Semileptonic b decays and asymmetries

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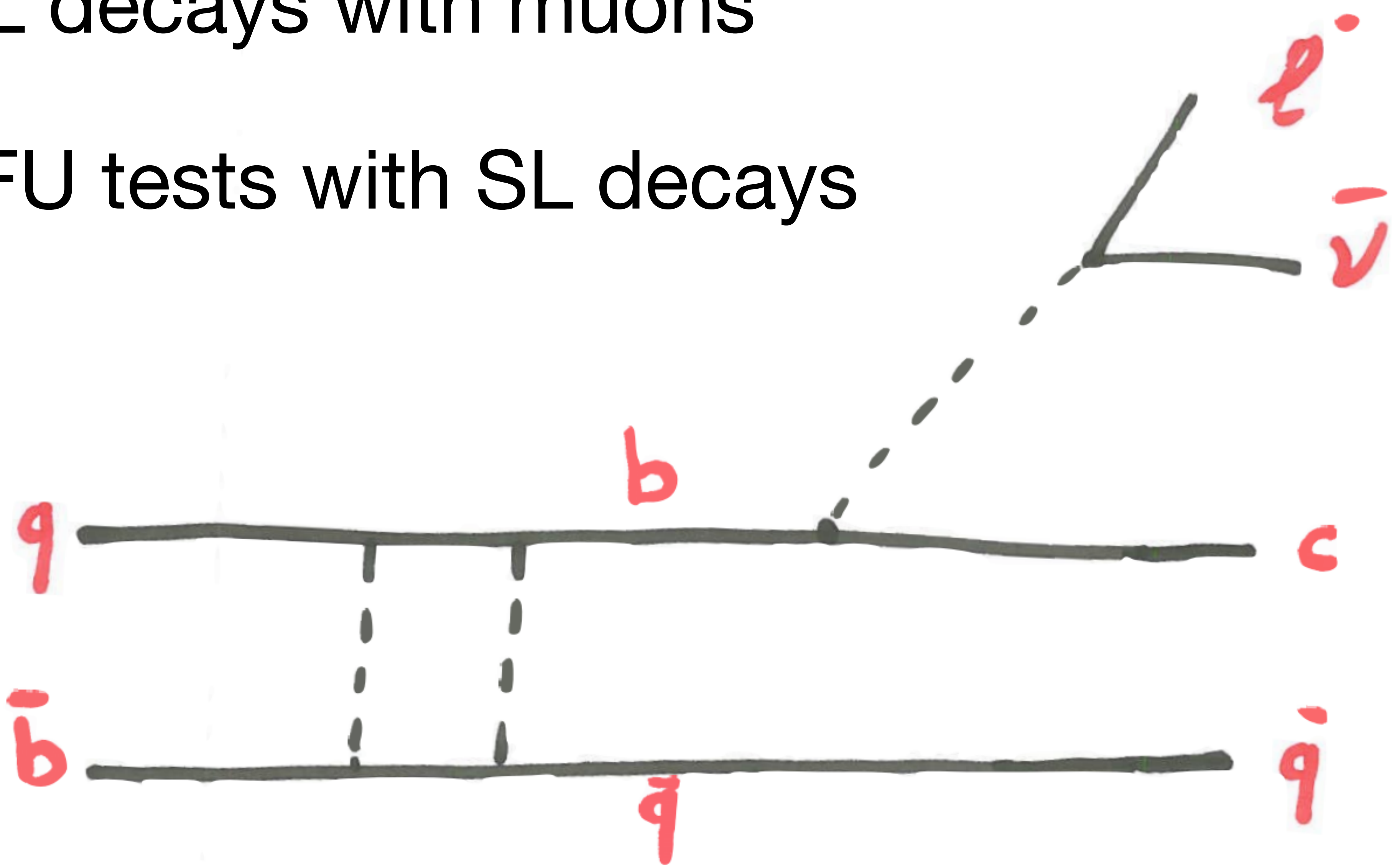
UK flavour meeting in Durham
4-6 September 2017

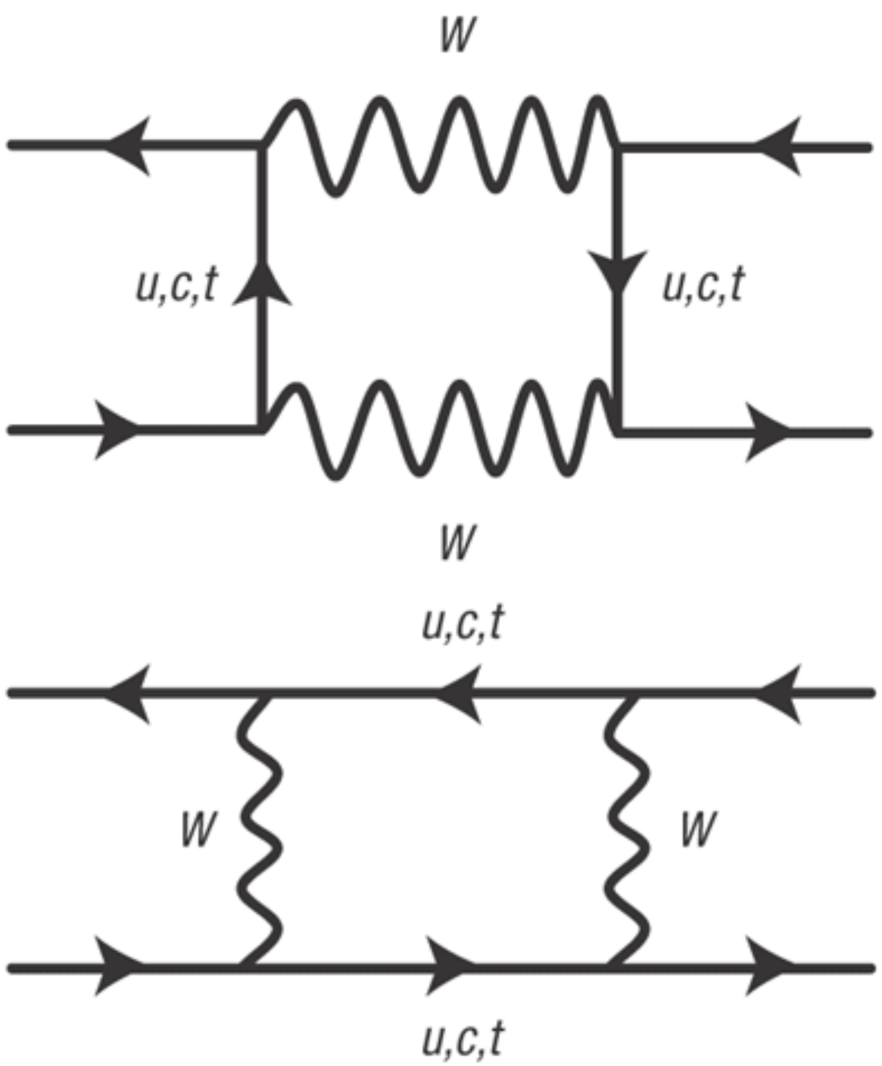
Outline

- Semileptonic asymmetries
- SL decays with muons
- LFU tests with SL decays



Semileptonic asymmetries

$$a_{\rm sl} = \frac{\Gamma(\overline{B} \to B \to f) - \Gamma(B \to \overline{B} \to \bar{f})}{\Gamma(\overline{B} \to B \to f) + \Gamma(B \to \overline{B} \to \bar{f})} \approx \mathrm{Im}\left(\frac{\Gamma_{12}}{\mathrm{M}_{12}}\right)$$



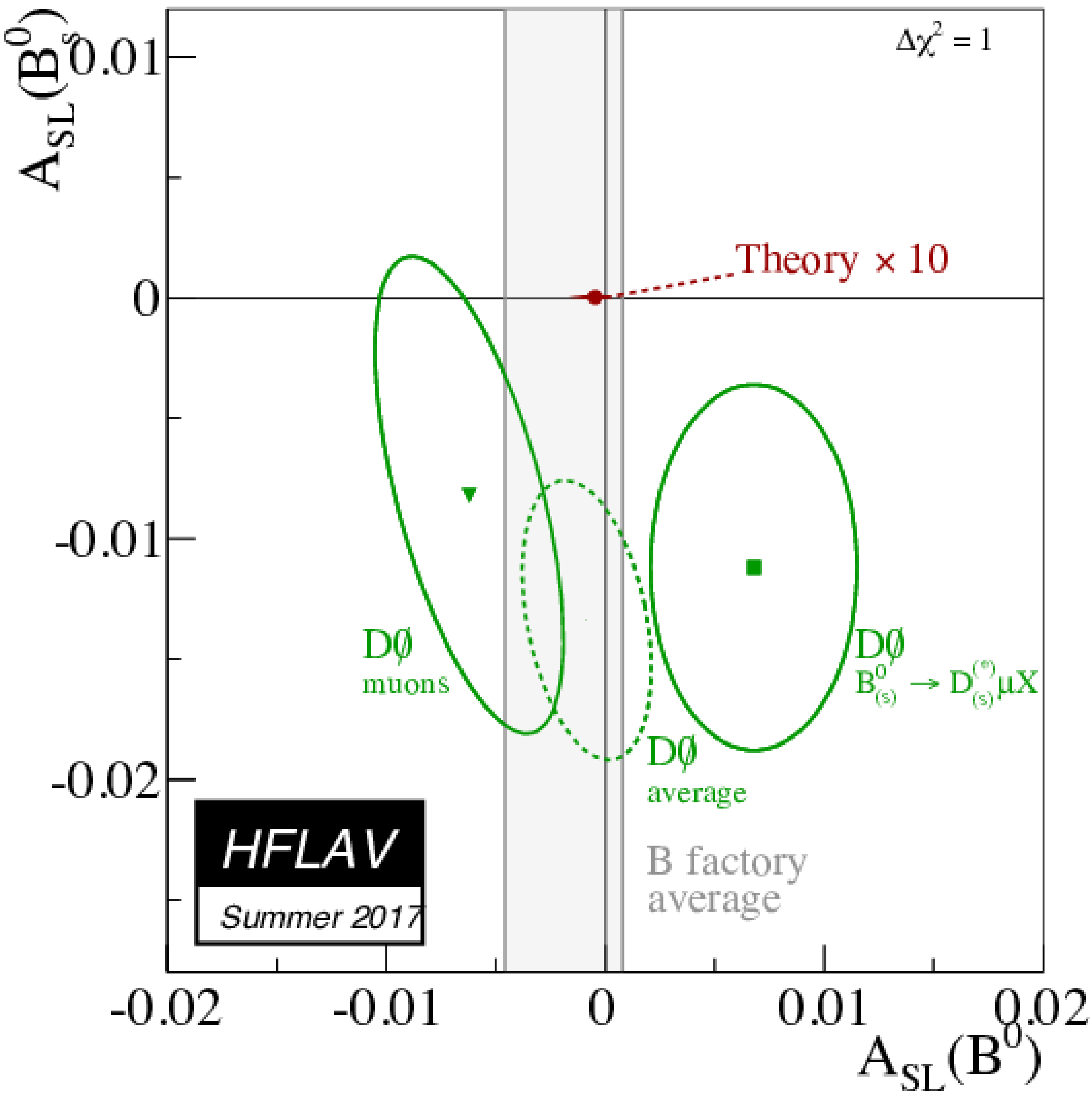
SM predictions[1,2]

$a_{\rm sl}^{s} = (2.22 \pm 0.27) \times 10^{-5}$

$a_{\rm sl}^{d} = (-4.7 \pm 0.6) \times 10^{-4}$

1. Lenz & Nierste, JHEP 06 (2007) 072. 0612167
2. Artuso, Borissov & Lenz, RMP 88 (2016) no.4, 045002 1511.09466

Landscape without LHCb



Note that the D0 dimuon asymmetry really sits in a 3D space of a_{sl}^s, a_{sl}^d and $\Delta\Gamma_d/\Gamma_d$.

10.1103/PhysRevD.87.074020, PRD 89, 012002 (2014) (U. Nierste pointed out (CKM 2014) that the $\Delta\Gamma_d$ correction was overestimated).

Complications

This observable requires flavour tagging:

$$a_{\rm sl} = \frac{\Gamma(\overline{B} \to B \to f) - \Gamma(B \to \overline{B} \to \bar{f})}{\Gamma(\overline{B} \to B \to f) + \Gamma(B \to \overline{B} \to \bar{f})}$$

Luckily we don't actually need tagging:

$$\frac{N(B,t) - N(\bar{B},t)}{N(B,t) + N(\bar{B},t)} = \frac{a_{\rm sl}}{2} \cdot \left[1 - \frac{\cos \Delta M t}{\cosh \frac{\Delta\Gamma t}{2}}\right]$$

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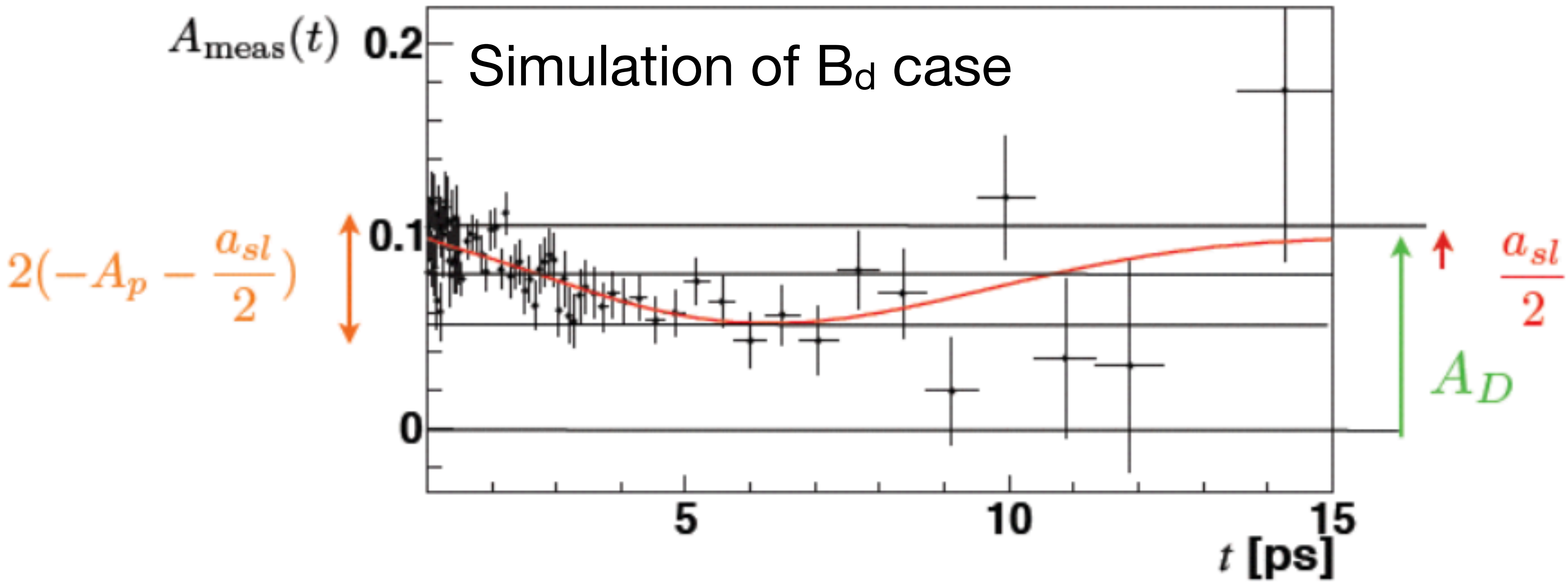
$$= \frac{a_{\rm sl}}{2} - \left[a_P + \frac{a_{\rm sl}}{2}\right] \cdot \frac{\cos\Delta M t}{\cosh\frac{\Delta\Gamma t}{2}}$$

Accounting for the production asymmetry.

Complications



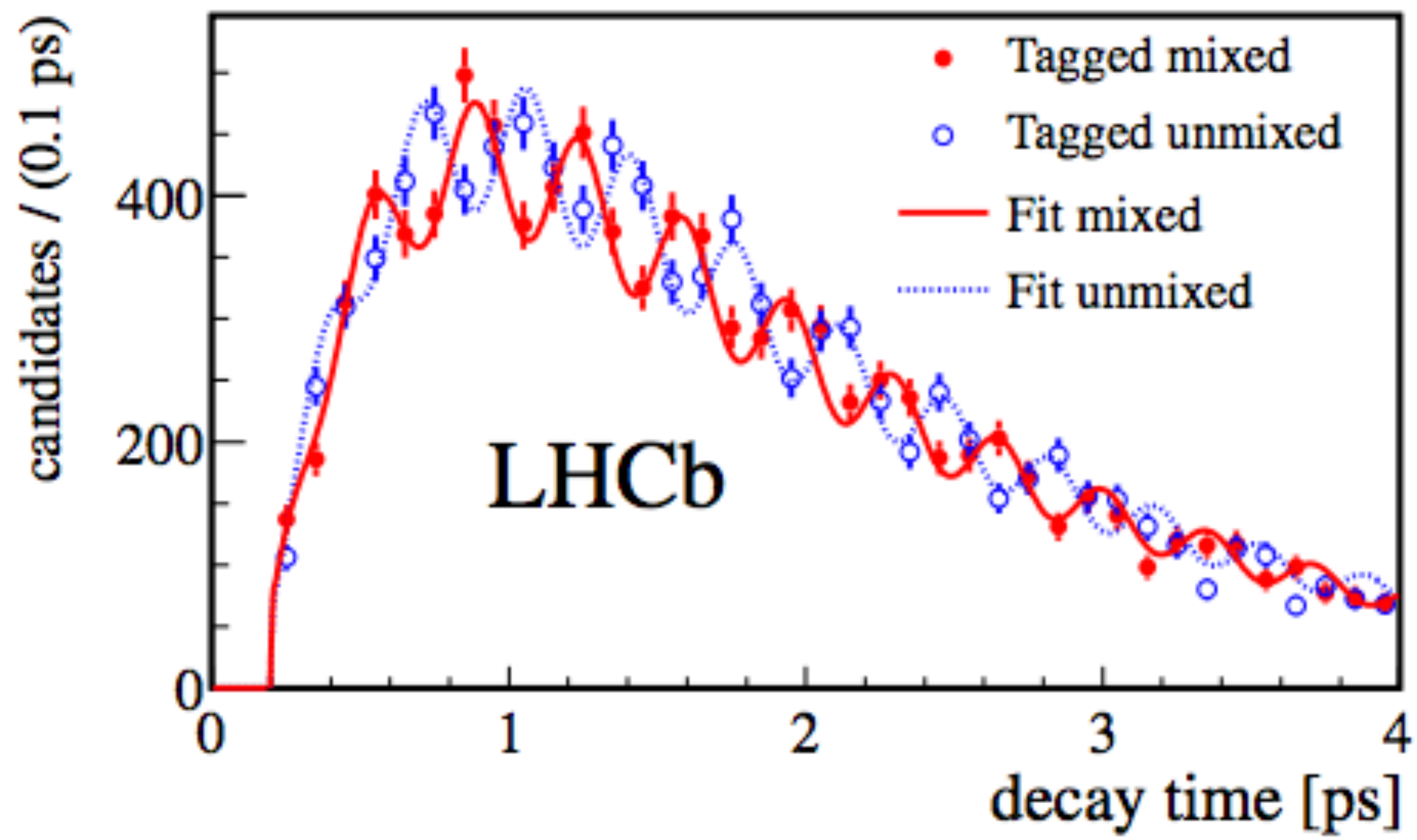
$$\frac{N(B,t)-N(\bar{B},t)}{N(B,t)+N(\bar{B},t)} = \frac{a_{\rm sl}}{2} - \left[a_P + \frac{a_{\rm sl}}{2}\right]\cdot\frac{\cos\Delta M t}{\cosh\frac{\Delta\Gamma t}{2}}$$

Accounting for the production asymmetry.

A simplification

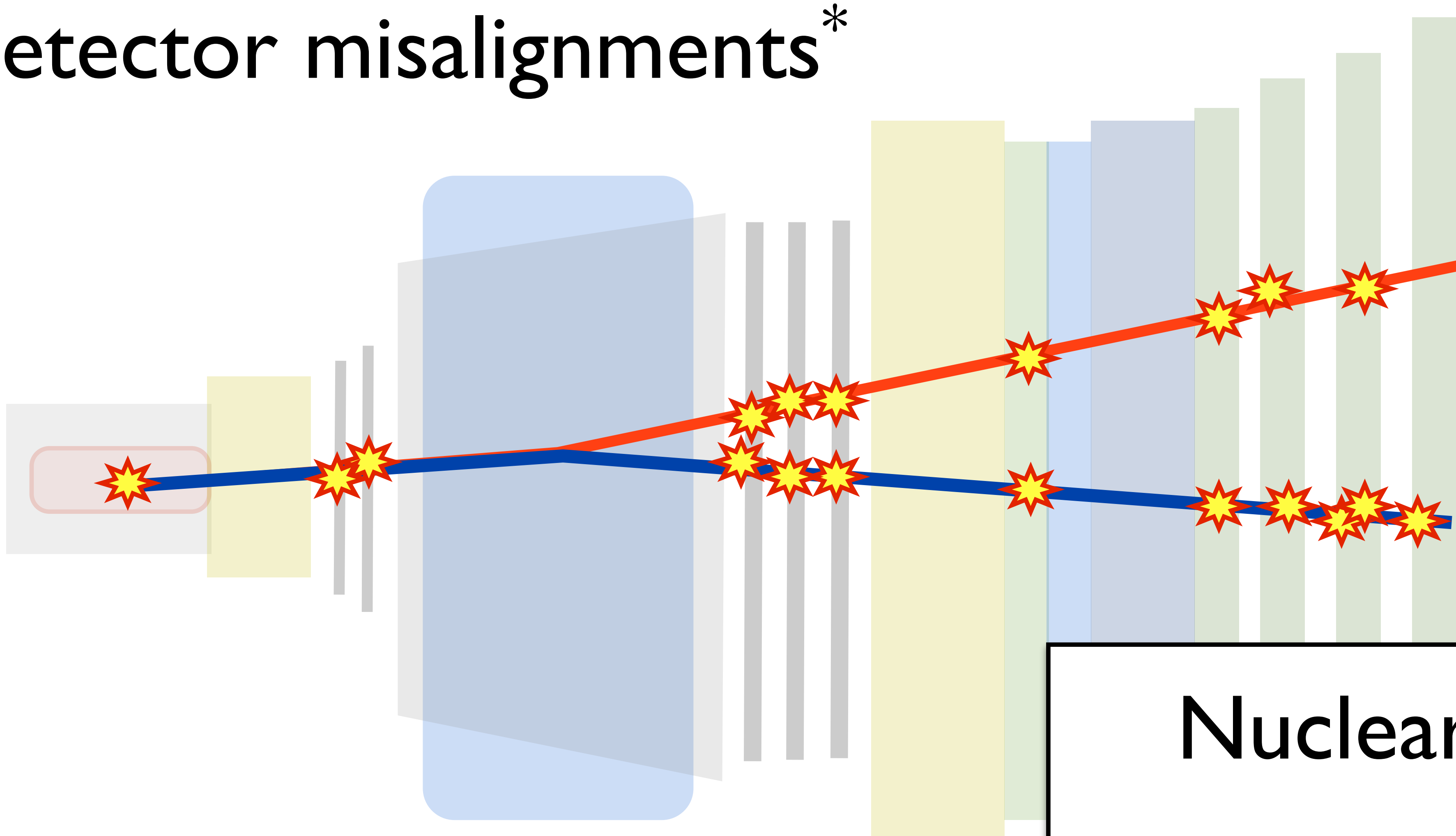
The fast B_s oscillations permit a simple untagged time-integrated approach for a_{sl}^{s}.

$$\frac{\int N(B,t) - \int N(\bar{B},t)}{\int N(B,t) + \int N(\bar{B},t)} \approx \frac{a_{\rm sl}}{2}$$



Detection asymmetries

Detector misalignments*



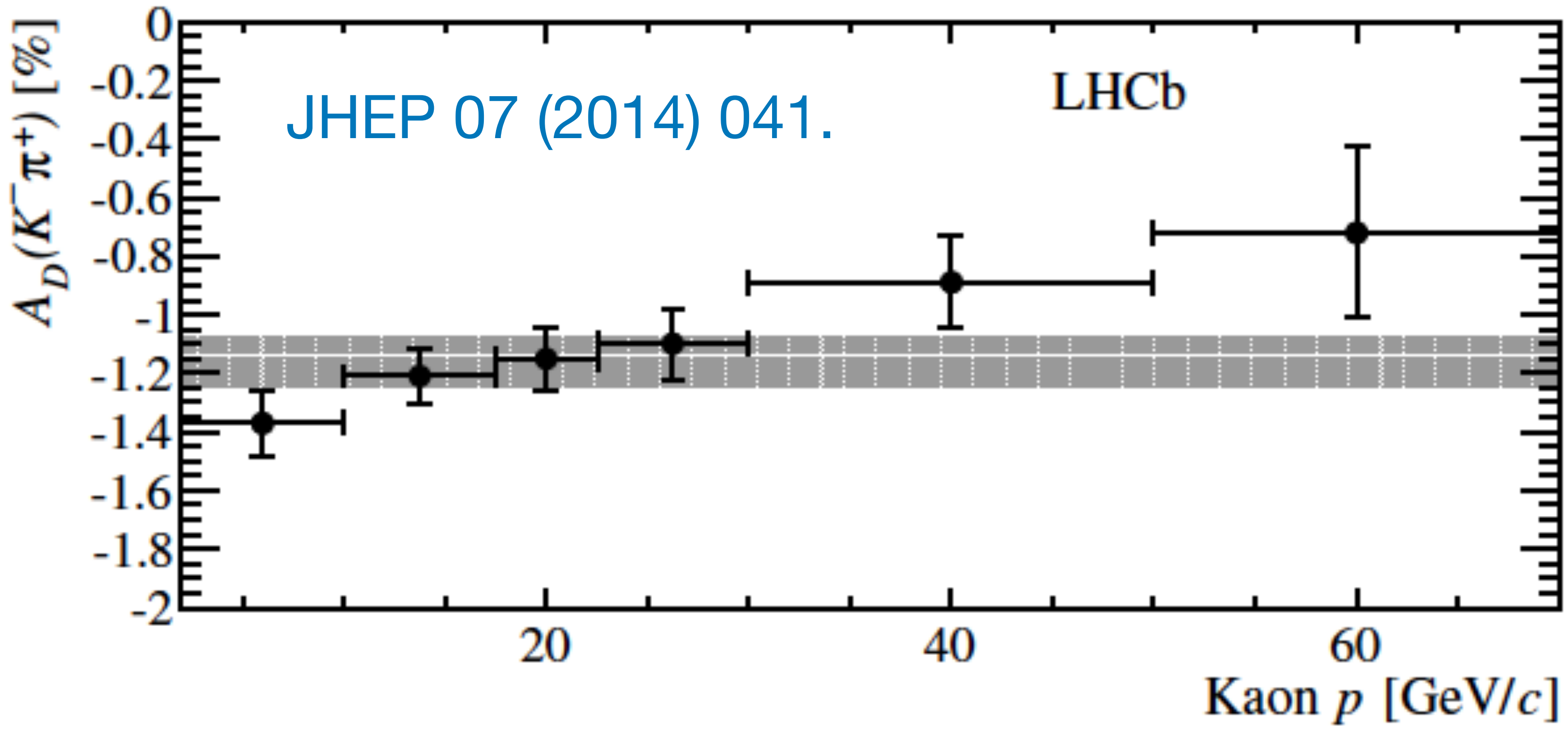
Nuclear interactions

$$\frac{\sigma(K^- N)}{\sigma(K^+ N)} \sim 1.3$$

*The ability to reverse our magnet field is crucial in controlling the systematic uncertainties associated to this source.
LHCb-PUB-2014-006

The kaon asymmetry

Method using combination of CF charm decays:

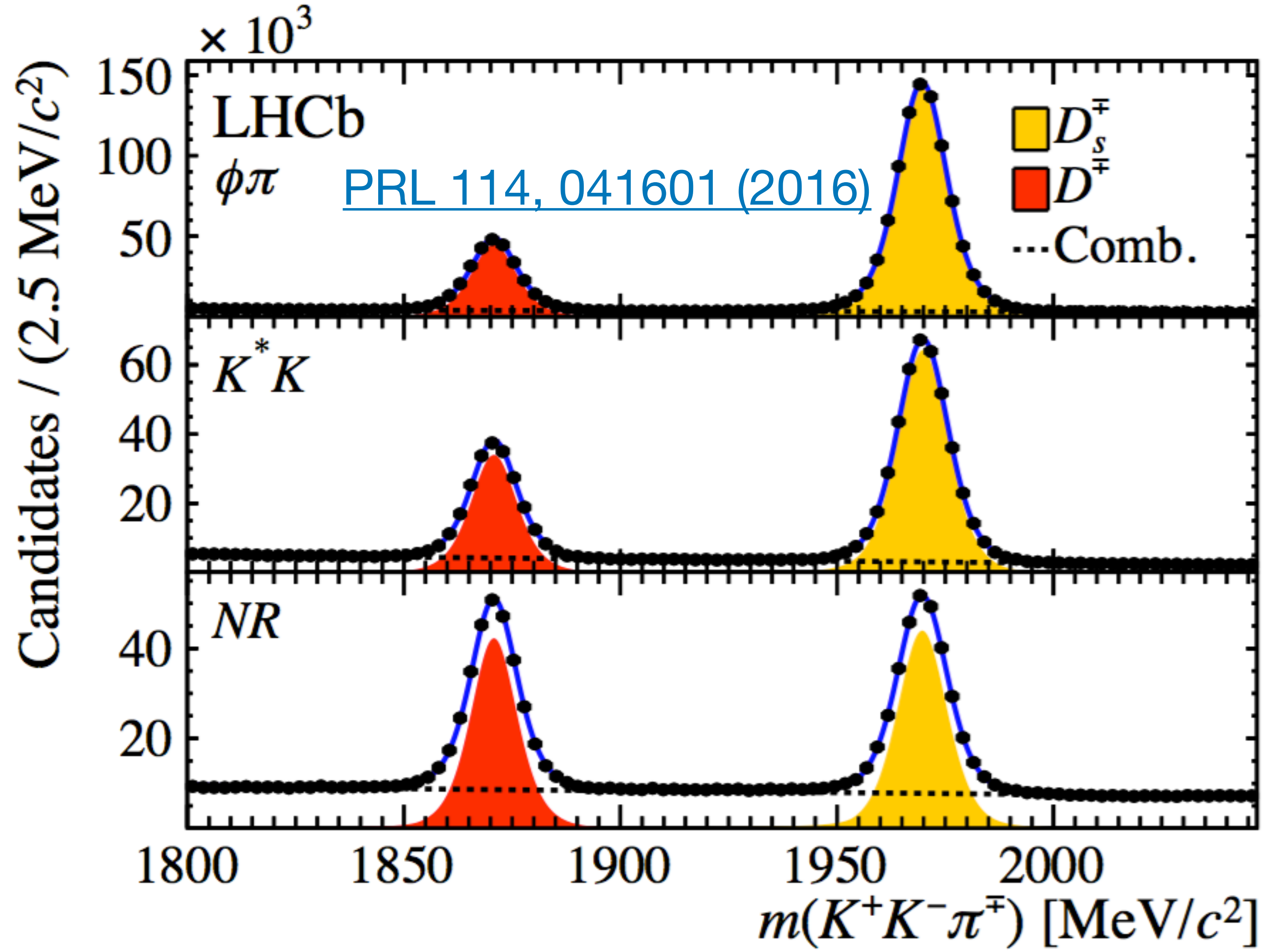


Still the single largest source of uncertainty for a_{sl}^{d}.
The specific limitation is our yield of $D^+ \rightarrow K_S\pi^+$ decays.

Completely new method in the pipeline for Run-II.

Backgrounds

Measurement of a_{sl}^s based on $B_s \to D_s \mu \nu X$.



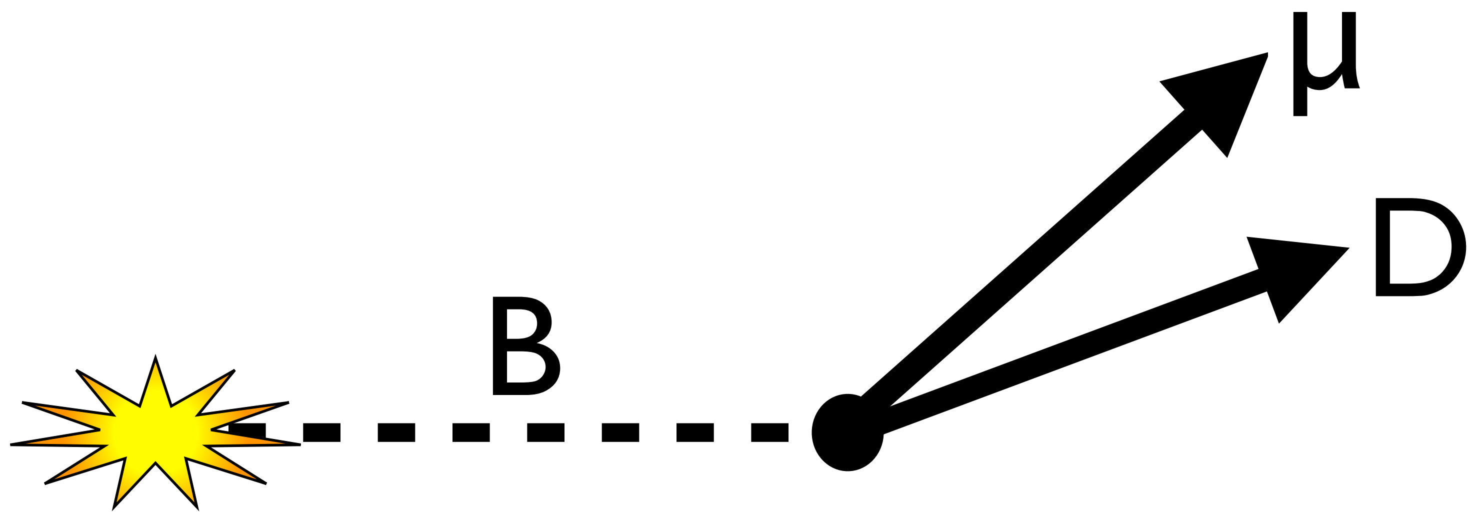
Straightforward to count

$D_s \to KK\pi$ decays…

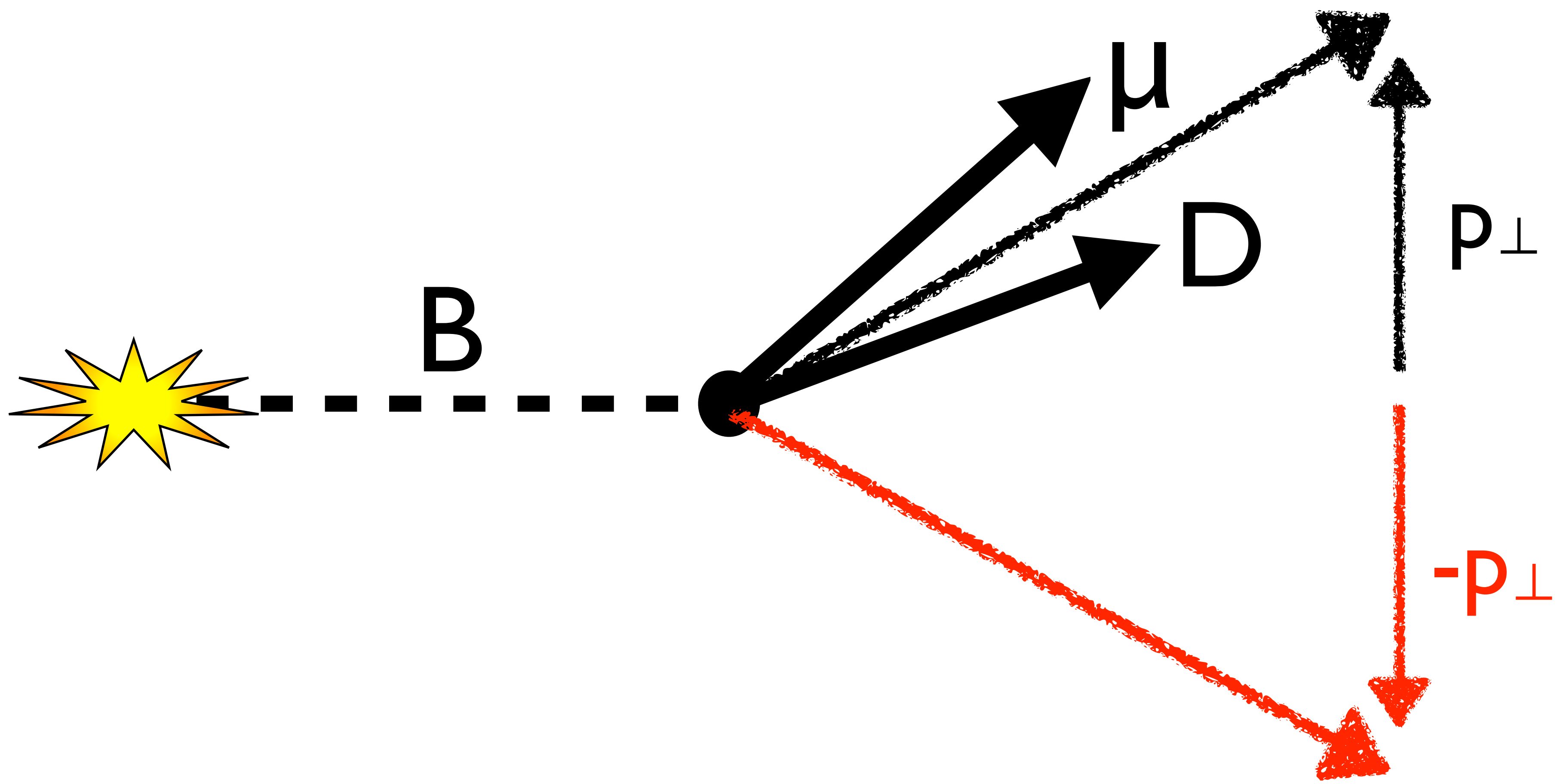
However, many sources of $D_s \mu X$, e.g: DDX, D_sKX etc…

Background fraction	(18 ± 6)%
Correction to a_{sl}^s	$(-0.04 \pm 0.06) \times 10^{-2}$

Corrected mass

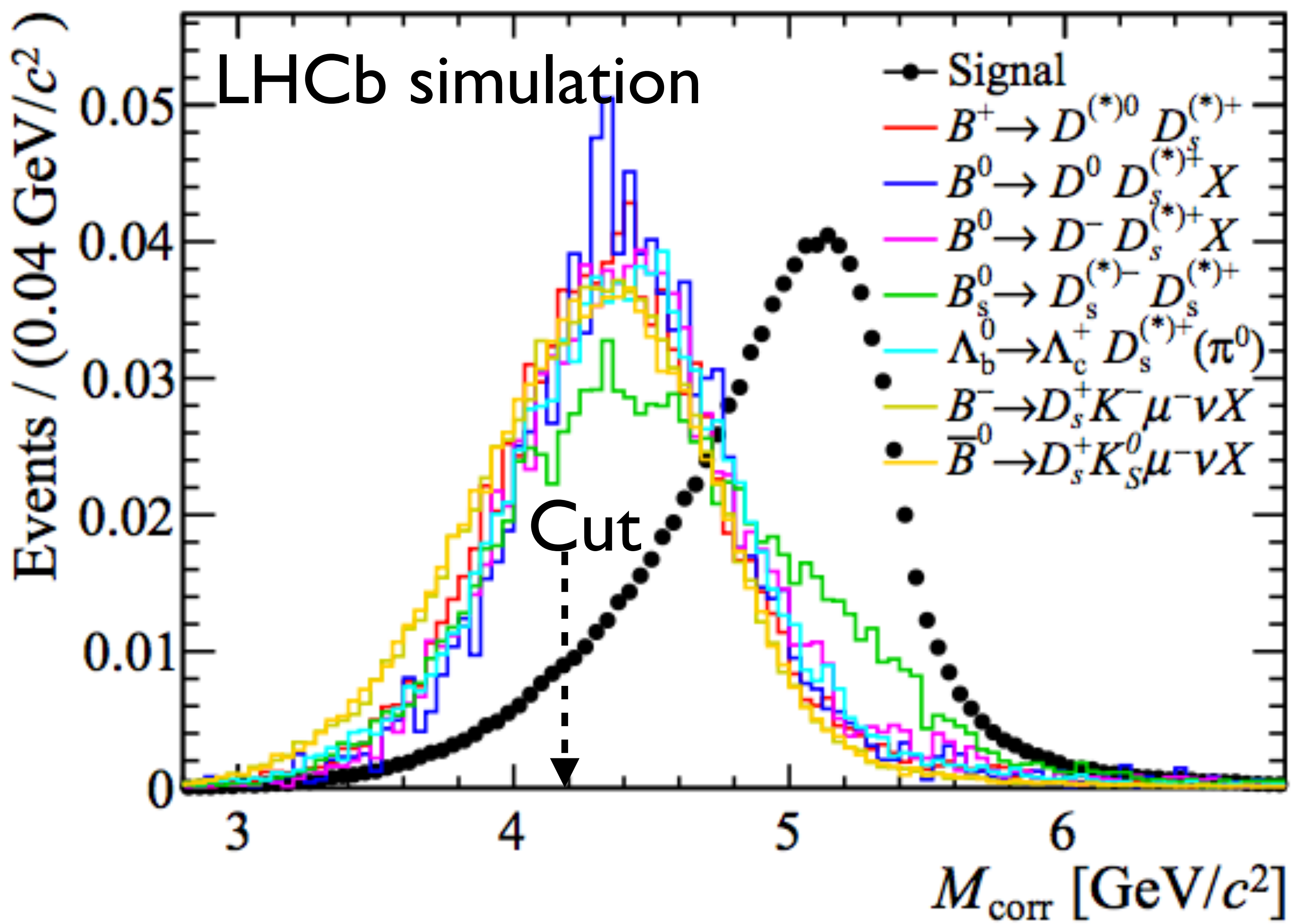


Corrected mass



$$M_{\mathrm{corr}} = \sqrt{m_{\mathrm{vis}}^2 + p_\perp^2} + p_\perp$$

Corrected mass



Future analyses could fit this distribution to subtract these backgrounds directly…

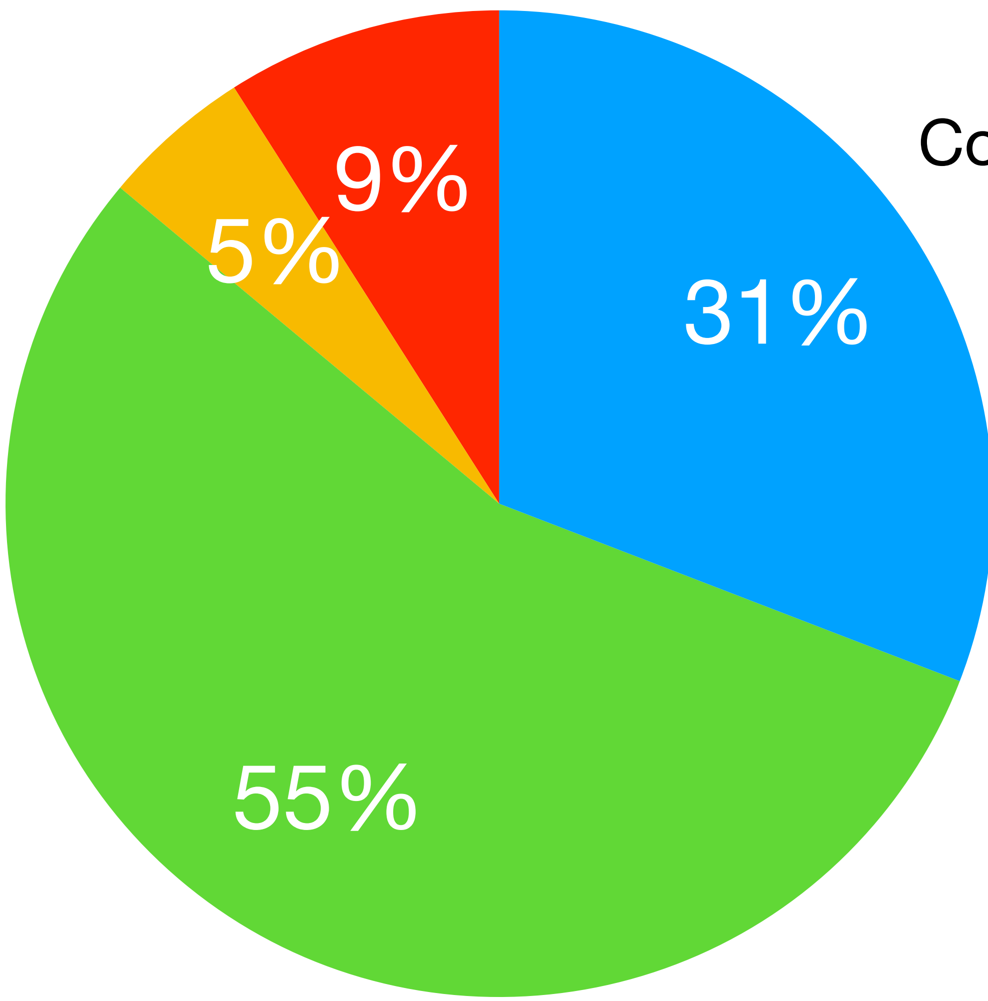
The LHCb Run-I results

$a^d_{\rm sl} = (-0.02 \pm 0.19 \pm 0.30)\%$

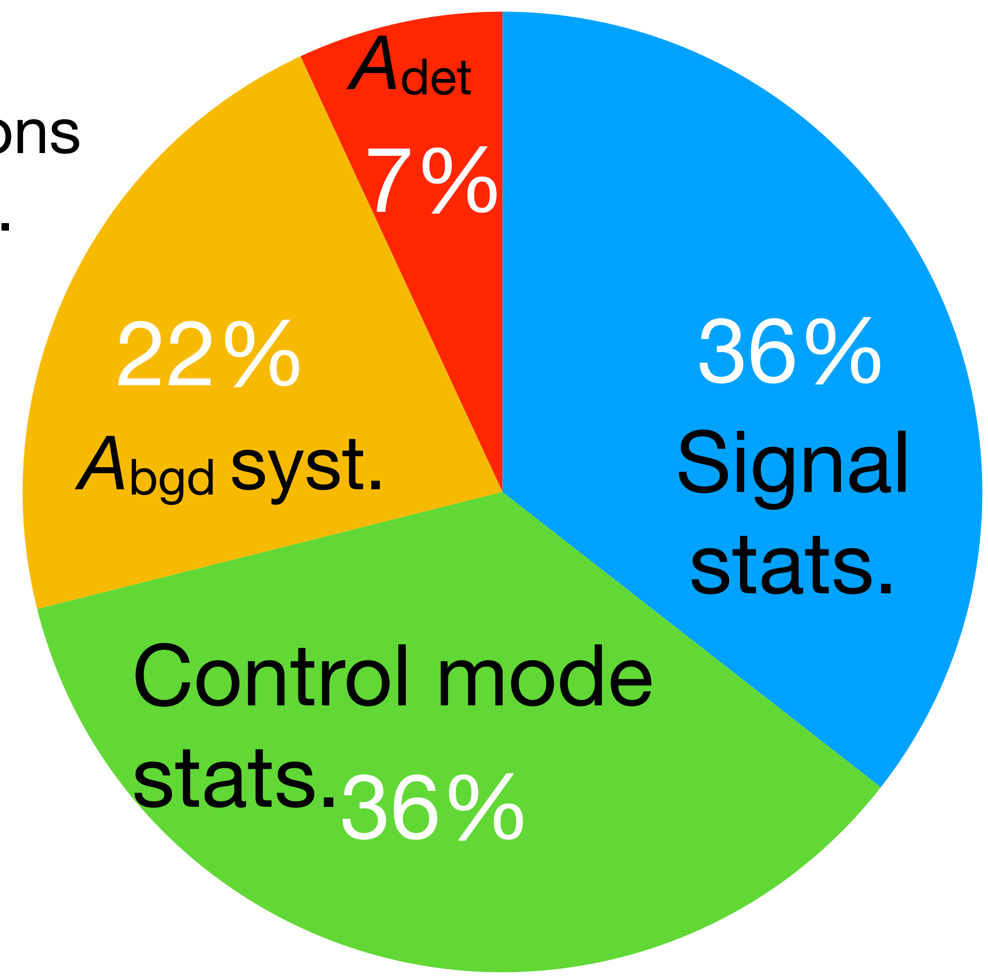
PRL 117, 061803 (2016)

$a^s_{\rm sl} = (0.39 \pm 0.26 \pm 0.20)\%$

PRL 114, 041601 (2015)



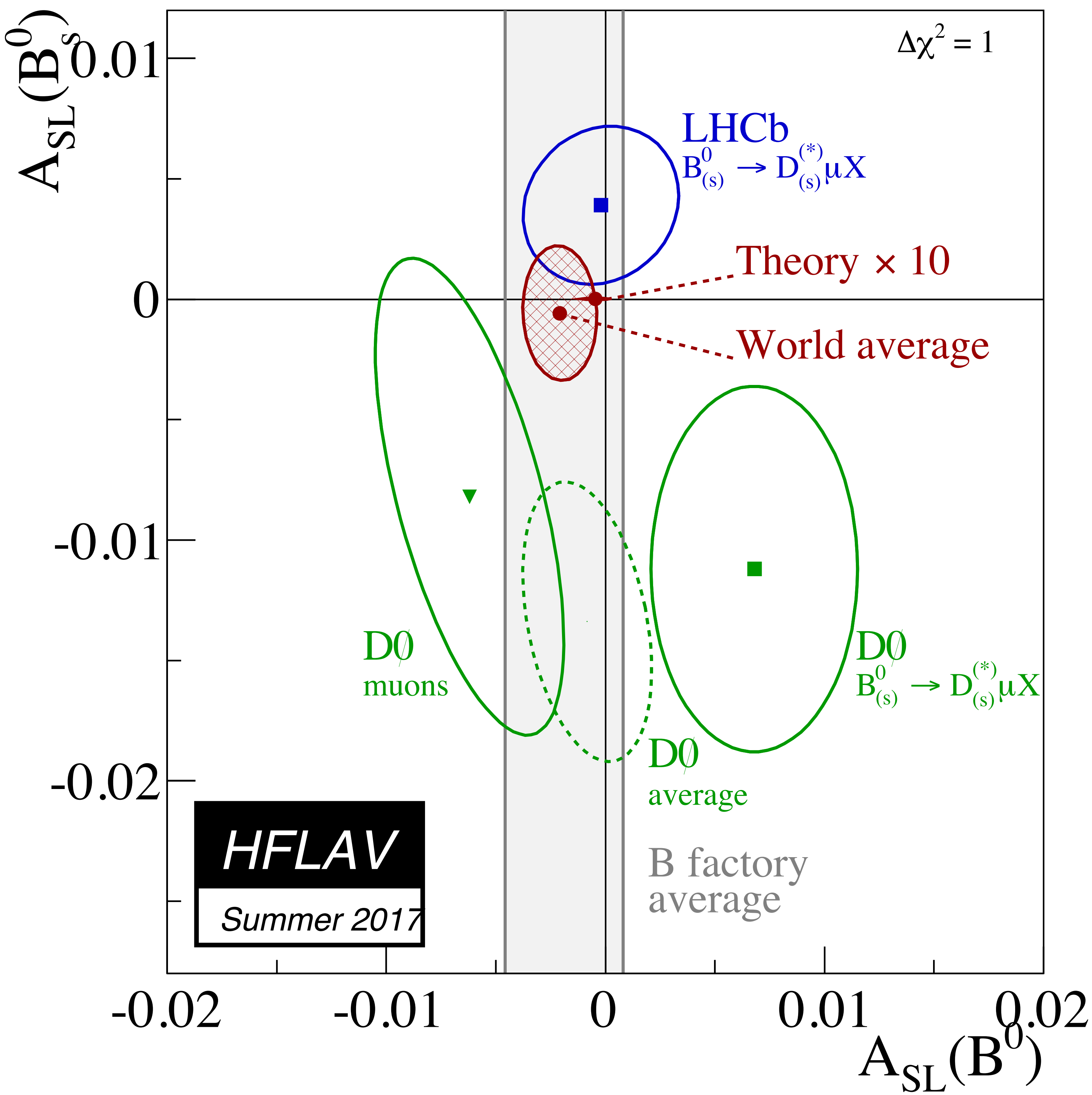
Contributions to error^2.



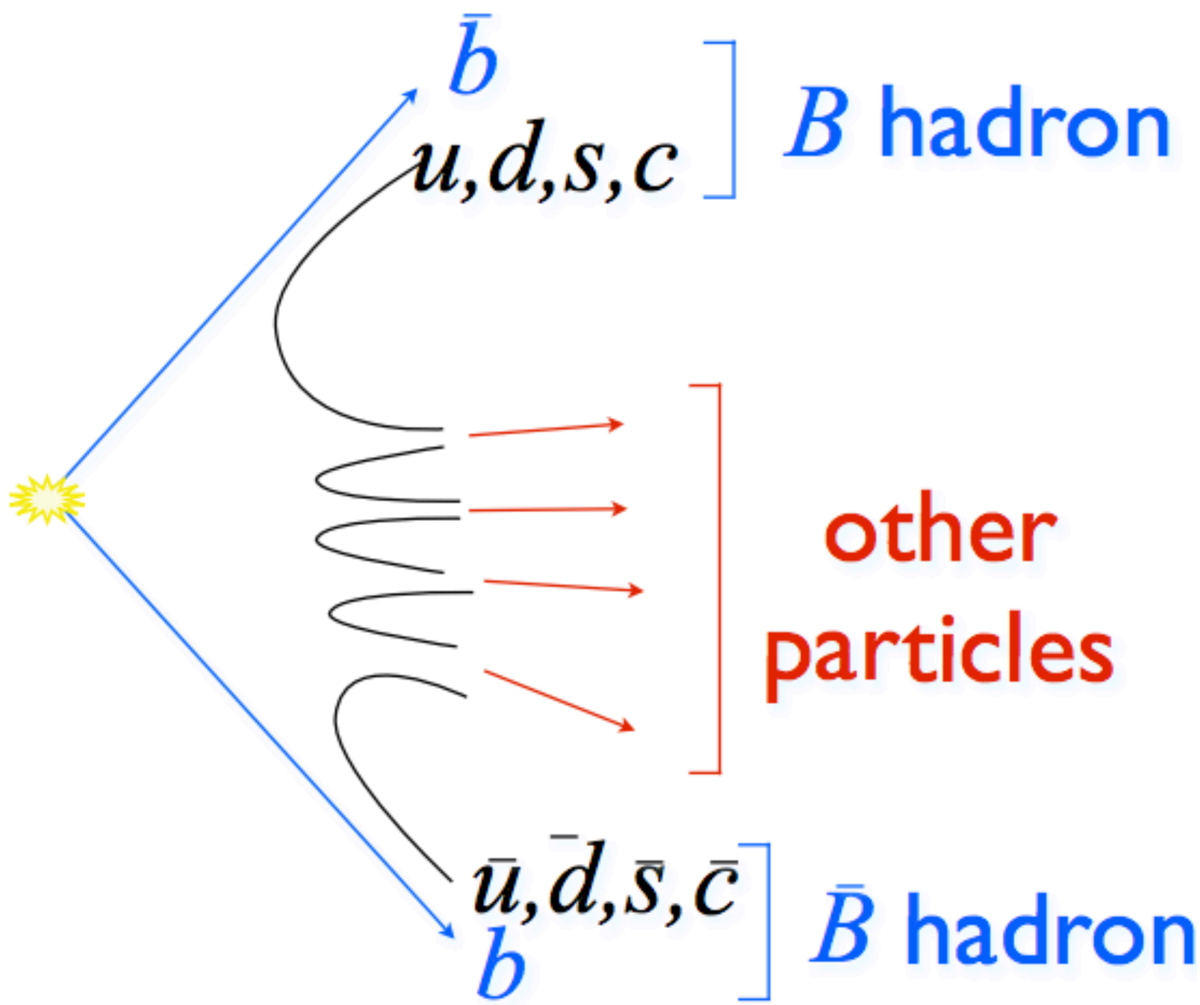
For measurements with Run-II and beyond, it is possible that we can scale statistically without hitting any systematic limit if we develop more sophisticated treatment of the (i) backgrounds and (ii) detection asymmetries.

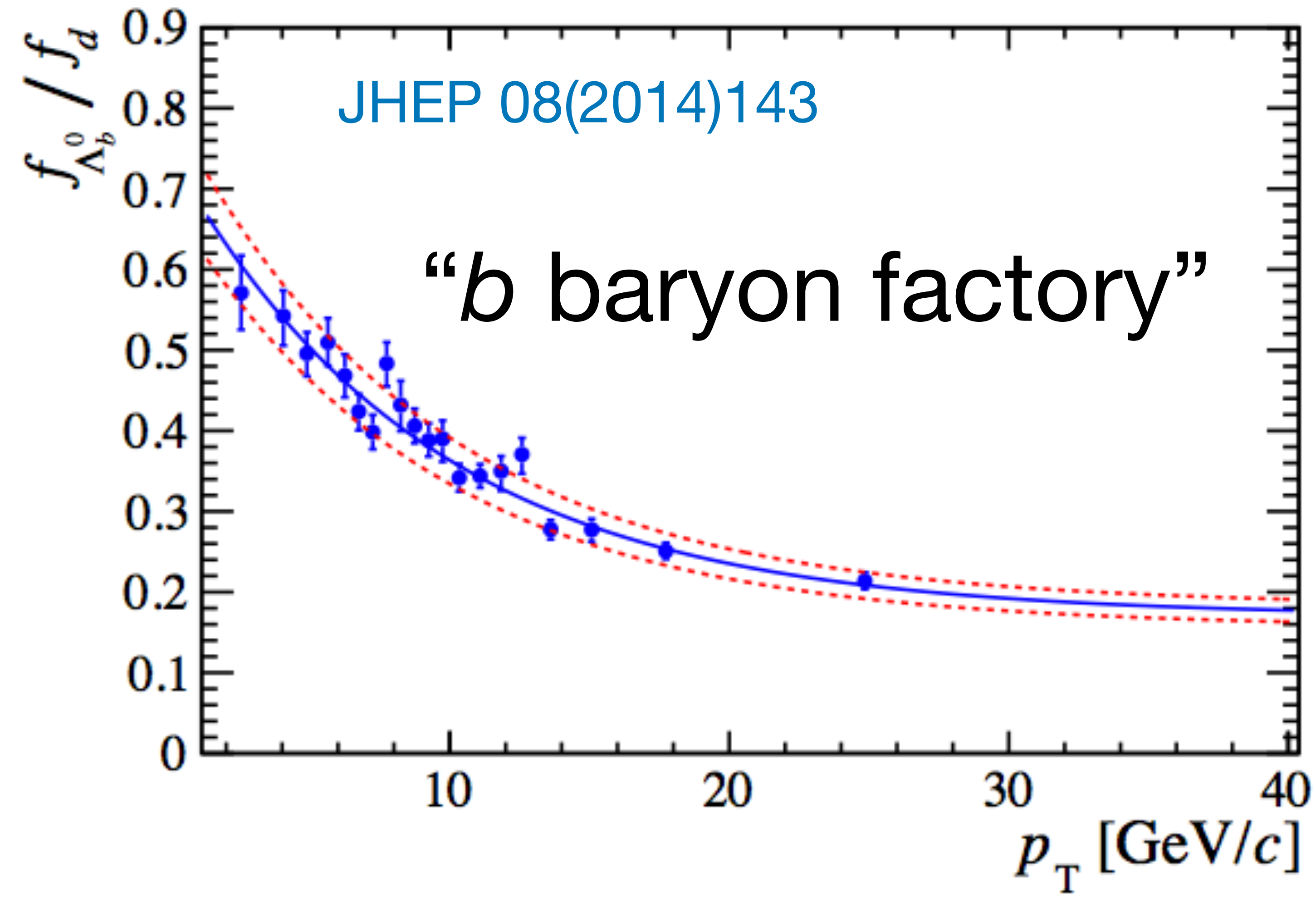
After LHCb Run-I

PRL 117, 061803 (2016)
PRL 114, 041601 (2015)



The true b factory





While we can't easily disentangle production and decay, we can measure decay rate ***ratios*** and/or ***shapes***.

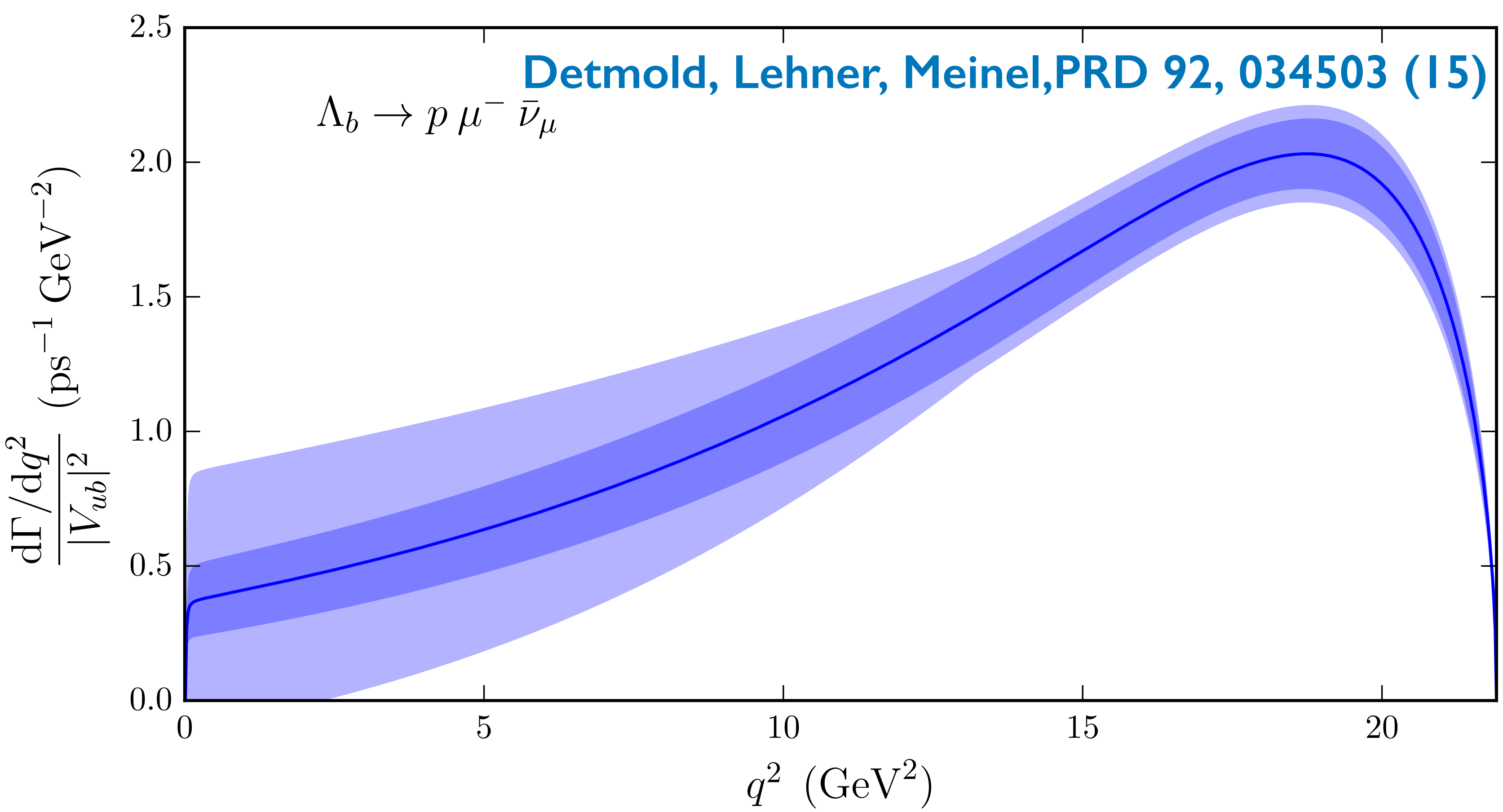
Nature Phys. 10 (2015) 1038

First exploitation

Measure the ratio

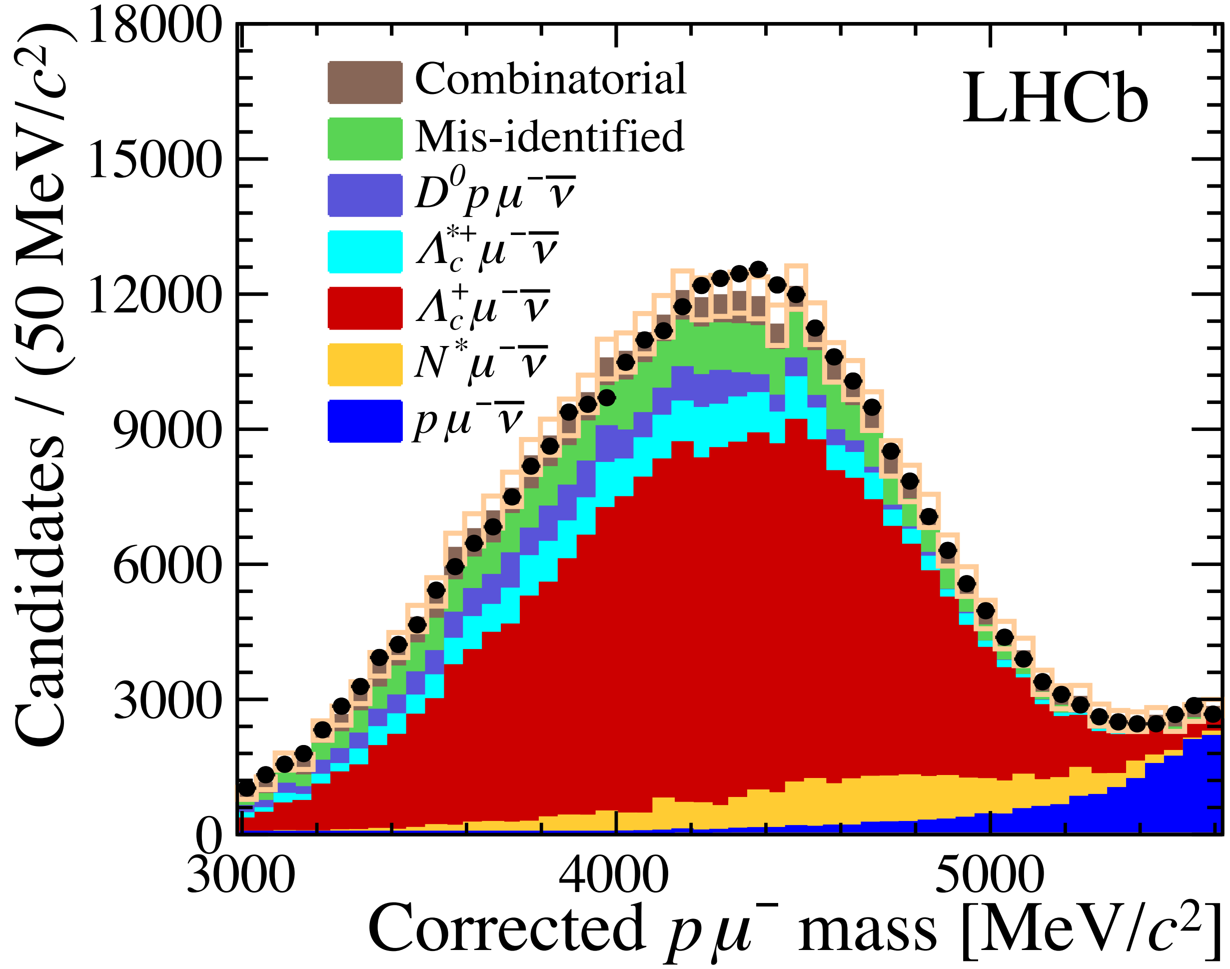
$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} R_{\rm FF}$$

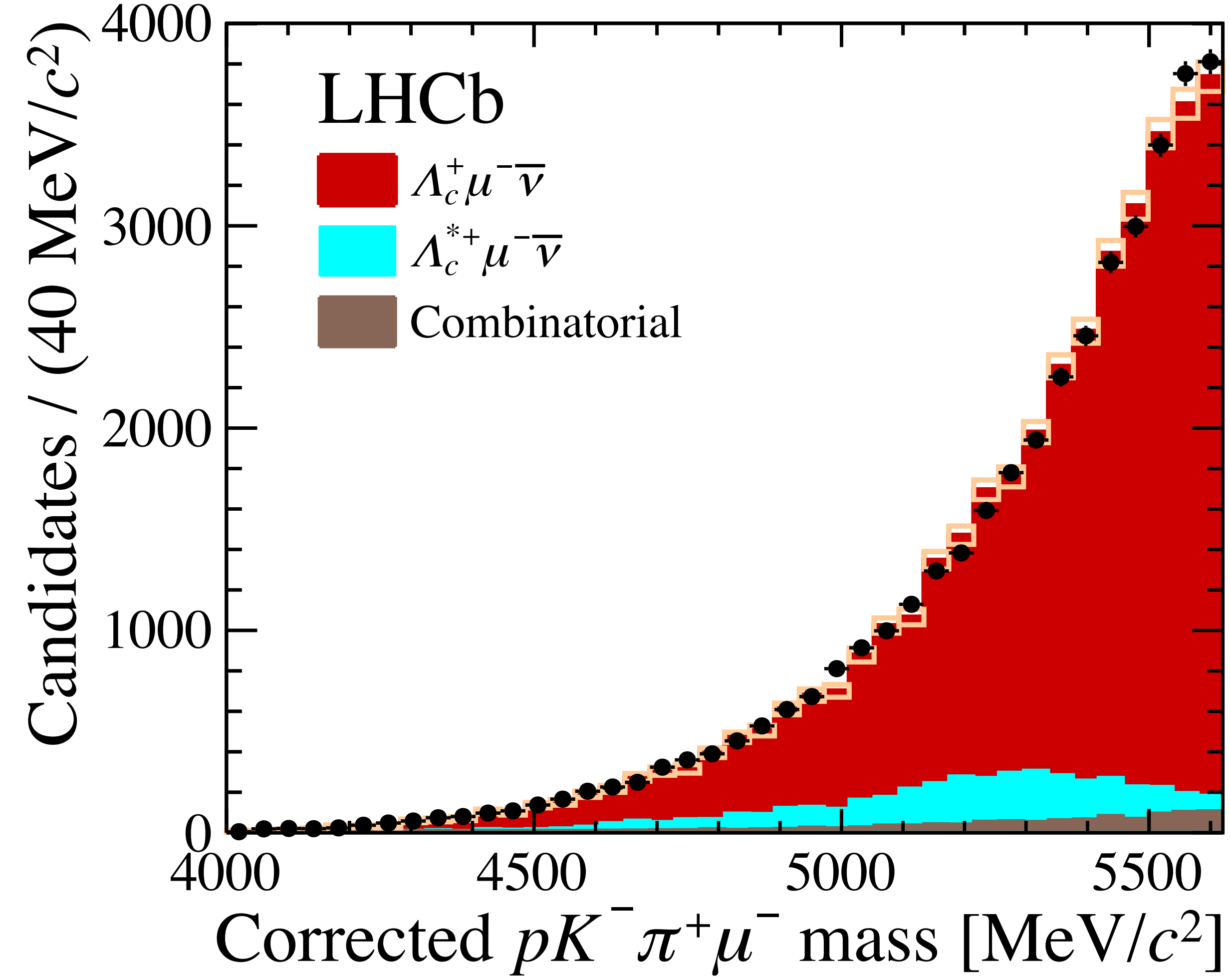
Lattice inputs for $R_{\rm FF}$, e.g. for the V_{ub} mode:



Nature Phys. 10 (2015) 1038

Our favourite variable



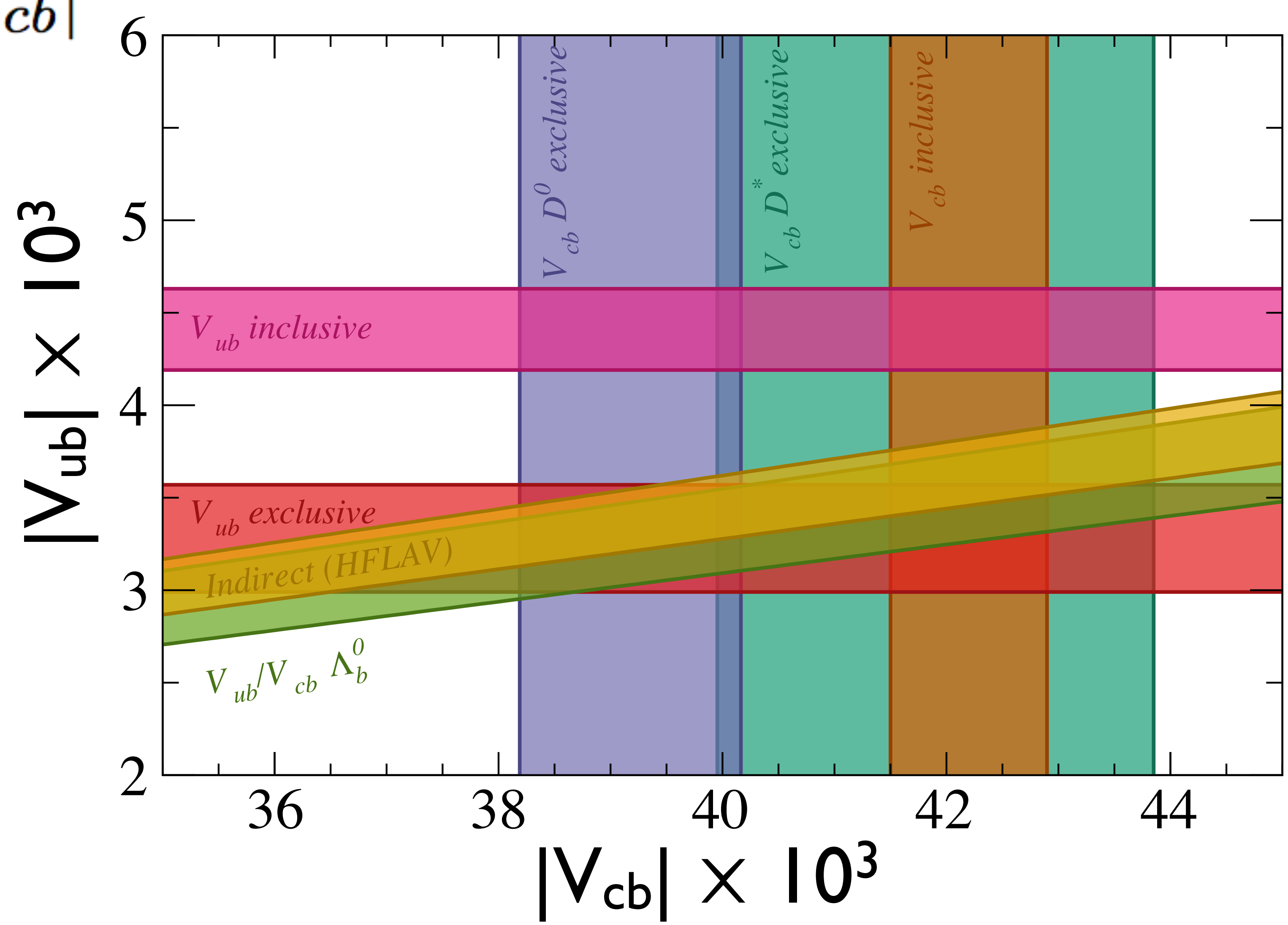


$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}} = (1.00 \pm 0.04(stat) \pm 0.08(syst)) \times 10^{-2}$$

Nature Phys. 10 (2015) 1038

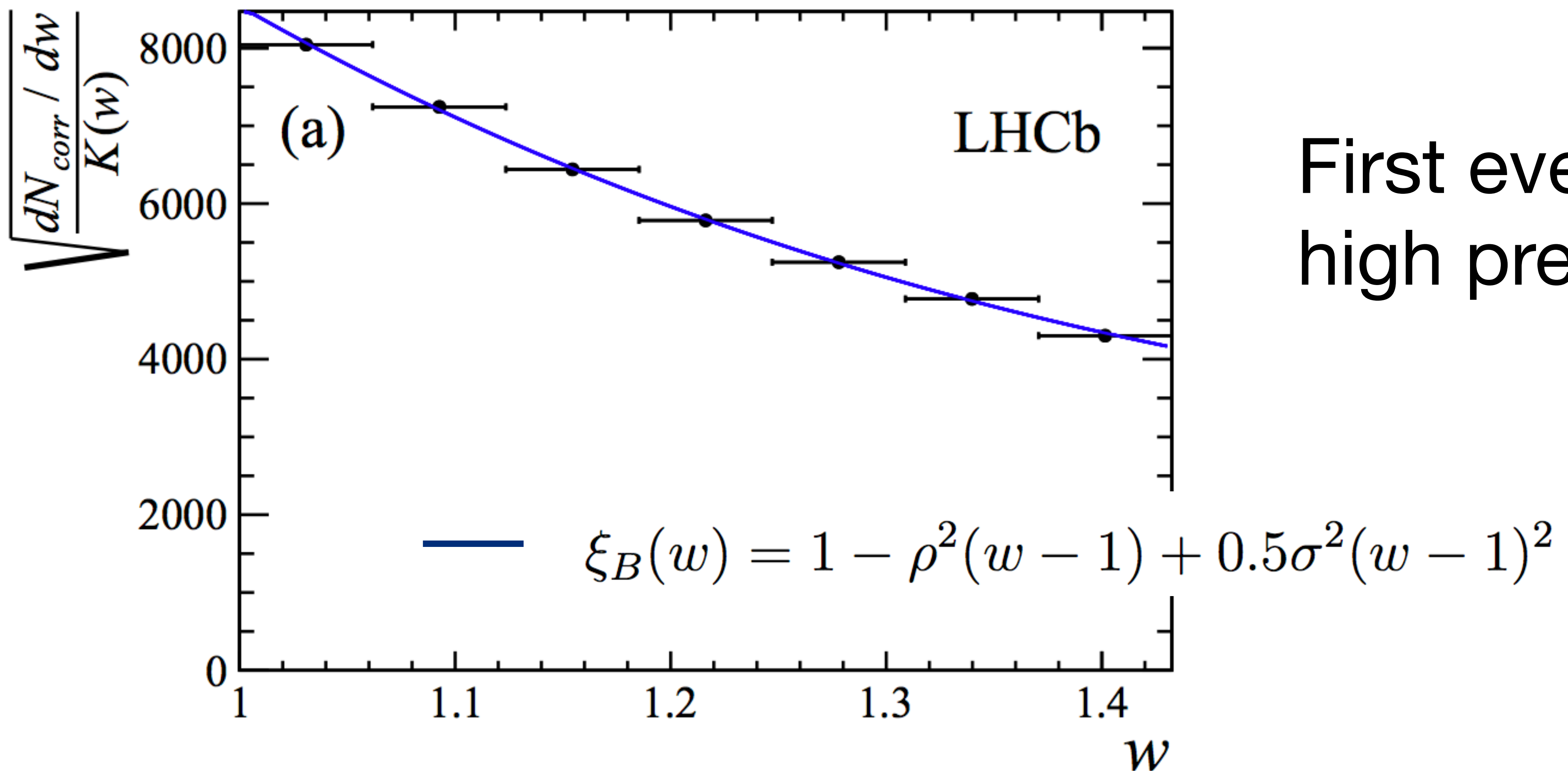
Impact of Λ_b analysis

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(\text{expt}) \pm 0.004(\text{lattice})$$



Precision already comparable with *B* meson based exclusive determinations, and complementary parametric dependence on different operators, e.g. RH currents.

Exclusive $\Lambda_b \to \Lambda_c \mu \nu$ study



First ever with high precision!

Shape	ρ^2	σ^2	correlation coefficient	χ^2/ DOF
Exponential*	1.65 ± 0.03	2.72 ± 0.10	100%	5.3/5
Dipole*	1.82 ± 0.03	4.22 ± 0.12	100%	5.3/5
Taylor series	1.63 ± 0.07	2.16 ± 0.34	97%	4.5/4

Consistent with predictions of HQET, sum rules, and relativistic quark model.

$|V_{cb}|$ itself.. surely not?

A possible strategy is to measure the ratio:

$$\mathcal{R} = \frac{BF(\Lambda_b \to \Lambda_c \mu\nu)}{BF(\Lambda_b \to [\Lambda_c X, D^0 p X, ...]\mu\nu)}$$

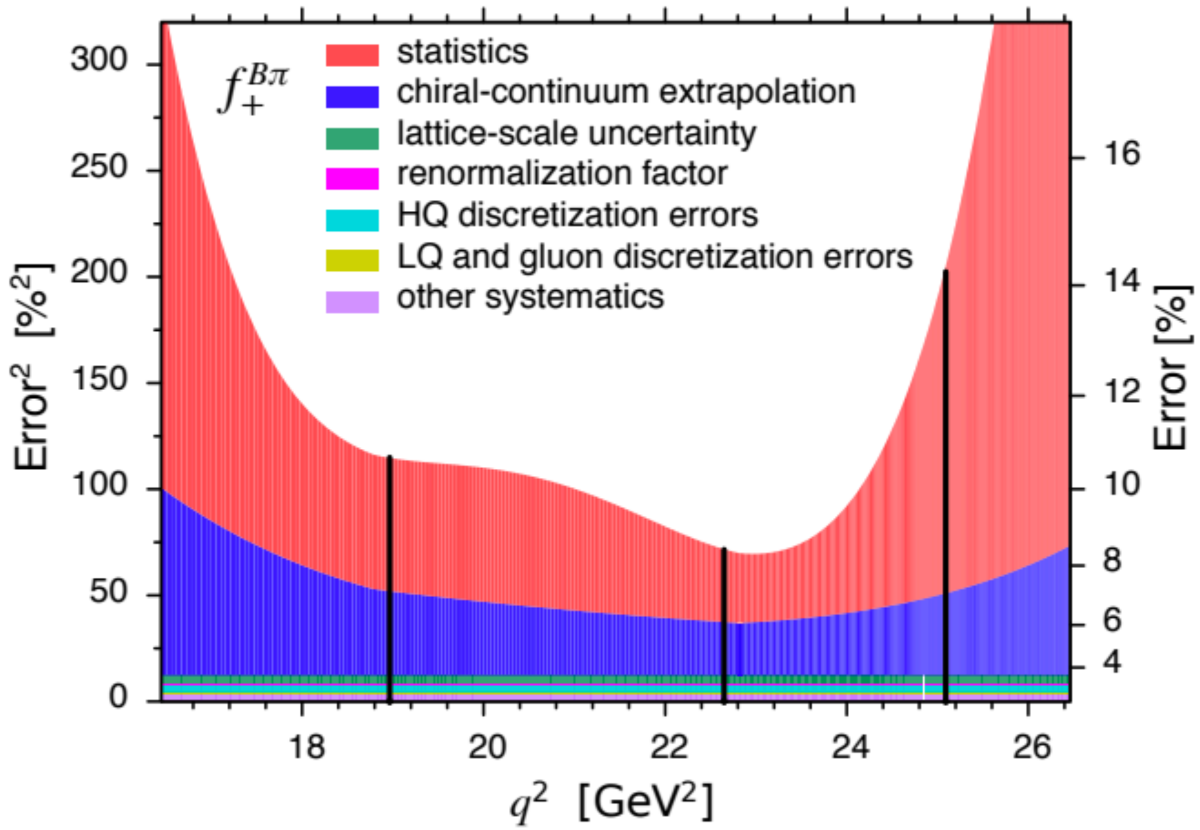
Isn't there a $|V_{cb}|$ in numerator and denominator?

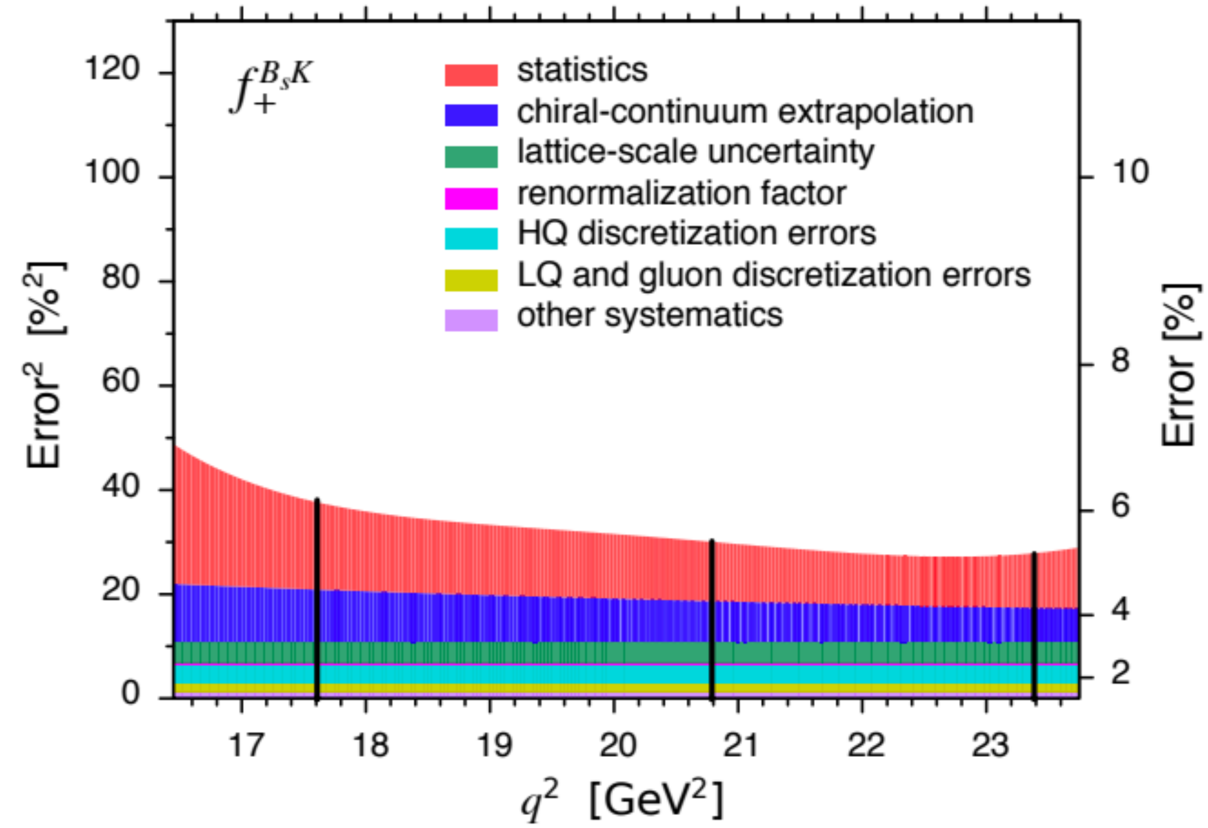
Relate the denominator to the measured lifetimes of the Λ_b and B, and the measured SL decay width of the B, and assume the equality of SL decay widths of all b species. E.g., Bigi et al., 1105.4574

Other SL decays with muons

Great prospects for $|V_{ub}|/|V_{cb}|$ determination with $B_s \to (K/D_s)\mu\nu$

From: UKQCD/RBC **PRD 91, 074510 (15)**





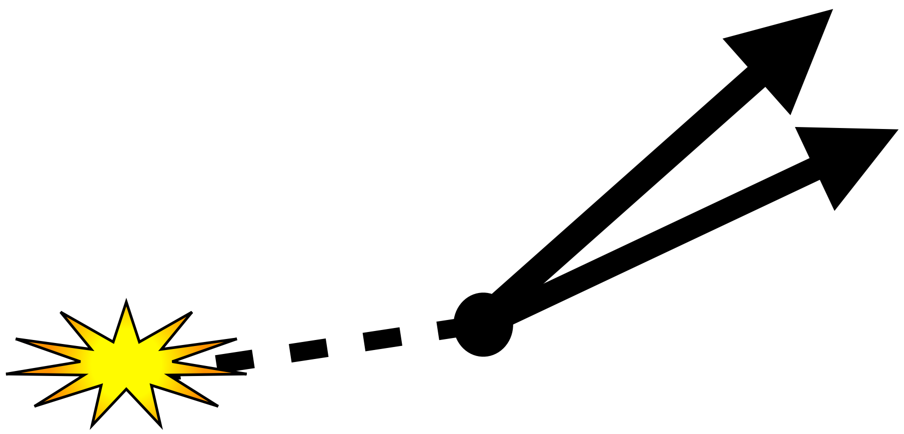
More challenging than $\Lambda_b \to p\mu\nu$, but we're working hard on it, so stay tuned.

Endless possibilities, e.g. $b \to \mu\mu\mu\nu$, $b \to \phi\mu\nu$, $b \to l\nu KKX$, $b \to pp\mu\nu$, various B_c decays…, other b baryons…

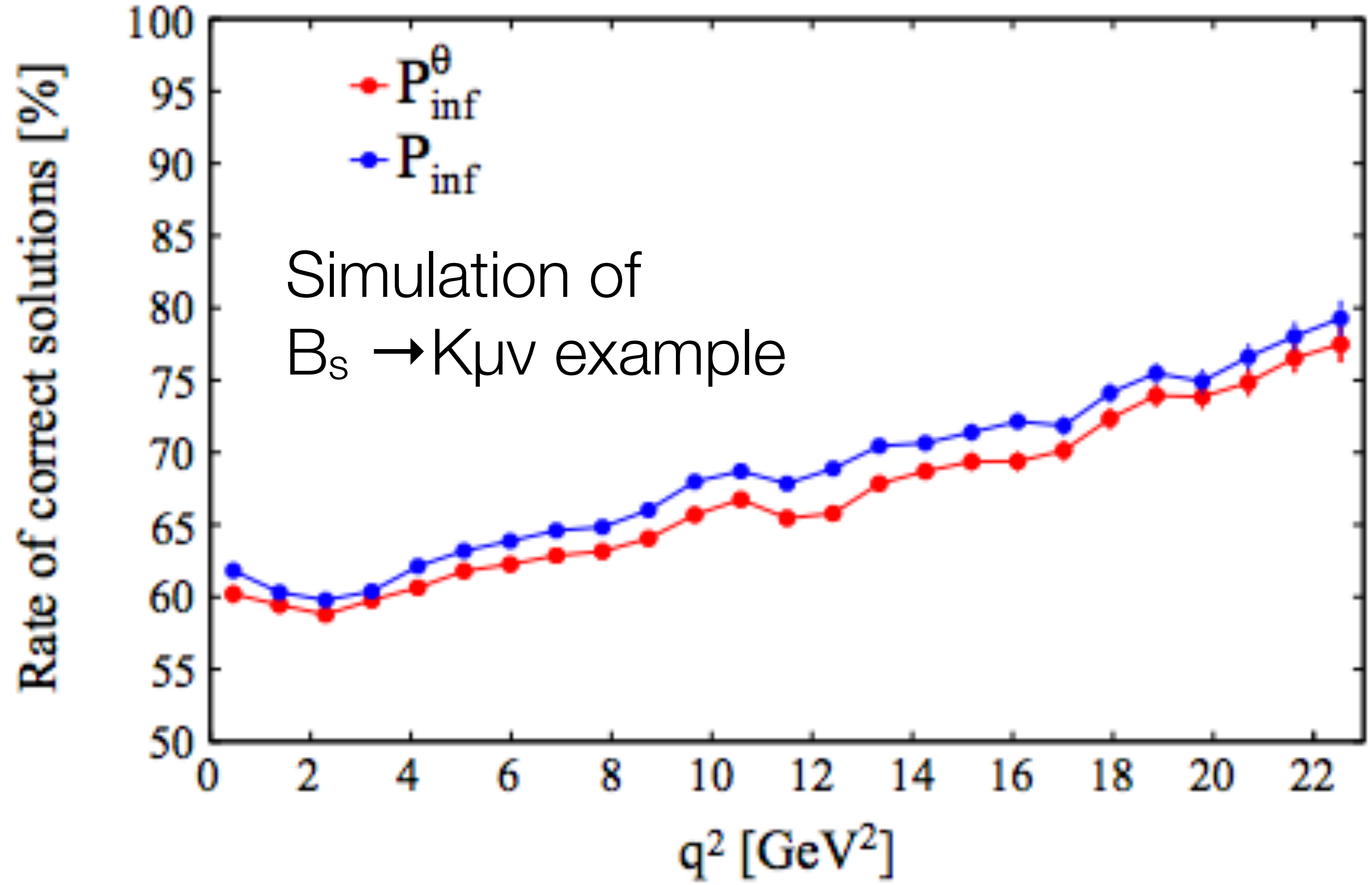
JHEP (2017) 2017: 21

How differential?

For decays with a single missing particle, we get a quadratic equation for the b momentum. Can we do better than a random choice of solutions?



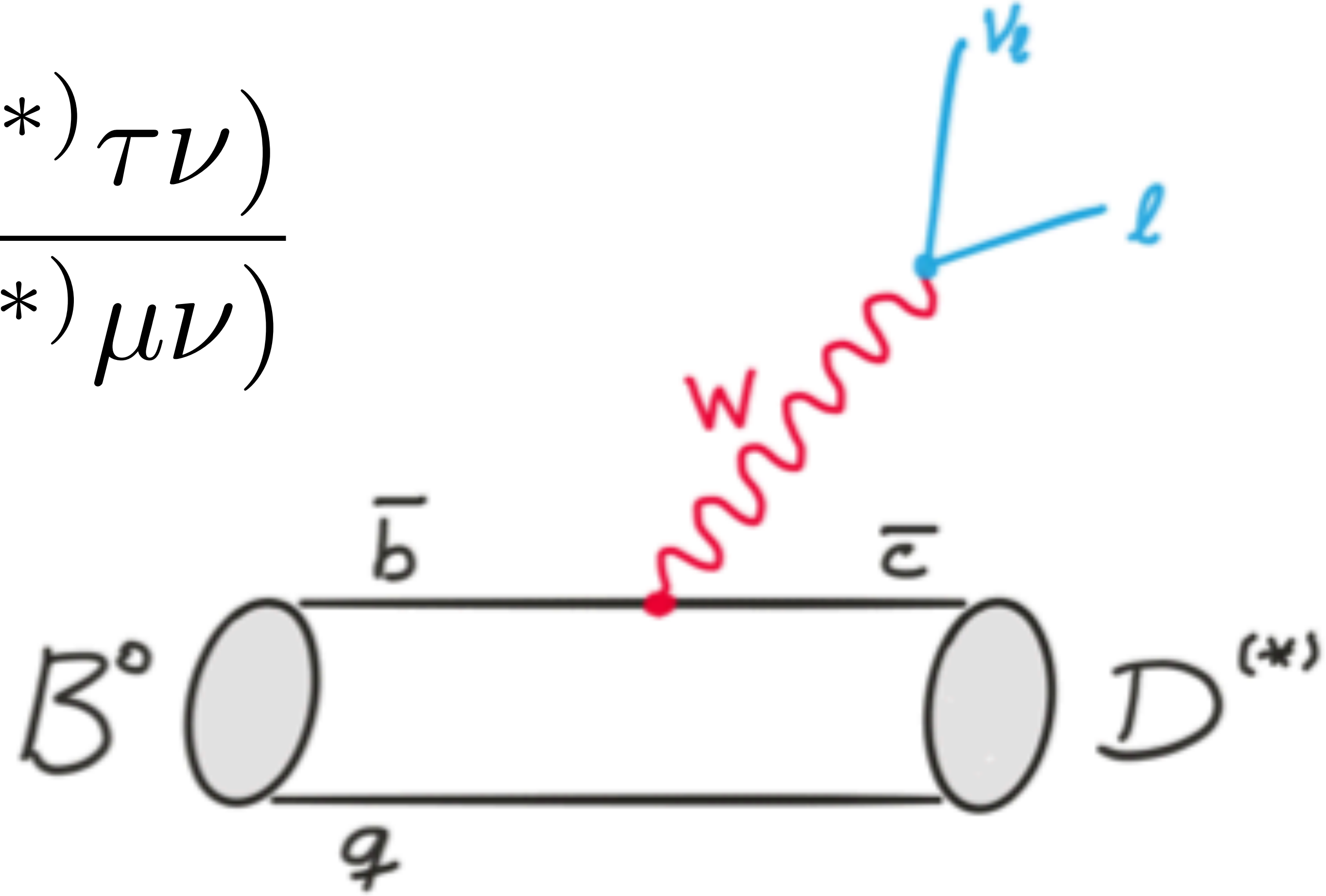
Simple unbiased regression approach based only on flight information.



Once luminosity/statistics allows, we can roughly double the number of bins in q^2 for the same bin purity!

Tree-level LFU tests

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



SM predictions[1,2]

$R(D) = 0.300 \pm 0.008$

$R(D^*) = 0.252 \pm 0.003$

Experiment

$R(D^*) \to 6\%$ precision

[BaBar, Belle, LHCb] combined [R(D), R(D*)] is 4σ from the SM.

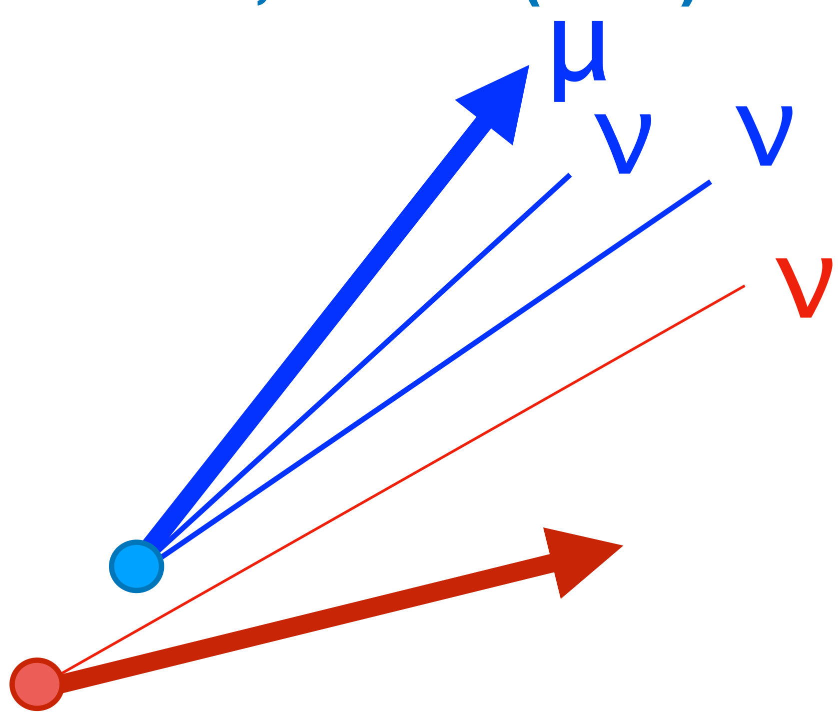
1. Fajfer, Kamenik, Nisandzic, PRD85 (12) 094025
2. Bigi, Gambino, PRD94 (16)

At LHCb

NEW

Leptonic

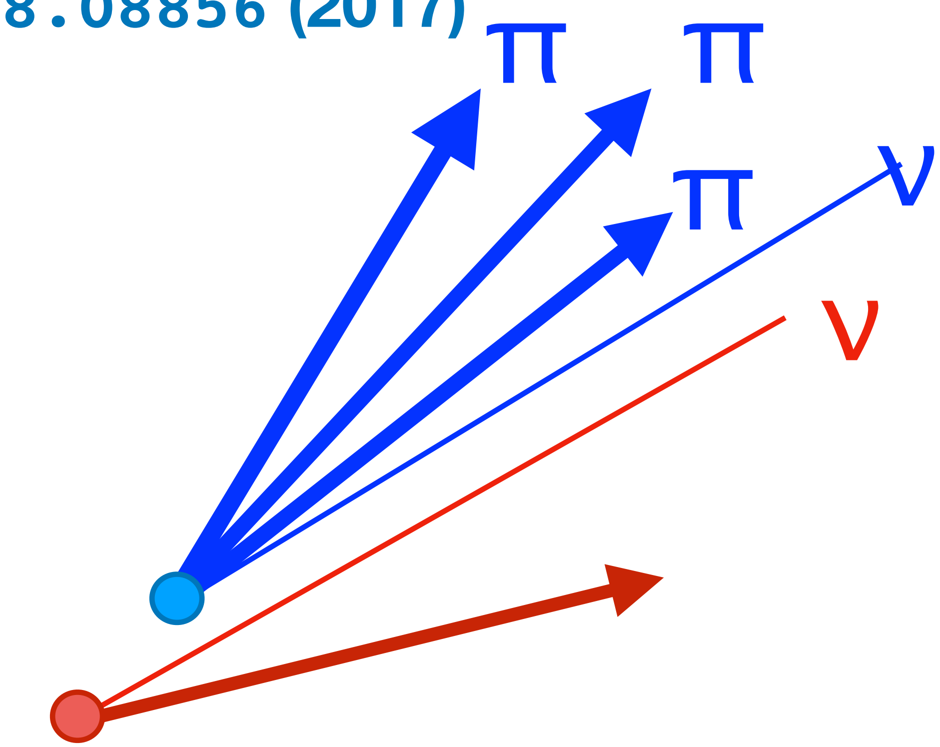
PRL 115, 111803 (2015)



τ BF ~ 18%

Three-prong hadronic

1708.08856 (2017)



τ BF ~ 10%

First ever analysis of this mode!

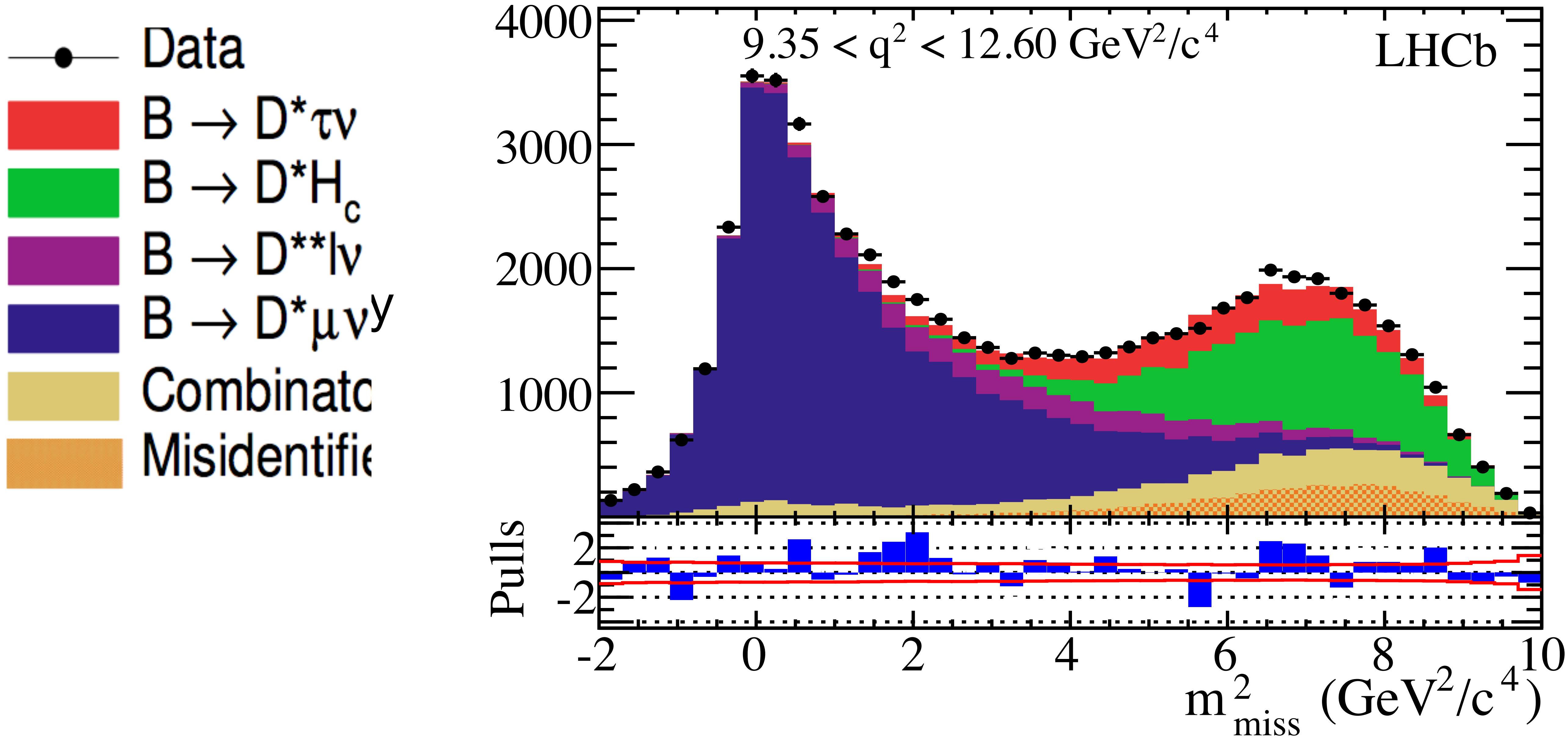
These signals are abundant, but they have soft signatures that are subject to huge backgrounds.
Common strategies: kinematics, isolation, (and τ flight).

PRL 115, 111803 (2015)

Muonic analysis

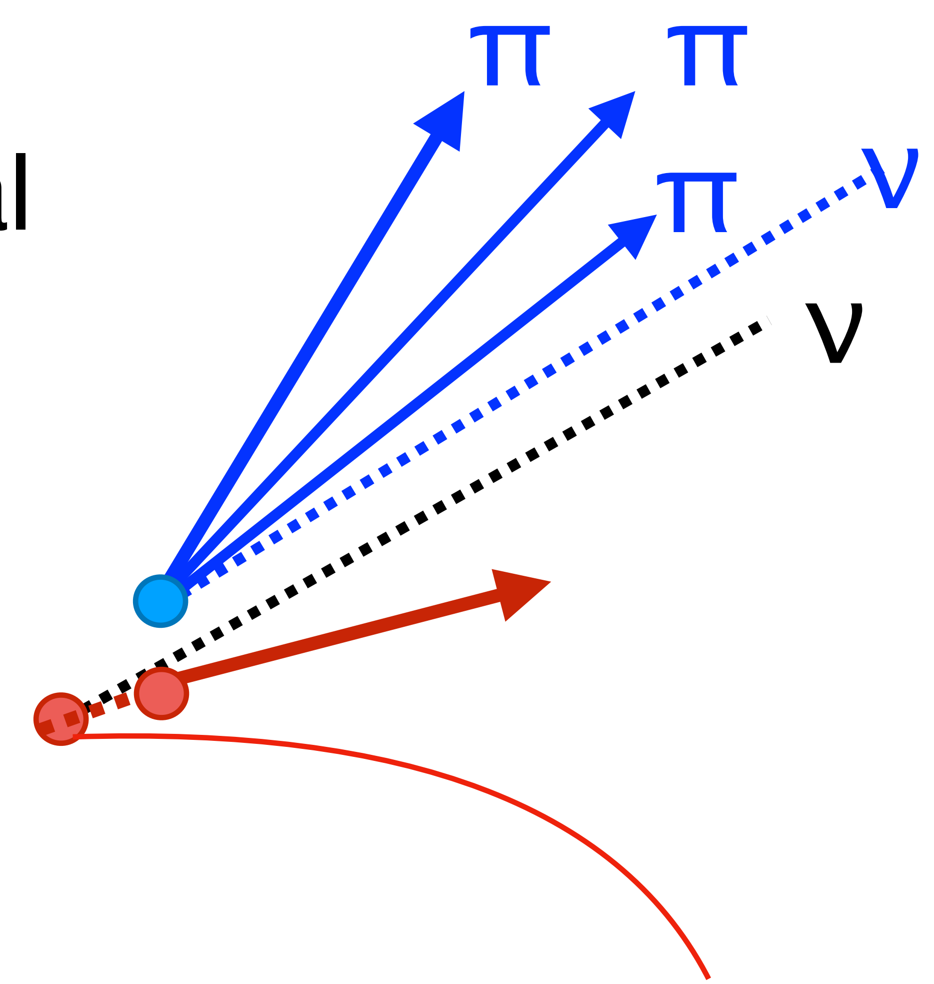
Fit in 4 coarse q^2 bins, m^2_{miss}, and E_μ.

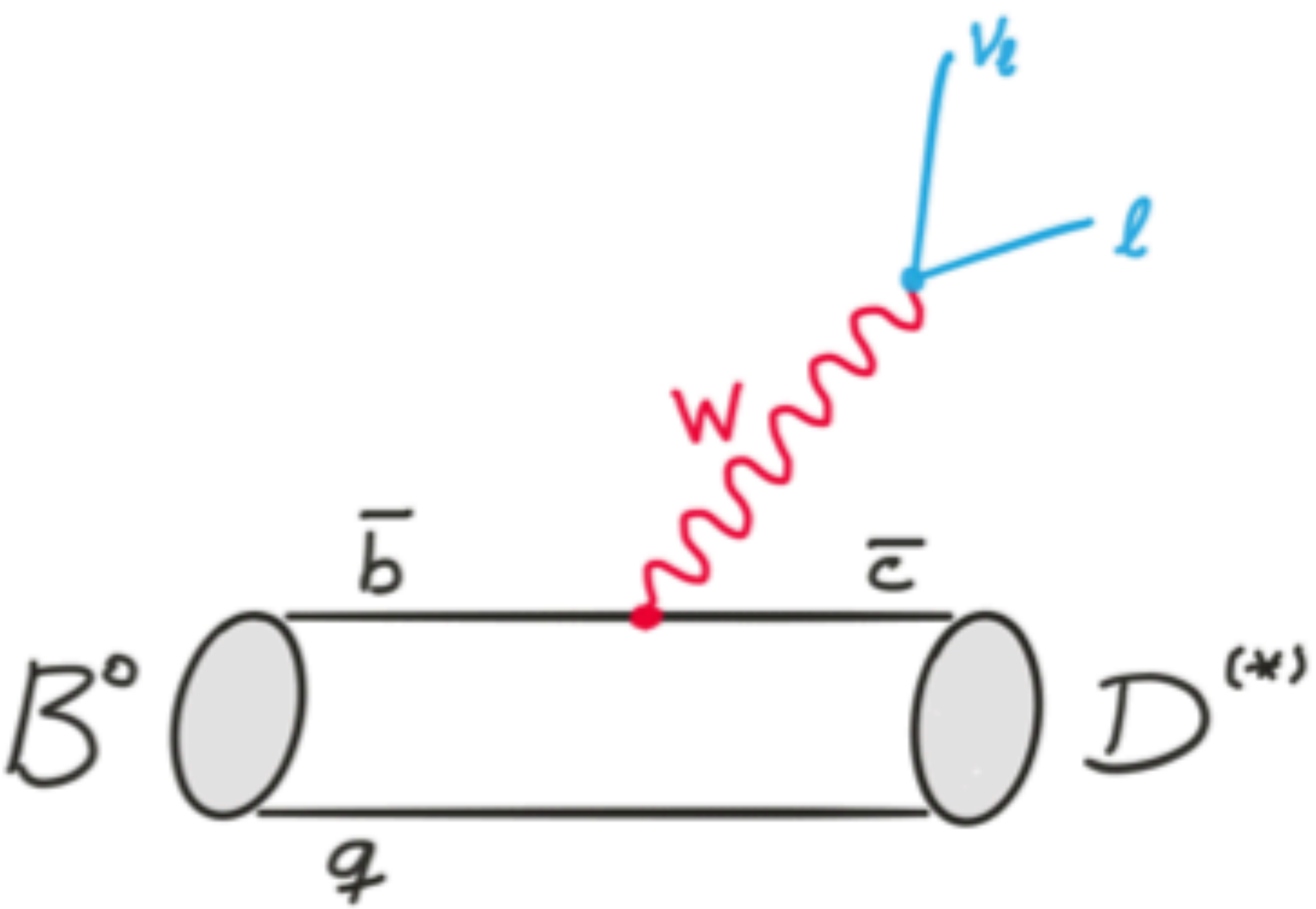
Here is the m^2_{miss} projection in the highest purity q^2 bin:



Three-prong analysis

The signal

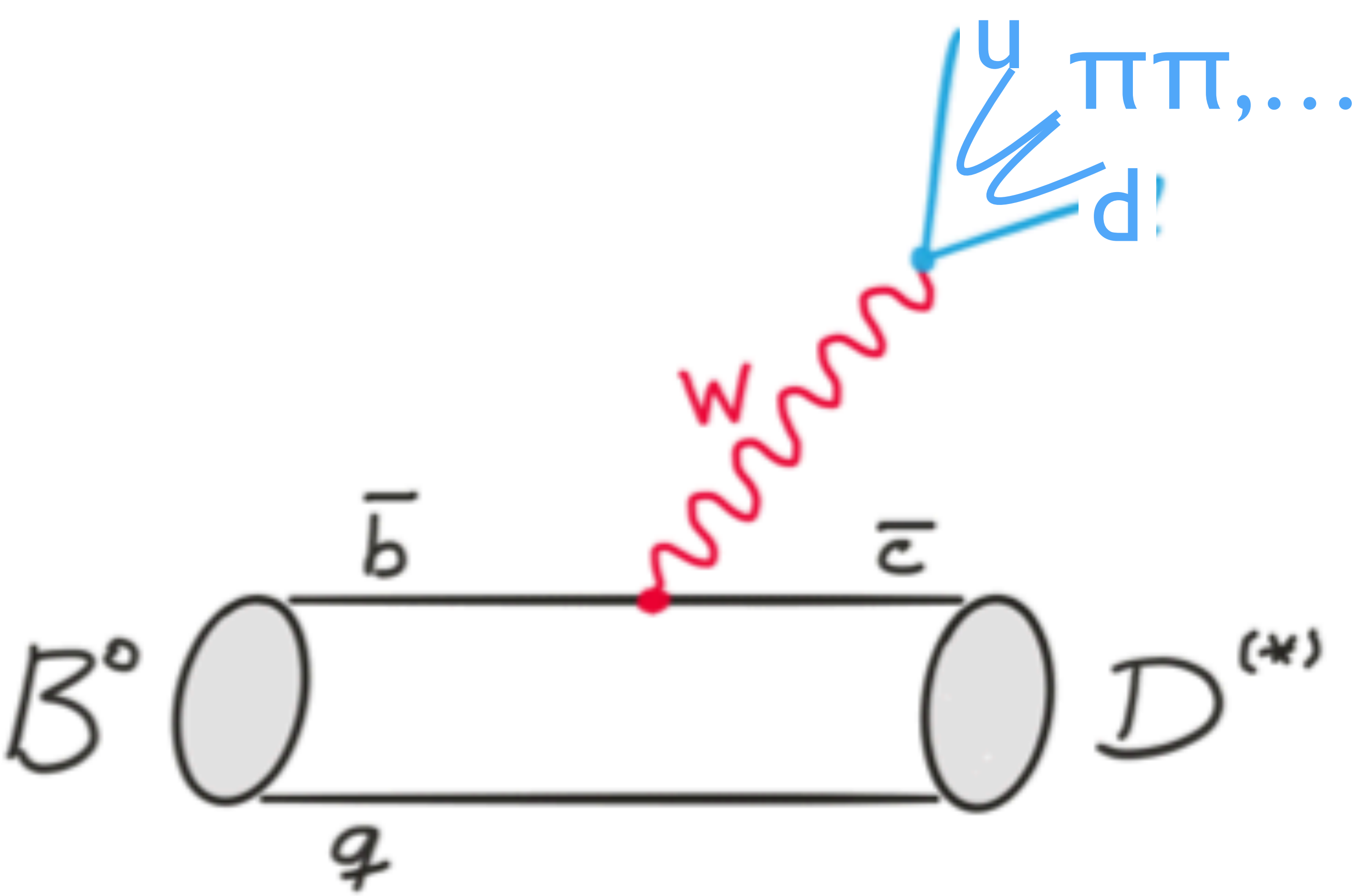


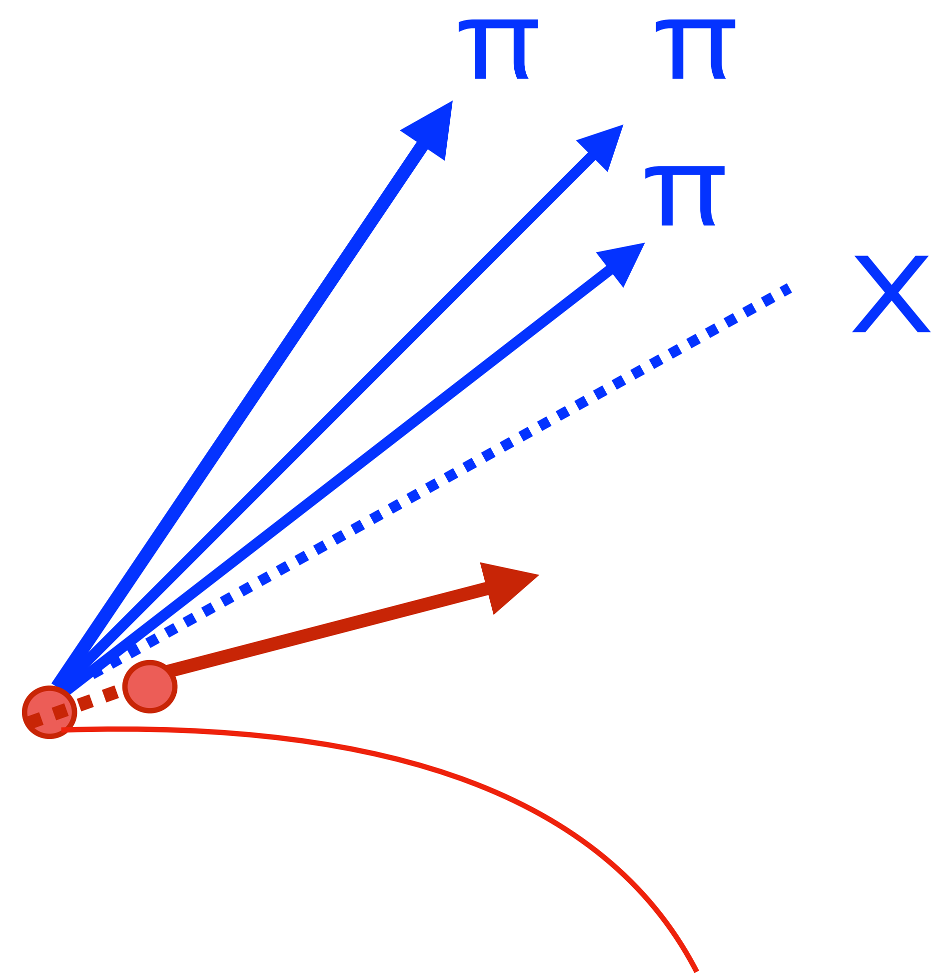


1708.08856 (2017)

Three-prong analysis

The first background





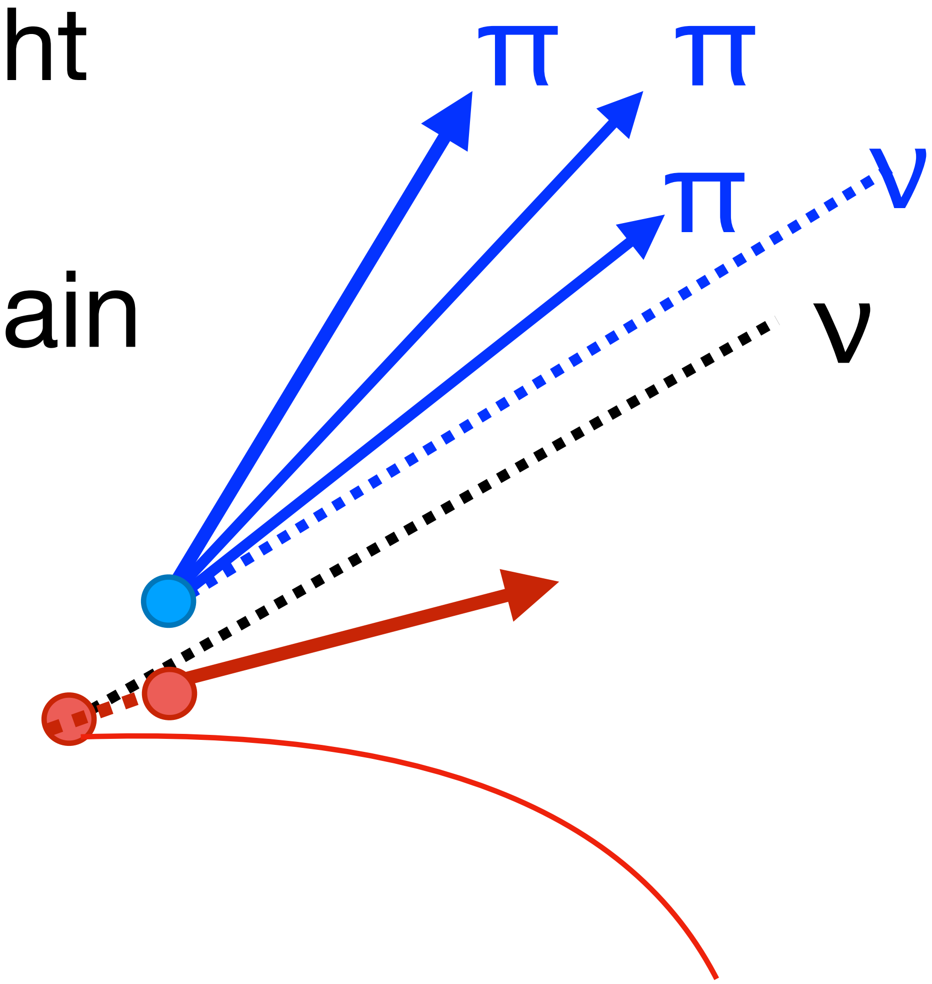
B/S ~ 100

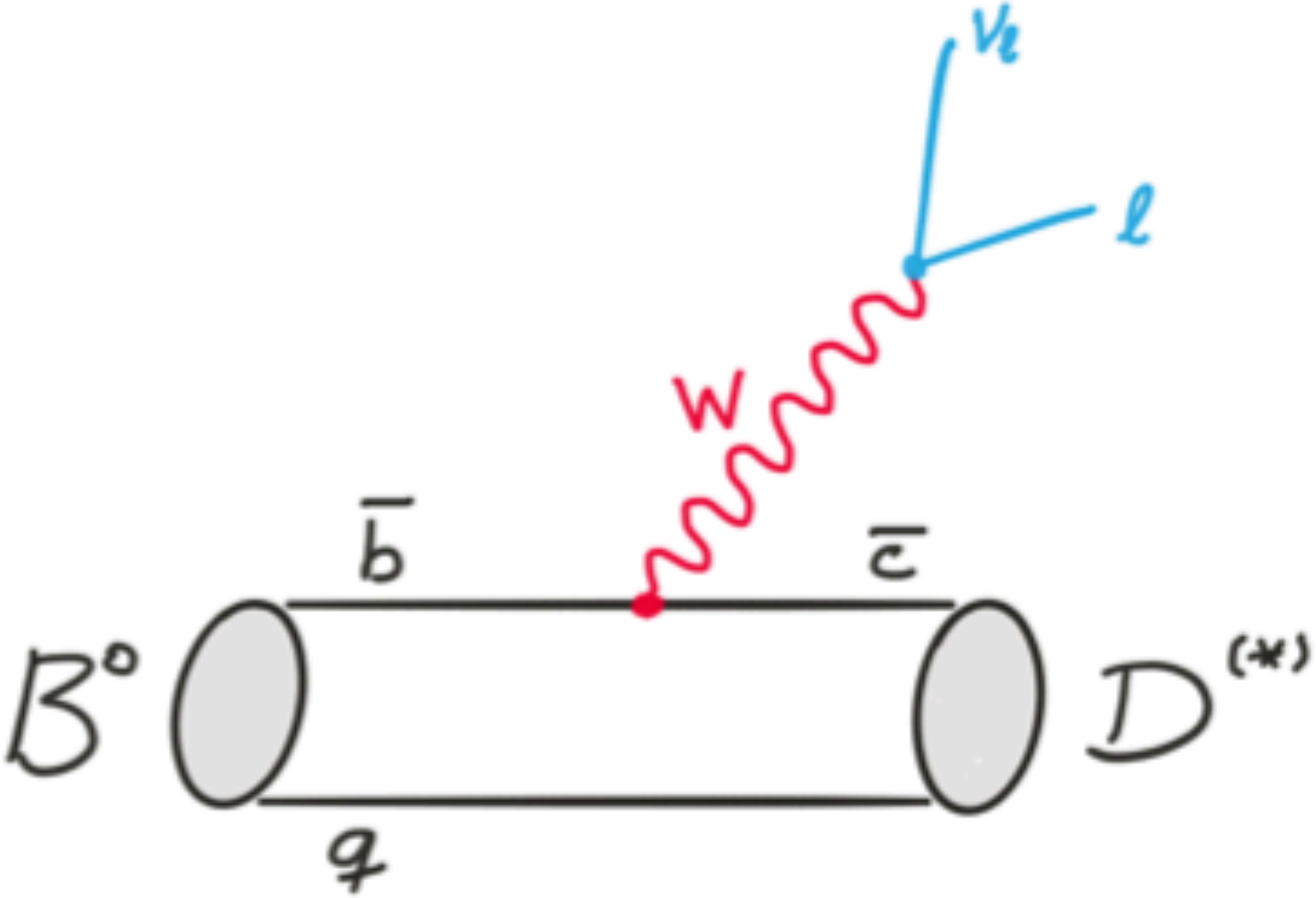
1708.08856 (2017)

Three-prong analysis

*D*3πX* almost entirely eliminated by harsh requirement on τ flight signature.

The signal again

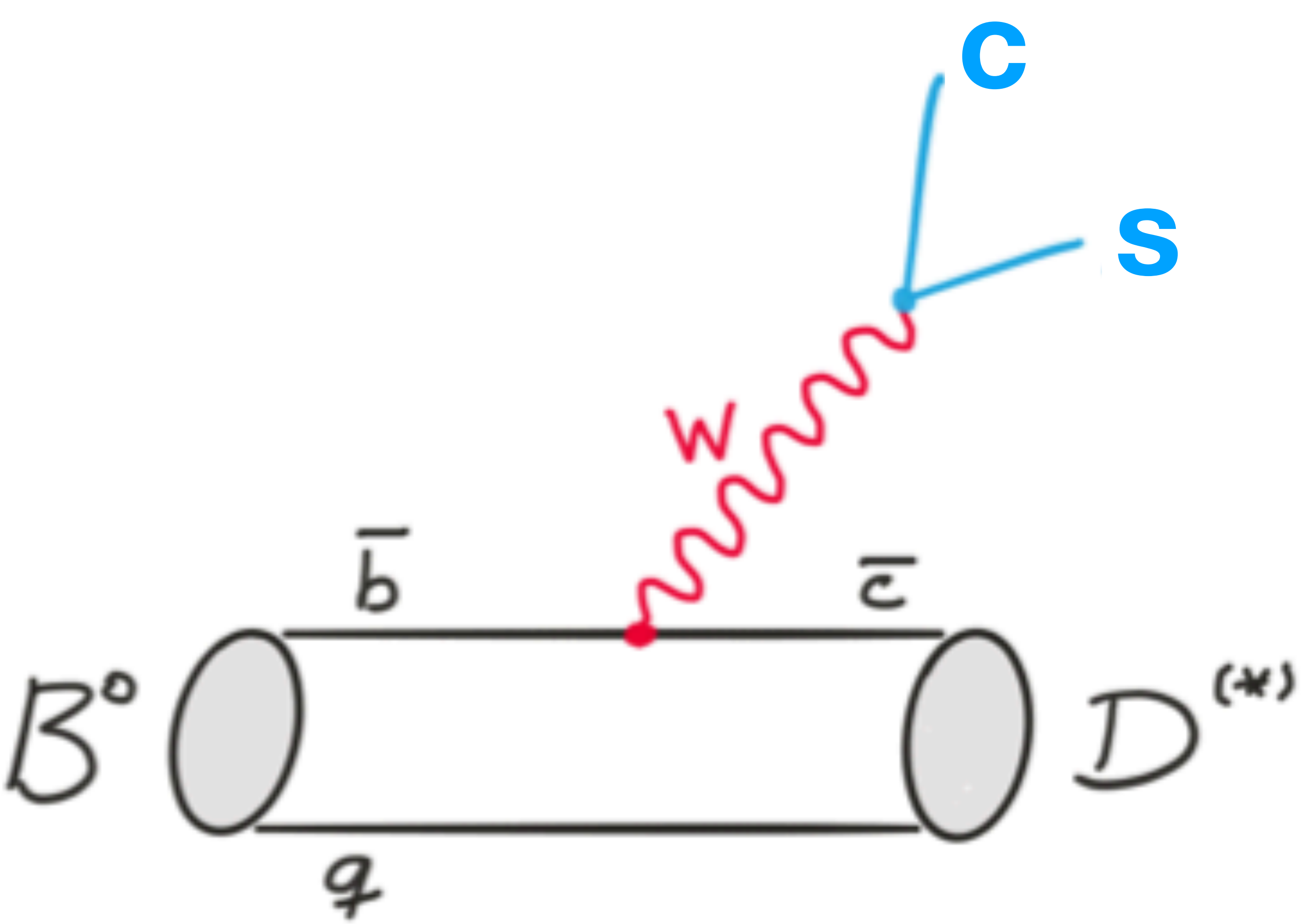


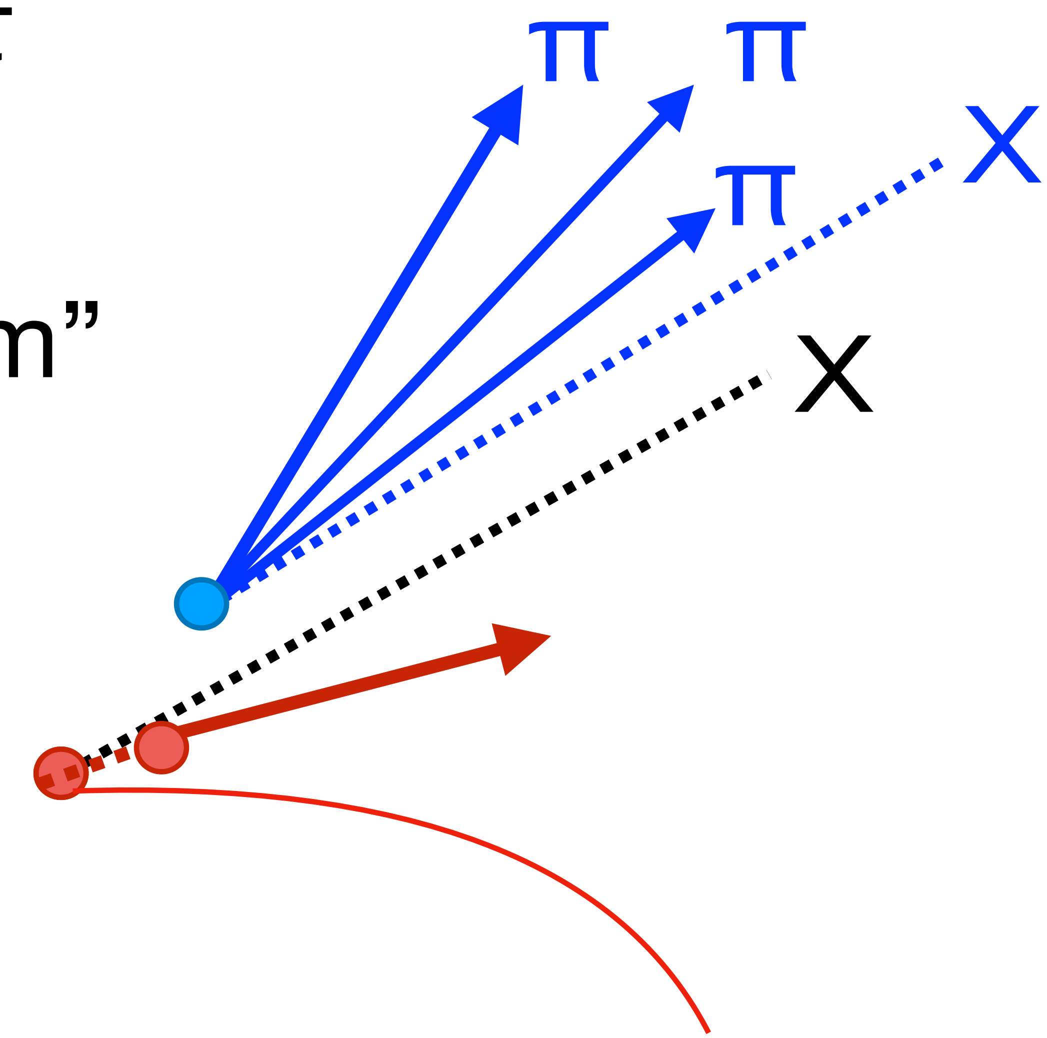


Three-prong analysis

"*Charm carrier*" mimics the τ flight, but B/S ~ 10 at this stage…

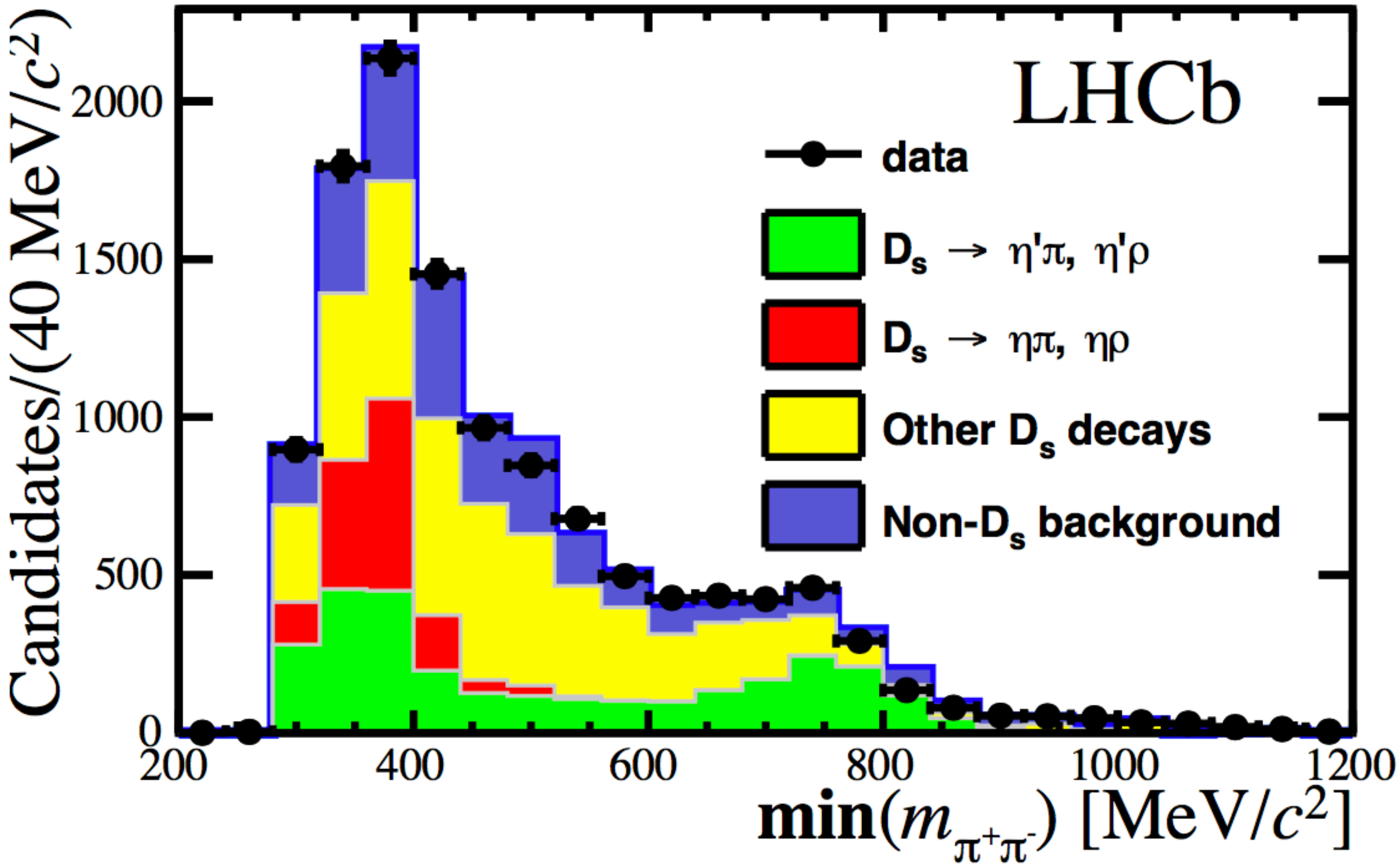
"Double charm"





Taming the double charm

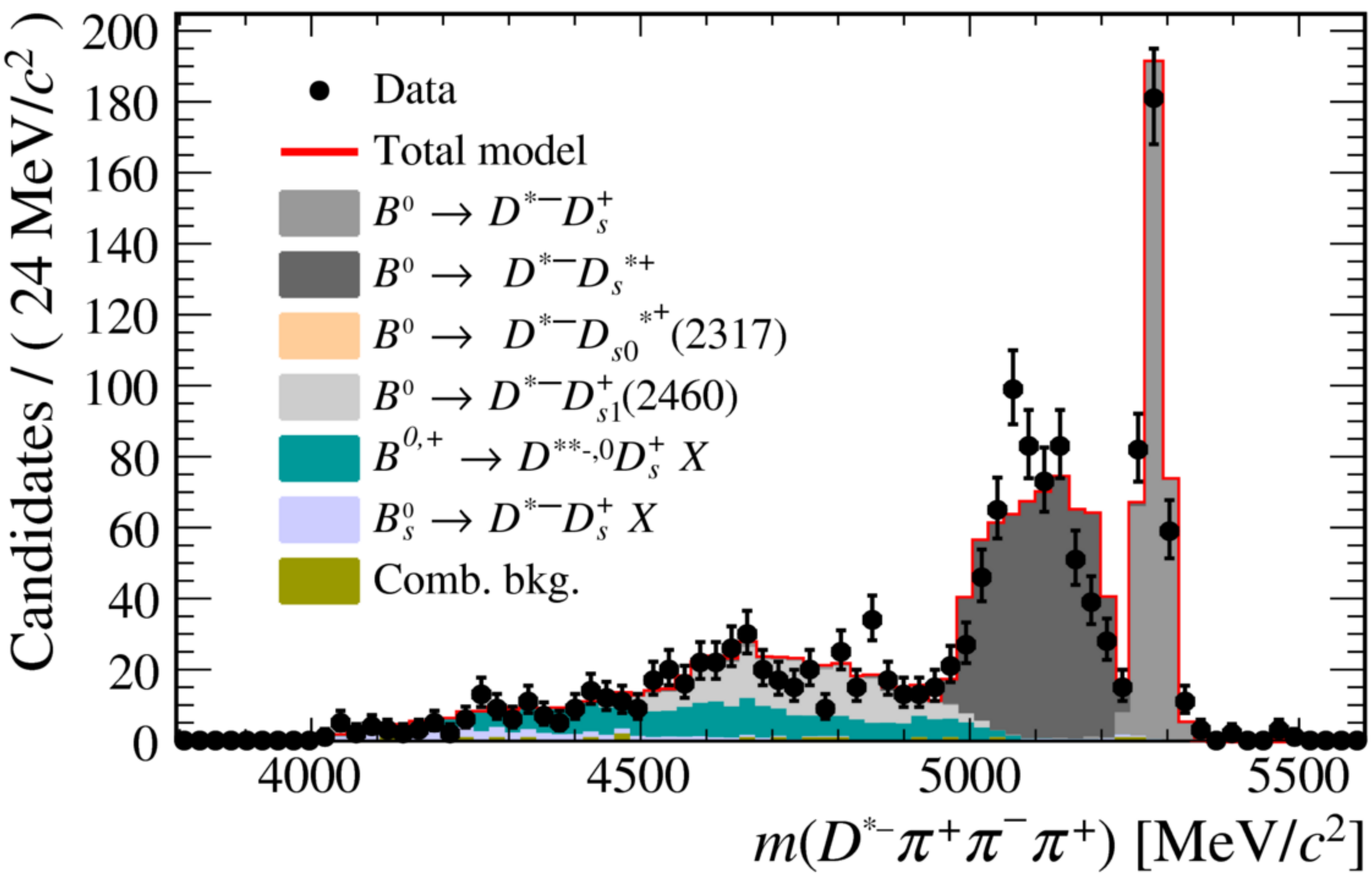
First we must control the $D_s \to 3\pi X$ modelling…



1708.08856 (2017)

Taming the double charm

Then the $B \to D^{*}D_{s}X$ modelling..



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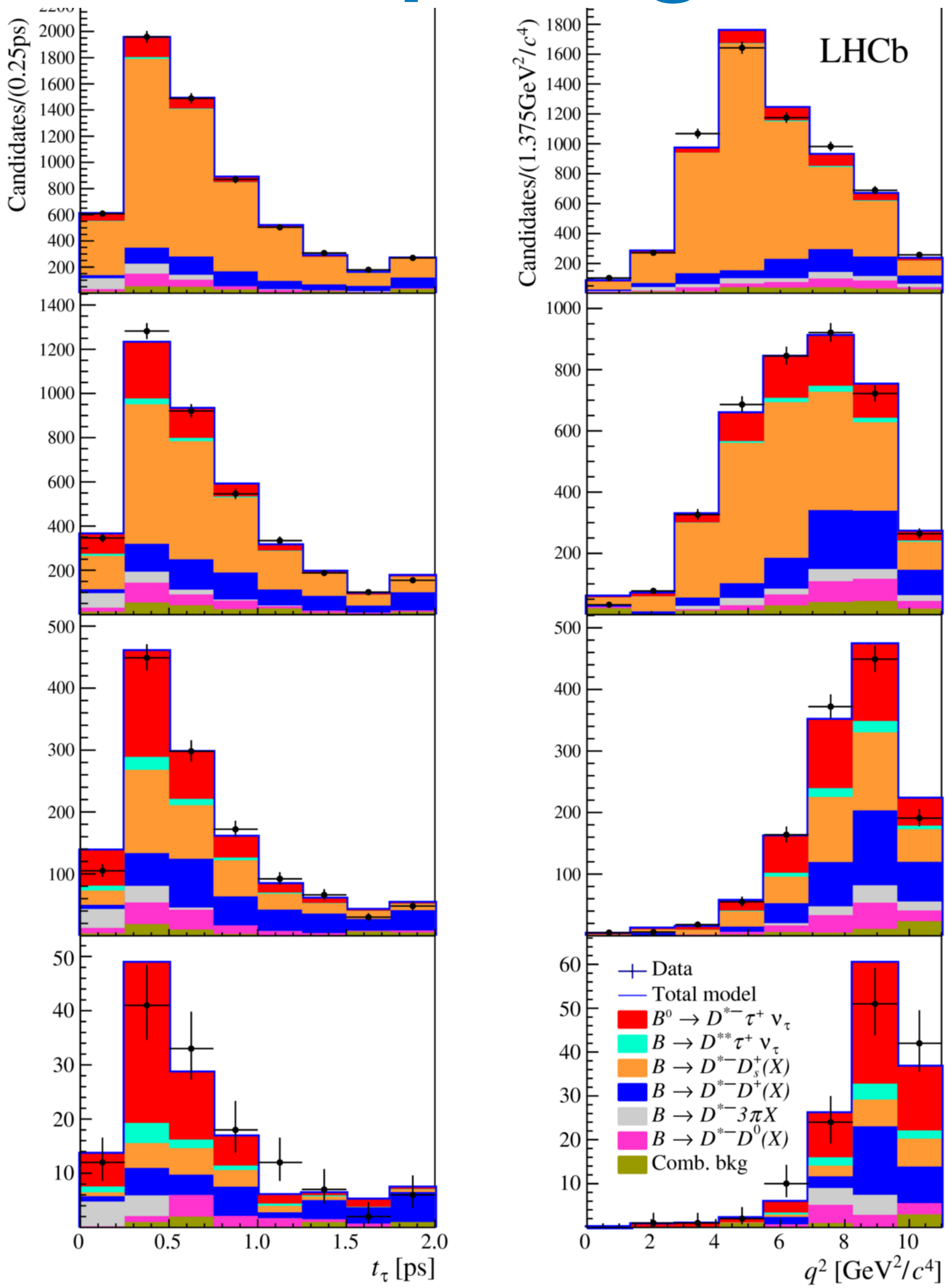
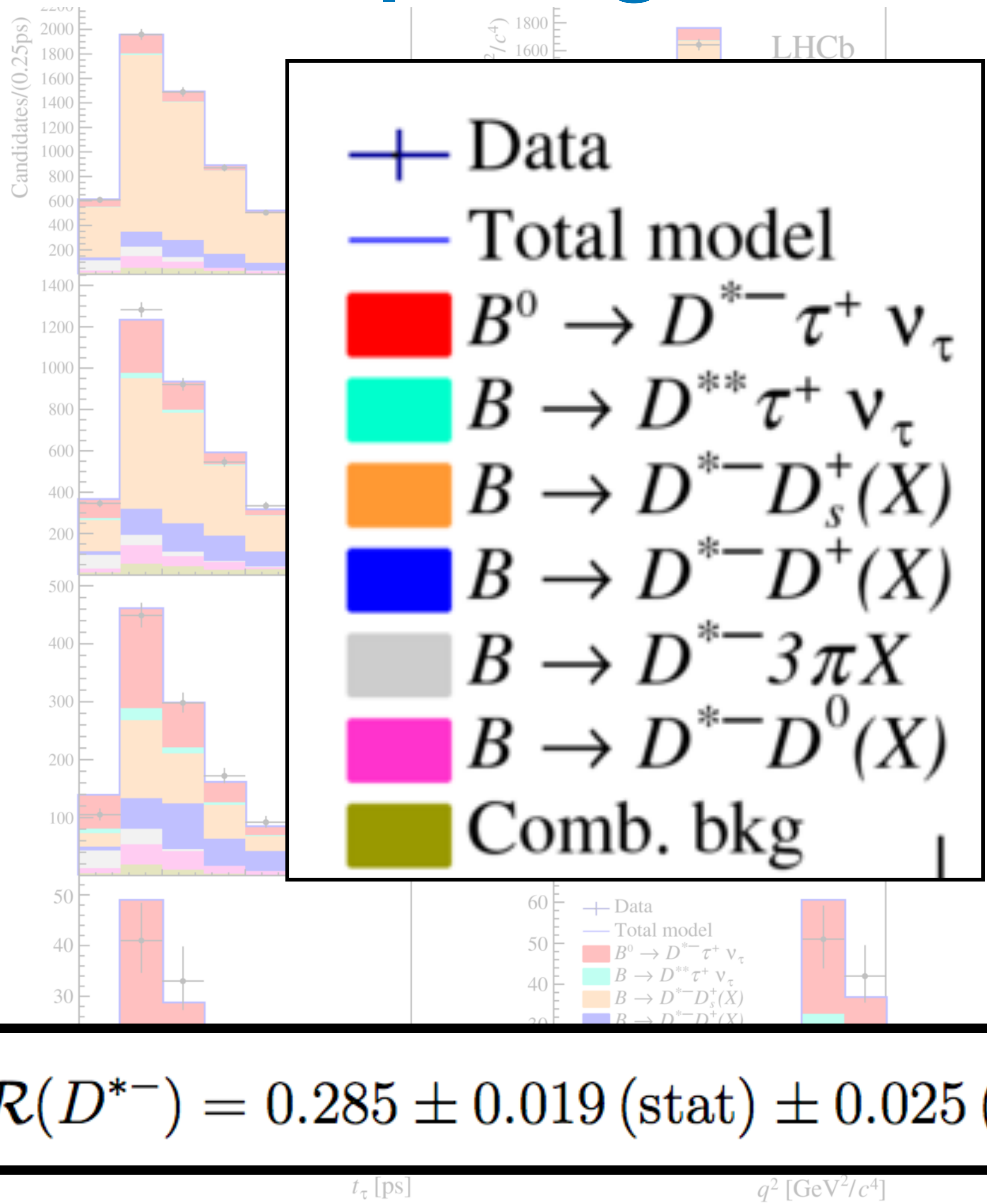
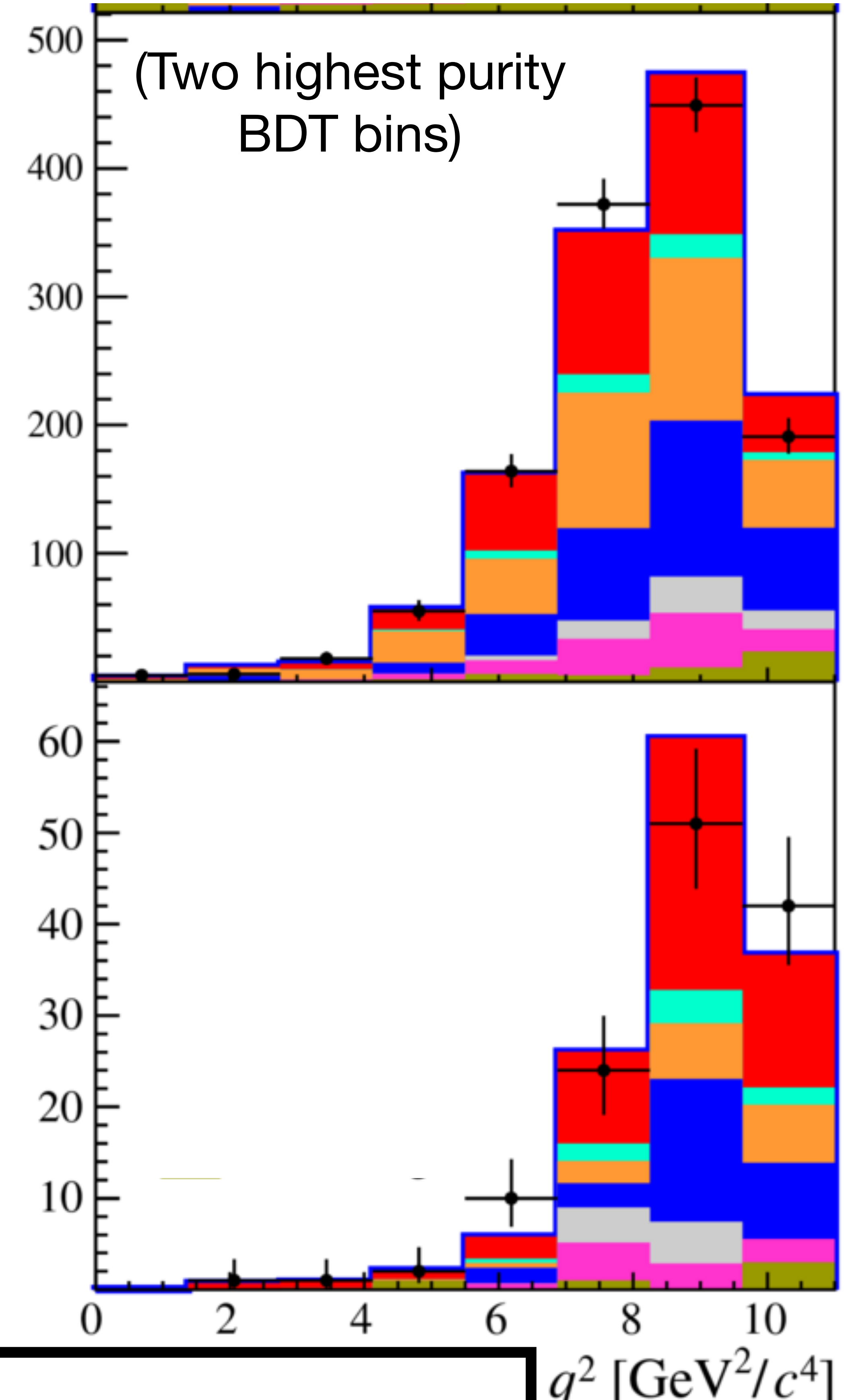
Three-prong fit



3D fit in q^2, τ lifetime, and a MVA discriminant..

Three-prong fit

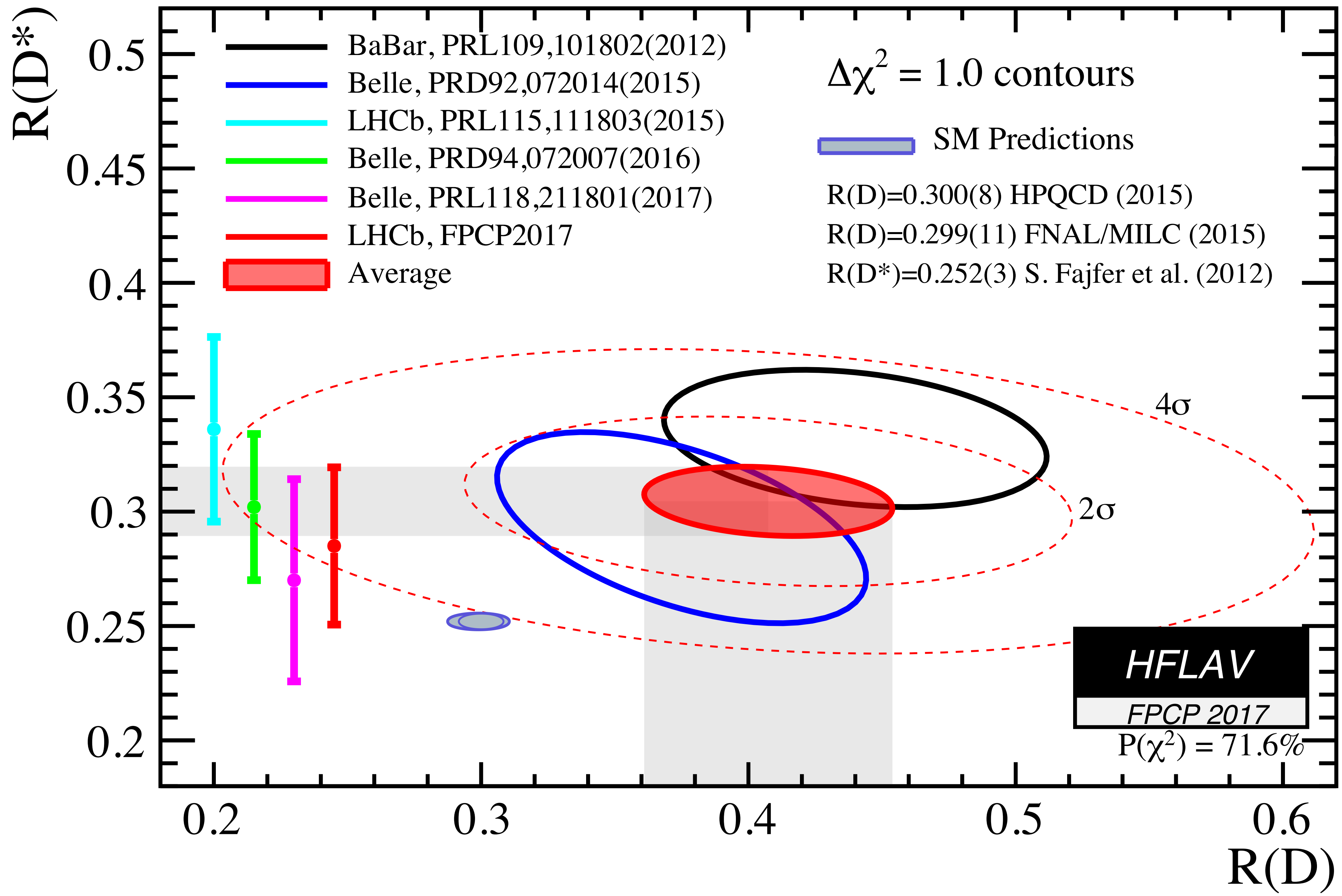




$$\mathcal{R}(D^{*-}) = 0.285 \pm 0.019\,(\text{stat}) \pm 0.025\,(\text{syst}) \pm 0.013\,(\text{ext})$$

Status and prospects

1708.08856 (2017)
PRL 115, 111803 (2015)



In the pipeline from LHCb: $R(D^{*+})$, $R(D^{+,0})$,$R(D_s^{(*)})$, $R(\Lambda^{(*)}_c)$, $R(J/\psi)$, $R(pp)$, $R(p)$, etc…

Tree-level e-μ tests

From Greljo, Isidori, Marzocca 1506.01705

Charged currents. The $b \to c(u)\tau\nu$ charged currents should exhibit a universal enhancement (independent of the hadronic final state). This implies, in particular, $R_{B\tau\nu} = R_D^{\tau/\mu} = R_{D^*}^{\tau/\mu}$. LFU violations between $b \to c(u)\mu\nu$ and $b \to c(u)e\nu$ can be as large as $O(1\%)$. The inclusive $|V_{cb}|$ and $|V_{ub}|$ determinations are enhanced over the exclusive ones because of the τ contamination in the corresponding samples.

Belle[1]: $R_{e\mu} = 0.995 \pm 0.022_{\mathrm{stat}} \pm 0.039_{\mathrm{syst}}$

Proposed approach at LHCb:

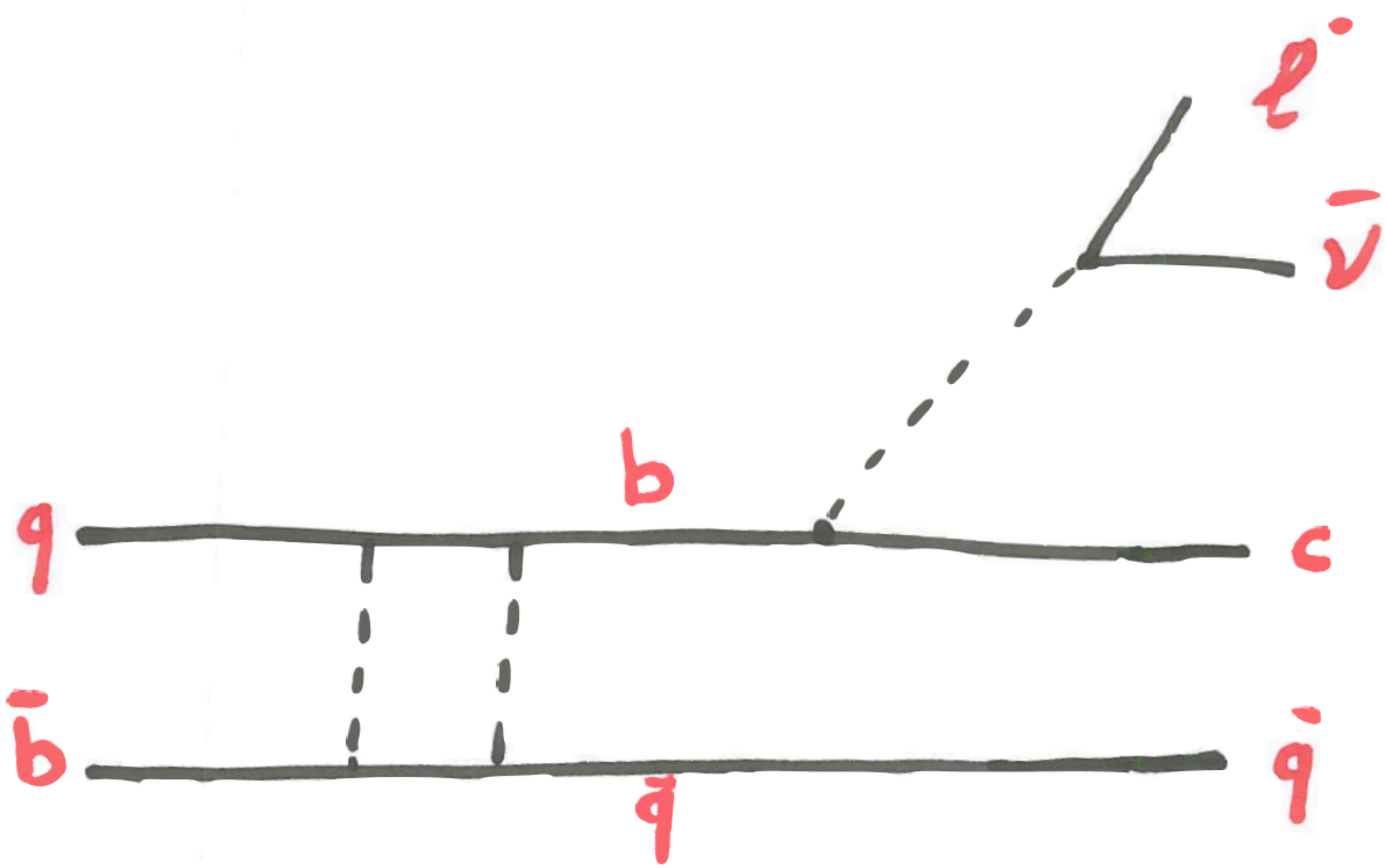
$$R_{e\mu} = \frac{B \to D^{(*)} e\nu \,/\, B \to D^{(*)} \mu\nu}{D^0 \to K e\nu \,/\, D^0 \to K \mu\nu}$$

Tentative goal with Run-I data: $\delta R_{e\mu} \approx$ few x 10^{-3}

1.Belle, 1510.03657 (2015)

Conclusions

Many interesting and unique LHCb results with semileptonic decays, and plenty more to look forward to!

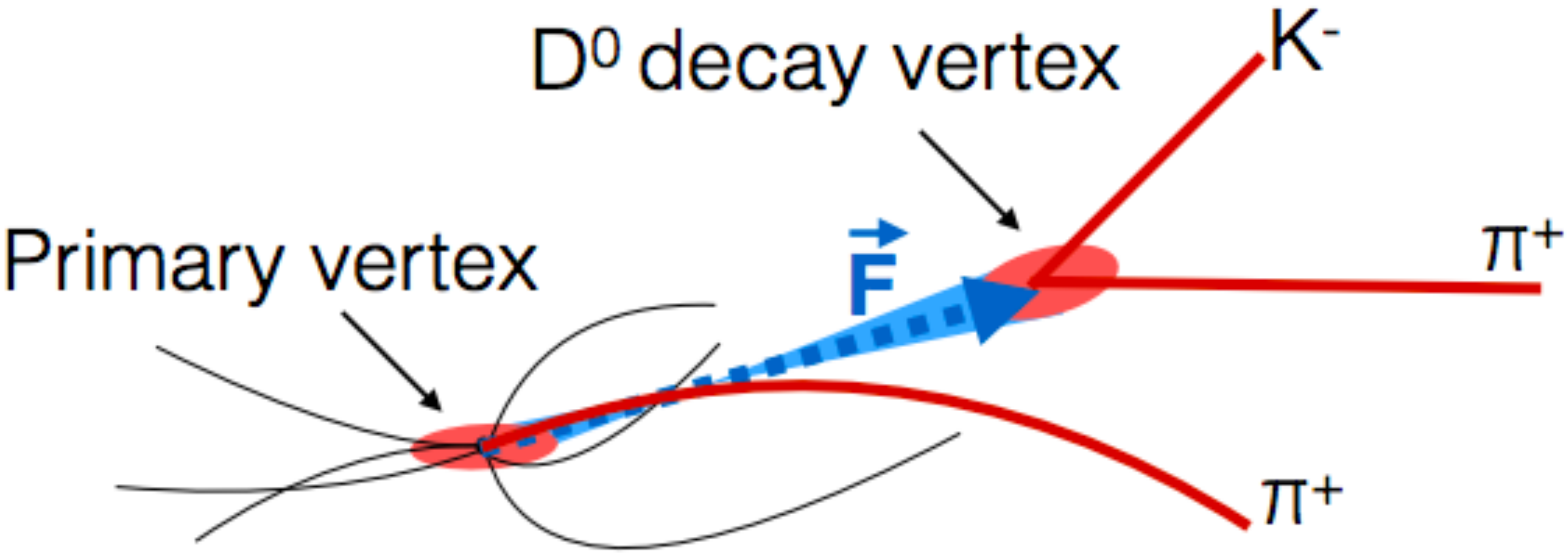


Backup slides start here…

Three-prong R(D*) systematics

Source	$\delta R(D^{*-})/R(D^{*-})[\%]$
Simulated sample size	4.7
Empty bins in templates	1.3
Signal decay model	1.8
$D^{**}\tau\nu$ and $D_s^{**}\tau\nu$ feeddowns	2.7
$D_s^+ \to 3\pi X$ decay model	2.5
$B \to D^{*-}D_s^+X$, $B \to D^{*-}D^+X$, $B \to D^{*-}D^0X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^{*-}3\pi X$ background	2.8
Efficiency ratio	3.9
Total uncertainty	8.9

Partial reconstruction method



Idea is to reconstruct the decay without requiring a full "long" track for one D^0 child. The kinematics can be fixed if this track has a direction determination from the VELO. We can then probe the detection asymmetries for the remainder of the tracking system. Method also works with K3pi decays. The 2 body D mode required new dedicated HLT lines which were introduced for Run-II.