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Felix Yu
JGU Mainz

Exploring the Physics Frontier with Circular Colliders, Aspen Center for Physics
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100 TeV!

- Within theory uncertainties, we'll have a large circular collider within the next few decades
  - Know the Standard Model is incomplete
  - Direct probe of the SM in new, uncharted territory
- Will quantify sensitivity improvements for dijet resonances compared to current and 14 TeV reach

  FY [1308.1077]
  - Z'_B (color singlet vector)
  - G' (color octet vector)
    - (*Quark compositeness, see L. Apanasevich, et. al. [1307.7149]*)
    - (*Level 2 KK gluon from UED, see K. Kong, FY [1308.1078]*)
    - (*RS gluon, see K. Agashe, et. al. [1310.1070]*)

Motivating dijets

- Dijets (and multijets) is the largest production rate at hadron colliders
- Experimentalist's standard candle
  - Detector response calibration
  - Most all NP searches rely on suppression of multijets
- Proving ground for testing collider reach
  - Sensitivity to new gauge bosons demonstrate impact of $\sqrt{s}$ and luminosity variation
- Dijet resonances are a standard signature in many BSM theories

For naturalness motivations, see N. Craig's talk

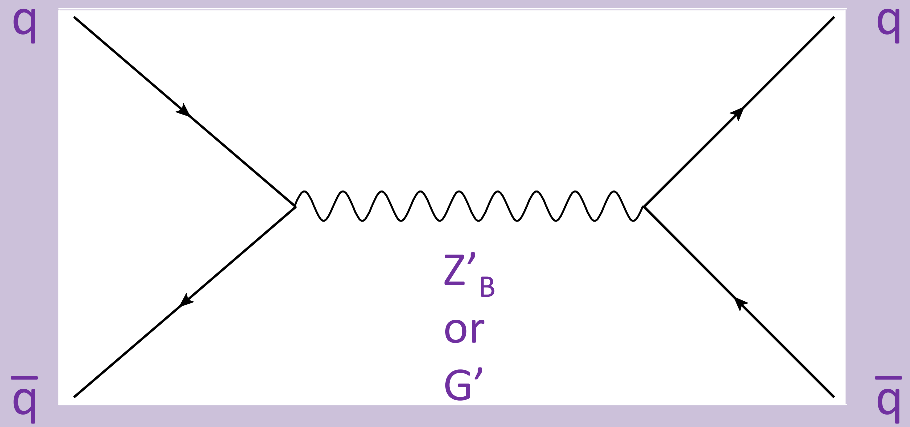
  - Focus on decay to quarks, complementary to leptonic decay

Dijet resonance models

- Many BSM models have additional gauge symmetry
  - Generic signature is a new vector resonance
  - An important class of models have leptophobic gauge bosons – adopt two flavor-universal benchmarks
    - Z'_B (baryon number coupled Z')
    - G' (coloron)
  - Z'_B is *s*-channel simplified model for DM production
- Separately, the simplest *s*-channel resonance at a high energy hadron collider is a dijet resonance
  - $q\bar{q}$ resonance
  - gg resonance: loop-induced (e.g. Higgs)
  - qg resonance: loop-induced
  - qq resonance: flavor constraints

Dijet resonance models

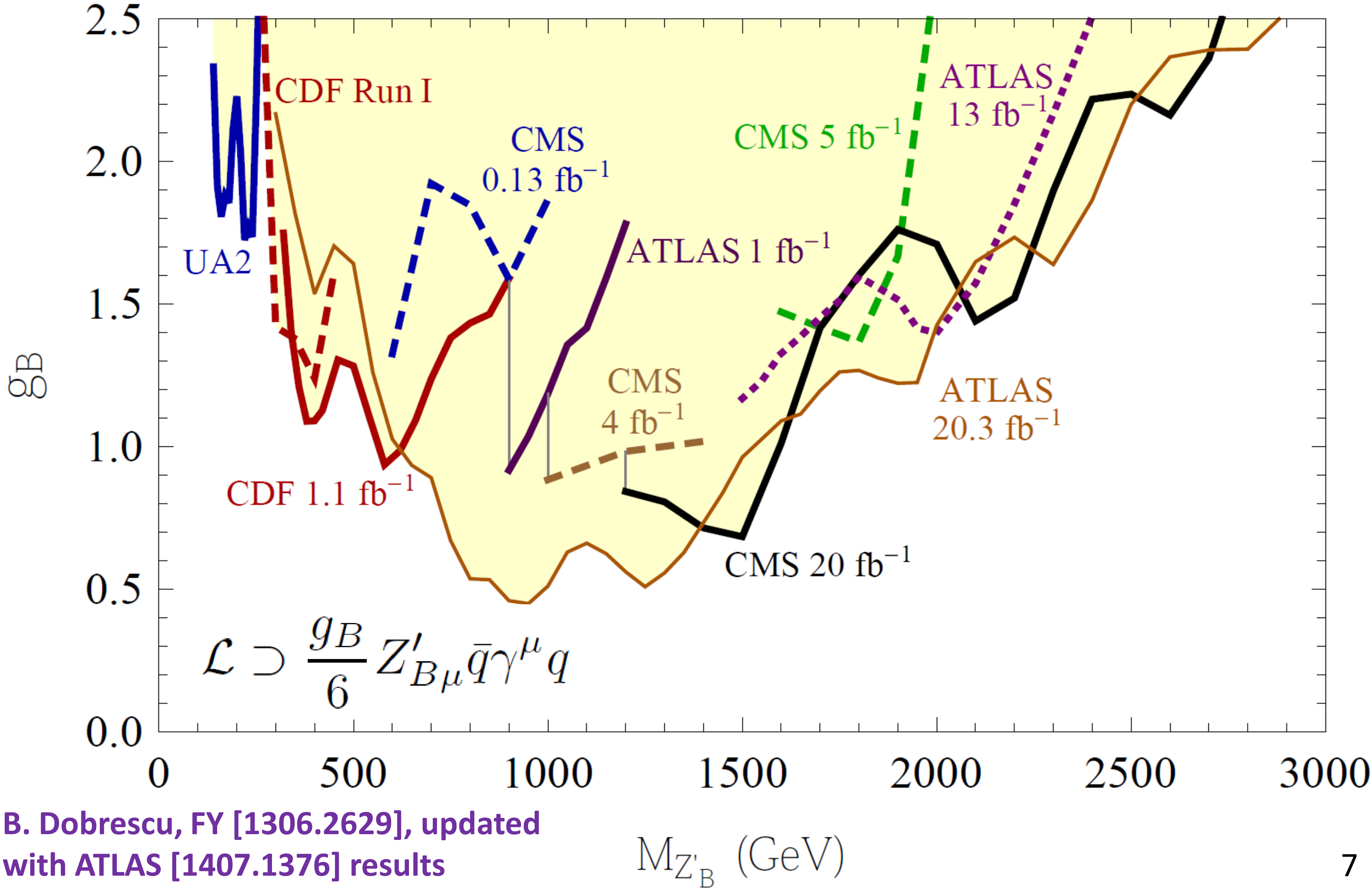
– Production and decay vertices use same coupling
– For $Z'_{B,}$ G' models, only have 2 parameters: **g** and **M**
  - Leptophobic, and no tree-level gluon coupling
  - Universal coupling to quarks – BR to jj (including $b\bar{b}$) only depends on mass
    – Interplay with $t\bar{t}$ resonance searches [*e.g.* RS gluon]
– Map effective rate (σ × Br × A) limits into **coupling vs. mass** plane



The coupling–mass mapping

- Higher energy colliders reach heavier resonances
  - But still probe weakly-coupled light resonances
  - Multijet trigger tracks run conditions
    - Leaves light dijet resonances relatively underprobed
- Fair comparison of different searches with different luminosities and colliders
- Simultaneously understand mass reach and coupling sensitivity

Current g_B vs. $M_{Z'}$ limits: Z'_B dijet resonance



B. Dobrescu, FY [1306.2629], updated with ATLAS [1407.1376] results

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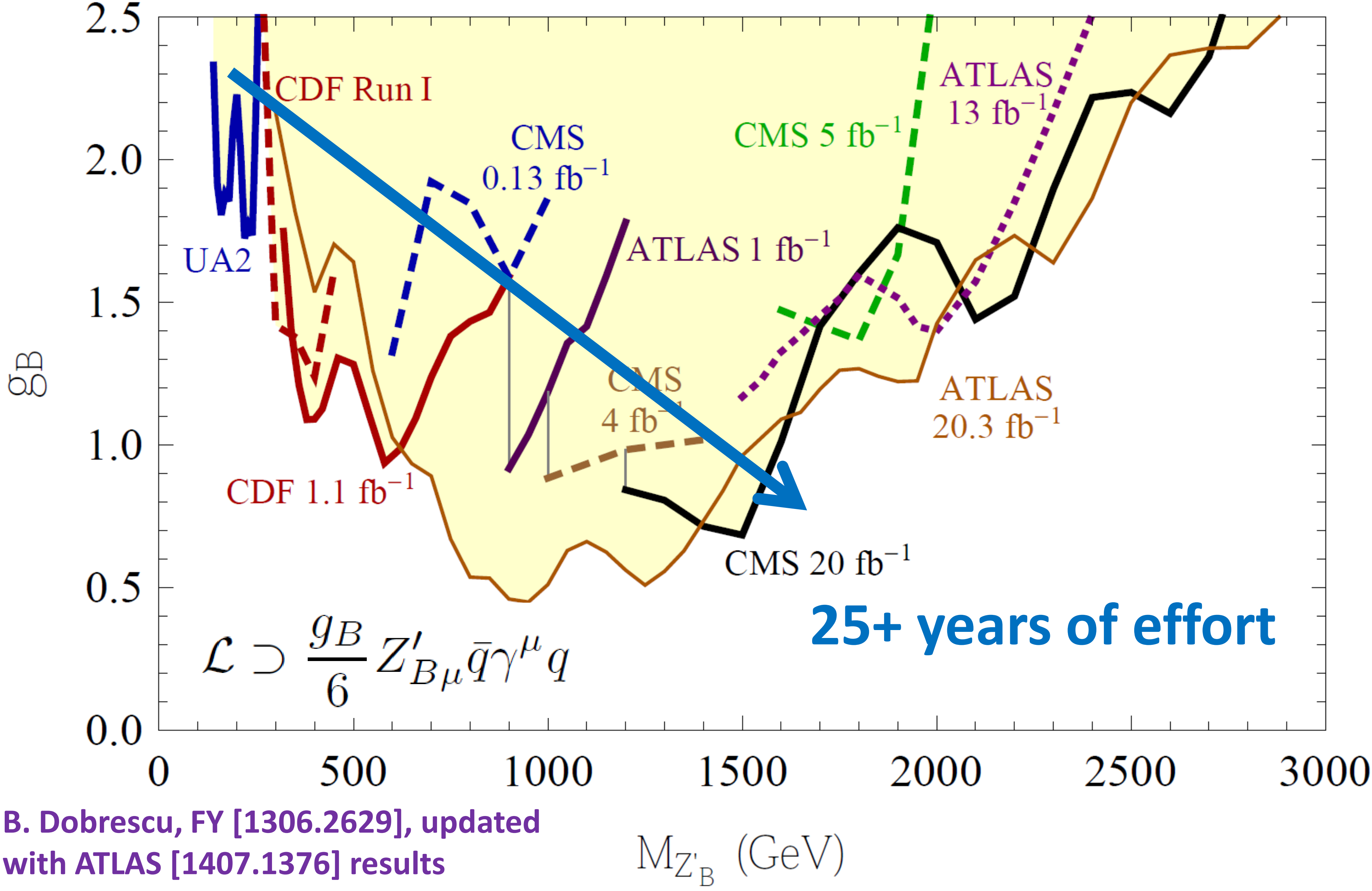
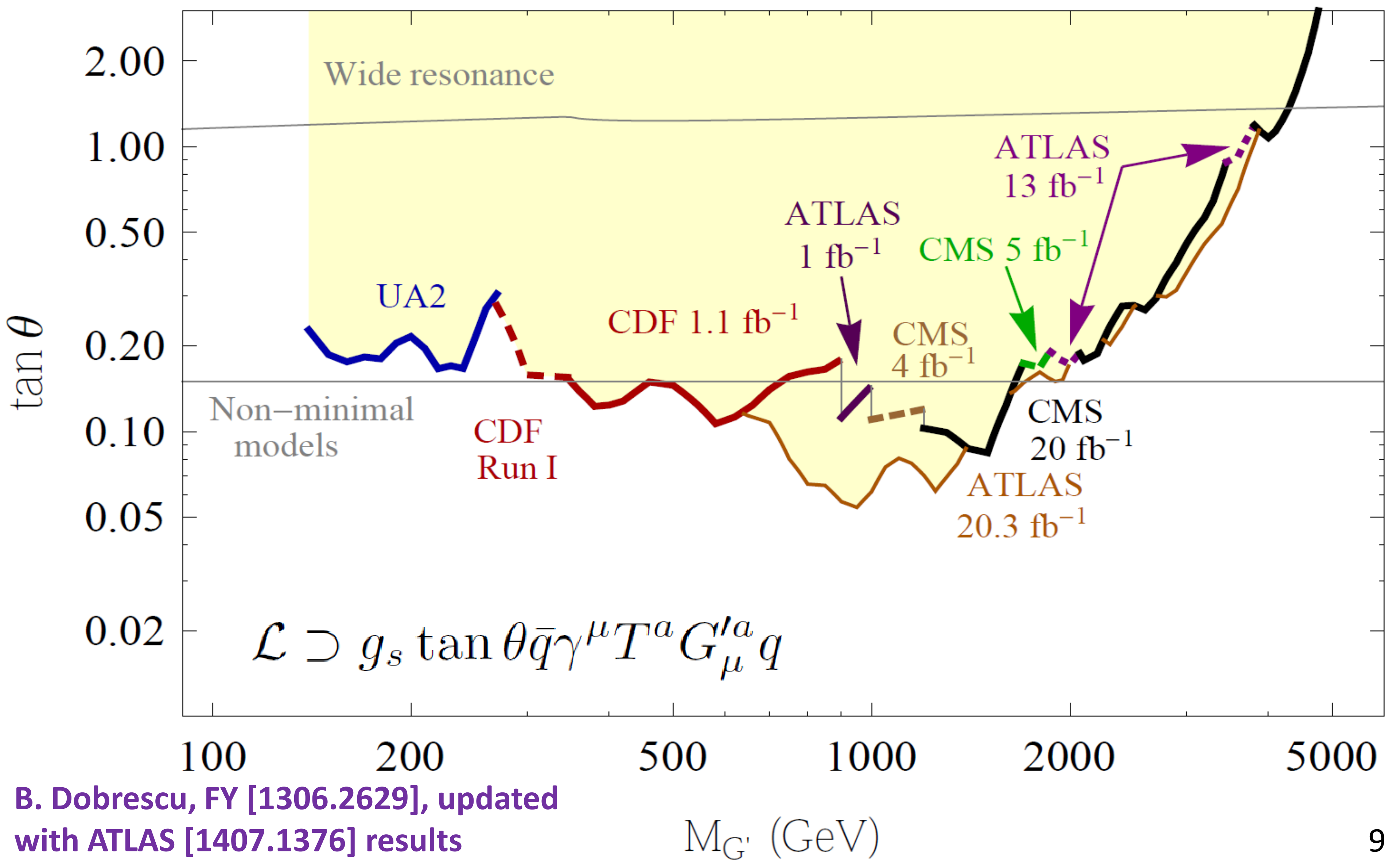


B. Dobrescu, FY [1306.2629], updated with ATLAS [1407.1376] results

Current tan θ vs. $M_{G'}$ limits: Coloron



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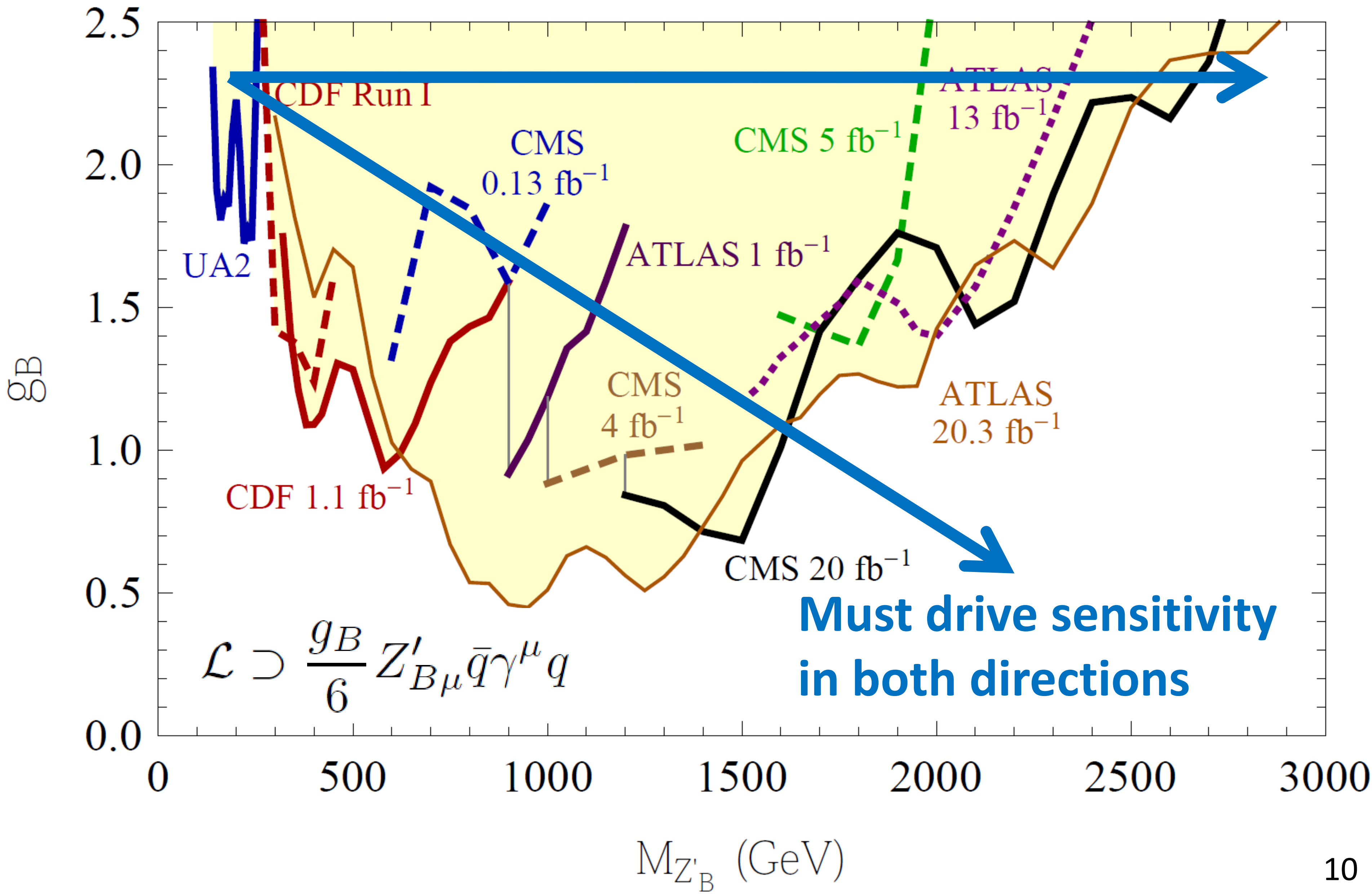
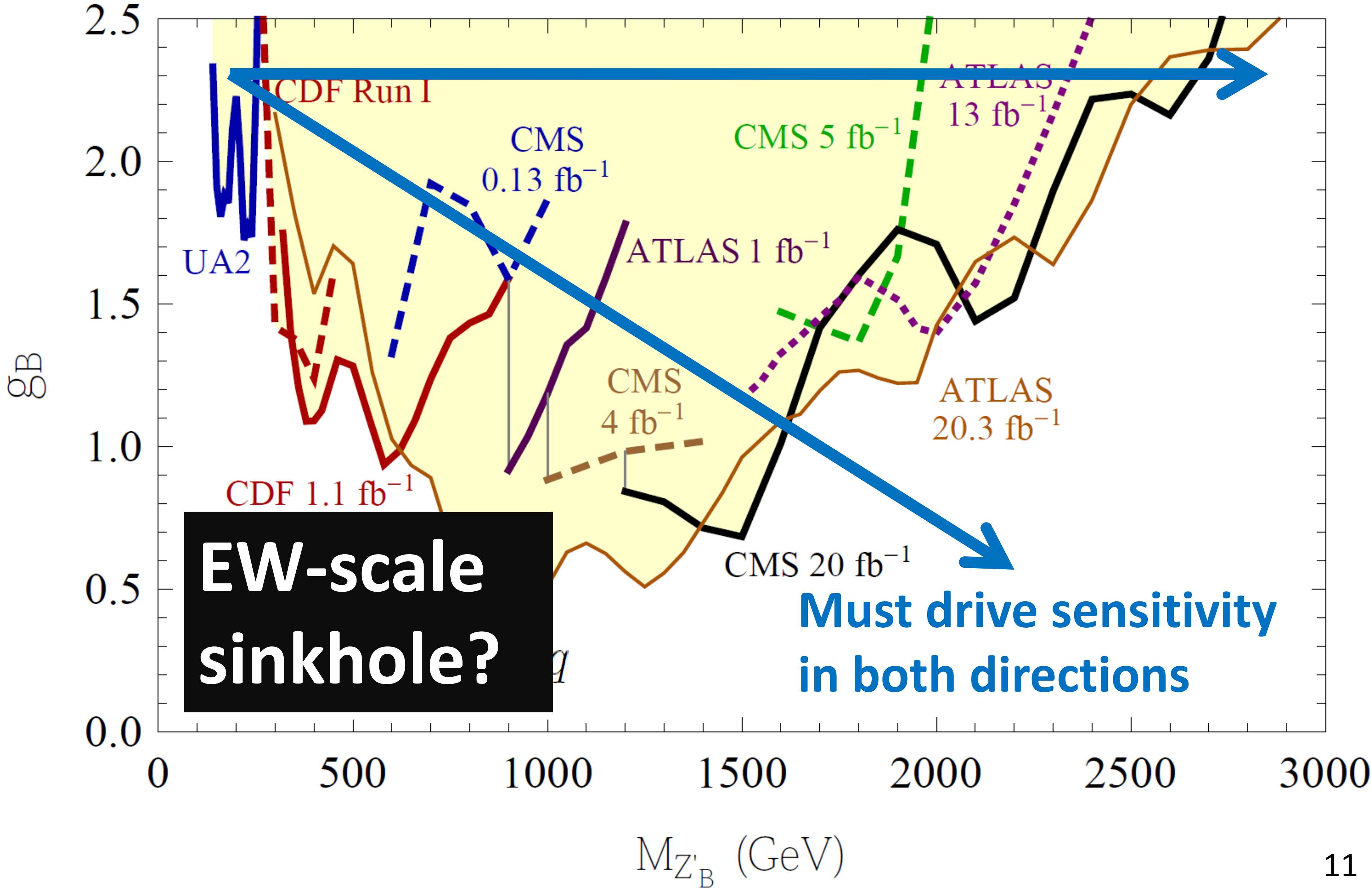
Onward and outward



Onward and outward

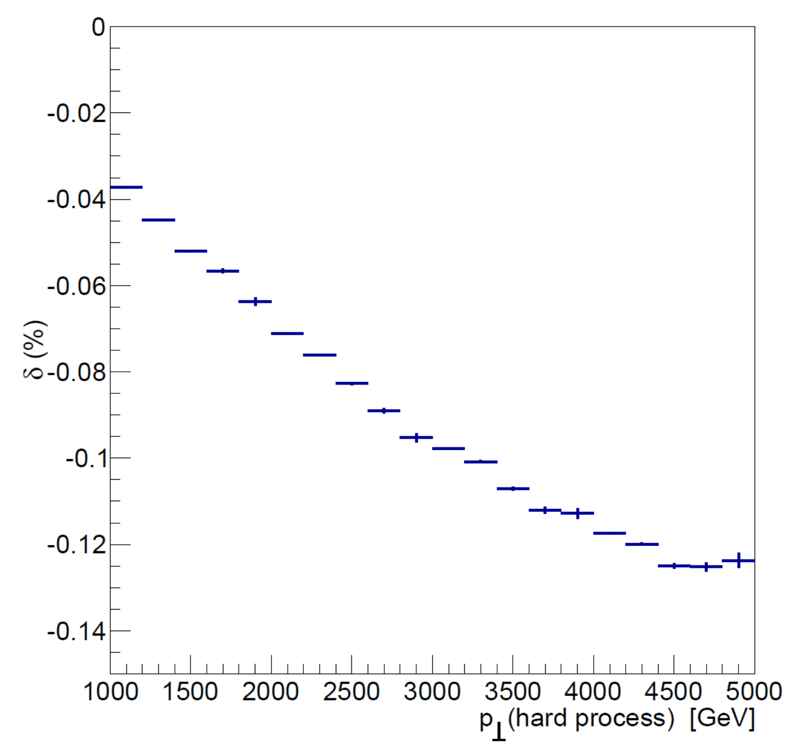


The 100 TeV leap

- Background is pure QCD production
- Complicated by EW Sudakovs, pileup, PDFs
  - See Larkoski (next) regarding pileup effects
- Motivates unified treatment of “weak jets”
- Motivates full NNLO QCD

  + NLO EW calculation

Veto fraction of events with a real weak boson emission



Christiansen, Sjöstrand [1401.5238]

Background estimation

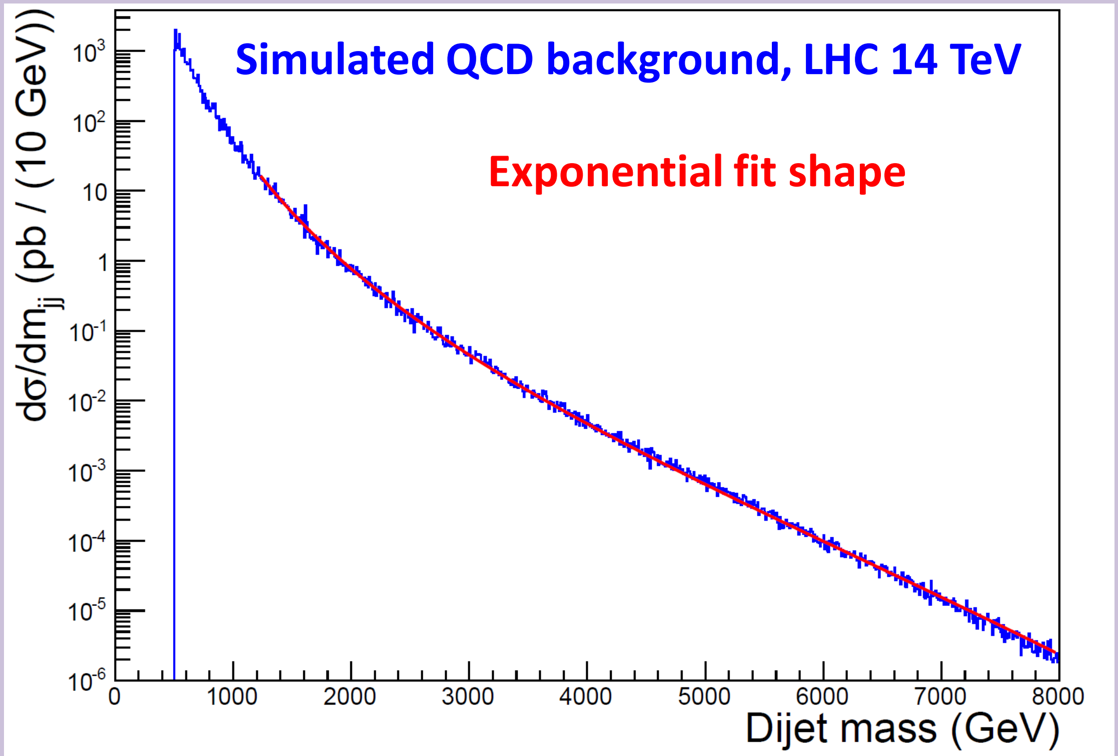
- Generate QCD background in bins of leading jet p_T using MadGraph5 + Pythia 6 with MLM matching
  - Cluster with FastJet, anti-k_T, R = 0.5

Follow similar procedure as CMS NOTE 2006/069 and CMS NOTE 2006/070

p_T bin	14 TeV	33 TeV	100 TeV	p_T bin	14 TeV	33 TeV	100 TeV
1	0.100 – 0.150	0.200 – 0.300	0.500 – 0.650	13	1.60 – 1.80	2.75 – 3.10	4.00 – 4.75
2	0.150 – 0.200	0.300 – 0.400	0.650 – 0.800	14	1.80 – 2.00	3.10 – 3.50	4.75 – 5.50
3	0.200 – 0.250	0.400 – 0.550	0.800 – 1.00	15	2.00 – 2.25	3.50 – 4.00	5.50 – 6.25
4	0.250 – 0.325	0.550 – 0.700	1.00 – 1.30	16	2.25 – 2.50	4.00 – 4.50	6.25 – 7.00
5	0.325 – 0.400	0.700 – 0.850	1.30 – 1.55	17	2.50 – 2.80	4.50 – 5.00	7.00 – 8.50
6	0.400 – 0.500	0.850 – 1.00	1.55 – 1.80	18	2.80 – 3.00	5.00 – 6.00	8.50 – 10.0
7	0.500 – 0.650	1.00 – 1.25	1.80 – 2.10	19	3.00 – 3.30	6.00 – 7.00	10.0 – 12.5
8	0.650 – 0.800	1.25 – 1.50	2.10 – 2.40	20	3.30 – 3.75	7.00 – 8.50	12.5 – 15.0
9	0.800 – 1.00	1.50 – 1.75	2.40 – 2.70	21	3.75 – 4.10	8.50 – 10.0	15.0 – 17.5
10	1.00 – 1.20	1.75 – 2.00	2.70 – 3.00	22	4.10 – 4.50	10.0 – 11.5	17.5 – 20.0
11	1.20 – 1.40	2.00 – 2.30	3.00 – 3.50	23	4.50 – 6.00	11.5 – 13.0	20.0 – 25.0
12	1.40 – 1.60	2.30 – 2.75	3.50 – 4.00	24	6.00+	13.0+	25.0+

Background estimation

- Generate QCD background in bins of leading jet p_T using MadGraph5 + Pythia 6 with MLM matching
  - Cluster with FastJet, anti-k_T, R = 0.5
  - Form dijet invariant mass spectrum



Flat K-factor of 1.40
No pile-up
No EW Sudakov
Minimal detector smearing
Dijet trigger left free

EW Sudakov and dijets

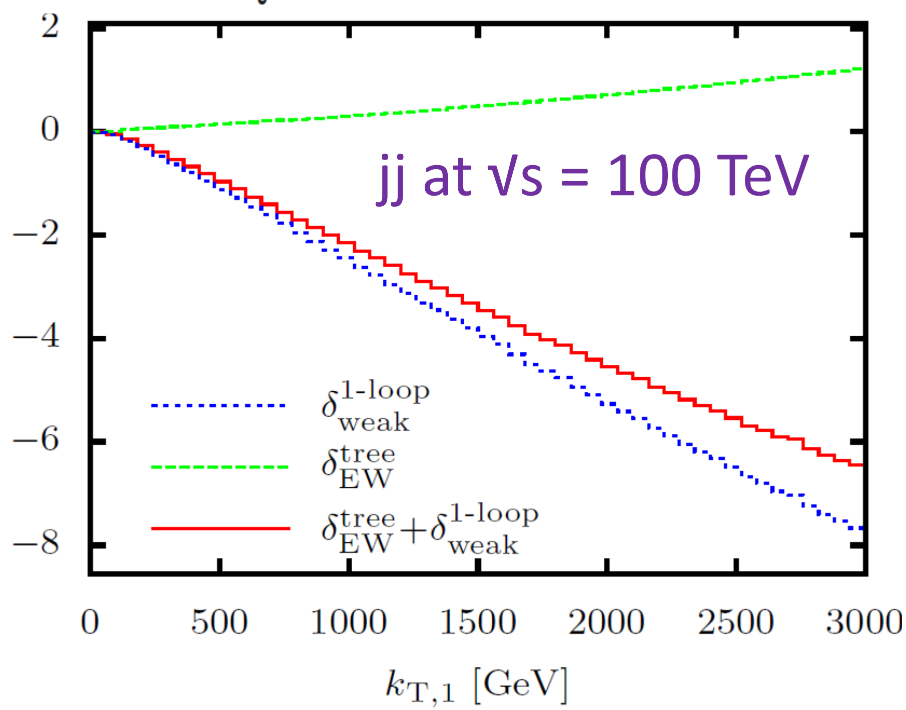
- EW virtual and tree corrections alter leading and subleading jet p_T

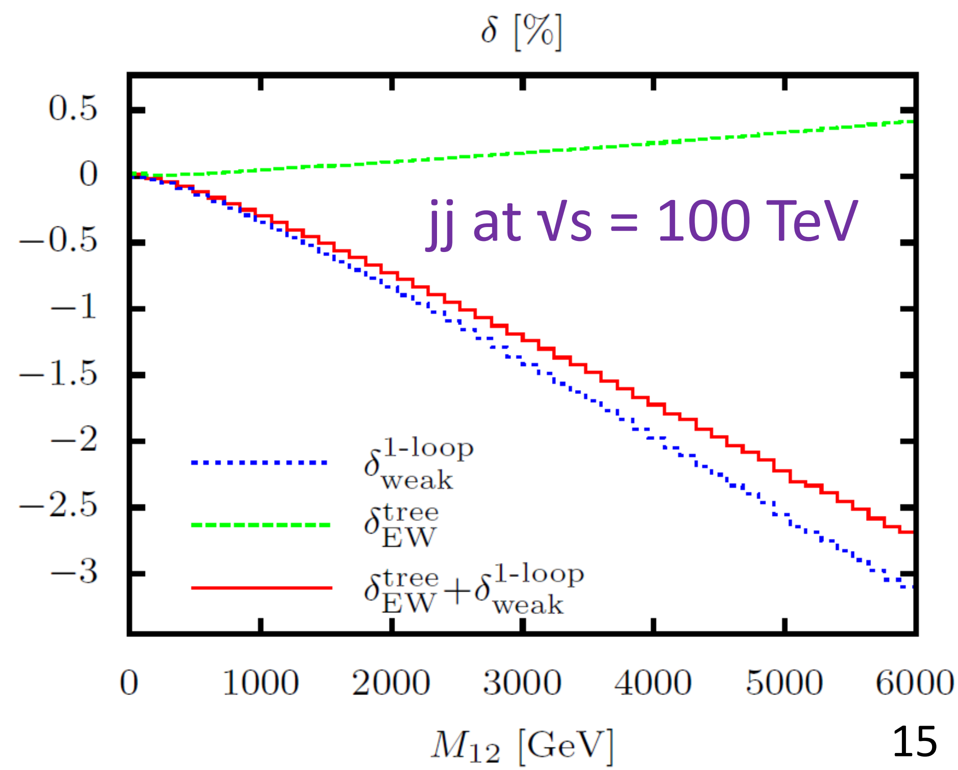
Mishra, et. al. [1308.1430]

  - Expect reduced effect if include real EW emission in shower

$$\sigma^{\rm NLO} = \sigma^0_{\rm QCD} \times (1 + \delta^{\rm tree}_{\rm EW}) \times (1 + \delta^{\rm 1\text{-}loop}_{\rm weak})$$
$$\simeq \sigma^0_{\rm QCD} \times (1 + \delta^{\rm tree}_{\rm EW} + \delta^{\rm 1\text{-}loop}_{\rm weak}).$$

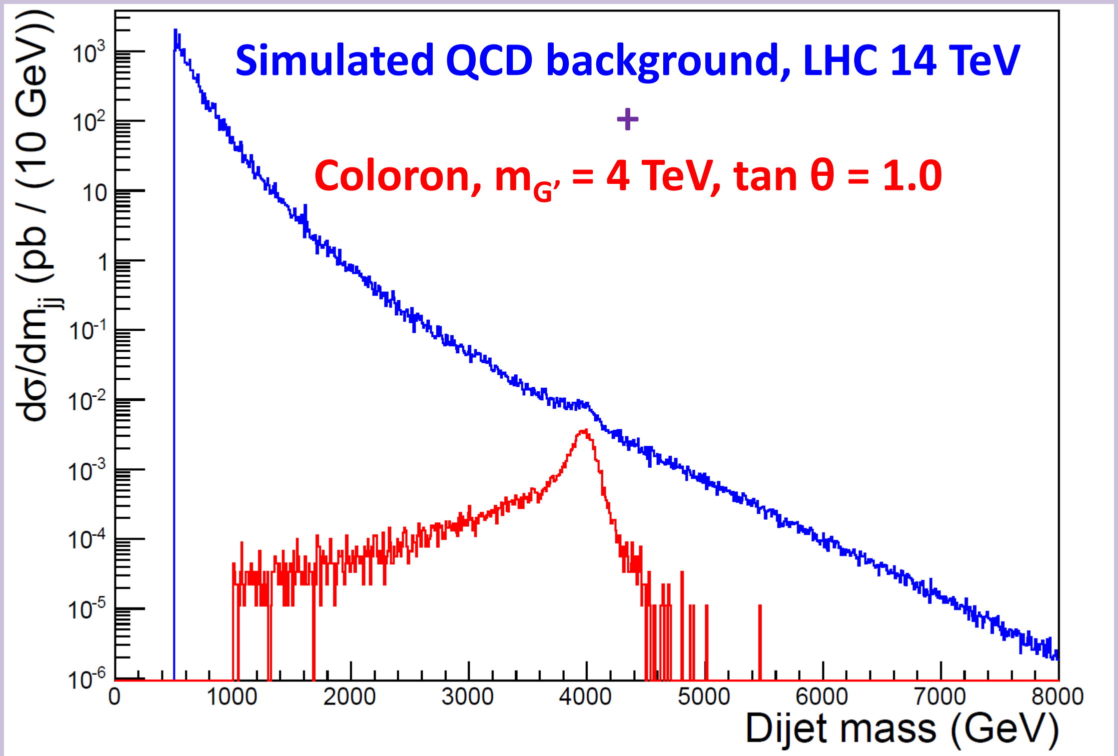
Not too significant for M_{jj}



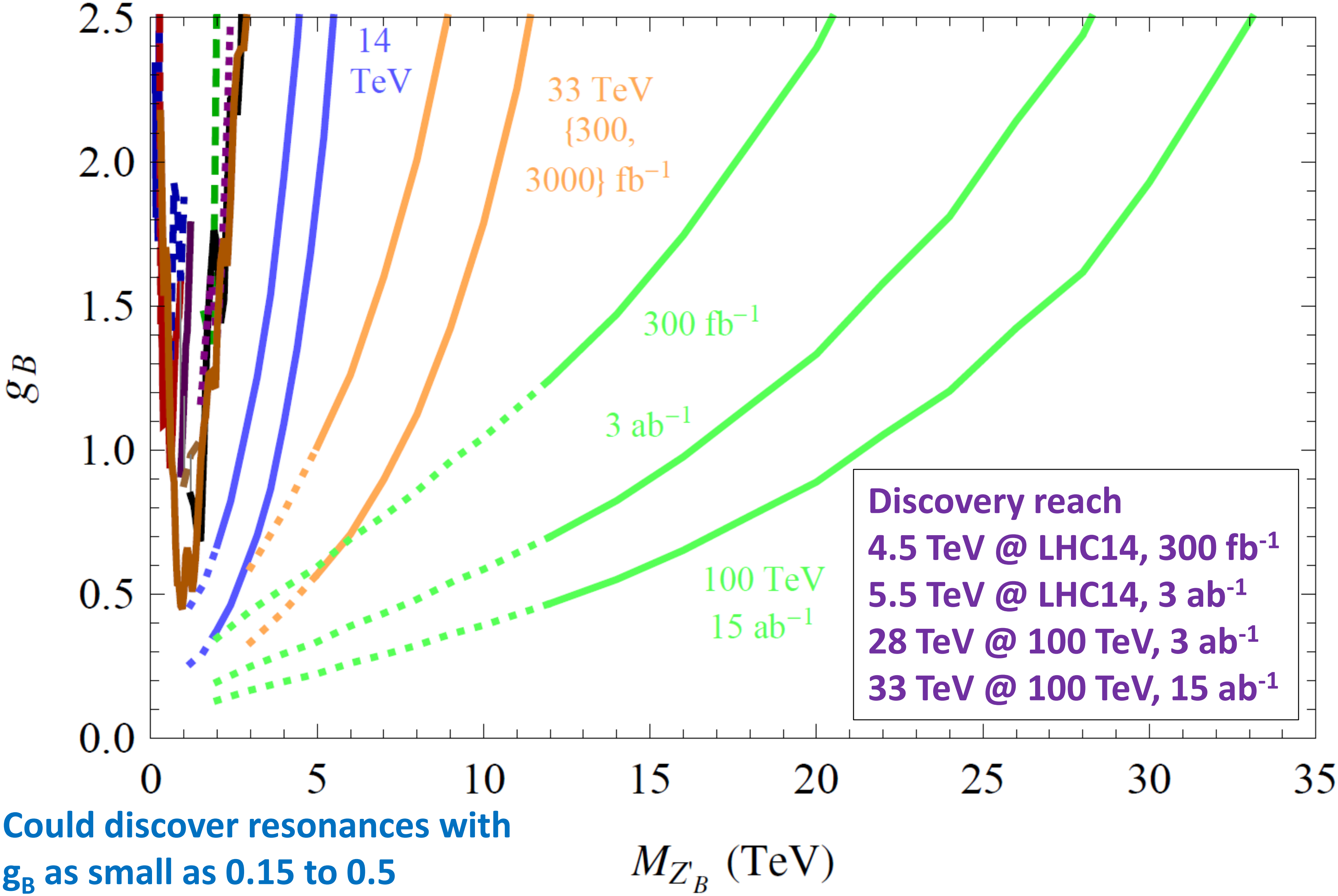


Estimating future sensitivity

- Bump hunt for narrow signal peak
- Impose cuts of CMS [1302.4794] analysis, modestly scaled up to 100 TeV
- Projections based only on statistical uncertainties

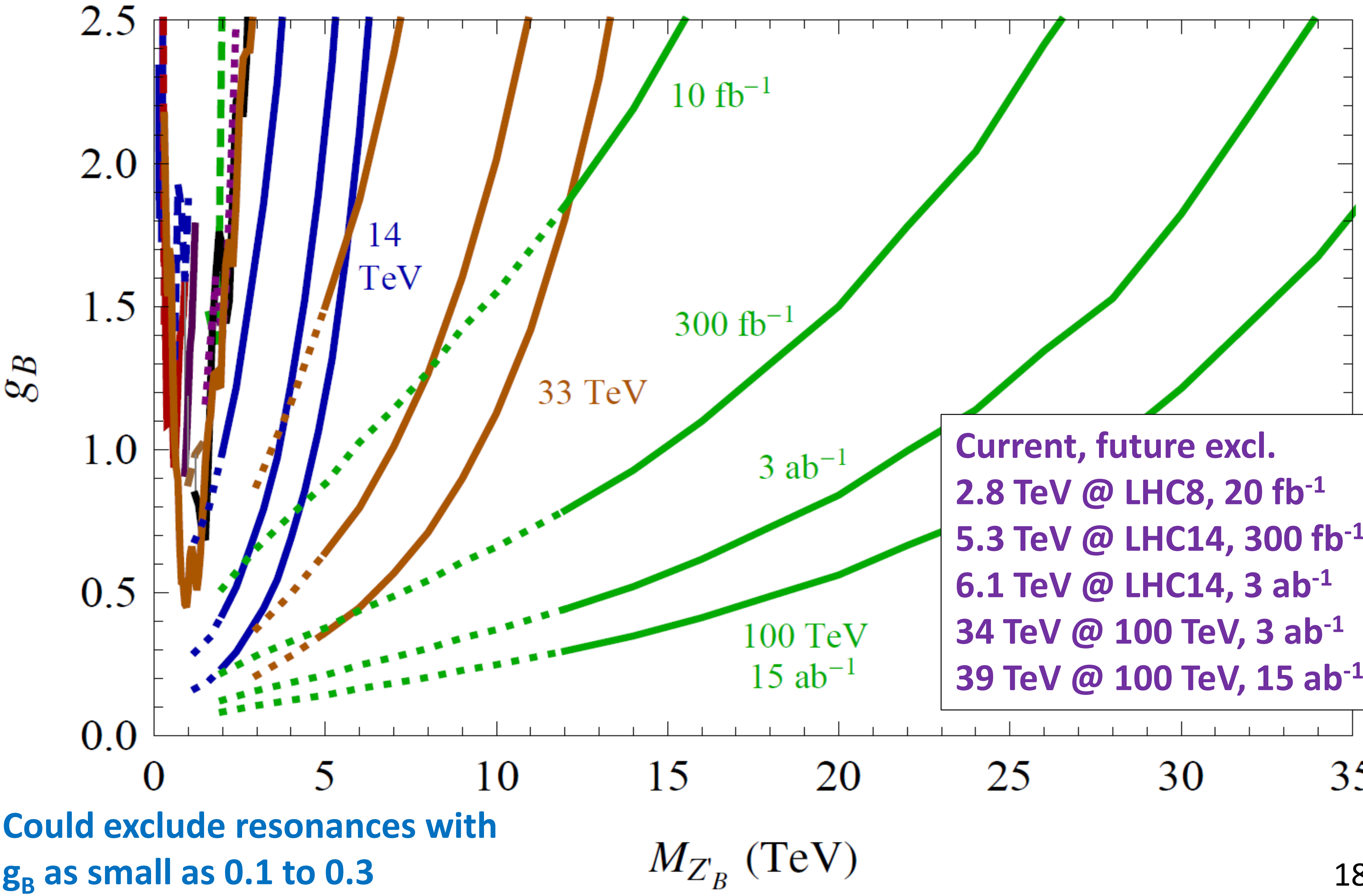


5σ discovery reach: Z'_B



Could discover resonances with g_B as small as 0.15 to 0.5

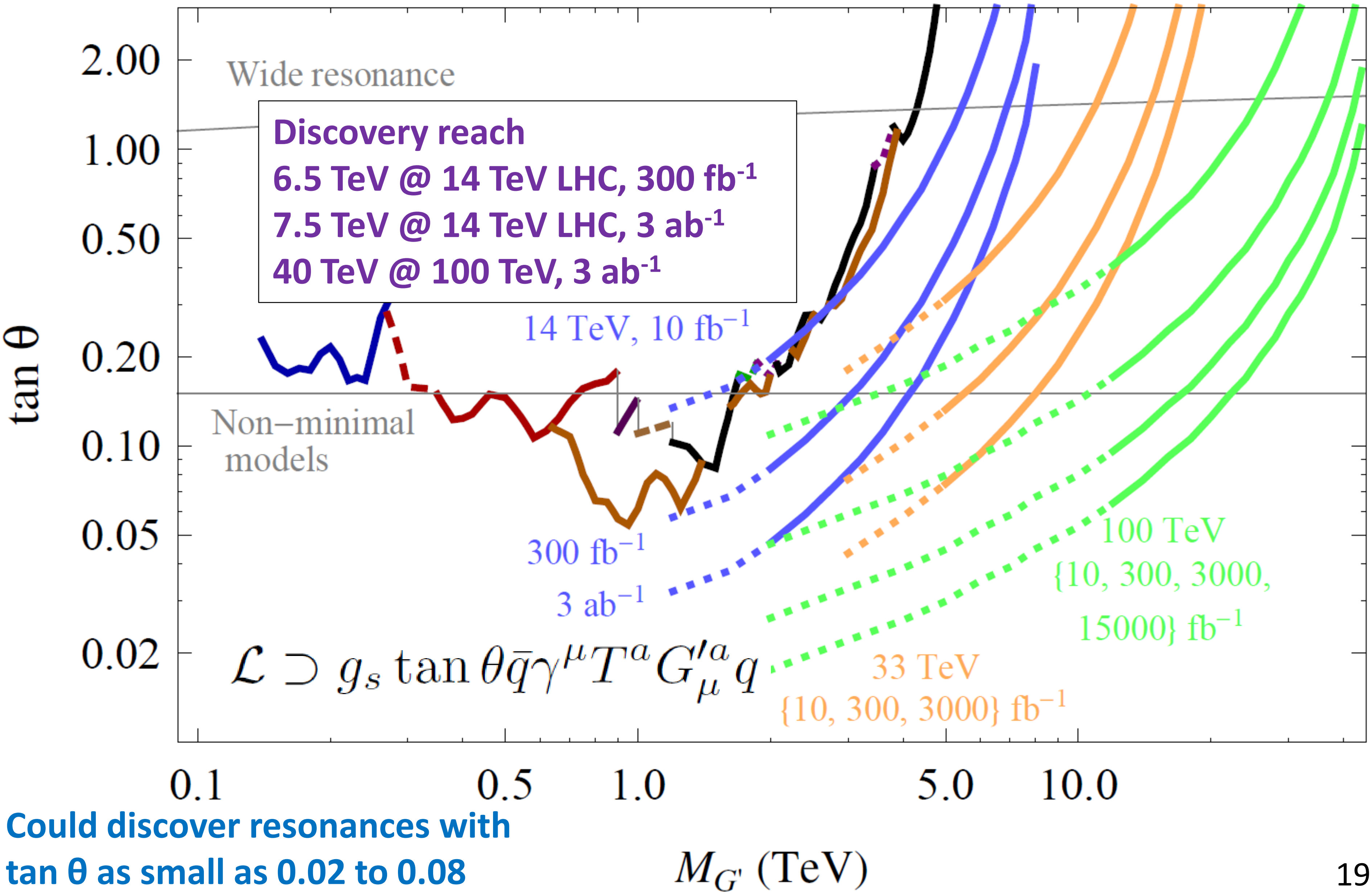
95% C.L. exclusion reach: Z'_B



Current, future excl.
2.8 TeV @ LHC8, 20 fb^{-1}
5.3 TeV @ LHC14, 300 fb^{-1}
6.1 TeV @ LHC14, 3 ab^{-1}
34 TeV @ 100 TeV, 3 ab^{-1}
39 TeV @ 100 TeV, 15 ab^{-1}

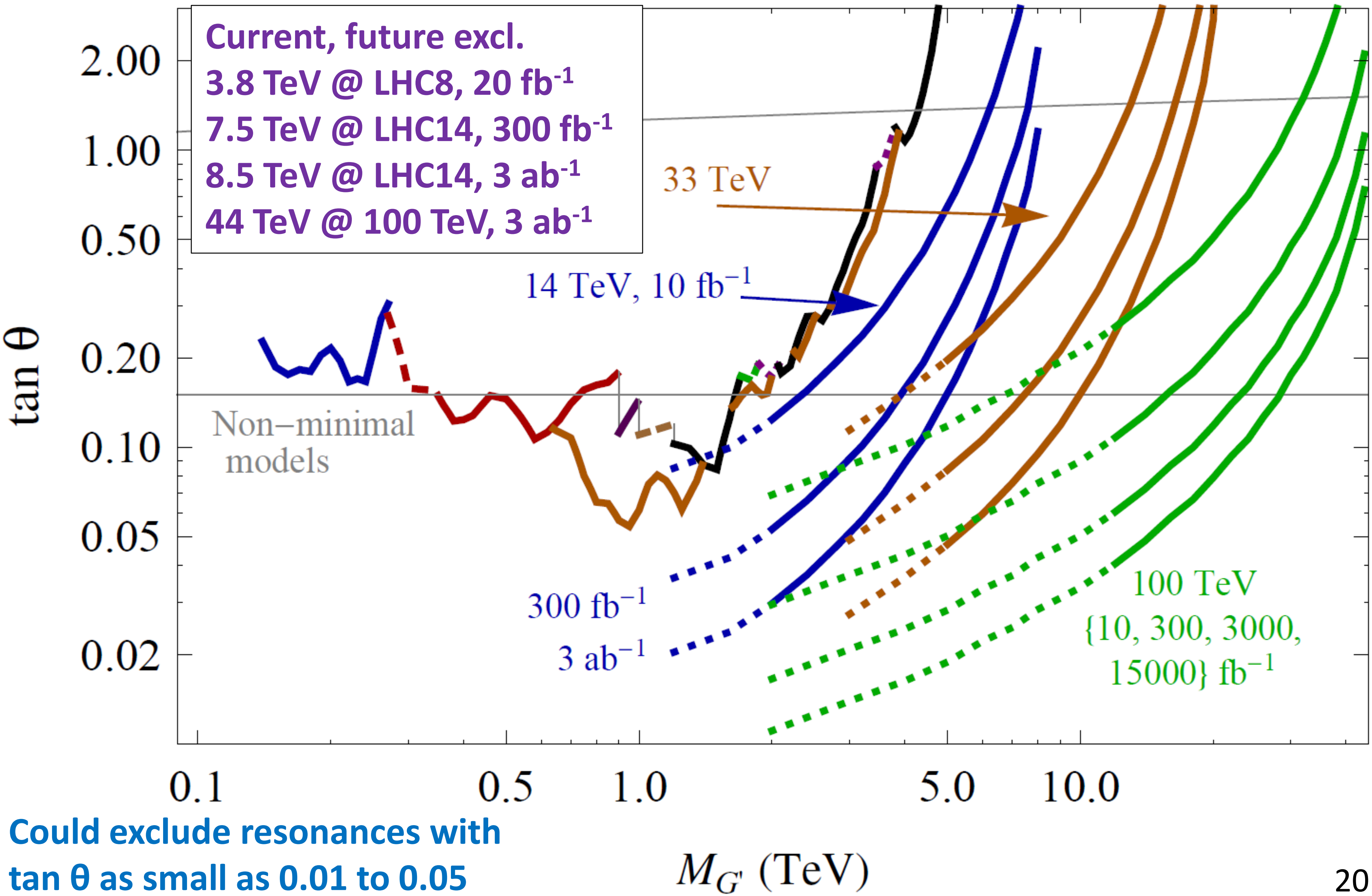
Could exclude resonances with g_B as small as 0.1 to 0.3

5σ discovery reach: G'



Could discover resonances with tan θ as small as 0.02 to 0.08

95% C.L. exclusion reach: G'

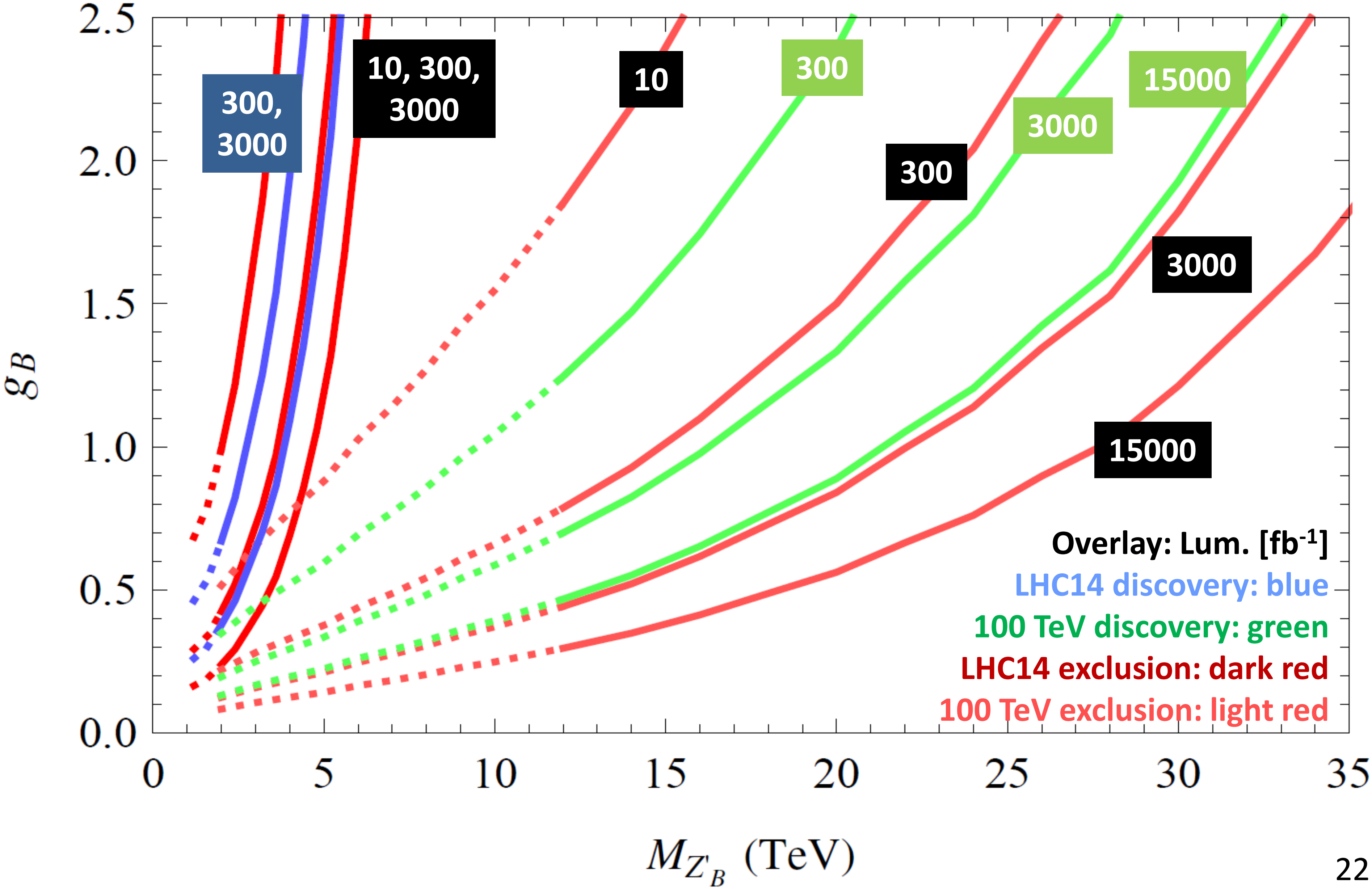


Could exclude resonances with
tan θ as small as 0.01 to 0.05

Physics in the 100 TeV multijet final state

- Prospects for sub-TeV mass window require alternate triggers (e.g. different final states)
  - Mainly pursue with current LHC data
    - W+jj, Z+jj, γ+jj, jjjj
- "Weak jets" as a new object class to use in analyses
- Post-discovery determination of resonance
  - Prospect for weak boson radiation to help determine LH or RH couplings
  - Also, color discriminants or jet energy profiles to distinguish gluons from quarks
    - *e.g.* see Chivukula, Simmons, Vignaroli (1412.3094)

Food for thought – √s, luminosity



Summary

- Understanding dijets is critical
  - If history holds, a dijet resonance search is likely the first BSM result from any future hadron collider
- Coupling–mass mapping provides a useful presentation of current limits and future sensitivities
  - A 100 TeV machine increases mass reach by a factor of 5-6 compared to 14 TeV
  - Weak-scale couplings require low triggers and large luminosity

Past searches

Collider $\sqrt{s}$ (TeV)	Experiment Luminosity (fb^{-1})	Mass Range (GeV)
$p\bar{p}$, 0.63	UA1 [2] 4.9×10^{-4}	150–400
	UA2 [3] 4.7×10^{-3}	80–320
	UA2 [4] 10.9×10^{-3}	140–300
$p\bar{p}$, 1.8	CDF [5] 2.6×10^{-6}	60–500
	CDF [6] 4.2×10^{-3}	200–900
	CDF [7] 1.9×10^{-2}	200–1150
	CDF [8] 0.11	200–1150
	D0 [10] 0.11	200–900
$p\bar{p}$, 1.96	CDF [9] 1.1	260–1400
pp, 7	ATLAS [11] 3.15×10^{-4}	300–1700
	ATLAS [12] 3.6×10^{-2}	600–4000
	ATLAS [13] 0.16	900–4000
	ATLAS [14] 0.81	900–4000
	ATLAS [15] 1.0	900–4000
	ATLAS [16] 4.8	1000–4000
	CMS [19] 2.9×10^{-3}	500–2600
	CMS [20] 1.0	1000–4100
	CMS [21] 5.0	1000–4300
	CMS [22] 0.13	600–1000
pp, 8	CMS [23] 4.0	1000–4800
	ATLAS [17] 5.8	1500–4000
	ATLAS [18] 13	1500–4800
	CMS [24] 20	1200–5300

Also, new ATLAS [1407.1376] results with 20.3 fb^{-1}, mass reach from 300-4400 GeV

MC QCD background

- Get smooth QCD background after generating MC in bins of leading jet p_T