Status of the B anomalies: part 1

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Particle Flavour Fever Summer School

13/08/18

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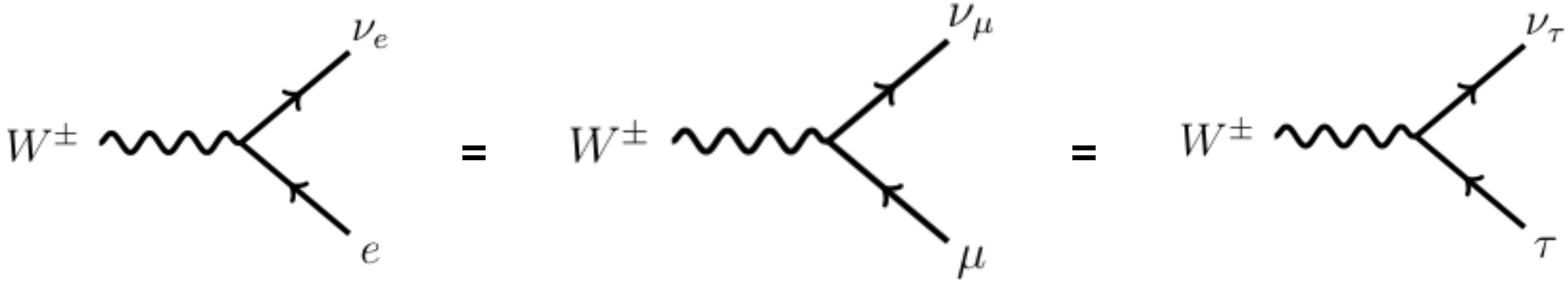
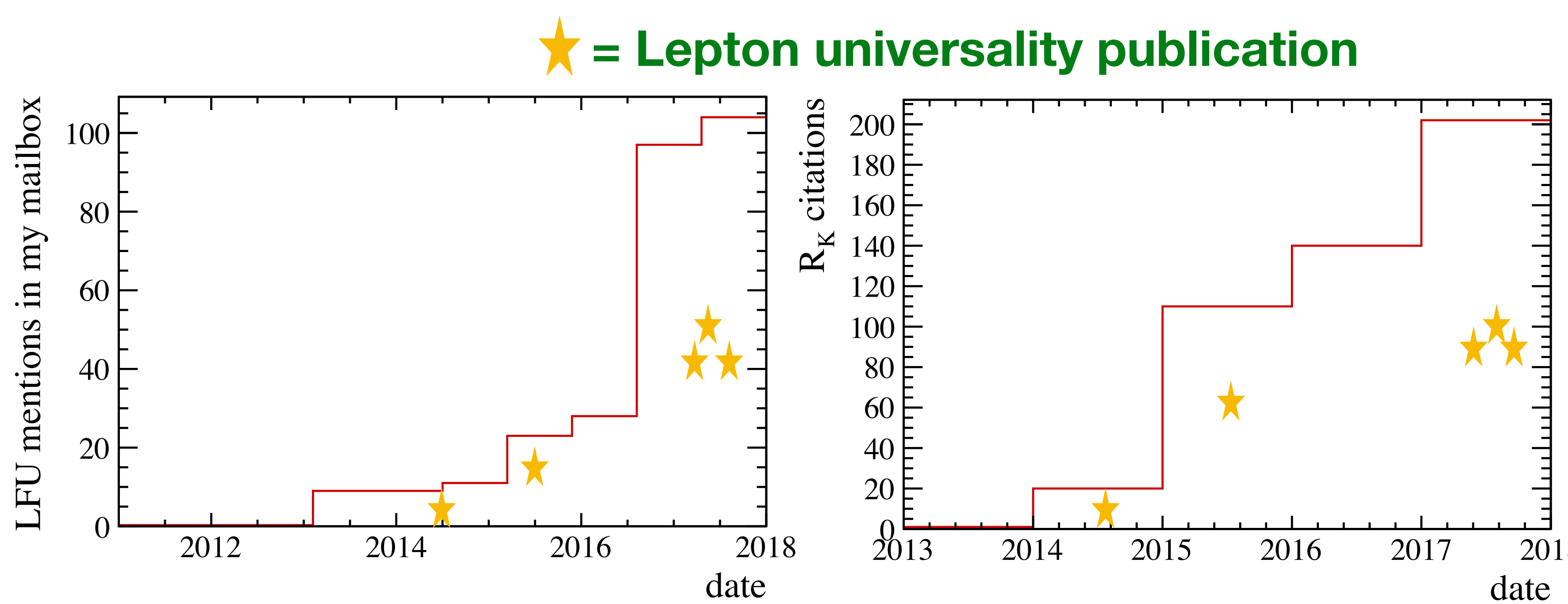
Lepton universality

This talk centres around experimental tests of lepton universality.

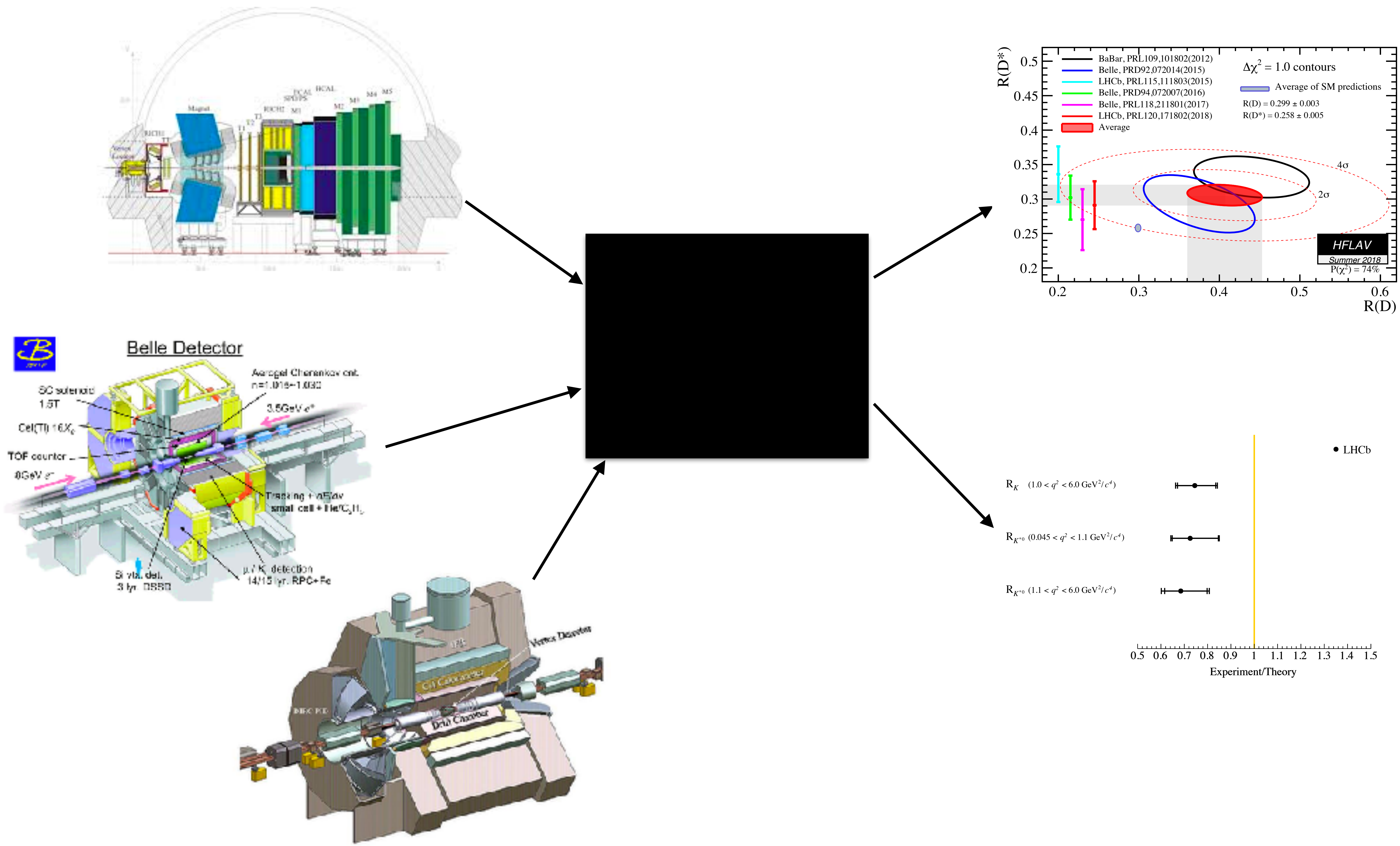


This very distinctive SM feature appears to be violated in semileptonic B decays

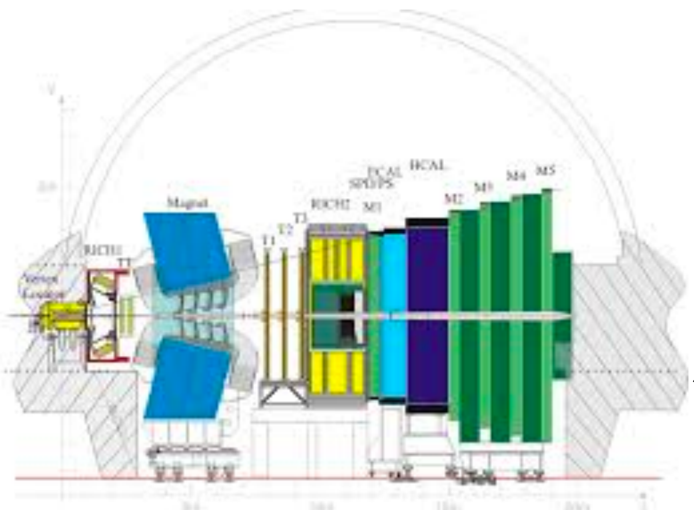
Its a very hot topic, at least in LHCb.

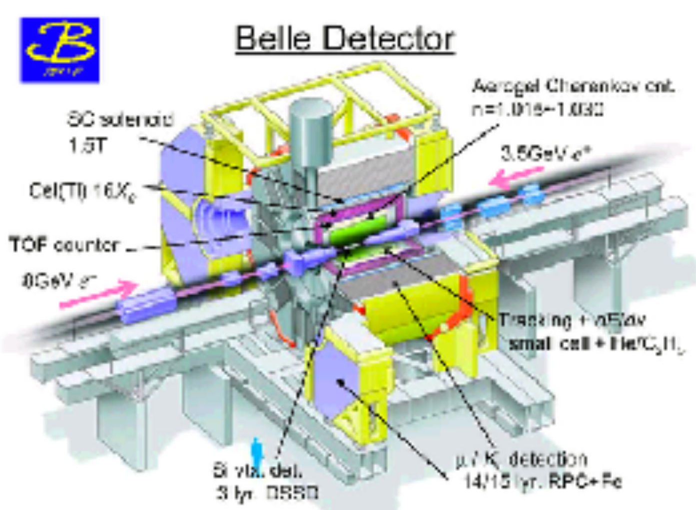


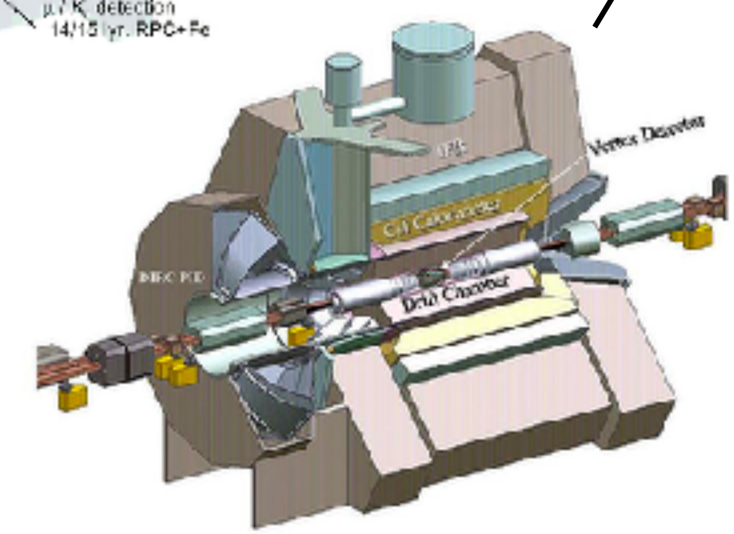
The black box

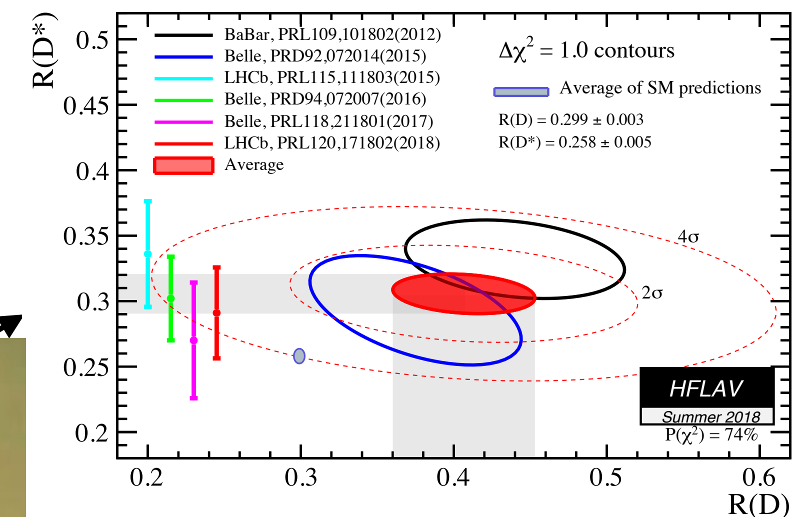


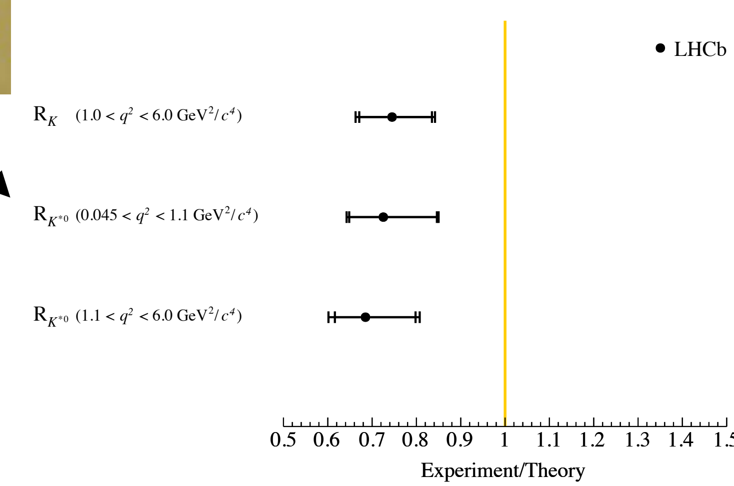
The black box











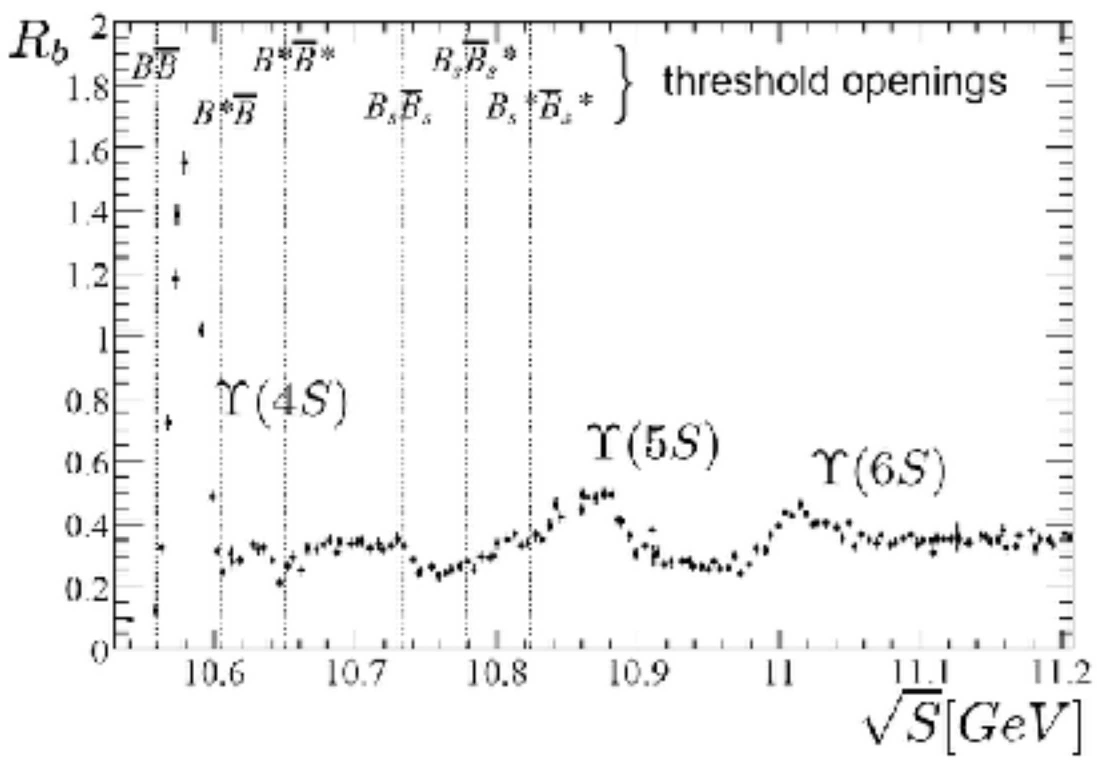
Outline

- Introduction to the relevant experiments
- Charged current tree-level anomalies (today)
- Neutral-current loop-level anomalies (Wednesday)
- Outlook

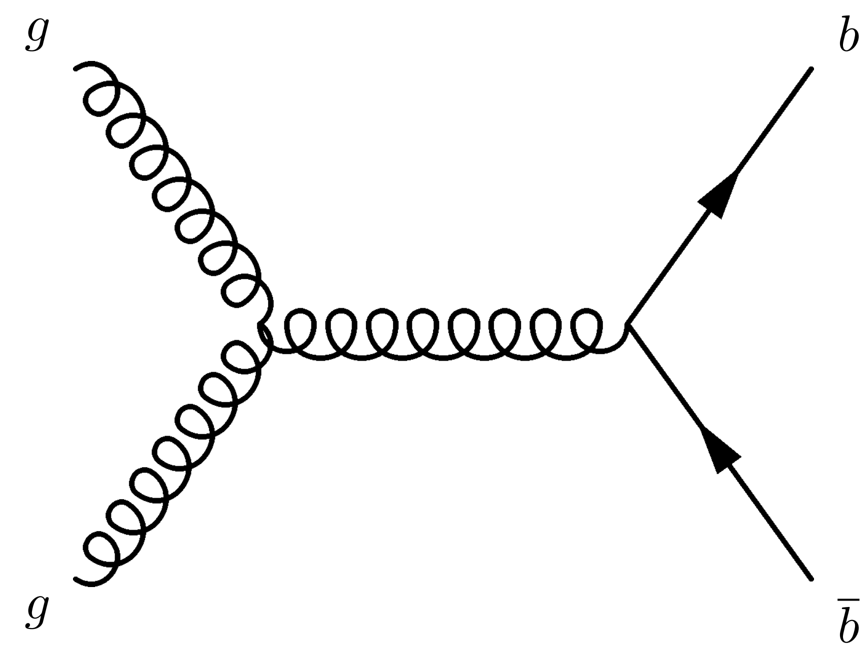
Let’s produce some Bs

- Firstly, let’s produce as many B’s as we can cope with.
- Can do this in two ways:

In e^+e^- collisions



At the LHC

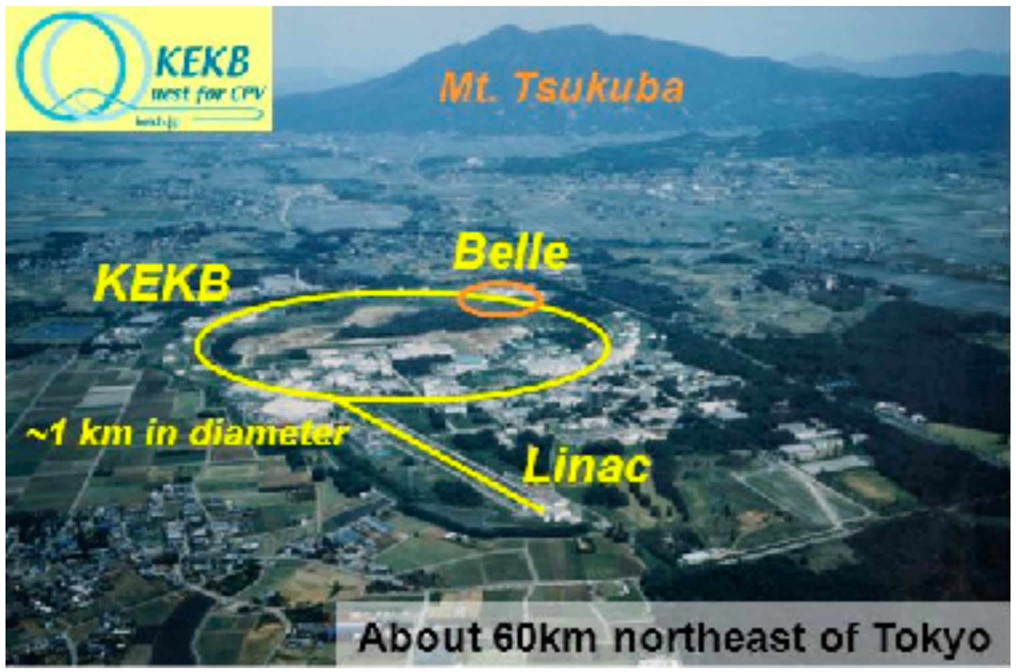


Both have advantages and disadvantages.

The experiments

- I will concentrate on the LHCb experiment, but its interesting to compare to the B-factories, as they are quite different approaches.

~2000-2010

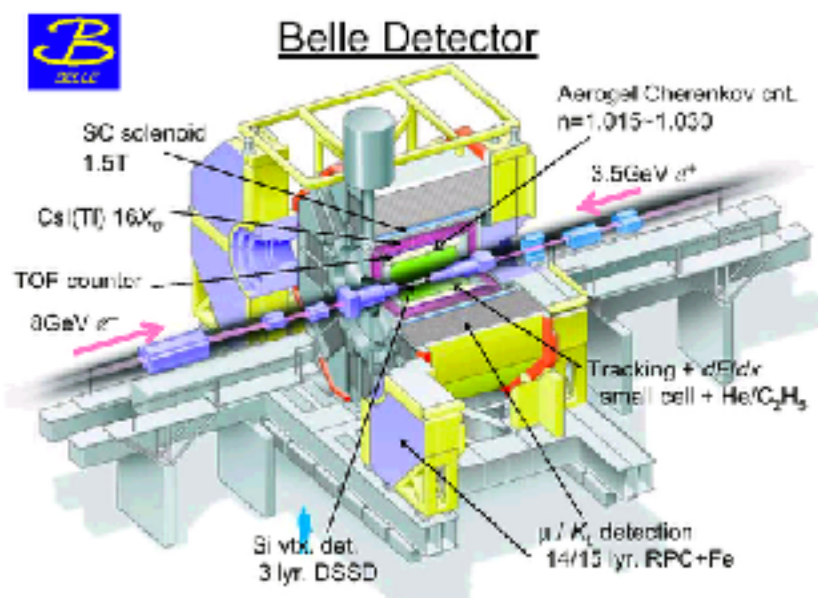


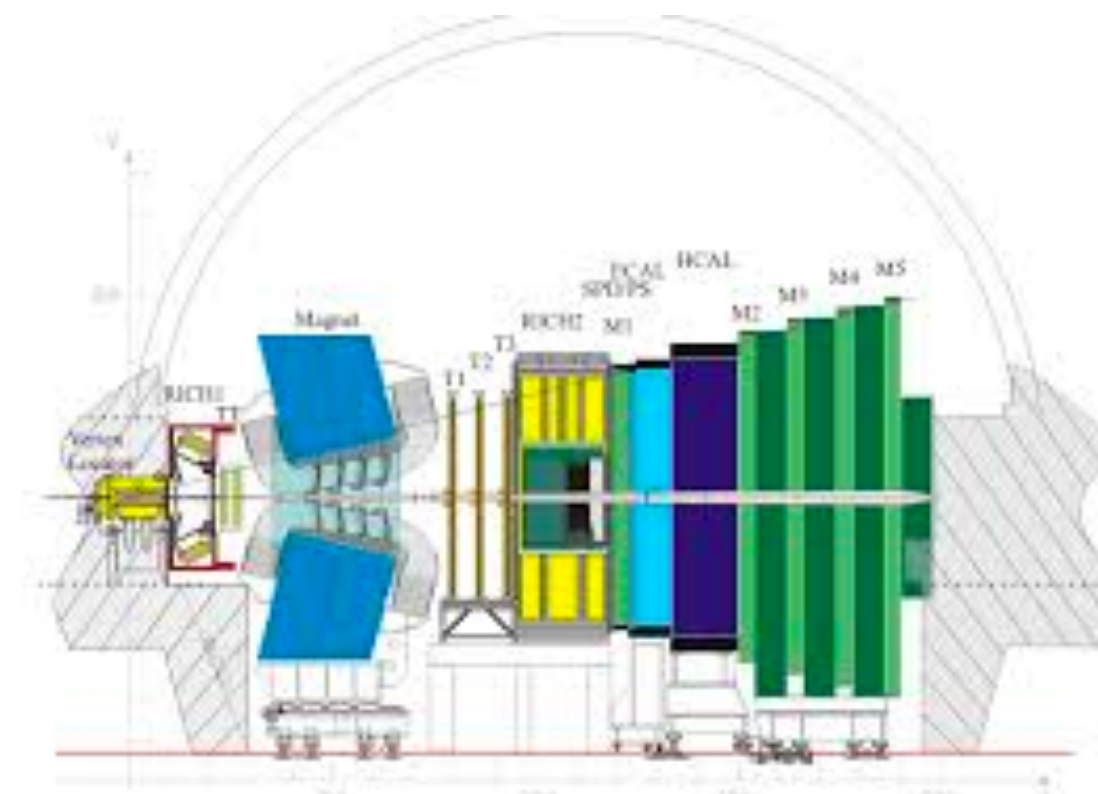
2009-present

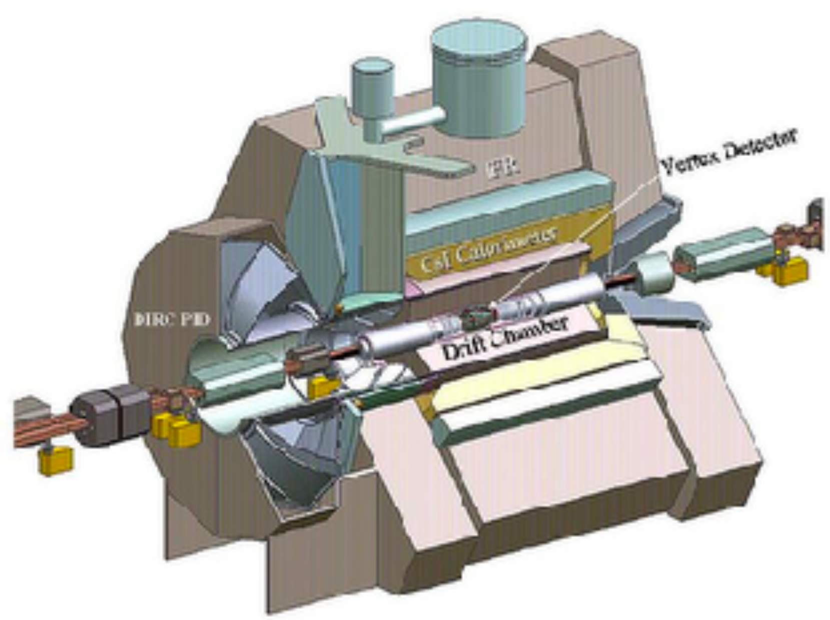
~2000-2008

The experiments

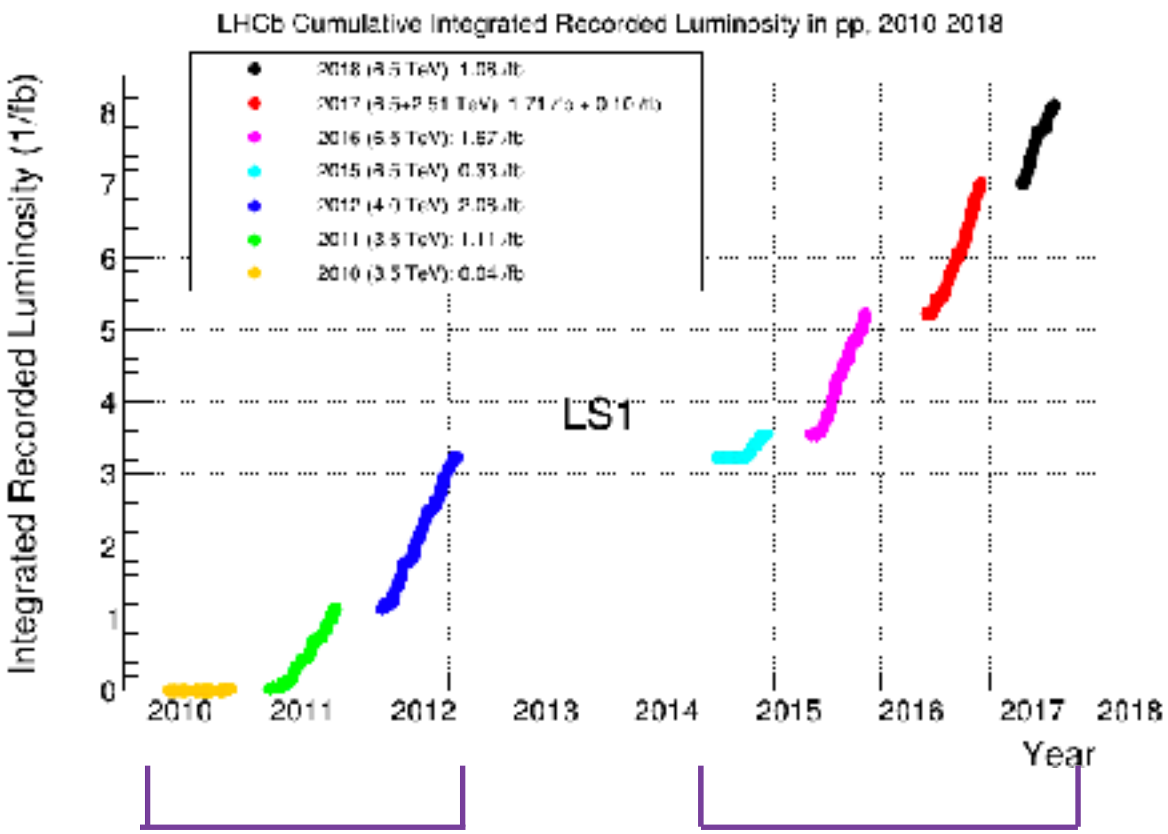
- I will concentrate on the LHCb experiment, but its interesting to compare to the B-factories, as they are quite different approaches.





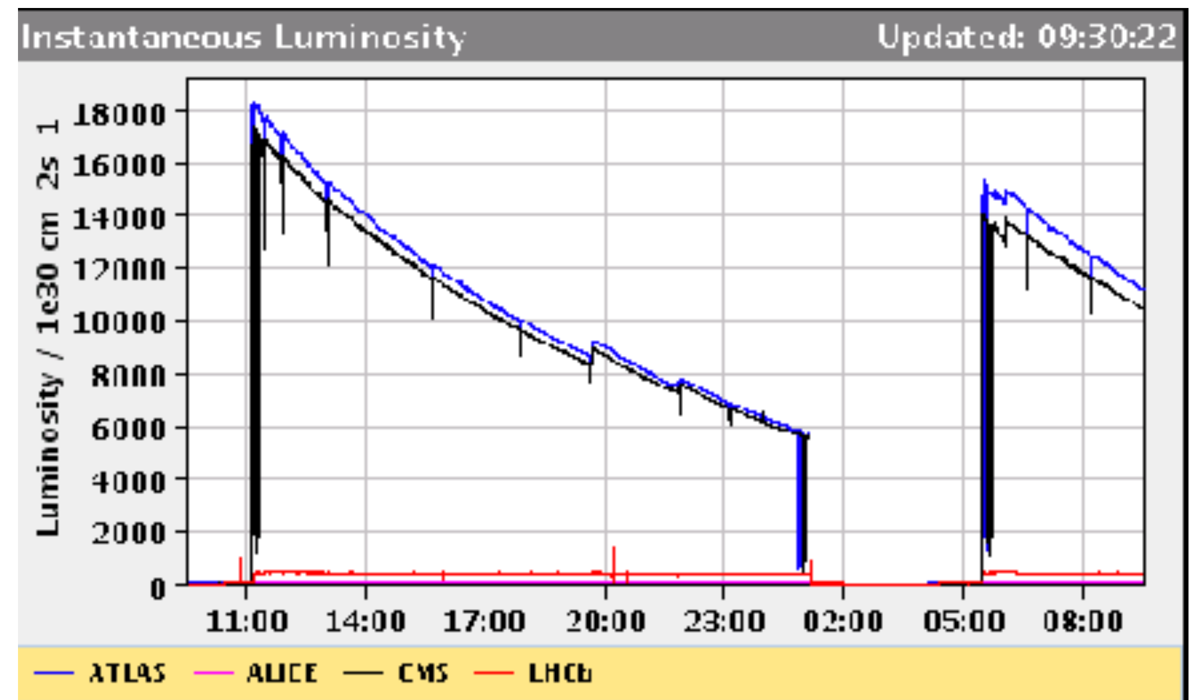


LHCb luminosity



Run I

Run II



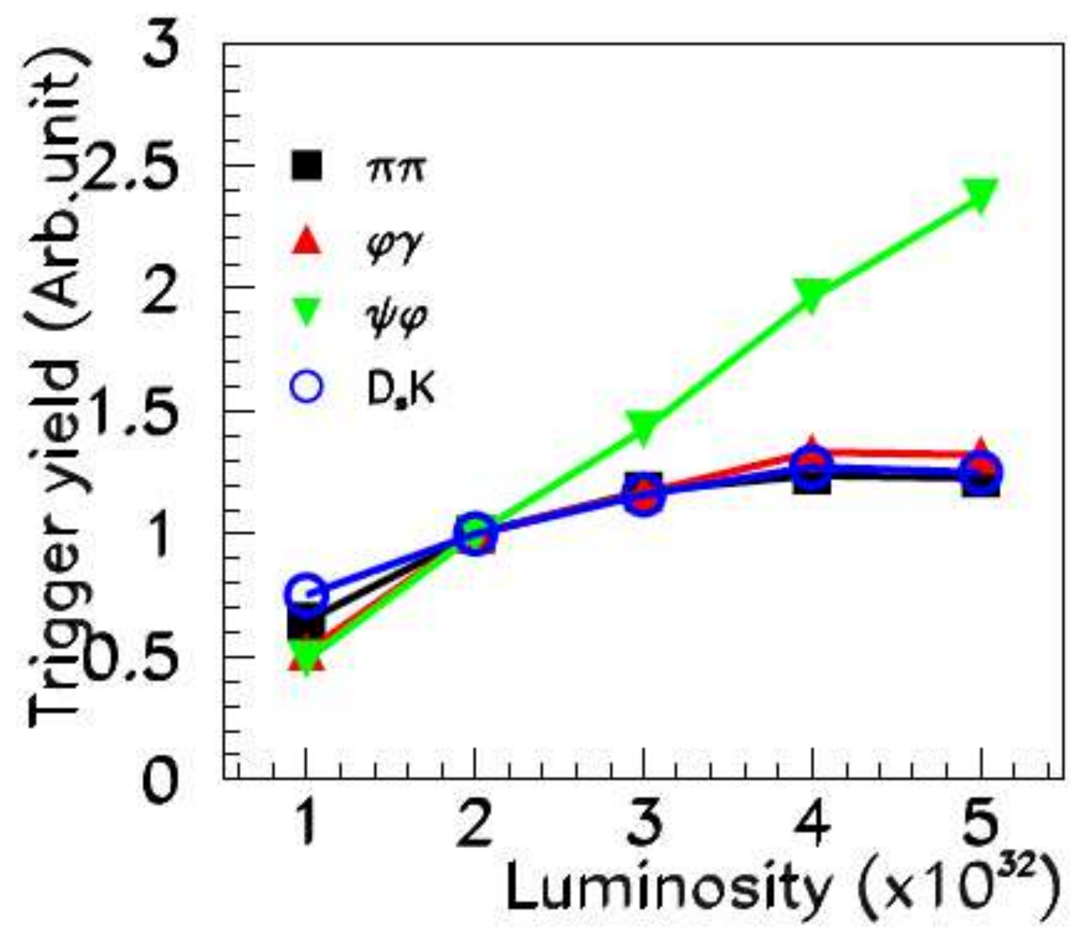
- Why don't we run at the same luminosity as CMS/ATLAS?

The luminosity bottleneck

- Collision rate ~30Mhz
- Electronics can read out at 1Mhz.
  - Must make trigger decisions based on only partial information.

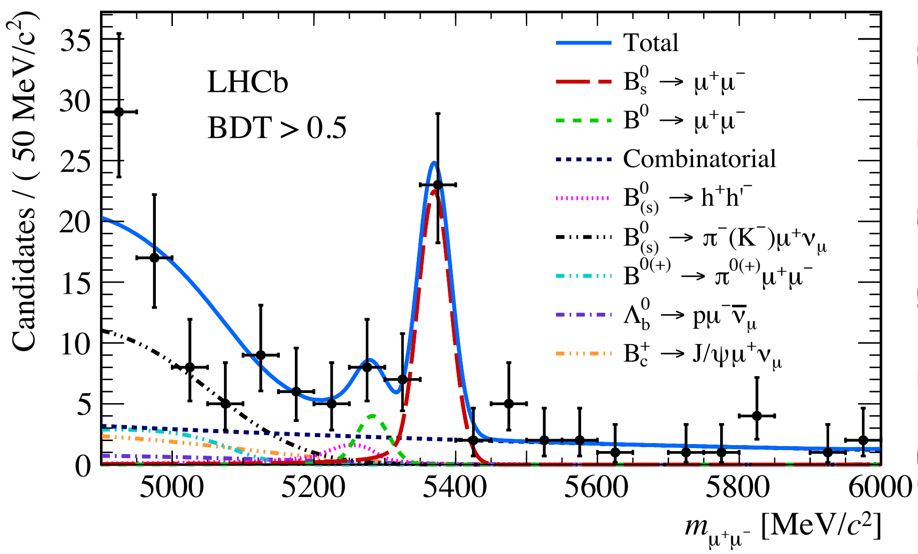
Require high PT muon or high ET ECAL/HCAL cluster.

This saturates rather quickly for hadronic B decays.



What’s important for B physics

- Good mass resolution



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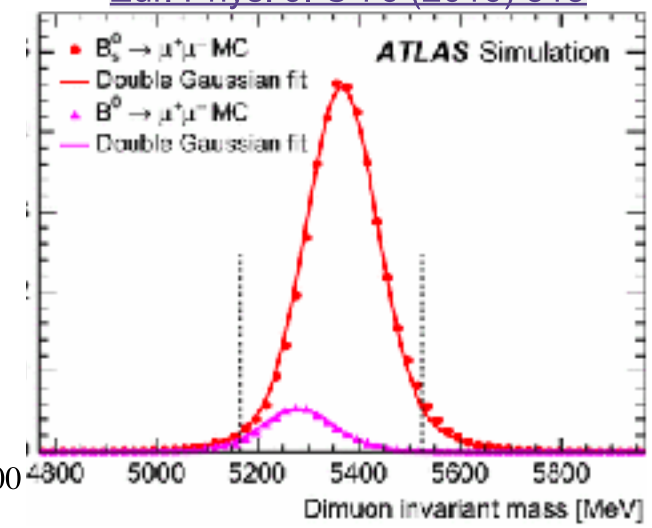
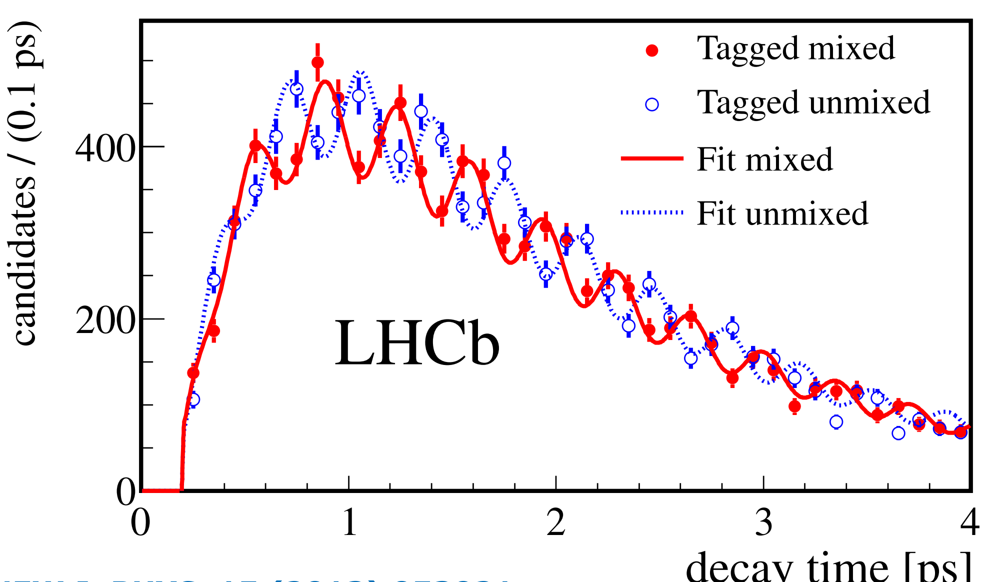


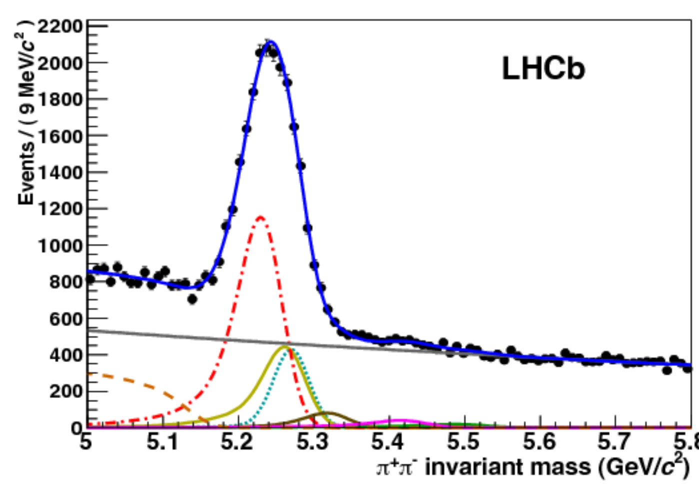
- Vertex resolution



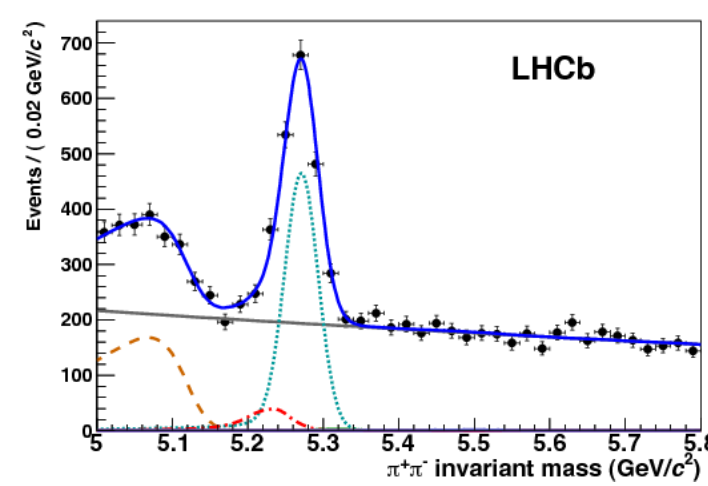
NEW J. PHYS. 15 (2013) 053021

- Hadron PID discrimination

Before PID



After PID



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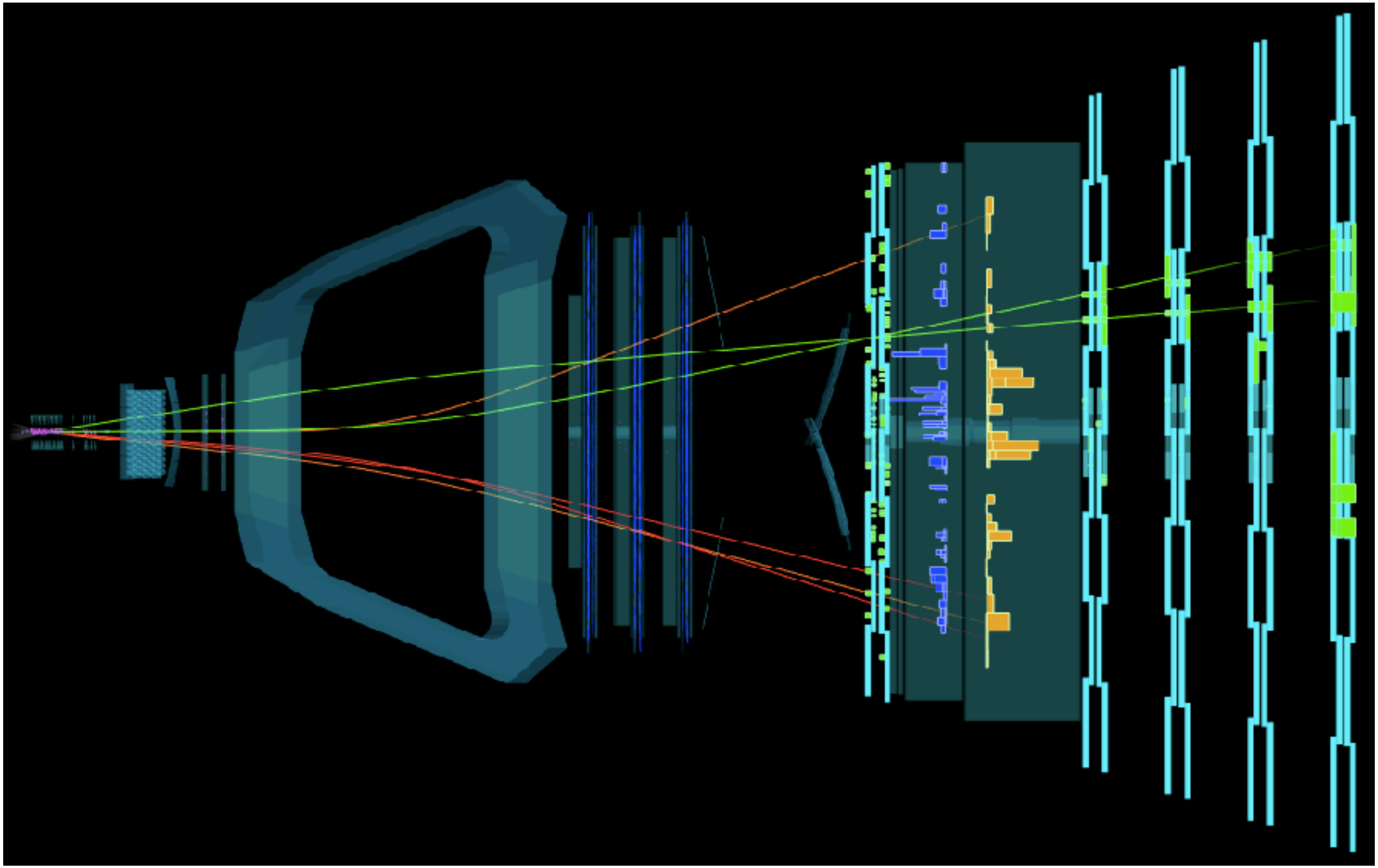
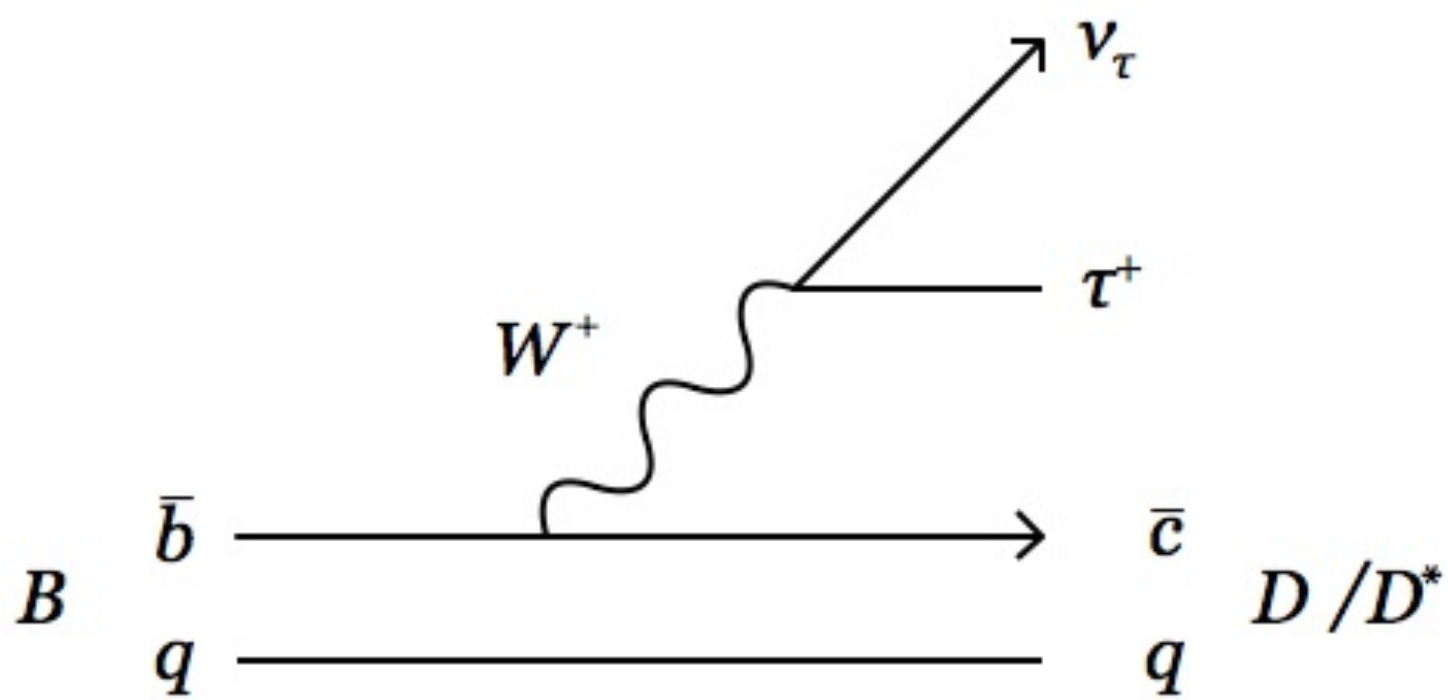
The signals



Why semi-leptonic decays?

- A decay is semi-leptonic if its products are part leptons and part hadrons.



$$\frac{d\Gamma}{dq^2}(B \to D\ell\nu) \propto$$

$$G_F^2 |V_{cb}|^2 f(q^2)^2$$

EW QCD

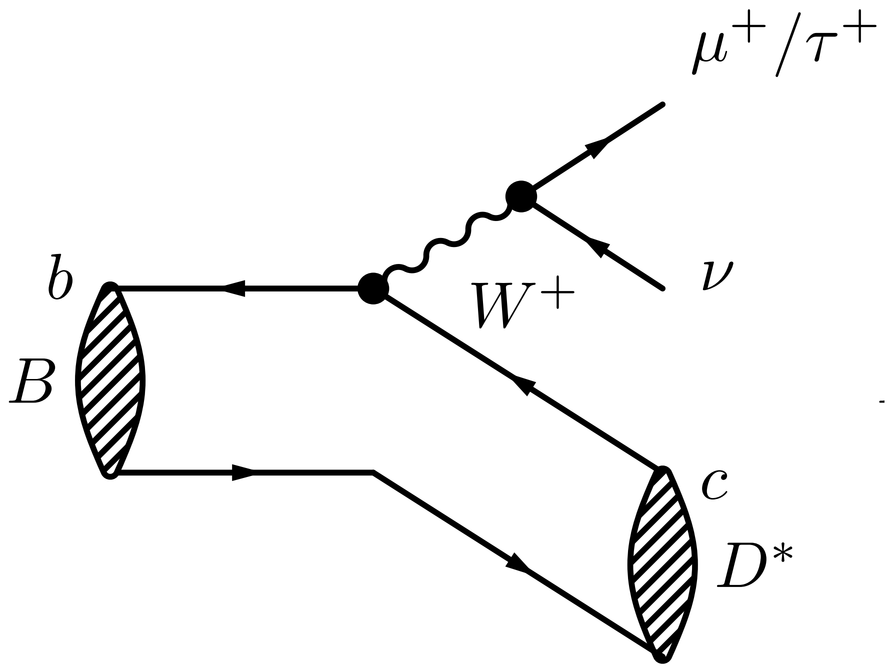
- These decays can be factorised, greatly simplifying theoretical calculations.

- Lepton universality ratios further cancel theoretical uncertainties.

Types of semi-leptonic decay

Two types of semi-leptonic B decay

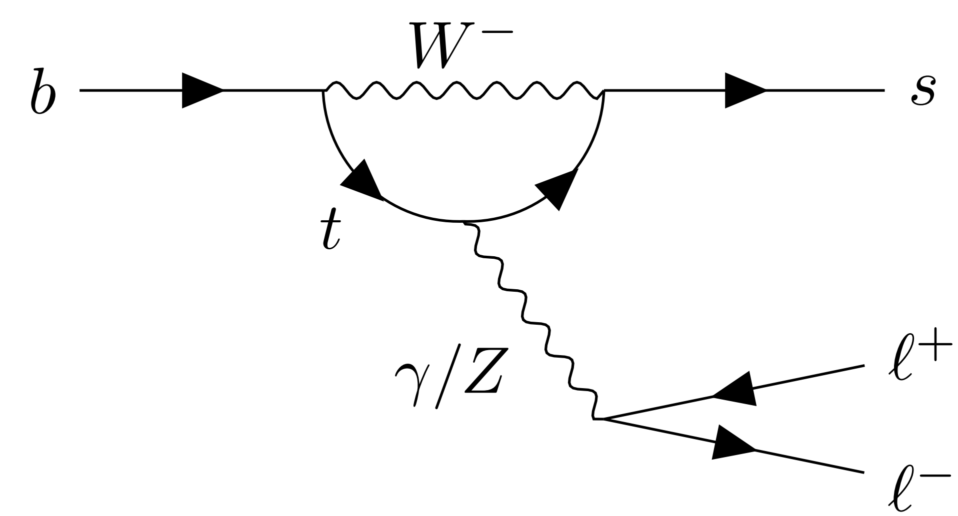
Charged current



Can proceed via tree level -large O(%) branching fractions.

NP sensitivity up to about 1 TeV

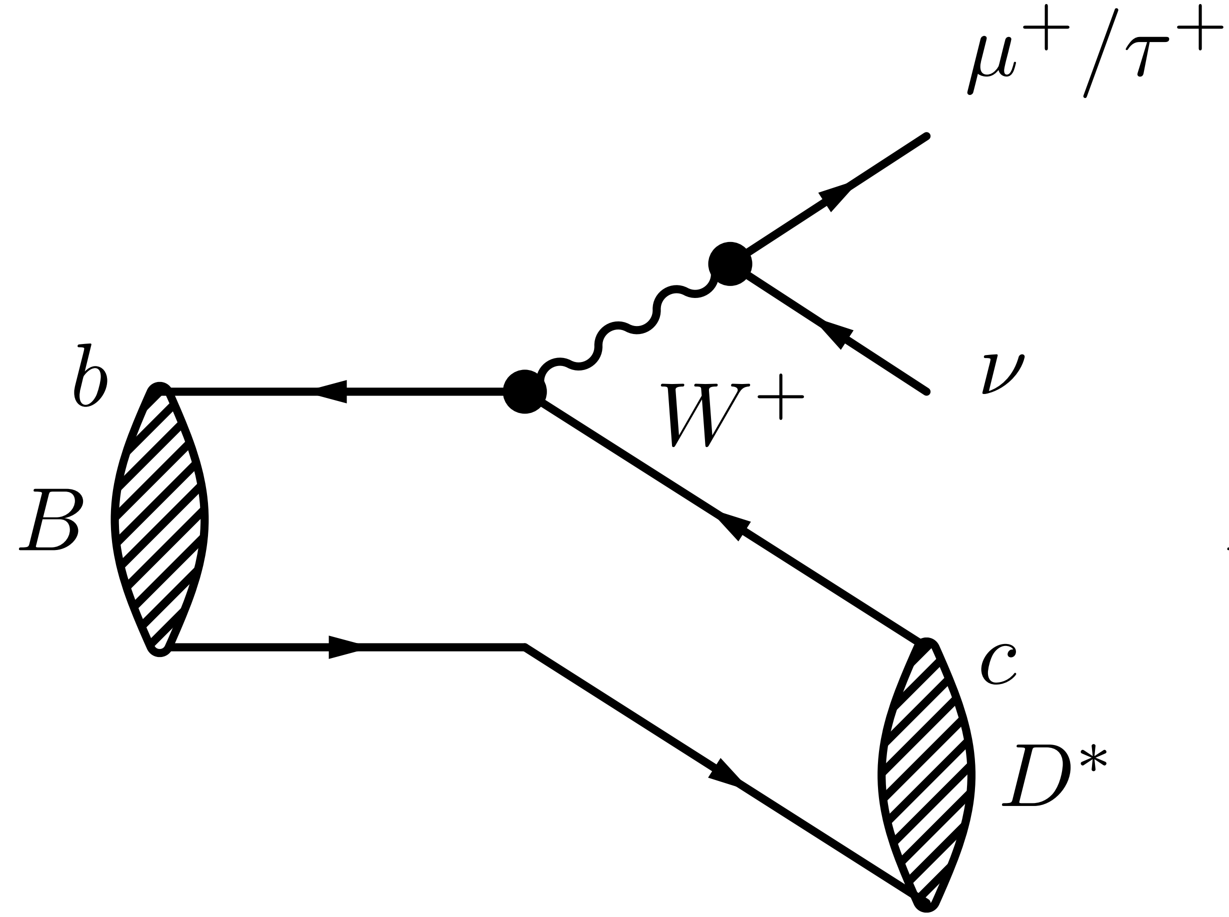
Neutral current



Forbidden at tree level - low O(10^{-6}) branching fractions.

NP sensitivity up to about 50 TeV

Tree-level $b \to c\ell\nu$ transitions



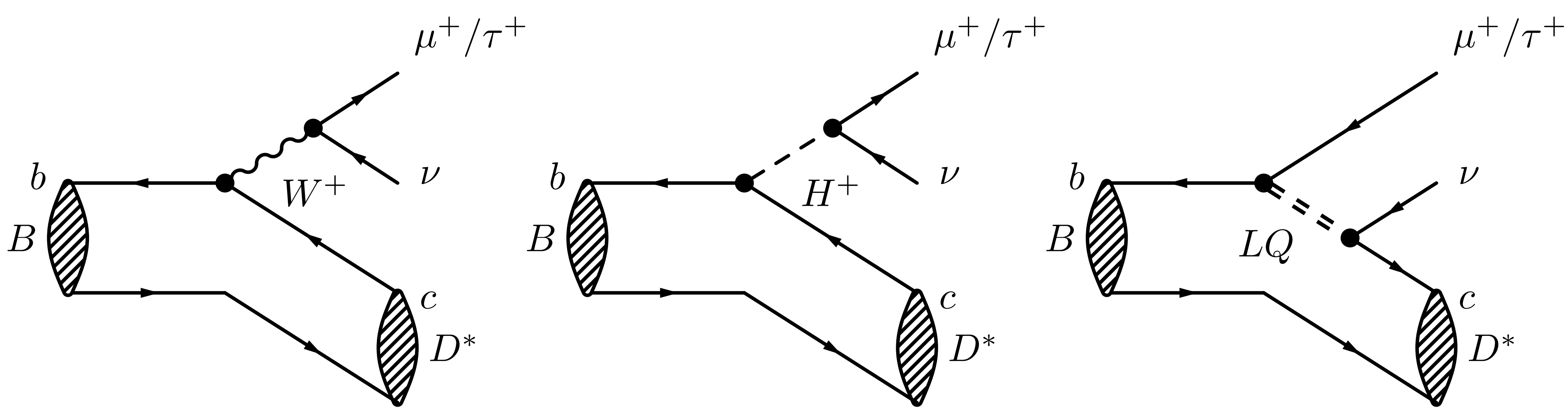
R(D*)

- Large rate of charged current decays allow for measurement in semi-tauonic decays.

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

- Form ratio of decays with different lepton generations.
- Cancel QCD/expt uncertainties (90% of R(D*), 50% of R(D)).

- R(D*) sensitive to any physics model favouring 3rd generation leptons (e.g. charged Higgs).



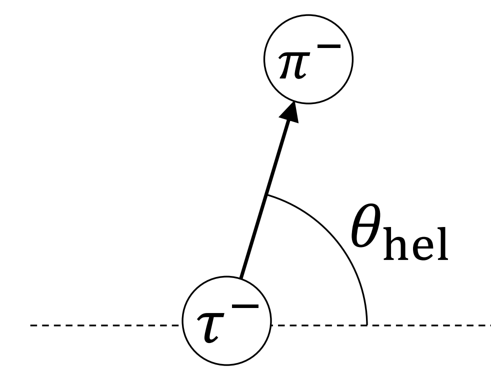
Who has made measurements

- Three experiments have made measurements

	BaBar	Belle	LHCb
#B's produced	O(400M)	O(700M)	O(800B)*
Production mechanism	$\Upsilon(4S) \to B\bar{B}$	$\Upsilon(4S) \to B\bar{B}$	$pp \to gg \to b\bar{b}$
Publications	Phys.Rev.Lett 109, 101802 (2012) Phys. Rev. D 88, 072012 (2013)	Phys.Rev.D 92, 072014 (2015) Phys. Rev. D 94, 072007 (2016) Phys. Rev. D 97, 012004 (2018)	Phys.Rev.Lett.115, 111803 (2015) Phys. Rev. Lett. 120, 171802 (2018)

* during run 1 of the LHC

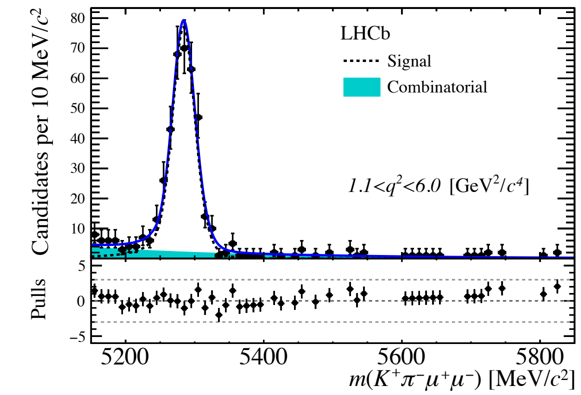
Tau decays

$\tau \to \mu\nu\nu$	$\tau \to 3\pi\nu$	$\tau \to \pi\nu$
Large statistics	More kinematic information	Good polarimeter
Efficiency largely cancels with muonic mode $B \to D^*(\tau \to \mu\nu\nu)\nu$ vs $B \to D^*\mu\nu$	Precise tau flight information	
Tau decay well understood	No background from muonic modes	Tau decay well understood

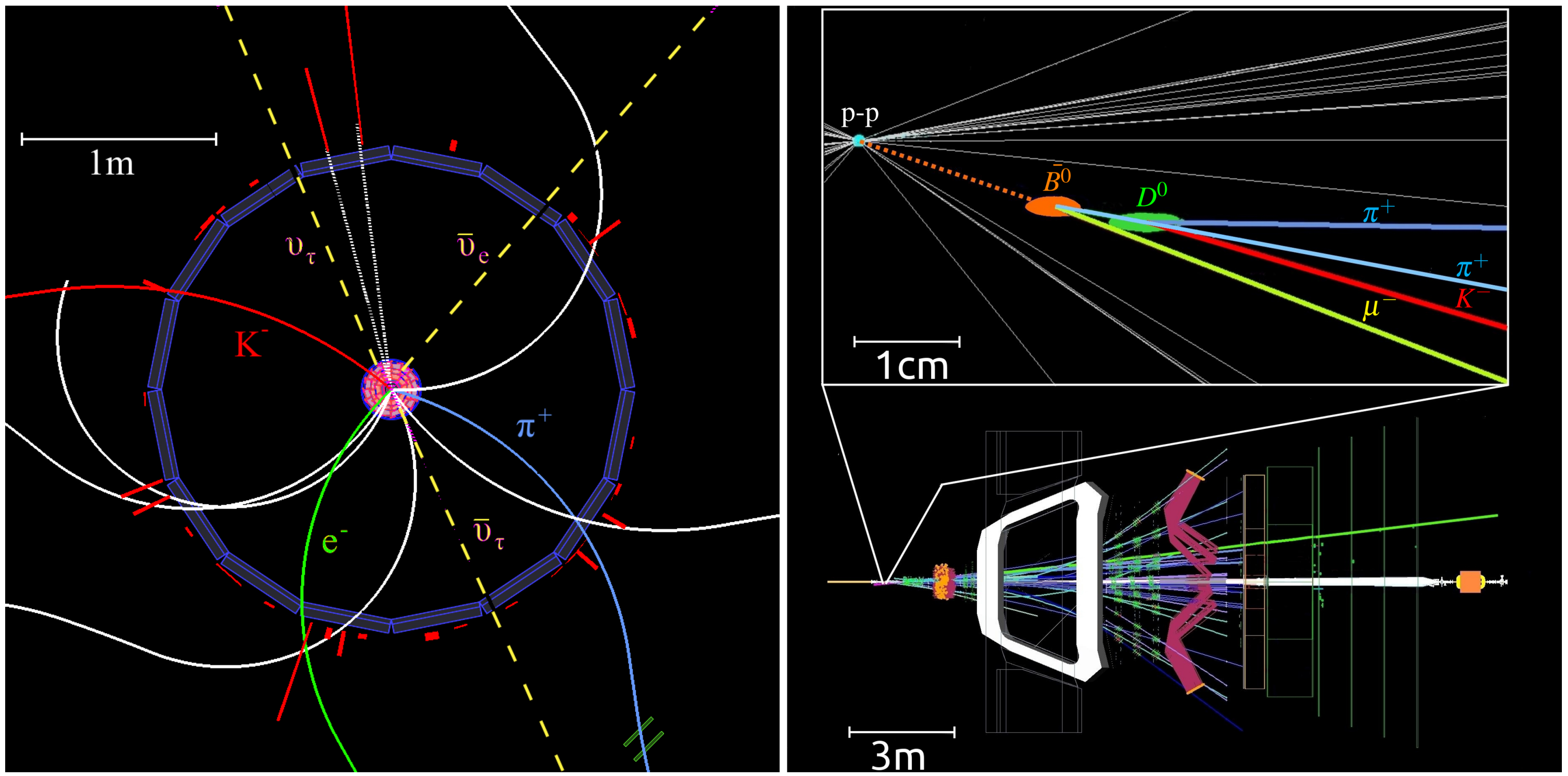
I will start with the measurements using $\tau \to \mu\nu\nu$

The problem with neutrinos

- At least two neutrinos in the final state (three if using $\tau \rightarrow \mu\nu\nu$)
    - No sharp peak to fit in any distribution:



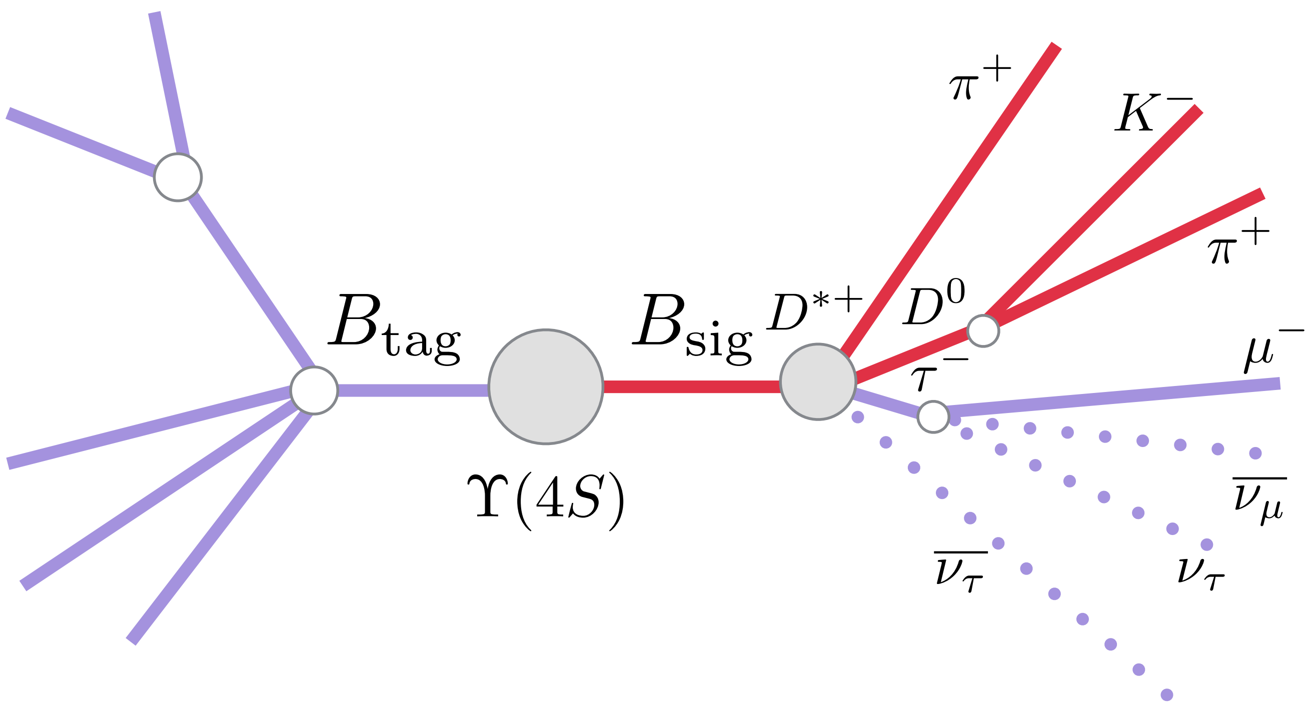
- Difficult to reconstruct B rest frame (used to discriminate signal and backgrounds).



Nature volume 546, pages 227–233

Reconstruction at the B-factories

- At B-factories, gain a lot information using a ‘tagging’ technique.



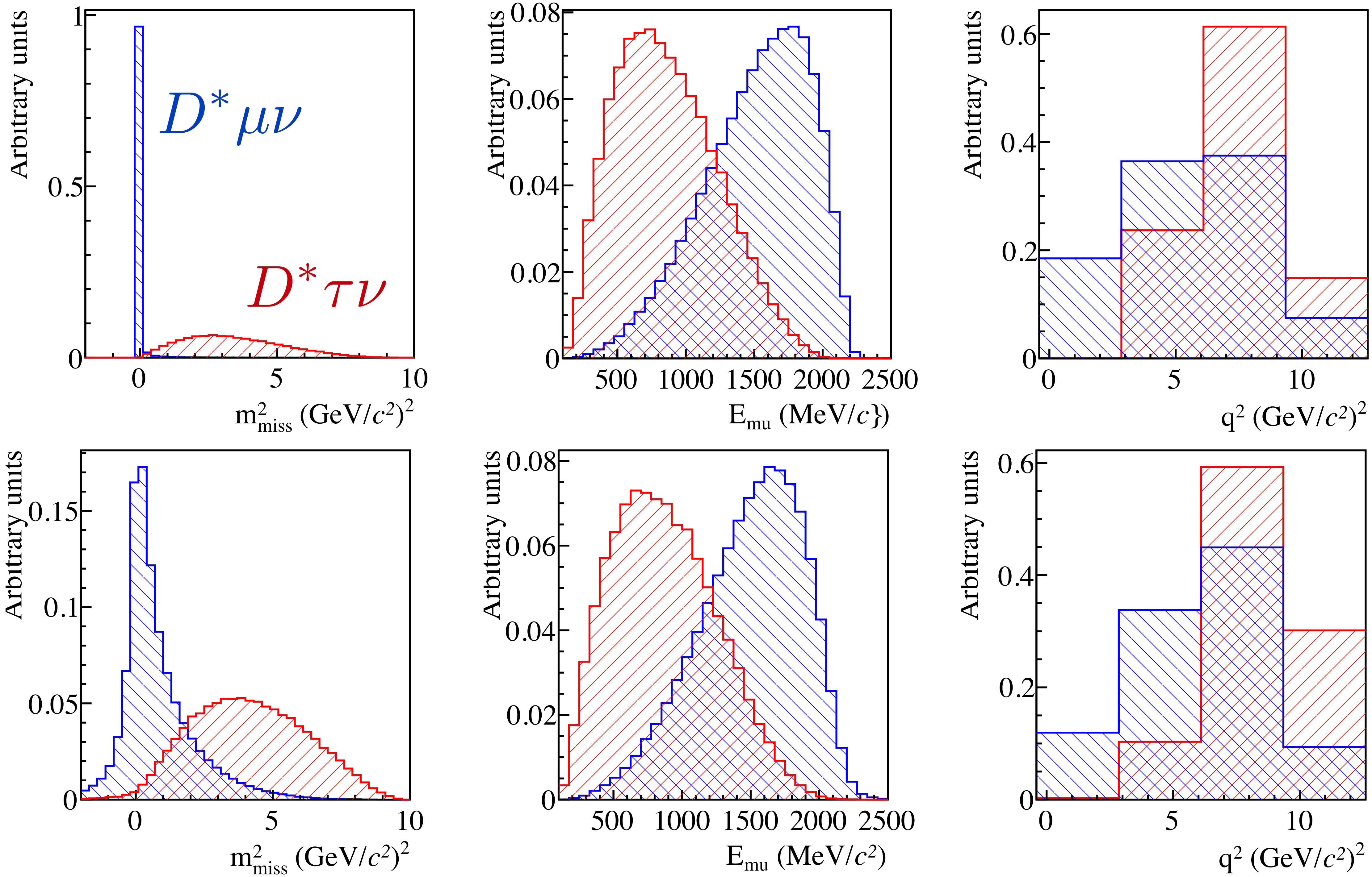
- Cleanest is to fully reconstruct hadronic decays: ε ~ 0.1%.
  - Over 2000 final states are reconstructed.
- Can also use semileptonic decays: ε ~ 0.2%.
  - Better efficiency but information is lost.

Belle II’s new algorithm improves things by a factor over a factor 2.

Things don't get much worse

Perfect resolution

LHCb resolution

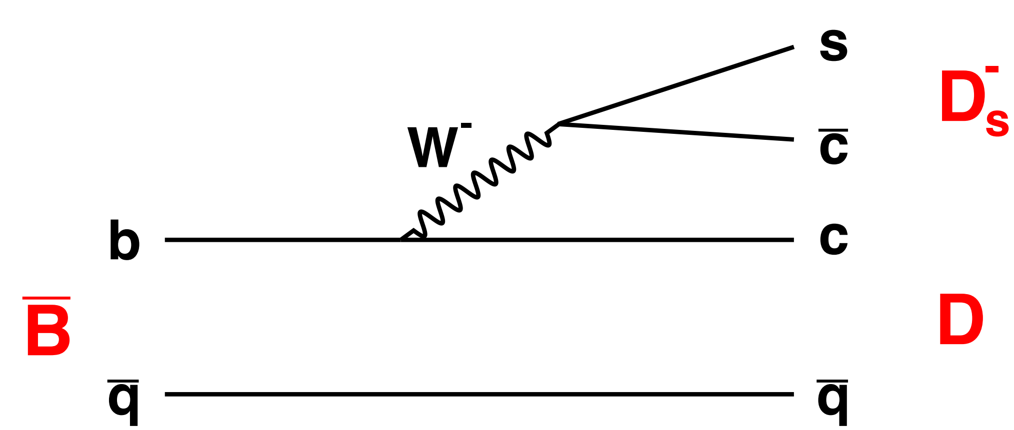


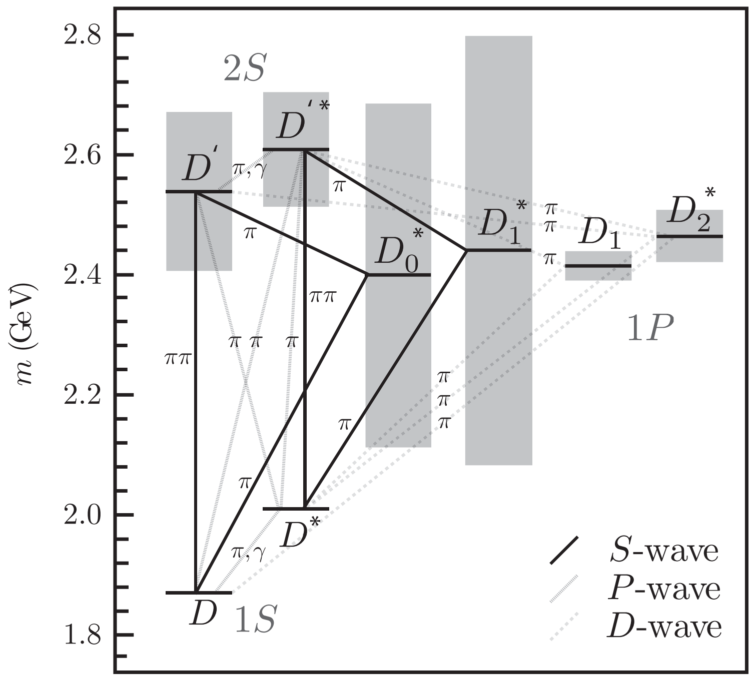
In the end $B \to D^{(*)}\mu\nu$ is not such a problem.

Backgrounds

- Most complicated background is $B \to D^{(*)}(D_s^+ \to \mu X)$

- Not such a problem for the B-factories, why?





- Another important background comes from SL decays to excited charm states, $B \to D^{(**)}\mu\nu$

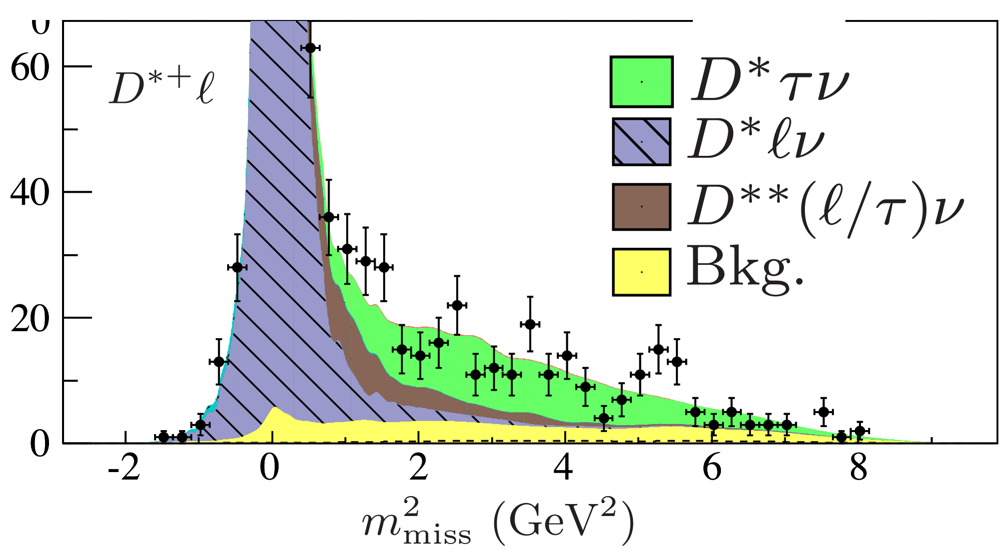
- Missing more than a neutrino causes you to look more like a tau.

Signal fits

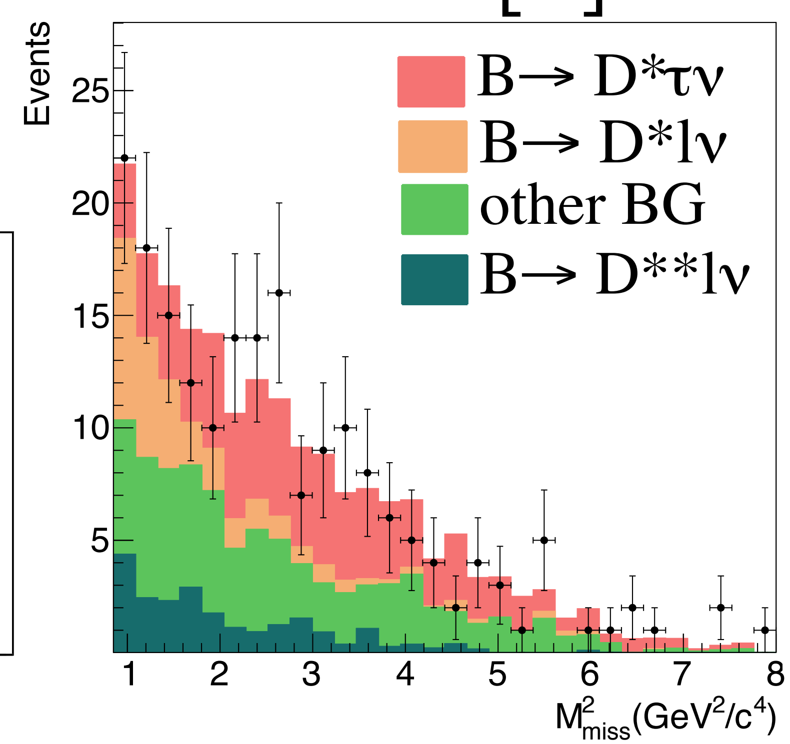
- Three main backgrounds:

$$B \to D^{*}\ell\nu$$
$$B \to D^{**}\ell\nu$$
$$B \to D^{*}DX$$

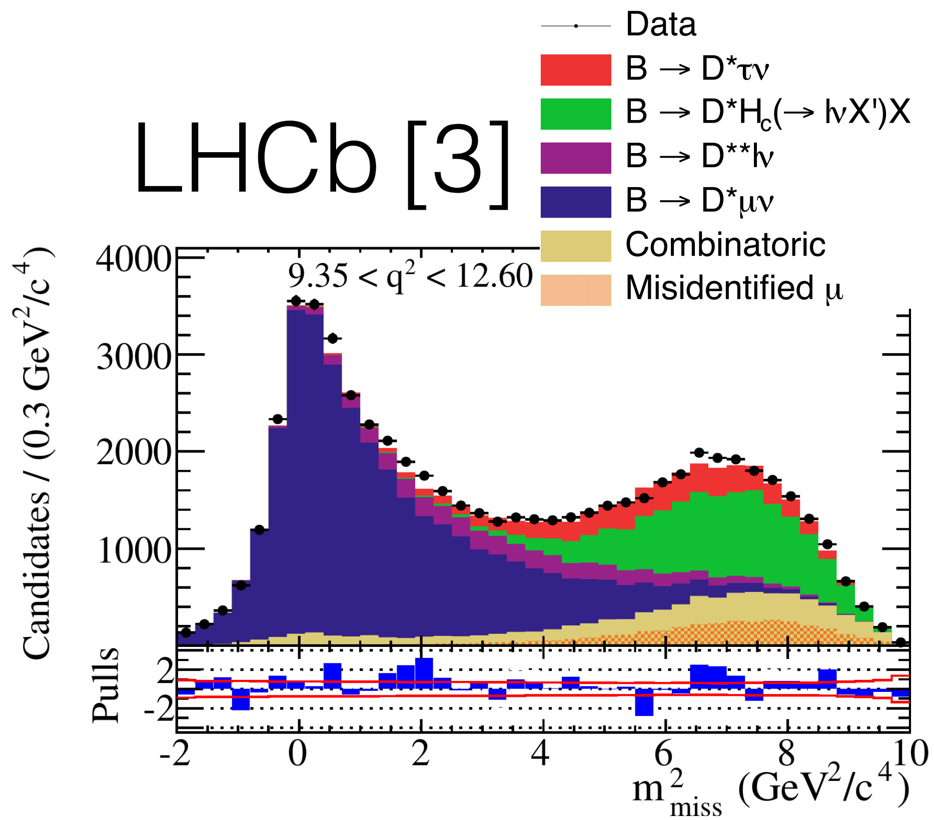
BaBar [1]



Belle [2]



LHCb [3]



- Fit variables which discriminate between muon and tauonic mode.

- LHCb fit is 3D also to lepton energy and q^2.

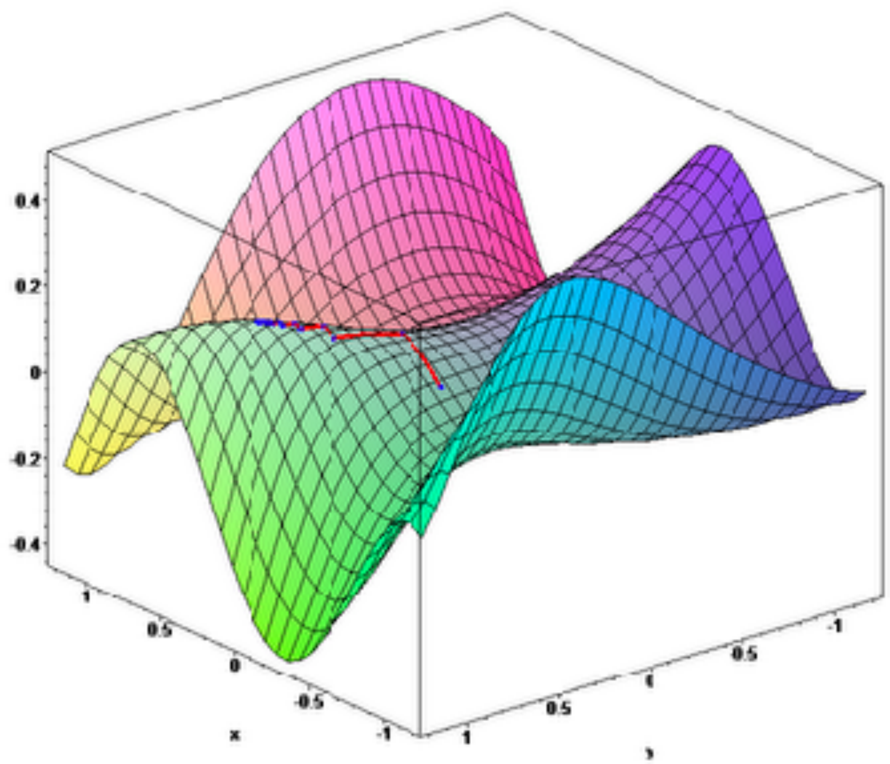
[1] Phys. Rev. D 88, 072012 (2013)

[2] Phys.Rev.D 92, 072014 (2015)

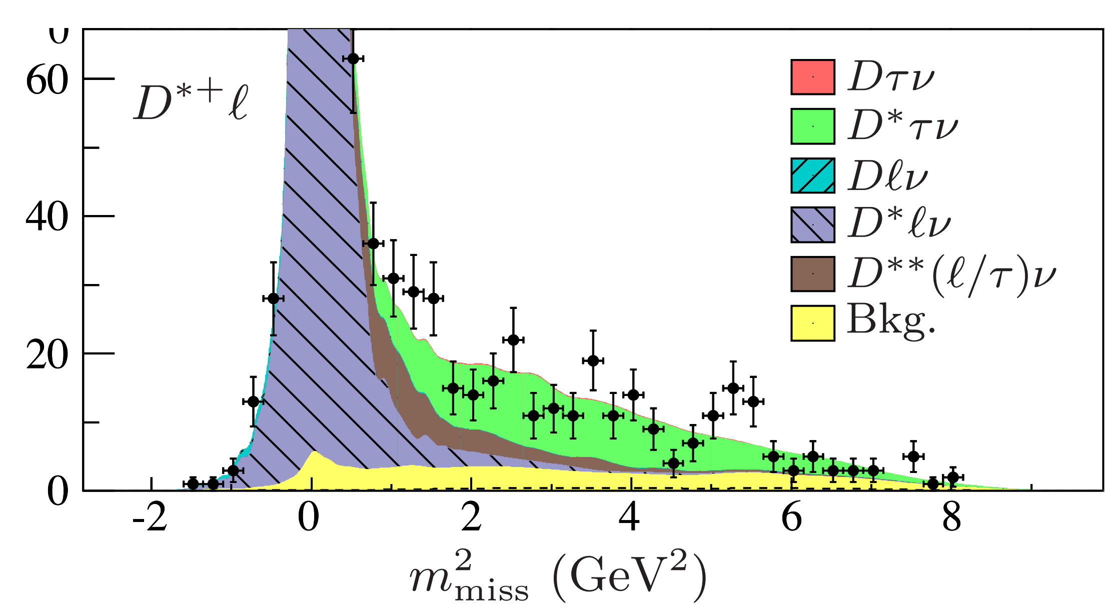
[3] Phys.Rev.Lett.115, 111803 (2015)

Aside: Likelihood fits

- General steps to determine a signal yield:
  - Write down a probability density function, PDF, as a function of parameters, λ.
  - Find the values of λ which maximise the likelihood that the PDF describes the data (using gradient descent).



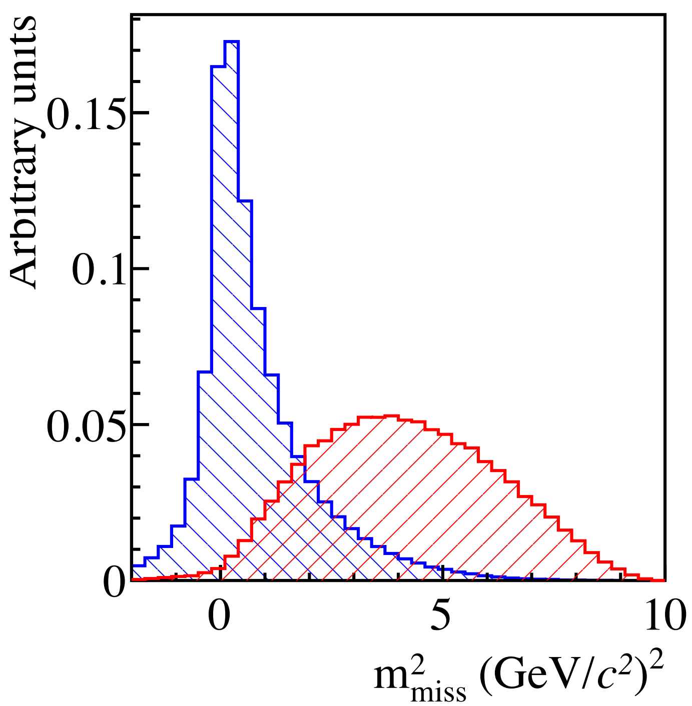
- Once a tolerance has been achieved, calculate the second derivate (Hessian matrix) to determine the uncertainties.



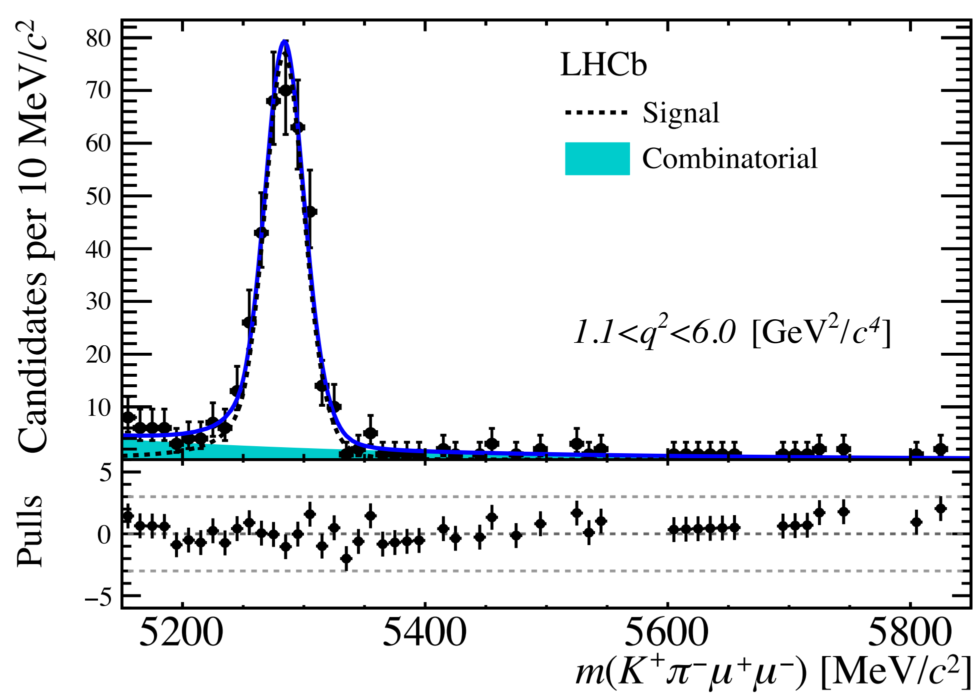
Template fits

- The fits use ‘templates’ to fit the data.
    - This just means the PDFs are non-parametric.
- For the LHCb case, we use histograms as the PDF.

Templates



Parametric



- Tends to be more tricky to introduce shape variation and MC uncertainties into template fits.

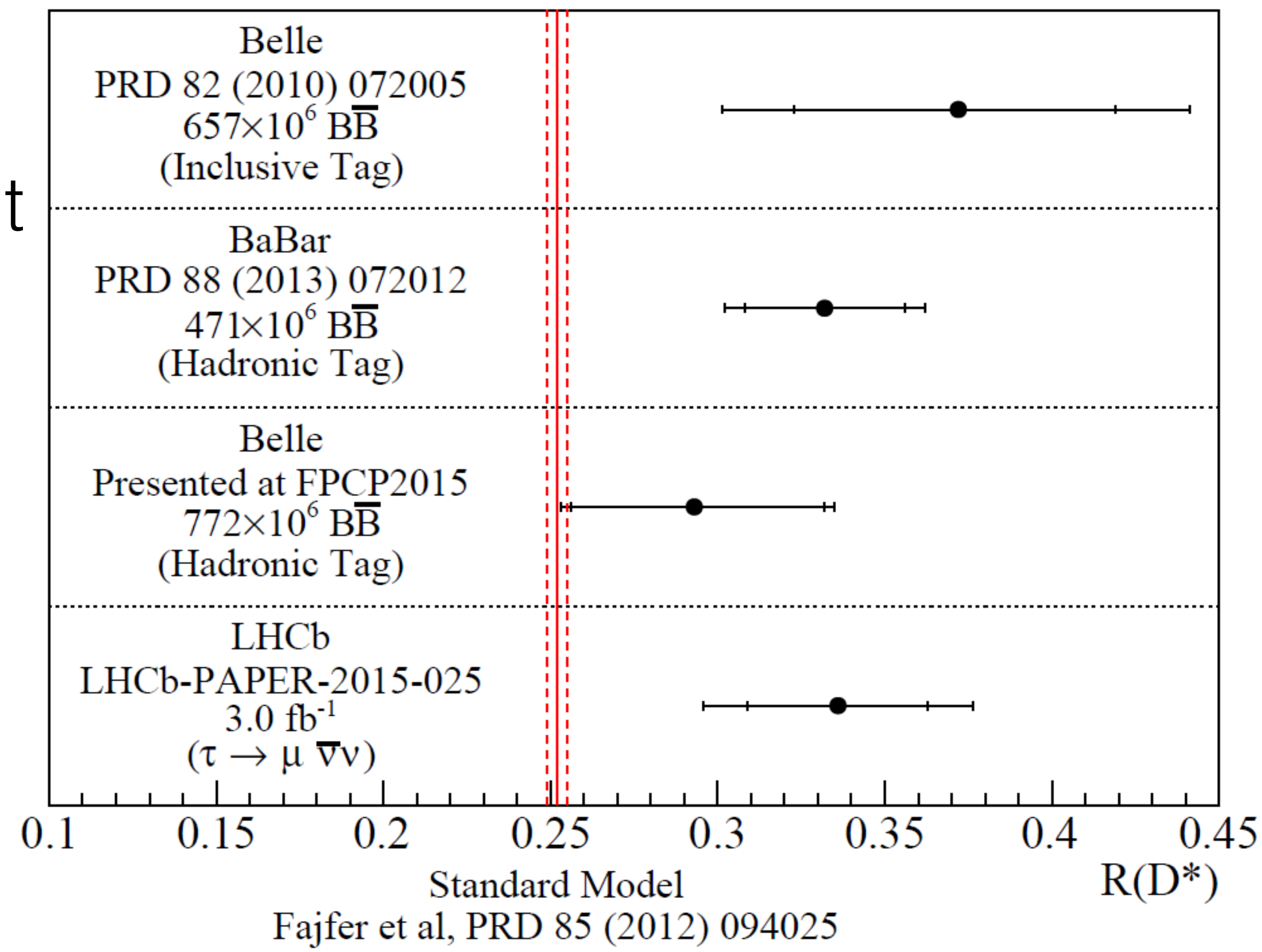
Blinding

- All NP sensitive analyses are blinded, which means that the result is not looked at until the last second (once the analysis procedure has been finalised).
- This is an incredibly important part of an analysis, to avoid conscious and unconscious bias.
    - Avoid training a selection on the data itself.
    - What if an alternative model gives a much closer to result to the SM?

Hints of an excess?

- All experiments see an excess in the number of $B \to D^* \tau \nu$ candidates.

- What's interesting is that the experiments have rather different systematic sources.

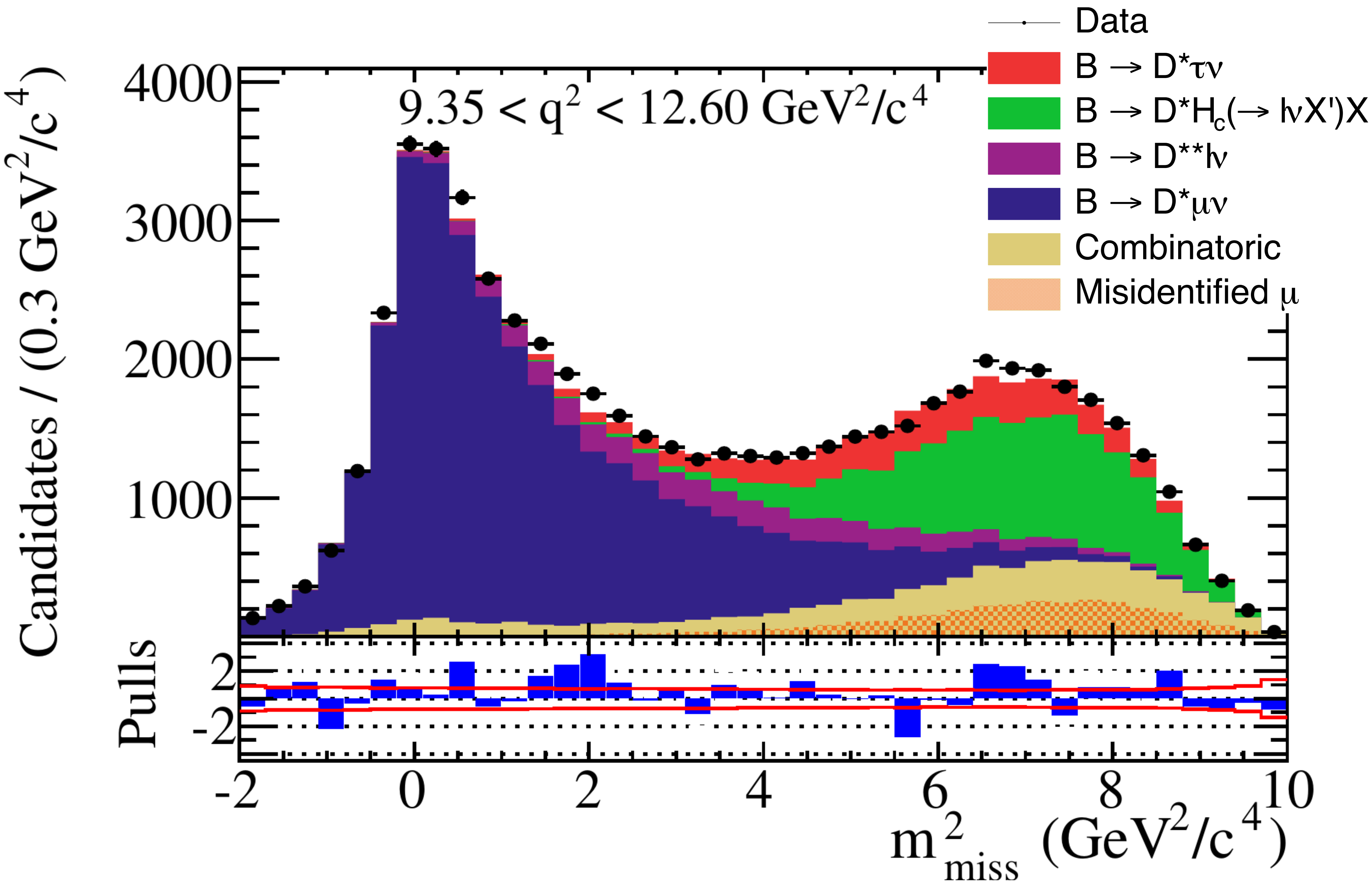


Aside: Systematic uncertainties

- The definition of a systematic uncertainty is a bit fuzzy.
  - Wide definition of anything that isn't the uncertainty on the signal dataset.
  - Narrow definition of anything that won't scale with luminosity.
- In reality, its anything that you cannot parameterise in the fit.
  - Multiplying your likelihood by a Gaussian PDF which describes an systematic uncertainty is usually the best way of including an uncertainty.
  - Changing something and recomputing the result is not a very good way to do things.

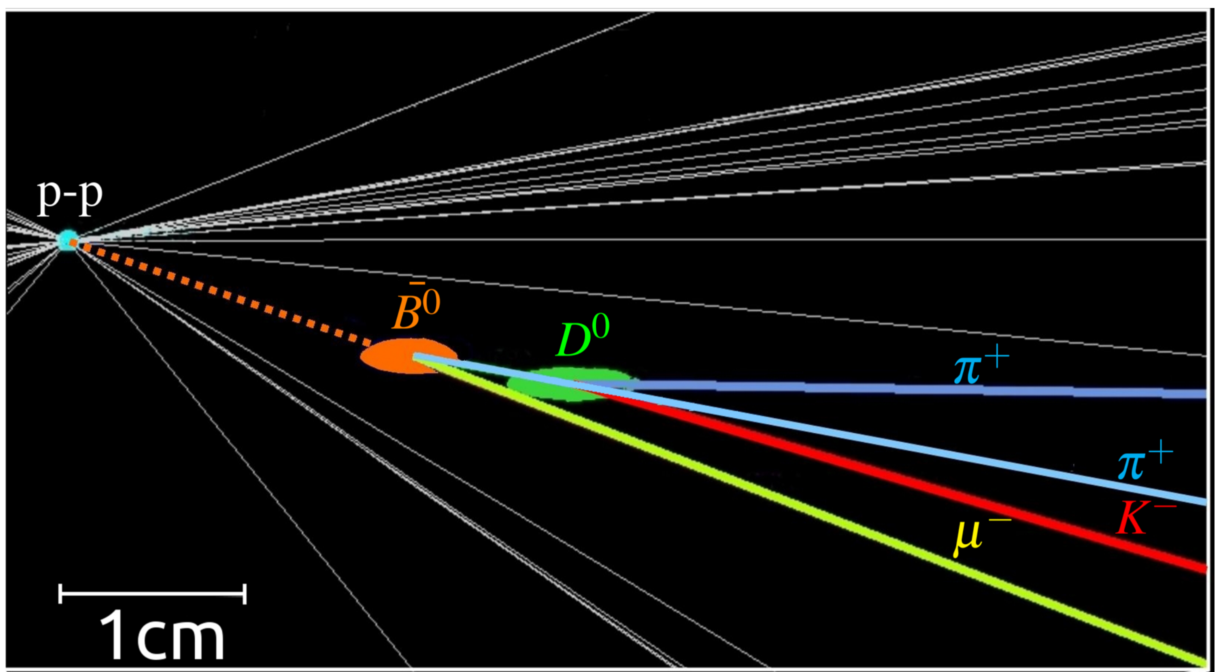
Systematic uncertainties

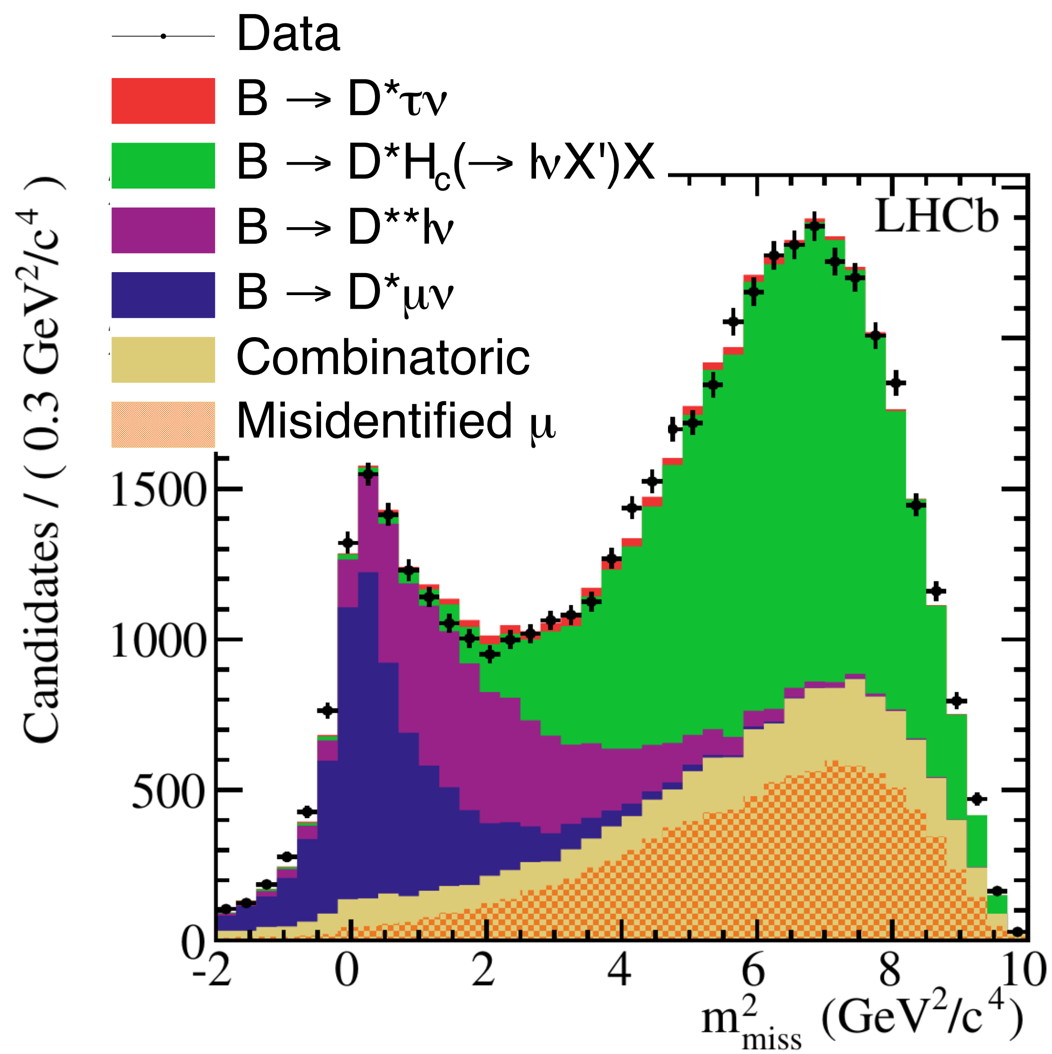
- So what can we be worried about in this measurement?



R(D*) control samples

Anti-isolate signal to enrich particular backgrounds.





This goes directly into the fit. Ill be talking about the all the sources.

Systematic uncertainties

- Systematic uncertainties affect the fit shapes and the efficiencies.

BaBar, Phys. Rev. D 88, 072012 (2013)

Source of uncertainty	$\mathcal{R}(D^0)$	$\mathcal{R}(D^{*0})$	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$
	Fractional uncertainty (%)					
Additive uncertainties						
PDFs						
MC statistics	6.5	2.9	5.7	2.7	4.4	2.0
$\overline{B} \to D^{(*)}(\tau^-/\ell^-)\overline{\nu}$ FFs	0.3	0.2	0.2	0.1	0.2	0.2
$D^{**} \to D^{(*)}(\pi^0/\pi^\pm)$	0.7	0.5	0.7	0.5	0.7	0.5
$\mathcal{B}(\overline{B} \to D^{**}\ell^-\overline{\nu}_\ell)$	1.0	0.4	1.0	0.4	0.8	0.3
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)$	1.2	2.0	2.1	1.6	1.8	1.7
$D^{**} \to D^{(*)}\pi\pi$	2.1	2.6	2.1	2.6	2.1	2.6
Cross-feed constraints						
MC statistics	2.6	0.9	2.1	0.9	2.4	1.5
$f_{D^{**}}$	6.2	2.6	5.3	1.8	5.0	2.0
Feed-up/feed-down	1.9	0.5	1.6	0.2	1.3	0.4
Isospin constraints	–	–	–	–	1.2	0.3
Fixed backgrounds						
MC statistics	4.3	2.3	4.3	1.8	3.1	1.5
Efficiency corrections	4.8	3.0	4.5	2.3	3.9	2.3
Multiplicative uncertainties						
MC statistics	2.3	1.4	3.0	2.2	1.8	1.2
$\overline{B} \to D^{(*)}(\tau^-/\ell^-)\overline{\nu}$ FFs	1.6	0.4	1.6	0.3	1.6	0.4
Lepton PID	0.6	0.6	0.6	0.5	0.6	0.6
$\pi^0/\pi^\pm$ from $D^* \to D\pi$	0.1	0.1	0.0	0.0	0.1	0.1
Detection/Reconstruction	0.7	0.7	0.7	0.7	0.7	0.7
$\mathcal{B}(\tau^- \to \ell^-\overline{\nu}_\ell\nu_\tau)$	0.2	0.2	0.2	0.2	0.2	0.2
Total syst. uncertainty	12.2	6.7	11.4	6.0	9.6	5.5
Total stat. uncertainty	19.2	9.8	18.0	11.0	13.1	7.1
Total uncertainty	22.7	11.9	21.3	12.5	16.2	9.0

LHCb, PHYS. REV. LETT. 115, 111803 (2015)

Model uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

Simulated sample size

- The largest uncertainty in both cases is the size of simulation.

BaBar, Phys. Rev. D 88, 072012 (2013)

Source of uncertainty	$\mathcal{R}(D^0)$	$\mathcal{R}(D^{*0})$	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$
	Fractional uncertainty (%)					
Additive uncertainties						
PDFs						
MC statistics	6.5	2.9	5.7	2.7	4.4	2.0
$\overline{B} \to D^{(*)}(\tau^-/\ell^-)\overline{\nu}$ FFs	0.3	0.2	0.2	0.1	0.2	0.2
$D^{**} \to D^{(*)}(\pi^0/\pi^\pm)$	0.7	0.5	0.7	0.5	0.7	0.5
$\mathcal{B}(\overline{B} \to D^{**}\ell^-\overline{\nu}_\ell)$	1.0	0.4	1.0	0.4	0.8	0.3
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)$	1.2	2.0	2.1	1.6	1.8	1.7
$D^{**} \to D^{(*)}\pi\pi$	2.1	2.6	2.1	2.6	2.1	2.6
Cross-feed constraints						
MC statistics	2.6	0.9	2.1	0.9	2.4	1.5
$f_{D^{**}}$	6.2	2.6	5.3	1.8	5.0	2.0
Feed-up/feed-down	1.9	0.5	1.6	0.2	1.3	0.4
Isospin constraints	–	–	–	–	1.2	0.3
Fixed backgrounds						
MC statistics	4.3	2.3	4.3	1.8	3.1	1.5
Efficiency corrections	4.8	3.0	4.5	2.3	3.9	2.3
Multiplicative uncertainties						
MC statistics	2.3	1.4	3.0	2.2	1.8	1.2
$\overline{B} \to D^{(*)}(\tau^-/\ell^-)\overline{\nu}$ FFs	1.6	0.4	1.6	0.3	1.6	0.4
Lepton PID	0.6	0.6	0.6	0.5	0.6	0.6
$\pi^0/\pi^\pm$ from $D^* \to D\pi$	0.1	0.1	0.0	0.0	0.1	0.1
Detection/Reconstruction	0.7	0.7	0.7	0.7	0.7	0.7
$\mathcal{B}(\tau^- \to \ell^-\overline{\nu}_\ell\nu_\tau)$	0.2	0.2	0.2	0.2	0.2	0.2
Total syst. uncertainty	12.2	6.7	11.4	6.0	9.6	5.5
Total stat. uncertainty	19.2	9.8	18.0	11.0	13.1	7.1
Total uncertainty	22.7	11.9	21.3	12.5	16.2	9.0

LHCb, PHYS. REV. LETT. 115, 111803 (2015)

Model uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

A word on simulation

- At the LHC, it takes 25ns to produce an event.
- It takes about a minute for fully simulate an event.
- Roughly 1 in 100 collisions has a bb pair.
- The branching fractions of the decays involved are O(%) level, multiplied by O(10%) for the D decay.
- That still leaves 4 orders of magnitude difference in the production rate between simulation and data.
- Producing enough simulation is **difficult**, and usually requires lots of tricks.

$B \to D^{**}\tau\nu$

- The next one is related to $B \to D^{**}\tau\nu$ decays.

BaBar, Phys. Rev. D 88, 072012 (2013)

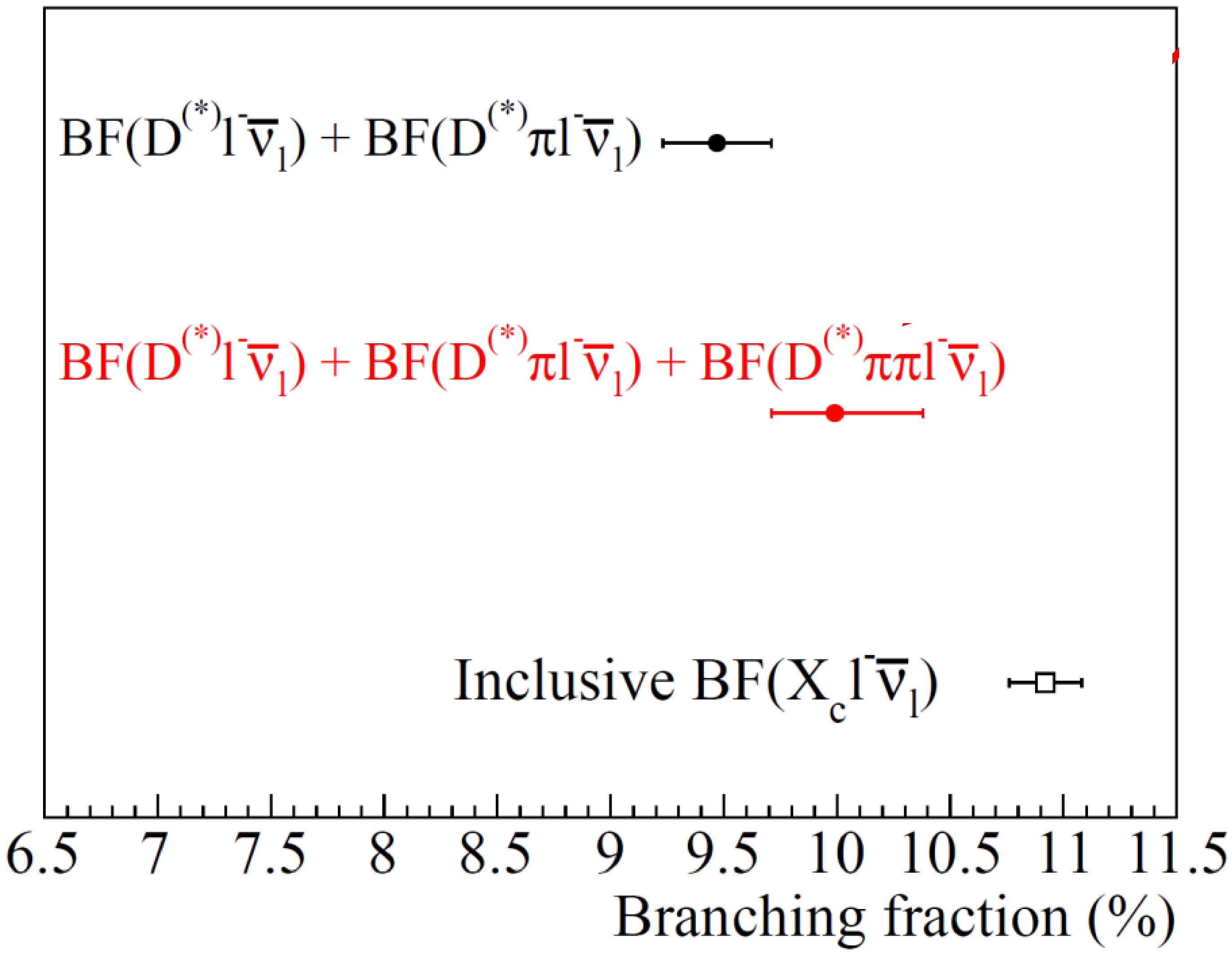
Source of uncertainty	Fractional uncertainty (%) $\mathcal{R}(D^0)$	$\mathcal{R}(D^{*0})$	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$
Additive uncertainties						
PDFs						
MC statistics	6.5	2.9	5.7	2.7	4.4	2.0
$\overline{B} \to D^{(*)}(\tau^-/\ell^-)\overline{\nu}$ FFs	0.3	0.2	0.2	0.1	0.2	0.2
$D^{**} \to D^{(*)}(\pi^0/\pi^\pm)$	0.7	0.5	0.7	0.5	0.7	0.5
$\mathcal{B}(\overline{B} \to D^{**}\ell^-\overline{\nu}_\ell)$	1.0	0.4	1.0	0.4	0.8	0.3
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)$	1.2	2.0	2.1	1.6	1.8	1.7
$D^{**} \to D^{(*)}\pi\pi$	2.1	2.6	2.1	2.6	2.1	2.6
Cross-feed constraints						
MC statistics	2.6	0.9	2.1	0.9	2.4	1.5
$f_{D^{**}}$	6.2	2.6	5.3	1.8	5.0	2.0
Feed-up/feed-down	1.9	0.5	1.6	0.2	1.3	0.4
Isospin constraints	–	–	–	–	1.2	0.3
Fixed backgrounds						
MC statistics	4.3	2.3	4.3	1.8	3.1	1.5
Efficiency corrections	4.8	3.0	4.5	2.3	3.9	2.3
Multiplicative uncertainties						
MC statistics	2.3	1.4	3.0	2.2	1.8	1.2
$\overline{B} \to D^{(*)}(\tau^-/\ell^-)\overline{\nu}$ FFs	1.6	0.4	1.6	0.3	1.6	0.4
Lepton PID	0.6	0.6	0.6	0.5	0.6	0.6
$\pi^0/\pi^\pm$ from $D^* \to D\pi$	0.1	0.1	0.0	0.0	0.1	0.1
Detection/Reconstruction	0.7	0.7	0.7	0.7	0.7	0.7
$\mathcal{B}(\tau^- \to \ell^-\overline{\nu}_\ell\nu_\tau)$	0.2	0.2	0.2	0.2	0.2	0.2
Total syst. uncertainty	12.2	6.7	11.4	6.0	9.6	5.5
Total stat. uncertainty	19.2	9.8	18.0	11.0	13.1	7.1
Total uncertainty	22.7	11.9	21.3	12.5	16.2	9.0

LHCb, PHYS. REV. LETT. 115, 111803 (2015)

Model uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

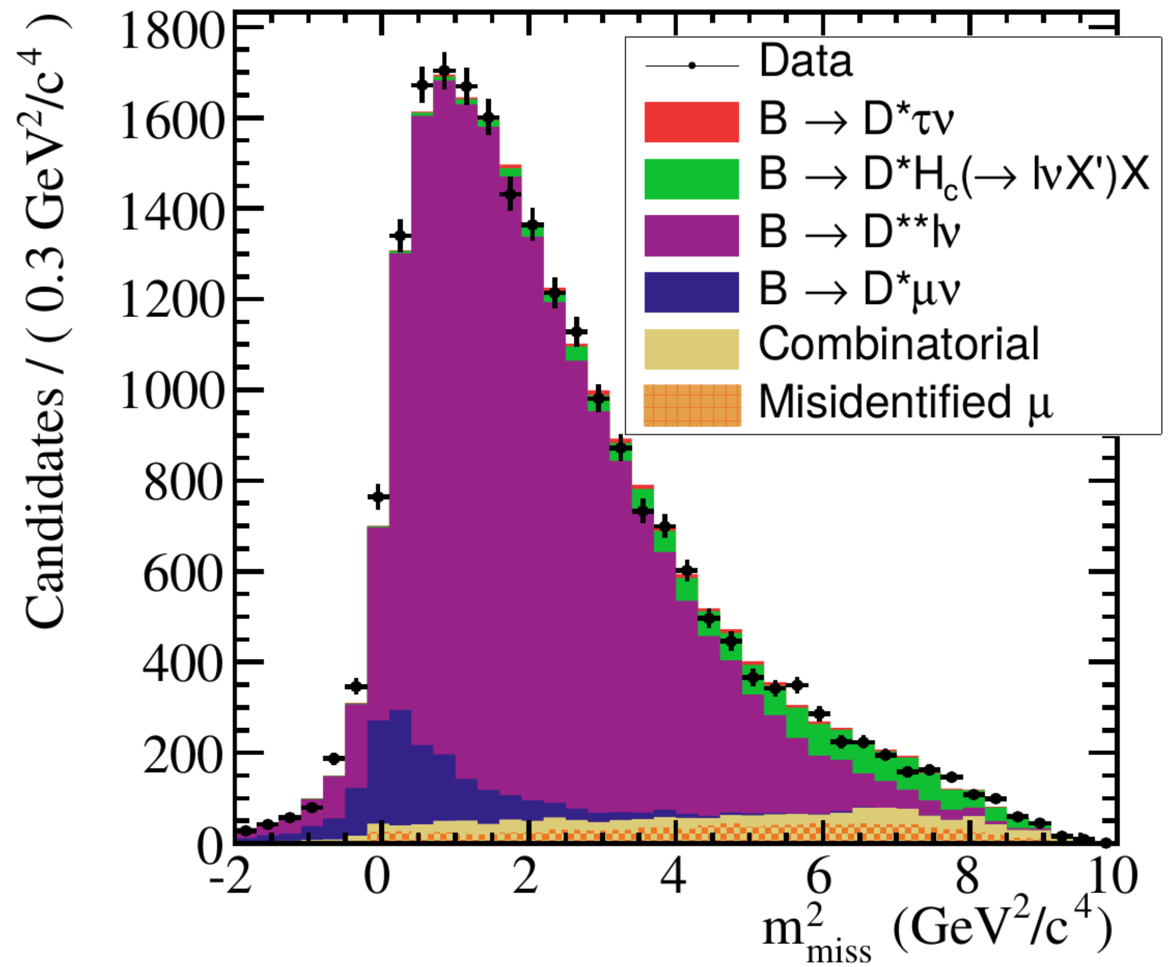
$B \to D^{**}\tau\nu$

- People are worried about $B \to D^{**}\tau\nu$, it has its own puzzles.



From S. Hirose @ FPCP 2016

LHCb, PRL115,111803(2015)



- For the LHCb measurement it is controlled using data with an extra pion added to the D*.

Form factor uncertainties

- The uncertainty on QCD has an impact on the measurements.

BaBar, Phys. Rev. D 88, 072012 (2013)

Source of uncertainty	Fractional uncertainty (%) $\mathcal{R}(D^0)$	$\mathcal{R}(D^{*0})$	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$
Additive uncertainties						
PDFs						
MC statistics	6.5	2.9	5.7	2.7	4.4	2.0
$\boxed{B \to D^{(*)}(\tau^-/\ell^-)\overline{\nu}\text{ FFs}}$	0.3	0.2	0.2	0.1	0.2	0.2
$D^{**} \to D^{(*)}(\pi^0/\pi^{\pm})$	0.7	0.5	0.7	0.5	0.7	0.5
$\mathcal{B}(\overline{B} \to D^{**}\ell^-\overline{\nu}_\ell)$	1.0	0.4	1.0	0.4	0.8	0.3
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)$	1.2	2.0	2.1	1.6	1.8	1.7
$D^{**} \to D^{(*)}\pi\pi$	2.1	2.6	2.1	2.6	2.1	2.6
Cross-feed constraints						
MC statistics	2.6	0.9	2.1	0.9	2.4	1.5
$f_{D^{**}}$	6.2	2.6	5.3	1.8	5.0	2.0
Feed-up/feed-down	1.9	0.5	1.6	0.2	1.3	0.4
Isospin constraints	–	–	–	–	1.2	0.3
Fixed backgrounds						
MC statistics	4.3	2.3	4.3	1.8	3.1	1.5
Efficiency corrections	4.8	3.0	4.5	2.3	3.9	2.3
Multiplicative uncertainties						
MC statistics	2.3	1.4	3.0	2.2	1.8	1.2
$\boxed{B \to D^{(*)}(\tau^-/\ell^-)\overline{\nu}\text{ FFs}}$	1.6	0.4	1.6	0.3	1.6	0.4
Lepton PID	0.6	0.6	0.6	0.5	0.6	0.6
$\pi^0/\pi^{\pm}$ from $D^* \to D\pi$	0.1	0.1	0.0	0.0	0.1	0.1
Detection/Reconstruction	0.7	0.7	0.7	0.7	0.7	0.7
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LHCb, PHYS. REV. LETT. 115, 111803 (2015)

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$\boxed{B^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}\text{ form factors}}$	0.6
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$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
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Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
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Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
$\boxed{\text{Form-factors}}$	0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

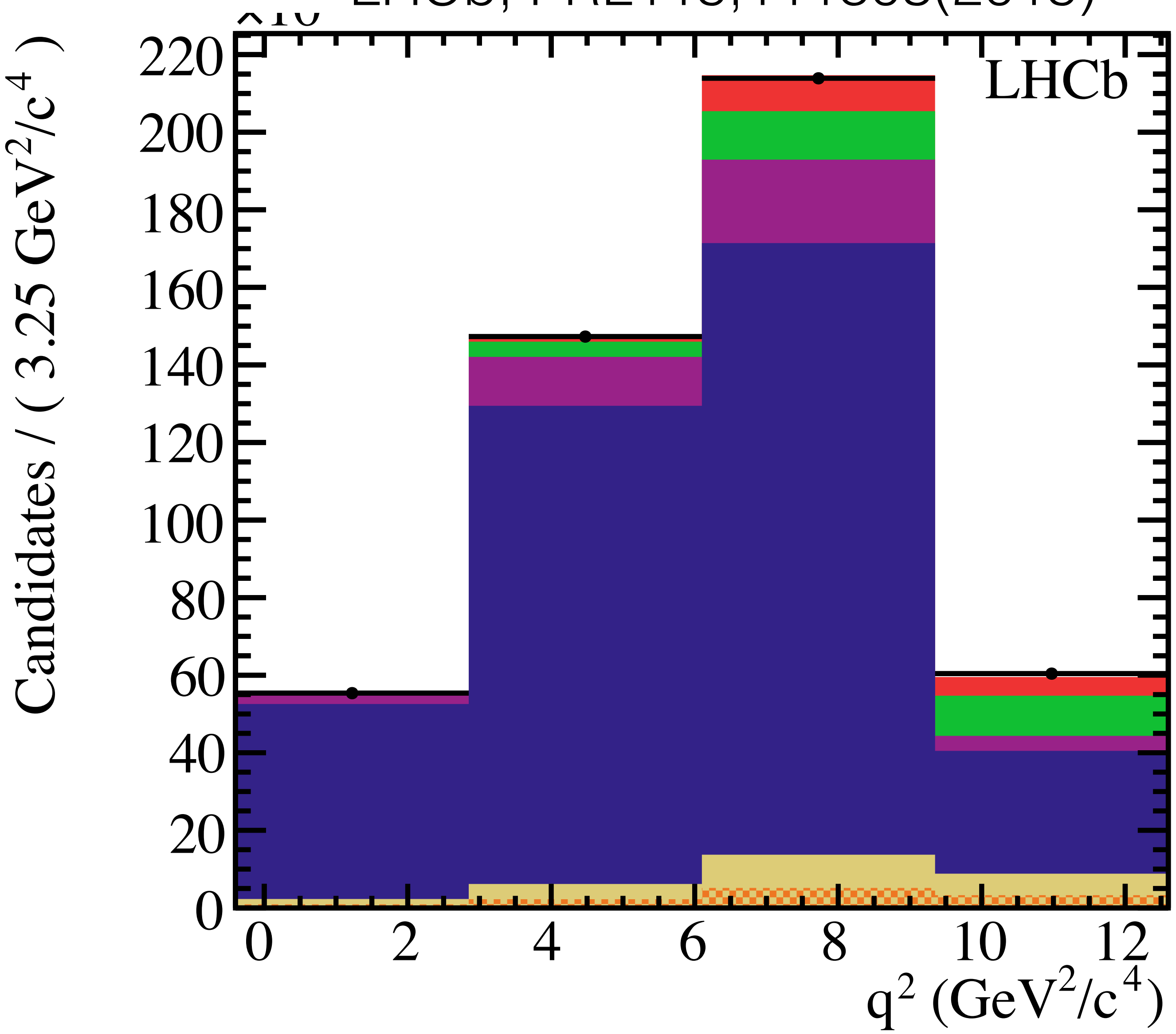
Form factor uncertainties

- The uncertainty on QCD has an impact on the measurements.

$$\frac{d\Gamma}{dq^2}(B \to D\ell\nu) \propto$$

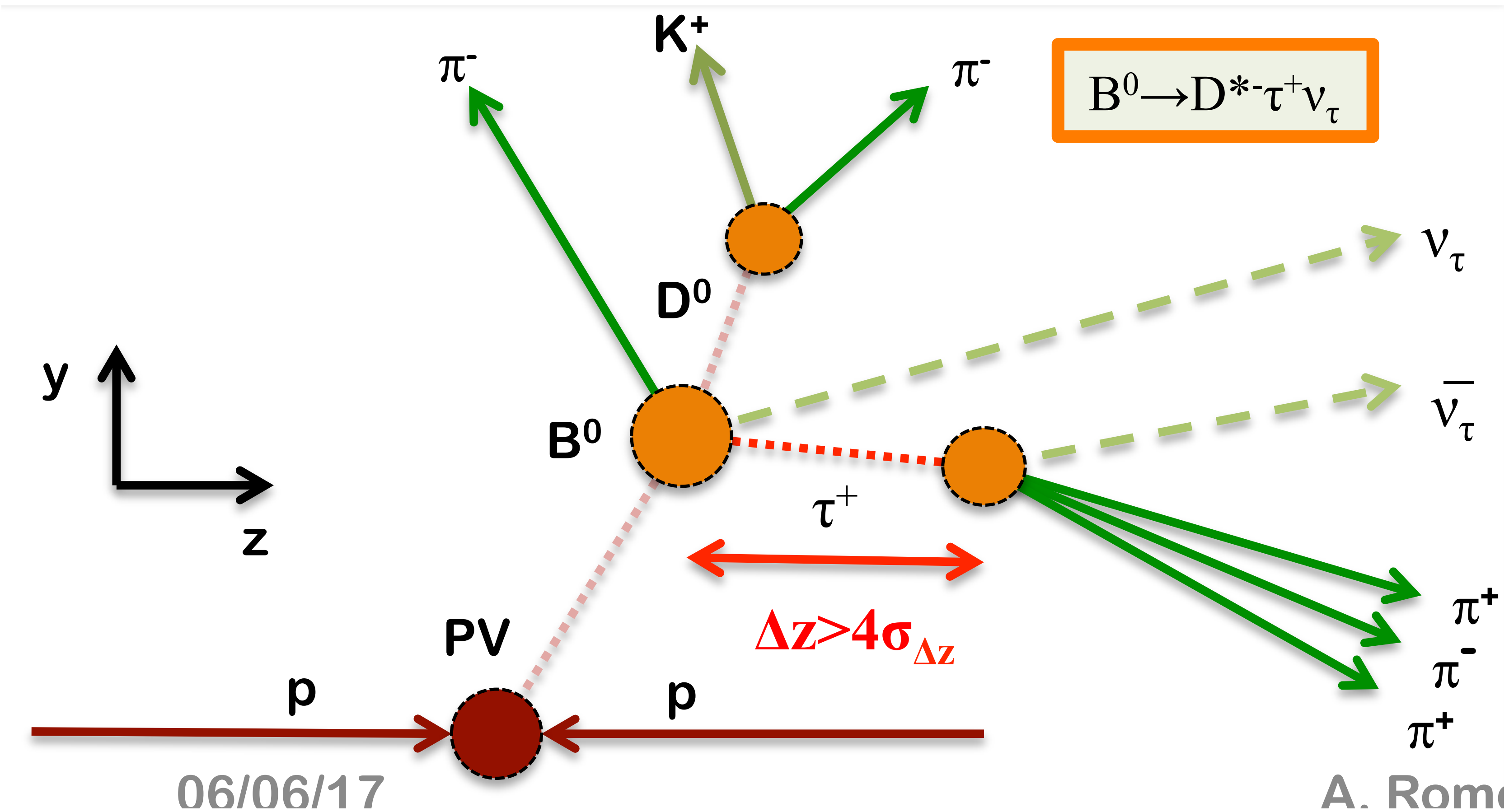
$$\underbrace{G_F^2 |V_{cb}|^2}_{\text{EW}} \underbrace{f(q^2)^2}_{\text{QCD}}$$

LHCb, PRL115,111803(2015)



If you fit q^2 to determine the signal, then your measurement will depend on QCD

$\tau \to 3\pi\nu$



π^-
K^+
π^-
$B^0 \to D^{*-}\tau^+\nu_\tau$
ν_τ
D^0
y
B^0
$\bar{\nu}_\tau$
z
τ^+
PV
$\Delta z > 4\sigma_{\Delta z}$
π^+
p
p
π^-
π^+
06/06/17
A. Rom

Latest LHCb measurement

Phys. Rev. Lett. 120, 171802 (2018)

- First measurement with $\tau^+ \to \pi^+\pi^-\pi^+ X$ decays.
  - No background from $B \to D^{*(*)}\ell\nu$.
- Normalise signal yield to decay $B^0 \to D^{*-}\pi^+\pi^-\pi^+$

$$\boxed{K_{had}(D^*) = \frac{BR(B^0 \to D^{*-}\tau^+\nu_\tau)}{BR(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}} = \frac{N(B^0 \to D^{*-}\tau^+\nu_\tau)}{N(B^0 \to D^{*+}\pi^-\pi^+\pi^-)} \times \frac{1}{BR(\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau)} \times \frac{\varepsilon(B^0 \to D^{*+}\pi^-\pi^+\pi^-)}{\varepsilon(B^0 \to D^{*-}\tau^+\nu_\tau)}$$

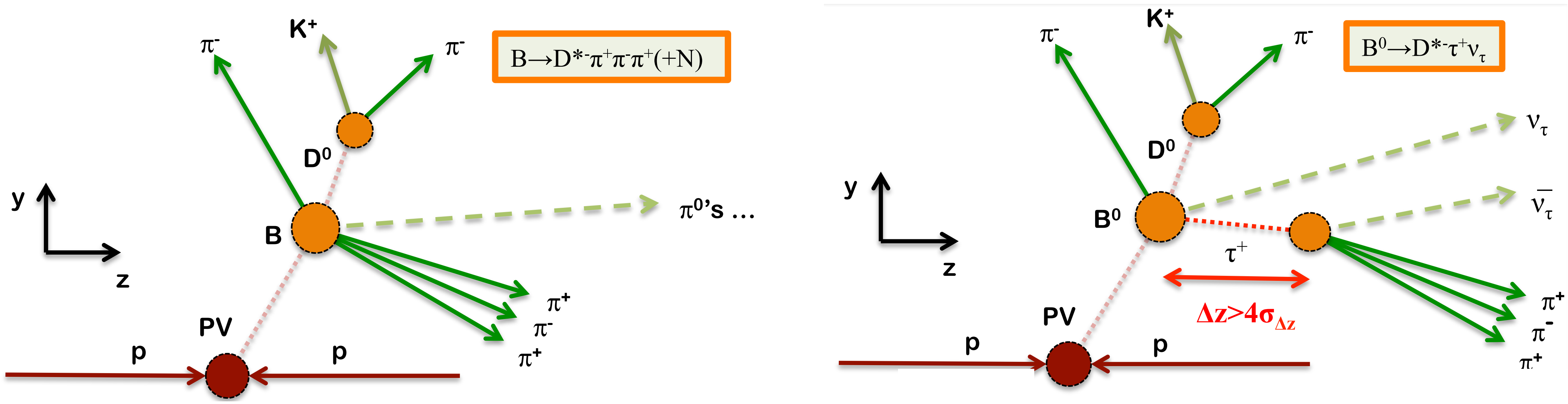
$$R(D^*) = K_{had}(D^*) \times \frac{BR(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{BR(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

- Why don’t we just directly measure R(D*)?

Flight distance cut

Phys. Rev. Lett. 120, 171802 (2018)

- Huge background from $B \to D^{(**)} 3\pi X$
- Reduced by requiring a flight significance > 4σ.



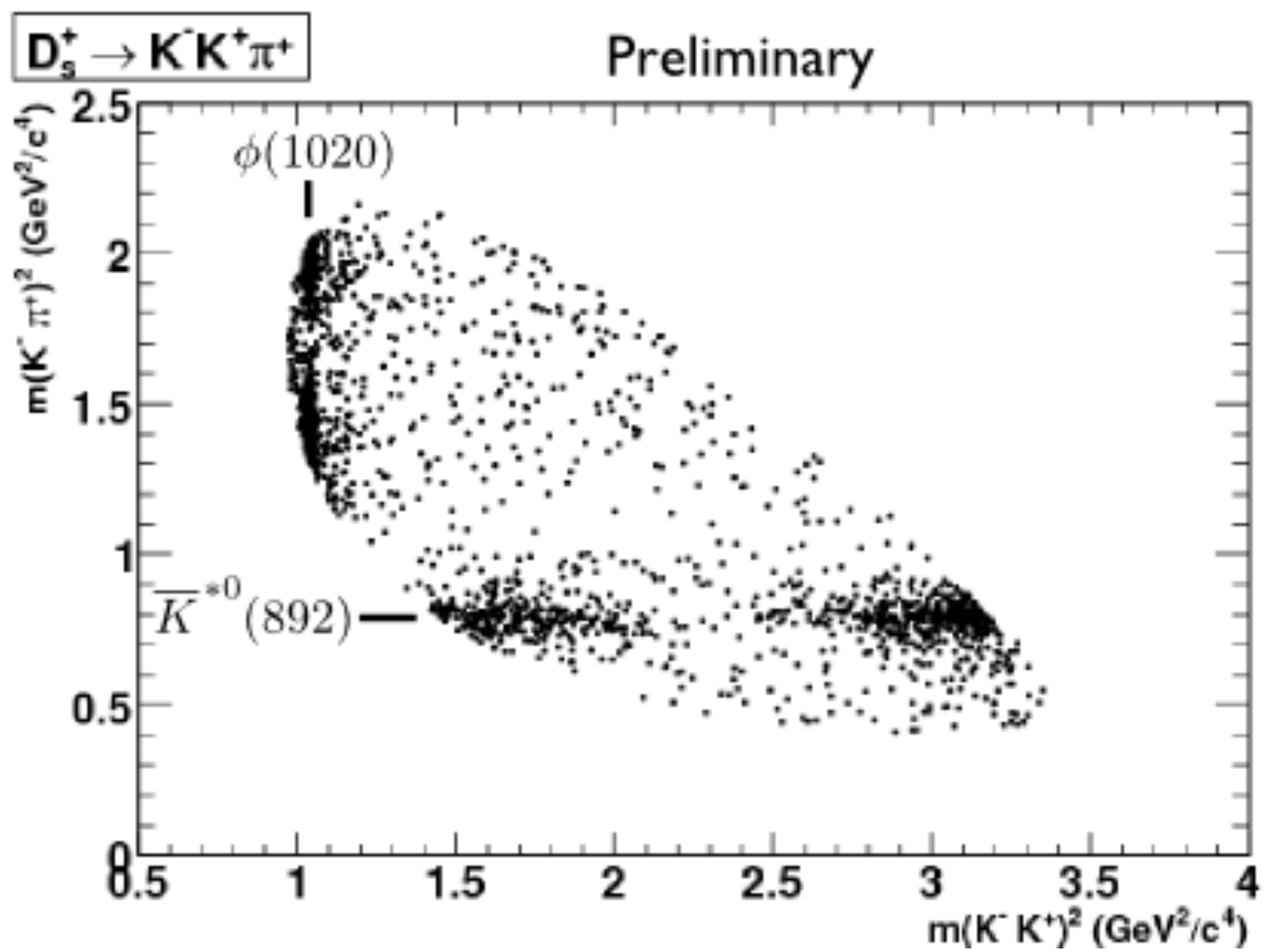
- Why don't the B-factories do this?

The 3π dynamics

Phys. Rev. Lett. 120, 171802 (2018)

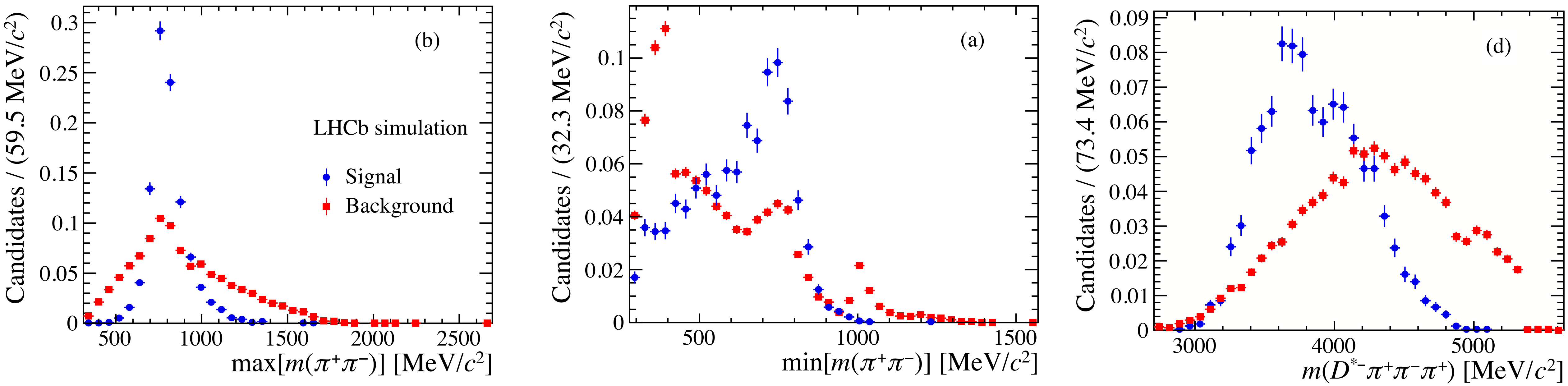
- Largest background from $B \to D^{(*)}(D_s^+ \to 3\pi X)X$
- Exploit the difference in the 3π dynamics between the D and the τ.

Example Dalitz plot



BDT discriminant

- Largest background from $B \to D^{(*)}(D_s^+ \to 3\pi X)X$

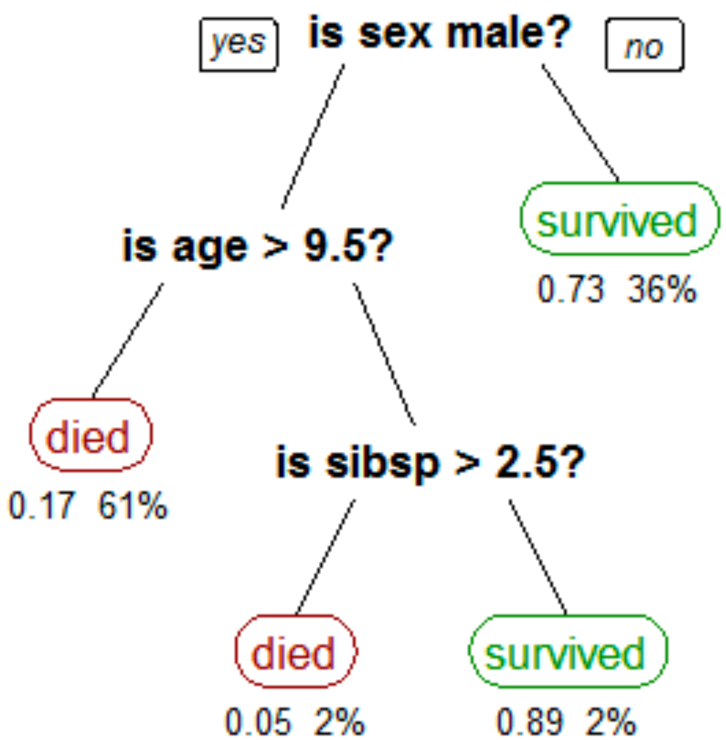


- Can combine this information into a multivariate classifier.
  - A multivariate classifier is something which uses machine learning to exploit correlations between variables.
  - A good example is a BDT.

What is a BDT?

- A decision tree is a series of selections which can isolate different categories of data.

Survivors of Titanic



- A decision tree can be trained on data by, splitting the sample recursively until the discrimination doesn't get any better.

- Sequential selections can exploit correlations in features.

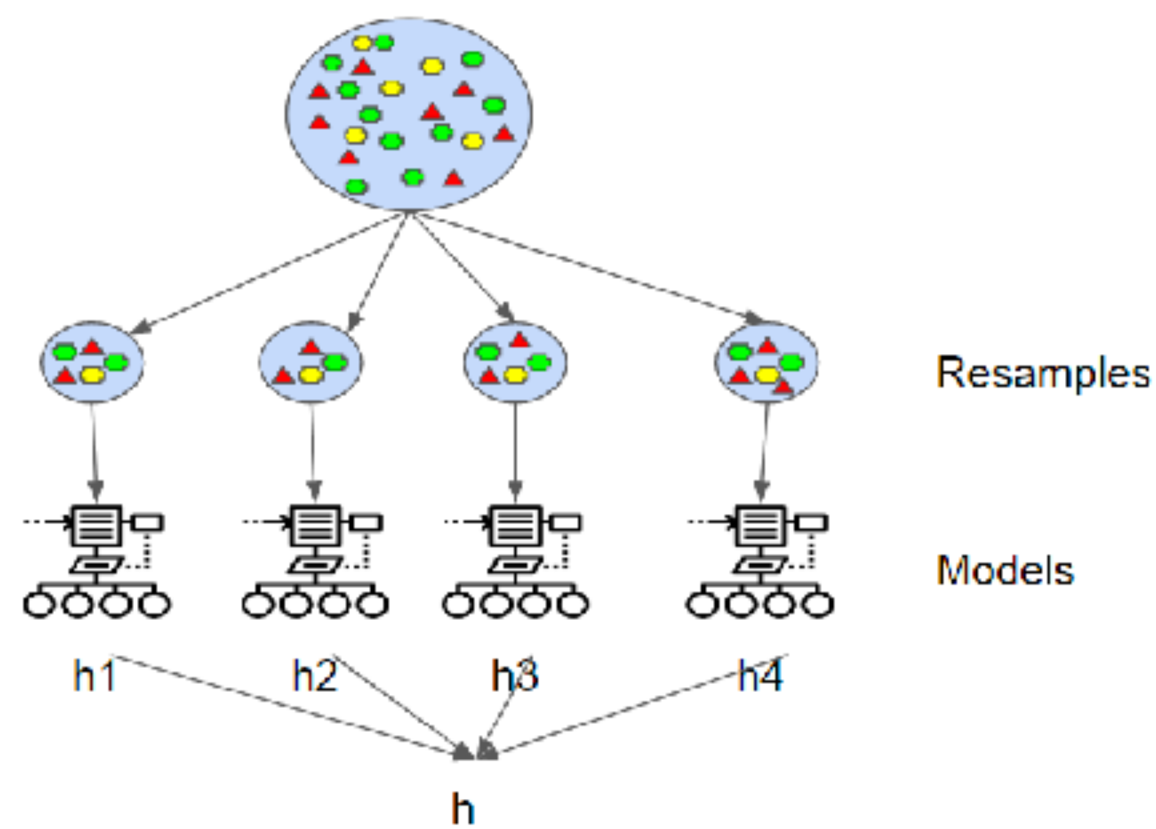
Boosting

- The problem is that decision trees can quite easily follow statistical fluctuations in the data, known as overfitting.

- This can be remedied by creating an ensemble of trees (boosting).

- Several approaches exist, the easiest to imagine is bagging, whereby a random sample of the input is taken and a used to train a decision tree.

- More efficient methods also exist e.g. AdaBoost.

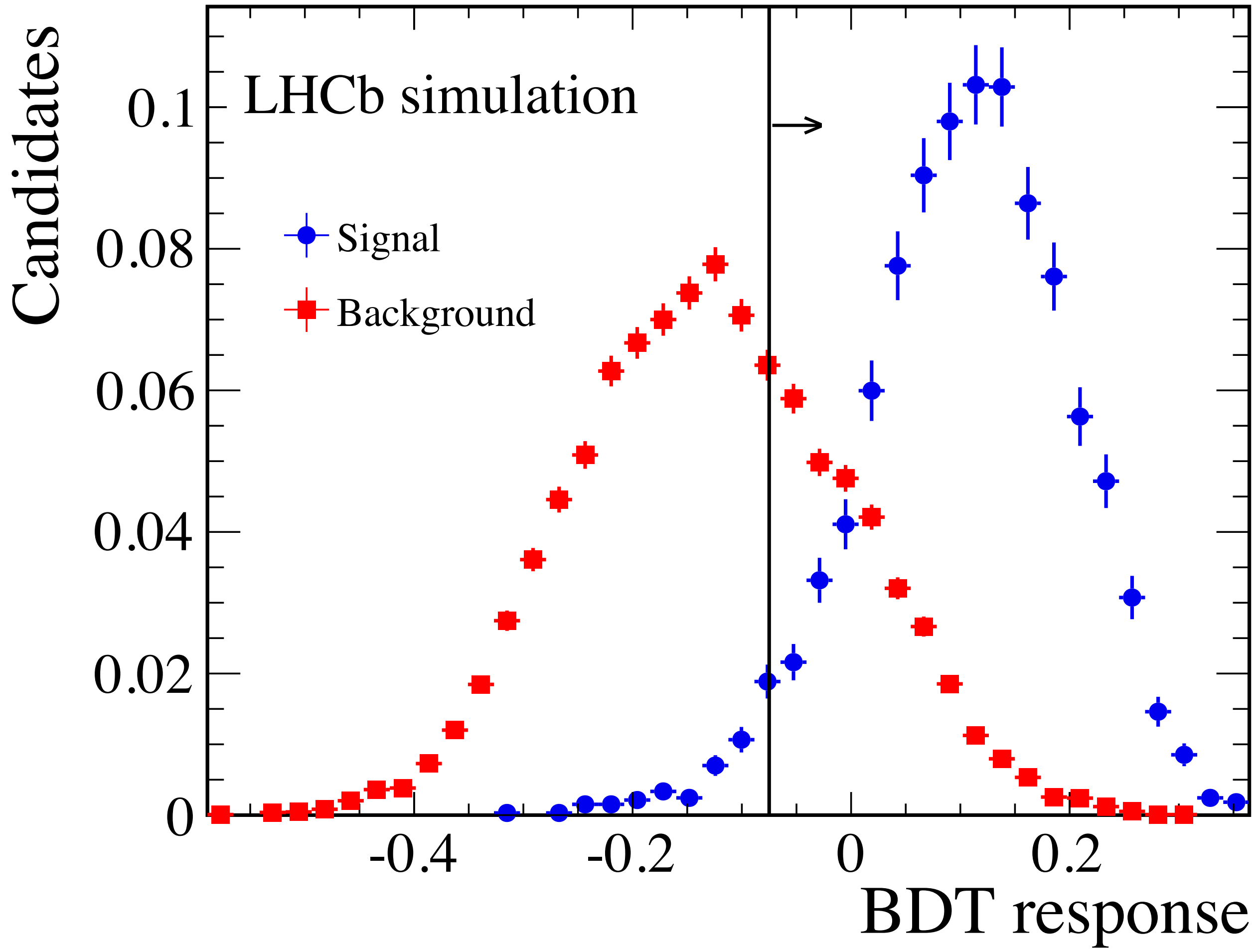


Fit variables

- Once the BDT has been combined, fit it to discriminate background from signal.

- Also use the τ decay time as it is generally a bit shorter than charm hadrons.

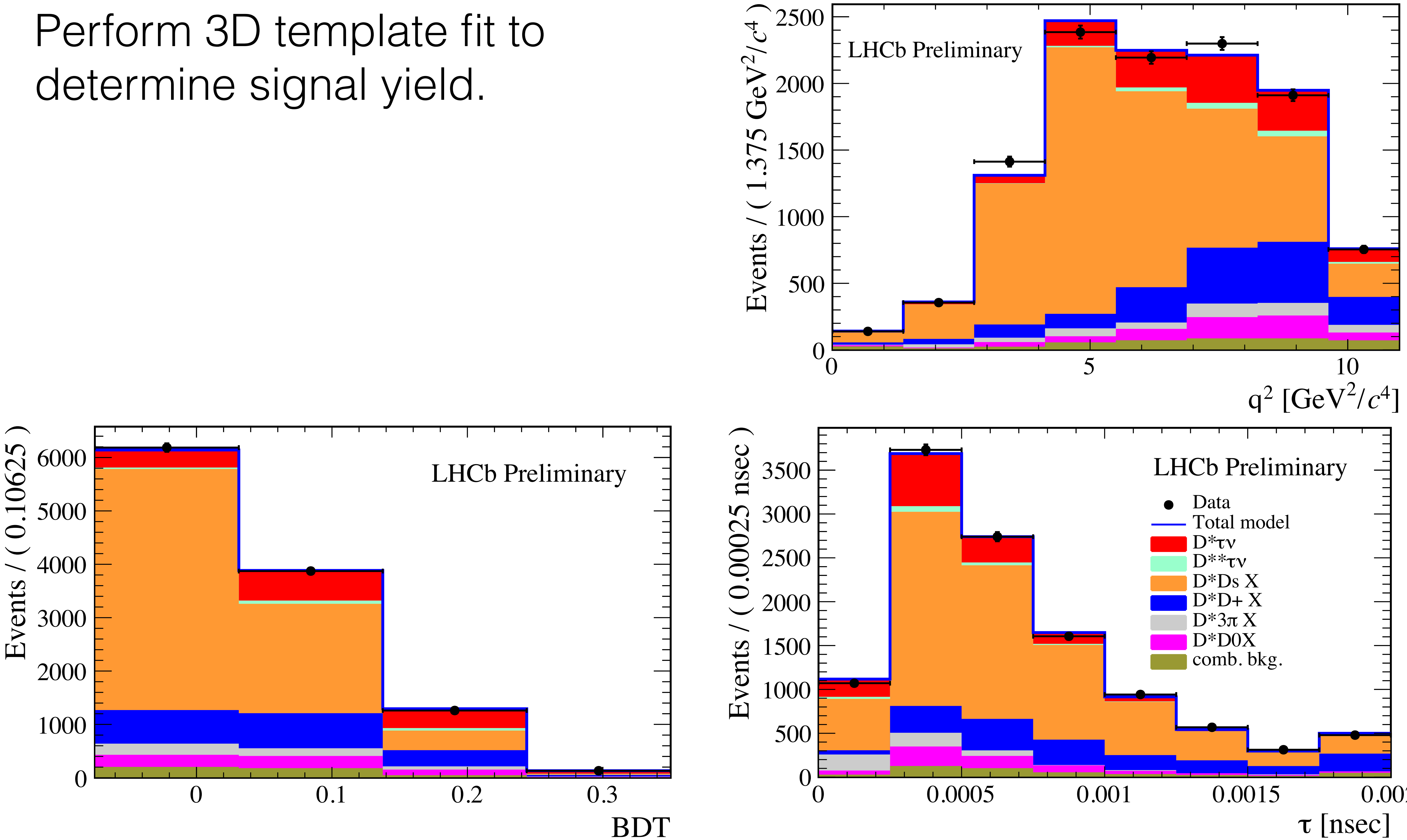
- Final variable is q^2, similar to the muonic analysis.



Signal fit

Phys. Rev. Lett. 120, 171802 (2018)

- Perform 3D template fit to determine signal yield.



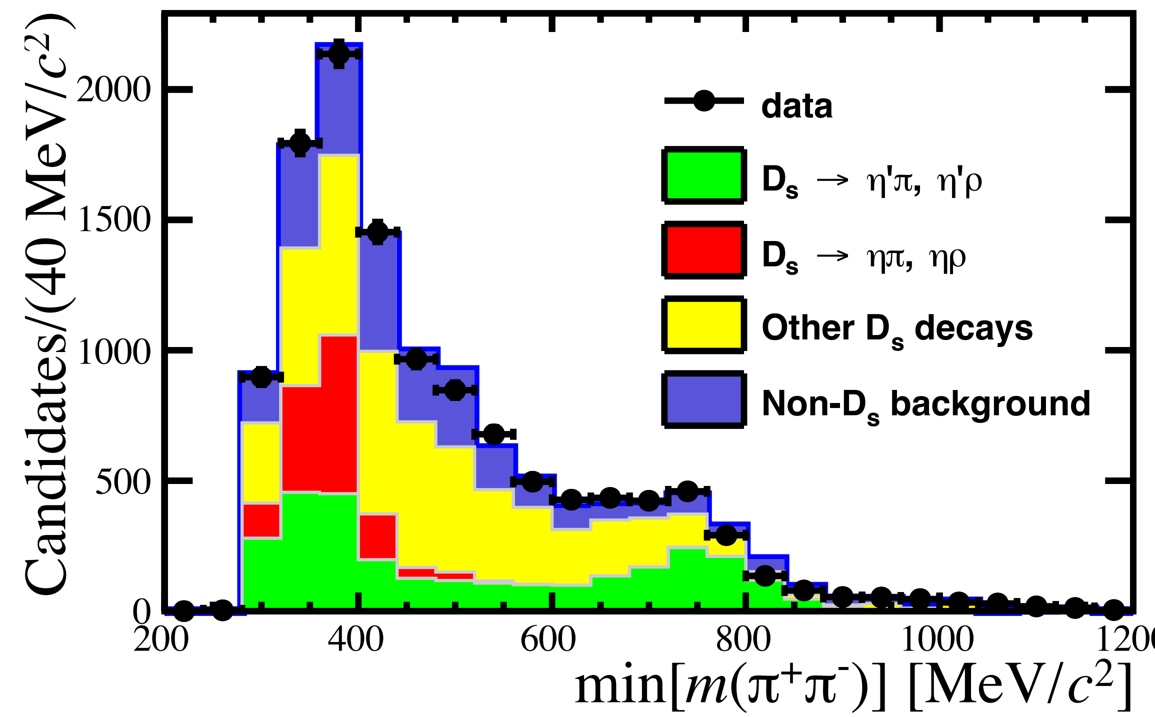
Control over backgrounds

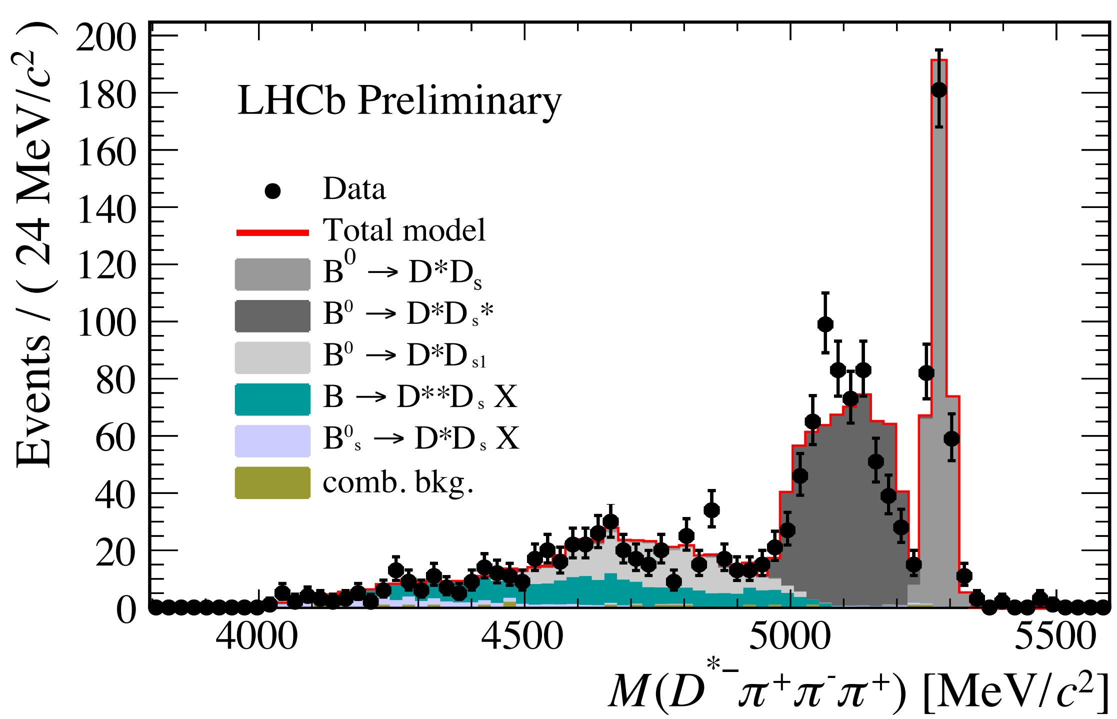
Phys. Rev. Lett. 120, 171802 (2018)

- Both the B and D decay part of $B \to D^{(*)}(D_s^+ \to 3\pi X)X$ need to be controlled.

- Isolate the background by looking at the low BDT region.

- This is used to control the D_s^+ decay.





- The B decay part is isolated by looking at fully reconstructed $D_s^+ \to 3\pi$

Result

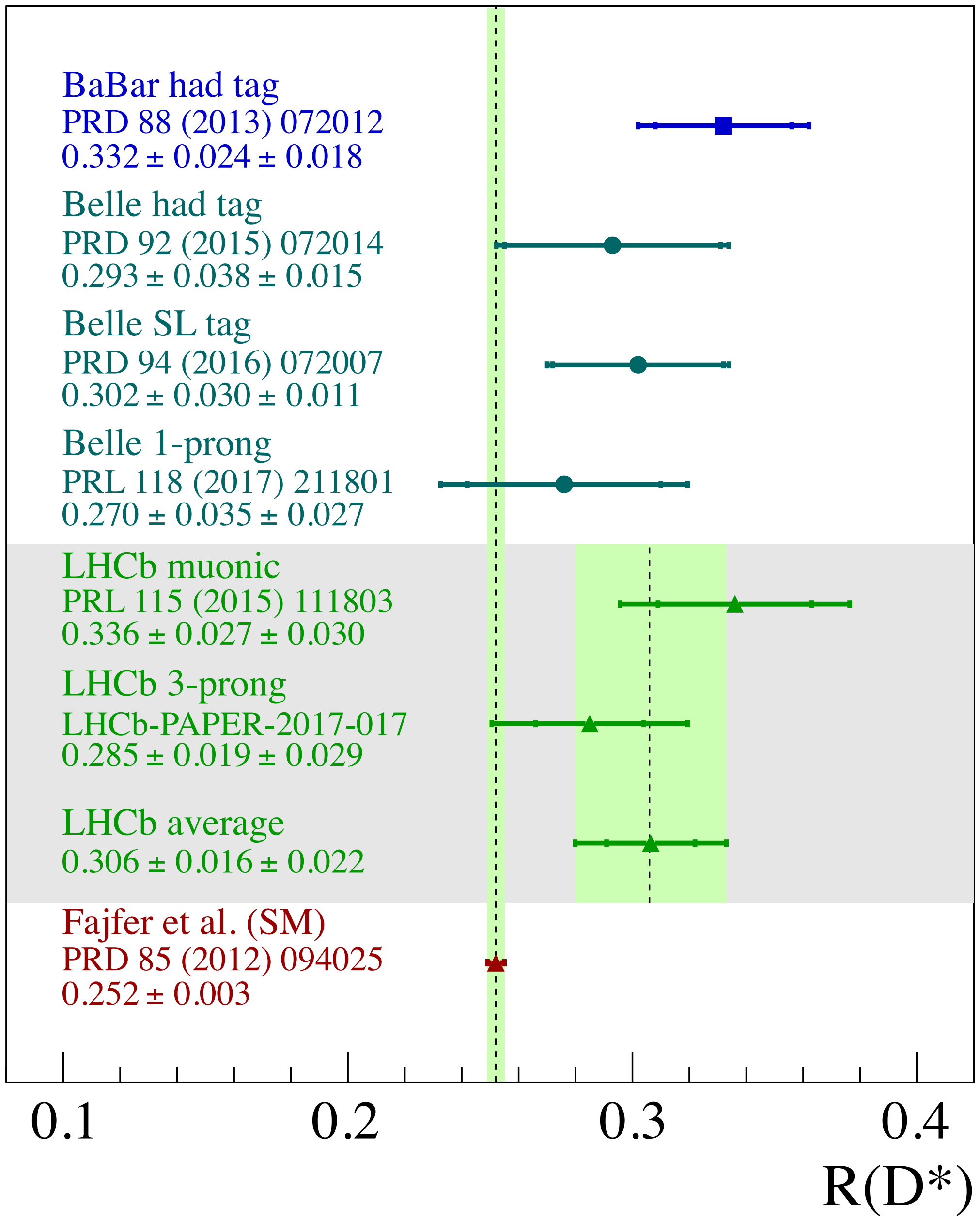
Phys. Rev. Lett. 120, 171802 (2018)

- Combine signal yield, efficiencies and external info to determine $R(D^*)$.

$$K_{had}(D^*) = \frac{BR(B^0 \to D^{*-}\tau^+\nu_\tau)}{BR(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}$$

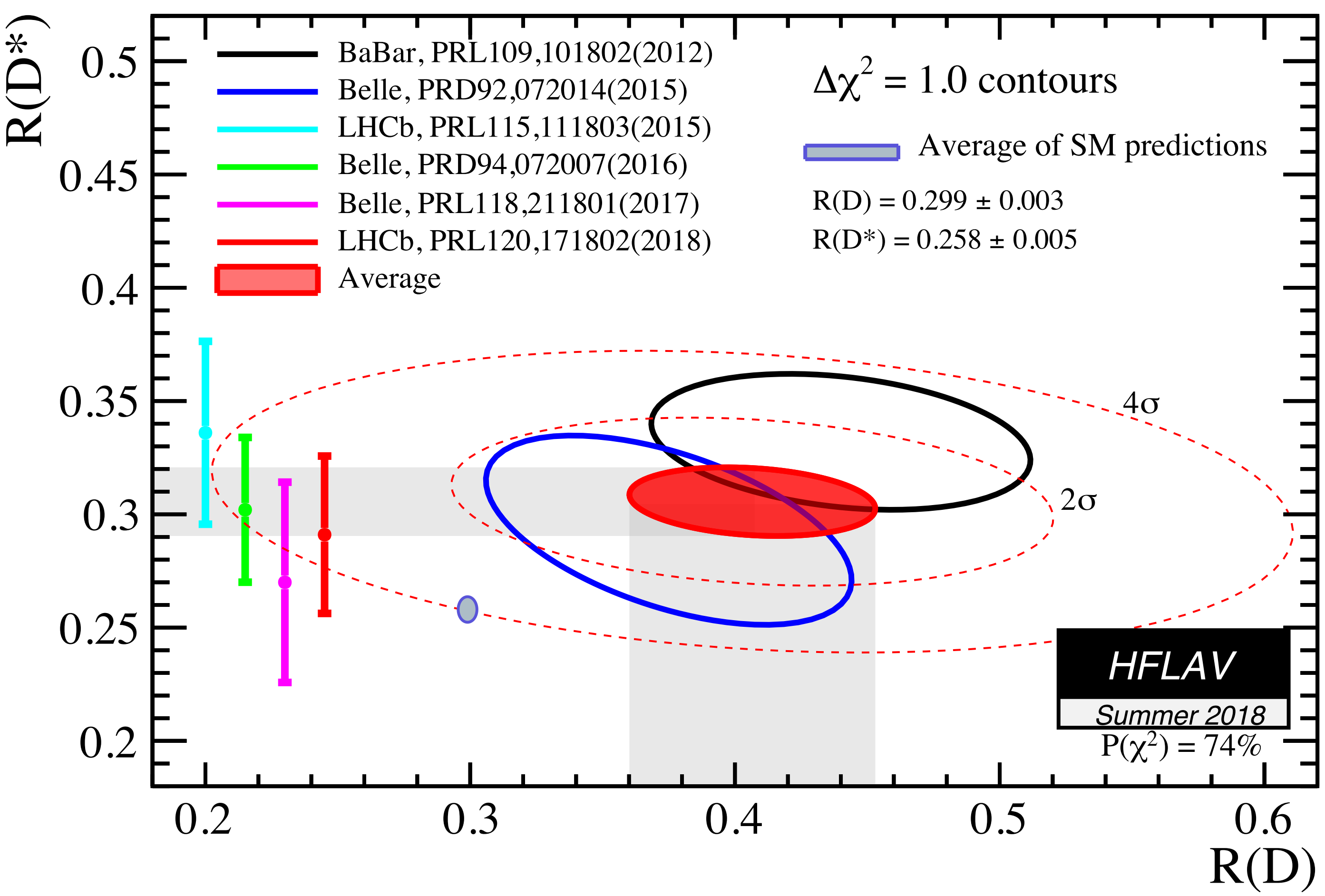
$$R(D^*) = K_{had}(D^*) \times \frac{BR(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{BR(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

- Dominant systematics from external BFs, efficiency corrections and background shapes.



Combination

- All experiments see an excess of signal w.r.t. SM prediction.



Horizontal bands refer to R(D*), ellipses refer to both R(D*,D)

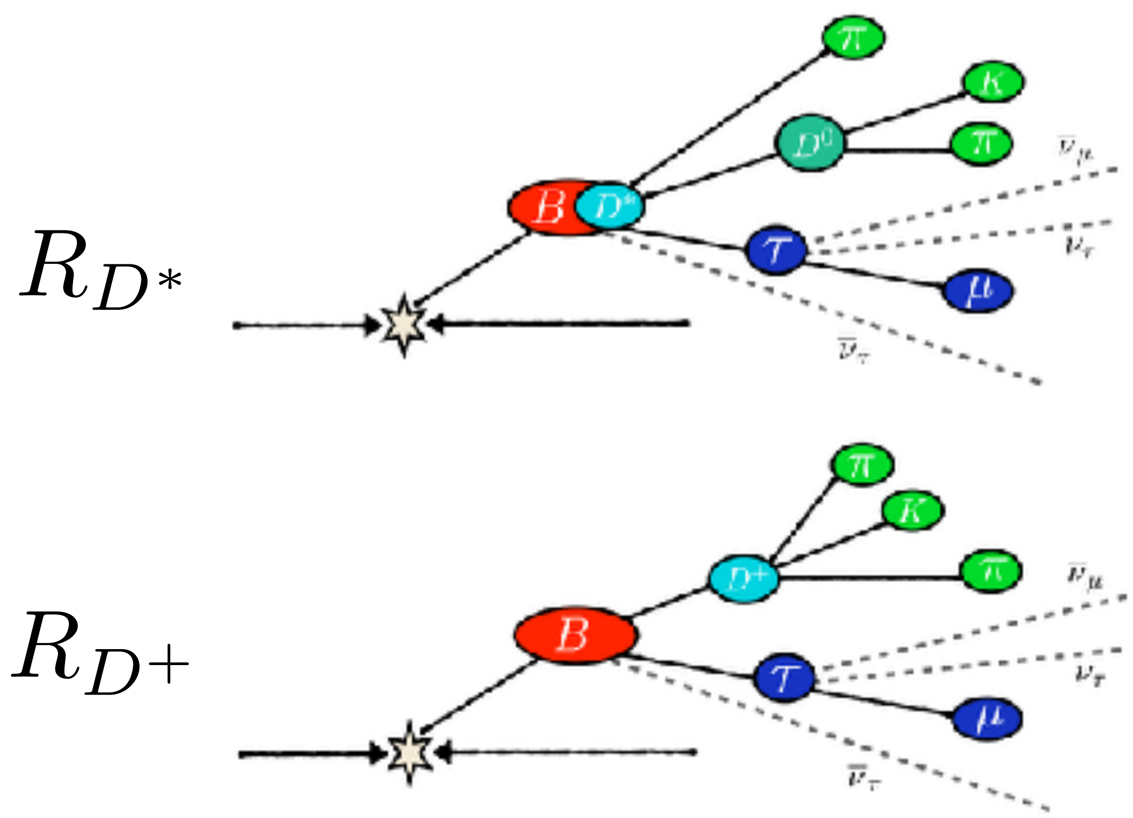
Latest HFLAV average [1] quotes **3.8σ** from SM prediction

[1] https://hflav-eos.web.cern.ch/hflav-eos/semi/summer18/RDRDs.html

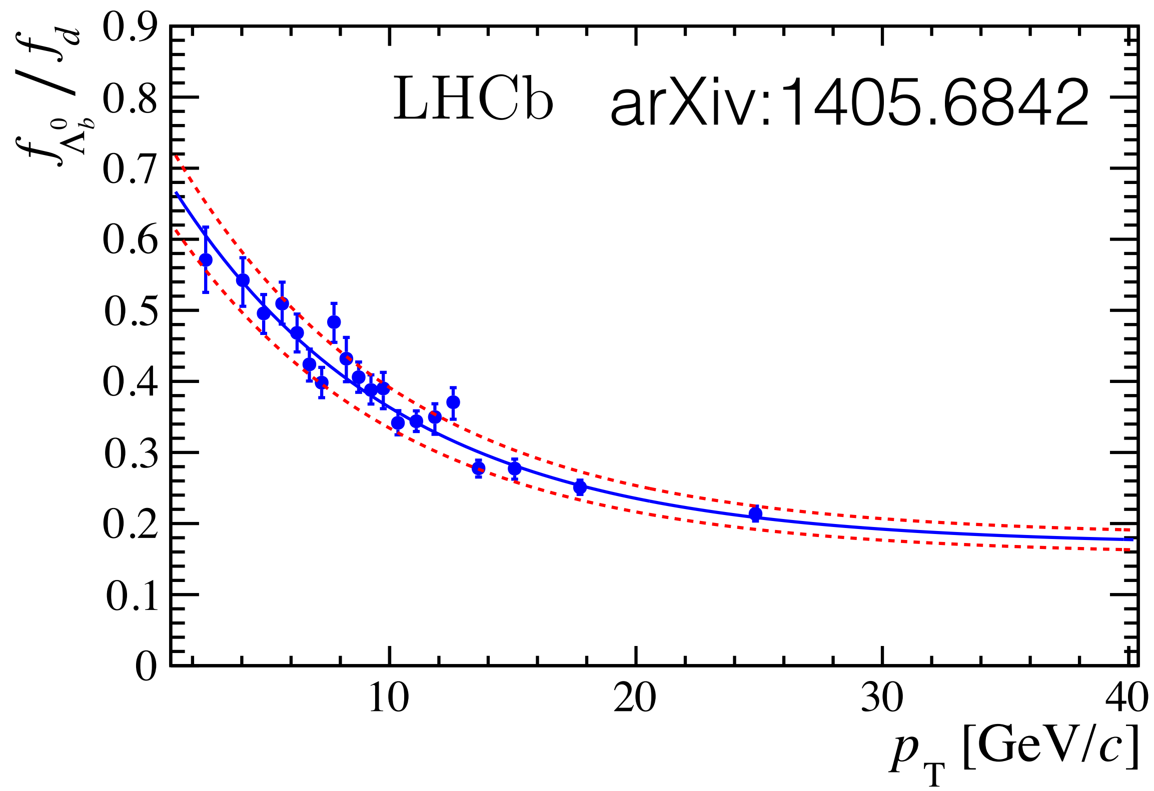
What now?

- Main priority is to clarify the existence of any NP signal.

Improve the precision of R_{D^*} ratios.



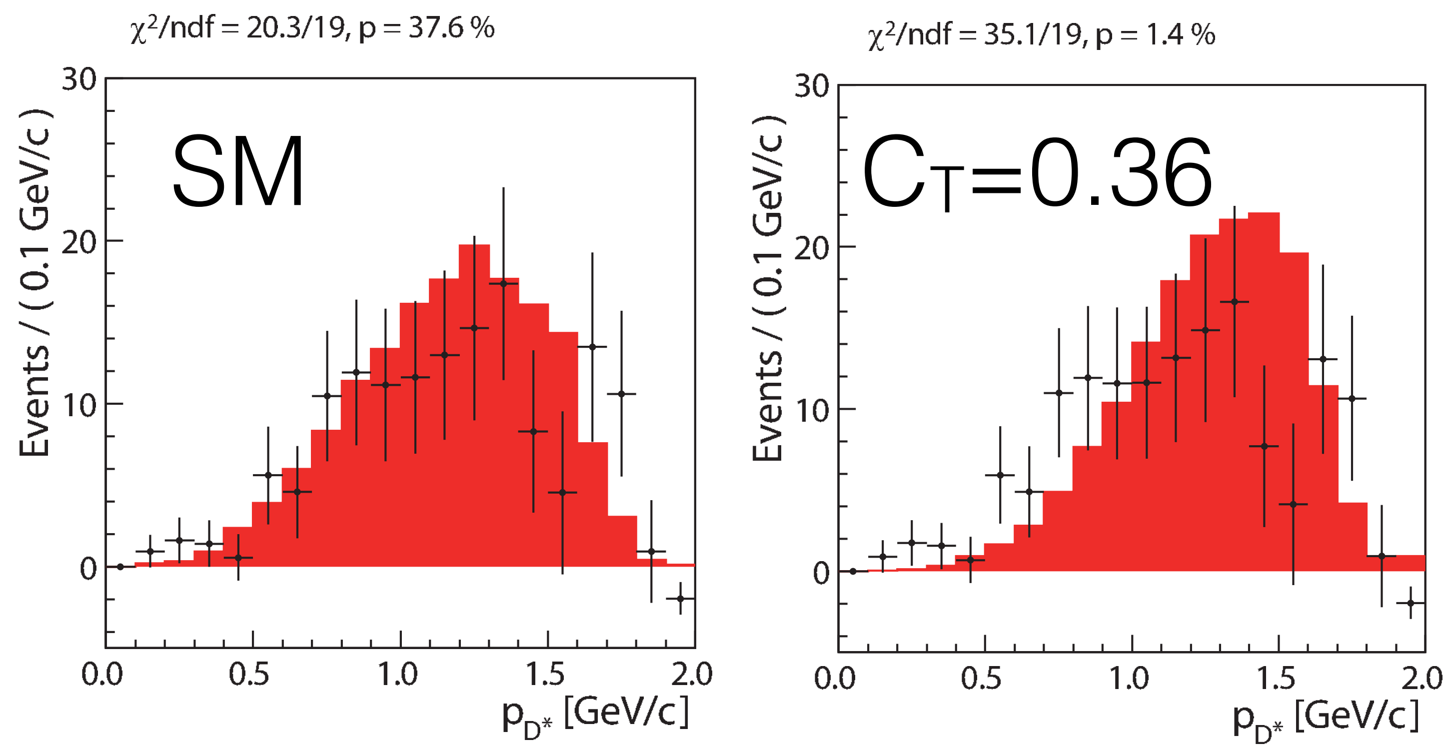
Explore other b-hadron systems.



- We are already doing this with the current data in hand.

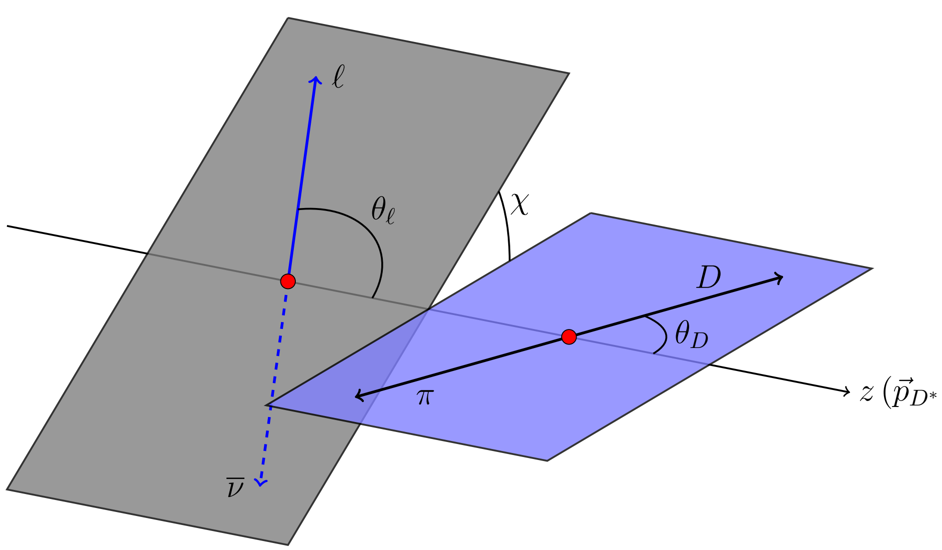
Beyond R measurements

- NP can also alter angular distribution of decay products.
  - e.g. charged Higgs boson would mean isotropic distribution of the lepton pairs.



Belle compared the D* momentum for different models.

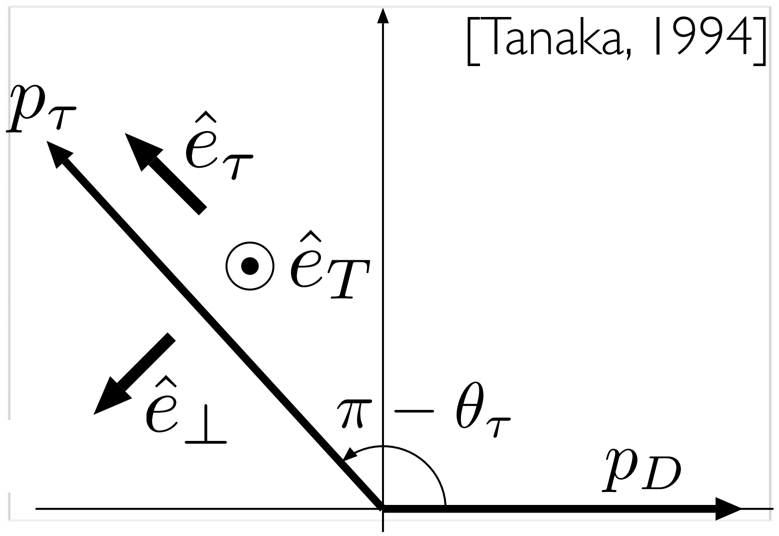
Eventually want to do a fully angular analysis of the decay.

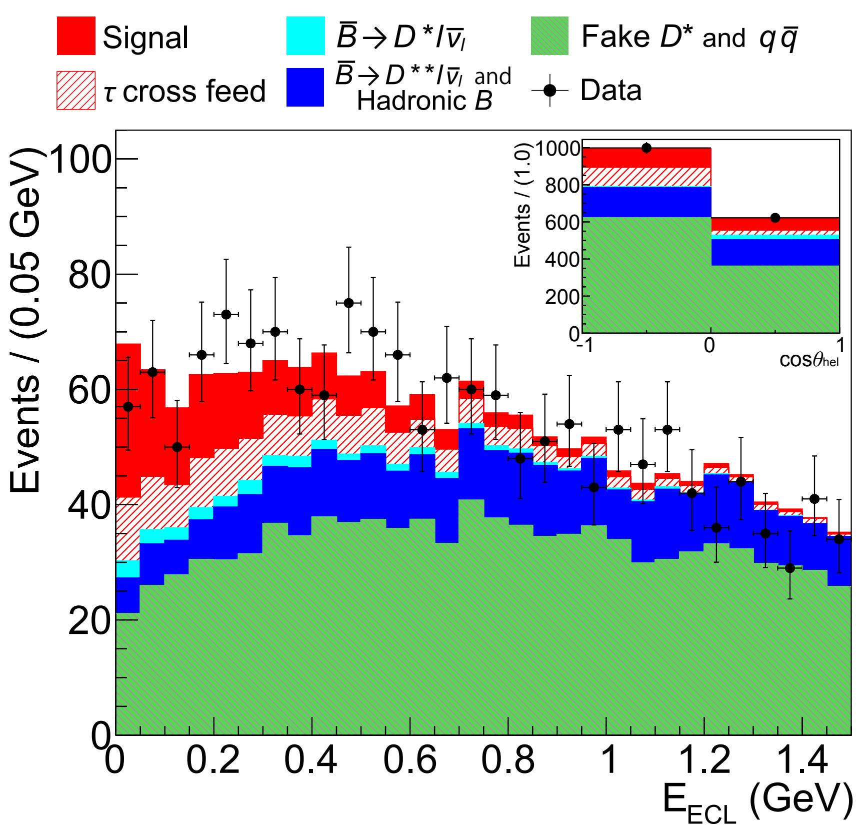


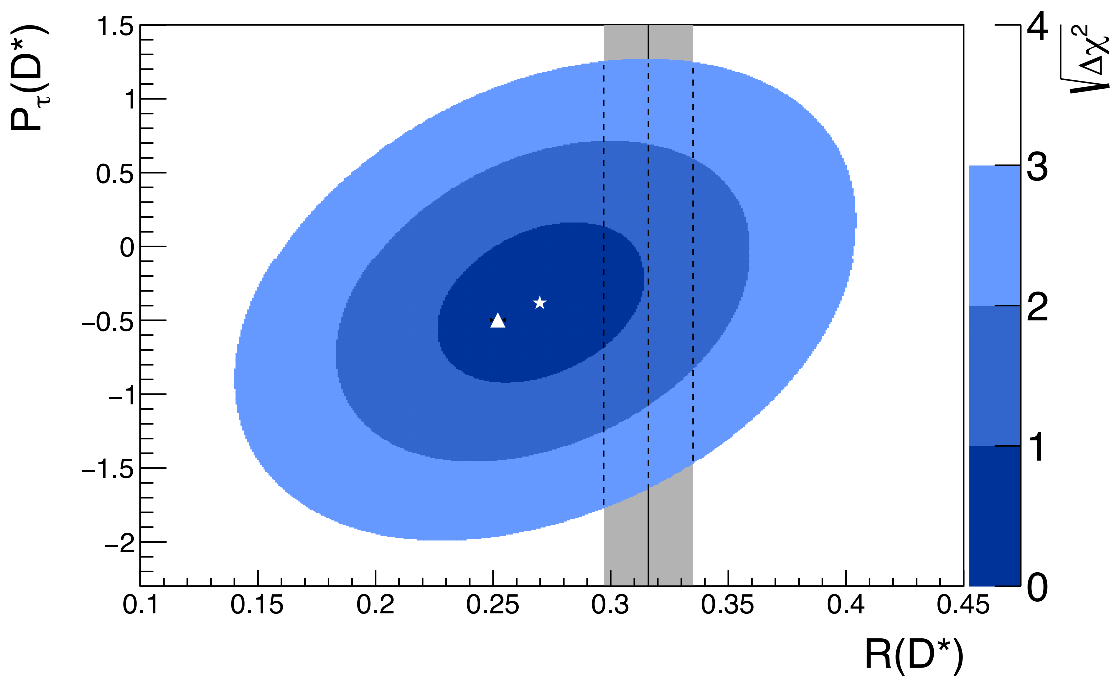
Latest result from Belle

arXiv:1612.00529, submitted to PRL

- First result to use hadronic $\tau \to \pi\nu$ decays.







- Also first measurement to measure τ polarisation.

Future measurements

- We at LHCb are furiously working on several R measurements.
  - R(D), R(Λ_c) with muonic and semileptonic tau decays.
  - Some of these will try to relax the physics assumptions behind the signal models.
  - We are also looking at the feasibility of an angular analysis, resolution is key here.
- Belle-II will also come online soon: they will also make precise measurements including ones inaccessible to LHCb: e.g. B—>τν.

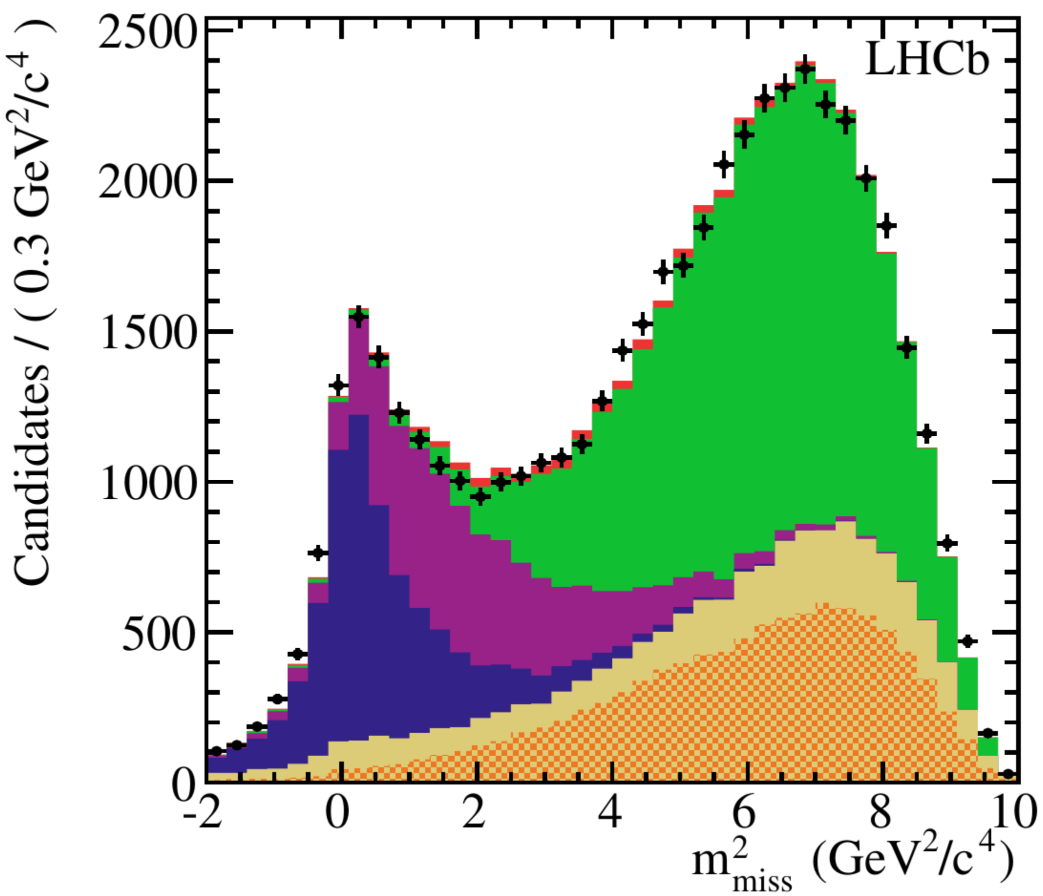
Half-time

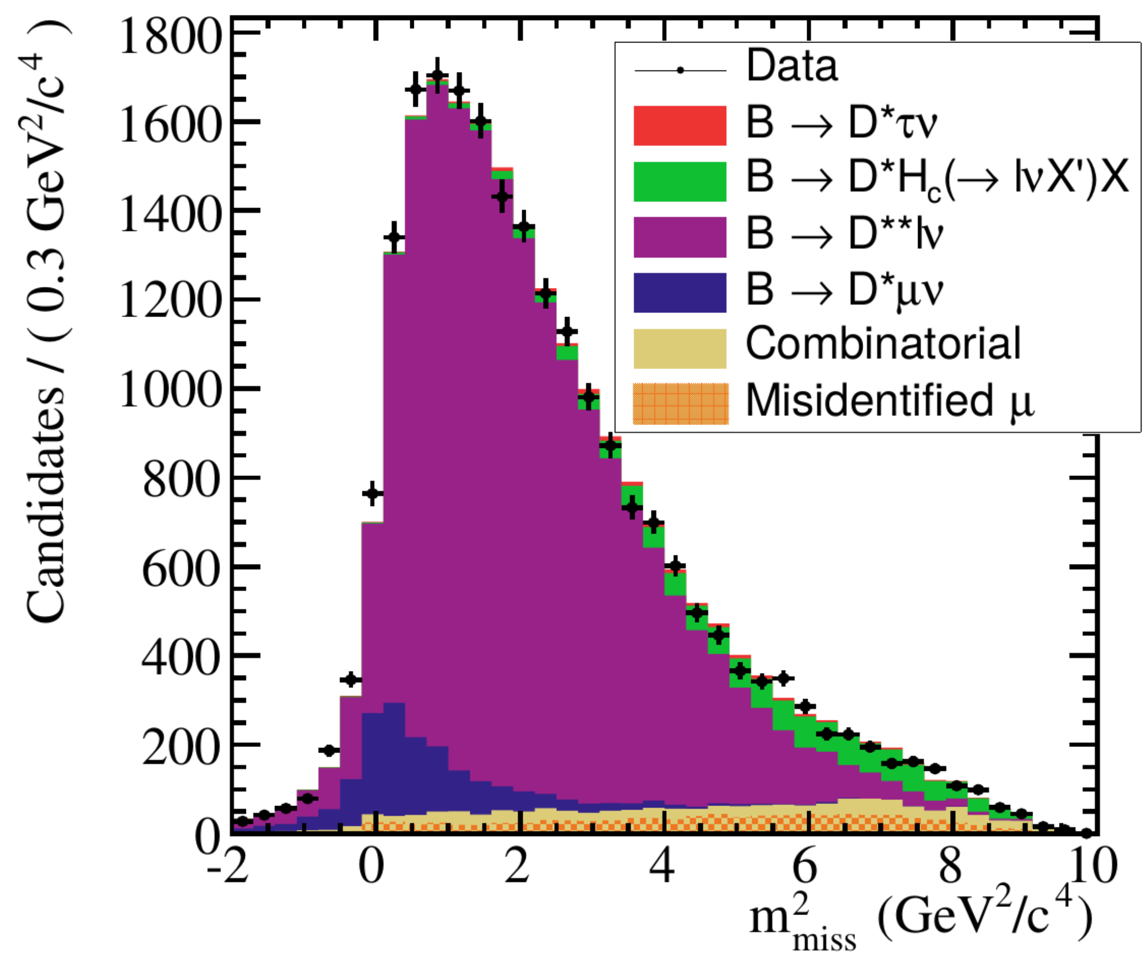
- LHCb and the B-factories have collected a huge number of B decays and have tools to study them in great detail.
- They all point towards a larger than expected decay rate of $B \to D^{*}\tau\nu$ but no single measurement is above 3σ still inconslusive.
- The measurements are difficult and complicated, but I hope I have convinced you that the systematic uncertainties are well understood and calculated.
- The future is bright for these measurements, with new R measurements and angular analyses on the horizon.
- Next lecture we will move to. $b \to s\ell\ell$ which is rather different (easier) experimental challenge.

Back-ups

R(D*) control samples

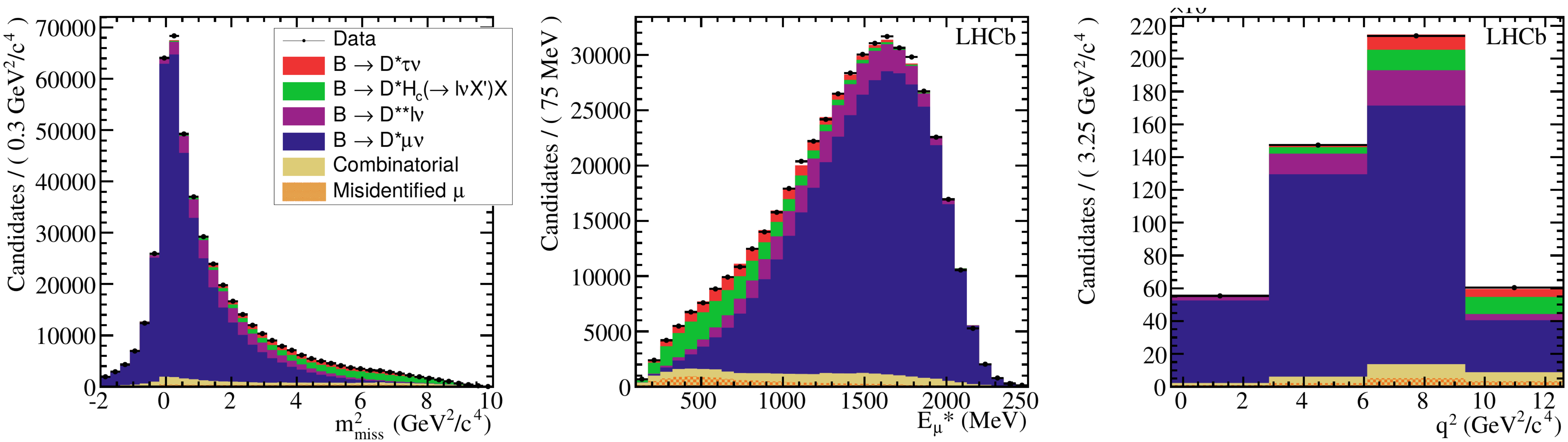
Anti-isolate signal to enrich particular backgrounds.





R(D*) 3D fit

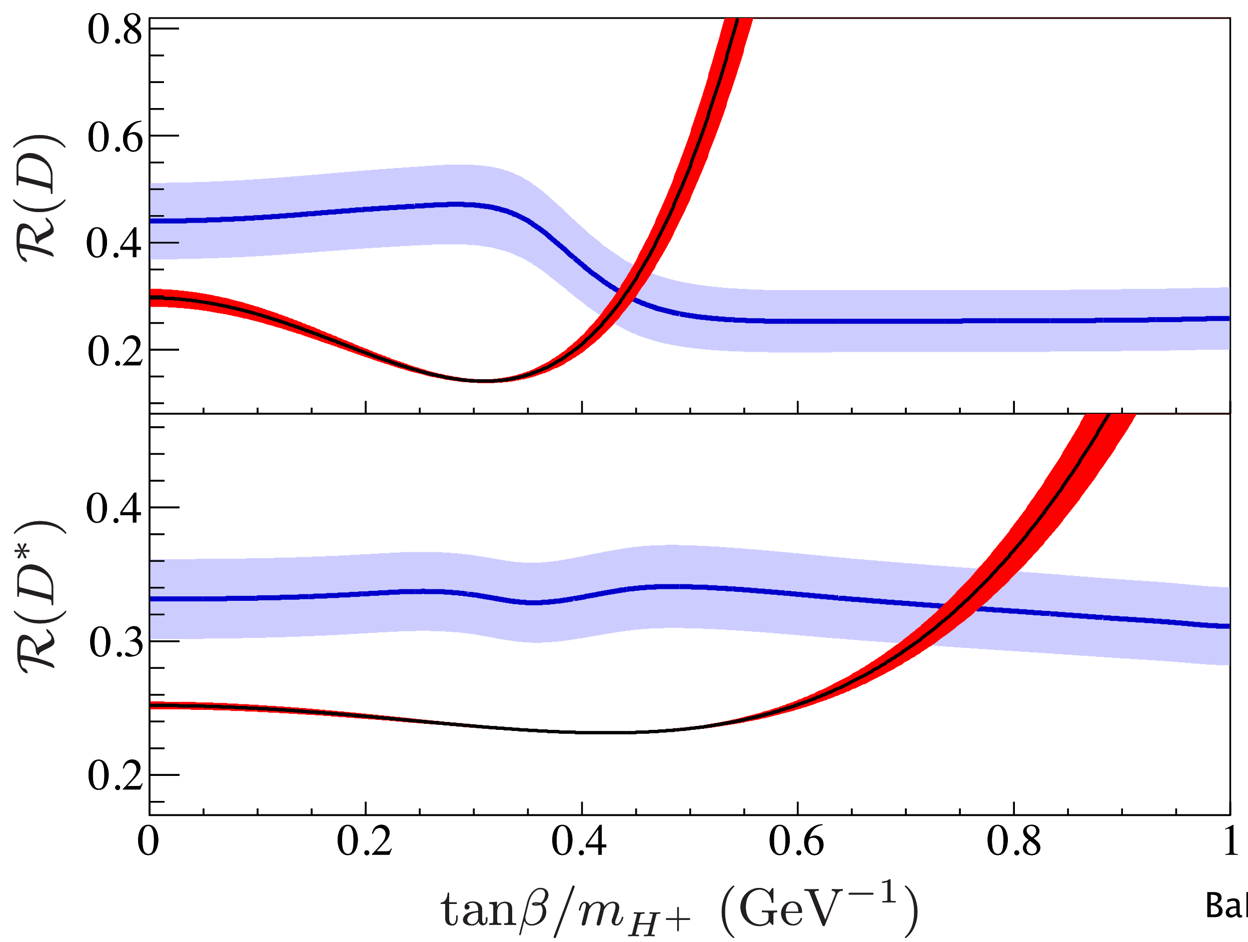
3D fit used to discriminate signal from backgrounds



Good agreement seen everywhere

Can 2HDM explain it?

- BaBar's sees a similar enhancement to both R(D) and R(D*).
  - This isn't what you'd expect from a 2HDM type II.

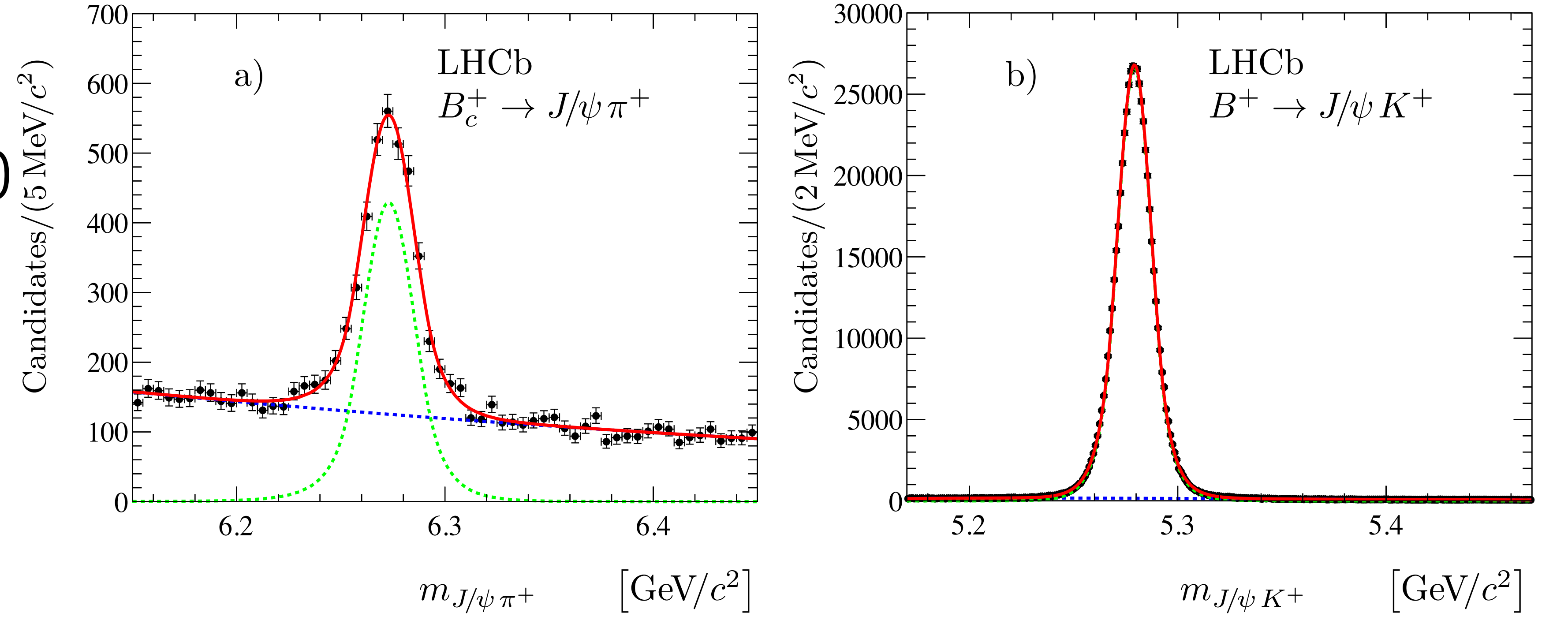


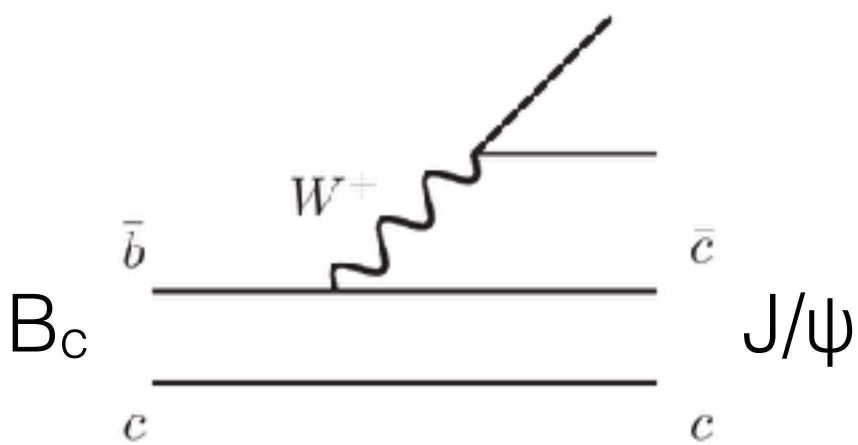
BaBar, Phys. Rev. D 88, 072012 (2013)

Testing LFU with other hadrons

- Unlike at the B-factories, b-quarks at the LHC are free to hadronise into all sorts of different flavoured particles.

- An example is the B_c meson, produced ~ 200 times less often than regular b-hadrons.





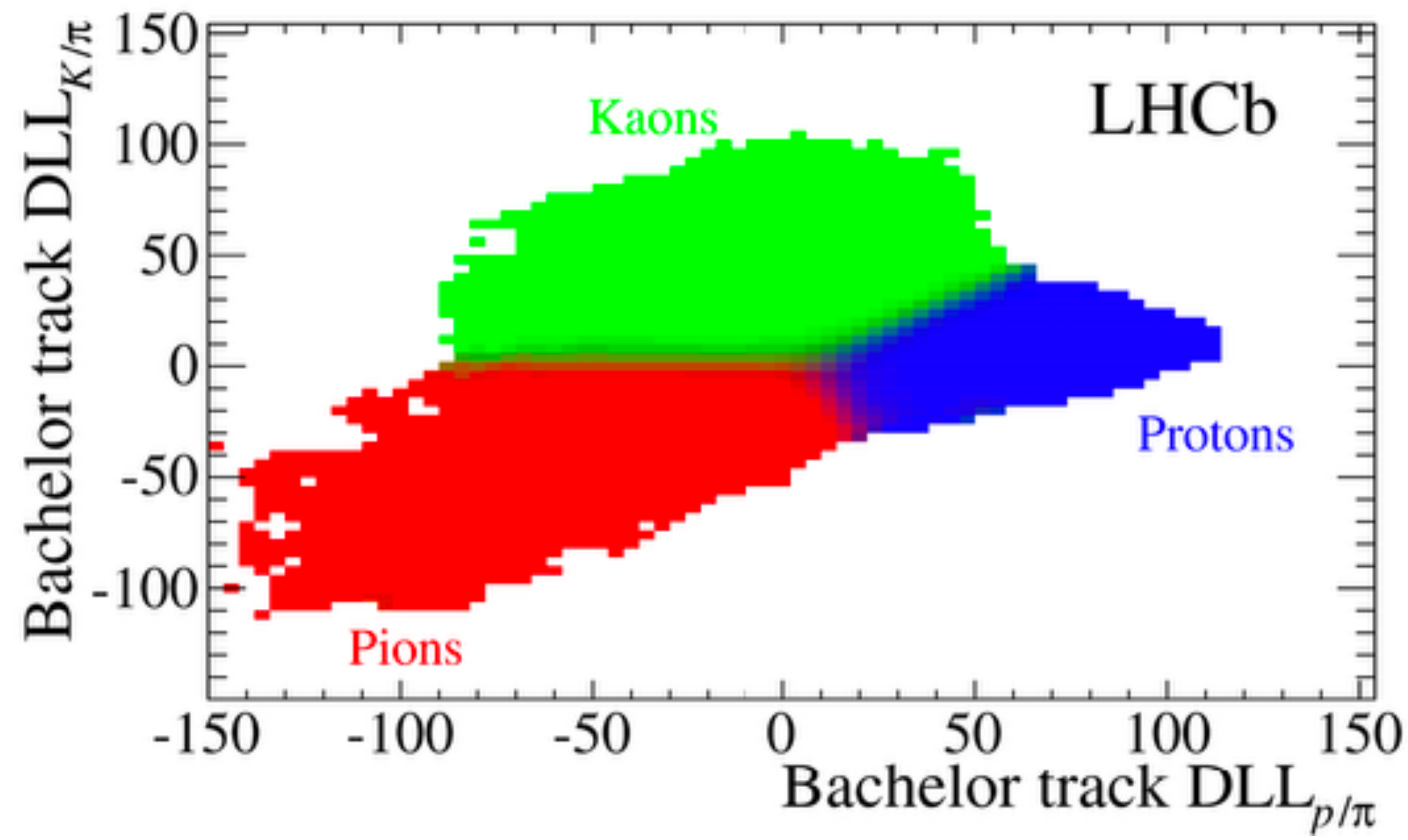
- Testing lepton universality here involves measuring the ratio R(J/ψ).

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}\left(B_c^+ \to J/\psi\tau^+\nu_\tau\right)}{\mathcal{B}\left(B_c^+ \to J/\psi\mu^+\nu_\mu\right)}$$

The main issue

- Due to the low B_c production, get a huge amount of background from B—>J/ψ h X decays, where the h decays into a muon.

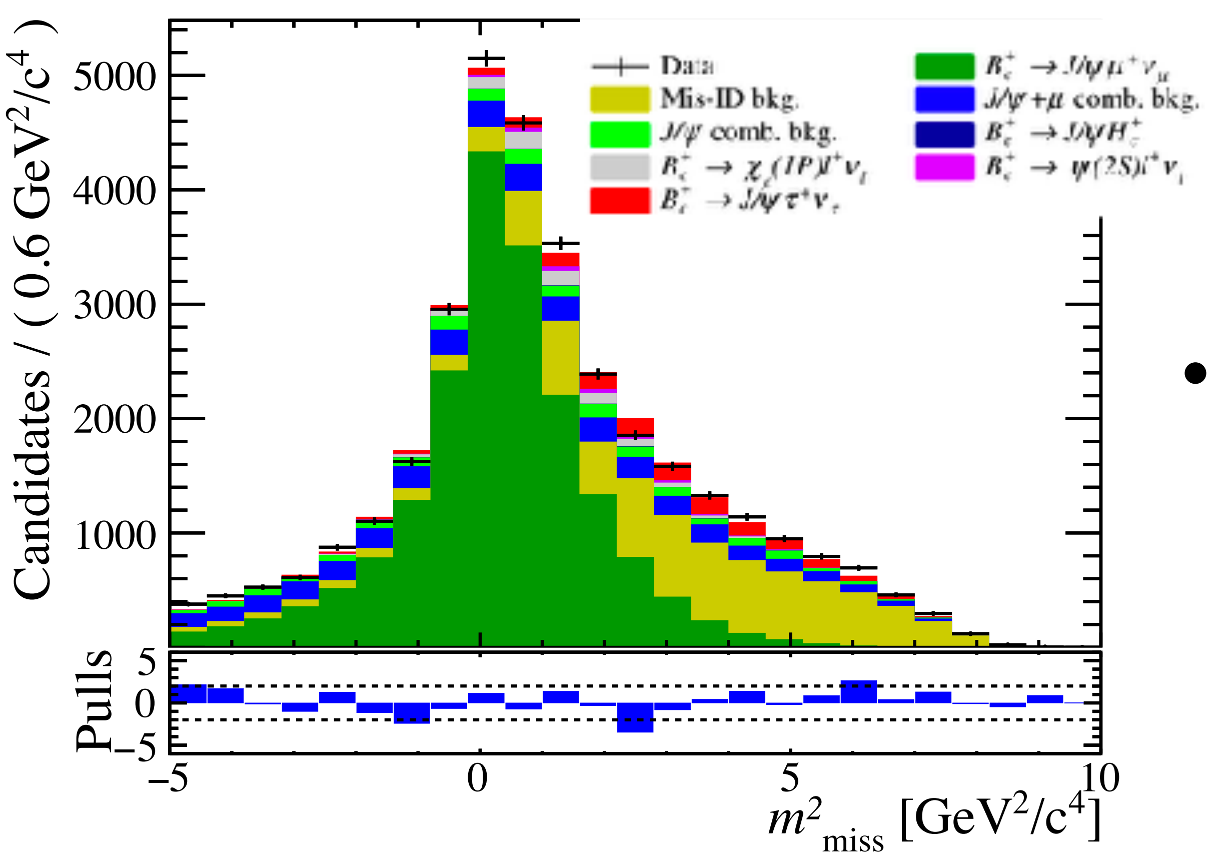
- Control samples obtained in the data by reversing the muon ID requirements, and selecting specific hadron species using the RICH information.



- Main difficulty is controlling cross-feed between the different hadron species.

R(J/ψ) measurement

- Similar approach to R(D*) measurement.
- Main difference due to large presence of fake muon background (due to low B_c production rate).



$$\mathcal{R}(J/\psi) = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$$

- Within two sigma of SM and NP models