Prospects for measurements with semileptonic decays in Upgrade II

3rd Workshop on LHCb Upgrade II 21-23 March 2018

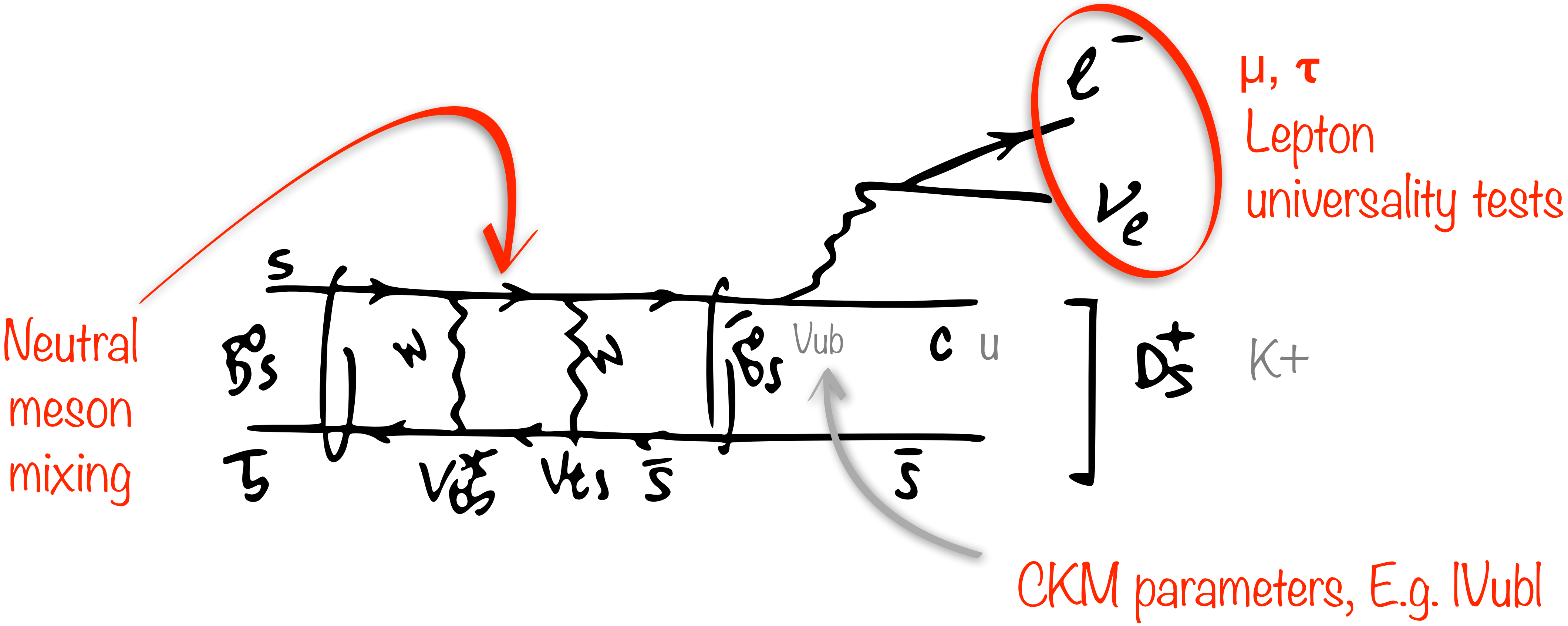
Lucia Grillo[1] for the SLWG

Thanks to everybody who contribute with studies
and to the Upgrade II LHCC physics document

[1] University of Manchester, UK

In this talk:

- Charged-current, tree-level (focus on b-hadron) semileptonic decays



- Large branching fractions, systematic uncertainties to be estimated
- Theoretical uncertainty controllable, could be further reduced by Lattice calculation improvements
- What can the SL physics programme gain with a phase-II upgrade? how does this vary according to the different detector/data flow choices?

In this talk:

- What can the SL physics programme gain with a phase-II upgrade?
  - Semileptonic asymmetries
  - CKM parameters determination
  - Lepton universality tests/study of semitauonic decays

- How does this vary according to the different detector/data flow choices?
  - VELO RF foil removal
  - ECAL
  - Additional tracking stations on magnet

Material for this talk has been taken from:

- Semileptonic WG meetings: SLWG 05/08/15, SLWG 03/05/17, SLWG 18/10/17
- Upgrade II LHCC physics document in preparation
- Additional reference and discussions [several link have restricted access, sorry about that]

Challenges (analysis and computational)

- Need to cope with the partial reconstruction
  - Different approximation strategies in order to optimise the resolutions
  - Tools to cope with background events, E.g. isolation tool to suppress charged and neutral particles

- For several measurement the leading systematics is already MC statistics
  - In this talk we assume we will find a solution for that….

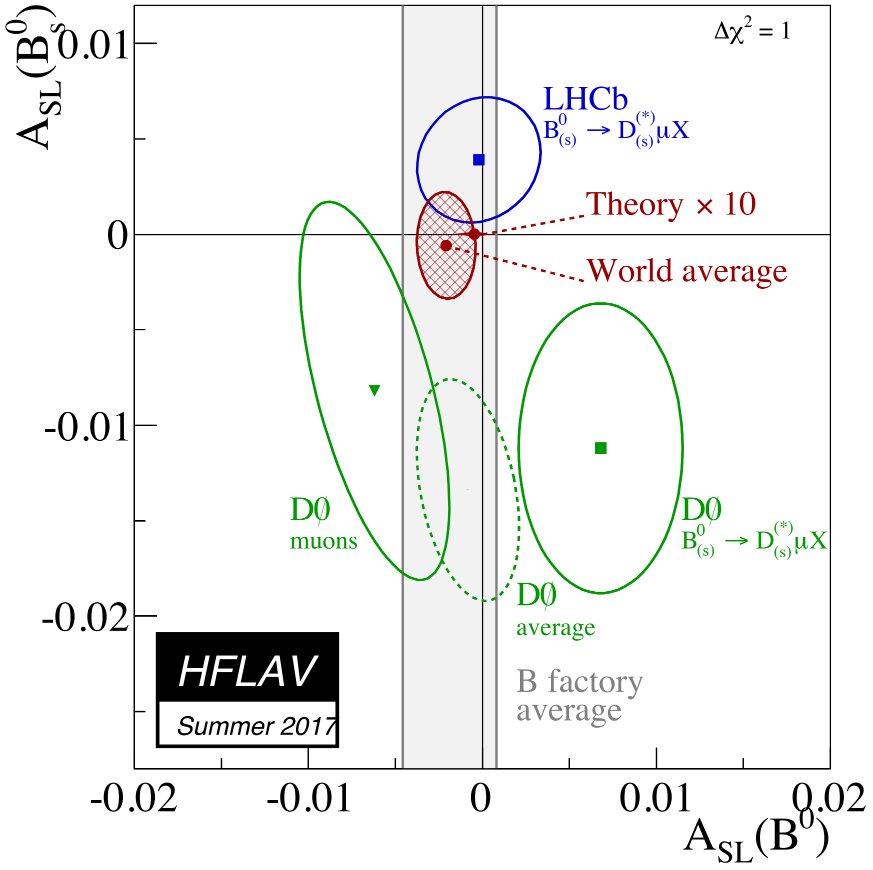
Semileptonic asymmetries

- CPV in neutral meson mixing studied by measuring the semileptonic asymmetries

$$a_{\rm sl}^q = \frac{\Gamma(\bar{B}_q \to B_q \to f) - \Gamma(B_q \to \bar{B}_q \to \bar{f})}{\Gamma(\bar{B}_q \to B_q \to f) + \Gamma(B_q \to \bar{B}_q \to \bar{f})} = \mathcal{I}m(M_{12}^q/\Gamma_{12}^q)$$

- LHCb measured the untagged charge asymmetry of the final state particles (time dependent, in the B0 case)

$$A_{\rm meas}^q(t) = \frac{\Gamma(f,t) - \Gamma(\bar{f},t)}{\Gamma(f,t) + \Gamma(\bar{f},t)} = \frac{a_{\rm sl}^q}{2} + A_{\rm D} - \left(A_{\rm P}^q + \frac{a_{\rm sl}^q}{2}\right)\frac{\cos(\Delta M_q t)}{\cosh(\Delta\Gamma_q t/2)}$$



Challenges:

- Disentangle CP asymmetry and detection asymmetry AD (and production asymmetry AP for the B0 case)
- Control the physics background

[Phys. Rev. Lett. 114, 041601 (2015)]

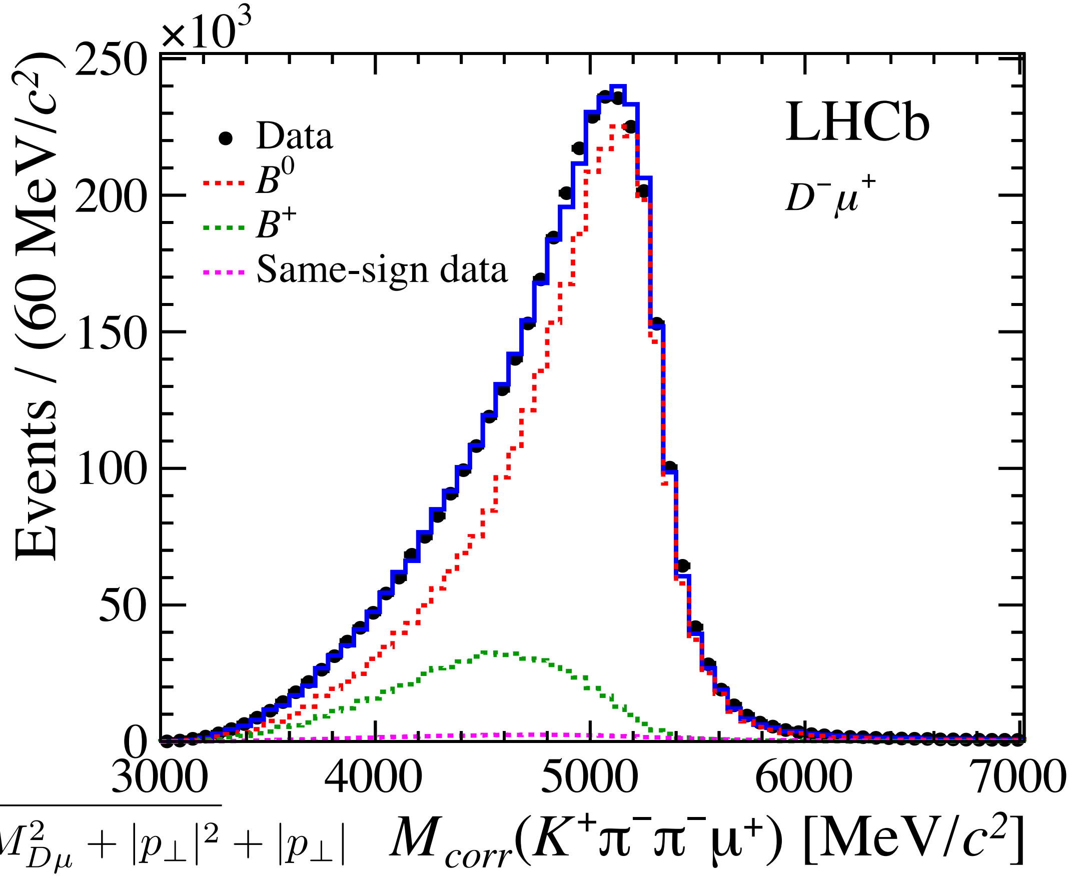
[Phys. Rev. Lett. 117, 061803 (2016)]

Control the systematics to the 10^-4 level

- Better control of **detection asymmetries** (higher statistics of Charm control samples used and new, better techniques to measure them)
- References for detection asymmetries: LHCb-INT-2015-012, LHCb-INT-2017-023, LHCb-INT-2018-006 in preparation
- Final determination of detection asymmetries has to be data driven, but (bespoke, high statistics) MC can maybe help us to more reliably/accurately apply the data driven corrections to the measurement
- Use the corrected mass dimension to subtract all Xb -> D(s) mu nu X **physics backgrounds**
- benefit from the proposed RF foil removal; unfortunately different luminosities in magnet-up and magnet-down (see EOI)

Source of uncertainty	a^d_{sl}
Detection asymmetry	0.26
B^+ background	0.13
Λ^0_b background	0.07
B^0_s background	0.03
Combinatorial D background	0.03
k-factor distribution	0.03
Decay-time acceptance	0.03
Knowledge of Δm_d	0.02
Quadratic sum	0.30

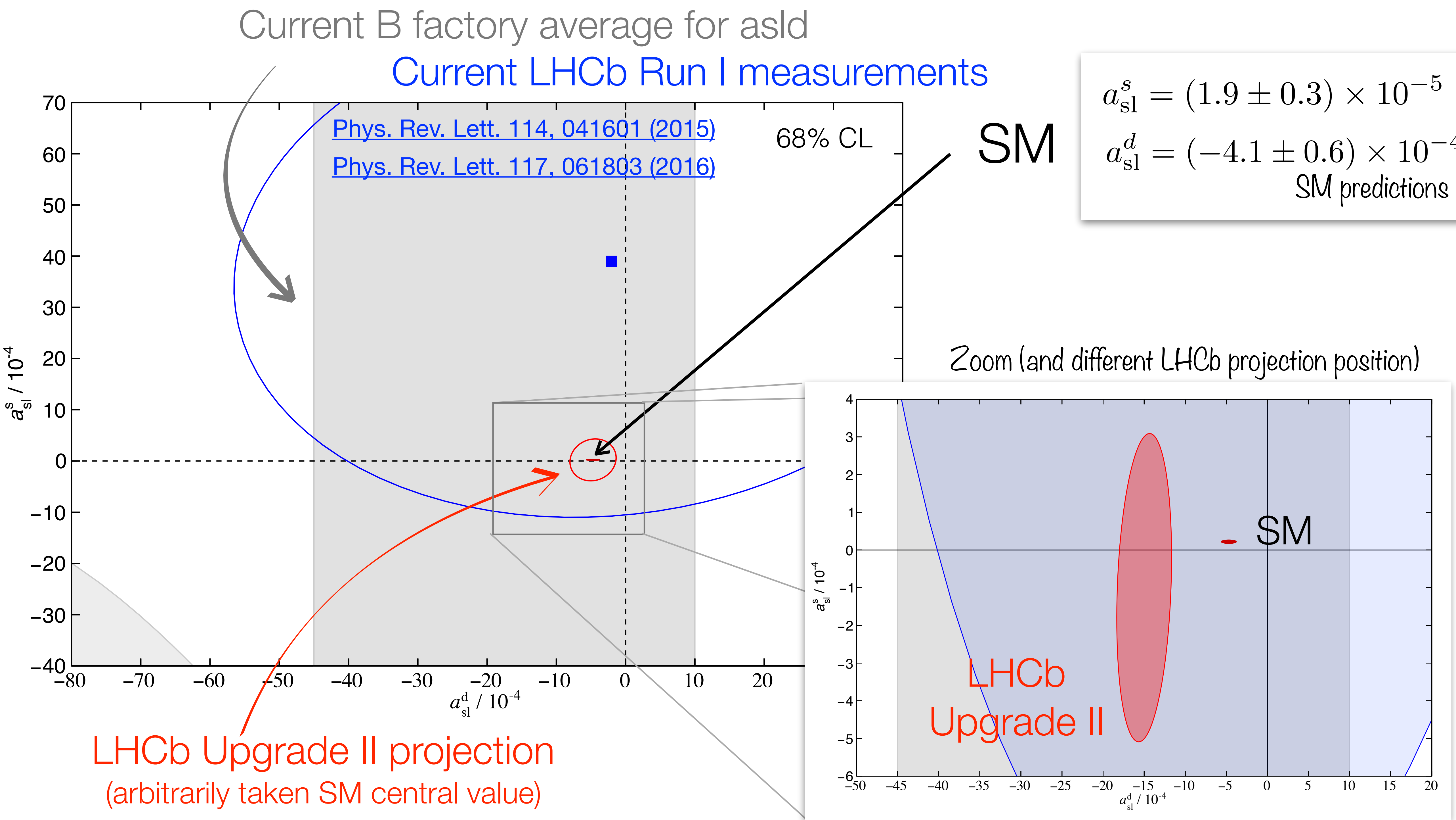
Taken asld Phys. Rev. Lett. 114, 041601 (2015) as example



$M_{corr} = \sqrt{M^2_{D\mu} + |p_\perp|^2} + |p_\perp|$

$a_{\mathrm{sl}}^s / a_{\mathrm{sl}}^d$ with 300fb^{-1}

Mika Vesterinen



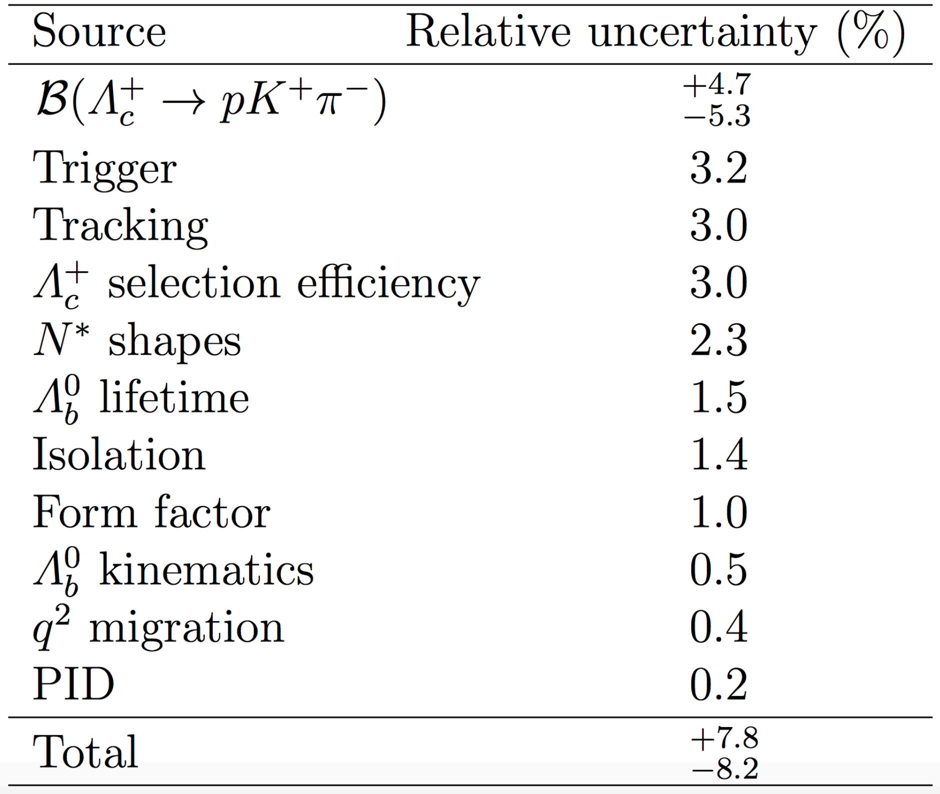
$$a_{\mathrm{sl}}^s = (1.9 \pm 0.3) \times 10^{-5}$$
$$a_{\mathrm{sl}}^d = (-4.1 \pm 0.6) \times 10^{-4}$$
SM predictions

- Don’t trust too much asls/asld correlation

|Vub| measurements

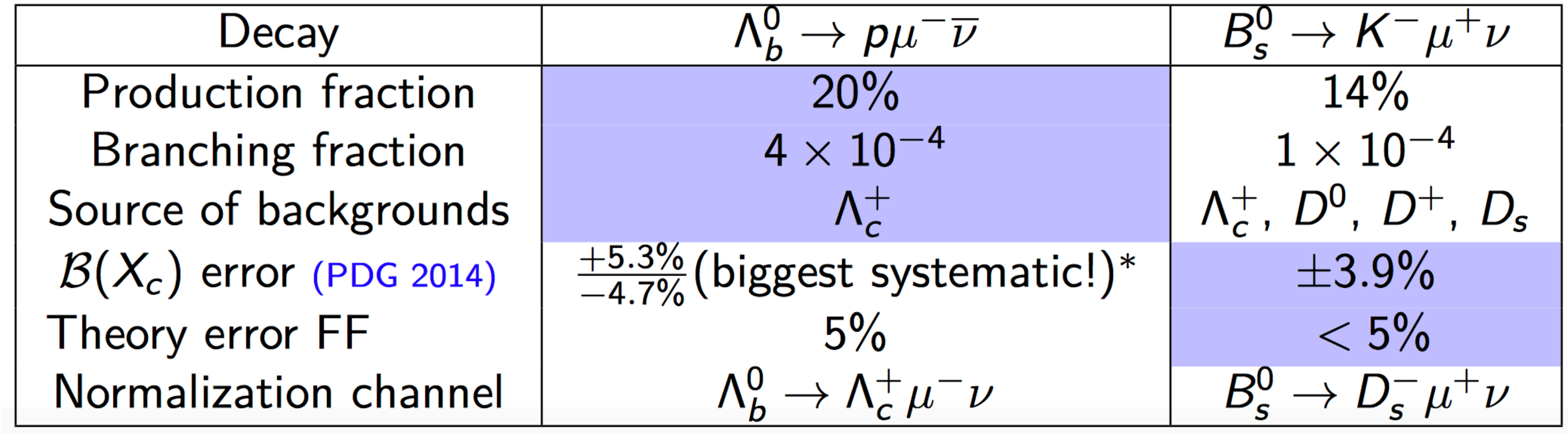
- |Vub| already systematically limited in Λb->pmunu, Bs->Kmunu analysis on-going
- Expected 15M Λb->pmunu events (Before resolution quality selection) at the end of Upgrade-I for high q2 region (>15GeV)
- Expected 2M Bs->Kmunu events at the end of Upgrade-I for full q2 region
- Shape information profits from the increase in the data sample statistics: this could improve fits in lattice and data

Nature Physics 10 (2015) 1038



Source	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$
Trigger	3.2
Tracking	3.0
Λ_c^+ selection efficiency	3.0
N^* shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b^0 kinematics	0.5
q^2 migration	0.4
PID	0.2
Total	$^{+7.8}_{-8.2}$

Slavomira Stefkova, ICHEP 2016



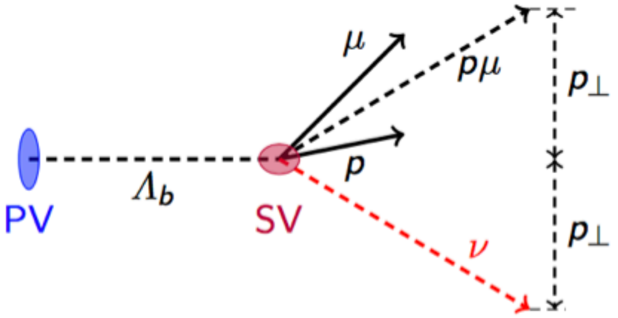
Decay	$\Lambda_b^0 \to p\mu^-\overline{\nu}$	$B_s^0 \to K^-\mu^+\nu$
Production fraction	20%	14%
Branching fraction	4×10^{-4}	1×10^{-4}
Source of backgrounds	Λ_c^+	Λ_c^+, D^0, D^+, D_s
$\mathcal{B}(X_c)$ error (PDG 2014)	$^{+5.3\%}_{-4.7\%}$ (biggest systematic!)*	$\pm 3.9\%$
Theory error FF	5%	$< 5\%$
Normalization channel	$\Lambda_b^0 \to \Lambda_c^+\mu^-\nu$	$B_s^0 \to D_s^-\mu^+\nu$

RF foil removal

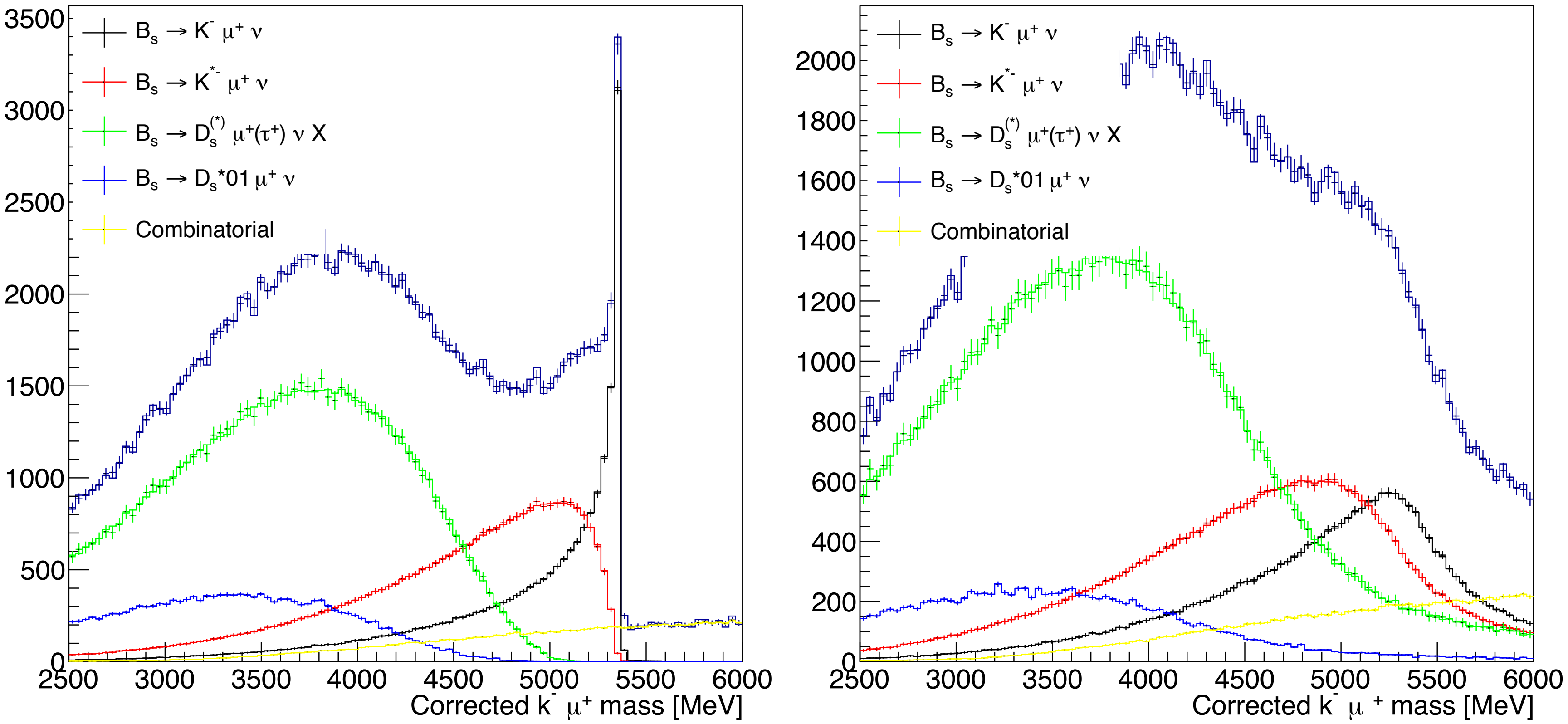
Iwan Smith, HL-LHC workshop poster update @SLWG 18/10/17

- Benefits from improved vertex (especially secondary) precision:
  - Improved resolution of variable typically used by SL decays, E.g. corrected mass, q^2 → improved separation among different components in fits
  - Higher efficiency
  - Better background rejection: Better IP, DIRA, DOCA, Vertex χ^2, Better charged track isolation

$$M_{corr} = \sqrt{p_{\perp}^{2} + M_{p\mu}^{2}} + p_{\perp}$$



- Reducing/removing the RF foil is equivalent to increase size of the dataset



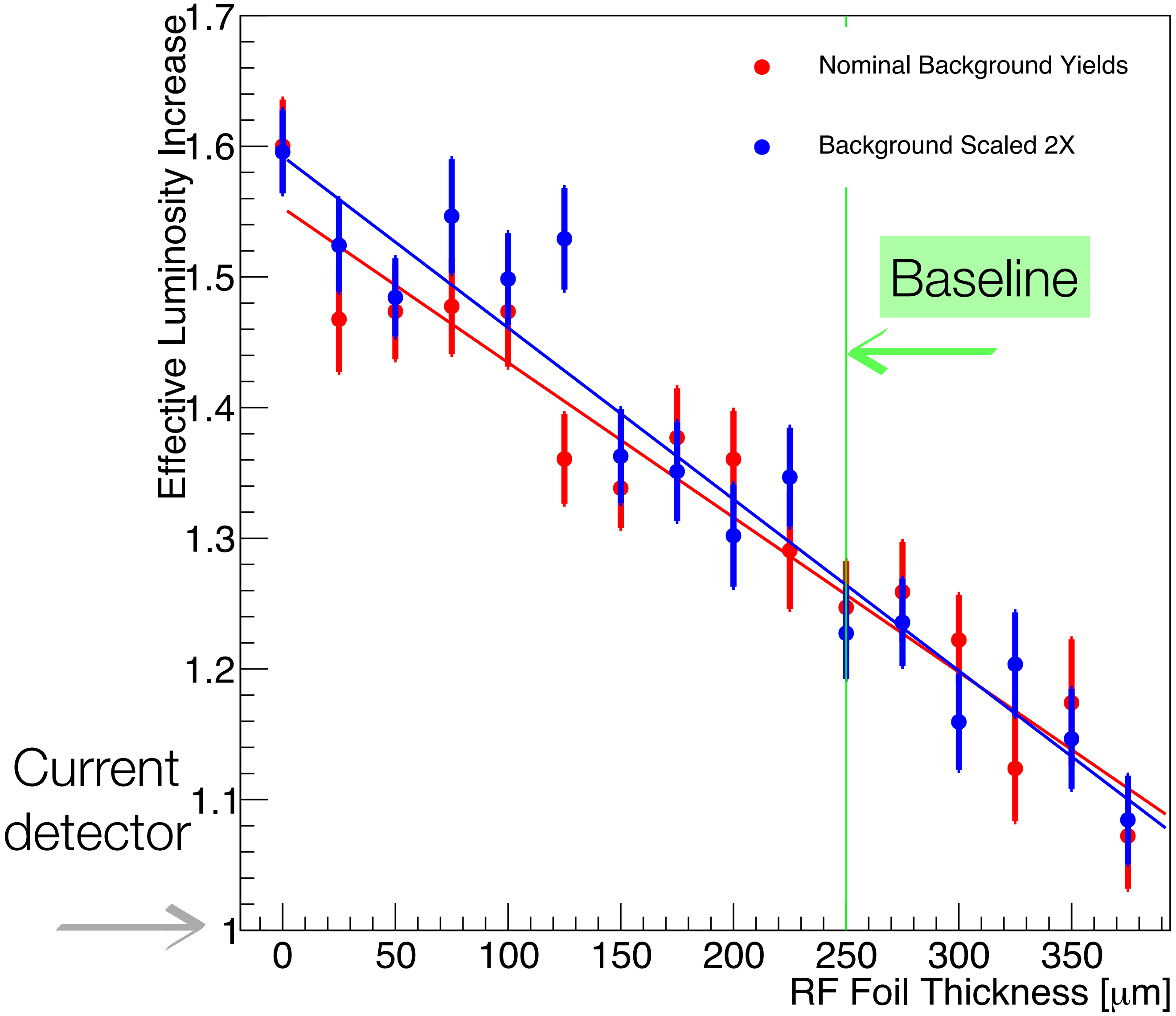
Perfect resolution

LHCb resolution

RF foil removal

Iwan Smith, HL-LHC workshop poster update @SLWG 18/10/17

- Improvements on the studies shown last year
  - Improved vertex resolution model, E.g. accounting for pT dependence
  - Improved procedure used for the study, fit, uncertainty estimation



Baseline

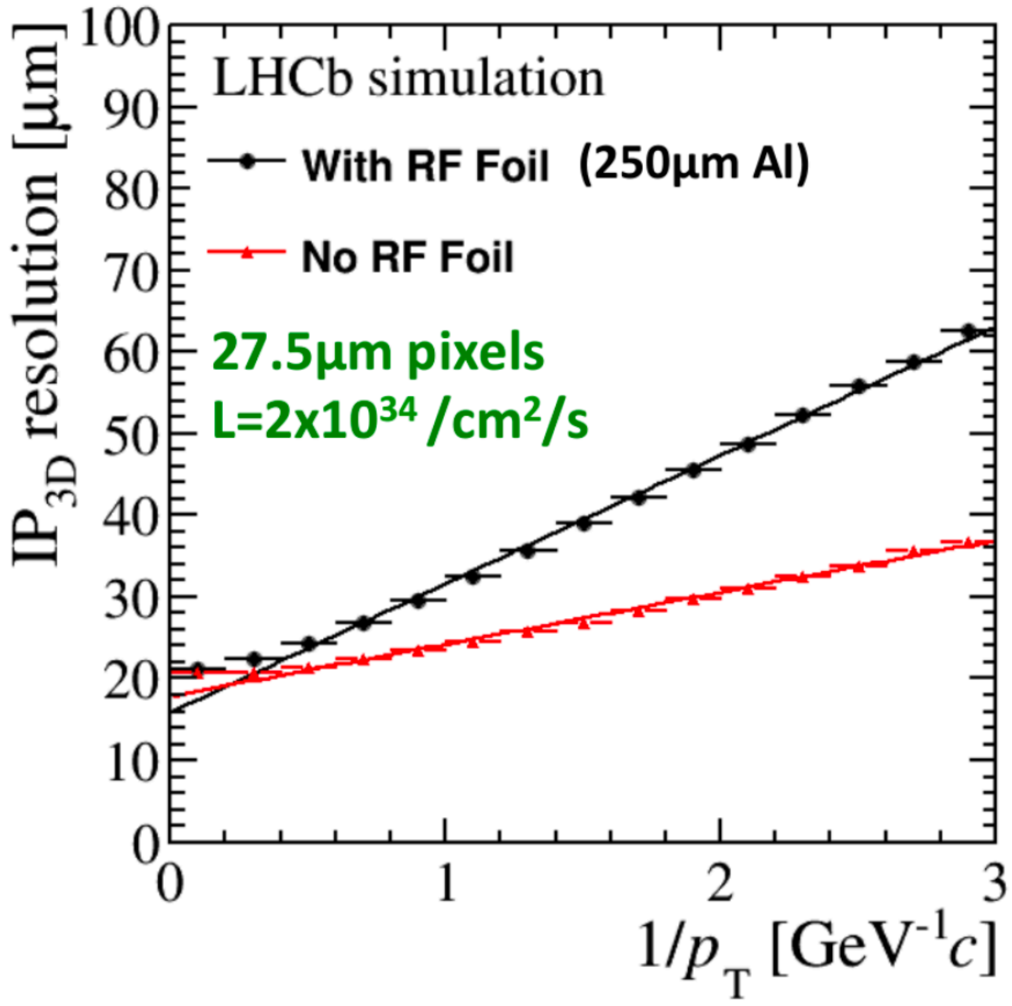
Current detector

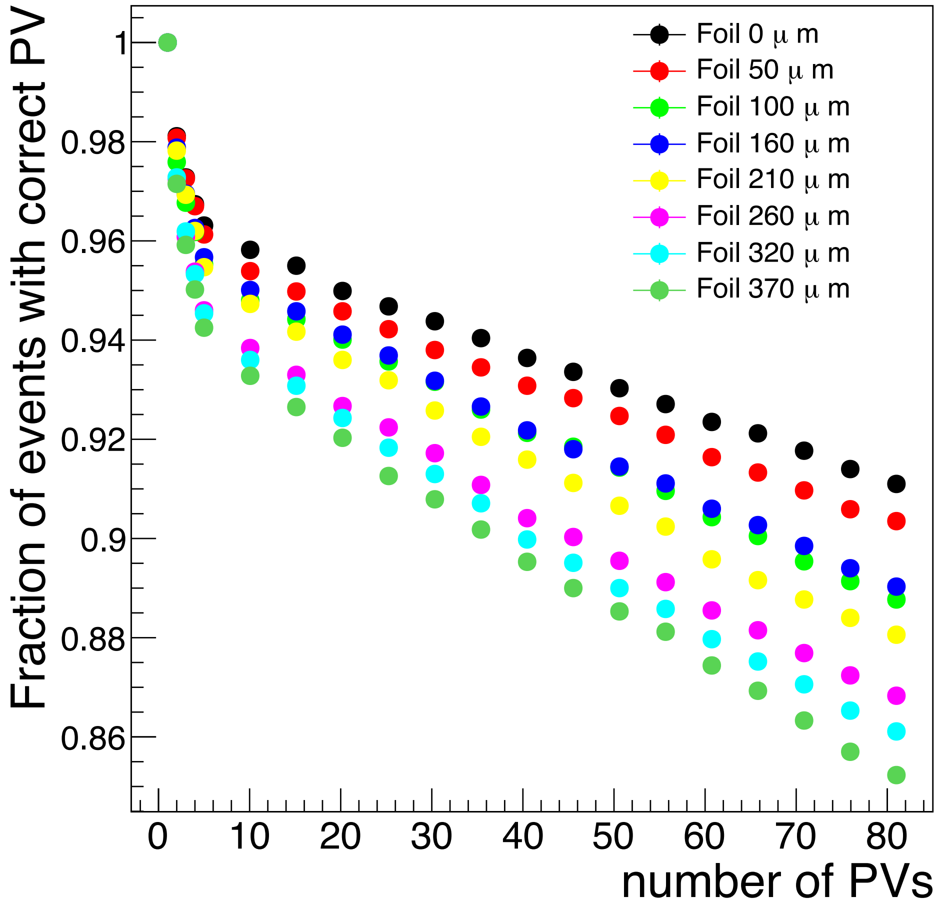
- Scan in RF foil thickness of VeloPix
- RF foil thickness has clear impact on sensitivity
- No RF foil gives 25% gain in effective luminosity from fit resolution alone

RF foil removal

Greg Ciezarek, HL-LHC workshop 01/11/2018

- Background rejection (not only relevant for SL)
- Background: random track combinations, tracks from PVs (largest, but easier to remove, E.g. IP), tracks from mixtures of heavy flavour decays (dominant)
- Upgrade II: pileup 1.4 (now)→ ~55. Prompt background vastly increases , can we still remove it easily? + Overlapping heavy-flavour increases by a factor ~ 3.5 relative to signal





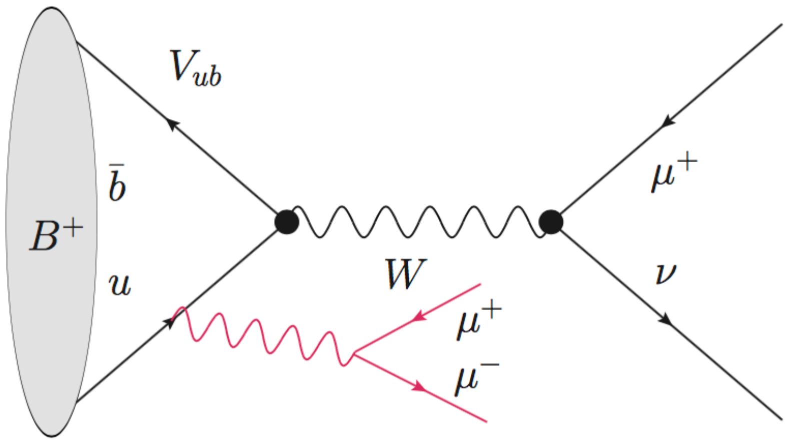
Nearly doubles IP resolution at low pT

30% reduction in wrong PV association

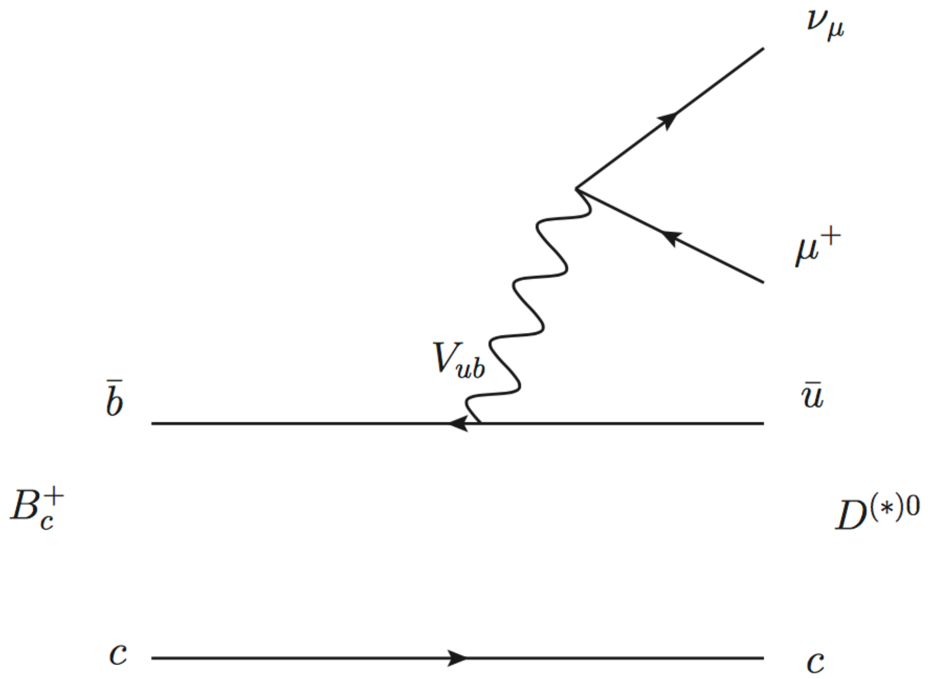
Additional |Vub| determinations

- Inclusive/Exclusive |Vxb| determination
- Hard |Vxb| inclusive determinations in LHC environment, but maybe LHCb can help Belle II to understand more exotic contributions

- |Vub| through leptonic decays
- B→3μν to complement B→μνγ discovery (Belle II)
- Rare decays → likely statistically limited by the end of Upgrade I



- |Vub| through Bc semileptonic decays
- Expected Bc→D0μνX candidates: 100 in 3fb^{-1}, 5k in 50fb^{-1}, 30k in 300fb^{-1}
- Large combinatorial background expected, increased luminosity and improvements to vertex resolution essential



|Vcb| measurements

- Determination of |Vcb| will be increasingly important also for other precision measurements, as it will become the limiting factor in many SM predictions E.g. the branching fraction of Bs → μμ

- Building upon the measurement of the shape of Λb → Λc μν differential decay rate [Phys. Rev. D 96, 112005 (2017)], using Λb → Λc π as normalisation mode, using f Λb/fd and B0→Dπ branching fraction external input

$$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \nu) = \frac{N(\Lambda_b^0 \to \Lambda_c^+ \mu^- \nu)}{N(\Lambda_b^0 \to \Lambda_c^+ \pi^-)} \times \frac{\epsilon_\pi}{\epsilon_\mu} \times \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = |V_{cb}|^2 \tau_{\Lambda_b} \int_1^{w_{max}} \frac{d\Gamma'}{dw} \cdot dw$$

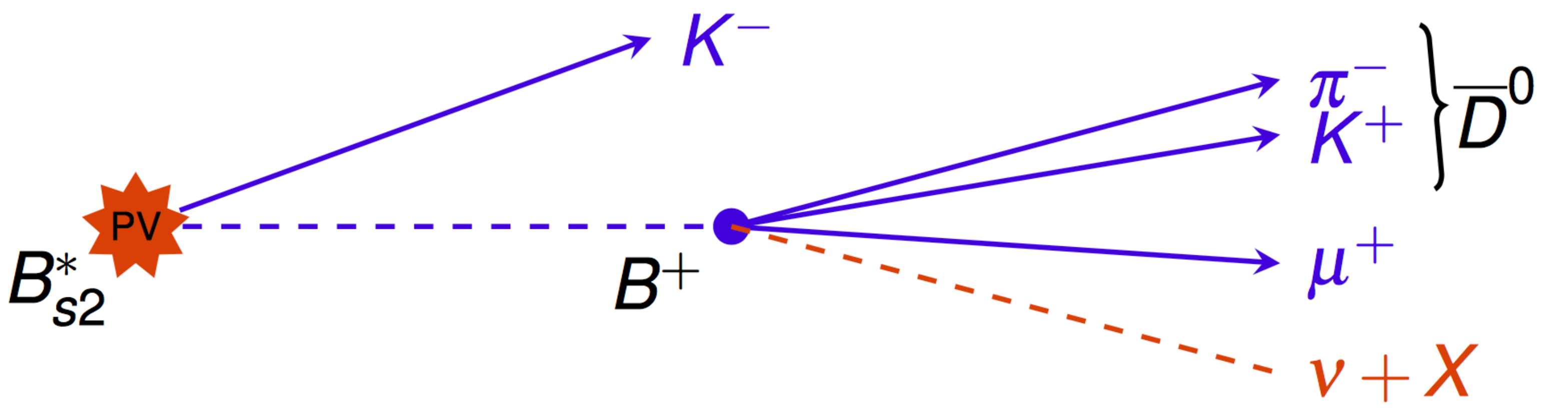
- Uncertainty on |Vcb| ~ 0.1% for Run-I dataset [see E.g. SLWG 10/06/15]

- To make a |Vcb| measurement at LHCb, experimental input from Belle II will be needed, but…

- The current uncertainty depends on the parametrisation used in the fit to the Form Factors. At the end of Upgrade II LHCb will have O(1B) of B→Dμν reconstructed and selected candidates that will improve the ultimate |Vcb| precision

Other opportunities

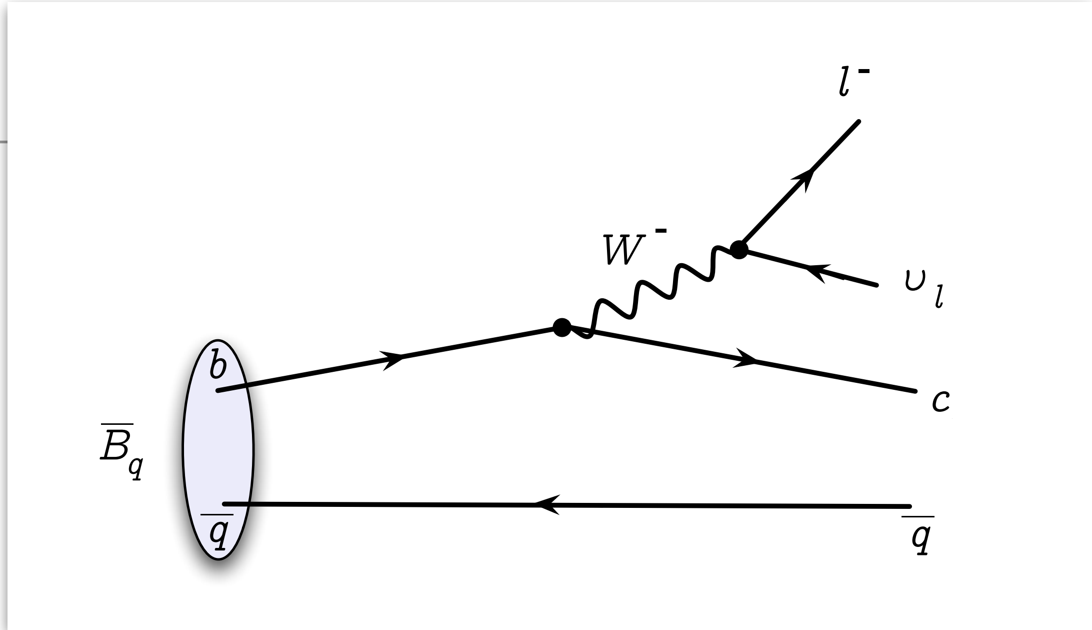
- Narrow decays of excited Bs mesons to B(⁎)+K– can be used to reconstruct B+ momentum [S. Stone, L. Zhang arXiv:1402.4205]

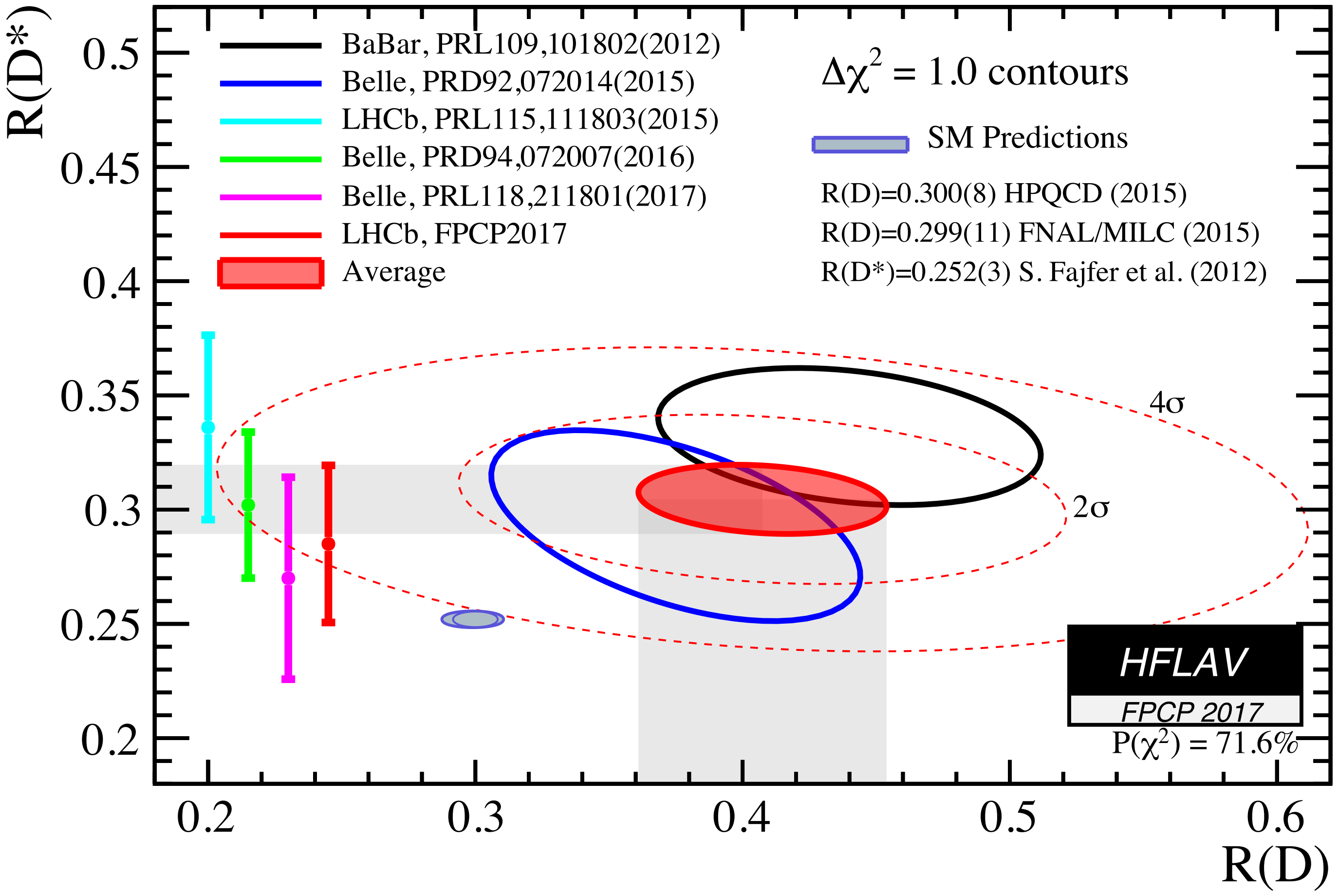


- μKπ vertex + K track + mass constraints to obtain the energy of the B+ meson. Then fully reconstruct the missing four-momentum
- First measurement focusing on D fractions in B+ →D0μνX at review stage now as proof of principle
- Expect ≈ 1/1000 reduction in selected candidates compared to B+ selection
- Tracking stations inside the magnet: 40% improvement in slow pions (see Sheldon Stone, talk 03/05/17)
- Decays such as Bs—>K*+μν would benefit from an upgraded calorimeter

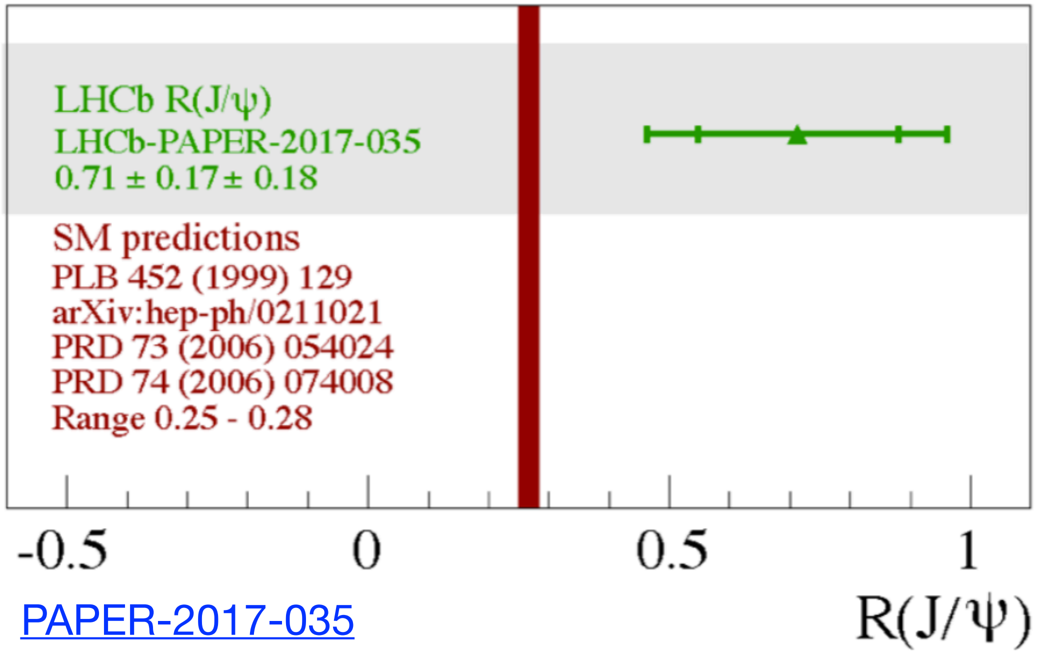
Semitauonic measurements

- Evidence of μ-τ lepton non-universality
- LHCb has started exploiting its potential in this area (3 Run-I measurement)
- What can we do in Upgrade I and II era?





$$R(X_c) = \frac{\mathcal{B}(X_b \to X_c \tau \nu)}{\mathcal{B}(X_b \to X_c l \nu)}$$



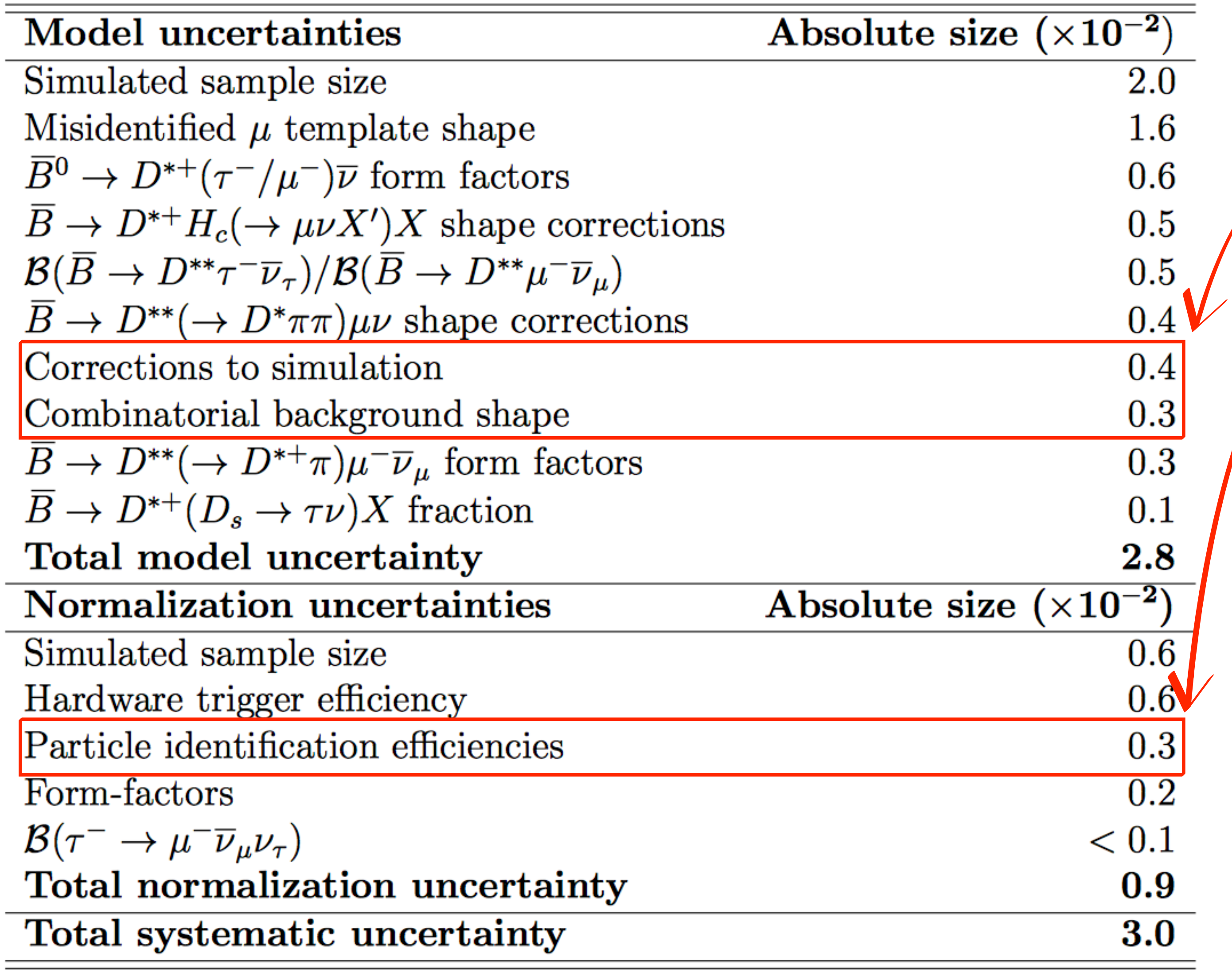
PAPER-2017-035

Projecting systematics

Brian Hamilton, Patrick Owen, Greg Ciezarek, Concezio Bozzi

- Take first R(D*) measurements with the τ reconstructed using the muonic and 3-prong final state

Systematic table from R(D*) muonic, Phys. Rev. Lett. 115, 111803



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**

- Assume that all the systematics can be reduced with the size of the input data except for those that are conservatively not expected to scale
- A factor 2 to be added for using also the ground state sample
- Improvement in trigger selection results in a factor 1.5

Projecting systematics

Brian Hamilton, Patrick Owen, Greg Ciezarek, Concezio Bozzi

- Take first R(D*) measurements with the τ reconstructed using the muonic and 3-prong final state
- Lepton universality test: $R(D^{*-}) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$ using 3-prong τ decays, strategy: use kinematic and topological properties to suppress background components and measure signal and normalisation yields

$$\mathcal{R}(D^{*-}) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)} \times \frac{\mathcal{B}(B^0 \to D^{*-}3\pi)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

Systematic table from R(D*) hadronic, LHCb-PAPER-2017-017 , LHCb-PAPER-2017-027

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
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0
Total uncertainty	9.1

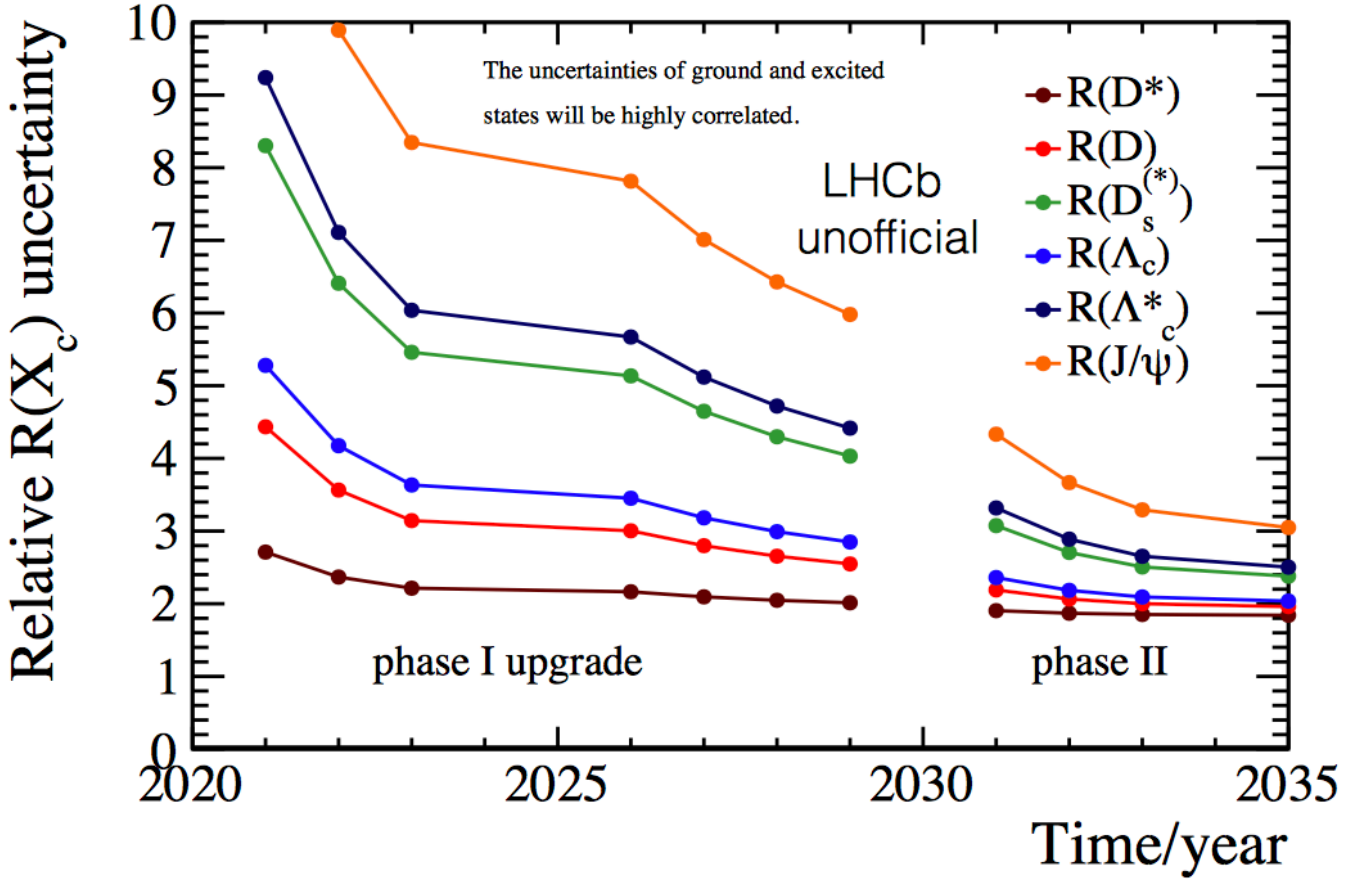
- Assume that all the systematics can be reduced with the size of the input data except for those that are conservatively not expected to scale or rely on external inputs

For the hadronic mode also efficiency and BF of normalisation mode will be relevant (input from Belle II/ BES II can help for the latter)

Projections (muonic + hadronic)

Brian Hamilton, Patrick Owen, Greg Ciezarek, Concezio Bozzi

- All hadron species can be used, different Form Factors, different NP sensitivities
- Production fractions and reconstruction efficiencies used to translate uncertainties



- Latest R(J/ψ) projection:
  - Assumption: Signal FF Lattice calculation within Upgrade I will allow to reduce by a factor of 2 the corresponding systematic
  - Absolute uncertainties for muonic mode: 0.075-0.080 end of Run-III, 0.05 end of Upgrade I, 0.02 end of Upgrade II (Run-I 0.25) PAPER-2017-035
  - Similar for the hadronic mode

- Phase-II will substantially benefit R(Xc) measurements of Bs, Λb0, Bc hadrons, not accessible at Belle II

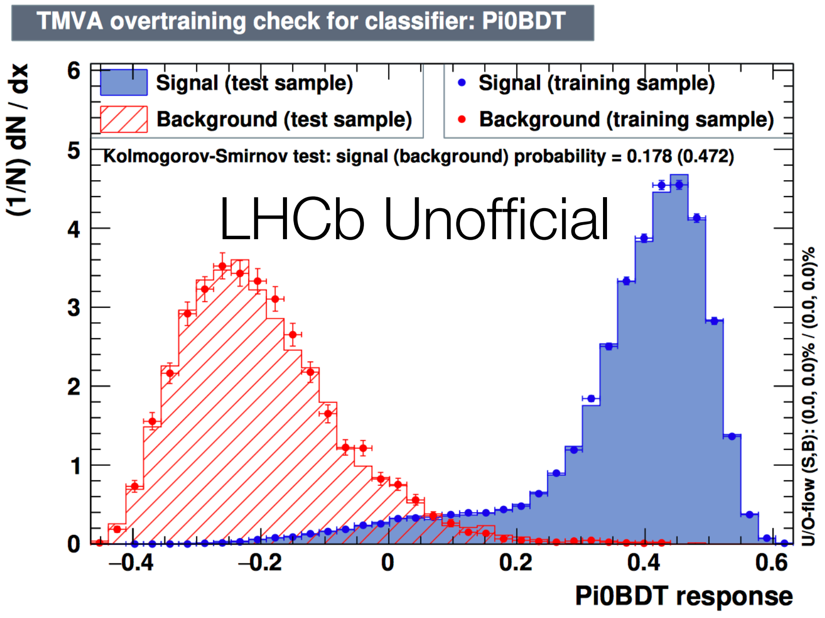
Reducing the correlation

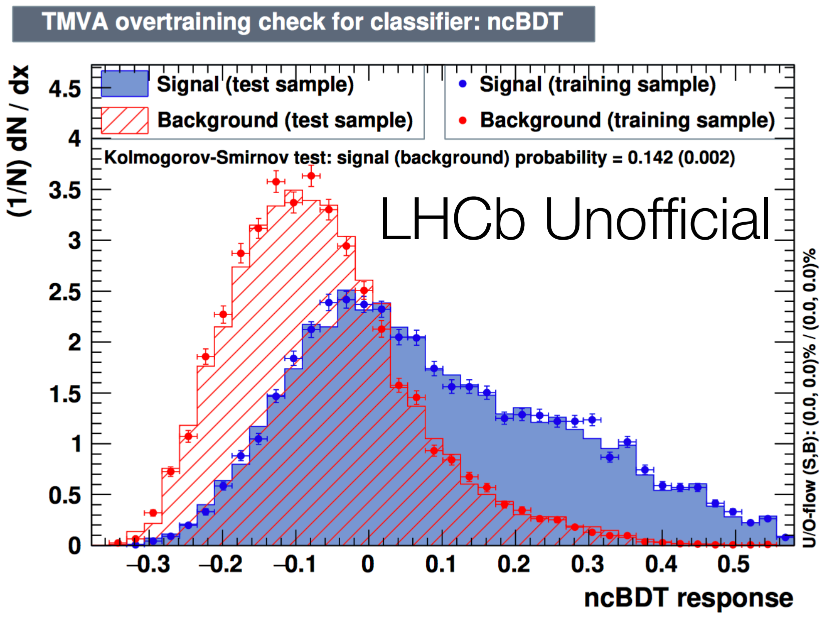
- Feed-down increases the correlation between R(Xc*) and R(Xc)
- To understand if R(Xc*) and R(Xc) are enhanced due to NP in the same, the correlation should be reduced/understood
- Better isolation can help. How to get better isolation?
  - Upgraded calorimeter would help reducing the feed-down from neutral signatures
  - Better vertex resolutions helps for the charged tracks isolation
  - Additional tracking station would help accepting/rejection soft pions

Neutral isolation

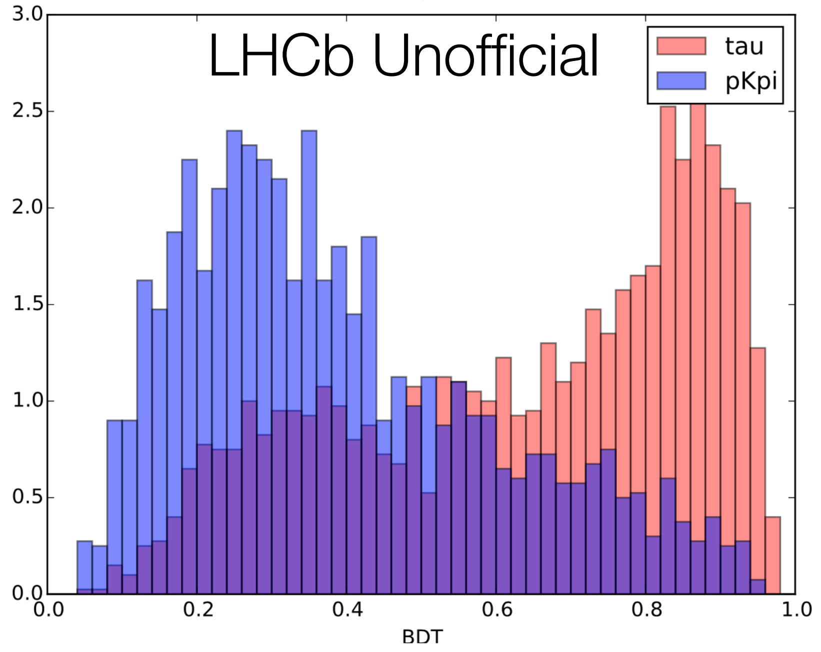
Julian Garcia Pardinas, Upgrade Calo 23/02/18,
Mark Smith SLWG 31/01/18

- Example of neutral isolation from R(D+) measurement to separate e.g. between B→D+μν and B→D*[→D+π^0]μν decays
- MVAs to Identify neutral pions from the signal, identify cones around the D+ direction that contain associated neutral candidates, combine the two





$B^+ \to p\bar{p}\tau^+\nu_\tau$, $B^+ \to p\Lambda_c^-\mu^+\nu_\mu$ with $\Lambda_c^- \to \bar{p}K^0\pi^0$



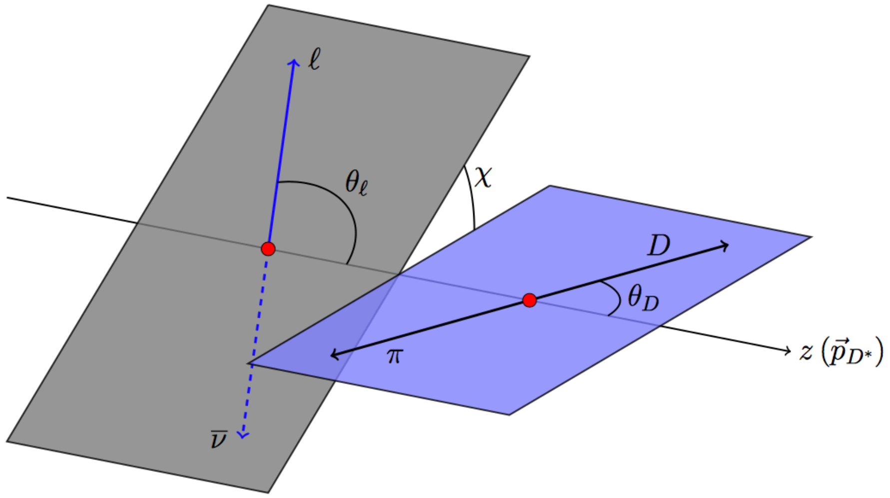
- Other example from R(p$\bar{p}$): BDT to find photons and neutral pions from the B
- In general not too bad separation, more a problem of efficiency (soft photons)
- Under investigation effects that impact efficiency

Additional decay modes and observables: semituonic Vub modes and angular analyses

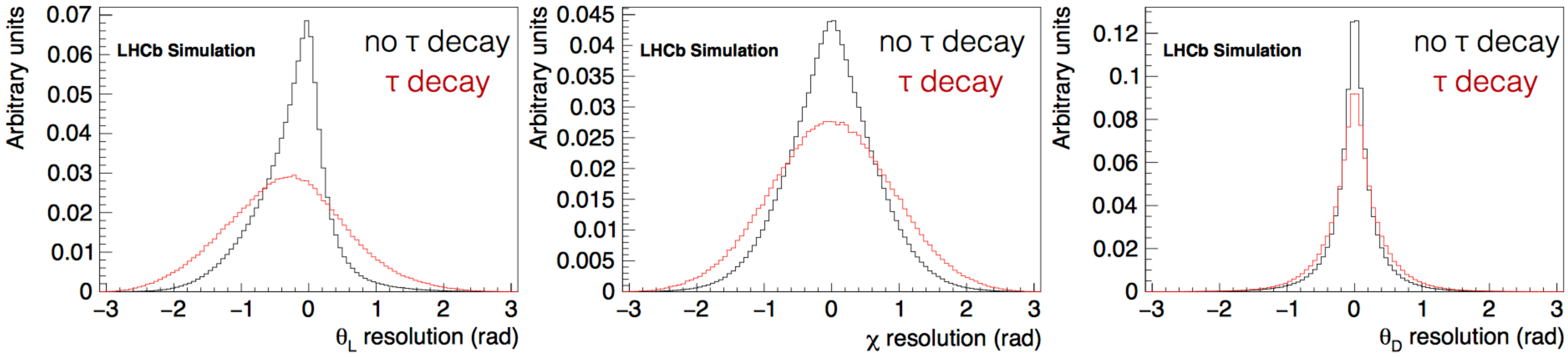
- By the end of Upgrade-II we can think about precision R(Xu) measurements, E.g. expect O(10k) $B \to p\bar{p}\tau\nu$ decays

- By the end of Upgrade-II we will have O(10M) B0->D*τν decays

- Possible to effort precision measurements of angular observables



- Hadronic and muonic analyses complement each other (purity versus efficiency, different sources of systematic uncertainties)



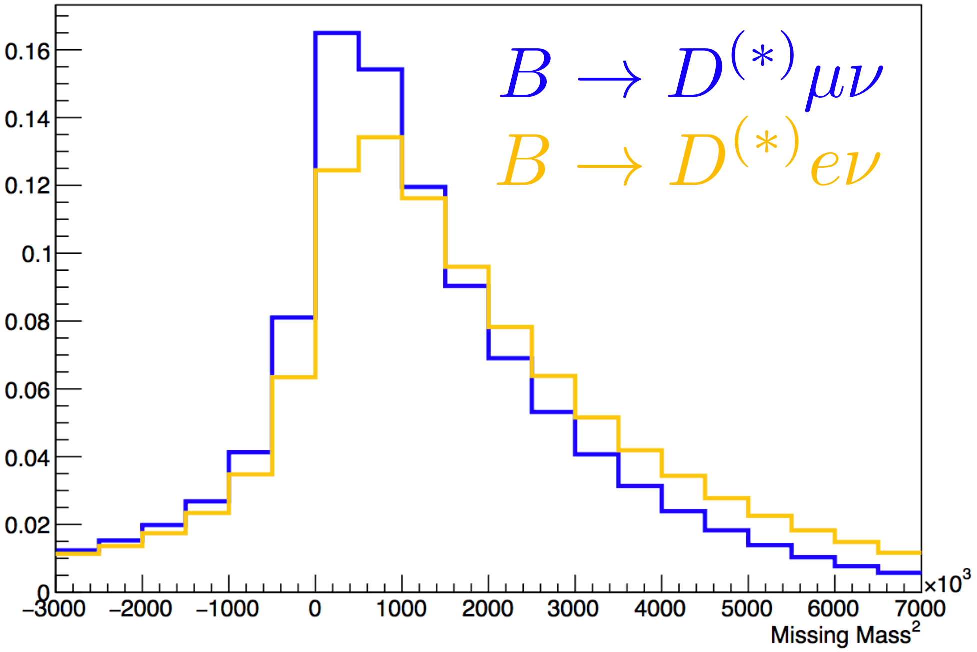
Additional observables: electrons

[Greg Ciezarek, A&S week 24/01/2018](#)

- Constraints on electron-muon universality in SL B from Belle (in |Vcb| measurements) consistent with R = 1 with precision of 4%.

- NP effects not widely studied, attempts to accommodate all B anomalies predict up to 2% deviations [A. Greljo, G. Isidori, D. Marzocca arXiv:1506.01705]

- Need to control efficiencies at sub-% level



- Foreseen single and double ratio measurements:

$$\mathcal{B}(B \to D^{(*)}\mu\nu)/\mathcal{B}(B \to D^{(*)}e\nu)$$

$$\boxed{\mathcal{B}(D^0 \to Ke\nu)/\mathcal{B}(D^0 \to K\mu\nu)}$$

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

- Ongoing for Run-II dataset, expected statistical precision ~0.2%, ongoing work on the systematics

- ECAL upgrade!

Summary

- Motivation for Upgrade II is strong if looking at SL measurements:
  - Most precise measurements for CPV in neutral meson mixing
  - Ultimate precision on |Vub| and |Vcb|
  - Unique programme for semitauonic decays
- We could profit from:
  - Upgraded ECAL: neutral isolation
  - RF foil removal: better vertex resolution improves signal resolution and background rejection
  - Tracking stations on magnet: acceptance of slow pions
  - [Computing: likely larger larger MC/data ratio, we also cannot save the full event… solutions to be found]
- We profit from keeping:
  - Reverse magnet polarity (ideally same luminosity, even though not possible…)
  - Large samples of CF charm decays
  - Good PID for soft muons and hadrons