
# B Physics & CP Violation

## Part 3/4

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# Outline

Part 1: Introduction to Flavour Physics

- What is flavour physics & why is it interesting?
- Brief history of discovery in flavour physics
- CKM mechanism and Unitarity Triangle (UT)
- B-physics Experiments

Part 2: CP violation & CKM measurements (Triumphs of the SM)

- Meson-antimeson oscillations
- Introduction to CP violation
- Measurement of UT angles
- Measurement of UT sides

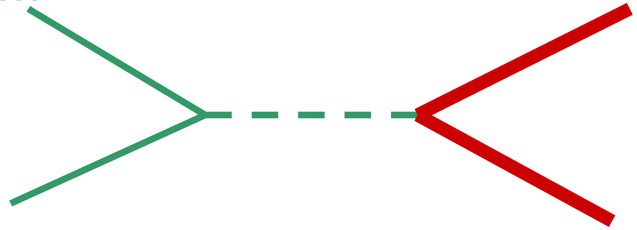
**Part 3: Search for New Physics**

- Radiative Decays
- Tauonic Decays
- Purely Leptonic Decays

Part 4: The future

- What do we hope to learn from current experiments
- The future of flavour physics

# Searches for New Phenomena




- **Energy Frontier**: Production of **new particles** from *collisions* at high-***Energy*** (**LHC**)
  - *Limited by Beam Energy*

- **Flavour Frontier**: **virtual production of new particles** to probe energies beyond the energy frontier.
  - Often **first clues** about new phenomena, e.g. **weak force**, **c, b, t** quarks, Higgs boson.
  - High precision required: very tiny effects

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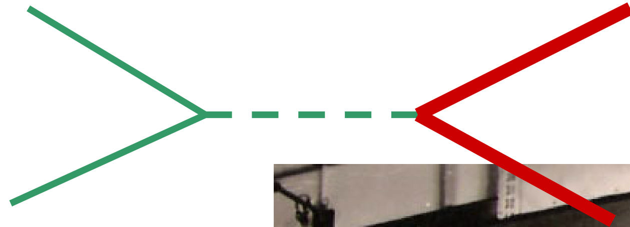


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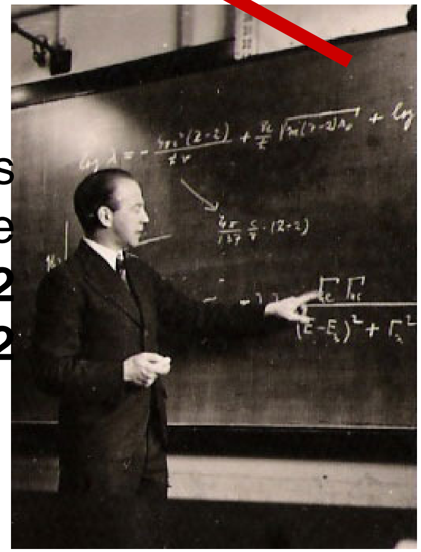
Uncertainty Principle
**$\Delta E\ \Delta t = \hbar/2$**
i.e. **$\Delta m\ \Delta t = \hbar/2$**



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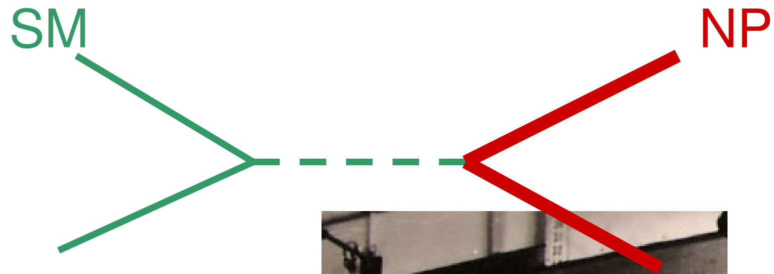


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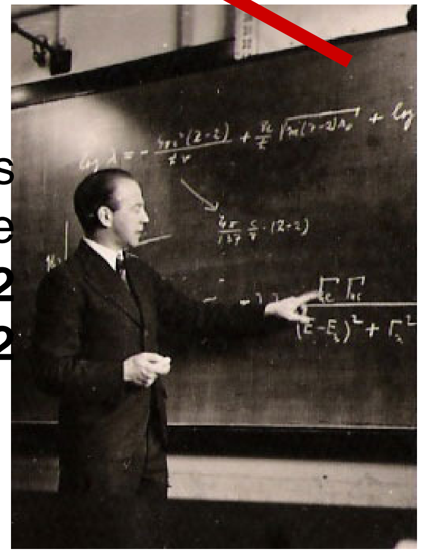

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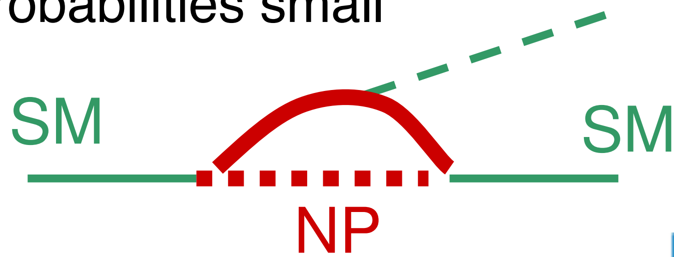
Highly virtual, thus probabilities small



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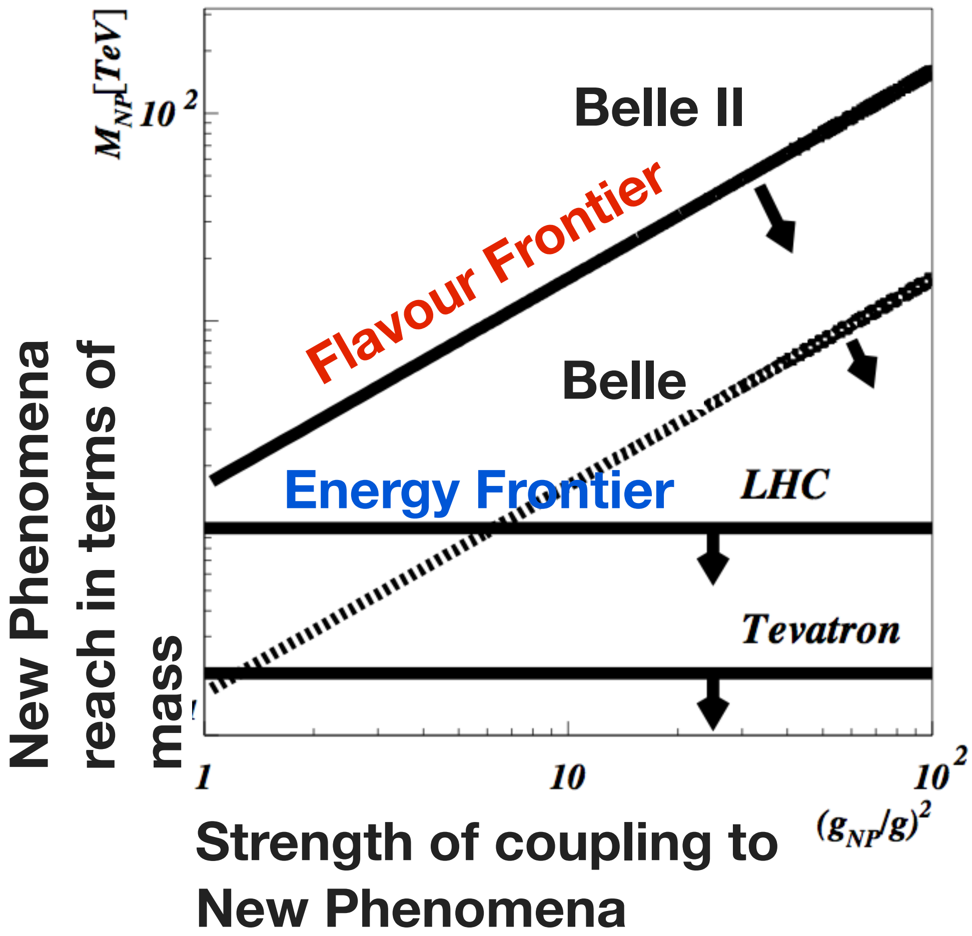




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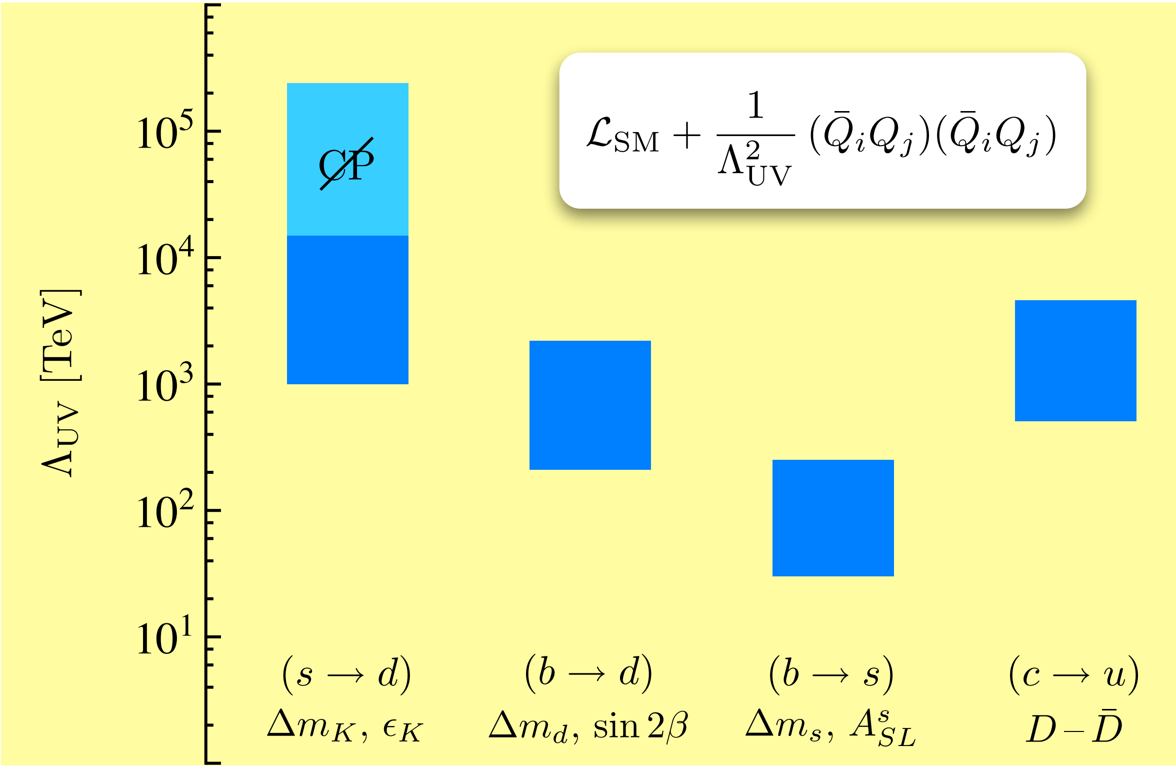
# Flavour as a high mass probe

## Bounds from Mixing and some CP observables




Generic bounds without a flavor symmetry

- Ways out

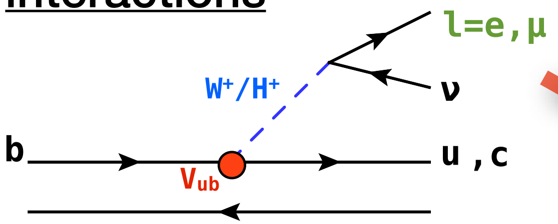
1. New particles have large masses >> 1 TeV
2. New particles have degenerate masses
3. Mixing angles in the new sector are small, same as in SM (MFV)
4. The above already implies strong constraints on NP

# New Phenomena DNA

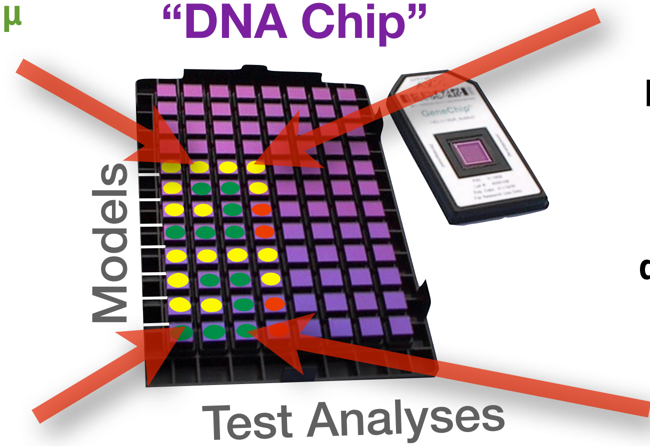
- **Different models predict different sets of quantum numbers/masses/ couplings.**

  Analyse meson (bound q anti-q pair) & lepton decays in a variety of signatures. e.g.

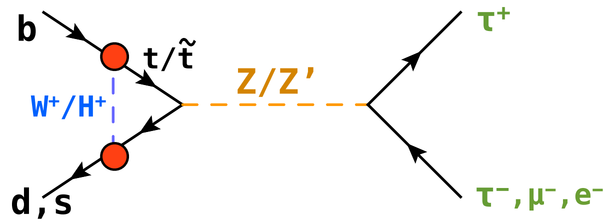
Precision tests of quark interactions



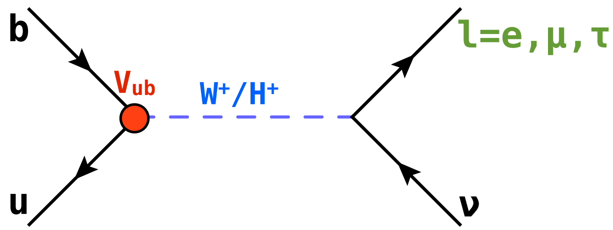

**New Physics "DNA Chip"**



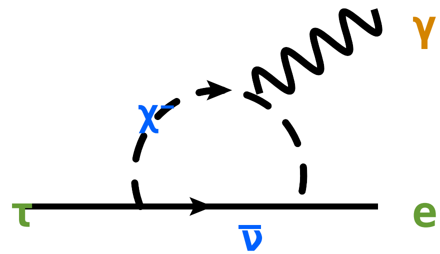

Flavour Changing Neutral Current Interactions




New Phenomena in rare decay processes




Search for lepton flavour violation (neutrino mass...)

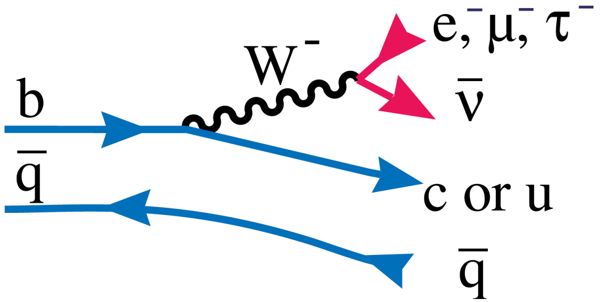


# Flavour Phenomenology

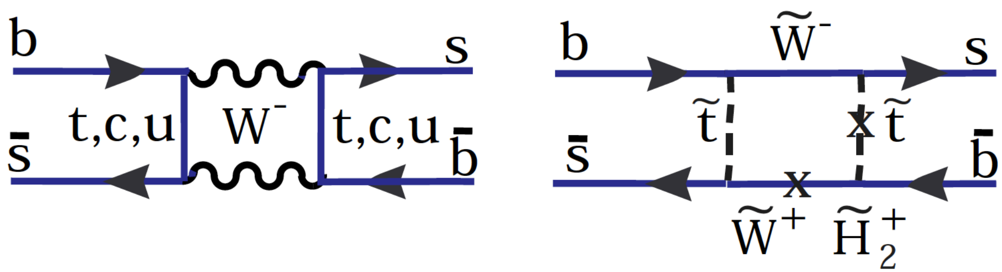
- Much recent activity on a variety of models including:
  - SUSY models (MSSM, CMSSM, BMSSM, ....)
  - SUSY-GUTs
  - Extra dimensions (UED, RS...)
  - Extended Higgs sectors
  - A 4th generation of quarks/leptons
  - New gauge bosons W’, Z’
  - Models featuring a **warped extra dimension** (Randall-Sundrum) offer a simultaneous geometrical **solution to the hierarchy** and **flavour problems**

# UT (CP violation) and New Physics

- You might have concluded from the last lecture that we had not seen New Physics,
  - yet what we observe is the sum of Standard Model + New physics. *How do we set limits on NP?*
- One Hypothesis: assume that tree level diagrams are dominated by SM and loop could contain NP



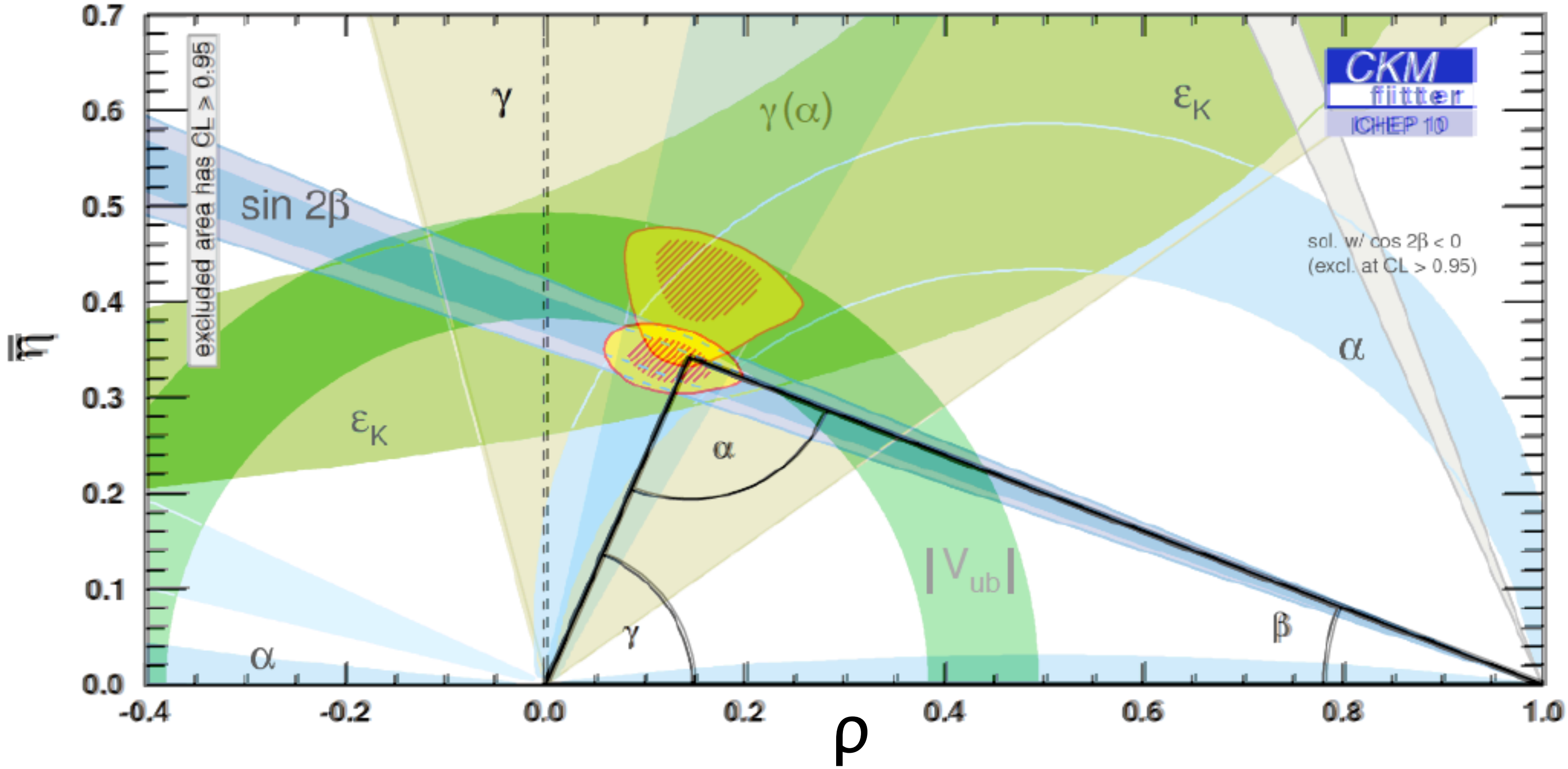

**Tree Diagram example**




**Loop diagram examples**

# They are consistent

- But consistency is only at the 5% level
- Same for $B_s$ (CP violation in $B \to J/\psi\ \Phi$):
  - limits on NP are not so strong



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Thursday, 29 August 13

# Rare B decays

1. Radiative and Electroweak Penguin Decays with Flavour Changing Neutral Currents (**FCNC**) that occur in the SM **only at the loop level**
   - high sensitivity to New Physics (NP) (can appear in the loop with size comparable to leading SM contributions)
   - Complementary to the direct production of new particles expected at LHC
2. Highly suppressed (i.e. helicity suppression) processes.

- Huge datasets collected at the two B-factories, BaBar and Belle, and the LHC experiments (already!) made it possible to explore these decays.

# Radiative & EW Pengiuns

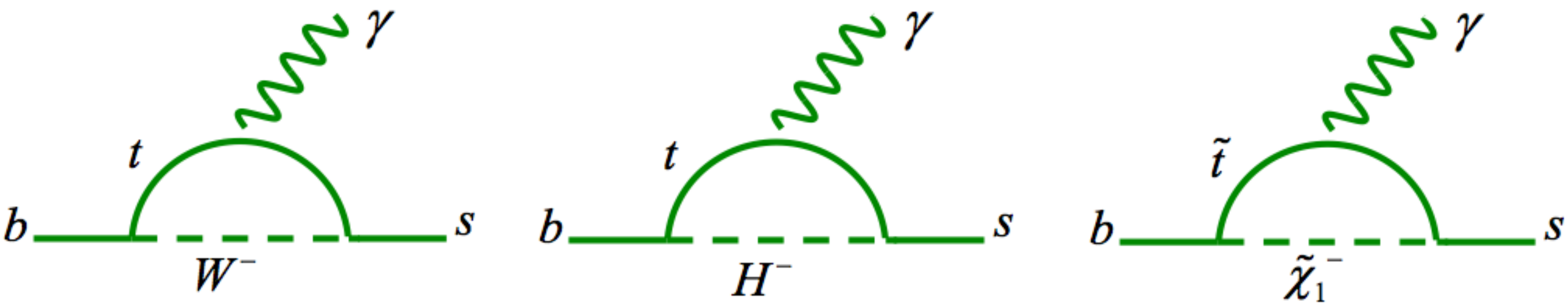
**$B \to X_s \gamma$, $B \to K^* l^+ l^-$**

# Important NP contributions to $BR(B \to X_s\gamma)$

Example search for new physics.

Flavor changing neutral currents (FCNC)

- Forbidden at tree level in the SM
- New, heavy particles likely to appear at loop level




Decay rate sensitive to *b* quark dynamics

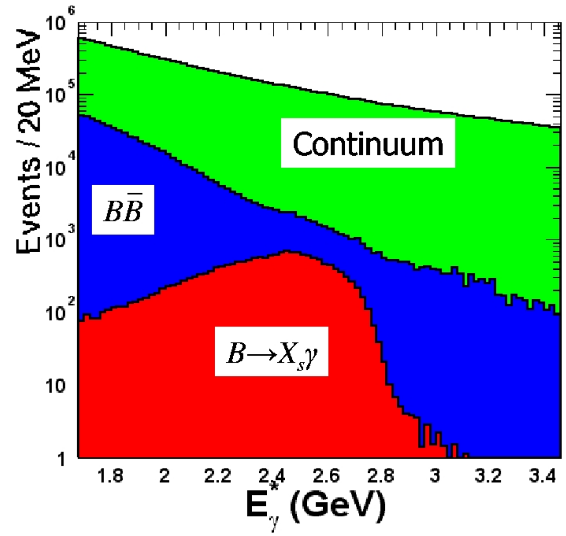
Used in conjunction with $B \to X_d\gamma$ for *Indirect* determination of $|V_{td}|/|V_{ts}|$

$$\Gamma(B \to X_s\gamma) = \frac{\alpha G_F^2 m_b^5}{32\pi^4}|V_{tb}V_{ts}|^2|C_7(m_b)|^2\left[1 + \frac{\lambda_1}{2m_b^2} - \frac{9\lambda_2}{2m_b^2} + \dots\right]$$

# b→sγ Backgrounds

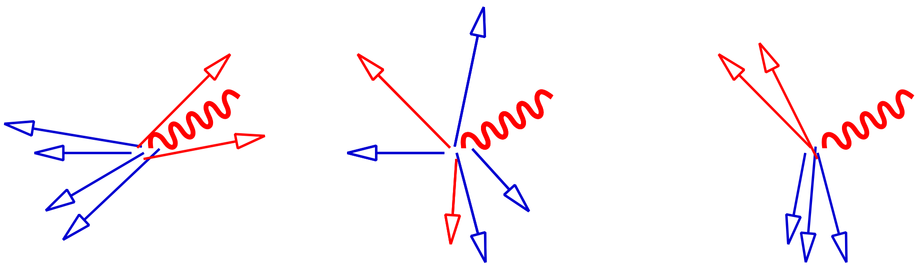
- Goals:
  - ▷ high efficiency
  - ▷ largest fraction of phase space
  - → Energy cut as low as posible
- Dominating backgrounds
  - ▷ merged $\pi^0$ from continuum events
  - ▷ (merged) $\pi^0$ from $B\bar{B}$ events

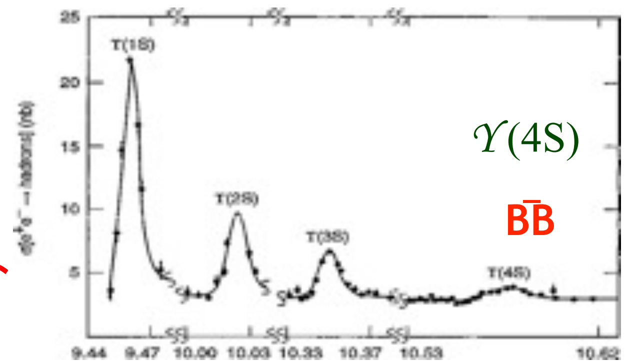
  Very bad for lower $E_\gamma$ cuts!




- Background fighting

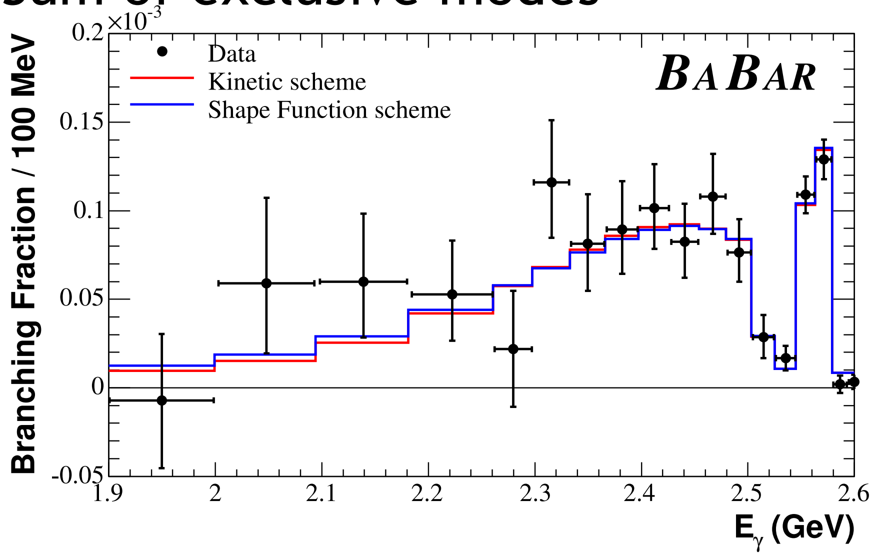
  -Identify secondary photon production



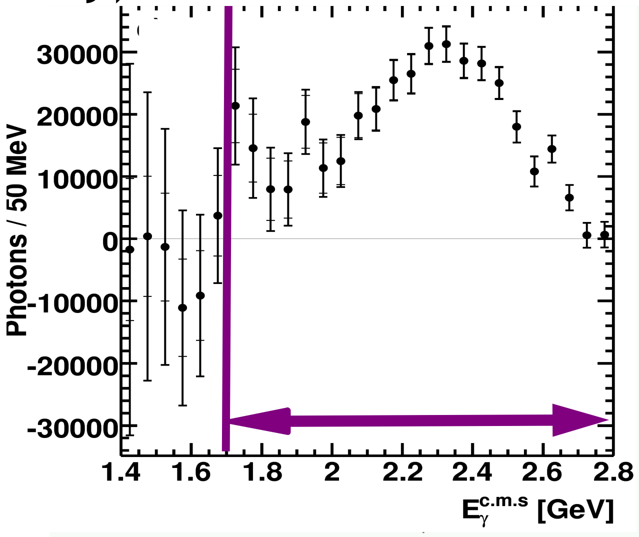


# Photon energy spectrum

- Sum of exclusive modes




- (fully) inclusive




- Differences in resolution: Photons from $B \to K^*\gamma$!
- Partial branching fractions $E_\gamma > 1.6$ GeV

BR(semi,$_{BABAR}$)=(3.49±0.20±0.50±0.04) x $10^{-4}$
BR(incl, $_{BELLE}$) =(3.47±0.15±0.40±0.01) x $10^{-4}$

# b→s γ Prediction

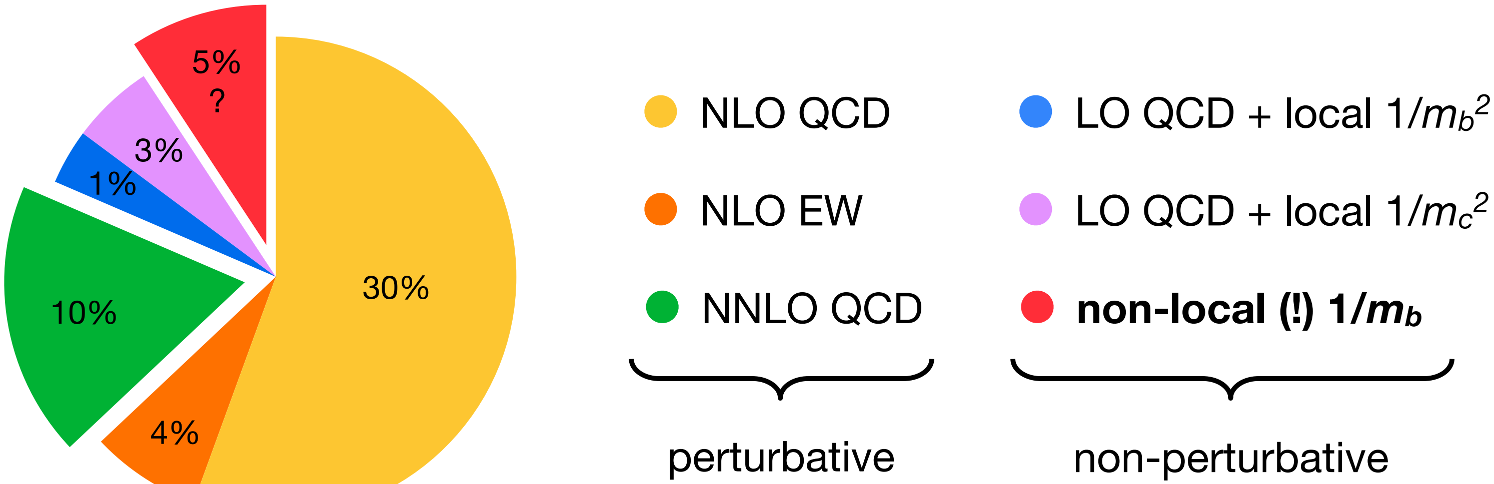
Not easy though…Decay rate sensitive to $b$ quark mass, dynamics, etc.

$$\mathcal{B}(B \to X_s\gamma)^{E_\gamma > 1.6\ \mathrm{GeV}}_{\mathrm{SM}} = \mathcal{B}(B \to X_c e\bar{\nu})_{\mathrm{exp}} \left[\frac{\Gamma(b \to s\gamma)}{\Gamma(b \to ce\bar{\nu})}\right]_{\mathrm{LO}}$$

$$\times \left\{ 1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\alpha) + \mathcal{O}(\alpha_s^2) + \mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{m_b^2}\right) + \mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{m_c^2}\right) + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{m_b}\right) \right\}$$

Misiak et al. (2006) [$\mathcal{O}(\alpha_s^2)$]

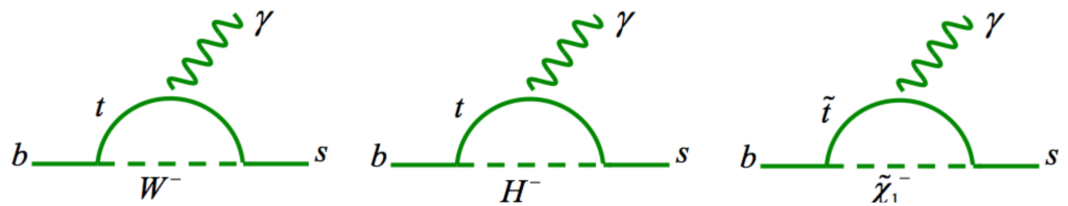
Benzke, Lee, MN, Paz (2010) [$\mathcal{O}(\Lambda_{\mathrm{QCD}}/m_b)$]

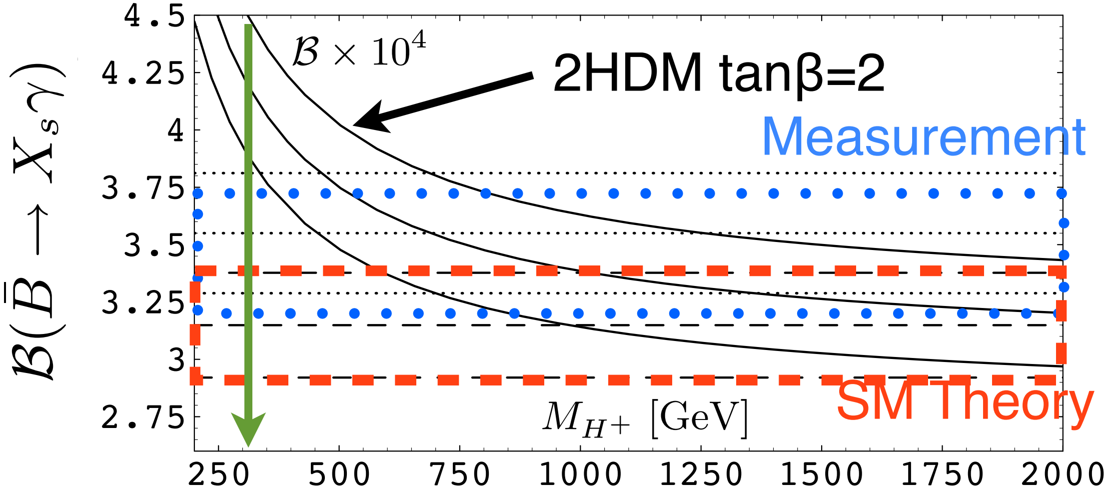



relative size of corrections compared to leading-order (LO) branching ratio

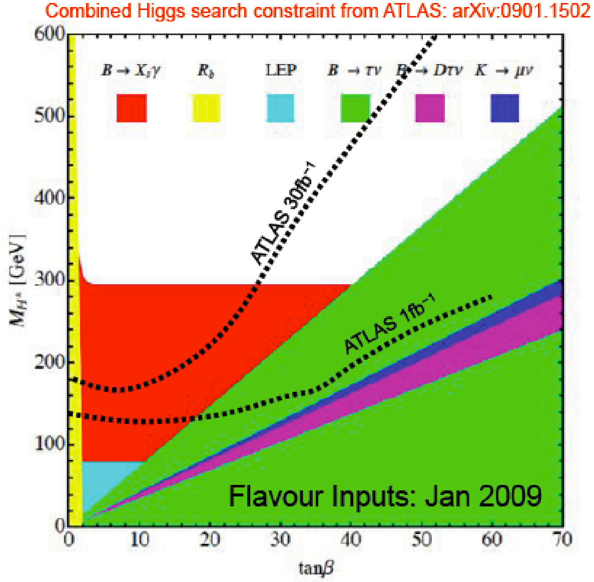
# Strong constraints on NP

- Measured (3.43±0.21±0.07) $10^{-4}$
- Theory (3.15±0.23) $10^{-4}$ (NNLL) Misiak arXiv 1010.4896
- Ratio 1.13±0.11, Limits **most** NP models
- e.g. 2HDM
  - m($H^+$)>316 GeV



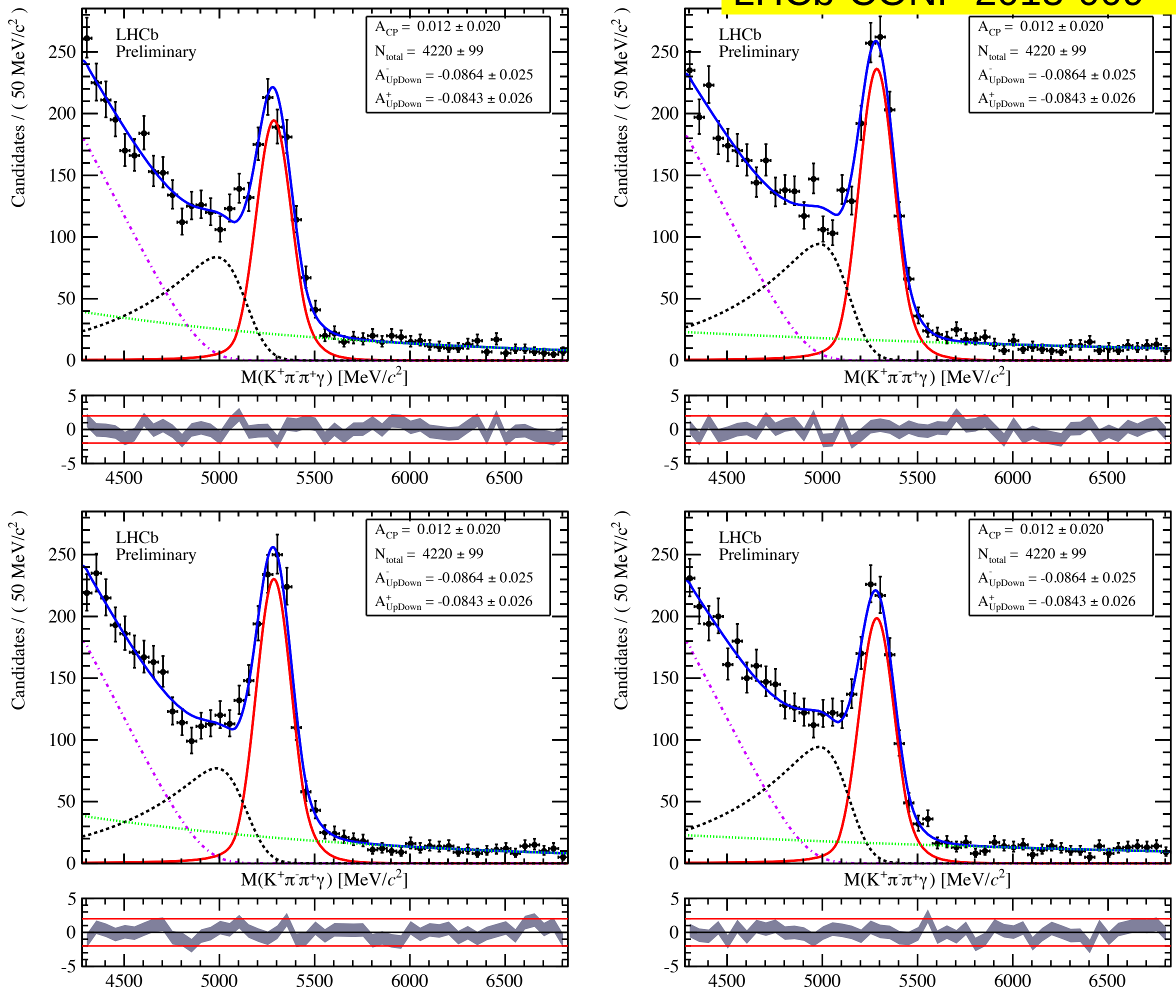

Combined Higgs search constraint from ATLAS: arXiv:0901.1502



# Photon Polarisation

- New LHCb measurement LHCb-CONF-2013-009 of **$B^+ \to K^+\pi\pi\gamma$**
- compare γ direction relative to $K^+\pi\pi$ plane
  - Equivalent to Parity violation.
  - Polarisation amplitude $A_{ud}$

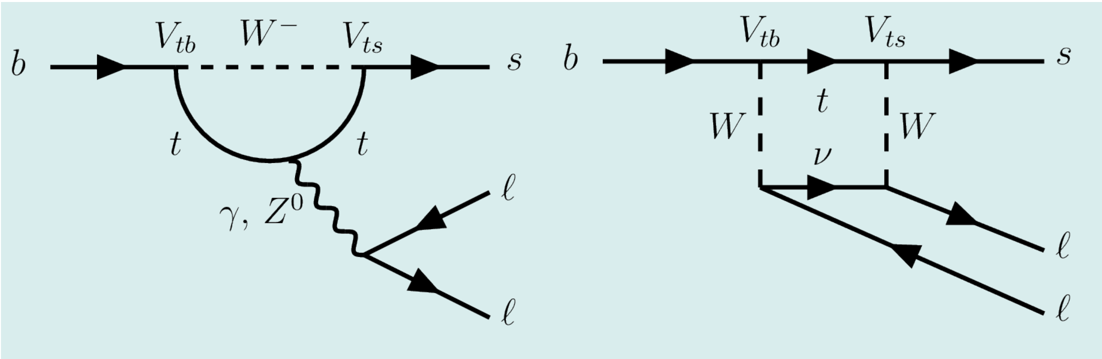
LHCb-CONF-2013-009




$$\mathcal{A}_{\rm ud} = -0.085 \pm 0.019\,({\rm stat}) \pm 0.003\,({\rm syst})$$

# $B^0 \to K^{*0}\, l^+ l^-$

- Similar to $B \to X_s\gamma$, where $X_s = K^*$, **but more diagrams** (ways for NP to enter)




new particles can enter loops

- Rare. $BR(B \to llK^*) = (3.3 \pm 1.0) \cdot 10^{-6}$
  - Several variables can be studied: forward backward $A_{FB}$ asymmetry, is well predicted,
    - Sensitive to Supersymmetry, Any 2HDM, Fourth generation, Extra dimensions, Axions . . .***NP right handed currents***

# Operator Product Expansion

- To Build an effective theory for b physics
  - take the weak part of the SM
  - integrate out the heavy fields (W, Z, t)

$$\mathcal{L}_{\text{(full EW}\times\text{QCD)}} \longrightarrow \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED}\times\text{QCD}}\left(\begin{smallmatrix}\text{quarks} \neq t \\ \text{\& leptons}\end{smallmatrix}\right) + \sum_n C_n(\mu)\, Q_n$$

$Q_n$ – local interaction terms (operators), $C_n$ – coupling constants (Wilson coefficients)

- Wilson coefficients
  - encode information on the weak scale
  - are calculable and known in the SM ( at least to leading order)
  - are affected by new physics

  - for K*μμ we care about $C_7$ (also affects b→s γ), $C_9$ and $C_{10}$

# Effective Operators

$$\mathcal{H}_W^{\Delta B=1,\Delta C=0,\Delta S=-1} = 4\frac{G_F}{\sqrt{2}}\Big(\lambda_c^s(C_1(\mu)Q_1^c(\mu) + C_2(\mu)Q_2^c(\mu))$$
$$+\lambda_u^s(C_1(\mu)Q_1^u(\mu) + C_2(\mu)Q_2^u(\mu)) - \lambda_t^s\sum_{i=3}^{10} C_i(\mu)Q_i(\mu)\Big)$$

where the $\lambda_q^s = V_{qb}^* V_{qs}$ and the operator basis is given by

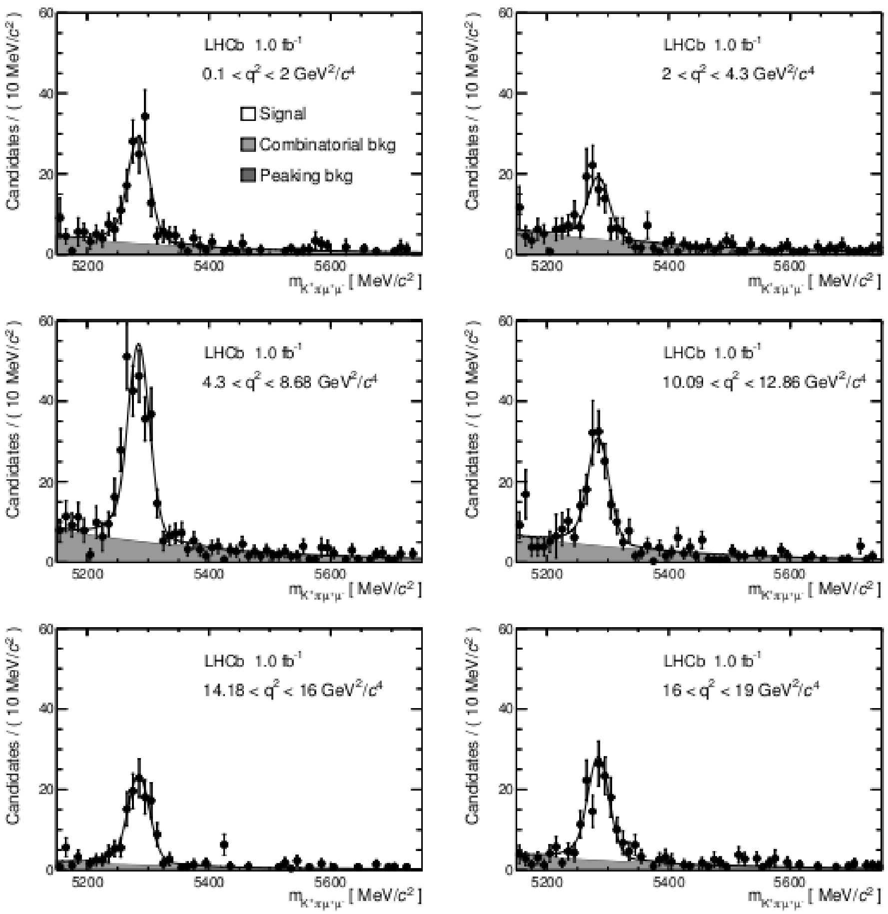
$$Q_1^q = \bar{b}_L^\alpha \gamma^\mu q_L^\alpha \, \bar{q}_L^\beta \gamma_\mu s_L^\beta \qquad Q_2^q = \bar{b}_L^\alpha \gamma^\mu q_L^\beta \, \bar{q}_L^\beta \gamma_\mu s_L^\alpha$$
$$Q_3 = \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q \bar{q}_L^\beta \gamma_\mu q_L^\beta \qquad Q_4 = \bar{b}_L^\alpha \gamma^\mu s_L^\beta \sum_q \bar{q}_L^\beta \gamma_\mu q_L^\alpha$$
$$Q_5 = \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q \bar{q}_R^\beta \gamma_\mu q_R^\beta \qquad Q_6 = \bar{b}_L^\alpha \gamma^\mu s_L^\beta \sum_q \bar{q}_R^\beta \gamma_\mu q_R^\alpha$$
$$Q_7 = \frac{3}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q e_q \bar{q}_R^\beta \gamma_\mu q_R^\beta \qquad Q_8 = \frac{3}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\beta \sum_q e_q \bar{q}_R^\beta \gamma_\mu q_R^\alpha$$
$$Q_9 = \frac{3}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum e_q \bar{q}_L^\beta \gamma_\mu q_L^\beta \qquad Q_{10} = \frac{3}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\beta \sum e_q \bar{q}_L^\beta \gamma_\mu q_L^\alpha$$

Four-fermion operators (except $Q_{7\gamma}$ & $Q_{8g}$) – dimension 6

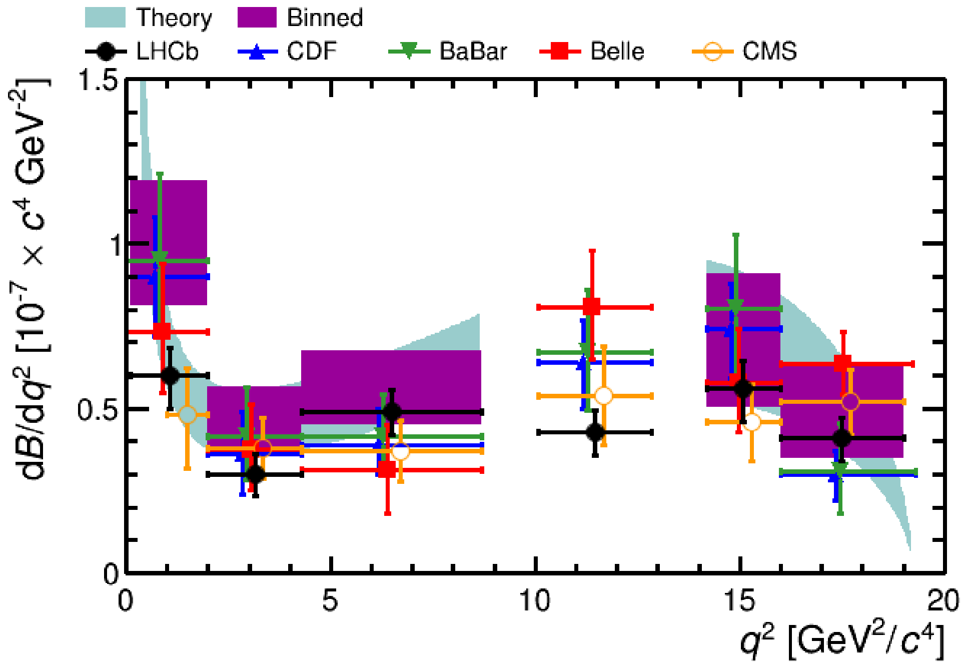
$$Q_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{b}_L^\alpha \sigma^{\mu\nu} F_{\mu\nu} s_L^\alpha$$
$$Q_{8g} = \frac{g_s}{16\pi^2} m_b \bar{b}_L^\alpha \sigma^{\mu\nu} G_{\mu\nu}^A T^A s_L^\alpha$$

$$Q_{9V} = \frac{1}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\alpha \, \bar{l}\gamma_\mu l$$
$$Q_{10A} = \frac{1}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\alpha \, \bar{l}\gamma_\mu \gamma_5 l$$

# $B^0 \to K^{*0} l^+ l^-$



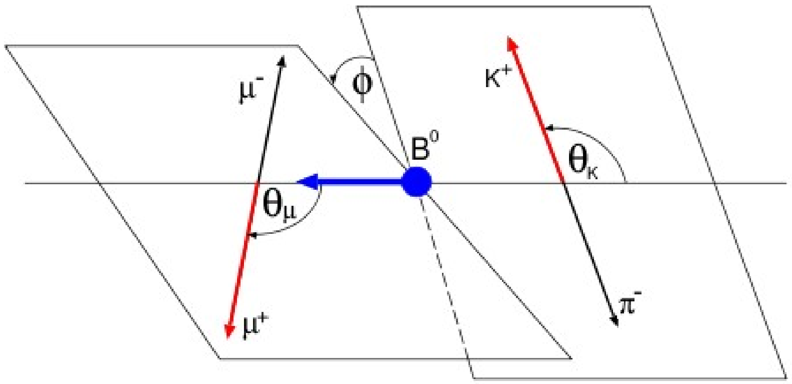

LHCb arXiv:1304.6325
See also CDF PRL 108 (2012) 081807
BaBar PRD 86 (2012) 032012
ATLAS-CONF-2013-038 & CMS BPH-11-009



# Angular distributions and A$_{FB}$

- A lot of information in the full $\theta_l$, $\theta_K$ and $\phi$ distributions
- Many observables depending on $q^2 = m^2(\mu\mu)$

$$\frac{d^2\Gamma}{dq^2\, d\cos\theta_l} = \frac{3}{8}\left[(1+\cos^2\theta_l)\, H_T(q^2) + 2\,\cos\theta_l\, H_A(q^2) + 2\,(1-\cos^2\theta_l)\, H_L(q^2)\right]$$

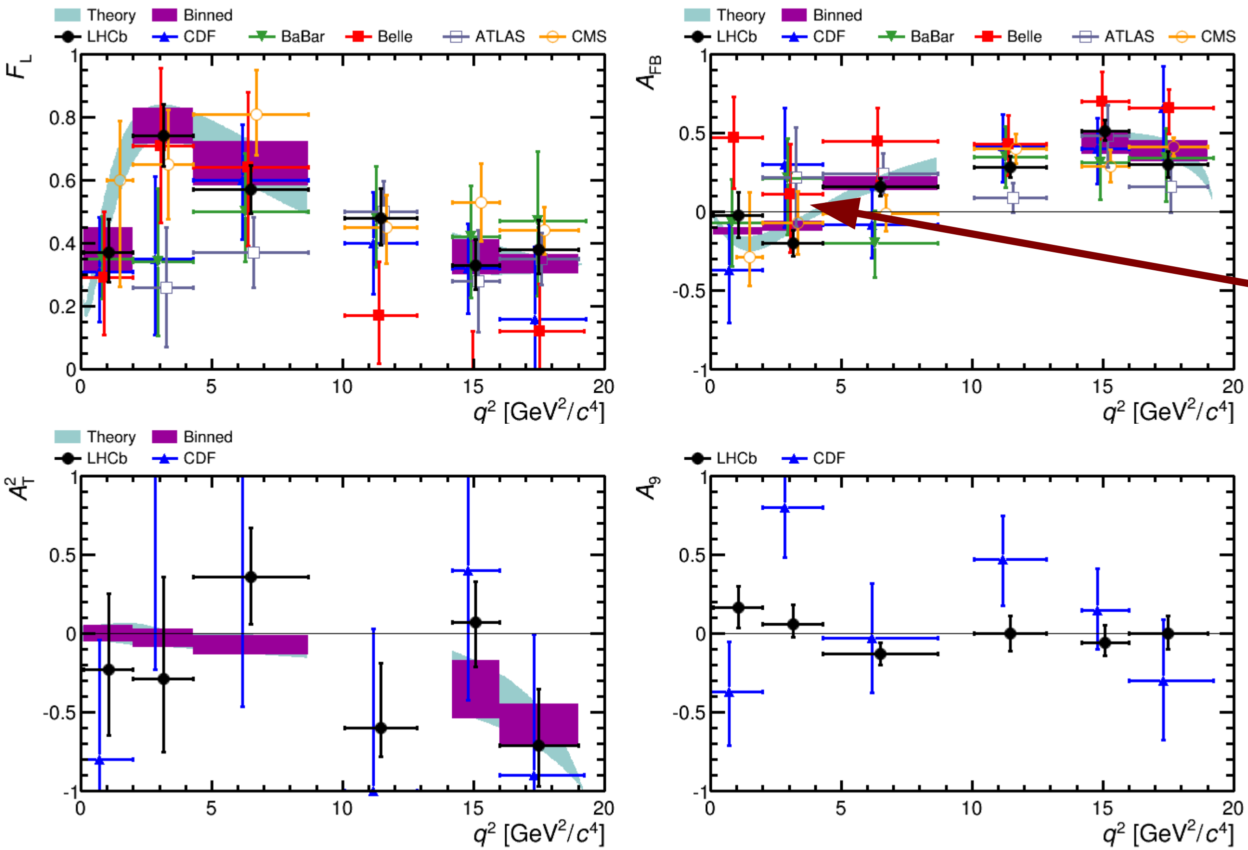



$$H_T(q^2) \propto 2q^2\left[\left(C_9 + 2C_7\,\frac{m_b^2}{q^2}\right)^2 + C_{10}^2\right]$$

$$H_A(q^2) \propto -4q^2 C_{10}\left(C_9 + 2C_7\,\frac{m_b^2}{q^2}\right),$$

$$H_L(q^2) \propto \left[(C_9 + 2C_7)^2 + C_{10}^2\right].$$

# Angular Analysis of $B^0 \to K^{*0} l^+ l^-$



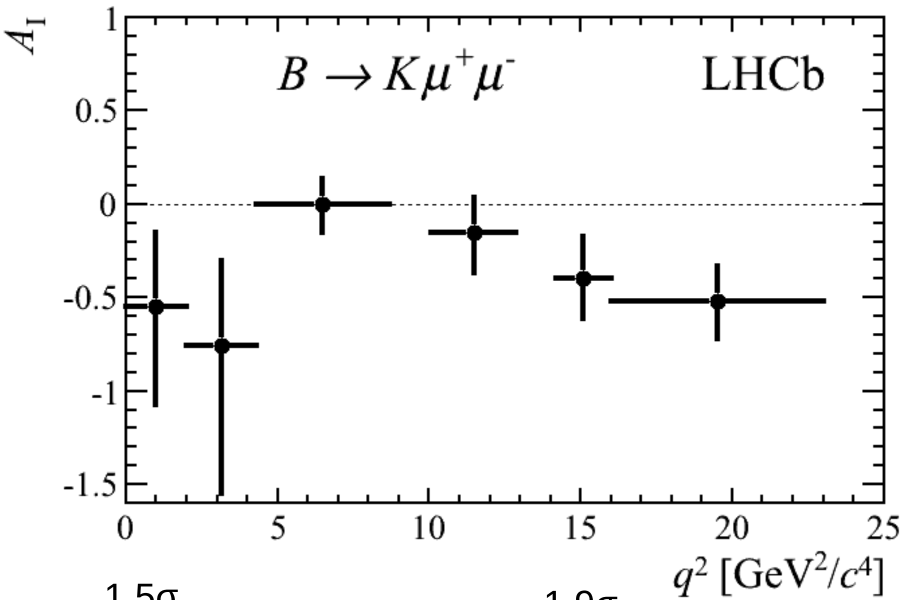

First measurement of zero-crossing point of $A_{FB}$

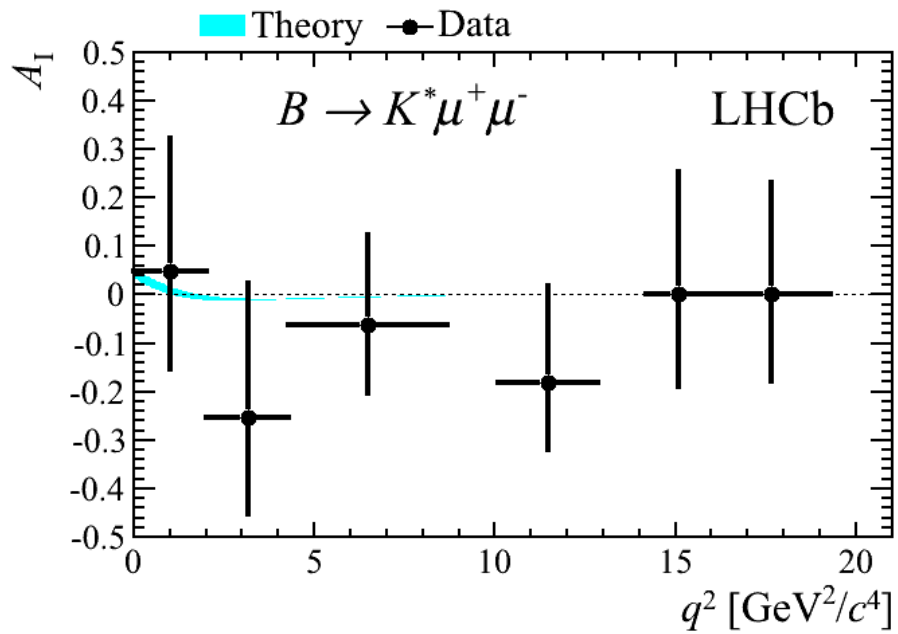
$q^2_0 = (4.9 \pm 0.9)\ \mathrm{GeV}^2/c^4$

Consistent with SM expectation

No deviation from the Standard Model here

# Isospin asymmetry in B→K$^{(*)}$μμ




1.5σ

1.9σ

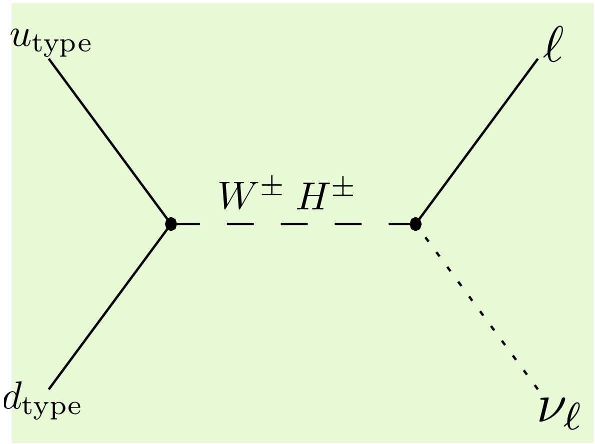
1.9σ

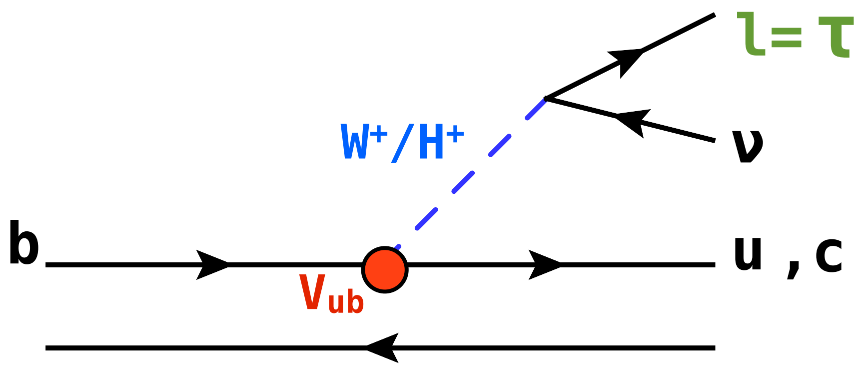
3.0σ

Deviation from zero integrated over $q^2$ ~ 4.4σ
Consistent with previous measurements
(BaBar, Belle, CDF)

Consistent with zero & with SM prediction
Consistent with previous measurements
(BaBar, Belle, CDF)

# Tauonic Decays: B→D$^{(*)}\tau\nu$



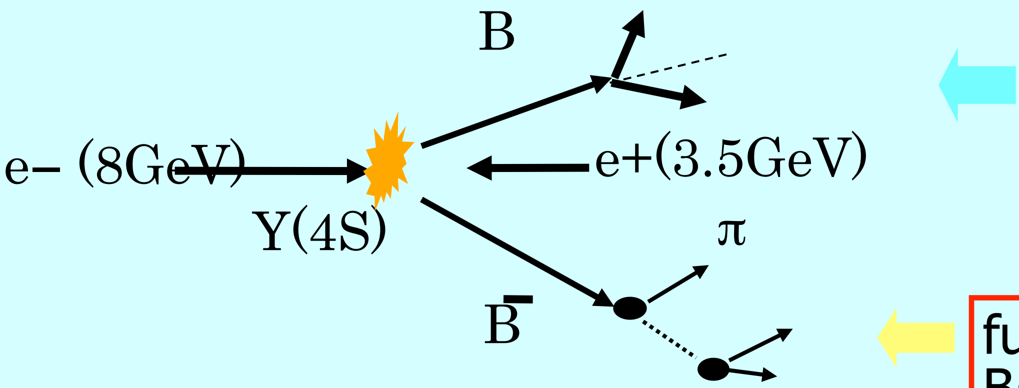

$$R_{NP} = \frac{BR(B \to \tau\nu_\tau)_{SM+NP}}{BR(B \to \tau\nu_\tau)_{SM}}$$

$$R_{SUSY} = [1 - \frac{\tan^2\beta}{1+\epsilon_0 \tan^2\beta}\frac{M_B^2}{M_H^2}]^2$$

$$R_{2HDM,MFV} = \left[1 - \frac{m_B^2}{m_H^2}\frac{\tan^2\beta}{1+(\epsilon_0+\epsilon_1)\tan\beta}\right]^2$$

# Power of e⁺e⁻, example: Full Reconstruction Method

- Fully reconstruct one of the B mesons to
  - Tag B flavor/charge
  - Determine B momentum
  - Exclude decay products of one B from further analysis




Decays of interest
- $B \to X_u \, l \, \nu$,
- $B \to K \, \nu \, \nu$
- $B \to D \tau \nu$, $\tau \nu$
- $B \to \nu \nu$

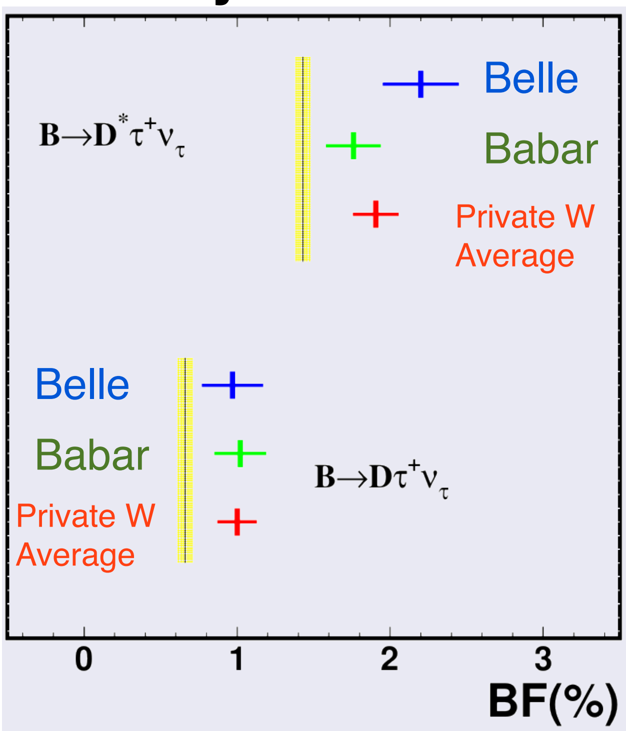
full reconstruction
$B \to D \pi$ etc. (0.1~0.3%)

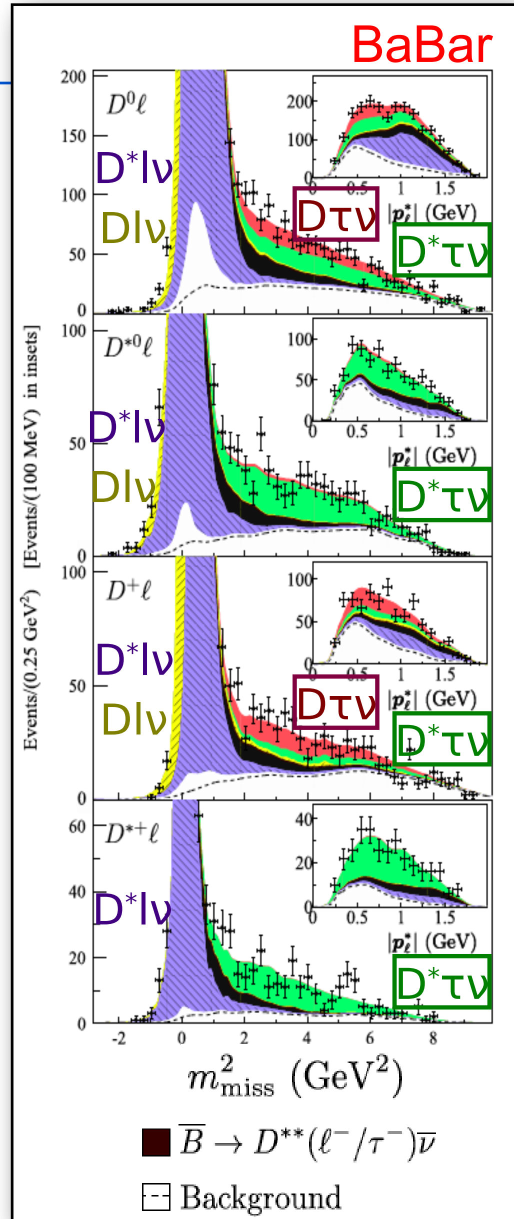
→ Offline B meson beam!

Powerful tool for B decays with neutrinos

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

- Reconstruct D(*) and lepton.
- Examine missing mass in recoiling B.
  - Should be consistent with 2-neutrinos from the tau.
- Large deviations from SM: Combined is almost 5 sigma! **The B-factories must perform complementary tests.**



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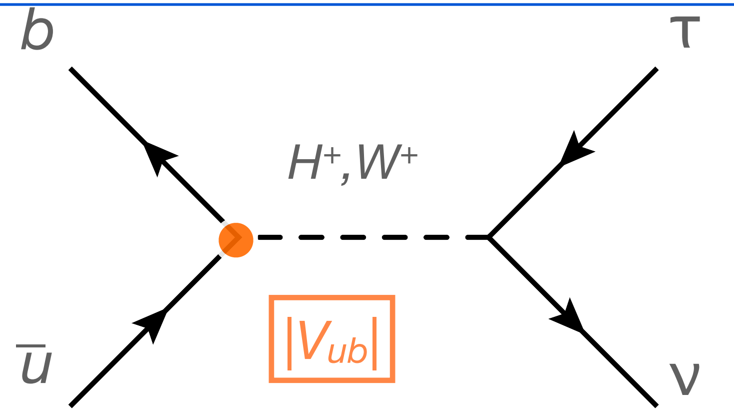
# Leptonic Decays

## $B_u \to \tau\, \nu$, $B_{d,s} \to \mu\, \mu$

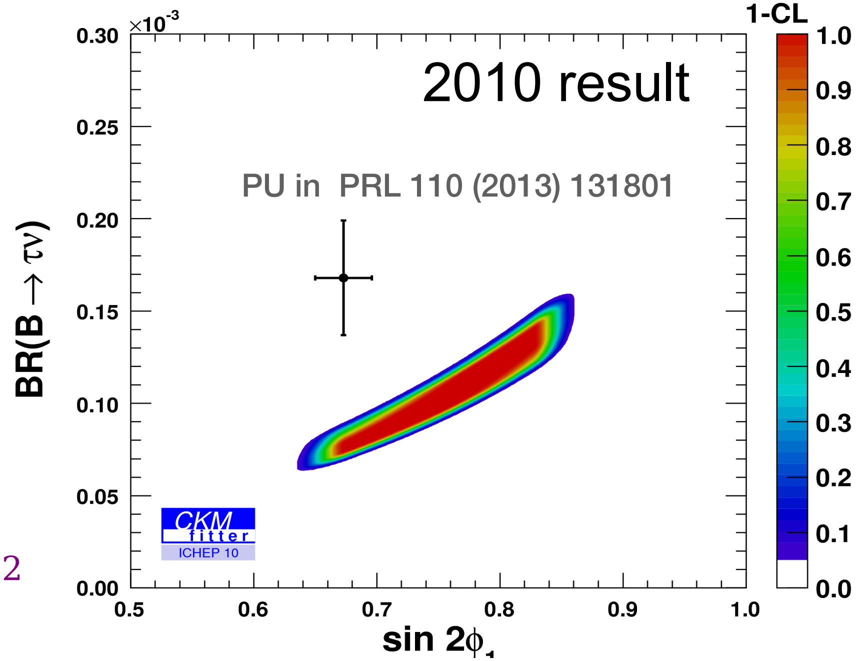
# B→τν Measurement

Rate related to *B* meson decay constant $f_B^2$, $|V_{ub}|^2$




$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

Helicity suppressed - very small in SM.
NP could interfere *e.g.* **charged Higgs, and** *change* the branching fraction

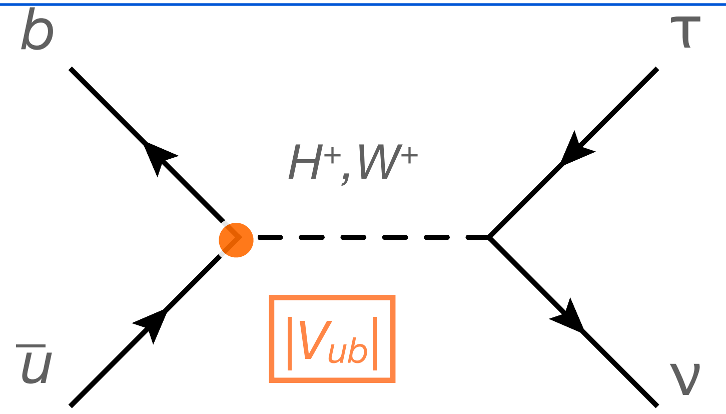



$$B(B^+ \to \tau^+ \nu) = B_{SM} \times \left(1 - \frac{m_B^2}{m_{H^+}^2} \tan^2\beta\right)^2$$

# B→τν Measurement

Rate related to *B* meson decay constant $f_B^2$, $|V_{ub}|^2$

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$




Helicity suppressed - very small in SM.
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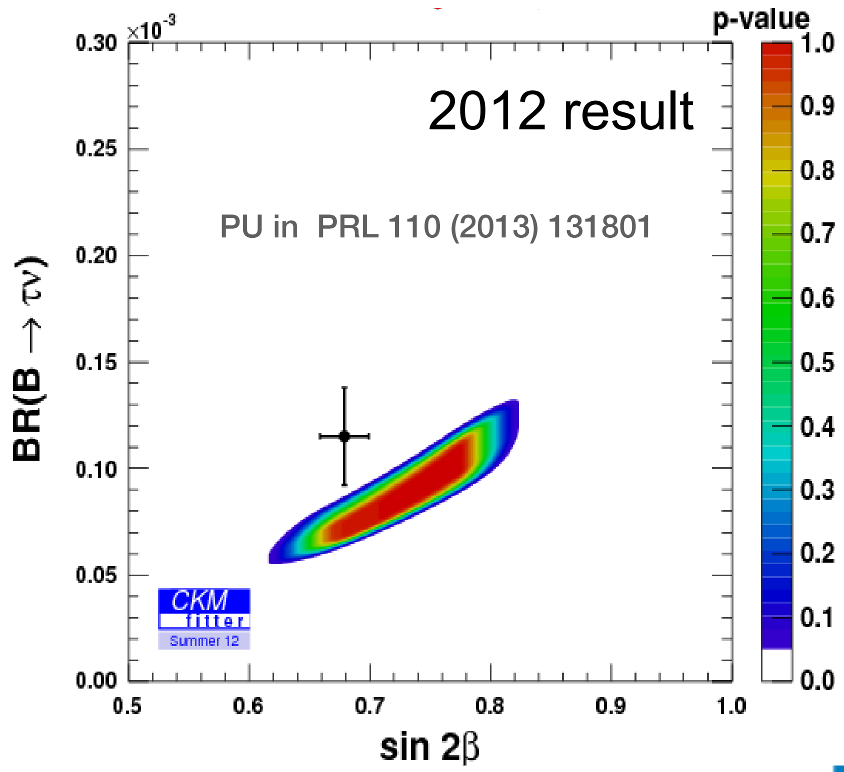
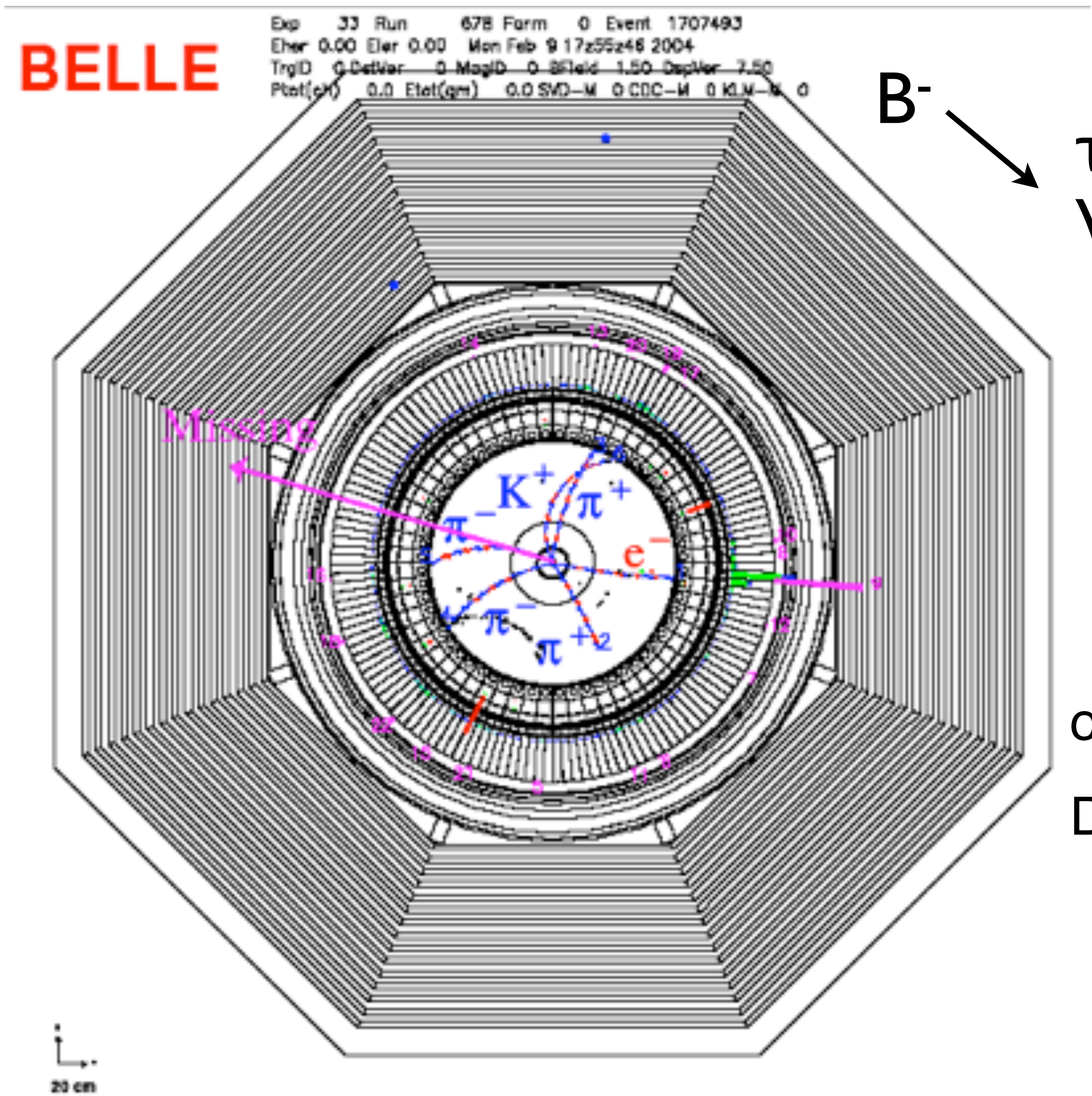



$$B(B^+ \to \tau^+ \nu) = B_{SM} \times \left(1 - \frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)^2$$

# Example of a B→τ ν candidate




$B^-$ → $\tau^-$ $\nu$

$\tau^-$ →
- $\mu^-\ \nu\ \nu$
- $e^-\ \nu\ \nu$
- $\pi^-\ \nu\ \nu$
- $\pi^-\ \pi^0\ \nu$
- $\pi^-\ \pi^+\ \pi^-\ \nu$

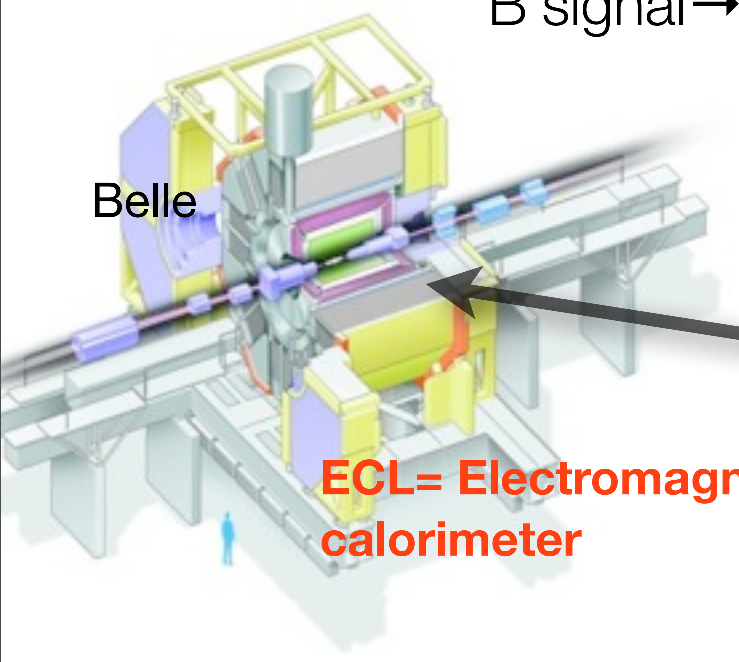
other B: $B \to D^0\ \pi$,

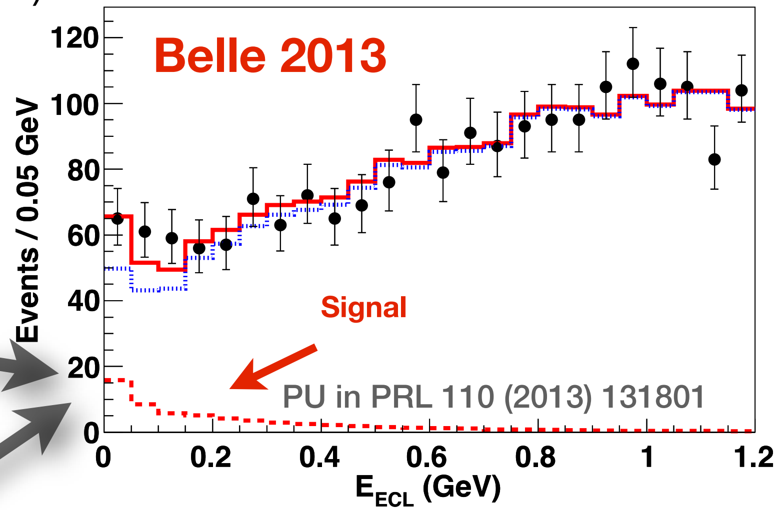
$D^0 \to K\pi\pi\pi$

# Belle 2013 Result

$e^+e^- \to B^+_{tag}B^-_{signal}$

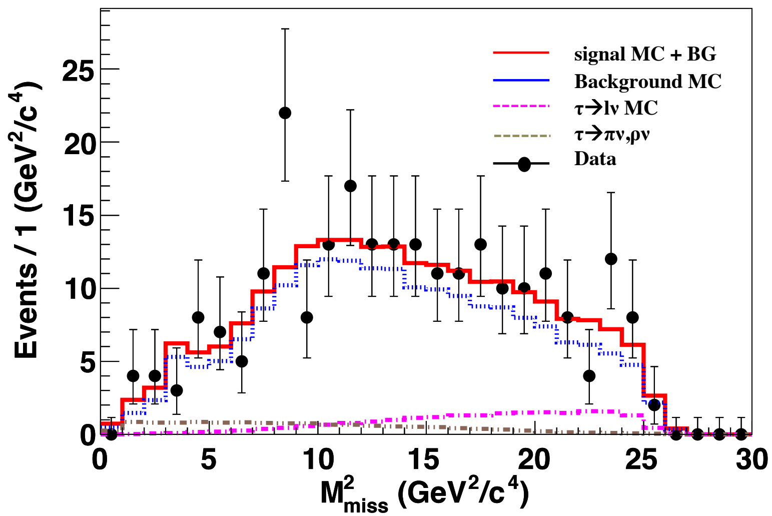
$B^-_{signal} \to \tau(\mu\nu\nu, e\nu\nu, \pi\nu, \rho\nu)\nu$




**Signal (B→τν):**

Zero or small value of $E_{ECL}$ arising only from beam background

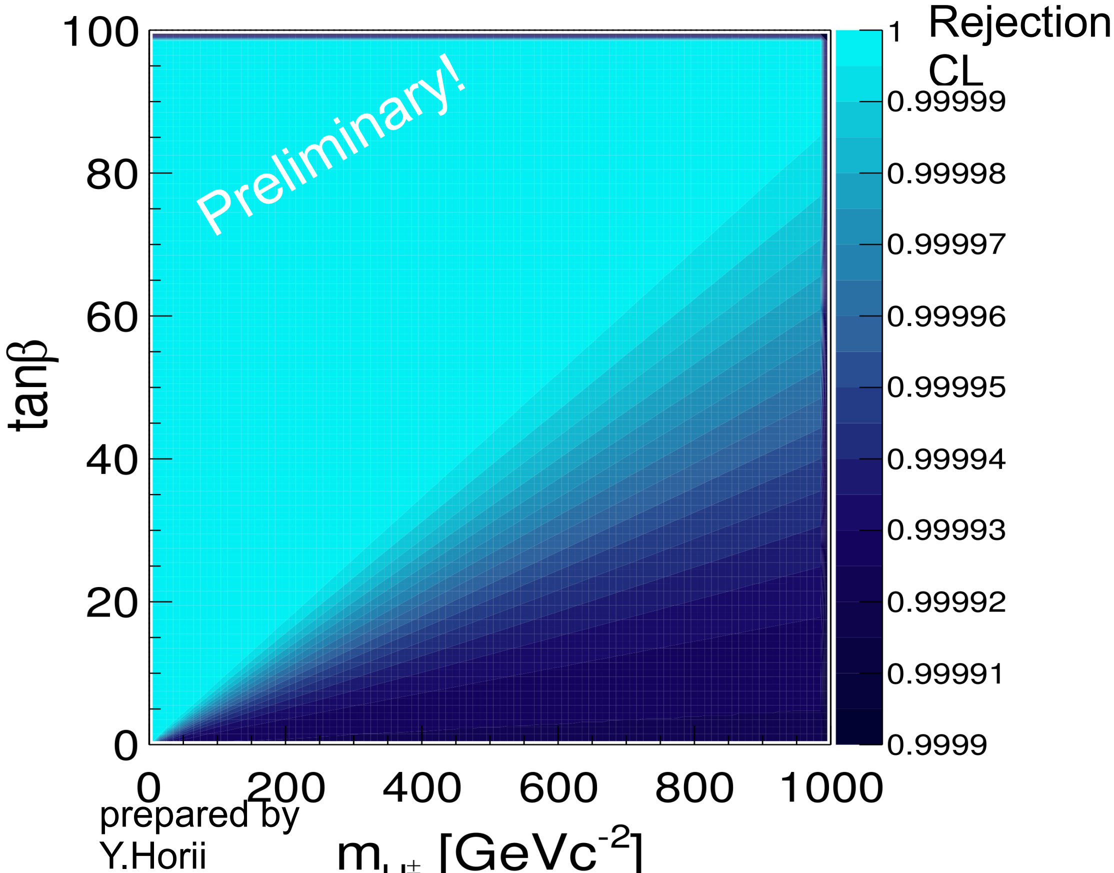



**Consistent with SM**

# Charged Higgs: Type II 2HDM

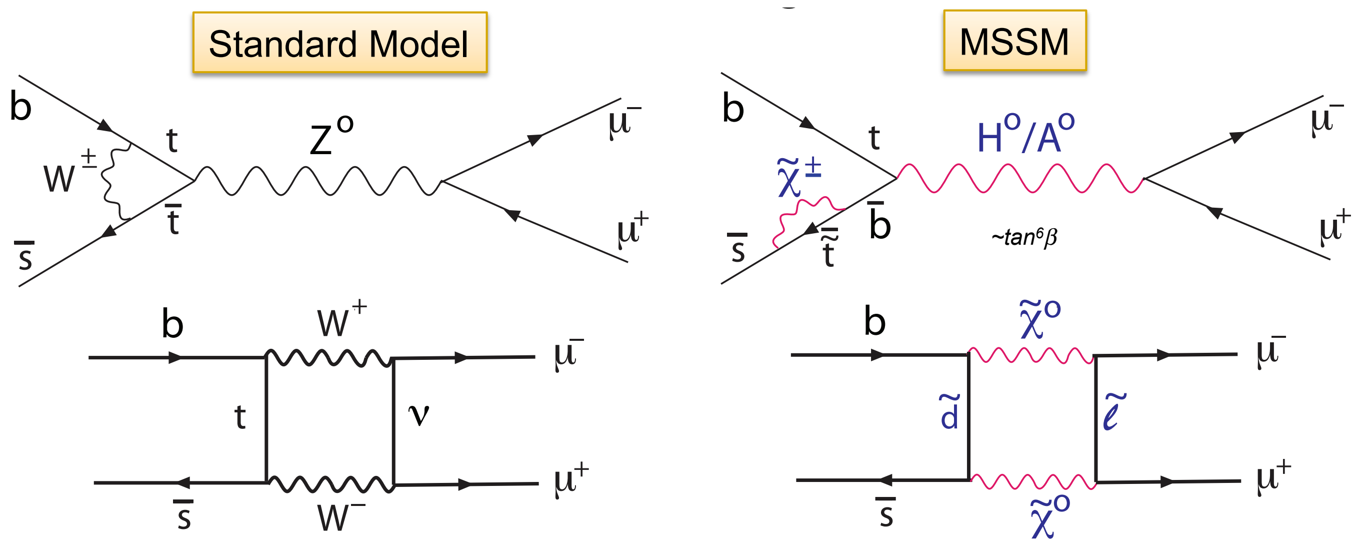
- **Type II 2HDM Global fit (Frequentist)**
- **Belle + BaBar : $B \to \tau\nu$ + $B \to D\tau\nu$ + $B \to D^*\tau\nu$**

- Everything *white* is ruled out....



# $B_s \to \mu^+\mu^-$

- Powerful, clean way of testing for New Physics
- Very small in the SM: NP can make large contributions
- Many NP models possible, not just supersymmetry.

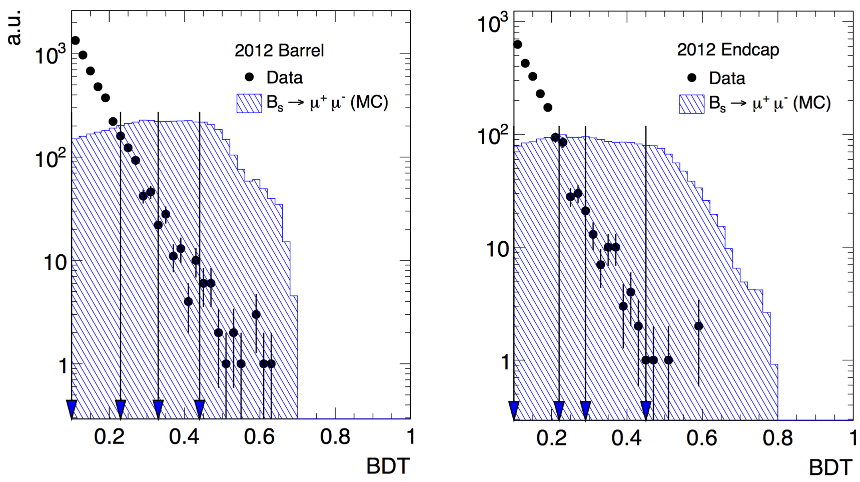



$$BR(B_s \to \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-8} \qquad BR(B_s \to \mu^+\mu^-)^{MSSM} \propto \tan^6\beta / M_{A0}^4$$

# $B_s \to \mu^+\mu^-$ selection

Details: http://indico.cern.ch/conferenceDisplay.py?confId=265347

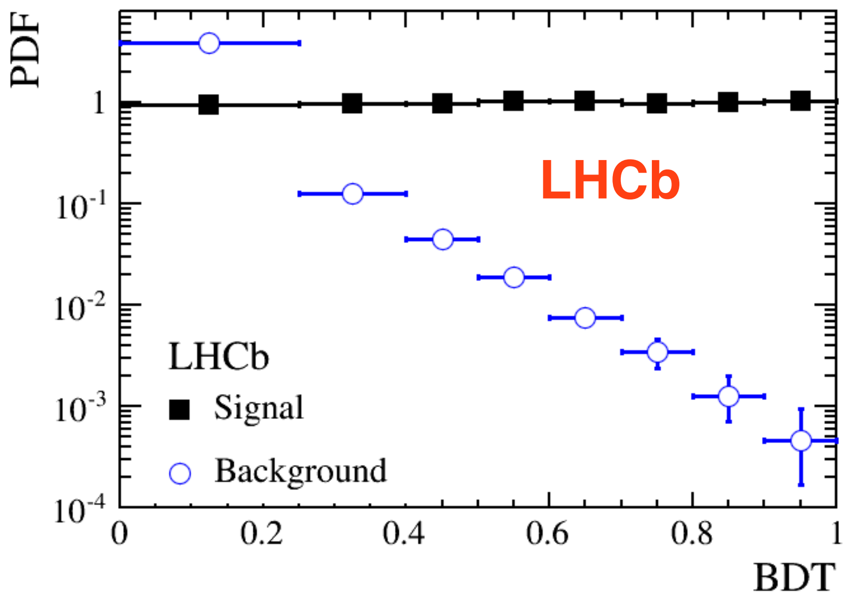
**CMS**



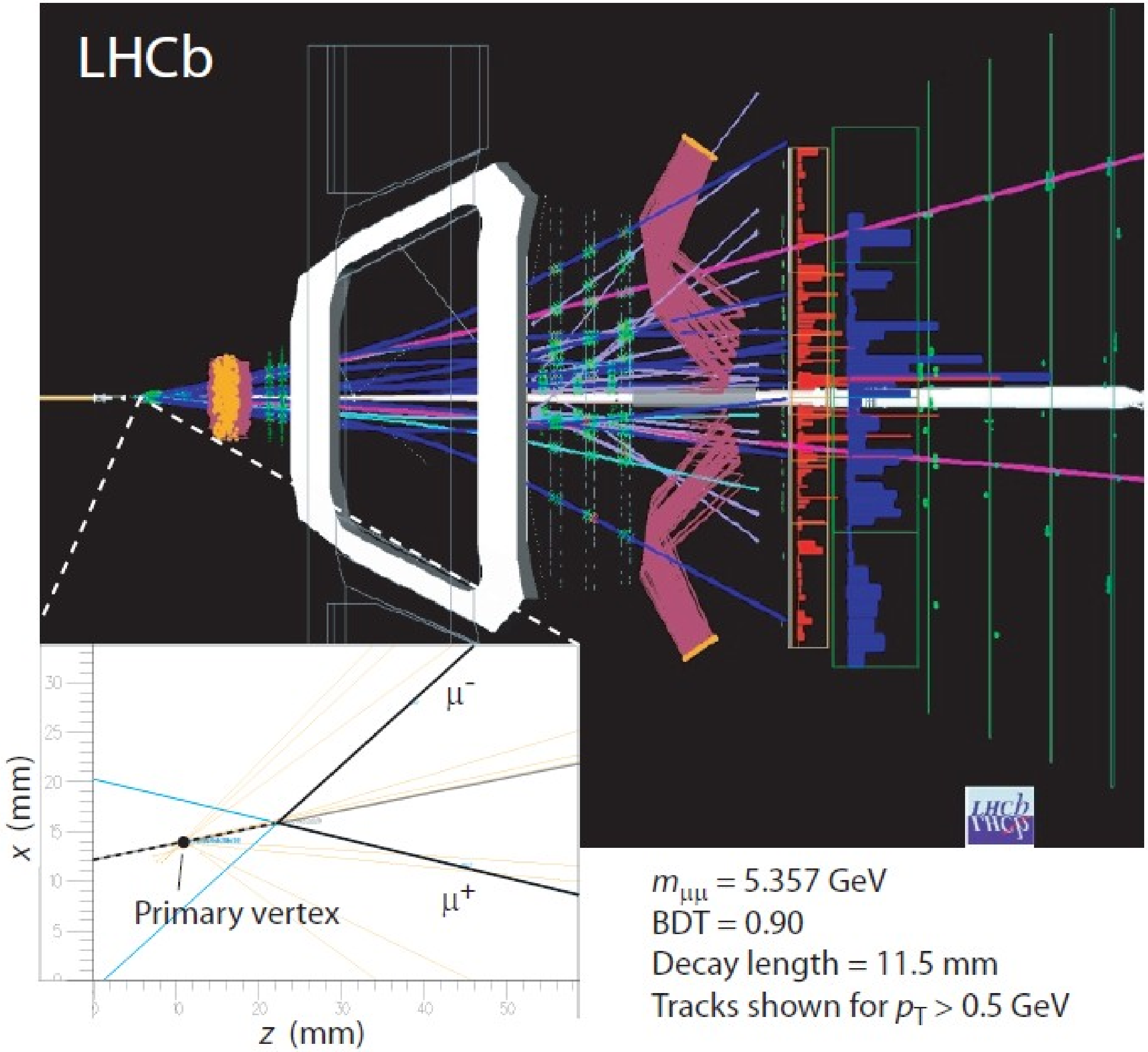

- Produce a **very large sample** of B mesons
- **Trigger** efficiently on dimuon signatures

- **Reject background**
  - **vertex** resolution (identify displaced vertex): B impact parameters, B lifetime, B $p_T$
  - **mass** resolution (identify B peak)
  - **muon** identification (reject background from B decays with misidentified pions): muon isolation, impact parameter of muons,

- typical to combine various discriminating variables into a **multivariate classifier**
  - e.g. Boosted Decision Tree algorithm

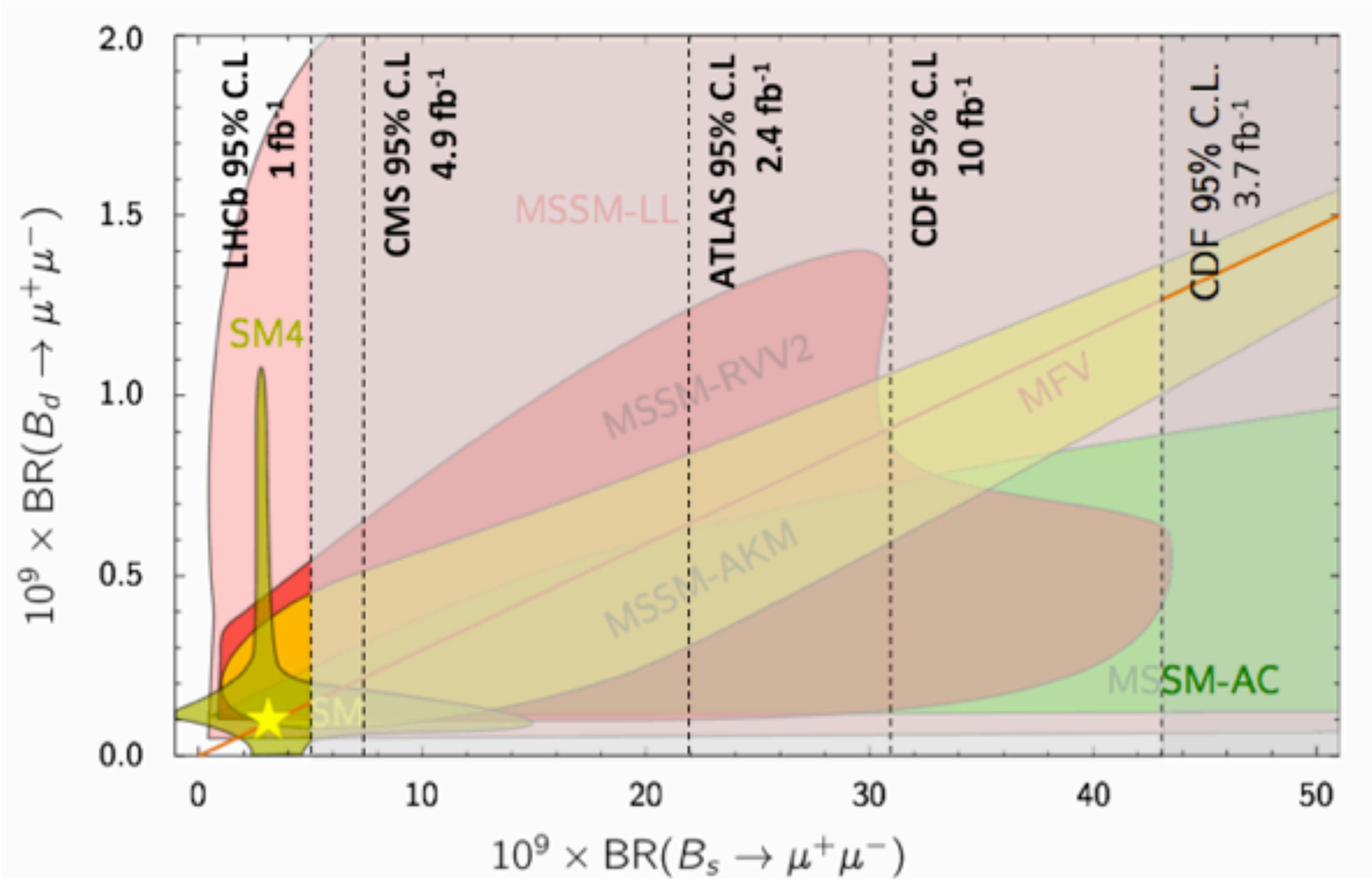


# $B_s \to \mu^+\mu^-$ : LHCb candidate




$m_{\mu\mu} = 5.357$ GeV
BDT = 0.90
Decay length = 11.5 mm
Tracks shown for $p_T > 0.5$ GeV

# 2012 Status



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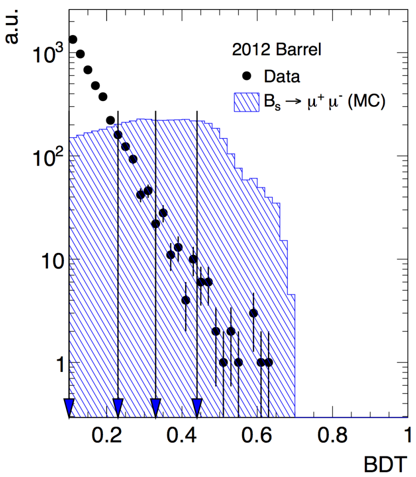
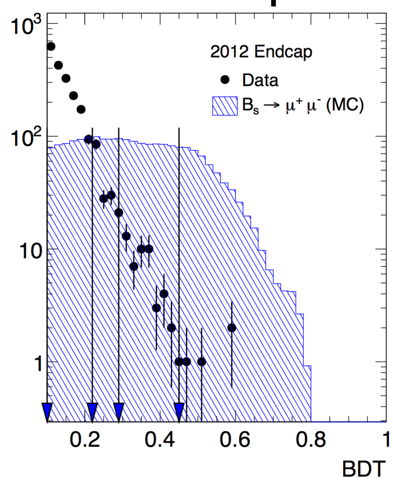
# CMS Mass Distributions

BDT

Barrel

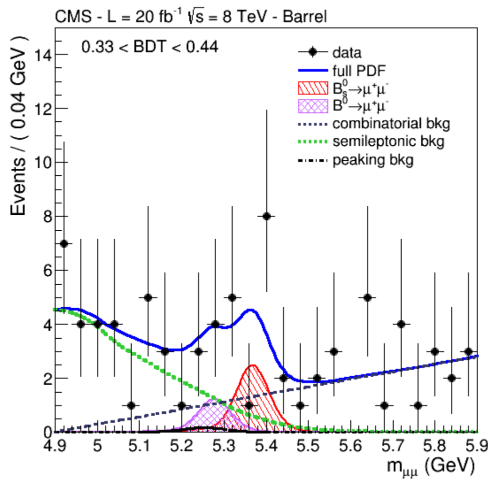



Endcap

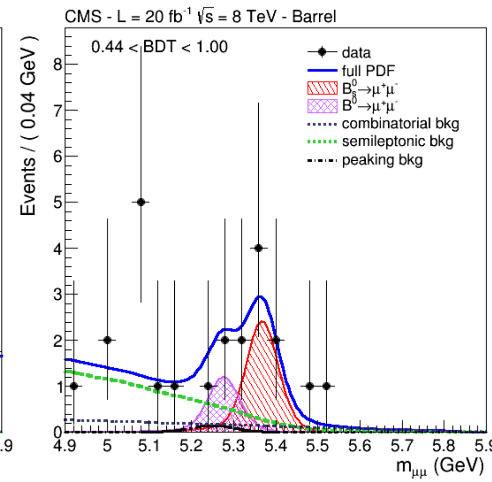


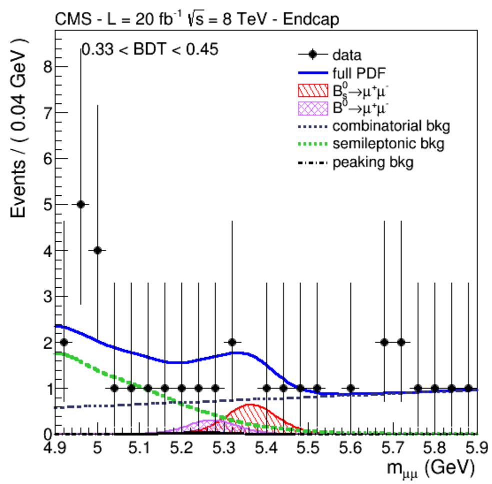

Barrel

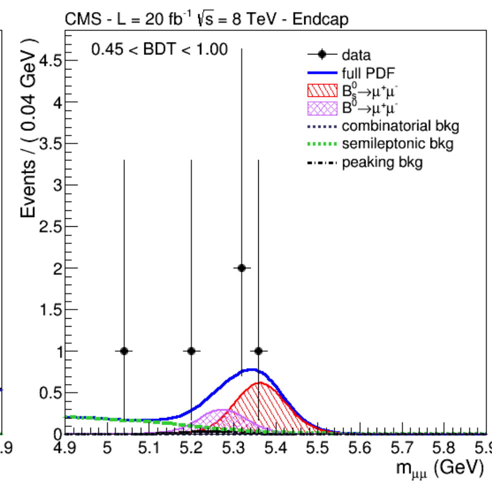
2012 BDT bin 3




2012 BDT bin 4



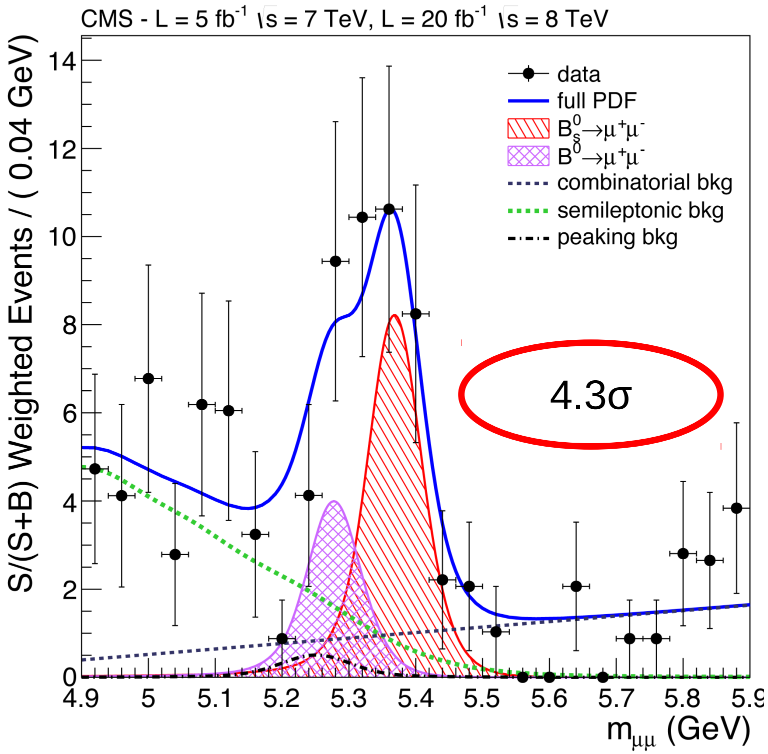



# Bso

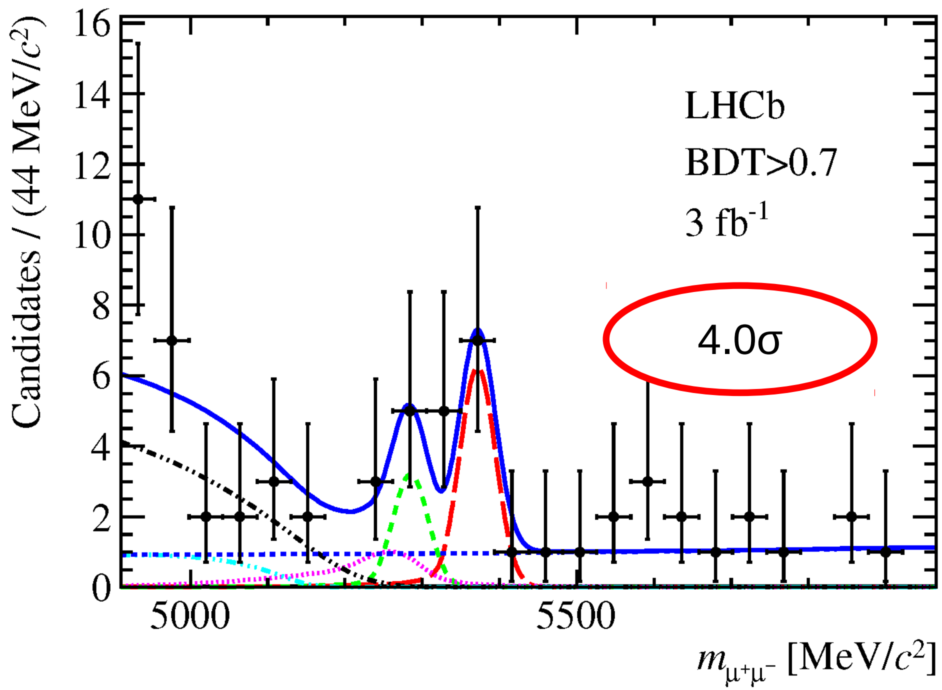
latest results from CMS & LHCb

CMS arXiv:1307.5025

LHCb arXiv:1307.5024

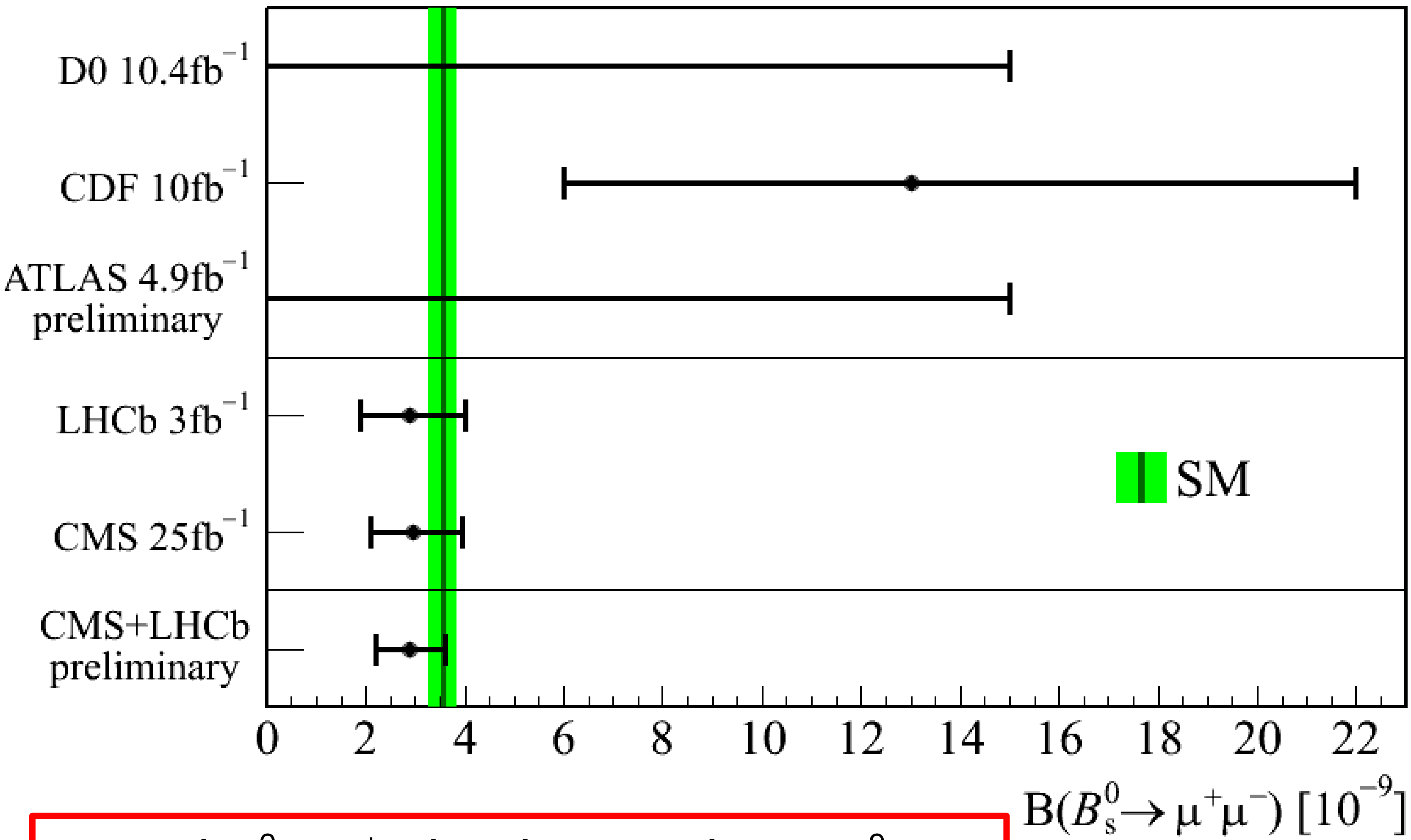



Events weighted by S/(S+B)




Only events with BDT > 0.7

# Results




$$B(B_s^0 \rightarrow \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

# Results


**Popular physics theory running out of hiding places**

By Pallab Ghosh
Science correspondent, BBC News

**Researchers at the Large Hadron Collider have detected one of the rarest particle decays seen in nature.**

The finding deals a significant blow to the theory of physics known as supersymmetry.

Many researchers had hoped the LHC would have confirmed this by now.

Supersymmetry, or Susy, has gained popularity as a way to explain some of the inconsistencies in the traditional theory of subatomic physics known as the Standard Model.

The new observation, reported at the Hadron Collider Physics conference in Kyoto and outlined in an as-yet unpublished paper, is not consistent with many of the most likely models of Susy.

Prof Chris Parkes, who is the spokesperson for the UK participation in the LHCb experiment, told BBC News: "Supersymmetry may not be dead but these latest results have certainly put it into hospital."

Supersymmetry predicts heavy versions of all the particles we know about - "super particles"

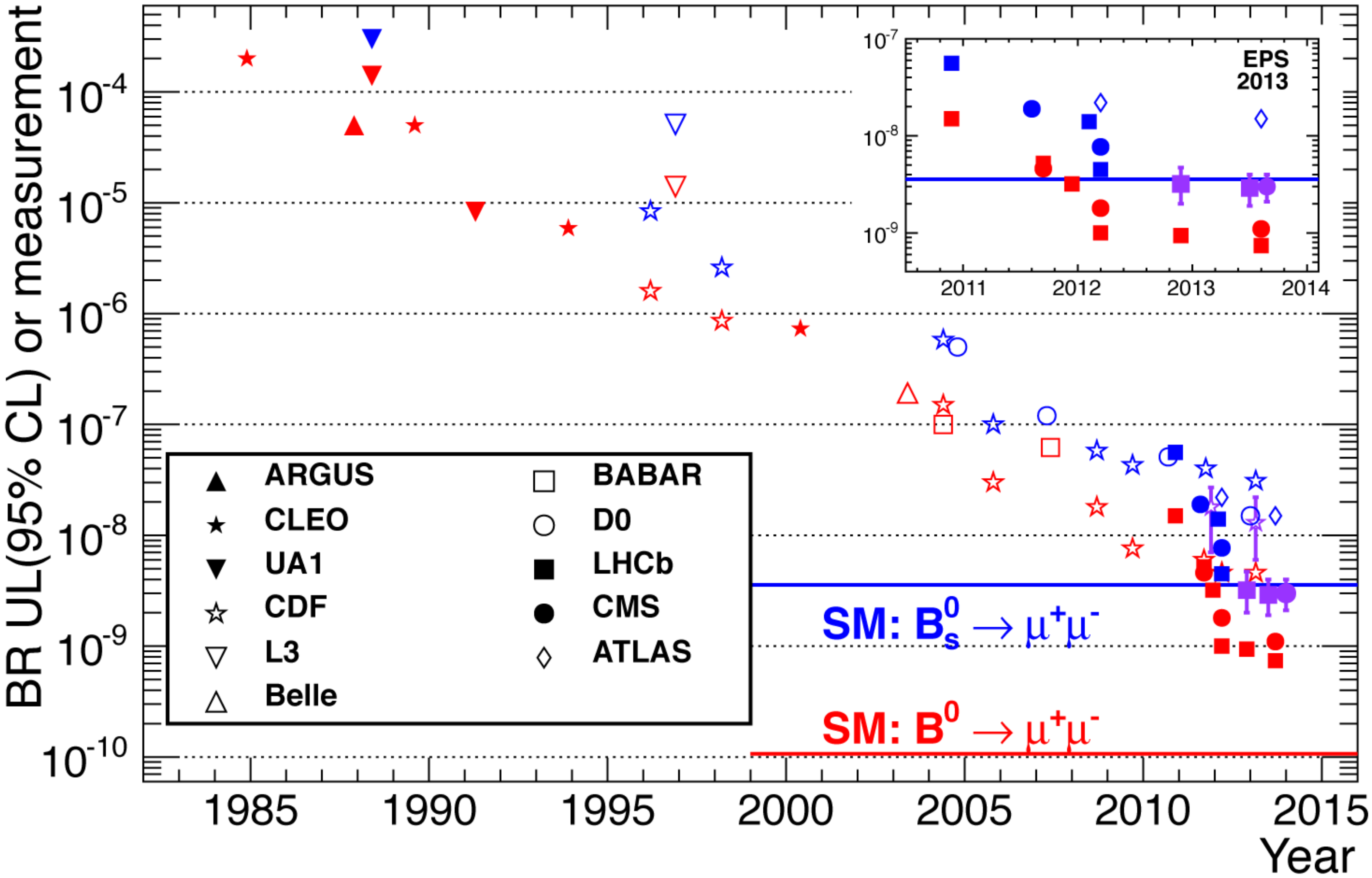
Related Stories

LHC puts supersymmetry in doubt

Higgs results 'get even stronger'

Higgs-like particle 'discovered'

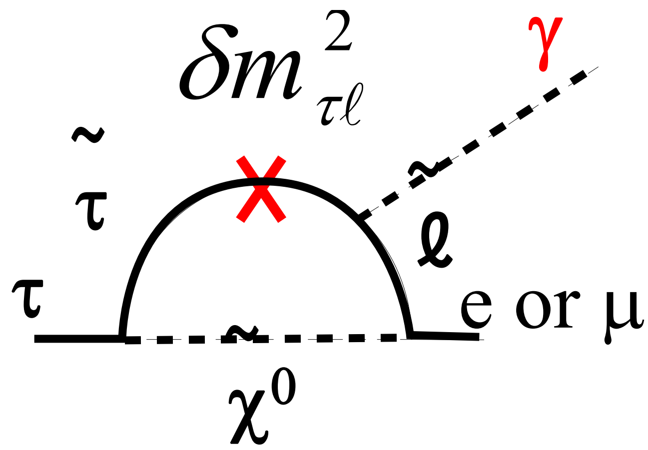
$B(B_s^0$ … $) \times 10^{-9}$

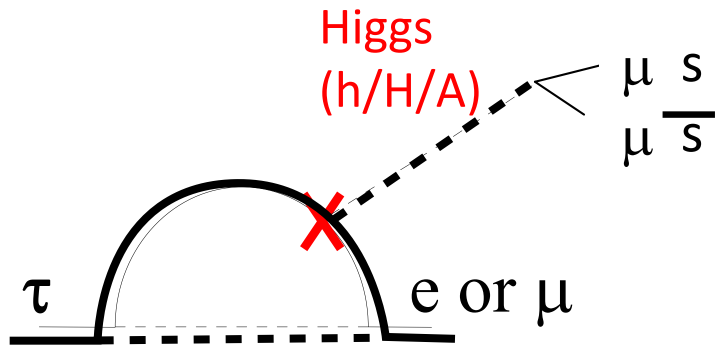

BR UL(95% CL) or measurement
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
1985
1990
1995
2000
2005
2010
2015
Year
ARGUS
CLEO
UA1
CDF
L3
Belle
BABAR
D0
LHCb
CMS
ATLAS
SM: $B_s^0 \to \mu^+\mu^-$
SM: $B^0 \to \mu^+\mu^-$
EPS
2013
2011
2012
2013
2014

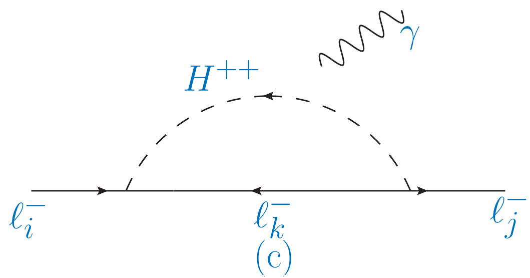
# Lepton Decays

# τ lepton flavour violation

- LFV provides a **theoretically clean** null test of the SM
- τ decays studied at **B-factories.** Dedicated experiments do μ LFV.
  - MEG (μ→eγ) new results 2011.
- NP may induce LFV at one-loop due to
  - slepton mixing,
  - $H^{++}$, e.g. **Babu-Zee** models,
  - Neutral higgs boson.
  - or LNV due to Majorana neutrinos.
- upper limits in SUSY e.g. BR~$10^{-7}$
  - TeV scale sensitivity!



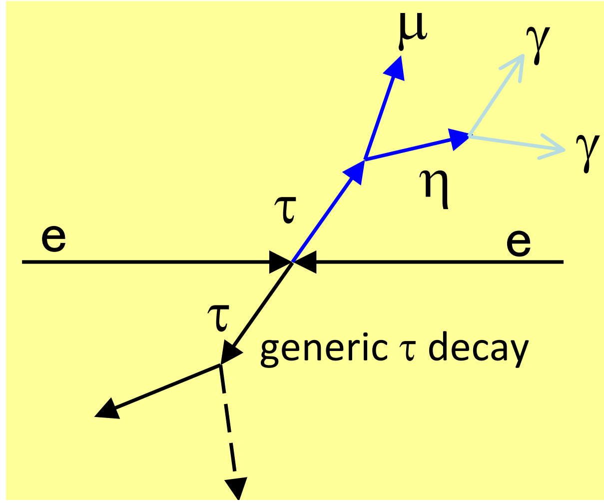



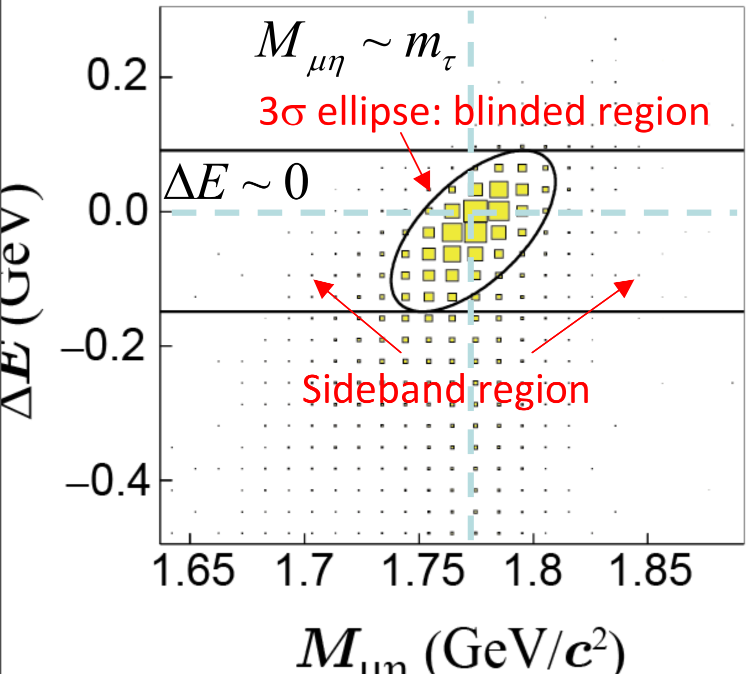
# Experimental technique

$e^+e^- \rightarrow \tau^+\tau^-$

Br~85%

- $\tau^-$ → 1 prong + missing (tag side)
- $\tau^+$ → $\mu+\eta$ (signal side) — Fully reconstructed
  - $\eta$ → $\gamma+\gamma$



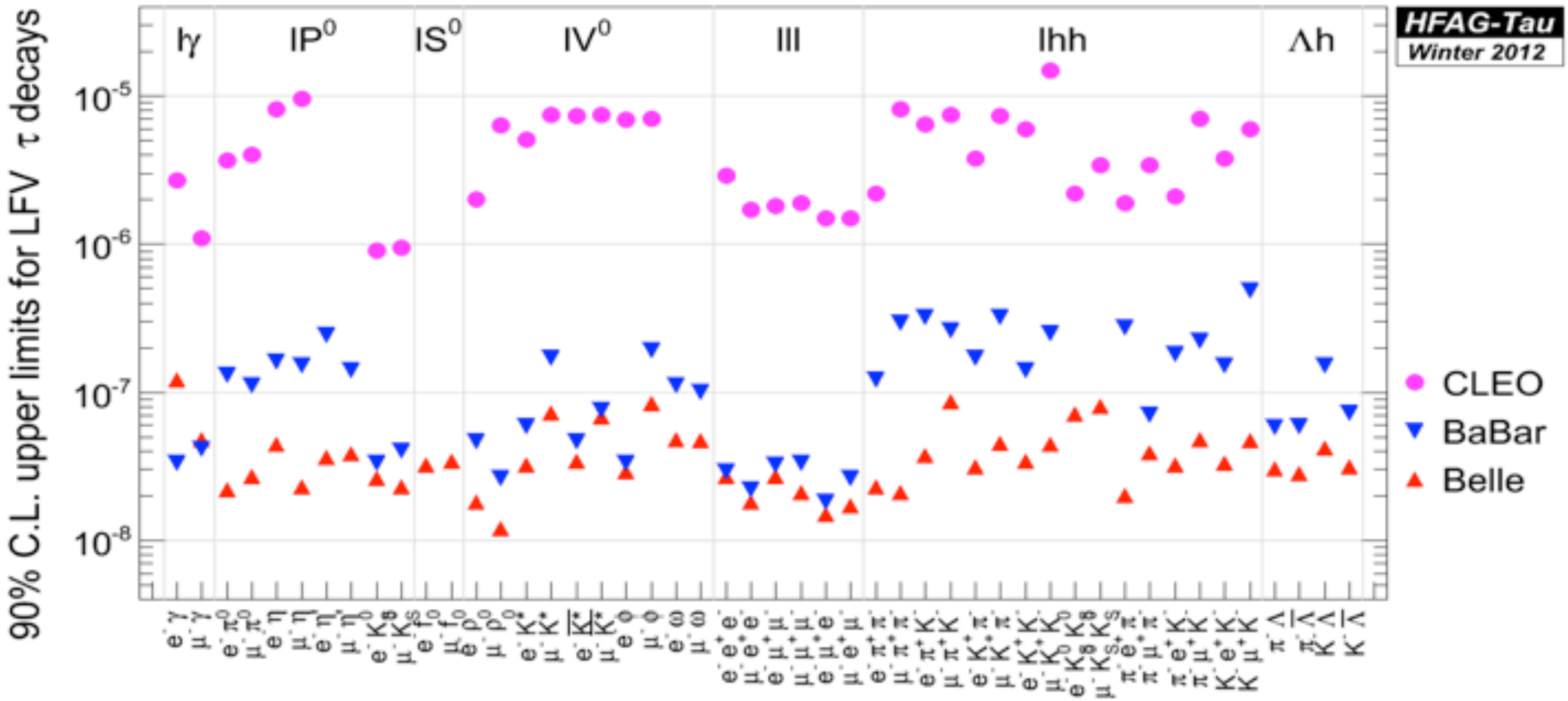

Signal extraction: $M_{\mu\eta}$–$\Delta E$ plane

$$M_{\mu\eta} = \sqrt{(E_{\mu\eta}^2 - p_{\mu\eta}^2)}$$

$$\Delta E = E_{\mu\eta}^{CM} - E_{beam}^{CM}$$

# Upper limits (2011 Summer)

- Almost all LFV modes measured with full B-factory data sets
  - Ratios of LFV decay BFs distinguish between NP models.
  - LHCb and CMS are preparing



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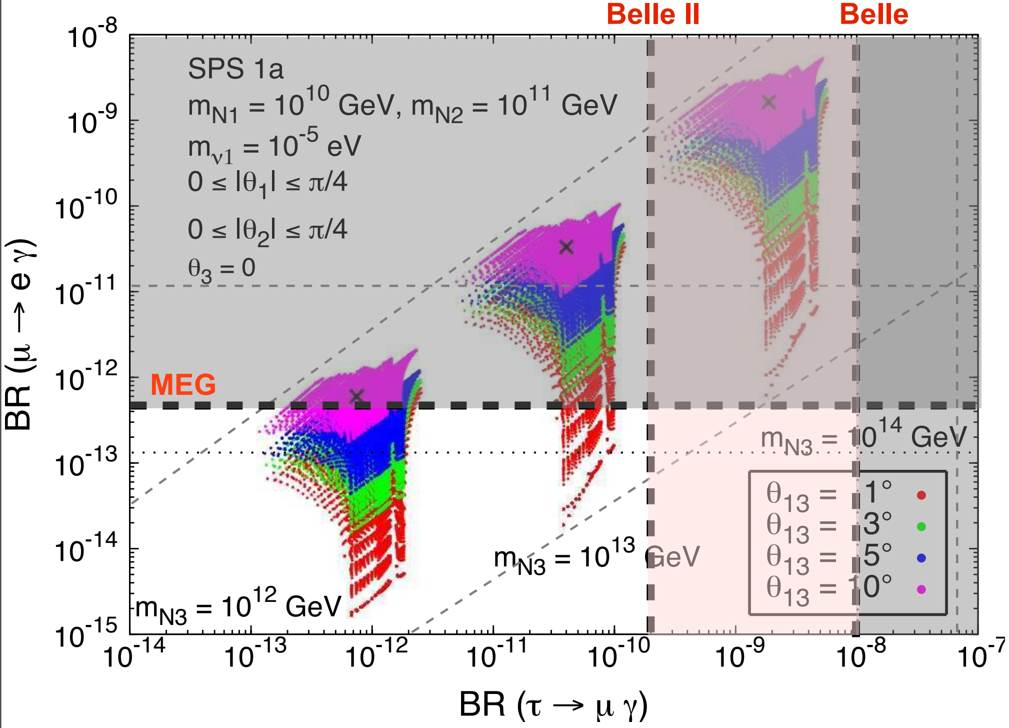
# LFV Impact On Models

## Seesaw

CMSSM model point with 3 massive RH *N* for various $m(N_3)$ and $\theta_{13}$

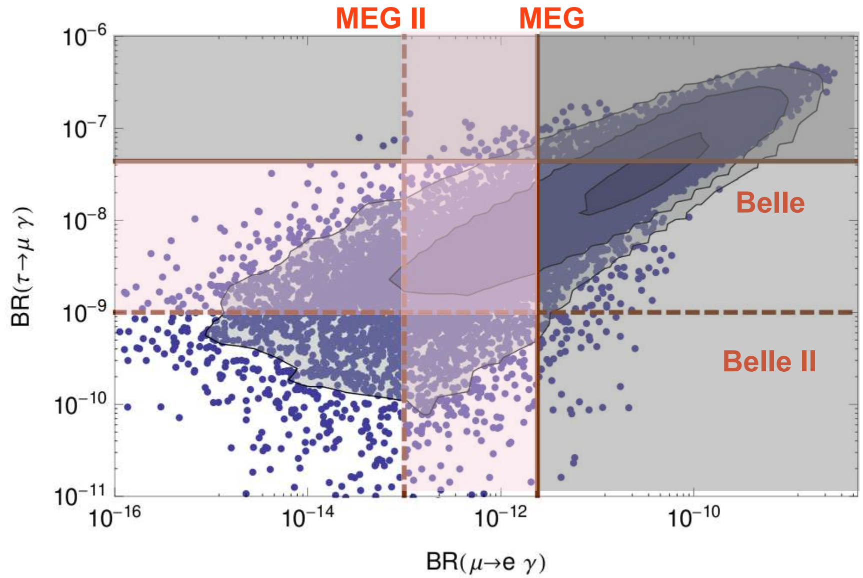



MEG Phys. Rev. Lett. 110, 201801 (2013)

S. Antush et al. JHEP, 11:090 (2006)

## SUSY

TeV scale slepton
ml3 « ml1,2




Eur.Phys.J. C72 (2012) 2126



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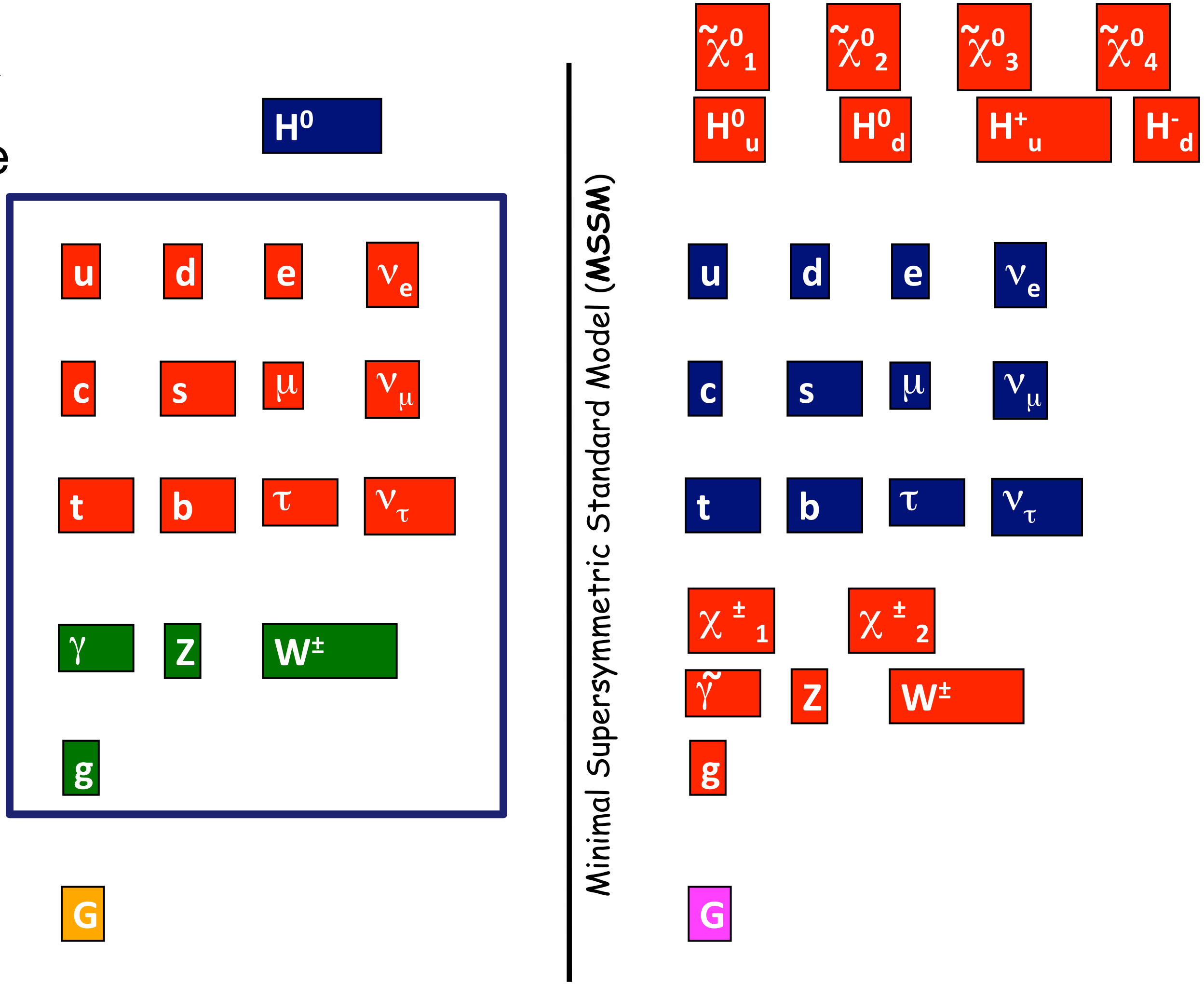
# End of Part 3

# Flavour Beyond the Standard Model

- **Supersymmetry (SUSY)** fundamental continuous symmetry connecting fermions and bosons

In principle expect SUSY partners to have same masses as SM states

- Not observed!
- SUSY must be a broken symmetry at low energy
- Two higgs doublets in SUSY
- **can give rise to large FCNC effects**



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# Flavour Beyond the Standard Model

- **Two Higgs doublet:**
  - **1 doublet = 4 degrees of freedom, 3 massive bosons -> 1 physical Higgs**
  - **2 doublets = 8 degrees of freedom, 3 massive bosons -> 5 physical Higgs**

The Higgs doublets acquire different v.e.v.'s and the mass matrix reads

$$\hat{m}_d^{ij} = \hat{h}_{d,1}^{ij} \mathrm{v}_1 + \hat{h}_{d,2}^{ij} \mathrm{v}_2$$

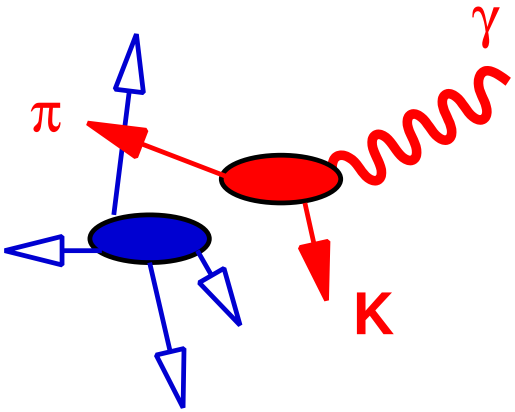
**Key parameter tanβ: ratio of higgs doublet VEVs.**

Diagonalisation of the mass matrix will not give diagonal Yukawa couplings

- **Will induce large, usually unacceptable FCNC in the Higgs sector**
- <u>Solution</u>:
  - One Higgs doublet couples **only to down quarks** and the other couples to **up quarks only**
  - Up and down sectors diagonalised independently, Higgs interactions remain **flavour diagonal at tree level**.

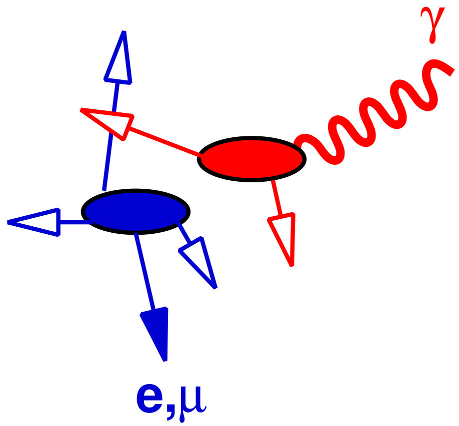
# Experimental techniques

- Sum of exclusive modes 'semi-inclusive'




- Sum of ca. 40 modes
- Full reconstruction of $B$
  - Good background rejection
  - ▷ Photon measured in $B$ restframe (better resolution!)
- Dominant systematics
  - ▷ missing final states

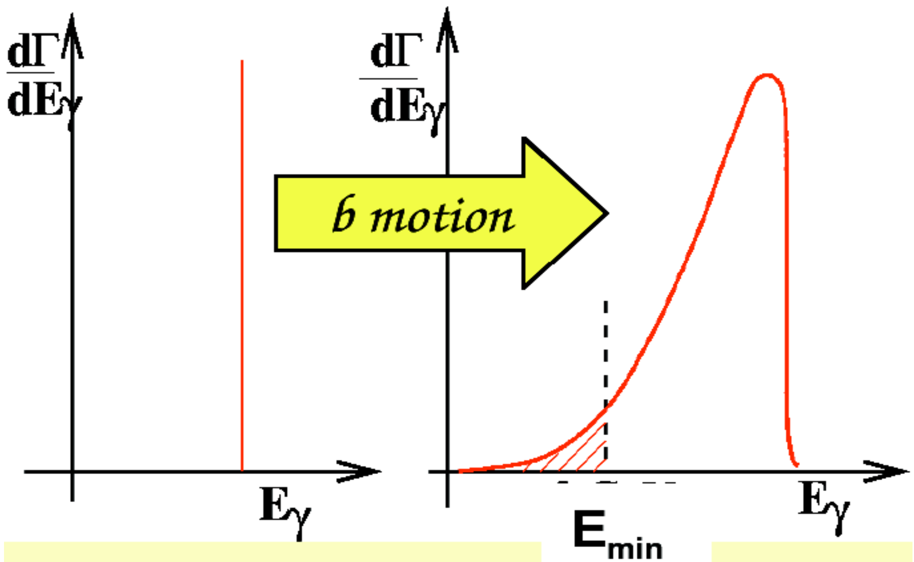
- (fully) inclusive




- High-energy photon
  - ▷ $E_\gamma^* > 1.5$ GeV
- Background reduction
  - ▷ lepton tag
- Dominant systematics
  - ▷ $B$ background subtraction

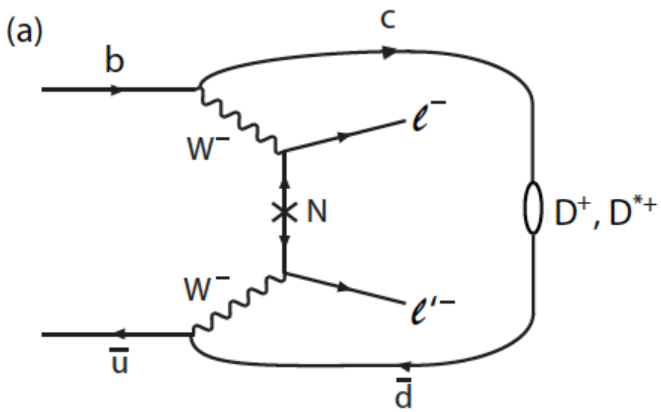
# Decay characteristics

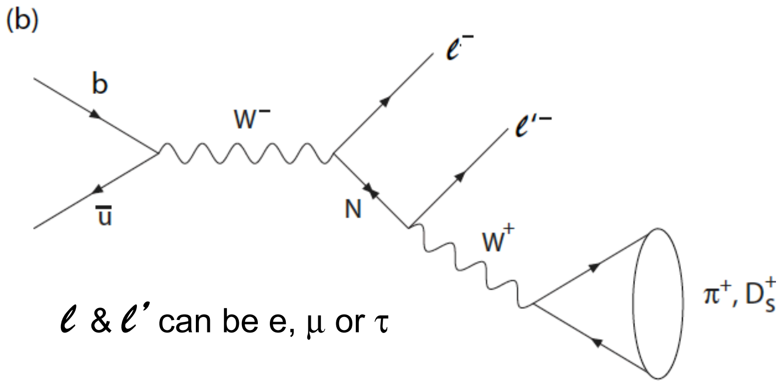
- Rate sensitive to new physics but not shape.
- At parton level, photon is monochromatic with E~$m_b$/2
  - Smeared by motion of b-quark inside the B-meson, and gluon emission
  - Complicated theoretical error on the prediction of the shape,
    - =>As much of the low energy tail must be measured to reduce this error.



# Majorana Neutrinos in B decays: m=0.2 - 5 GeV

- Same sign dilepton signature.
  - If they are **Majorana** and couple to ordinary neutrinos
  - Best limits are on μ modes




$\ell$ & $\ell'$ can be e, μ or τ