Z + Missing Energy Signal of a Warped Graviton at Hadron Colliders

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Based on:

C. -Y. Chen, H. D. and D. Kim, Phys. Rev. D **89**, 096007 (2014)

[arXiv:1403.3399 [hep-ph]]

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- The hierarchy problem
- Electroweak physics: $m_H \sim 100$ GeV
- Λ: cutoff scale of effective description (gravity, GUT, flavor, ...)
- Quantum corrections: $\delta m_H^2 \sim g^2 \Lambda^2/(16\pi^2)$
- For $\Lambda \gg m_H$ $\rightarrow$ apparent hierarchy
- $\Lambda \sim \bar{M}_P \sim 10^{18}$ GeV: 10^{-30} fine-tuning! Why is gravity so weak?

- Generally, *naturalness* is invoked
- Some new physics to explain smallness of m_H/Λ
- Supersymmetry? Extra dimensions? Compositeness? ...

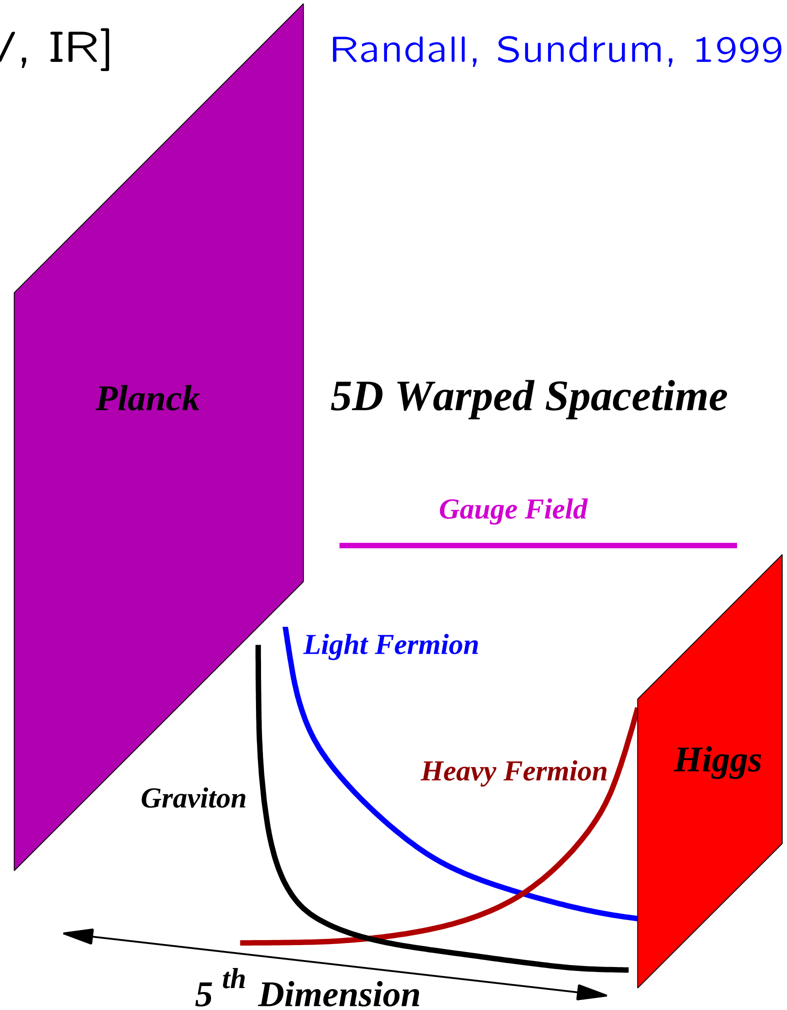
- Implies new physics near TeV-scale
- $\Lambda \leftrightarrow$ New physics scale

Warped 5D Models

- Based on 5D Randall-Sundrum (RS) model of hierarchy
  - $ds^2 = e^{-2kR\phi}\eta_{\mu\nu}dx^\mu dx^\nu - R^2 d\phi^2 \quad ; \quad \phi \in [0,\pi] \leftrightarrow$ [UV, IR]

Randall, Sundrum, 1999

  - 5^{th} dimension radius R, curvature scale k



- $\bar{M}_P \to e^{-kR\pi}\bar{M}_P \sim m_H$ for $kR \sim 12$

- Bulk SM: predictive picture of flavor

HD, Hewett, Rizzo, 1999; Pomarol, 1999

Grossman, Neubert, 1999; Gherghetta, Pomarol, 2000

- TeV-scale Kaluza Klein (KK) modes
  - IR brane localized

- Fluctuation of R: radion scalar
  - Stabilized R: *e.g.* Goldberger-Wise mechanism

Goldberger, Wise, 1999

★ Spin-2 KK gravitons G_n: Distinct signature of RS model

- Promising signal: $pp \to G_1 \to ZZ$
- Production of G_1 mainly through gg initial state

- Final state: longitudinal Zs
- Longitudinal modes from Higgs sector
- Localized near IR (Higgs) brane: unsuppressed KK coupling

- Golden channel: $ZZ \to 4\ell$ with $\ell = e, \mu$ Agashe, HD, Perez, Soni, 2007

- However, $Z(\to \ell^+\ell^-)Z(\to \nu\bar{\nu})$ signal has larger rate.
- Use of large $\not{E}_T$ a good handle on background
- Visible Z energy can approximately yield the mass of G_1.

Parameters

- Lightest warped KK graviton mass: $m_{G_1} = 3.83 \times ke^{-k\pi R}$
- Lightest warped KK gauge field mass: $m_{g_1} = 2.45 \times ke^{-k\pi R}$
- LHC/Precision bounds: $m_{KK}^{\text{gauge}} \gtrsim 2$ TeV
- Simple RS-type models: $m_{G_1} \gtrsim 2.5 - 3$ TeV
- Important parameter for warped graviton phenomenology: $c = k/\bar{M}_P$
- Assume $c \leq 2$ for reliable classical gravity approximations.

Agashe, HD, Perez, Soni, 2007

- No important LHC bounds on $m_{G_1} \gtrsim 1$ TeV for bulk SM

CMS collaboration, 2014

Signal, Background, and Cuts

- Signal: same flavor $\ell^+\ell^-$ and large missing energy

- Background:

- $Z(\rightarrow \ell^+\ell^-)Z(\rightarrow \nu\bar{\nu})$

- $W(\rightarrow \ell\nu)Z(\rightarrow \ell^+\ell^-)$ with missed ℓ from W

  - Small fraction of events for typical p_T^ℓ

  - For soft p_T^ℓ, remove background with hard $\not{E}_T$ cut

  - $\tau \rightarrow \mathrm{soft\,jets}$ not significant with our cuts

- $W(\rightarrow \ell\nu)W(\rightarrow \ell\nu)$

  - Require same flavor $\ell^\pm$ within Z mass window

- Signal and background: **CalcHEP3** and **MadGraph5**, respectively.
- CTEQ6L1 for PDFs.

- Pre-selection cuts for $\sqrt{s} = 14\,(100)$ TeV:

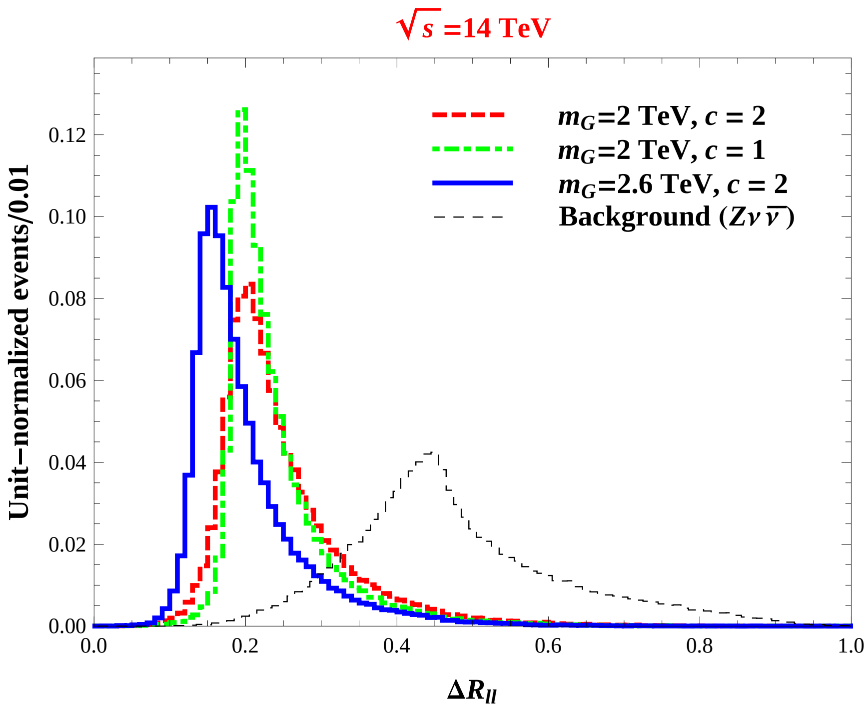
Adapted from arXiv:1111.3432 , [CDF Collaboration]

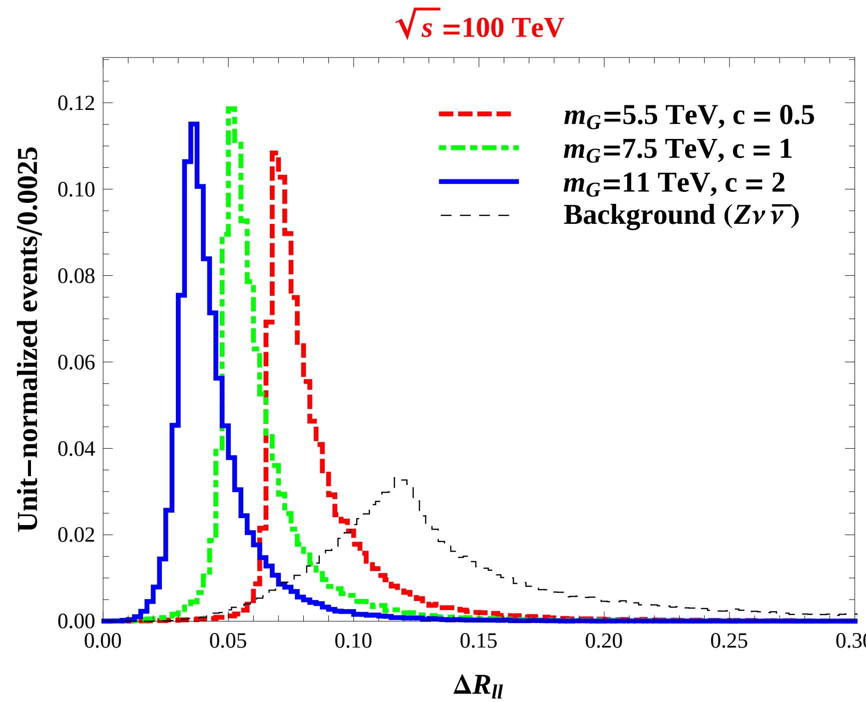
$$p_T^{\ell} > 25 \text{ GeV} \quad \text{and} \quad |\eta^{\ell}| < 2.4$$

$$\not{E}_T > 400\,(1500) \text{ GeV} \quad \text{and} \quad 66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$$

- Heavy G_1: boosted Z final states
- Additional cuts on $\not{E}_T$ and $\Delta R_{\ell\ell} \equiv \sqrt{(\Delta\phi^{\ell})^2 + (\Delta\eta^{\ell})^2}$ to improve S/B

After pre-selection cuts

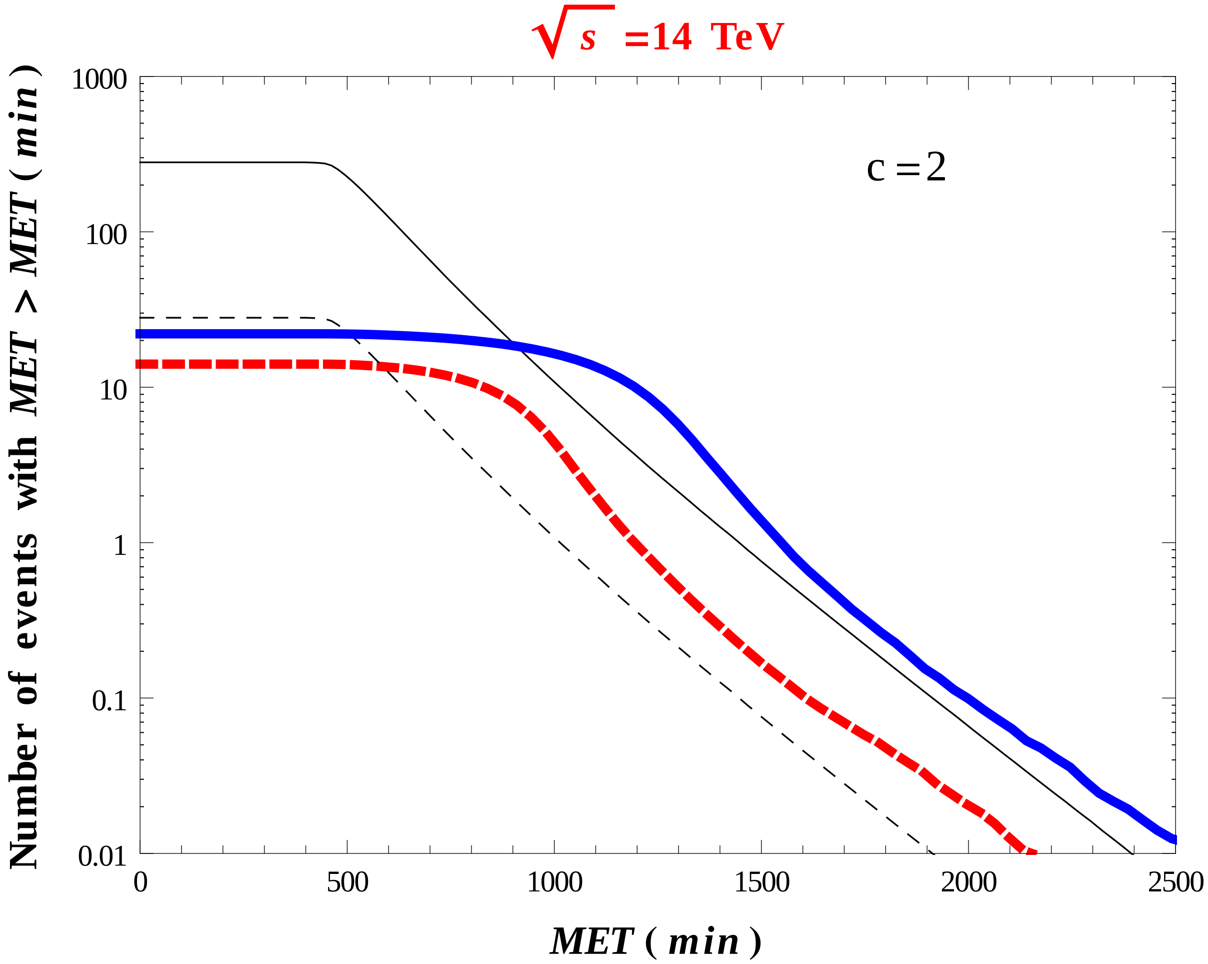




- Boosted Z from signal events
- Background events: dominated by threshold, larger $\Delta R_{\ell\ell}$
- Small $\Delta R_{\ell\ell}$ can reduce B:

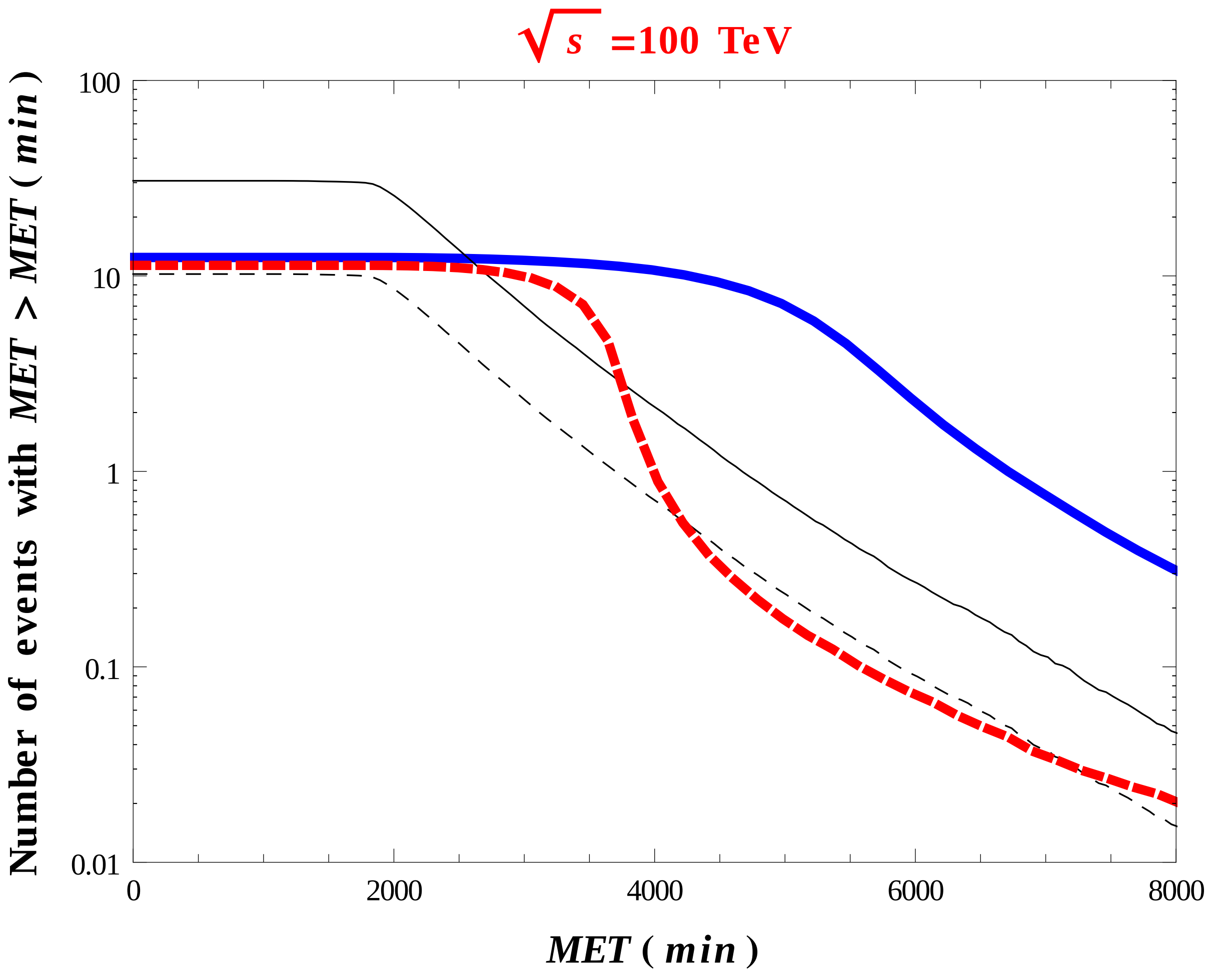
$\Delta R_{\ell\ell} < 0.4$ for $\sqrt{s} = 14$ TeV ; $\Delta R_{\ell\ell} < 0.1$ for $\sqrt{s} = 100$ TeV

After pre-selection and $\Delta R_{\ell\ell}$ cuts



- $m_{G_1} = 2$ TeV, 300 fb^{-1} (dashed)
- $m_{G_1} = 2.6$ TeV, 3 ab^{-1} (solid)

After pre-selection and $\Delta R_{\ell\ell}$ cuts



- $m_{G_1} = 7.5$ TeV, $c = 1$, 1 ab^{-1} (dashed)
- $m_{G_1} = 11$ TeV, $c = 2$, 3 ab^{-1} (solid)

HD, Chen, Kim, Phys. Rev. D **89**, 096007 (2014) [arXiv:1403.3399 [hep-ph]]

	(*i*)	(*ii*)	(*iii*)	(*iv*)	(*v*)	(*vi*)
$\sqrt{s}$ (TeV)	14	14	14	100	100	100
$\mathscr{L}$ (ab^{-1})	0.3	3	3	1	1	3
$c = k/\bar{M}_P$	2	1	2	0.5	1	2
m_{G_1} (TeV)	2	2	2.6	5.5	7.5	11
$\not{E}_T$ cut (TeV)	>0.8	>0.9	>1.2	>2.4	>2.9	>3.7
$\Delta R_{\ell\ell}$ cut	<0.4	<0.4	<0.4	<0.1	<0.1	<0.1
S	10	28	11	12	10	11
$S/\sqrt{B}$	5.7	6.4	5.4	5.1	6.2	6.5

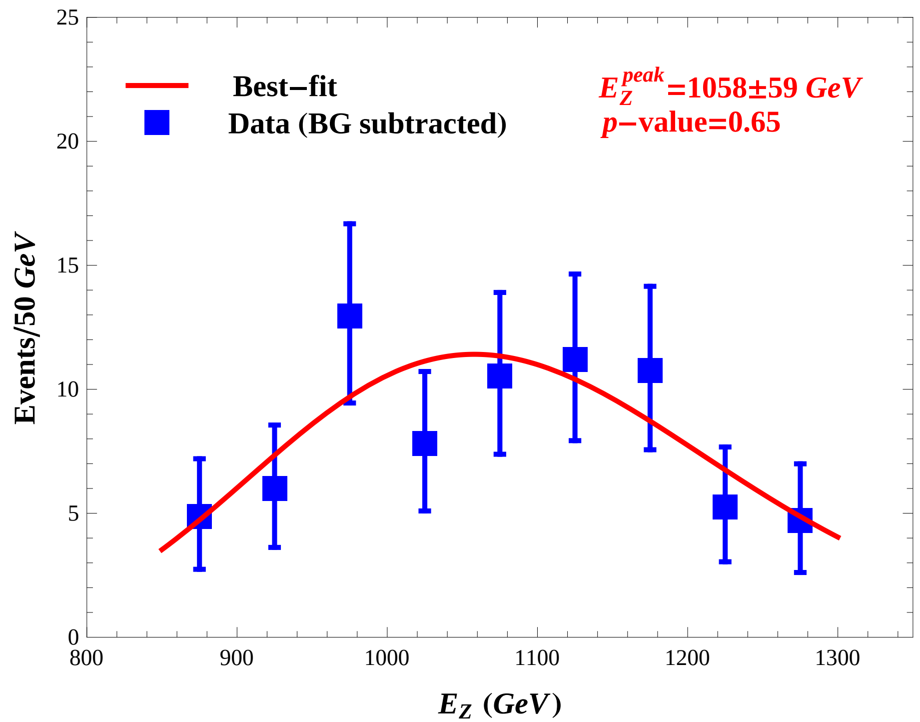
- Cut on $\not{E}_T$ near $\frac{1}{2}m_{G_1}$
- Required $S \geq 10$
- Over 5σ reach for 2-2.6 TeV G_1 at 14 TeV LHC with 0.3-3 ab^{-1}
- Typical reach for G_1 at a 100 TeV pp collider: ~ 10 TeV

Estimating m_{G_1} from E_Z^{vis}

- Adapt method of Agashe, Franceschini, Kim, [arXiv:1209.0772 [hep-ph]]
- Massless visible daughter energy peaks at decay rest frame value.
- For decaying particle produced near rest, peak is a cusp.
  - Heavy G_1 produced near rest, generally expect $E_Z^{\text{vis}} \simeq m_{G_1}/2$
- Use S and B templates:

$$f(E_Z) = N \exp\left[-w\left(\frac{E_Z}{E_Z^*} + \frac{E_Z^*}{E_Z} - 2\right)^q\right] \text{ with } q \sim 0.9 \quad \text{and} \quad f_{\text{BG}}(E) = N_{\text{BG}} \exp\left(-w_{\text{BG}}\sqrt{E}\right)$$

- Choose $m_{G_1} = 2$ TeV and $c = 2$, $\not{E}_T$ cut loosened to 0.7 TeV
- 200 pseudo-experiments with 3 ab^{-1} at 14 TeV
- B model: fit to event sample
- Fit the output after B subtraction



- We find

$$\langle E_Z^{\text{peak}} \rangle = 1052 \pm 53 \text{ GeV}$$

$$\Rightarrow \langle m_{G_1} \rangle = 2104 \pm 106 \text{ GeV}$$

Conclusions

- We studied detecting lightest warped graviton at pp colliders in

$$pp \to G_1 \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$$

- $\not{E}_T$ and $\Delta R_{\ell\ell}$ cuts efficient in rejecting SM background
- 14 TeV LHC reach:
  - 2 TeV (2.6 TeV) with $c \equiv k/\bar{M}_P = 2$ and 300 fb^{-1} (3 ab^{-1})
- 100 TeV pp collider:
  - Reach for $m_{G_1} \sim 10$ TeV with $c = 1$-2, and 3 ab^{-1}
- Adapted a recent proposal for mass measurement using only $E_Z^{\rm vis}$
  - $m_{G_1} = 2$ TeV and $c = 2$ and 3 ab^{-1} of 14 TeV LHC data
  - m_{G_1} could be deduced at the $\sim 5\%$ level.