Semileptonic b-hadron decays at LHCb

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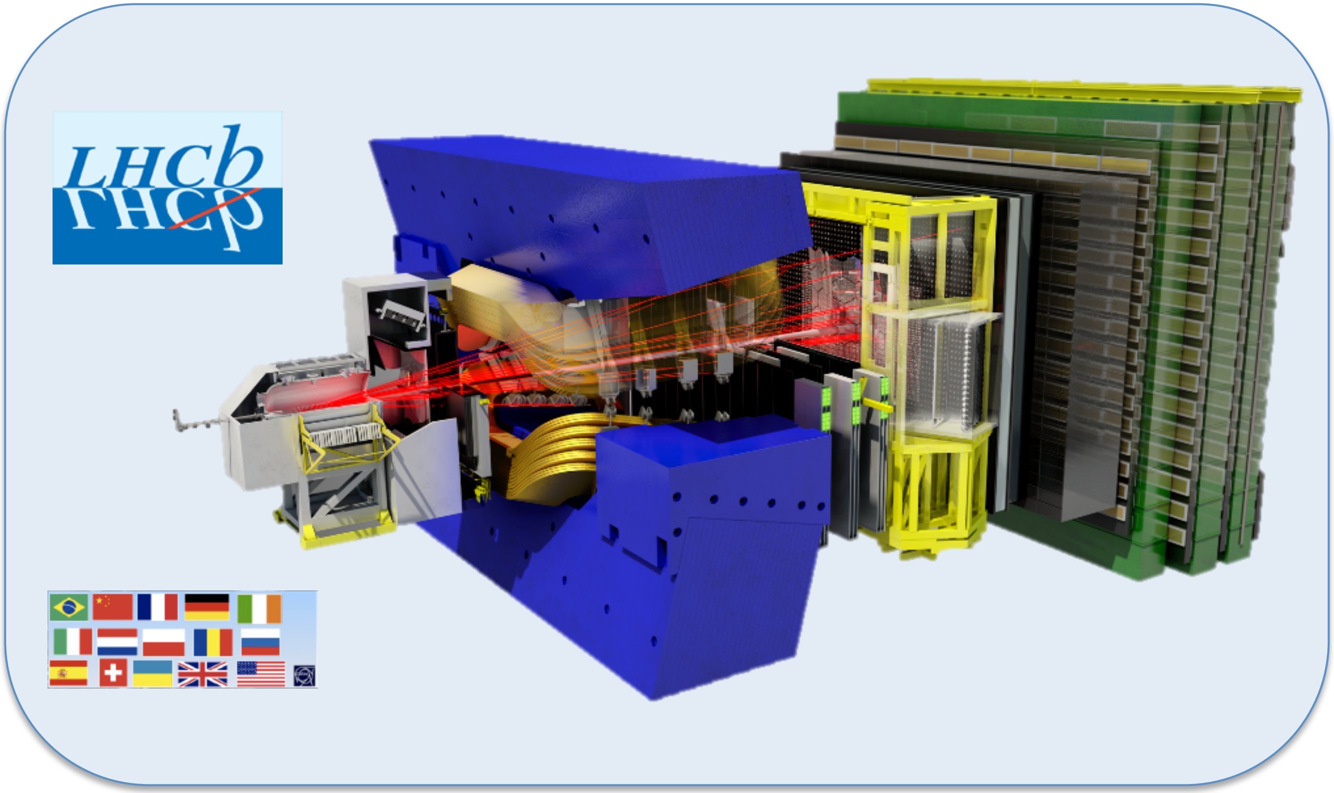
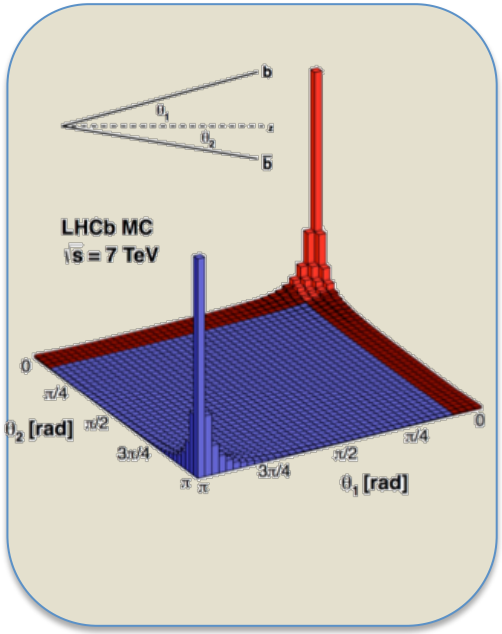
Neckarzimmern, March 17th 2016

Outline

- The LHCb detector and its current and foreseen datasets
- Recent results on
  - B^0 oscillation frequency Δm_d
  - Semileptonic asymmetries a_{sl}^s, a_{sl}^d
  - CKM matrix element $|V_{ub}|$
  - semi-tauonic $B \rightarrow D^* \tau \nu$ decays
- Outlook

Designed to study *b* and *c* decays





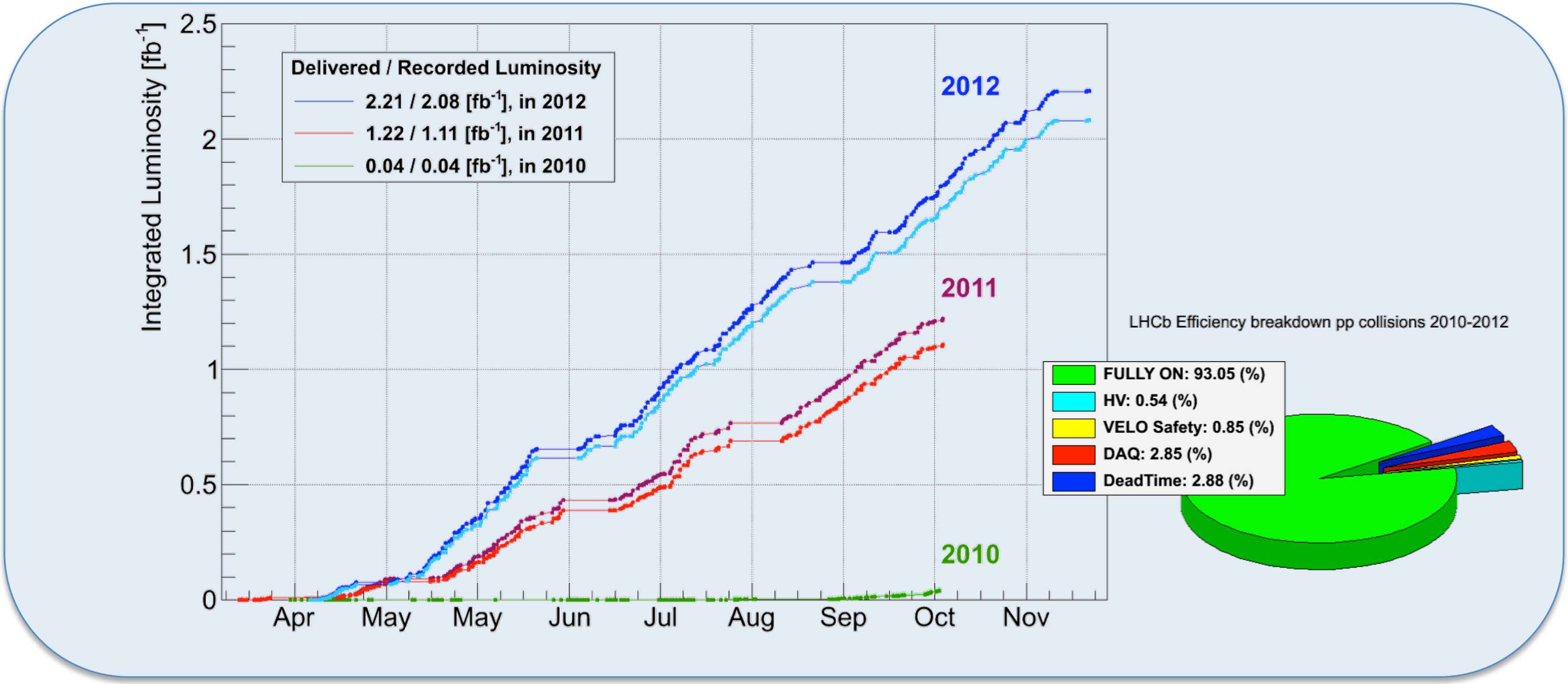
All *b*-hadrons produced
B^0, B^+, B_s, B_c, Λ_b, ...

Large production of beauty quarks:

$$\sigma(pp \to b\bar{b}X) = (284 \pm 20 \pm 49)\mu\mathrm{b} \quad @ \quad \sqrt{s} = 7\,\mathrm{TeV}$$

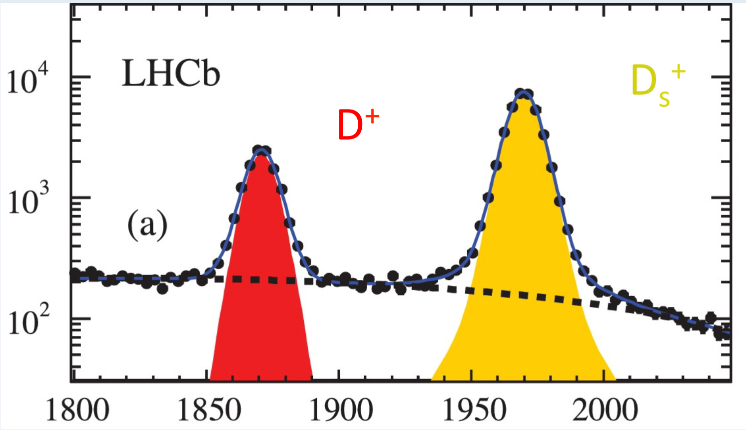
Phys. Lett. B 694 (2010) 209 (obtained from semileptonic decays).

Excellent performance

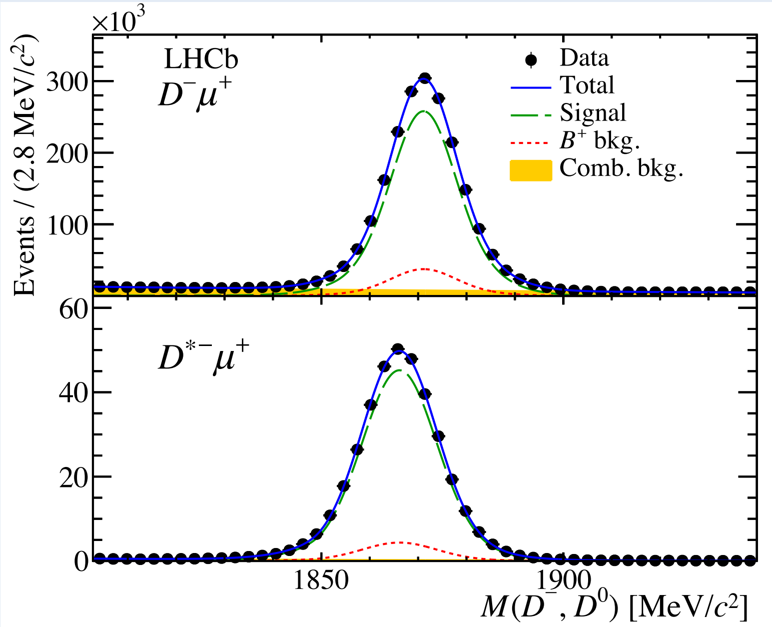


- 3/fb collected in run 1 at 7-8 TeV.
- Expect to collect another 5/fb in run 2. Collected 0.3/fb in 2015. LHC says 2016 is going to be a “luminosity year”
  - Note that at 13 TeV *bb* cross-section roughly doubles.
  - i.e. 4 times larger data sample than current.

Large and clean samples



[LHCb: PLB 728 (2014) 607-615]

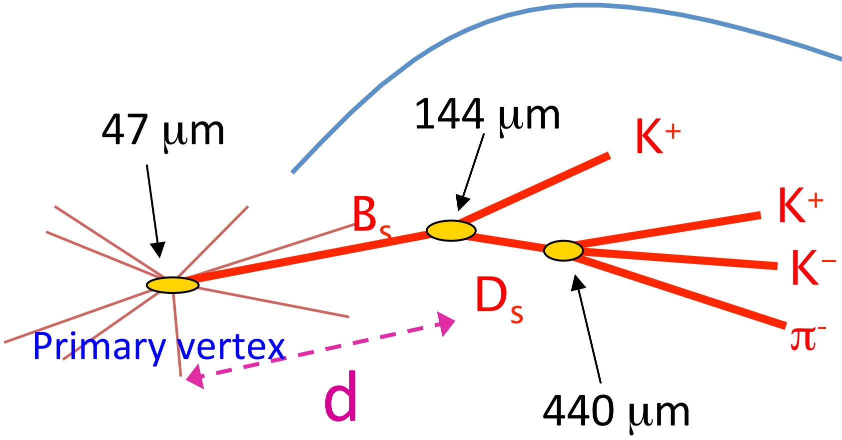


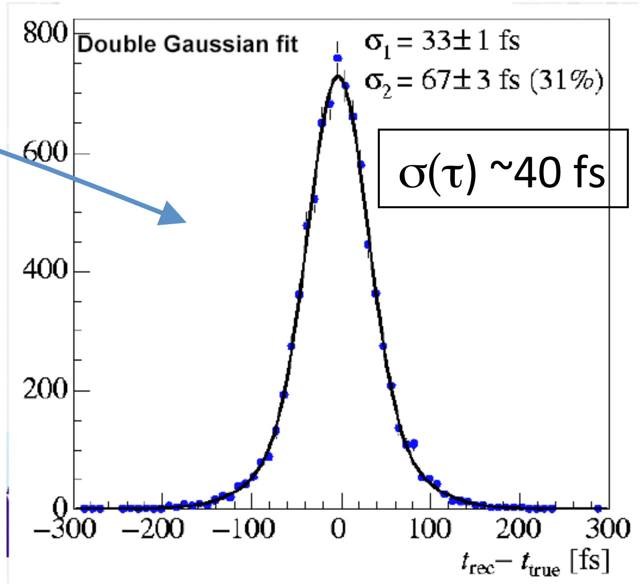
[LHCb: PRL 114, 041601 (2015)]

Millions of *B* candidates available.

Excellent vertex separation

Example: Bs → Ds K



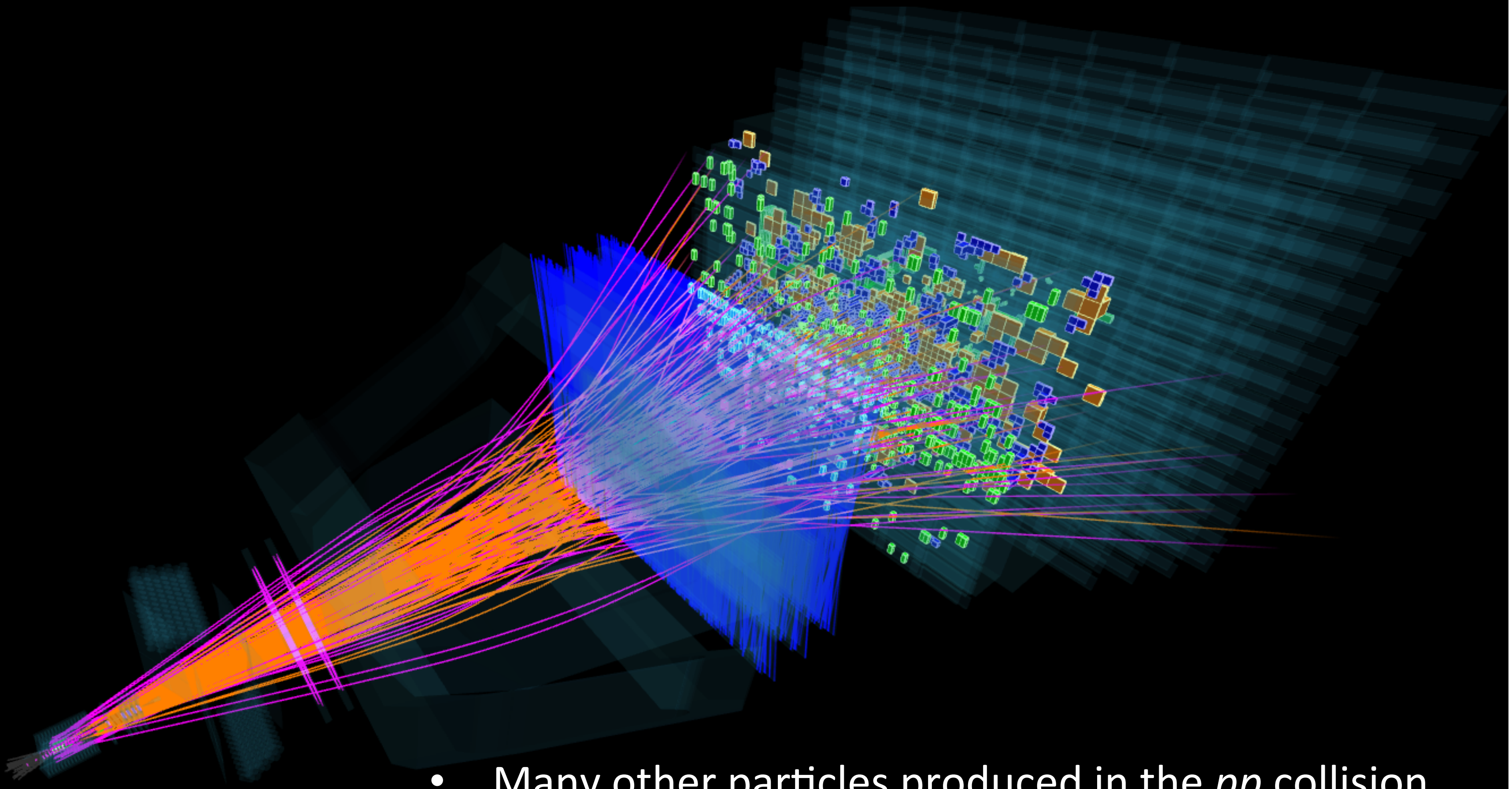


$\sigma(\tau)$ ~40 fs

Decay time resolution = 40 fs

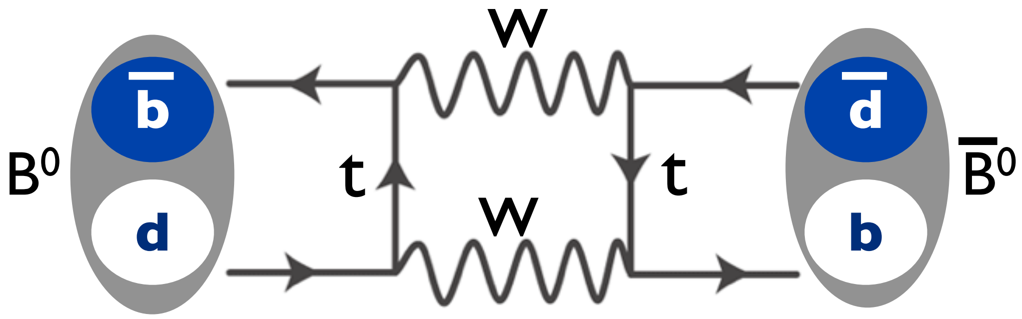
- Note: $t = d * m_B / p_B$
- p_B unknown in semileptonic decays, due to missing neutrino!

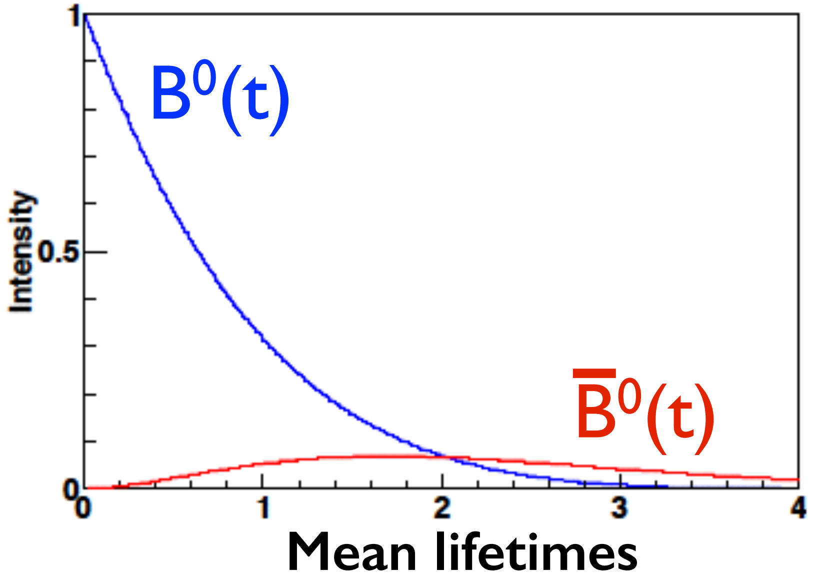
But… “dirty” hadronic enviroment



- Many other particles produced in the *pp* collision.
  - No possibility to use beam energy constraints.
- No kinematic constraints from other (tagging) *B*.
  - Also *b*-hadron production fractions poorly known.

Neutral meson mixing





Neutral meson mixing

- Time evolution of Schrödinger equation

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}^0(t)\rangle \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}^0(t)\rangle \end{pmatrix}$$

- "heavy" and "light" mass eigenstates:

$$|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$$

- With different masses and decay widths

$$\Delta m = m_H - m_L$$
$$\Delta\Gamma = \Gamma_L - \Gamma_H$$

- Probability to find anti-matter at time t in a "matter beam"

$$\propto e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\left(\Delta m t\right)\right]$$

Neutral meson mixing

- Mixing asymmetry

$$A(t) = \frac{N^{unmix}(t) - N^{mix}(t)}{N^{unmix}(t) + N^{mix}(t)} = \frac{\cos(\Delta m_d t)}{\cosh(\Delta\Gamma_d t/2)} + \frac{a}{2}\left[1 - \frac{\cos^2(\Delta m_d t)}{\cosh^2(\Delta\Gamma_d t/2)}\right]$$

$\Delta\Gamma_d \sim 0$

$a = 1 - \left|\frac{q}{p}\right|$

CP violation in mixing ~10^{-4}

Neutral meson mixing

- Mixing asymmetry

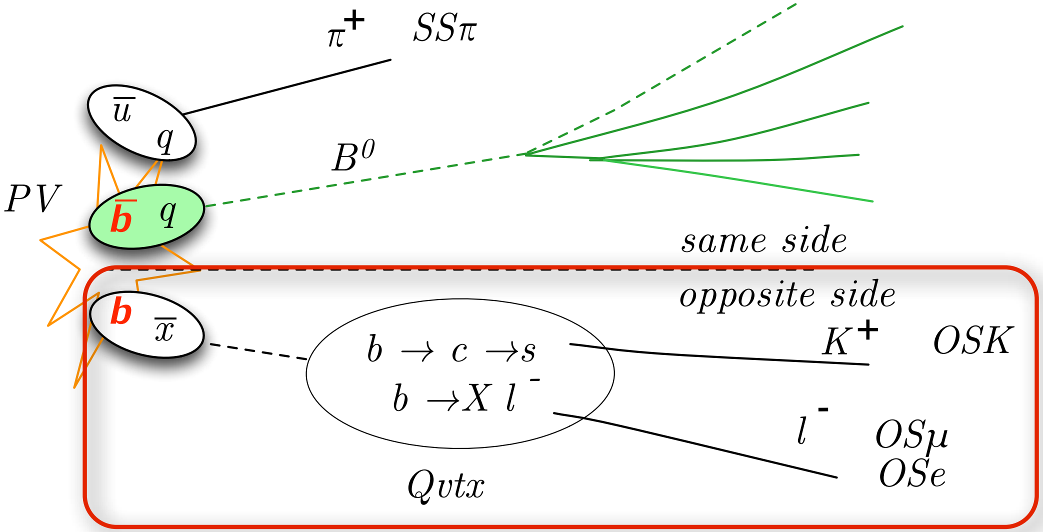
$$A(t) = \frac{N^{unmix}(t) - N^{mix}(t)}{N^{unmix}(t) + N^{mix}(t)} = \cos(\Delta m_d t)$$

Neutral meson mixing

- Mixing asymmetry

$$A(t) = \frac{N^{unmix}(t) - N^{mix}(t)}{N^{unmix}(t) + N^{mix}(t)} = \cos(\Delta m_d t) \times \mathbf{(1\text{-}2\omega)}$$

- **Flavour tagging** $\mathcal{P} = \epsilon_{tag}(1 - 2\omega)^2 \sim 2.4\%$

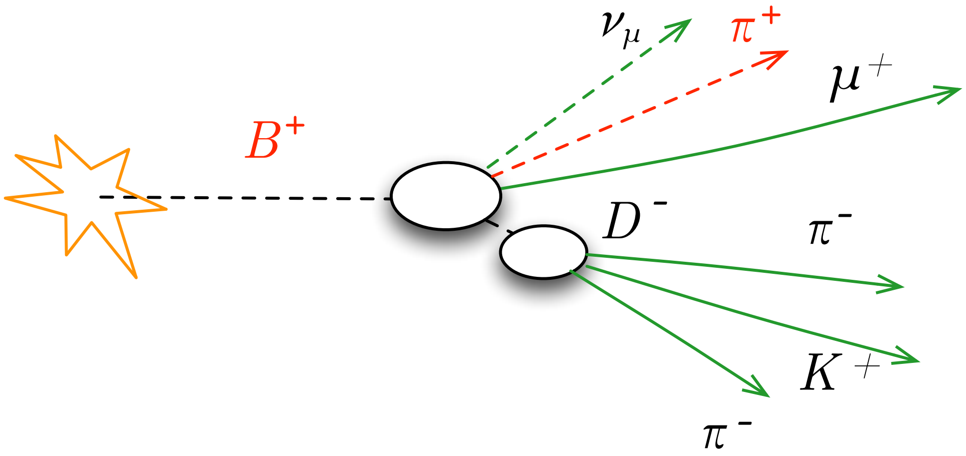


Neutral meson mixing

- Mixing asymmetry

$$A(t) = \frac{N^{unmix}(t) - N^{mix}(t)}{N^{unmix}(t) + N^{mix}(t)} = \cos(\Delta m_d t) \times (1\text{-}2\omega) + A_{B+}$$

- Flavour tagging
- Rejection of $B^+ \to D^{(*)-}\mu^+\nu_\mu X^+$ **background**



Neutral meson mixing

- Mixing asymmetry

$$A(t) = \frac{N^{unmix}(t) - N^{mix}(t)}{N^{unmix}(t) + N^{mix}(t)} = \left[\cos(\Delta m_d t) \times (1\text{-}2\omega) + A_{B+}\right] \boxed{\otimes_t R(t)}$$

- Flavour tagging
- Rejection of $B^+ \to D^{(*)-}\mu^+\nu_\mu X^+$ background
- **Decay time reconstruction**

Decay time reconstruction

- Using semileptonic $B^0 \to D^{(*)-}\mu^+\nu_\mu X$ decays

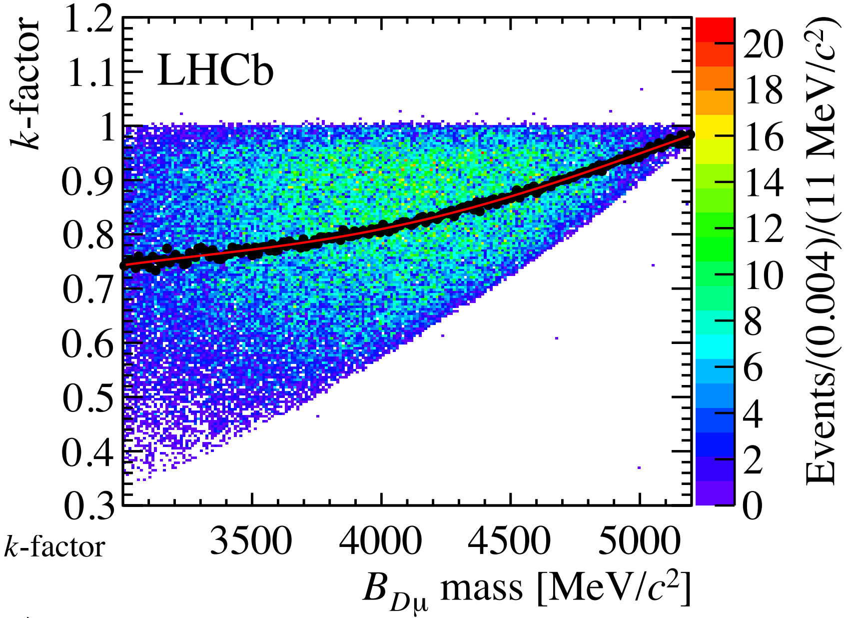
- The B momentum is inferred from the reconstructed on by means of a statistical correction taken from simulation

$$t = \frac{L \cdot M_{PDG}}{|\vec{p}|} \cdot k_{av}(M)$$

Reconstructed mass

Reconstructed momentum

$$k = p_{reco}/p_{true}$$



- The k-factor is also used to model the decay time resolution

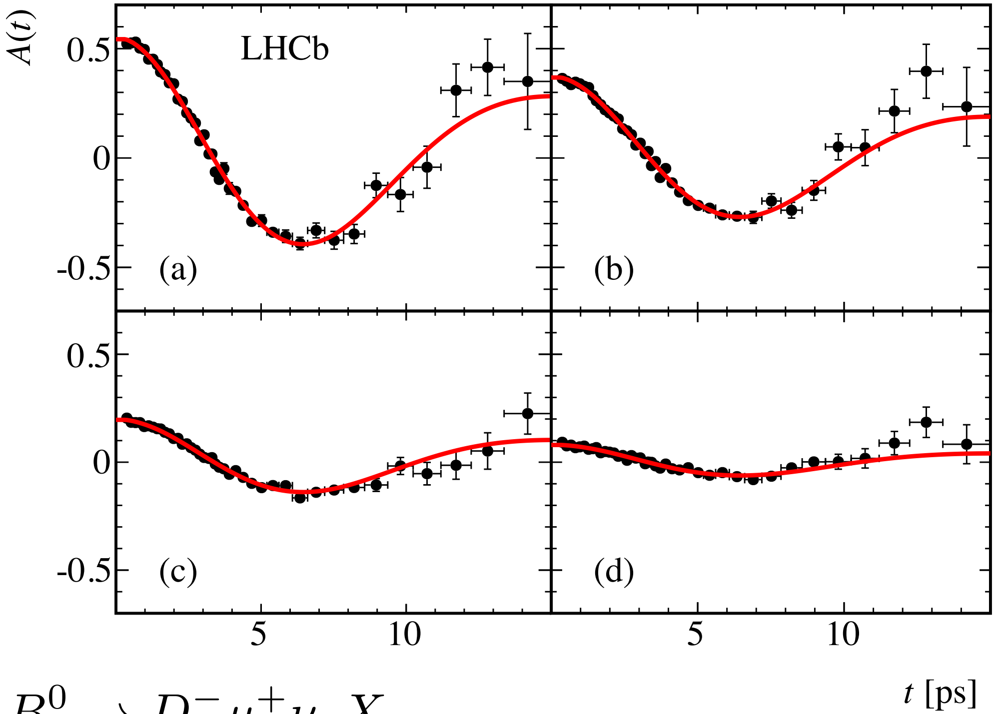
Corrected k-factor

$$\mathcal{P}_{sig} = \boxed{(T(t) \otimes_t R(t) \otimes_k F(k))} \cdot A(t)$$

LHCb-PAPER-2015-031

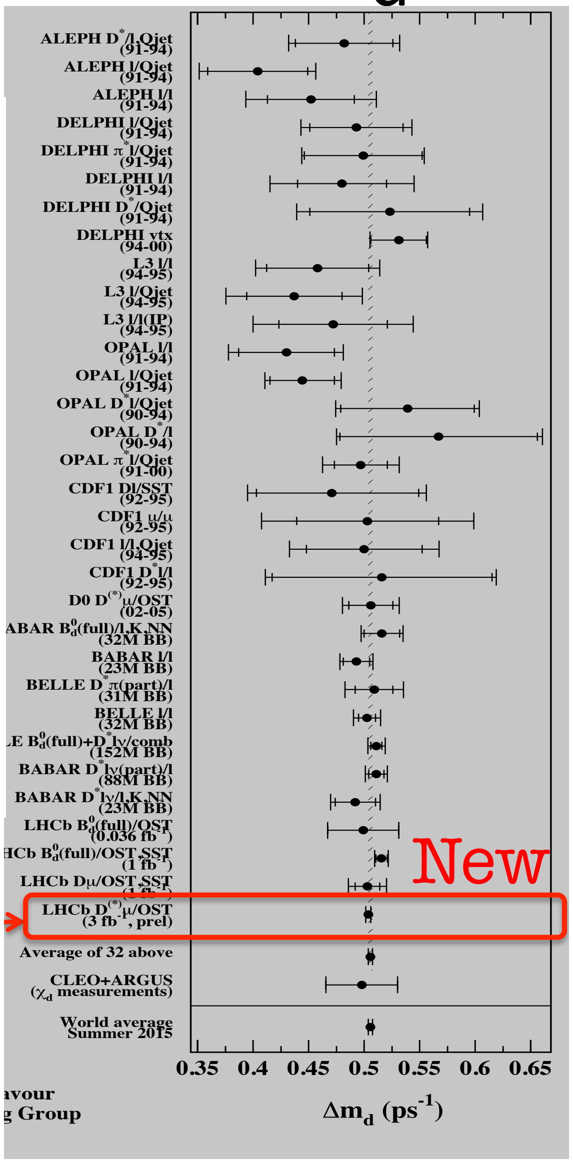
Precision measurement of Δm_d

- Fit to the time distributions in four bins of increasing mistag probability



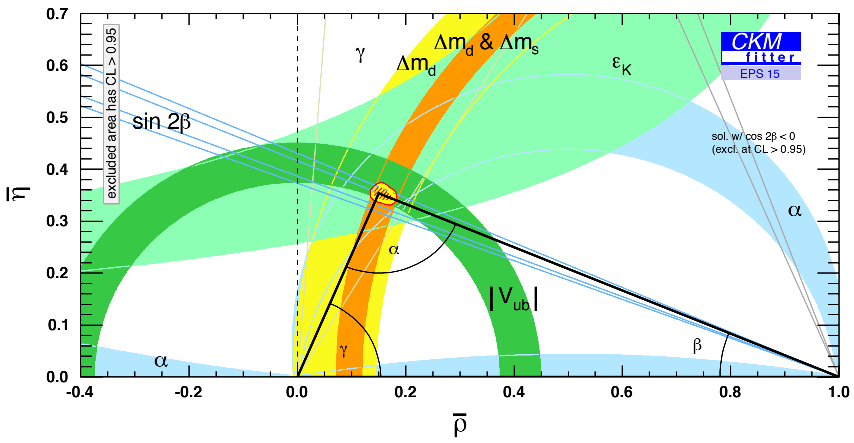
$B^0 \to D^- \mu^+ \nu_\mu X$

$$\Delta m_d = (505.0 \pm 2.1\,(\mathrm{stat}) \pm 1.0\,(\mathrm{syst}))\ \mathrm{ns}^{-1}$$



Constraints on CKM UT

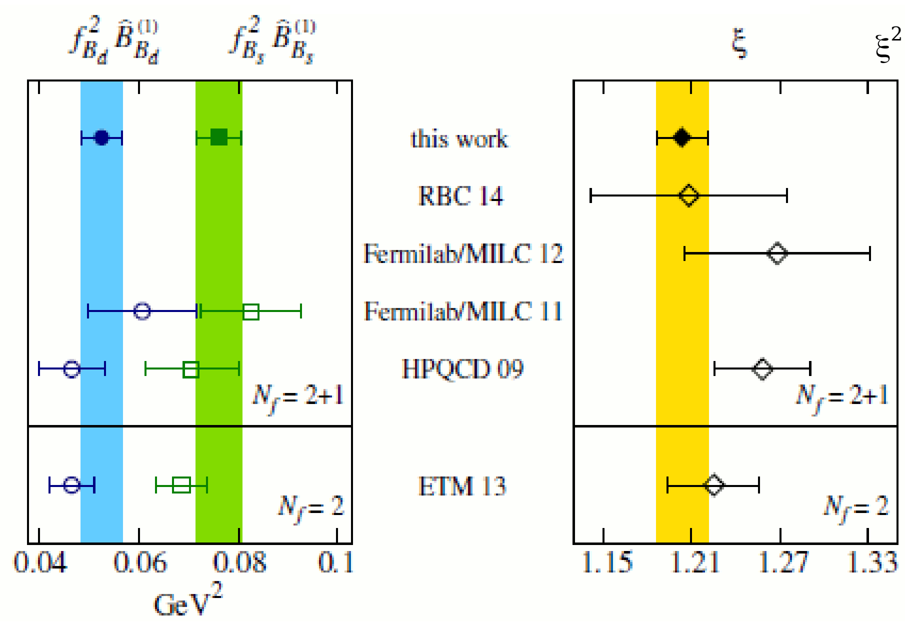
$$\Delta m_q = \frac{G_F^2 m_W^2 M_{B_q}}{6\pi^2} S_0(x_t)\eta_{2B} |V_{tq}^* V_{tb}|^2 f_{B_q}^2 \hat{B}_{B_q}^{(1)}$$



- High experimental precision somewhat "swamped" by hadronic uncertainties

- Recent results from Lattice QCD pave the way for tightening the mixing constraints on the unitarity triangle

FNAL/MILC
arXiv:1602.03560



$$\xi^2 = \frac{f_{B_s}^2 \hat{B}_{B_s}^{(1)}}{f_{B_d}^2 \hat{B}_{B_d}^{(1)}}$$

Neutral meson mixing

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- “heavy” and “light” mass eigenstates:

$$|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$$

- With different masses and decay widths

$$\Delta m = m_H - m_L$$
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- Probability to find anti-matter at time t in a “matter beam”

$$\propto e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\left(\Delta m t\right)\right]$$

Neutral meson mixing

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- “heavy” and “light” mass eigenstates:

$$|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$$

- With differ decay widt

$$\cos(\Delta m t)\Big]$$

- Probability matter at t beam”

Are they CP eigenstates?

$$a = 1 - \left|\frac{q}{p}\right|$$

Measures
CP violation in mixing

$$\mathcal{P}(\bar{B}\rightarrow B) \neq \mathcal{P}(B\rightarrow \bar{B})$$

CP Violation in mixing

- CP-violating semi-leptonic asymmetry

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

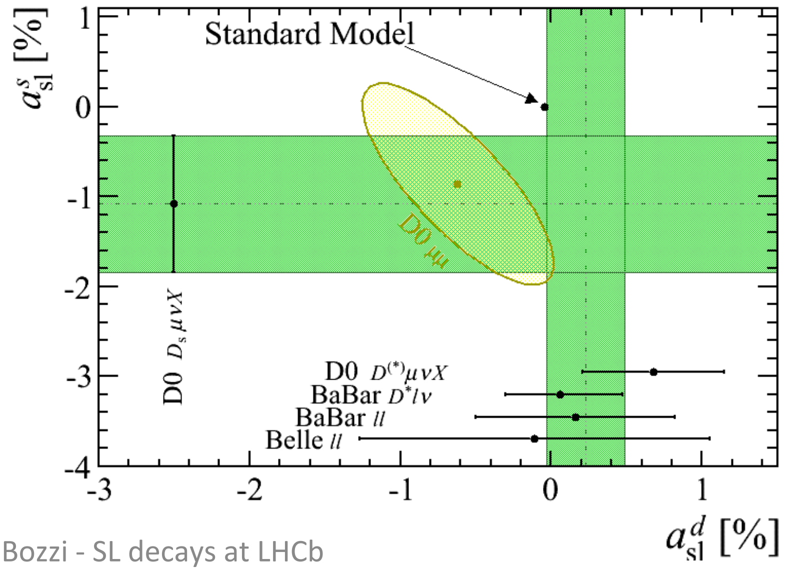
- SM prediction

A. Lenz, 2012, 1205.1444 [hep-ph]

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

TINY!!!

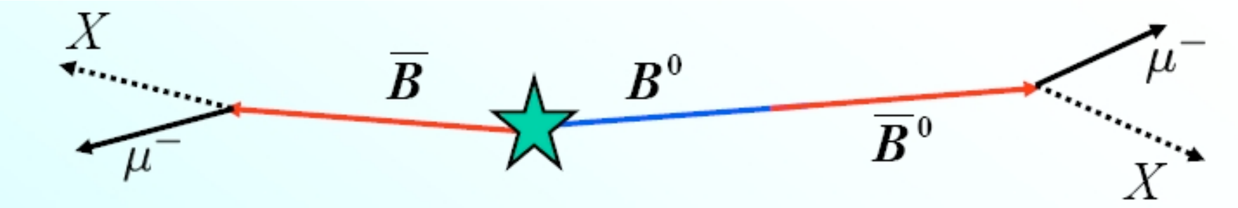
- Experimental status before LHCb



How to measure?

$$a_{\mathrm{sl}} = \frac{N(\bar{B}\to B \to f) - N(B\to\bar{B} \to \bar{f})}{N(\bar{B}\to B \to f) + N(B\to\bar{B} \to \bar{f})}$$

- Inclusive like-sign dilepton asymmetry



$$A_{\ell\ell} \equiv \frac{\Gamma(\ell^+\ell^+) - \Gamma(\ell^-\ell^-)}{\Gamma(\ell^+\ell^+) + \Gamma(\ell^-\ell^-)} = a_{\mathrm{sl}}$$

How to measure?

$$a_{\rm sl} = \frac{N(\bar{B}\rightarrow B \rightarrow f) - N(B\rightarrow \bar{B} \rightarrow \bar{f})}{N(\bar{B}\rightarrow B \rightarrow f) + N(B\rightarrow \bar{B} \rightarrow \bar{f})}$$

- Untagged asymmetry (used by LHCb)

$$A_{\rm meas}(t) = \frac{\Gamma(f,t) - \Gamma(\bar{f},t)}{\Gamma(f,t) + \Gamma(\bar{f},t)} = \frac{a^q_{\rm sl}}{2} - \frac{a^q_{\rm sl}}{2}\,\frac{\cos(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2)}$$

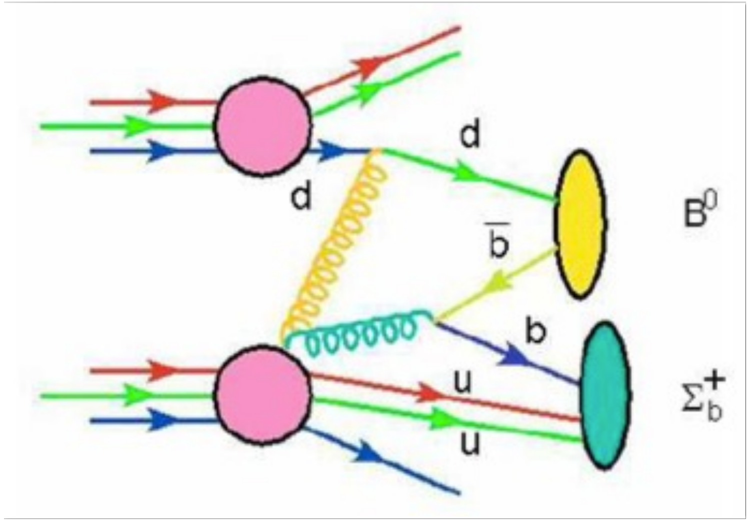
→ oscillating asymmetry as function of decay time

→ no need to know the flavour of the B meson at production

Spurious asymmetries

- Production asymmetry (~1%)

$$A_{\mathrm{P}} = \frac{\sigma(\bar{B}) - \sigma(B)}{\sigma(\bar{B}) + \sigma(B)}$$



$$A_{\mathrm{meas}}(t) = \frac{\Gamma(f,t) - \Gamma(\bar{f},t)}{\Gamma(f,t) + \Gamma(\bar{f},t)} = \frac{a^d_{\mathrm{sl}}}{2} - \left(A_{\mathrm{P}} + \frac{a^d_{\mathrm{sl}}}{2}\right)\frac{\cos(\Delta m_d t)}{\cosh(\Delta\Gamma_d t/2)}$$

Spurious asymmetries

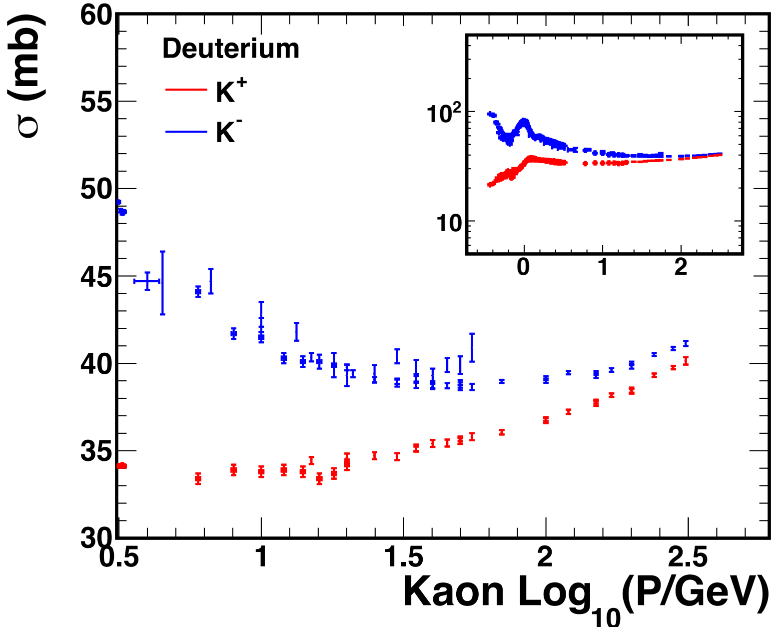
- Production asymmetry (~1%)

$$A_\mathrm{P} = \frac{\sigma(\bar{B}) - \sigma(B)}{\sigma(\bar{B}) + \sigma(B)}$$

- Detection asymmetries

$$A_D = \frac{\varepsilon(f) - \varepsilon(\overline{f})}{\varepsilon(f) + \varepsilon(\overline{f})}$$

Kaon detection asymmetry of ~ 10^{-2}

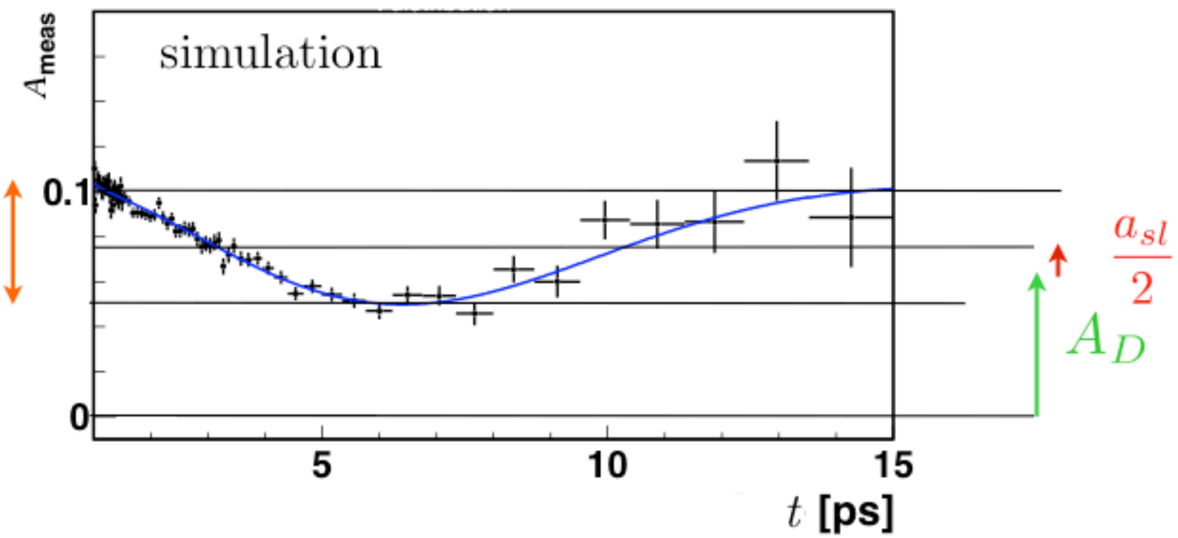


$$A_\mathrm{meas}(t) = \frac{\Gamma(f,t) - \Gamma(\bar{f},t)}{\Gamma(f,t) + \Gamma(\bar{f},t)} = \frac{a_\mathrm{sl}^d}{2} + \boxed{A_\mathrm{D}} - \left(A_\mathrm{P} + \frac{a_\mathrm{sl}^d}{2}\right)\frac{\cos(\Delta m_d t)}{\cosh(\Delta\Gamma_d t/2)}$$

Time-dependent a_{sl}

- Time-dependent fit to disentangle the *CP* violating asymmetry from the *B0* production asymmetry
- Independent determination of the detection asymmetries with control samples

$$-2(A_p + \frac{a_{sl}}{2})$$



$$A_{\rm P} = \frac{\sigma(\bar{B}) - \sigma(B)}{\sigma(\bar{B}) + \sigma(B)}$$

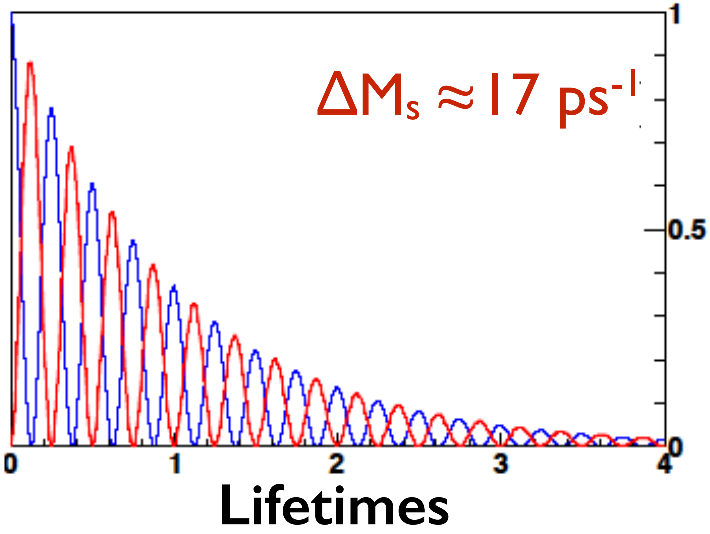
$$A_{\rm meas}(t) = \frac{\Gamma(f,t) - \Gamma(\bar{f},t)}{\Gamma(f,t) + \Gamma(\bar{f},t)} = \frac{a^d_{\rm sl}}{2} + A_{\rm D} - \left(A_{\rm P} + \frac{a^d_{\rm sl}}{2}\right)\frac{\cos(\Delta m_d t)}{\cosh(\Delta\Gamma_d t/2)}$$

“Simpler” for a_{sl}^{s}

- Time-integrated, untagged asymmetry

$$A_{\mathrm{meas}} = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})} = \frac{a_{\mathrm{sl}}^{s}}{2} + A_{\mathrm{D}} - \underbrace{\left(A_{\mathrm{P}} + \frac{a_{\mathrm{sl}}^{s}}{2}\right) \frac{\int e^{\Gamma_s t} \cos(\Delta m_s t)\epsilon(t)dt}{\int e^{\Gamma_s t} \cosh(\Delta\Gamma_s t/2)\epsilon(t)dt}}_{\sim 10^{-4}}$$

Effect of A_P is washed out by fast oscillations



“Simpler” for a_{sl}^{s}

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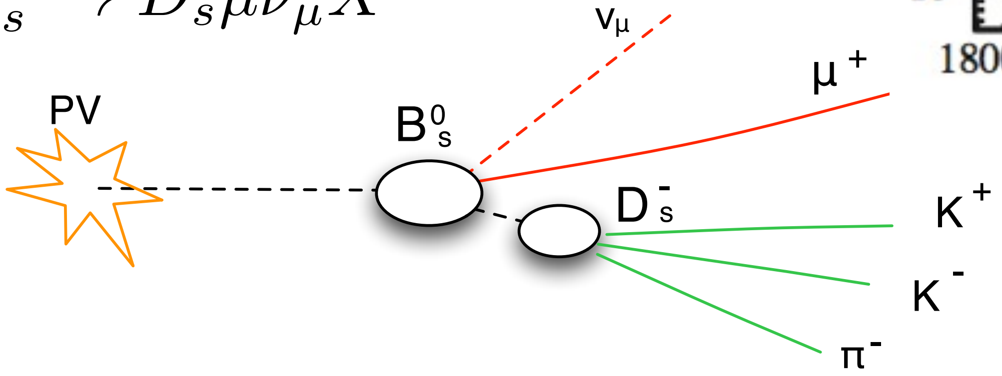
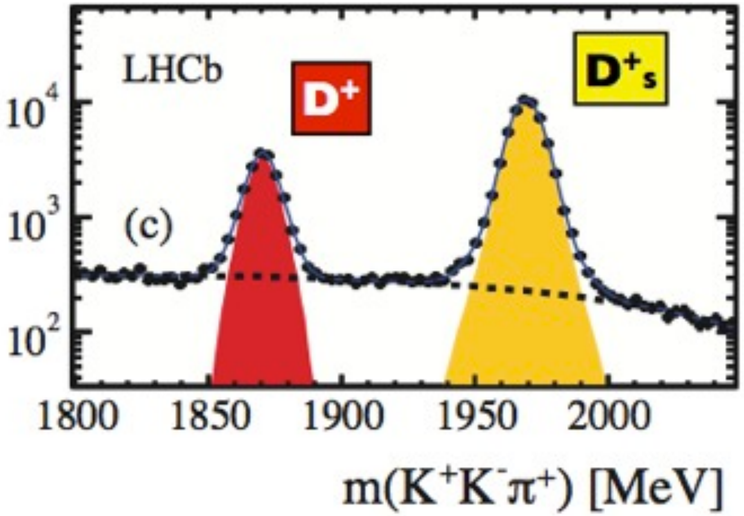
$$A_{\mathrm{meas}} = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})} = \frac{a_{\mathrm{sl}}^{s}}{2} + \boxed{A_{\mathrm{D}}}$$

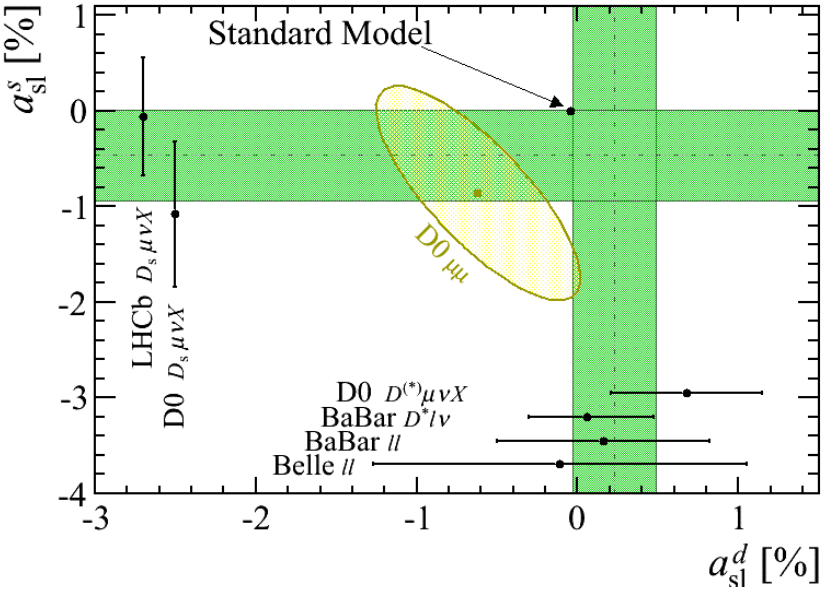
$$B_s^0 \to D_s \mu \nu_\mu X$$





- Main problem is detection asymmetry.
- Restrict to the ϕ→KK resonance: only $\mu^\pm\pi^\mp$ asymmetry contributes.

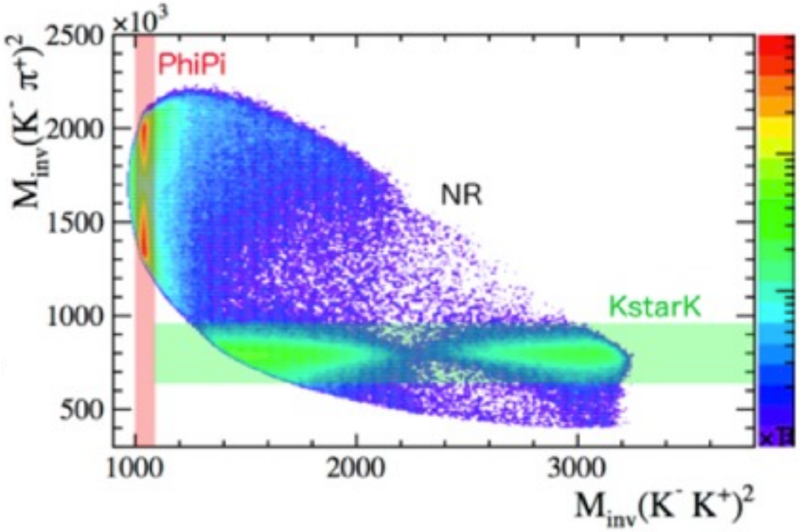
a_{sl}^{s} with 1fb^{-1}



$a_{sl}^{s} = (-0.06 \pm 0.50_{stat} \pm 0.36_{syst})\%$

Source	δ (%)
Tracking asymmetries	0.26
Muon asymmetries	0.16
Fitting	0.15
Backgrounds	0.10
Quadratic sum	0.36

- Measurement being updated to 3fb^{-1} using full KKπ Dalitz region

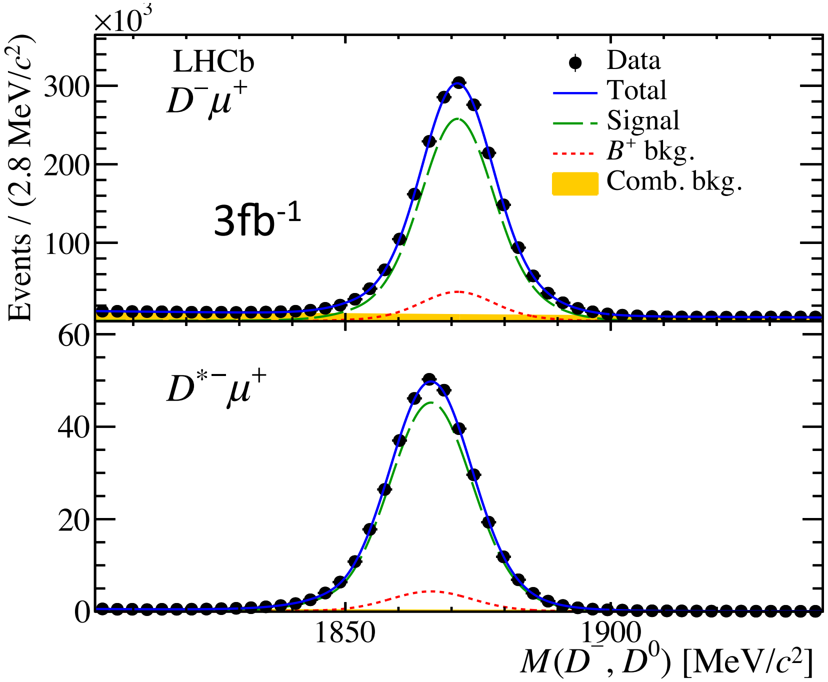


Measurement of a_{sl}^{d}

Plenty of candidates!

$B^0 \to D^{\pm}\mu^{\mp}\nu_{\mu}$ 1.8M

$B^0 \to D^{*\pm}\mu^{\mp}\nu_{\mu}$ 0.34M



Challenges:

- Detection asymmetry for the $\mu^{\pm}\pi^{\mp}K^{\pm}\pi^{\mp}$ final state
- Determination of B momentum → k-factor
- Background from charged B and baryon decays

$$B^+ \to D^{(*)-}\mu^+X^+$$

$$\Lambda_b^0 \to D^{(*)-}\mu^+X_n$$

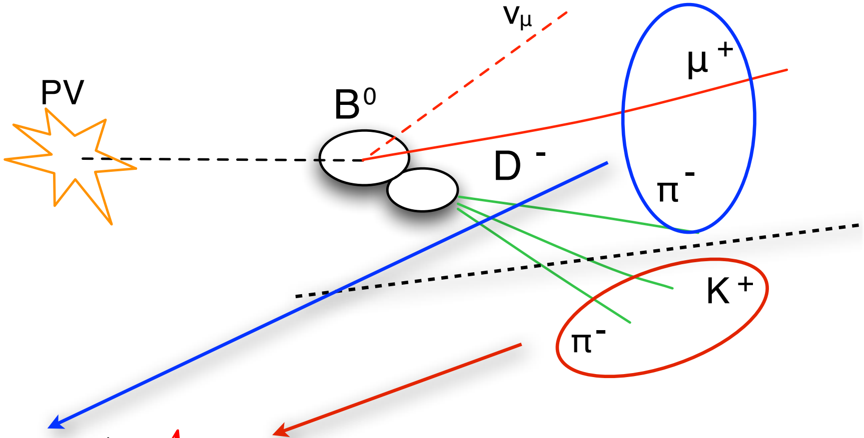
  - Normalization from simulation and measured BFs
  - production asymmetry from other measurements

$A_{\mathrm{P}}(B^+) = (-0.6 \pm 0.6)\%$ B+→J/ψK+

$A_{\mathrm{P}}(\Lambda_b^0) \sim (-0.9 \pm 1.5)\%$ $\Lambda_b^0 \to J/\psi p K^+$

Detection asymmetry

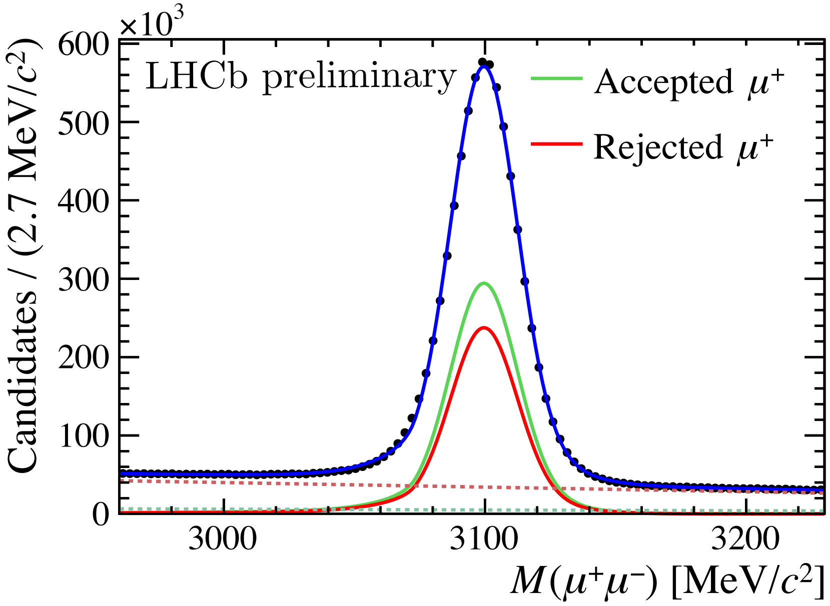
$$A_{\mathrm{D}} = \frac{\epsilon(\mu^+K^+\pi^-\pi^-) - \epsilon(\mu^-K^-\pi^+\pi^+)}{\epsilon(\mu^+K^+\pi^-\pi^-) + \epsilon(\mu^-K^-\pi^+\pi^+)}$$

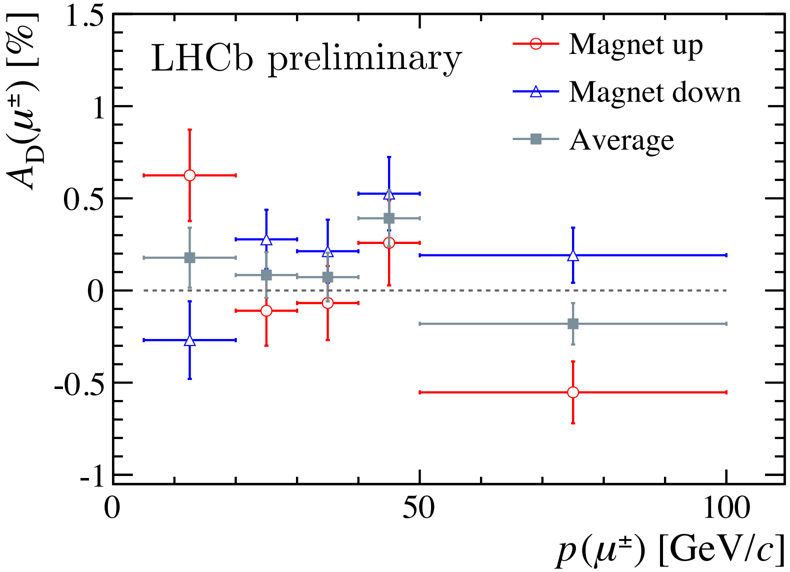


- Split into $A_D = A_{\mu\pi} + A_{K\pi}$
- Sources of asymmetry
  - Detector inefficiencies/misalignments/inhomogeneities
  - Different interaction with detector material (nuclear interactions…)
- Use control samples

Detection asymmetry: $A_{\mu\pi}$

- Tracking efficiencies depend on transverse momentum
  - Reweight data sample to obtain a good overlapping kinematic phase space between μ and π. Effective sample size reduced by factor ~0.8
- Muon-ID and trigger asymmetries: use tag-and-probe method on J/ψ→μμ decays





Overall uncertainty 0.04%

Detection asymmetry: $A_{K\pi}$

- Use prompt D^+ decays into $K\pi\pi$ and $K_S\pi$

$$
\begin{aligned}
A_{K\pi} \equiv{}& \frac{\epsilon(K^+\pi^-) - \epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-) + \epsilon(K^-\pi^+)} \\
={}& A(D \to K\pi\pi) \\
&- A(D \to K_S\pi) \\
&- A(K_S)
\end{aligned}
$$

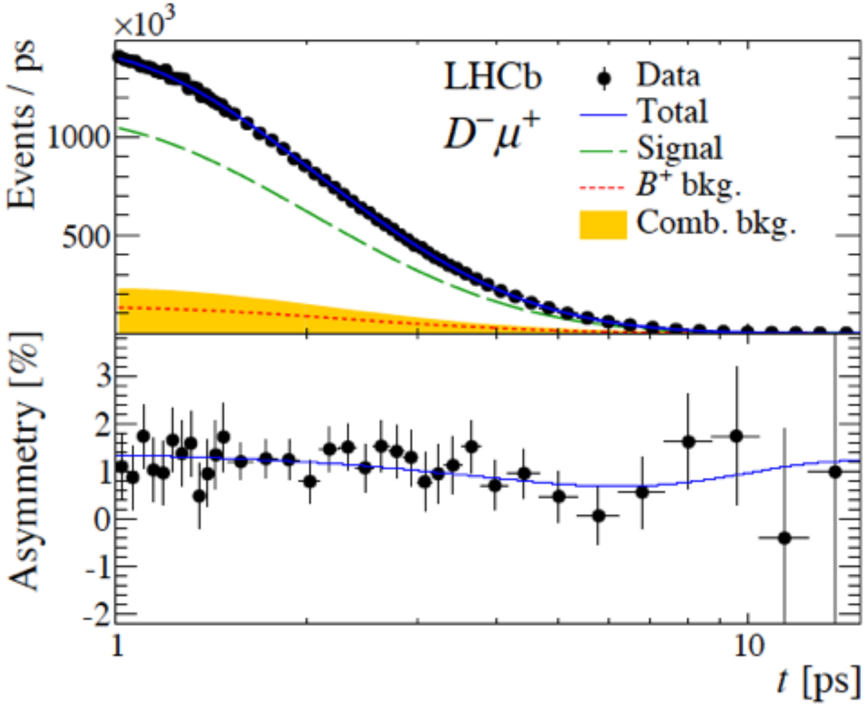
- Several kinematical re-weightings needed
- $A(K_S) = (0.054 \pm 0.011)\%$ [JHEP 07 (2014) 041]

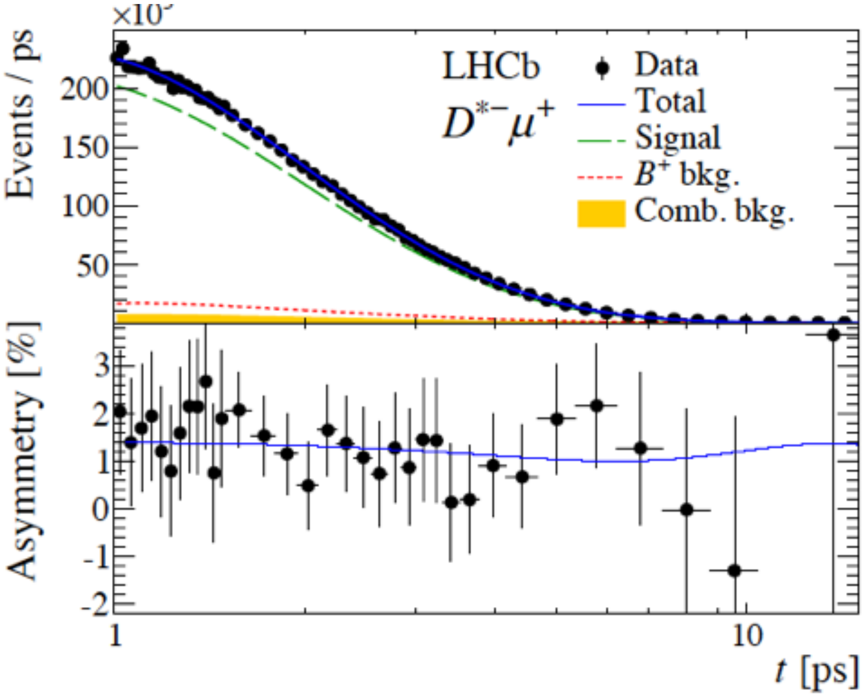
$$A_{K\pi} = (1.15 \pm 0.08(\mathrm{stat}) \pm 0.07(\mathrm{syst}))\%$$

Reweighted (for the D+ mode)

largest systematic uncertainty on a_{sl}^d

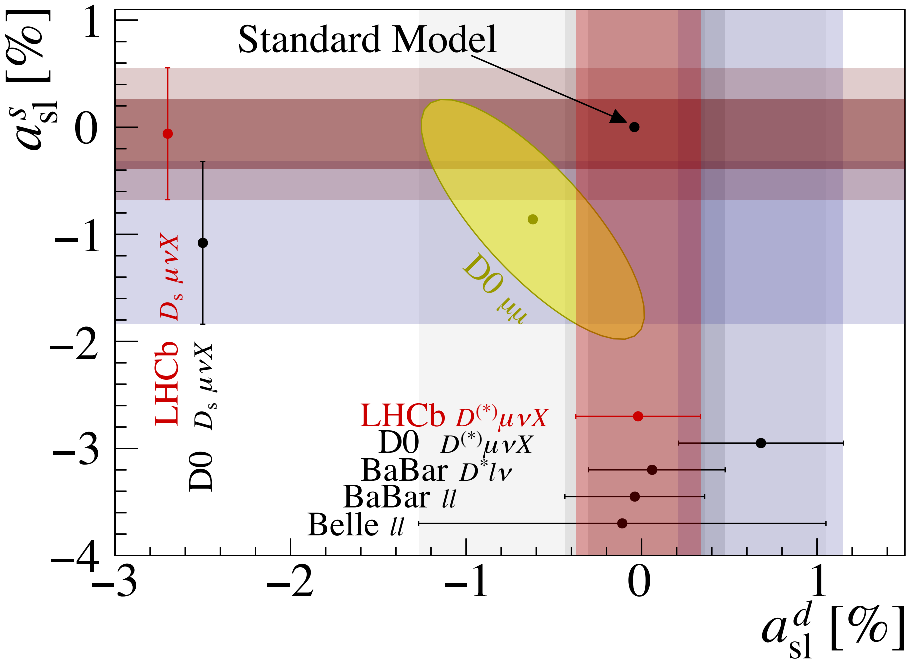
Results





$$a_{sl}^{d} = (-0.02 \pm 0.19_{stat} \pm 0.30)\%$$

Results



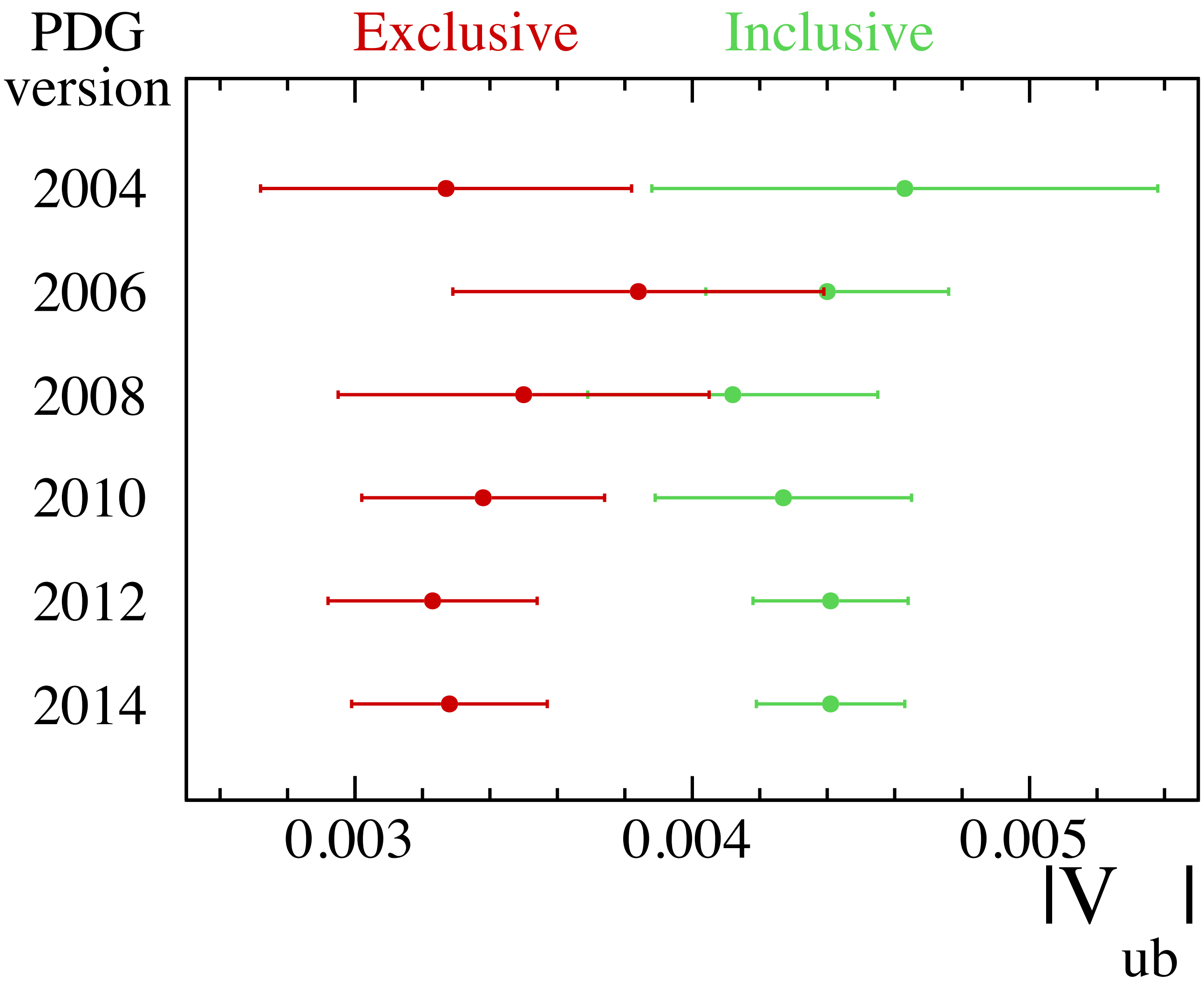
Systematics	
Source	**δ (%)**
Detection asymmetry	0.26
B plus	0.13
Baryonic background	0.07
Bs background	0.03
Fake D background	0.03
K-factor model	0.03
Decay time acceptance	0.03
Mixing frequency	0.02
Quadratic sum	0.30

Many of these are limited by control mode statistics

$$a_{sl}^{d} = (-0.02 \pm 0.19_{stat} \pm 0.30)\%$$

Most precise single measurement to date. Consistent with SM. Statistically limited

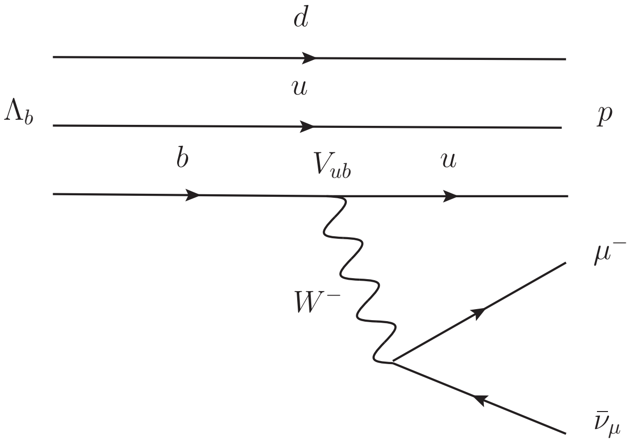
$|V_{ub}|$: tension^{TM}

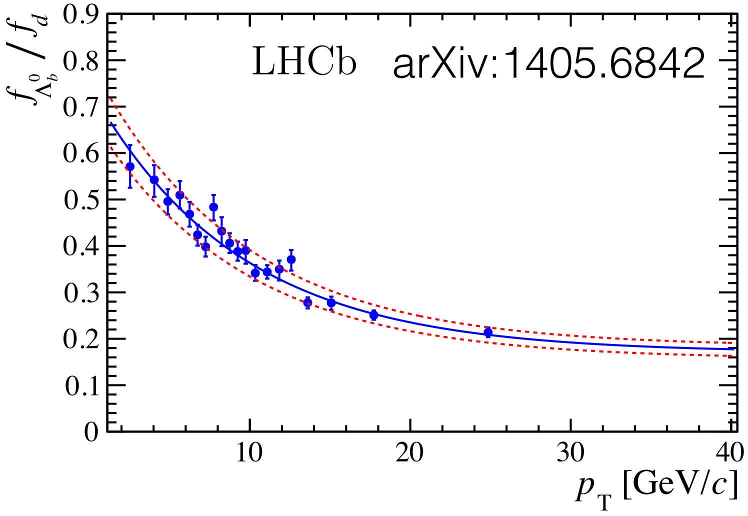


Measure $|V_{ub}|$ at hadron colliders?

The $\Lambda_b \rightarrow p\mu\nu$ decay

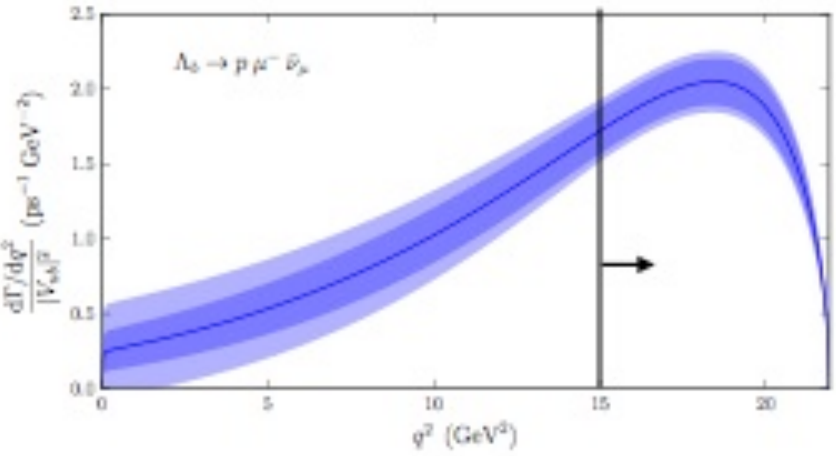
- Baryonic version of $B \rightarrow \pi l \nu$
- Cleaner at LHCb as protons are rarer than kaons/pions
- Λ_b not produced at B Factories, but produced at LHC half as often as B mesons
- Signature in detector: displaced muon-proton vertex
- Event though suppressed, it is not a rare decay
  - Expect 0.5M events after trigger and preselection
  - Only need ~10k to get good enough statistical precision
- Tight selection to control backgrounds and systematic effects

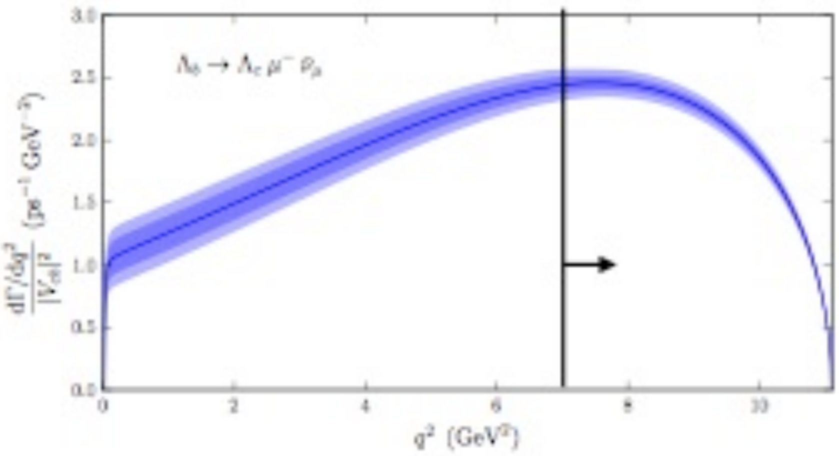




Analysis strategy

- Normalize signal yield to $\Lambda_b \to \Lambda_c(pK\pi)\mu\nu$
  - Cancel many systematic uncertainties, including the one related to the production of Λ_b baryons
- Restrict signal and normalization to kinematic region where LQCD is accurate:
  - $q^2 > 15\ GeV^2$ (signal) and $q^2 > 7\ GeV^2$ (normalization)





W. Detmold, C. Lehner, and S. Meinel, arXiv:1503.01421

Analysis strategy

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- Restrict signal and normalization to kinematic region where LQCD is accurate:
  - $q^2 > 15\ GeV^2$ (signal) and $q^2 > 7\ GeV^2$ (normalization)

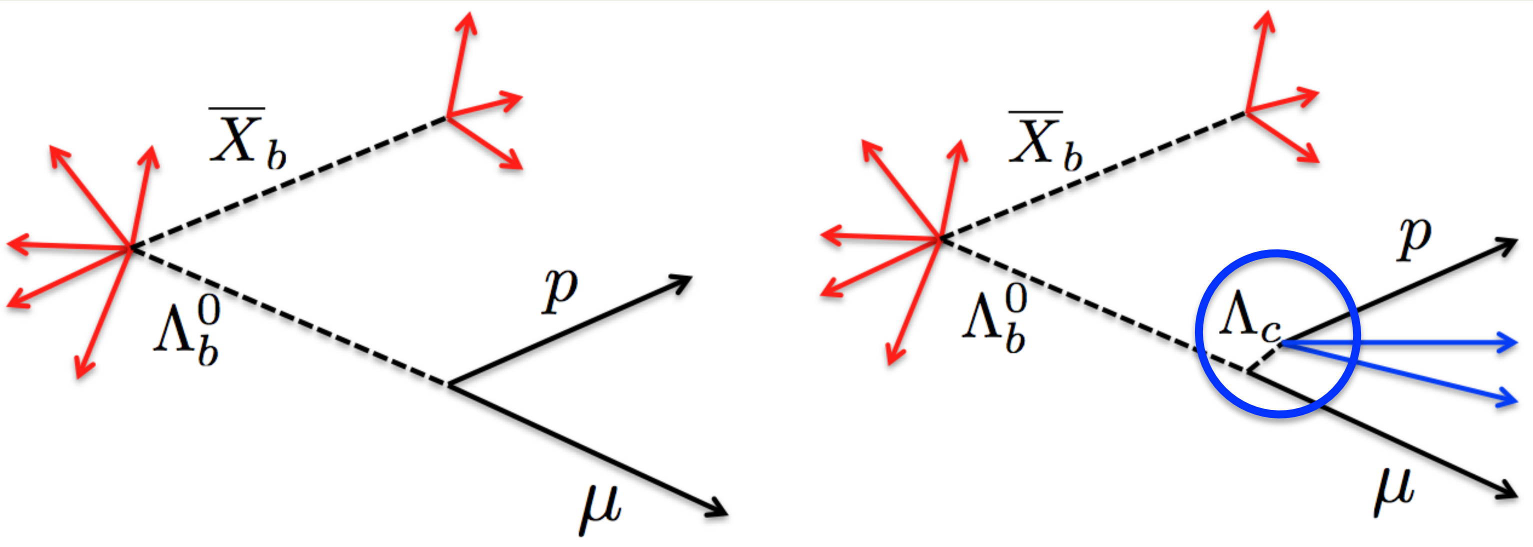
$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\ GeV^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\ GeV^2}} \cdot R_{\mathrm{FF}}$$

form factor ratio
5% uncertainty
on $|V_{ub}|$

$$R_{\mathrm{FF}} = (0.68 \pm 0.07)$$

W. Detmold, C. Lehner, and S. Meinel, arXiv:1503.01421

Isolation



Signal $\sim|V_{ub}|^2$

Background $\sim |V_{cb}|^2 \sim 100\ |V_{ub}|^2$

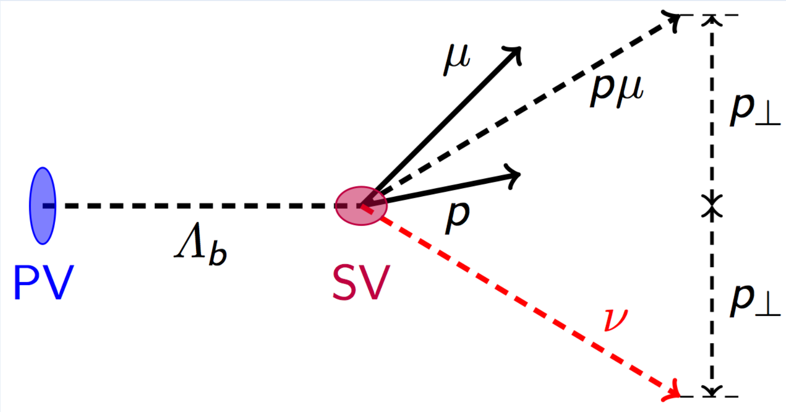
- Signal has no additional tracks coming from the secondary vertex
- Tight vertex rejects 50% of background due to Λ_c lifetime (0.2ps)
- Veto on charged tracks close to the pμ vertex — 90% rejection for 80% efficiency

Corrected mass

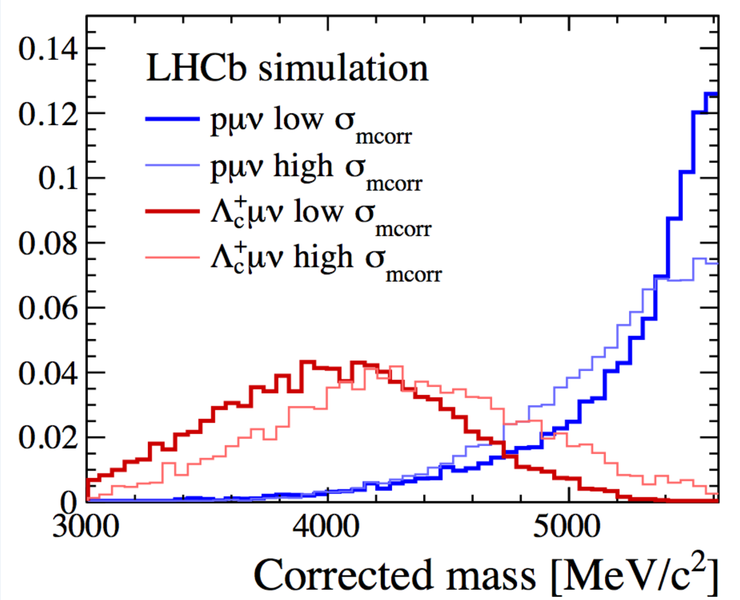
- No constraint from beam energy at a hadron machine
- Use constraint given by measurable flight direction

$$m_{\rm corr} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp$$

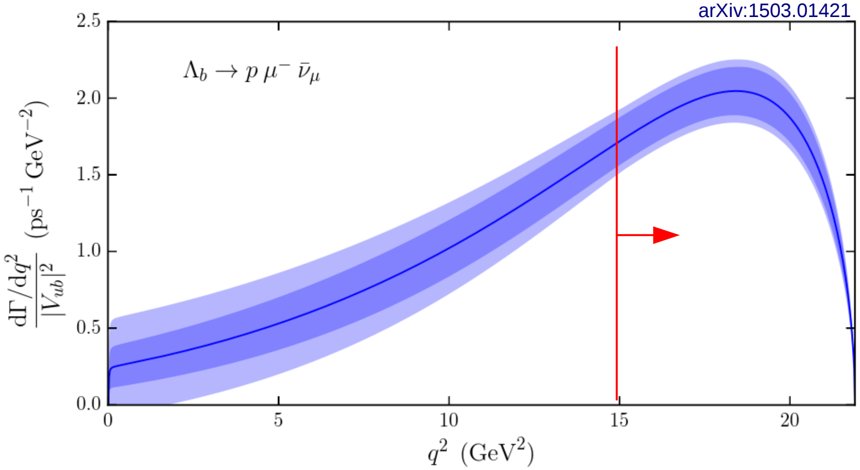
- Improve signal and background separation by requiring low uncertainty on m_{corr}



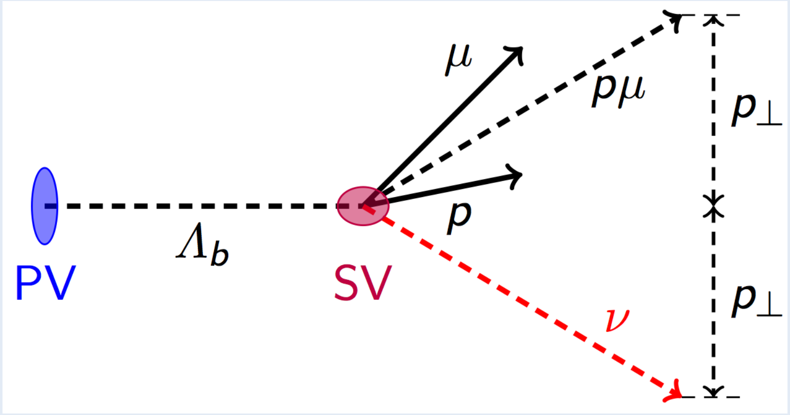
Nature Physics 11 (2015) 743

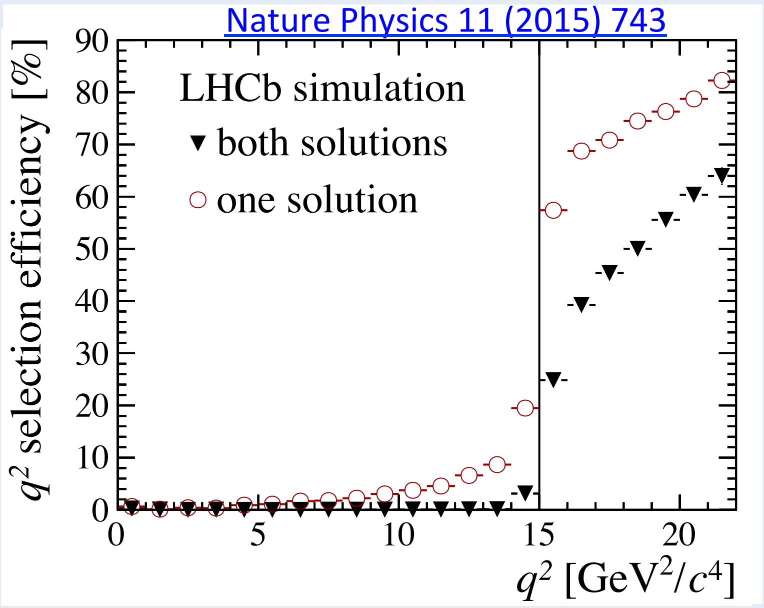


Reduced q^2 dependence


arXiv:1503.01421

- Using the Λ_b mass as a constraint → quadratic equation for p_ν → 2-fold ambiguity
- Theory most accurate at high q^2
- Require both solutions above 15GeV^2 to avoid cross-feed




Nature Physics 11 (2015) 743

Fit to data

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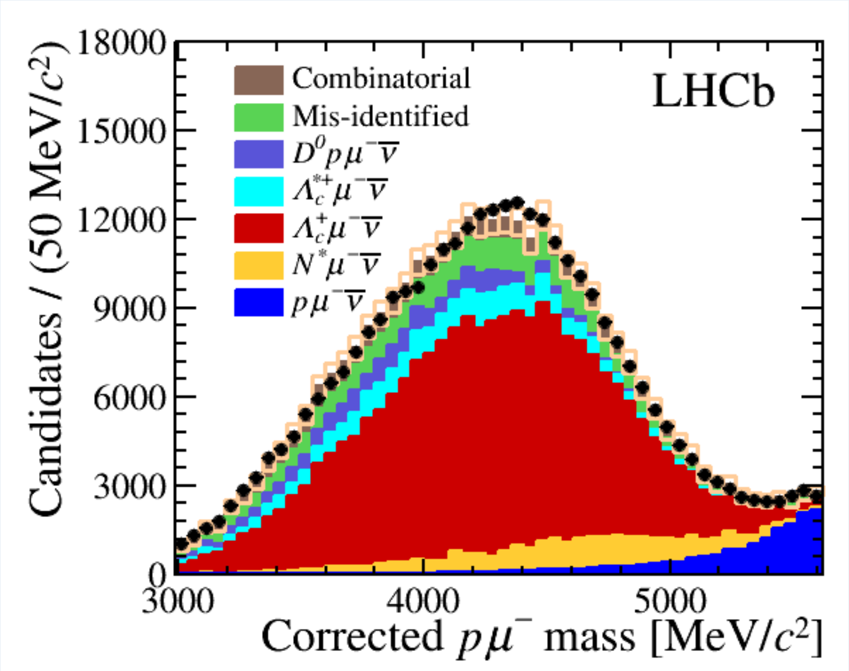
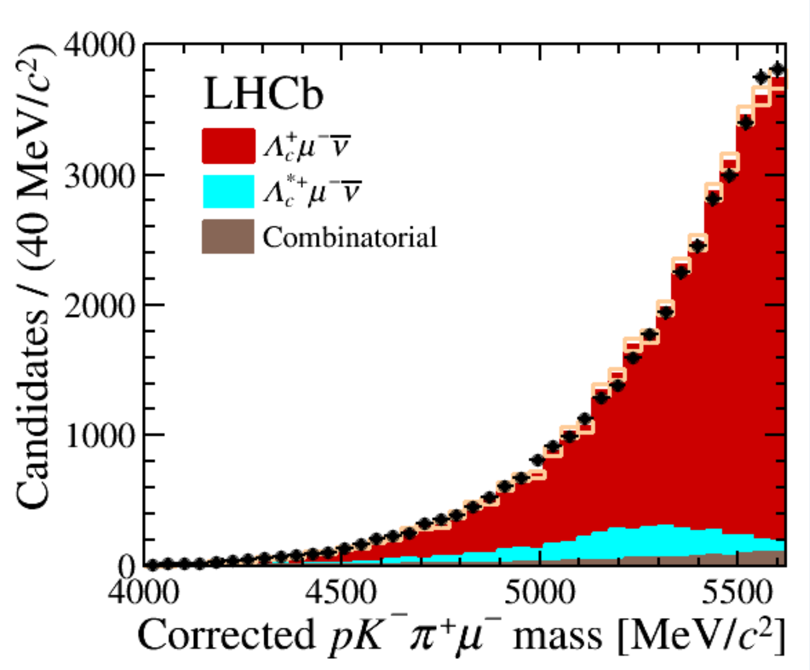




Signal: 17687 ± 733

Normalization: 34255 ± 571

Ratio of branching fractions

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu\nu)_{q^2>7\,\mathrm{GeV}^2}} = \frac{N(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2}}{N(\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu\nu)_{q^2>7\,\mathrm{GeV}^2}} \times \frac{\epsilon(\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu\nu)_{q^2>7\,\mathrm{GeV}^2}}{\epsilon(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2}} \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$$

- Relative efficiencies determined from simulation, with corrections from data. Main differences due to
  - Two extra tracks for normalization
  - Vertex efficiency (Λ_c lifetime)
  - Cut on corrected mass error

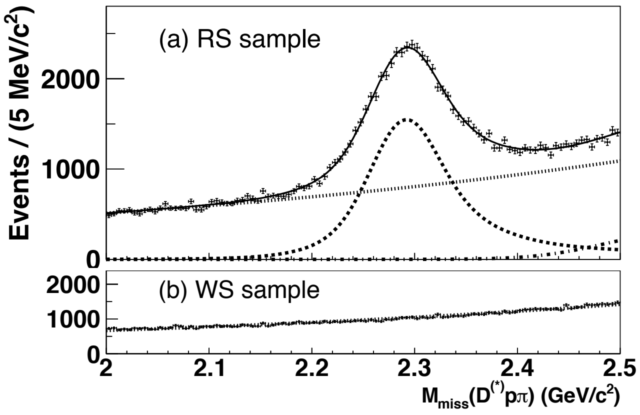
$$\frac{\epsilon(\Lambda_b^0 \to p\mu\nu)}{\epsilon(\Lambda_b^0 \to \Lambda_c\mu\nu)} = 3.52 \pm 0.20$$

Ratio of branching fractions

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu\nu)_{q^2>7\,\mathrm{GeV}^2}} = (1.00 \pm 0.04(stat) \pm 0.08(syst)) \times 10^{-2}$$

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	$^{+7.8}_{-8.2}$

- Dominated by single Belle measurement



(Belle) Phys. Rev. Lett. 113 (2014) 042002

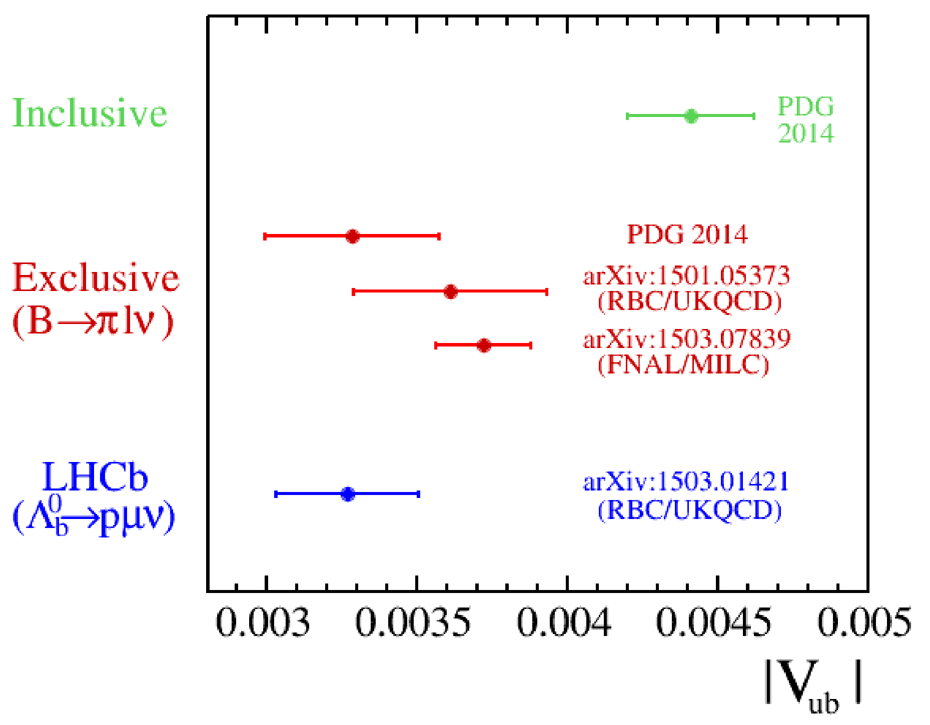
$|V_{ub}|$ result

Using PDG exclusive average of $|V_{cb}|$:

$$|V_{ub}| = (3.27 \pm 0.15_{\exp} \pm 0.17_{theory} \pm 0.06_{|Vcb|}) \times 10^{-3}$$

Nature Physics 11 (2015) 743

3.5σ away from inclusive average

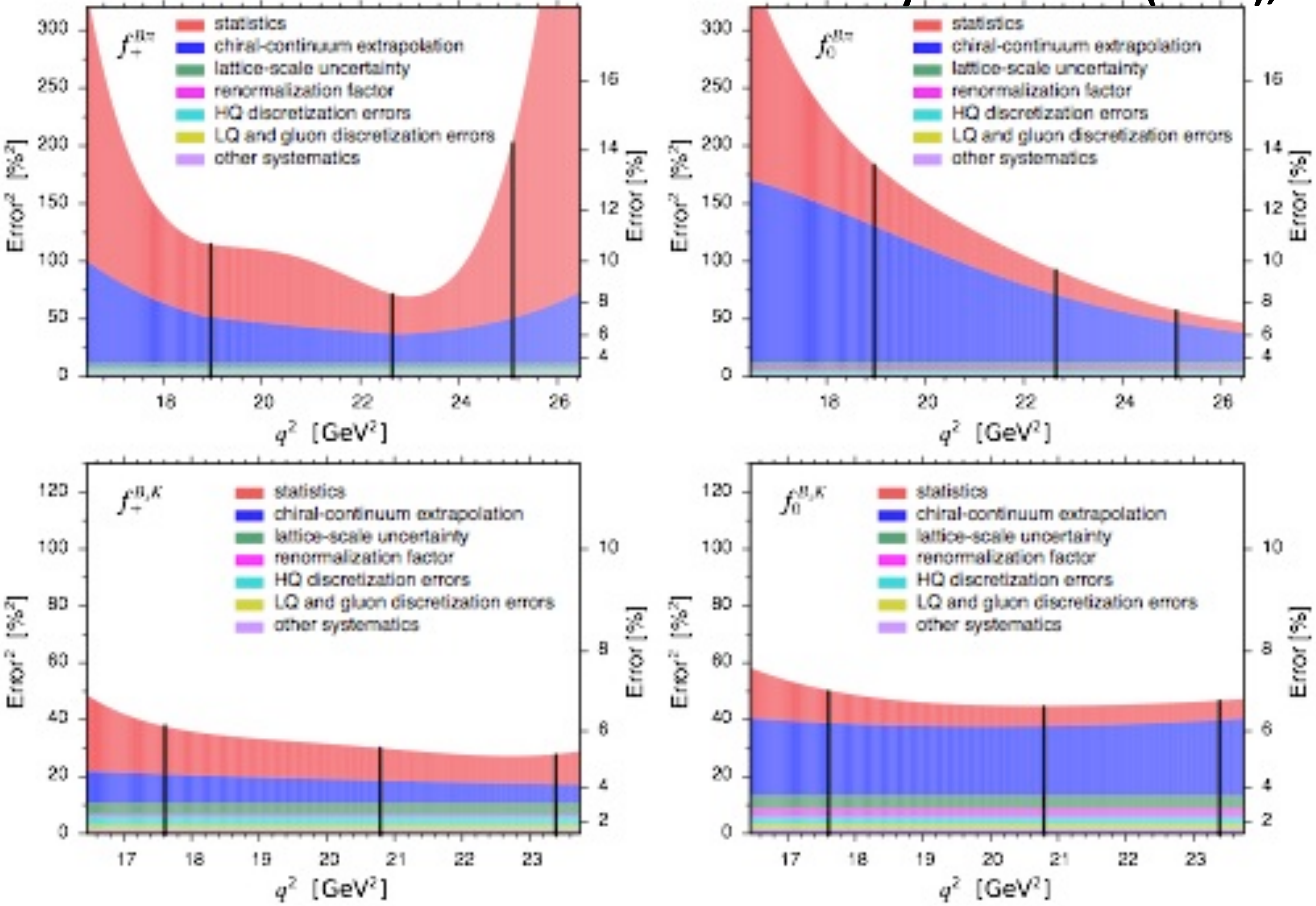


Measuring $|V_{ub}|$: $B_s \rightarrow K\mu\nu$

Phys. Rev. D91 (2015), 7074510

$B \rightarrow \pi\mu\nu$

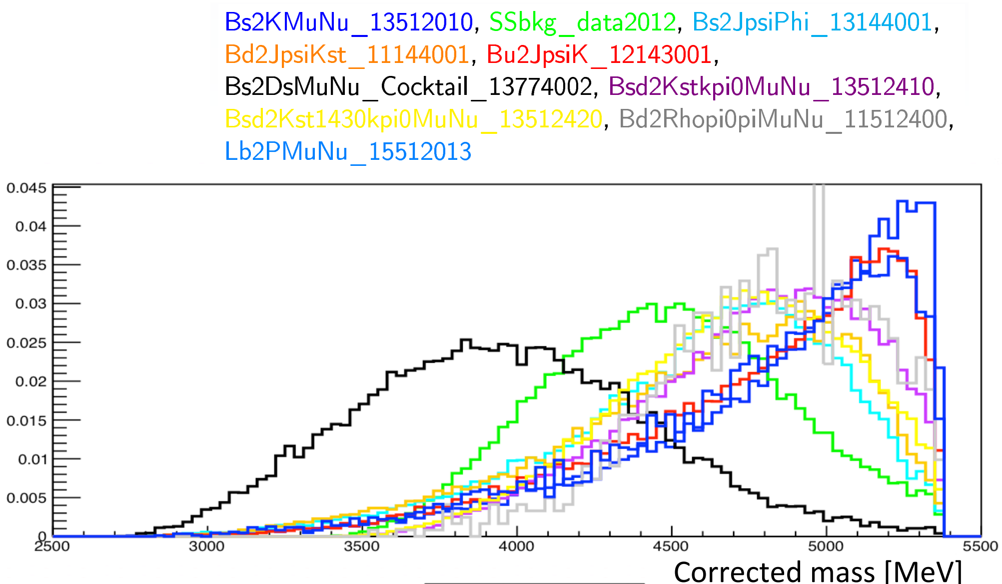
$B_s \rightarrow K\mu\nu$

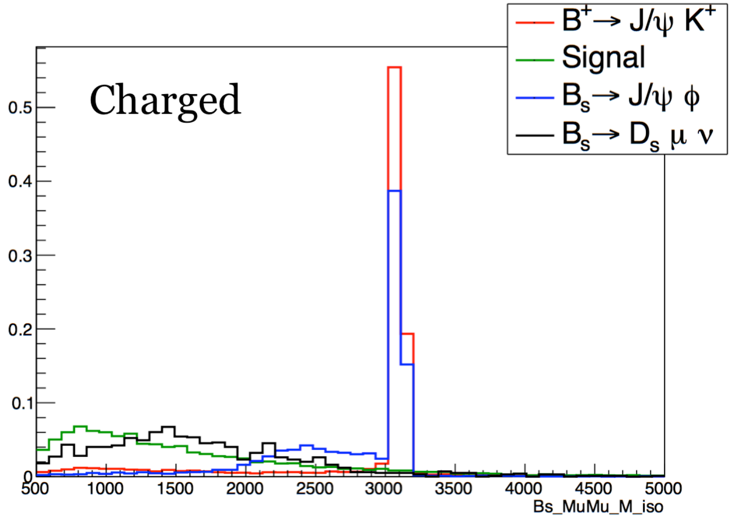


Error budget from Lattice QCD more favourable for $B_s \rightarrow K\mu\nu$ than $B \rightarrow \pi\mu\nu$

Measuring $|V_{ub}|$: $B_s \rightarrow K\mu\nu$

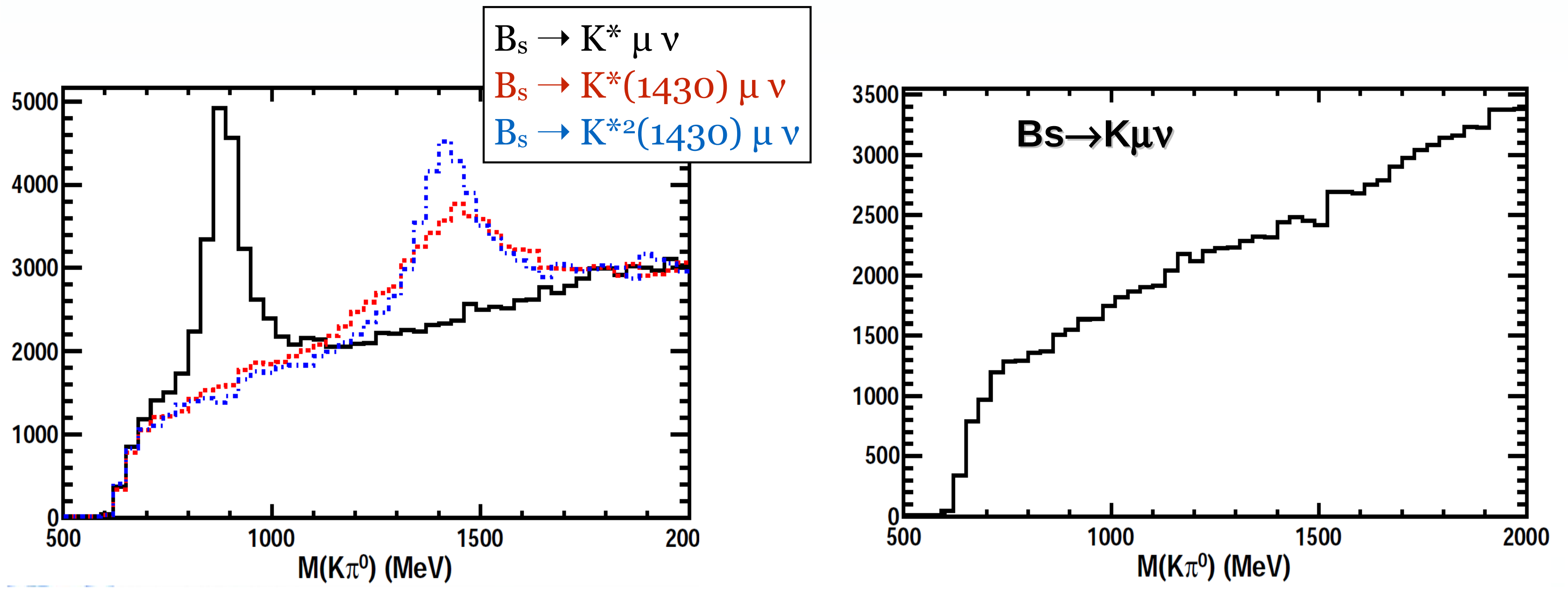
- Use corrected mass to distinguish between background components
- Use charged and neutral isolation criteria in BDT
- Veto partially reconstructed backgrounds





LHCb internal

Measuring $|V_{ub}|$: $B_s \rightarrow K\mu\nu$



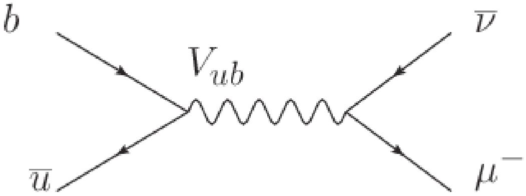
- Neutral isolation: Veto partially reconstructed K^{*+} backgrounds by looking at combination of photon pairs into π^0 candidates

Measuring $|V_{ub}|$: B→μν and $B_{(c)}$→φμν

- B→lν measures ff x $|V_{ub}|$, sensitive to NP at tree level
- Helicity suppressed!

  →Measure B→τν

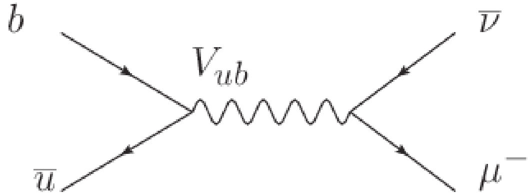
  → rather impossible at LHCb

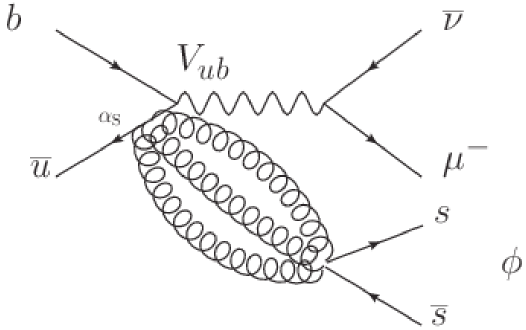


- Add gluons and measure B→φμν
- Look also for B_c→φμν
- BR(B+→φμν)/BR(B_c→φμν) ~ $|V_{ub}|^2/|V_{cb}|^2$!
- Analysis just starting
  - Building on work done for B_s→Kμν

Measuring $|V_{ub}|$: $B \rightarrow \mu\nu$ and $B_{(c)} \rightarrow \phi\mu\nu$

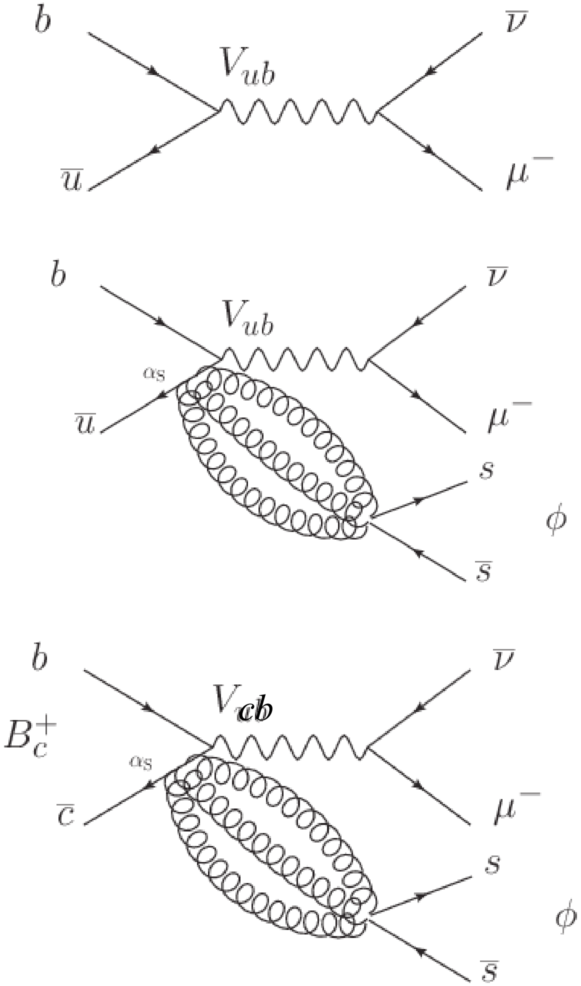
- $B \rightarrow l\nu$ measures ff x $|V_{ub}|$, sensitive to NP at tree level
- Helicity suppressed!
  - → Measure $B \rightarrow \tau\nu$
    - → rather impossible at LHCb
- Add gluons and measure $B \rightarrow \phi\mu\nu$
- Look also for $B_c \rightarrow \phi\mu\nu$
- $BR(B+ \rightarrow \phi\mu\nu)/BR(B_c \rightarrow \phi\mu\nu)$ ~ $|V_{ub}|^2/|V_{cb}|^2$!
- Analysis just starting
  - – Building on work done for $B_s \rightarrow K\mu\nu$





Measuring $|V_{ub}|$: $B\to\mu\nu$ and $B_{(c)}\to\phi\mu\nu$

- $B\to l\nu$ measures ff x $|V_{ub}|$, sensitive to NP at tree level
- Helicity suppressed!
  - → Measure $B\to\tau\nu$
    - → rather impossible at LHCb
- Add gluons and measure $B\to\phi\mu\nu$
- Look also for $B_c\to\phi\mu\nu$
- $BR(B+\to\phi\mu\nu)/BR(B_c\to\phi\mu\nu)$ $\sim |V_{ub}|^2/|V_{cb}|^2$!
- Analysis just starting
  - Building on work done for $B_s\to K\mu\nu$



Measuring $|V_{ub}|$: $B \rightarrow \mu\nu$ and $B_{(c)} \rightarrow \phi\mu\nu$

- $B \rightarrow l\nu$ measures ff x $|V_{ub}|$, sensitive to NP at tree level
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  - → Measure $B \rightarrow \tau\nu$
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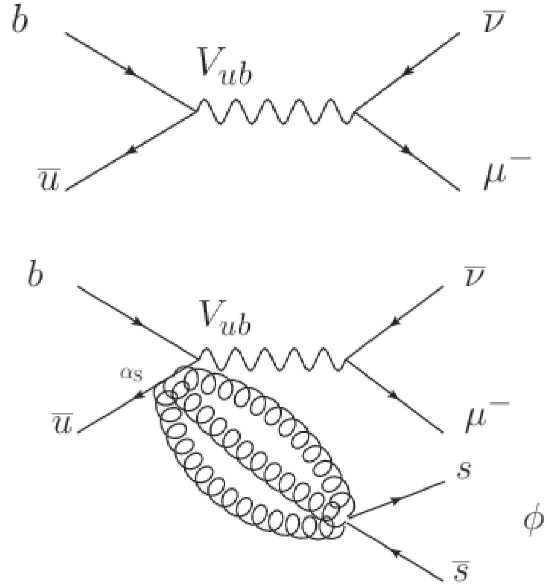
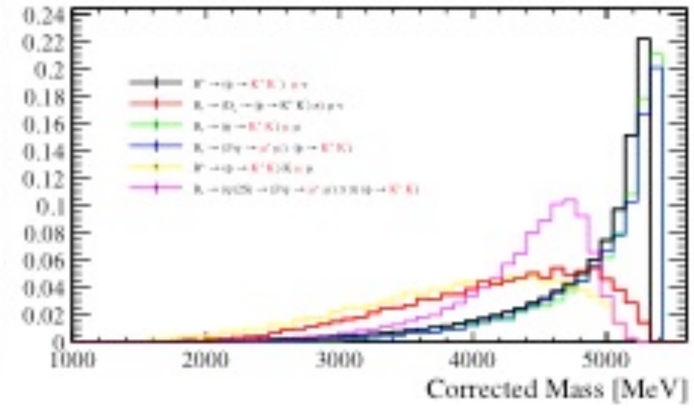
- Add gluons and measure $B \rightarrow \phi\mu\nu$
- Look also for $B_c \rightarrow \phi\mu\nu$
- $BR(B+ \rightarrow \phi\mu\nu)/BR(B_c \rightarrow \phi\mu\nu)$ ~ $|V_{ub}|^2/|V_{cb}|^2$!

- Analysis just starting
  - – Building on work done for $B_s \rightarrow K\mu\nu$

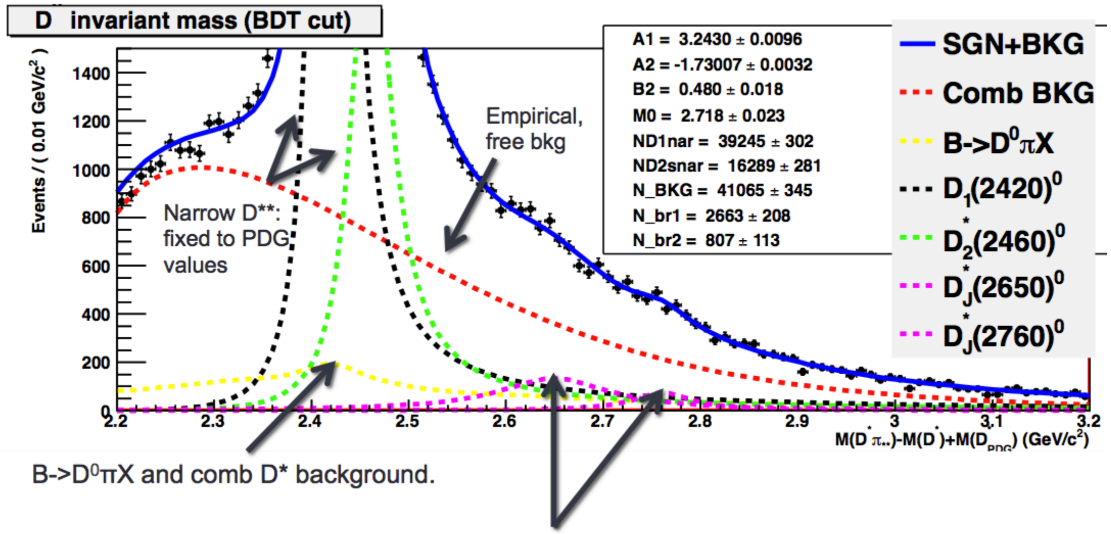




Semileptonic B decays in D**μν

- B → D**μν decays relatively poorly measured
- Sum of exclusive final states falls short of inclusive X_c μν
- Look for B → D**μν with D** → D*π by fitting D*π inv. mass

3fb^{-1}



Narrow D**: fixed to PDG values

Empirical, free bkg

B->D⁰πX and comb D* background.

Two new broad resonances: shapes taken from previous LHCb analysis in different production modes.

- Hints for decays into new resonances, previously unobserved
- Non-resonant D*π decays merged with combinatorial background

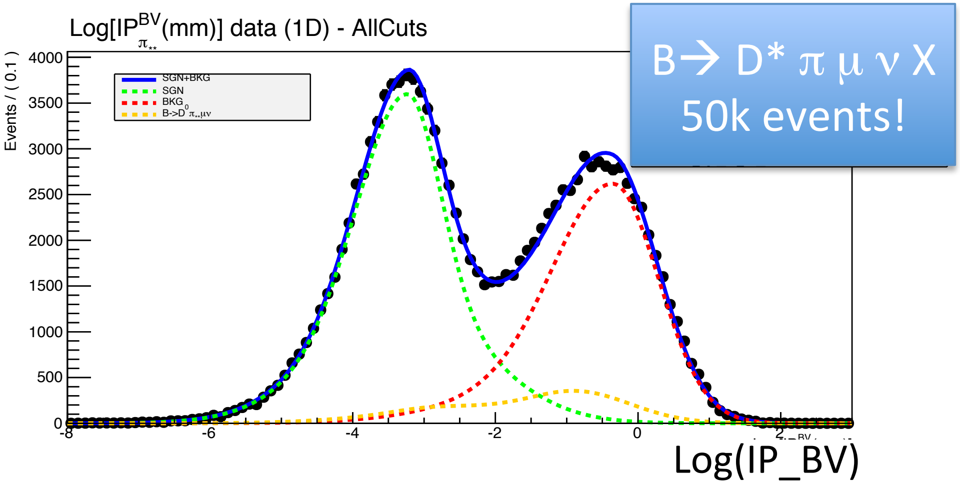
O(10^4) narrow resonances decays: Could also measure form factors!

State	Yield	Stat. error	Syst. error	Tot. error	Significance (σ)
$D_1(2420)^0$	39245	±302	±2037	±2059	19.1
$D_2^*(2460)^0$	16289	±281	±1391	±1419	11.5
$D_J^*(2650)^0$	2663	±208	±479	±522	5.1
$D_J^*(2760)^0$	807	±113	±179	±212	3.8

LHCb internal

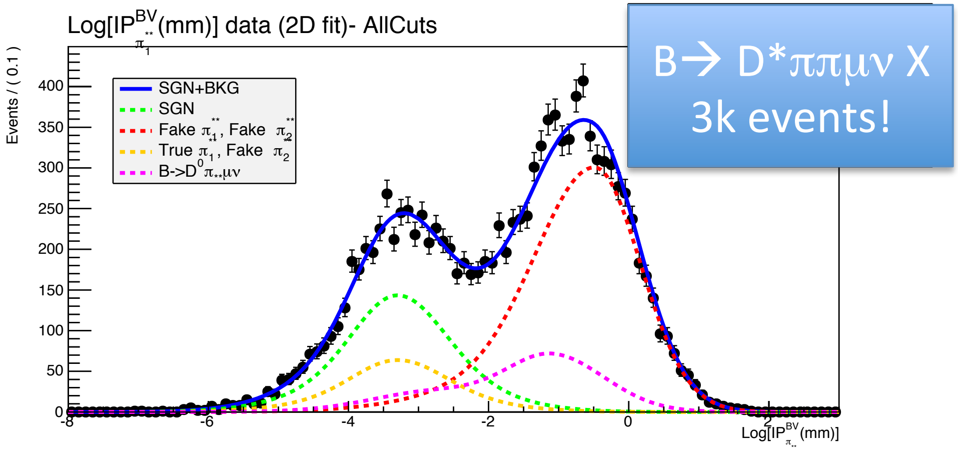
Semileptonic B decays in $D^{**}\mu\nu$

- Can also measure $D^*\pi(\pi)$ final states “inclusively” without looking at invariant mass
- Fit impact parameter with respect to $D^*\mu$ vertex



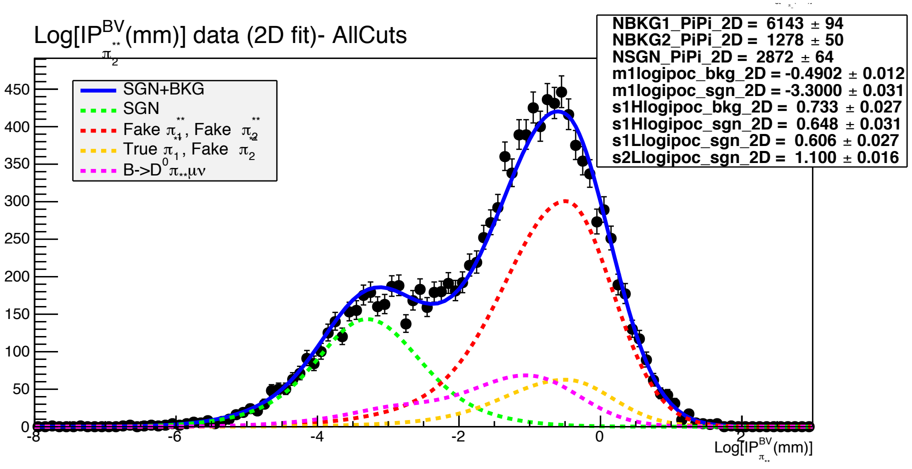
$B \rightarrow D^* \pi \mu \nu X$

50k events!



$B \rightarrow D^*\pi\pi\mu\nu X$

3k events!



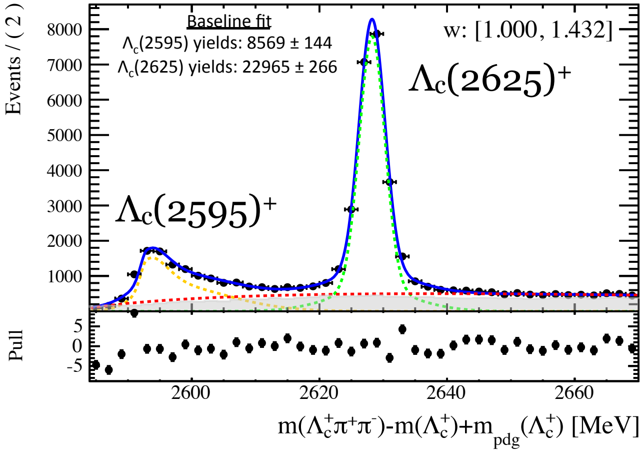
```
NBKG1_PiPi_2D =  6143 ± 94
NBKG2_PiPi_2D =  1278 ± 50
NSGN_PiPi_2D =  2872 ± 64
m1logipoc_bkg_2D = -0.4902 ± 0.012
m1logipoc_sgn_2D = -3.3000 ± 0.031
s1Hlogipoc_bkg_2D =  0.733 ± 0.027
s1Hlogipoc_sgn_2D =  0.648 ± 0.031
s1Llogipoc_sgn_2D =  0.606 ± 0.027
s2Llogipoc_sgn_2D =  1.100 ± 0.016
```

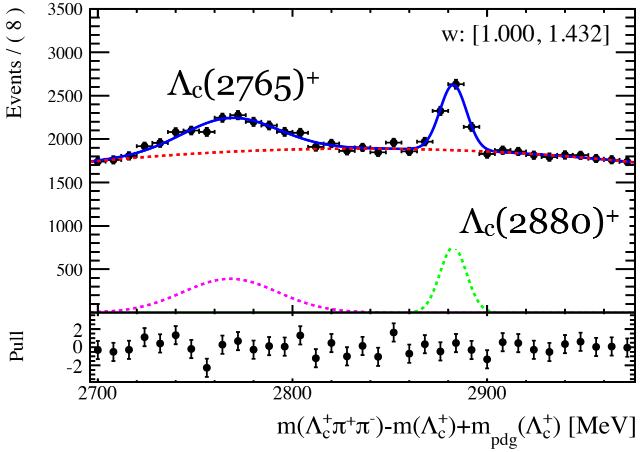
Λ_b form factors

$$\frac{d\Gamma(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}{dw} = \frac{G_F^2 m_{\Lambda_b}^5 |V_{cb}|^2}{24\pi^3} K(w) \xi_{\Lambda_b}^2(w)$$

$$\boxed{w = \frac{m(\Lambda_b)^2 + m(\Lambda_c)^2 - q^2}{2m(\Lambda_b)m(\Lambda_c)}}$$

- In HQET, the partial decay width is determined by six form factors
- In the heavy quark limit → "Isgur-Wise" function ξ(w)
- Parameters of this function can be determined by measuring the exclusive $\Lambda_b \to \Lambda_c \mu \nu$ rate, with $\Lambda_c \to p K \pi$, in bins of w
- Need to subtract feed-down from higher resonances



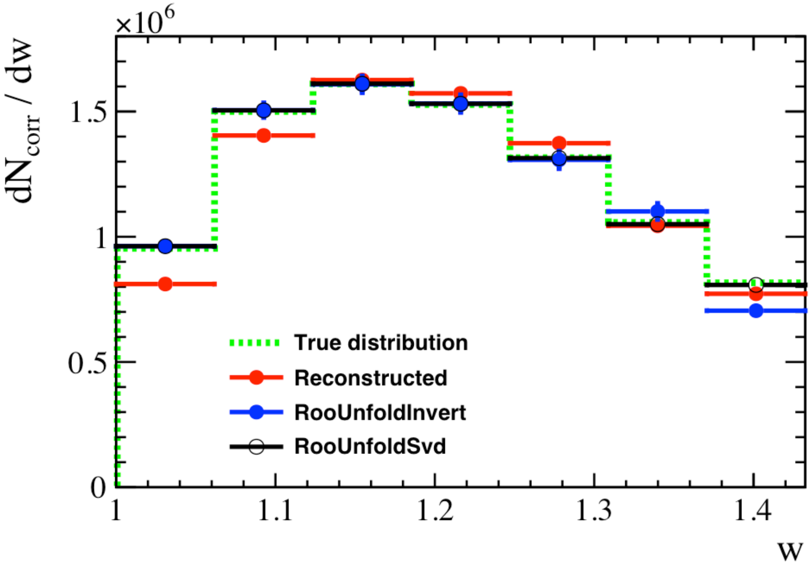


Λ_b form factors

$$\frac{d\Gamma(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}{dw} = \frac{G_F^2 m_{\Lambda_b}^5 |V_{cb}|^2}{24\pi^3} K(w) \xi_{\Lambda_b}^2(w)$$

$$w = \frac{m(\Lambda_b)^2 + m(\Lambda_c)^2 - q^2}{2m(\Lambda_b)m(\Lambda_c)}$$

- Unfold the measured w distribution and correct for efficiency

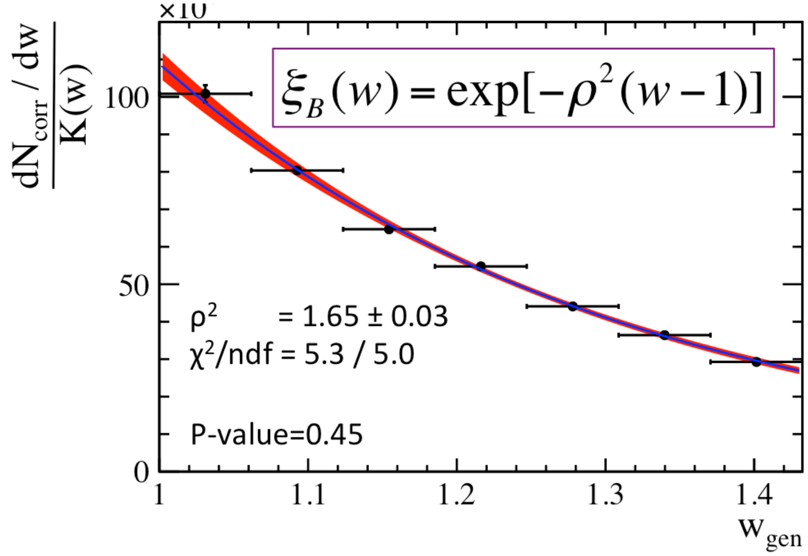


Λ_b form factors

$$\frac{d\Gamma(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}{dw} = \frac{G_F^2 m_{\Lambda_b}^5 |V_{cb}|^2}{24\pi^3} K(w) \xi_{\Lambda_b}^2(w)$$

$$\boxed{w = \frac{m(\Lambda_b)^2 + m(\Lambda_c)^2 - q^2}{2m(\Lambda_b)m(\Lambda_c)}}$$

- Unfold the measured w distribution and correct for efficiency
- Fit Isgur-Wise function (in the HQ limit)
- Repeat fit by using form factor parameterization from Lattice QCD



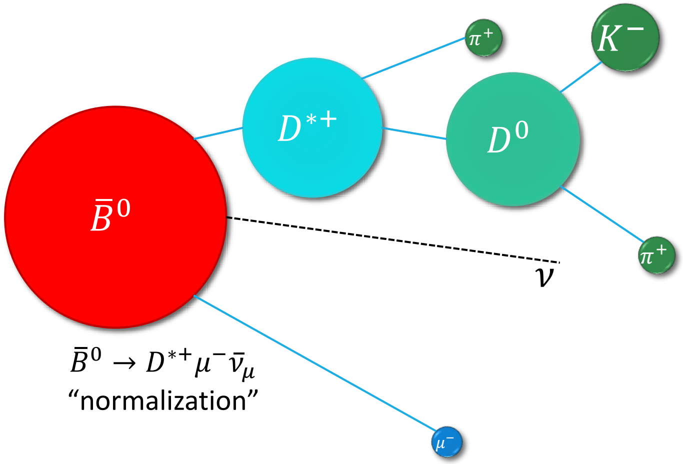
- Access to $|V_{cb}|$: need to find suitable normalization channel

Testing Lepton Flavour Universality with semi-tauonic B decays

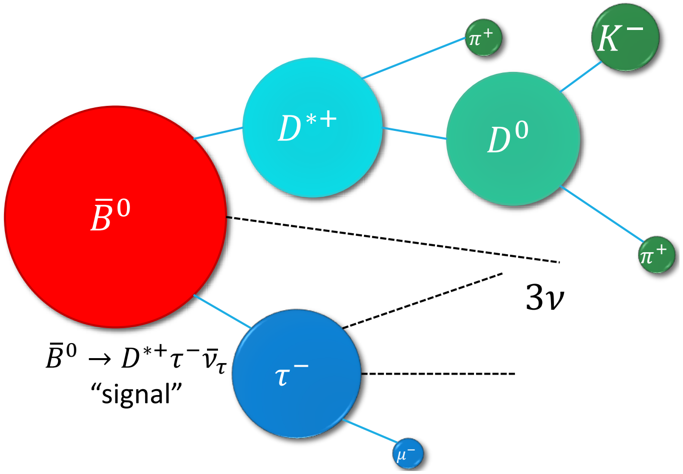
Measurement of $R(D^*) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$

- Theoretically clean, cancellation of form factor uncertainties
  - Dominant uncertainty due to knowledge of helicity-suppressed amplitude
  - SM: $R(D*)$ = 0.252(3)

    PRD **85** 094025 (2012)
- Use $\tau \to \mu\nu\nu$ decays
  - Same visible final state
  - Large well-measured BF (17%)



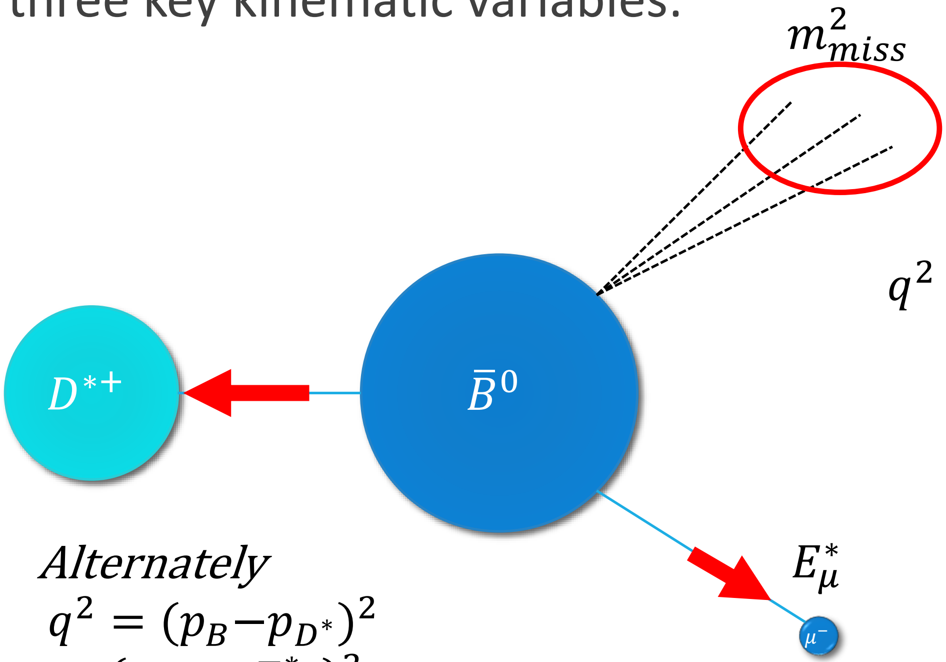
$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$
“normalization”



$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$
“signal”

Signal-to-background separation

In B rest frame, three key kinematic variables:



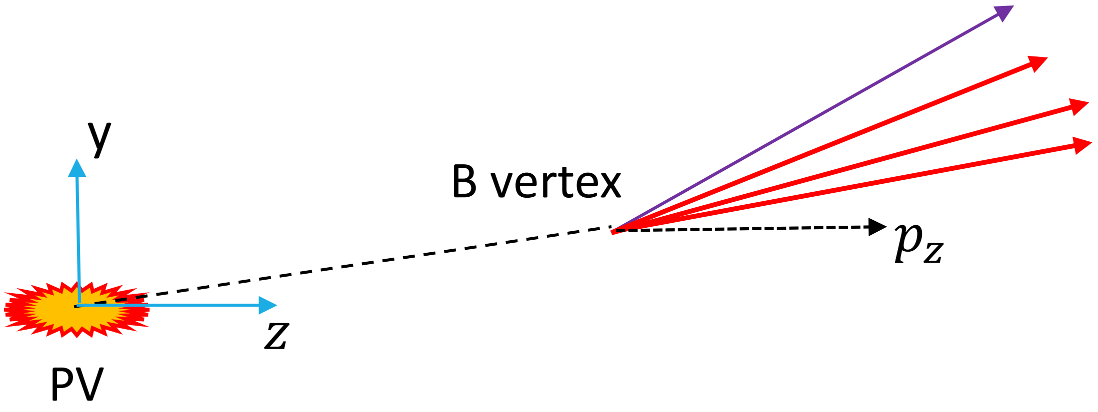
$$q^2 = (p_\ell + p_\nu)^2 = m^2_{W^*}$$

Alternately

$$q^2 = (p_B - p_{D^*})^2 = (m_B - E^*_{D^*})^2$$

$\boldsymbol{\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}}$	$\boldsymbol{\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}}$
$m^2_{miss} > 0$	$m^2_{miss} = 0$
E^*_l spectrum is soft	E^*_l spectrum is hard
$\mathrm{m}^2_\tau \leq q^2 \leq 10.6\ \mathrm{GeV}^2$	$0 \leq q^2 \leq 10.6\ \mathrm{GeV}^2$

Rest frame approximation at LHCb



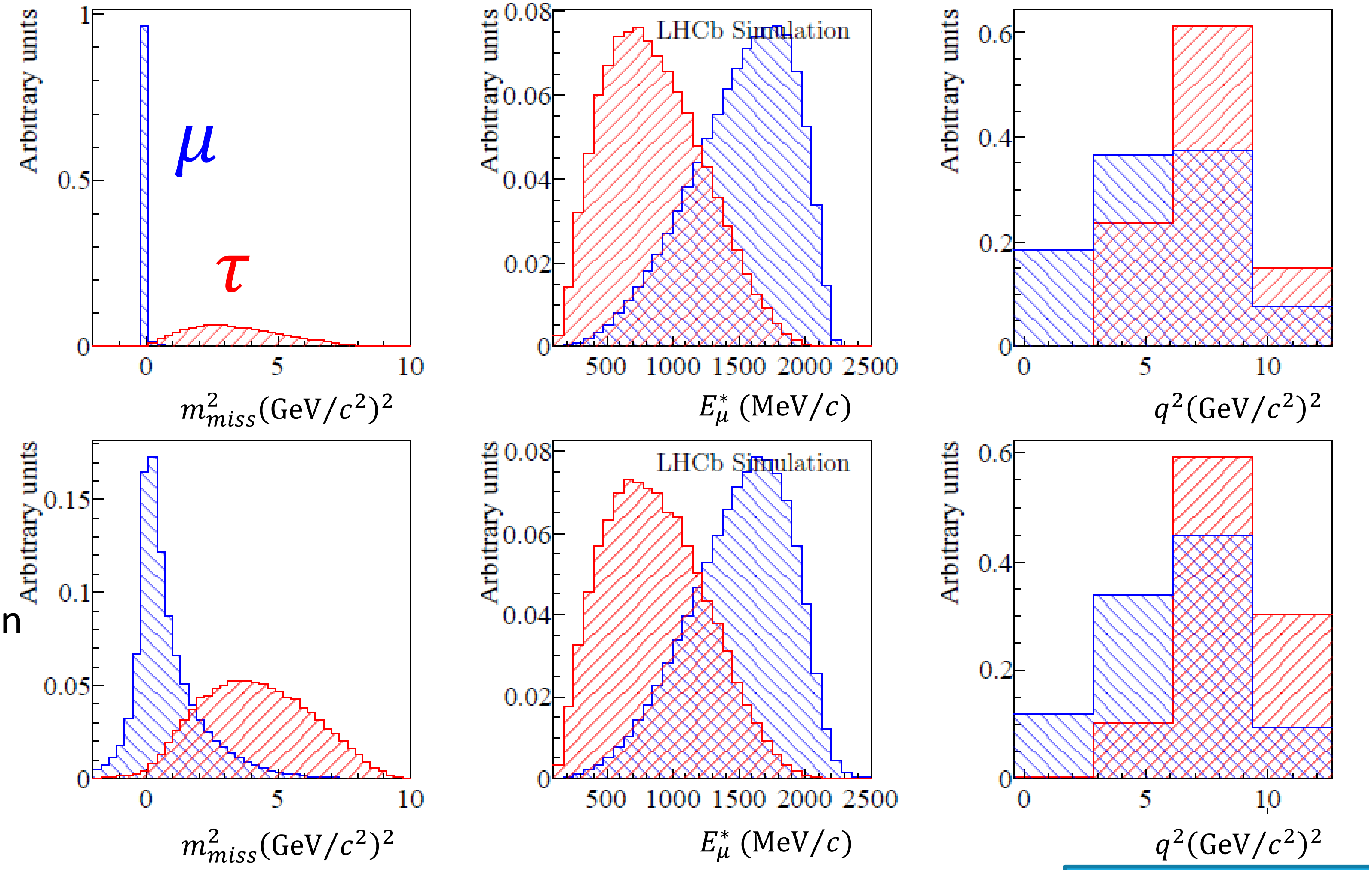
$$(\gamma\beta_z)_{\bar{B}} = (\gamma\beta_z)_{D^*\mu} \quad \Longrightarrow \quad (p_z)_{\bar{B}} = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$

- B boost along z >> boost of decay products in the rest frame
- Avoids 2-fold ambiguity when solving for B momentum with missing particles
- 18% resolution on B momentum approximation

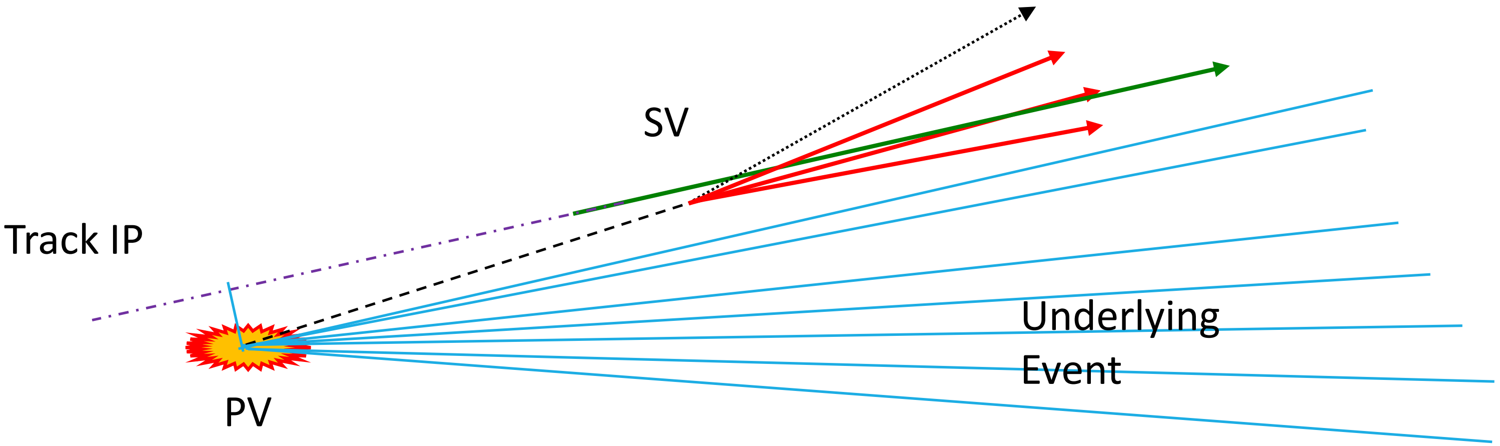
Reconstructed fit variables

MC Truth

Our Approximation

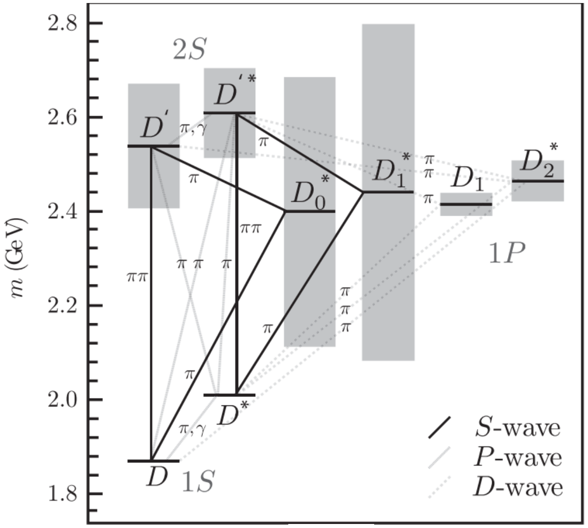


Partially reconstructed backgrounds



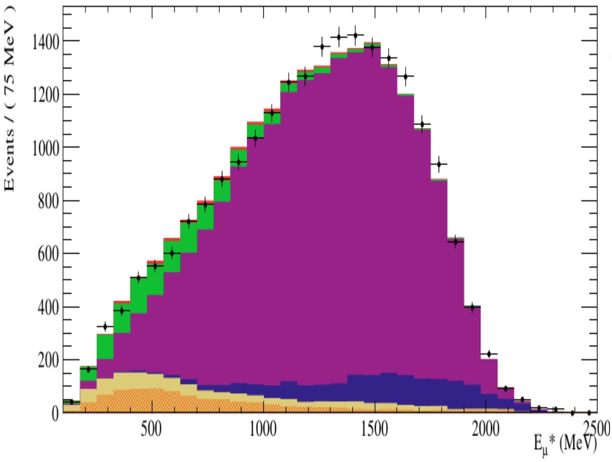
- Main backgrounds (other than normalization): **partially reconstructed B decays**
  - D*(*)$\mu\nu$, D*3πX, D*D(s)(*)X…
  - use **isolation criteria** (MVA) and/or **τ flight length**
- Assess compatibility of every other reconstructed track with D*μ vertex
  - Vertex quality with PV and SV, change in displacement of SV, pT, alignment of track and D*μ momenta
- Build BDT to discriminate "SV-like" and "PV-like" tracks
  - Use cuts to select signal-enriched and background-enriched samples, to be used as control samples

Semileptonic backgrounds

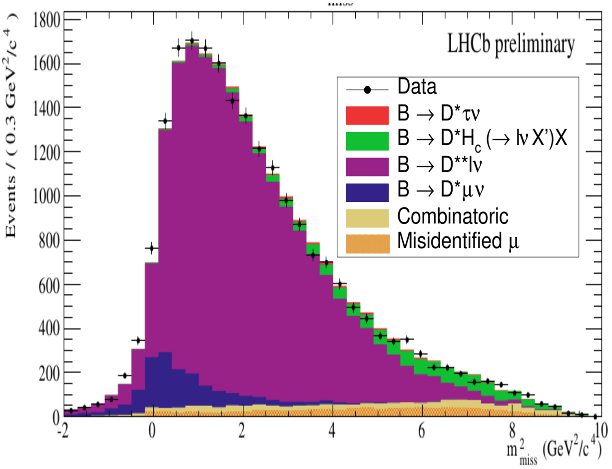


- Sizeable contributions from semileptonic decays to excited charm mesons
- Study their shapes with control samples enriched in **one** or two additional pions

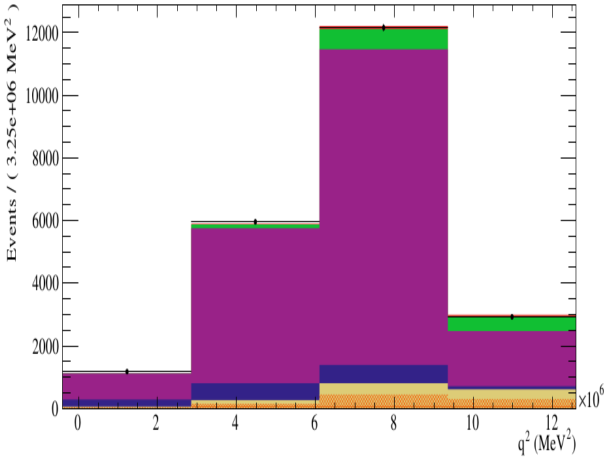
PRL 115, 111803 (2015)



E_μ



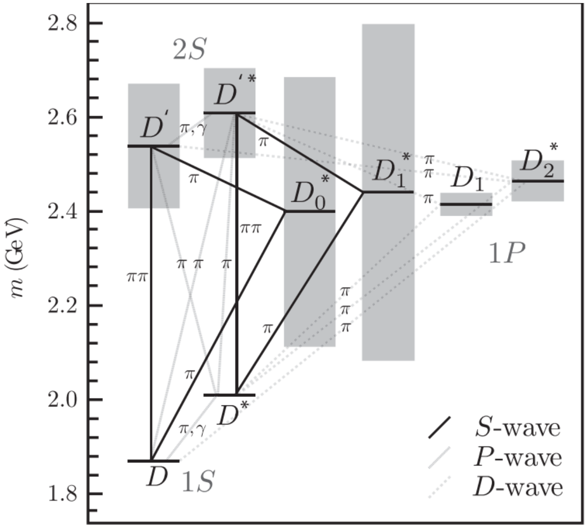
m^2_{miss}



q^2

PRL 115, 111803 (2015)

Semileptonic backgrounds



- Sizeable contributions from semileptonic decays to excited charm mesons
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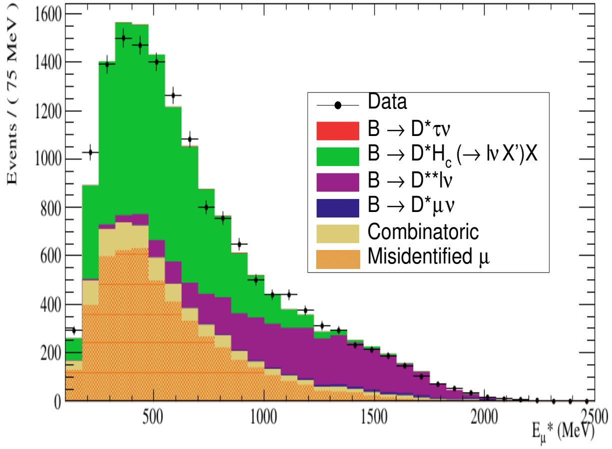
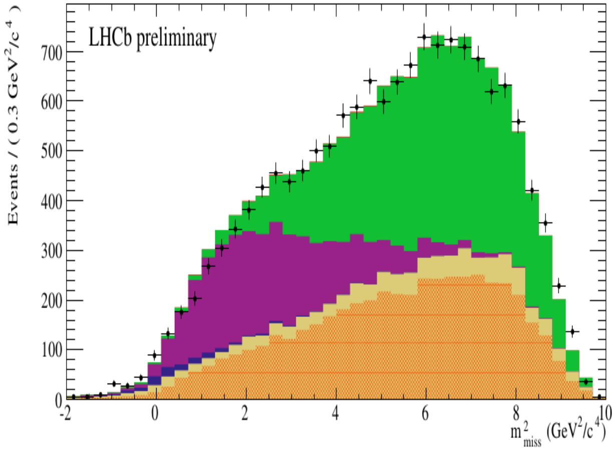
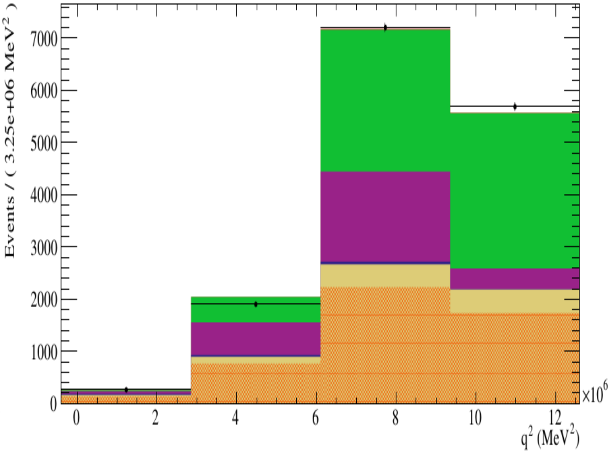
E_μ



m^2_{miss}



q^2

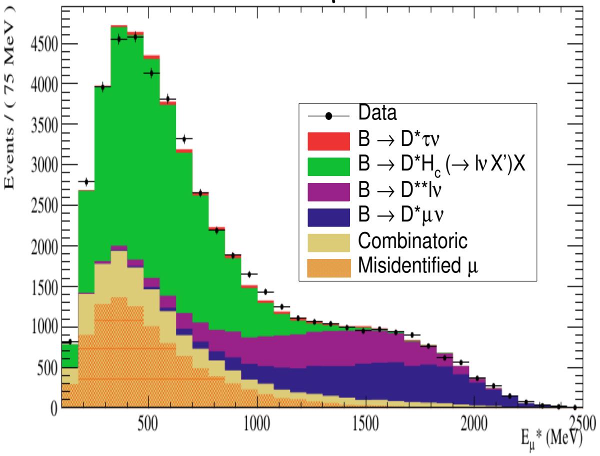


PRL 115, 111803 (2015)

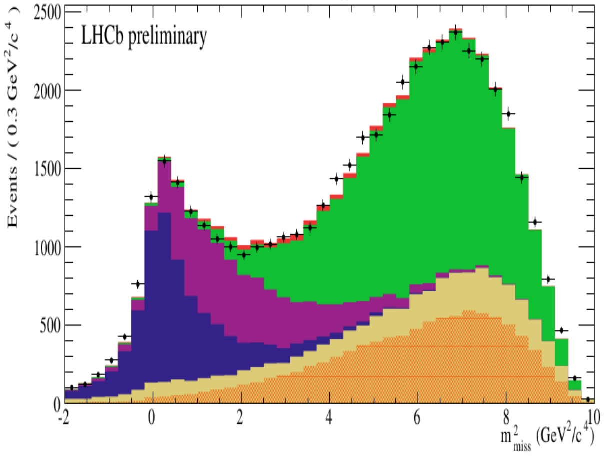
Double-charm backgrounds

- B→D*$D_{(s)}$X decays can lead to very similar shapes to the semitauonic decay (e.g. $B \rightarrow D^*\ D_s\ (\rightarrow \phi\mu\nu)$ + many others)
- Very large number of decays modes, physics models for many of them not well established
- Dedicated $D^*\mu K\pm$ control sample used to constrain **shapes**

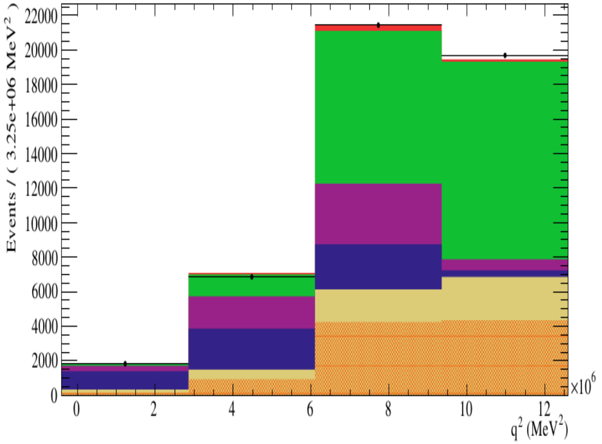
E_μ



m^2_{miss}



q^2



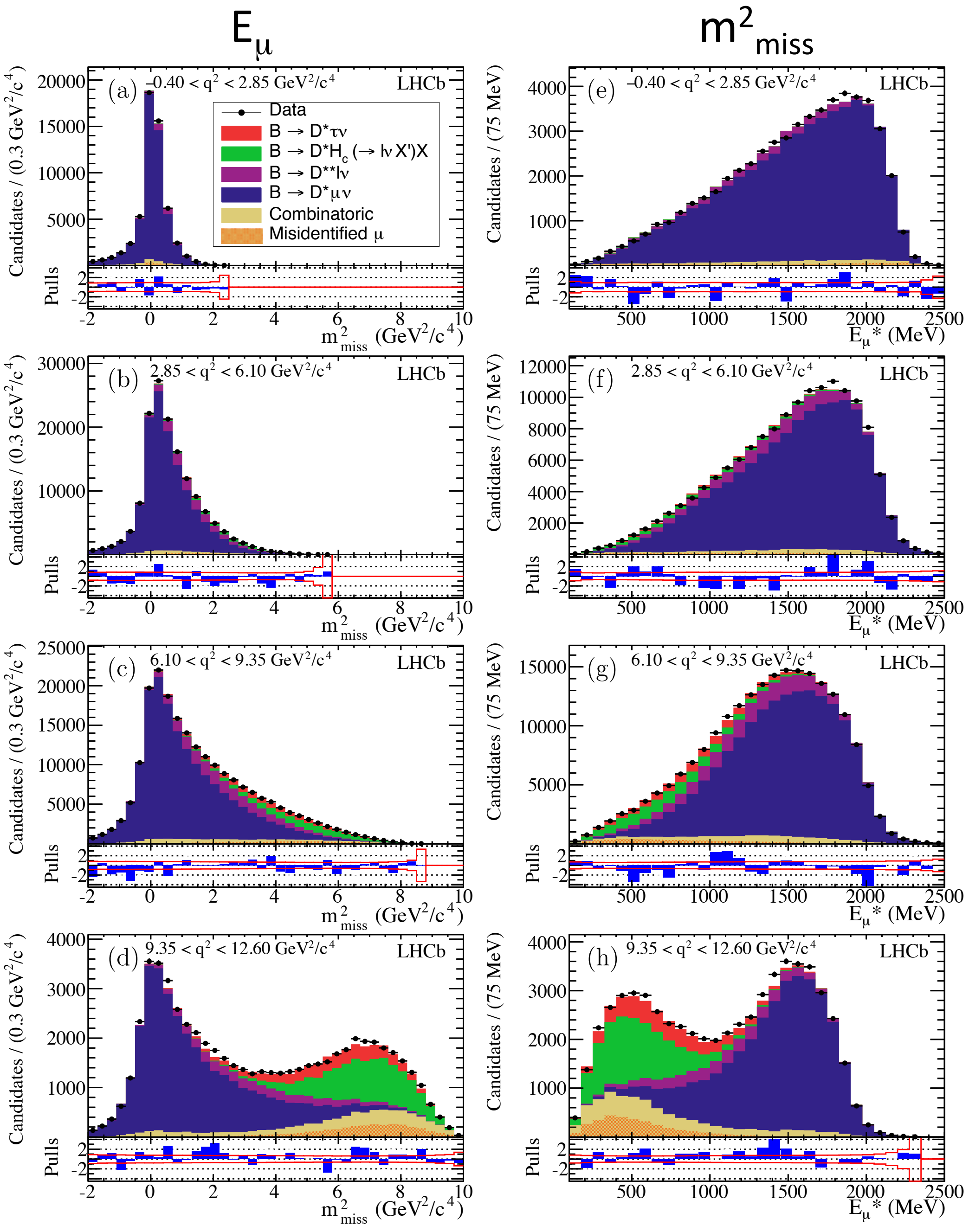
Signal region fit

- No additional particles
- 3D fit to m^2_{miss}, E_μ, in 4 bins of q^2.
- Simultaneously fit 3 control regions defined by isolation criteria

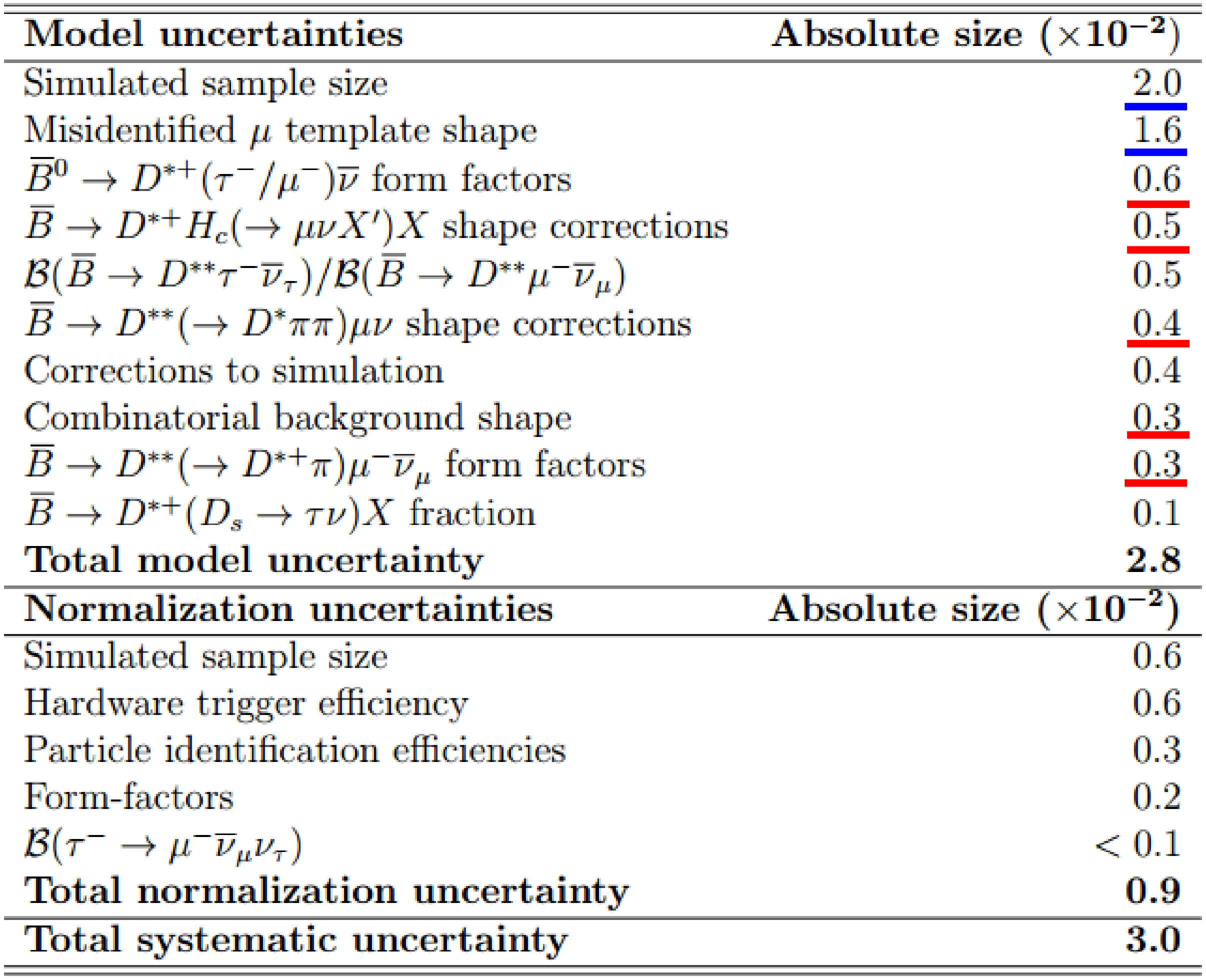
R(D*) = 0.336 ± 0.027 ± 0.030

- In agreement with Babar and Belle
- 2.1σ higher than the SM

PRL 115, 111803 (2015)



Systematics



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**

Expected to be reduced

Will scale down with more data

HFAG average of R(D) and R(D*)

SM prediction:

R(D*)=0.252 ±0.003

*PRD **85** (2012) 094025*

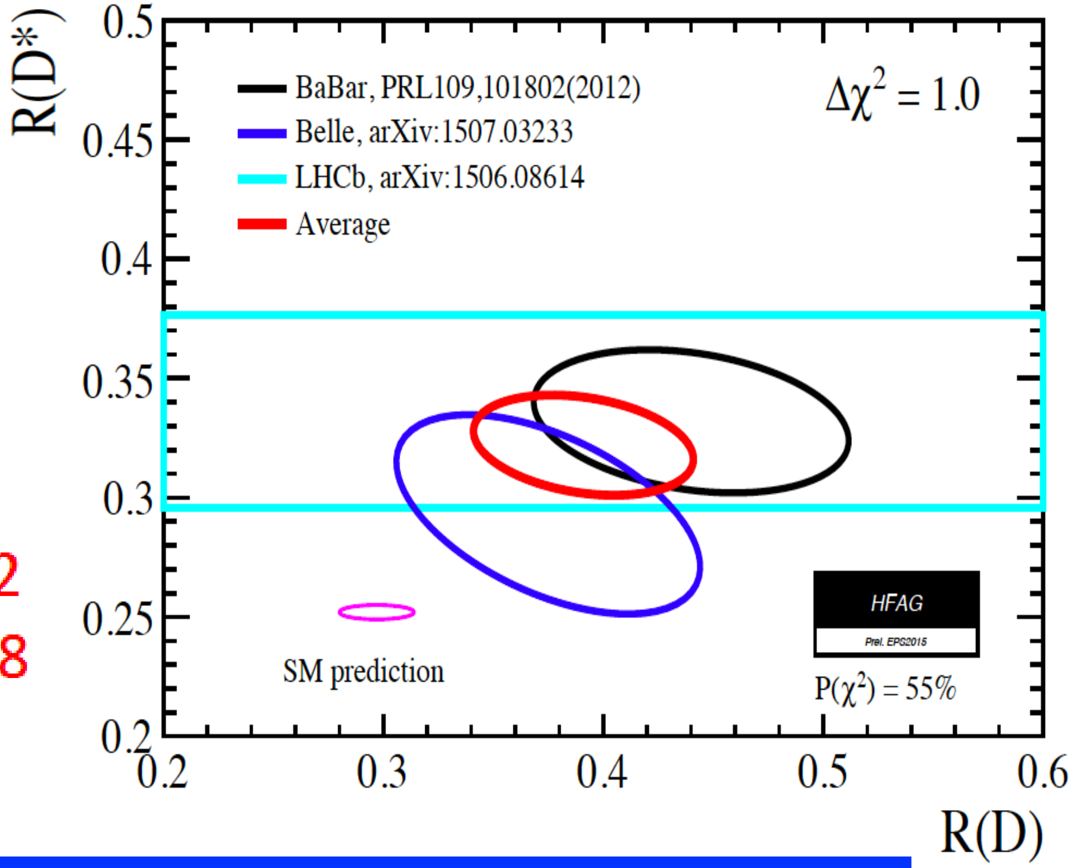
R(D) =0.297 ±0.017

*PRD **78** (2008) 014003*

Experimental average:

R(D*)= 0.322 ± 0.018 ± 0.012

R (D) = 0.391 ± 0.041 ± 0.028



Difference with the SM at 3.9σ level

Other semi-tauonic decays

B^+ & B^0

$R(D^0)/R(D^*)$ muonic,
$R(D^*)$ hadronic

B_c

$R(J/\psi)$ muonic

B_s

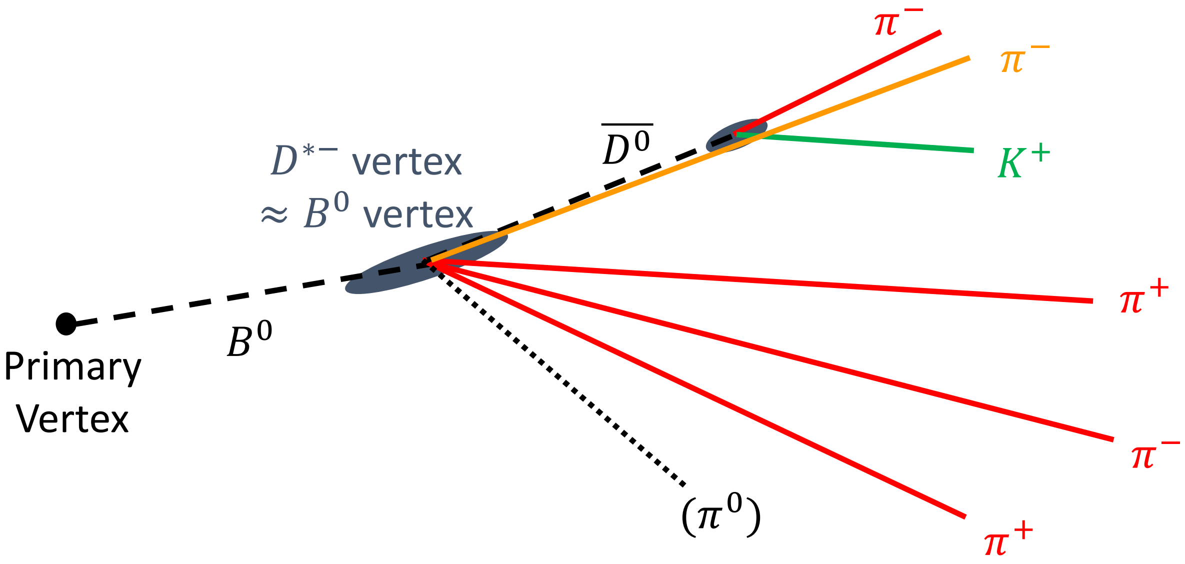
$R(D_s)$ muonic

Λ_b

$R(\Lambda_c^*)$ muonic,
$R(\Lambda_c)$ hadronic,
$R(\Lambda_c^*)$ hadronic

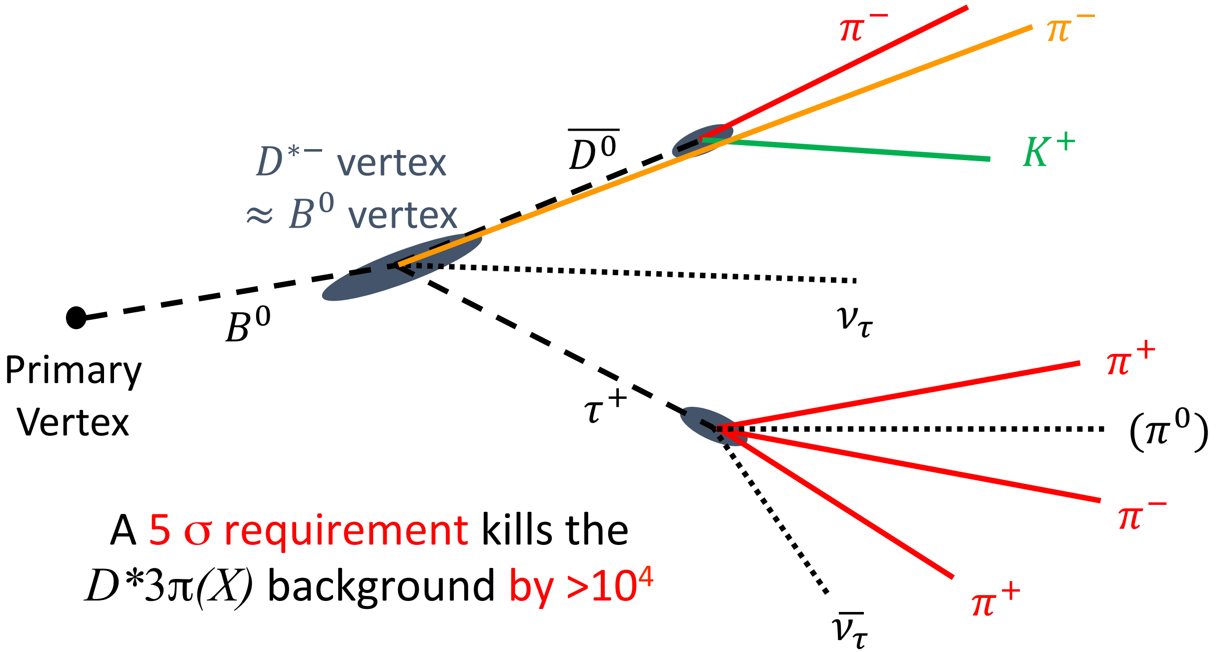
$B\rightarrow D^{*}\tau\nu$, with $\tau\rightarrow3\pi(\pi^0)$

- Doing semileptonic physics **without leptons in the final state!**
- The $B\rightarrow D^{*}\tau\nu$ decay, with $\tau\rightarrow3\pi(\pi^0)$ leads to a **$D^{*}3\pi(X)$ final state**
- Nothing is more common than this final state in a typical B decay
- $Br(B\rightarrow D^{*}3\pi(X))\ /\ Br(B\rightarrow D^{*}\tau\nu;\ \tau\rightarrow3\pi(\pi^0)\nu)_{SM}$ **~100**
- Suppress with ***inverted vertex topology***



$B \to D^* \tau \nu$, with $\tau \to 3\pi(\pi^0)$

- Doing semileptonic physics **without leptons in the final state!**
- The $B \to D^* \tau \nu$ decay, with $\tau \to 3\pi(\pi^0)$ leads to a **$D^*3\pi(X)$ final state**
- Nothing is more common than this final state in a typical B decay
- $Br(B \to D^*3\pi(X))$ / $Br(B \to D^* \tau \nu;\ \tau \to 3\pi(\pi^0)\nu)_{SM}$ **~100**
- Suppress with ***inverted vertex topology***



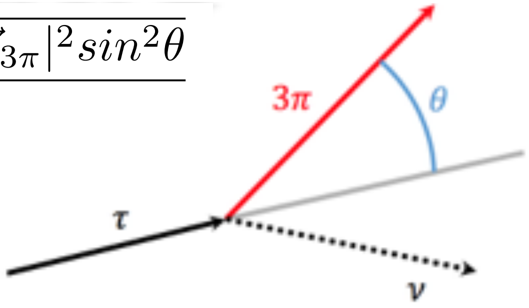
A 5 σ requirement kills the $D^*3\pi(X)$ background by $>10^4$

$B\to D^*\tau\nu$, with $\tau\to3\pi(\pi^0)$

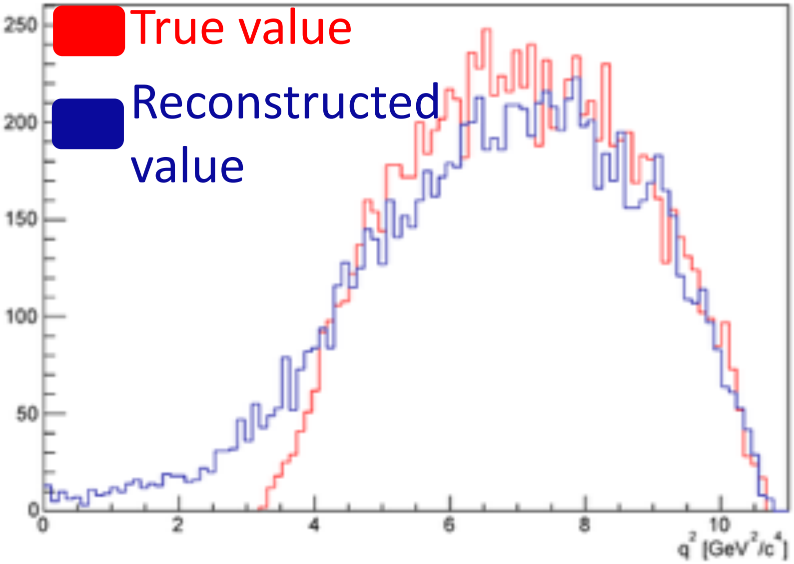
- Remaining background from B^0 decays where the 3π vertex is transported away from the D^0 vertex by a **charm carrier:** D_s, D^+ or D^0 (in order of importance)
- $Br(B\to D^{*}\text{'}D\text{'};\ \text{'}D\text{'}\to3\pi)\ /\ Br(B\to D^*\tau\nu;\ \tau\to3\pi(\pi^0)\nu)_{\rm SM}$ **~10**
- LHCb has **three very good 'weapons'** to suppress this background:
  - Background partial reconstruction
  - Dynamics of 2π, 3π system
  - Neutral isolation
- Use multi-variate analysis to maximize discrimination
- Expect statistical uncertainties at the 6% level
- Must keep systematic at the same level
  - Limitation due to the large error (11% PDG 2014) on the normalisation $Br(B^0\to D^*3\pi)$ is now overcome by new Babar measurement at 4%, shown last Sunday at Moriond EW!

Signal reconstruction

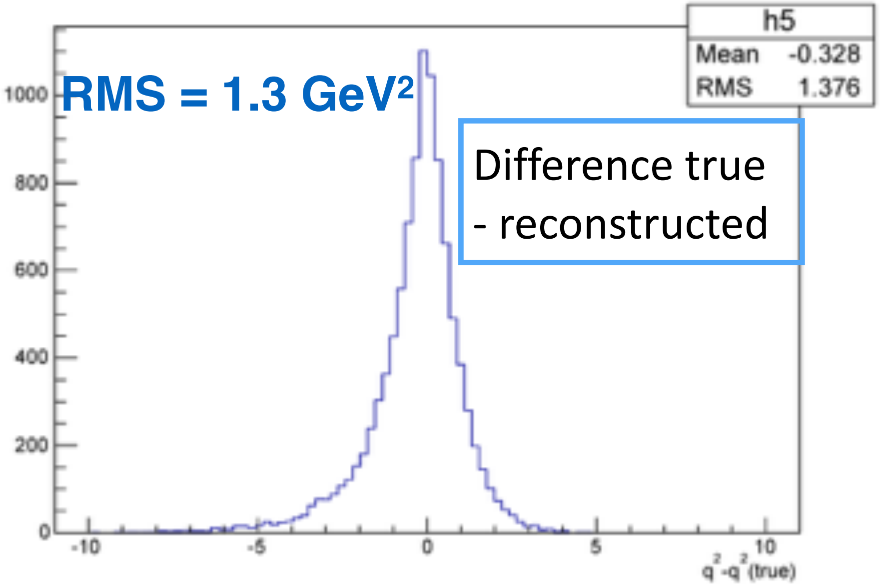
$$|\vec{p}_\tau| = \frac{(m_{3\pi}^2 + m_\tau^2)|\vec{p}_{3\pi}|cos\theta \pm E_{3\pi}\sqrt{(m_\tau^2 - m_{3\pi}^2)^2 - 4m_\tau^2|\vec{p}_{3\pi}|^2 sin^2\theta}}{2(E_{3\pi}^2 - |\vec{p}_{3\pi}|^2 cos^2\theta)}$$



- Reconstruct τ and B kinematics by exploiting vertex separation
- Choose θ such that argument of square root vanishes
- Good resolution on kinematical variables

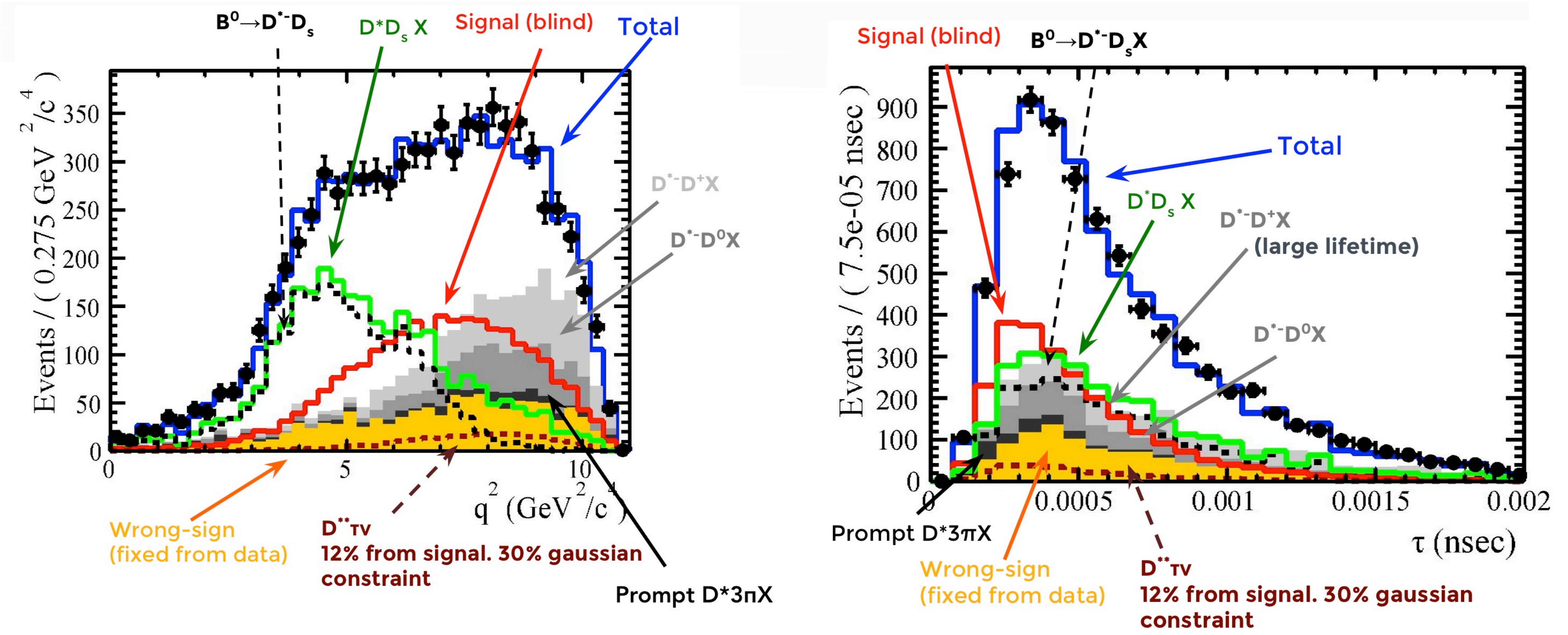

🟥 True value

🟦 Reconstructed value


RMS = 1.3 GeV²

Difference true - reconstructed

Current status



Statistical uncertainty on signal ~6%

Outlook

- The measurements of CP asymmetries in mixing (a_{sl}^{s}, a_{sl}^{d}) and of the CKM matrix element $|V_{ub}|$ show that it is possible to do precision physics in semileptonic decays of b hadrons even in the harsh environment of LHCb
- Decays with taus in the final state look promising. For $B \rightarrow D^{*}\tau\nu$:
  - Leptonic mode: same level of precision (~10%) as B Factories
  - 3-prong mode: aiming at statistical precision at the 6% level.
- Further exploit other modes with taus:
  - $B \rightarrow D^{0}\tau\nu$, $B_s \rightarrow D_s\tau\nu$, $\Lambda_b \rightarrow \Lambda_c\tau\nu$
- Several tools and techniques are being exploited to reconstruct SL decays, suppress backgrounds and disentangle "ground state" signals from higher "excitations"

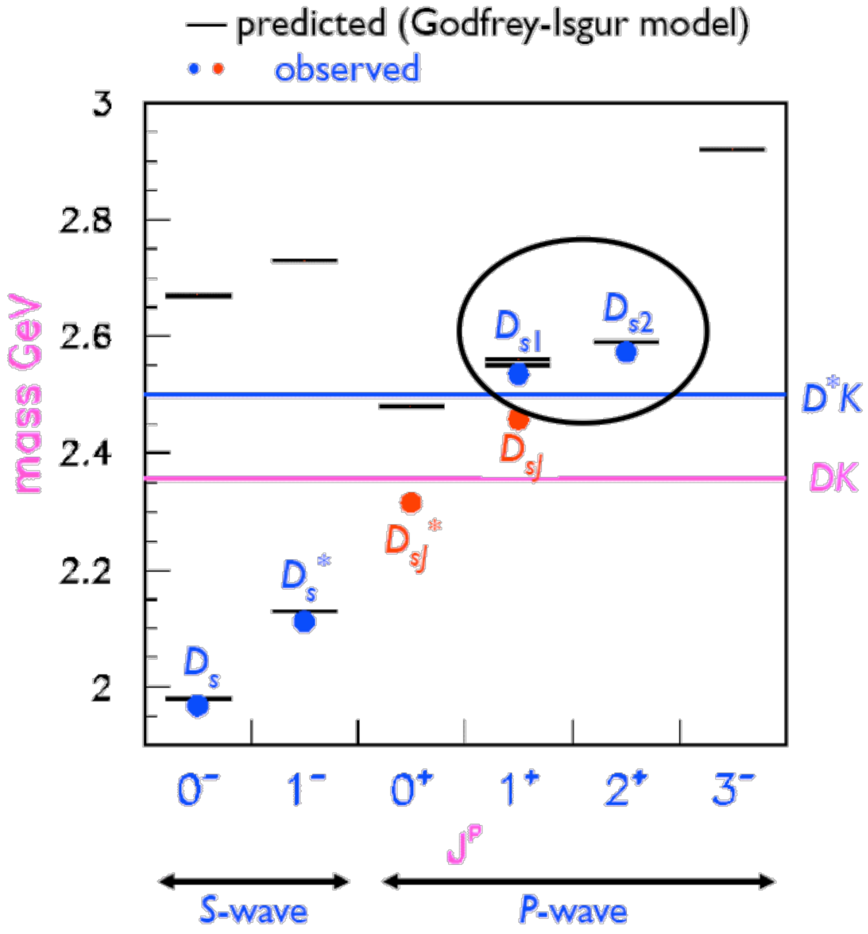
backup

Composition of SL width

- Even less experimental information of exclusive B_s decays.
- Final states with D^0K can be used to measure $B_s \rightarrow D_s^{**}\mu\,\nu$.

$$\boxed{D'_{s1}, D^*_{s2} \rightarrow D^{(*)}K}$$

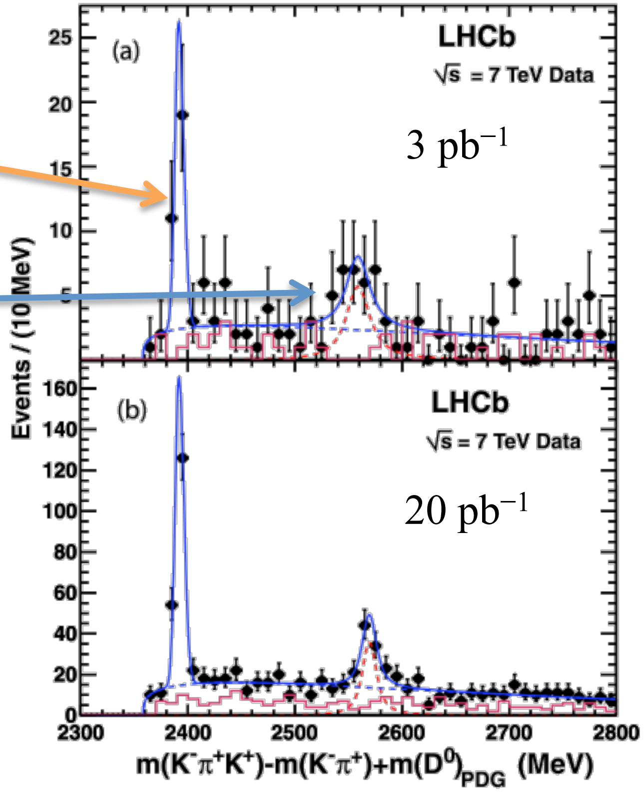
$$\boxed{D^{(*)}_{sJ} \rightarrow D_s^{(*)+} + n(\pi^0\ or\ \gamma)}$$



Composition of SL width

LHCb [PLB 698 (2011) 14]

- Observed D^0K spectrum from $B_s \rightarrow D_s^{**} \mu\,\nu$



$D_{s1}(2536)^+ \rightarrow D^*(2007)^0 K^+$

(missed π^0 or γ)

$D_{s2}(2573)^+ \rightarrow D^0 K^+$

Significance: 8.3σ

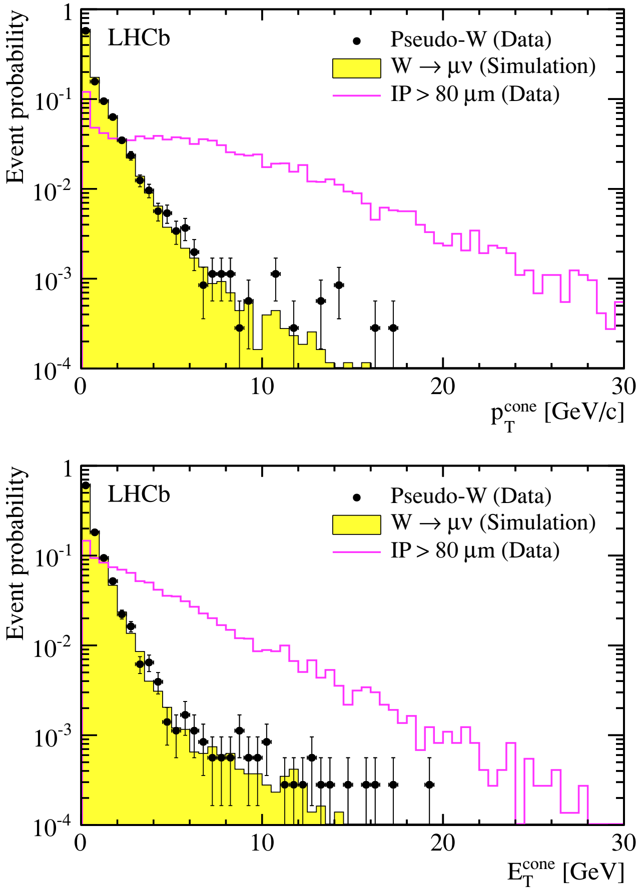
$$\frac{\mathcal{B}(\overline{B}{}^0_s \rightarrow D_{s2}^{*+} X \mu^- \overline{\nu})}{\mathcal{B}(\overline{B}{}^0_s \rightarrow D_{s1}^{+} X \mu^- \overline{\nu})} = 0.61 \pm 0.14 \pm 0.05.$$

$$\frac{\mathcal{B}(\overline{B}{}^0_s \rightarrow D_{s2}^{*+} X \mu^- \overline{\nu})}{\mathcal{B}(\overline{B}{}^0_s \rightarrow X \mu^- \overline{\nu})} = (3.3 \pm 1.0 \pm 0.4)\%$$

$$\frac{\mathcal{B}(\overline{B}{}^0_s \rightarrow D_{s1}^{+} X \mu^- \overline{\nu})}{\mathcal{B}(\overline{B}{}^0_s \rightarrow X \mu^- \overline{\nu})} = (5.4 \pm 1.2 \pm 0.5)\%,$$

Improving isolation

JHEP06(2012)058
Inclusive W and Z production in the forward region at √s = 7 TeV



- Transverse momentum & energy in a cone around muon in W decays successfully employed in measurement of inclusive W production
- Possible use in SL decays as discriminating variables to veto decays with extra “activity”.

Semileptonic publications

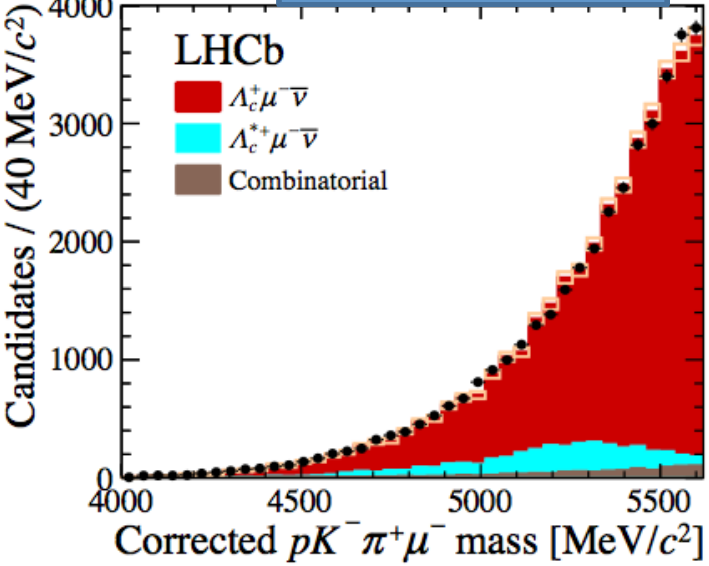
- CP violation and $\Delta m_{d,s}$ studies
  - Semileptonic asymmetries
  - CP violation in charm
  - B_s, B_d oscillations

a_{sl}^{d} [PRL 114, 041601 (2015)]
a_{sl}^{s} [PLB 728 (2014) 607]
ΔA_{CP} [JHEP 07 (2014) 041] and [PLB 723 (2013) 33]
A_{Γ} [arXiv:1501.06777]
$\Delta m_{d,s}$ [EPJC 73 (2013) 12, 2655]

- $b\underline{b}$ cross section at 7 TeV [PLB 694 (2010) 209]
- b-hadron production fractions [PRD 85 (2012) 032008]
- $B_s \to D_s^{**} X \mu \nu$ branching ratio [PLB 698 (2011) 14]
- V_{ub} measurement [arXiv:1504.01568, submitted to Nature Physics]

$\Lambda_b \rightarrow \Lambda_c$ form factor

- Use $\Lambda_b \rightarrow \Lambda_c \, \mu \, \nu$, with $\Lambda_c \rightarrow p \, K \, \pi$.
- Add 2 pions to observe of excited $\Lambda_c(2595)$ and $\Lambda_c(2625)$
  - Subtract from inclusive $\Lambda_c \, \mu \, X$
- Use neutrino-reconstruction to get 4-velocity transfer, *w*
  - Use SVD method for deconvolution
- Analysis in advanced state.
  - Expect uncertainty on $\rho^2 \approx 0.08$
  - Systematics from w resolution, detector efficiencies and Λ_c^* modeling
- Is there a good normalization channel to extract V_{cb} ?

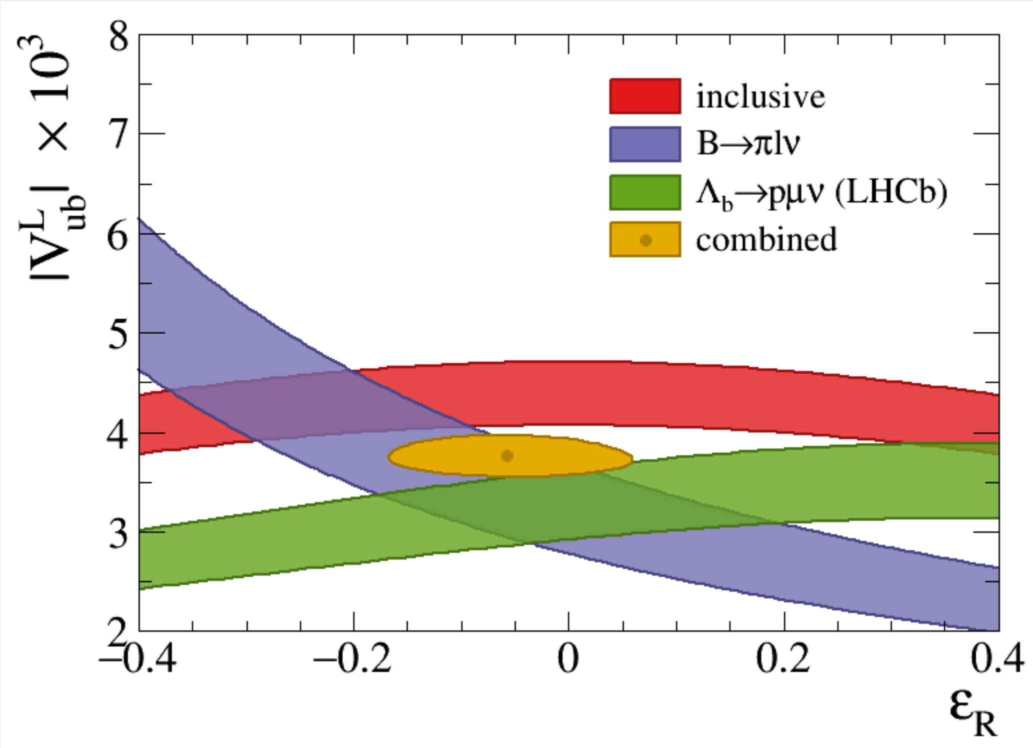


From V_{ub} paper

Right-handed currents?

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V^L_{ub}(\bar{u}\gamma_\mu P_L b + \epsilon_R \bar{u}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu P_L l) + h.c.$$

The dependence on a right handed current is different for $\Lambda_b \rightarrow p\mu\nu$ as there is also an axial vector current



arXiv:1504.01568, submitted to Nature Physics

Right-handed currents disfavoured

Can we do more at LHCb?

- Exclusive measurements are **challenging**
- First exclusive $|V_{ub}|$ using $\Lambda_b \to p\ \mu\ \nu$ **paves the way for other semileptonic decays**
  - $\Lambda_b \to \Lambda_c\ \mu\ \nu$
  - $B \to \rho(\pi\pi)\mu\nu$
  - $B_s \to K\mu\nu$ and $B_s \to D_s\mu\nu$
  - Other options: B_c?
- Problem: **normalization** to CF decay (as in V_{ub}).
- Normalization uncertainties:
  - *bb* cross-section → **19%**

    LHCb: [PLB 694 (2010) 209]
    - Need normalization channel, or
    - use (almost) fully reconstructed OS tag.
  - *b*-hadron production fractions

    LHCb: [PRD 85 (2012) 032008]
    - Branching fractions for B_s and Λ_b **not well known**.
- Precision on **rest-frame observables** (q^2).
  - Neutrino reconstruction
  - Same-side tagging

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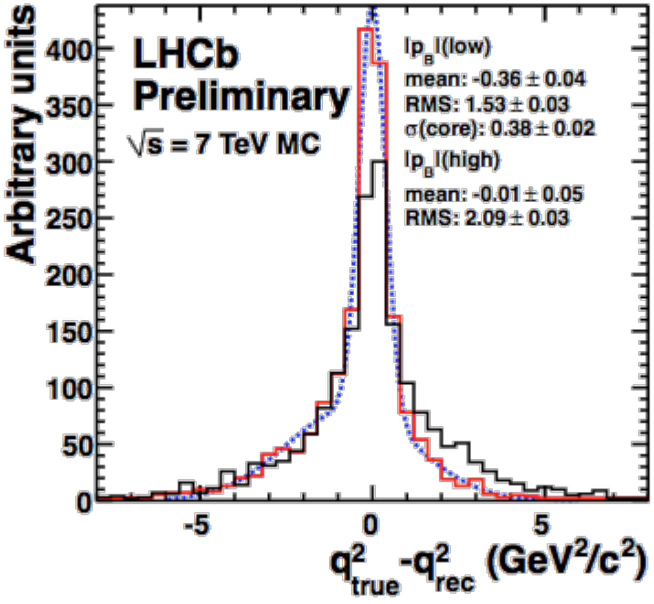
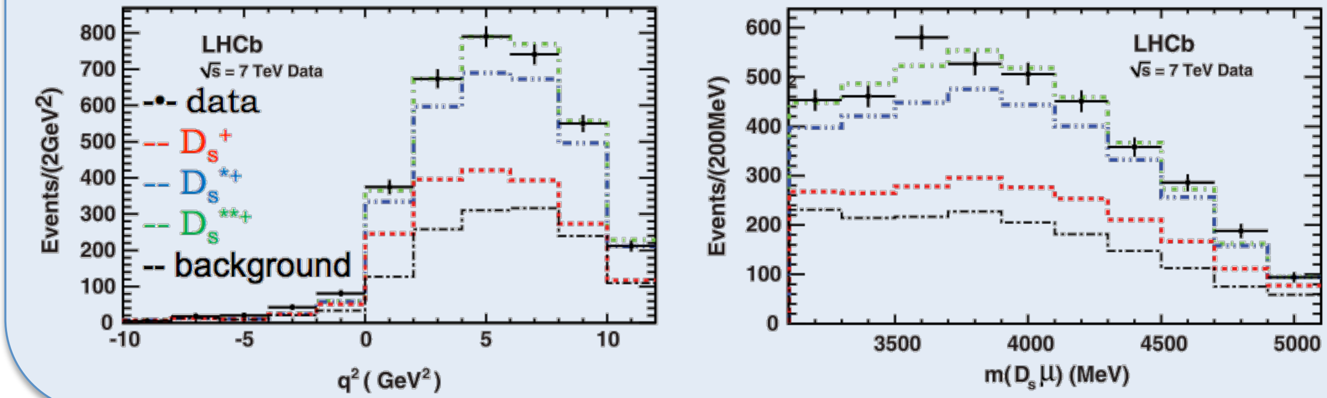
Urquijo [arXiv:1102.1160]



Separate higher D_s & Λ_c resonances

2D fits to q^2 and m_{vis}

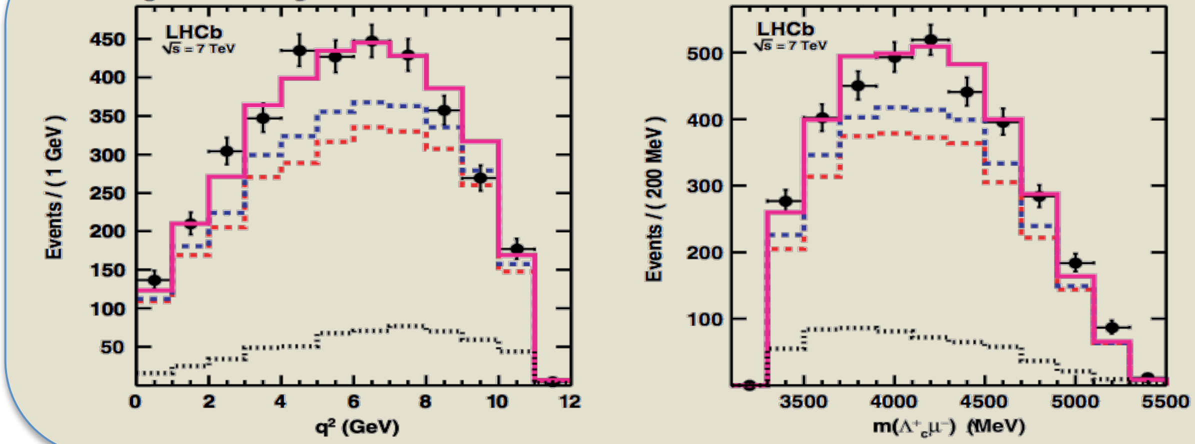
$\overline{B}{}_s^0 \to D_s^{+(*)(**)}\mu^-\overline{\nu}$



[PRD 85 (2012) 032008]

- Use D and D^{*+} form factors for D_s and D_s^*
- Fix fraction D_s^*/D_s=D^*/D=2.42

$\Lambda_b^0 \to \Lambda_c^{+(**)}\mu^-\overline{\nu}$



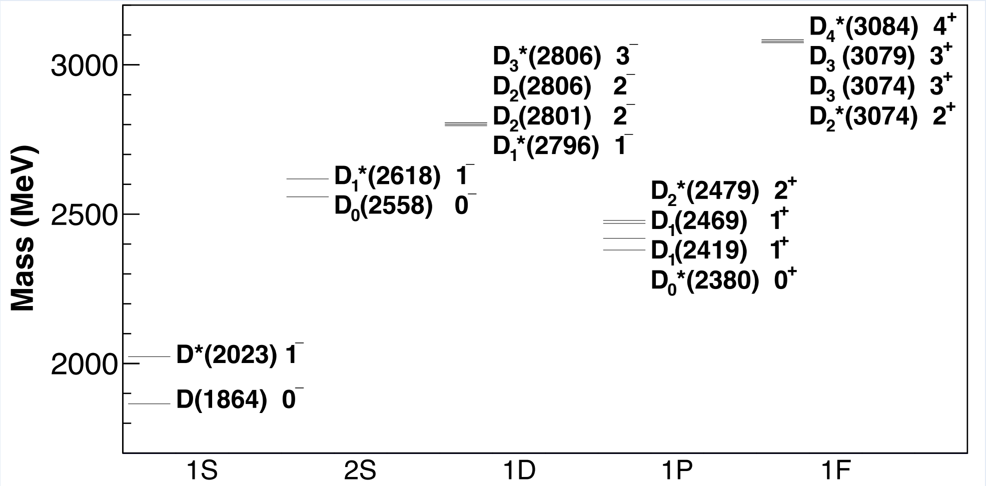
[PRD 85 (2012) 032008]

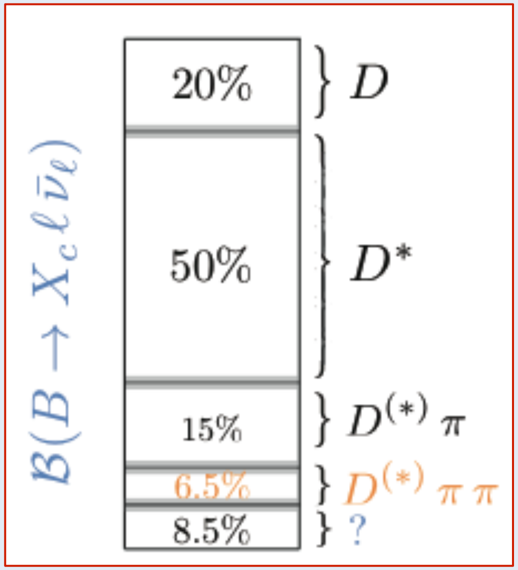
Ratio $\Lambda_c(2595)/\Lambda_c(2625)$ fixed to prediction:
[Phys. Rev. C 72 035201 (2005)]

Composition of SL width

Composition of inclusive $B \to X_c l \nu$ width not fully understood.

- Recent update by BaBar bridges half of the gap.
- 8.5% still unknown.

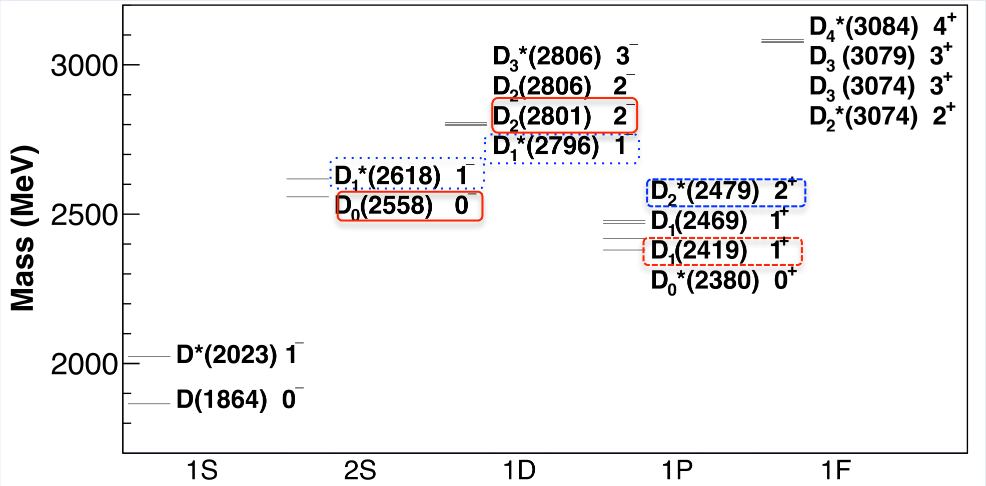


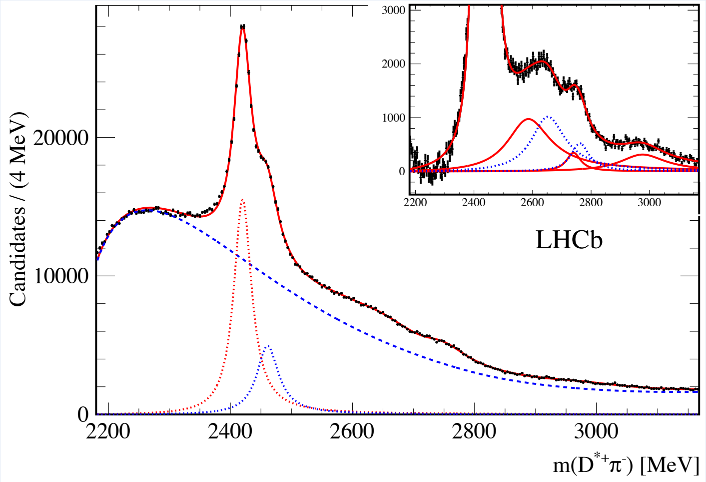


From F. Bernlocher, CKM14

Composition of SL width

- LHCb can study for resonant $B \to X_c\, l\, \nu$ structure
  - Including radial excitations $D^{(*)\prime}$
  - High statistics invariant mass spectrum
- **Example**: spectroscopy from **prompt** samples:

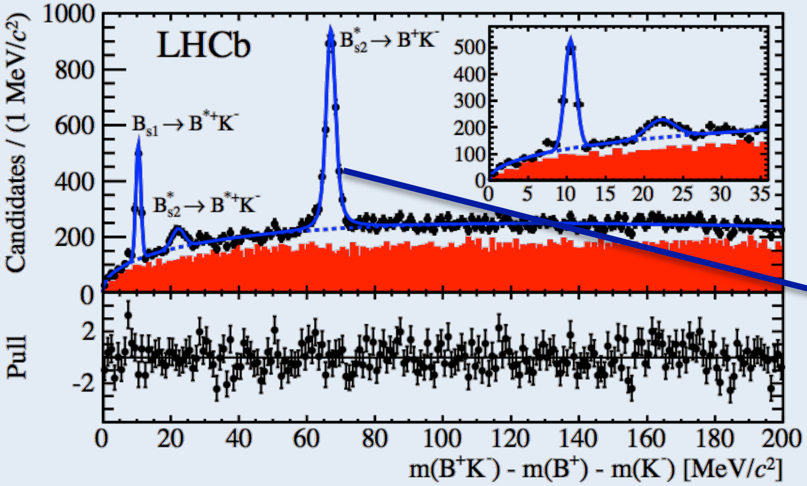




LHCb [JHEP 09 (2013) 145]

Same-side tagging (B_{s2}^{*})

- **Narrow width**: $B_{s2}^{*} \rightarrow B^{+} K^{-}$ additional constraint



[Phys. Rev. Lett. 110 (2013) 151803]

~3000 candidates/fb

- Possible use for:
  - $B^{+} \rightarrow \rho(\pi\pi)\,\mu\,\nu$: **Angular analysis** to extract form factors and $|V_{ub}|$
  - $B^{+} \rightarrow D\,\mu\,\nu$: Study of D^{**} states and in $D^{0}\tau\nu$.
  - $B^{+} \rightarrow KK\,\mu\,\nu$: ***ss*-popping** in *b*→*u*. First measurement of $B^{+} \rightarrow \varphi\,\mu\,\nu$
- Extend to **neutral B mesons**: $B_{s2}^{*} \rightarrow B^{0} K^{0}$

Big picture

$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ (normalization)

$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$
(signal)

$\bar{B}^0 \to D^{**+}\mu^-\bar{\nu}_\mu + \bar{B}^0 \to D^{**+}\tau^-\bar{\nu}_\tau$
$\bar{B}^- \to D^{**0}\mu^-\bar{\nu}_\mu + \bar{B}^- \to D^{**0}\tau^-\bar{\nu}_\tau$
$D^{**} \to D^{*+}\pi$ (3 states each, 6 PDFs)

$\bar{B}_s^0 \to D_s^{**+}\mu^-\bar{\nu}_\mu$
$D_s^{**+} \to D^{*+}K_S^0$, (2 states, 1 free param)

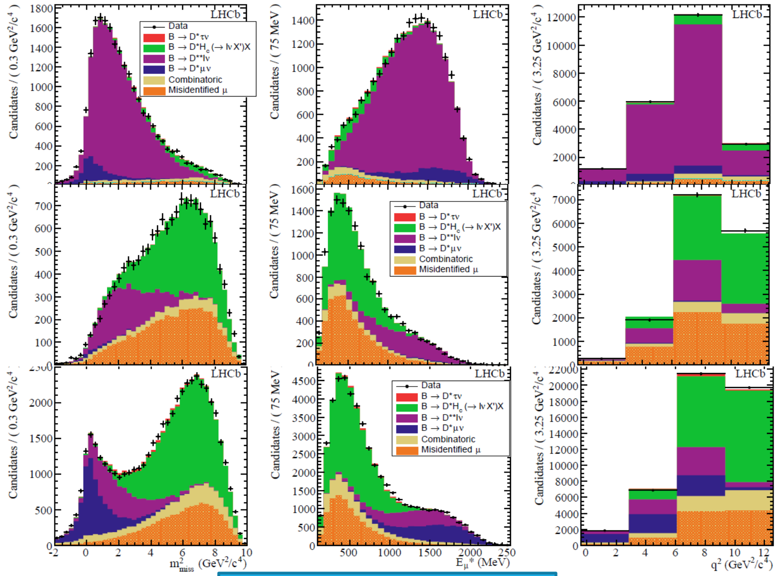
$B^{+,0} \to \bar{D}^{**}\mu^+\nu_\mu$
$\bar{D}^{**} \to D^{*-}\pi\pi$, (cocktail)

$\bar{B} \to D^{*+}H_c(\to \mu\nu X')X$
$+\bar{B} \to D^{*+}D_s^-(\to \tau^-\bar{\nu}_\tau)X$

combinatorial D^{*+}
combinatorial $D^{*+}\mu^-$

$h \to \mu$ misidentification

Control sample fits to constrain shapes

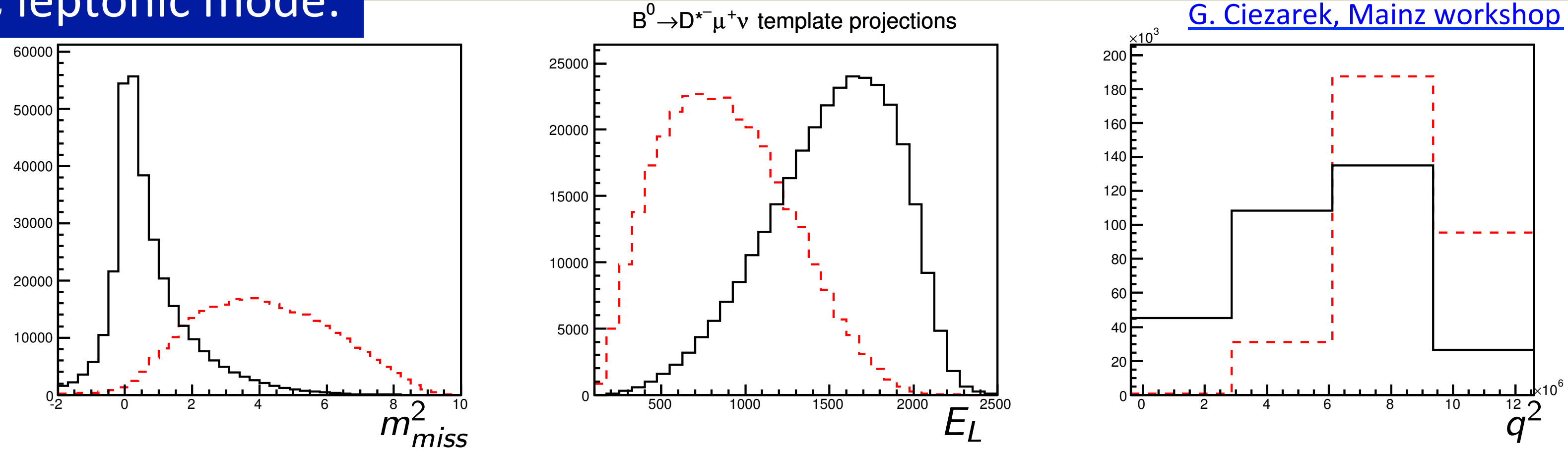


$B \rightarrow D^* \tau \nu$ at LHCb

- Experimentally challenging due to **additional neutrino(s)**
- Two tau decay modes being studied:

  leptonic: $\tau \rightarrow \mu \nu_\mu \nu_\tau$ 3-prong: $\tau \rightarrow 3\pi(\pi^0)\nu_\tau$
- Main backgrounds: **partially reconstructed B decays**
  - D*(*)μν, D*3πX, D*D(s)(*)X…
  - use **isolation criteria** (MVA) and/or **τ flight length**
- Find and fit distributions which differentiate **signal** and **background**.

τ leptonic mode:



G. Ciezarek, Mainz workshop

$B \to D^* \tau \nu$ at LHCb

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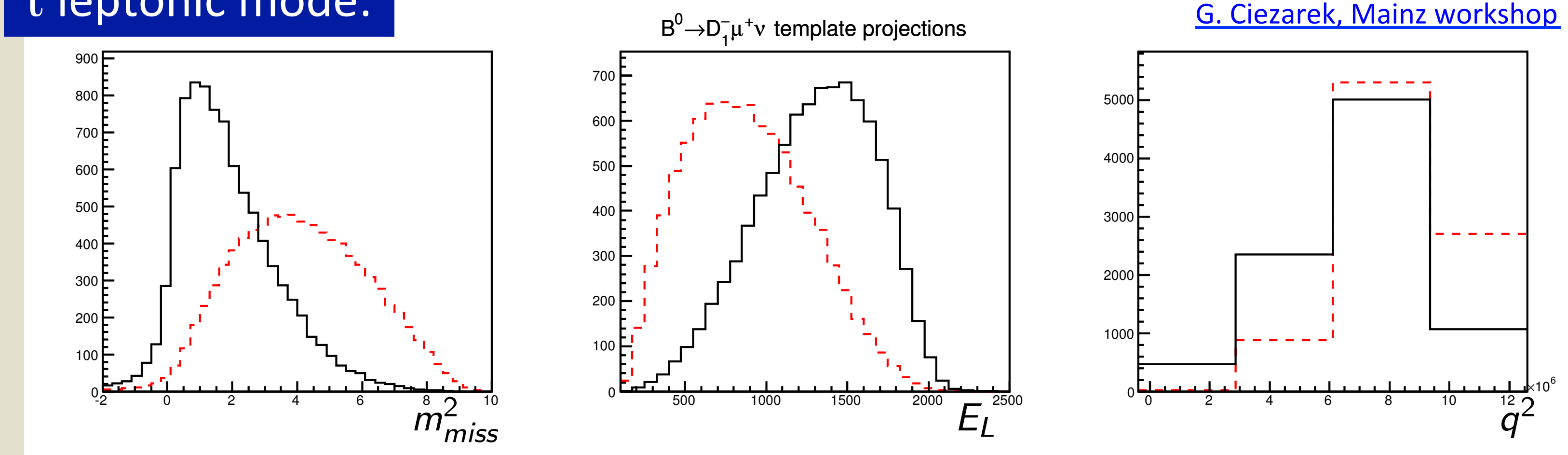
τ leptonic mode:



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Toy data (leptonic mode)

B rest frame variables computed with "boost approximation":

- *B* boost >> energy release in the decay
- Assume $\gamma\beta_{z,\text{visible}} = \gamma\beta_{z,\text{total}}$
- Use *B* flight direction to measure transverse component of missing momentum
- ~18% resolution on *B* momentum

Example of templates obtained with toy data

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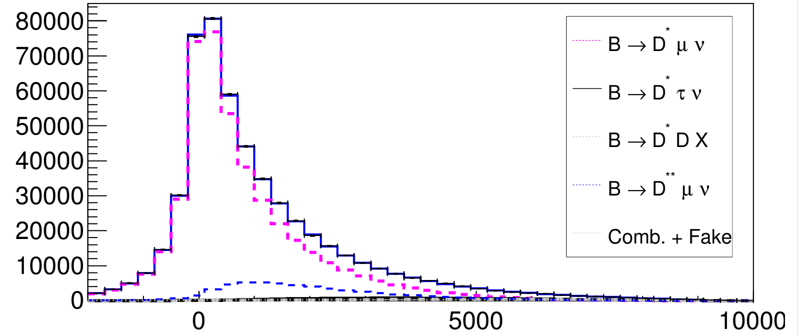

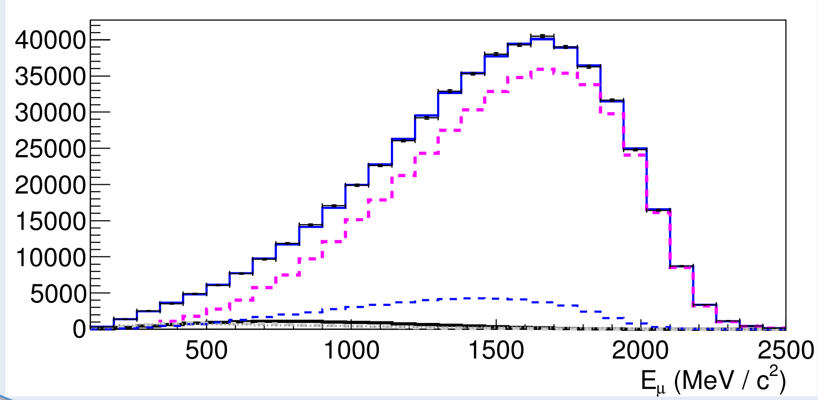

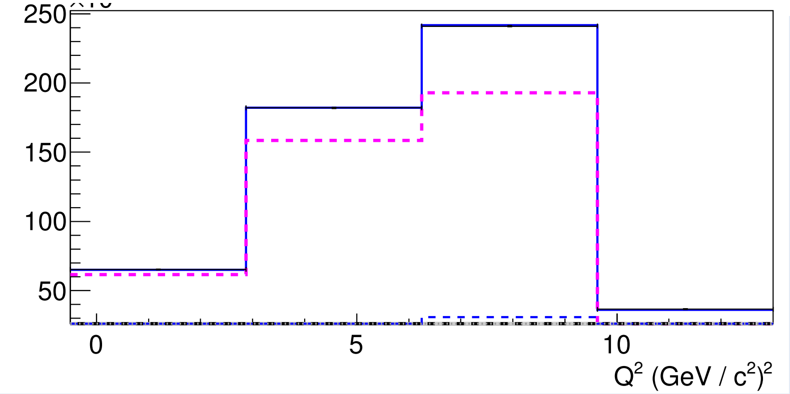

Control samples (leptonic mode)

Get templates directly from data. Look for events:

- with one or more tracks selected by isolation MVA, to get samples enriched in $B \to D^{**}(D^{*}\pi(\pi))\mu\nu$
- with a track with loose kaon ID, to get a sample enhanced in $B \to D^{*}DX$

Example of templates for $B \to D^{**}(D^{*}\pi)\mu\nu$ obtained with toy data

[G. Ciezarek, Mainz workshop]