Can B hadronic help?

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Belle II Physics Week, Oct 30—Nov 2 2023, KEK

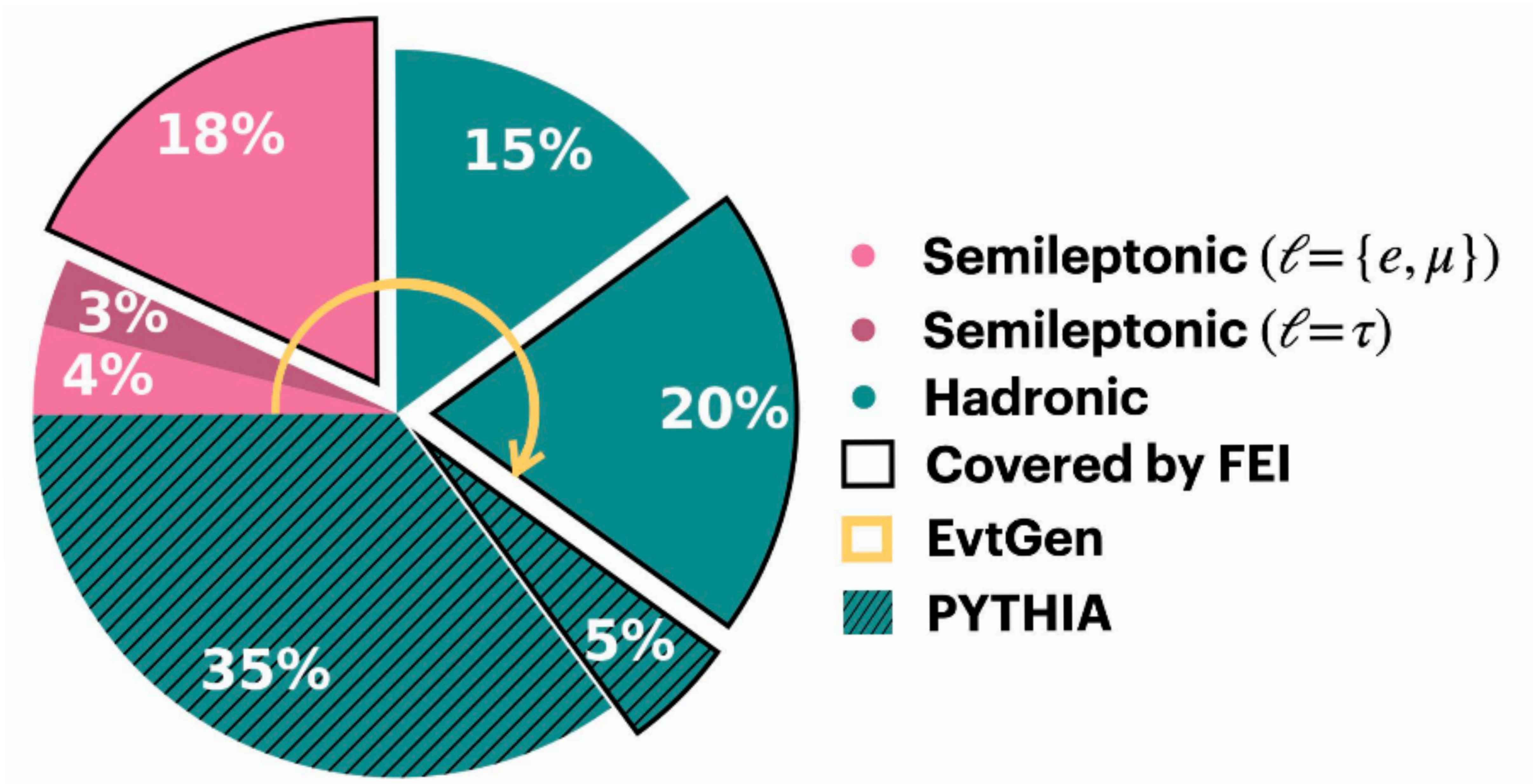
Idea of the talk

Discuss activities in B hadronic group that impact $|V_{cb}|$
(and SL analysis in general)

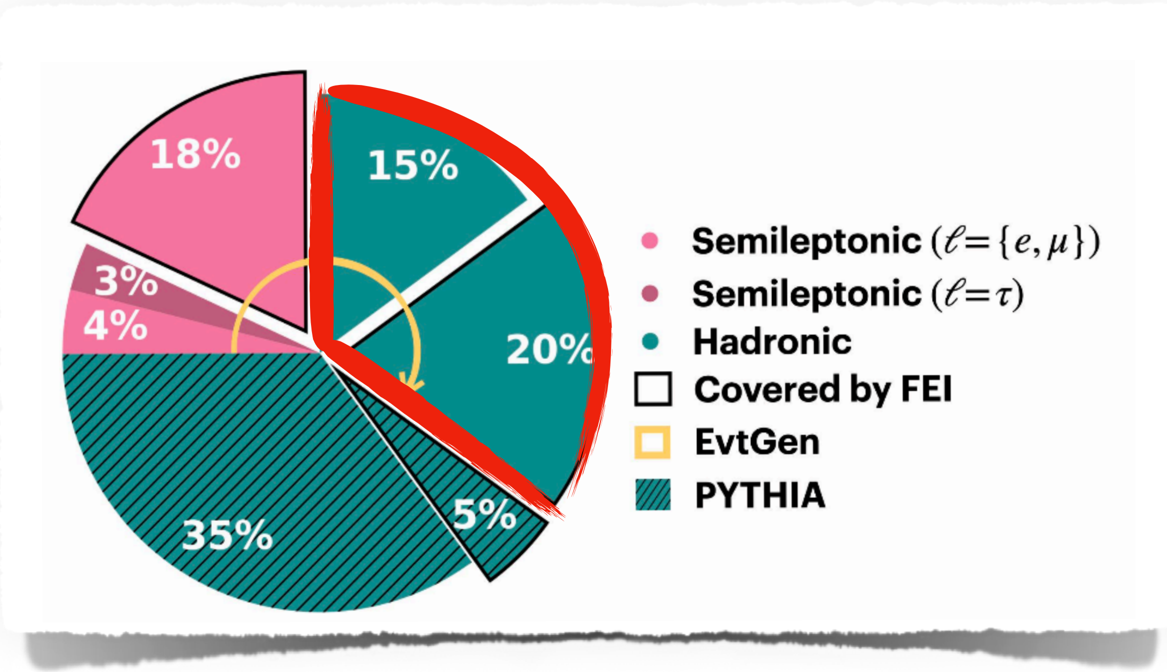
- Supporting measurements for hadronic B tagging
- Measurements that could provide info for SL gap
- Measurements that could help understanding D** nature (more questions than anything else…)

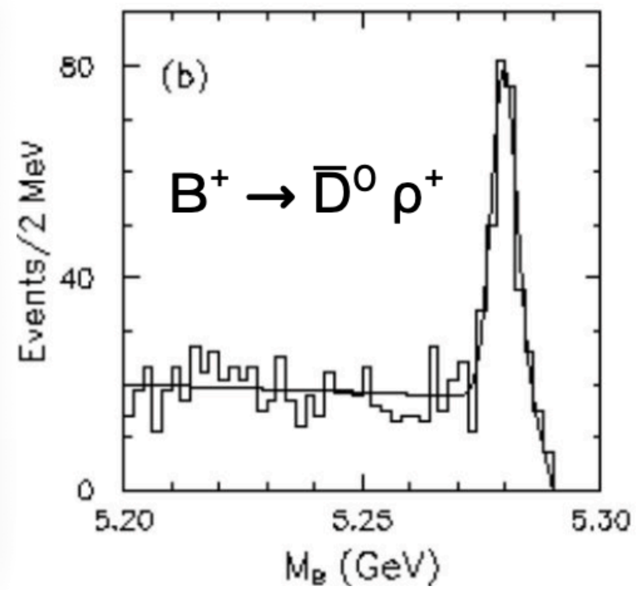
A much larger gap

Credit Vidya Sagar Vobbilisetti



What we know is not enough



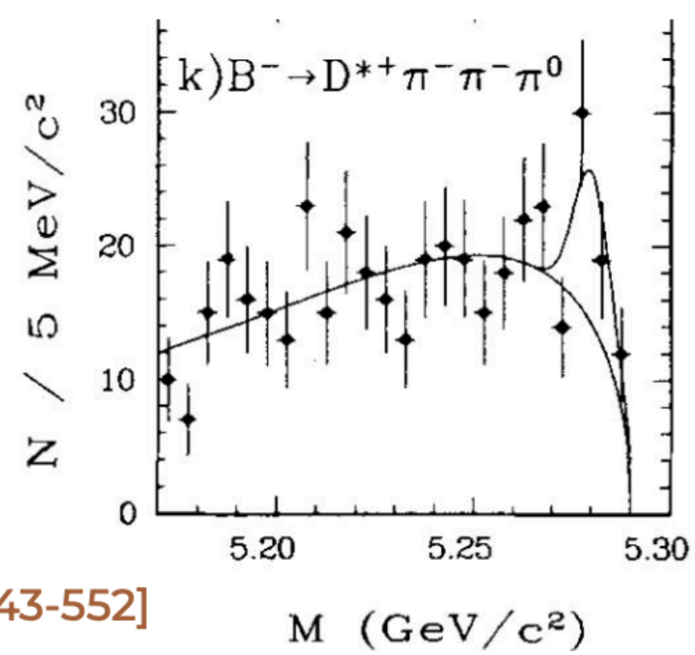


CLEO, 0.89 fb^{-1}
29 years ago
Uses M_{bc}
$\mathcal{B} = (1.34 \pm 0.18)\%$
13% uncertainty!

[PRD 50 (1994) 43-68]

ARGUS, 229 pb^{-1}
33 years ago
Uses M_{bc}
$\mathcal{B} = (1.5 \pm 0.7)\%$
47% uncertainty!

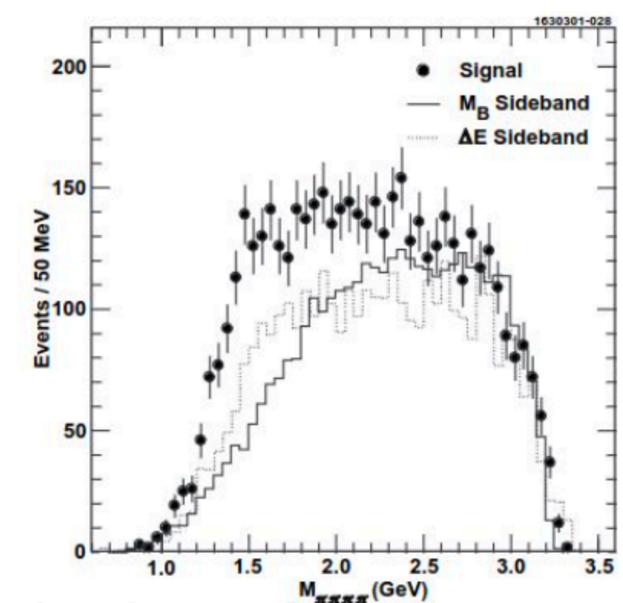
[Z.Phys.C 48 (1990) 543-552]



$B^+ \to \bar{D}^{*0} \pi^+ \pi^+ \pi^- \pi^0$

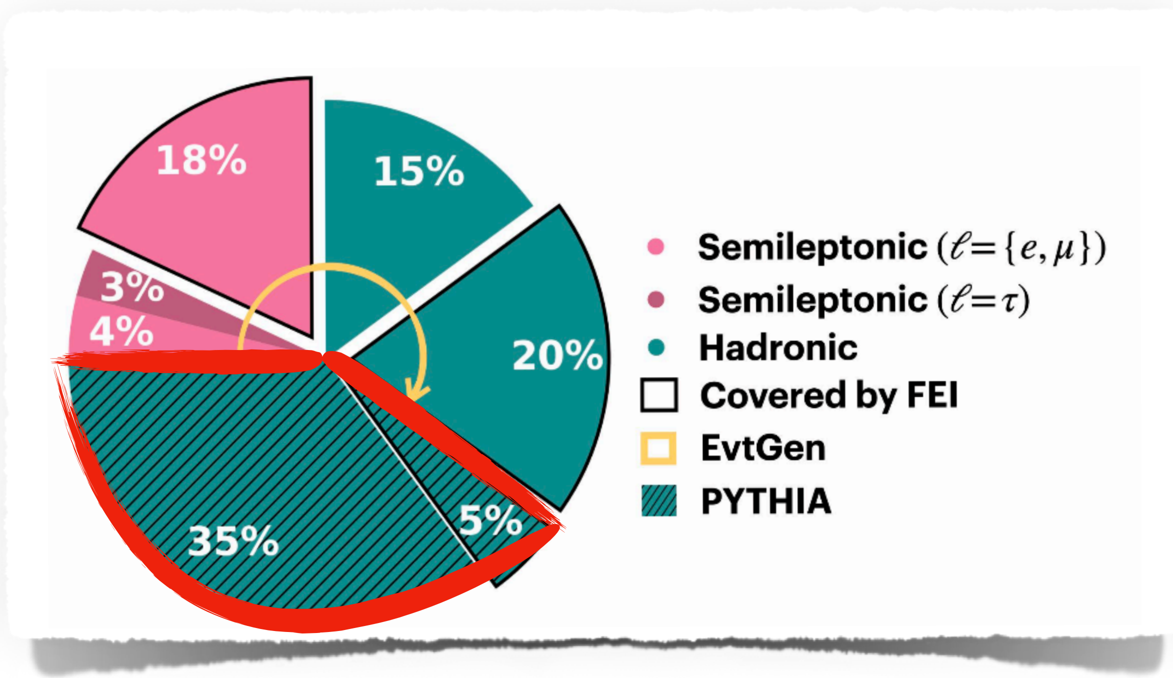
CLEO, 9 fb^{-1}
22 years ago
Uses M_{bc}
$\mathcal{B} = (1.8 \pm 0.4)\%$
22% uncertainty!

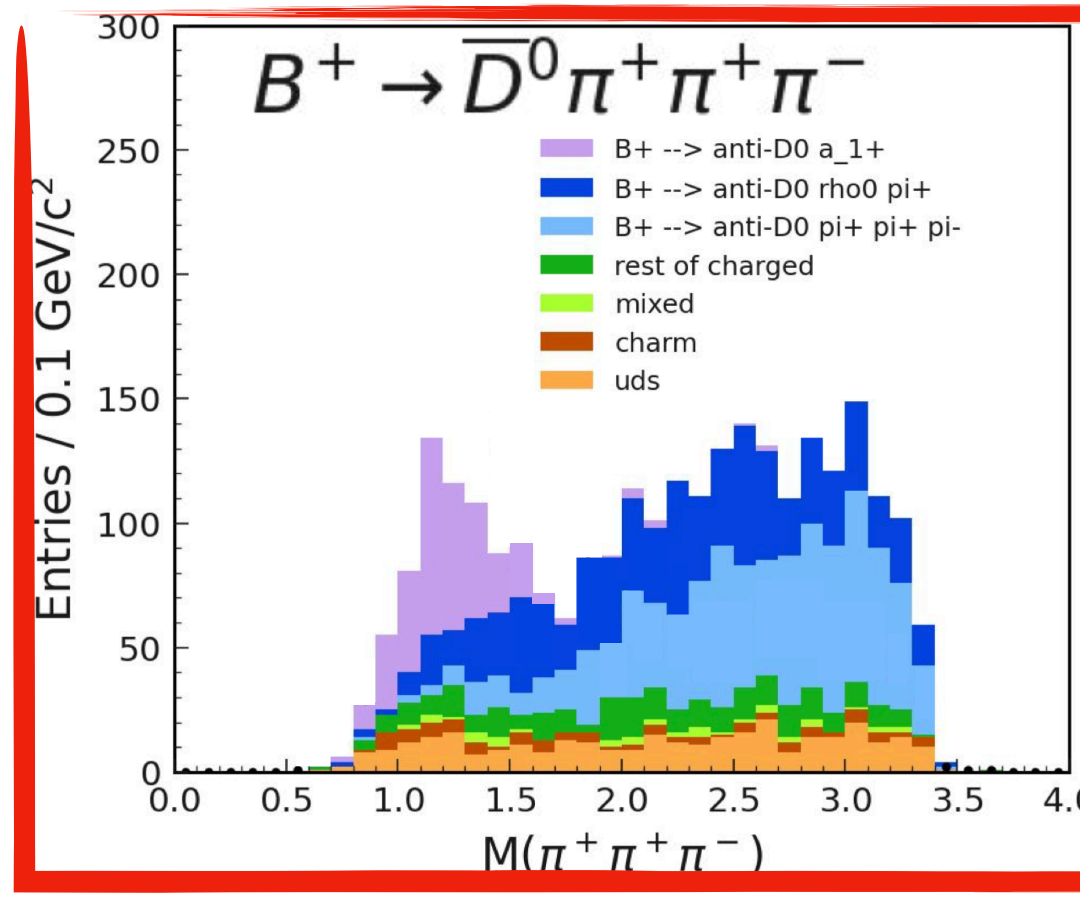
But model? ⇒ ρ'?

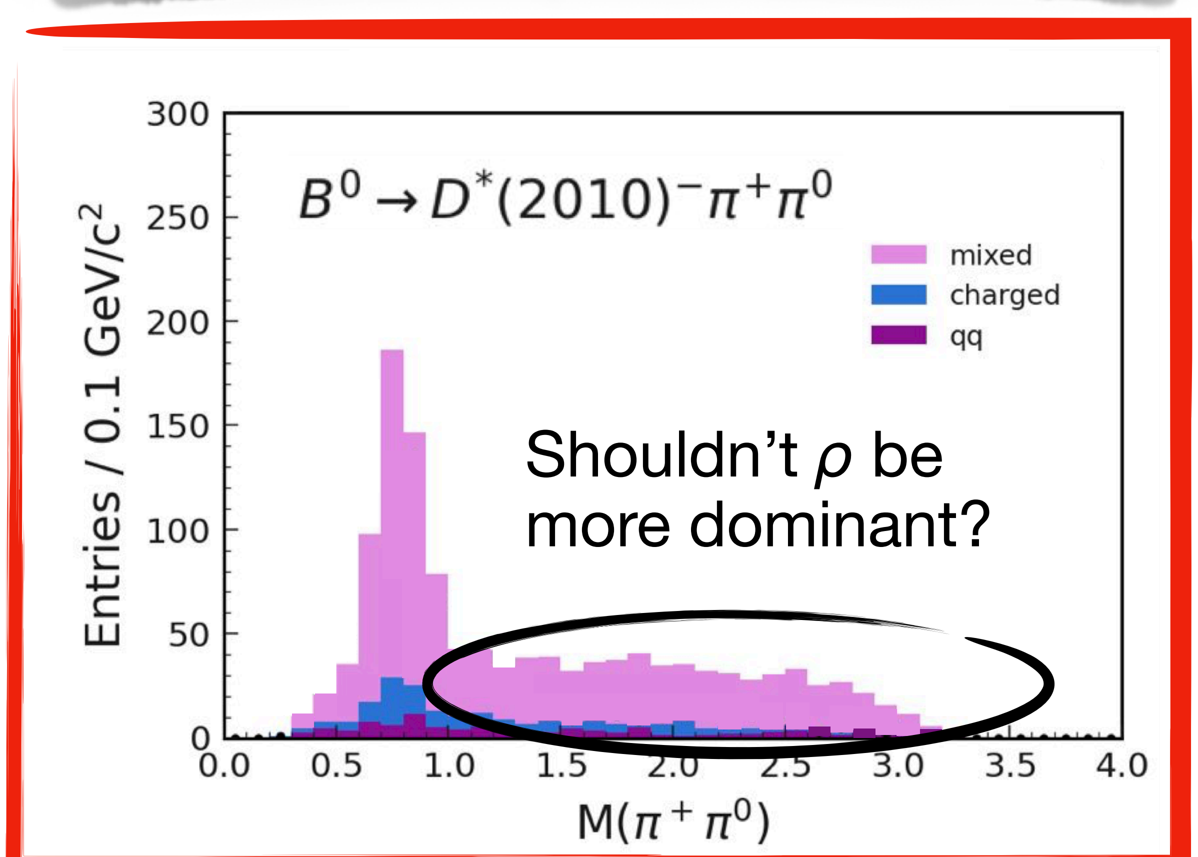


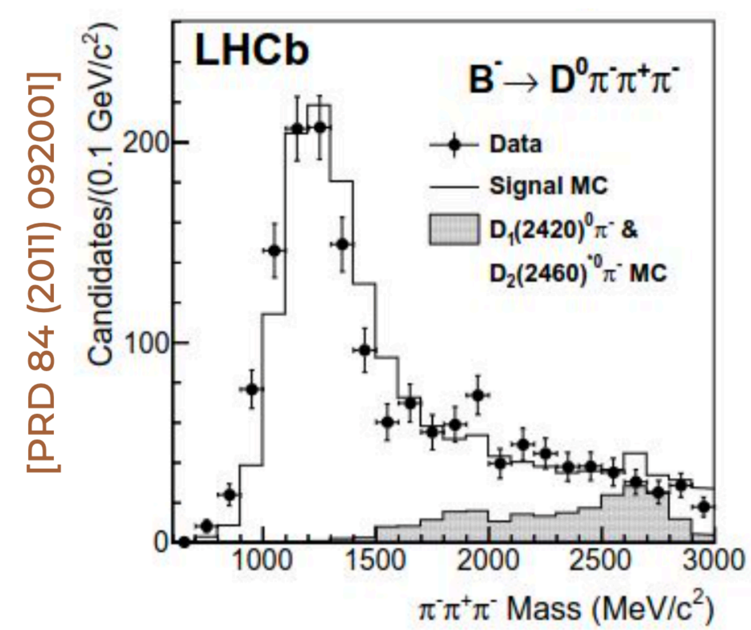
[PRD 64 (2001) 092001]

Pythia is not tuned for that







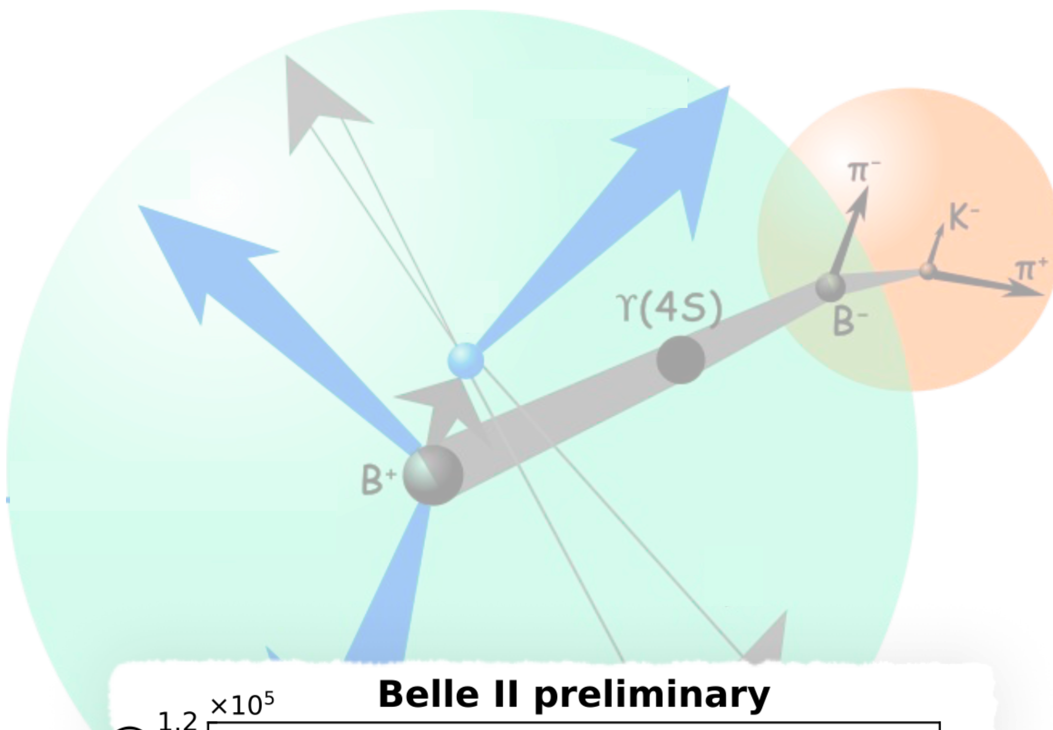


LHCb, 35 pb^{-1}
12 years ago

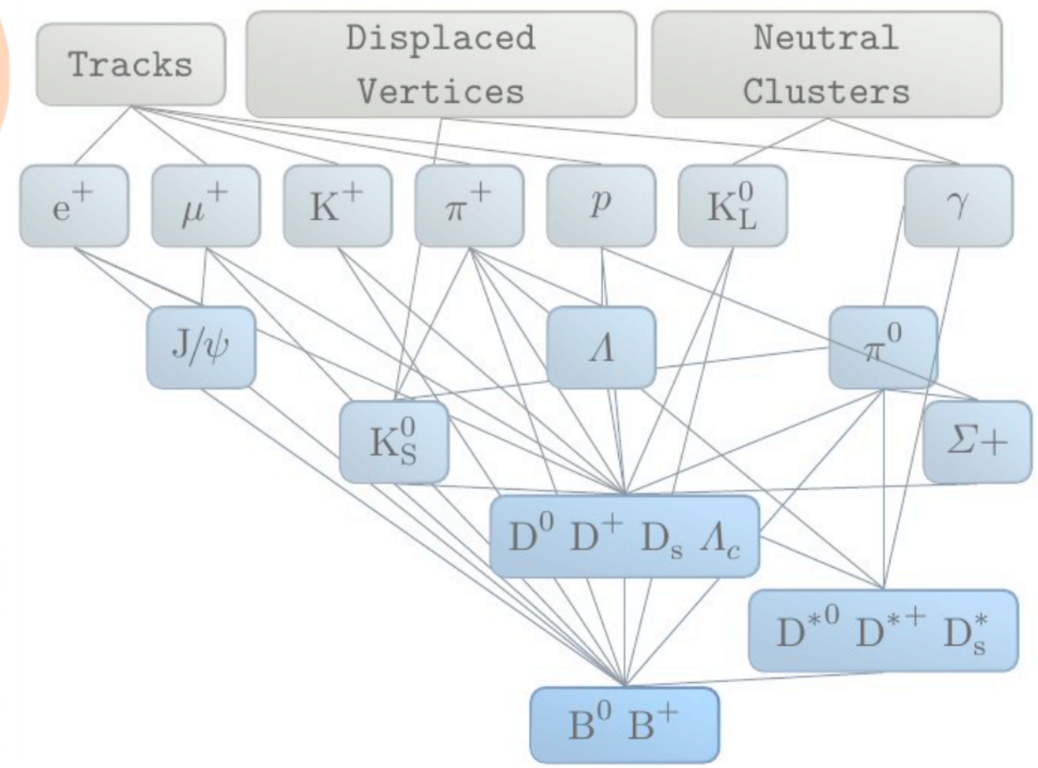
But
$\mathcal{B}(B^+ \to \overline{D}^0 a_1^+)$
not provided!

Neutrino reconstruction

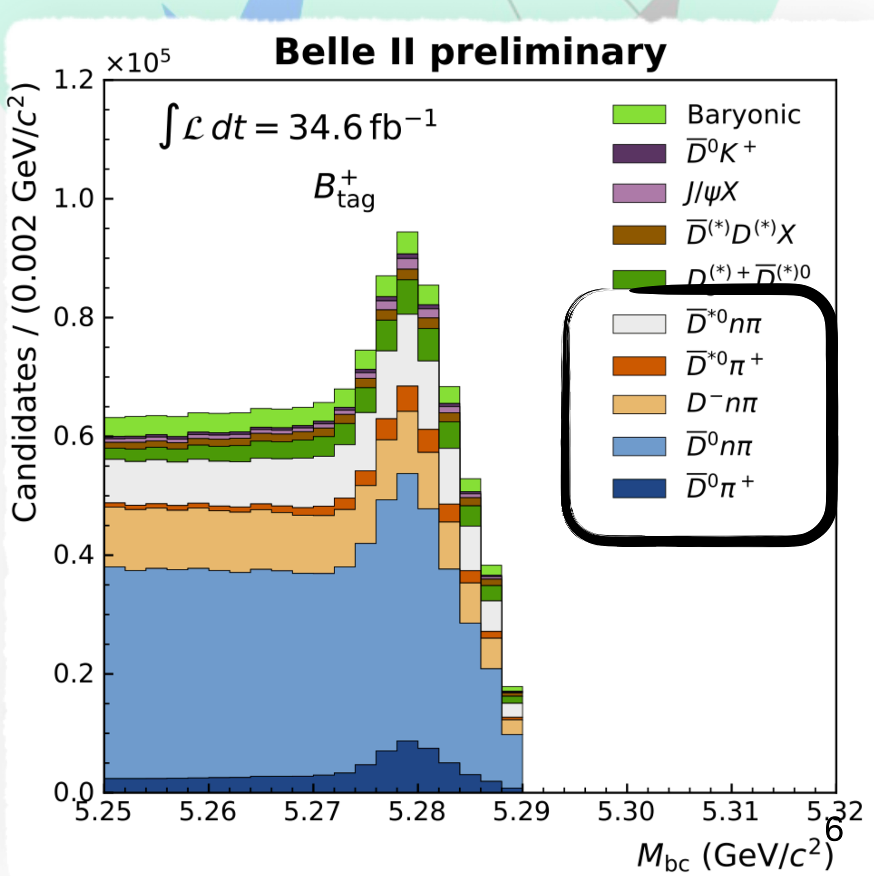
Hadronic B tagging: best purity and you get the B momentum vector.



Tagging algorithm (FEI)



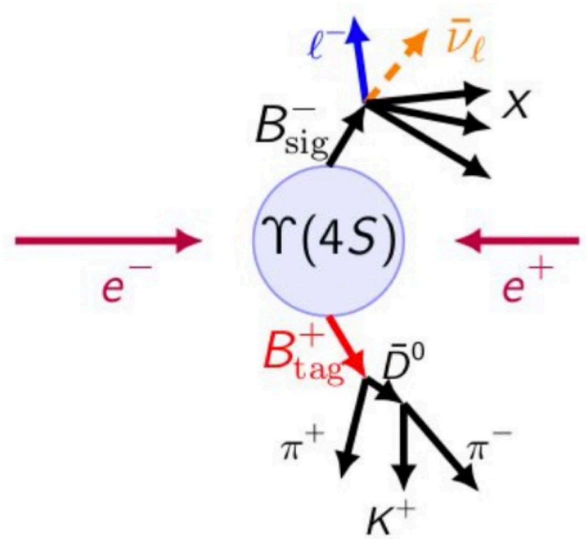
arXiv:2008.06096

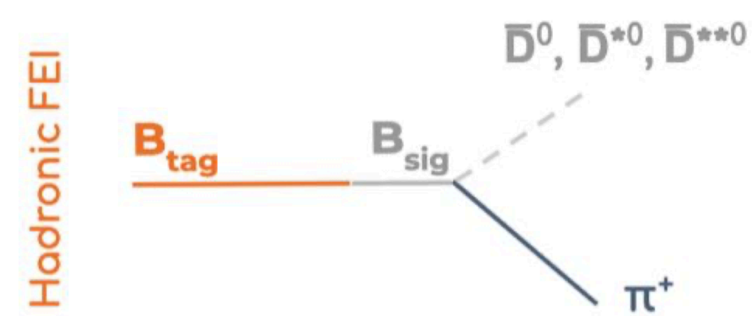


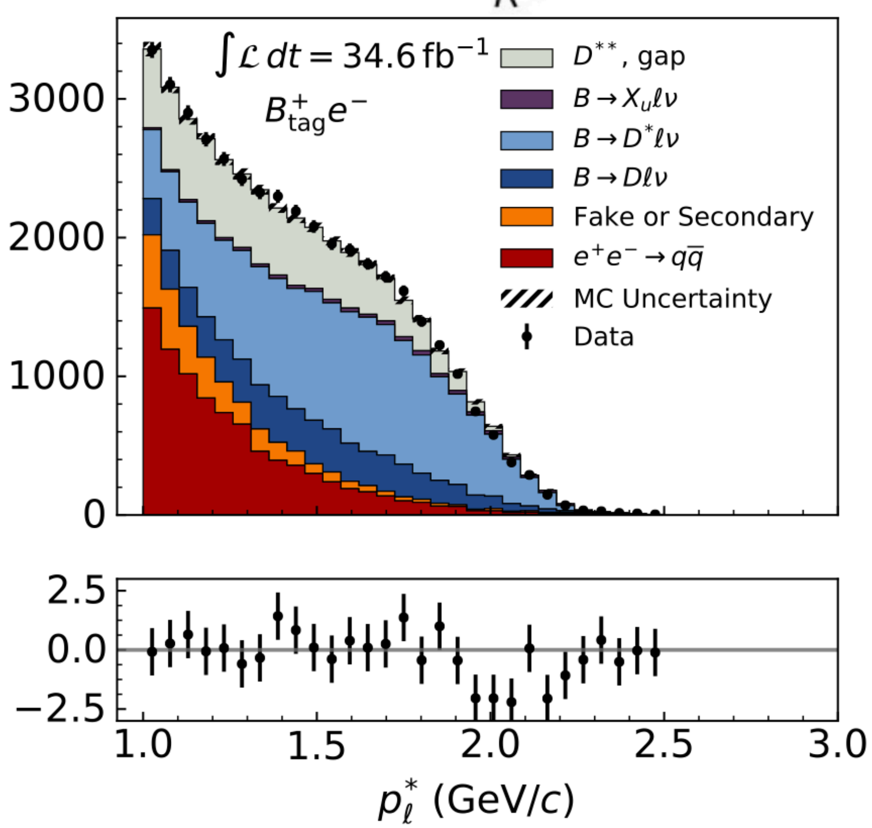
Mostly O(10) $B \rightarrow D^{(*)}$ nπ mπ^0.
BDT for each decay ***trained on simulation.***

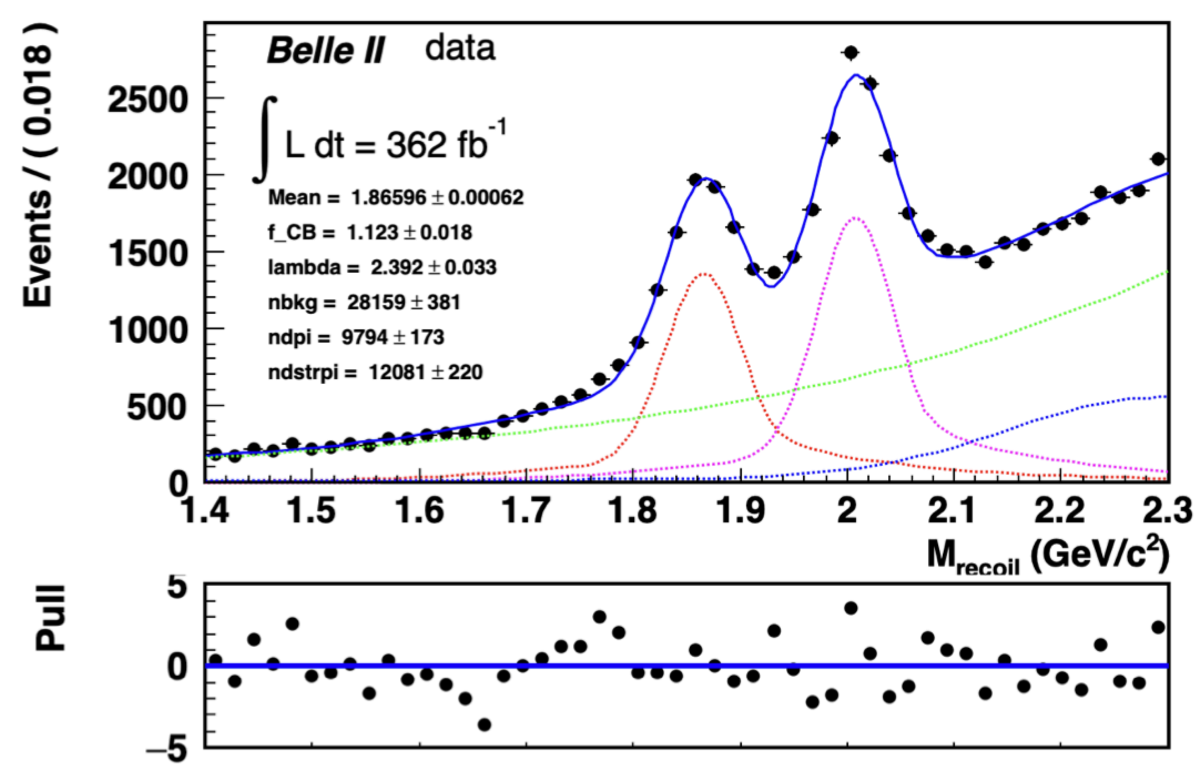
Need to calibrate the efficiency

Large data-MC discrepancy in the tagging efficiency.
Need calibration factors derived from control data,
spoil precision for normalisation (see Bob’s talk from yesterday).

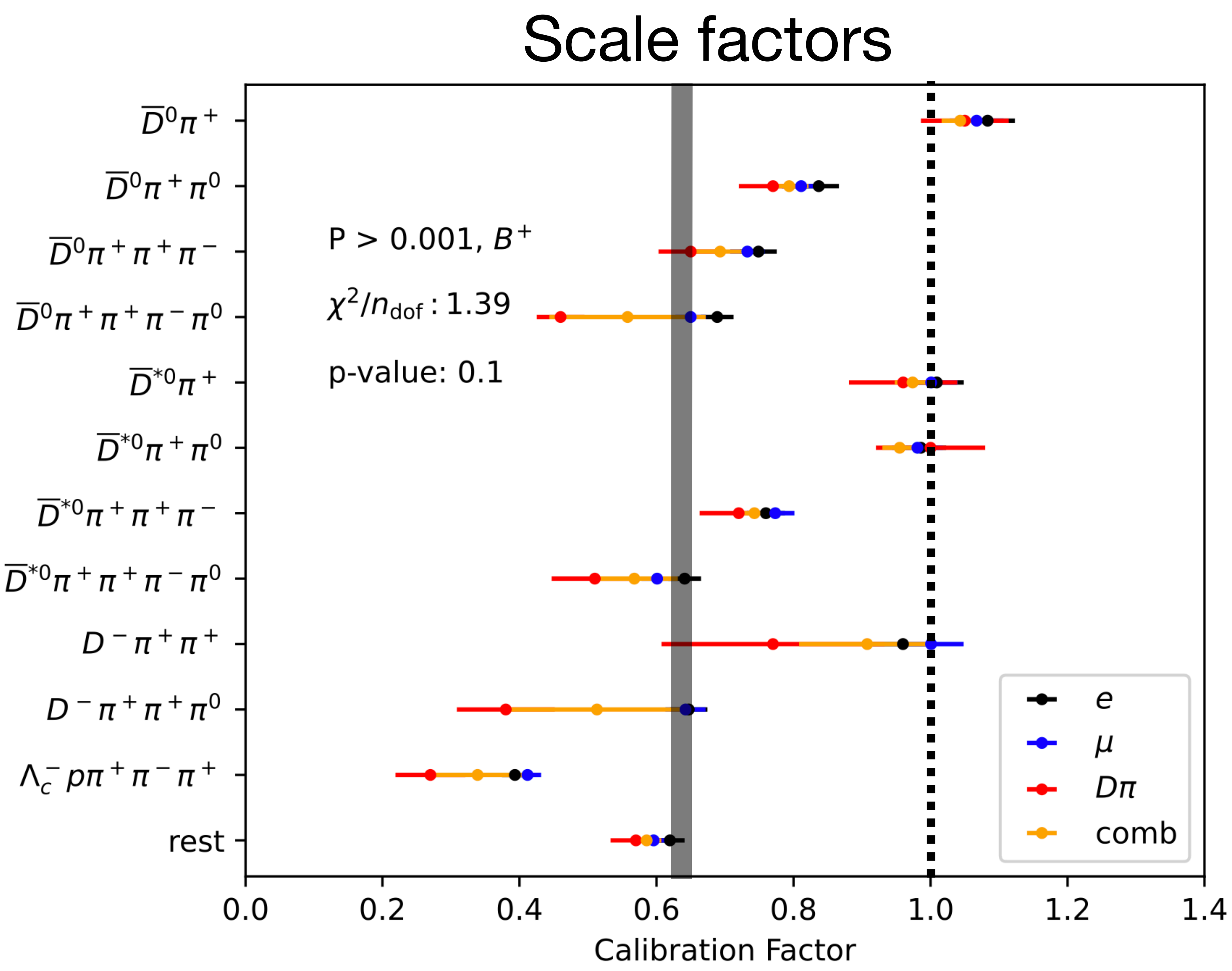




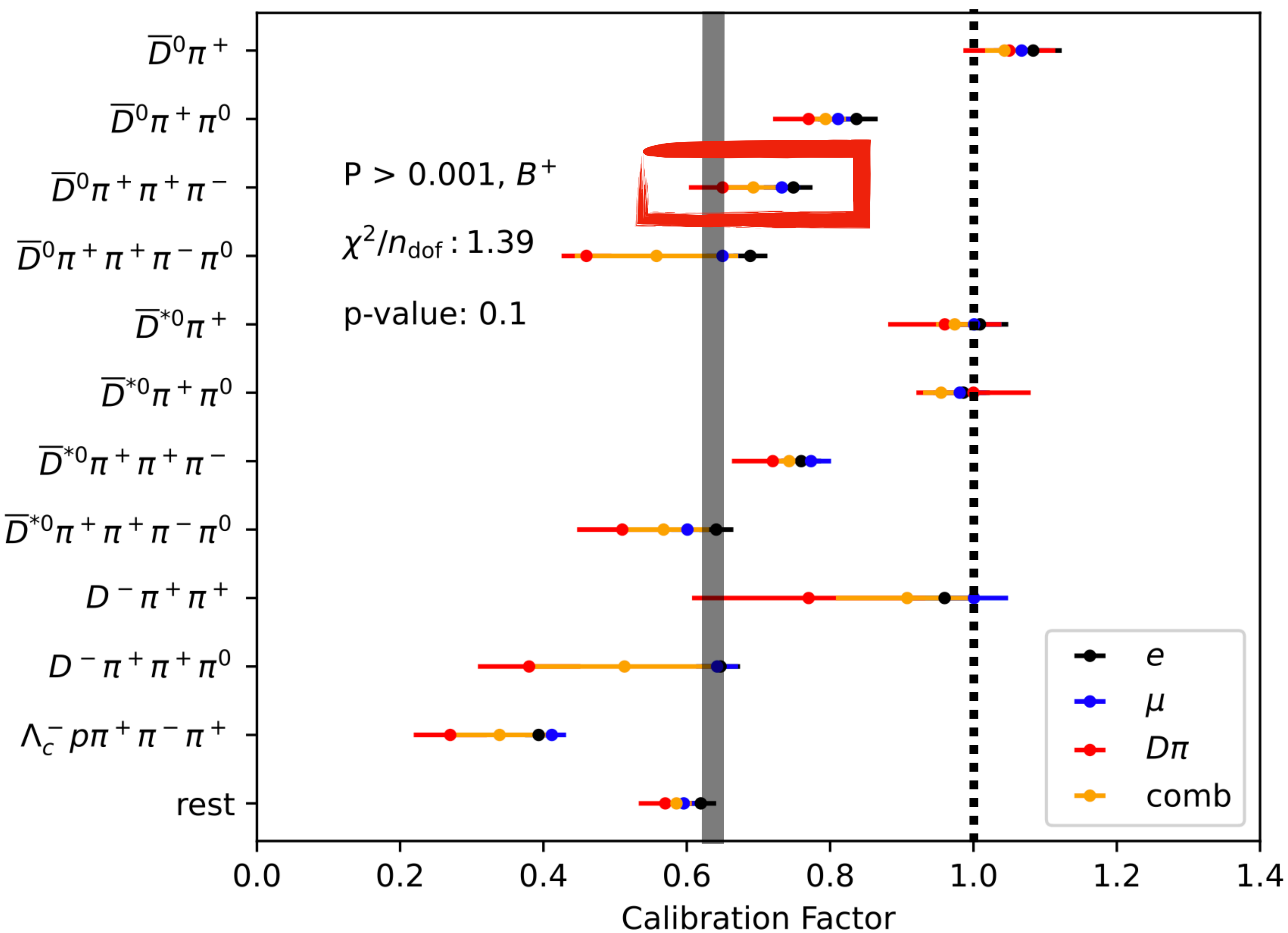


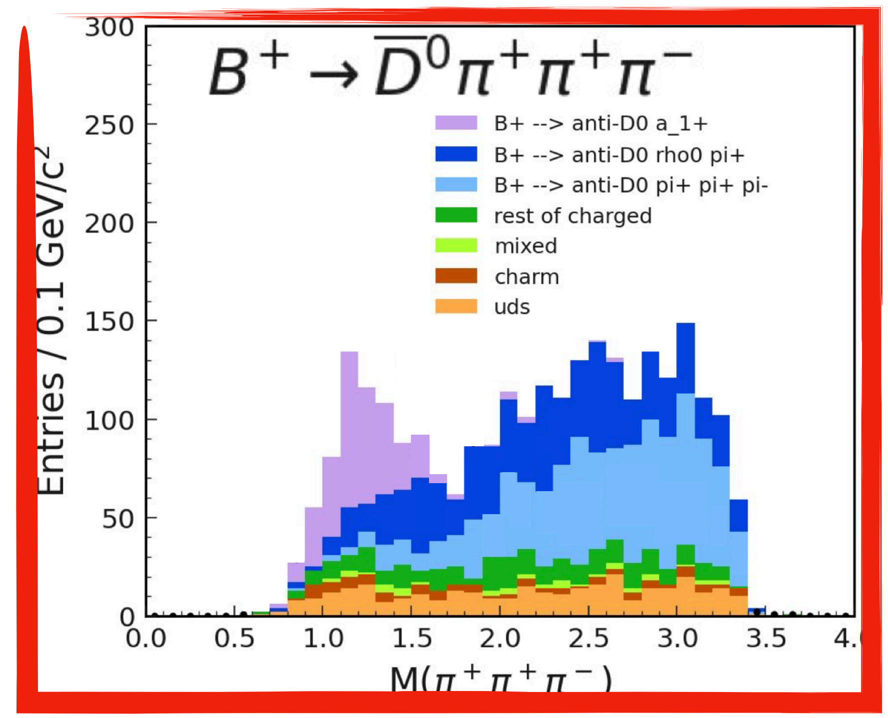


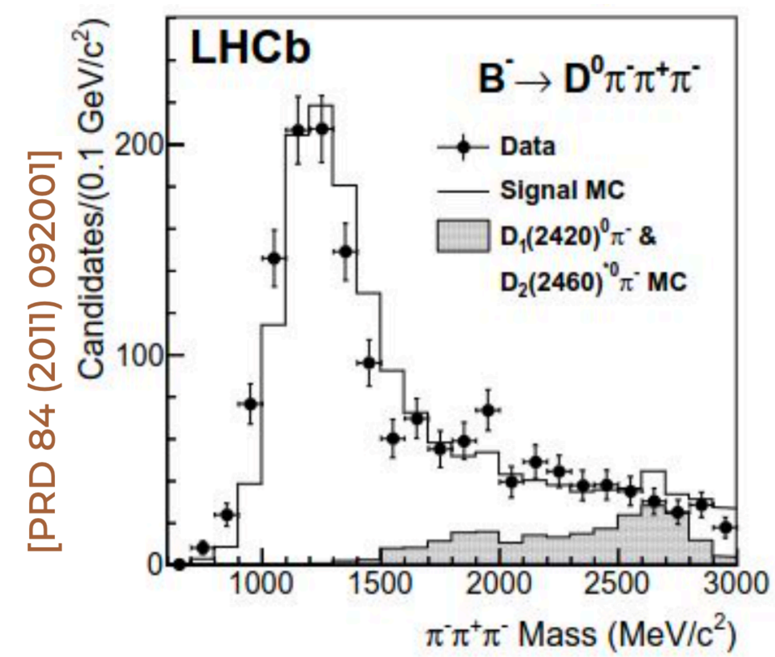
Impact of our B hadronic knowledge



Impact of our B hadronic knowledge





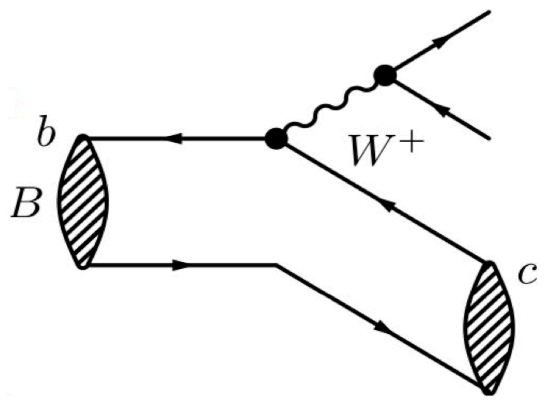


Not only an issue of normalisation. Poor modelling leads to suboptimal selection, lower purity.

Any bias on B momentum vector or resolution?

Improving our decay table

Updated measurements + simple model



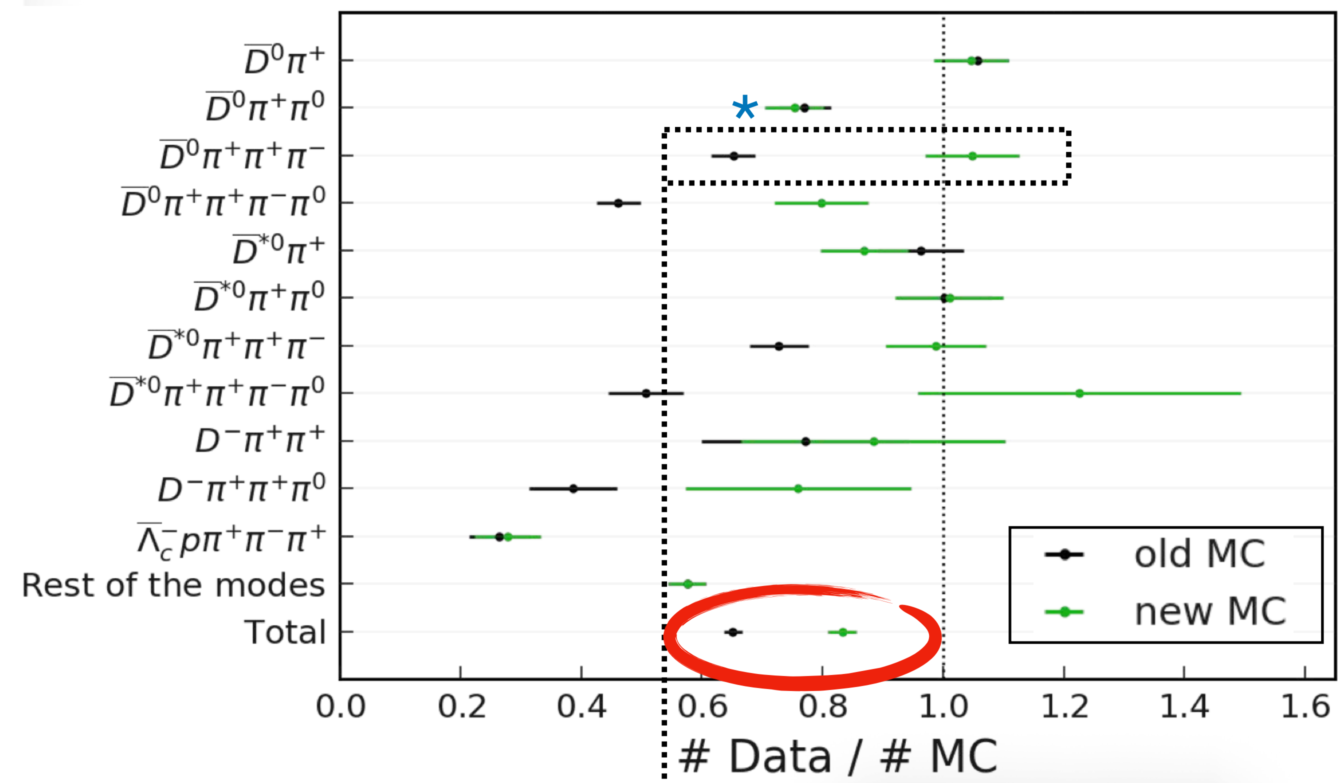
X = π, ρ, a_1, ωπ, ρππ, ηπ

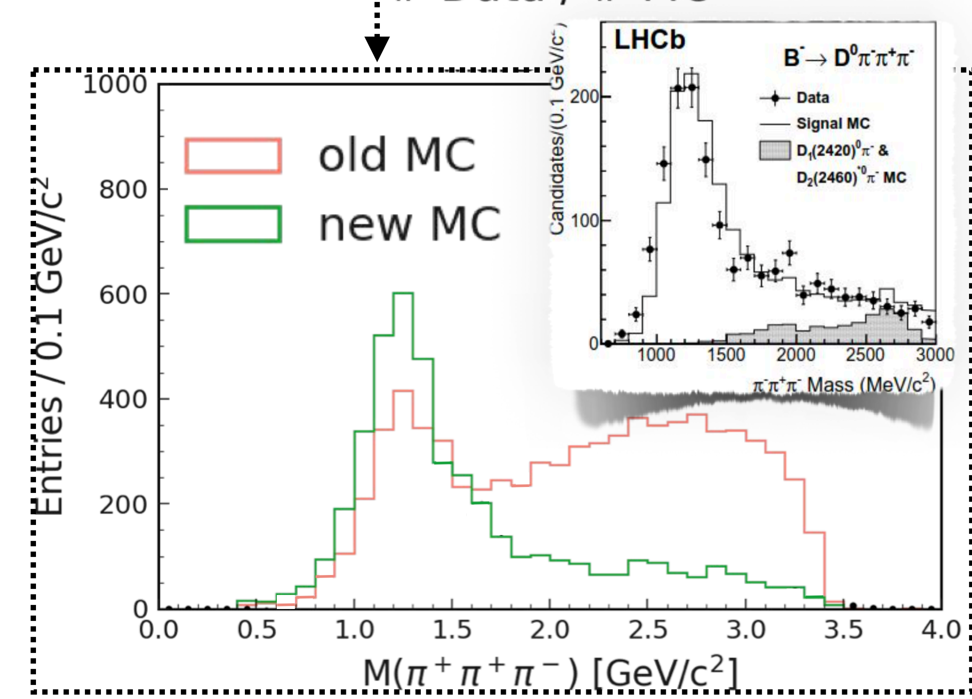
Y = D, D*, D**

2 primary rules:

- $D^0 X : D^{*0} X : D^{**0} X$ ~= 1 : 1 : 1
  (based on observation from D π^- : D* π^- : D** π^- and D ρ^- : D* ρ^-)
- Y π^- : Y ρ^- : Y a_1^- ~= 1 : 2.5 : 2.5
  (based on predictions and confirmed with τ → h ν decays)
- 3π π^0 is hard to model without some sort of ρ' resonance
  - For **ωπ** we fix from measurements.
  - For **ρππ** and **ηπ**, we let PYTHIA generate it.
- The fraction of 4 different D** is fixed based on observations.

Scale factors

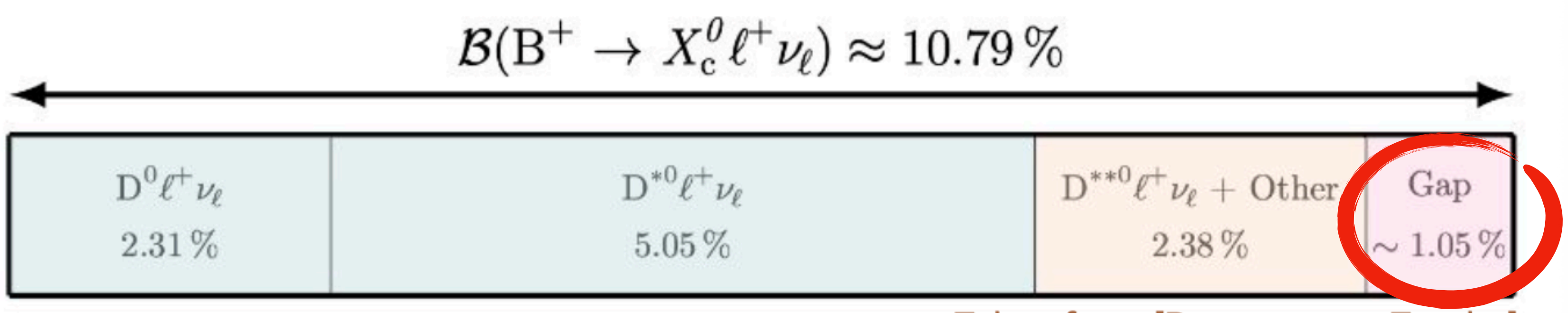




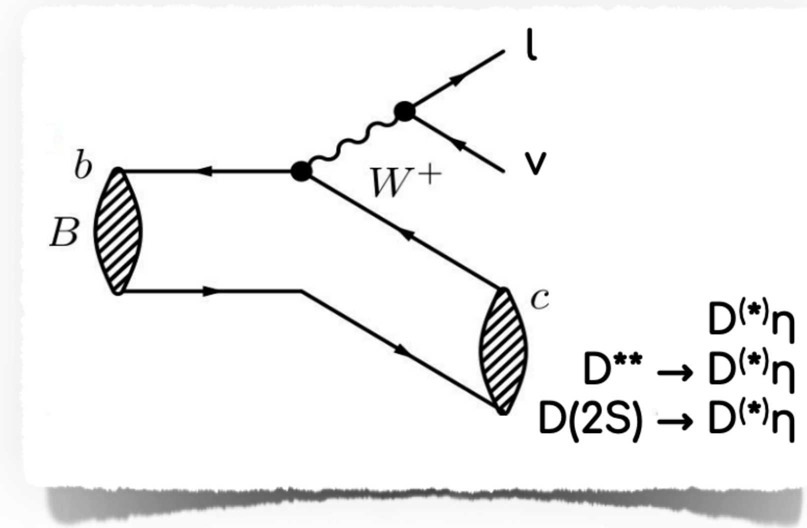
Setting up a program to improve our references. Ongoing measurements for *B→Dρ, B→Dππ, B→D(*)KK(*) …

Supporting information for the SL gap

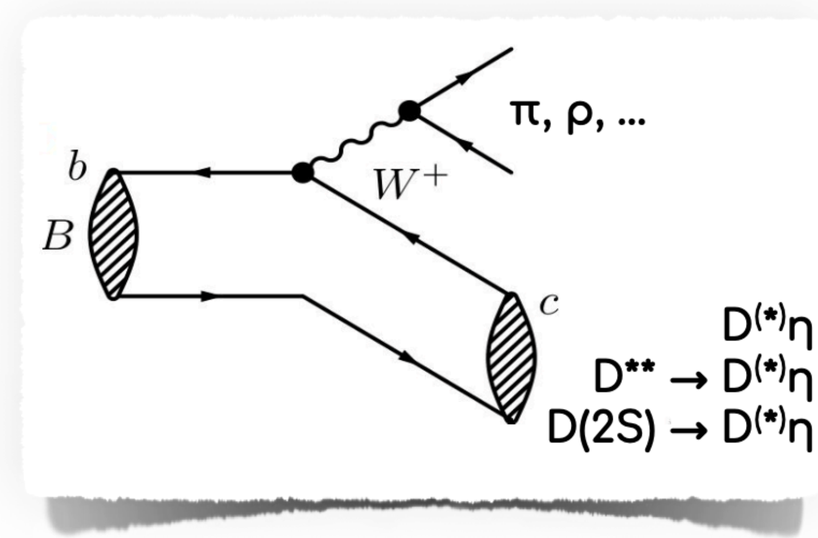
Searching for $B^0 \to D^{*-}\eta\pi^+$



Taken from [Raynette van Tonder]



- Models used in current exp analyses fill the gap with $B \to D^{(*)}\eta l\nu$, either non-resonant or through $(D^{(*)}\eta)$ from D^{**} or $D(2S)$ states.
- Unobserved so far. Studying feasibility of a search.
- Complement info with hadronic $B \to D^{(*)}\eta\pi$, also unobserved (but generated by Pythia in our simulation!).
- Focus on D^* first. From SL gap, $BR(B \to D^*\eta l\nu) \sim 4 \times 10^{-3}$, naively should expect $BR(B \to D^*\eta\pi) \sim 2 \times 10^{-4}$



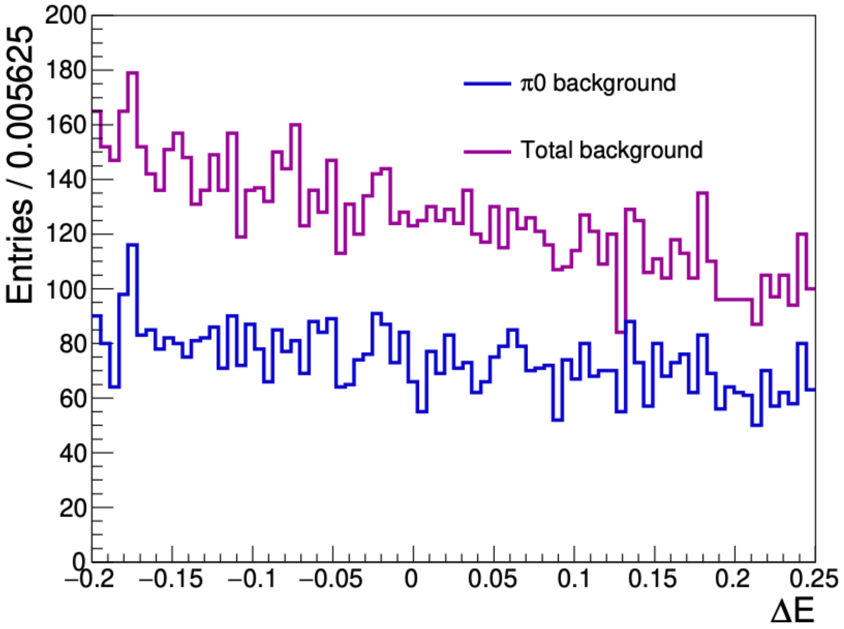
$B^0 \to D^{*-}\eta\pi^+$ analysis strategy

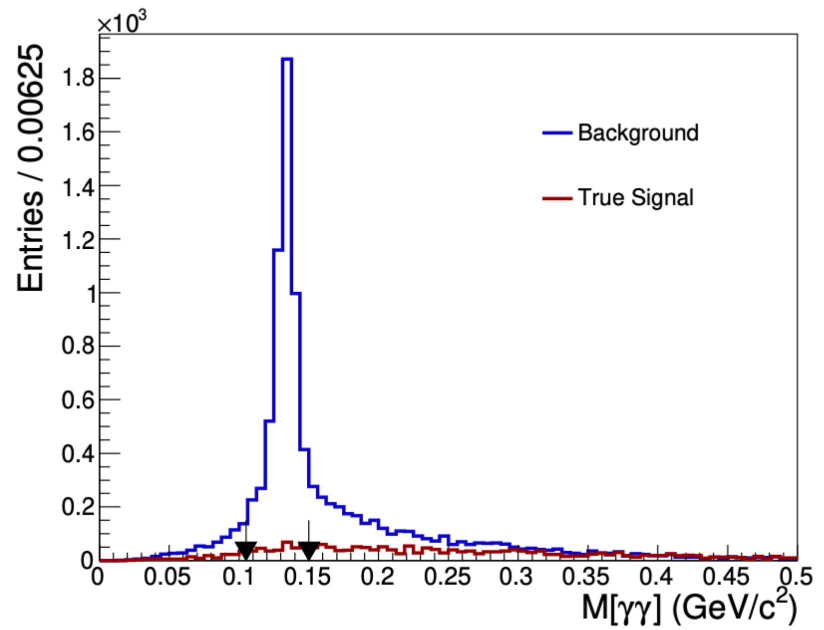
- Use $\eta \to \gamma\gamma$ first (cleaner), $D^* \to D^0(\to K\pi)\pi$.
  Suppress continuum with R_2.
  Veto $\pi^0 \to \gamma\gamma$ to further reduce background.

- Veto $B \to D^*D_s(\to \eta\pi)$ in the signal sample, used as control data to validate sensitivity (BR~1.3×10^{-4}).
  - $B \to D^*\rho(\to \pi\pi^0)$ control sample at high statistics (BR~7×10^{-3})

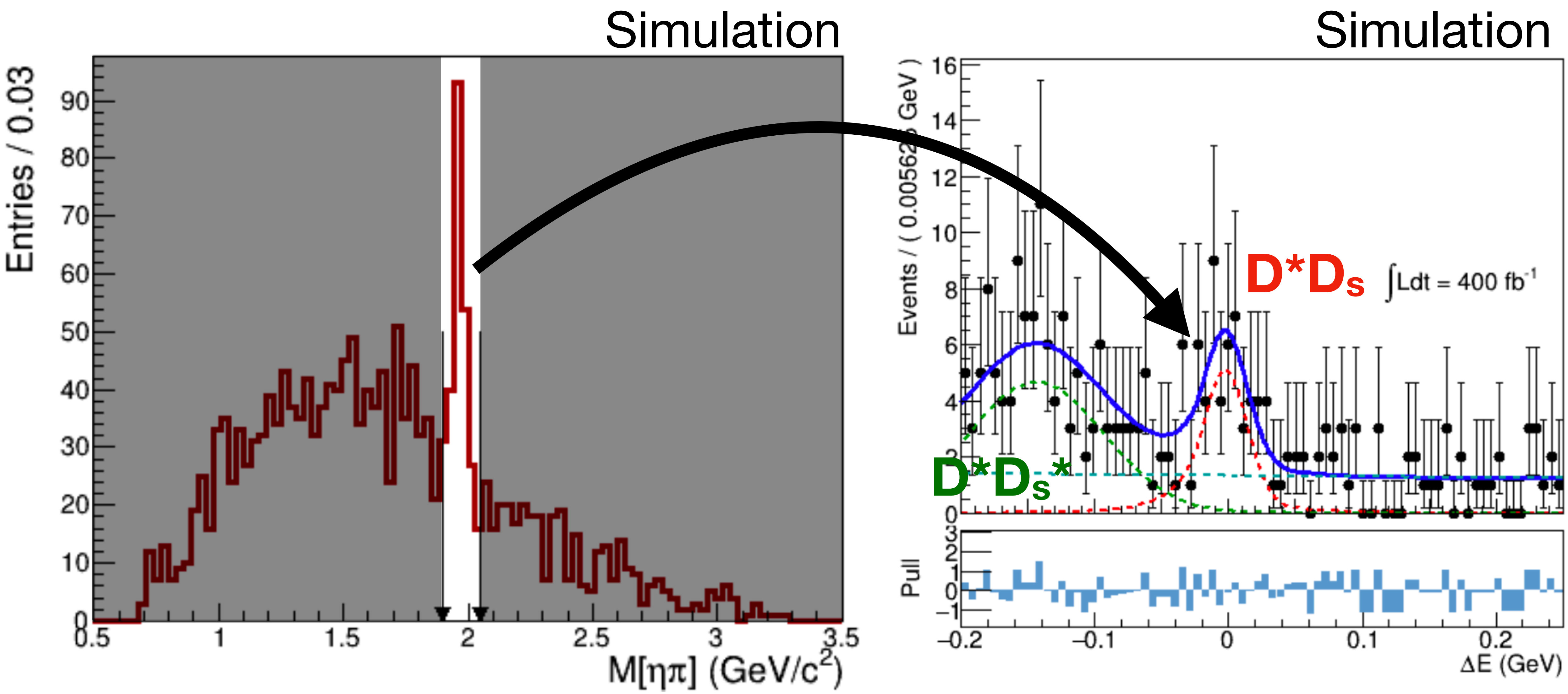
- Fit ΔE to extract the signal.
  - integrated in $m(D^*\eta)$, assuming different origins.
  - in bins of $m(D^*\eta)$

- Determine upper limits in different cases to estimate sensitivity in Belle II data:
  can we probe BR~10^{-4}?





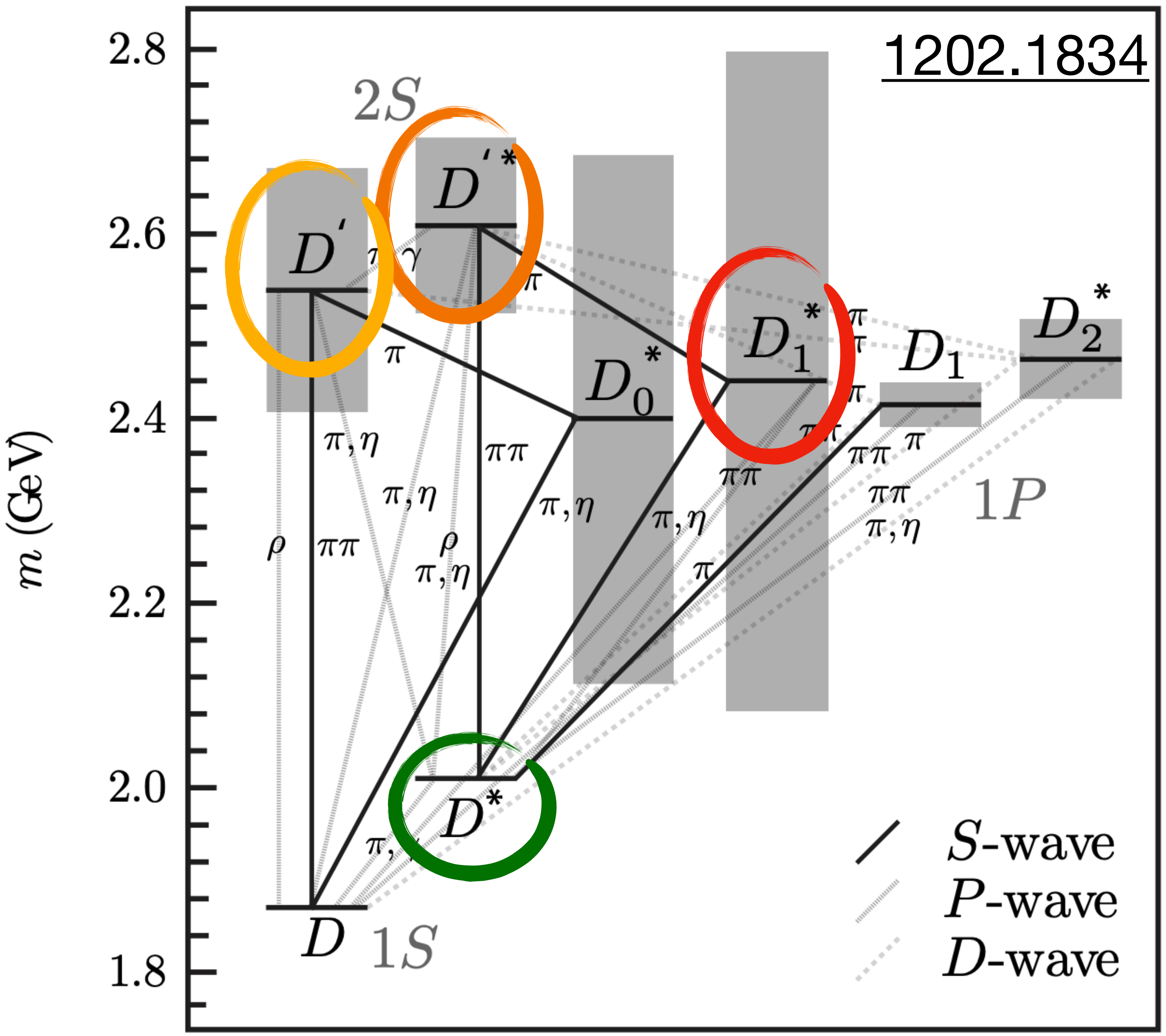
$B^0 \to D^{*-} D_s^+ (\to \eta\pi^+)$ control sample



In realistic simulation, the control sample is observed with 5.8σ and we measure BR in agreement with that in input (PDG value).

Build confidence on the sensitivity reach to ~10^{-4}.

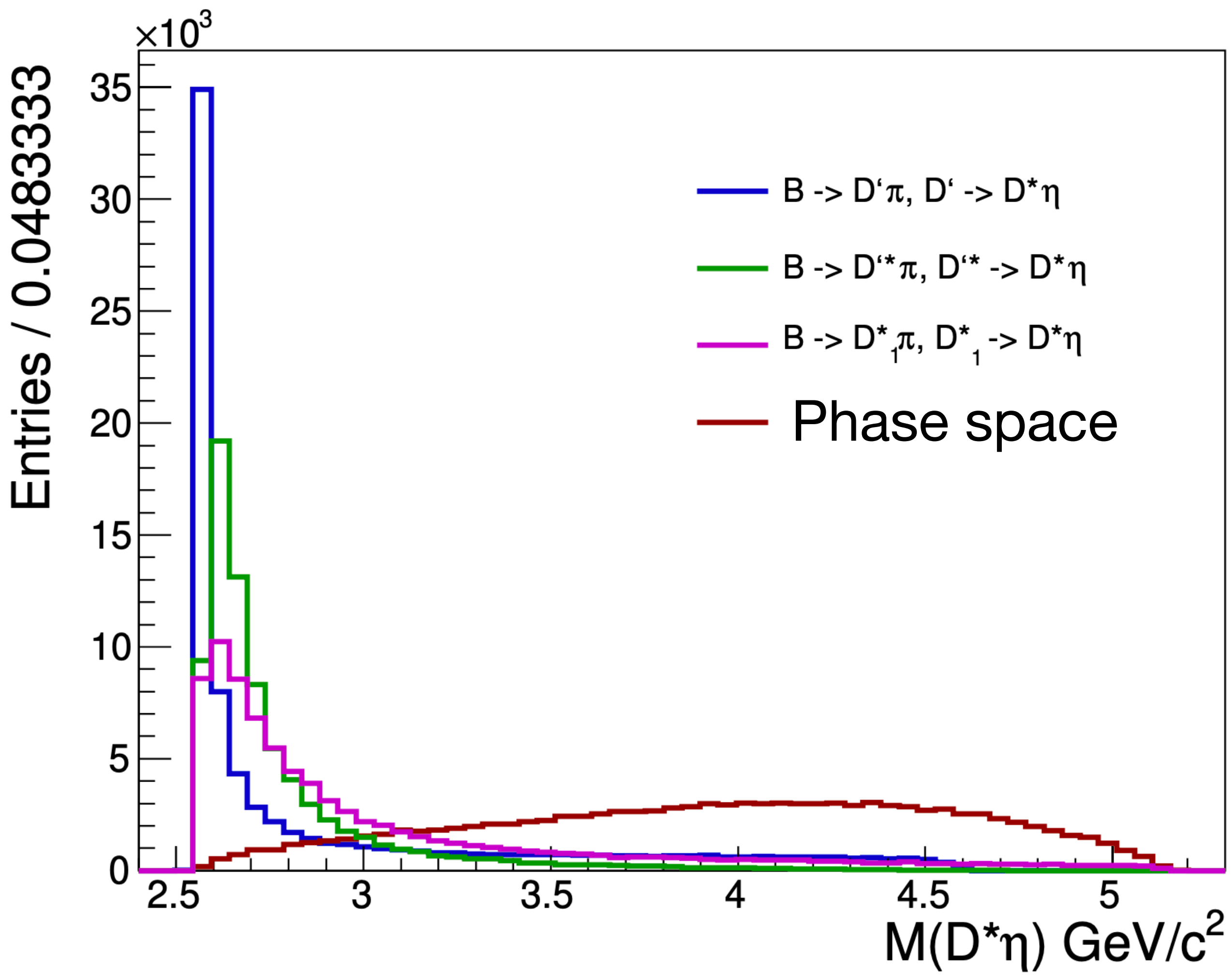
Modelling the $B^0 \to D^{*-}\eta\pi^+$ decay

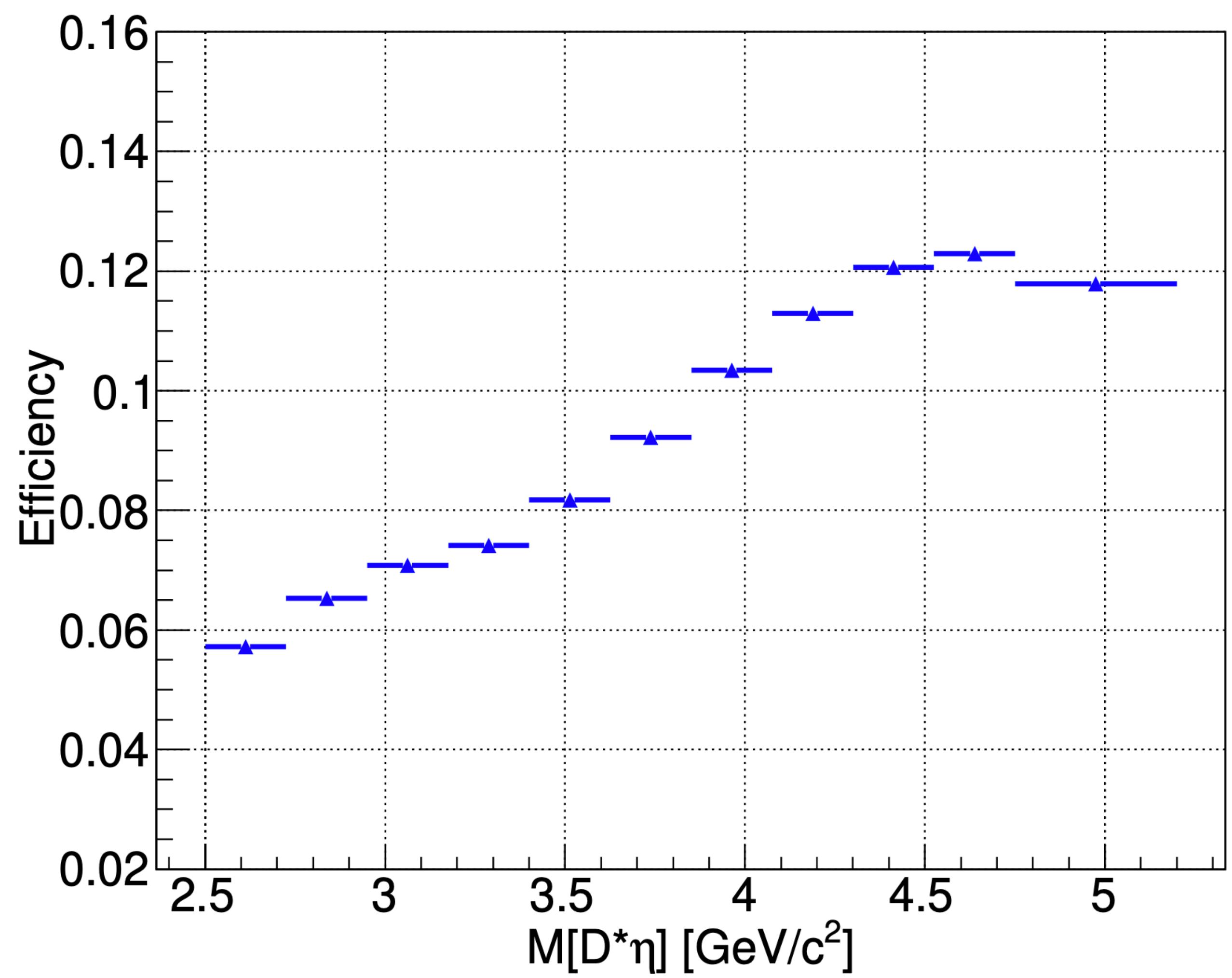


Notation	$s_l^{\pi_l}$	J^P	m (GeV)	Γ (GeV)
D	$\frac{1}{2}^-$	0^-	1.87	
D^*	$\frac{1}{2}^-$	1^-	2.01	
D_0^*	$\frac{1}{2}^+$	0^+	2.40	0.28
D_1^*	$\frac{1}{2}^+$	1^+	2.44	0.38
D_1	$\frac{3}{2}^+$	1^+	2.42	0.03
D_2^*	$\frac{3}{2}^+$	2^+	2.46	0.04
D'	$\frac{1}{2}^-$	0^-	2.54	0.13
D'^*	$\frac{1}{2}^-$	1^-	2.61	0.09

Have different models to test sensitivity (use also phase space for comparison)

Efficiency for different models



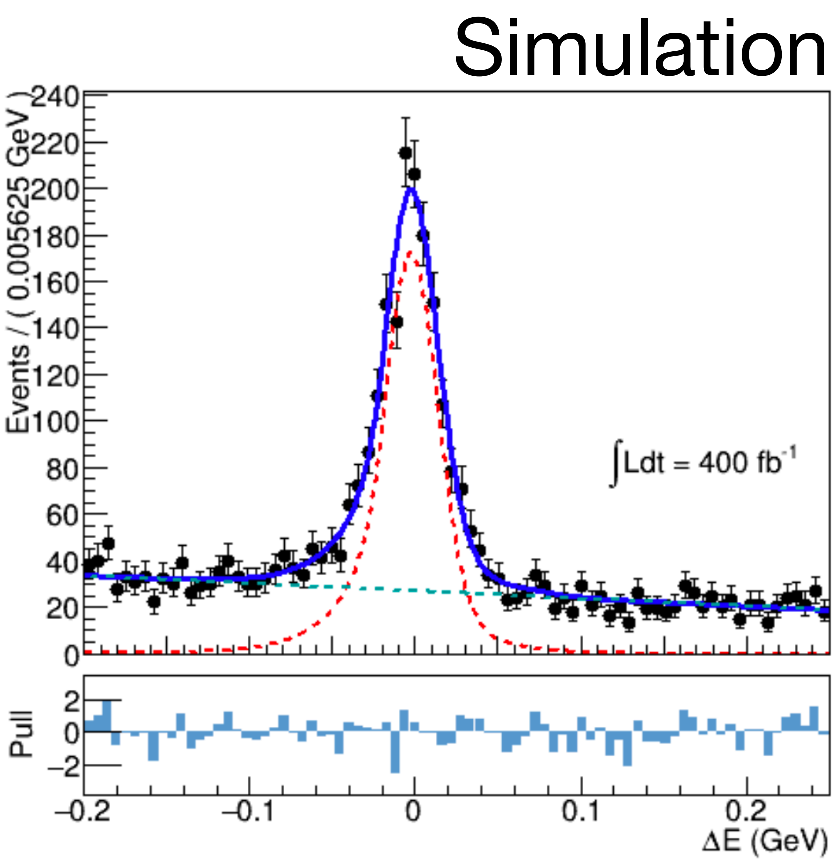


	Phase space	$B^0 \to D^{'*}\pi^+$	$B^0 \to D^{'}\pi^+$	$B^0 \to D_1^*\pi^+$
Signal efficiency	9.5%	5.5%	5%	5.1%

Fitting the signal

(Using phase space model as example)

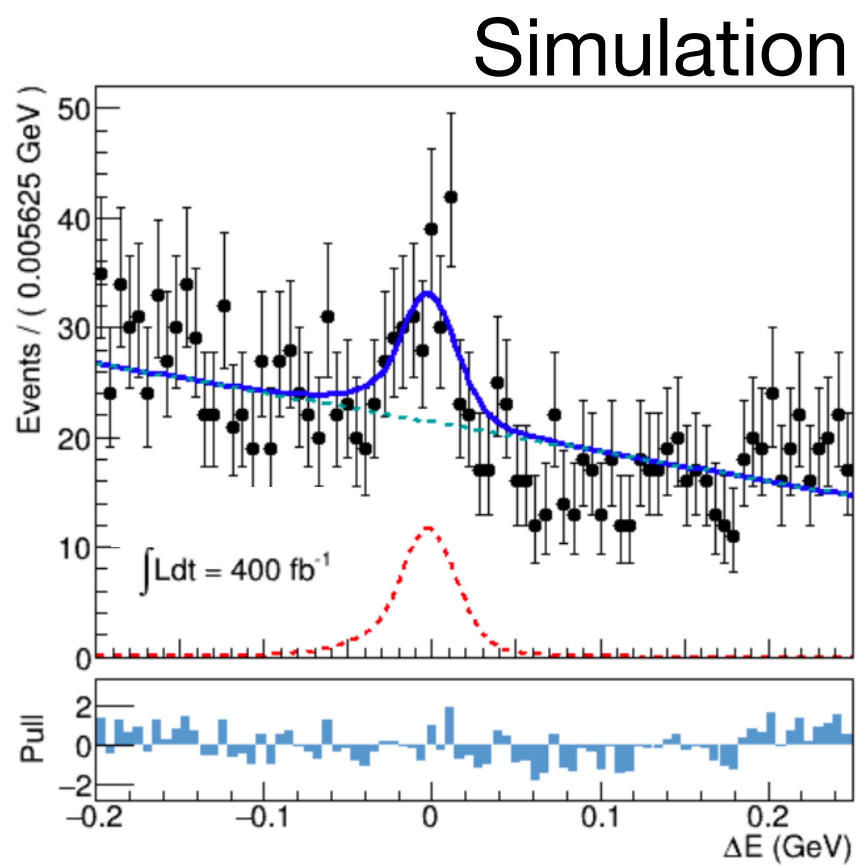
$BR_{gen} = 3.4 \times 10^{-3}$



$N_{sig} = 1560 \pm 50$

$BR = (3.6 \pm 0.1) \times 10^{-3}$

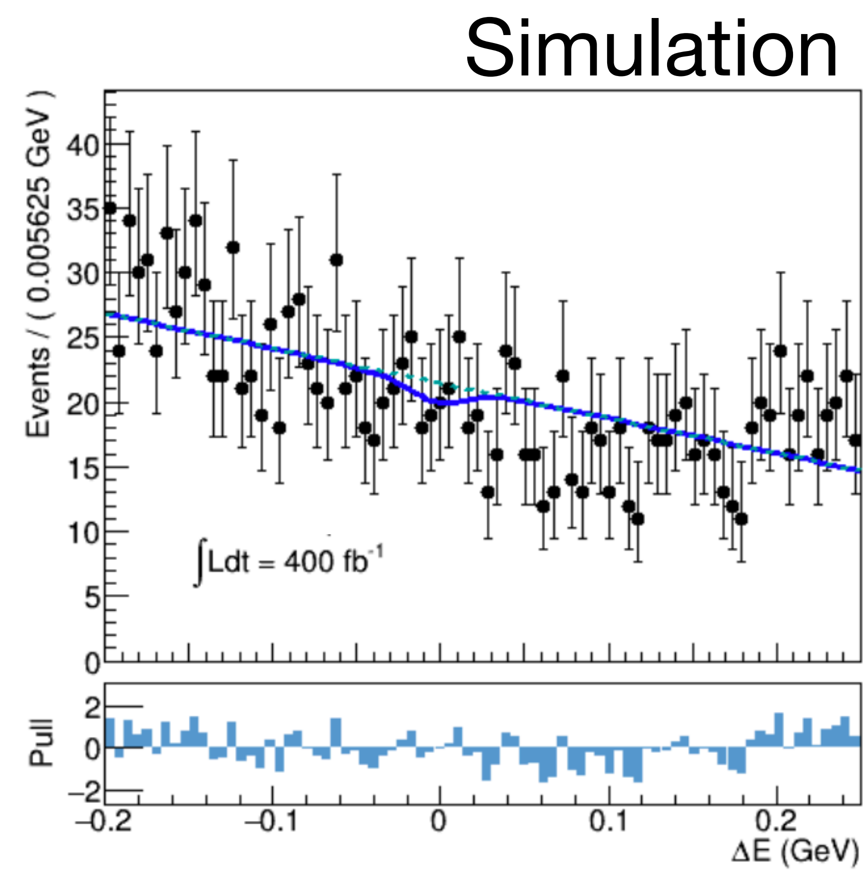
$BR_{gen} = 0.3 \times 10^{-3}$



$N_{sig} = 100 \pm 22$

$BR = (0.25 \pm 0.05) \times 10^{-3}$

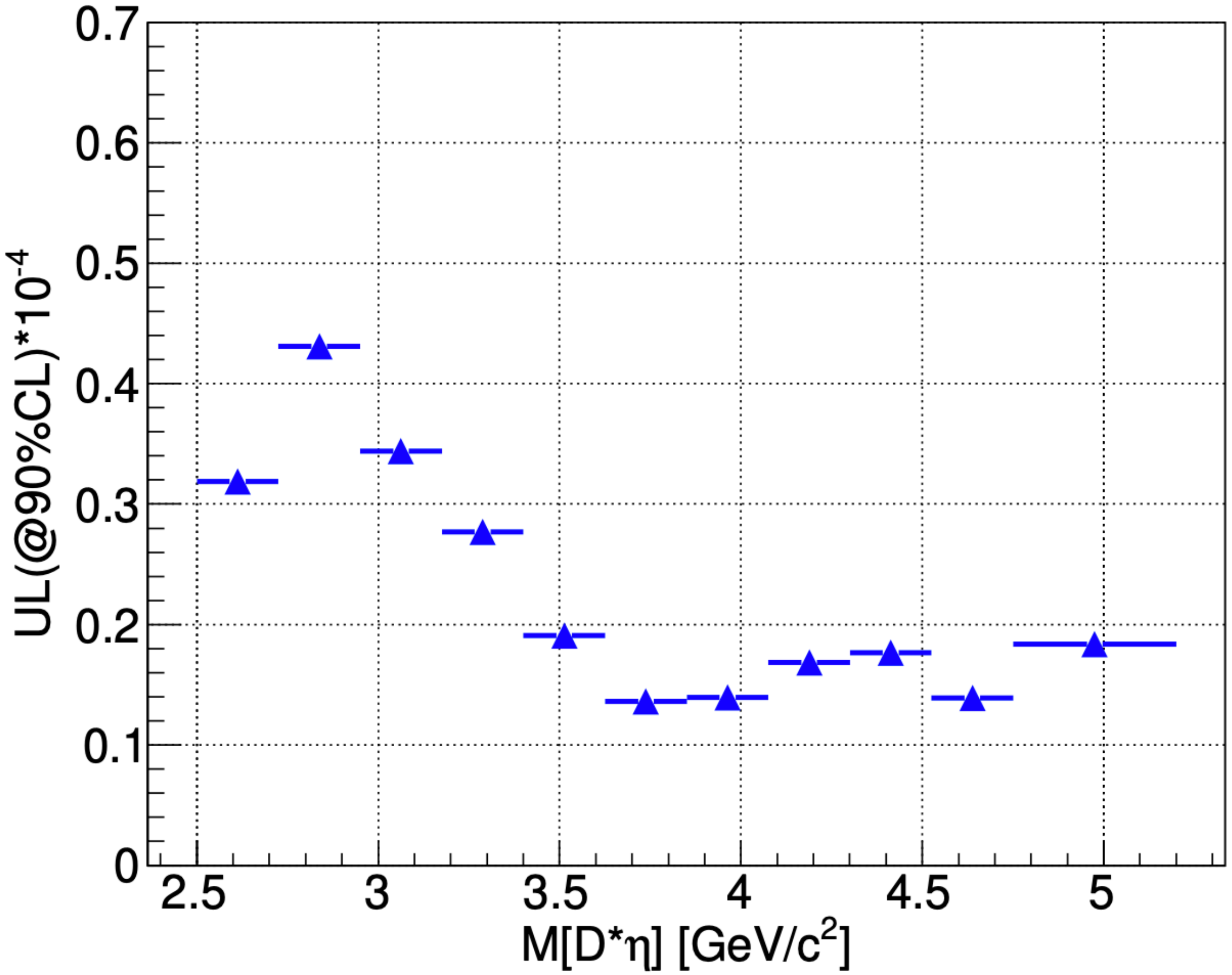
$BR_{gen} = 0$



$N_{sig} = -10 \pm 20$

$< 0.7 \times 10^{-4}$ @90%CL

Prospects



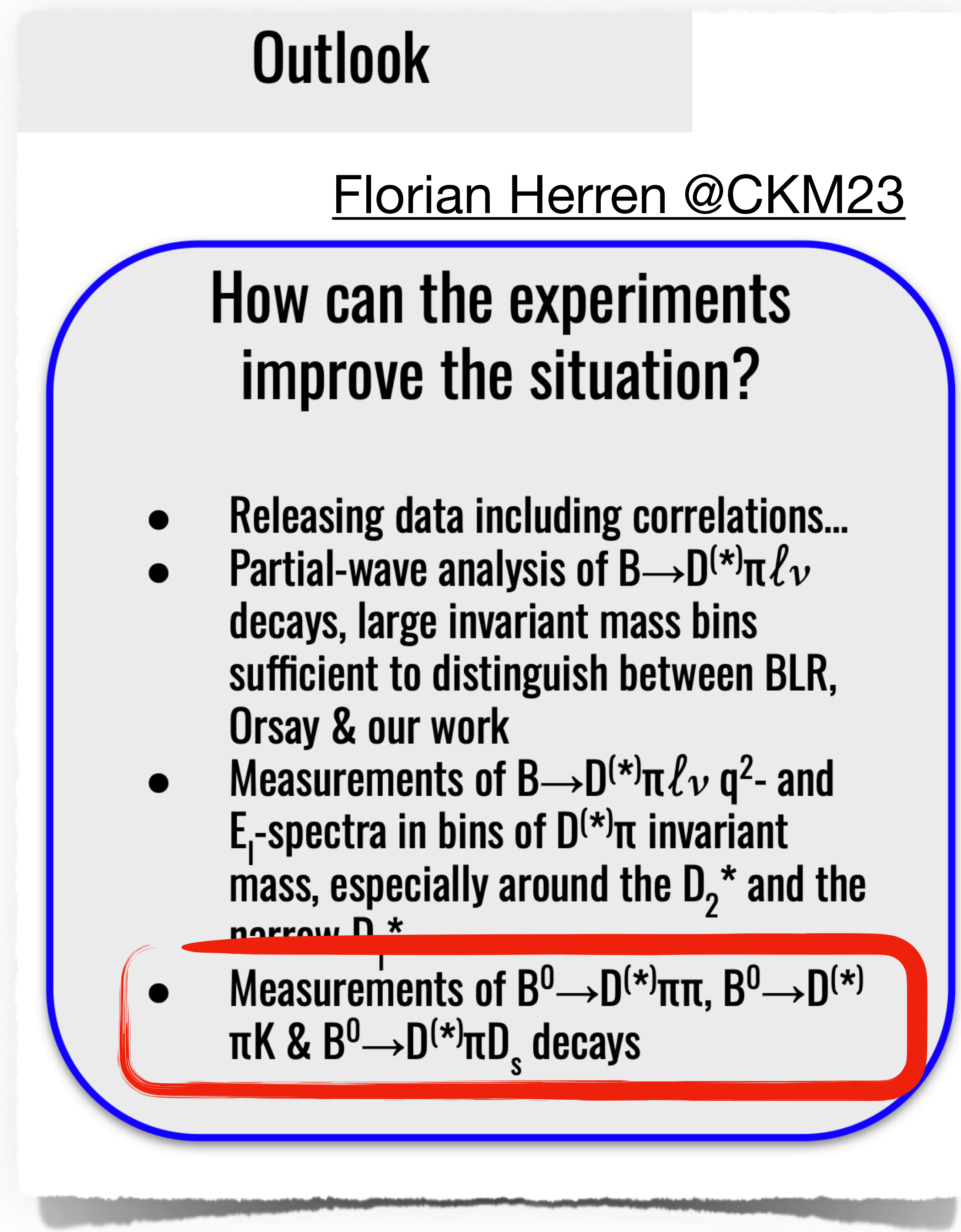
- From model used to fill SL gap, BR($B \to D^* \eta l \nu$)~4×10^{-3}, naively should expect BR($B \to D^* \eta l \nu$)~2×10^{-4}
- We are sensitive to this BR in the current Belle II dataset. Extending the analysis to Belle+Belle II to boost the reach.
- Would be very helpful to have better prediction and link with SL mode BR.

	Phase space	$B \to D^{'*} \pi$	$B \to D^{'} \pi$	$B \to D_1^* \pi$
UL(90% CL) (10^{-4})	0.68	0.65	0.71	0.82

Towards $B \rightarrow D^{**} X$?

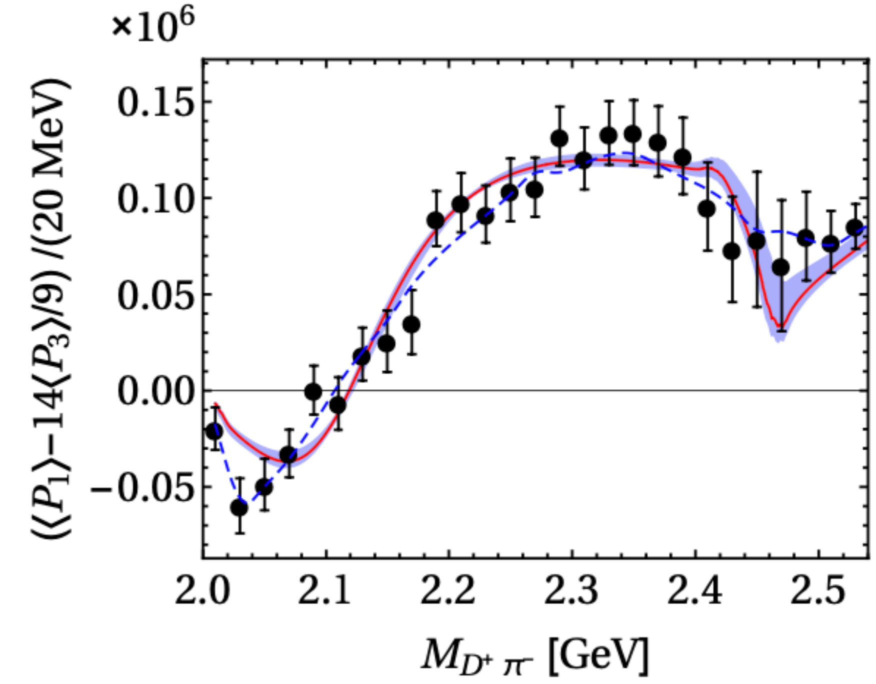
Why B→D**X?

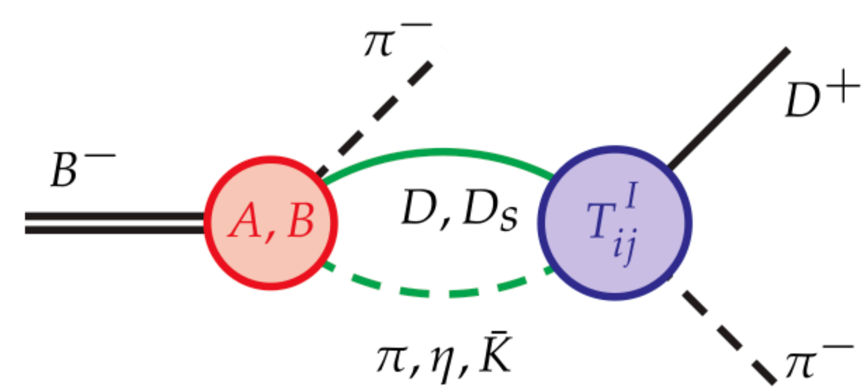
- B→D**lv poorly known (Florian just presented the status).
- Most Belle (II) analysis uses BLR-LLSW model (1606.09300,1711.03110).
- Some recent observations
  - LeYaouanc,Leroy,Roudeau: need to include virtual B→D* component
  - Belle analysis (2211.09833) observes significantly lower BR(B→D_0*)

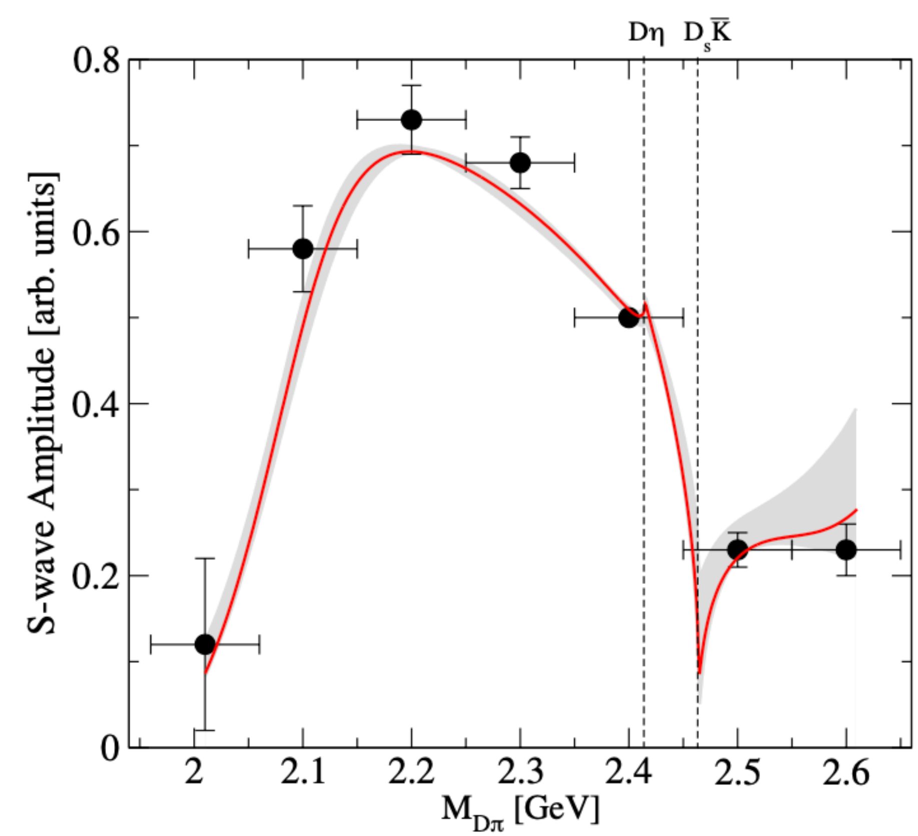


$B^+ \to D^- \pi^+ \pi^+$ analysis

- 2012.04599: D_0^* is a two pole structure with masses at 2.1 and 2.45 GeV (instead that 2.3 GeV) compatible with lattice and LHCb data (1608.01289)
- Use partial waves amplitudes and decomposed in production (weak) vertex and a rescattering vertex
- Need more data to resolve the cusp structure for unambiguous interpretation.
- Are we doomed by LHCb superior sample size for track-only final states?

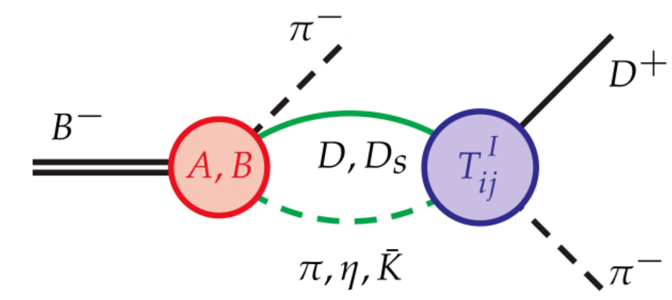






Belle II potential?

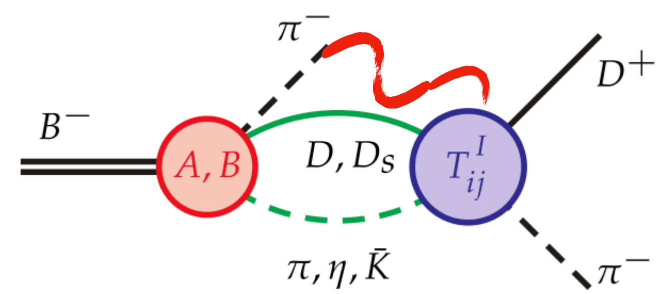
- Can profit from our strength with neutrals, can provide complementary information.
    - B→Dηπ proves again useful.
- Certainly much more to exploit.



Process	Production amplitude
$B^- \to D^0\pi^0\pi^-$	$\frac{1}{F_0}(c_1 + c_4)p_D \cdot p_\pi$
$B^- \to D^0\eta\pi^-$	$\frac{1}{\sqrt{3}F_0}(c_1 + c_4 + 2c_2 + 2c_6)p_D \cdot p_\eta$
$B^- \to D^+\pi^-\pi^-$	$\frac{2\sqrt{2}}{F_0}(c_1 + c_4)p_D \cdot p_\pi$
$B^- \to D_s^+K^-\pi^-$	$\frac{\sqrt{2}}{F_0}(c_1 + c_4)p_{D_s} \cdot p_K$

Reaction	Weak production vertex
$B_s^0 \to \bar{D}^0K^-\pi^+$	$E_K\big((c_2 + c_4) + (d_2 + d_4)\big)$
$B_s^0 \to D^-\bar{K}^0\pi^+$	$E_K\big((c_1 + c_4) + (d_1 + d_4)\big)$
$B_s^0 \to \bar{D}_s\eta\pi^+$	$\frac{\sqrt{2}}{\sqrt{3}}\frac{M_{D_s}}{M_D}E_\eta\big((c_6 - c_4) - d_4\big)$
$B_s^0 \to \bar{D}_s\pi^0\pi^+$	$\sqrt{2}\frac{M_{D_s}}{M_D}E_\pi d_6$
$B^0 \to \bar{D}^0\pi^-\pi^+$	$E_\pi\big((c_2 + c_3 + c_4 + 2c_5) + (d_2 - d_3 + d_4)\big)$
$B^0 \to D^-\eta\pi^+$	$\frac{1}{\sqrt{6}}E_\eta\big((c_1 + 2c_3 + c_4 + 2c_6) + (d_1 + d_4)\big)$
$B^0 \to D_s^-K^0\pi^+$	$\frac{M_{D_s}}{M_D}E_K\big((c_3 + c_4) - (d_3 - d_4)\big)$
$B^0 \to D^-\pi^0\pi^+$	$-\frac{1}{\sqrt{2}}E_\pi\big((c_1 + c_4) + (d_1 - 2d_3 + d_4 - 2d_6)\big)$
$B^0 \to \bar{D}^0\pi^-K^+$	$-\sin\theta_1 E_\pi\big((c_2 + c_4) + (d_2 + d_4)\big)$
$B^0 \to D^-\pi^0K^+$	$-\sin\theta_1\frac{1}{\sqrt{2}}E_\pi\big(-(c_4 - c_6) - (d_4 - d_6)\big)$
$B^0 \to D^-\eta K^+$	$-\sin\theta_1\frac{1}{\sqrt{6}}E_\eta\big((c_4 - c_6) + (d_4 + 3d_6)\big)$
$B^0 \to D_s^-K^0K^+$	$-\sin\theta_1\frac{M_{D_s}}{M_D}E_K\big((c_1 + c_4) + (d_1 + d_4)\big)$
$B^- \to D^0\pi^0K^-$	$-\sin\theta_1\frac{1}{\sqrt{2}}E_\pi\big((c_1 + c_4 + c_2 + c_6) - (d_1 - d_2 - d_4 - d_6)\big)$
$B^- \to D^0\eta K^-$	$-\sin\theta_1\frac{1}{\sqrt{6}}E_\eta\big((c_1 + c_4 - c_2 - c_6) - (d_1 - 3d_2 - d_4 - 3d_6)\big)$
$B^- \to D^+\pi^-K^-$	$-\sin\theta_1 E_\pi\big((c_1 + c_4) - (d_1 - d_4)\big)$
$B^- \to D_s^+K^-K^+$	$-\sin\theta_1\frac{2M_{D_s}}{M_D}E_K(c_1 + c_4)$

Belle II potential?



- Can profit from our strength with neutrals, can provide complementary information.

  - B→Dηπ proves again useful.

- Certainly much more to exploit.

- Key question is: how much from this can be casted into useful information for B→D** l nu decays?

- Can we exploit isospin relation to bound non-factorisable effects?

$B^- \to D^0\pi^0K^-$	$-\sin\theta_1 \frac{1}{\sqrt{2}} E_\pi\big((c_1+c_4+c_2+c_6)-(d_1-d_2-d_4-d_6)\big)$
$B^- \to D^0\eta K^-$	$-\sin\theta_1 \frac{1}{\sqrt{6}} E_\eta\big((c_1+c_4-c_2-c_6)-(d_1-3d_2-d_4-3d_6)\big)$
$B^- \to D^+\pi^-K^-$	$-\sin\theta_1 E_\pi\big((c_1+c_4)-(d_1-d_4)\big)$
$B^- \to D_s^+K^-K^+$	$-\sin\theta_1 \frac{2M_{D_s}}{M_D} E_K(c_1+c_4)$

Priorities?

Where should we focus?

- Trivial priority: enhancing hadronic tagging needs better hadronic references. This is true for tagged SL measurements and any ME analysis in Belle II.

- And then?

  - $B \to D^{(*)} \eta \pi$ decays seem another clear one.

  - $B \to D \pi \pi$ can certainly help in shedding light in the nature of D^{**} states and line-shape studies. However:

    - need a strategy to bound rescattering effects to translate information to SL counterparts (can we resort to isospin symmetries? What else?)

    - Need to build more expertise in Belle II for amplitude analysis. Need to catch up with LHCb on this.

Backup

Bounding rescattering with isospin

From https://arxiv.org/pdf/1505.01710.pdf

$$A(\overline{D}^0\rho^+) = \sqrt{3}A_{3/2},$$
$$A(D^-\rho^+) = \sqrt{1/3}A_{3/2} + \sqrt{2/3}A_{1/2},$$
$$A(\overline{D}^0\rho^0) = \sqrt{2/3}A_{3/2} - \sqrt{1/3}A_{1/2},$$

$$\rightarrow \quad A(\overline{D}^0\rho^+) = A(D^-\rho^+) + \sqrt{2}A(\overline{D}^0\rho^0).$$

Heavy-quark limit and factorisation:

$$R_{D\rho} \equiv \frac{|A_{1/2}|}{\sqrt{2}|A_{3/2}|} = 1 + \mathcal{O}(\Lambda_{\rm QCD}/m_b)$$

$$\delta_{D\rho} = \mathcal{O}(\Lambda_{\rm QCD}/m_b)$$

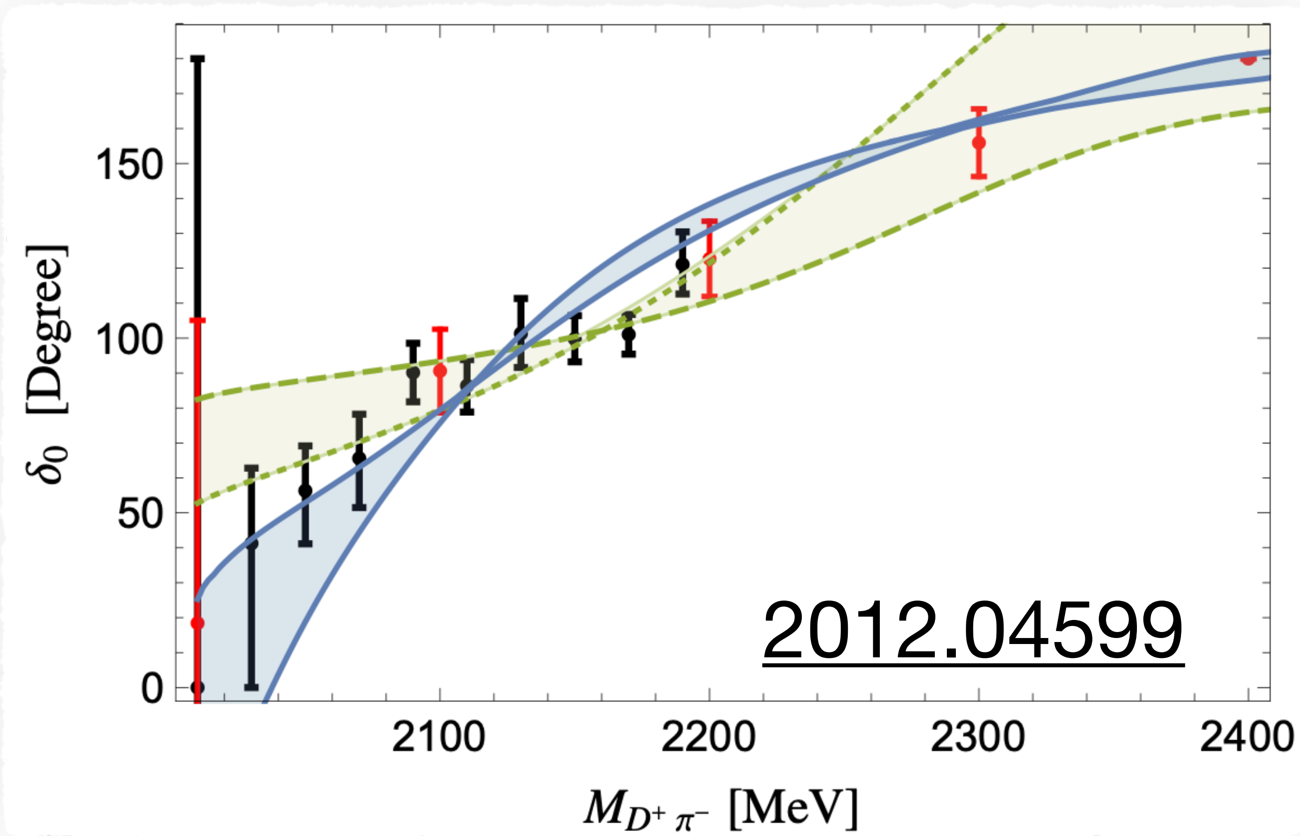
Rescattering phase

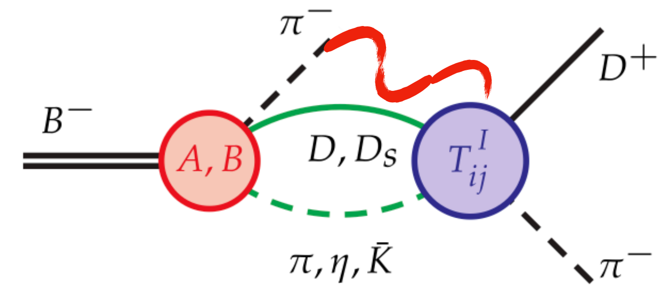
$$R_{D\rho} = \sqrt{\frac{1}{2}}\left(\frac{3\,(\mathcal{B}(D^-\rho^+) + \mathcal{B}(\overline{D}^0\rho^0))}{\mathcal{B}(\overline{D}^0\rho^+)} \times \frac{\tau_{B^+}}{\tau_{B^0}} - 1\right)^{1/2}$$

$$\cos\delta_{D\rho} = \frac{1}{4R_{D\rho}} \times \left(\frac{\tau_{B^+}}{\tau_{B^0}} \times \frac{3\,(\mathcal{B}(D^-\rho^+) - 2\,\mathcal{B}(\overline{D}^0\rho^0))}{\mathcal{B}(\overline{D}^0\rho^+)} + 1\right)$$

Model	$R_{D\rho}$	$\cos\delta_{D\rho}$
Isobar	0.69 ± 0.15	$0.984^{+0.113}_{-0.048}$
K-matrix	0.69 ± 0.15	$0.987^{+0.114}_{-0.048}$

Belle II potential?





- Key question is: how much from this can be casted into useful information for B→D** l nu decays?

- Can we exploit isospin relation to bound non-factorisable effects?

$B^- \to D^0\pi^0K^-$	$-\sin\theta_1 \frac{1}{\sqrt{2}} E_\pi\big((c_1+c_4+c_2+c_6)-(d_1-d_2-d_4-d_6)\big)$
$B^- \to D^0\eta K^-$	$-\sin\theta_1 \frac{1}{\sqrt{6}} E_\eta\big((c_1+c_4-c_2-c_6)-(d_1-3d_2-d_4-3d_6)\big)$
$B^- \to D^+\pi^-K^-$	$-\sin\theta_1 E_\pi\big((c_1+c_4)-(d_1-d_4)\big)$
$B^- \to D_s^+K^-K^+$	$-\sin\theta_1 \frac{2M_{D_s}}{M_D} E_K(c_1+c_4)$

B→D**D_s?

- Constrain FF for B->D** tau nu?
- Exploit recoil method? Do something similar to BaBar (~200/fb) for B->$D^{(*)}D_s^{(*)}$?

https://arxiv.org/abs/hep-ex/0605036