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Extra Dimensions at Colliders

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Asymptotic Safety meets Particle Physics

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Outline

Motivation

- Goal: Testing predictions of Asymptotically Safe Gravity (ASG)
- Problem: gravity in 4 dimensions is weak $\Rightarrow$ hard to measure
- Chance: gravity in (large) extra dimensions
  - might be accessible at the LHC
  - ASG program works for more than 4 dimensions
  - existing implementations for (large) extra dimensions
  - Injecting ASG into existing implementations for large extra dimensions

(Large) Extra Dimensions

- Gravity weak: hard to measure
- $M_{\text{Planck}} \gg$ all other scales $\Rightarrow$ hierachy problem
- compactified extra dimensions?

$$V \sim \frac{m_1 m_2}{M_{\text{Planck}}^{d-2}} \frac{1}{r^{d-3}} \quad \underset{d>4, r \gg R}{\Rightarrow} \quad V \sim \underbrace{\frac{m_1 m_2}{(M_D \cdot R)^{d-2}}}_{M_{\text{Planck}}} \frac{1}{r} \tag{1}$$

- Kaluza-Klein decomposition: Graviton mass spectrum

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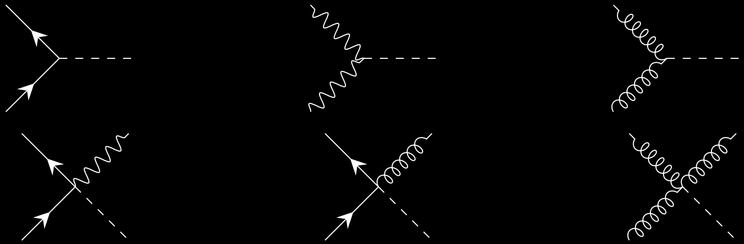
Graviton Interactions

$$\mathcal{L}_{\text{Grav,int}} = -\frac{1}{M_{\text{D}}} G^{(k)}_{\mu\nu} T^{\mu\nu} \qquad (2)$$



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Real Gravitons

- $E_{\mathrm{T,miss}} + \gamma$
- $E_{\mathrm{T,miss}}$ + jet
- $E_{\mathrm{T,miss}} + Z$

virtual Gravitons

inv. mass + angular dist. in

- Drell-Yan
- Diphotons
- Dijets

Already provided by Pythia8!

Black Holes

- more transverse events
- production treshold
- particle multiplicity

Black Hole Generators

- CHARYBDIS
- BlackMax
- TRUENOIR
- CATFISH
- QBH3.0

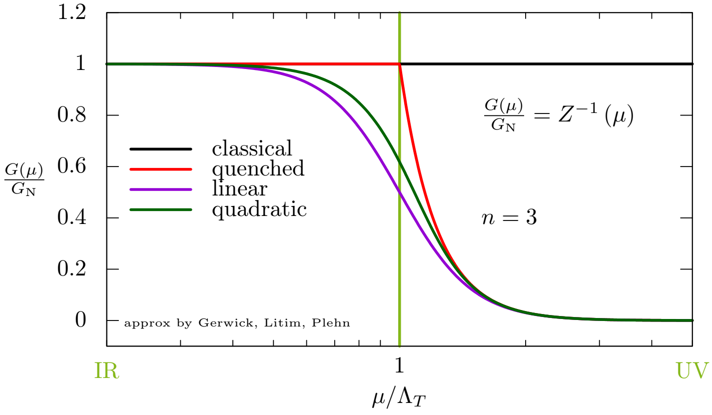
Injecting Asymptotic Safety

Several papers: e.g. [arxiv:1002.0260; arxiv:0912.2653; arxiv:1101.5548; arxiv:0707.3983]

Implementation: HET department: Maximilian Demmel, Jan Philipp Dabruck, Henning Sedello, Magdalena Zenglein

Newtons Running Coupling $\rightarrow \frac{d\sigma_{m,AS}}{d\hat{t}} = \frac{d\sigma_{m,LED}}{d\hat{t}} \cdot Z^{-1}$

Λ_T: transistion scale from classical to fixed point regime



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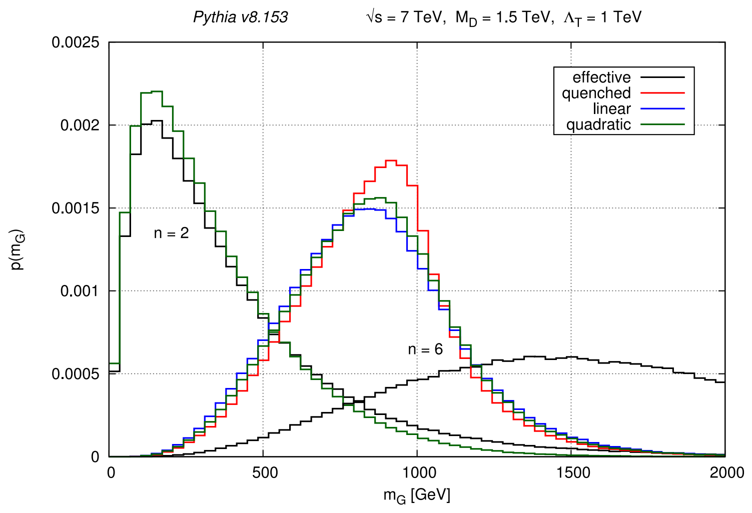
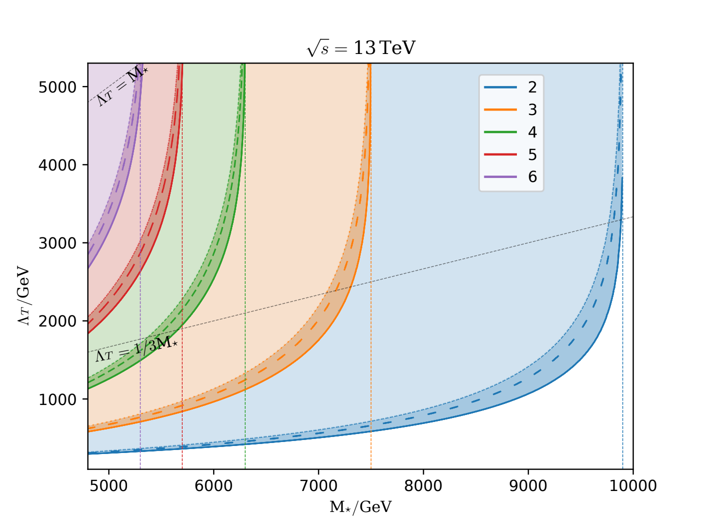
Monojet Mass Spectra

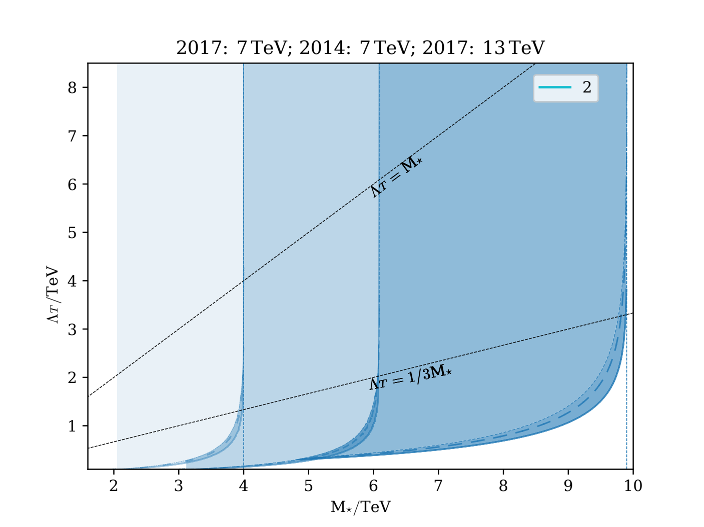


[Dabruck]

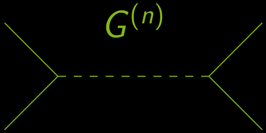
$E_{\mathrm{T,miss}}$+jet CMS



$E_{\mathrm{T,miss}}$+jet CMS



Kaluza-Klein Sums



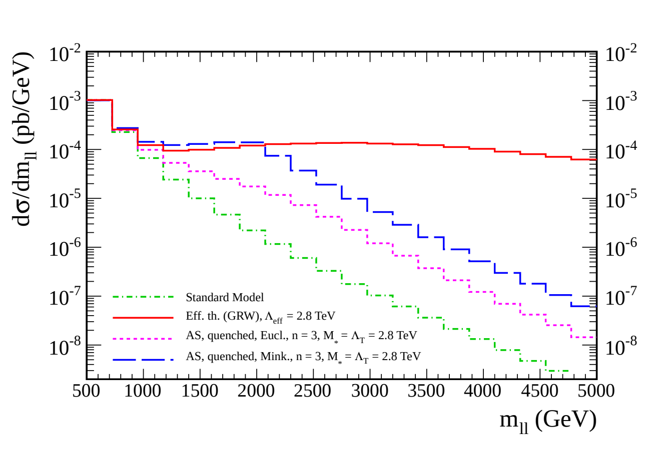
- Kaluza-Klein-Sum $\mathcal{S}\left(s\right)$ and Tensorial Part Factorization

$$\mathcal{A} = \frac{1}{\overline{M}_{\mathrm{D}}^2} \sum_n \left[\frac{T_{\mu\nu} P^{\mu\nu\alpha\beta} T_{\alpha\beta}}{s - m^2} \right] = \underbrace{\frac{1}{\overline{M}_{\mathrm{D}}^2} \sum_n \frac{1}{s - m^2}}_{\mathcal{S}(s)} \underbrace{T_{\mu\nu} T^{\mu\nu}}_{\mathcal{T}}$$

- Small mass splitting $\Delta m \sim \frac{1}{R}$: $\mathcal{S} \to$ AS-dressed integral

$$\mathcal{S}\left(s\right) \to \frac{S_{n-1}}{M_{\mathrm{D}}^{n+2}} \int_0^\infty \mathrm{d}m \frac{m^{n-1} Z^{-1}}{s - m^2 + i\epsilon}, \qquad Z^{-1} = Z^{-1}\left(\mu\left(s, m\right), \Lambda_{\mathrm{T}}\right)$$

Invariant Dimuon Distribution



[Sedello]

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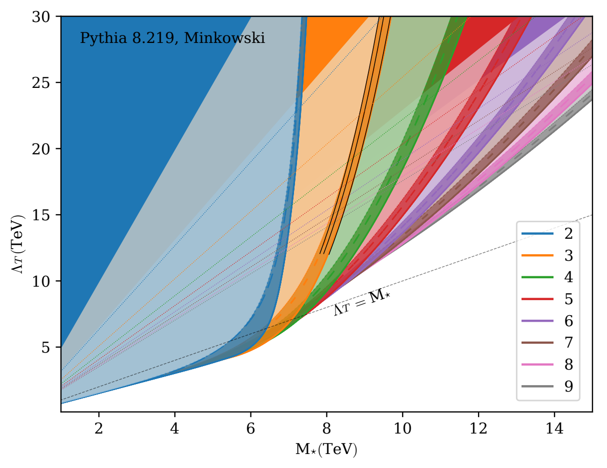
$\ell\ell$-CMS, 13 TeV, 36 fb^{-1}, $\Lambda_{\mathrm{eff}} = 6.9$ TeV



$$g_{\mathrm{NG}} = \Lambda_T^{d-2} G_{\mathrm{N}}^{(d)}$$

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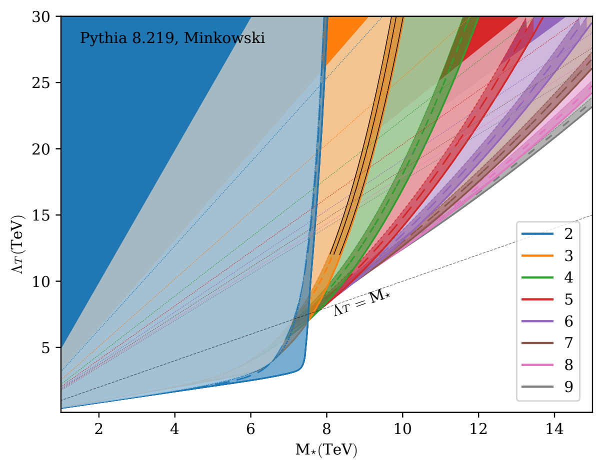
$\gamma\gamma$-Atlas, 13 TeV, 36.7 fb^{-1}, $\Lambda_{\text{eff}} = 7.2$ TeV



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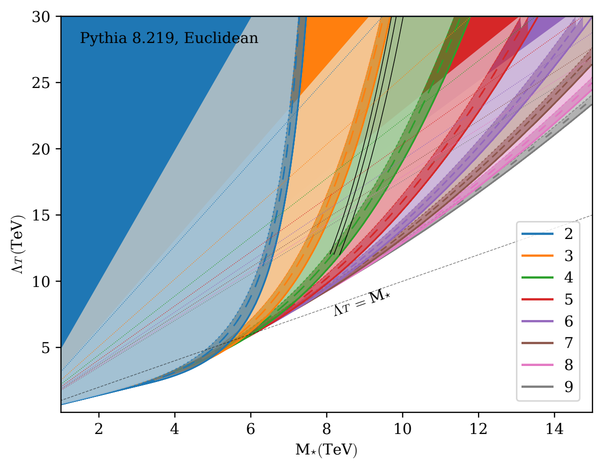


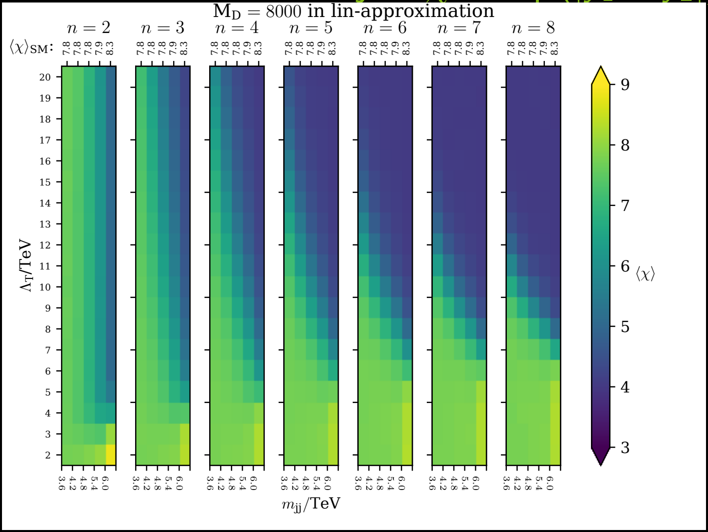
$$g_{\text{NG}} = \Lambda_T^{d-2} G_{\text{N}}^{(d)}$$

Comparison of total cross section LED+SM

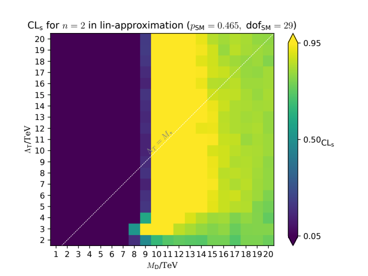
$|\eta| < 2.5$, NNPDF2.3

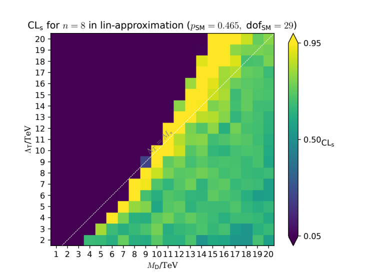
	Drell-Yan	Diphoton	Dijet
$m_{\text{inv,min}}/\text{TeV}$		$\sigma_{\text{tot}}/\text{mb}$	
1	5.1×10^{-9}	3.7×10^{-9}	1.0×10^{-4}
3	2.5×10^{-9}	1.9×10^{-9}	6.5×10^{-7}
5	4.7×10^{-10}	3.9×10^{-10}	1.2×10^{-7}
7	4.8×10^{-11}	4.2×10^{-11}	1.1×10^{-8}
9	2.7×10^{-12}	2.5×10^{-12}	2.7×10^{-10}

Angular Distribution of AS-Dijets $\chi = \exp\left(|y_1 - y_2|\right)$



CL_s heatmaps for CMS-Dijets

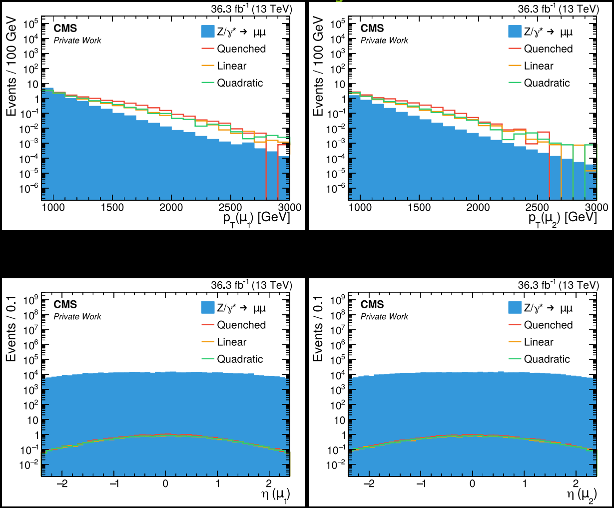




work in progress:

- fine grid for border region
- fit border region
- calc bounds for different approximatoins

AS Drell-Yan Graviton Analysis from CMS Data



[Radziej]

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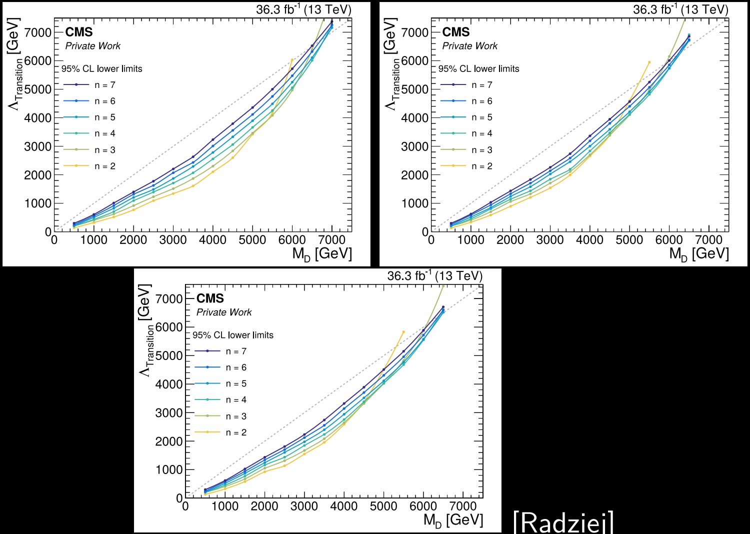
Bounds!



[Radziej]

Black Holes

Schwarzschild radius in d dimensions $\rightarrow$ geometric cross section

$$r_S = \frac{k(n)}{M_D}\left(\frac{M_{BH}}{M_D}\right)^{\frac{1}{d-3}} \qquad M_{BH} \rightarrow \sqrt{\hat{s}}: \quad \sigma\left(\sqrt{\hat{s}}\right) \sim \pi r_S^2 \qquad (3)$$

AS Black Holes with Charge, Color, and Spin

QBH3.0

- Quantum Black holes in (L)ED with charge, color, spin, Greybodyfactor corrections, different M_{D} -conventions
- Based on Pythia $\rightarrow$ PDF, hadronization, etc

Asymptotically Save Gravity

[arxiv:0707.4644]:

$$\sigma_{\mathrm{AS}}\left(\sqrt{\hat{s}}\right) = \sigma_{\mathrm{LED}}\theta\left(\sqrt{s} - m_{\mathrm{min}}\right) \cdot Z\left(\sqrt{\hat{s}}\right)^{\frac{-1}{d-3}} \tag{4}$$

AS Black Holes with Charge, Color, and Spin

QBH3.0

- Quantum Black holes in (L)ED with charge, color, spin, Greybodyfactor corrections, different M_{D} -conventions
- Based on Pythia $\rightarrow$ PDF, hadronization, etc

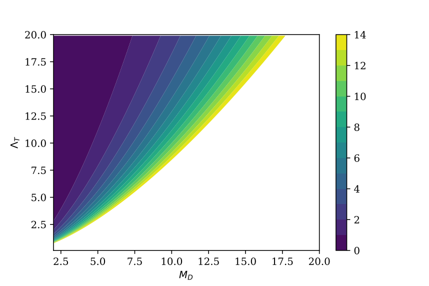
Asymptotically Save Gravity

[arxiv:1002.0260]

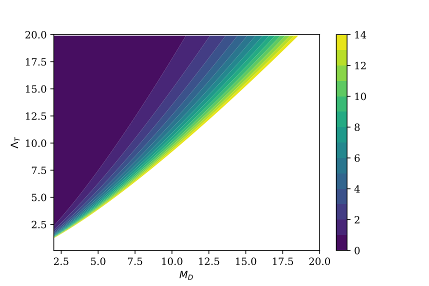
$$\sigma_{\mathrm{AS}}\left(\sqrt{\hat{s}}\right) = \sigma_{\mathrm{LED}}\theta\left(\sqrt{s} - m_{\mathrm{min}}\right) \cdot Z\left(M_{\mathrm{D}}\left(\frac{M_{\mathrm{D}}}{\sqrt{\hat{s}}}\right)^{\frac{1}{d-3}}\right)^{\frac{-1}{d-3}} \quad (4)$$

Minimal Black Hole Mass - Work in Progress

$n = 2$



$n = 6$



Guess (still under investigation)

$$m_{\text{min}}^2 = \frac{M_\star^d}{\Lambda_T^{d-2}} \tag{5}$$

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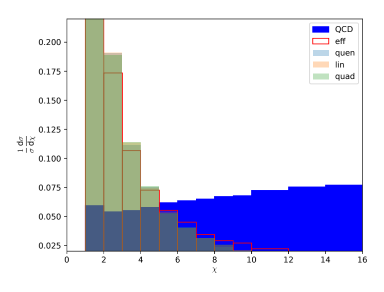
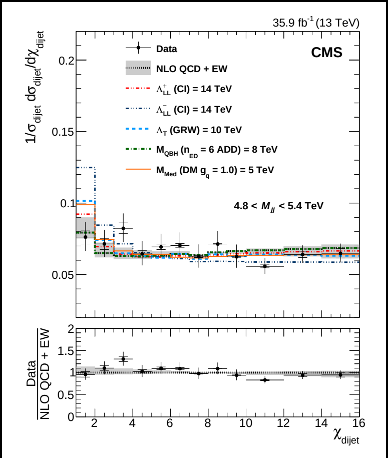
QBH Dijets: $\chi = \exp\left(|y_1 - y_2|\right), \; n = 6$



$\Lambda_T = 6$ TeV, $M_D = 4$ TeV
4.8 TeV $< m_{jj} <$ 5.4 TeV



[arxiv:1803.08030]

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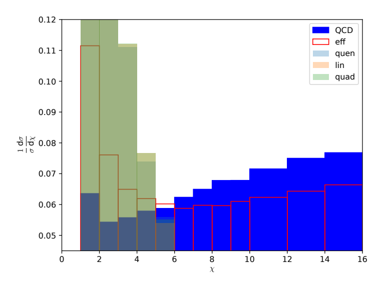
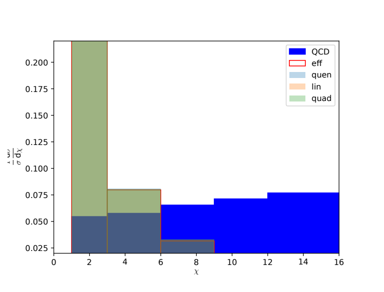
QBH Dijets: $\chi = \exp\left(|y_1 - y_2|\right), \ n = 6$



$\Lambda_T = 6$ TeV, $M_D = 5$ TeV
3.6 TeV $< m_{jj} <$ 4.2 TeV



$M_D = 5$ TeV
$m_{jj} > 6$ TeV

Summary

- ASG could be probed at Colliders
- Real gravitons
  - give strongest bounds for small number of extra dimensions
  - cannot probe fixed point regime if transistion scale is to high
- Virutal gravitons
  - bounds are stronger with increasing number of extra dimensions
  - allways sensitive to fixed point regime
- Quantum Black Holes
  - Cannot probe full parameter space
- Spring 2020: Dijet and QBH-Bounds

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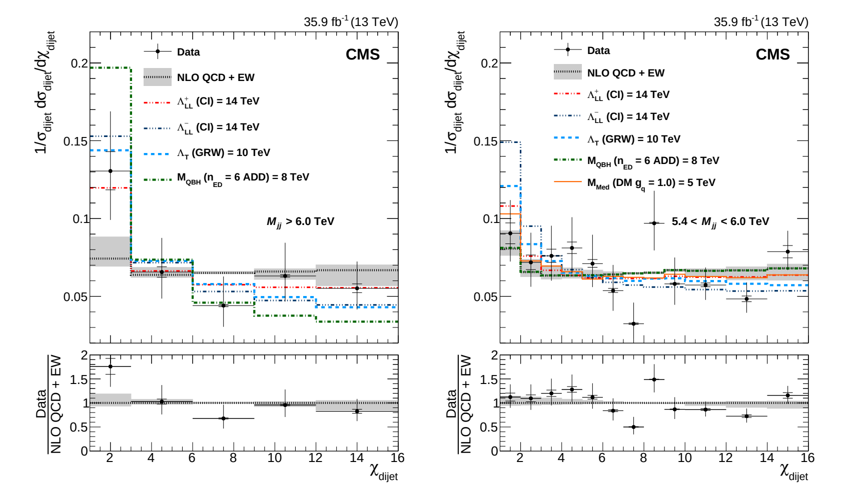
Dijets: $\chi = \exp\left(|y_1 - y_2|\right)$



[arxiv:1803.08030]

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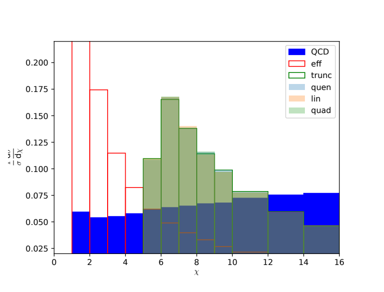
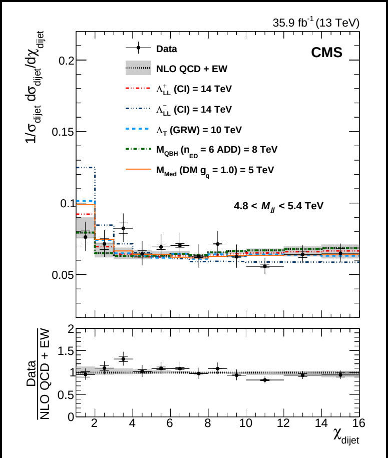
Virtual Graviton Dijets: $\chi = \exp(|y_1 - y_2|)$



$\Lambda_T = M_D = 2\,\text{TeV}$



[arxiv:1803.08030]

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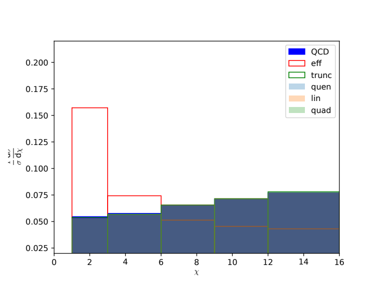
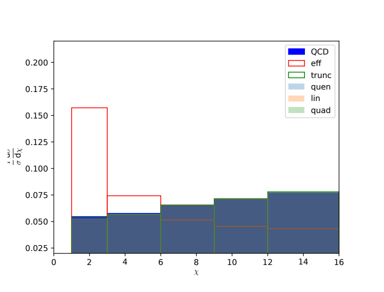
Virtual Graviton Dijets: $\chi = \exp\left(|y_1 - y_2|\right)$



$\Lambda_T = 6\,\text{TeV}, M_D = 2\,\text{TeV}$



$\Lambda_T = M_D = 0\,\text{TeV}$

Bounds, Bounds, Bounds

CMS + ATLAS: search for LED $\rightarrow$ no significant excess

real Gravitons limits on M_D

virt Gravitons limits on Λ_cutoff

Asymptotic Safety? Reinterpretation of bounds!

- recalculation of σ_tot in search bin
- single scale $\rightarrow$ line in $M_\mathrm{D} - \Lambda_T$ plane

Latest and strongest bounds on real Graviton emission

Search	$\sqrt{s}$	$\mathcal{L}$	M_D/TeV				
	TeV	fb^{-1}	$n=2$	$n=3$	$n=4$	$n=5$	$n=6$
$G+j$ (CMS)	13	35.9	9.0	7.5	6.3	5.7	5.3
$G+j$ (ATLAS)	13	36.1	7.7	6.2	5.5	5.1	4.8
$G+\gamma$ (CMS)	13	35.9		2.85	2.86	2.88	2.98
$G+\gamma$ (ATLAS)	13	3.2	2.3	2.5	2.6	2.7	2.8
$G+\gamma$ (ATLAS)	13	3.2	1.9	1.9	1.85	1.8	1.8
$G+Z$ (CMS)	13	35.9	2.77	2.31	2.35	2.40	2.47

Latest and strongest bounds on virtual Graviton exchange

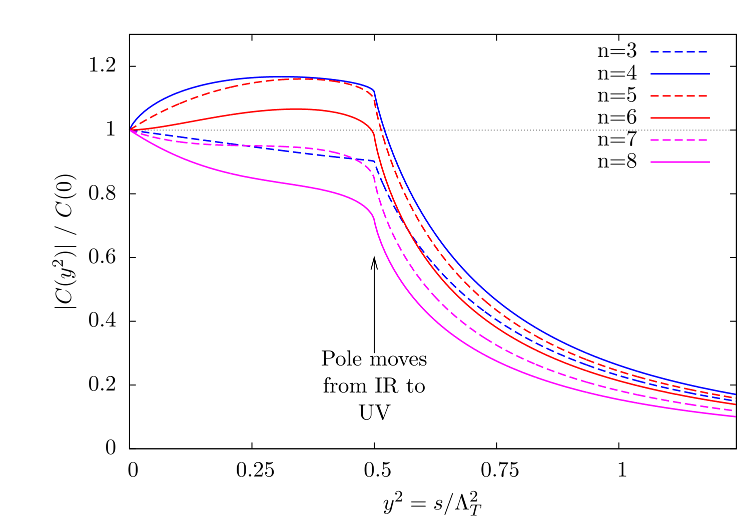
Search	$\sqrt{s}$ TeV	$\mathcal{L}$ fb^{-1}	K-Factor	Λ_{eff} TeV
$\ell\ell$ (ATLAS)	8	20	1	4.2
$\ell\ell$ (ATLAS)	8	20	1	4.0
$\ell\ell$ (CMS)	13	36	1.3	6.9
$\gamma\gamma$ (ATLAS)	13	36.7	1.4	7.2
$\gamma\gamma$ (CMS)	13	35.9	1	7.8
jj (CMS)	13	35.9	1	10.1

QBH: Bounds on Minimal Mass from CMS

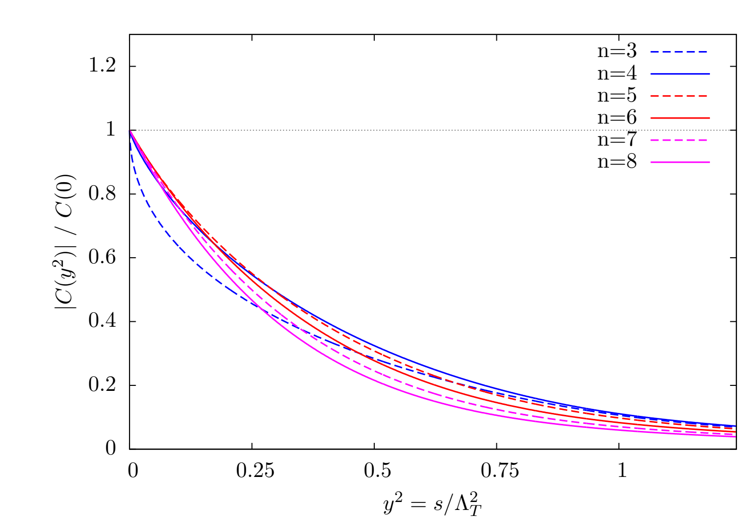
Angular Distribution: 8.2 TeV
Mass Spectrum:

M_D /TeV	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$
2	5.9	6.1	6.2	6.2	6.3
3	5.7	5.8	6.0	6.0	6.0
4	5.4	5.7	5.8	5.9	5.9
5	5.2	5.5	5.6	5.7	5.8

Dimensionless KK-Sum Minkowski



Dimensionless KK-Sum Euclidean



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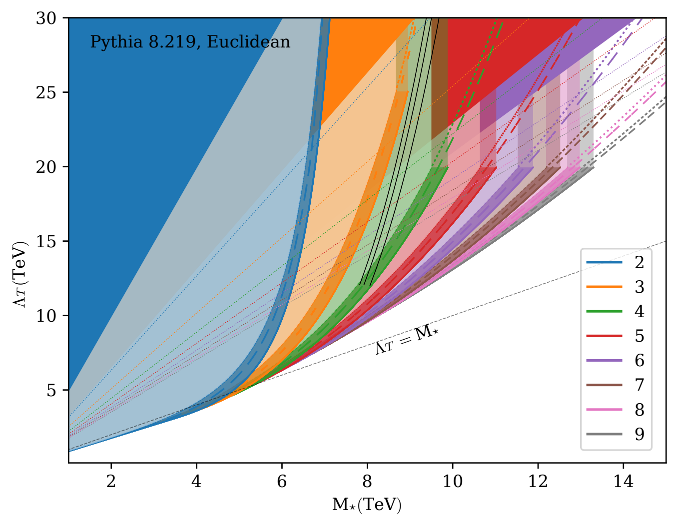
$\ell\ell$-CMS, 13 TeV, 36 fb^{-1}, $\Lambda_{\text{eff}} = 6.9$ TeV



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