Search for $B^0_{s(d)} \rightarrow \mu^+\mu^-$ at CMS

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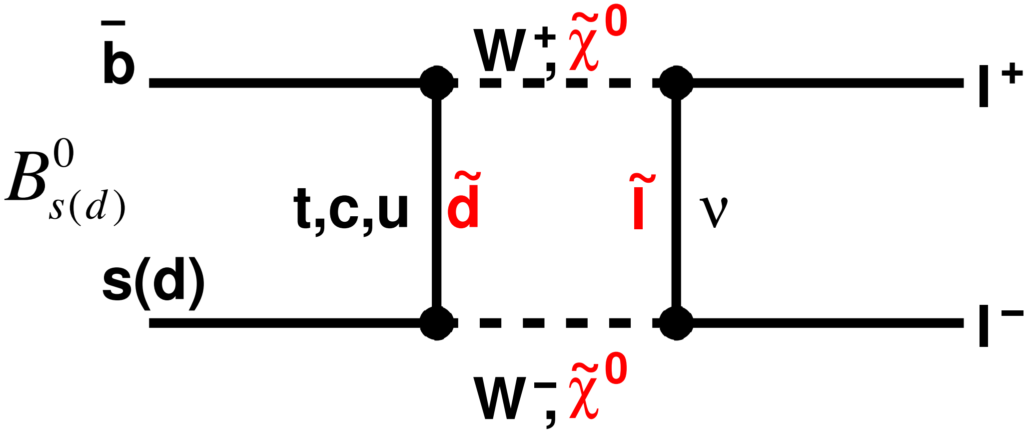
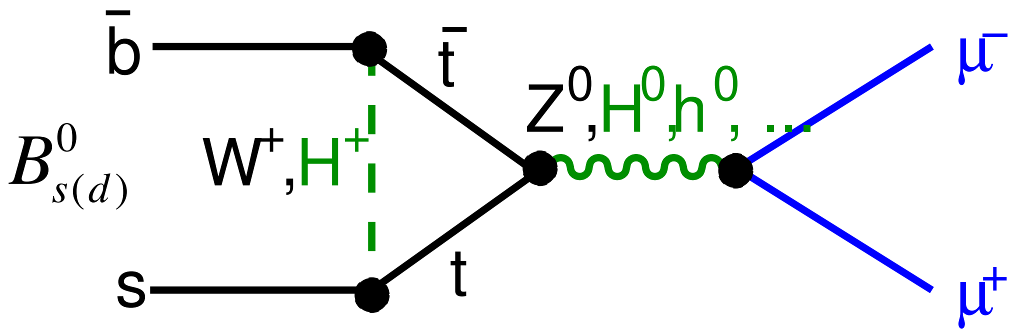
Motivation: sensitivity to new physics

- The rare flavor changing neutral current decays are highly suppressed in the SM

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$$

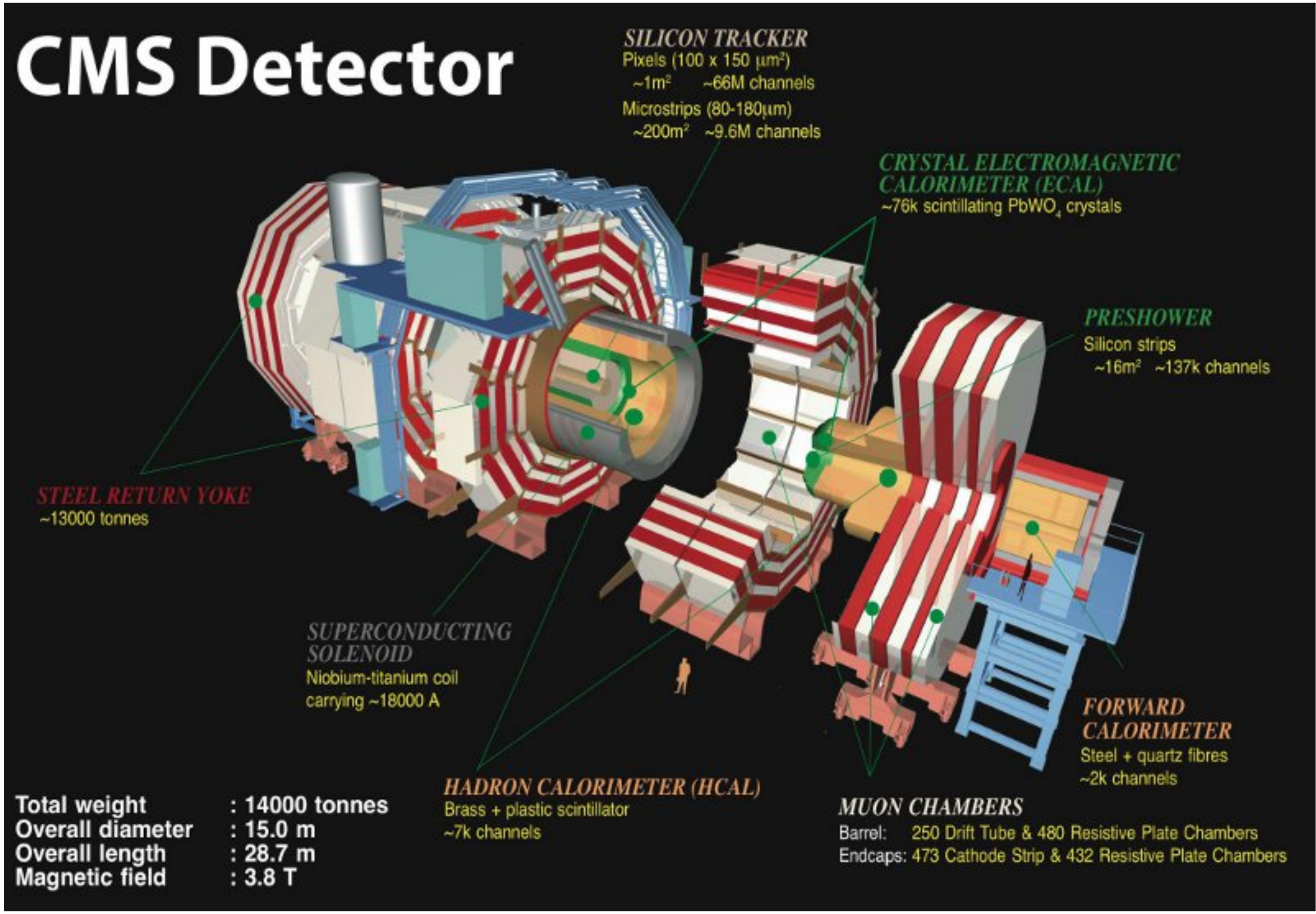




- New physics scenarios can significantly enhance the BR's
  - In MSSM BR ∝ $(\tan\beta)^6$
  - Especially sensitive to models with extended Higgs sectors
- Small theoretical uncertainties and high sensitivity to NP make this a Golden Channel

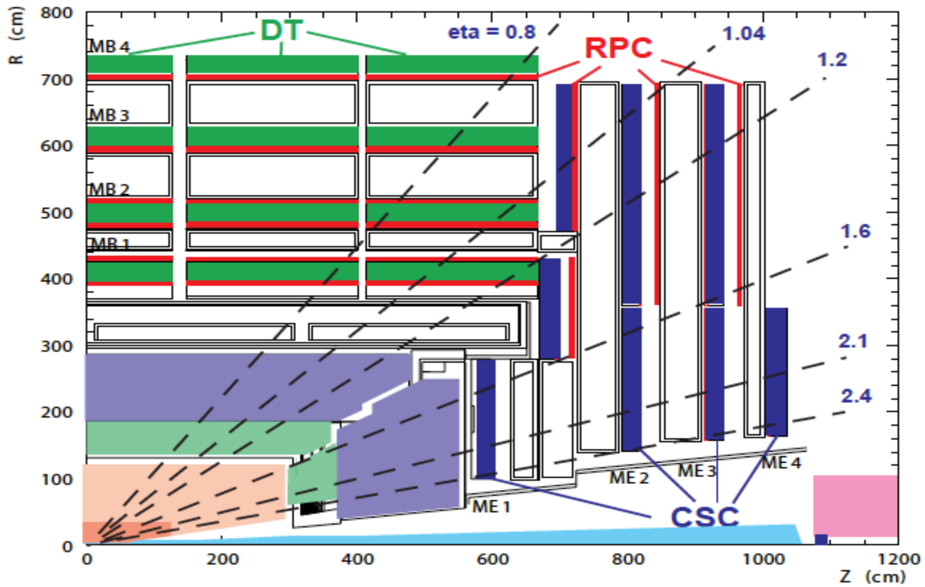
The CMS detector

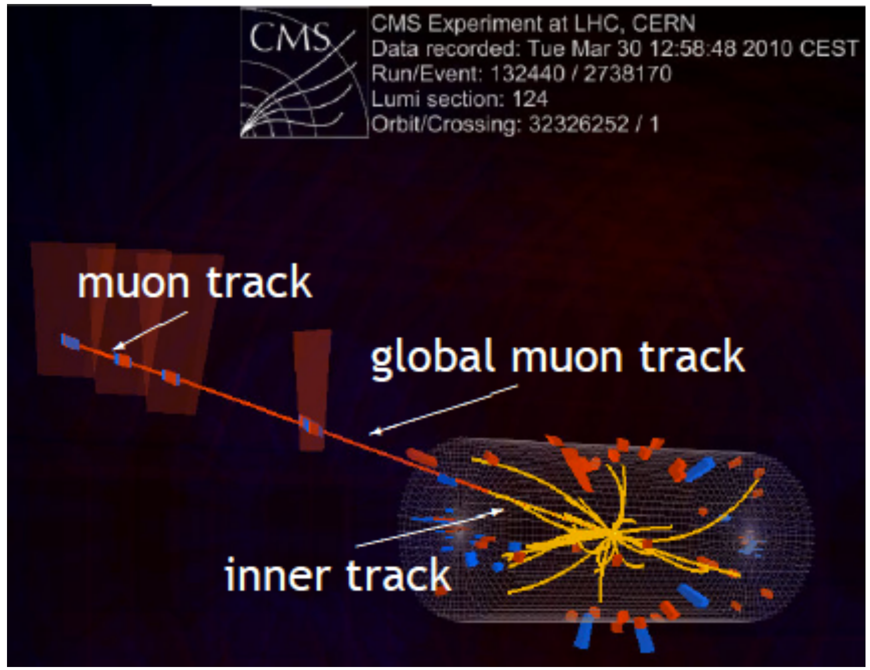
- All silicon inner tracker with p_T resolution ~1% and d_0 resolution ~20 μm for tracks in this analysis
- Tracking efficiency > 99% for central muons
- Redundant muon system triggers and records muons with $p_T > 3$ GeV and $|\eta| < 2.4$



Muon reconstruction

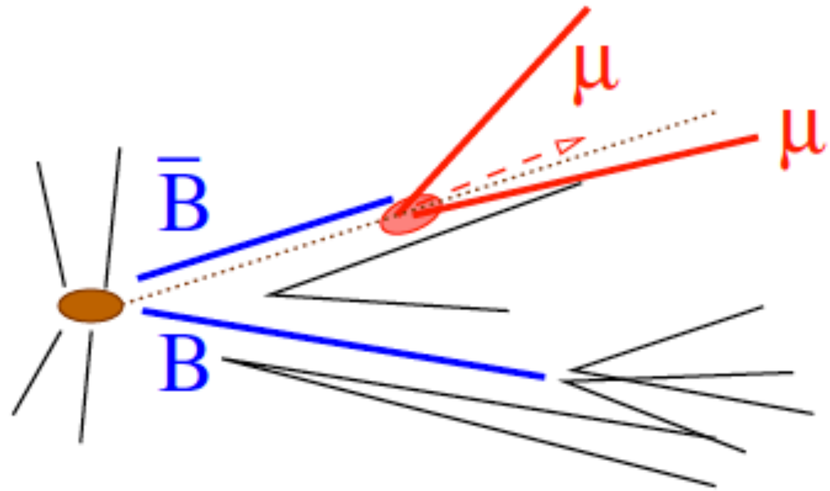
- Muons reconstructed with three detector technologies
  - Drift tubes
  - Cathode strip chambers
  - Resistive plate chambers
- Muons required to be found by each of two reconstruction algorithms
  - Outside-in: stand alone track in muon system matched to a compatible track in silicon tracker
  - Inside-out: silicon track matched to compatible hits in muon system
- Low muon mis-ID rates
  - $< 0.3\%$ for pions and kaons
  - $< 0.05\%$ for protons

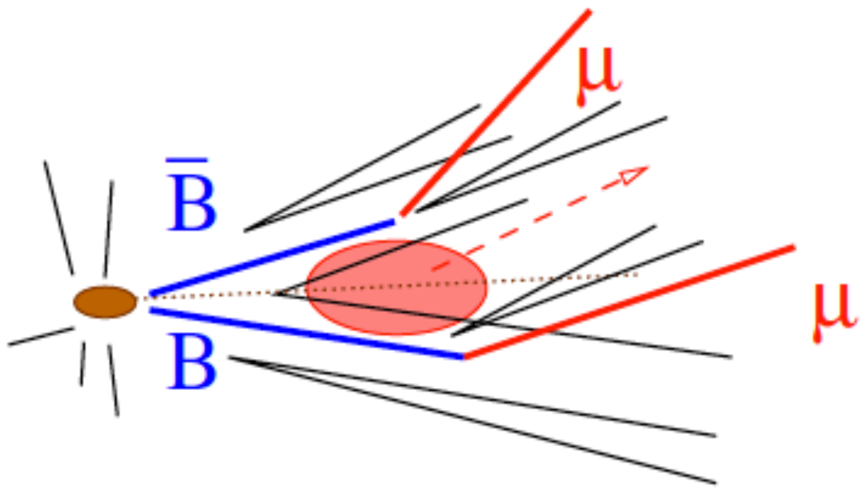




Analysis overview

- Signal
  - Clean B decay with only 2 muons
  - Long-lived B produces well separated vertex
- Background
  - 2 semi-muonic B decays
  - A semi-muonic B decay plus a misidentified charged hadron
  - Rare single B decays, such as
    - $B_s^0 \to K^- K^+$ (peaking)
    - $B_s^0 \to K^- \mu^+ \nu$ (non-peaking)

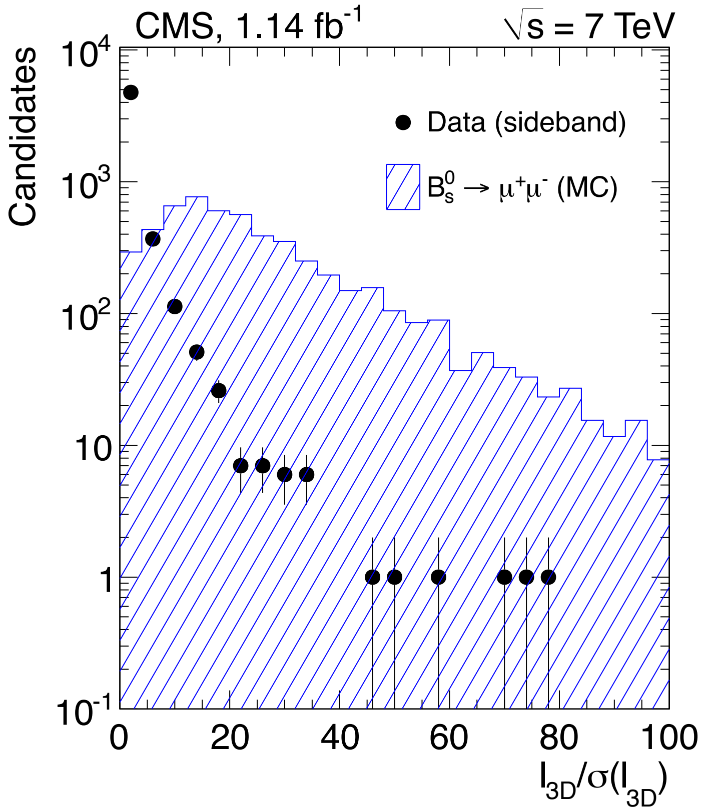


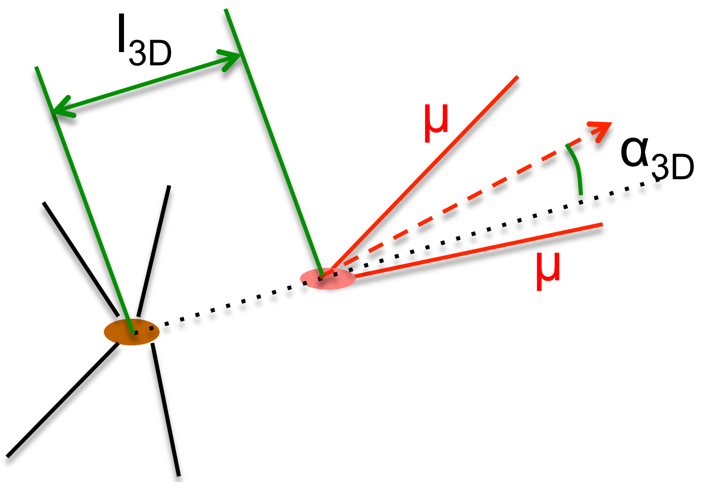


- Main handles: good dimuon vertex; correct B mass; momentum pointing to interaction point

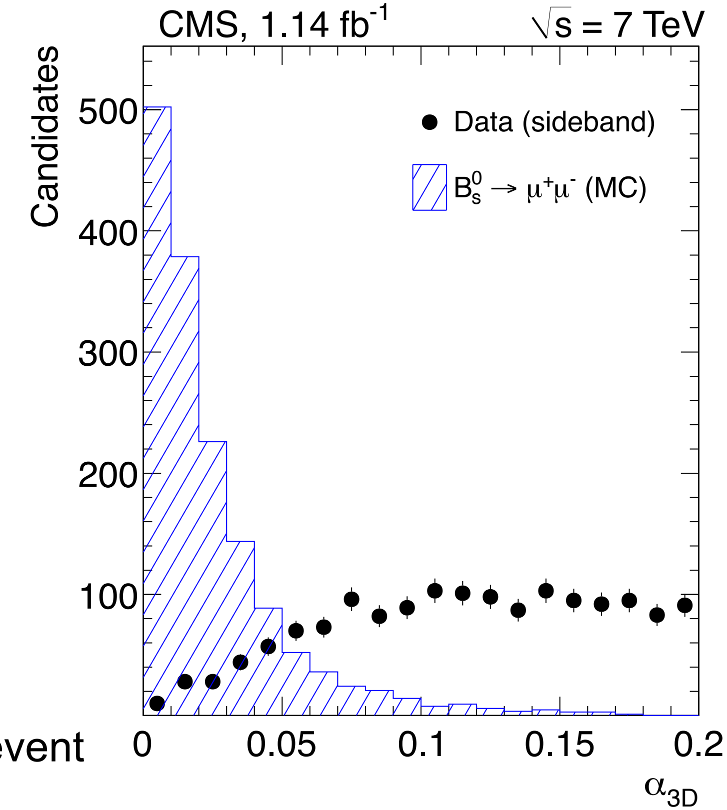
Signal selection

- Mass windows: 5.2-5.3 GeV for B^0 and 5.3-5.45 GeV for B_s^0
- Split into barrel (both $|\eta_\mu| < 1.4$) and endcap channels
- $l_{3D} > 15$ or $20\ \sigma$, $\alpha_{3D} < 0.050$ or 0.025
- $p_{T\mu} > 4.5$ or 4.0 GeV, $p_{TB} > 6.5$ GeV,
- B fit $\chi^2/\mathrm{dof} < 1.6$, dca min > 0.15 mm (endcap only), isolation (next slide)





- Select best primary vertex based on consistency with B candidate momentum direction
- Average of 5.5 primary vertices per event

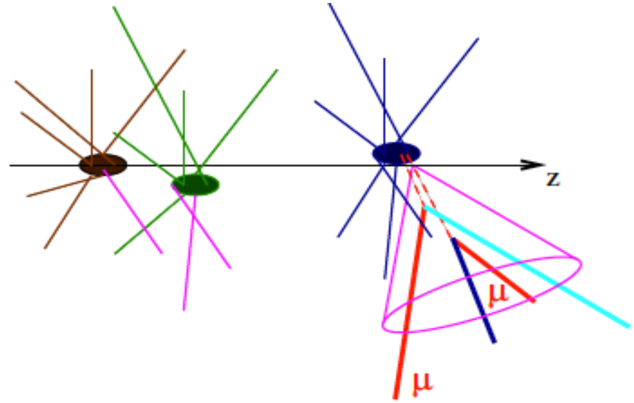


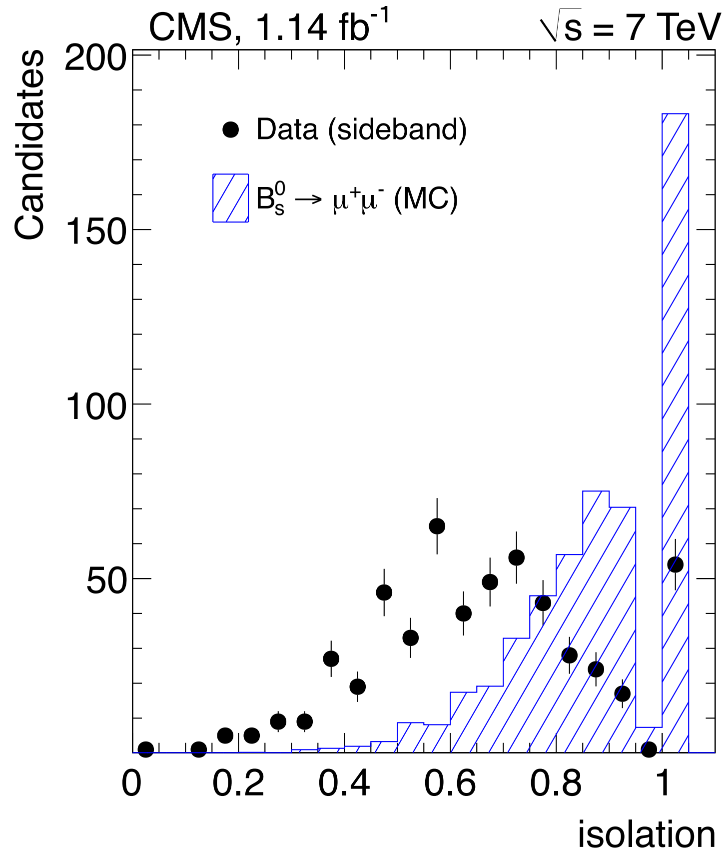
Signal selection: isolation

- Require relative isolation of muon pair

$$I = \frac{p_\perp(\mu^+\mu^-)}{p_\perp(\mu^+\mu^-) + \sum_{\Delta R<1} p_\perp}$$

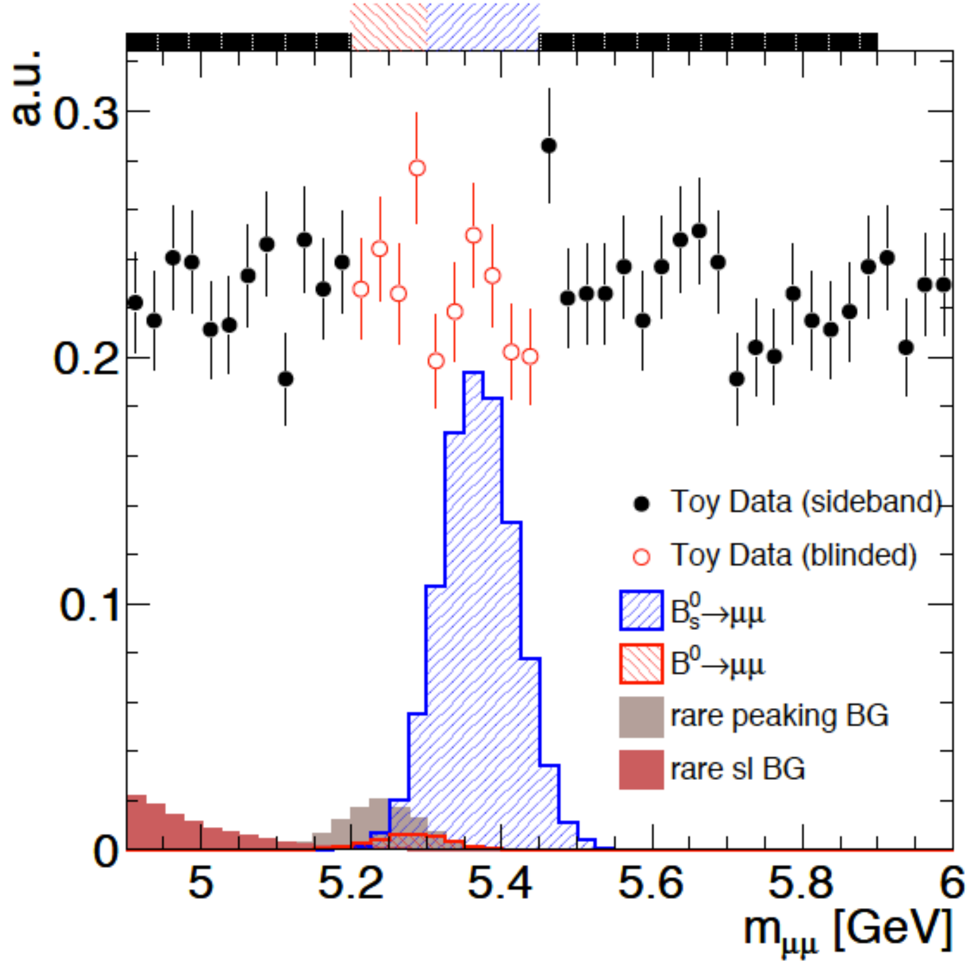
  - Cone of $\Delta R = 1$ around the dimuon momentum
  - Include all tracks with $p_T > 900$ MeV from same primary vertex or within 500 µm of B vertex
  - Require isolation > 0.75
- All selection criteria have been optimized for limit sensitivity with a grid search before unblinding signal region





Background estimation

- Non-peaking background measured in data
  - Count events in B mass sidebands 4.80-5.20 GeV and 5.45-6.00 GeV
  - Interpolate to signal region with assumption of flat shape
- Peaking background obtained from MC with inputs from data
  - $B \rightarrow hh$ backgrounds with two muons from misidentified charged hadrons peak in B mass
  - Measure muon mis-ID rates in data from identified $K_S \rightarrow \pi\pi$, $\phi \rightarrow KK$ and $\Lambda \rightarrow p\pi$ samples



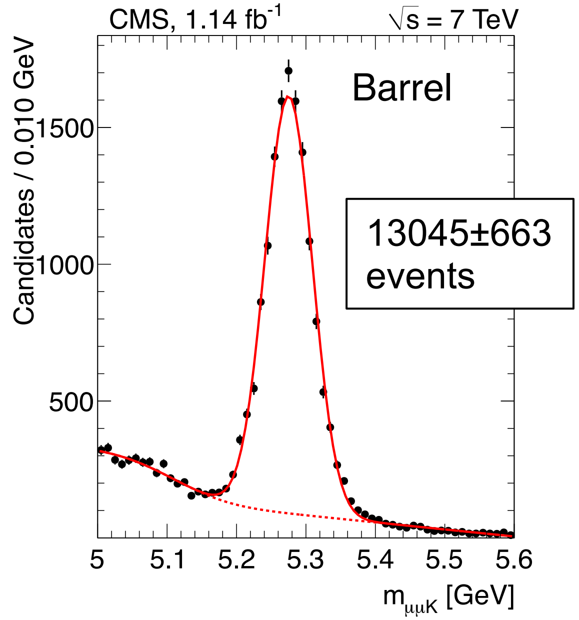
  - Use MC without muon selection cuts to simulate backgrounds and apply fake rate measurements from data
  - Affects B^0 more than B_s^0 because backgrounds peak low

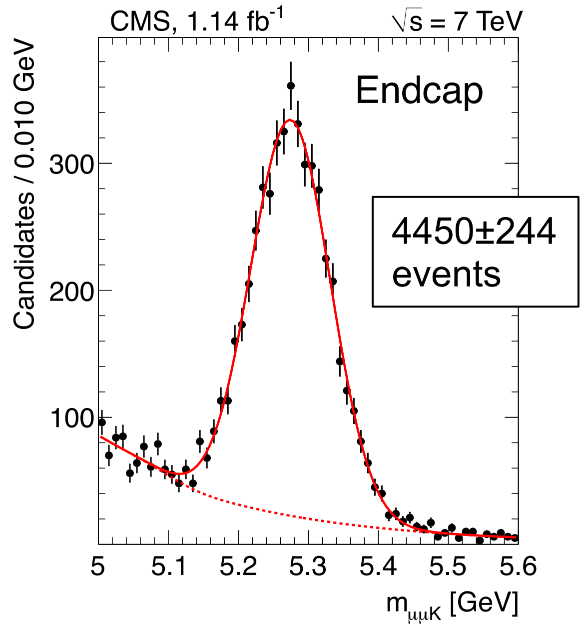
BR calculation: normalized to B^+

- Measure $B_s^0 \to \mu^-\mu^+$ branching fraction relative to normalization channel $B^+ \to J/\Psi(\mu^-\mu^+)K^+$
  - Reduce many systematic effects with similar reconstruction and triggering techniques

$$\boxed{B(B_s^0 \to \mu\mu) = \frac{N(B_s^0 \to \mu\mu)}{N(B^+ \to J/\Psi K)} \times \frac{\varepsilon_{B^+}}{\varepsilon_{B_s}} \times \frac{f_u}{f_s} \times B(B^+ \to J/\Psi K)}$$

- $B(B^+ \to J/\Psi K)$ is well known and relatively large
- Take f_u/f_s from PDG
- Only need relative efficiency terms
- No need for absolute luminosity measurement
- Same reconstruction cuts for B^+, plus require two muons bend away from each other to aid trigger efficiency calculation



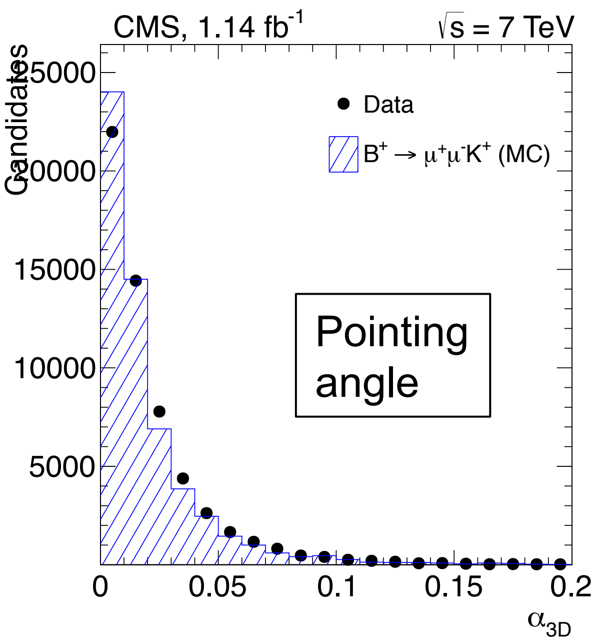


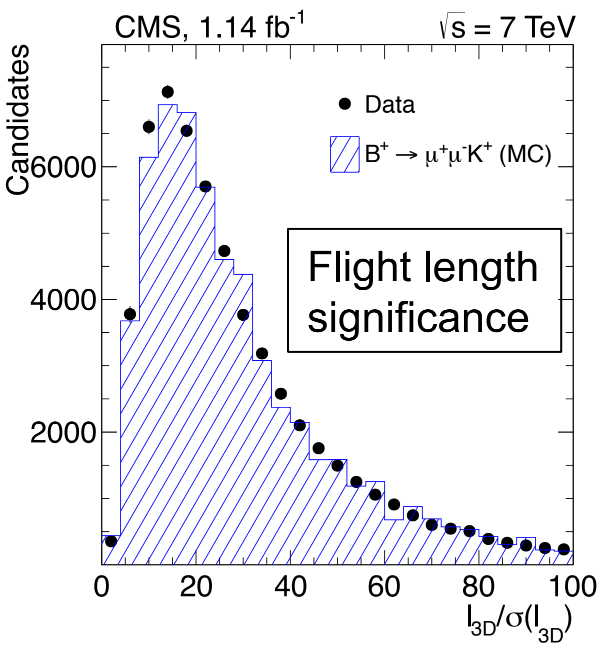
Selection efficiency

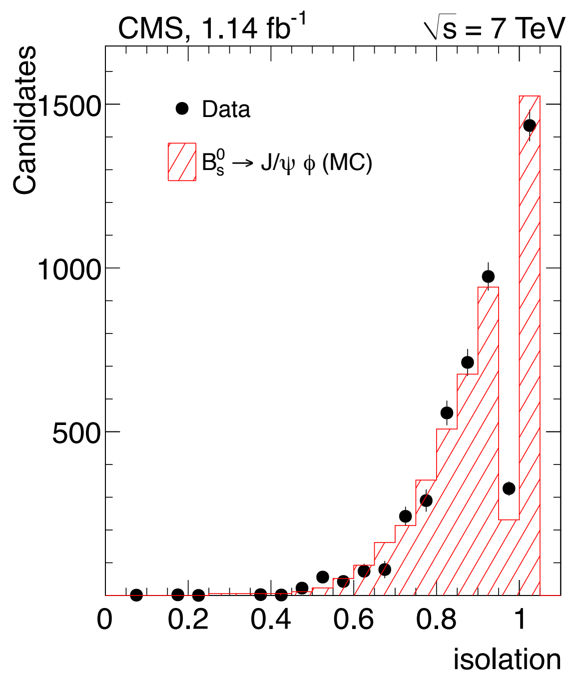
- Signal and normalization efficiencies calculated in MC
  - Overall signal efficiency 0.4% in the barrel and 0.2% in the endcap
  - Overall normalization efficiency 0.08% (0.03%) in the barrel (endcap)
- Validate MC performance with control samples:

$$B_s^0 \to J/\Psi(\mu^-\mu^+)\phi \qquad\qquad B^+ \to J/\Psi(\mu^-\mu^+)K^+$$

- Good agreement observed
- Residual differences used as systematics







Trigger efficiency

- Signal trigger
  - Opposite charge muons with mass 4.8-6.0 GeV
  - $p_{T\mu}$> 2 GeV, $p_{T\mu\mu}$ > 4 GeV
- Normalization trigger
  - Opposite charge muons with mass 2.9-3.3 GeV
  - $p_{T\mu}$> 3 GeV, $p_{T\mu\mu}$ > 6.9 GeV
  - cos α > 0.9, $\mu\mu$ vertex fit probability > 0.5%
- Trigger efficiency measured after selection cuts ≈ 80%
  - Stable with time
  - Measured in MC
  - Cross checked with measurement in data

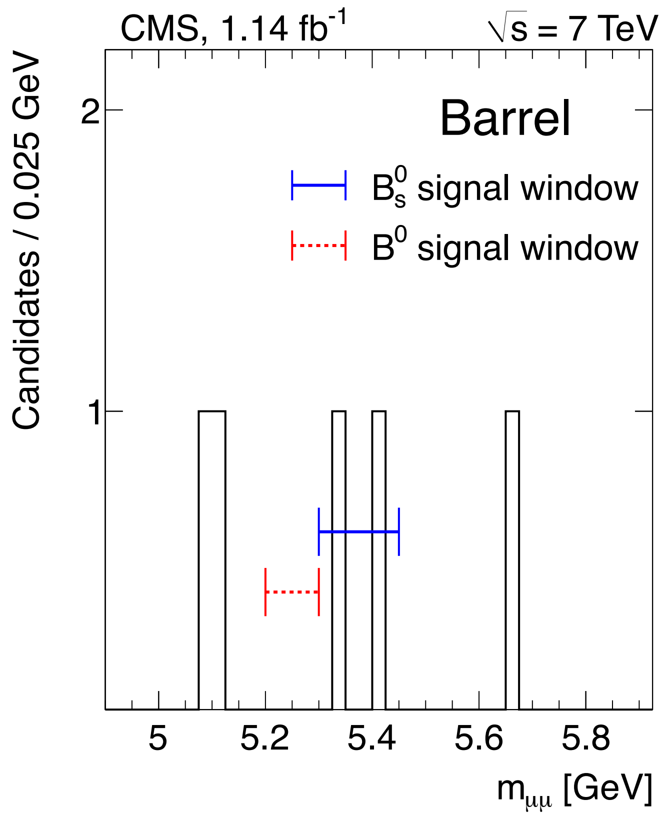
Systematic uncertainties

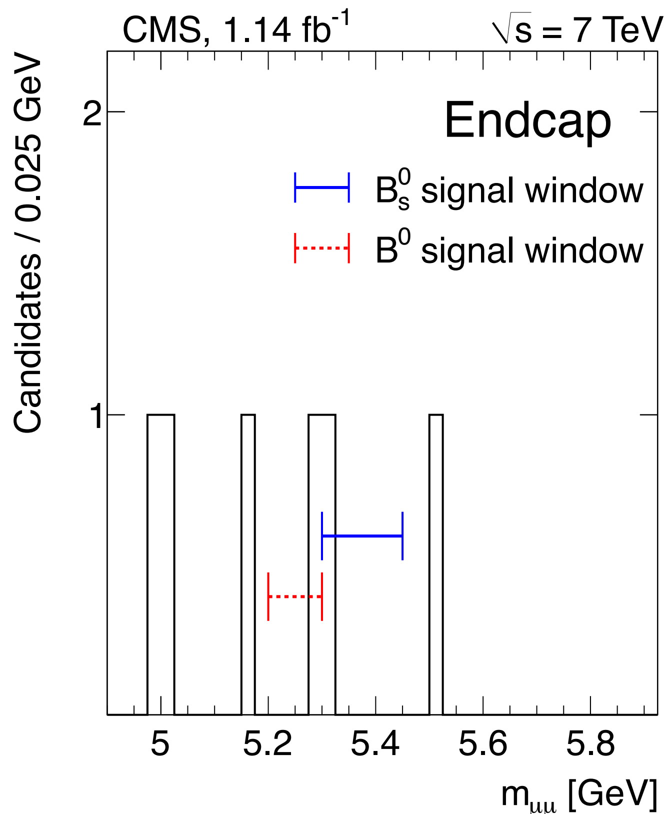
Fragmentation functions from PDG	13%
Background	4%
- Loosened selection cuts; inverted isolation studies	
Signal	
- Acceptance: variation from different bb production processes	4%
- Selection efficiency: comparison of data and MC cut by cut	8%
- Track momentum scale: from J/ψ resonance reconstructed mass	3%
Normalization	
- Selection efficiency: comparison of data and MC cut by cut	5%
- Hadron track efficiency: from data with D^* decay studies	4%
- Yield fits: variation of fitting functions	5%
Muon identification and trigger	
- Evaluated from data/MC differences	
- Muon identification efficiency ratio	5%
- Trigger efficiency ratio	3%
Total	19%

Results

	Barrel		Endcap	
	$B^0 \to \mu^+\mu^-$	$B^0_s \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$	$B^0_s \to \mu^+\mu^-$
ε_{tot}	$(3.6 \pm 0.4) \times 10^{-3}$	$(3.6 \pm 0.4) \times 10^{-3}$	$(2.1 \pm 0.2) \times 10^{-3}$	$(2.1 \pm 0.2) \times 10^{-3}$
N^{exp}_{signal}	0.065 ± 0.011	0.80 ± 0.16	0.025 ± 0.004	0.36 ± 0.07
N^{exp}_{comb}	0.40 ± 0.23	0.60 ± 0.35	0.53 ± 0.27	0.80 ± 0.40
N^{exp}_{peak}	0.25 ± 0.06	0.07 ± 0.02	0.16 ± 0.04	0.04 ± 0.01
N_{obs}	0	2	1	1

- Observation consistent with expectation from background + SM signal in all 4 channels





Branching fraction upper limits

- Upper limits for $B_s^0 \to \mu^- \mu^+$ and $B^0 \to \mu^- \mu^+$ computed with CLs

$$\begin{array}{lcll}
\mathcal{B}(B_s^0 \to \mu^+\mu^-) & < & 1.9 \times 10^{-8} & (95\%\,\mathrm{C.L.}) \\
\mathcal{B}(B_s^0 \to \mu^+\mu^-) & < & 1.6 \times 10^{-8} & (90\%\,\mathrm{C.L.}) \\
\mathcal{B}(B^0 \to \mu^+\mu^-) & < & 4.6 \times 10^{-9} & (95\%\,\mathrm{C.L.}) \\
\mathcal{B}(B^0 \to \mu^+\mu^-) & < & 3.7 \times 10^{-9} & (90\%\,\mathrm{C.L.})
\end{array}$$

Submitted to PRL
arXiv:1107.5834

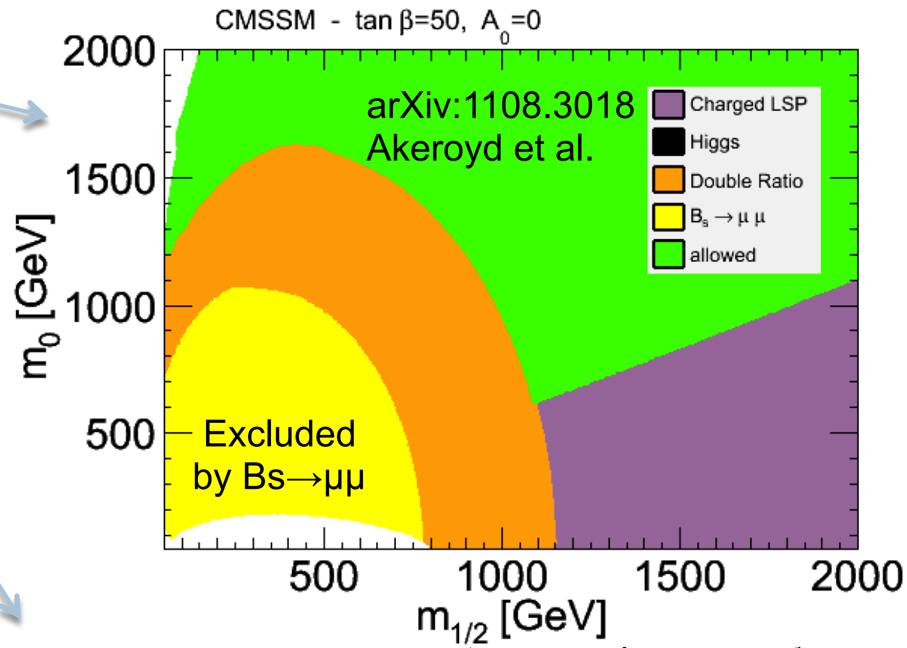
- Expected 95% upper limits: 1.8×10^{-8} for B_s^0
  4.8×10^{-9} for B^0
- Background-only p values: 0.11 for B_s^0 (1.2 σ)
  0.40 for B^0 (0.3 σ)
- p value for CDF B_s^0 result (5.6×SM) = 0.05

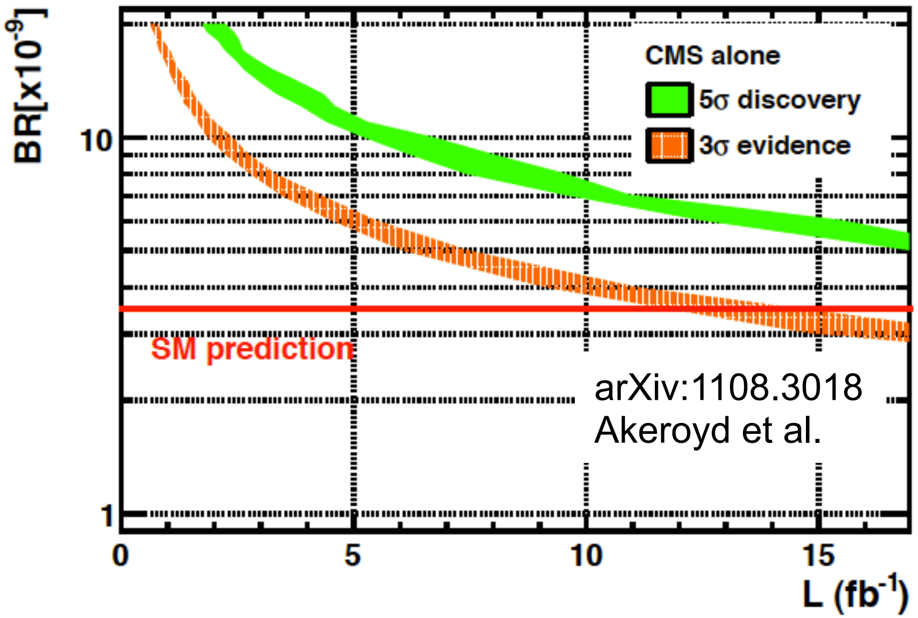
Combination with LHCb

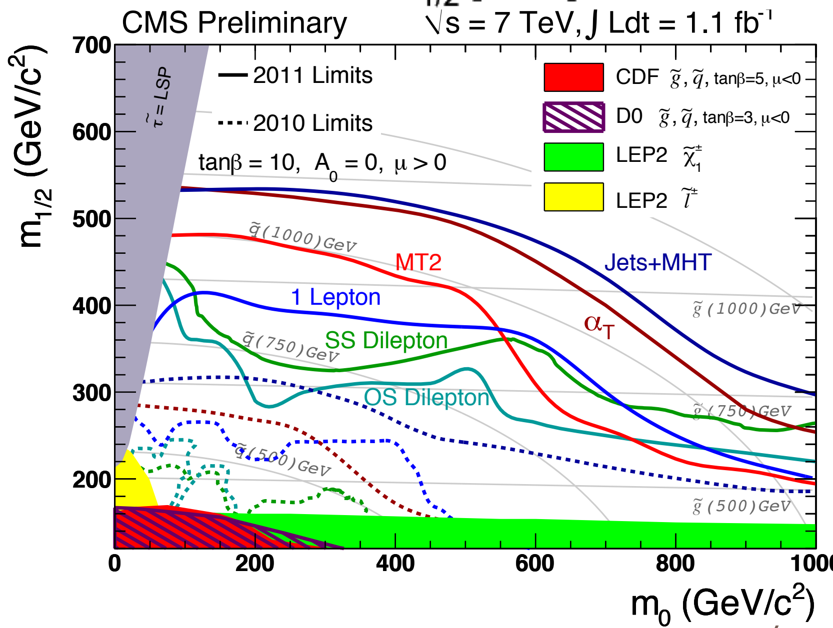
- The two LHC results for $B_s^0 \to \mu^- \mu^+$ have been combined to produce an upper limit of 1.1×10^{-8} at 95% confidence
- All uncertainties treated as uncorrelated, except for f_s/f_d, which is taken to be 100% correlated between the measurements
- Same CL_s upper limit procedure as used for CMS and LHCb results independently
- Background-only p value = 8%, background plus SM signal p value = 55%, CDF central value p value = 0.3%
- Public as CMS PAS BPH-11-019

Prospects and interpretation

- New limit constrains CMSSM parameter space beyond direct searches for many large tan β scenarios
  - Dependent on A_0 (see talk by C. Beskidt)
- Standard model branching fraction projected to be within reach in the next few years





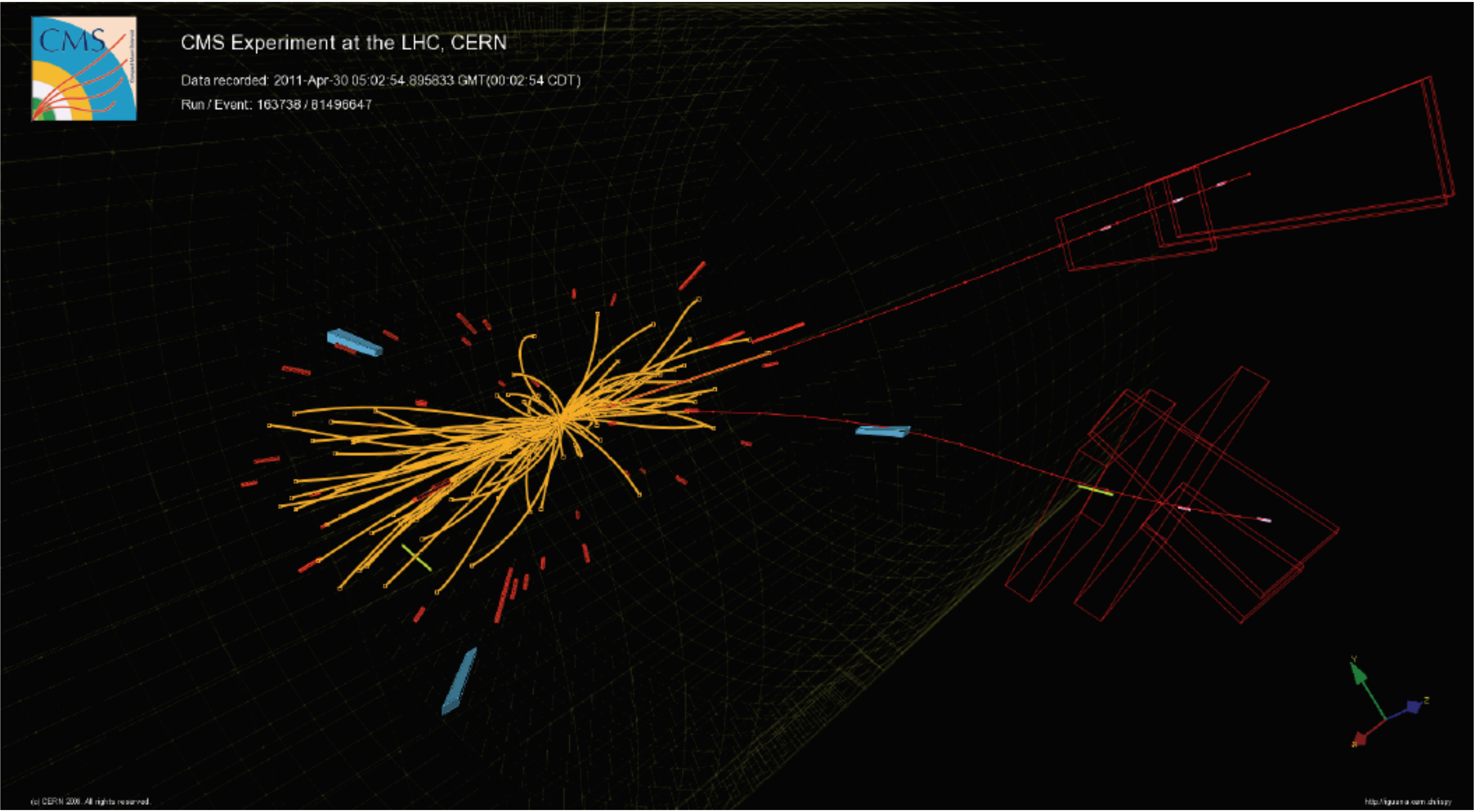


Conclusion

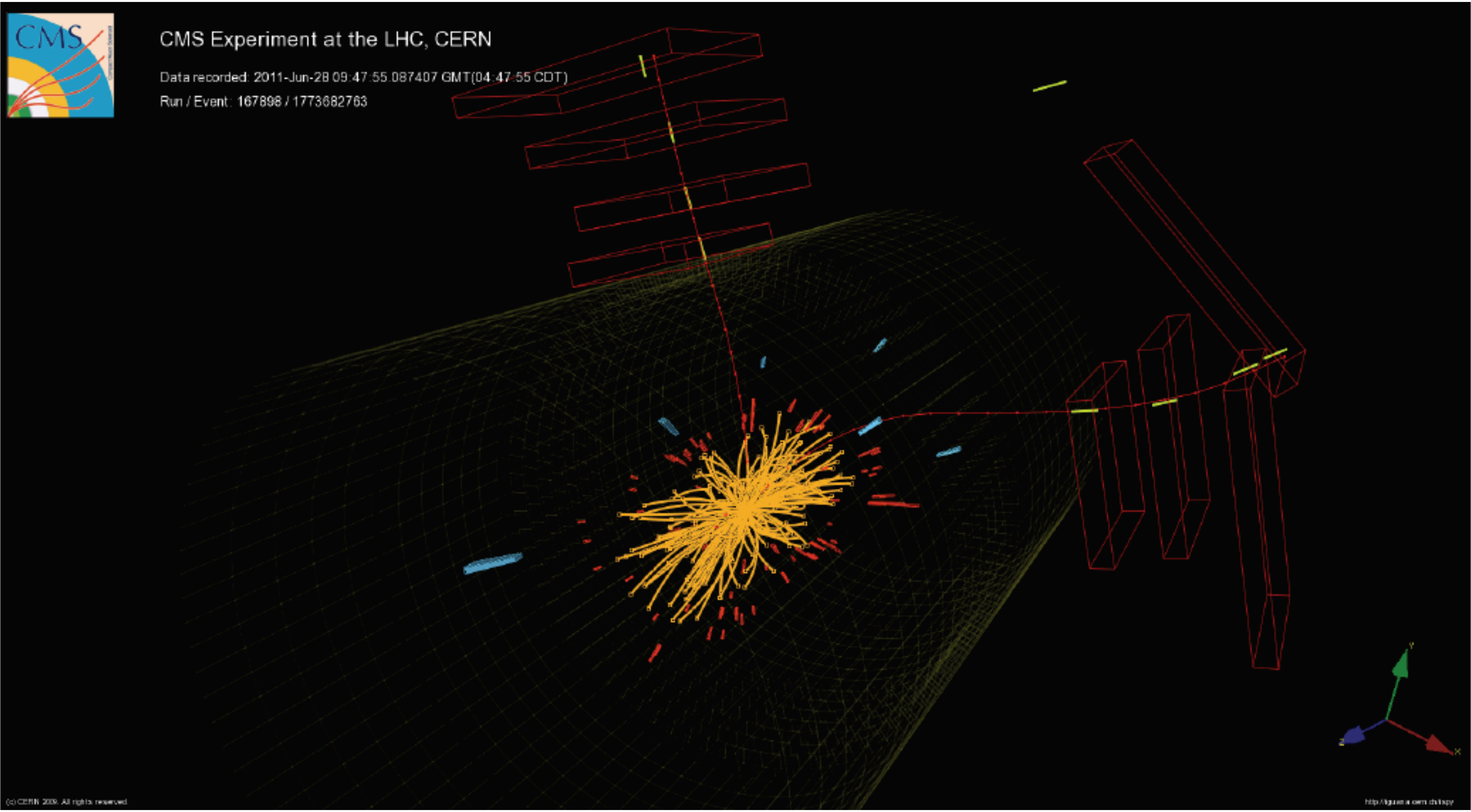
- First results from CMS presented for the search for the rare decays $B_s^0 \to \mu^-\mu^+$ and $B^0 \to \mu^-\mu^+$
- No significant excess observed above expected background plus standard model signal
- Prospects for future updates are bright
  - LHC luminosity increasing very rapidly
  - Multivariate analysis will replace cut-n-count
  - Current combined LHC limit at 95% confidence is just 3.4 times the SM branching fraction—still room left for new physics, but it's closing fast

Extra slides

Candidate event

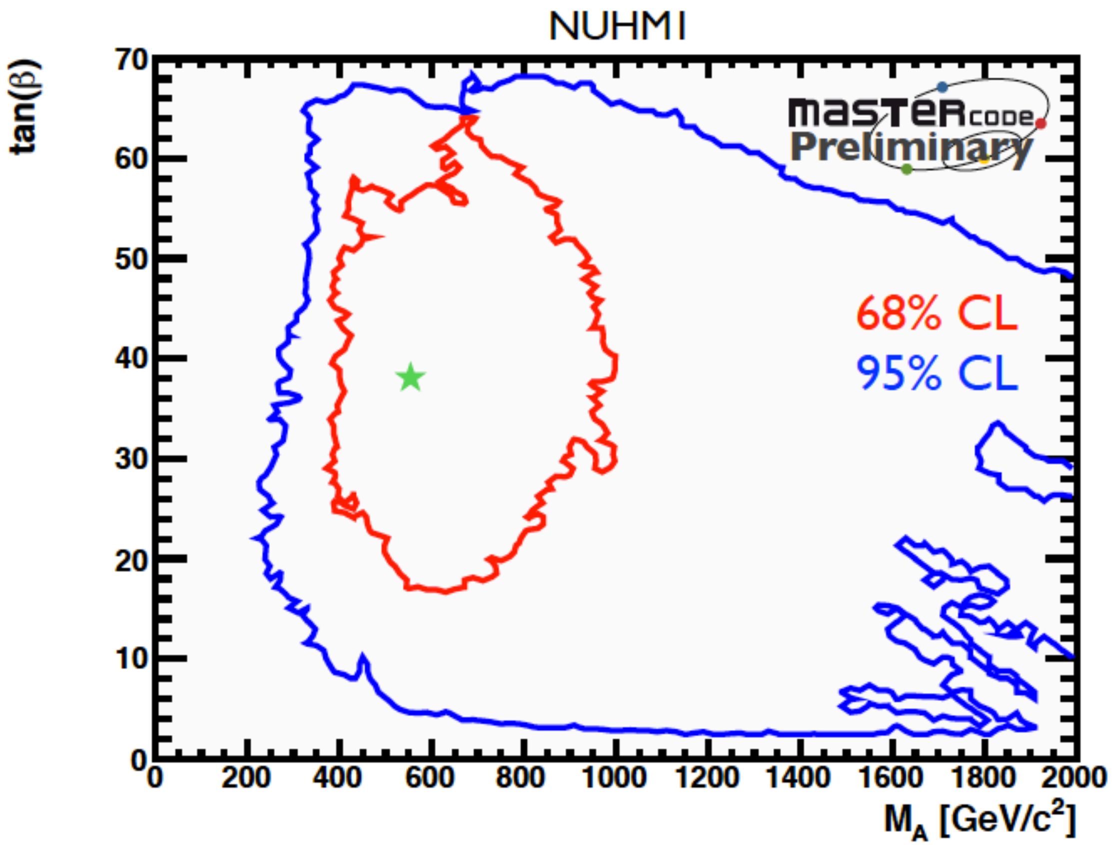


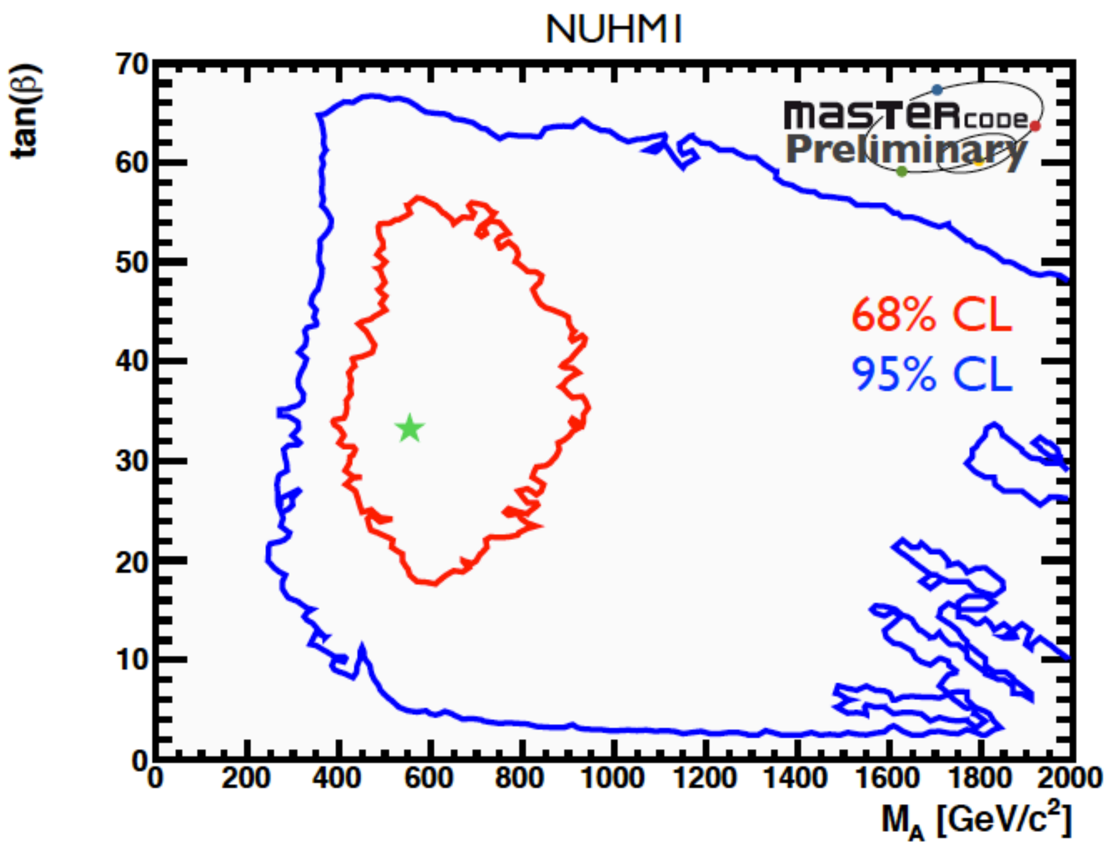
Candidate event



Non-universal Higgs masses fits

- 2011 direct searches only on left
- 2011 direct + Bs→μμ on right

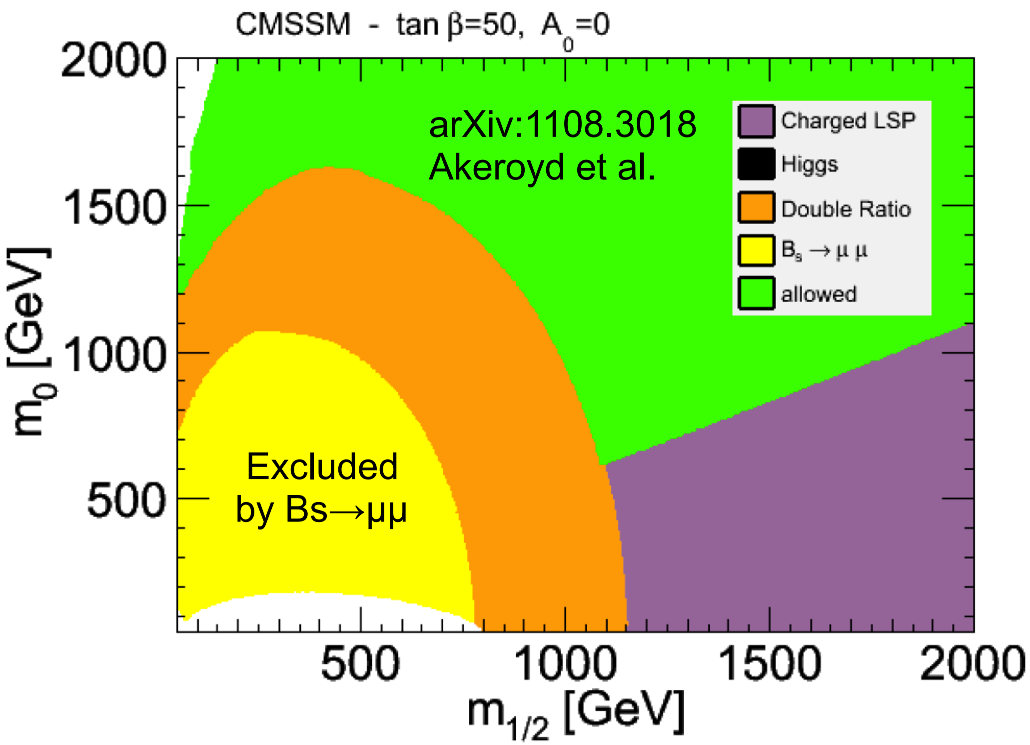


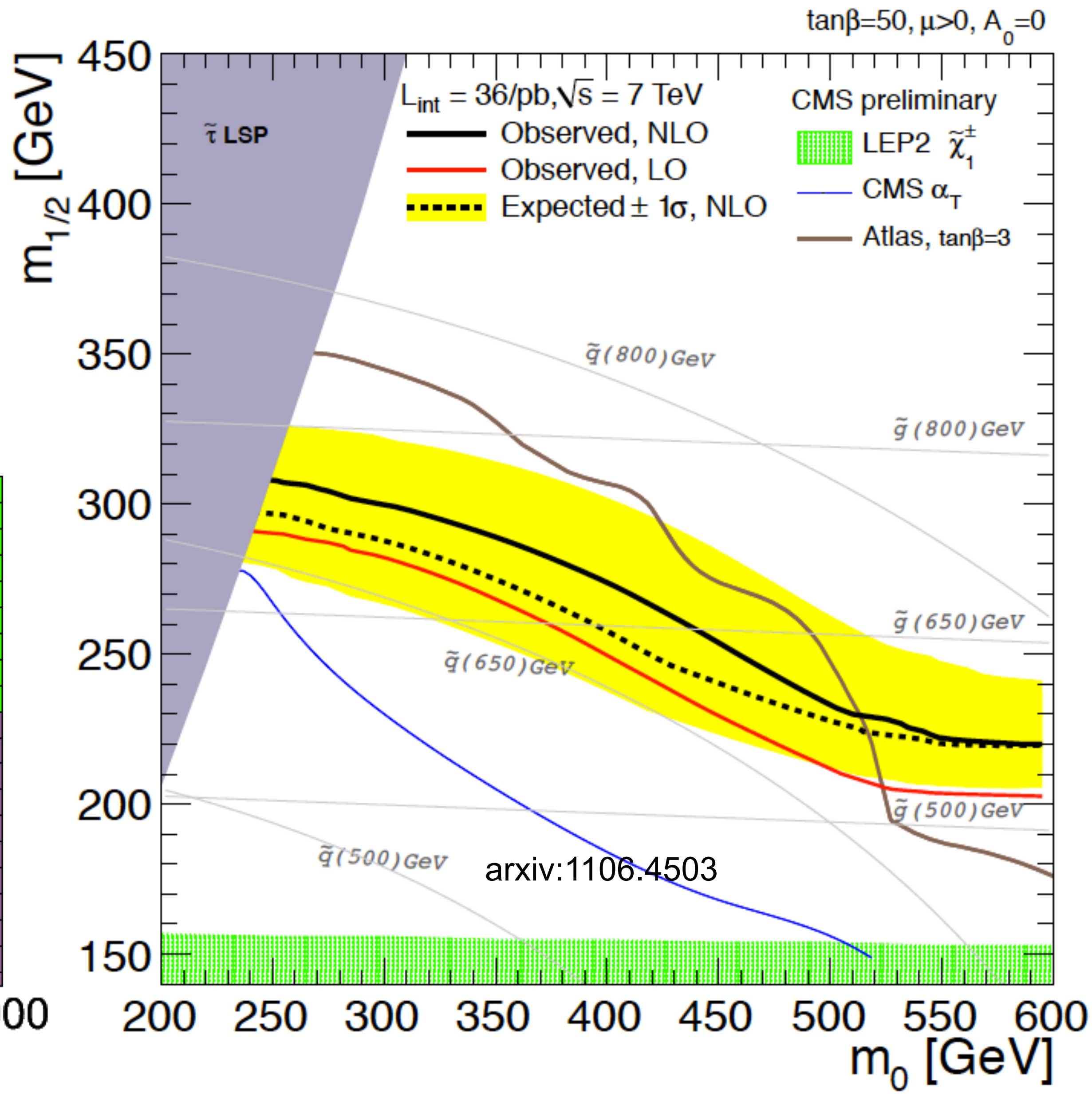


Frederic Ronga, Mastercode collaboration, Implications of LHC results

Comparison to direct searches

- 2010 tan β = 50 exclusion from direct CMS hadronic SUSY search





Pileup independence

- Check influence of multiple primary vertices on selection cuts: isolation and flight length significance
- No significant dependence found in signal MC or control sample data