Heavy Flavour Physics Workshop
Sapienza, Università di Roma, 17 Feb 2020

Semileptonic Decays:
recent results and opportunities

Marcello Rotondo

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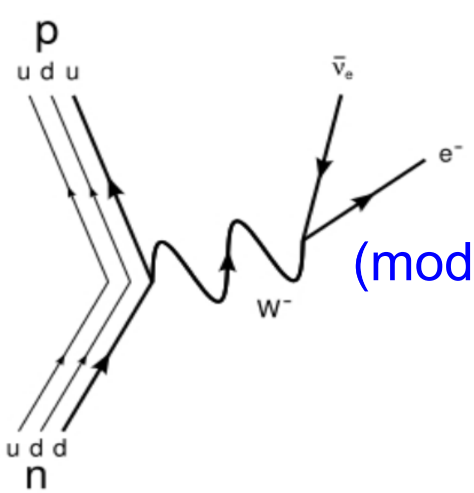
Semileptonic decays

Nucleon β-decays



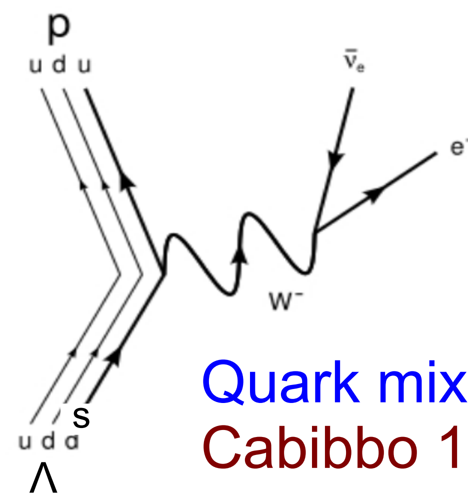
Fermi 4-body interaction

$$G_F \approx 1.17 \times 10^{-5} GeV^{-2}$$

(modern language) W-boson exchange

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8m_W^2}$$

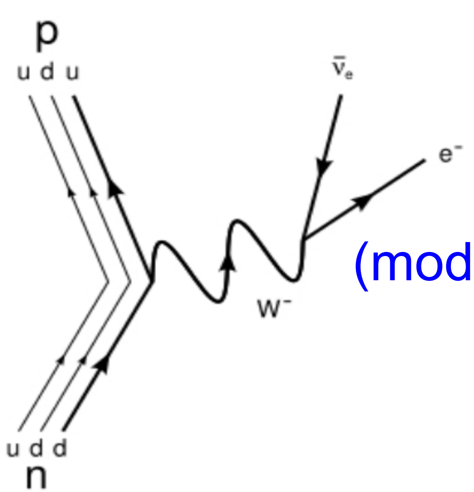
Hyperon semileptonic decays



Quark mixing:
Cabibbo 1961

Semileptonic decays

Nucleon β-decays



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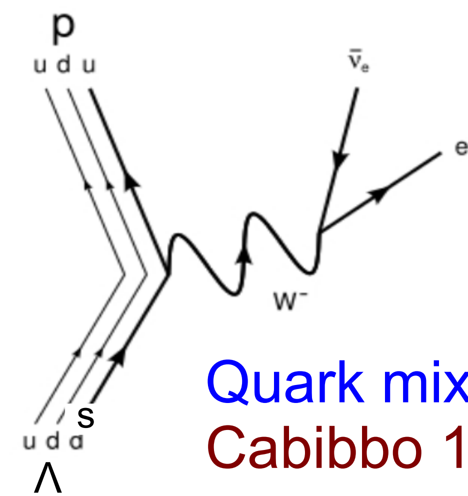

Quark mixing:
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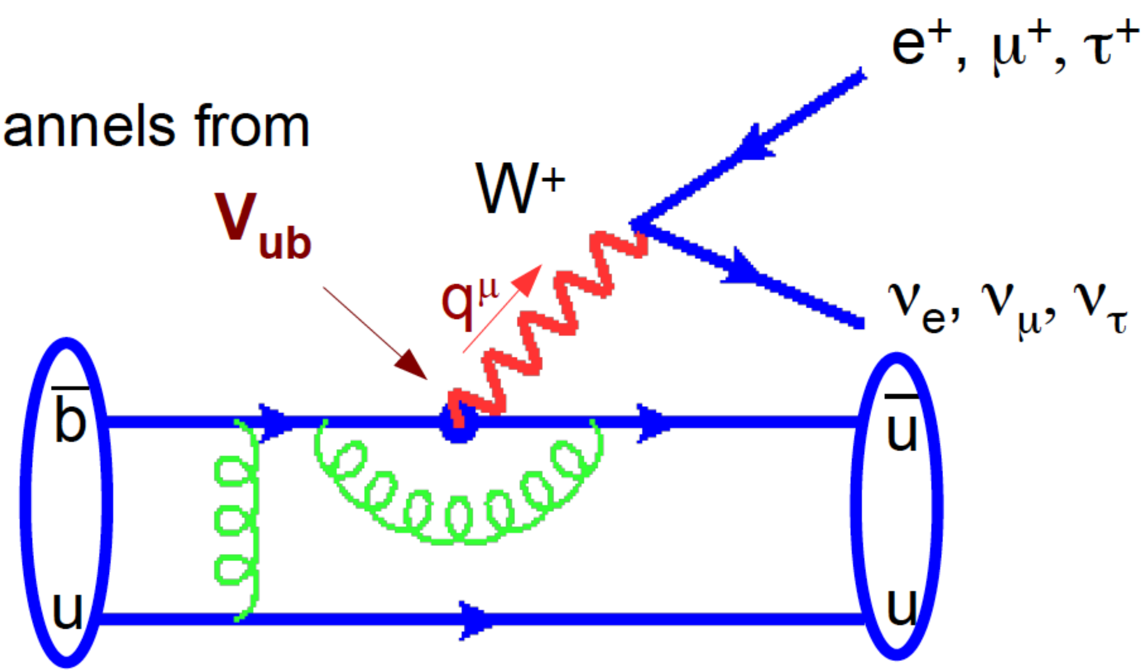
- Semileptonic decays are clean channels from theoretical point of view:

$$\mathcal{M}(B \to \pi \ell^- \overline{\nu}) = -i\frac{G_F}{\sqrt{2}} \cdot V_{ub} \cdot L^\mu H_\mu$$

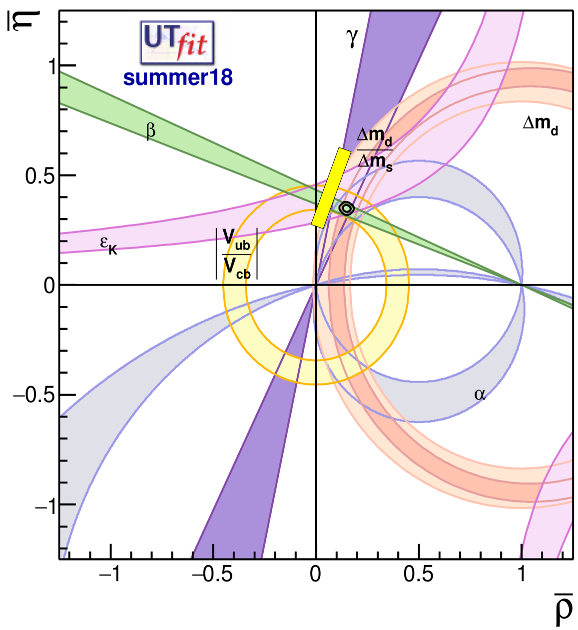
- Factorization of the hadronic and leptonic current: no final state interactions



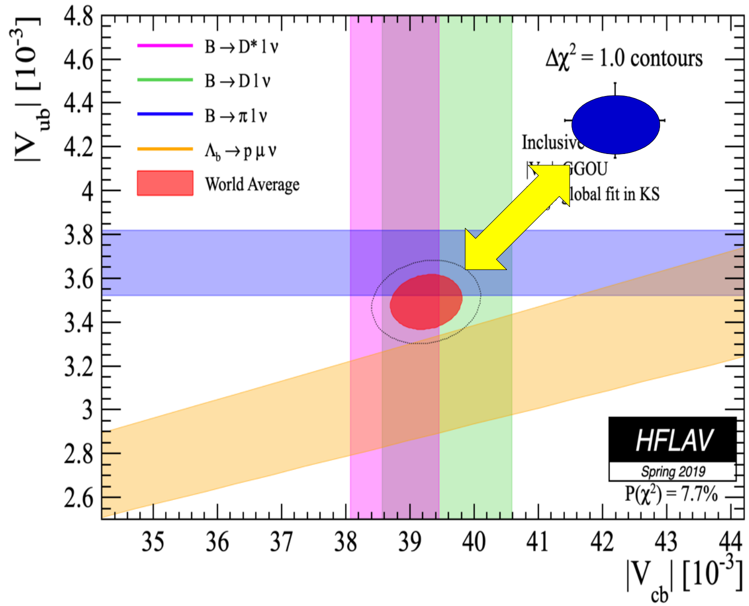
Why semileptonic B decays ?

… at least three reasons:

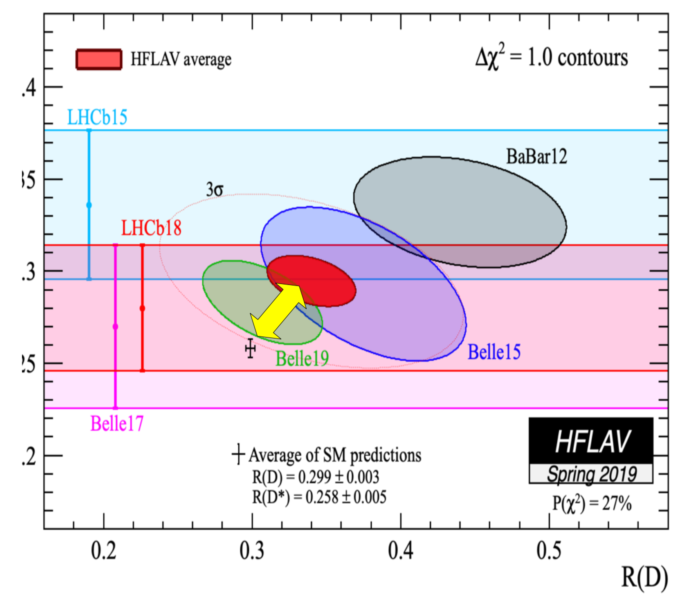
$$\frac{\Gamma(B \to D^{(*)}\tau\nu_\tau)}{\Gamma(B \to D^{(*)}\ell\nu_\ell)}$$



$|V_{xb}|$ provide crucial inputs for indirect search of New Physics



$|V_{ub}|$ and $|V_{cb}|$ discrepancies between different determinations: 3σ effect

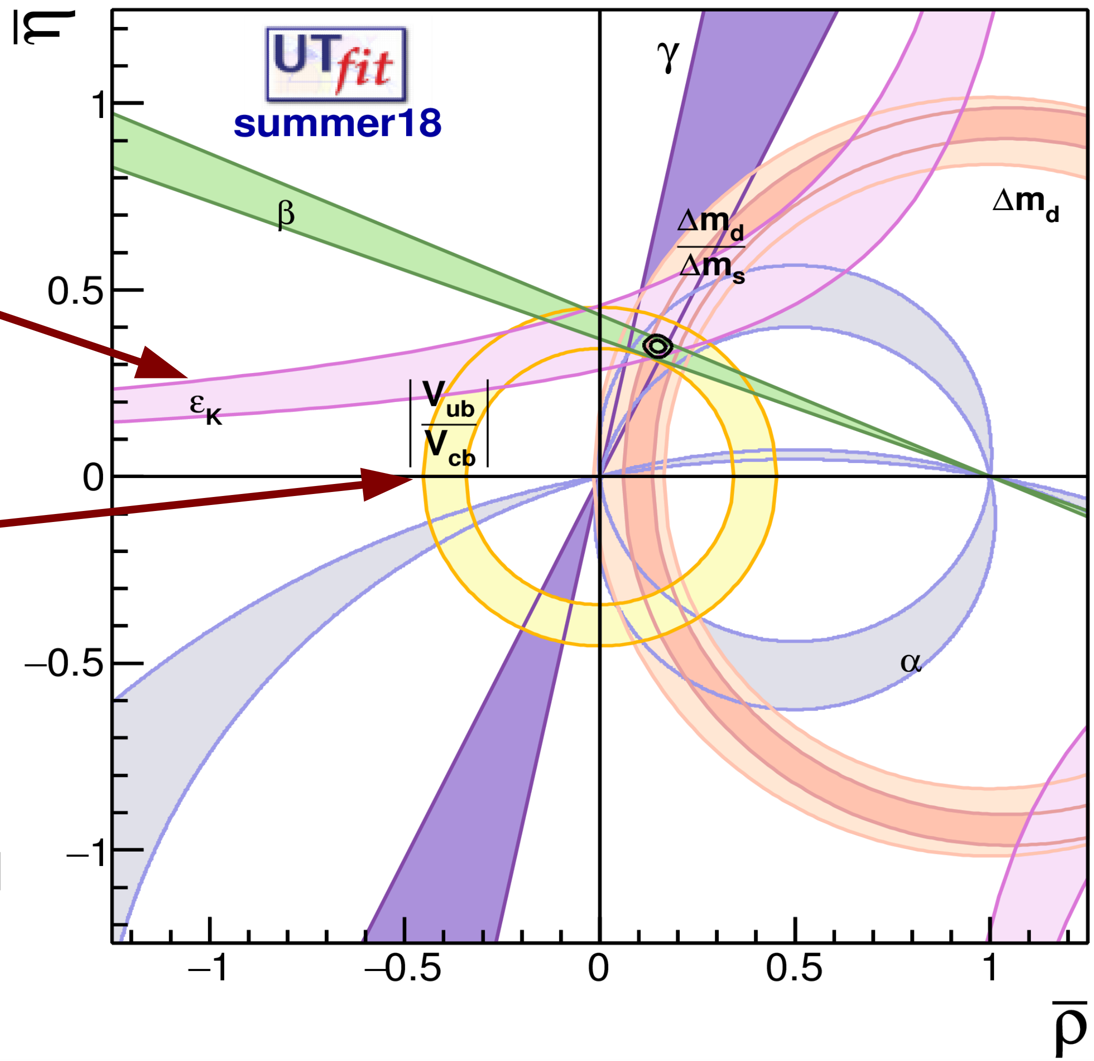


Difference with expectations @ about 3σ

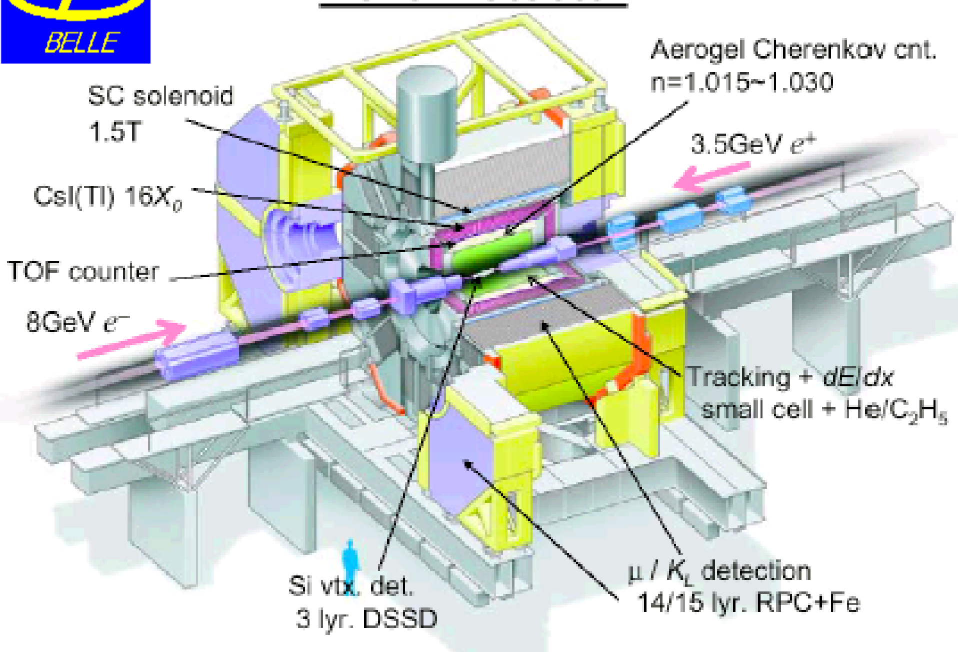
UT Status (Summer 2018)

- Prediction of FCNC processes $\propto |V_{tb}V_{ts}|^2 \approx |V_{cb}|^2[1+O(\lambda^2)]$

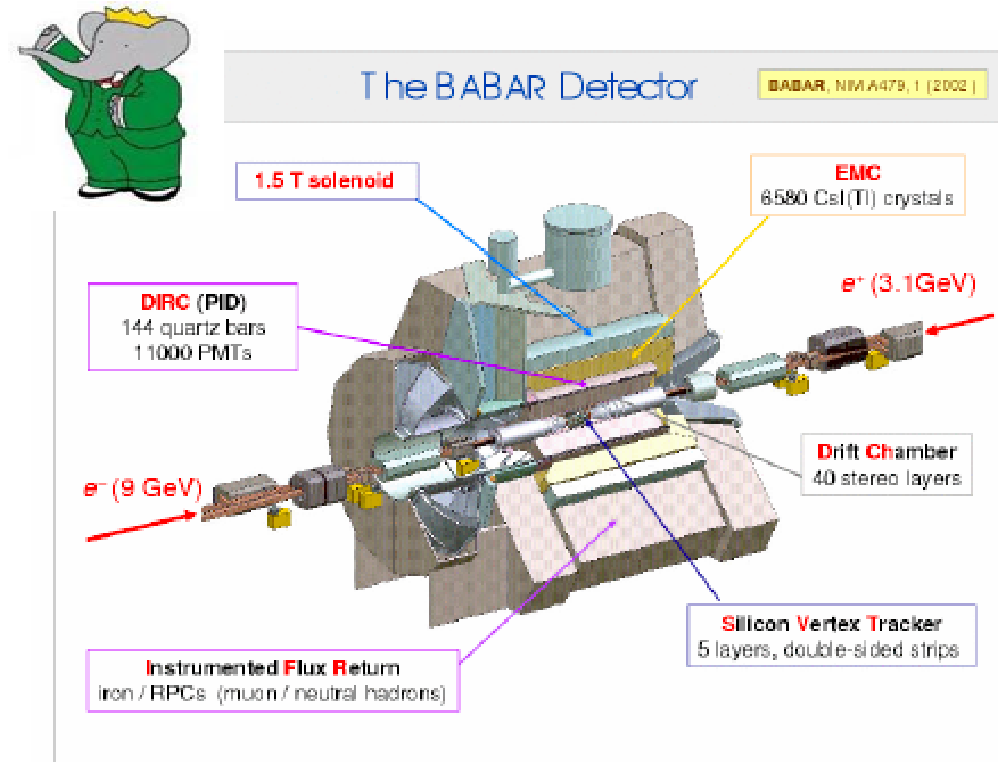
- $|V_{cb}|$ plays an important role in the determination of UT
  - $\epsilon_K \approx x|V_{cb}|^4 + \ldots$
- $|V_{ub}|$ is the side opposite to angle β
  - Tree level .vs. loops
- It is the smallest CKM matrix element:
  - It could be more sensitive to any small violation of the CKM paradigm



Experiments: B-Factories



@ KEK Japan: 1999-2009



@ SLAC: 1999-2008

B-Factories: hermetic detectors, low background, access (mainly) at $B^{0/+}$

About (771 + 467)x10^6 e^+e^- → BB events in the Belle+BaBar data

Belle and KEK is being upgraded

Belle II

Belle-II will collect $50ab^{-1}$ by ~2026

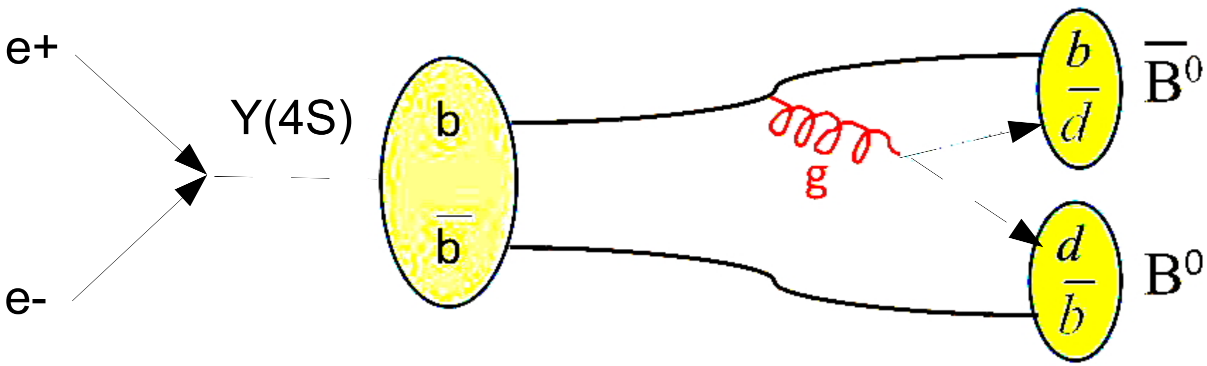
B-hadron production

$$\mathcal{N} \propto \mathcal{L} \cdot \sigma$$

- B-Factories: e^+e^- running at $\sqrt{s}\sim$ 10.58 GeV

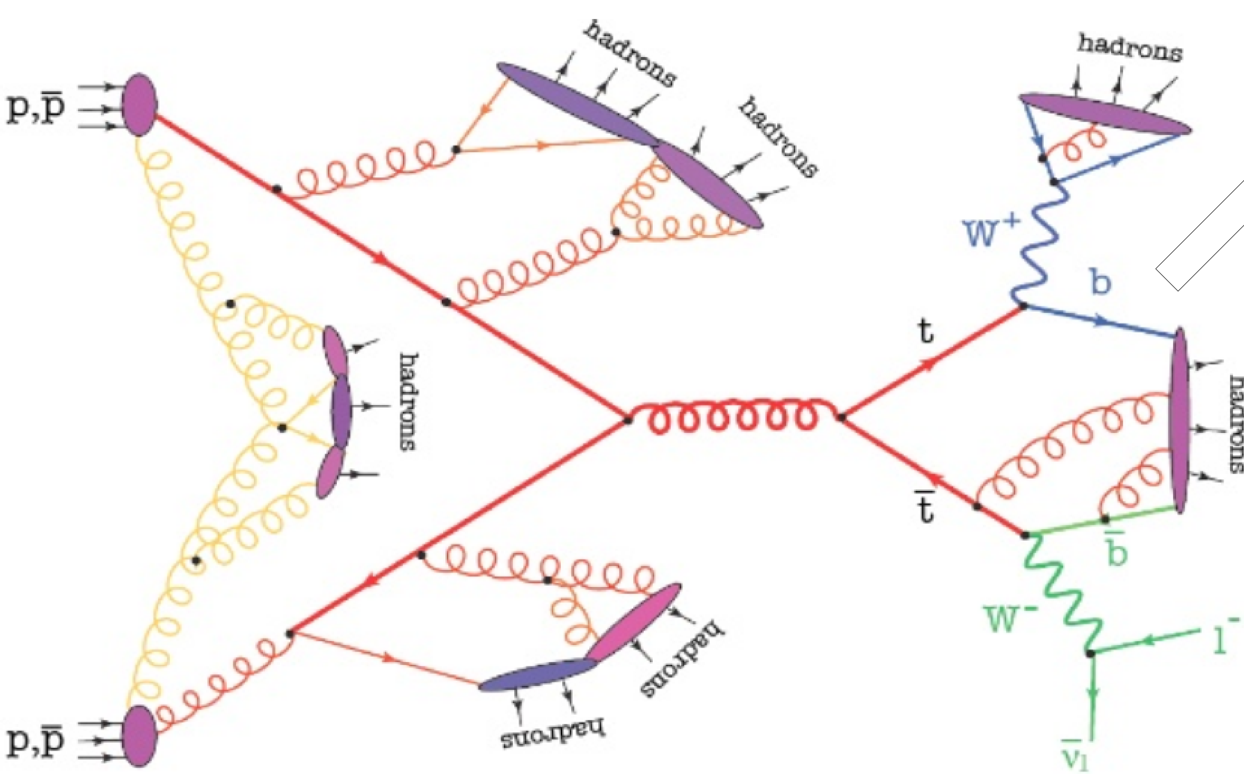
$$\sigma(e^+e^- \to \Upsilon(4S)) = 1.06 \text{ nb}$$

$$BF(\Upsilon(4S) \to B\overline{B}) \approx 100\%$$



BaBar: 430 fb^{-1}
Belle: 640 fb^{-1}
Belle-II expected 50 ab^{-1}

- Hadron machines: high energy pp (or $p\overline{p}$) collision



b-hadrons

$$\sigma(pp \to b\overline{b})_{7\ TeV} \approx 295 \cdot 10^3\text{nb}$$

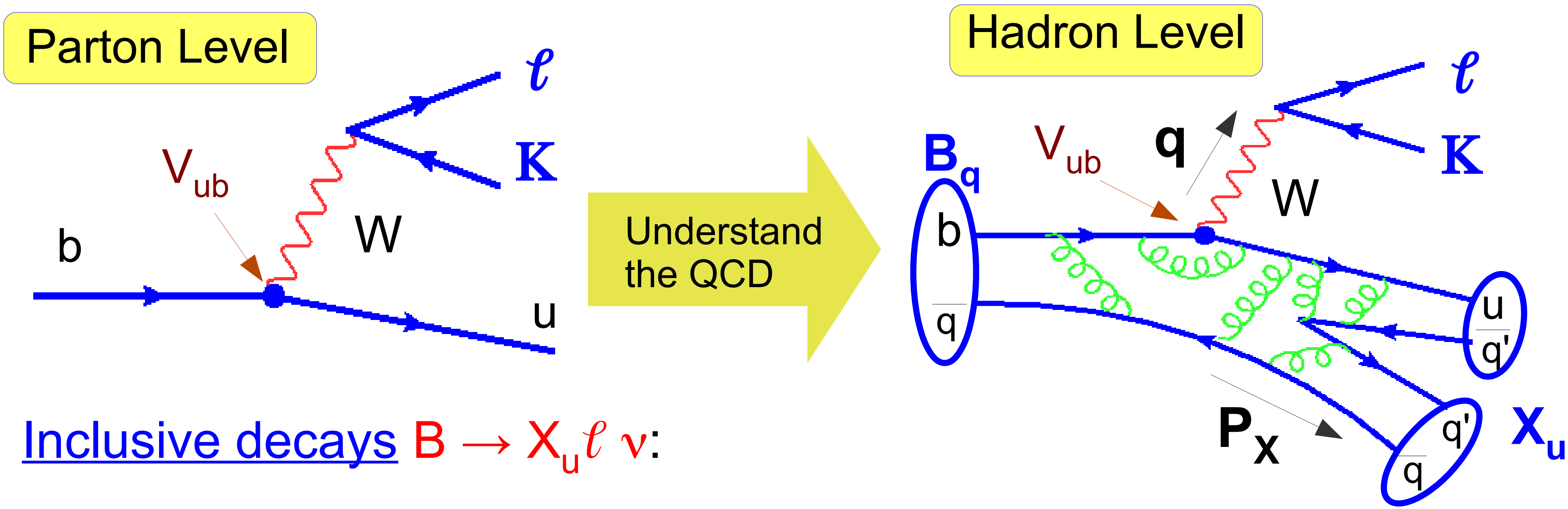
$$\sigma(pp \to b\overline{b})_{13\ TeV} \approx 600 \cdot 10^3\text{nb}$$

The b-quarks can hadronize in any kind of b-hadron
B_d, B_u, Λ_b, B_s, Ξ_b, Σ_b, Ω_b, B_c ...

LHCb: 3 fb^{-1} + 6 fb^{-1}

$|V_{ub}|$

Measurements of $|V_{ub}|$



- Inclusive decays $B \to X_u \ell \nu$:
  - Need to know QCD corrections to parton level decay rate
  - Operator Product Expansion predicts the total rate Γ_u
- Exclusive decays $B \to \pi \ell \nu \,/\, \rho \ell \nu$
  - QCD effects are embedded in the form factors

$$\frac{d\mathcal{B}(B \to \pi \ell \nu)}{dq^2} = |V_{ub}|^2 \frac{G_F^2 \tau_B}{24\pi^3} p_\pi^3 |f_+^{B\pi}(q^2)|^2$$

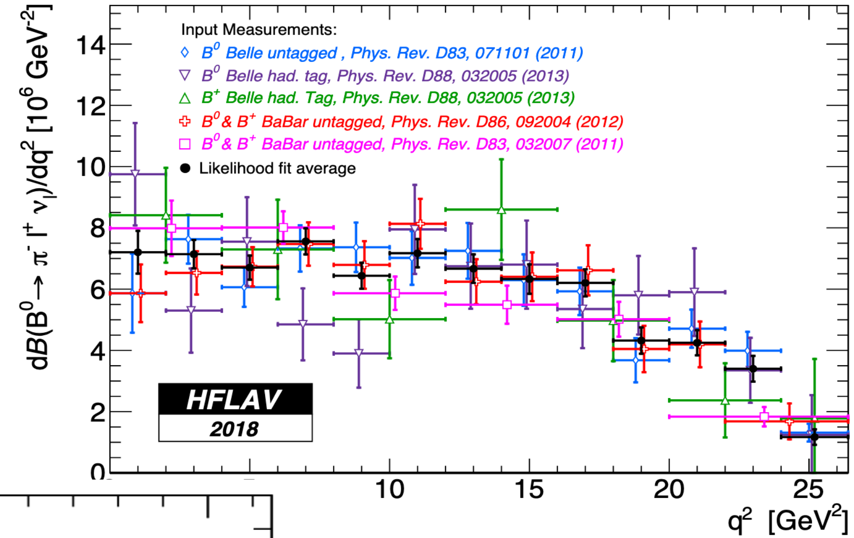
Leptons are considered massless: only one FF $B \to \pi$

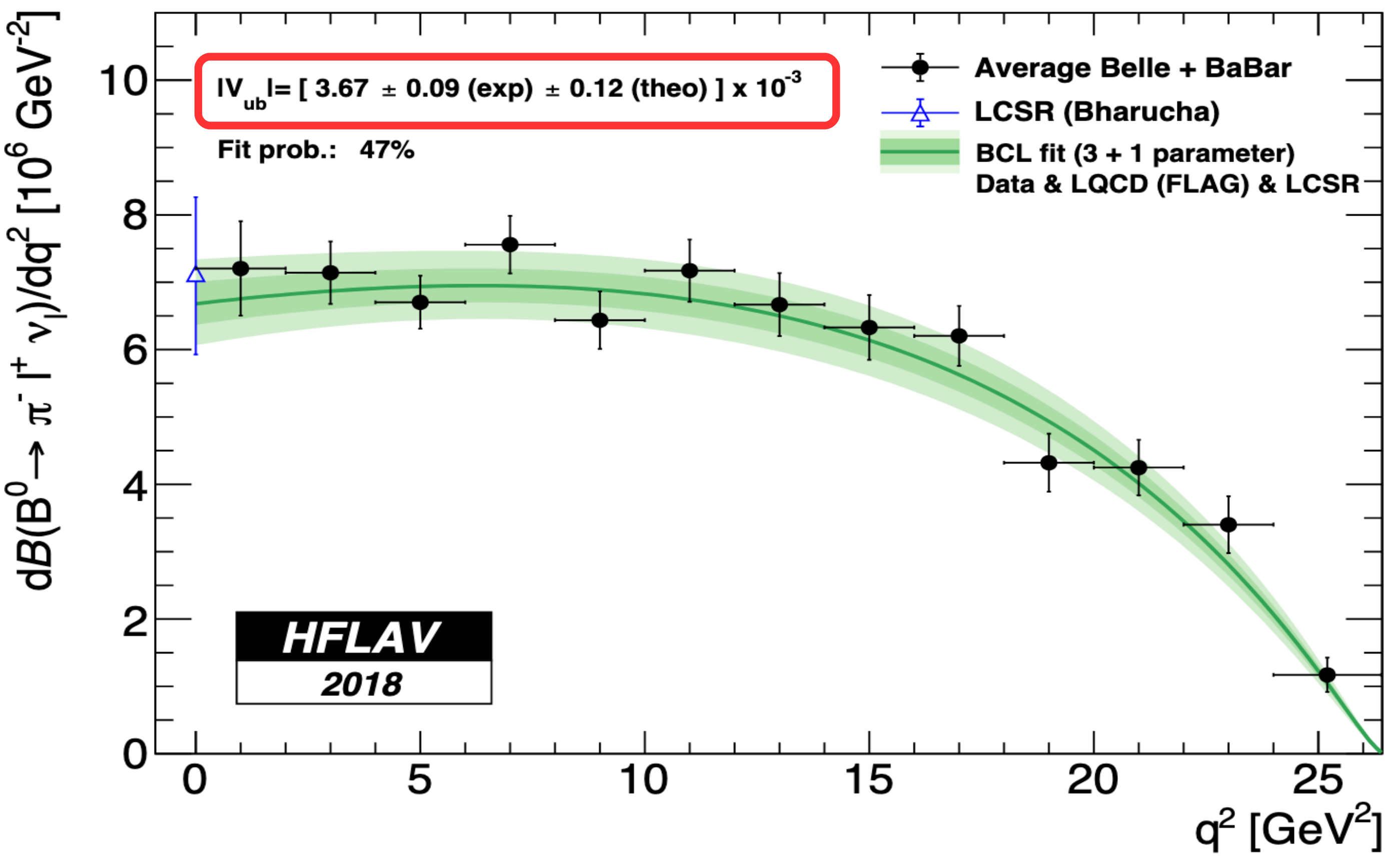
The state of the art at the B-Factories

$$B^0 \to \pi^+ \ell^- \bar{\nu}$$

$$B^- \to \pi^0 \ell^- \bar{\nu}$$

1) Many different experimental measurements:
Tagged and untagged
2) Signal extracted in bins of q^2





Results of the HFLAV combined fit of the experimental data and theoretical inputs:

- Lattice QCD (HPQCD, FNAL,…) at high q^2
- light Cone Sum Rules at low q^2

Semileptonic decays

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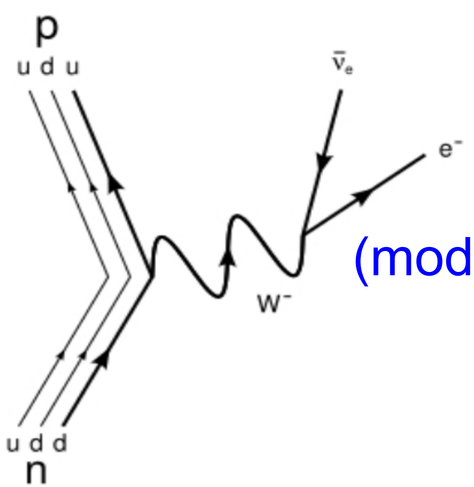

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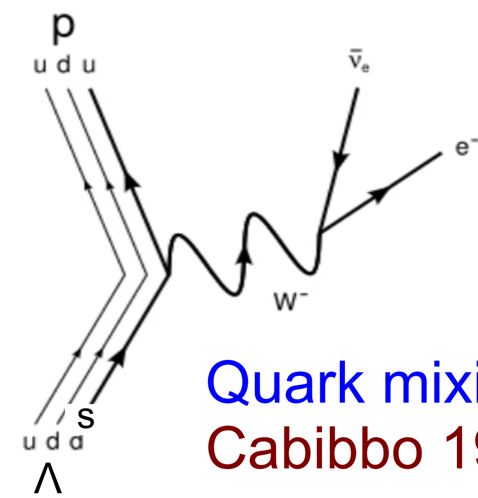

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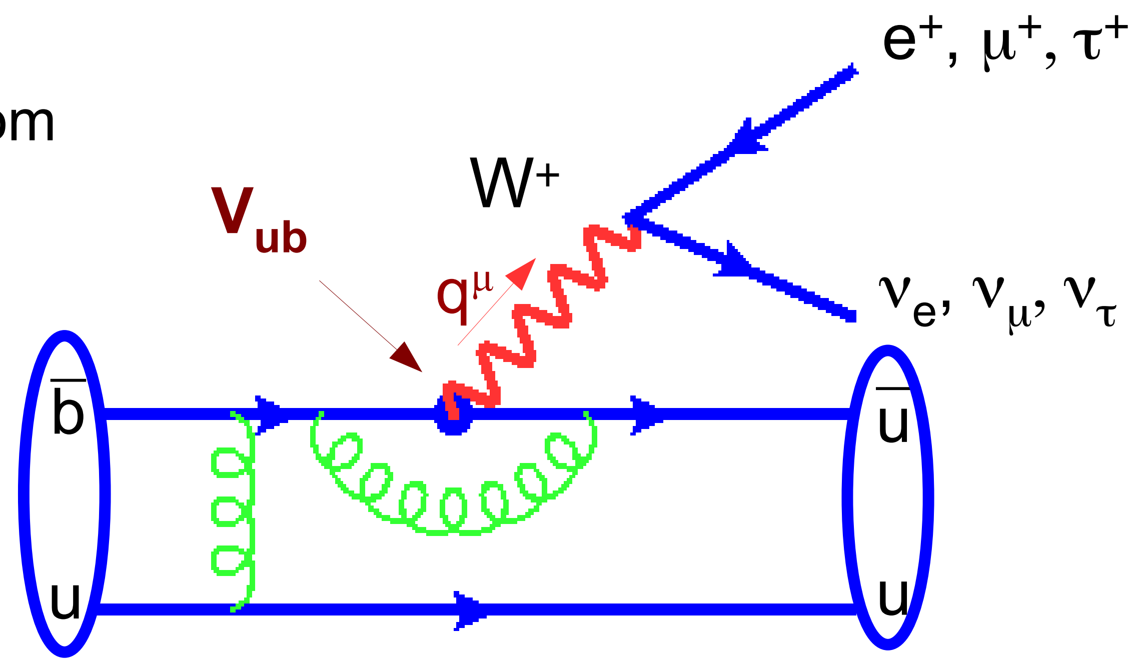
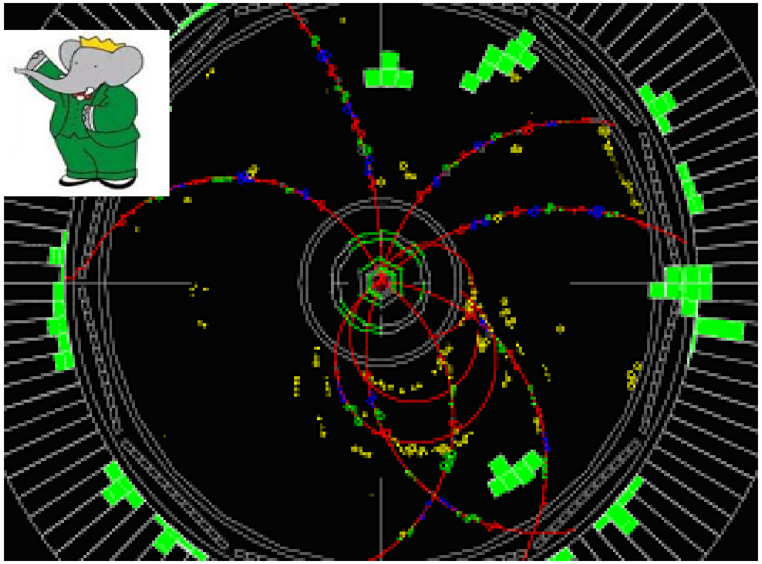
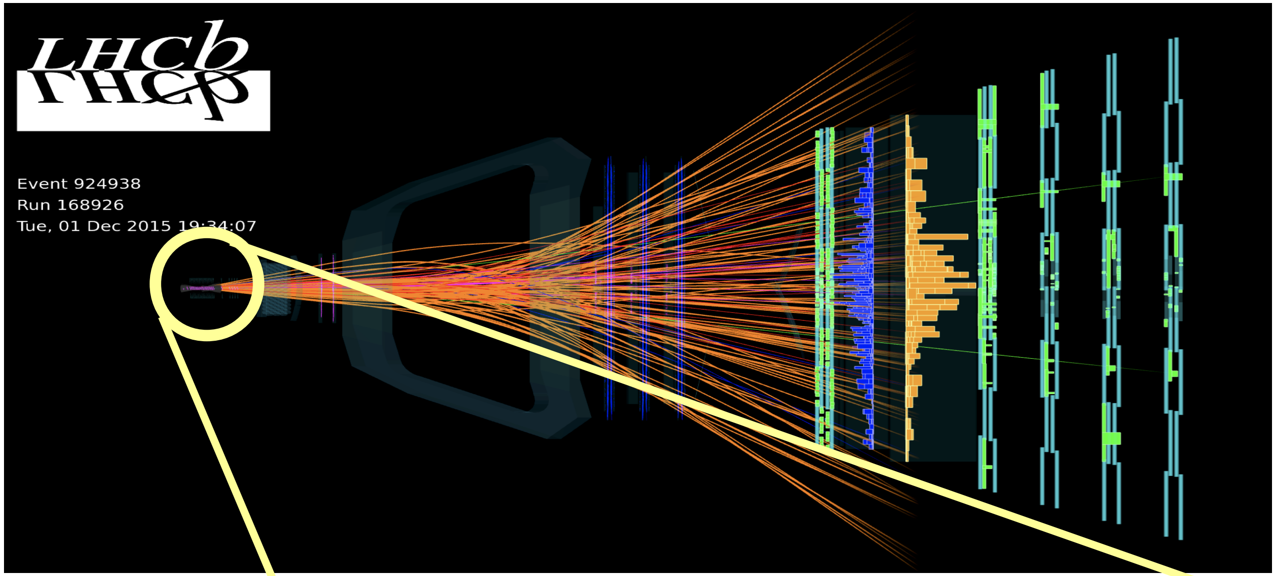
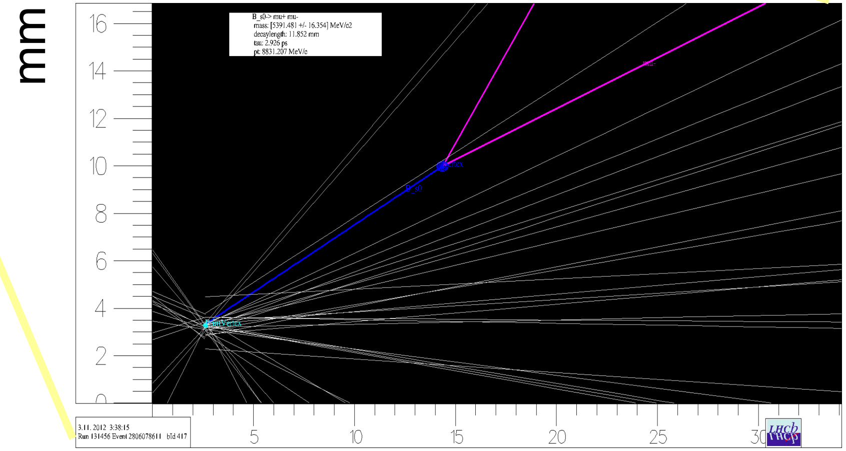


Semileptonics at LHCb!





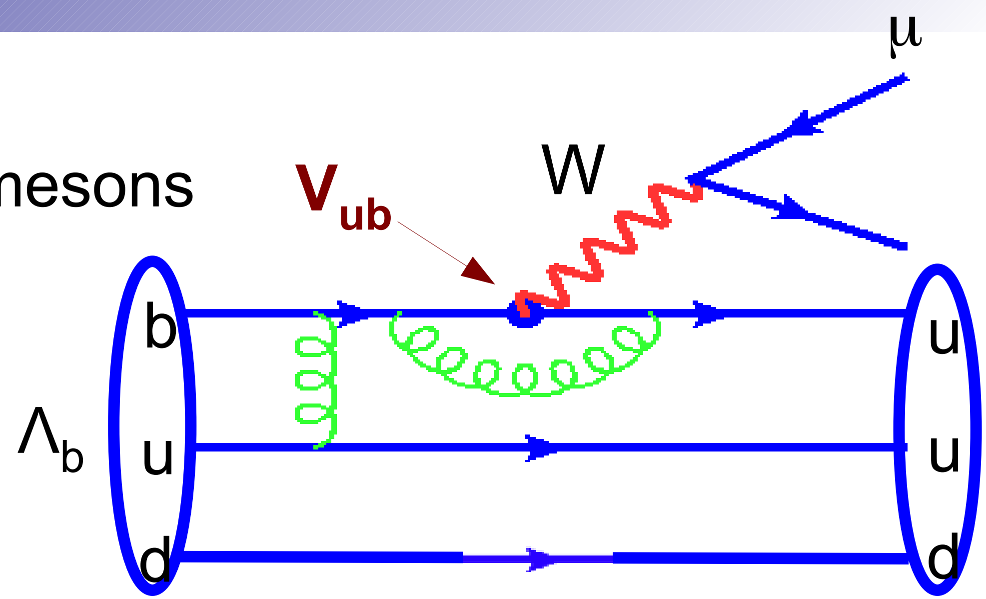


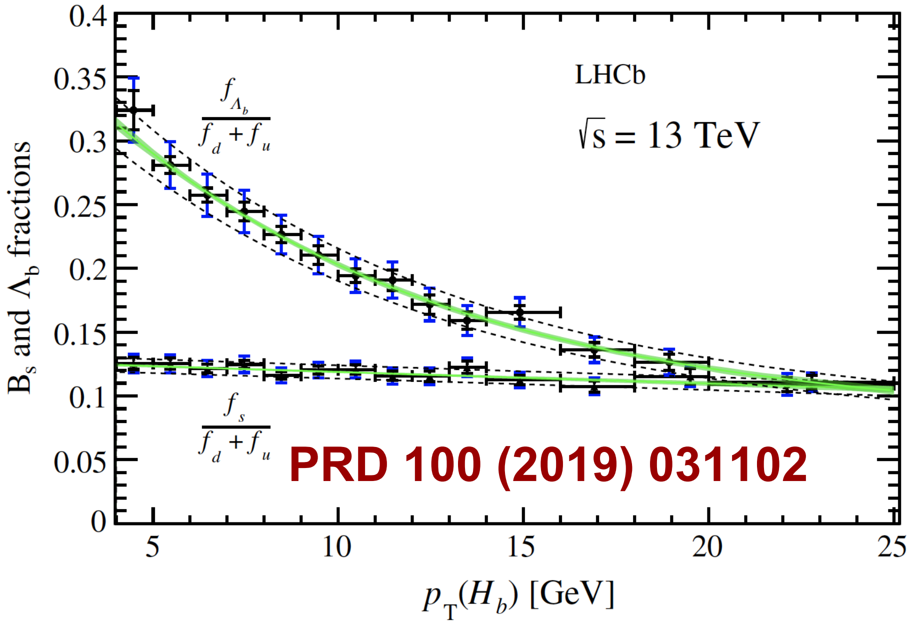
- At LHCb the key ingredients are:
  - Lepton identification
  - Trigger threshold to low-pT
  - Decay vertex separation from the primary vertex to identify the b-hadron decays: b-hadron flight length is ~1cm

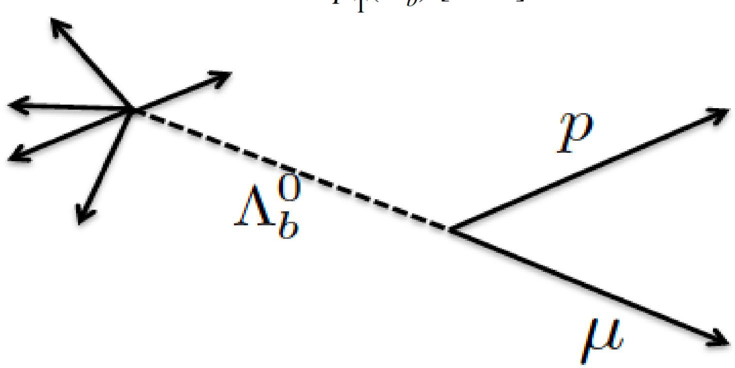
$|V_{ub}|$ with $\Lambda_b \to p\mu\nu$ @ LHCb

Nature Phys.11(2015)743

- The b-baryon decays provided complementary information to B mesons
- Λ_b Produced copiously







- Kinematic constraints allow the determination of the $p_{\Lambda b}$ (modulo 2-fold ambiguity)
- Large background from $\Lambda_b \to \Lambda_c\mu\nu$
- LHCb determines (in the high q2 region) the ratio

$$R_{exp} = \frac{\mathcal{B}(\Lambda_b \to p\mu\nu)}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)}$$

Signal

Normalization

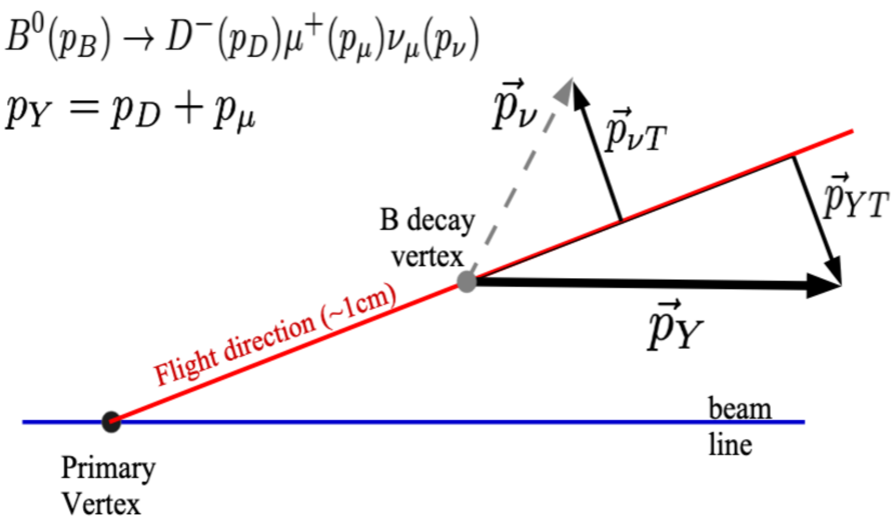
Reconstruction of the q^2

arXiv:1912.09562

The knowledge of the Λ_b momentum $P_{\Lambda b}$ is needed to measure $q^2=(P_{\Lambda b} - P_p)^2$

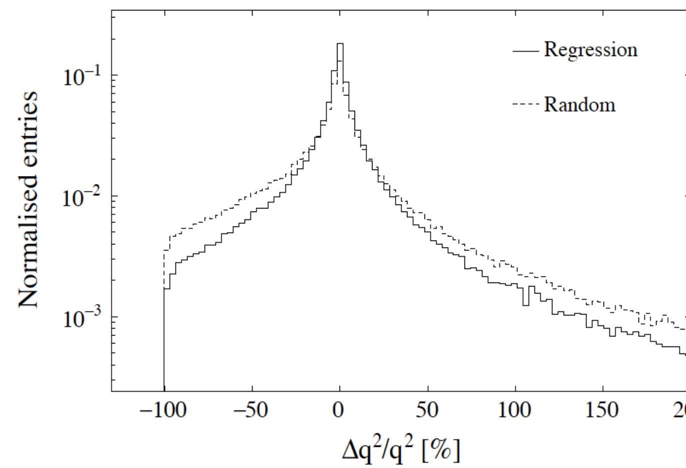
$$m_\nu^2 = (P_{\Lambda_b} - P_p - P_\mu)^2 = (P_{\Lambda_b} - P_Y)^2 = 0$$

$$E_{\Lambda_b}^2 = m_{\Lambda_b}^2 + |\vec{P}_{\Lambda_b}|^2$$



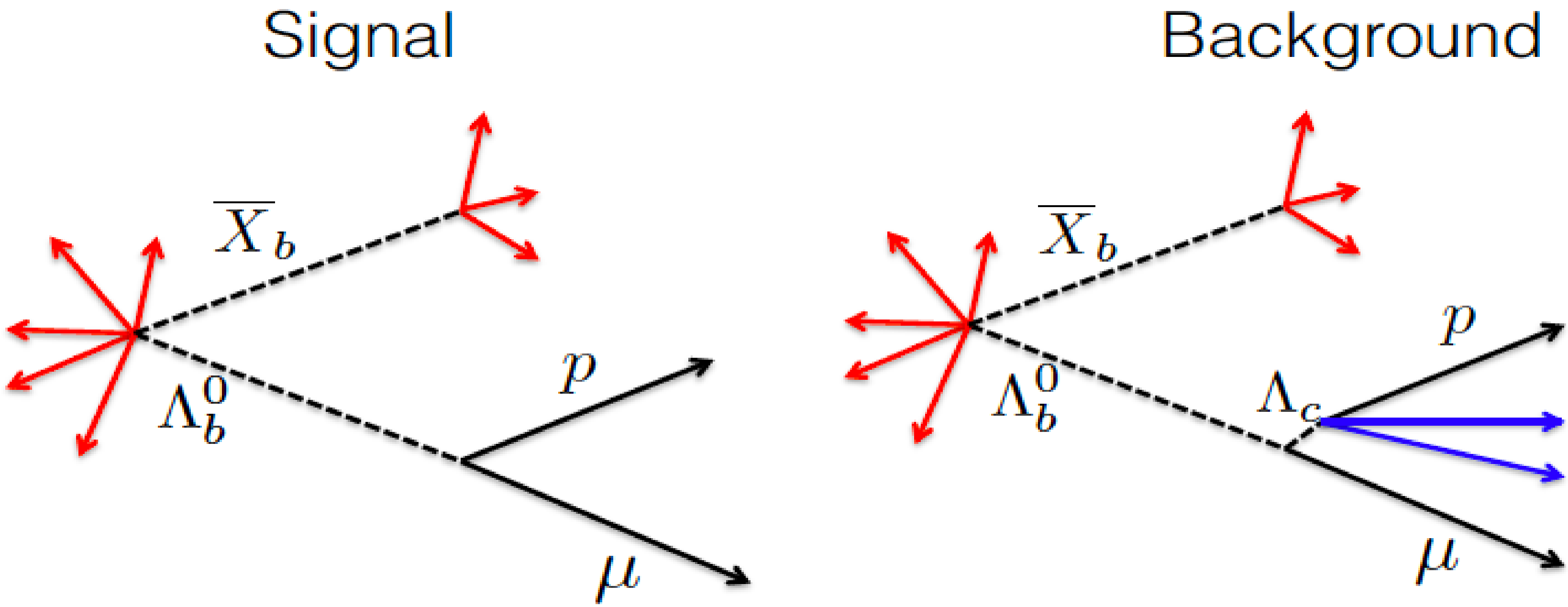
Hypothesis of just 1-neutrino missing, known masses of the particles, and the well-measured Λb flight direction gives the momentum with a 2-fold ambiguity

- Ciezarek et al. JHEP02(2017)021
  - The q^2 resolution can be improved exploiting other information as decay length and angle with respect to the beam line
  - Important when angular variables will be considered
  - Improvements foreseen exploiting Machine Learning



$\Lambda_b \to p\mu\nu$: Isolation criteria

Nature Phys.11(2015)743



Excellent PID allows clean p identification

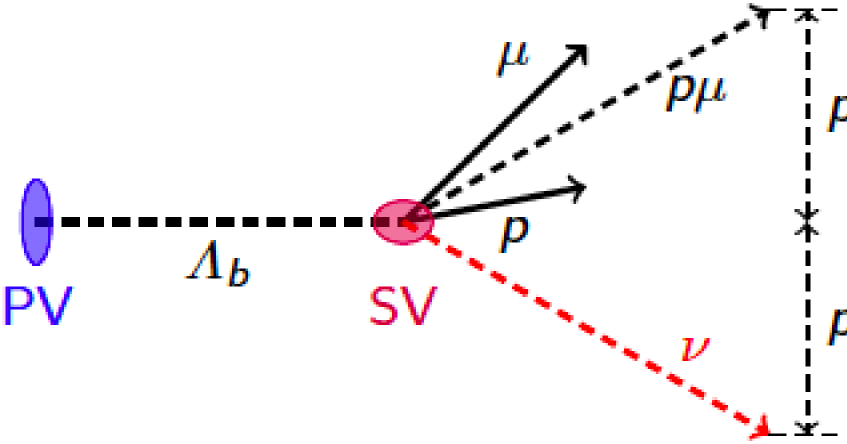
- Require isolated proton-muon vertex
  - A multivariate classifier to distinguish between these two configurations
- Powerful tool to reduce background from other b-hadrons: 90% rejection & 80% efficiency
  - very difficult to isolate against neutral particles: main backgrounds

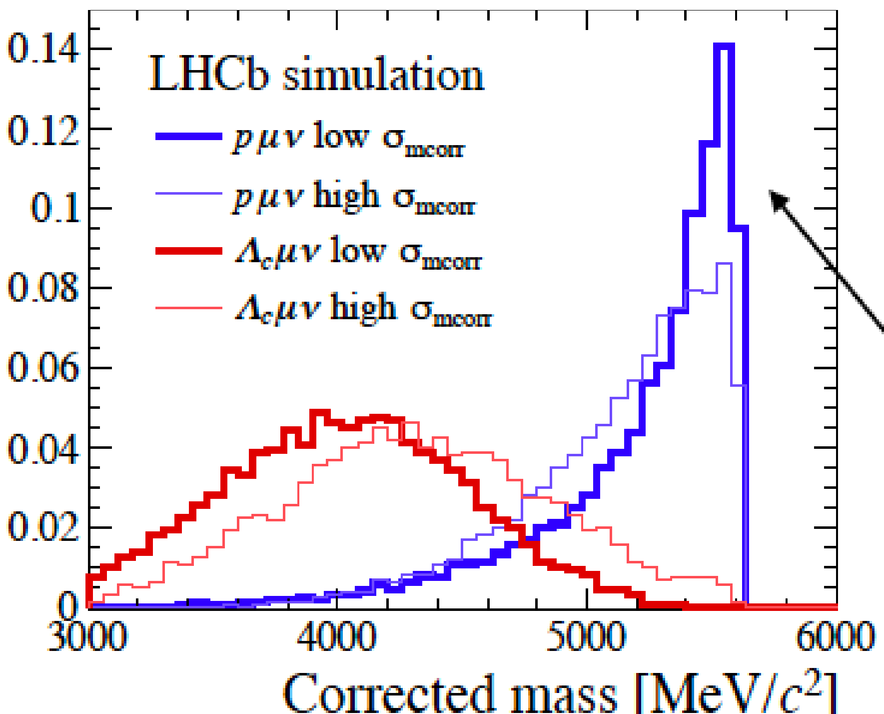
$\Lambda_b \to p\mu\nu$: corrected mass

Nature Phys.11(2015)743

- Use the corrected mass to discriminate signal from the remaining background

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





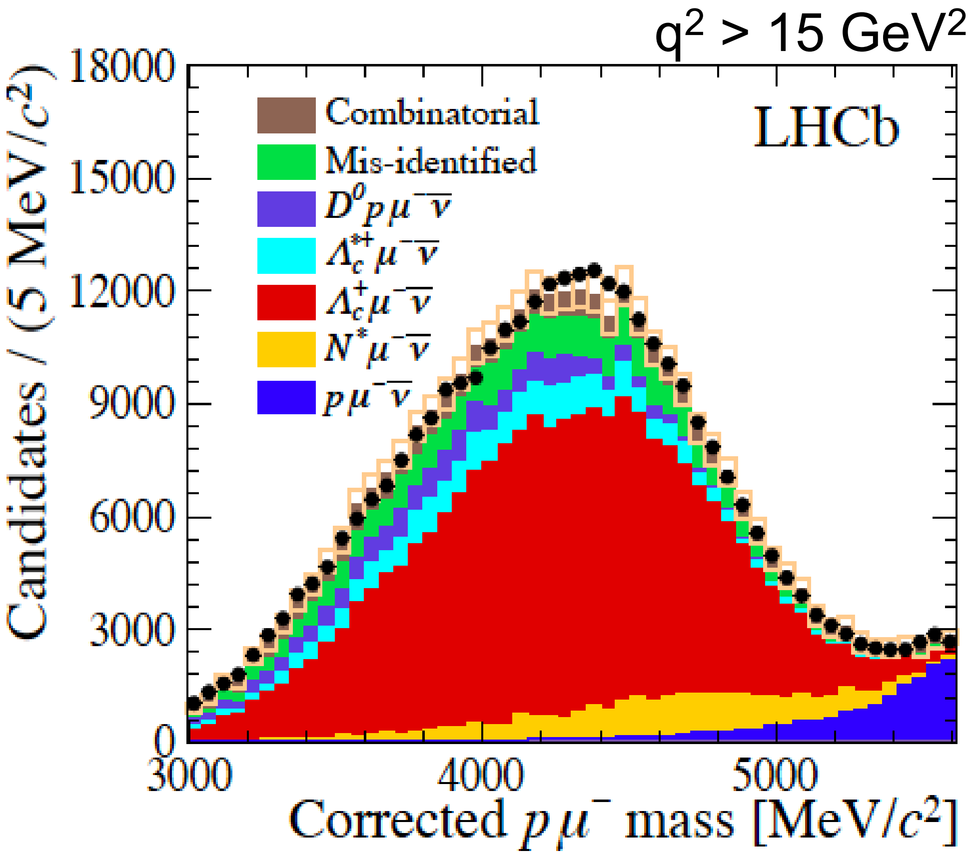
Calculate uncertainty for each event and reject candidates with M_{corr} uncertainty greater than 100MeV only (~23% survive).

The signal peaks even with a missing particle!

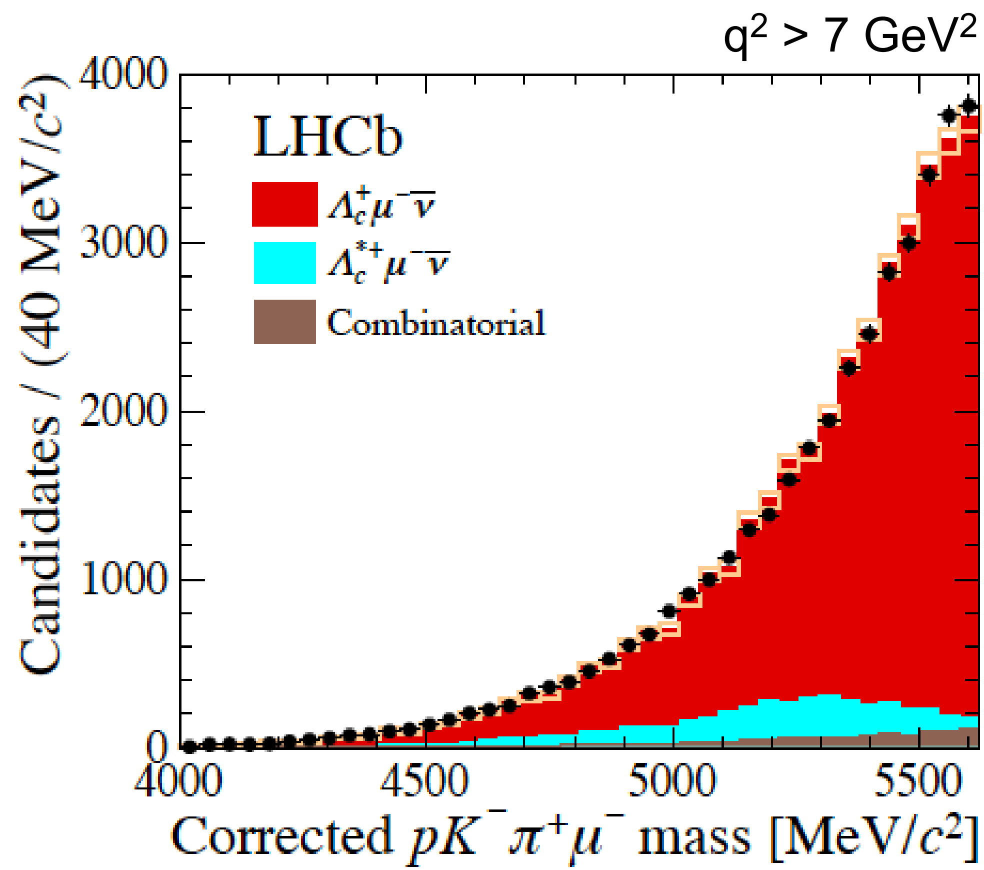
$\Lambda_b \rightarrow p\mu\nu$: signal fits

Nature Phys.11(2015)743

Signal N=17687 ± 733



Normalization N=34255 ± 571

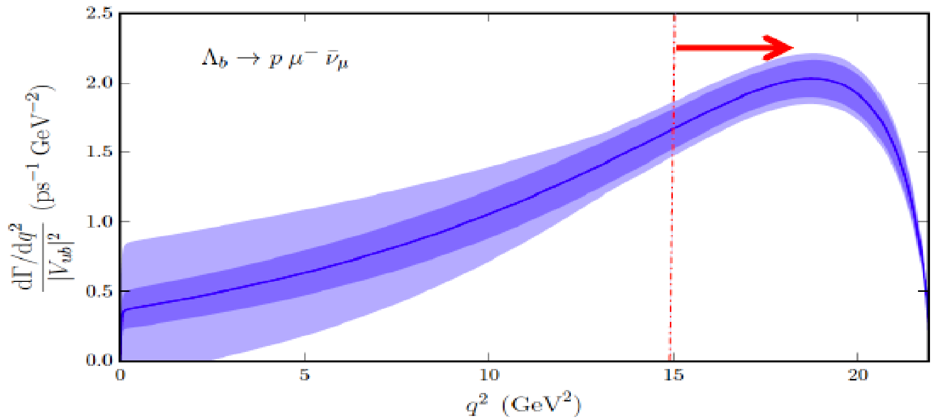


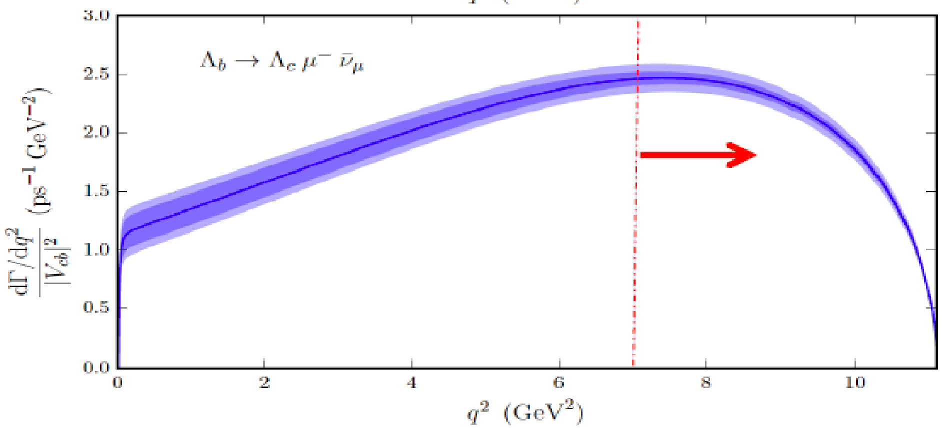
$R_{exp} = 0.92 \pm 0.04(\text{stat}) \pm 0.07(\text{syst}) \times 10^{-2}$

Systematics dominated by BF($\Lambda_c \rightarrow pK\pi$), trigger and tracking efficiency

Theory input

Detmold et al PRD92(2015)034503





- Most recent calculation based on 2-1 L-QCD calculation using RBC & UKQCD configurations
- The most reliable theory predictions of the ratio of FF are obtained for:
  - $\Lambda_b \to \Lambda_c\, \mu\nu$ $q^2 > 7$ GeV^2
  - $\Lambda_b \to p\, \mu\nu$ $q^2 > 15$ GeV^2

$$\frac{V_{ub}}{V_{cb}} = \sqrt{\frac{R_{exp}}{R_{TH}}}$$

Nature Phys.11(2015)743

First measurement of $\Lambda_b \to p\, \mu\nu$

First $|V_{ub}|$ in hadronic environments

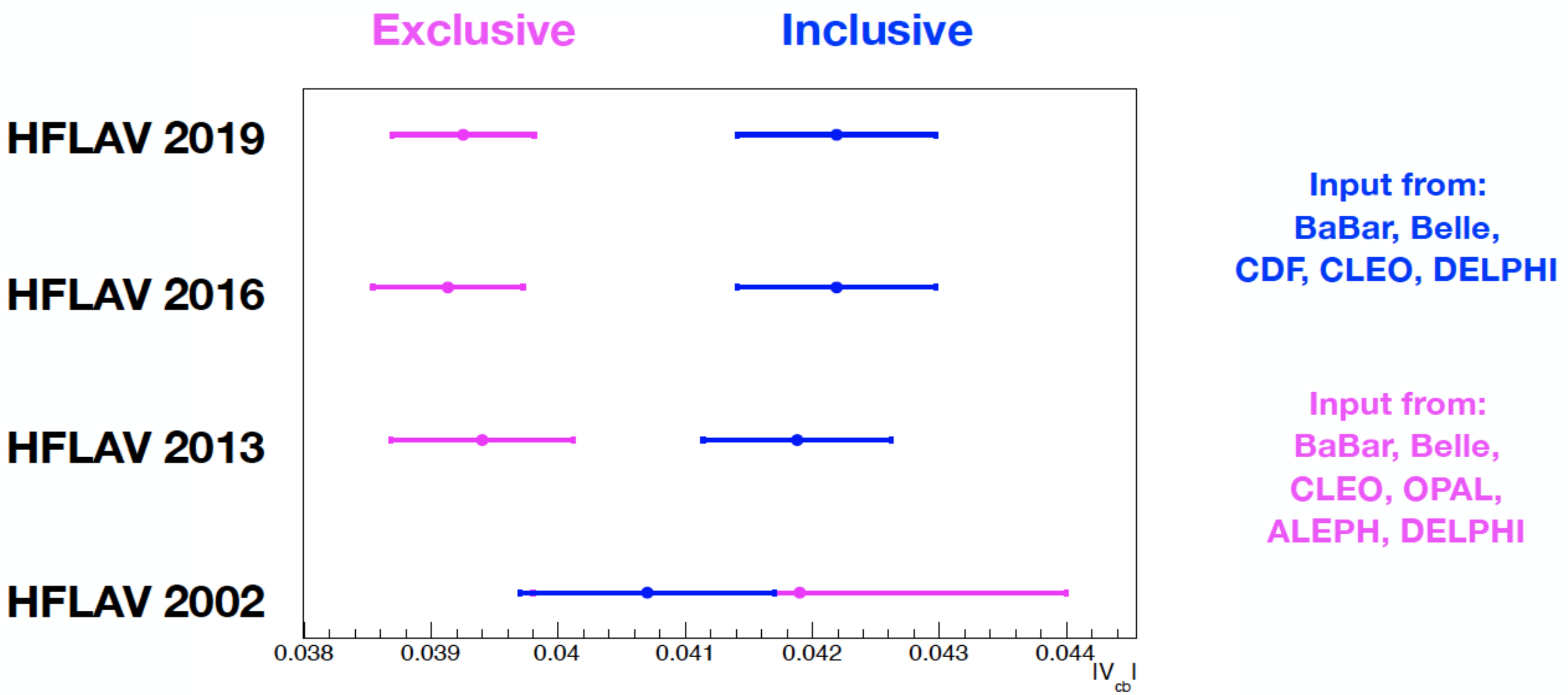
$$\frac{|V_{ub}|}{|V_{cb}|} = 0.079 \pm 0.004_{Exp.} \pm 0.004_{F.F.}$$

$|V_{cb}|$

Measurements of $|V_{cb}|$

- Inclusive decays $B \to X_c \ell \nu$:
  - HQE is the successful tool to include perturbative and non-perturbative QCD corrections

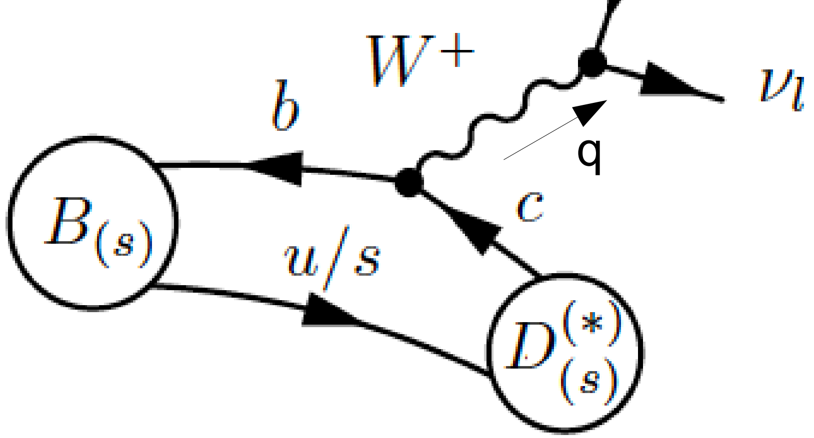
- Exclusive decays $B \to D\ell\nu$ / $D^*\ell\nu$
  - QCD effects are embedded in the form factors



Exclusive $|V_{cb}|$

- $B \to D\ell\nu$ and $B \to D^*\ell\nu$ provide clean way to extract $|V_{cb}|$

$$w = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$$

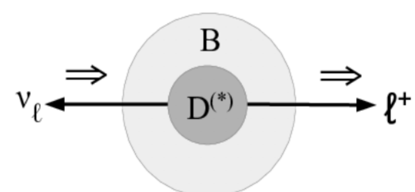


$$\frac{d\Gamma(B \to D\ell\nu)}{dq^2} = \frac{G_F^2 |V_{cb}|^2}{24\pi^3} \frac{(q^2 - m_\ell^2)^2 \sqrt{E_D^2 - m_D^2}}{q^4 m_B^2} \times \left[\left(1 + \frac{m_\ell^2}{2q^2}\right) m_B^2 (E_D^2 - m_D^2) |f_+(q^2)|^2 + \frac{3 m_\ell^2}{8q^2} (m_B^2 - m_D^2)^2 |f_0(q^2)|^2 \right]$$

$B \to D$: for $\ell = e$ and $\ell = \mu$, only $f_+(q^2)$ plays a role
$B \to D^*$: three form factors

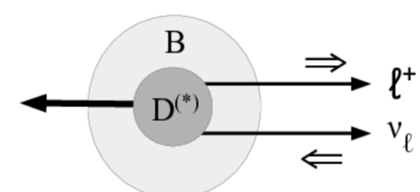
- FF computed from Lattice-QCD

- Lattice-QCD reliable close to zero-recoil regime



$q^2 = q^2_{max}$

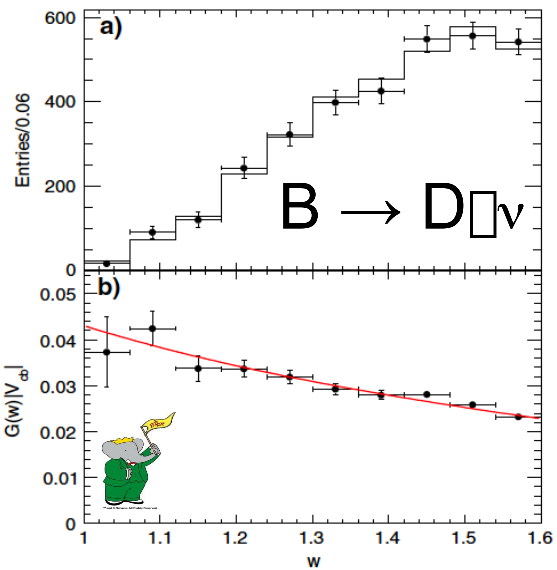
$w = 1$

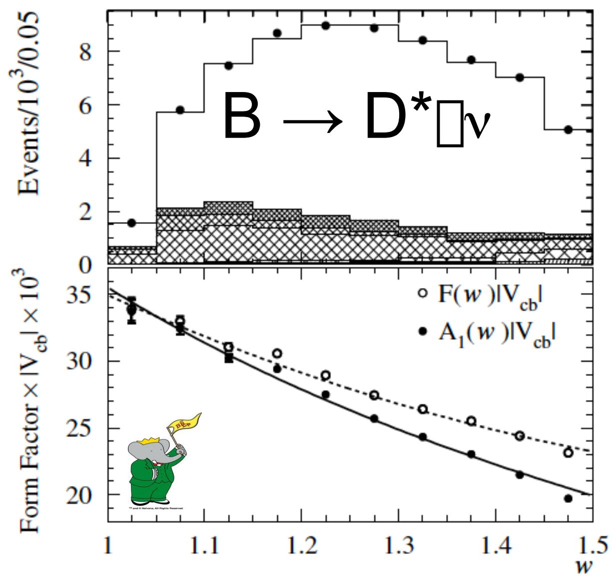


$q^2 = q^2_{min} = m_\ell^2 \approx 0$

$w \approx 1.5$

$|V_{cb}|$ and Form Factors parameterizations





- Phase space is reduced to 0 in the zero-recoil region
- Need an extrapolation to w=1 which has to rely on a form factor parameterization

- BGL Boyd, Grinstein, Lebed Phys.Rev.Lett 74, 4603 (1995)

$$f_i(z) = \frac{1}{P_i(z)\phi_i(z)} \sum_{n=0}^{N} a_{i,n} z^n, \qquad z(w) = \frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}}$$

Coefficient $a_{i,n}$ free parameters

The unitarity and analyticity of the FF assure bounds on the sum of the $a_{i,n}{}^2$

- CLN Caprini, Lellouch, Neubert Nucl.Phys.B530, 153 (1998)

$B \to D\ell\nu$

$$\mathcal{G}(z) = \mathcal{G}(1)(1 - 8\rho^2 z + (51\rho^2 - 10)z^2 - (252\rho^2 - 84)z^3)$$

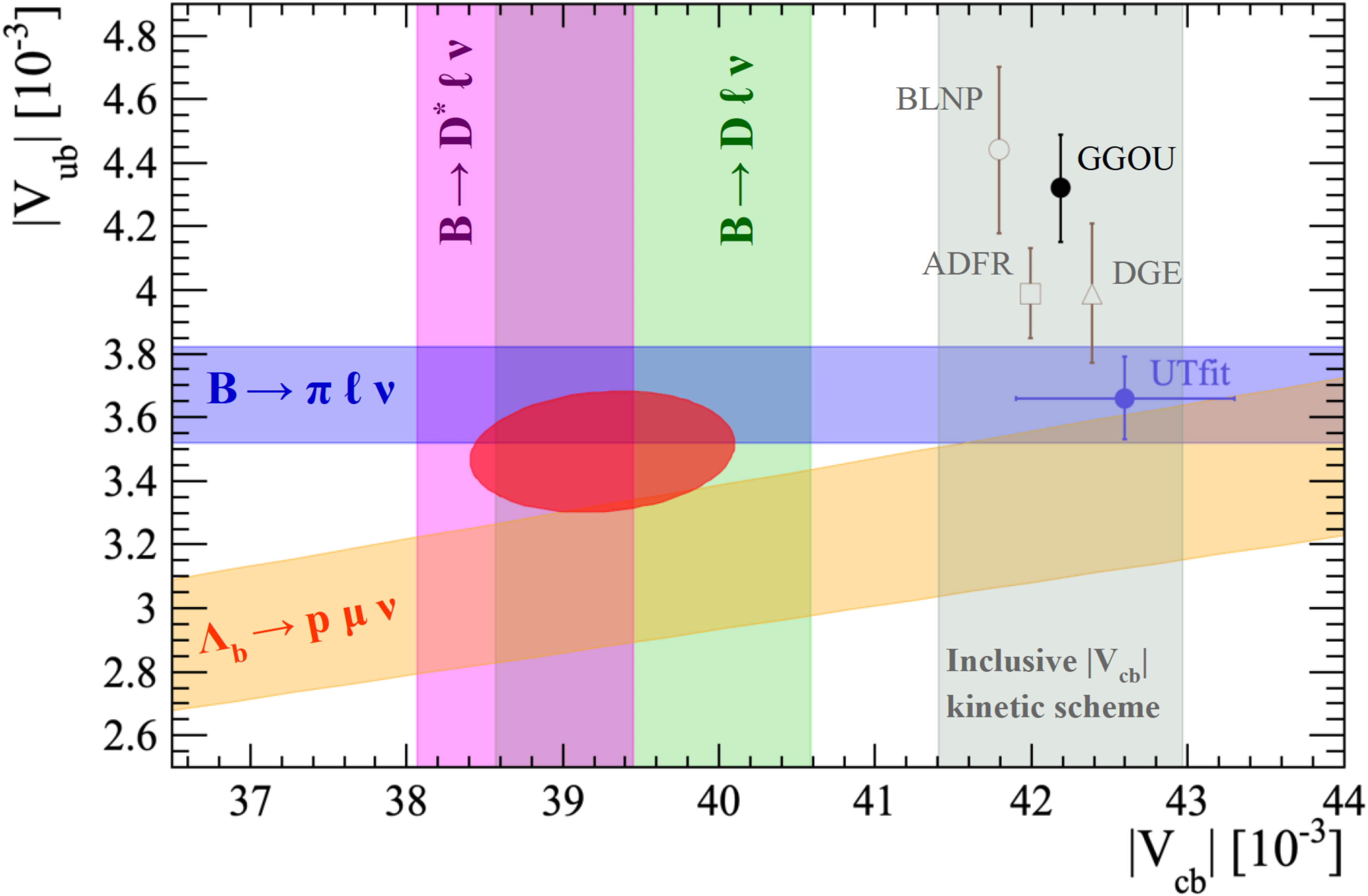
Higher order coefficient connected with the slope ρ^2

$B \to D^*\ell\nu$

$$h_{A_1}(w) = h_{A_1}(1)\left[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3\right],$$

$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$

$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2$$



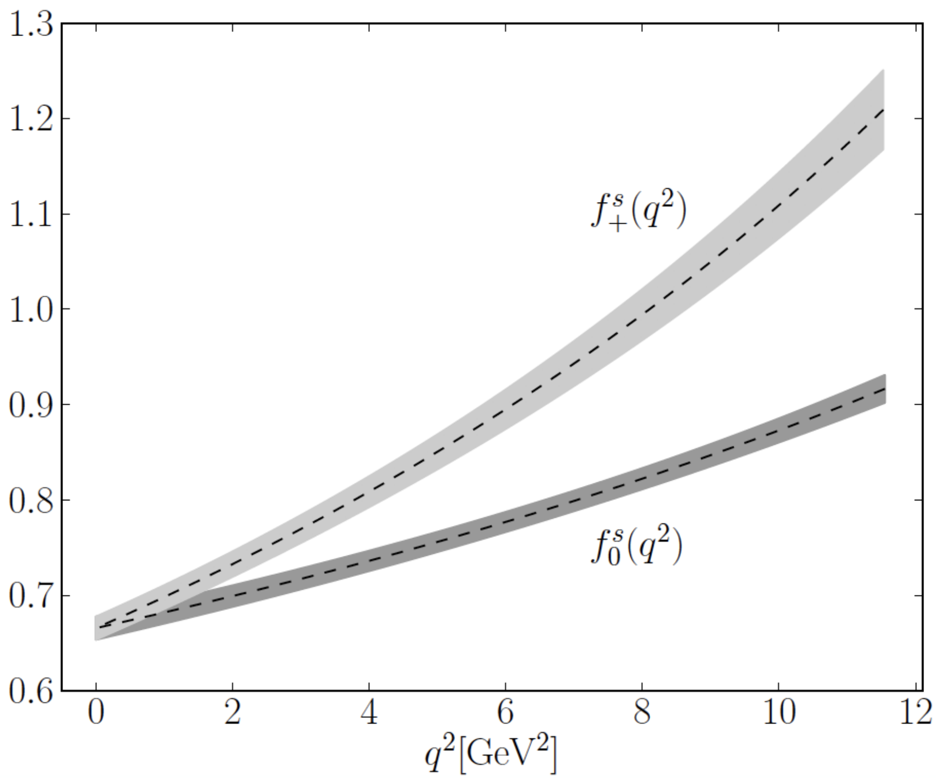
$|V_{ub}|$ [10^{-3}]
$|V_{cb}|$ [10^{-3}]
$B \to D^* \ell \nu$
$B \to D \ell \nu$
$B \to \pi \ell \nu$
$\Lambda_b \to p \mu \nu$
BLNP
GGOU
ADFR
DGE
UTfit
Inclusive $|V_{cb}|$
kinetic scheme

B_s semileptonic decays

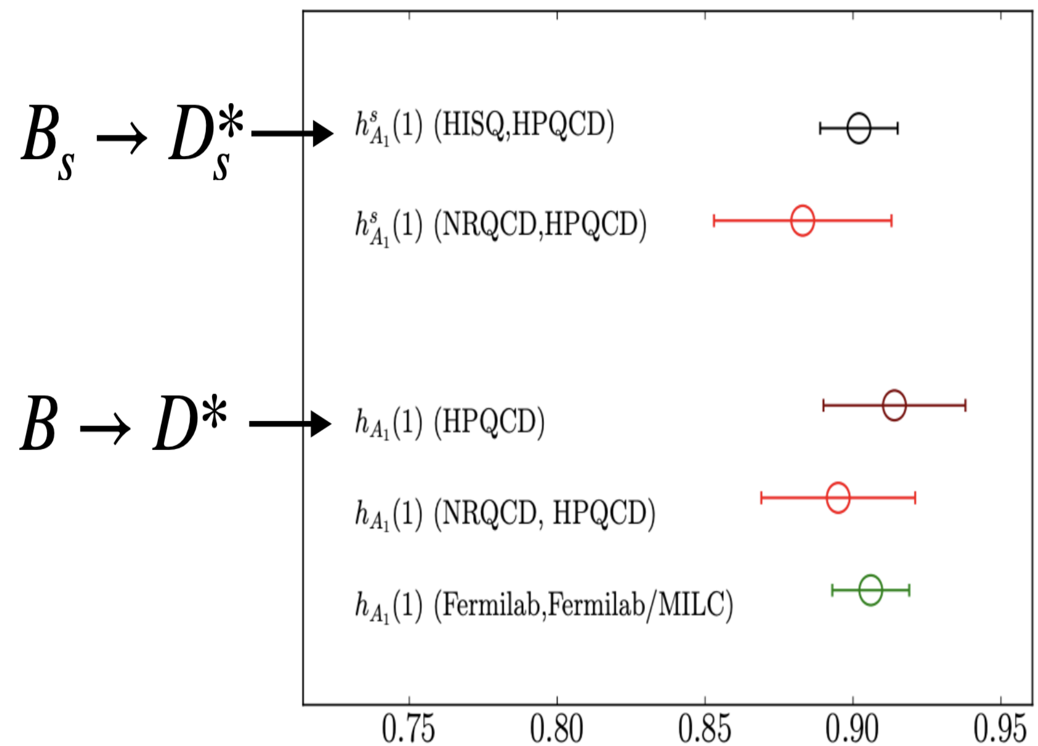
- Complementary measurements to those from B^0 and B^+
- Advantages:
  - Lattice calculations easier due to heavier spectator quark, so predictions are more precise
  - For the $B_s \to D_s^*$: the *zero-width* approximation of the D_s^* should work better than the B case (no $D\pi$ pollution)

Golden modes for Lattice-QCD

HPQCD, arXiv 1906.00701
FF in the full q^2 range



HPQCD, PRD 99 (2019) 114512

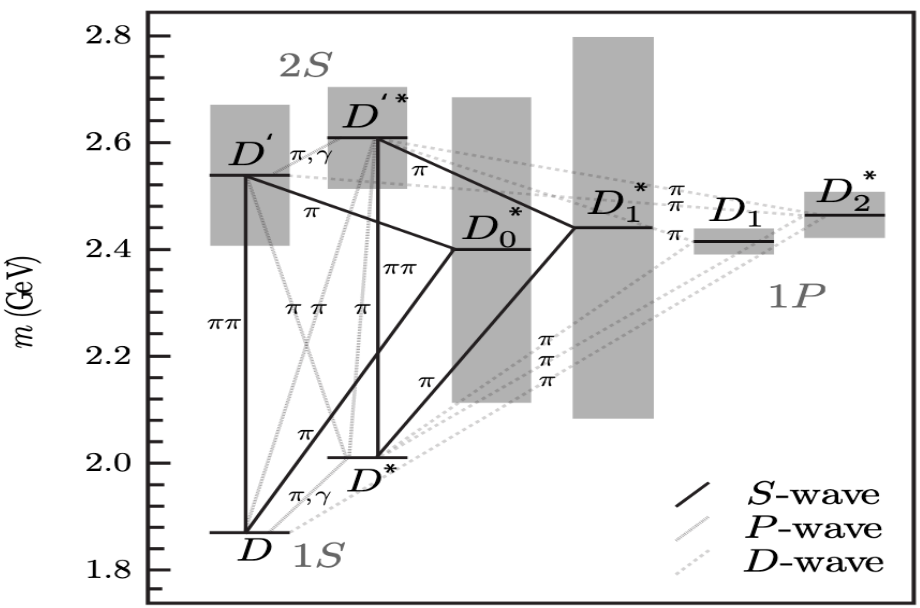


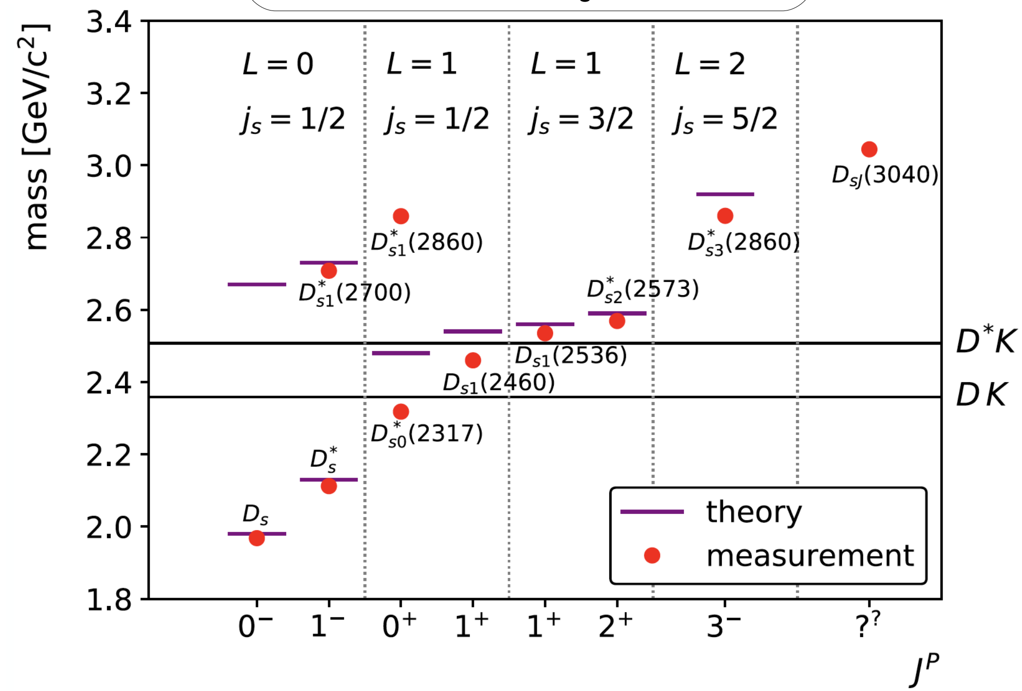
B_s semileptonic decays

- Complementary measurements to those from B^0 and B^+
- Advantages:
  - Lattice calculations easier due to heavier spectator quark, so predictions are more precise
  - For the $B_s \to D_s^*$: the *zero-width* approximation of the D_s^* is more valid than the B case (no $D\pi$ pollution)
  - Experimental point: different background composition from excited D_s states than in the $B \to D^*$ case

Golden modes for Lattice-QCD

$D_s(2317) \to D_s\pi^0$ >90%
$D_{s1}(2460) \to D_s^*\ \pi^0$ ~50%
D_sX ~50%





LHCb Measurement of $|V_{cb}|$

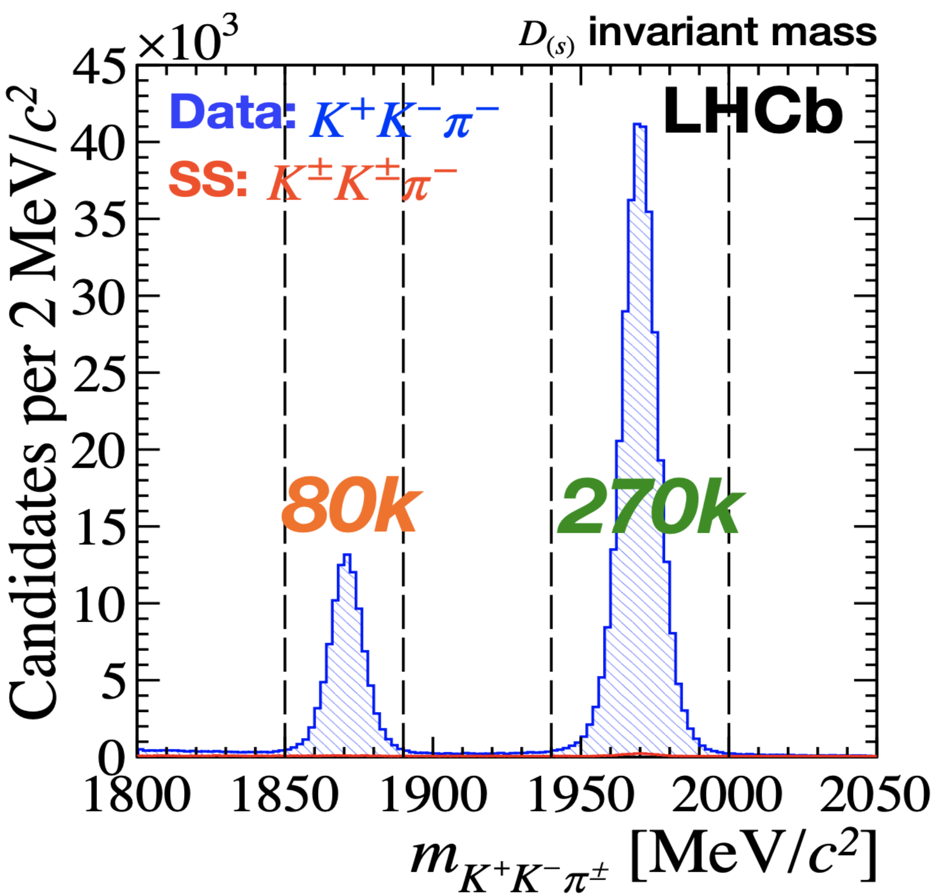
ArXiv:2001.03225

- Extract $|V_{cb}|$ from B_s decays $B_s \to D_s \mu\nu$ and $B_s \to D_s^* \mu\nu$
- Normalized to $B^0 \to D^- \mu\nu$ and $B^0 \to D^{*-} \mu\nu$
  - The BF($B^0 \to D^{(*)-} \mu\nu$) are known well from B-Factories

$$\mathcal{R} \equiv \frac{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^- \mu^+ \nu_\mu)},$$

$$\mathcal{R}^* \equiv \frac{\mathcal{B}(B_s^0 \to D_s^{*-} \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu_\mu)}$$

- The D^- and the D_s are reconstructed in the same final state $D_{(s)} \to KK\pi$
- Decrease the systematic uncertainties: same particles and similar kinematic in the final state
- Only the D^- and the D_s are constructed
- The D_s and the D_s^*(and D^- and D^{*-}) are separated kinematically (with m_{corr})



LHCb Measurement of |Vcb|

ArXiv:2001.03225

$$\mathcal{R} \equiv \frac{\mathcal{B}(B_s \to D_s \mu\nu)}{\mathcal{B}(B^0 \to D^- \mu\nu)} = \frac{N_s}{N_d} \cdot \frac{\epsilon_d}{\epsilon_s} \frac{f_d}{f_s} \cdot \frac{\mathcal{B}(D^- \to KK\pi)}{\mathcal{B}(D_s \to KK\pi)}$$

External inputs
fs/fd from
PRD(2019) 031102
BFs from PDG

Signal yields and normalization yields from fit
Efficiencies evaluated from simulation, adjusted for
Data/MC differences based on control samples

Analogous expression
for R* (additional BF of the D*)

LHCb Measurement of |Vcb|

ArXiv:2001.03225

$$\mathcal{R} \equiv \frac{\mathcal{B}(B_s \to D_s \mu\nu)}{\mathcal{B}(B^0 \to D^- \mu\nu)} = \frac{N_s}{N_d} \cdot \frac{\epsilon_d}{\epsilon_s} \cdot \frac{f_d}{f_s} \cdot \frac{\mathcal{B}(D^- \to KK\pi)}{\mathcal{B}(D_s \to KK\pi)}$$

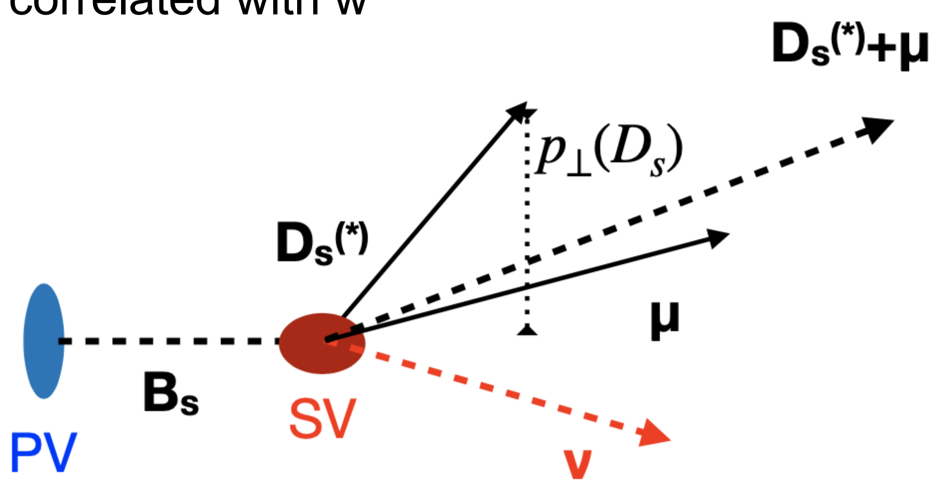
External inputs
fs/fd from PRD(2019) 031102
BFs from PDG

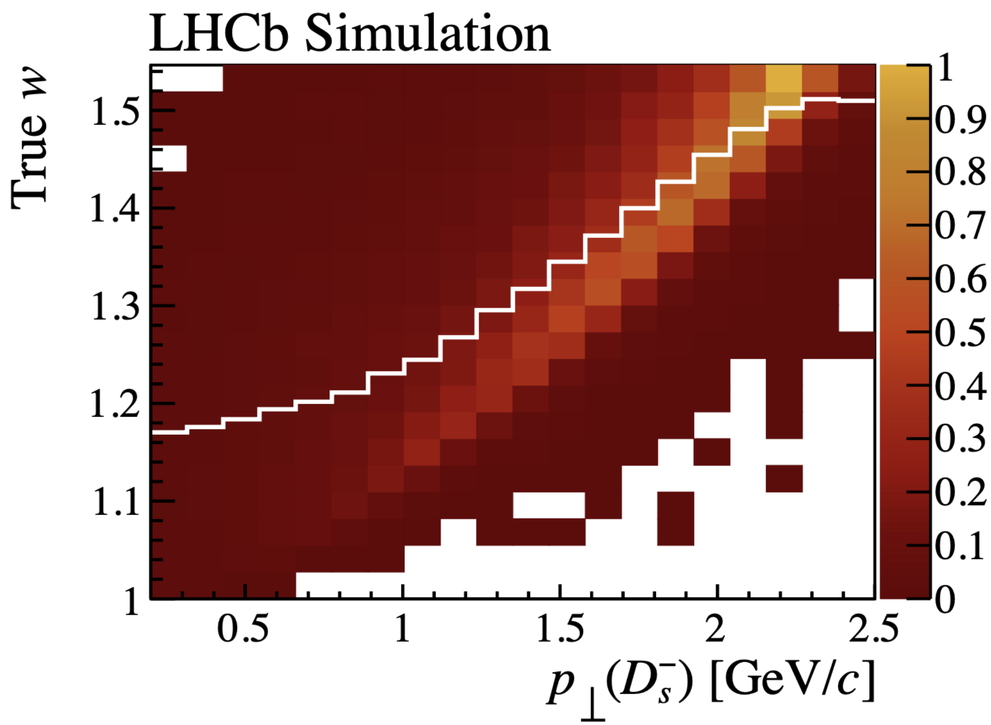
Signal yields and normalization yields from fit
Efficiencies evaluated from simulation, adjusted for Data/MC differences based on control samples

Analogous expression for R* (additional BF of the D*)

- N_s can be written in terms of $|V_{cb}|$ and the form factors: also the form factors can be determined by a proper fit of the signal candidates

- The transverse momentum of the D_s is correlated with w

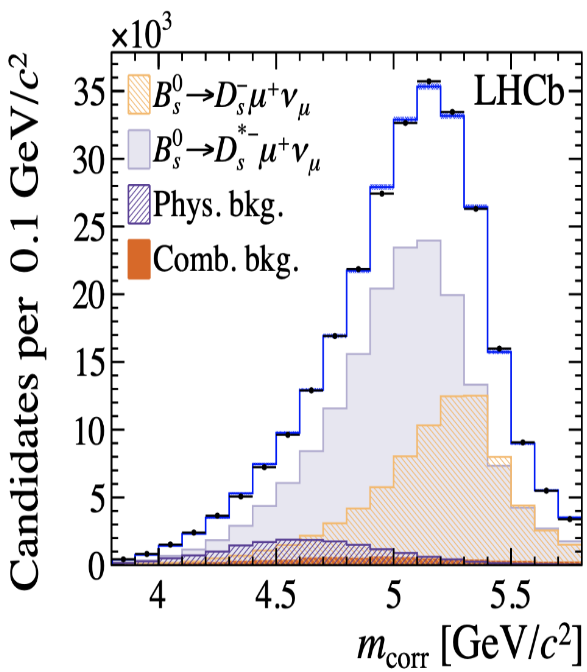


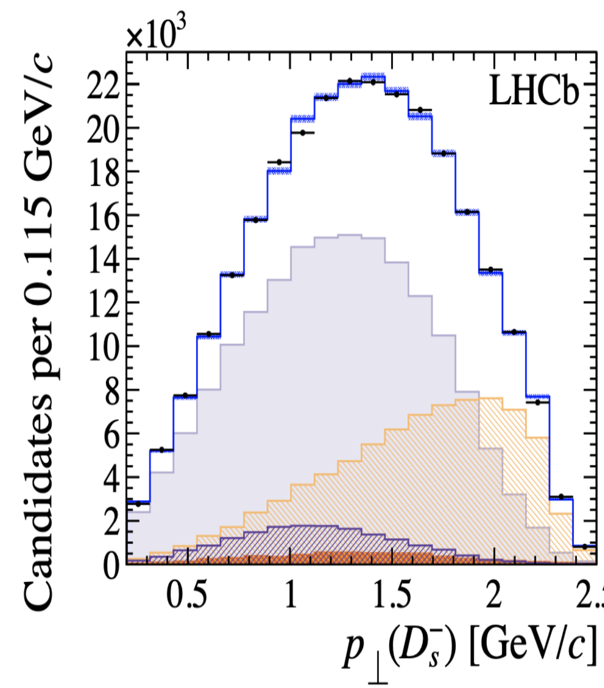


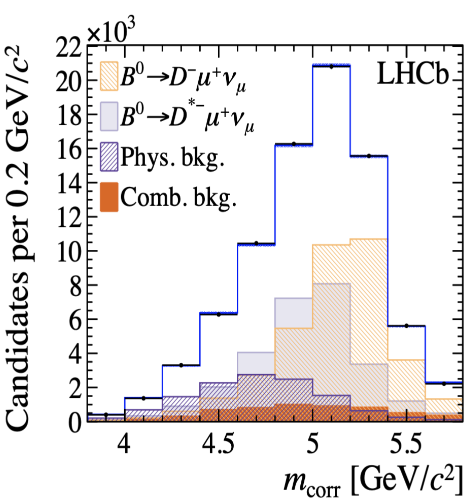
Fit to the signal and normalization

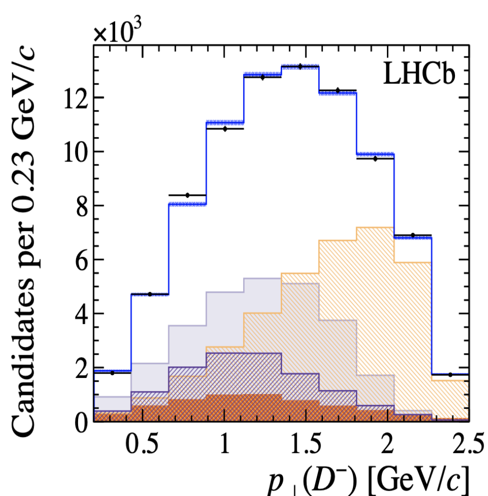
- Template fit to m_{corr} and $p_{\perp}(D_s)$ identify the signal yields and provides a simultaneous measurement of the ratios R(*) and the form factors

	$\mathcal{R}$ $[10^{-1}]$	$\mathcal{R}^*$ $[10^{-1}]$
$f_s/f_d \times \mathcal{B}(D_s^- \to K^+K^-\pi^-)(\times\tau)$	0.4	0.4
$\mathcal{B}(D^- \to K^-K^+\pi^-)$	0.3	0.3
$\mathcal{B}(D^{*-} \to D^- X)$	–	0.2
$\mathcal{B}(B^0 \to D^-\mu^+\nu_\mu)$	–	–
$\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$	–	–
$m(B_s^0)$, $m(D^{(*)-})$	–	–
η_{EW}	–	–
$h_{A_1}(1)$	–	–
External inputs (ext)	0.5	0.5
$D_{(s)}^- \to K^+K^-\pi^-$ model	0.5	0.4
Background	0.4	0.6
Fit bias	0.0	0.0
Corrections to simulation	0.0	0.0
Form-factor parametrization	0.0	0.1
Experimental (syst)	0.6	0.7
Statistical (stat)	0.5	0.5









$$\mathcal{R} = 1.09 \pm 0.05_{stat} \pm 0.06_{syst} \pm 0.05_{ext}$$

$$\mathcal{R}^* = 1.06 \pm 0.05_{stat} \pm 0.07_{syst} \pm 0.05_{ext}$$

First measurements of these SL branching ratios

Results on $|V_{cb}|$

ArXiv:2001.03225

$$|V_{cb}|_{\mathrm{CLN}} = (41.4 \pm 0.6(\mathrm{stat}) \pm 0.9(\mathrm{syst}) \pm 1.2(\mathrm{ext})) \times 10^{-3}$$

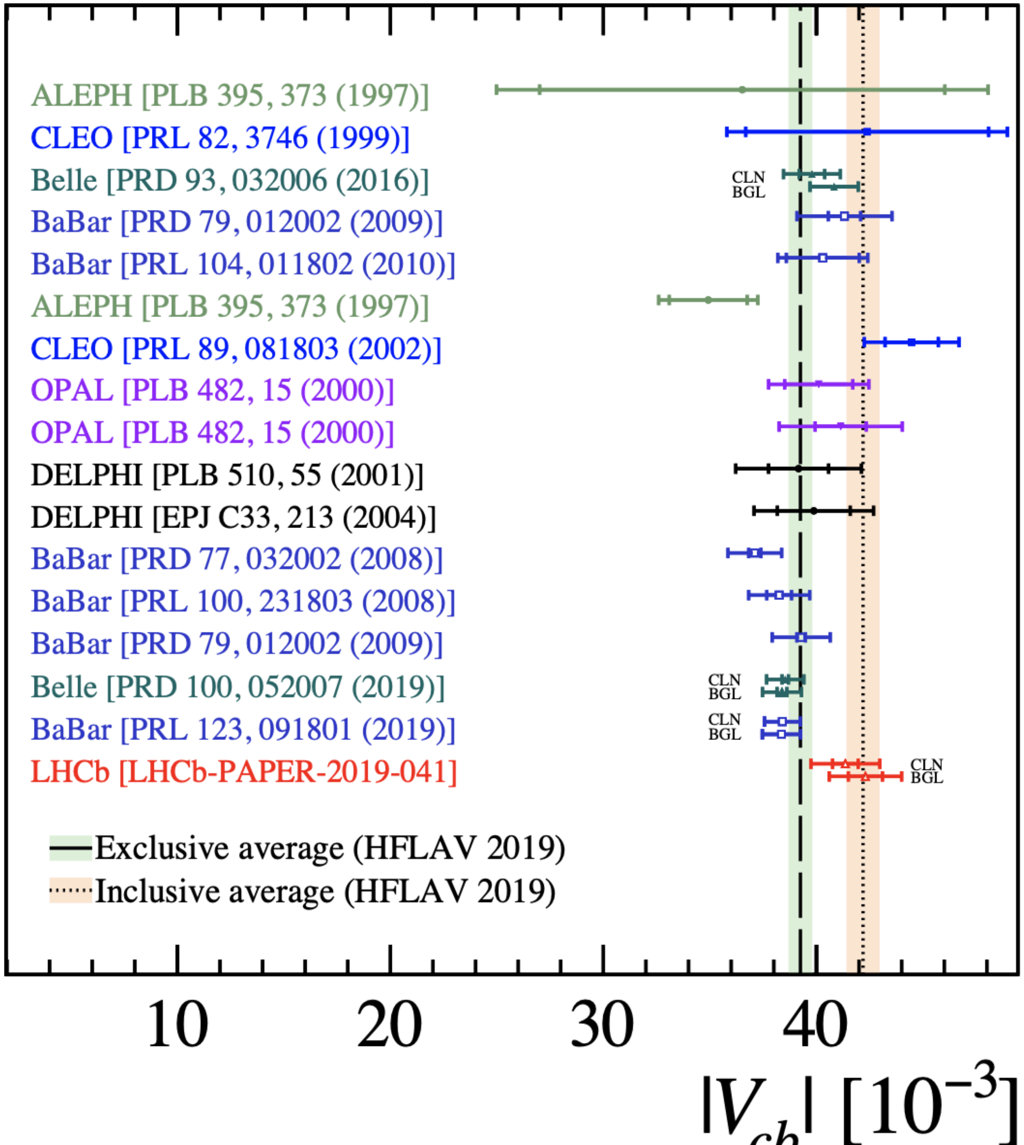
$$|V_{cb}|_{\mathrm{BGL}} = (42.3 \pm 0.8(\mathrm{stat}) \pm 0.9(\mathrm{syst}) \pm 1.2(\mathrm{ext})) \times 10^{-3}$$

- First measurement of $|V_{cb}|$ using B_s
- First measurement of $|V_{cb}|$ in an hadronic environment

- The results are consistent between CLN and BGL
- Results compatible with world average for both inclusive and exclusive determinations

- Uncertainty not competitive with b-factories: limited by knowledge of fs/fd

The approach can be applied also to B^0 decays!



Study of $B_s \to D_s^* \mu\nu$

- Determination of the differential decay rate $d\Gamma/dq^2$
- Measure more precisely the form factors in the CLN and BGL parametrisations

$$\frac{d\Gamma(B_s^0 \to D_s^{*-}\mu^+\nu_\mu)}{dq^2} = \frac{G_F^2\,|V_{cb}|^2\,|\eta_{\mathrm{EW}}|^2\,|\vec{p}\,|q^2}{96\,\pi^3\,m_{B_s^0}^2}\left(1-\frac{m_\mu^2}{q^2}\right)^2 \times\left[\left(|H_+|^2+|H_-|^2+|H_0|^2\right)\left(1+\frac{m_\mu^2}{2\,q^2}\right)+\frac{3}{2}\frac{m_\mu^2}{q^2}|H_t|^2\right]$$

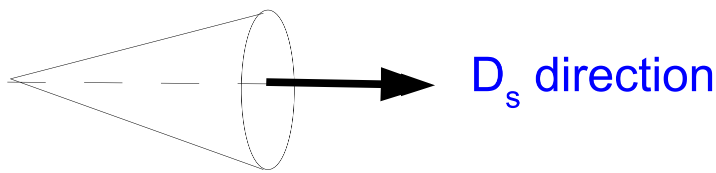
Analysis Strategy

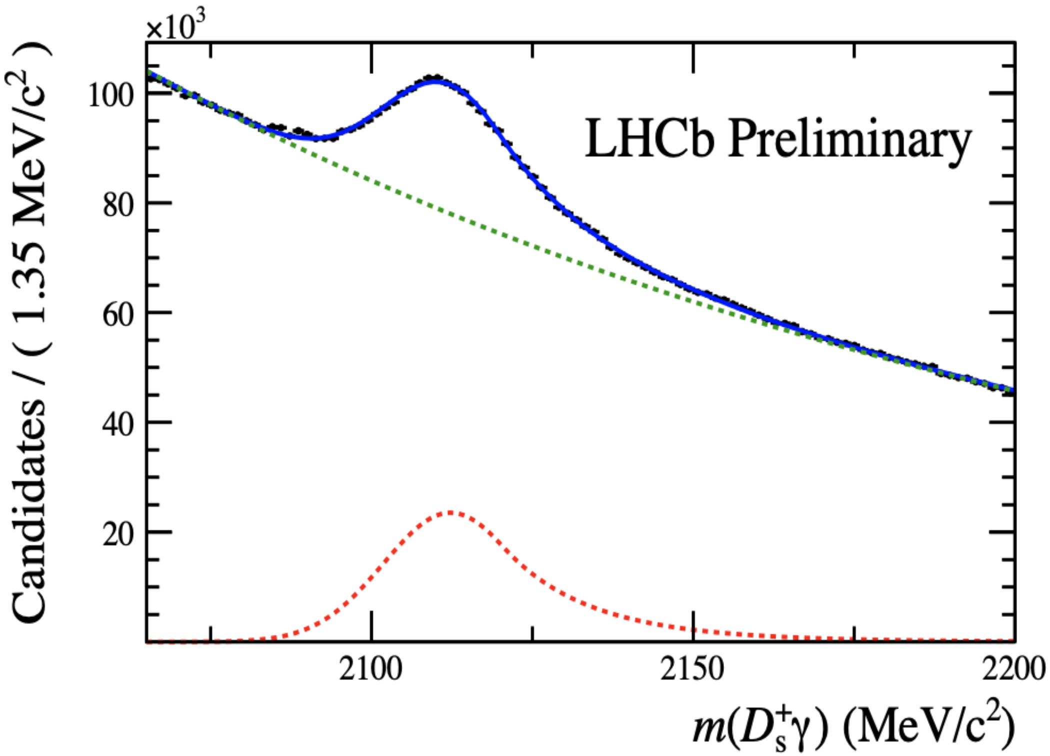
- Extract the production rate of $B_s \to D_s^* \mu\nu$ as a function of w (2016 data)
  - Fully reconstruct $D_s^* \to D_s\gamma$
  - Use templates from simulation, properly correctly for data/MC differences from control samples
- Corrected the raw yields for detector resolution (unfolding) and selection/reconstructed efficiencies
- Fit the unfolded and efficiency corrected spectrum with different parameterisations
  - CLN: fit only ha1(w) and slope the single parameter
  - BGL: fir the leading form factor f(w) with two parameters
    - In both cases: the other functions taken from external sources

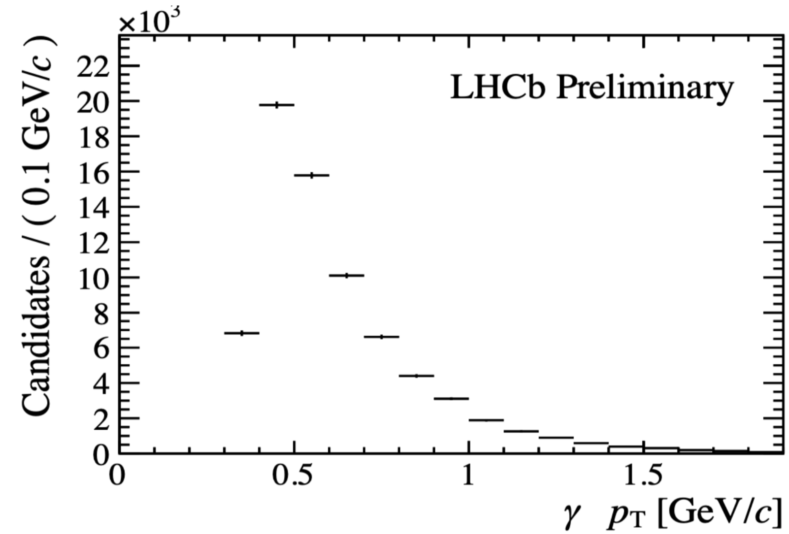
Candidate selection

$D_s^+\gamma$	$(93.5 \pm 0.7)\%$
$D_s^+\pi^0$	$(5.8 \pm 0.7)\%$
$D_s^+e^+e^-$	$(6.7 \pm 1.6) \times 10^{-3}$

- Fully reconstruct the $D_s^* \rightarrow D_s\gamma$
  - Requires the selection of soft photons within a cone around the D_s direction





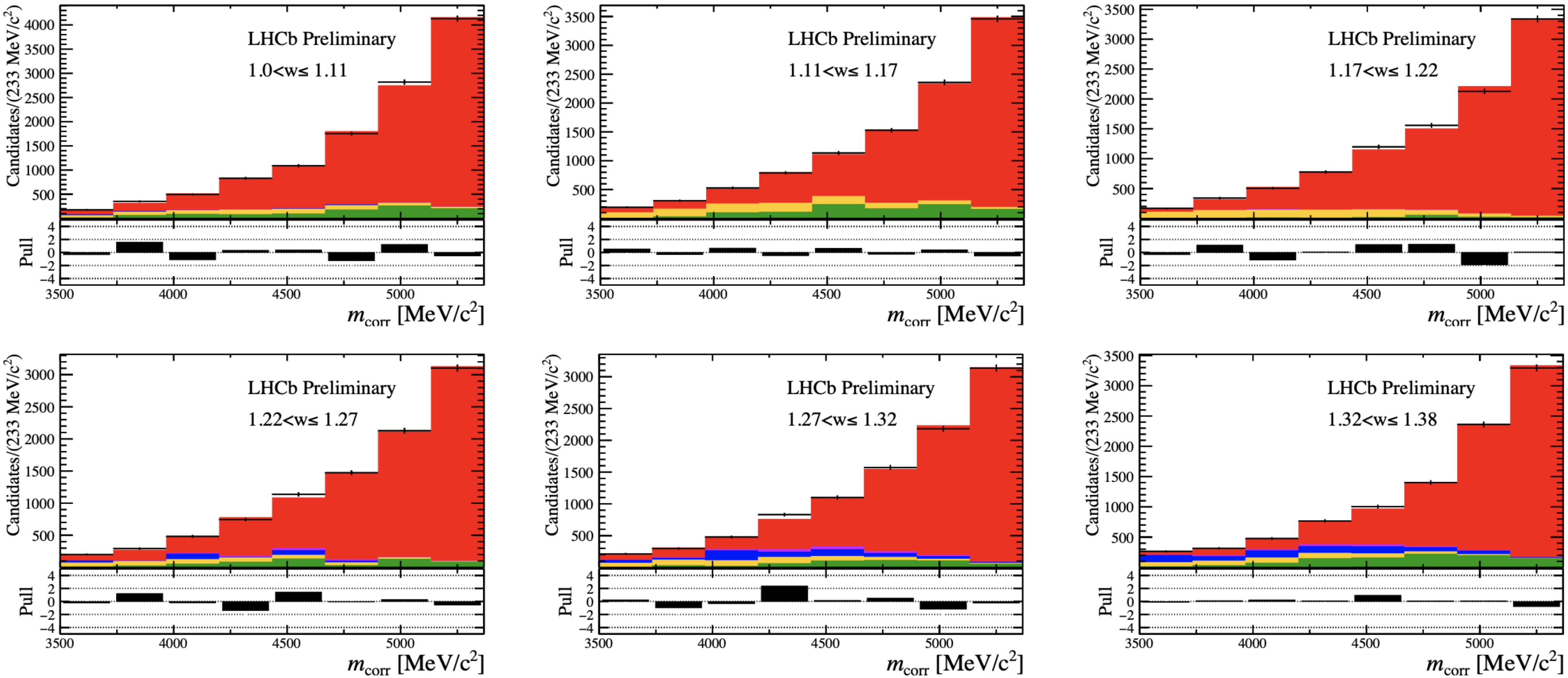


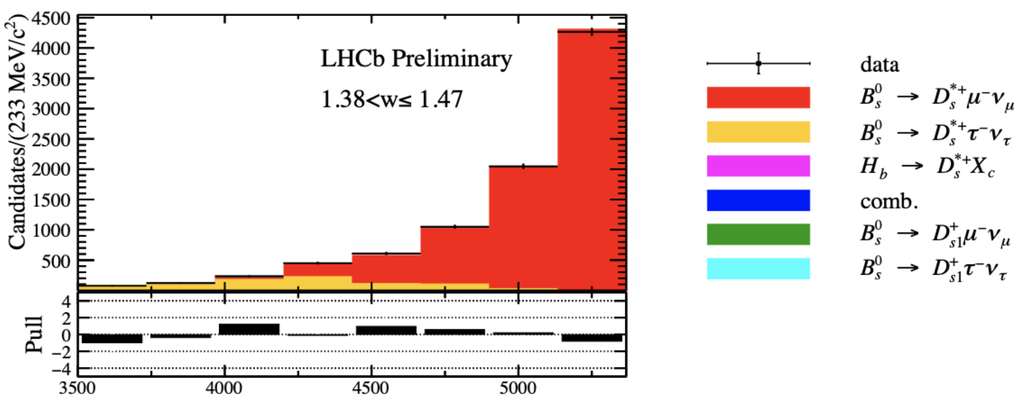
- Most important backgrounds

$$B_s \rightarrow D_s\tau\nu \ (\tau \rightarrow \mu)$$
$$B_s \rightarrow D_{s1}\mu\nu \ (D_{s1} \rightarrow D_s^* X)$$
$$H_b \rightarrow D_s^* X_c \ (X_c \rightarrow \mu)$$

- Isolation of the muon candidate
- Required a minimum muon p_T

Signal yields

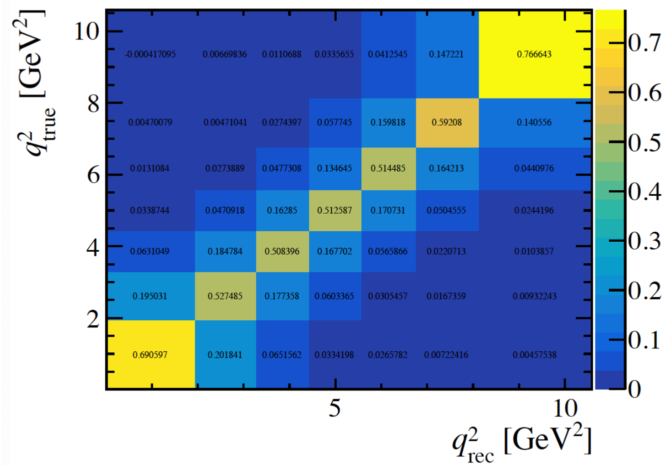


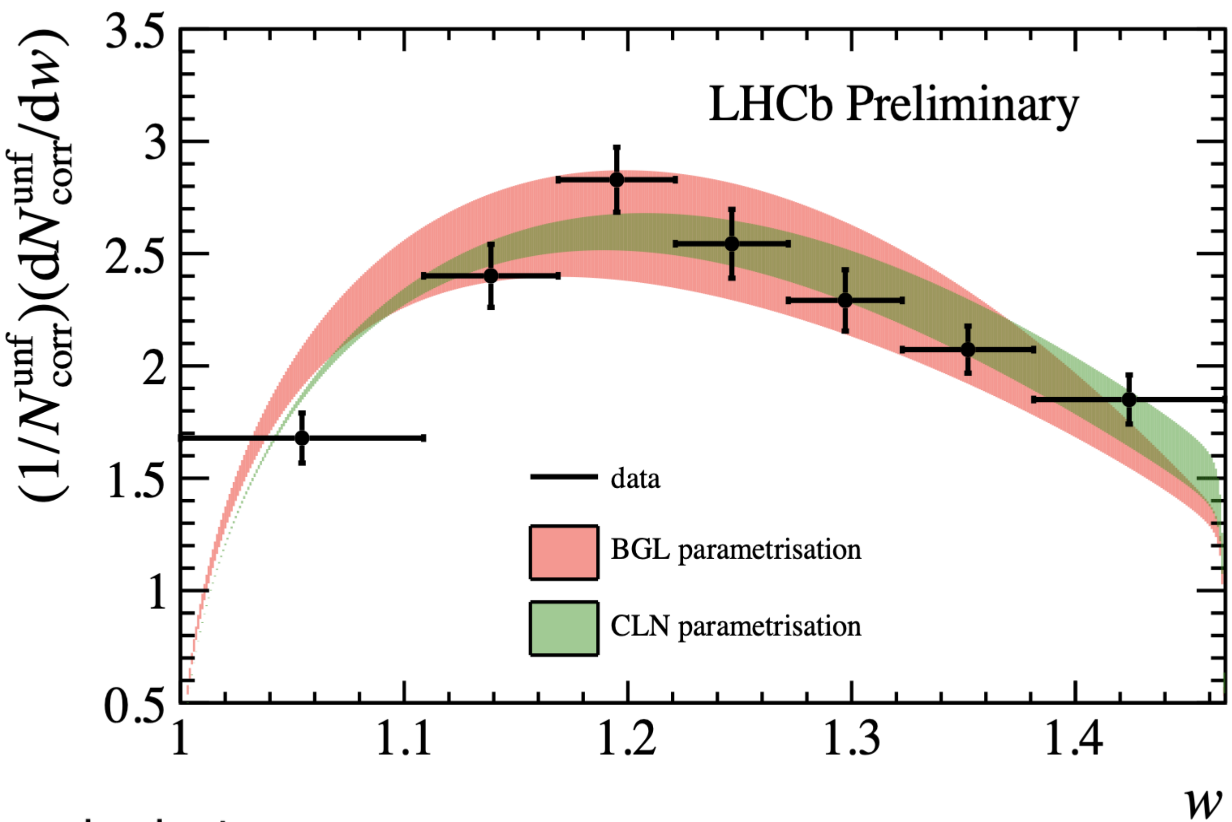


Extremely pure signal samples

$B_s \rightarrow D_s^* \mu \nu$ spectrum

Migration matrix needed for the unfolding





- For CLN parametrisation

$$\rho^2 = 1.16 \pm 0.05(\text{stat}) \pm 0.07(\text{syst})$$ massive leptons

$$\rho^2 = 1.17 \pm 0.05(\text{stat}) \pm 0.07(\text{syst})$$ massless leptons

- For BGL parametrisation

$$a_1^f = -0.002 \pm 0.034(\text{stat}) \pm 0.046(\text{syst})$$
$$a_2^f = 0.93^{+0.05}_{-0.20}(\text{stat})\,^{+0.04}_{-0.38}(\text{syst})$$

Parameters in agreement with the results on $B \rightarrow D^* \ell \nu$ from b-Factories
No significant SU(3) breaking!

These results and techniques are paving the road for ongoing tests of LFU in the B_s sector

$B \rightarrow D^{(*)} \tau \nu$

Lepton Universality

- Lepton Universality is a key feature of the Standard Model
- The only difference between electrons, muons and taus is the mass
  - Once corrected for the lepton masses, the decays with electrons, muons and taus should be identical!
  - LFU Violation would be a clear signature of BSM Physics

- 1) Deviations with expectations observed in b→s transitions

$$R(K) = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)} \qquad R(K^*) = \frac{\mathcal{B}(B \to K^*\mu^+\mu^-)}{\mathcal{B}(B \to K^*e^+e^-)}$$

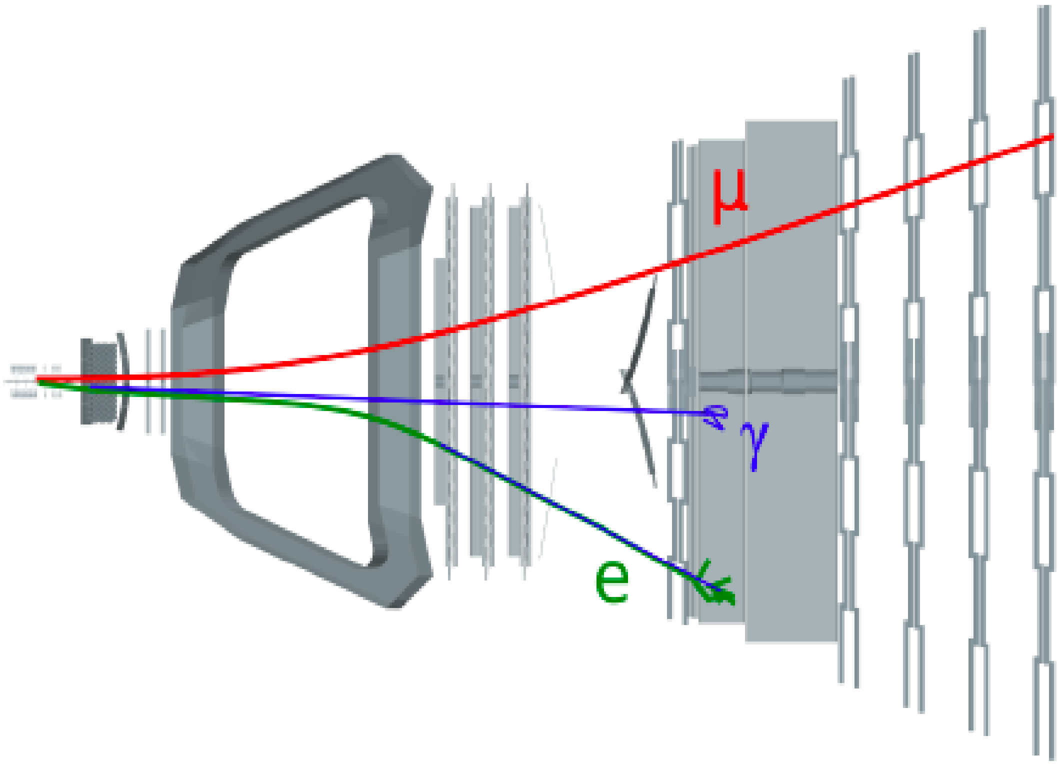
- 2) Deviations with expectations observed in b→c transitions

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

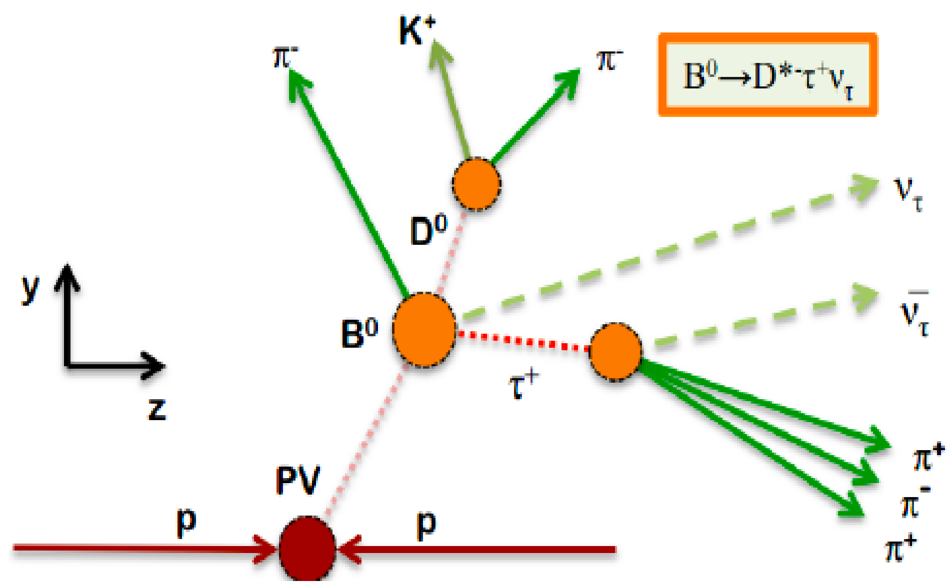
- <u>The SM predictions have reduced unknown hadronic contributions!</u>

Lepton Identification is Not Universal

- **Muons:**
  - Stable within LHCb
  - No radiation
- **Electrons:**
  - Bremssthrahlung emission in the detector: partially recovered from a detected γ
  - Contamination from γ conversions



- **Taus**:
  - Short lifetime: we see only the products
  - Neutrinos in the final state: $\tau \to \mu\nu\nu$, $\tau \to \pi\nu$, $\tau \to \pi\pi\pi\nu$
  - Large contamination from other heavy meson decays



$B \to D^{(*)}\tau\nu$: measurements

- Experiment can access directly *R*(D) and *R*(D*) ratios

$$\mathcal{R}(D) = \frac{\Gamma(B \to D\tau\nu_\tau)}{\Gamma(B \to D\ell\nu_\ell)_{\ell = e,\mu}}$$

$$\mathcal{R}(D^*) = \frac{\Gamma(B \to D^*\tau\nu_\tau)}{\Gamma(B \to D^*\ell\nu_\ell)}_{\ell = e,\mu}$$

Signal

$\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$

Normalization
(largest background)

$$\mathcal{R}(D^{(*)}) = \frac{N_{sig}}{N_{norm}} \times \frac{\epsilon_{norm}}{\epsilon_{sig}}$$

Several experimental and theoretical uncertainties cancel in ratio
- $D^{(*)}$ reconstruction / Particle ID /tracking eff.
- $|V_{cb}|$ & Form Factors (partially)

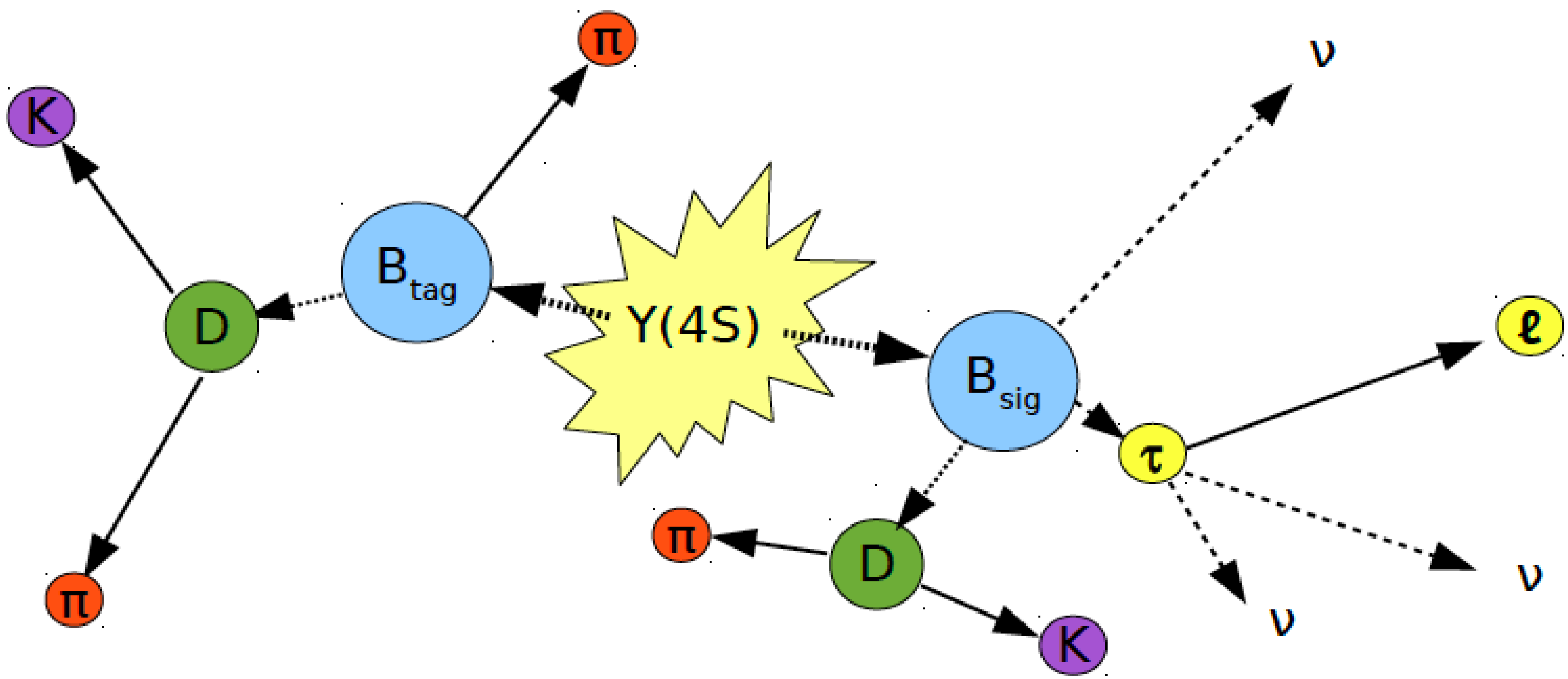
Very precise SM prediction

R(D) = 0.299 ± 0.004 σ = 1.0%
R(D*) = 0.258 ± 0.005 σ = 2.0%

Tagging at BFactories

Weak signal signature

- Many neutrinos in the final state
- Lack of kinematics constraints in the final state



- Tag B determines charge and momentum of signal B
- All remaining particles must come from signal B: Little activity in the Calorimeter

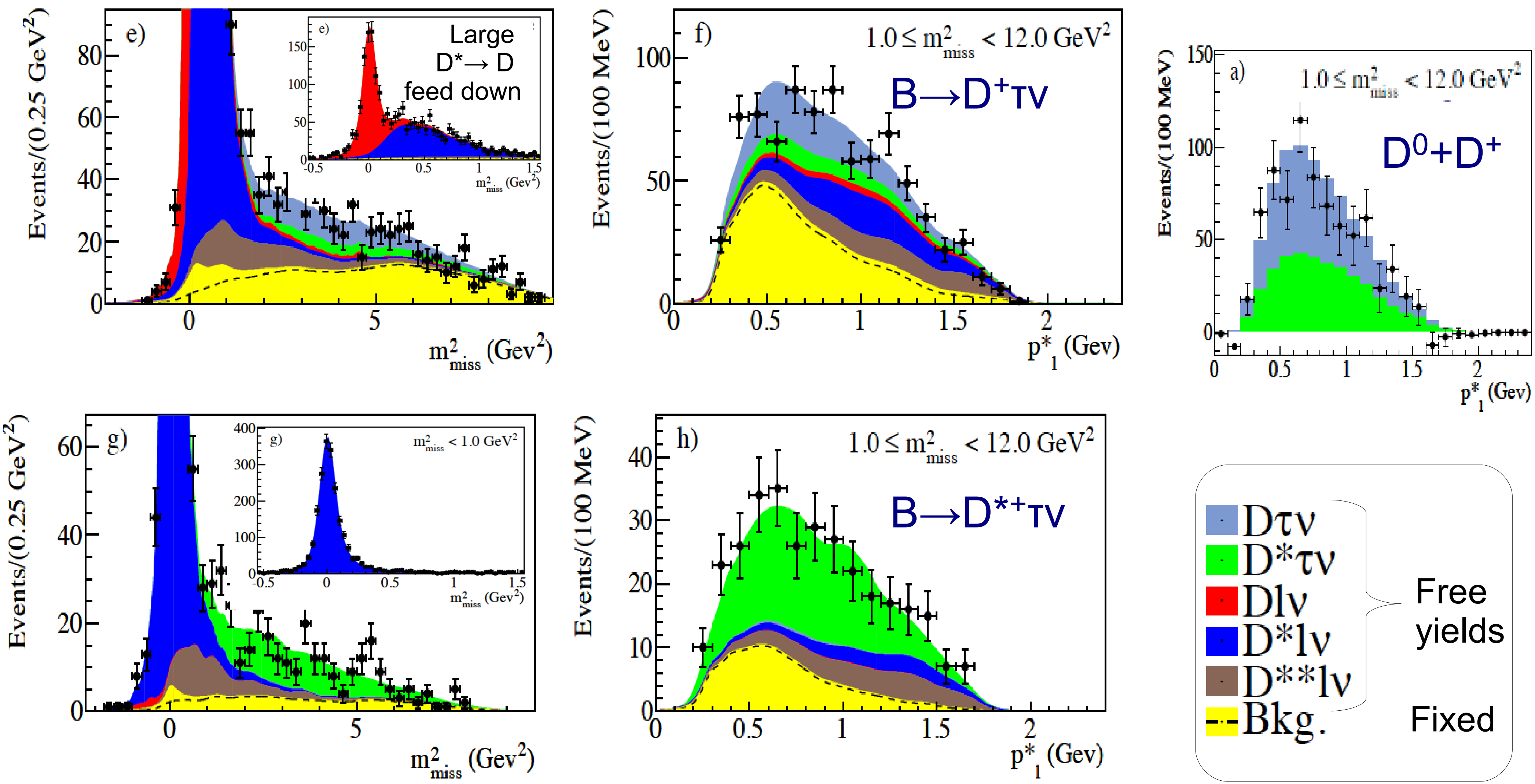
Results of Fit $B \to D^{(*)}\tau\nu$

PRL109,101802(2012)
PRD88,072012(2013)

Signal signature:

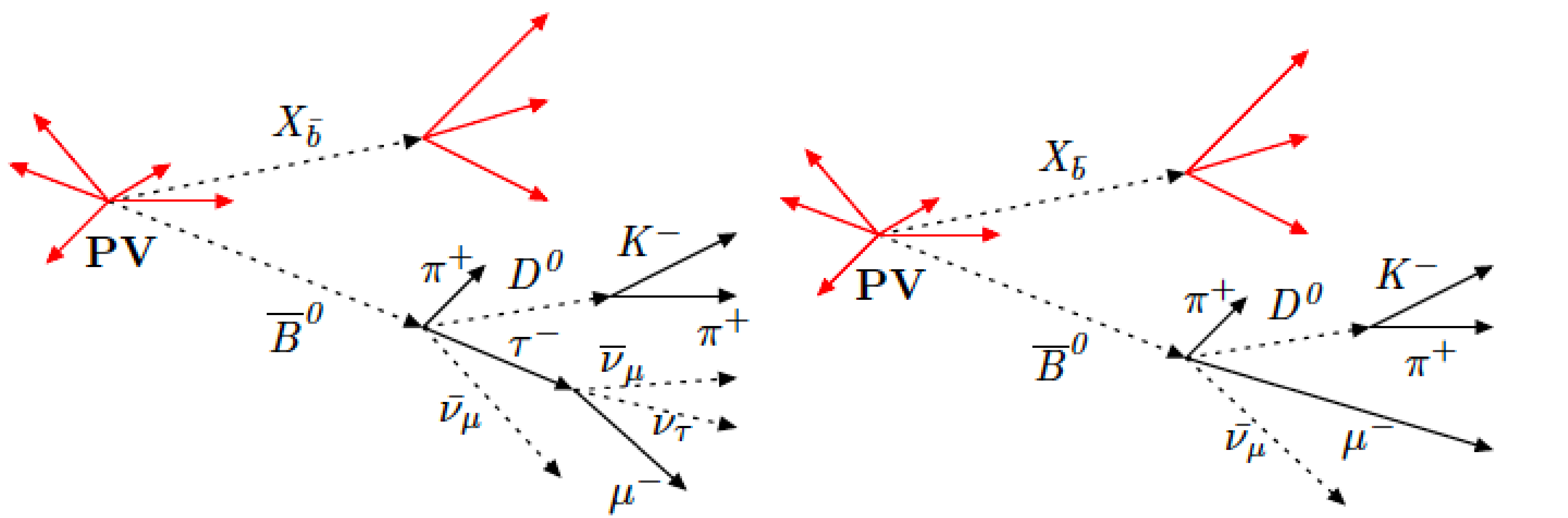
→ Large missing momentum
→ Softer muon from Tau decays

$m_{miss}^2 = (p_{e+e-} - p_{tag} - p_{D(*)} - p_\ell)^2$
p^*_ℓ in the B_{sig} rest-frame



R(D*) at LHCb

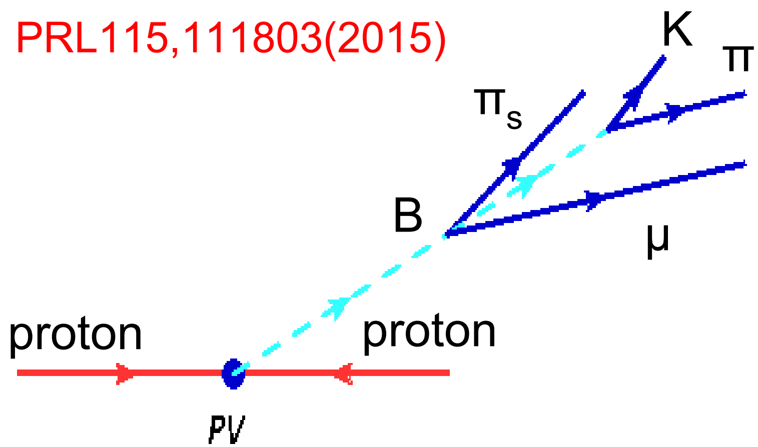
Signal ($B^0 \to D^{*+}\tau^-\overline{\nu}_\tau$) Normalisation ($B^0 \to D^{*+}\mu^-\overline{\nu}_\mu$)



- Trigger on the charm component (to not bias the signal extraction)
- Selection exploiting excellent LHCb performances of the VELO and the particle identification
- Full selection efficiency ratio $\varepsilon_\tau / \varepsilon_\mu$ = (77.6 ± 1.4) %
  - Lower p_T and worst vertex in the tau decay

B rest-frame determination

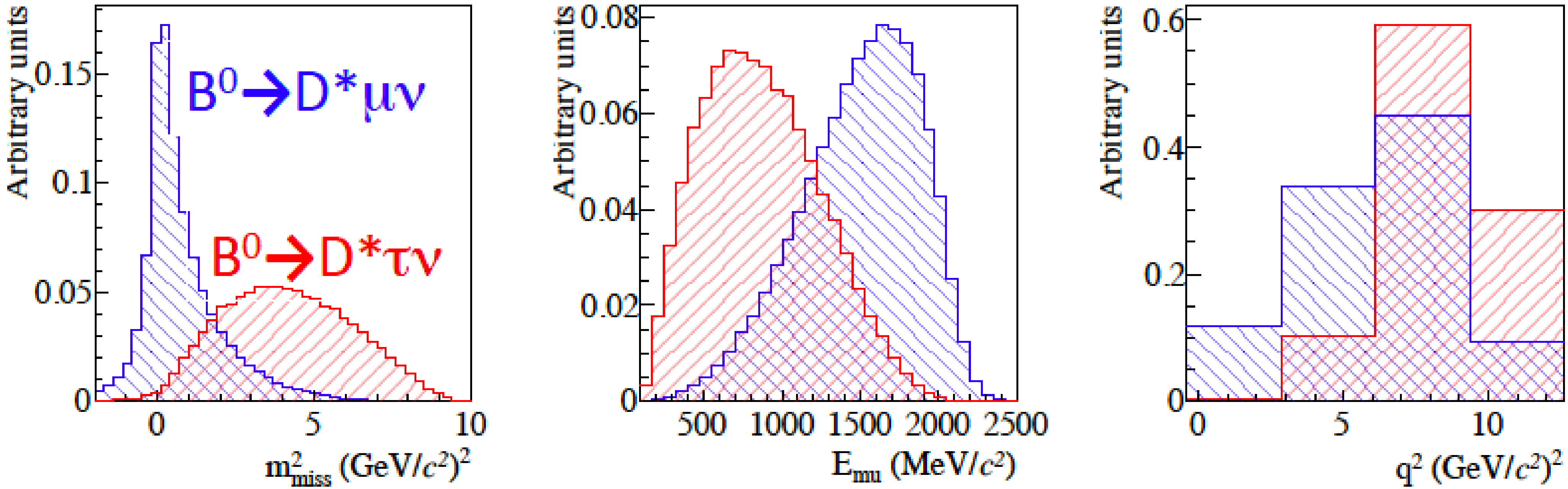
PRL115,111803(2015)



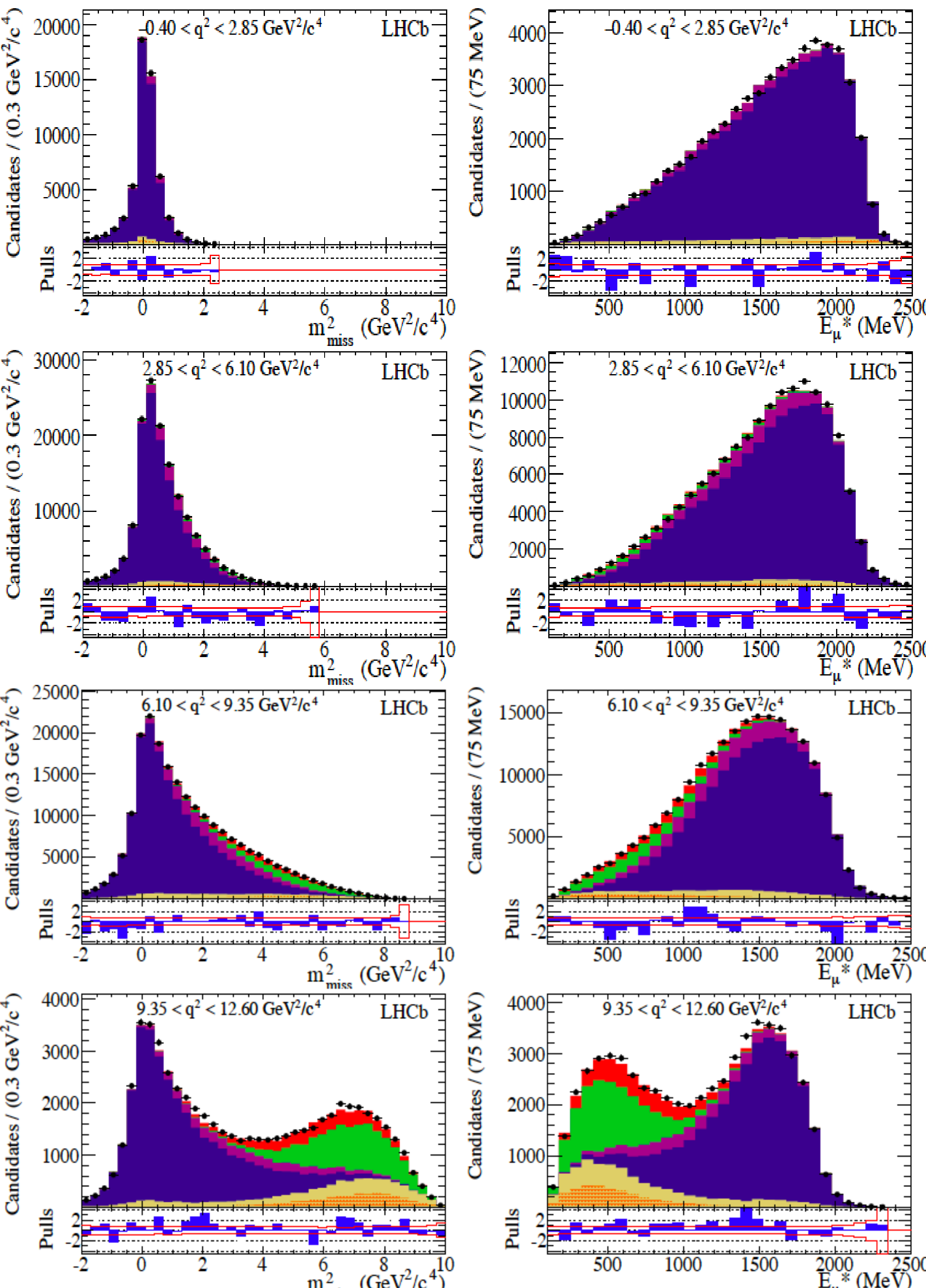
- B momentum unknown in production from pp collision in LHCb
  - B mainly from gg → $b\bar{b}$
- Transverse missing momentum is know but no way of measuring longitudinal component
  - B boost >> energy released in the decay
  - ~18% resolution on p_B

boost-approximation

$$p_z(B^0) = \frac{m_{B^0}}{m(D^*\mu)} p_z(D^*\mu)$$



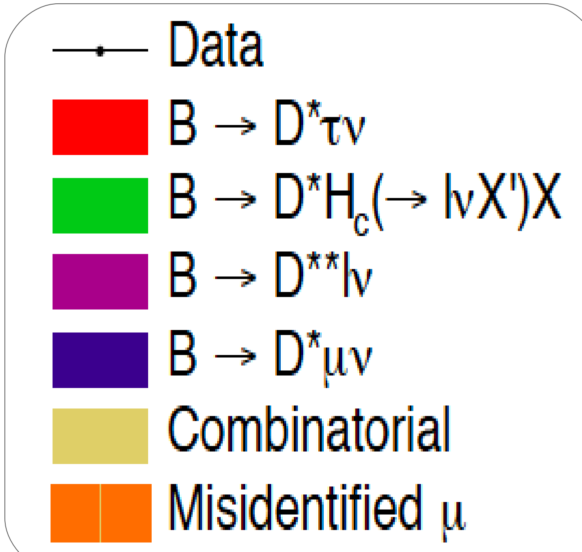
Results (4 q^2 bins)



- Binned 3-D fit in m_{miss}^2, E_μ and q^2 (40 x 30 x 4 bins)

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

- In agreement with BaBar and Belle measurements
- 2.1σ higher than SM



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

PRL120(2018)171802
PRD97(2018)072013

- Compared to leptonic τ decay, the largest source of contamination comes from $B\to D^*3\pi X$ decays: completely different backgrounds, and new opportunities to control them!
- Signal normalized to $B\to D^*3\pi$

$$K(D^*) \equiv \frac{Br(B^0\to D^{*-}\tau^+\nu_\tau)}{Br(B^0\to D^{*-}3\pi)} = \frac{N_{D^*\tau\nu_\tau}}{N_{D^*3\pi}} \times \frac{\varepsilon_{D^*3\pi}}{\varepsilon_{D^*\tau\nu_\tau}} \times \frac{1}{Br(\tau^+\to 3\pi(\pi^0)\bar{\nu}_\tau)}$$

- Signal and normalization share the same visible final state
  - Cancel most of the systematics: PID, trigger, tracking efficiency

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

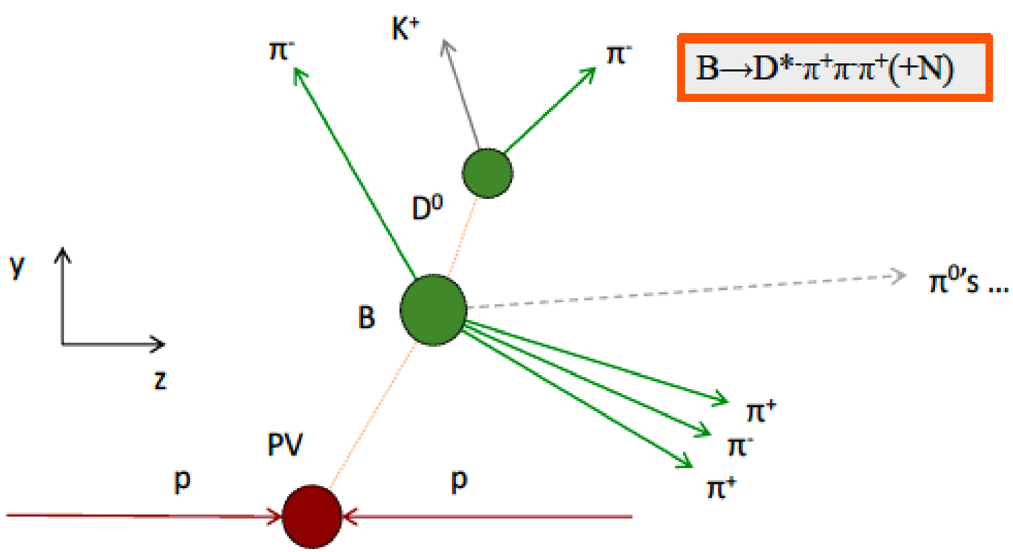
4% precision from PDG2017

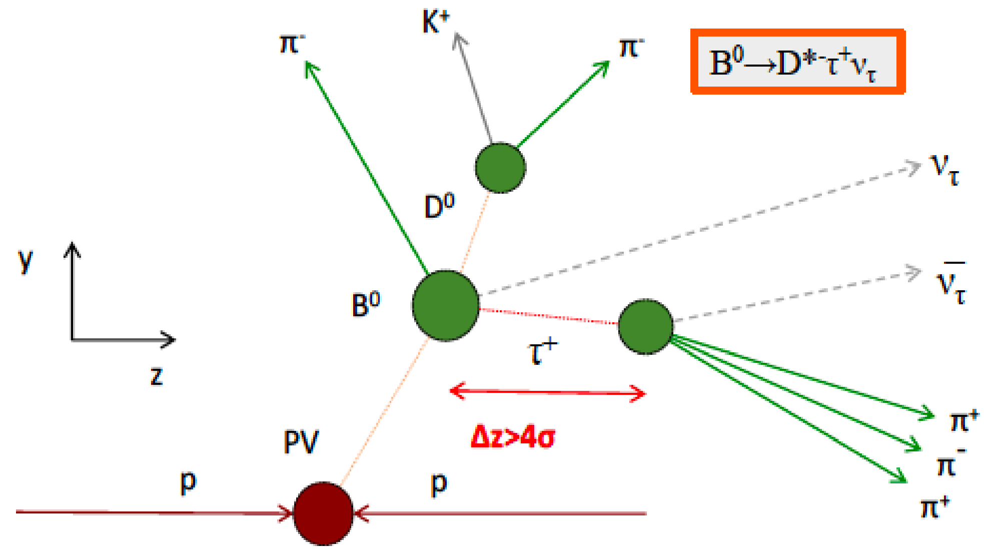
2%precision from HFLAV2018

B → D*τν: background reduction

PRL120(2018)171802
PRD97(2018)072013

- Decay topology exploited to suppress the abundant background from $H_b \to D^*3\pi X$ (BR ~ 100 x Signal)





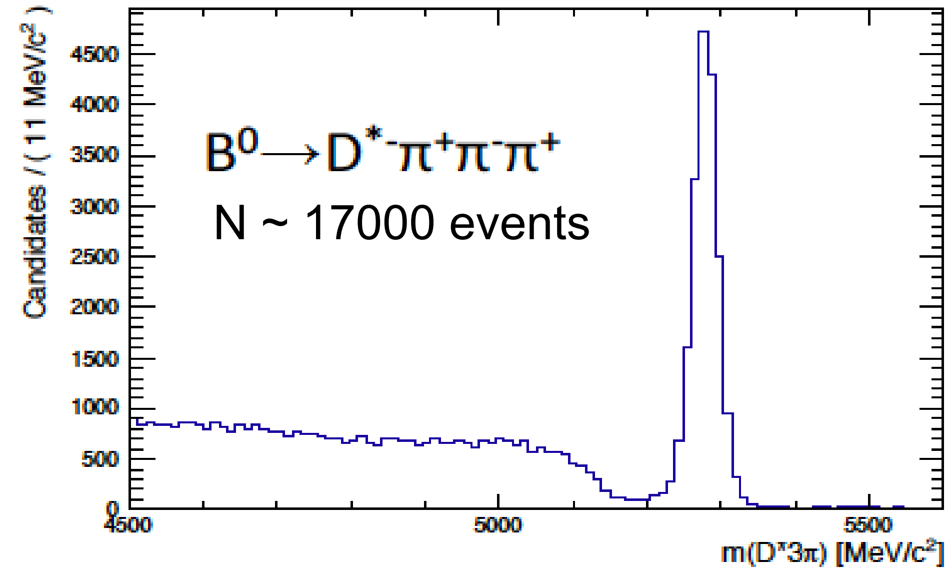
- Minimum distance between H_b and τ required: reduce these background by a factor 1000
- Remaining backgrounds contains two charm hadrons:
  - uses informations from additional energy around the t direction, and the resonant structure in the $D^*3\pi$ system (BDT)

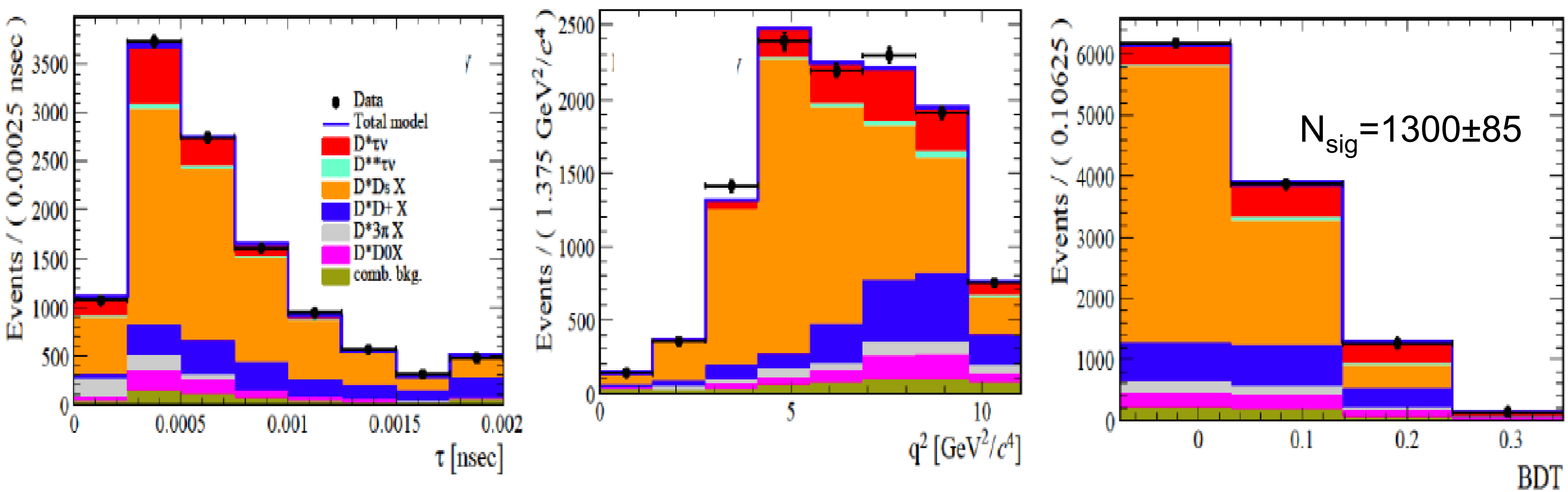
- $X_b \to D^{*-} D_s^+ X$: ~10 x signal
- $X_b \to D^{*-} D^+ X$: ~1 x signal
- $X_b \to D^{*-} D^0 X$: ~0.2 x signal

Fit results

PRL120(2018)171802
PRD97(2018)072013

- Normalization mode
- Signal extracted from 3D fit on
  - q^2 (8 bins)
  - 3π decay time (8 bins)
  - BDT (4 bins)

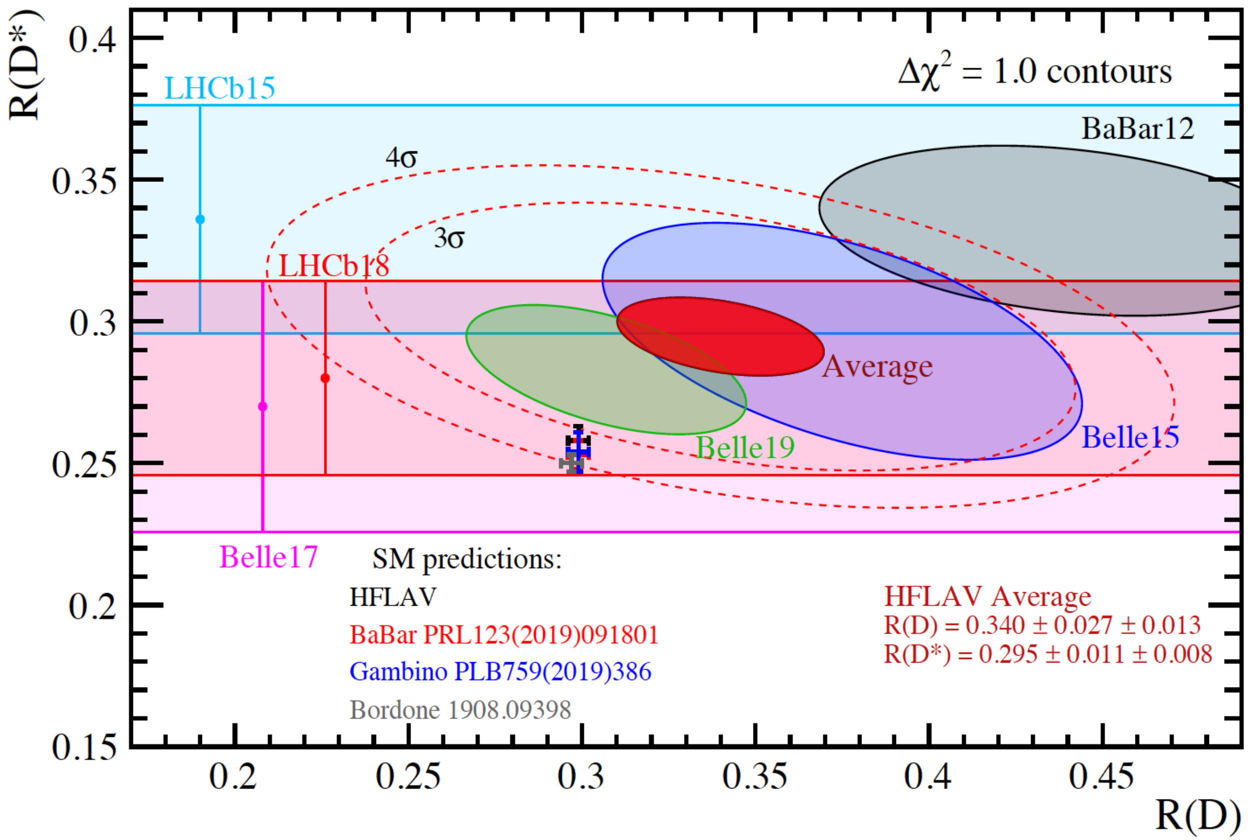




$R(D^*) = 0.283 \pm 0.019 \pm 0.025 \pm 0.013$ (from external inputs)

Status of R(D)-R(D*)

Isospin breaking due to QED PRL120(2018)261804



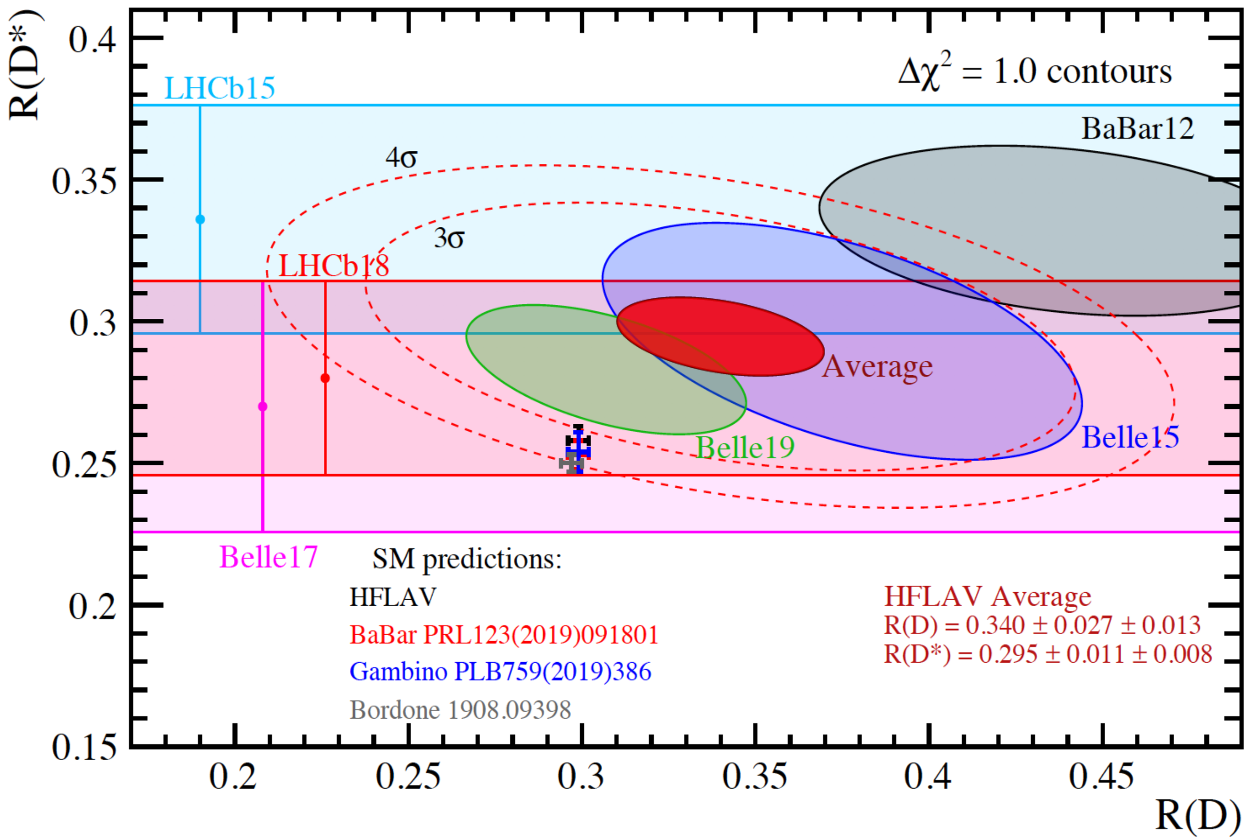
$$R(D^*) = 0.295 \pm 0.011 \pm 0.008$$
$$R(D) = 0.340 \pm 0.027 \pm 0.013$$

- The uncertainty on the additional form factors needed for massive leptons (Ht) is the dominant source of uncertainty

- How reliable are these predictions?
  - QED corrections?
  - Form-Factors from Lattice?

	R(D)	R(D*)	RD-RD* #σ from SM	RD* only #σ from SM
Bernlochner et al. PRD95(2017)115008	0.299±0.003	0.257 ± 0.003		
Bigi et al. JHEP1711(2017)061		0.260 ± 0.008		
Jaiswal el al. JHEP1712(2017)060	0.299±0.004	0.257 ± 0.005		
HFLAV	**0.299±0.004**	**0.258 ± 0.005**	**3.08**	**2.5**
BaBar PRL123(2019),091801		0.253 ± 0.005	3.43	2.8
Gambino et al. PLB795(2019)386		0.254 ± 0.007	3.16	2.6
Bordone et al. ArXiv:1908.09398 (no exp.)	0.298±0.003	0.247 ± 0.006	3.77	3.2
Bordone el al. ArXiv:1908.09398	0.297±0.003	0.250 ± 0.003	3.87	3.2

Status of R(D)-R(D*)



$$R(D^*) = 0.295 \pm 0.011 \pm 0.008$$
$$R(D) = 0.340 \pm 0.027 \pm 0.013$$

- The uncertainty on the additional form factors needed for massive leptons (Ht) is the dominant source of uncertainty
- Common systematics:
  - $B \to D^{**}$ / $B \to D^*X_c$
  - QED correction: PHOTOS

	R(D)	R(D*)	RD-RD* #σ from SM	RD* only #σ from SM
Bernlochner et al. PRD95(2017)115008	0.299±0.003	0.257 ± 0.003		
Bigi et al. JHEP1711(2017)061		0.260 ± 0.008		
Jaiswal el al. JHEP1712(2017)060	0.299±0.004	0.257 ± 0.005		
HFLAV	**0.299±0.004**	**0.258 ± 0.005**	**3.08**	**2.5**
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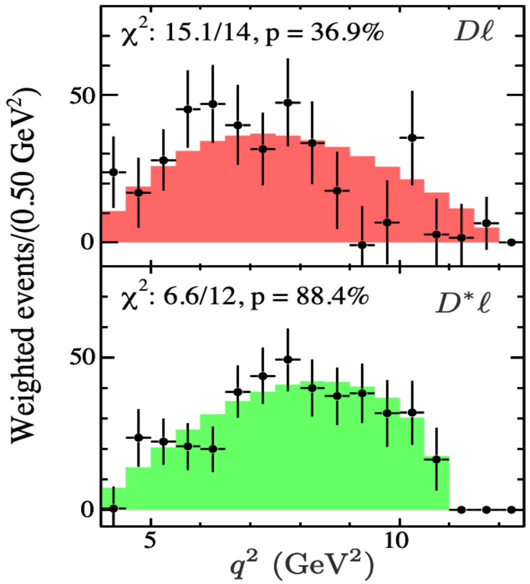
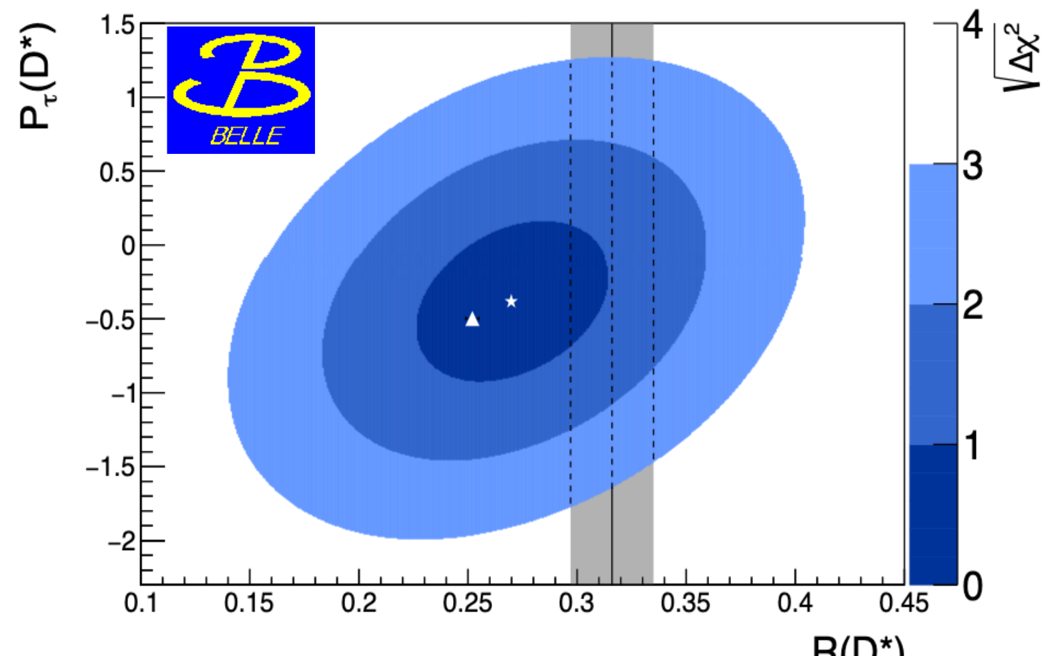
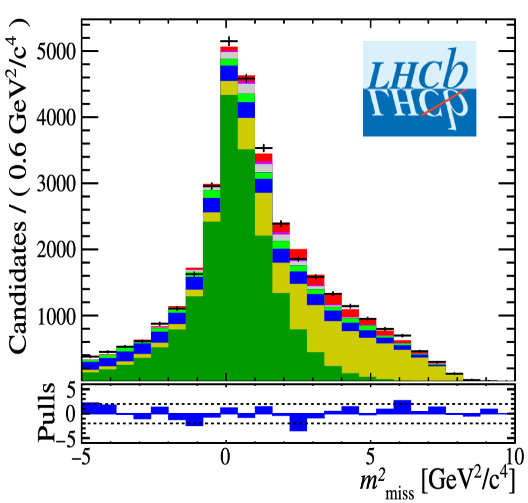
Beyond R(D)-R(D*) observables



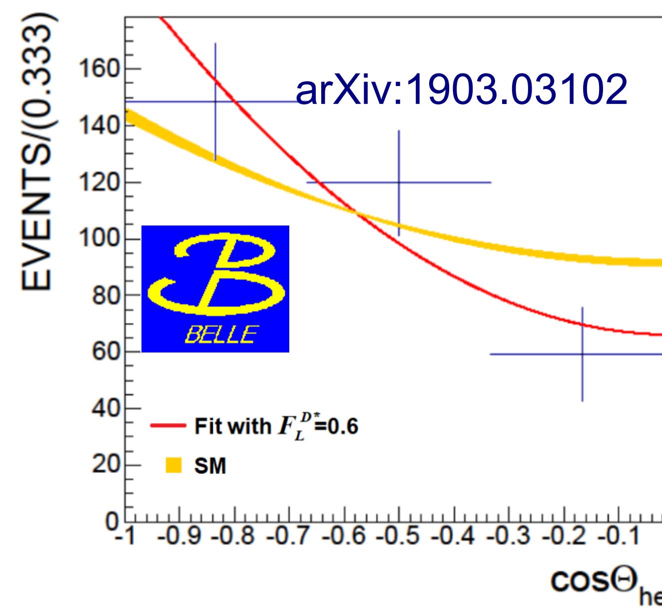


$$\mathcal{R}(J/\Psi) = \frac{\mathcal{B}(B_c \to J/\Psi \tau \nu)}{\mathcal{B}(B_c \to J/\Psi \mu \nu)}$$



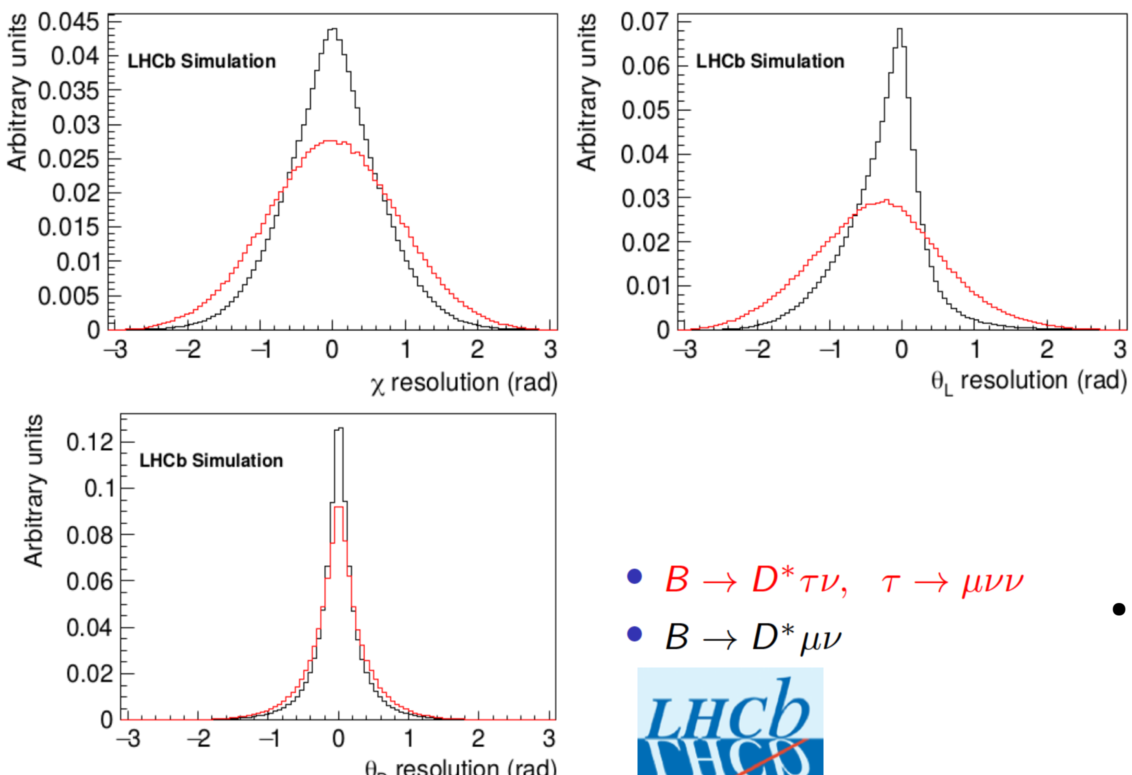
R(J/Ψ)=0.71 ± 0.17 ± 0.18

2σ higher than the SM

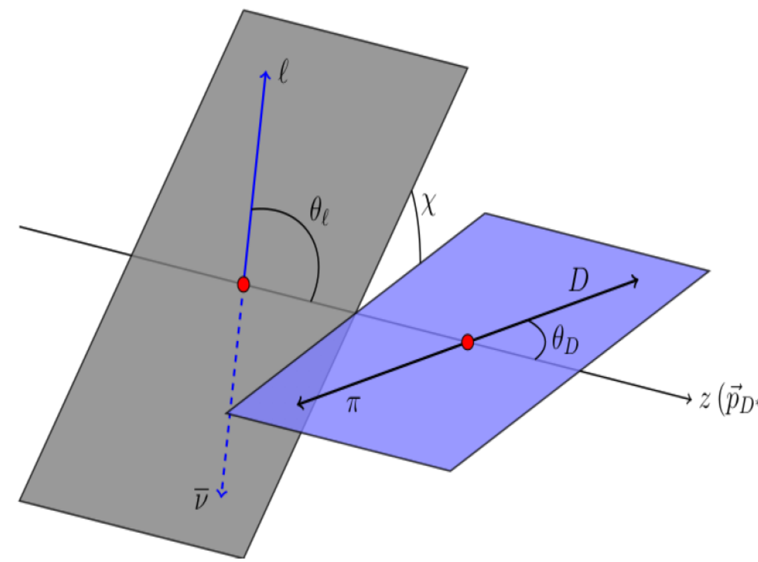


Angular analyses

- B→D* and $B_s \to D_s^*$: rich angular structure can be exploited:
  - Strong sensitivity to NP Wilson coefficients (for example in arXiv:1602.03030)
  - Belle-II will further analyses these decays
  - With the very high statistics collected in LHCb it is possible to perform angular analysis even with a quite poor resolution on the angular observables

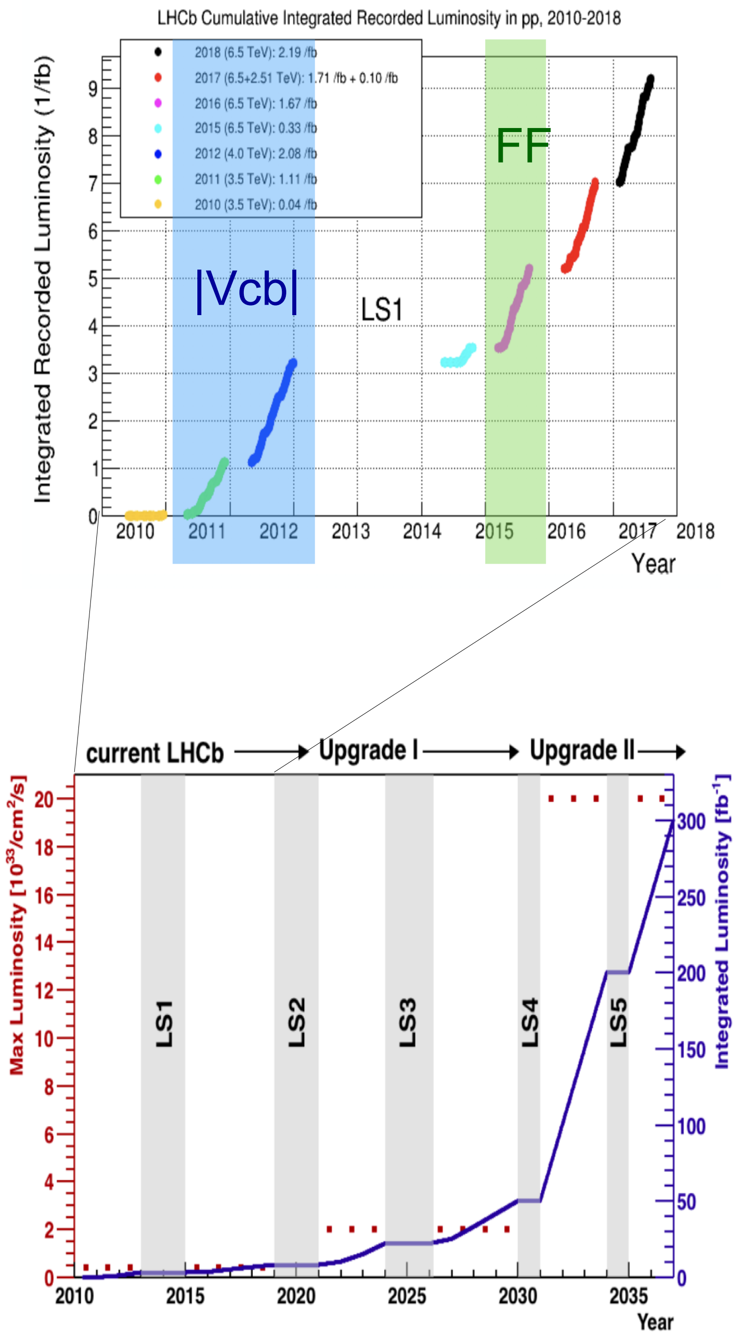


- $B \to D^* \tau\nu, \quad \tau \to \mu\nu\nu$
- $B \to D^* \mu\nu$

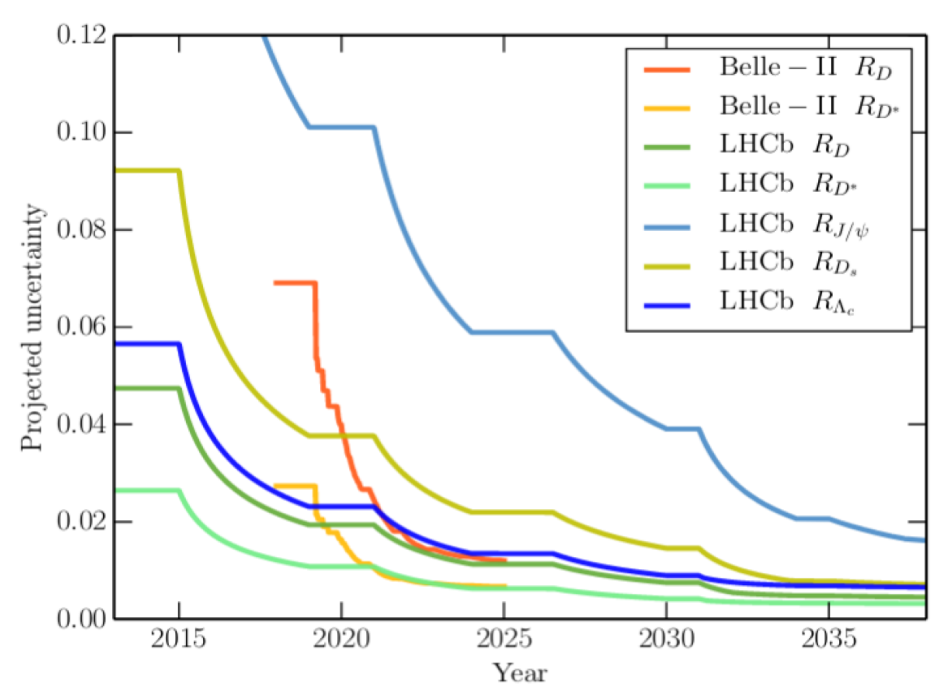


- For B→D* with hadronic tau, a novel approach has been proposed in D. Hill et al. JHEP11(2019)133

Future steps: larger data samples



- In the coming years of data taking the integrated luminosity will greatly increase
- The higher statistics in the control regions will help in constraining the background model
- MC statistics is the limiting systematic in the present measurements
  - Fast simulations already developed arXiv:1810.10362



ArXiv:1809.06229

Conclusions

- Semileptonic decays of the B-hadrons are a rich mine of good physics
- They requires close interplay between theorists and experimentalist

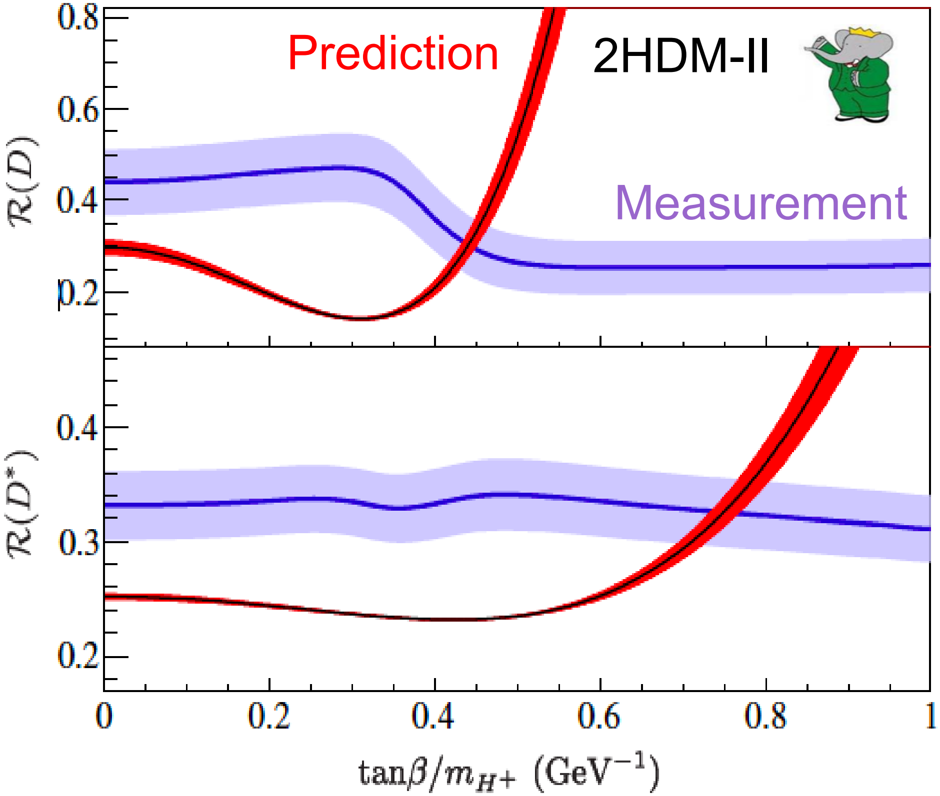
- CKM elements: the Inclusive-Exclusive puzzle have to be understood!
  - Inclusive measurements will be dominated by Belle-II in the near future!
  - On exclusive measurements LHCb has shown un-expected great capabilities

- The R(D)-R(D*) anomalies requires further checks
  - Studies in different hadrons are ongoing: $R(D_s)$, $R(D_s^*)$, $R(\Lambda_c)$, $R(J/\Psi)$
  - Exploit $b \rightarrow u$ transitions: $R(\pi)$, $R(\rho)$, R(p)
  - With the increasing in precision, it is crucial to consider effects not considered so far: QED corrections

  - If these anomalies are due to fluctuations, limited QCD understanding, systematics, we will know soon!
  - Crucial to exploit all the data we already have in LHCb
  - Belle-II could confirm/disprove (<u>Confirmations are important as first measurements!</u>)

Backup

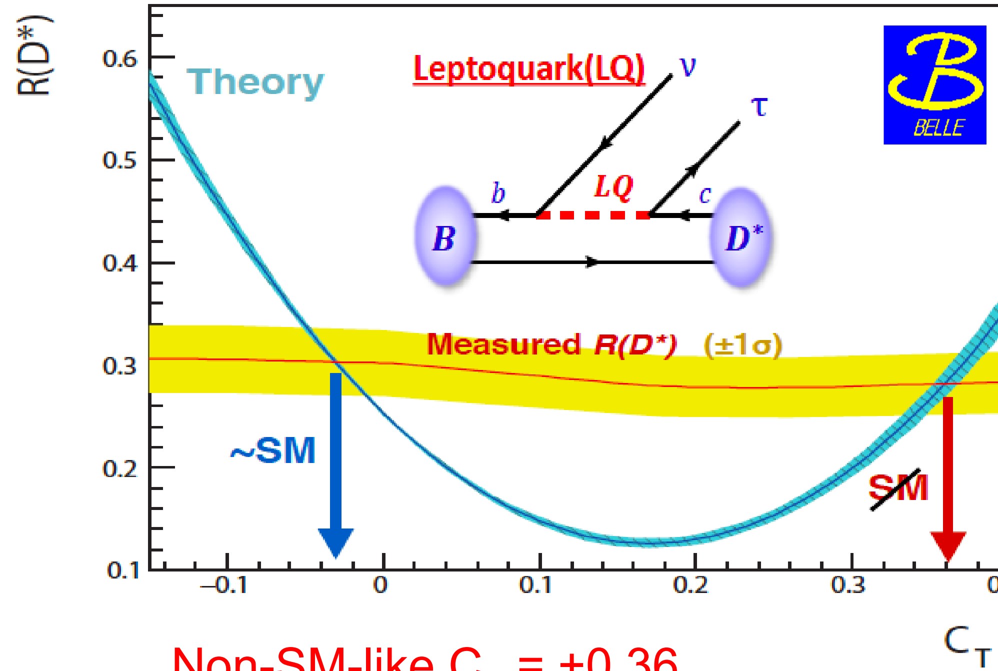
Large New Physics Effect! H^2,LQ, ?-



$$\mathcal{R}(D) \Longrightarrow \tan\beta/m_H = 0.44 \pm 0.02$$
$$\mathcal{R}(D^*) \Longrightarrow \tan\beta/m_H = 0.75 \pm 0.04$$

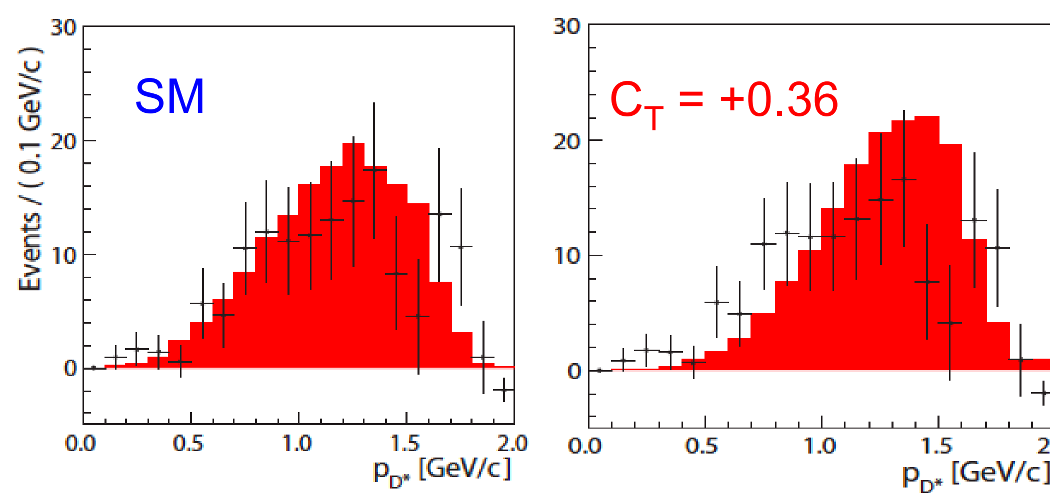
- The combination of R(D) and R(D*) excludes the 2HDM-II
- More general 2HDM-III can explain the data (more parameters)

LQ from PRD 87,034028(2013)



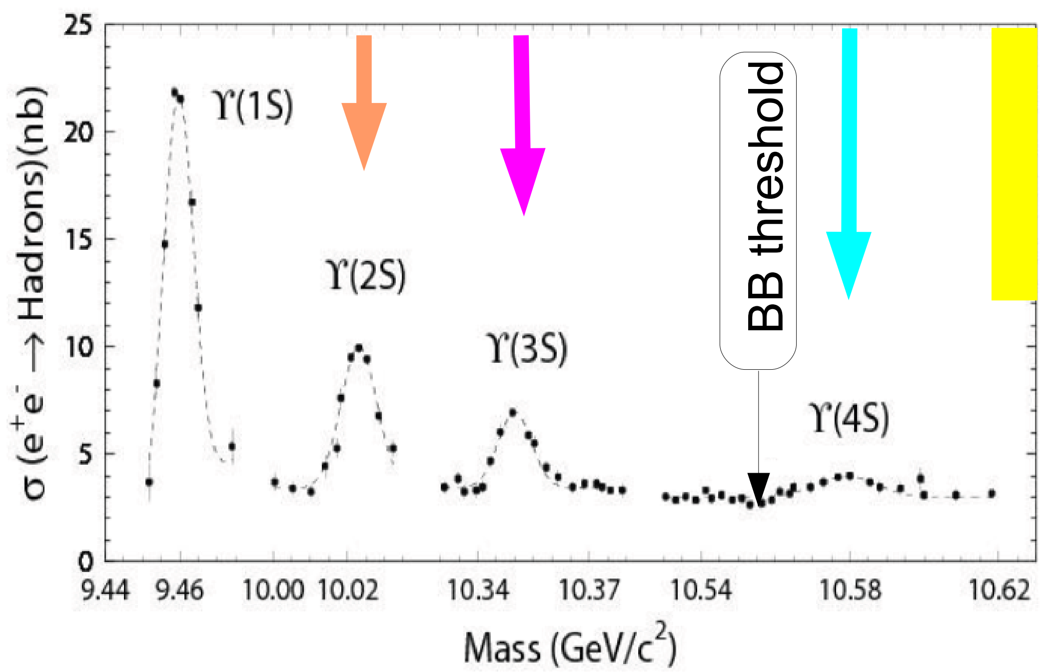
Non-SM-like C_T = +0.36

But disagreement in D* momentum

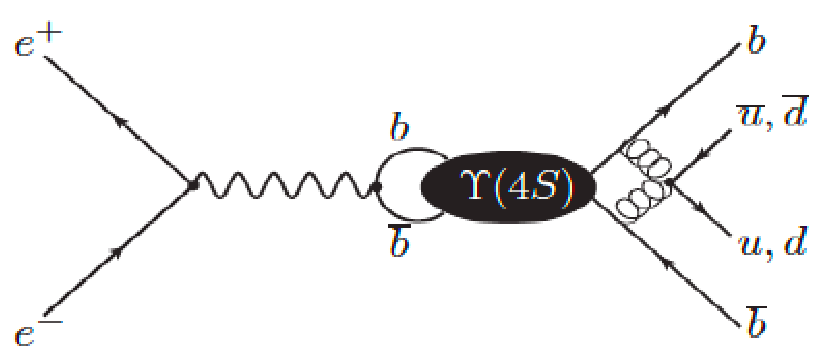


B-Factories BaBar and Belle

- CM energy of the Y(4S) = 10.58 GeV most of the time
  - Large production of B meson from Y decays
  - $\sigma_{10.58GeV}(e^+e^- \rightarrow bb) = 1.06nb$
  - Run at Y(5S) allows to access the B_s mesons



$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$$

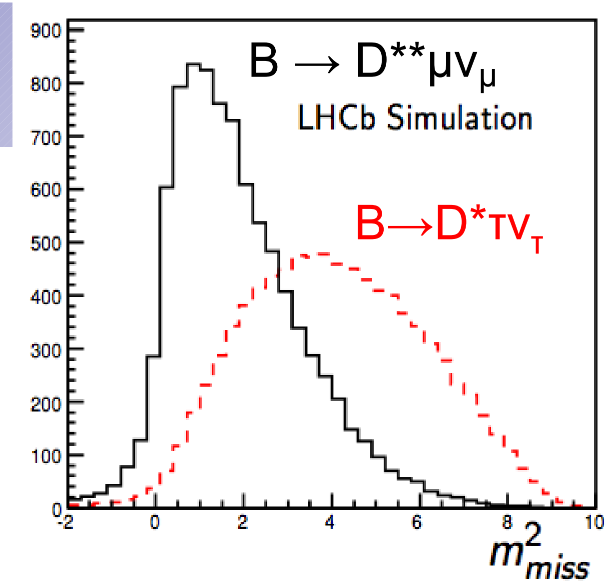


B-Factories: hermetic detectors, low background, Excellent PID, access (mainly) at $B^{0/+}$

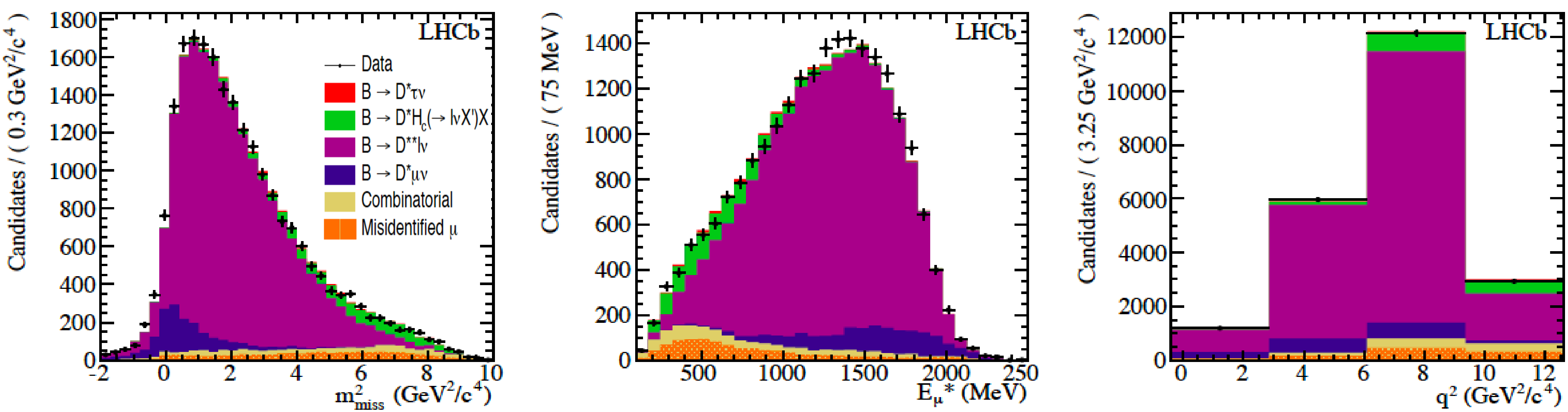
About (771 + 467)x10^6 $e^+e^- \rightarrow$ BB events in the Belle+BaBar data

D** backgrounds

- $B \to D^{**}\mu\nu_\mu$ where D** refers to any resonant or non resonant excited charm state
  - Separate templates for narrow resonances $D_1(2420)$, $D_2^*(2460)$, $D_1'(2430)$
  - Form Factor from LLSW model with slope of IW function floated



D*μπ control sample



- $B \to D^*\pi\pi\mu\nu_\mu$ recently measured by BaBar
  - Modelled using ISGW2 parameterization
  - q^2 distribution tuned on data with **D*μππ** control sample

D** Background is ~12% of the normalization mode