Fun physics at the LHC

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Edinburgh

Cambridge 11/2008

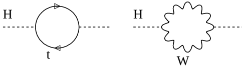
Outline

Effective Standard–Model

Data vs renormalizable Standard Model

- dark matter? [only solid evidence for new physics, weak–scale?]
- $(g-2)_\mu$? [loop effects around weak scale?]
- flavor physics? [new operators above 10^4 GeV?]
- neutrino masses? [see-saw at 10^{11} GeV?]
- gauge–coupling unification? [something happening above 10^{16} GeV?]
- gravity? [mostly negligible below 10^{19} GeV]

$\Rightarrow$ obviously effective theory, cutoff negotiable



Problem with fundamental Higgs

- mass driven to cutoff: $\delta m_H^2/m_H^2 \propto g^2(2m_W^2+m_Z^2+m_H^2-4m_t^2)\;\Lambda^2$
- easy solution: tune counter term
- whole idea of fundamental gauge theories betrayed, evil
- or new physics at TeV scale: supersymmetry
  extra dimensions
  little Higgs, Higgsless, composite Higgs...
- typically cancellation by new states or discussing away high scale
- beautiful concepts, challenged at TeV scale

$\Rightarrow$ whatever is there - LHC's job to sort it out

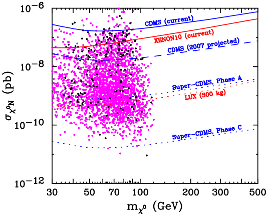
Effective Standard Model in the LHC era

Expectations from the LHC [Uli Baur’s rule: ‘there is always new physics at higher scales’]

- find light Higgs?
- find new physics stabilizing Higgs mass?
- see dark–matter candidate?

Particle theory and new physics

- model–independent analyses likely not helpful
- testing testable hypotheses [theory: e.g. Higgs sector and underlying theory?]
  discrete hypotheses: spins,....
  continuous hypotheses: masses,...
- link to other observations [DM+Tevatron: Hooper, TP, Valinotto]
- reconstruction of Lagrangian [theory+experiment]



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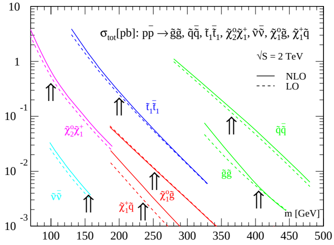
Special about LHC [except bigger than Tevatron]

- beyond inclusive searches [that was Tevatron]
  lots of strongly interacting particles
  cascade decays to DM candidate
- general theme: try to survive QCD

⇒ aim at underlying theory



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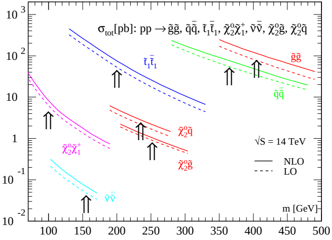
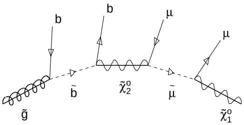


Masses from cascades



Cascade decays [Atlas-TDR, you Cambridge people]

- if new particles strongly interacting and LSP weakly interacting
- like Tevatron: jets + missing energy
- tough: $(\sigma \mathrm{BR})_1/(\sigma \mathrm{BR})_2$ [model dependence, QCD uncertainty]
  easier: cascade kinematics [$10^7 \cdots 10^8$ events]
- long chain $\tilde{g} \to \tilde{b}\bar{b} \to \tilde{\chi}_2^0 b\bar{b} \to \mu^+\mu^- b\bar{b}\tilde{\chi}_1^0$
- thresholds & edges

$$0 < m^2_{\mu\mu} < \frac{m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\ell}}}{m_{\tilde{\ell}}} \; \frac{m^2_{\tilde{\ell}} - m^2_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}$$

$\Rightarrow$ new–physics mass spectrum from cascade kinematics

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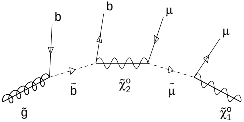

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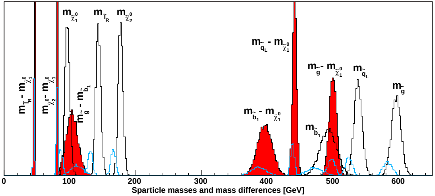
⇒ new–physics mass spectrum from cascade kinematics

Gluino decay [Gjelsten, Miller, Osland, Raklev...]

- all decay jets b quarks [otherwise
- no problem: off-shell [Catpiss]
- no problem: jet radiation?
- gluino mass to $\sim 1\%$



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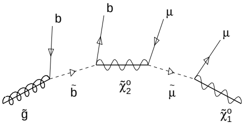

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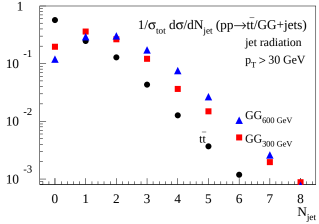
Likely bad ideas [Tait & TP; Alwall, Maltoni, de Visscher]

- decay jets vs QCD radiation
- collinear initial state radiation [$p_{T,j} < M_{\mathrm{hard}}$]
- proper description: CKKW/MLM [in MadEvent]
- $\langle N_{\mathrm{jet}} \rangle$ dependent on hard scale
- study: two heavy states

⇒ QCD basics useful at LHC...



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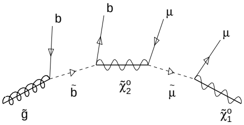

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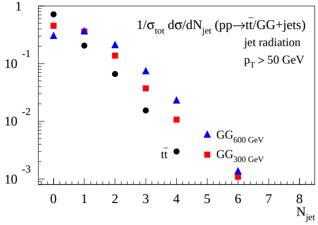

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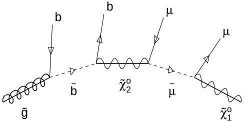

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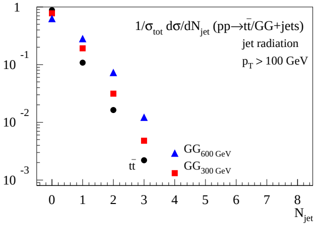


Underlying parameters

From kinematics to weak–scale parameters [Fittino; SFitter: Lafaye, TP, Rauch, Zerwas]

- parameters: weak-scale Lagrangian
- measurements: better edges than masses,
  branching fractions, rates,... [NLO, of course]
  flavor, dark matter, electroweak constraints,...
- errors: general correlation, statistics & systematics & theory [flat theory errors!]
- problem in grid: huge phase space, no local maximum?
  problem in fit: domain walls, no global maximum?
  problem in interpretation: bad observables, secondary maxima?

Probability maps of new physics [Baltz,...; Roszkowski,...; Allanach,...; SFitter]

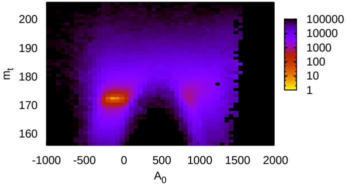
- want to evaluate probability of model being true $p(m|d)$
- can compute fully exclusive likelihood map $p(d|m)$ over m [tough]
- additional LHC challenge: remove poor directions [e.g. endpoints vs rates]
- Bayesian: $p(m|d) \sim p(d|m)\ p(m)$ with theorists' bias $p(m)$ [cosmology, BSM]
  frequentist: best–fitting point $\max_m p(d|m)$ [flavor]
- LHC era: (1) compute high-dimensional map $p(d|m)$
  (2) find and rank local best-fitting points
  (3) predict additional observables

Correlations and errors

Toy model: MSUGRA map from LHC [LHC endpoints with free y_t]

- model unrealistic but useful testing ground [will do anything for citations]
- weighted Markov chains: several times faster
- SFitter output #1: fully exclusive likelihood map
  SFitter output #2: ranked list of local maxima
- strong correlation e.g. of A_0 and y_t [including all errors]

$\Rightarrow$ correlations and secondary maxima significant [0709.3985]



χ^2	m_0	$m_{1/2}$	$\tan\beta$	A_0	μ	m_t
0.3e-04	100.0	250.0	10.0	-99.9	+	171.4
27.42	99.7	251.6	11.7	848.9	+	181.6
54.12	107.2	243.4	13.3	-97.4	-	171.1
70.99	108.5	246.9	13.9	26.4	-	173.6
88.53	107.7	245.9	12.9	802.7	-	182.7
...						

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A word on errors

- central values secondary locally
- statistical errors Gaussian
  systematic errors Gaussian, correlated
  theory errors flat
- RFit scheme [CKMFitter]

$$\chi^2 = -2 \log \mathcal{L} = \vec{\chi}_d^{\,T} \; C^{-1} \; \vec{\chi}_d$$

$$\chi_{d,i} = \begin{cases} 0 & |d_i - \bar{d}_i| < \sigma_i^{(\text{theo})} \\ \frac{\mathcal{D}|d_i - \bar{d}_i| - \sigma_i^{(\text{theo})}}{\mathcal{D}\sigma_i^{(\text{exp})}} & |d_i - \bar{d}_i| > \sigma_i^{(\text{theo})} \end{cases} ,$$

$$C_{i,i} = 1 \qquad C_{i,j} = C_{j,i} = \frac{0.99 \; \sigma_i^{(\ell)} \; \sigma_j^{(\ell)} + 0.99 \; \sigma_i^{(\text{j})} \; \sigma_j^{(\text{j})}}{\sigma_i^{(\text{exp})} \; \sigma_j^{(\text{exp})}}$$

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A word on errors

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- statistical errors Gaussian
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  theory errors flat
- theory error sizeable

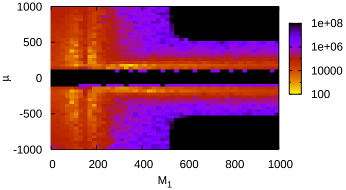
	SPS1a	$\Delta^{\text{theo}-\text{exp}}_{\text{zero}}$	$\Delta^{\text{expNoCorr}}_{\text{zero}}$	$\Delta^{\text{theo}-\text{exp}}_{\text{zero}}$	$\Delta^{\text{theo}-\text{exp}}_{\text{gauss}}$	$\Delta^{\text{theo}-\text{exp}}_{\text{flat}}$
		masses	endpoints			
m_0	100	4.11	1.08	0.50	2.97	2.17
$m_{1/2}$	250	1.81	0.98	0.73	2.99	2.64
$\tan\beta$	10	1.69	0.87	0.65	3.36	2.45
A_0	-100	36.2	23.3	21.2	51.5	49.6
m_t	171.4	0.94	0.79	0.26	0.89	0.97

$\Rightarrow$ errors mean: endpoints instead of masses

TeV-scale MSSM: SFitter

MSSM map from LHC

- shifting from 6D to 19D parameter space [killing grids, Minuit, laptop–style fits...]
- Markov chain globally + hill climber locally
- SFitter outputs #1 and #2 still the same [weighted Markov chain plus hill climber]
- three neutralinos observed [left: Bayesian — right: likelihood]



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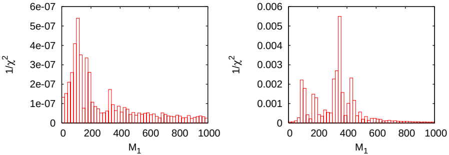

- quality of fit not always useful

	$\mu < 0$				$\mu > 0$			
M_1	96.6	175.1	103.5	365.8	98.3	176.4	105.9	365.3
M_2	181.2	98.4	350.0	130.9	187.5	103.9	348.4	137.8
μ	-354.1	-357.6	-177.7	-159.9	347.8	352.6	178.0	161.5
tan β	14.6	14.5	29.1	32.1	15.0	14.8	29.2	32.1
M_3	583.2	583.3	583.3	583.5	583.1	583.1	583.3	583.4
$M_{\tilde{\mu}_L}$	192.7	192.7	192.7	192.9	192.6	192.6	192.7	192.8
$M_{\tilde{\mu}_R}$	131.1	131.1	131.1	131.3	131.0	131.0	131.1	131.2
A_t $(-)$	-252.3	-348.4	-477.1	-259.0	-470.0	-484.3	-243.4	-465.7
A_t $(+)$	384.9	481.8	641.5	432.5	739.2	774.7	440.5	656.9
m_A	350.3	725.8	263.1	1020.0	171.6	156.5	897.6	256.1
m_t	171.4	171.4	171.4	171.4	171.4	171.4	171.4	171.4

$\Rightarrow$ means probably much more work to do...

Beyond the LHC

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- theory errors not negligible [rates for focus–point scenarios]
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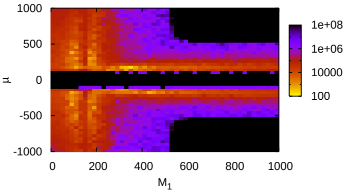

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- strongly correlated and promising

	LHC	LHC $\otimes (g-2)$	SPS1a
$\tan\beta$	**10.0 ± 4.5**	**10.3 ± 2.0**	**10.0**
M_1	102.1 ± 7.8	102.7 ± 5.9	103.1
M_2	193.3 ± 7.8	193.2 ± 5.8	192.9
M_3	577.2 ± 14.5	578.2 ± 12.1	577.9
$M_{\tilde\mu_L}$	193.2 ± 8.8	194.0 ± 6.8	194.4
$M_{\tilde\mu_R}$	135.0 ± 8.3	135.6 ± 6.3	135.8
$M_{\tilde q3_L}$	481.4 ± 22.0	485.6 ± 22.4	480.8
$M_{\tilde b_R}$	501.7 ± 17.9	499.2 ± 19.3	502.9
$M_{\tilde q_L}$	524.6 ± 14.5	525.5 ± 10.6	526.6
$M_{\tilde q_R}$	507.3 ± 17.5	507.6 ± 15.8	508.1
m_A	406.3 ± $\mathcal{O}(10^3)$	411.1 ± $\mathcal{O}(10^2)$	394.9
μ	350.5 ± 14.5	352.5 ± 10.8	353.7

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(2) use BR($B_s \to \mu\mu$) with stop–chargino sector [Hisano, Kawagoe, Nojiri]

- 7% error on f_{B_s} by 2015 crucial [Della Morte, Del Debbio; SFitter + Jäger, Spannowsky]
- perturbative effects secondary

	no theory error			$\Delta\mathrm{BR}/\mathrm{BR} = 15\%$	
	true	best	error	best	error
$\tan\beta$	**30**	**29.5**	**3.4**	**29.5**	**6.5**
M_A	344.3	344.4	33.8	344.3	31.2
M_1	101.7	100.9	16.3	100.9	16.4
M_2	192.0	200.3	18.9	200.3	18.8
M_3	586.4	575.8	28.8	575.8	28.7
μ	345.8	325.6	20.6	325.6	20.6
$M_{\tilde{t},R}$	430.0	400.4	79.5	399.8	79.5

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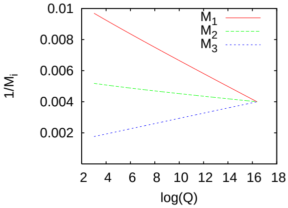
Renormalization group bottom–up [SFitter + Kneur]

– SUSY breaking, unification, GUT?

– scale-invariant sum rules? [Cohen, Schmalz]

⇒ solidly inference from weak scale



Large extra dimensions

Remember the hierarchy problem

– fundamental scalars bad with high scale present

– weakness of gravity means large Planck scale $G_N = 1/(16\pi M_{\text{Planck}})^2$

⇒ solution: another reason why we see huge non-fundamental M_{Planck}

Large extra dimensions (ADD) [Antoniadis, Arkani-Hamed, Dimopoulos, Dvali]

– Einstein–Hilbert action for low fundamental Planck scale

$$\begin{aligned} S = -\frac{1}{2}\int d^4x\sqrt{|g|}\,M_D^2\,R \to & -\frac{1}{2}\int d^{4+n}x\sqrt{|g|}\,M_D^{2+n}\,R \\ & = -\frac{1}{2}(2\pi r)^n\int d^4x\sqrt{|g|}\,M_D^{2+n}\,R \\ & \equiv -\frac{1}{2}\int d^4x\sqrt{|g|}\,M_{\text{Planck}}^2\,R \end{aligned}$$

⇒ express M_{Planck} in terms of fundamental M_D

$$M_{\text{Planck}} = M_D\,(2\pi r M_D)^{n/2}$$

Numbers to make it work

– free parameter $rM_D \gg 1$

– constraints from gravity tests above $\mathcal{O}(\text{mm})$

⇒ signatures of strong gravity in extra dimension?

$M_D = 1$ TeV	
n	r
1	10^{12} m
2	10^{-3} m
3	10^{-8} m
...	...
6	10^{-11} m

Effective KK theory

Toy model: only gravitons in extra dimensions

- expand the metric [graviton field h]

$$ds^2 = g_{MN}^{(4+n)} dx^M dx^N = \left(\eta_{MN} + \frac{1}{M_D^{n/2+1}} h_{MN} \right) dx^M dx^N$$

- matter in Einstein's equation [no cosmological constant]

$$R_{AB} - \frac{1}{2+n} g_{AB} R = - \frac{1}{M_D^{2+n}} \begin{pmatrix} T_{\mu\nu}(x)\, \delta^{(n)}(y) & 0 \\ 0 & 0 \end{pmatrix}$$

- Fourier transformation of extra dimensions [KK excitations for periodic boundary conditions]

$$h_{AB}(x;y) = \sum_{m_1=-\infty}^{\infty} \cdots \sum_{m_j=-\infty}^{\infty} \frac{h_{AB}^{(m)}(x)}{\sqrt{(2\pi r)^n}} e^{i \frac{m_j y_j}{r}}$$

- universal interactions of KK gravitons [$h_{AB} \to G_{\mu\nu}$, QCD massless]

$$(\Box + m_k^2)\, G_{\mu\nu}^{(k)} = \frac{1}{M_{\text{Planck}}} \left[-T_{\mu\nu} + \left(\frac{\partial_\mu \partial_\nu}{\hat{m}^2} + \eta_{\mu\nu} \right) \frac{T_\lambda^\lambda}{3} \right] = \frac{-T_{\mu\nu}}{M_{\text{Planck}}}$$

- tiny KK mass splitting [$M_D = 1$ TeV]

$$\delta m \sim \frac{1}{r} = 2\pi M_D \left(\frac{M_D}{M_{\text{Planck}}} \right)^{2/n} = \begin{cases} 0.003\ \text{eV} & (n=2) \\ 0.1\ \text{MeV} & (n=4) \\ 0.05\ \text{GeV} & (n=6) \end{cases}$$

⇒ continuum of weakly interacting gravitons at the LHC

Effektive KK theory at the LHC

Effective KK theory [Giudice, Rattazzi, Wells; Han, Lykken, Zhang;...]

- real radiation of continuous KK tower $[dm/d|k| = 1/r; (d\sigma) \propto 1/M_{\text{Planck}}^2]$

$$(d\sigma) \to \int dm \, (d\sigma) \, S_{n-1} m^{n-1} r^n = \int dm \, (d\sigma) \, \frac{S_{n-1} \, m^{n-1}}{(2\pi M_D)^n} \left(\frac{M_{\text{Planck}}}{M_D} \right)^2$$

- higher-dimensional operator from virtual graviton exchange [s–channel in DY]

$$\mathcal{A} = \frac{1}{M_{\text{Planck}}^2} \frac{1}{s - m_{\text{KK}}^2} \to \frac{S_{\delta-1}}{2} \frac{\Lambda^{n-2}}{M_D^{n+2}}$$

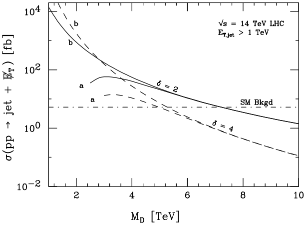
- $1/M_D^2$ interactions for KK tower

⇒ like any effective theory valid for $E < M_D$

Real emission $pp \to G_{\text{KK}}$+jets [Giudice, Rattazzi, Wells; Vacavant, Hichliffe...]

- recoil against hard jet $[E_j \sim M_D]$
  background: radiation of $Z \to \nu\bar{\nu}$
- $\mathcal{M} = 0$ for $E_{\text{parton}} > \Lambda_{\text{cutoff}}$
  $\mathcal{M} = 0$ automatically for $m_{\text{KK}} > E_{\text{parton}}$
- effective cutoff: steep gluon density
- little UV sensitivity for $\Lambda_{\text{cutoff}} \to \infty$

⇒ explicit cutoff not crucial



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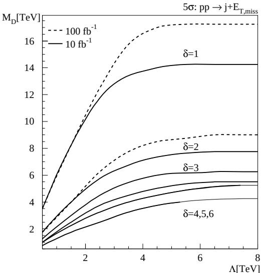


Virtual gravitons at LHC

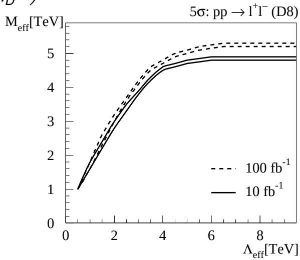
Effective theory of virtual gravitons [Giudice & Strumia; Giudice, Strumia, TP; Kachelries & Plümacher,...]

- virtual graviton in s channel $pp \to \mu^+\mu^-$ [$q\bar{q}$ and gg initial states]
- reconstructed $m_{\mu\mu}$ for photon, Z, graviton
- loop-induced D6 operator [axial vector–axial vector]

$$\mathcal{O} = \frac{1}{16}\,\frac{1}{M_D^2}\,\frac{\pi^{n-2}}{\Gamma^2(n/2)}\,\left(\frac{\Lambda_{\text{cutoff}}}{M_D}\right)^{2n+2}$$

- tree-induced D8 operator [leading constant in $\sqrt{s}/\Lambda_{\text{cutoff}}$]

$$\mathcal{S} = \frac{S_{n-1}}{M_D^{2+n}}\int dm\,\frac{m^{n-1}}{s+m^2} = \begin{cases} \dfrac{4\pi}{M_{\text{eff}}^4} & \text{(effective scale)} \\ \dfrac{S_{n-1}}{M_D^4}\,\dfrac{1}{2}\left(\dfrac{\Lambda_{\text{cutoff}}}{M_D}\right)^{n-2} & \text{(NDA)} \\ \dfrac{S_{n-1}}{M_D^4}\,\dfrac{1}{n-2}\left(\dfrac{\Lambda_{\text{cutoff}}}{M_D}\right)^{n-2} & \text{(cutoff }\Theta\text{)} \end{cases}$$



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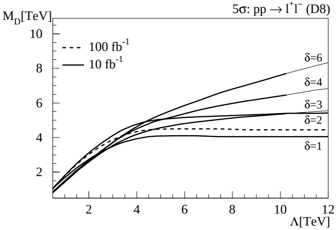
- two-dimensional integration over (m, s)
  cutoff requiring $m \lesssim M_D$
  additional cutoff for $\sqrt{s} \lesssim M_D$
- rates scaling $M_D^\text{max} \sim \Lambda_\text{cutoff}^{(n-2)/(n+2)}$

$\Rightarrow$ breakdown of effective theory



String theory completion

String theory as UV completion [e.g. Cullen, Perelstein, Peskin; Antoniadis, Benakli, Laugier...]

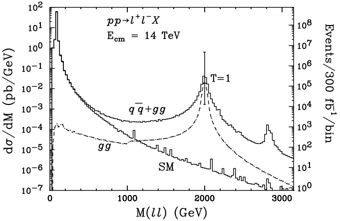
- ‘In particular, the only known framework that allows for a self-consistent description of quantum gravity is string theory’
- Regge excitations of Standard Model [Burikham, Figy, Han]
- compute different helicity contributions, like

$$\mathcal{A}(e_L^+ e_R^- \to \gamma_L \gamma_R) = -2e^2 \sqrt{\frac{u}{t}} \left(\frac{u}{s} + \frac{t}{s} - 1 \right) = 2e^2 \sqrt{\frac{u}{t}}$$
$$= -2e^2 \sqrt{\frac{u}{t}} \left(\frac{u}{s}\, \mathcal{S}(s,t) + \frac{t}{s}\, \mathcal{S}(s,u) - \mathcal{S}(t,u) \right)$$

- with Veneziano form factor

$$\mathcal{S}(s,t) = \frac{\Gamma(1-\alpha' s)\,\Gamma(1-\alpha' t)}{\Gamma(1-\alpha'(s+t))} = \frac{\Gamma(1-s/M_S^2)\,\Gamma(1-t/M_S^2)}{\Gamma(1-(s+t)/M_S^2)}$$
$$= 1 - \frac{\pi^2}{6}\,\frac{st}{M_S^4} + \mathcal{O}\left(M_S^{-6}\right)$$

- dominant over KK because $M_{\text{eff}} \gg M_S$ closed-string gravitons suppressed
- effective operator below string scale
- string resonances: $\sqrt{n}\, M_S$



Renormalization flow of gravity

Renormalization flow of gravity [Reuter; Litim; Wetterich;...]

- Einstein–Hilbert action with running $G(\mu)$ and $\Lambda(\mu)$

$$\Gamma_k = 1/(16\pi G_k) \int d^{4+n}x \sqrt{g}\, [-R(g) + \cdots]$$

- dimensionless coupling $g(\mu) = G(\mu)\, \mu^{2+n} = G_0\, Z_G^{-1}(\mu)\, \mu^{2+n}$
- attractive finite UV fixed point [anomalous dimension: $\eta = -\mu \partial_\mu \log Z_G \propto g$]

$$\mu \frac{\partial}{\partial \mu} g_*(\mu) = (2 + n + \eta(g_*))\;\; g_*(\mu) = 0 \qquad \text{for} \qquad g_* \neq 0 \qquad \eta(g_*) = -2 - n$$

- gravity asymptotically free in UV $G(\mu) \sim g_* \mu^{-(2+n)}$

⇒ coupling weak enough for finite LHC predictions?

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UV–safe gravity [Weinberg (1979)]

- gravity really non–fundamental because $G \propto 1/M_D^{2+n}$?
- ’t Hooft’s perturbative renormalizability: finite number of counter terms
- Wilson’s renormalizability: no unphysical UV divergences

- consistent theory beyond perturbation theory [no ghosts: Weinberg & Gomez]
- fixed point seen for $\sqrt{|g|}\,R^8$ and including matter [no proof; not perturbative series]
- great idea for gravity — great for LHC

Fixed-point form factor

Naive form factor [Hewett & Rizzo]

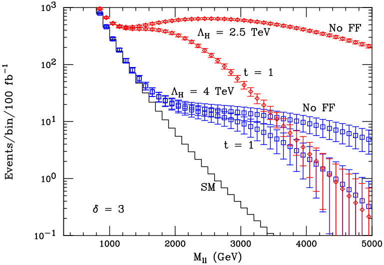
- dress *s*-channel coupling

$$\frac{1}{M_D^{2+n}} \longrightarrow \frac{1}{M_D^{2+n}}\; F(s) = \frac{1}{M_D^{2+n}} \; \left(1 + \left(\frac{\sqrt{s}}{t M_D} \right)^{2+n} \right)^{-1}$$

- avoids matching of *s* integration (unitarity)

$$\frac{1}{M_D^{2+n}}\; F(s) \sim \frac{1}{M_D^{2+n}} \; \left(\frac{t M_D}{\sqrt{s}} \right)^{2+n} \sim \frac{1}{s^{(2+n)/2}}$$

- improvement of *s* integration/matching
- still cutoff in KK-mass integration



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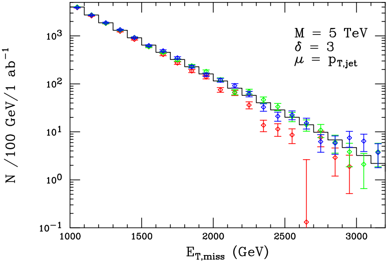
- improvement of s integration/matching
- still cutoff in KK-mass integration
- also applicable to graviton emission [less impressive effect]



Fixed-point completion

Modified graviton propagator [Reuter; Fischer & Litim]

- effective action: $\Gamma_k = 1/(16\pi G_k) \int d^{4+n}x \sqrt{g}\, [-R(g) + \cdots]$
- IR — no running; M_D regime — strong effects; UV — fixed point

- iterative approach: start with anomalous dimension of graviton

$$P(s,m) = \begin{cases} \dfrac{1}{s+m^2} & \sqrt{s}, m < k_{\text{trans}} \\ \dfrac{M_D^{n+2}}{(s+m^2)^{n/2+2}} & \sqrt{s}, m > k_{\text{trans}} \end{cases}$$

- IR and UV contributions to D8 operator [leading in $\sqrt{s}/m$, matched to $1/s^2$]

$$\mathcal{S}^{\,(\text{FP})} = \frac{S_{n-1}}{M_D^4} \left(\frac{k_{\text{trans}}}{M_D} \right)^{n-2} \frac{n-1}{n-2} = (1 + (n-2))\;\; \mathcal{S}^{(\Theta)}$$

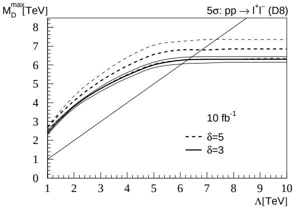
- needed and not needed:
  (1) transition scale $k_{\text{trans}} \sim M_D$ [anomalous dimension modeled]
  (2) no artificial Λ_{cutoff} for m integration
  (3) matching/cutoff for s integration

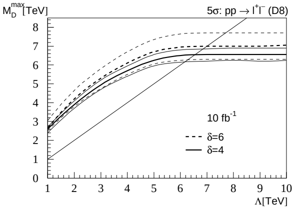
⇒ UV fixed point indeed solution to our problems

Fixed-point completion

test with artificial Λ_{cutoff} setting $\mathcal{M}_{\text{KK}} = 0$

- perfect decoupling, as expected [similar to real emission]
- mild effects for $k_{\text{trans}} = M_D \pm 10\%$ [more details to be studied]
- reach largely independent of n





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Shape of graviton kernel

- shift to larger $m_{\ell\ell}$ [shown $n = 3$]
  small $m_{\ell\ell}$: factor $\mathcal{S} \propto (n-1)$
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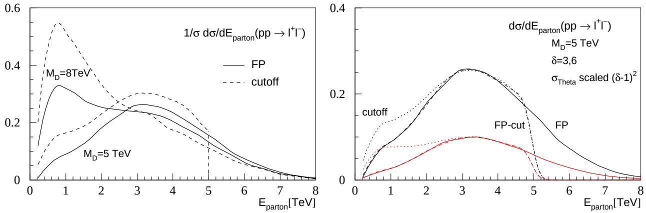

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predicted LHC rates

- $\mathcal{S}^{(\text{FP})}$: UV regime in addition to $\mathcal{S}^{(\Theta)} \equiv \mathcal{S}^{\text{IR}}$

σ[fb]	$n = 3$			$n = 6$		
M_D	2 TeV	5 TeV	8 TeV	2 TeV	5 TeV	8 TeV
$\mathcal{S}^{(\text{NDA})}$	43.6	0.18	0.0053	263	1.11	0.031
$\mathcal{S}^{(\Theta)}$	173	0.72	0.0204	66	0.28	0.008
$\mathcal{S}^{(\text{FP})}$	408	1.24	0.0317	398	1.21	0.031

$\Rightarrow$ proof of concept quantitatively very promising

Outlook

Understanding the TeV scale

(1) look for solid new–physics signals

(2) measure weak–scale Lagrangian

(3) determine fundamental physics

- construct new–physics hypotheses
- compute reliable predictions
- avoid getting killed by QCD
- enjoy toying around with UV gravity

⇒ LHC more than a discovery machine!