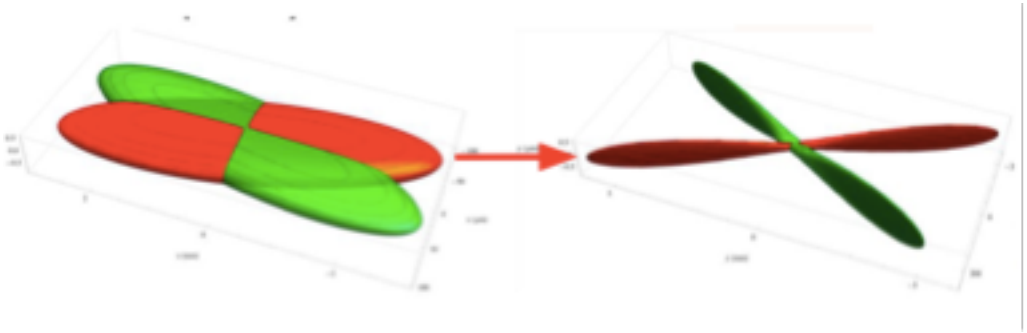
Background:



- Belle II spatial resolution is is twice as good as @ BABAR/Belle.
- Pixels @ $r = 14$mm:



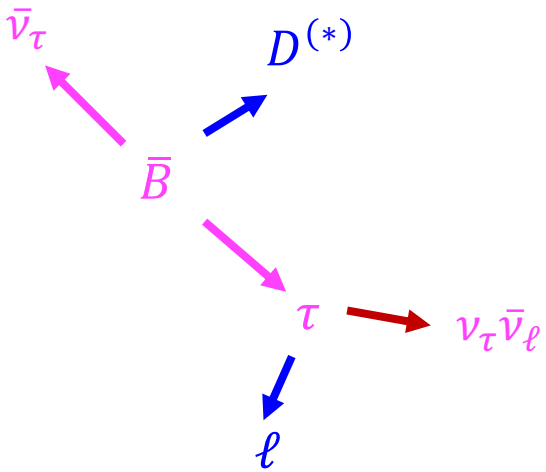
- Nanobeam collision scheme:



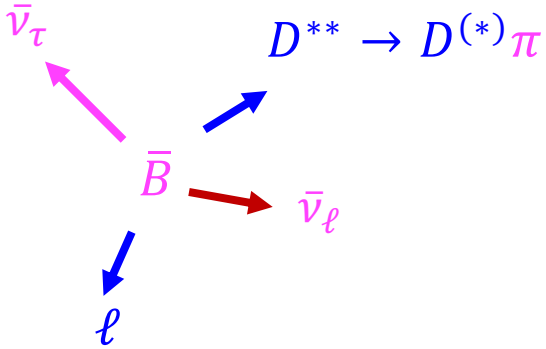
- Average τ flies only 45 μm, less than the Belle II spatial resolution,
- S-B separation weaker than for m^2_{miss} etc.
- But exploit model independence to check $\bar{B} \to D^{**}\ell\bar{\nu}$ yield in the analysis fit

Distance between B vertex & lepton

Signal:

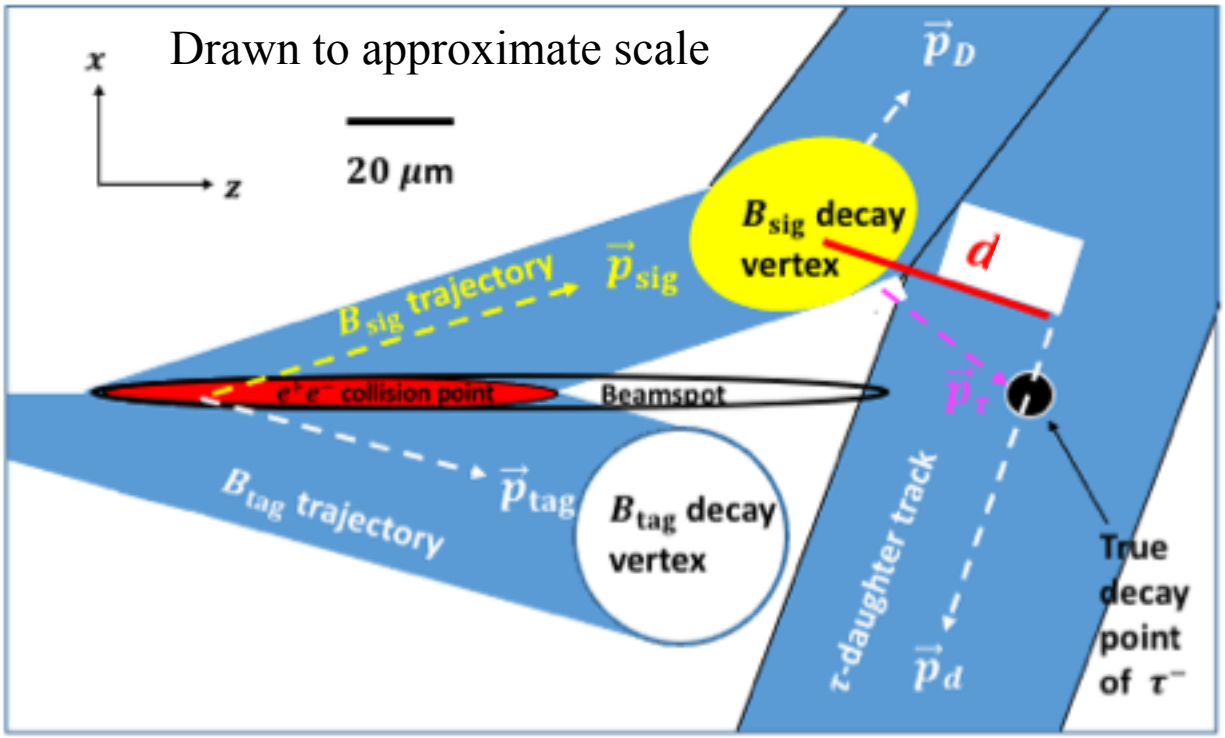


Background:



Exploit:

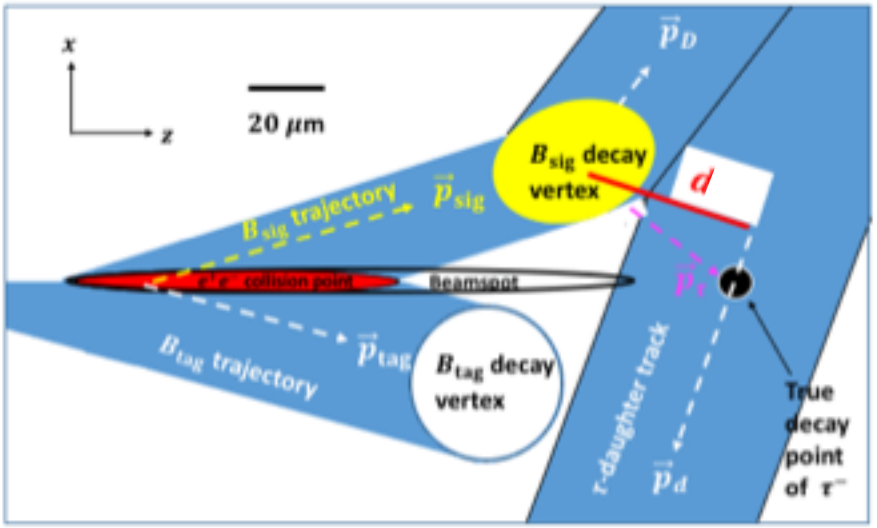
- Reconstruction of recoil B
- Very small beamspot
- Detector spatial resolution



Study with Belle II GEANT4 simulation

- Not a complete analysis
- Studies only the separation between signal and $\bar{B} \to D^{**}\ell\bar{\nu}$
- Study only $B^- \to D^0\tau^-\bar{\nu}$ (signal) & $B^- \to D^{**0}\ell^-\bar{\nu}$ (background)
  - $D^0\tau^-\bar{\nu}$: $\tau^- \to K^-\pi^+$
  - $D^{**0}\ell^-\bar{\nu}$: $D^{**0} \to D^0\pi^+$
- Assume correct tag-B and signal-B reconstruction
  - Misreconstruction background is already handled with other analysis variables
- Results reflect a current snapshot of the reconstruction & analysis software

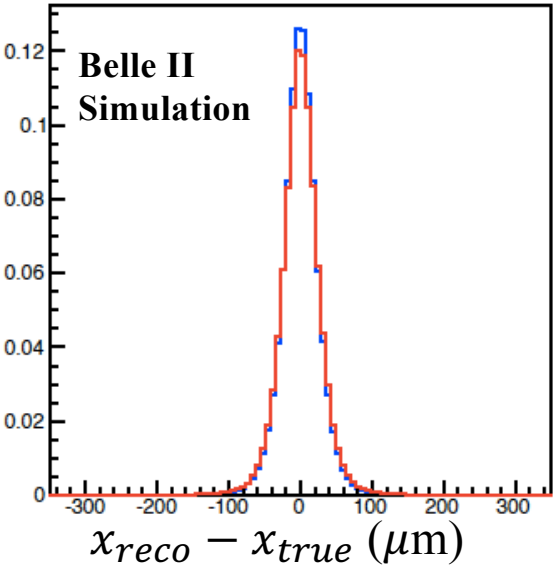
Signal-B position resolution



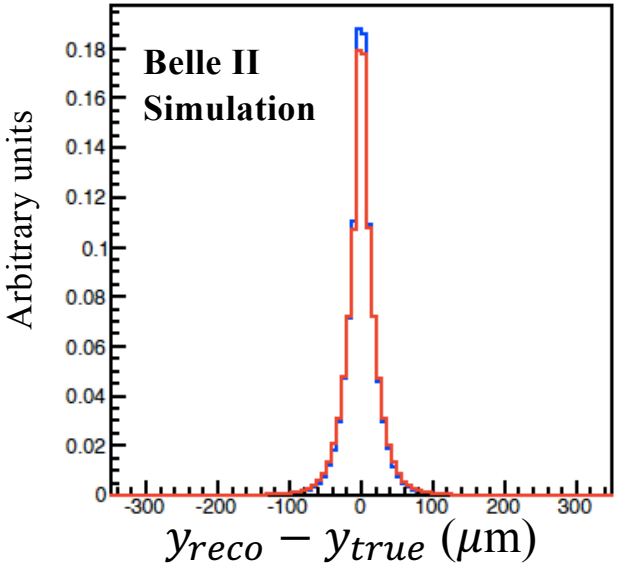
$D\tau\bar{\nu}$

$D^{**}\ell\bar{\nu}$

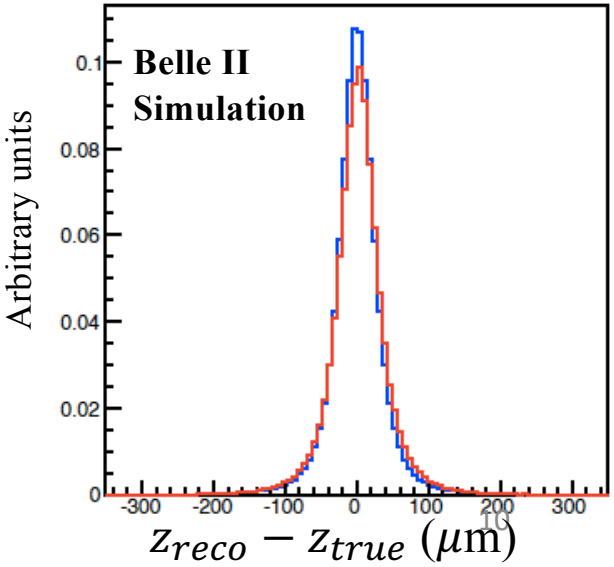
$\sigma_x = 27\ \mu\text{m}$



$\sigma_x = 24\ \mu\text{m}$

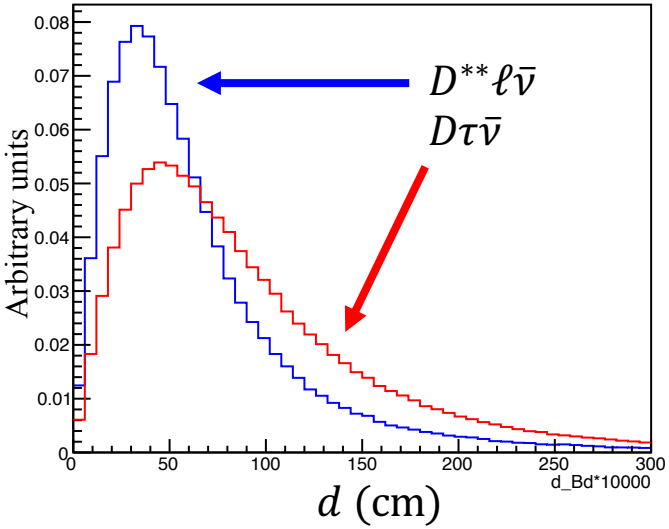


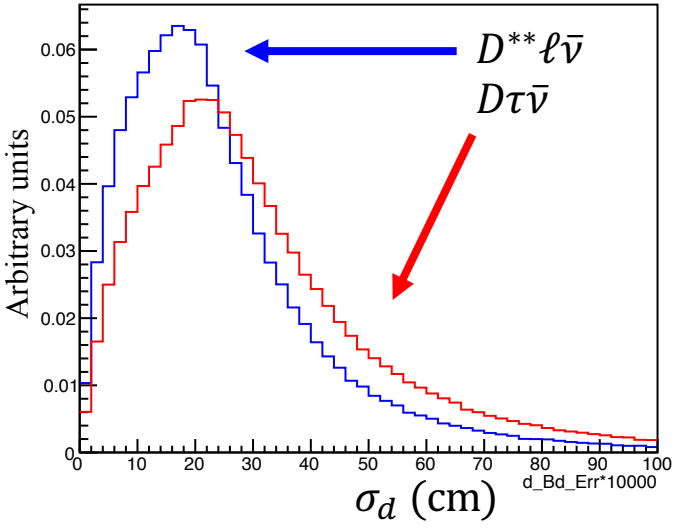
$\sigma_x = 37\ \mu\text{m}$



The distance d in $\tau \to \ell\nu\bar{\nu}$

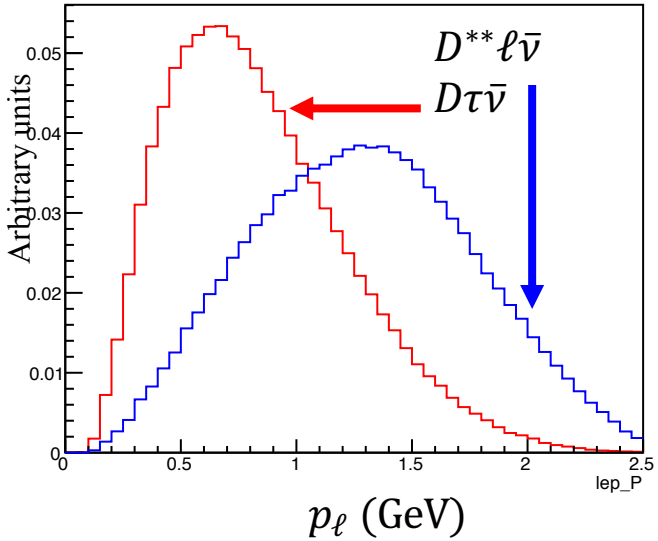
S-B separation is partly due to larger signal σ_d,

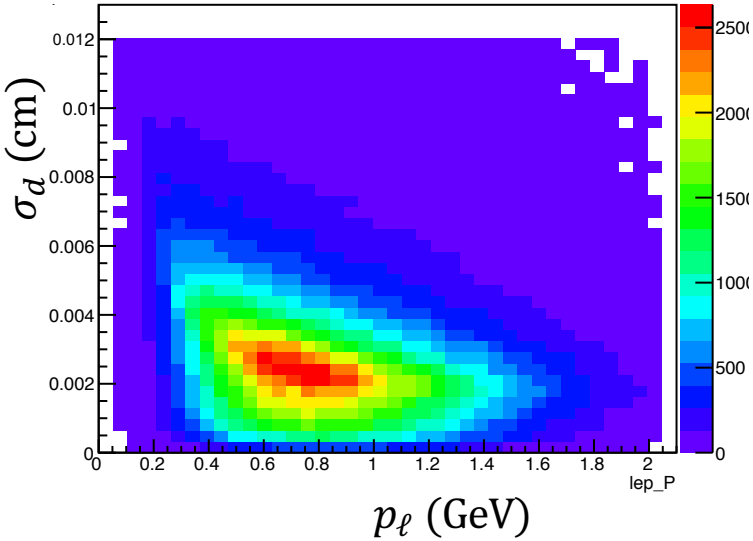




which is due mostly to the softer lepton.

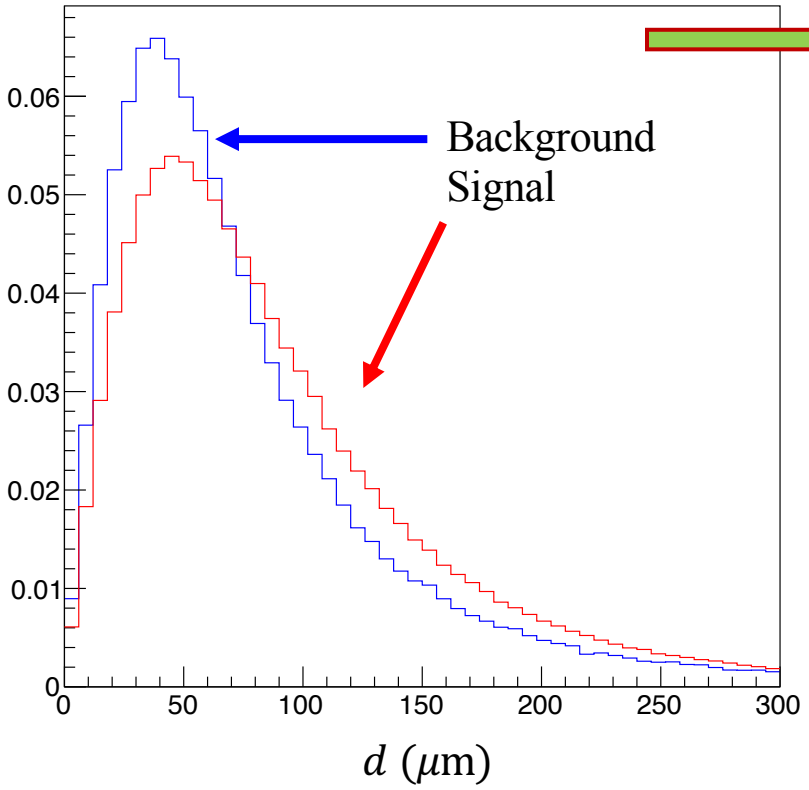
But p_ℓ is already among the analysis kinematic variables, so it isn't new.



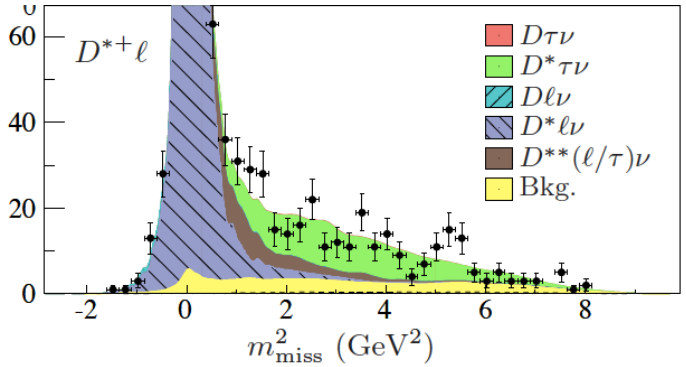


The distance d in $\tau \to \ell\nu\bar{\nu}$

After reweighting background events by lepton momentum:



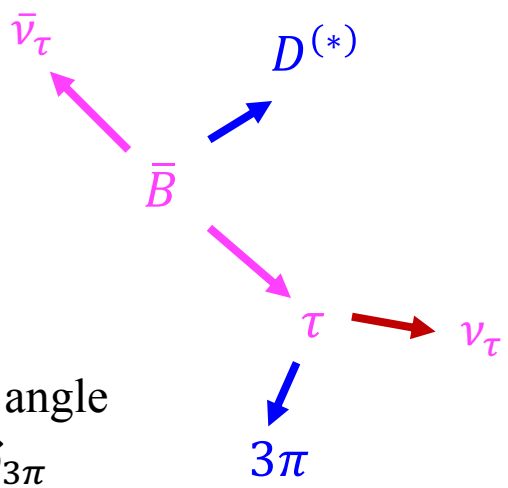
- The S-B separation is small
- But sufficient for verifying that the kinematic-variable fit gives the correct fraction of non-τ events.



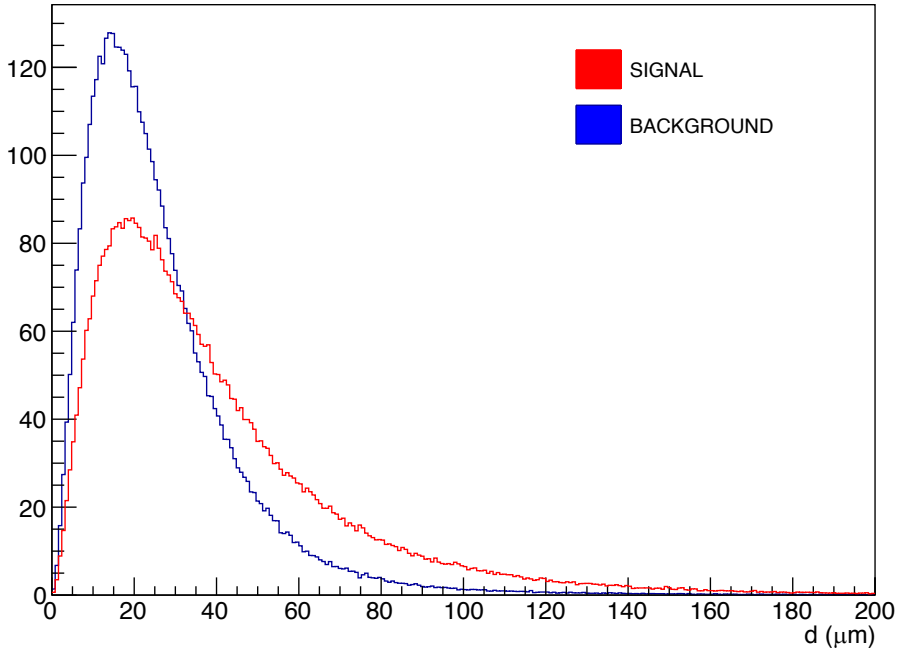
- Approximating signal and background yields from the BABAR analysis scaled to Belle II luminosity (×100), we find that a fit to the d distribution gives the prompt-lepton background yield with a ~10% error per mode $(D^0, D^+, D^{*0}, D^{*+})$

The distance d in $\tau \to 3\pi\nu$

Simulated background chosen just to test the capability to "see" the τ displacement:
$\bar{B} \to D3\pi2\nu$ with same kinematic distributions as signal

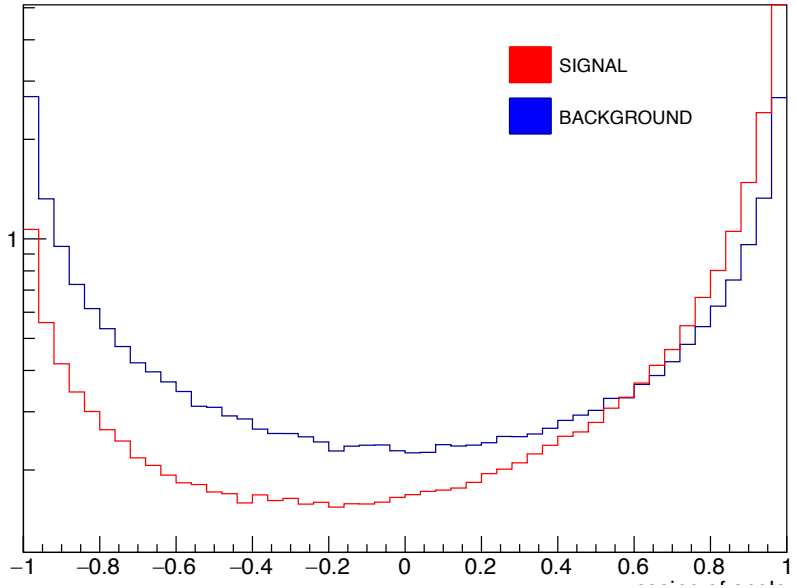


3-track vertex has much better resolution than single lepton:



d (μm)

Also measure the angle θ b/w $\vec{d}$ and $\vec{p}_{3\pi}$



$\cos\theta$

Summary

- $\bar{B} \to D^{(*)}\tau\bar{\nu}$ is an important part of the the physics programs of Belle II and LHCb
- In the $\tau \to \ell\nu\bar{\nu}$ mode, $\bar{B} \to D^{**}\ell\bar{\nu}$ background presents a systematic challenge
- Exploit Belle II's spatial resolution and small beamspot to obtain a new, model-independent handle on this background: distance d between the signal-B decay position and the lepton
- In the $\tau \to 3\pi\nu$ mode, 3 pions give improved precision on d and additional background suppression from the angle θ between $\vec{d}$ and the 3-pion momentum vector.
- Even better resolution expected for $\bar{B} \to \tau\bar{\nu}$. Currently under study.