Perspectives from Belle II

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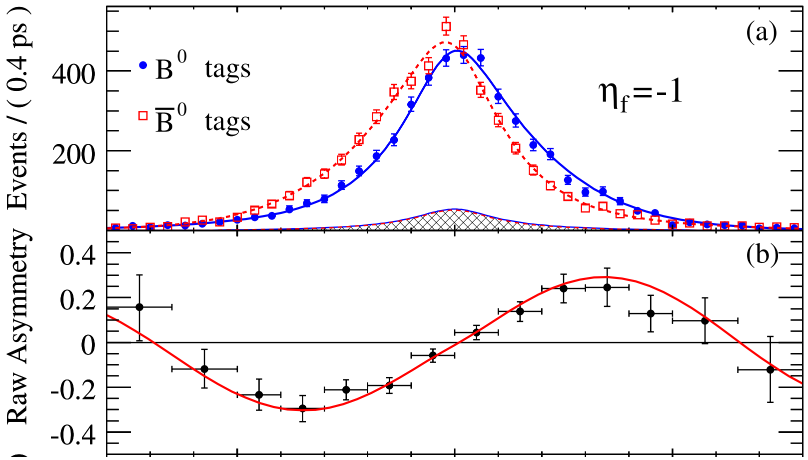
University of Napoli *Federico II* and INFN

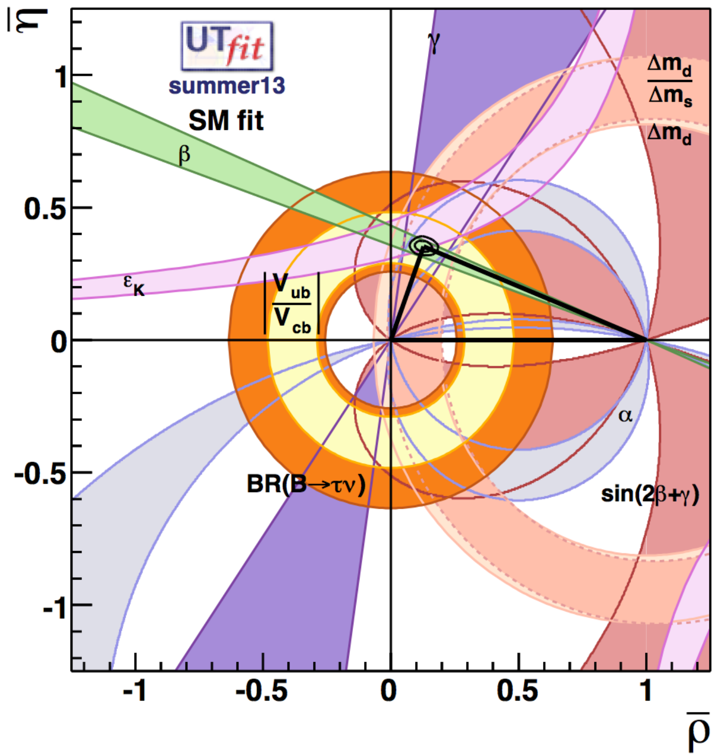
A Taste of Flavour Physics
1-2 March 2016, Perugia, Italy

Outline

- Physics motivations
- Status of the project
- Physics program highlights

Belle and BaBar achievements





Successful experimental program

Established CP violation in B system and remarkable consistency of the CKM mechanism of the SM

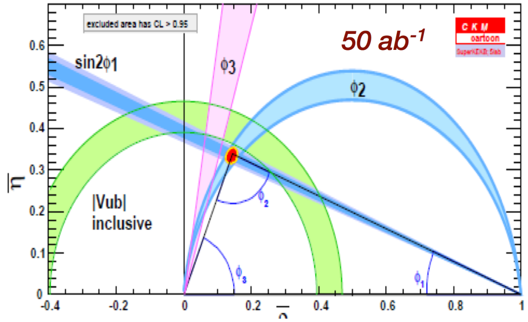
Nobel Prize in Physics In 2008 awarded to Kobayashi and Maskawa

2008

The role of flavour in the search for NP

Despite the BaBar and Belle experimental efforts SM did not break down.

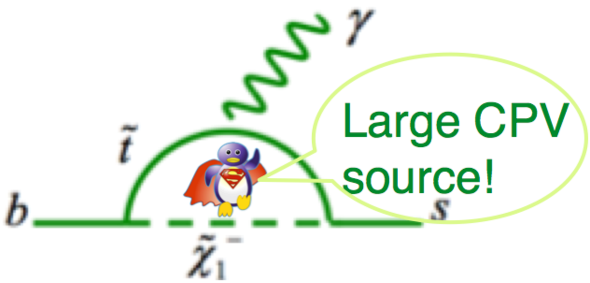
The triumph of the SM continued with the Higgs boson found where it was expected …and nothing else …yet



Mission of Belle II and LHCb

Scenario A: new particles or interactions ARE found with direct search at LHC
→ Reveal the flavour structure of NP

Scenario B: New Physics keeps hiding
→ Extend the search to even higher mass scales looking at many possible effects at low energy



KEKB upgrade to SuperKEKB

Channel	Belle	BaBar	Belle II (per year)
$B\bar{B}$	7.7×10^8	4.8×10^8	1.1×10^{10}
$B_s^{(*)}\bar{B}_s^{(*)}$	7.0×10^6	–	6.0×10^8
$\Upsilon(1S)$	1.0×10^8		1.8×10^{11}
$\Upsilon(2S)$	1.7×10^8	0.9×10^7	7.0×10^{10}
$\Upsilon(3S)$	1.0×10^7	1.0×10^8	3.7×10^{10}
$\Upsilon(5S)$	3.6×10^7	–	3.0×10^9
$\tau\tau$	1.0×10^9	0.6×10^9	1.0×10^{10}

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorentz factor

Beam current

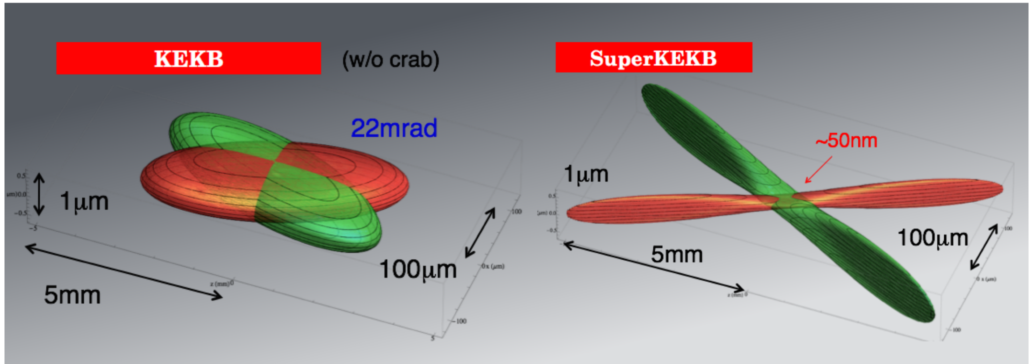
Beam-Beam parameter

Geometrical reduction factors (crossing angle, hourglass effect)

Beam aspect ratio at IP

Vertical beta function at IP

Minimum value is limited by hourglass effect



	E (GeV) LER/HER	β*$_y$ (mm) LER/HER	β*$_x$ (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm^{-2}s^{-1})
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

Instantaneous luminosity 40x KEKB luminosity

nano-beams scheme

(first proposed by P. Raimondi for SuperB)

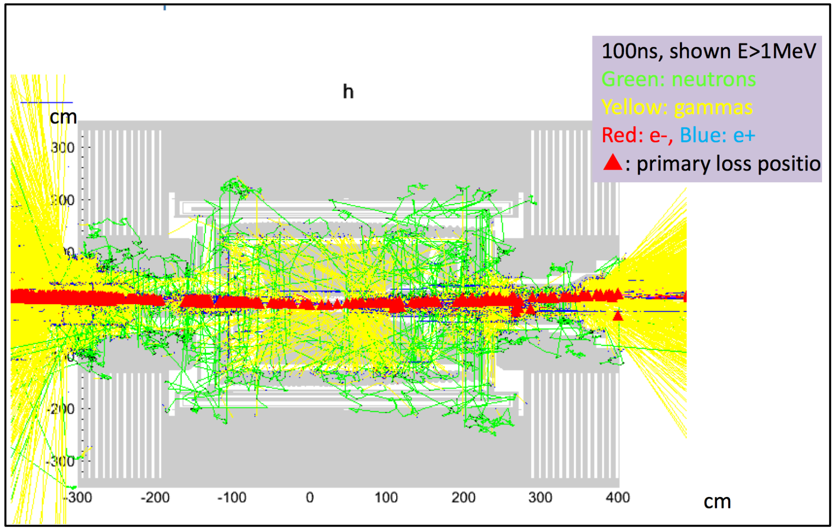
Upgrades on many accelerator components

2x higher currents

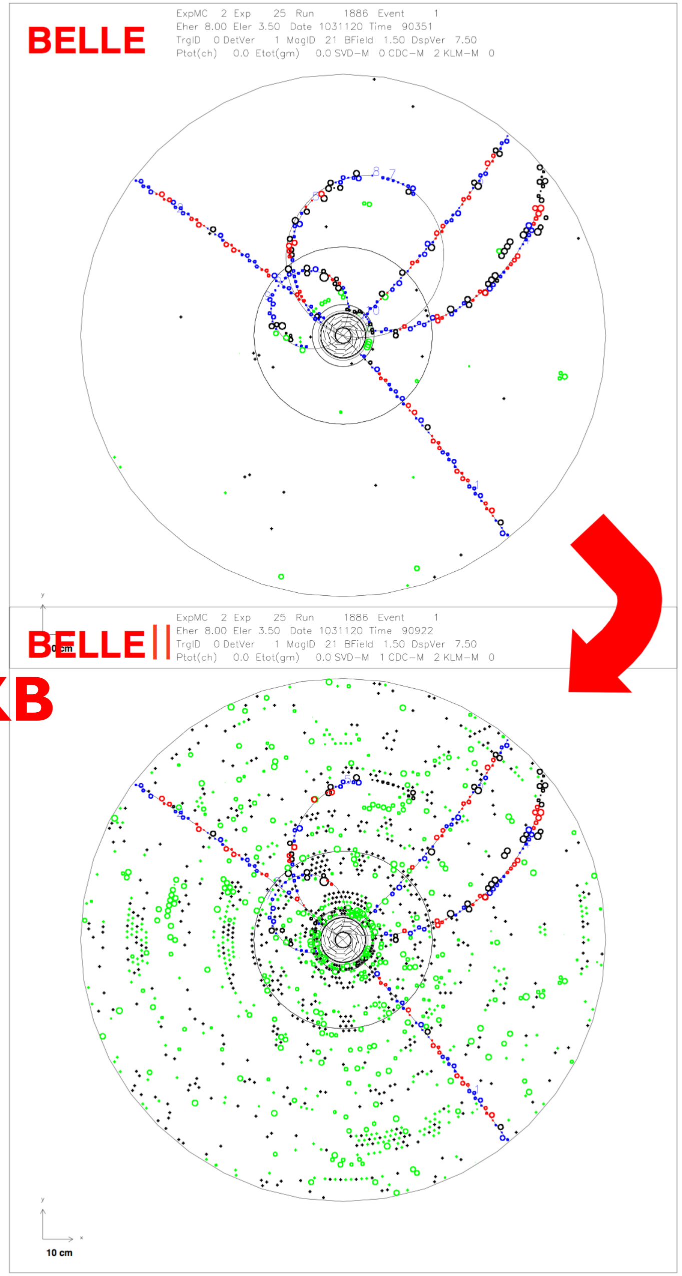
Costruction done. Commissioning started right now.

First turns of positrons and electrons single beams expected very soon

Belle II detector upgrade



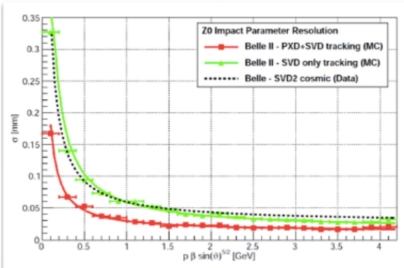
Toucheck
Rad. Bhabha
2-photon

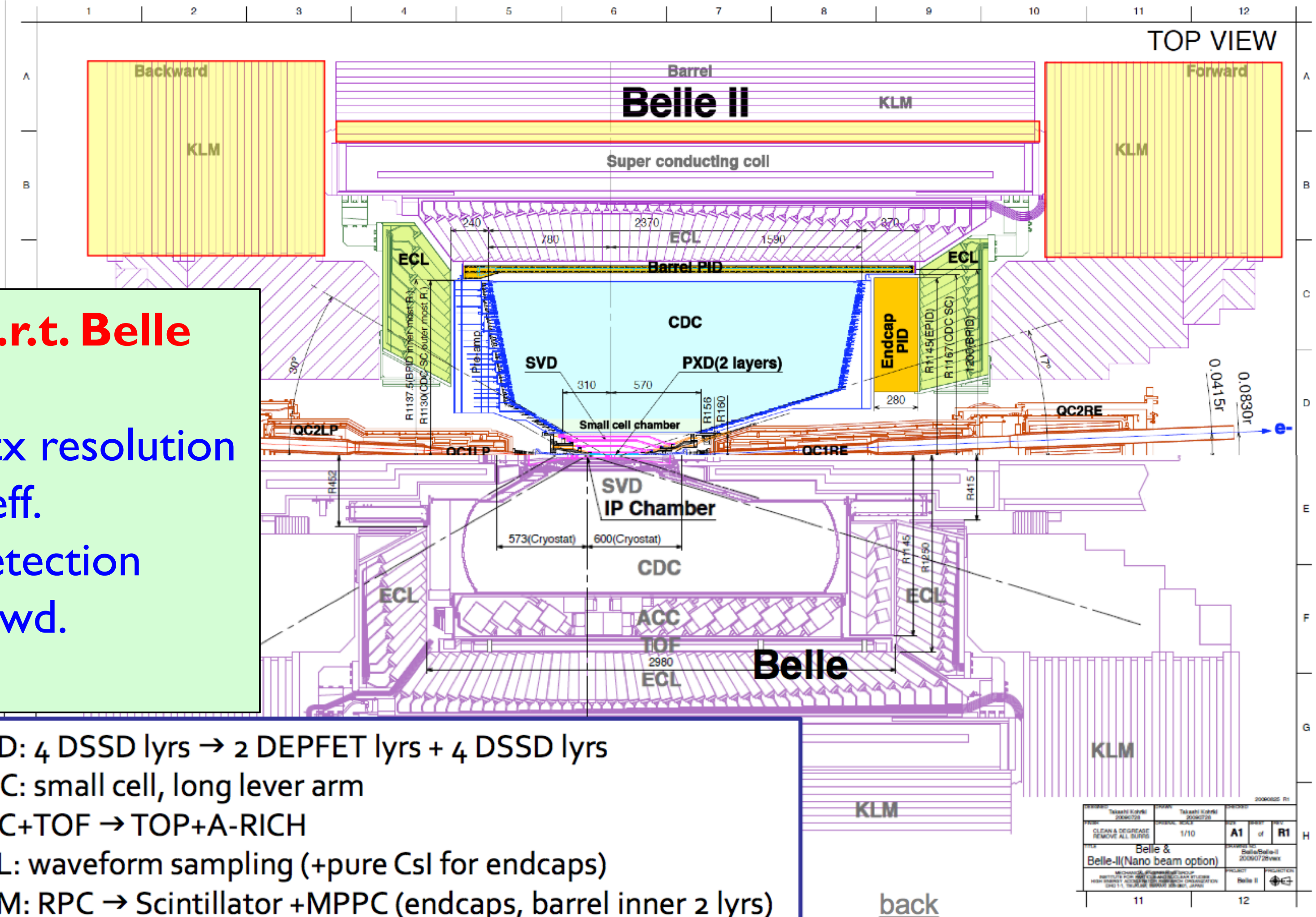


Beam related backgrounds 10-20x KEKB

Occupancy in detector
pile-up in calorimeter
fake hits
radiation damage
Higher event rates (L1 trigger: 20 kHz)

Belle II upgraded detector



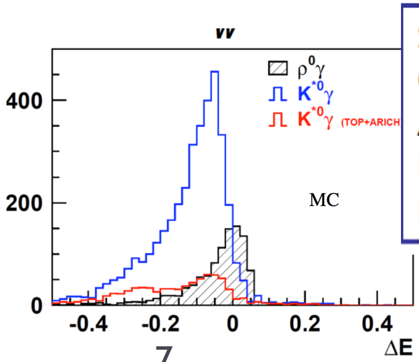


Improvements w.r.t. Belle

IP and secondary vtx resolution
Ks reconstruction eff.
Muon ID and KL detection
K identification in Fwd.

SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

back



Belle II unique capabilities

Exactly 2 quantum correlated B mesons at $\Upsilon(4S)$

No trigger bias – almost 100% for B pairs

Excellent efficiency and resolution in tracking as well as in detecting photons, K_L, π^0
→reconstruction of intermediate resonances
→Dalitz plot studies

Clean environment (compared to hadron machines) allows "full interpretation" of the event
→ powerful tool for physics with missing energy (many neutrinos) or fully inclusive analyses

Large sample of D and τ with low background

Physics deliverables

Improved precision on CKM elements and UT angles

Search for CP violation phases:
- tree level decays
- penguins, including neutral modes

Inclusive measurements $b \to s/d\ \gamma$ $b \to s\ l\ l$

ACP in radiative decays

Missing energy modes
$B \to l\ \nu$ $B \to K\ \nu\ \nu$, $B \to X_{u,c}\ l\ \nu$

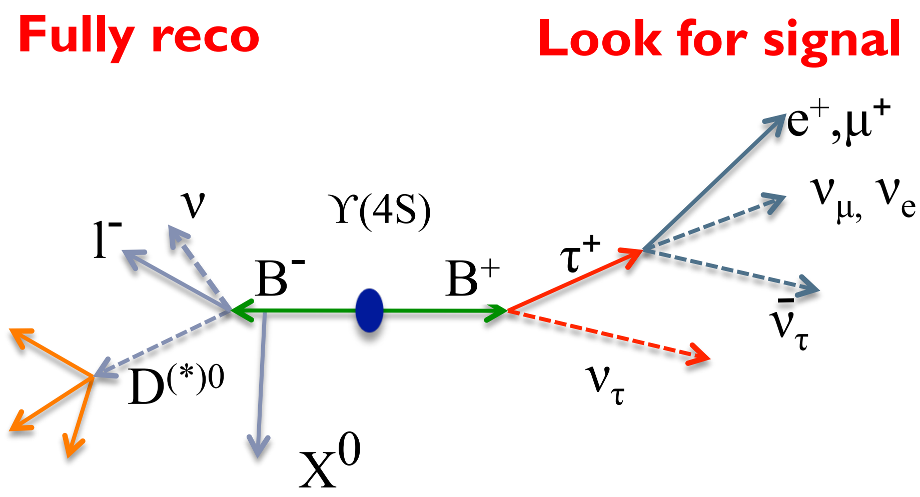
LFV in $\tau \to l\ \gamma$, $l\ l\ l$

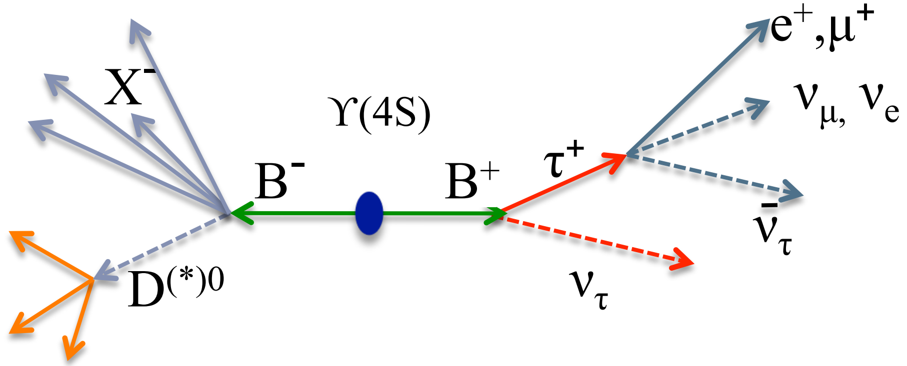
Dark matter, spectroscopy, Hidden sector

Full event interpretation (tagged analyses)

- For signal with weak exp. signature like
  - Decay with missing momentum (many neutrinos in the final state)
  - Inclusive analyses
- background rejection improved fully reconstructing the companion B (tag)

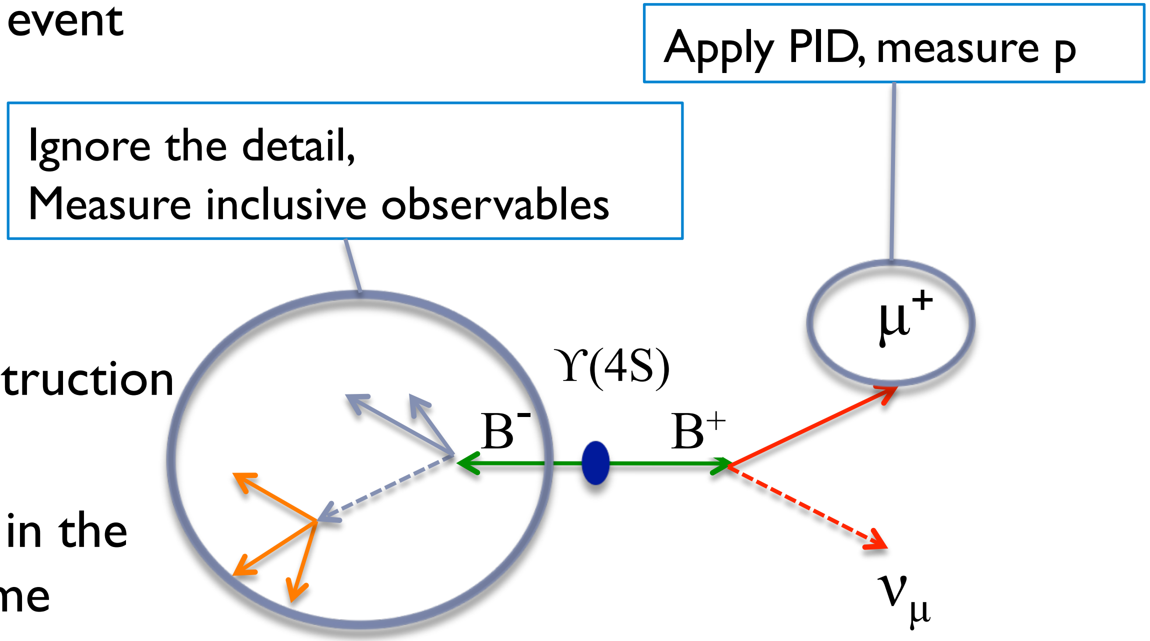
- Tag with semileptonic decays
  - PRO: Higher efficiency ε_{tag} ~ 1.5%
    CON: more backgrounds, B momentum unmeasured
- Tag with hadronic decays
  - PRO: much cleaner events,
    B momentum reconstructed
    CON: smaller efficiency ε_{tag} ~ 0.2%





Untagged analyses still possible

- Inclusive on the rest of the event when the signal signature strong enough
- $B \rightarrow \pi l \nu$
  - Loose neutrino reconstruction
- $B \rightarrow \mu \nu$
  - Monochromatic muon in the final state in B rest frame
    - Smeared in the CM frame

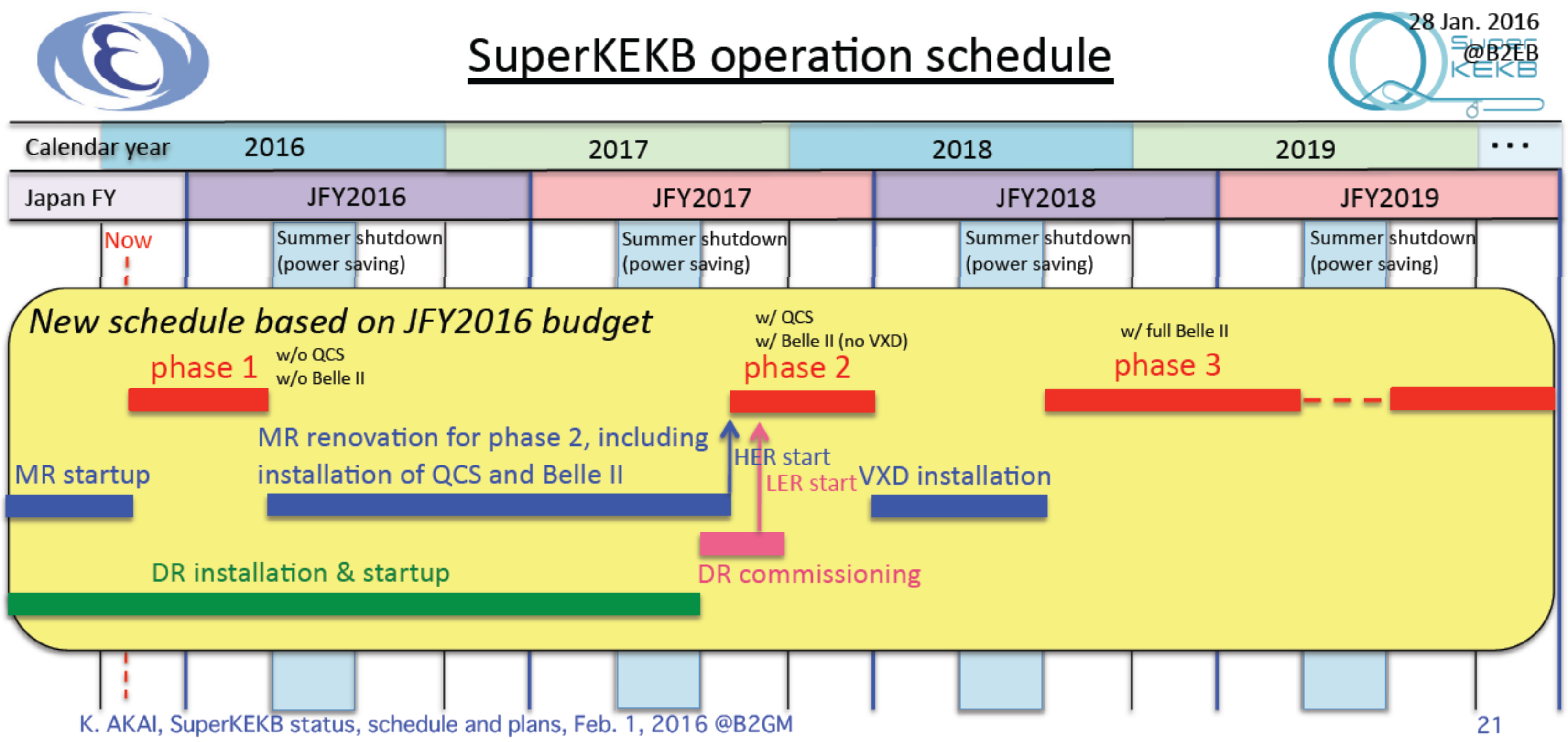


High efficiency but large backgrounds, too

Belle II Collaboration

Belle II already a large collaboration with Institutes from Asia Europe and North America

When?



SuperKEKB operation schedule
28 Jan. 2016
@B2EB
Calendar year
2016
2017
2018
2019
• • •
Japan FY
JFY2016
JFY2017
JFY2018
JFY2019
Now
Summer shutdown (power saving)
Summer shutdown (power saving)
Summer shutdown (power saving)
Summer shutdown (power saving)
New schedule based on JFY2016 budget
phase 1
w/o QCS
w/o Belle II
w/ QCS
w/ Belle II (no VXD)
phase 2
w/ full Belle II
phase 3
MR startup
MR renovation for phase 2, including installation of QCS and Belle II
HER start
LER start
VXD installation
DR installation & startup
DR commissioning
K. AKAI, SuperKEKB status, schedule and plans, Feb. 1, 2016 @B2GM
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Physics Highlights

(selected topics of a vast program)

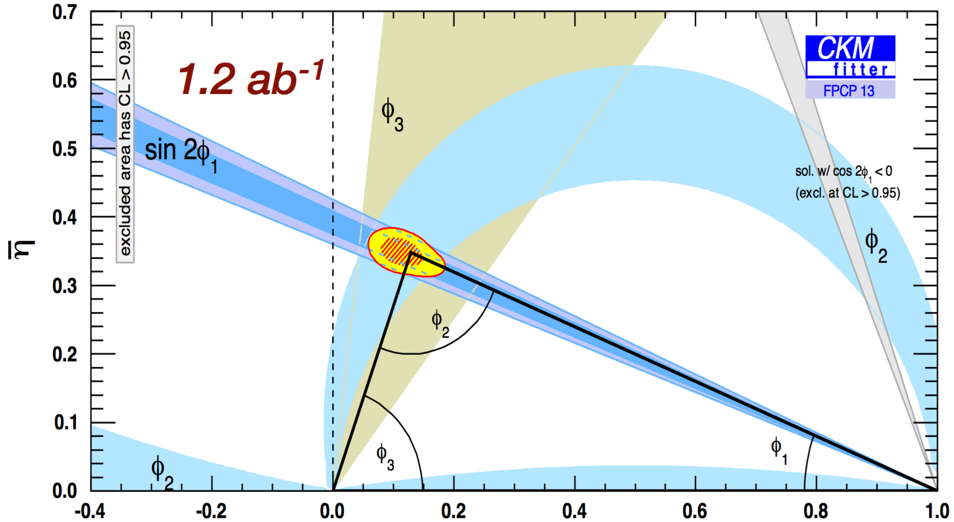
CKM UT angles

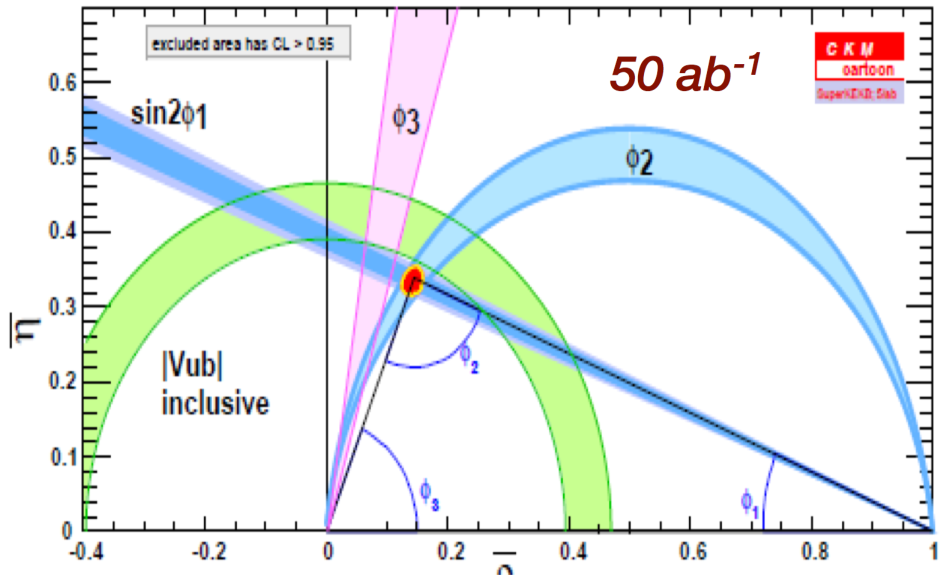
Uncertainties on UT angles will be substantially reduced

Competitive with LHC-b
In addition accurate measurements on many final states (with neutrals):
ex: B→ππ, ρπ, ρρ etc…

UT	2014	Belle II
α	4° (WA)	**1°**
β	0.8° (WA)	**0.2°**
γ	8.5° (WA) 14°(Belle)	**1-1.5°**

Measurement of γ and |Vub| can have the role of setting the SM baseline for interprenting deviations as NP signals



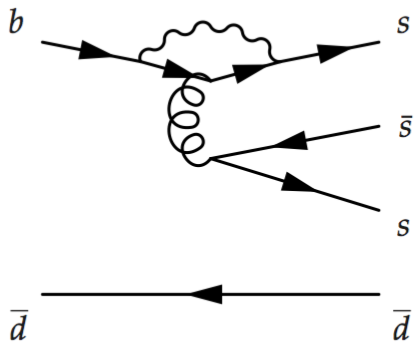


Additional sources of CPV

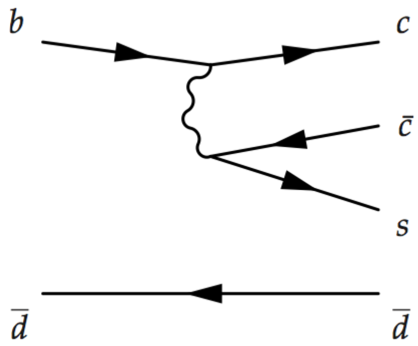
$B^0 \to \phi K^0$

$B^0 \to \eta' K^0$

$B^0 \to K^0 K^0 K^0$

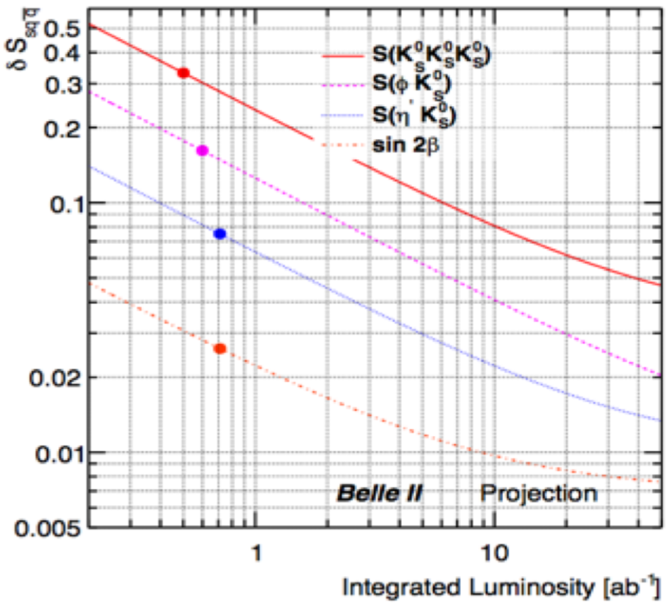


VS



$B^0 \to J/\psi K^0$

Belle II projections



0.033 $S(K^0K^0K^0)$

0.018 $S(\phi K^0)$

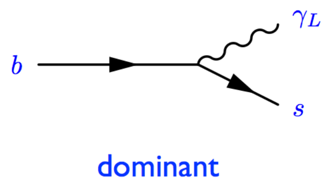
0.011 $S(\eta' K^0)$

0.008 $S(J/\psi K^0)$

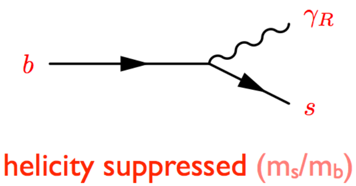
Prospects for δS(b→s) = 0.01 @ 50ab-1

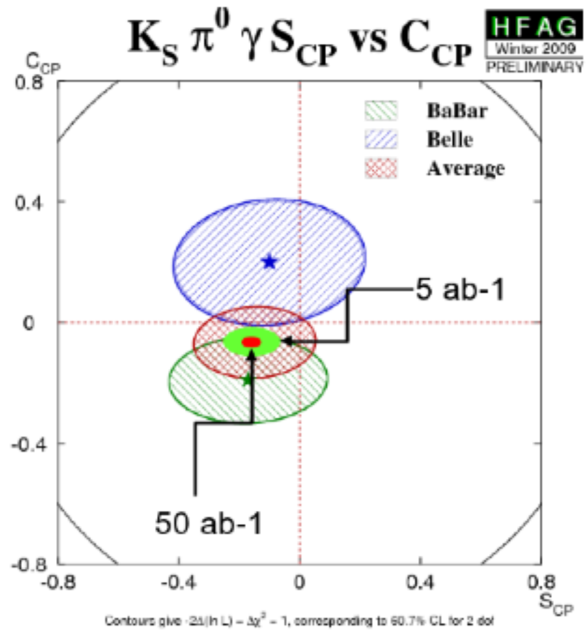
Need theory uncertainty on SM be competitive

Mixing induced CPV with radiative peng.



and

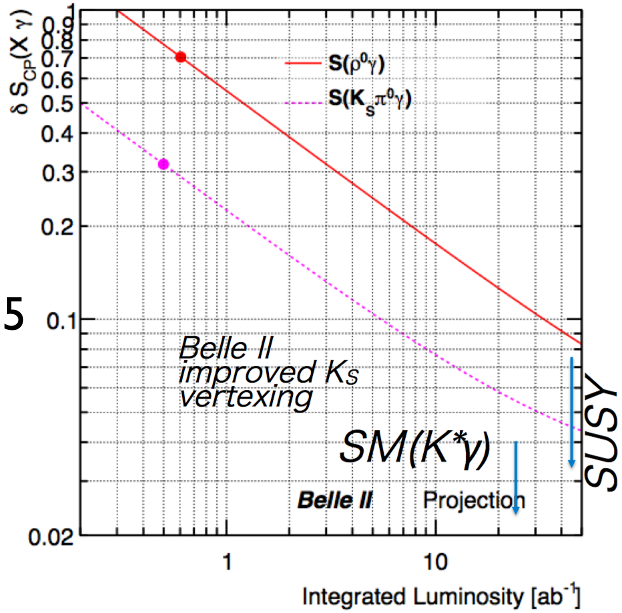




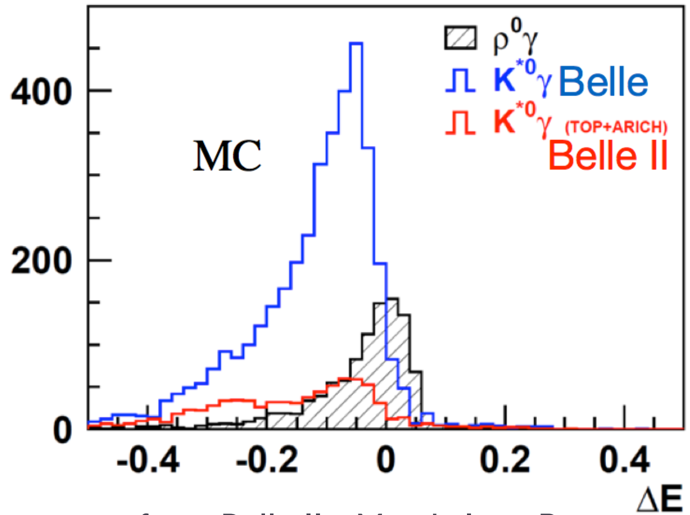
In SM helicity suppression.
BSM RH current may enhance interference
→ TD CP asymmetry

SM exp: S ~ - 0.03

Left-right models up to 0.5



TOP + ARICH PID

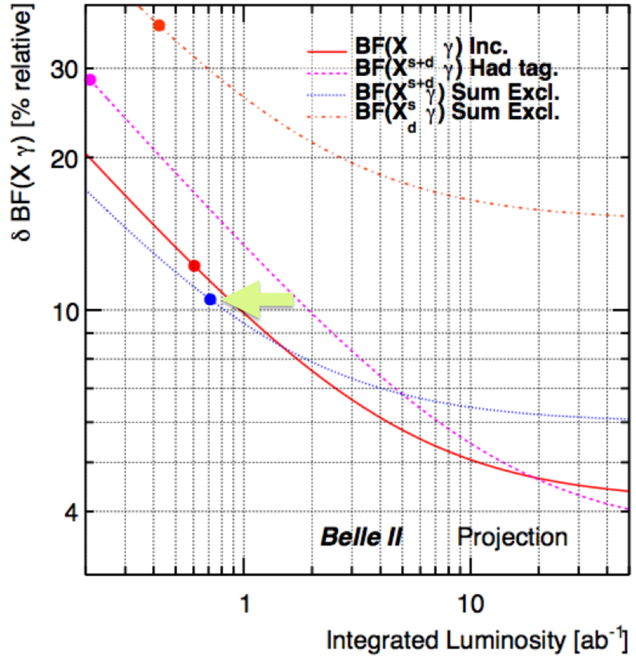


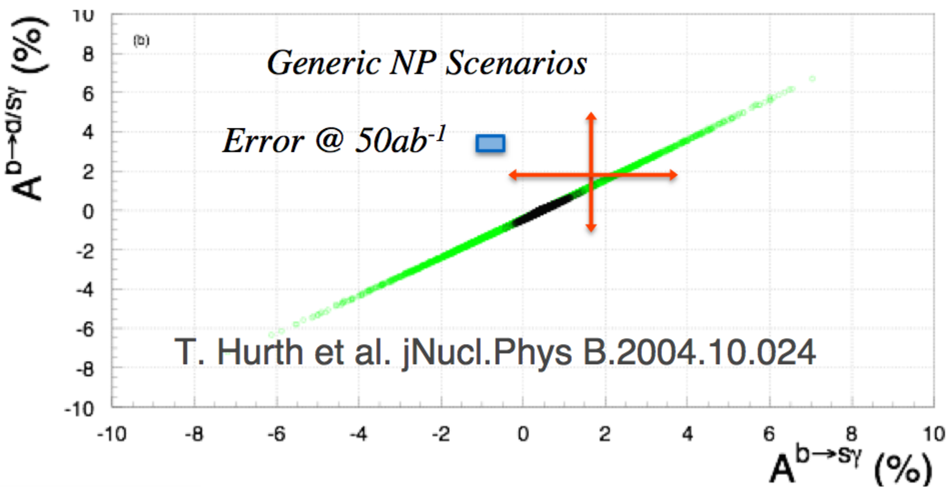
Inclusive radiative b→ s/d γ

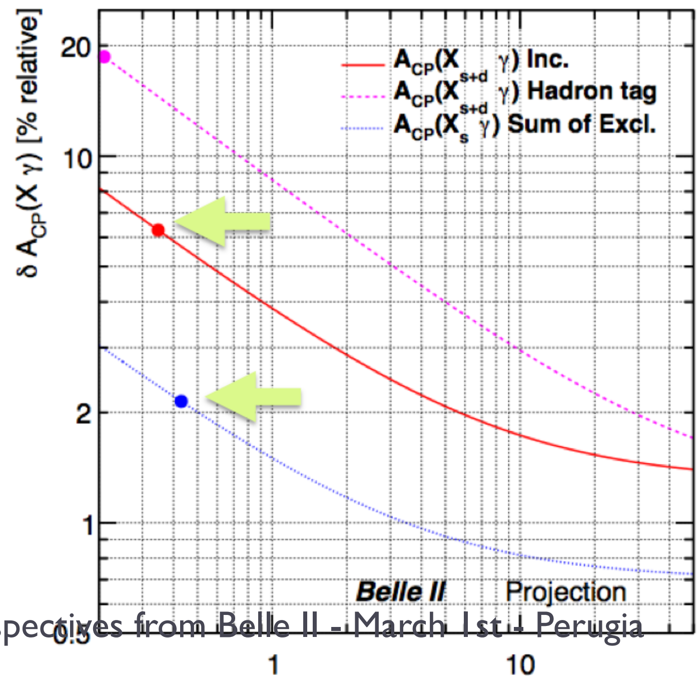
Two exp. techniques: sum of exclusive modes or inclusive
Sum of exclusive shows disagreements with simulated fragmentation models

Rate
Experimental uncertainty at 5% level

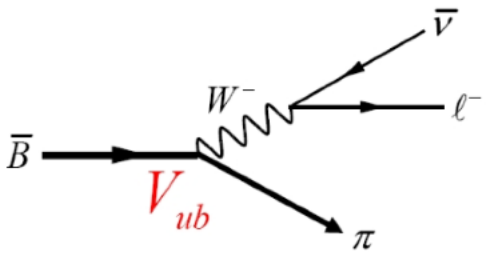
A_{CP} may be a test of NP: expected experimental error: 0.5%







|Vub| extraction from b → u

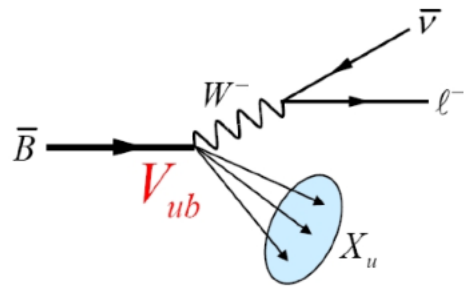


$$\frac{d\Gamma(B\to \pi l\nu)}{dq^2} = \frac{G_F^2}{24\pi^3} p_\pi^3 |V_{ub}|^2 \times |f(q^2)|^2$$

Theory input: form factors from Lattice and sum rules

Experimentally more constrained

Both untagged & tagged analyses

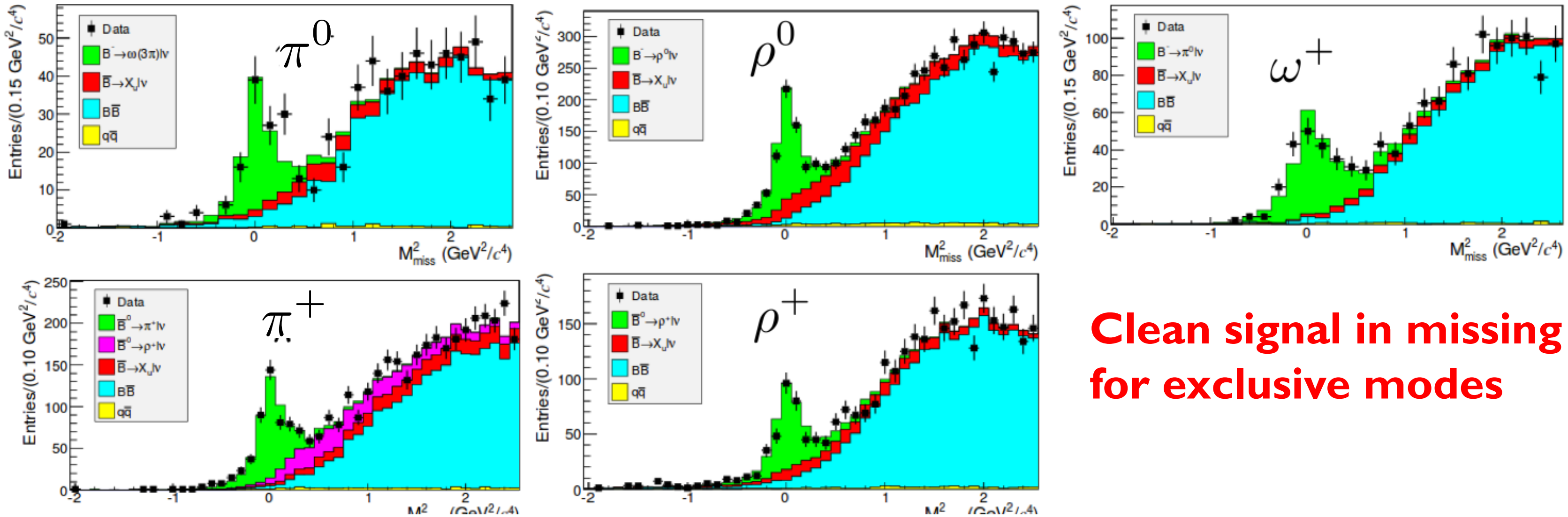


$$\Gamma_{SL} = |V_{ub}|^2 \frac{G_F^2 m_b^5}{192\pi^3} \times A_{pert} \times A_{non-pert}(1/m_b)$$

Theory input: OPE
Huge b→c l ν background
Must select phase space region (M_x, q^2,p_l) to enhance B→ u signal
Need theory to extrapolate to full rate
Tight selections jeopardize theory extrapolation

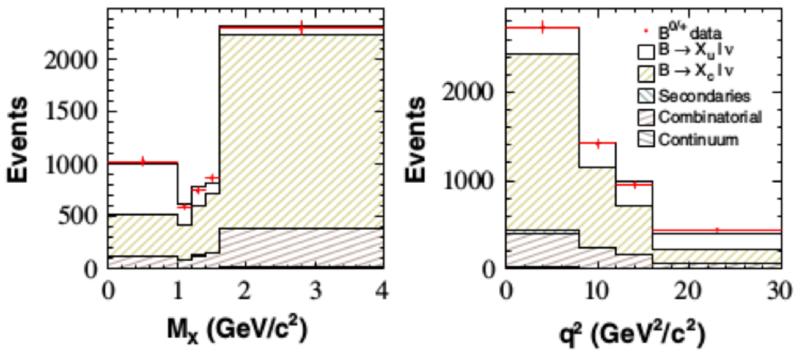
Current Measurements with hadronic tag

Belle exclusive



Clean signal in missing mass for exclusive modes

Belle inclusive



b → u l ν signal enhanced w.r.t. b → c backgrounds in low M_X and high q^2 but

important: control on systematics effects from charm background composition and u quark fragmentation → can be improved with Belle II

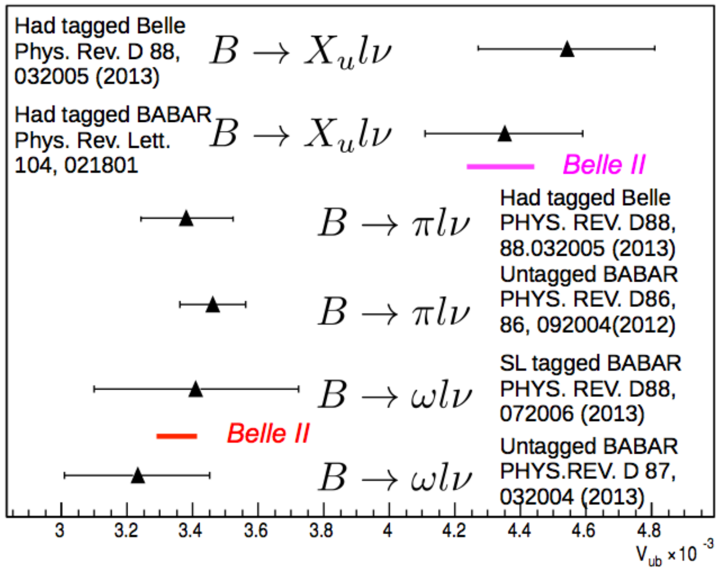
Extrapolation to Belle II (1)

$|V_{ub}|_{exc}$ vs $|V_{ub}|_{inc}$ "tension" is still here after years of experimental and theoretical efforts
Just statistics?

A systematic effect in experiment. or theory or both?

Belle II expected to settle this.

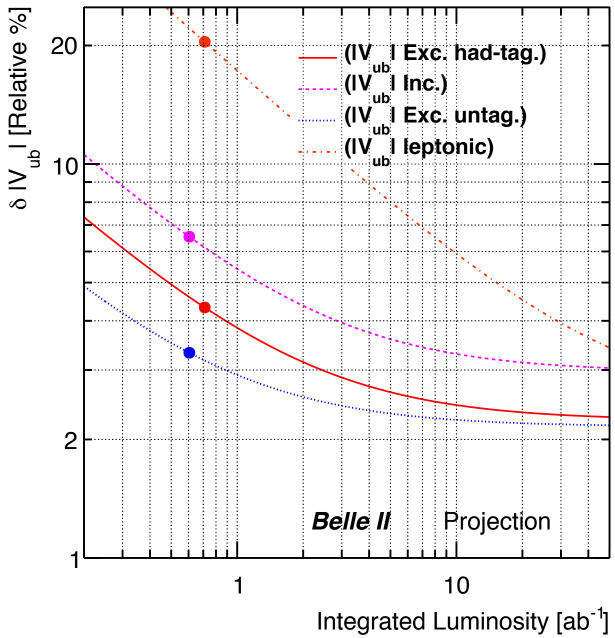
Alexander Ermakov (FPCP14):



Belle II will reduce the uncertainties on |Vub|

Provide much more consistency checks for theory and experimental effects

|Vub| extrapolation for Belle II (2)



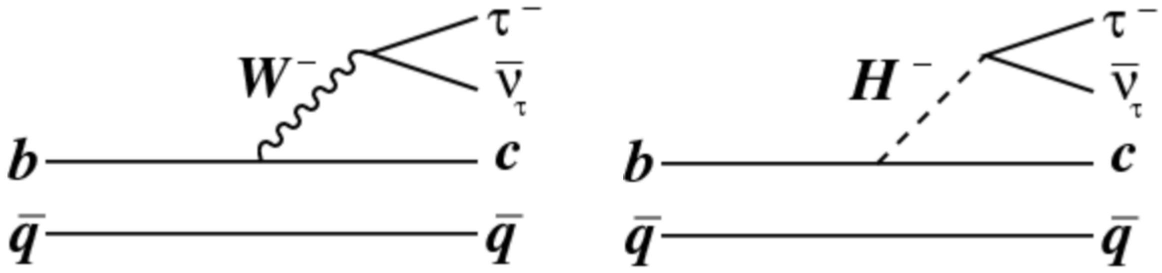
	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\lvert V_{ub}\rvert$ exclusive (had. tagged)					
711 fb^{-1}	3.0	(2.3, 1.0)	3.8	8.7 (2.0)	9.5 (4.3)
5 ab^{-1}	1.1	(0.9, 1.0)	1.7	4.0 (2.0)	4.4 (2.6)
50 ab^{-1}	0.4	(0.3, 1.0)	1.1	2.0	2.3
$\lvert V_{ub}\rvert$ exclusive (untagged)					
605 fb^{-1}	1.4	(2.1, 0.8)	2.9	8.7 (2.0)	9.1 (4.0)
5 ab^{-1}	0.5	(0.8, 0.8)	1.2	4.0 (2.0)	4.2 (2.4)
50 ab^{-1}	0.2	(0.3, 0.8)	0.9	2.0	2.2
$\lvert V_{ub}\rvert$ inclusive					
605 fb^{-1} (old B tag)	4.5	(3.7, 1.6)	6.0	2.5−4.5	6.5−7.5
5 ab^{-1}	1.1	(1.3, 1.6)	2.3	2.5−4.5	3.4−5.1
50 ab^{-1}	0.4	(0.4, 1.6)	1.7	2.5−4.5	3.0−4.8

Assumption is theory error down to 2% for exclusive and 2-4 % for inclusive modes

Most promising are exclusive analysis with hadronic tags: to perform clean and detailed exploration of exclusive b→ u modes spectra.
Improvements on theory predictions need as well (B → ρ l ν lattice)

Untagged analyses still competitive for |Vub| measurement

B → D* τ ν



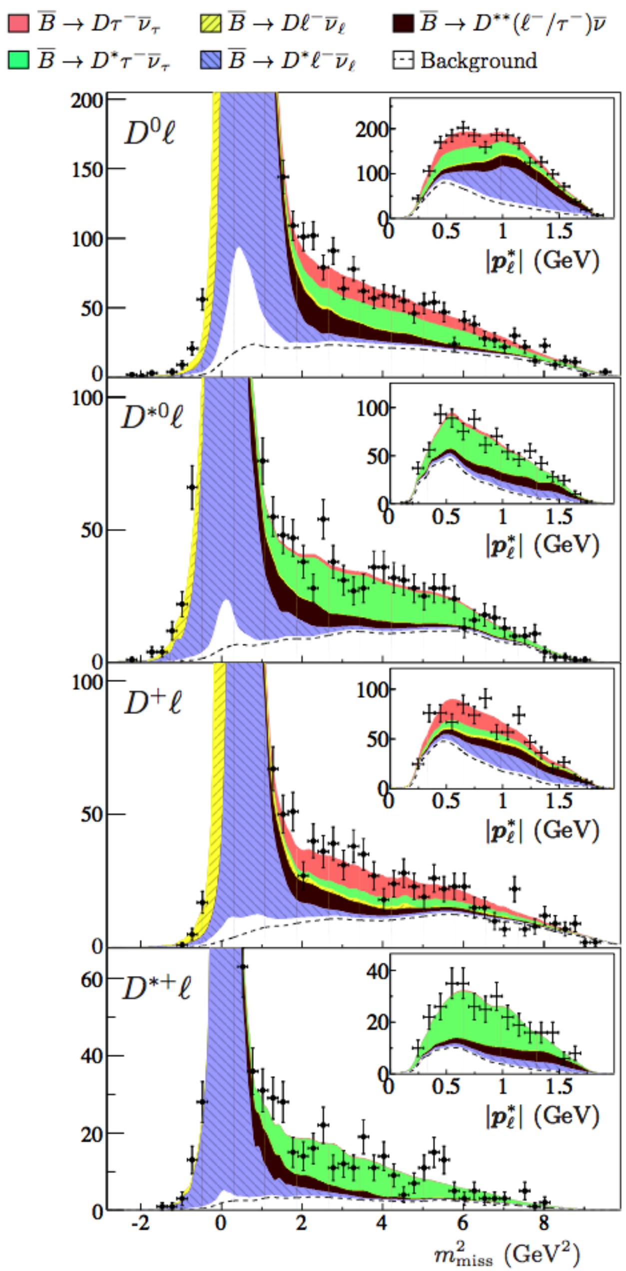
Input for SM prediction:
- exp: |Vcb| measurement
- theory: form factor

New Physics from Charged Higgs

Measure a ratio R = B(B→ $D^{(*)}$ τ ν)/B(B→$D^{(*)}$lν)

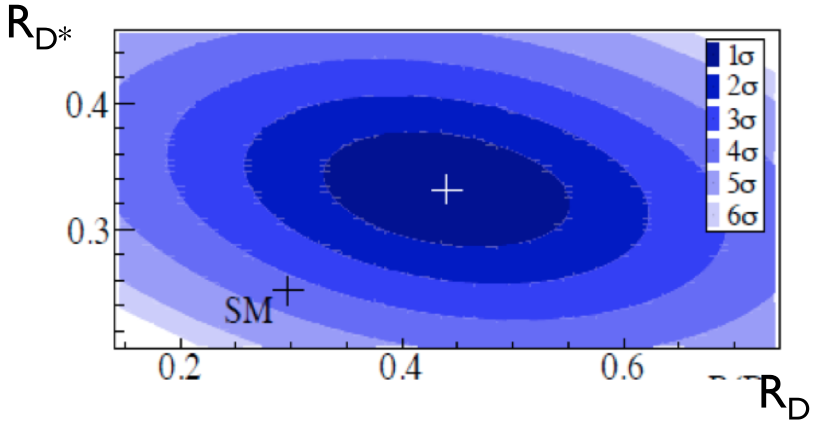
Experimentally hard: signature is not a peak on a smooth background!

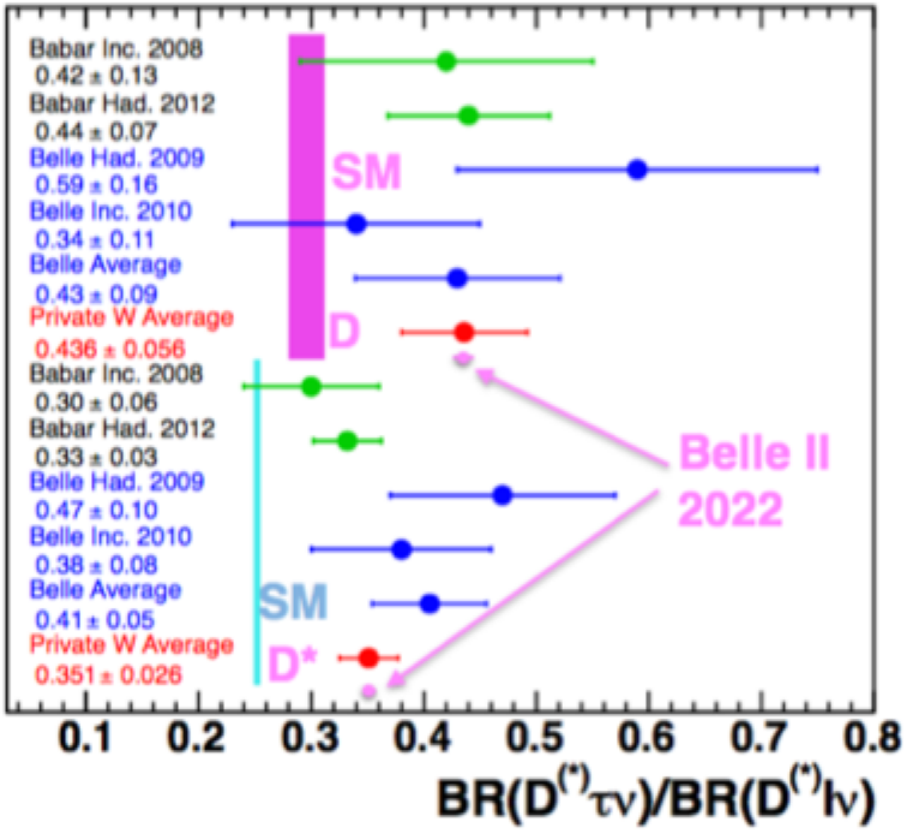
Data driven methods to control the backgrounds (combinatorial and D** backgrounds)



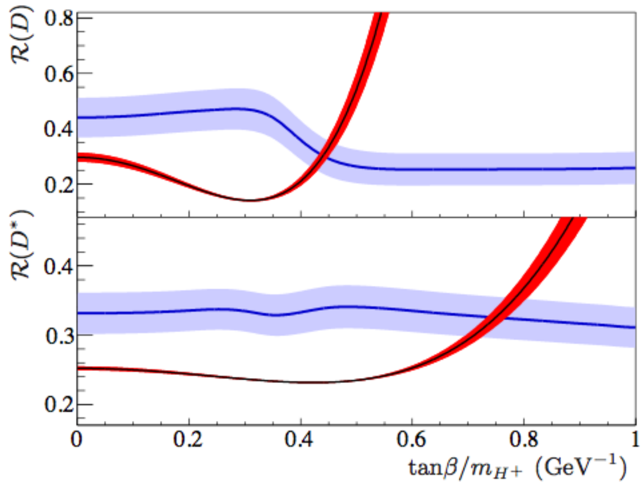
B → D* τ ν

Surprise: 3σ excess over SM prediction!





Surprise: kills the 2HDM Type II



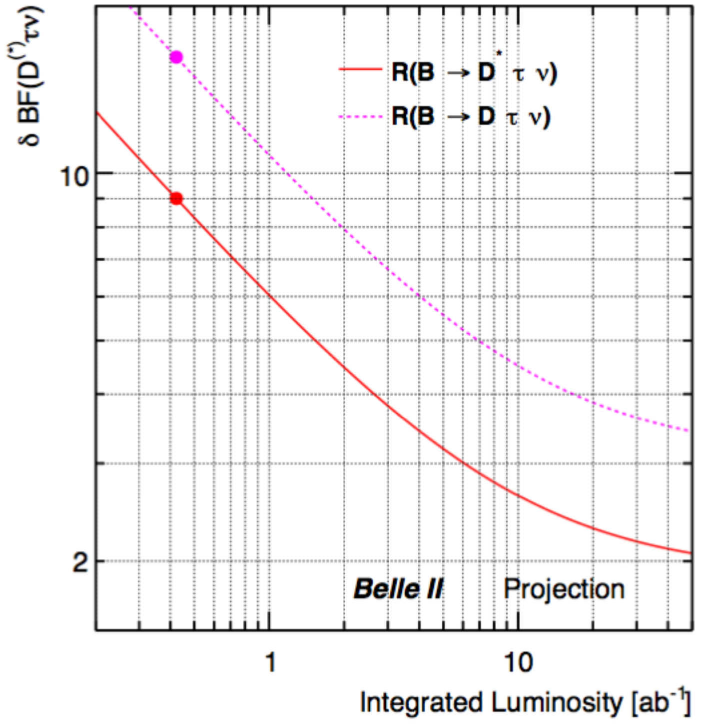
Belle II improvements in B→D*τν

Confirm the excess with few ab^{-1}

With more data, better understanding of backgrounds tails under the signal.

We also expect a better understanding of B → D** l ν (most delicate BG)

Measure differential distribution



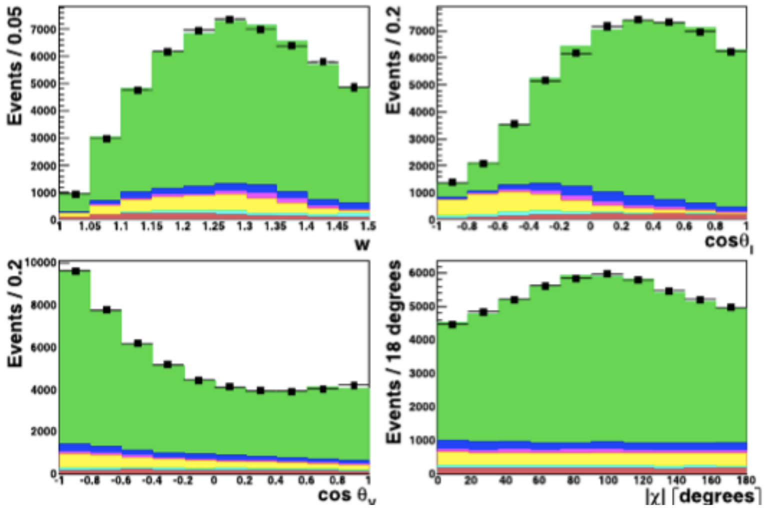
Expected Uncertainties

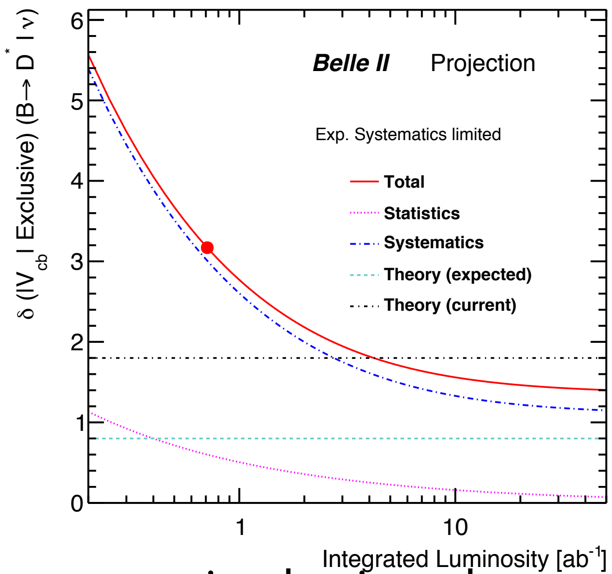
Ratio	5 ab^{-1}	50 ab^{-1}
R_{D*}	3%	2%
R_D	6%	3%

Uncertainty dominated by systematics

|Vcb| exclusive B → D* l ν

•Currently most accurate measurement of |Vcb| from B → D* l ν exclusive decay





Belle measurement has 5% total uncertainty, already systematics dominated
Expect theo uncertainty from 2% → below 1% with Belle II taking data
Most of the systematics are detector related and can improve with Belle II apparatus and scale with luminosity.
Experimental irreducible component estimated at 1% level

B→ D* l ν and B→D l ν

	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\lvert V_{cb}\rvert$ exclusive : F(1)					
711 fb^{-1}	0.6	(2.8, 1.1)	3.1	1.8	3.6
5 ab^{-1}	0.2	(1.1, 1.1)	1.5	1.0	1.8
50 ab^{-1}	0.1	(0.3, 1.1)	1.2	0.8*	1.4
$\lvert V_{cb}\rvert$ exclusive : G(1)					
423 fb^{-1}	4.5	(3.1, 1.2)	5.6	2.2	3.6
5 ab^{-1}	1.3	(0.9, 1.2)	2.0	1.5*	2.7
50 ab^{-1}	0.6	(0.4, 1.2)	1.4	1.0*	1.7

Similar level of accuracy from B→ D l ν and B→ D l ν*

$B \to X_c\, l\, \nu$ inclusive at Belle II

(Modest) improvement of experimental uncertainties expected.

- Better determination of $B \to D^{**}\, l\, \nu$ component
- Improved control on the tag B normalization
- Largest experimental systematics from PID and tracking

We expect a 0.5% ultimate systematic uncertainty

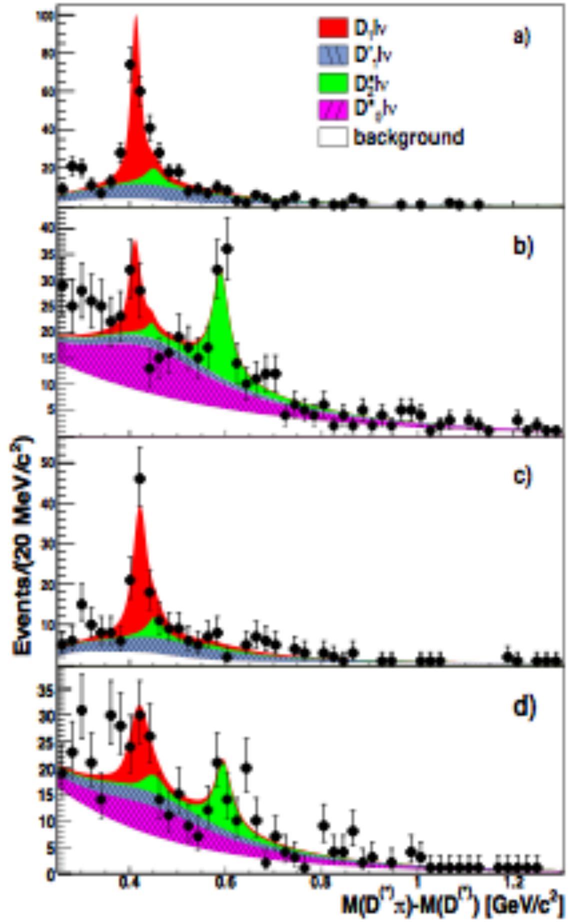
We assume theory uncertainty at 1% that will saturate the error budget

Belle II deliverables:

Detailed exploration of $B \to D\, n\pi\, l\, \nu$

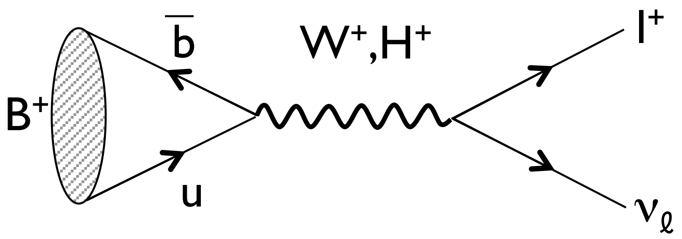
Solve "puzzles" like the gap between inclusive and exclusive Vcb

Check if exclusive modes saturate inclusive rate



Fitted $D^{(*)}\pi$ mass spectrum of Phys.Rev.Lett. 101 (2008) 261802

$B \to l\,\nu$



Very clean theoretically, hard experimentally

SM contribution helicity suppressed

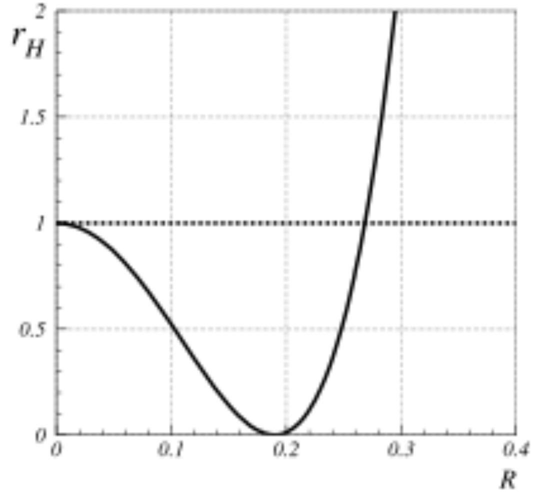
Sensitive to NP contribution (charged Higgs)

$$\mathcal{B}(B \to l\nu) = \frac{G_F^2 m_B}{8\pi} m_l^2 (1 - \frac{m_l^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B$$

$$\mathcal{B}(B \to l\nu) = \mathcal{B}(B \to l\nu)_{SM} \times r_H$$

$$r_H = (1 - \tan^2\beta \frac{m_B^2}{m_H^2})^2$$

in 2HDM type II



Standard Model Predictions

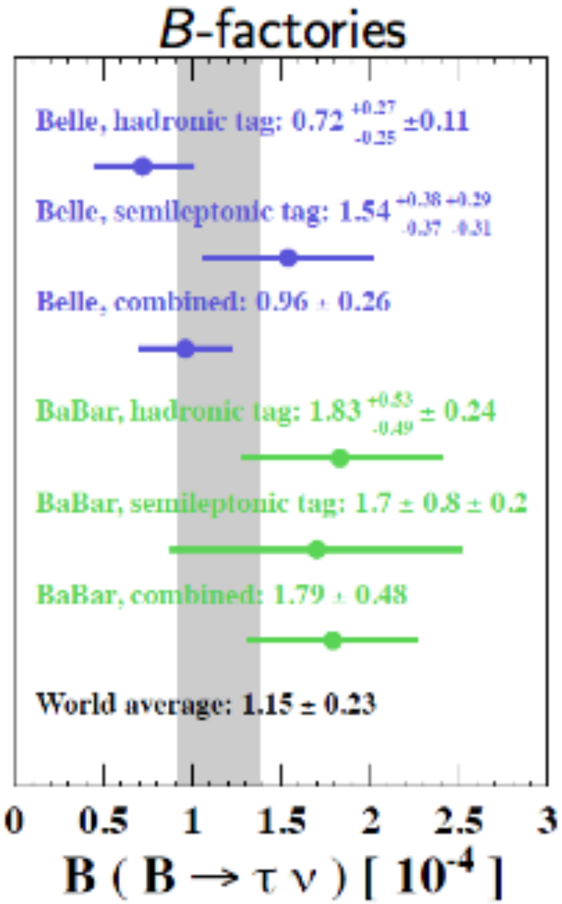
Mode	$\mathcal{B}(B^+ \to \ell^+ \nu_\ell)$	
$\tau\nu_\tau$	$(1.01 \pm 0.29) \times 10^{-4}$	*Accessible with current data sets*
$\mu\nu_\mu$	$\sim 0.45 \times 10^{-6}$	*Need Belle II statistics*
$e\nu_e$	$\sim 0.8 \times 10^{-11}$	*Beyond the reach of experiments*

Belle II can also test lepton flavour universality

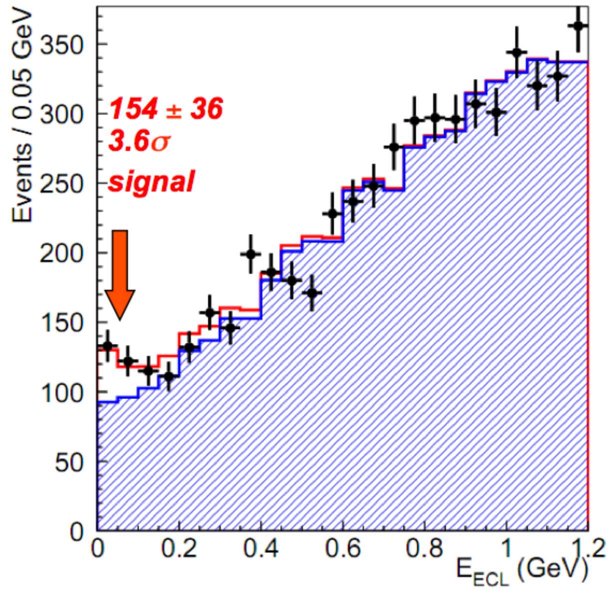
$$R^{\tau e} = \frac{\Gamma(B \to e\nu)}{\Gamma(B \to \tau\nu)}$$

$$R^{\tau\mu} = \frac{\Gamma(B \to \mu\nu)}{\Gamma(B \to \tau\nu)}$$

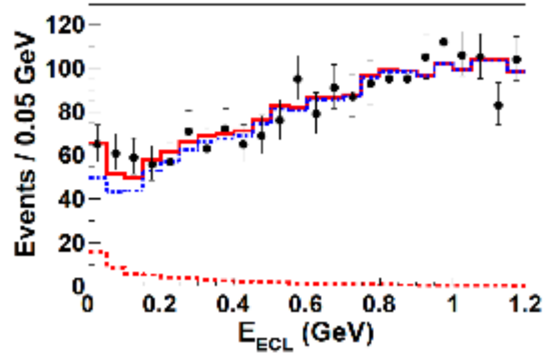
Belle and BaBar measurements



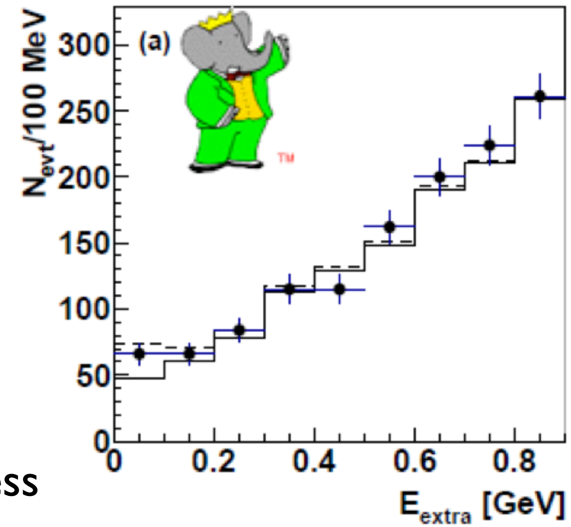
Belle semileptonic tag



Belle Hadronic tag



BaBar Hadronic tag



New Belle semileptonic tag results further reduce the excess

$\mathcal{B}(B \to \tau\nu) = (1.14 \pm 0.22) \times 10^{-4}$ PDG 2015

B → μ ν and B → e ν

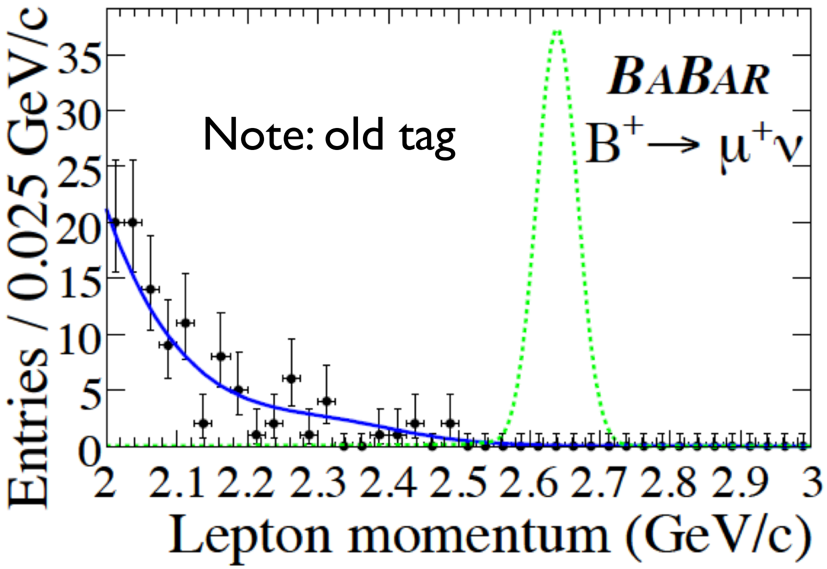
Monochromatic lepton in the B rest frame

Almost background free with tagged analyses

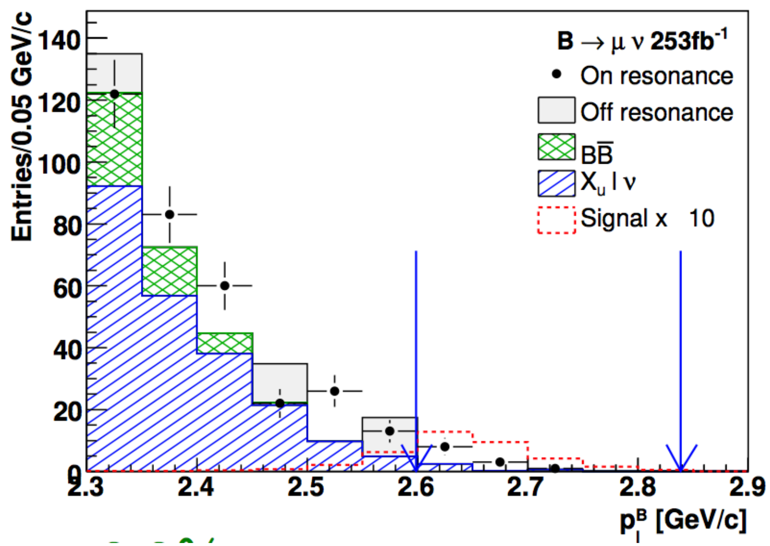
$\mathcal{B}(B \to \mu\nu) < 5.6 \times 10^{-6}$

$\mathcal{B}(B \to \mu\nu) < 1.7 \times 10^{-6}$

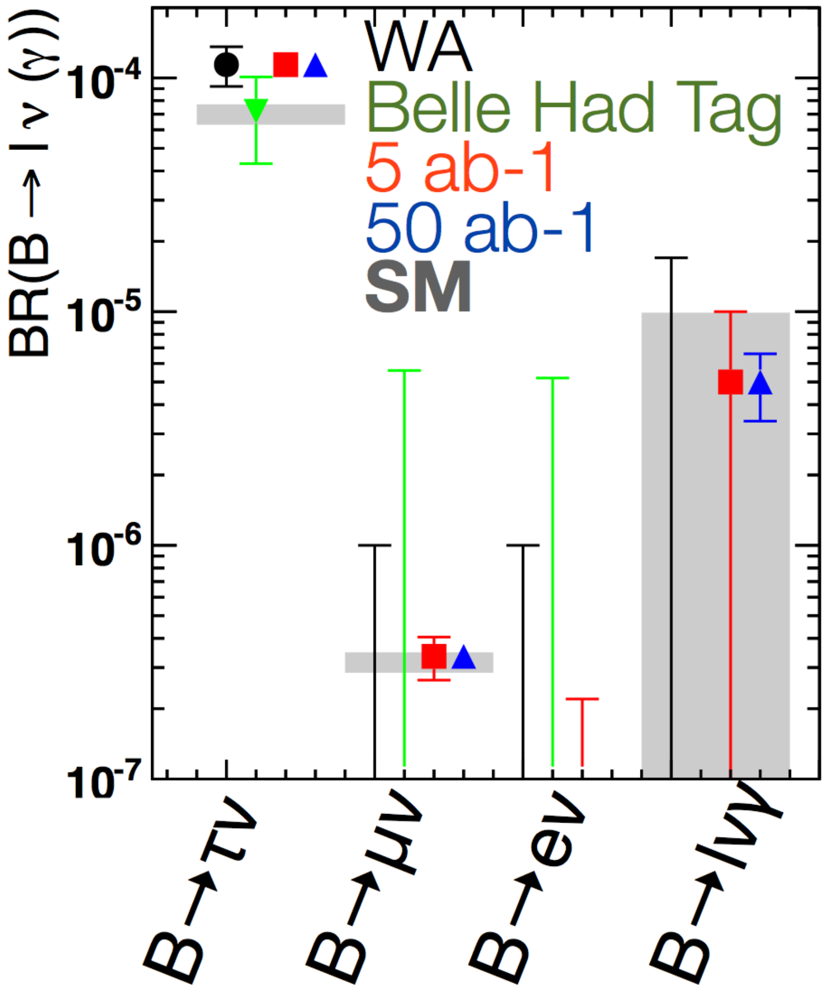
Hadronic tag BaBar



Semileptonic tag Belle



Belle II outlook for leptonic B decays



Extrapolated B → τ ν uncertainty
10% after 5 ab^{-1} and 3%-5% after 50 ab^{-1}
Dominated by systematics

Extrapolated B → μ ν uncertainty
20% after 5 ab^{-1} and 7% after 50 ab^{-1}

B → e ν SM prediction out of reach,
Sensitivity to B.R. of 7 10^{-8} with 50 ab^{-1}

Q:What is the ultimate the ultimate experimental systematic uncertainty?
Naïve guess : 3%

Electroweak penguins with charged leptons

B→ K* μ μ decays FB asymmetry

the q^2 distribution zero crossing precisely known in SM

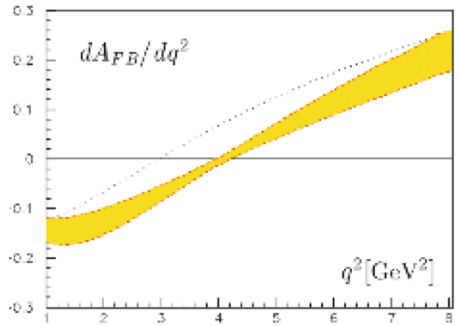
LHC-b will reach a 2% accuracy

Belle II: smaller statistics but adds

- Clean electron mode $B \to K^{(*)} e\, e$
- inclusive analysis of $B \to X_s\, l^+ l^-$
- third generation $B \to K\, \tau\, \tau$

$K^* \ell^+ \ell^-$

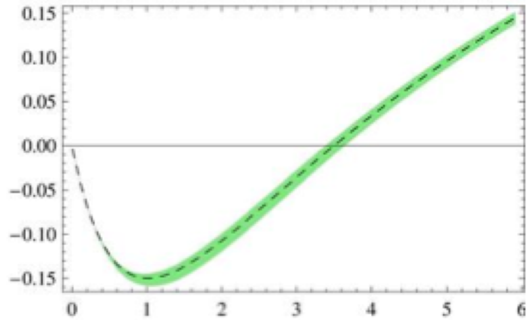
[Ali et al.,EPJ,C47(2006) 625]



$$q_0^2 = \left(4.07^{+0.16}_{-0.13}\right)\ \text{GeV}^2$$

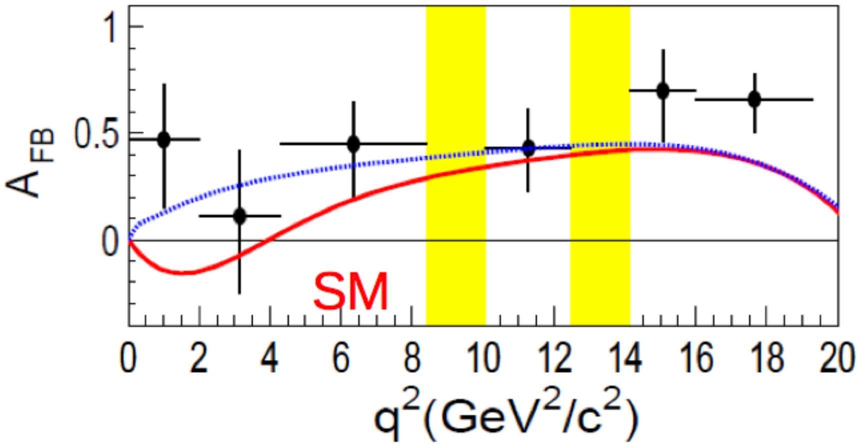
$X_s \ell^+ \ell^-$

[Huber et al., NPB 802 (2008) 40]

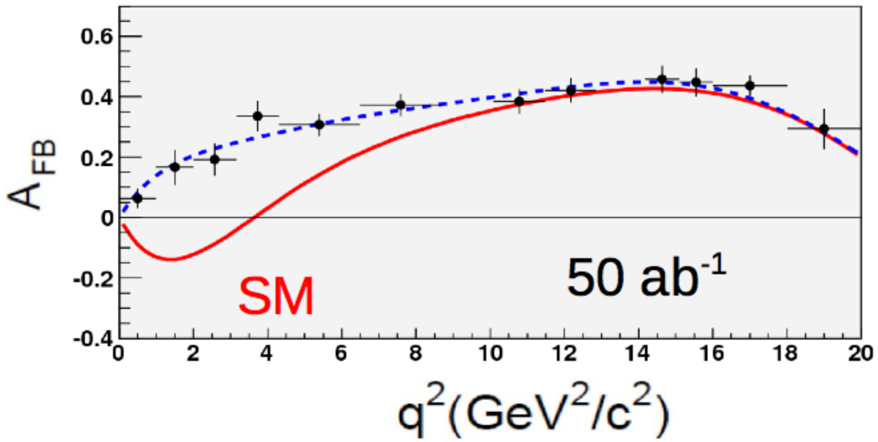


$$(q_0^2)_{\mu\mu} = (3.50 \pm 0.12)\ \text{GeV}^2$$
$$(q_0^2)_{ee} = (3.38 \pm 0.11)\ \text{GeV}^2$$

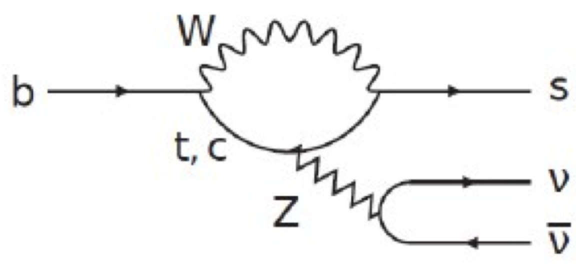
Belle : Phys Rev Lett 103 171801 (2009)



Extrapolation to Belle II with 50 ab^{-1}

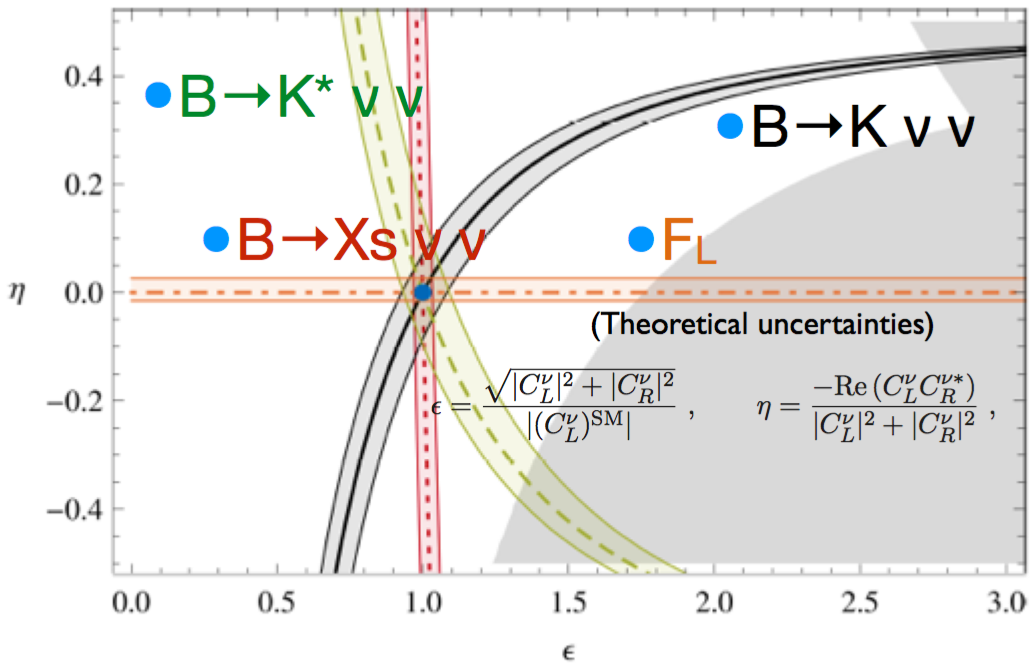


Electroweak penguins with neutrinos

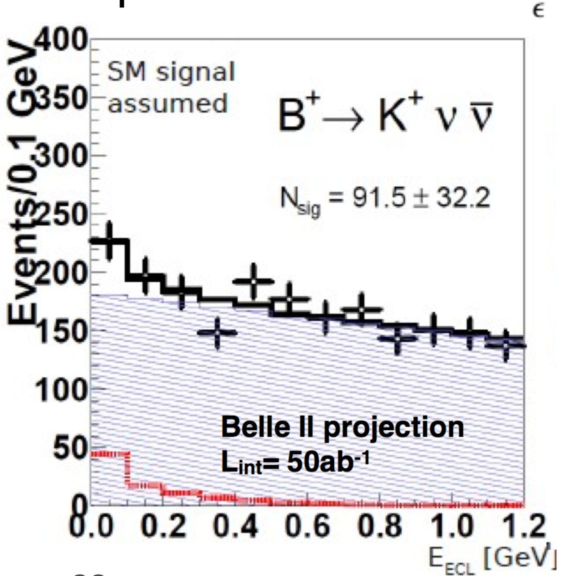


B → K(*) ν ν possible only at Belle II

Altmannshofer et al., JHEP 0904:022,2009



Extrapolation to Belle II



Extrapolation to Belle II 30% accuracy assuming SM

With with one tag method only (hadronic)

To be considered: improvements in PID, tagging efficiency, better K_L rejection, background rejection with ECL timing…

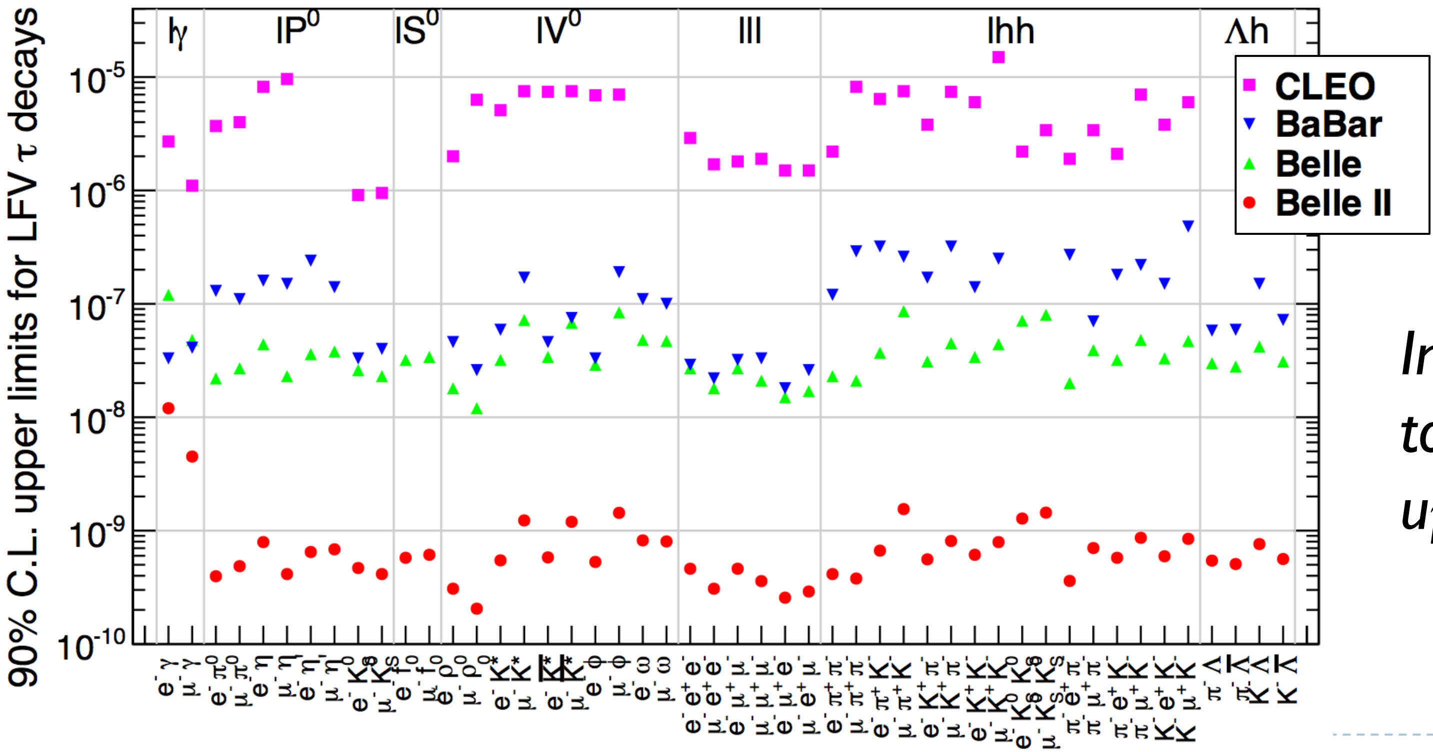
Lepton Flavour Violation in Tau decays

LFV in τ decays clean null test of SM

$\tau \to \mu\mu\mu$ and eee background free searches

LHCb not competitive (?)

	reference	$\tau \to \mu\gamma$	$\tau \to \mu\mu\mu$
SM + heavy Maj ν_R	PRD 66(2002)034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547(2002)252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68(2003)033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66(2002)115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566(2003)217	10^{-10}	10^{-7}



Improvements up to 50x on all upper limits

Charm

Charm recoil technique

Based on hadronic B full reconstruction

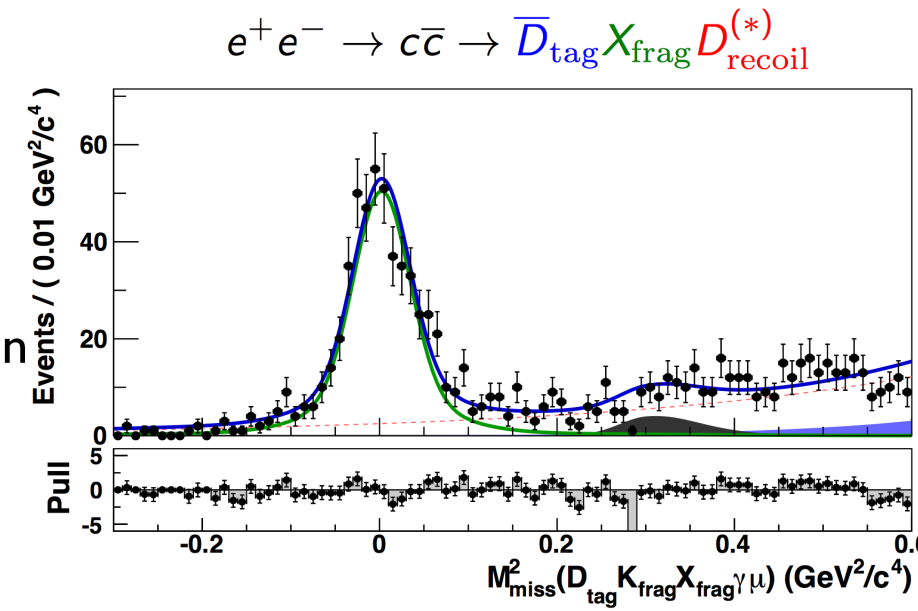
D→ μ ν at 1% and D →τ ν at 3%

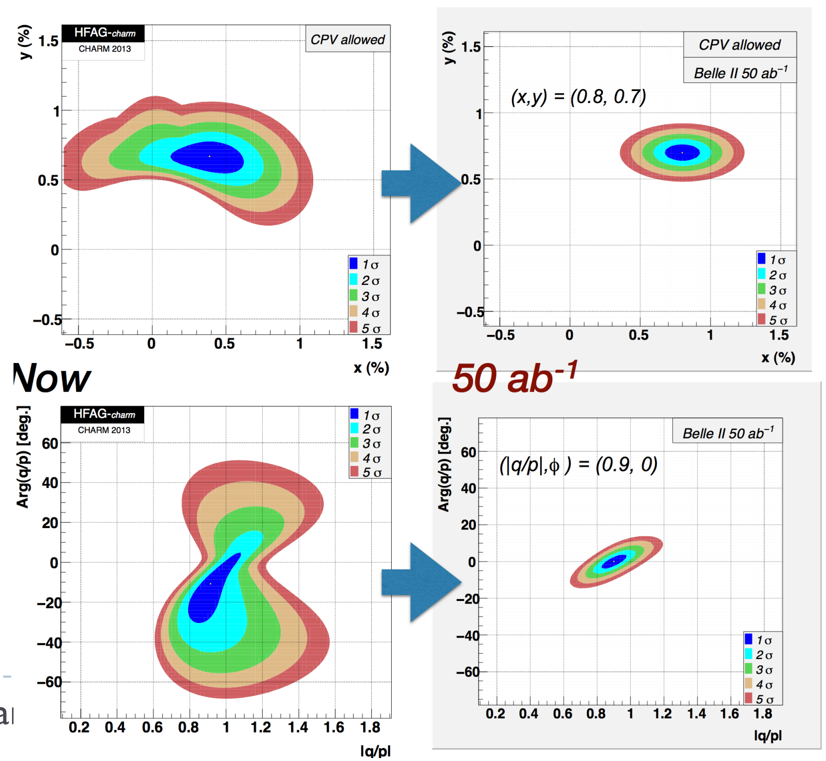
D →γ γ sensitivity at 10^{-7}

(help constrain LD in D→μμ)

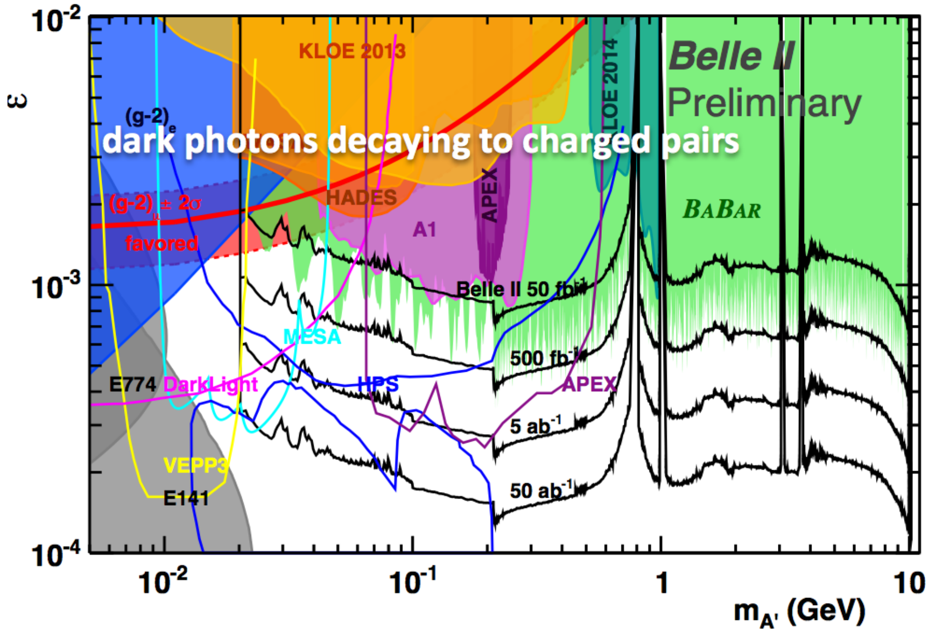
D→ νν (dark scalar)

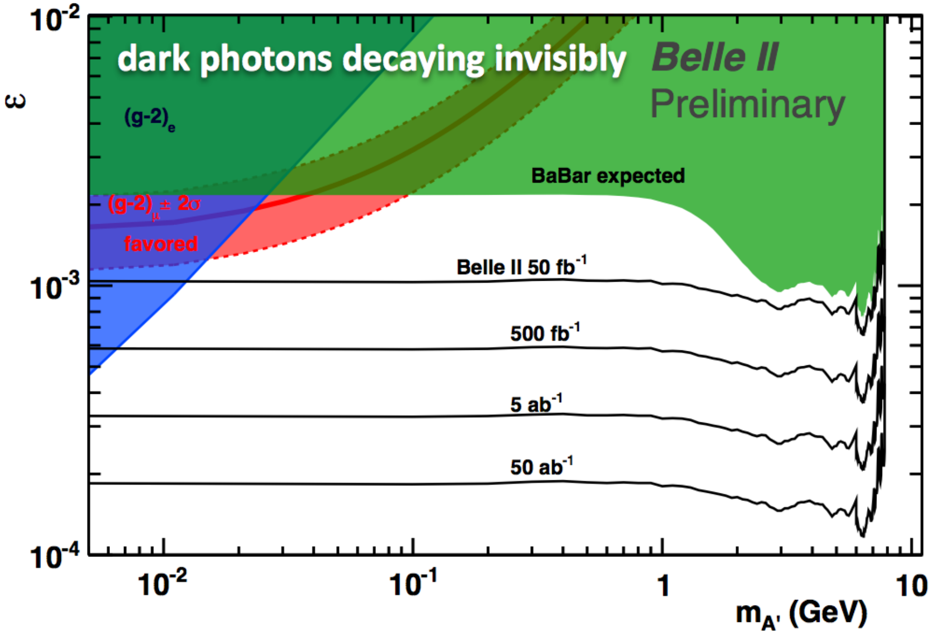
Complement and cross check measurements where LHCb will dominate





Dark Sector





Dark γ to Leptons	Radiative production of A' via ee→γA'
Dark Light Higgs	Y(2S,3S)→A^0 γ, A^0→ invisible, single γ trigger.
Dark Matter	Non-resonant production in ee→A' γ, A^0→*invisible*
Dark Higgs-strahlung	ee → A'h', h'→ A'A'(*), l+l- or hadrons.

Belle II Theory Interface Platform

https://belle2.cc.kek.jp/~twiki/bin/view/Public/B2TIP

Joint theory-experiment effort to study the potential impacts of the Belle II program, and complementarity with LHCb.

2 workshops a year, starting in June 2014. **Received very well by theory and Belle II.**

What's new in Belle II compared to Babar/Belle?
- ➡ Efficiencies and precision of the new hardware
- ➡ New analysis softwares and methods

What's new in theory after Babar/Belle & LHCb result?
- ➡ Progresses in QCD
- ➡ New physics models and their constraints
- ➡ New observables

→ **NEW IDEAS** ←

Deliverable: "KEK yellow report" by the end of 2016

Next workshop May 23-25 Pittsburg (USA)

Conclusions

- Belle II Physics program very rich and complementary to LHC-b
  - Unique capabilities of the machine/detector greatly improve the discovery potential
- SuperKEKB construction completed in 2015. Commissioning started in 2016
- Physics run anticipated to start end of 2017 without vertex detector
- Physics run with the full detector when safe i.e. autumn 2018
- Belle II unique place to solve current puzzles and find New Physics
  - More accurate theory predictions and new ideas to be exploited
  - Refinements of experimental techniques to let systematic uncertainties shrink with statistics
  - We are building the details of the physics Program
    - An experiment-theory effort on-going:
      Belle II experiment Theory Interface Platform (B2TIP)
      https://belle2.cc.kek.jp/~twiki/bin/view/Public/B2TIP