Triviality and Vacuum Instability

[Repetition]

Renormalization Group Equation (RGE):

for the self coupling λ …

$$\frac{d\,\lambda}{d\,\log Q^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda y_t^2 - 3y_t^4 - \frac{3}{2}\lambda\left(3g_2^2 + g_1^2\right) + \frac{3}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

Bounds at large and small λ:

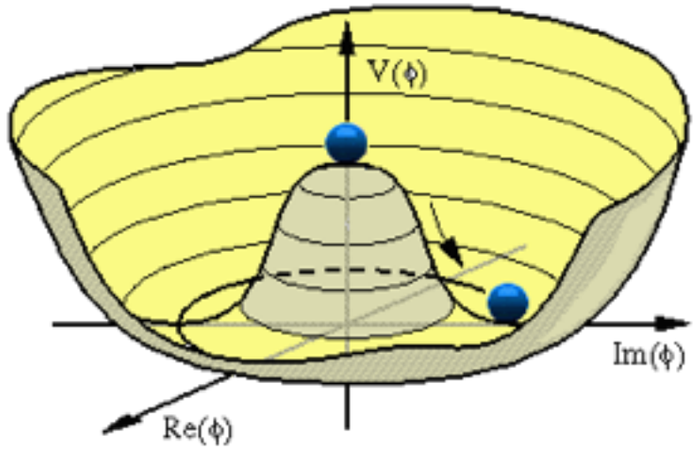
large λ: [λ ≫ y_t,g_i]

$$\lambda(Q^2) = \left[-\frac{3}{4\pi^2}\log\frac{Q^2}{v^2} + \frac{1}{\lambda_0}\right]^{-1} = \lambda_0\left[1 - \frac{3}{4\pi^2}\lambda_0\log\frac{Q^2}{v^2}\right]^{-1}$$

small λ: [λ ≪ y_t,g_i]

$$\lambda(Q^2) \sim \quad \lambda_0 \quad + \frac{1}{16\pi^2}\underbrace{\left[-\frac{12m_t^4}{v^4} + \frac{3}{16}\left(2g_2^4 + \left(g_2^2 + g_1^2\right)^2\right)\right]}_{\text{negative!}}\log\frac{Q^2}{v^2}$$

Triviality and Vacuum Instability



Higgs Potential:

$$V(\phi) = -\mu\phi^2 + \lambda\phi^4$$

Norm.

$\lambda(q)$

Higgs self coupling

depends on M_H

From RGE and $M_H \propto \lambda(v^2)$

[Running self coupling]

M_H

with $M_H \propto \lambda(v^2)\cdot v^2$

[v: vacuum expectation value]

Upper bound: $q_\infty < \Lambda$

[Triviality, Landau Pole]

Lower bound: $q_0 < \Lambda$

[Vacuum Instability]

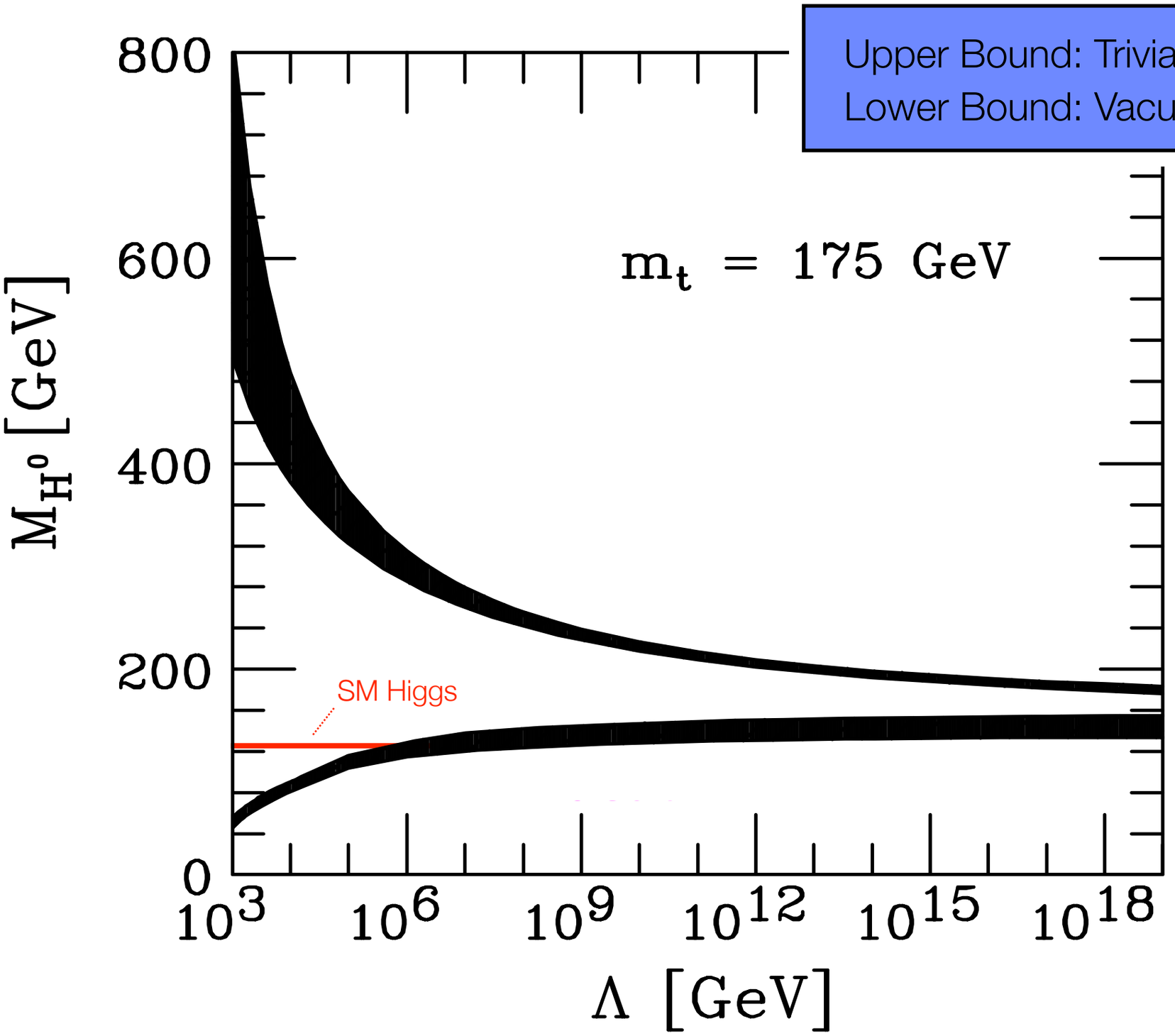
q_∞, q_0 } Must be larger than scale Λ at which SM breaks down

q

scale

Triviality and Vacuum Instability

[Repetition]

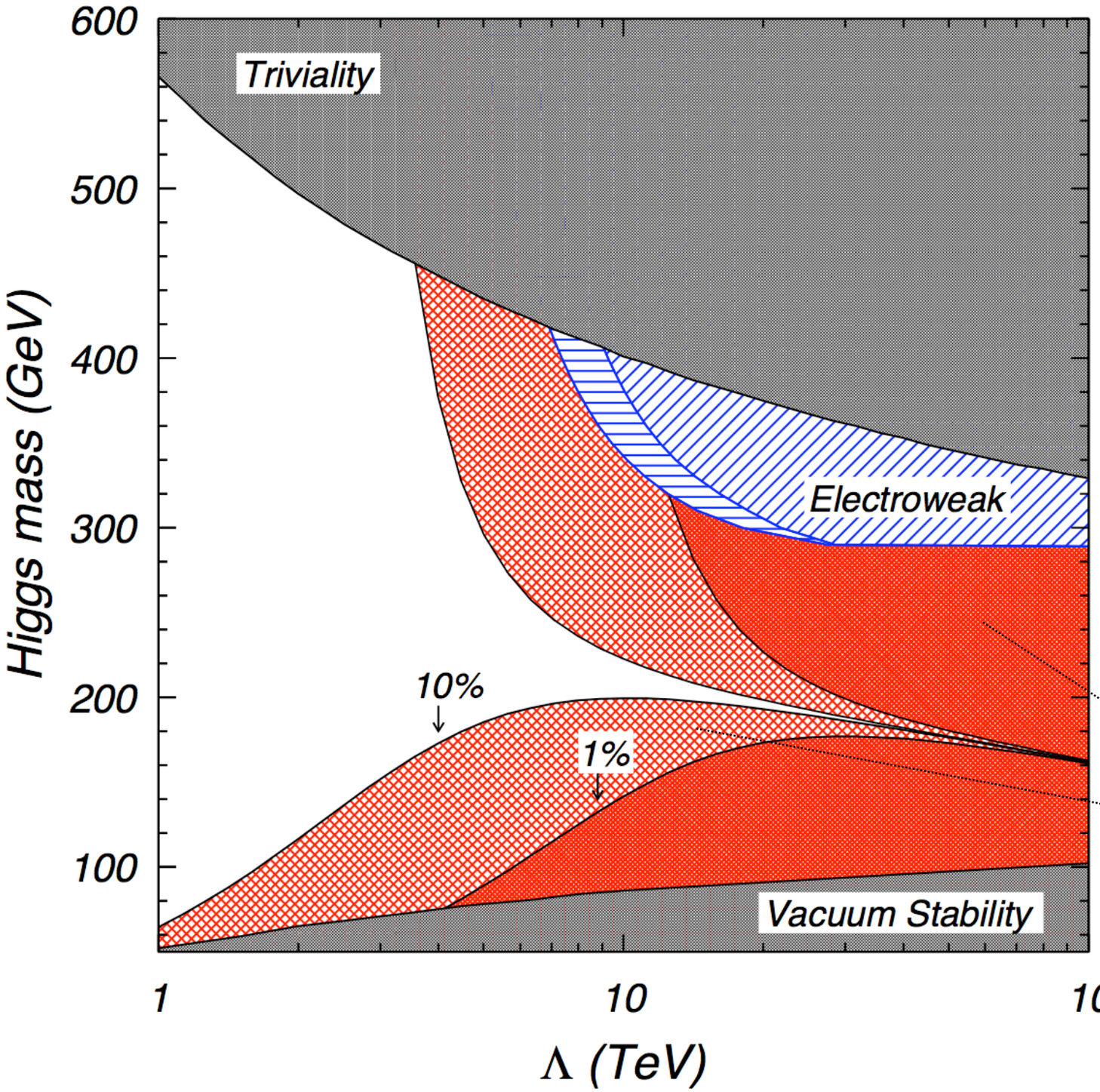


Upper Bound: Triviality
Lower Bound: Vacuum stability

Scale Λ:

energy scale at which physics beyond the SM sets in

Consequences of a Light Higgs



Constraints
even harder when
considering fine-tuning

New physics at
a few TeV?

Excluded to
avoid fine-tuning

What Theorists Think About ...

[Repetition]

There exists a large number of models which predict new physics at the TeV scale accessible @ LHC ...

- Grand Unified Theories (SU(5), O(10), E6, …)
  embed SM gauge group in larger symmetry
- Supersymmetry (SUSY - around since a long time)
- Extended Higgs sector
  e.g. in SUSY models
- Leptoquarks
- New heavy gauge bosons
- Technicolour
- Compositeness
- Extra dimensions

Any of this is what
the LHC still hopes for ...

... in addition to the Higgs

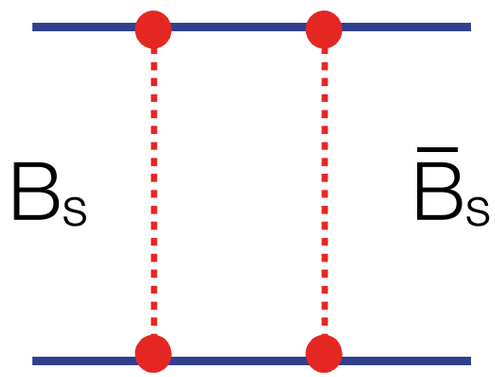
Indirect Higgs Searches

Probing New Physics with B Mesons

courtesy U.Uwer

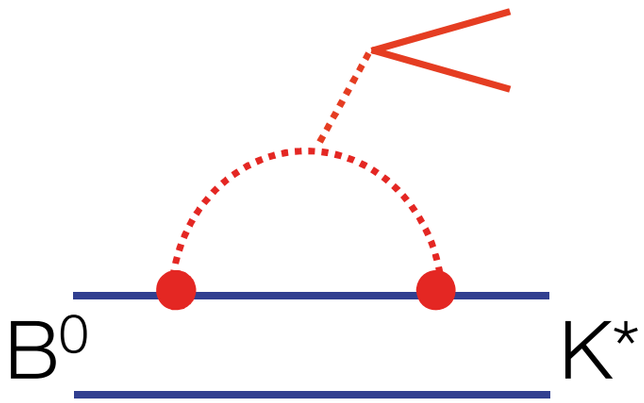
LHCb Key Measurements

B_s mixing phase Φ_s



$A_{CP}(B_s \to J/\psi\, \Phi)$

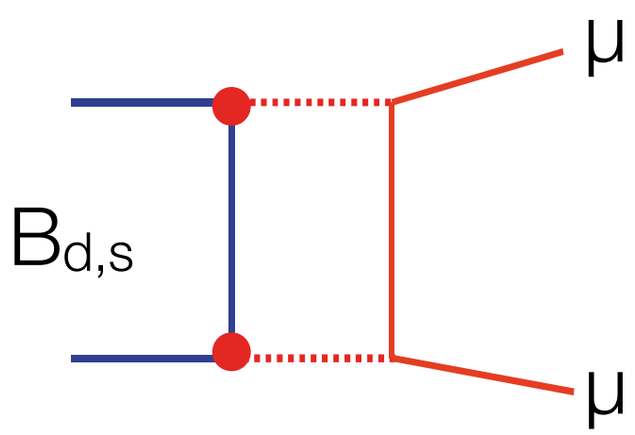
b ➛ sγ Penguins



$B_d \to K^*\mu\mu$

$B_d \to K^*\gamma$

Rare Decays



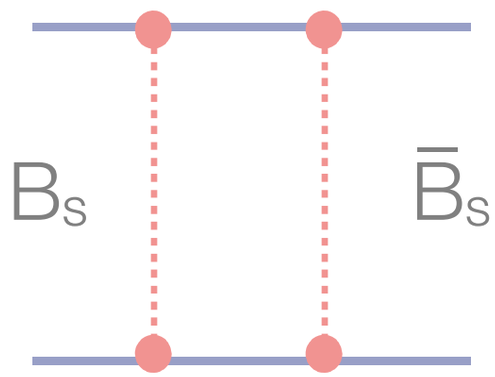
$B_{d,s} \to \mu\mu$

Also:
Measurement of the CKM angle γ in tree level decays

courtesy U.Uwer

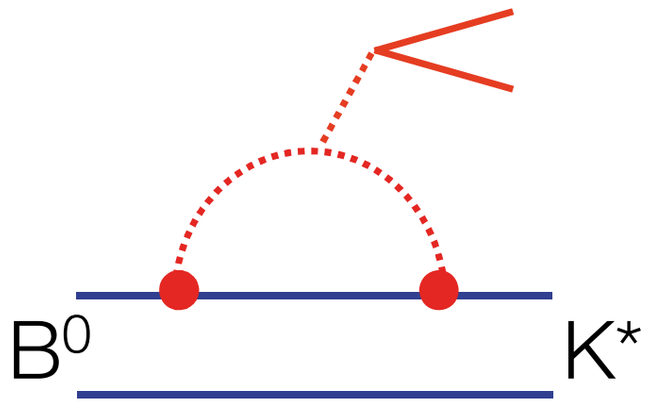
LHCb Key Measurements

B_s mixing phase Φ



$A_{CP}(B$

b ➛ sγ Penguins



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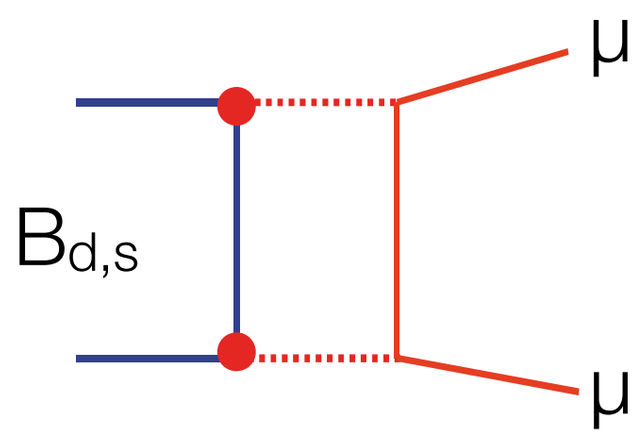
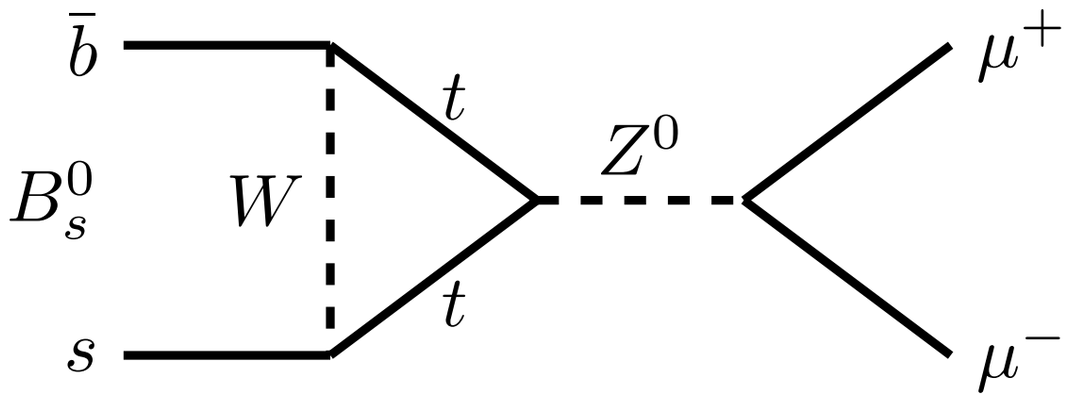
Rare Decays



$B_{d,s} \to \mu\mu$

Also:
Measurement of the CKM angle γ in tree level decays

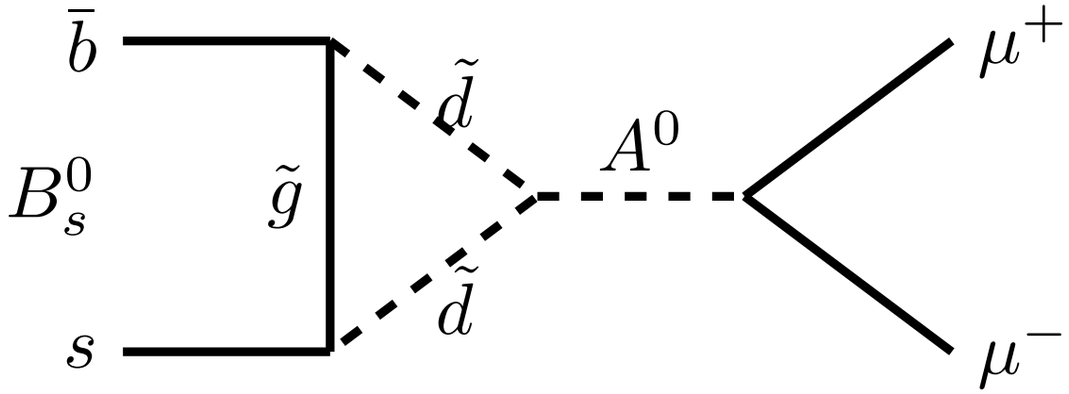
Rare Decays – e.g. $B_s \rightarrow \mu\mu$



SM

Loop and helicity suppressed

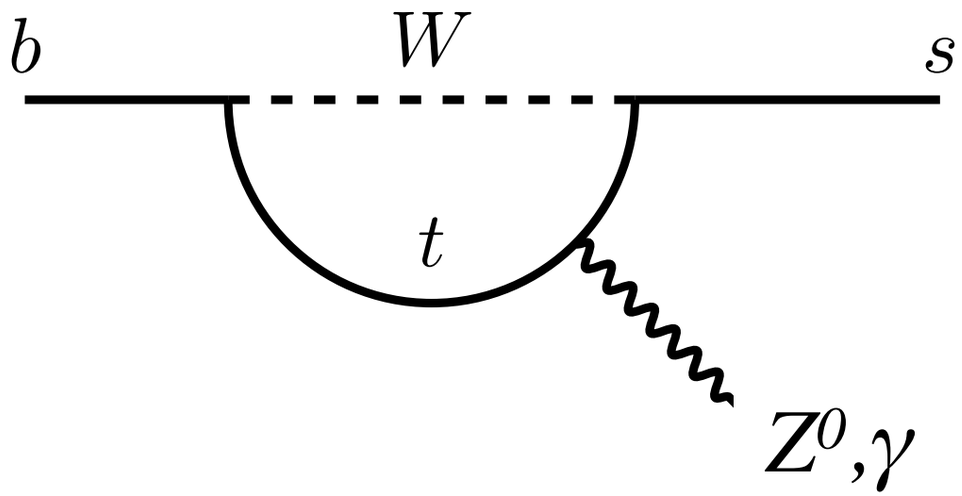
[BR ≈ 3×10^{-9}]



NP

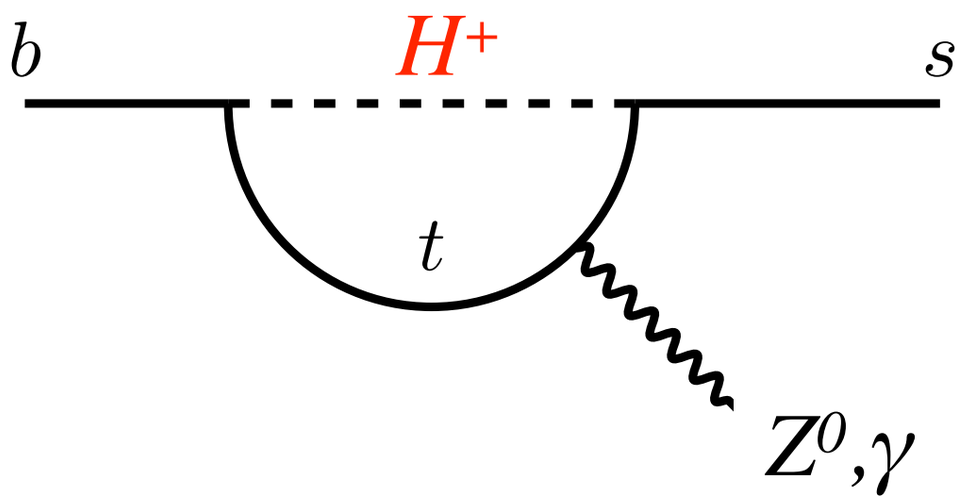
Extended Higgs Sector
MSSM, 2HDM

b ➛ sγ Penguins



SM

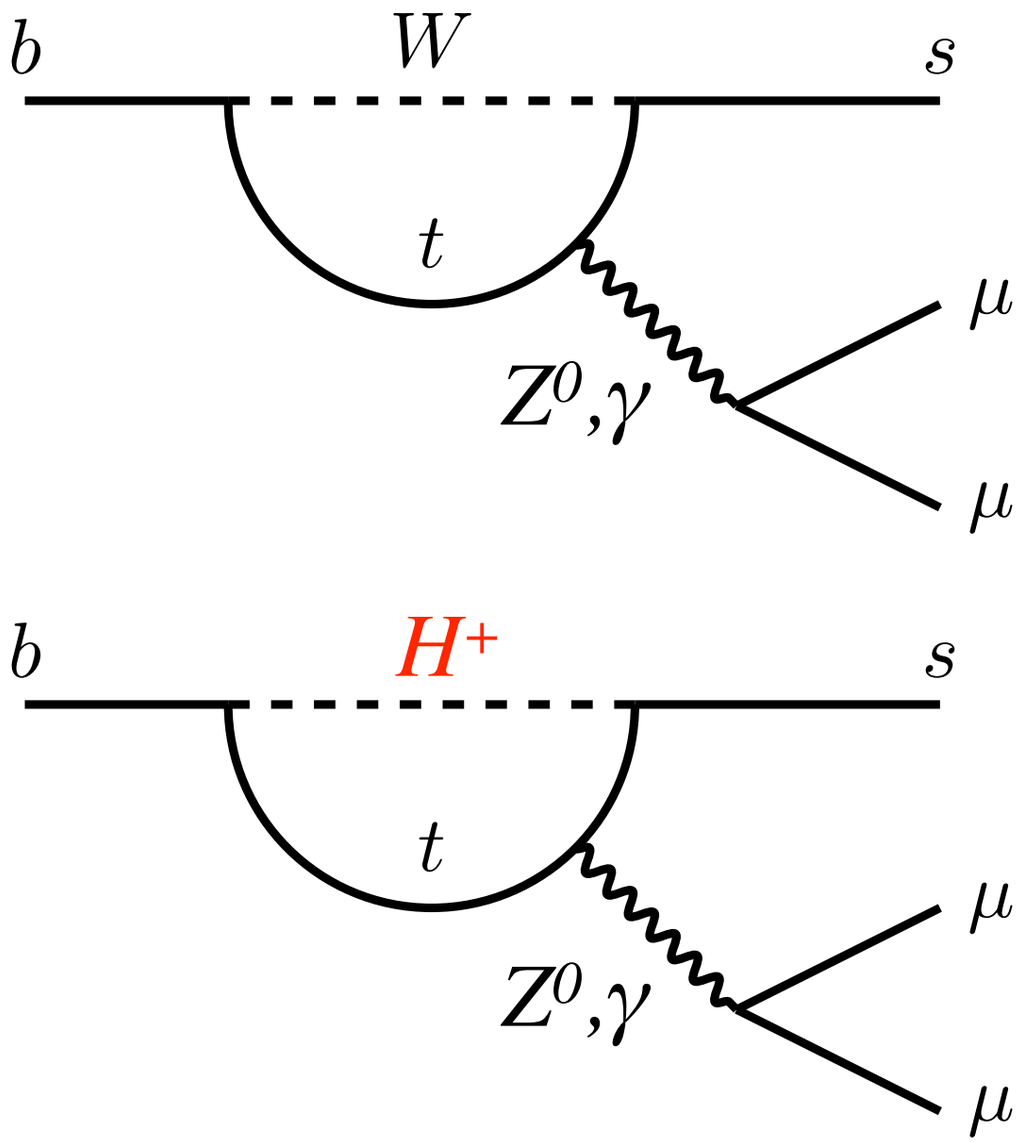
Flavor Changing NC
Loop suppressed



NP

Extended Higgs Sector
MSSM, 2HDM

b ➛ sγ Penguins



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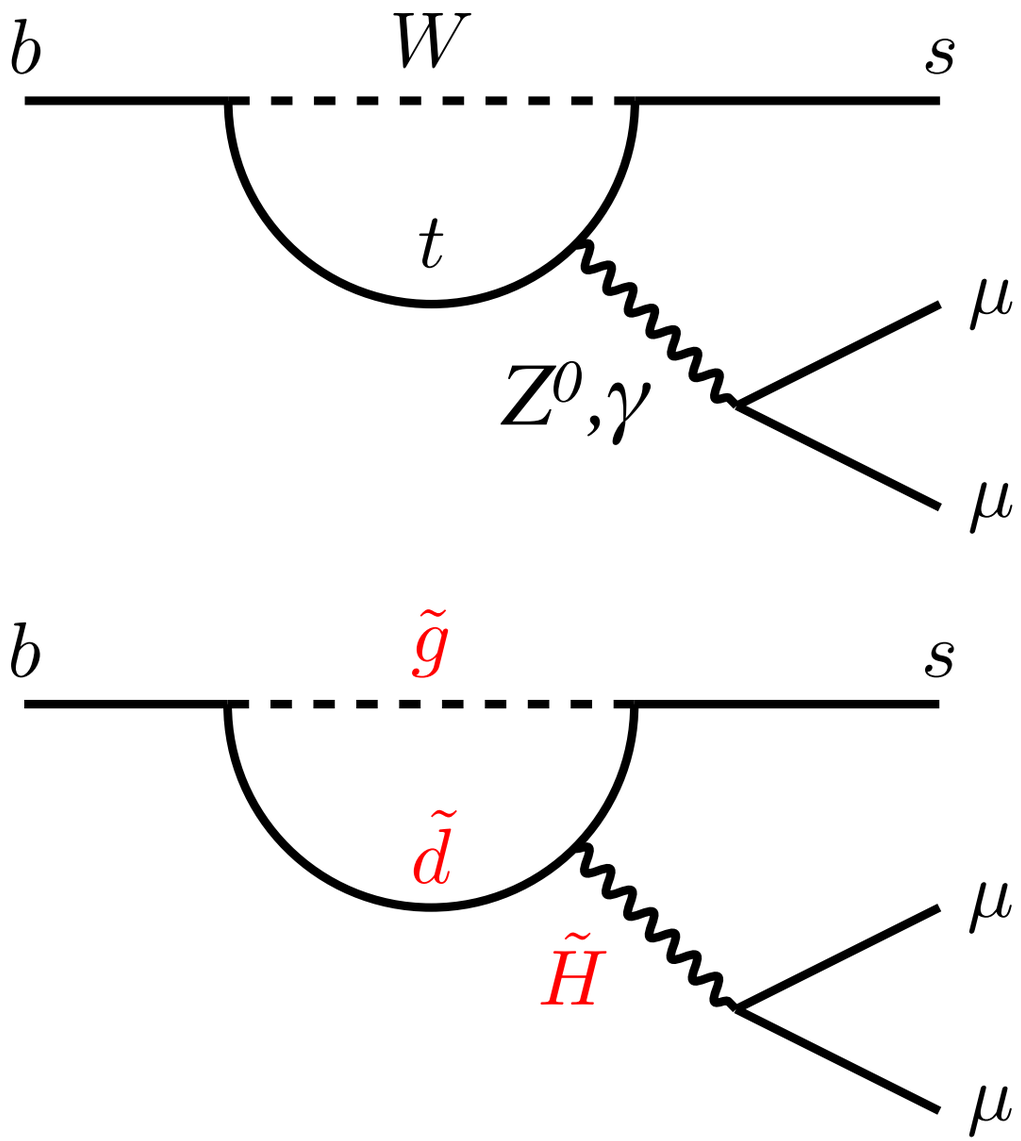
NP

Extended Higgs Sector
MSSM, 2HDM

b ➛ sγ Penguins



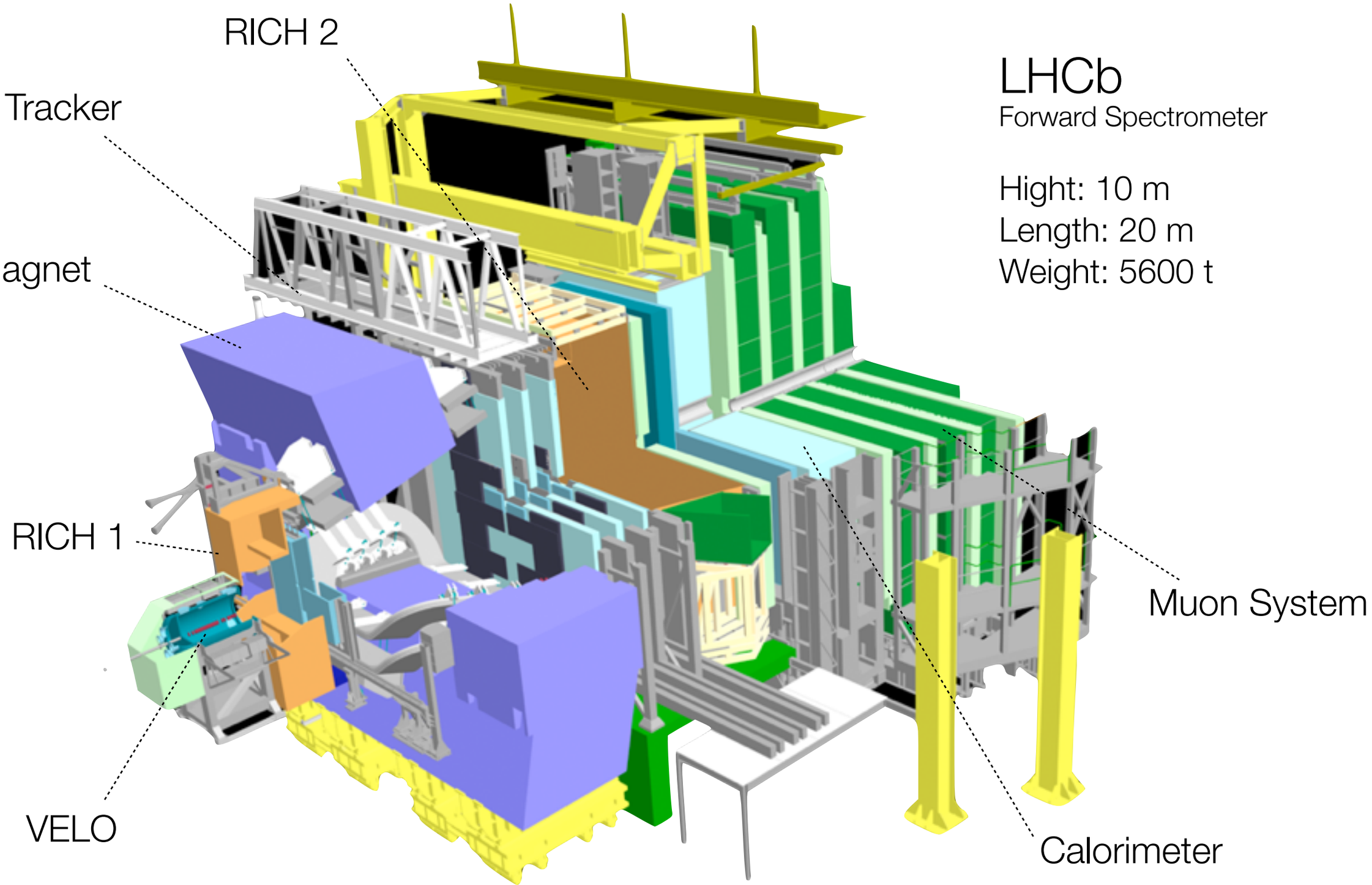
SM

Flavor Changing NC
Loop suppressed

NP

Extended Higgs Sector
MSSM, 2HDM

LHCb Detector



LHCb

Forward Spectrometer

Hight: 10 m
Length: 20 m
Weight: 5600 t

LHCb Parameters ...

pp collisions at $\sqrt{s}$ = 7, 10, 14 TeV

σ_{inel} ~ 100 mb

$\sigma_{b\bar{b}}$ ~ 500 μb [~ 250 μb @ 7 TeV]

Forward production of bb ...

$B^{\pm}$, B^0, B_s, B_c, Λ_b, ...

$\mathcal{L}$ ~ 2×10^{32} cm^{-2} s^{-1}

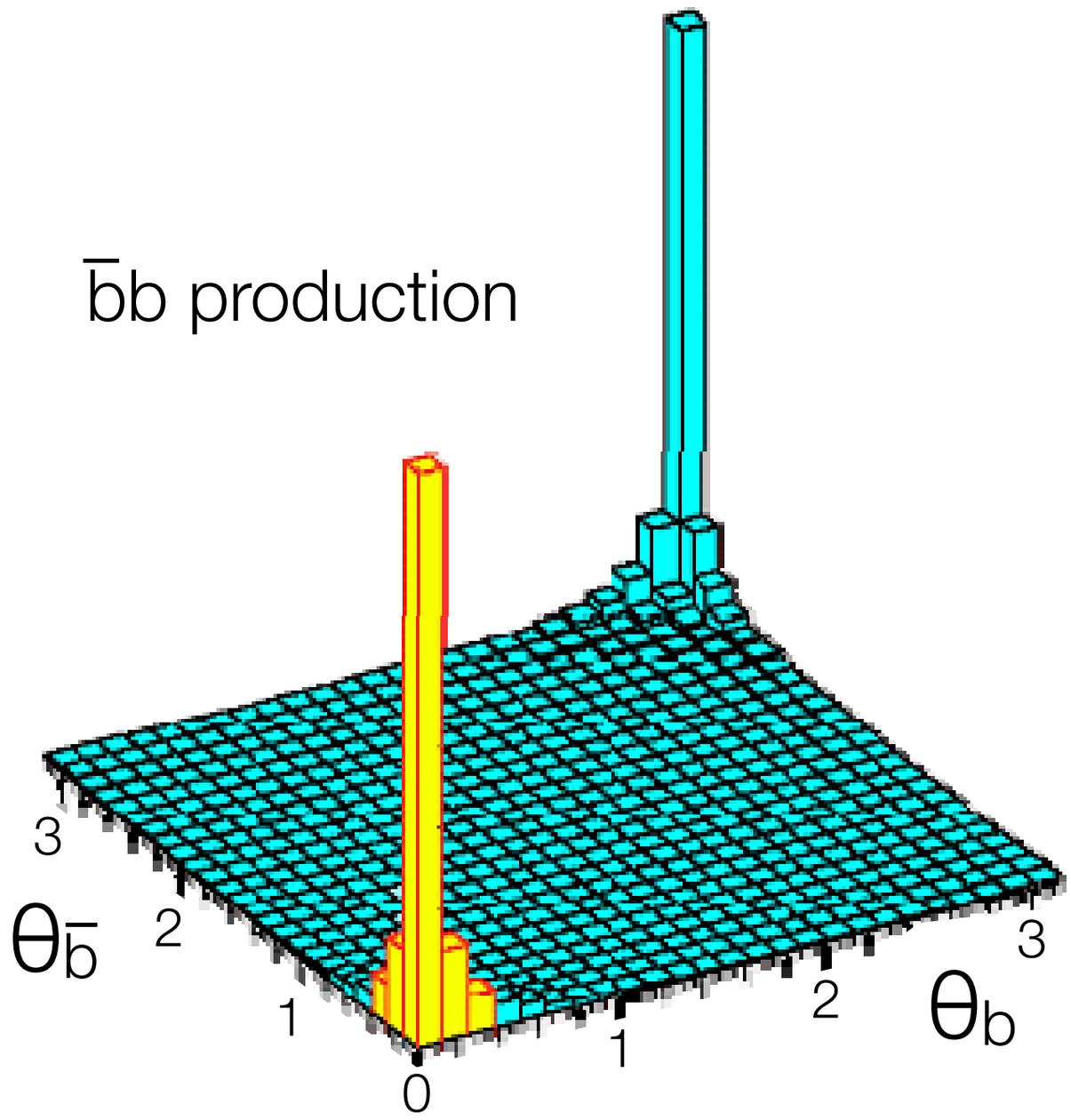
50 kHz bb events in LHCb

ca. 10^{12} bb events/year (2 fb^{-1})

0.7 interactions/bunch crossing

[ATLAS: 5 – 25]

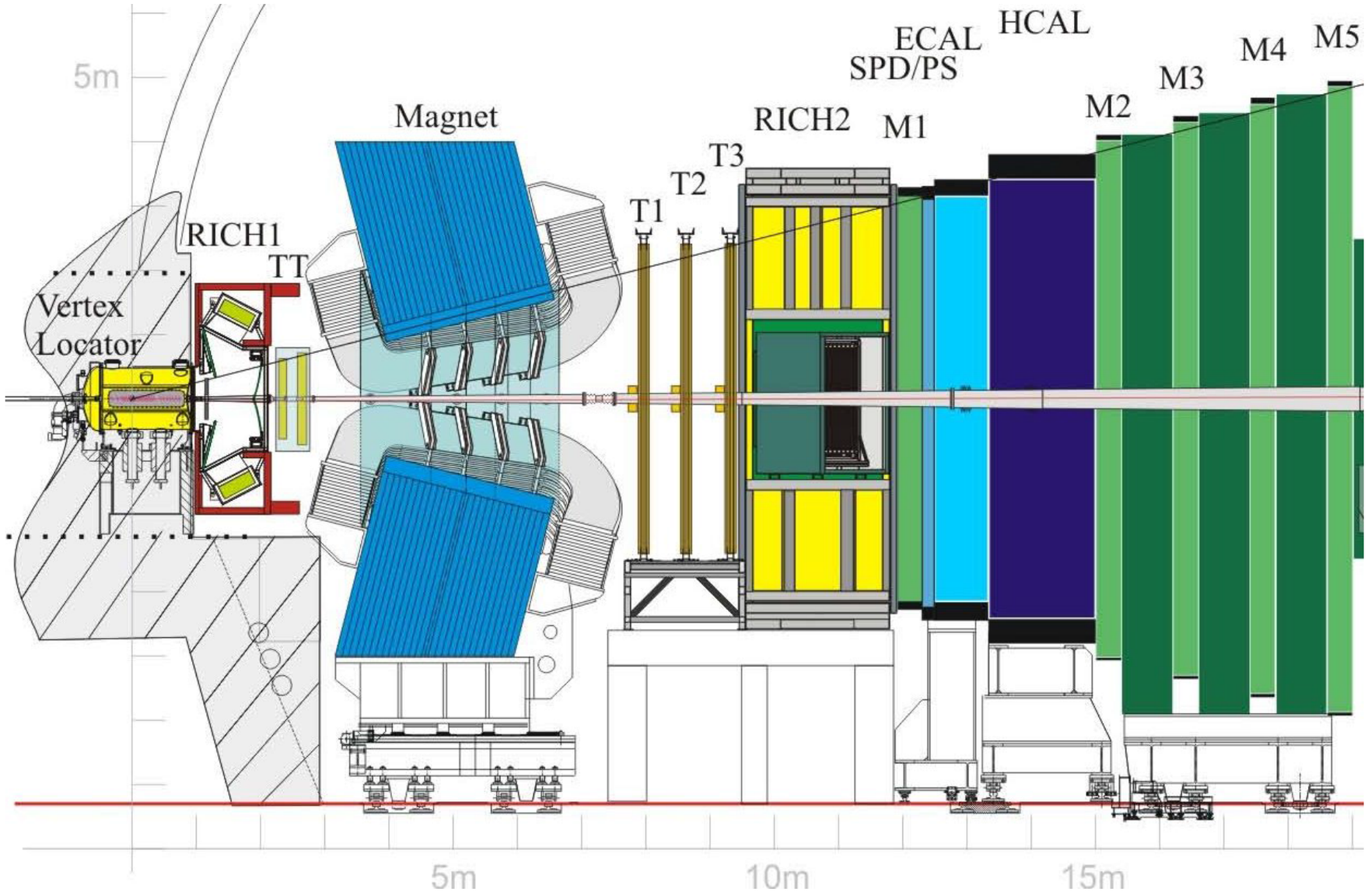
Charged particle multiplicity
ca. 30/unit of rapidity.



LHCb Detector

Forward spectrometer …

Emphasis on tracking & particle identification …

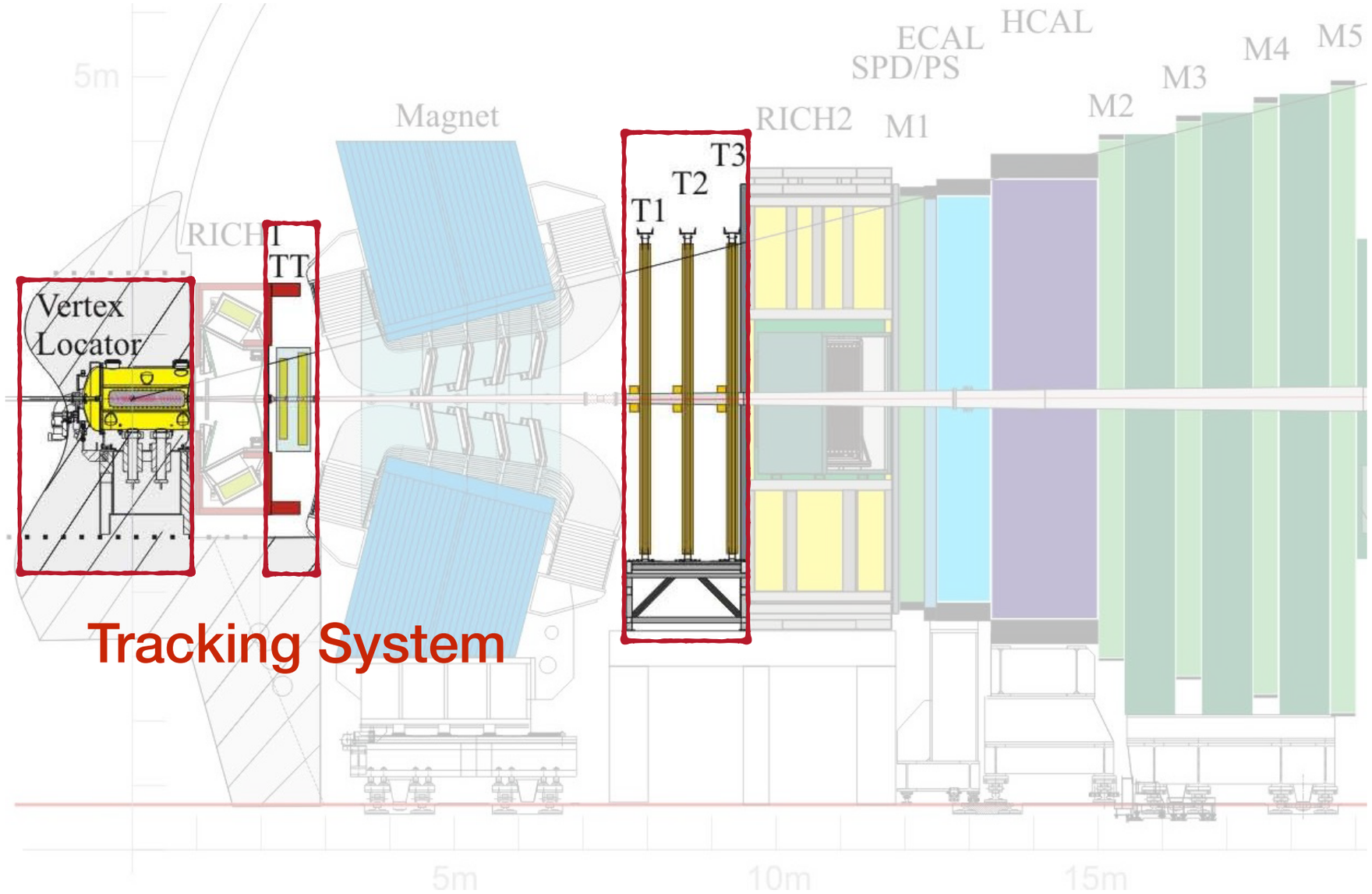


LHCb – Vertexing and Tracking

Vertex detector 8mm from beam ➛ excellent IP resolution: 20μm

Long lever arm, excellent momentum resolution δp/p ~ 0.4 - 0.6 %

Mass resolution for two body B-decays ~ 25 MeV

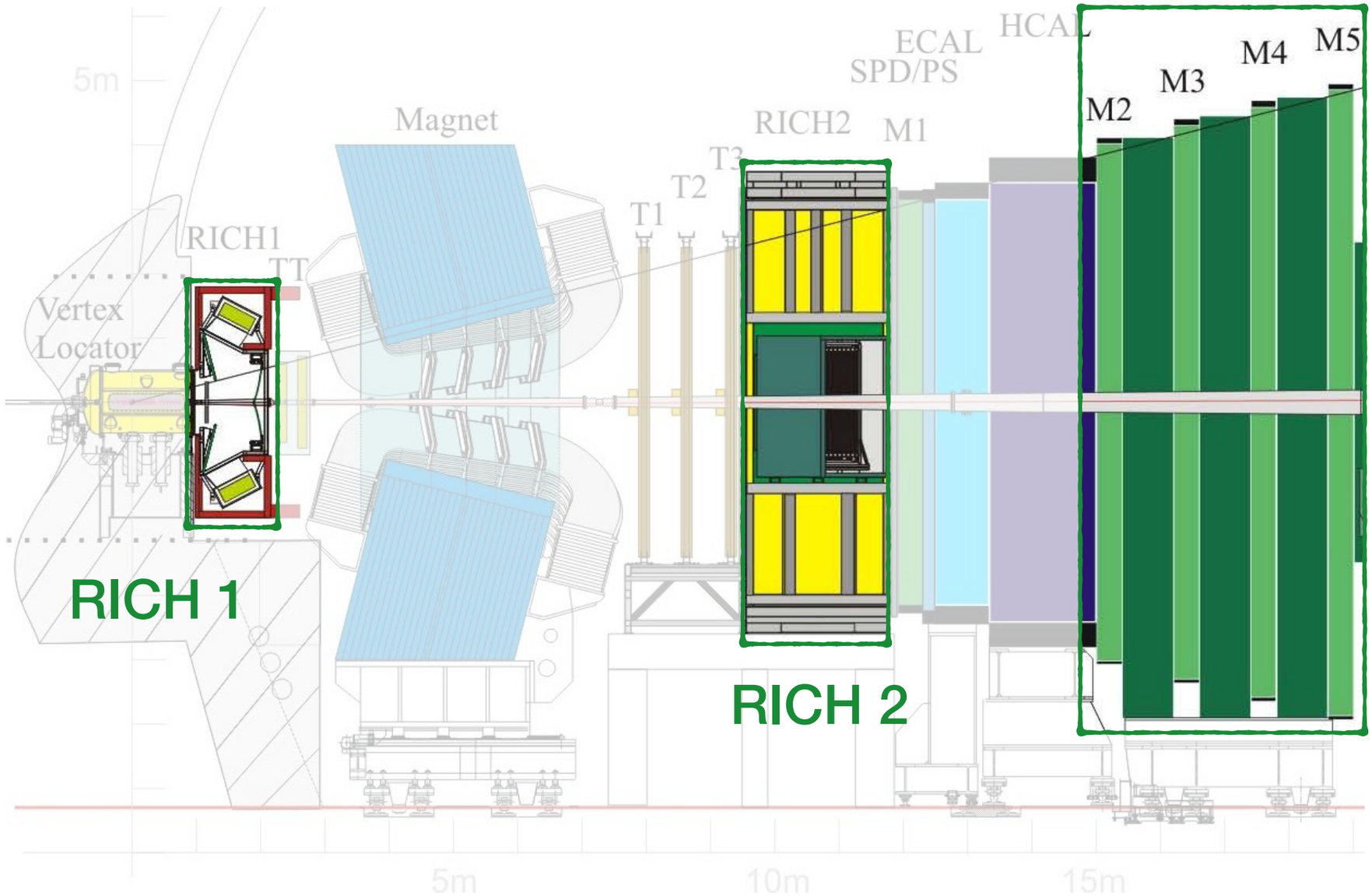


LHCb – Particle Identification & Trigger

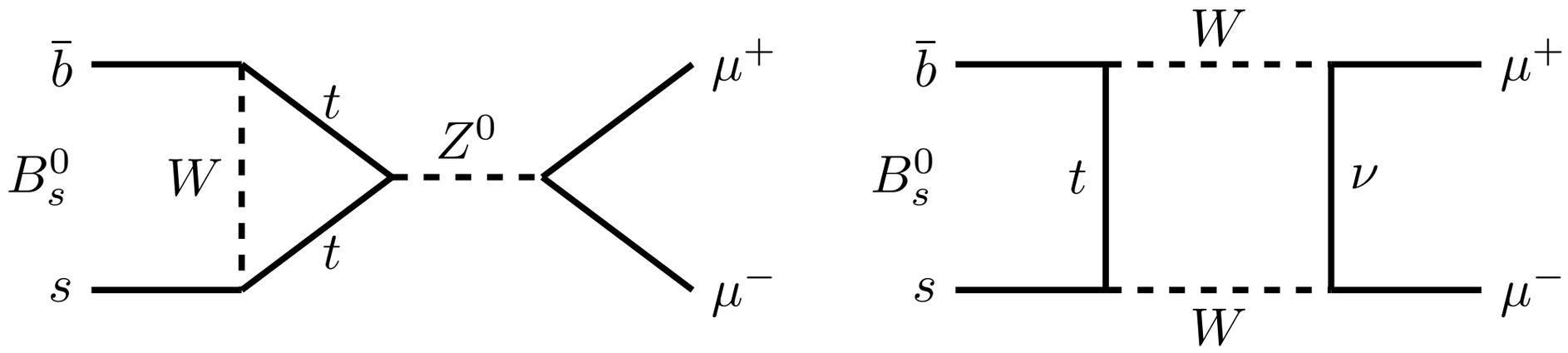
Muon identification: $\varepsilon_{\mu\to\mu} \sim 97\%$ $\varepsilon_{\pi\to\mu} \sim 1 - 3\%$

Muon trigger efficiency: $\varepsilon_{Trig} \sim 70 - 90\%$

Good Kπ-separation via RICH: $\varepsilon_{K\to K} \sim 95\%$ $\varepsilon_{\pi\to K} \sim 5\%$



$B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ [SM]



Purely leptonic final state; theoretically and experimentally clean …

[SM: $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ loop (GIM) and helicity suppressed …]

SM prediction (B^0 suppressed by $|V_{td}/V_{ts}|^2$):

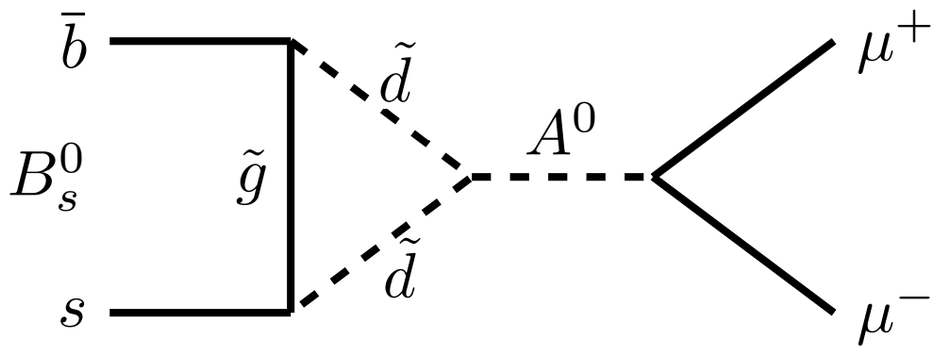
$$B(B_s^0 \to \mu^+\mu^-)_{SM} = (3.35 \pm 0.28) \cdot 10^{-9}$$
$$B(B^0 \to \mu^+\mu^-)_{SM} = (1.07 \pm 0.10) \cdot 10^{-10}$$

[Eur. Phys. J. C72 (2012) 2172]
[arXiv:1207.1158]

Sizable life time difference $\Delta\Gamma_s$, correction for time integrated measurement: $B(B_s^0 \to \mu^+\mu^-)^{\Delta\Gamma}_{SM} = (3.56 \pm 0.30) \cdot 10^{-9}$

[arXiv:1207.1158]

$B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ [BSM]



NP

Extended Higgs Sector
MSSM, 2HDM

Purely leptonic final state; theoretically and experimentally clean …

[SM: $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ loop (GIM) and helicity suppressed …]

Beyond the SM:

Interesting models with extended Higgs sector: MSSM, 2HDM …

MSSM: $B(B_s^0 \to \mu^+\mu^-)_{SM} \propto \tan^6\beta/m_A^4$

[→ constrains the remaining MSSM parameter space …]

Signal and Background Classification

Selection:

Two well identified muons …
Good common vertex …
well separated from any pp primary vertices …

Signal and background classification:

Multivariate classifier: BDT …

Trained on MC samples
[Signal, bb ➛ μμX background …]

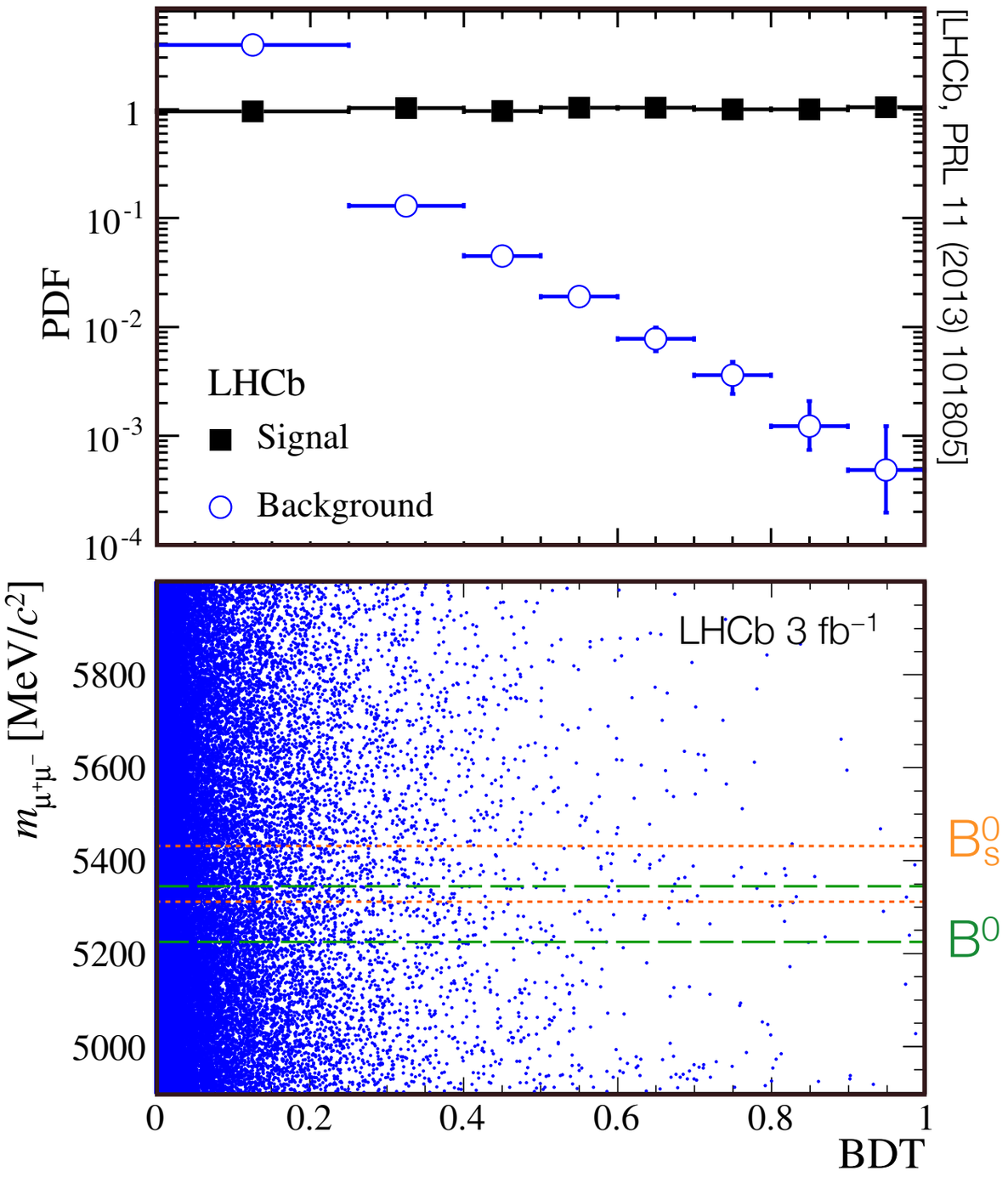
Calibrated using data
[B^0 ➛ hh, di-muon mass sidebands …]

Invariant μμ mass …

Signal described by Crystal Ball function …
Peak values and resolution from B^0 ➛ hh …

$\sigma(B_s^0) = 23.2 \pm 0.4$ MeV
$\sigma(B^0) = 22.8 \pm 0.4$ MeV

Resolution consistent with estimate from
power law interpolation of di-muon resonances J/ψ, Υ, …

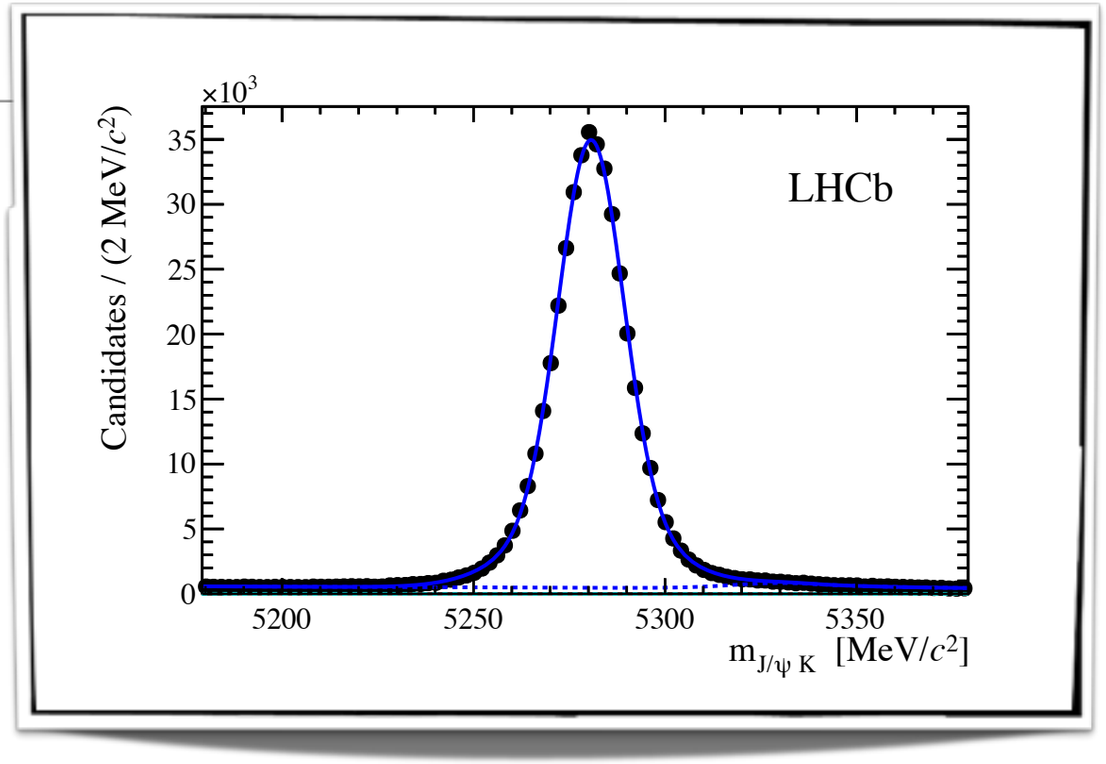


Normalization Procedure

$$\mathcal{B} = \frac{N(B^0 \to \mu\mu)}{N(B^0)}$$

$$= \frac{N^{\rm obs}(B^0 \to \mu\mu)}{\epsilon N(B^0)}$$

? ?



Convert observed events to branching fraction using normalization channels …

$B^\pm \to J/\psi K^\pm$: similar trigger criteria, different N_{tracks}

$B^0 \to K^+\pi^-$: different trigger, same N_{tracks}

consistent results

Then:

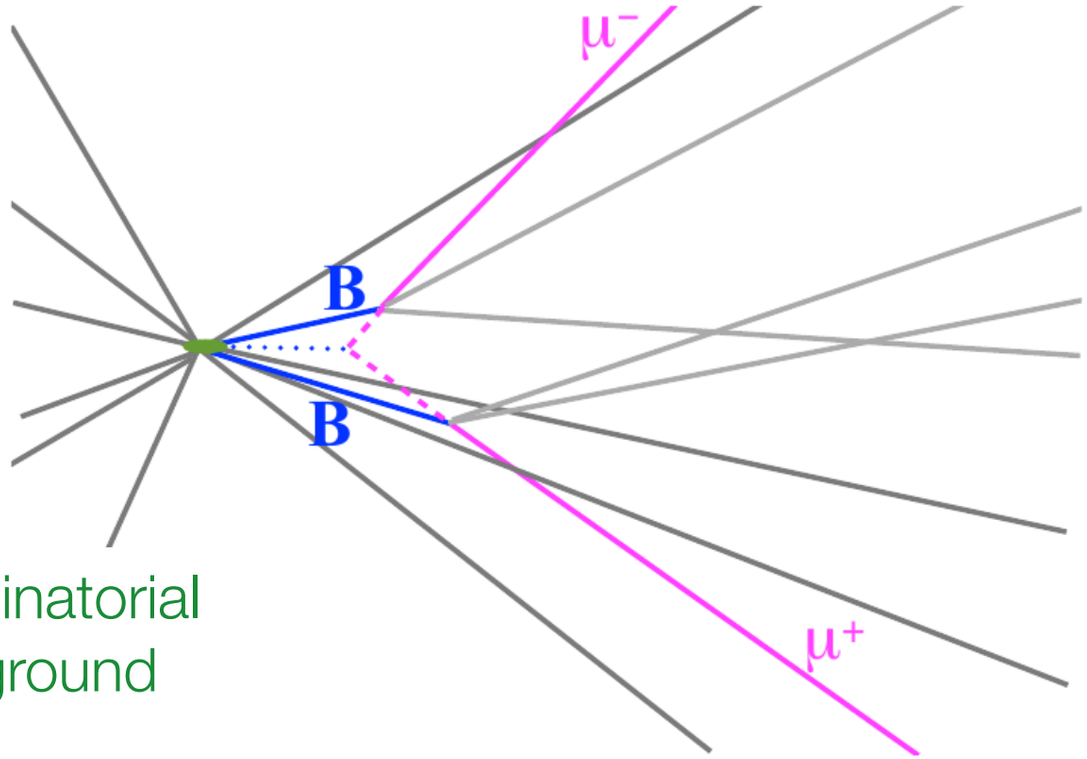
$$\mathcal{B}_{\rm sig} = \mathcal{B}_{\rm cal} \times \frac{\epsilon^{\rm rec}_{\rm cal}\,\epsilon^{\rm sel}_{\rm cal}}{\epsilon^{\rm rec}_{\rm sig}\,\epsilon^{\rm sel}_{\rm sig}} \times \frac{\epsilon^{\rm trig}_{\rm cal}}{\epsilon^{\rm trig}_{\rm sig}} \times \frac{f_{\rm cal}}{f_{\rm sig}} \times \frac{N_{\rm sig}}{N_{\rm cal}} = \alpha \times N_{\rm sig}$$

from MC
checked with data

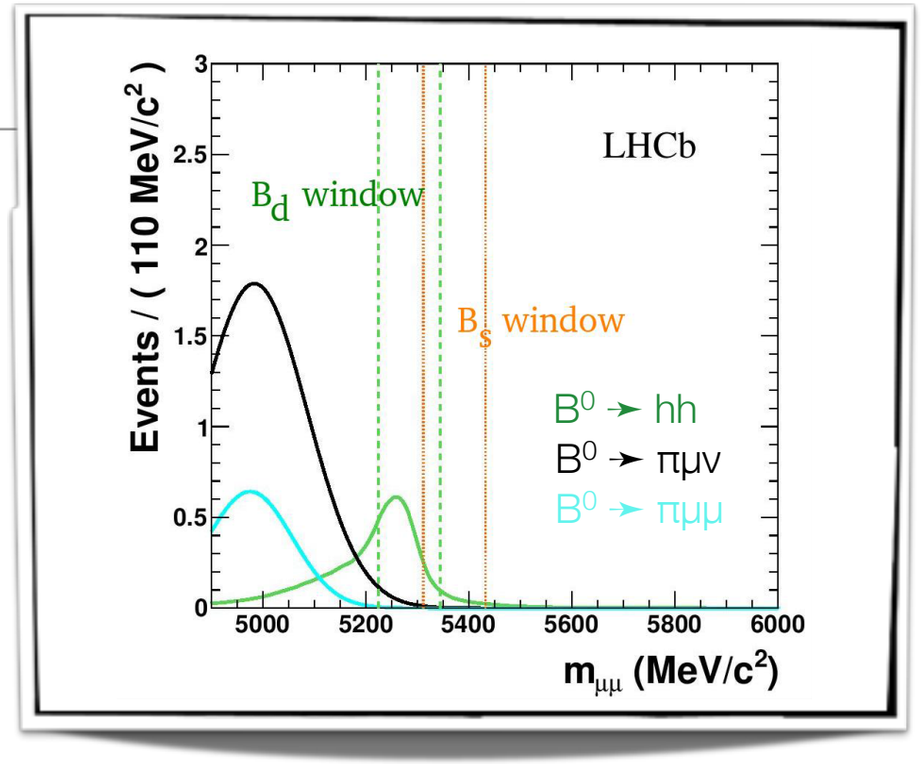
from data

hadronization fraction ratio f_s/f_d
[measured, arXiv:1301.5286]

Background Determination



Combinatorial Background



Combinatorial background from $bb \to \mu^+\mu^-$ described by exponential function …

$B^0 \to h^+h^-$; h = π,K with double mis-identification calibrated using data …

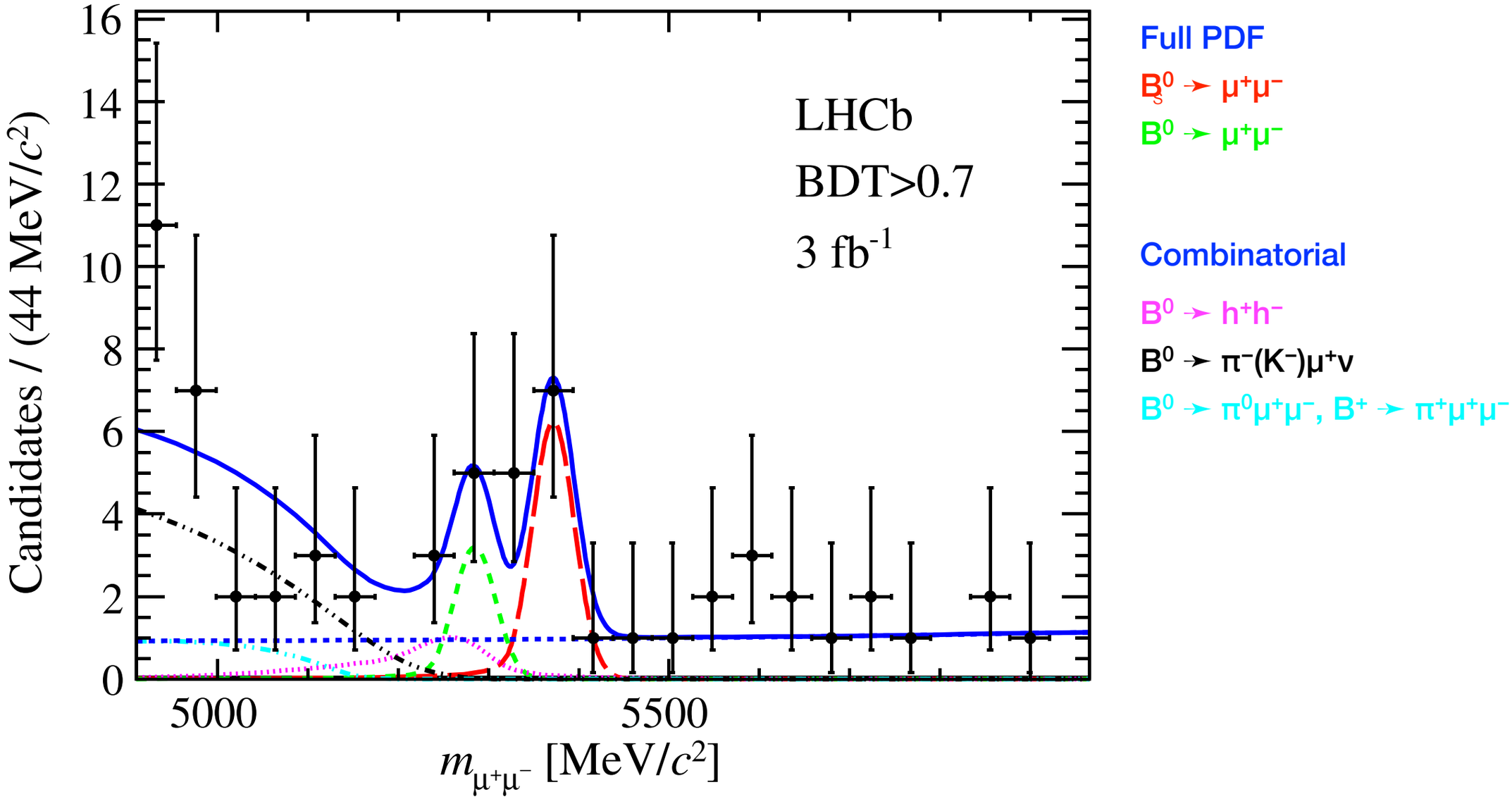
Semi-leptonic exclusive backgrounds
$B^0 \to \pi\mu\nu$, $B \to \pi\mu\mu$ negligible in B^0 mass window …

Determine expected background yields from normalization to
$B^+ \to J/\psi K^+$, di-muon invariant mass and BDT shape from MC

Invariant Mass Distribution …

[LHCb, PRL 11 (2013) 101805]

… of the selected B^0 candidates …

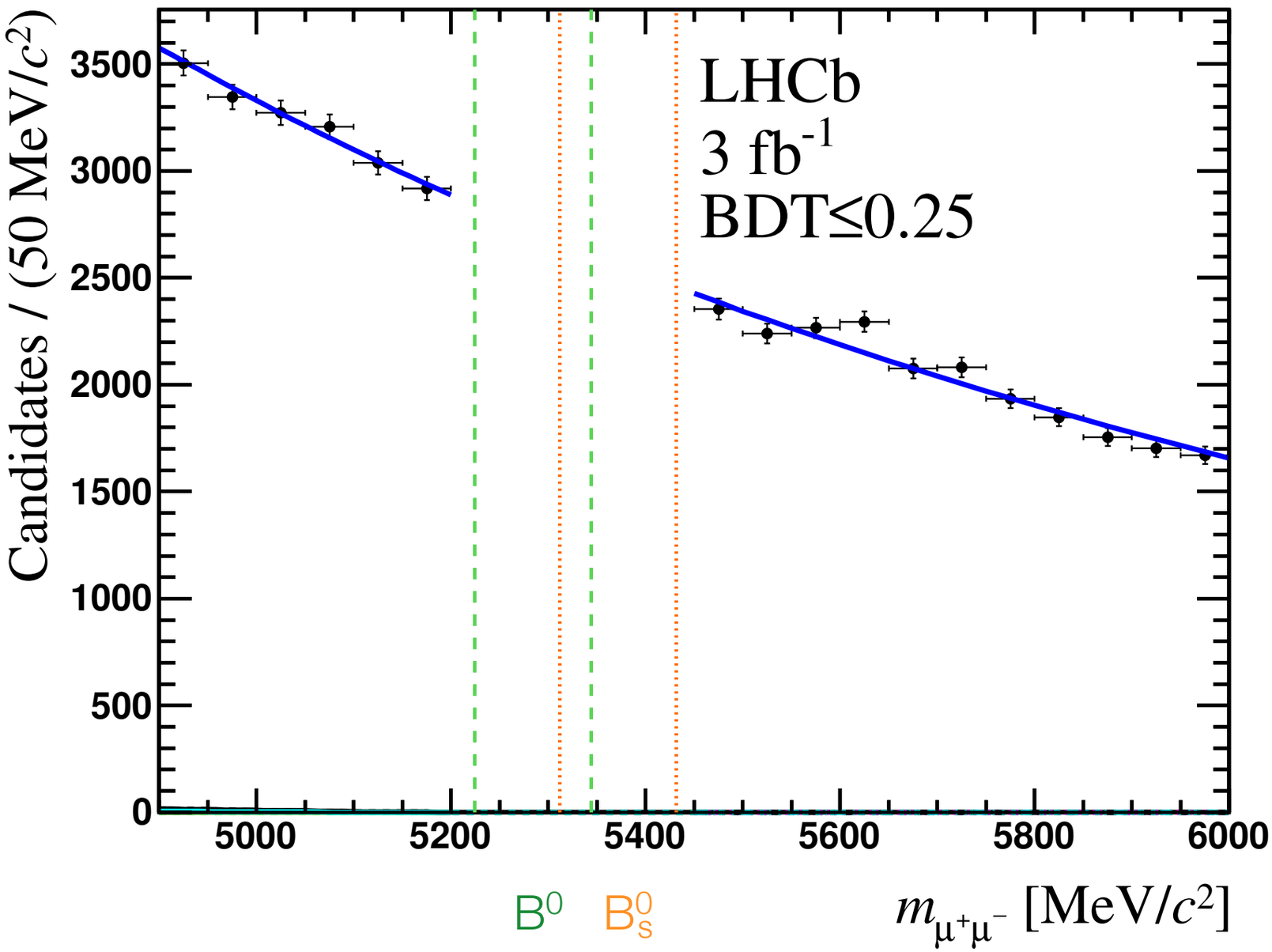


Invariant Mass Distribution …

[LHCb, PRL 11 (2013) 101805]

[Additional Material]

… of the selected events in first BDT bin …



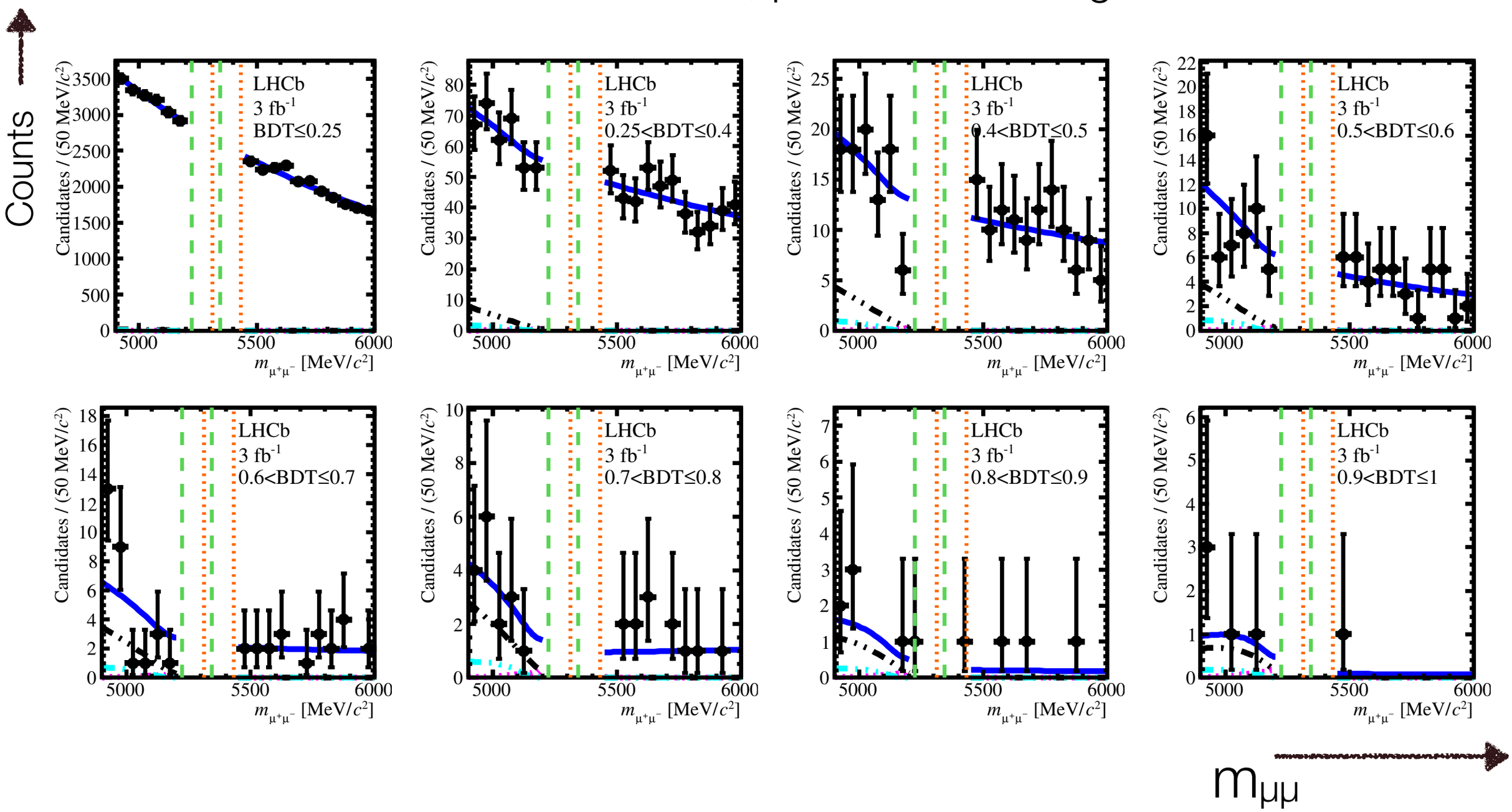
Data shown
prior to unblinding …

Invariant Mass Distribution …

[LHCb, PRL 11 (2013) 101805]

[Additional Material]

… for all 8 BDT bins; prior to unblinding …



[LHCb]

[$B^0 \to \mu^+\mu^-$]

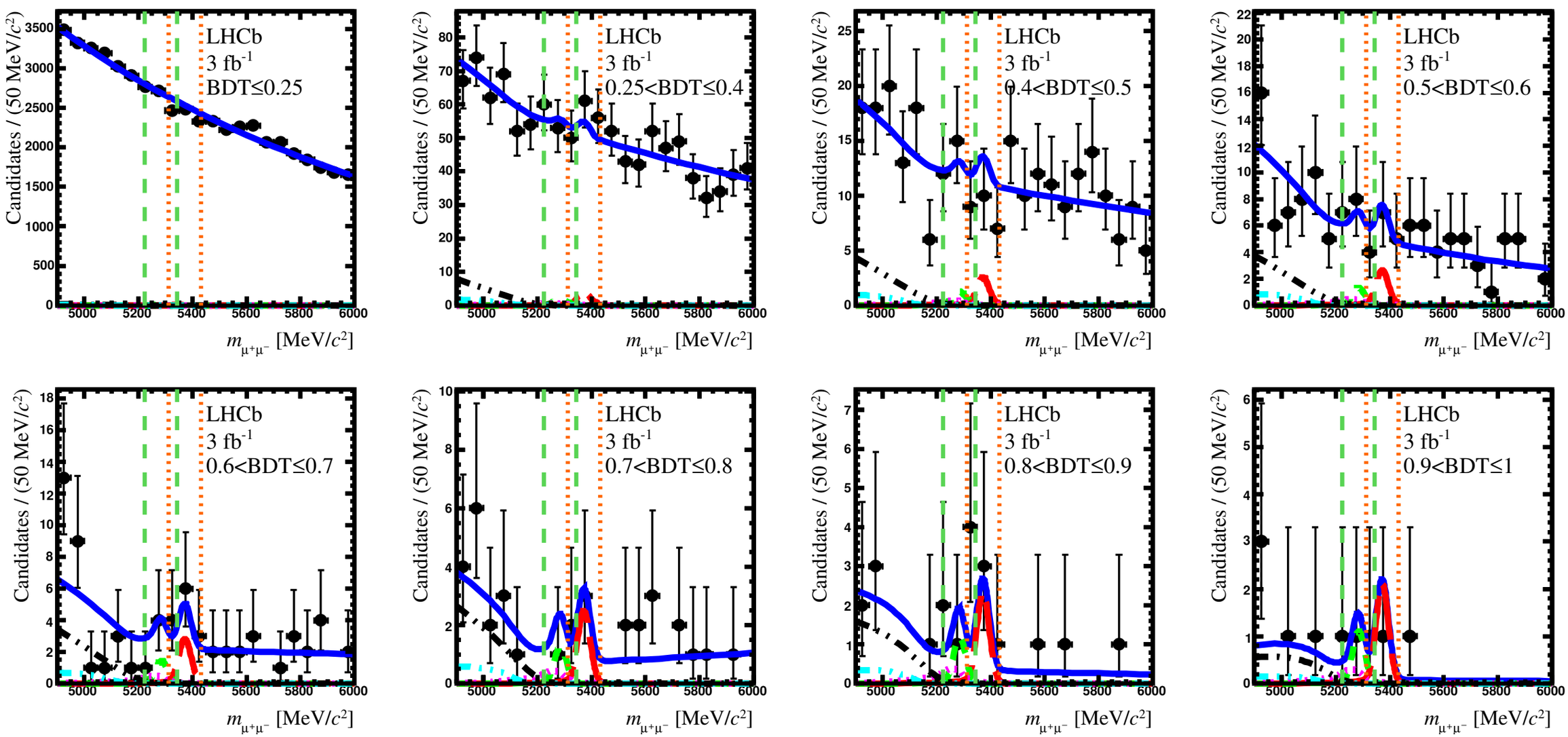
Invariant Mass Distribution …

[LHCb, PRL 11 (2013) 101805]

[Additional Material]

… for all 8 BDT bins; after unblinding …

Counts



$m_{\mu\mu}$

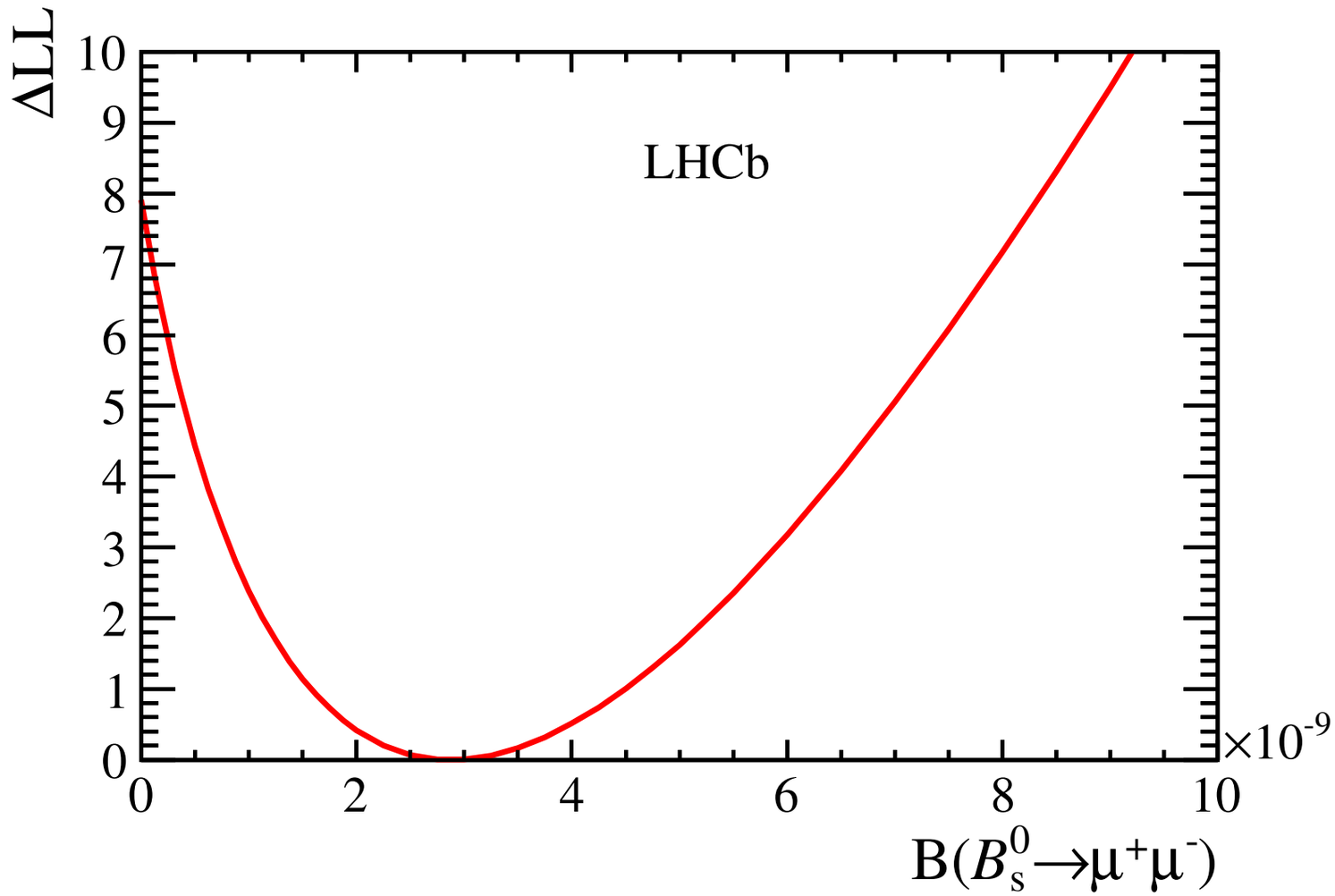
Log-Likelihood Fit …

[LHCb, PRL 11 (2013) 101805]

[Additional Material]

BR determination:

Simultaneous un-binned maximum-likelihood fit to mass projections of all eight BDT bins …



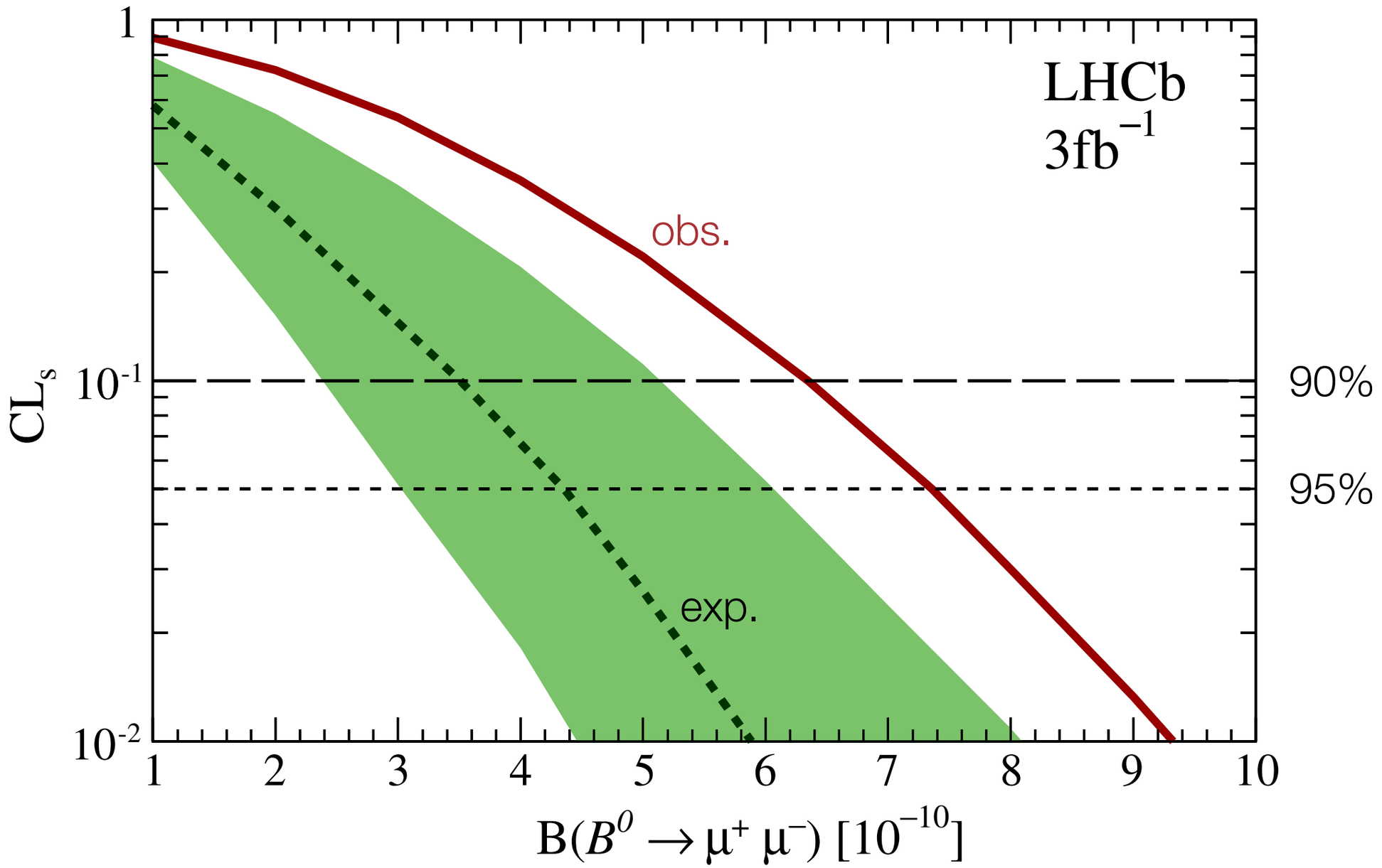
Result:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(\text{stat})^{+0.3}_{-0.1}(\text{syst})) \times 10^{-9} \quad [4\sigma]$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(\text{stat})^{+0.6}_{-0.4}(\text{syst})) \times 10^{-10} \quad [<2\sigma]$$

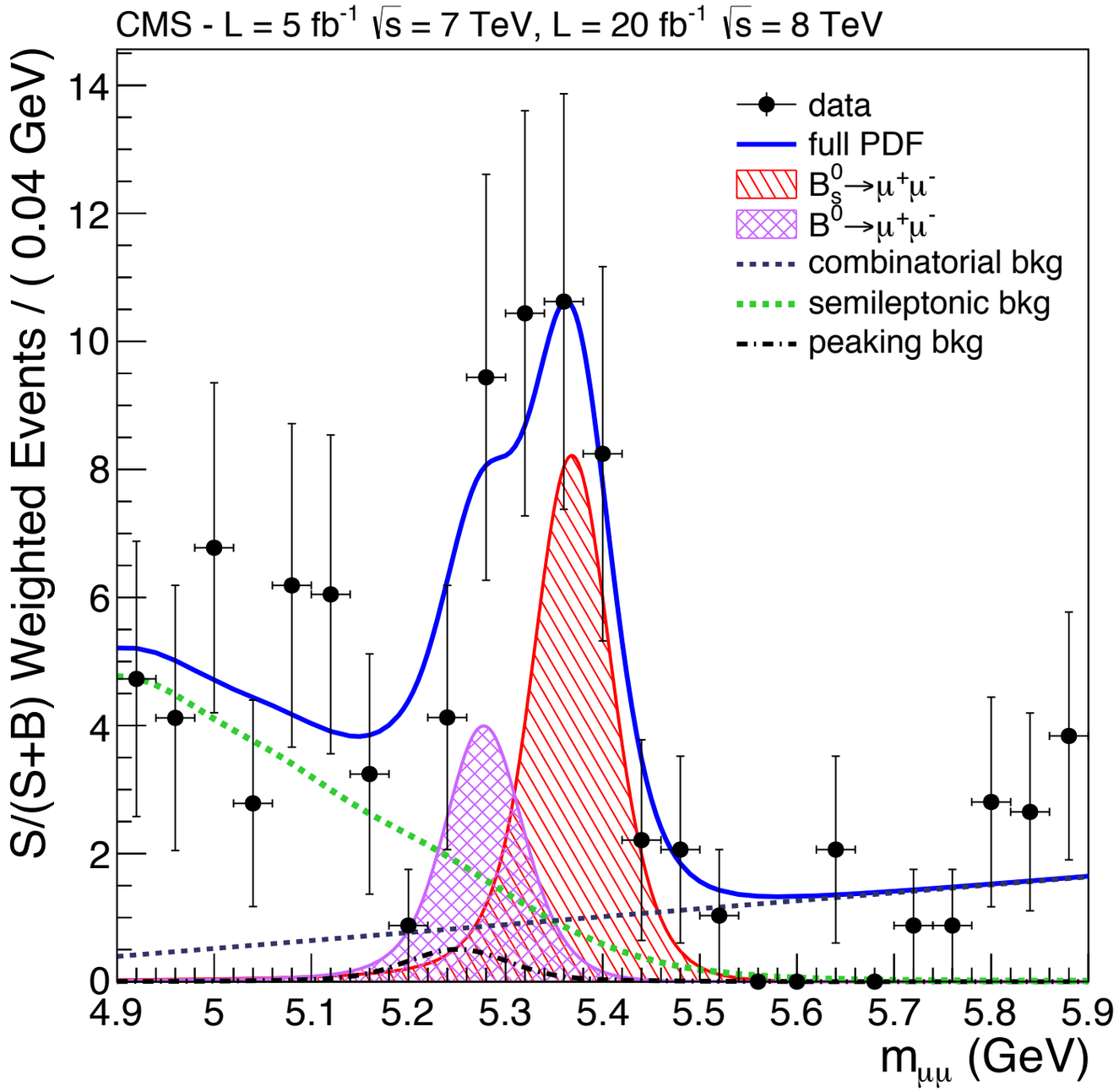
Limit for $B^0 \to \mu^+\mu^-$

[LHCb, PRL 11 (2013) 101805]



CMS Result for $B_s^0 \to \mu^+\mu^-$

[CMS, PRL 111 (2013) 101804]



Combined invariant mass plot

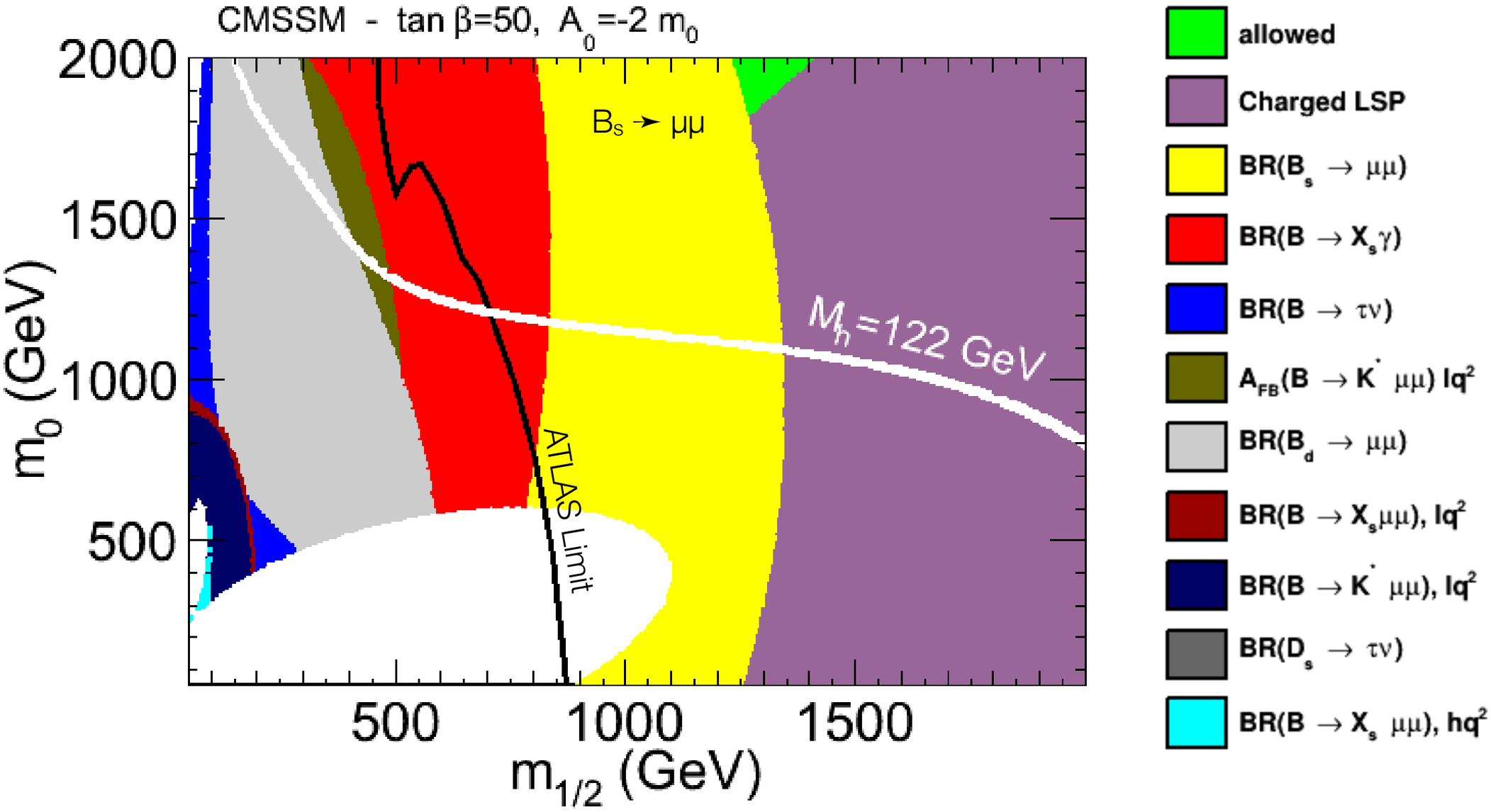
Individual categories are weighted with signal-to-background ratio

Result:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$

Implications on SUSY [with extra Higgs]

[Mahmoudi, arXiv:1310.2556v1]



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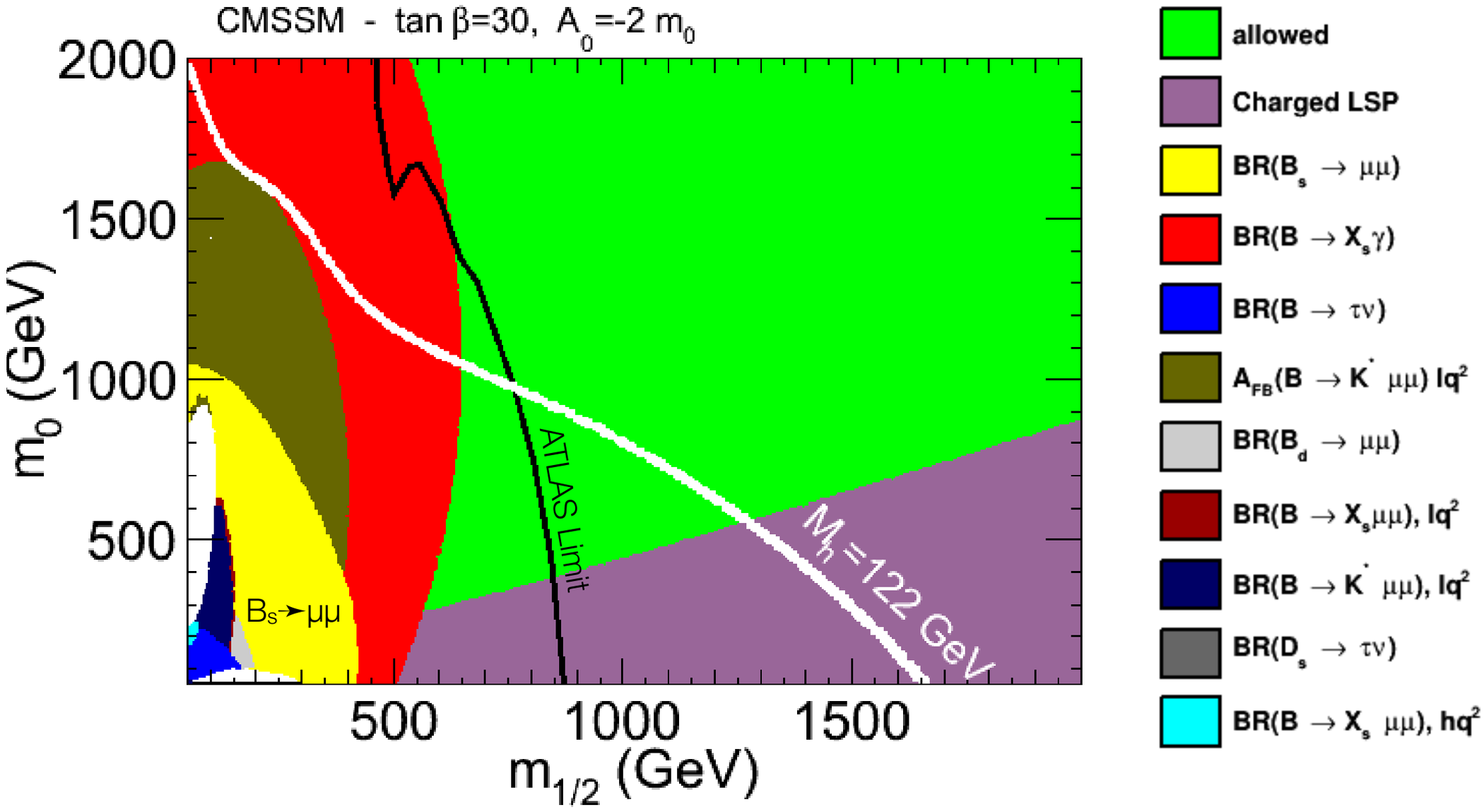
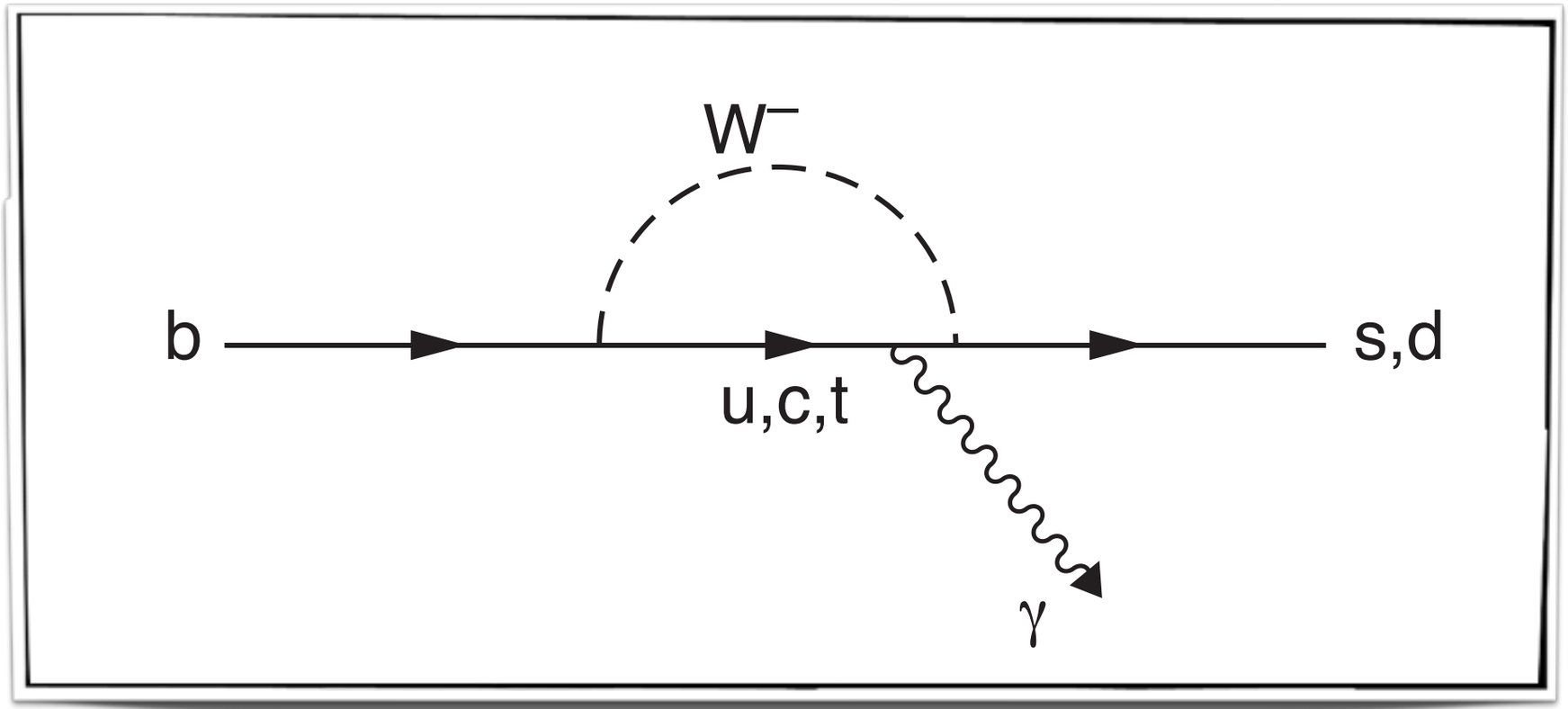
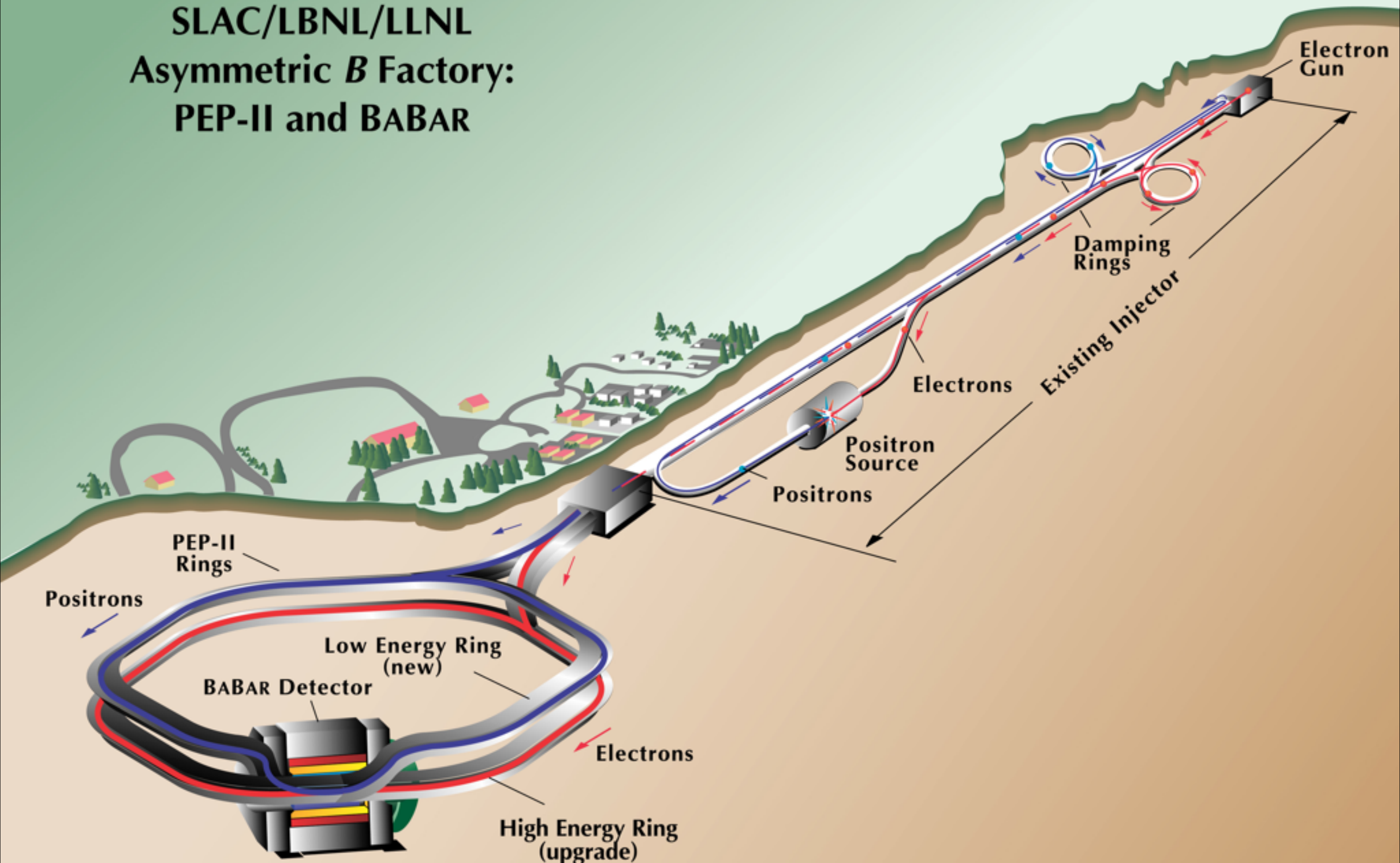


b ➔ sγ Penguins

at BaBar [and Belle]



SLAC/LBNL/LLNL Asymmetric *B* Factory: PEP-II and BABAR

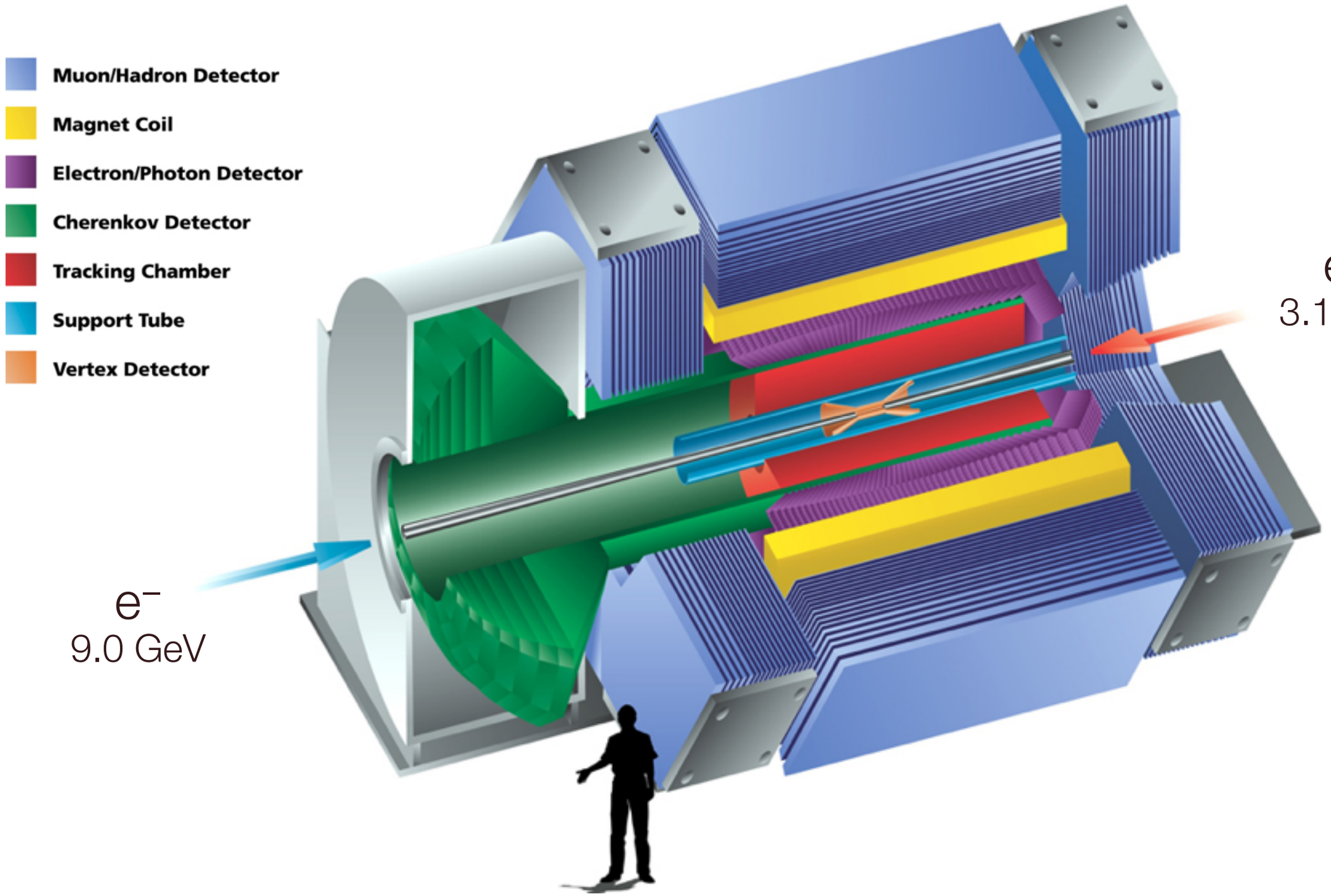


Both Rings Housed in PEP Tunnel

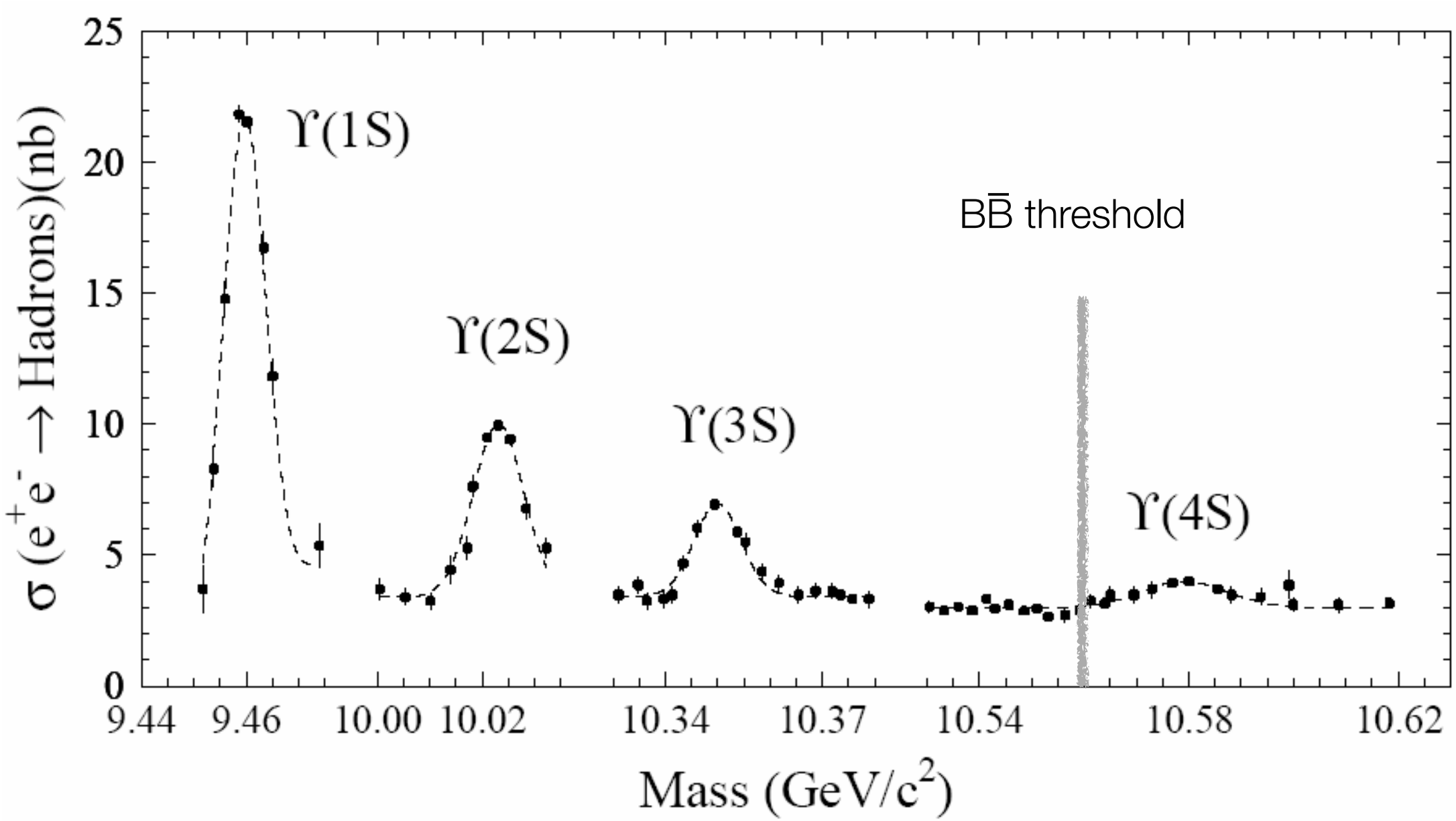
7-98
6555A61

The BaBar Experiment

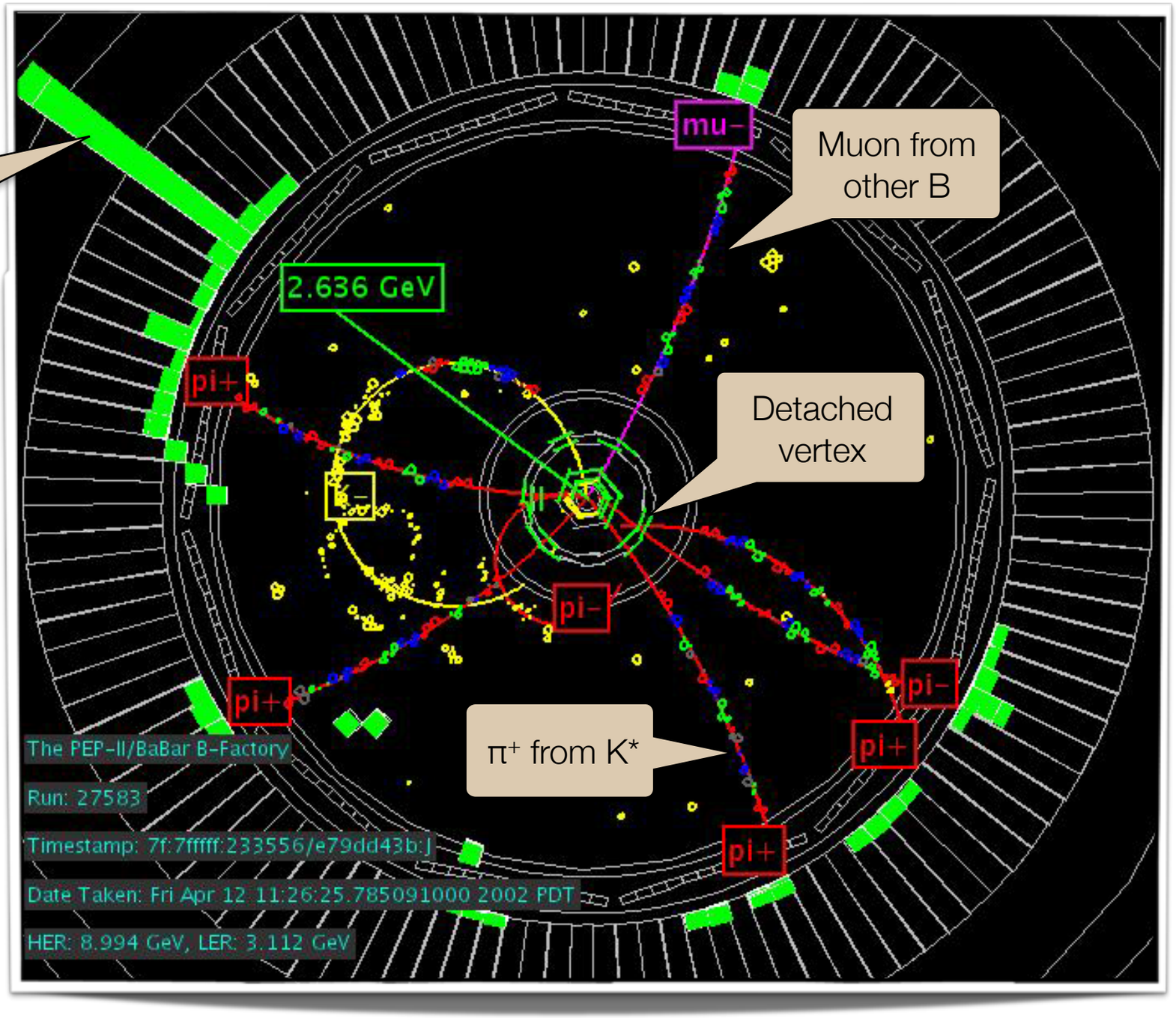
Forward Boost
Clean environment
Good Particle ID
Hermetic detector



BaBar Operation @ Y(4S)



Radiative Penguin Signature



High energy photon

Muon from other B

Detached vertex

π^+ from K*

Note:
Events tend to be isotropic

[BaBar]

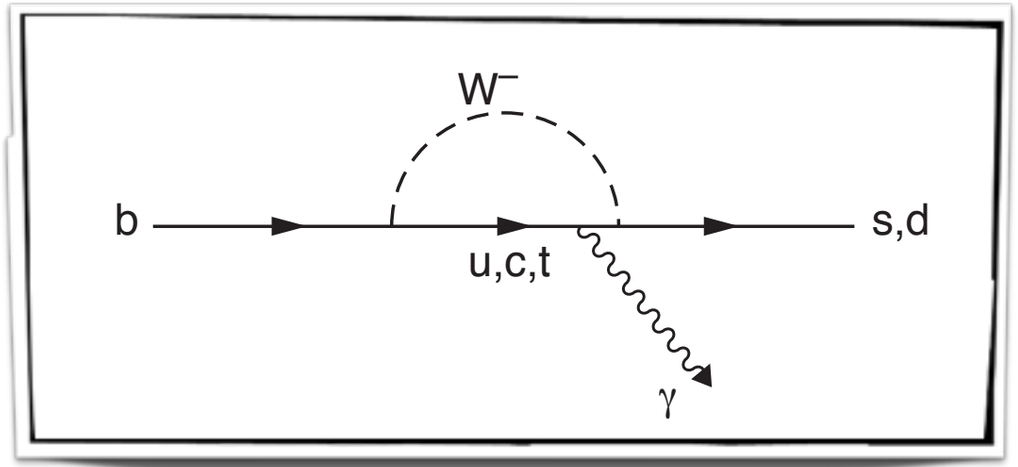
Radiative Penguin

[arXiv:1207.5772v2]

Investigate …

$$B \rightarrow X_s\gamma$$

[SM: BR($B \rightarrow X_s\gamma$) = $(3.14 \pm 0.22) \times 10^{-4}$]
[for $E_\gamma^* > 1.6$ GeV]



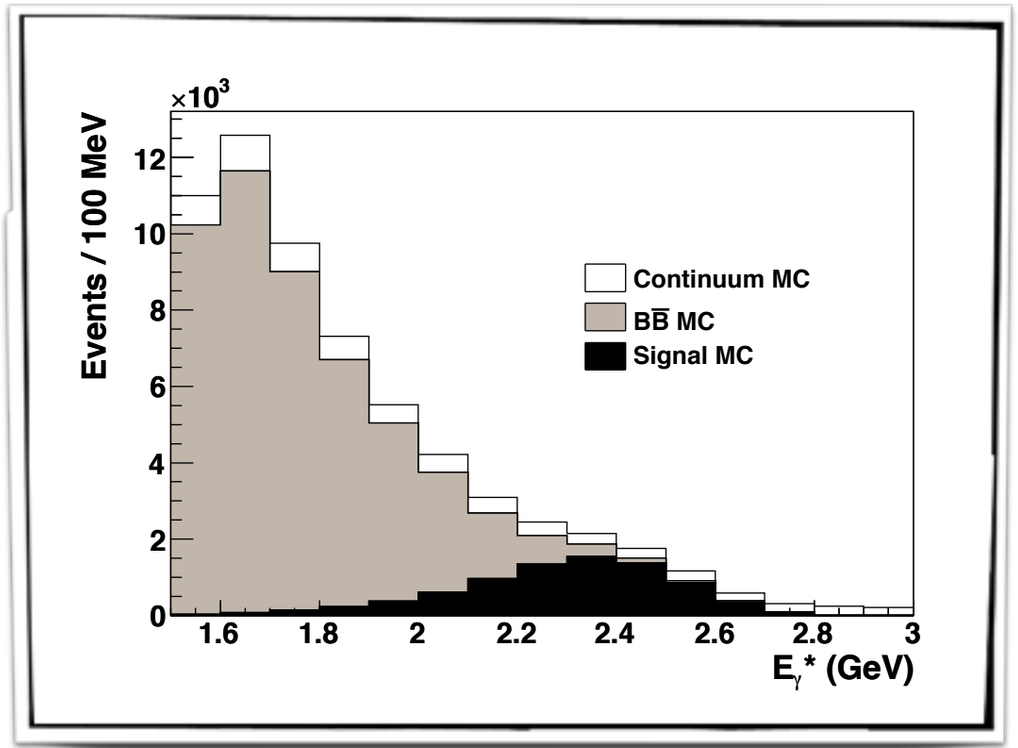
Fully inclusive Analysis:

Hadronic Events: ≥ 3 tracks; spherical
[explore more isotropic topology of BB events]
[qq and ττ events more jet-like]

High energy isolated photon
[veto η,π^0 decays]

Tagging of charged lepton
[opposite side B-decay]

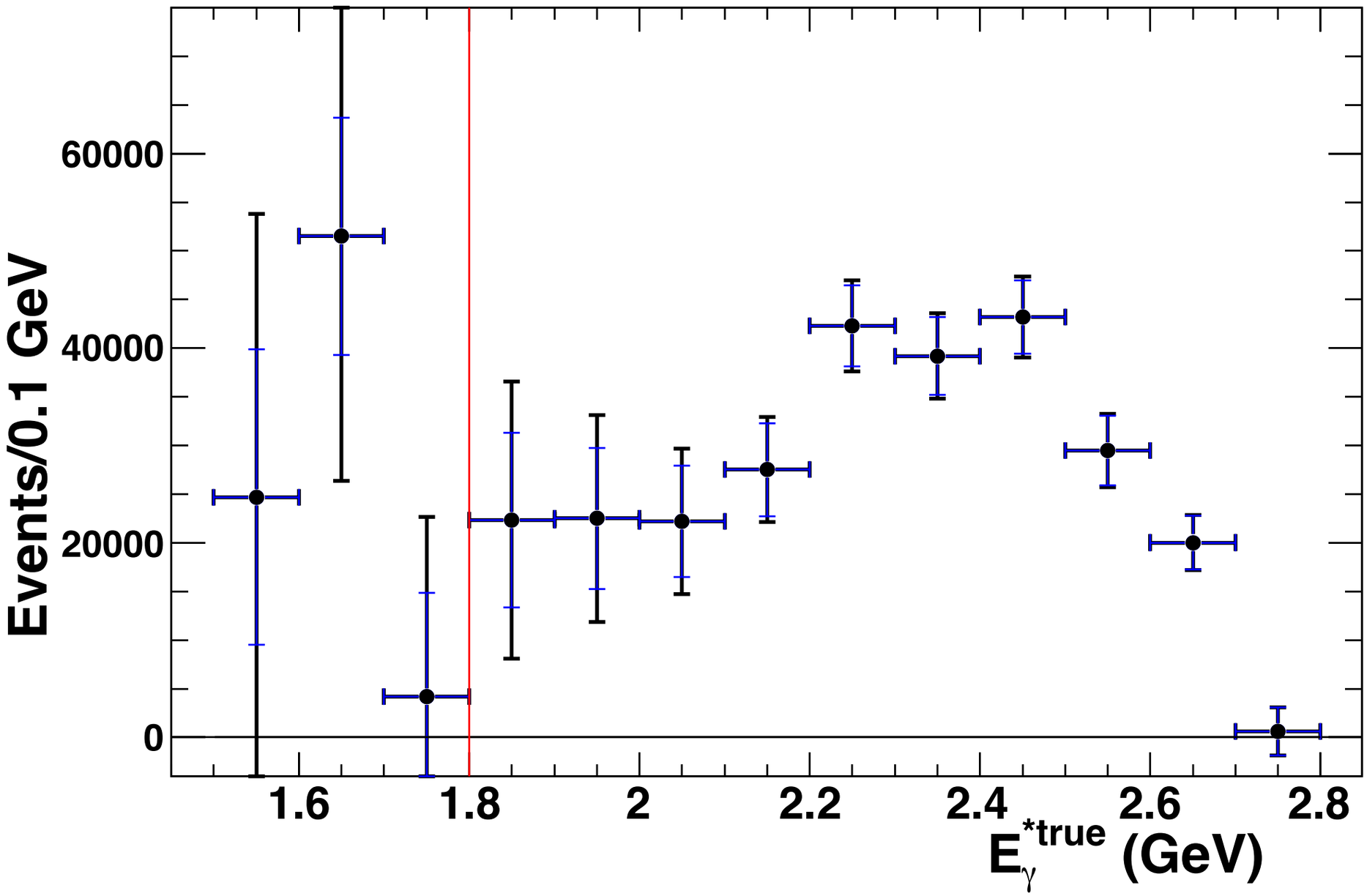
continuum and BB background estimated using data …



[BaBar]

Final Photon Spectrum

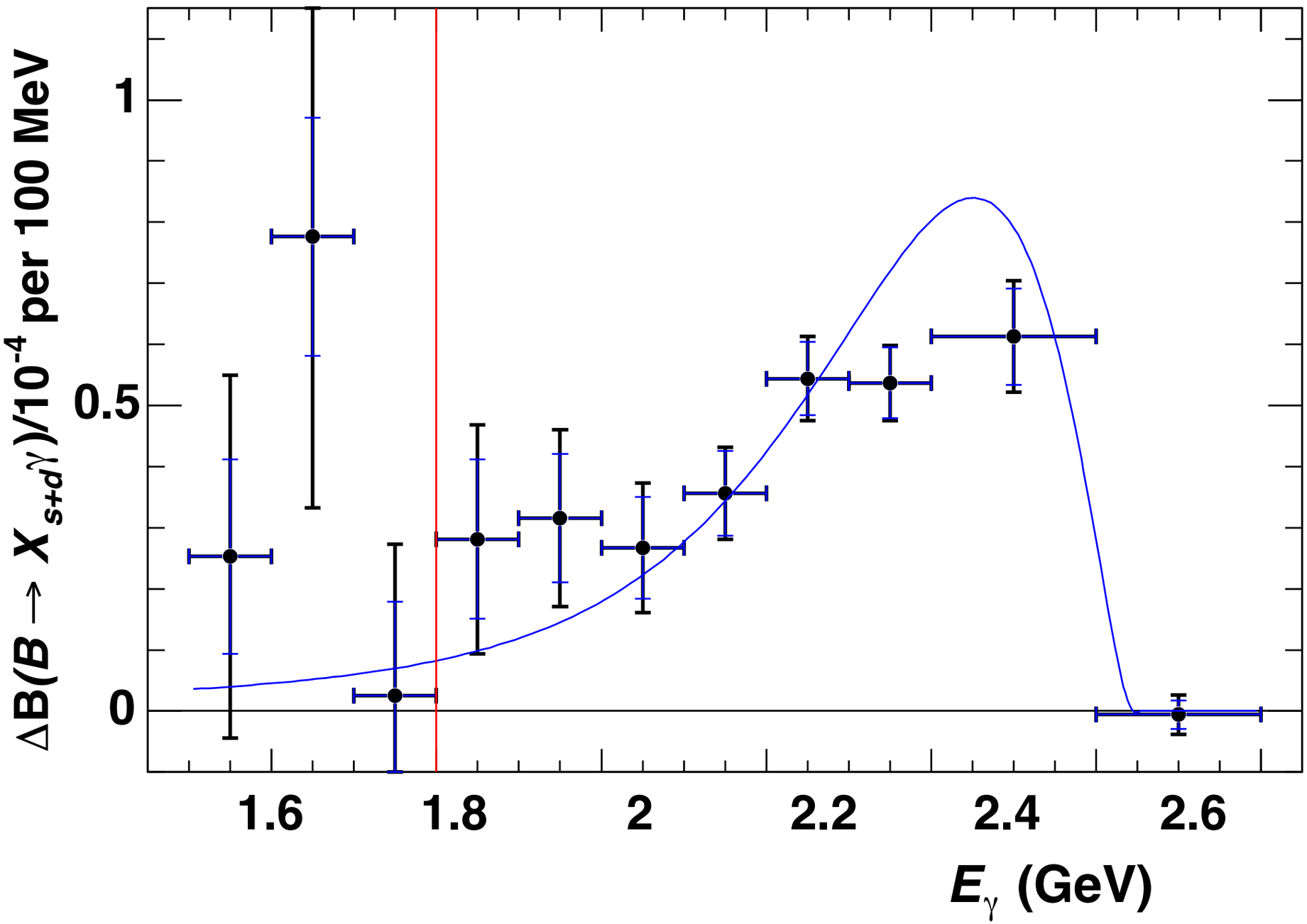
[arXiv:1207.5772v2]



[BaBar]

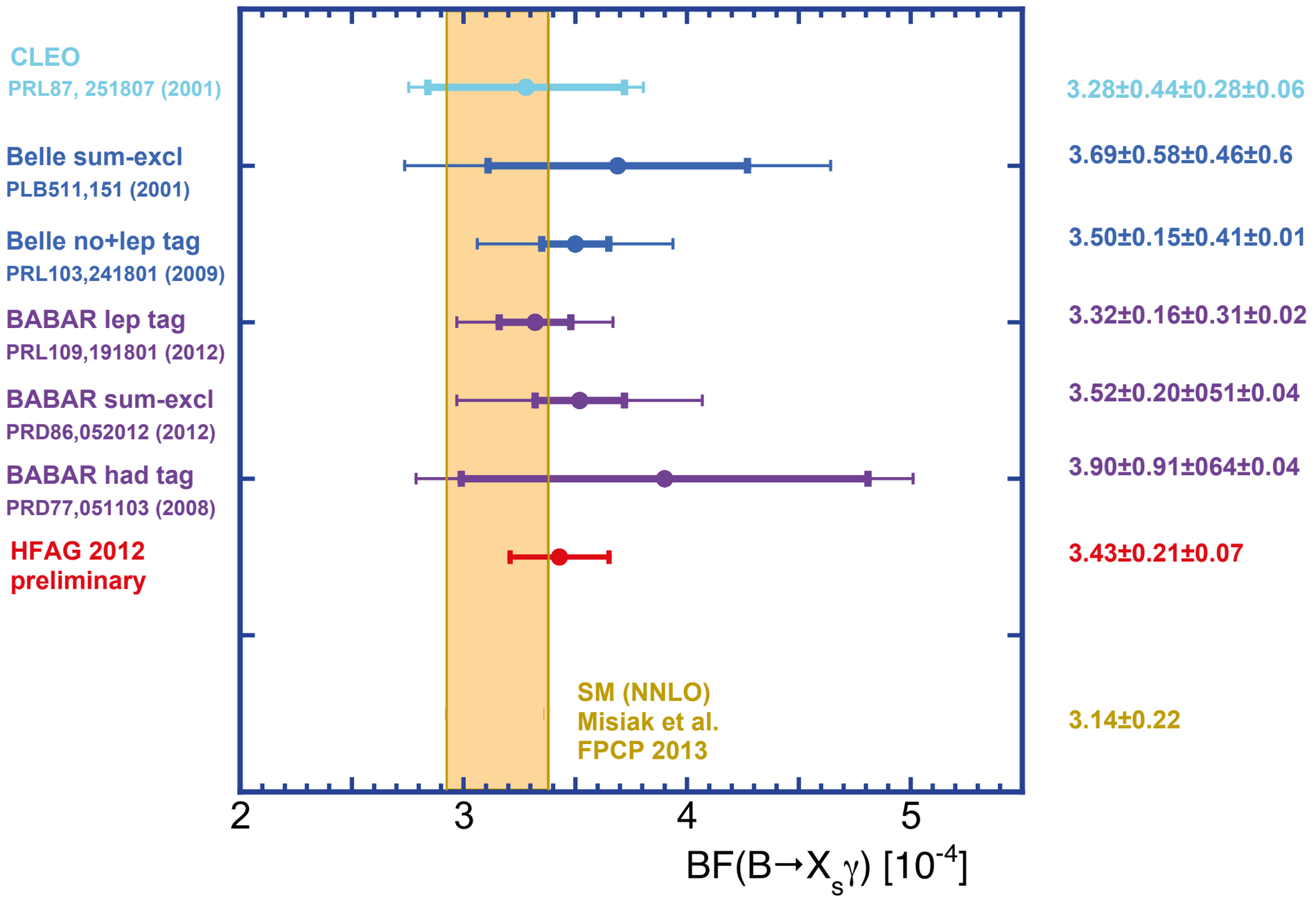
Partial Event Fraction

[arXiv:1207.5772v2]



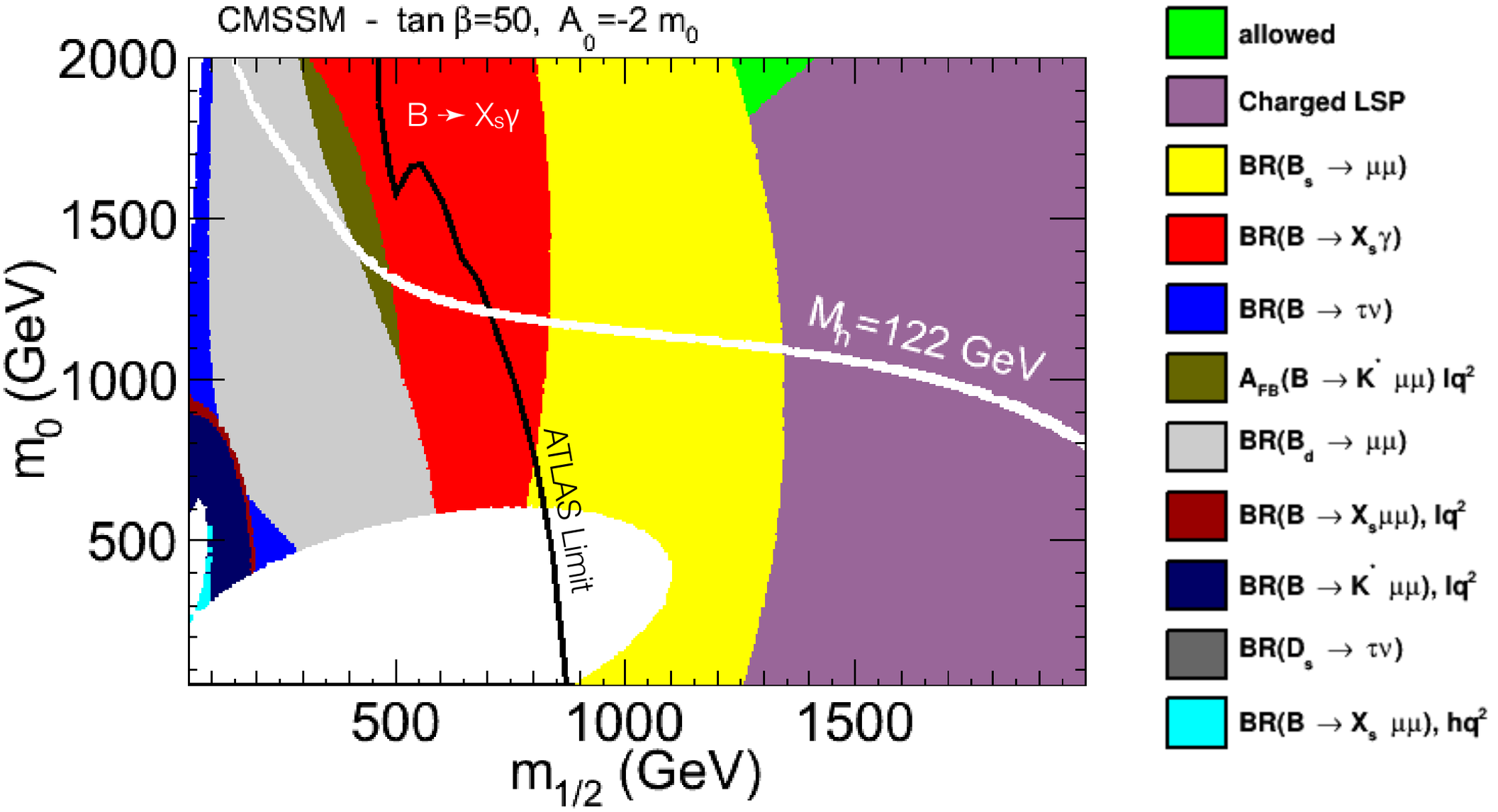
Comparison of B ➛ $X_s\gamma$ Results

[arXiv:1309.1327v1]



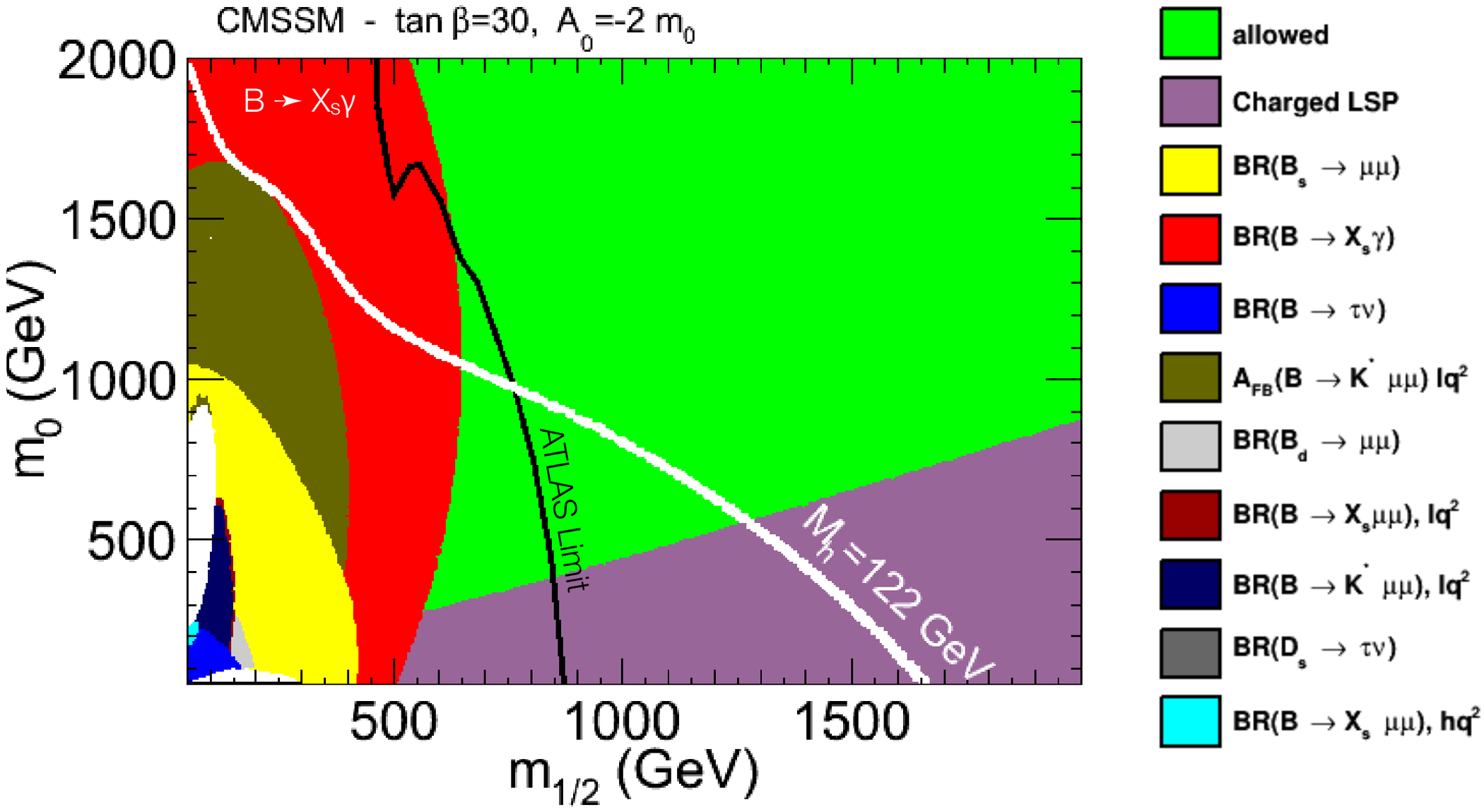
Implications on SUSY [with extra Higgs]

[Mahmoudi, arXiv:1310.2556v1]



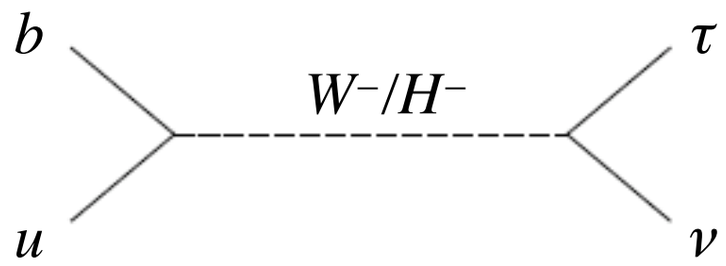
Implications on SUSY [with extra Higgs]

[Mahmoudi, arXiv:1310.2556v1]

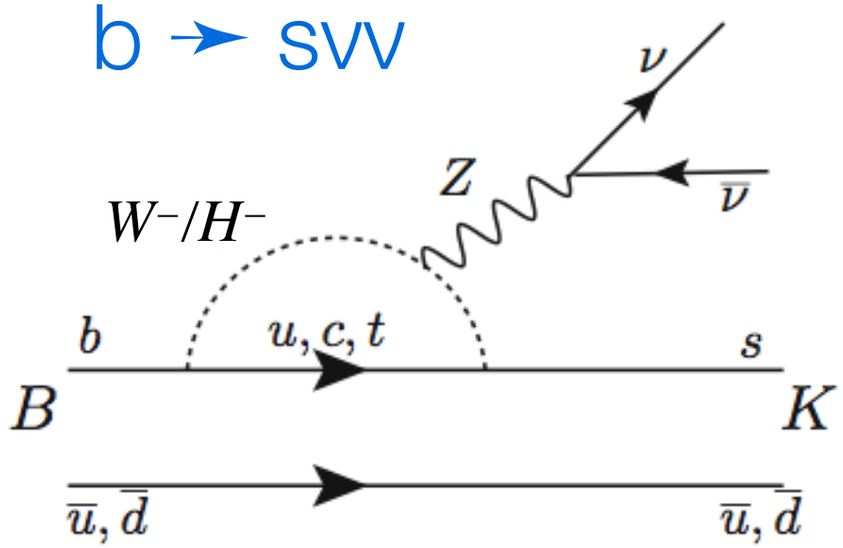


Other Search Channel Examples

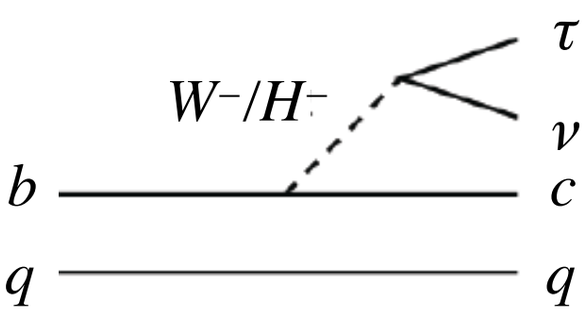
B → τν



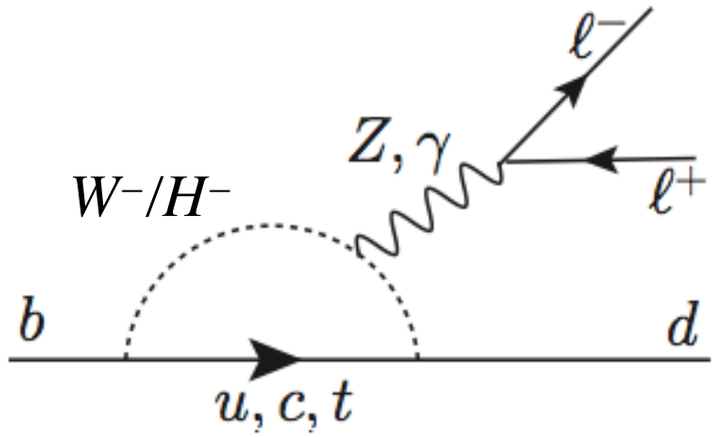
b → sνν



B → D*τν

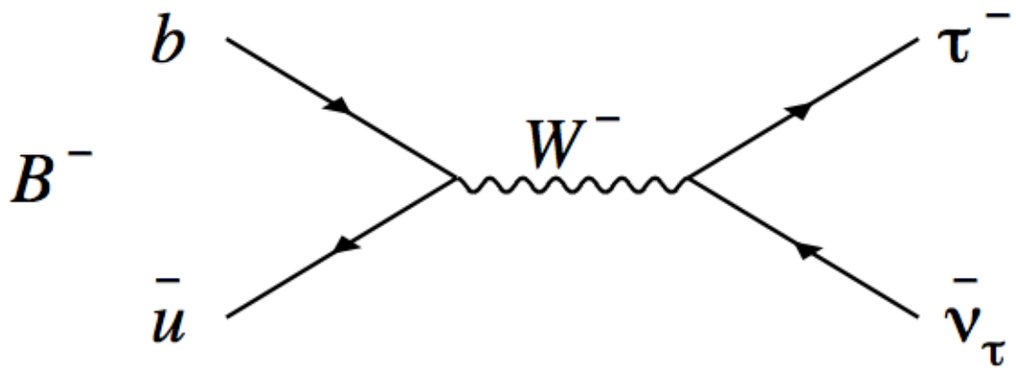


b → dll

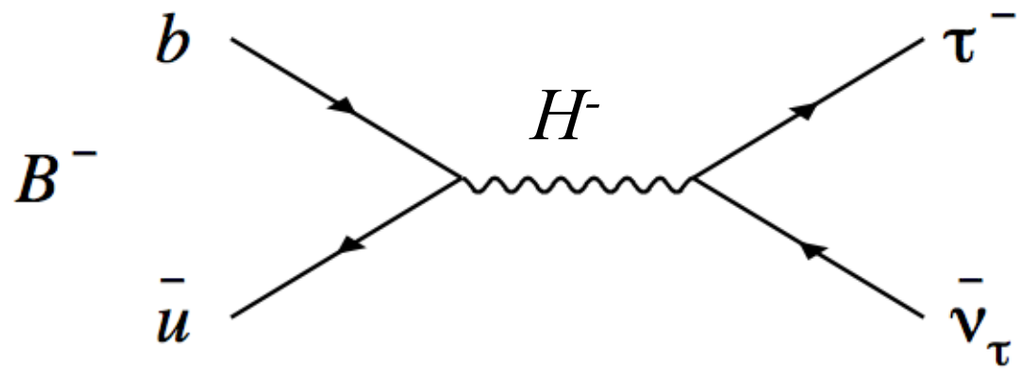


Search for Charged Higgs in B ➔ τν

Standard Model



Type II HDM

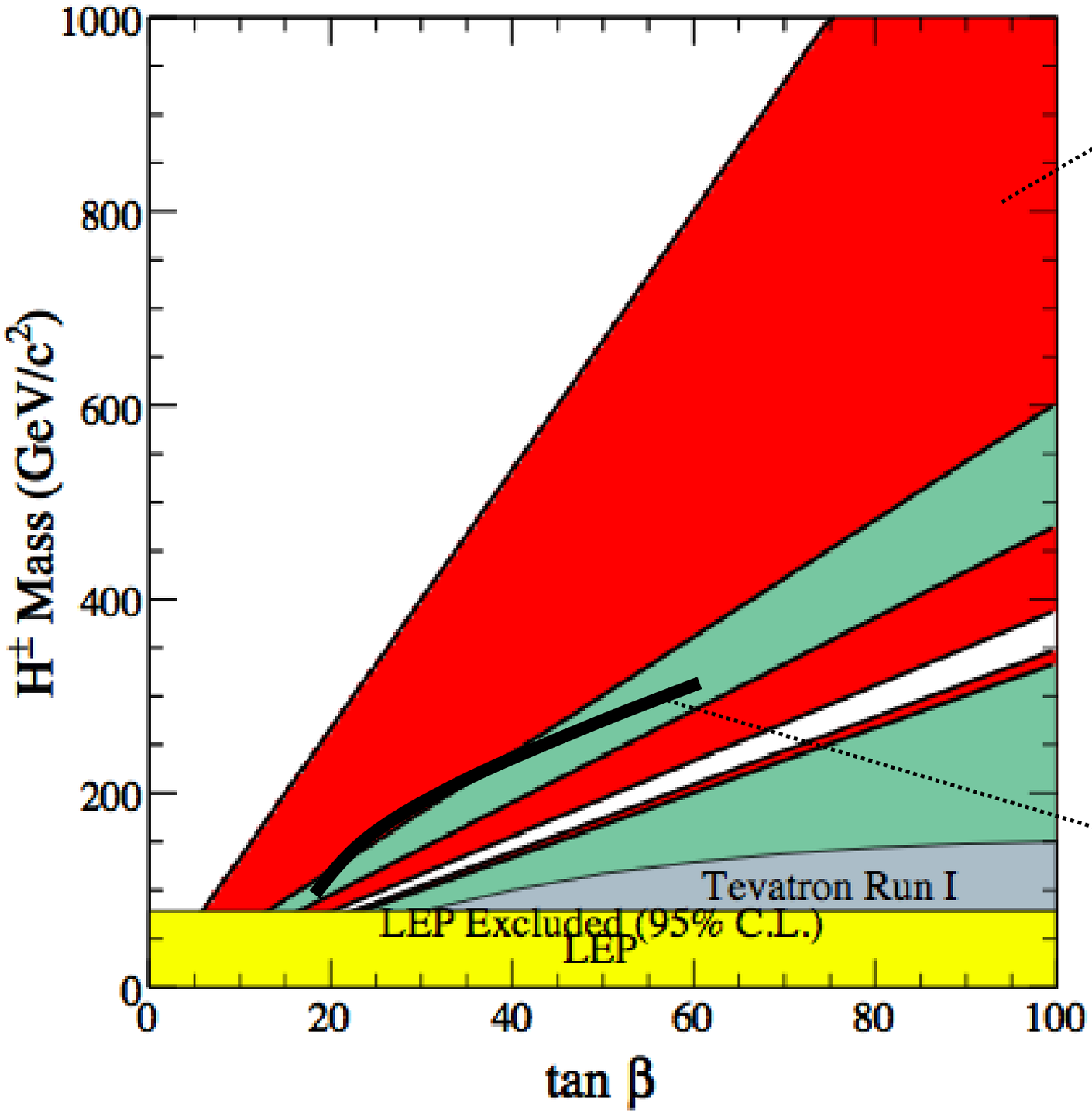


$$\mathcal{B}(B^- \to \tau^- \bar{\nu}) = \mathcal{B}_{\rm SM} \times r_H \qquad r_H = \left(1 - \tan^2\beta \frac{m_{B^-}^2}{m_{H^-}^2}\right)^2$$

[W.S.Hou, PRD 48, 2342 (1993)]

Charged Higgs Discovery Potential

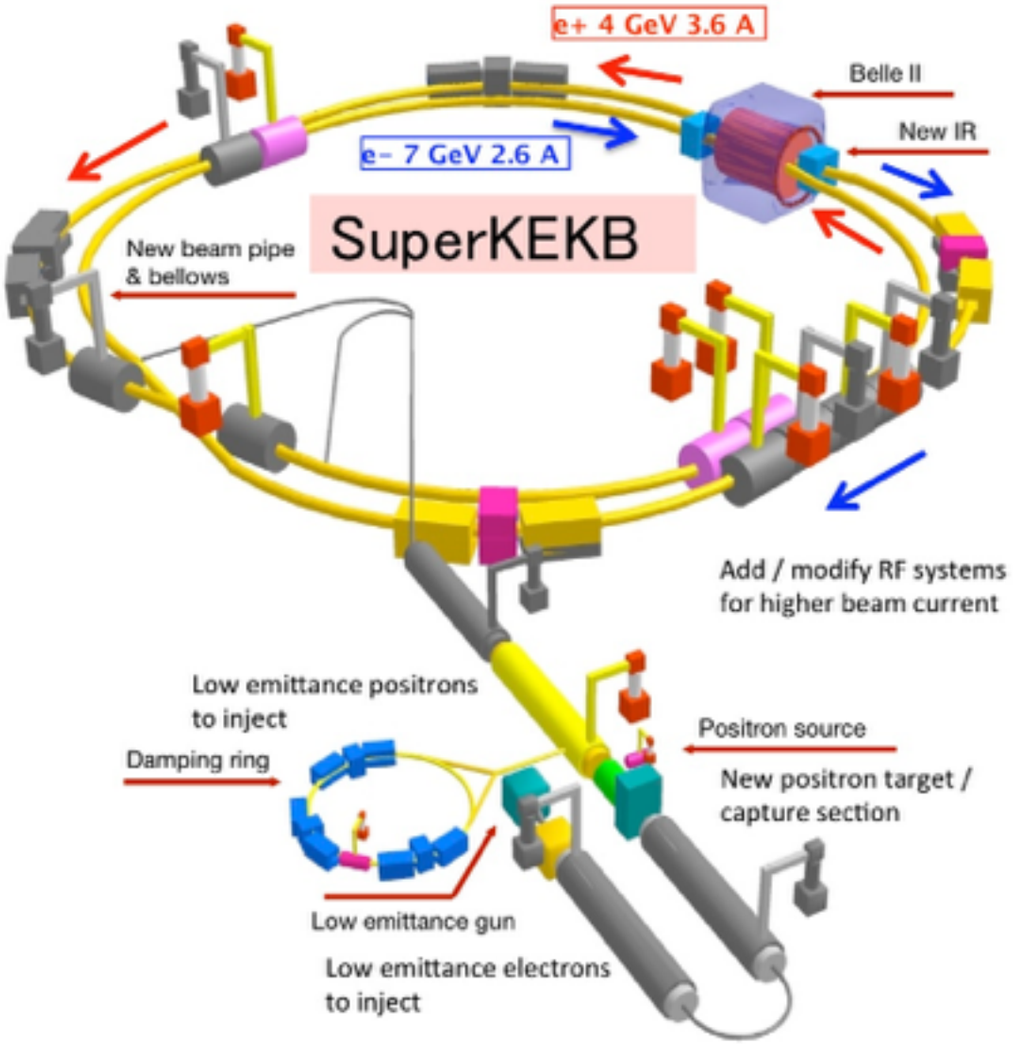
[arXiv:0901.0512]

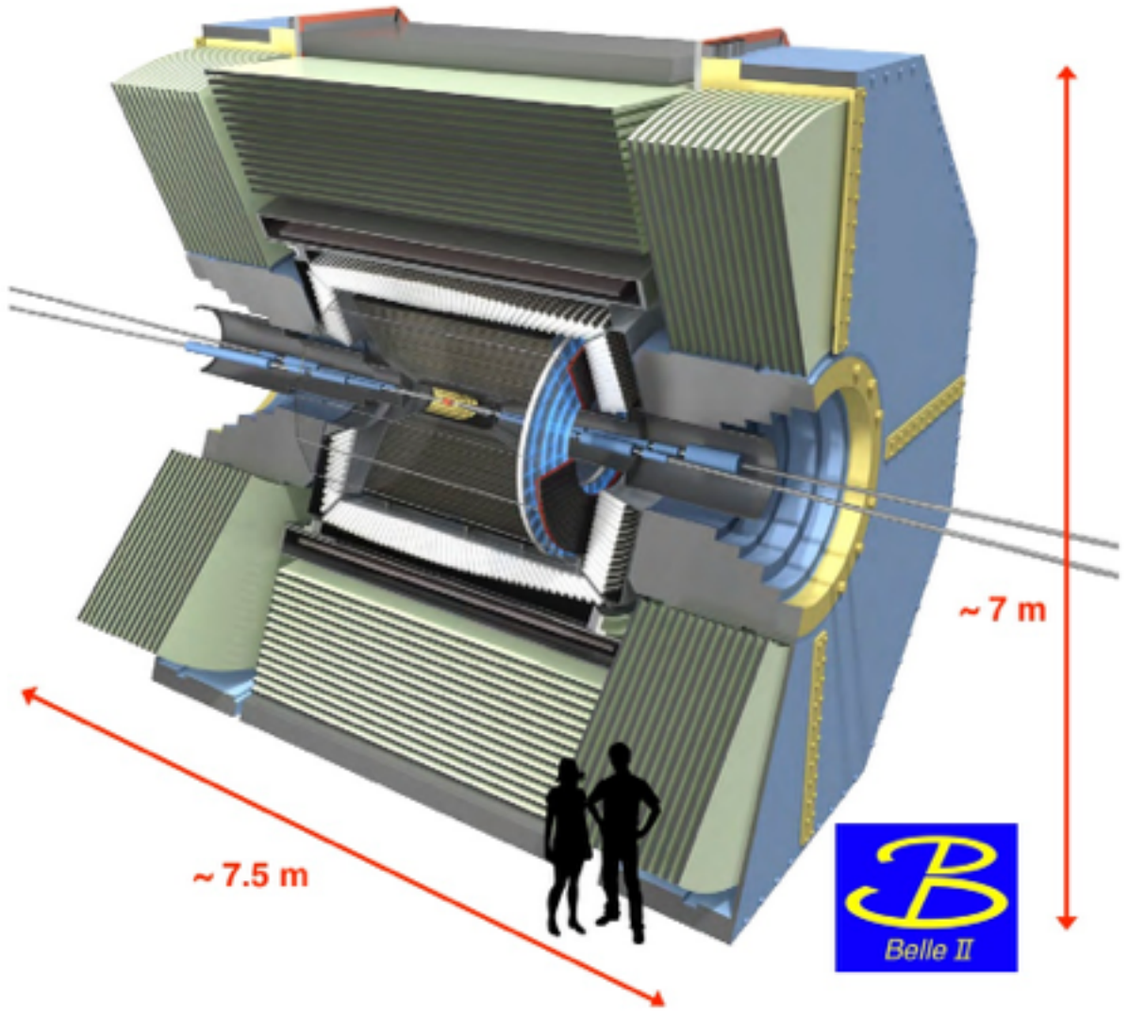


Belle II
5σ discovery potential
for charged Higgs
[50 ab^{-1}]

ATLAS
5σ discovery potential
for charged Higgs
[14 TeV, 30 fb^{-1}]

Belle II and SuperKEKB



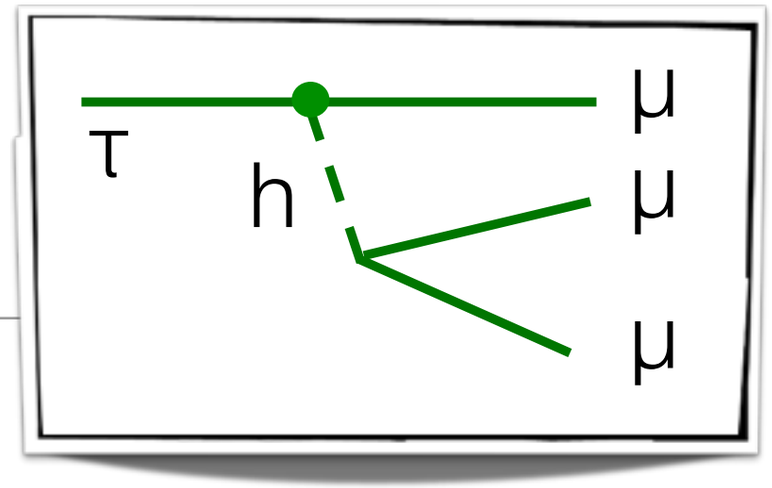


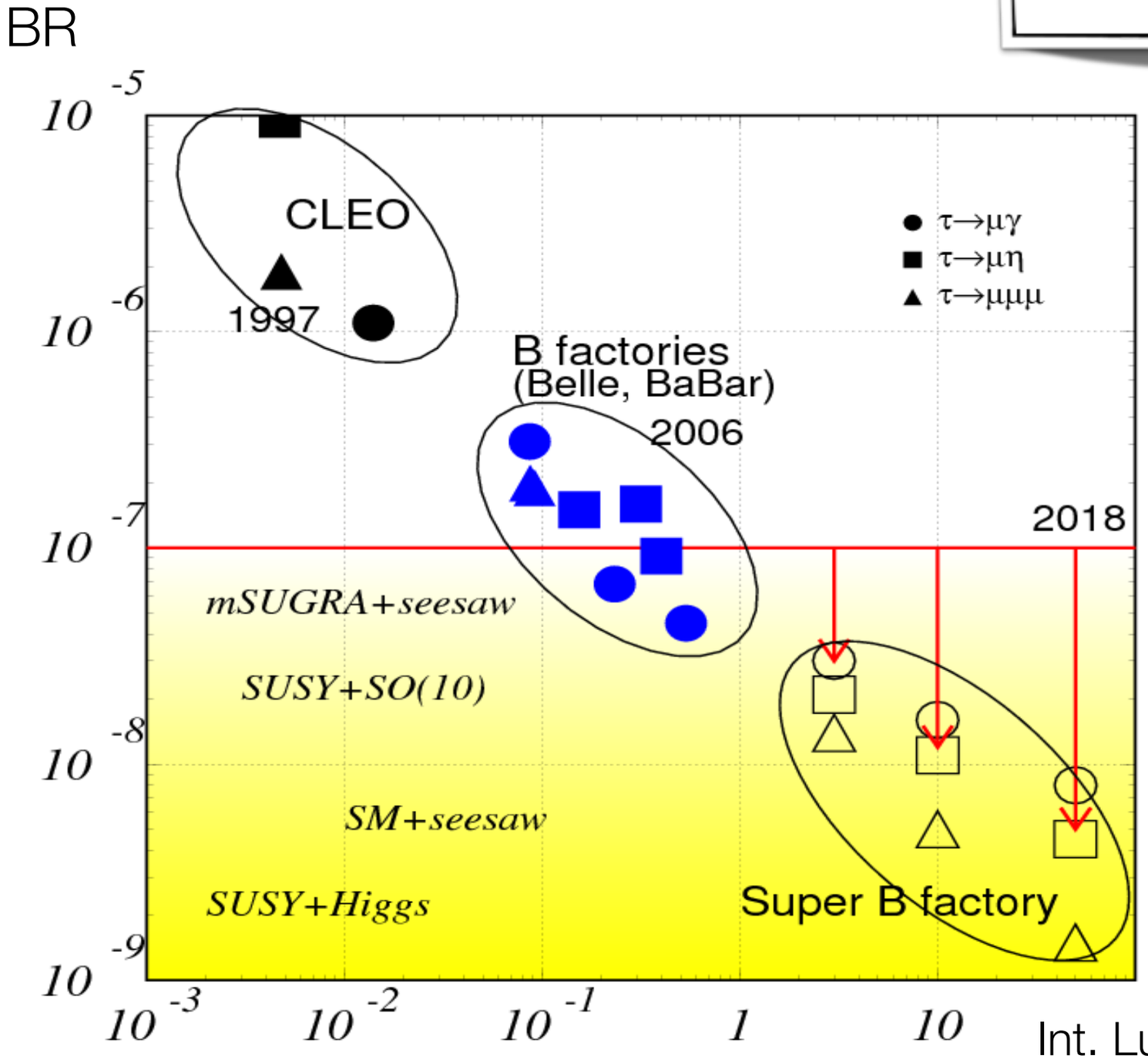
Belle II Physics Sensitivity

[arXiv:1002.5012]

Observable	Belle 2006 ($\sim$0.5 ab^{-1})	SuperKEKB (5 ab^{-1})	SuperKEKB (50 ab^{-1})	†LHCb (2 fb^{-1})	†LHCb (10 fb^{-1})
Radiative/electroweak $b \to s$ transitions					
$\mathcal{S}_{K^0_S\pi^0\gamma}$	0.32	0.10	0.03	-	-
$\mathcal{B}(B \to X_s\gamma)$	13%	7%	6%	-	-
$A_{CP}(B \to X_s\gamma)$	0.058	0.01	0.005	-	-
C_9 from $\overline{A}_{\rm FB}(B \to K^*\ell^+\ell^-)$	-	11%	4%		
C_{10} from $\overline{A}_{\rm FB}(B \to K^*\ell^+\ell^-)$	-	13%	4%		
C_7/C_9 from $\overline{A}_{\rm FB}(B \to K^*\ell^+\ell^-)$	-		5%		7%
R_K		0.07	0.02		0.043
$\mathcal{B}(B^+ \to K^+\nu\nu)$	†† $< 3\ \mathcal{B}_{\rm SM}$		30%	-	-
$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$	†† $< 40\ \mathcal{B}_{\rm SM}$		35%	-	-
Radiative/electroweak $b \to d$ transitions					
$\mathcal{S}_{\rho\gamma}$	-	0.3	0.15		
$\mathcal{B}(B \to X_d\gamma)$	-	24% (syst.)		-	-
Leptonic/semileptonic B decays					
$\mathcal{B}(B^+ \to \tau^+\nu)$	3.5σ	10%	3%	-	-
$\mathcal{B}(B^+ \to \mu^+\nu)$	†† $< 2.4\mathcal{B}_{\rm SM}$	4.3 ab^{-1} for 5σ discovery		-	-
$\mathcal{B}(B^+ \to D\tau\nu)$	-	8%	3%	-	-
$\mathcal{B}(B^0 \to D\tau\nu)$	-	30%	10%	-	-
LFV in τ decays (U.L. at 90% C.L.)					
$\mathcal{B}(\tau \to \mu\gamma)$ [10^{-9}]	45	10	5	-	-
$\mathcal{B}(\tau \to \mu\eta)$ [10^{-9}]	65	5	2	-	-
$\mathcal{B}(\tau \to \mu\mu\mu)$ [10^{-9}]	21	3	1	-	-

Belle II Physics Sensitivity





Sensitivity to LFV