SPIN DETERMINATION OF HEAVY S-CHANNEL DIPHOTON RESONANCES AT THE LHC

QCD @ WORK

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Preamble

- Heavy quantum states (***M*** **≥ 1 TeV**) predicted by New Physics models.
- Manifestations at colliders:
  - [M>E_{CM}] → Indirect deviations from SM predictions
  - Direct production → peaks in cross sections.
- Cleanest: dilepton and/or diphoton events.
- Discovery reach: peak observation over SM background at some $\boldsymbol{M_R}$ => allowed region on model parameters.
- Identification reach: identify source of the observed peak (different models can give same $\boldsymbol{M_R}$ and same number of events under the peak) ↔ test of peak/resonance quantum numbers.

- "Confusion regions" of model parameters.
- Spin identification of the observed peak ➔ discrimination of models against each other in confusion regions.

Model examples for diphoton production

- Gravity with one warped extra dimension ⇔ spin-2 graviton resonance [Randall-Sundrum, 1999].
- Heavy scalar exchange ⇔ spin-0 [Barbieri et al., 2011]
- Both exchanged in $p+p \to \gamma\gamma + X$
- Similar mechanism for $p+p \to l^+l^- + X, [l = e, \mu]$ except spin-1 also possible
- Tool for discrimination: angular-integrated asymmetry $\boldsymbol{A_{CE}}$; NLO in QCD.

[Phys.Rev. D84, 115008, Dec. 2011; and refs. here]

Angular analysis & BSM physics:

- *Allanach* et al. (2000, 2002)
- *Cousins* et al. (2005)
- *Belotelov* et al. (2006)
- *Feldman* et al. (2006)
- ATLAS and CMS Technical reports
- *Osland* et al. (2008→2009)
- *Melnikov* et al. (2010)
- *Diener* et al. (2010)
- *Davoudiasl* et al. (2009)
- *Murayama* et al. (2009)
- *Boudjema* et al. (2009)
- *Antipin* et al. (2009)
- *De Rujula* et al. (2010)
- *Cheng-Wei Chiang* et al. (2011)

Basic observables for $p + p \to R \to \gamma\gamma$.

- ($y \equiv$ rapidity of lepton pair, $M \equiv$ dilepton mass, $z \equiv \cos\theta$)

I) Production cross section: $\sigma(R_{\gamma\gamma}) = \int_{-z_{cut}}^{z_{cut}} dz \int_{M_R-\Delta M/2}^{M_R+\Delta M/2} dM \int_{-Y}^{Y} dy \frac{d\sigma}{dM\, dy\, dz}$

$\to$ number of events under the peak (discovery):

Minimal number of signal events over SM bckgrnd: [$signal \equiv \max(5\cdot\sqrt{N_B},\ 10)$]

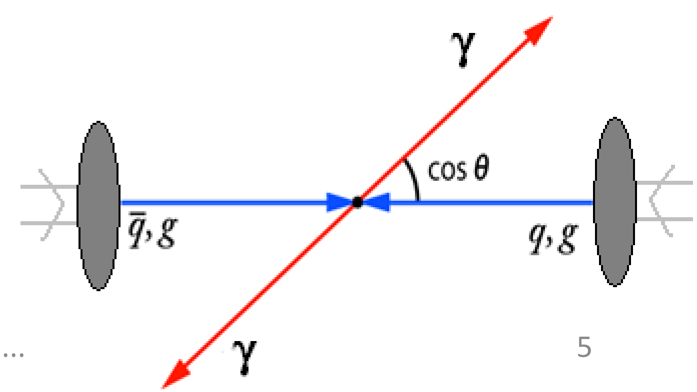
II) Angular distribution $\frac{d\sigma}{dz} = \int_{M_R-\Delta M/2}^{M_R+\Delta M/2} dM \int_{-Y}^{Y} \frac{d\sigma}{dM\, dy\, dz} dy$

- ATLAS, CMS cuts
- Parton distribution functions $f_q(\xi, M)$ – CTEQ6
- Partonic cross sections $\hat{\sigma}$ ***[Giudice et al., 1999; Han et al., 1999]***
- Angular dependent K-factors

$\bar{q}q, gg \to G, S \to \gamma\gamma$

C.M. $\gamma\gamma$ **system:**

$z \equiv \cos(\theta)$



SPIN-2 diphoton

RS1 model with one warped extra dimension

[Randall – Sundrum, 1999]

- $\mathrm{d}s^2 = \left(e^{-2k|y|}\right)^2 \eta_{\mu\nu}\,\mathrm{d}x^\mu\,\mathrm{d}x^\nu + \mathrm{d}y^2$

  → **warp factor,** $k > 0$ **(5D curvature)**

- Fundamental mass scales (G = Newton constant)

  $\bar{M}_{Pl} = 1/\sqrt{8\pi G}; \quad M_* = M^{(5)}$

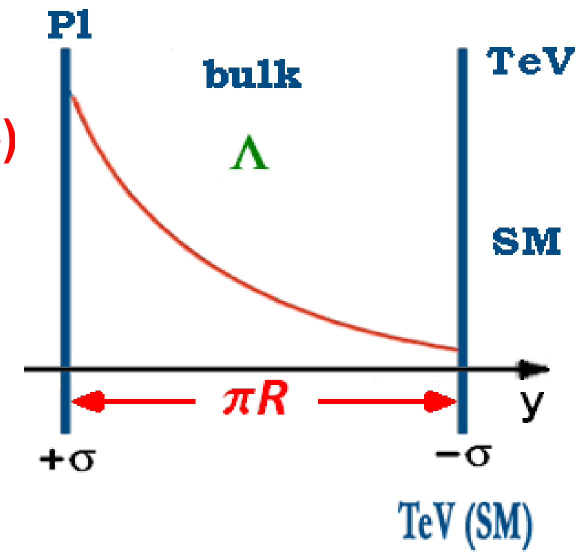
- 4D effective theory gives $\bar{M}_{Pl}^2 = \frac{M_*^3}{k}\left(1 - e^{-2k\pi R}\right)$

- "Natural" model assumption: $\bar{M}_{Pl} \sim M_* \sim k$

- Mass spectrum on Planck brane $\propto \bar{M}_{Pl} \sim 10^{15}\ \mathrm{TeV}$

- Mass spectrum on TeV brane exponentially warped down: $\Lambda_\pi = \bar{M}_{Pl}\, e^{-k\pi R} \sim \mathrm{TeV}$ for $kR \sim 11!$

$$L = \int d^4x \left[\frac{1}{\bar{M}_{Pl}} h_{\mu\nu}^{(0)}(x)\, T^{\mu\nu} + \frac{1}{\Lambda_\pi} \sum_{n=1}^{\infty} h_{\mu\nu}^{(n)}(x)\, T^{\mu\nu} \right]$$



$x^M \equiv (x^\mu, y)$

$\mathrm{d}s^2 = G_{MN}\,\mathrm{d}x^M\,\mathrm{d}x^N$

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & . & . & . \\ . & 1 & . & . \\ . & . & 1 & . \\ . & . & . & 1 \end{pmatrix}$$

- RS-model parameters and notations:
  - $M_1 \equiv M_G$ mass of first KK graviton (expected $M_G \approx$ TeV)
  - $c = k/\overline{M}_{Pl}$ coupling to matter [universal]

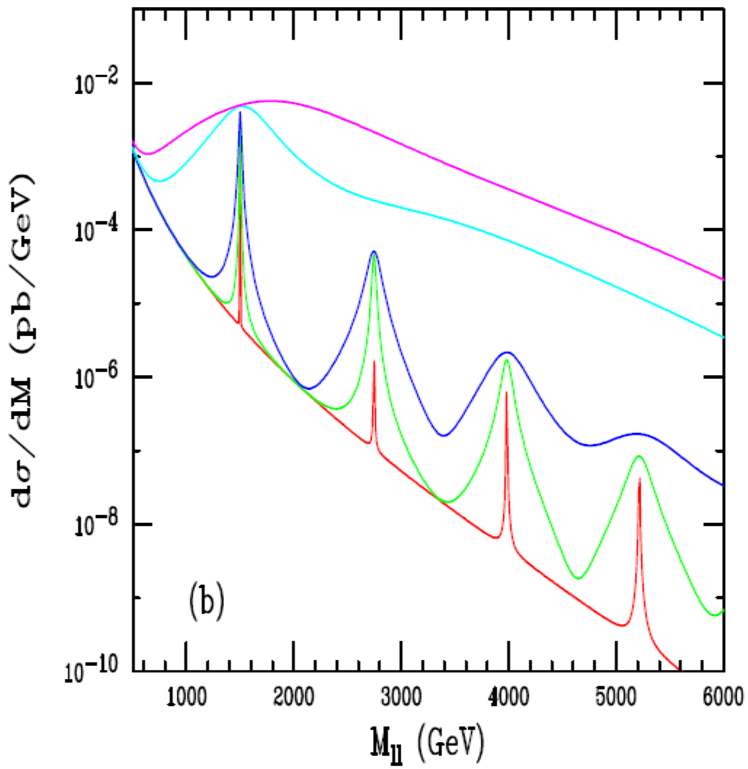
- Unevenly spaced spectrum:

  $M_n = (x_n/x_1)\, M_G$ distinctive of the model by itself

- "Theoretical" constraints:
  - $0.01 \leq c \leq 0.1$
  - $\Lambda_\pi < 10$ TeV

Width $\Gamma_n = \rho\, M_n\, x_n^2\, c^2$:

narrow resonances for small ***c***



M_1=1.5 TeV and subsequent tower states at LHC (c = 1, 0.5, 0.1, 0.05, 0.2, and 0.01, from top to bottom). **[*Davoudiasl et al.*]**

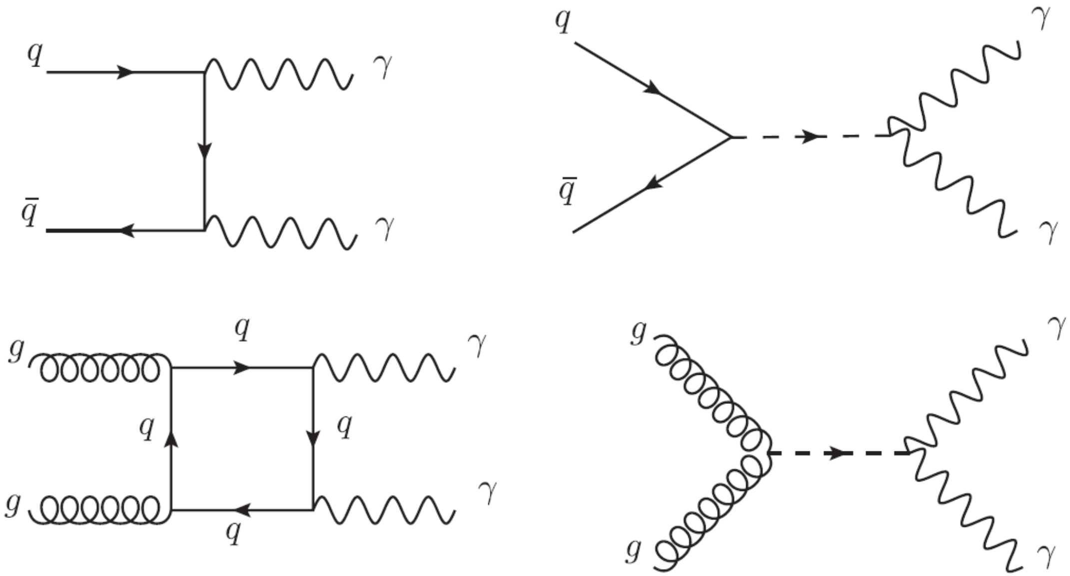
LHC 7TEV, 5 fb^{-1}:

$M_G > 910$ GeV ($c = 0.01$)

$M_G > 2160$ GeV ($c = 0.1$)

[ATLAS-CONF-2012-007; CERN-PH-EP-2012-157]

- “- ->- -” is G or S



- $z \equiv \cos(\theta)$
- $\dfrac{d\hat{\sigma}}{dz}(gg \to G \to \gamma\gamma) \propto 1 + 6z^2 + 4z^4$
- $\dfrac{d\hat{\sigma}}{dz}(q\bar{q} \to G \to \gamma\gamma) \propto 1 - z^4$
- Notice Spin-1 $\not\to \gamma\gamma$: $\dfrac{G \to \gamma\gamma}{G \to l^+ l^-} \simeq 2$

SPIN-0 diphoton

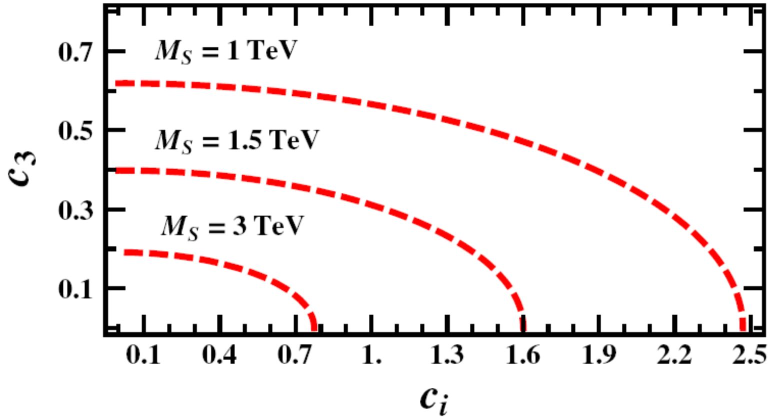
[Barbieri et al, 2011]

- $\mathcal{L}_{Scalar} = c_3 \frac{g_S^2}{\Lambda} \vec{G}_{\mu\nu} \vec{G}^{\mu\nu} S + c_2 \frac{g^2}{\Lambda} \vec{W}_{\mu\nu} \vec{W}^{\mu\nu} S + c_1 \frac{g'^2}{\Lambda} B_{\mu\nu} B^{\mu\nu} S + \sum_f c_f \frac{m_f}{\Lambda} \bar{f} f S$
- Reminiscent of composite model: ***Λ*** ~ TeV; $\boldsymbol{c_i}$ ~ 1
- Dominant cross section:

$$\frac{d\hat{\sigma}}{dz}(gg \to S \to \gamma\gamma) \propto \text{independent of } z$$

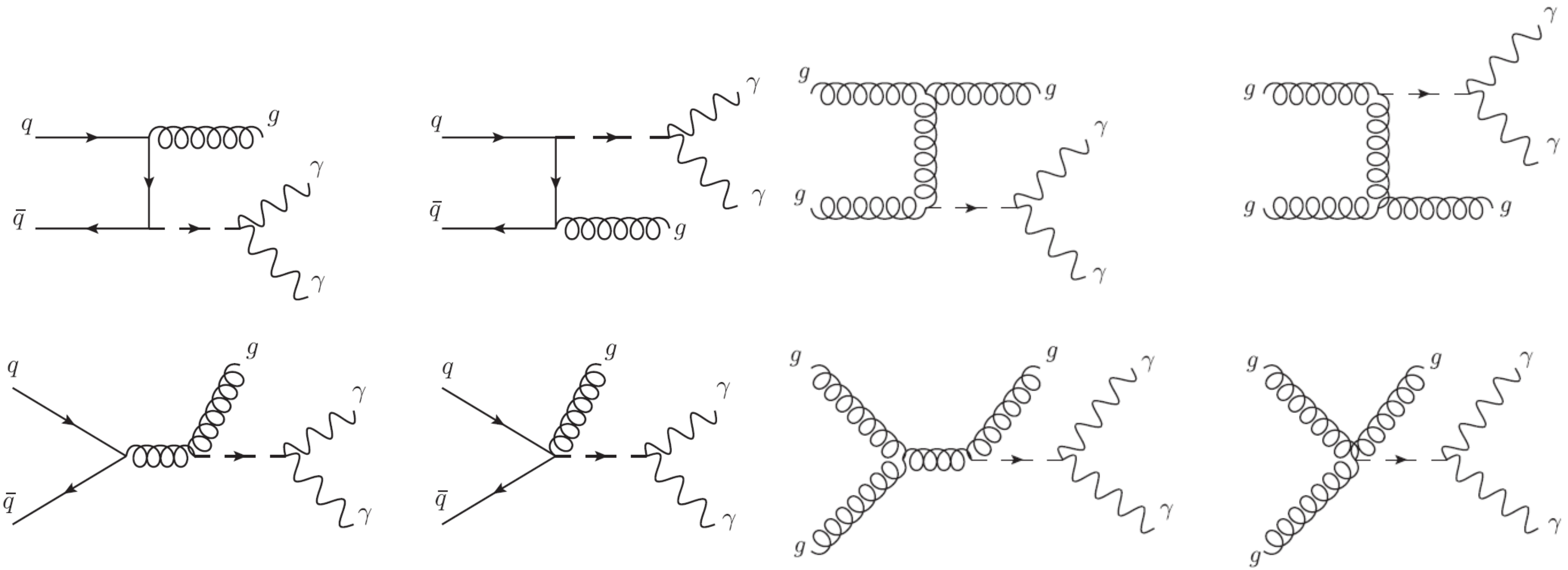
- $\boldsymbol{c_i}$ constrained by $\Gamma_S \leq \Delta M \quad (\Gamma_S \propto M_S)$

will choose ***Λ*** = 3 TeV



NLO – QCD effects

- "- ->- -" is for G or S exchange



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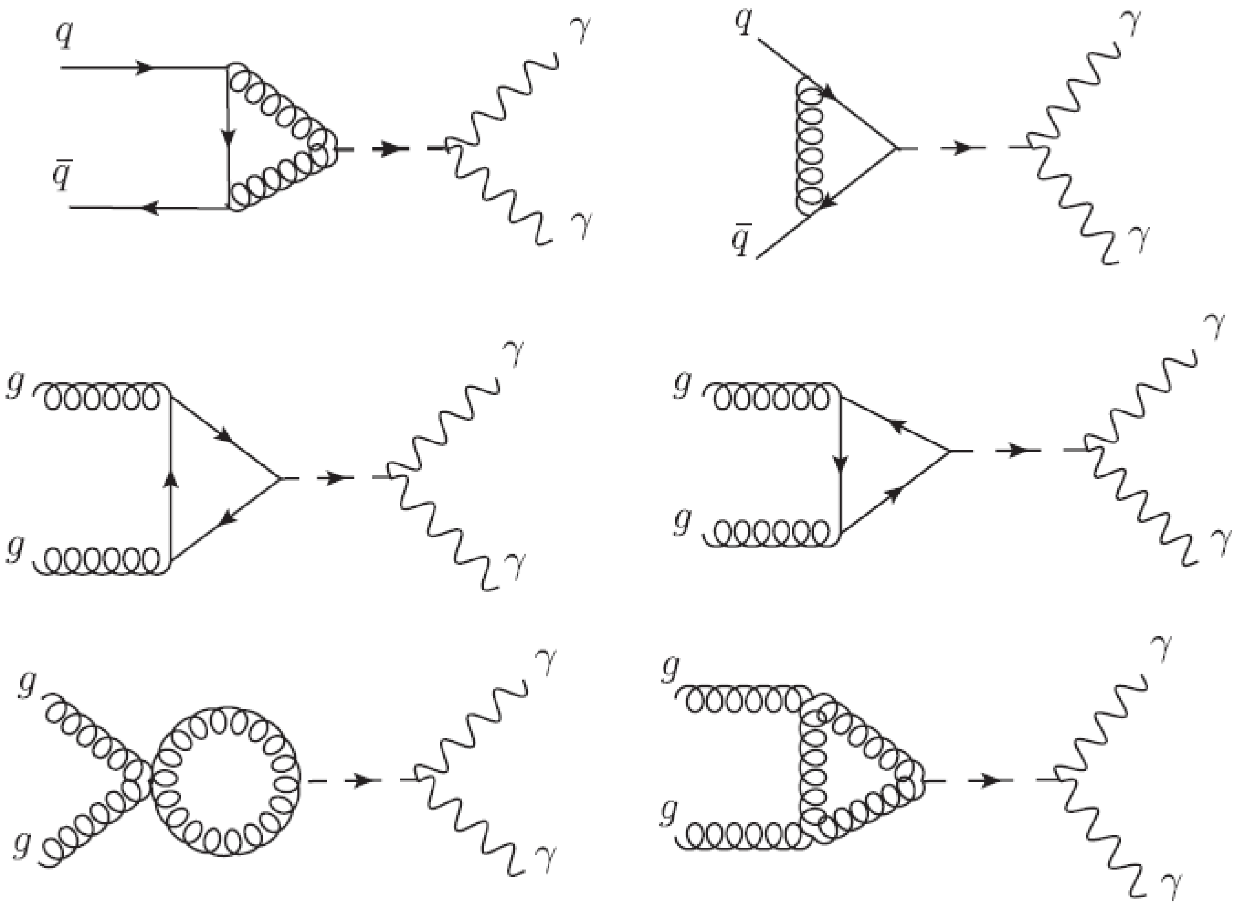


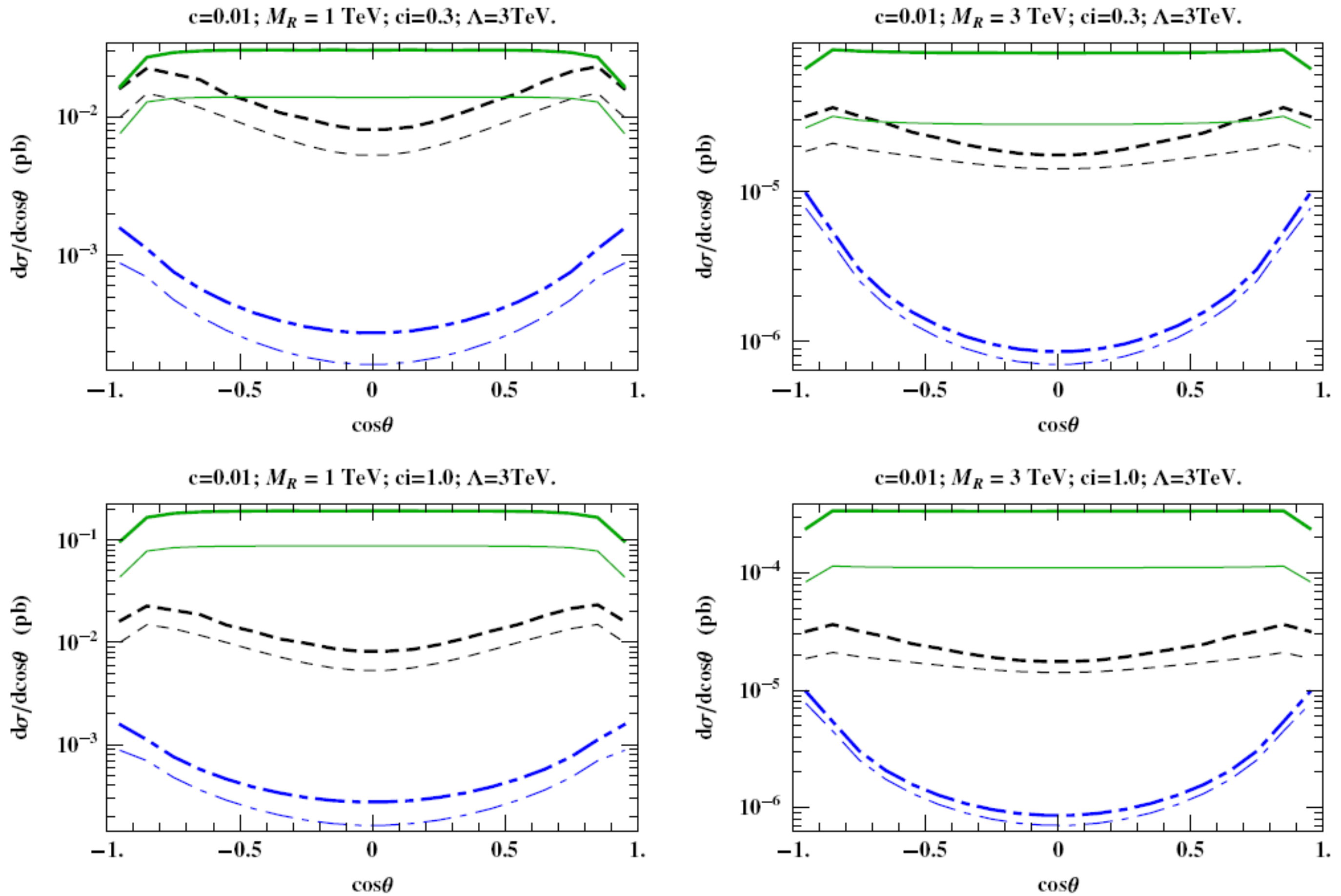
- "Direct" photons from hard partonic interactions ➔ SIGNAL
- *vs* "Fragmentation" photon from parton fragmentation
- Photon "isolation" criteria → cuts must be applied
- "Cones" $R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$ ➔ events with $R(\gamma,\gamma) < R_0$ discarded

  "Conventional" $R_0 = 0.4$
- QCD & QED collinear singularities ($m_{\text{parton}} = 0$)

  ⮡ factored in fragmentation functions [uncertain]
- Alternate for photon isolation from hadronic jets [Frixione]
  - $R(\gamma, jet) < R_0$ discarded
  - $E_T^{had}(R) \leq E_T^{iso} \left(\frac{1-\cos R}{1-\cos R_0} \right)^n$ for any $R < R_0$ accepted; $[E_T^{iso} = 15\,\text{GeV},\ n = 2]$
- Fragm. photons suppressed, conventional QCD singularities undisturbed

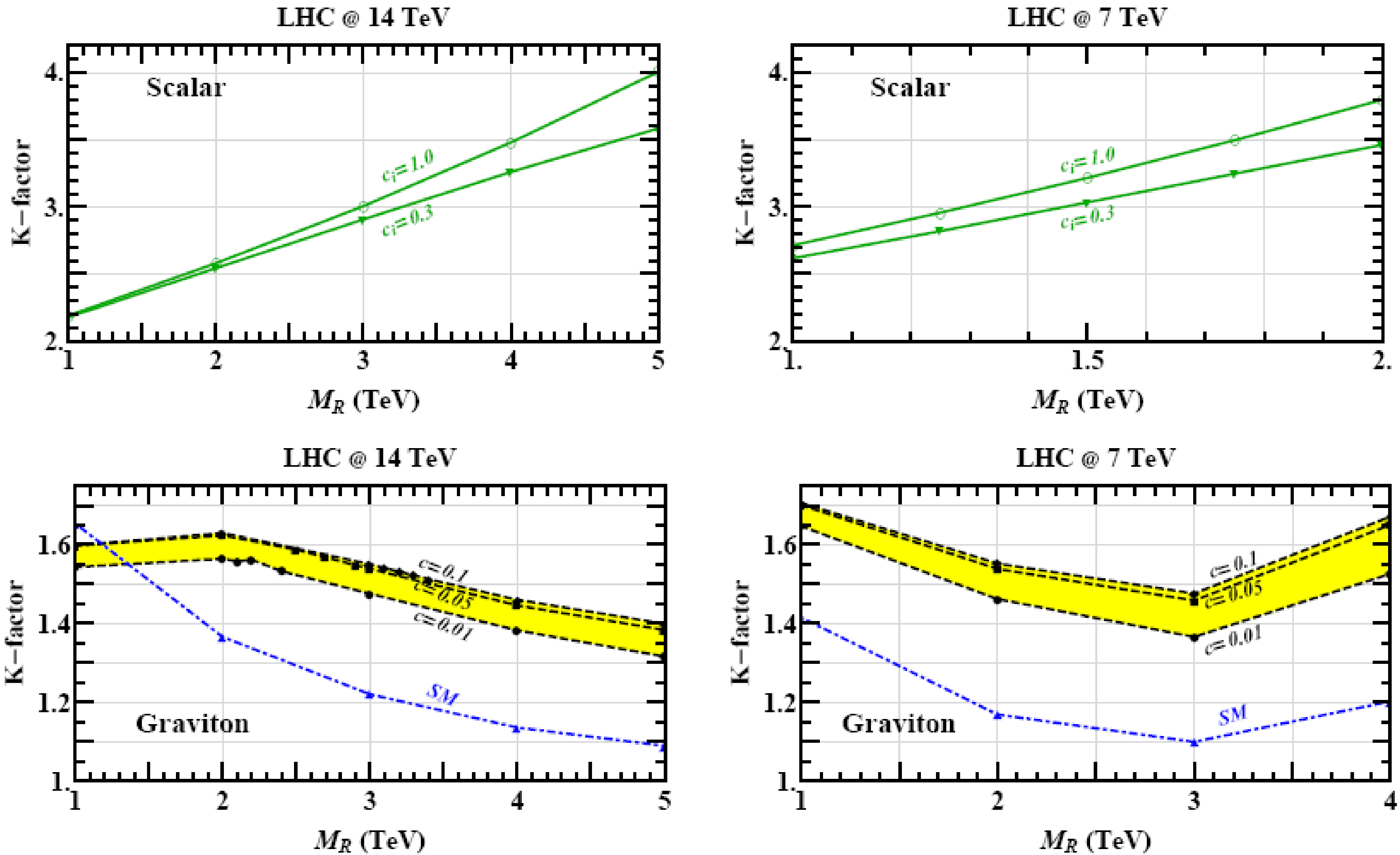
Results for angular distributions

- $\dfrac{d\sigma}{d\cos\theta}$



Reproduce LO shape to a good extent.

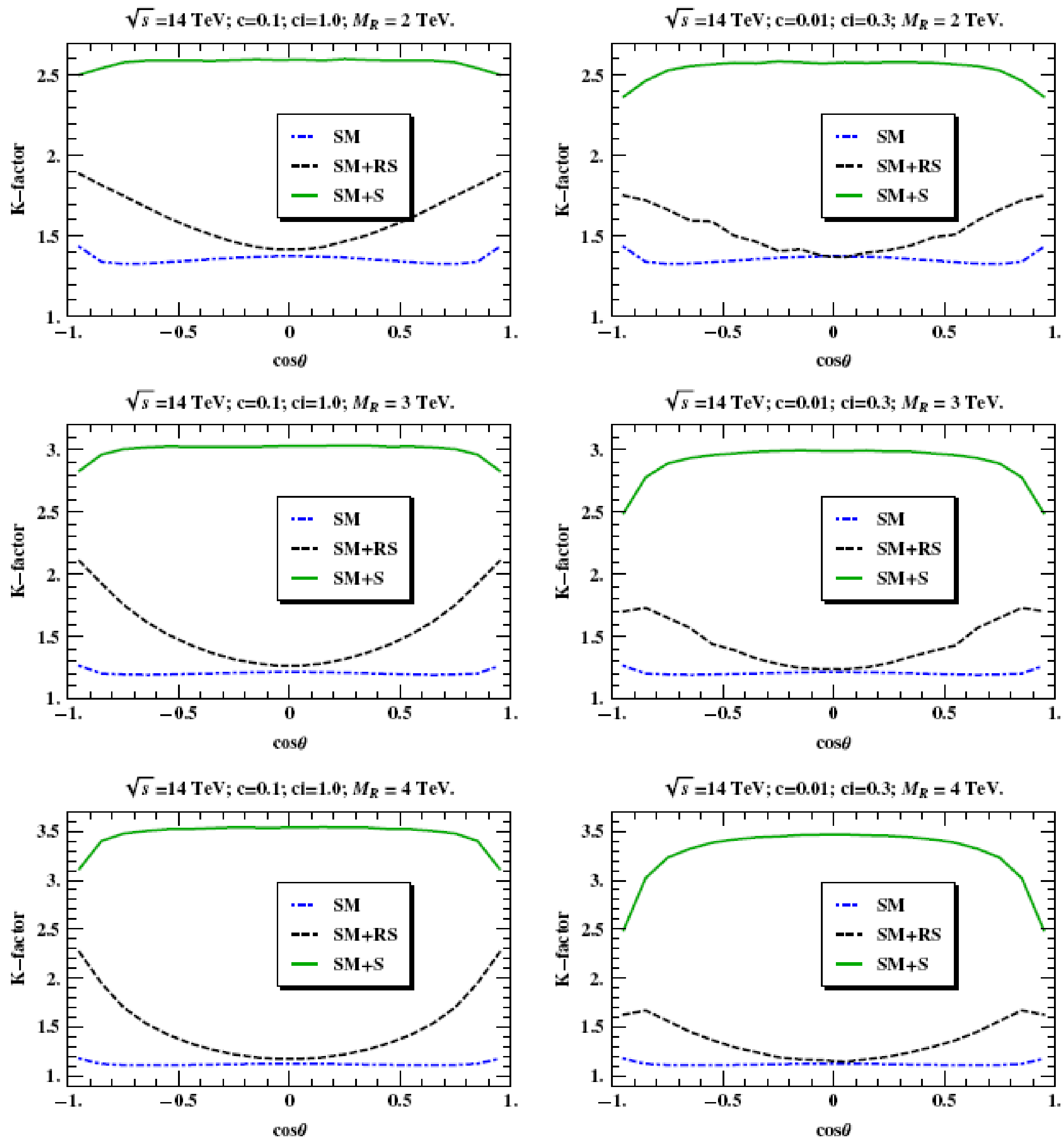
- K-factors $K = \dfrac{\sigma_{SM}^{NLO} + \sigma_{NP}^{NLO}}{\sigma_{SM}^{LO} + \sigma_{NP}^{LO}}$, any kind of cross section
- Rather large (2.5 – 3.0) for Scalar exchange:



K-factor vs M_R for 14 TeV (left panel) and 7 TeV (right panel) LHC.

Experimental cuts: p > 40 GeV; |η| < 2.4; ε = 80%; photon isolation criteria

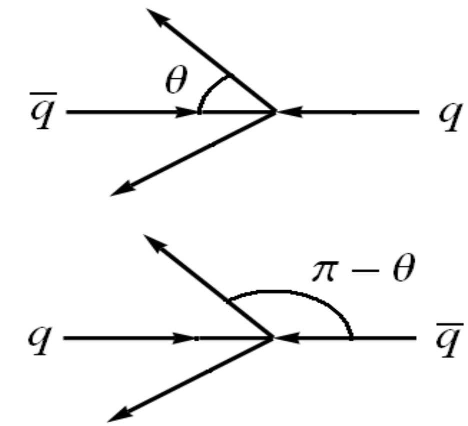
K-factor *vs.* cosθ, 14 TeV LHC.



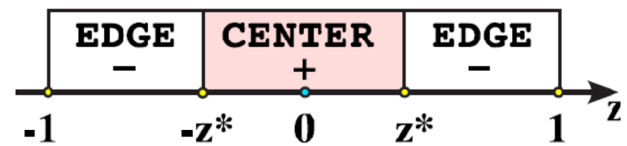
Resonance spin-angular analysis

- Event-by-event boost to CM frame

  and sign of $z = \cos\theta$



- Centre-Edge Asymmetry: $A_{CE} = \dfrac{\sigma_{CE}(R_{\gamma\gamma})}{\sigma(R_{\gamma\gamma})}$



$$\sigma_{CE}(R_{\gamma\gamma}) = \left[\int_{-z^*}^{z^*} - \left(\int_{-1}^{-z^*} + \int_{z^*}^{1}\right)\right] \frac{d\sigma(R_{\gamma\gamma})}{dz}\, dz$$

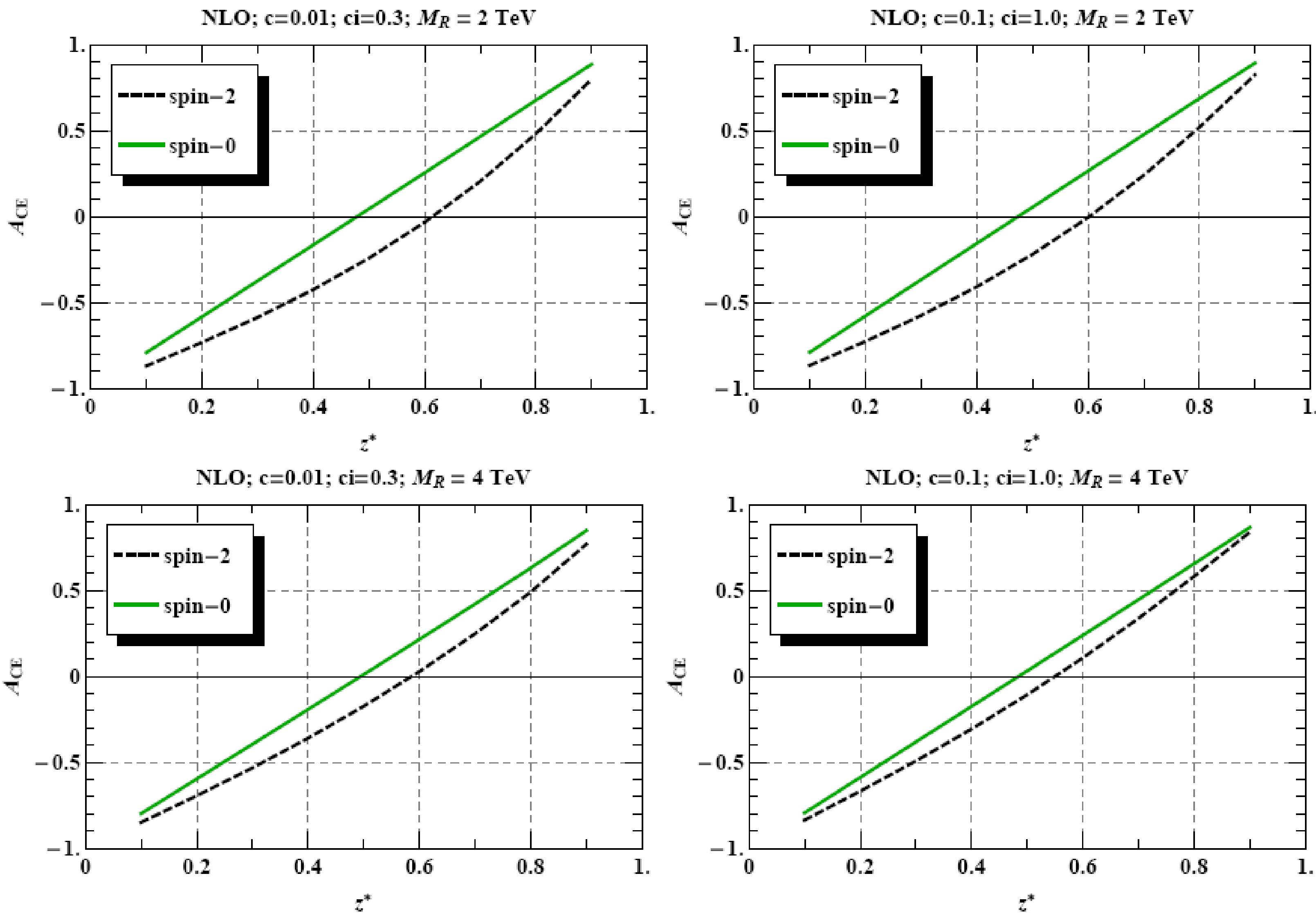
z-symmetric integration!

- Expectations: – ratios of cross sections – minimized syst.uncert.

  – angular integrated – statistics

  – same for spin-1 Z's and SM – useful for DY

NLO A_{CE} asymmetry *vs.* z* for the process pp→γγ+X at the 14 TeV LHC



- Same number of peak events
- z* ≈ 0.5 "optimal"

Constraints for identification reach of G →γγ

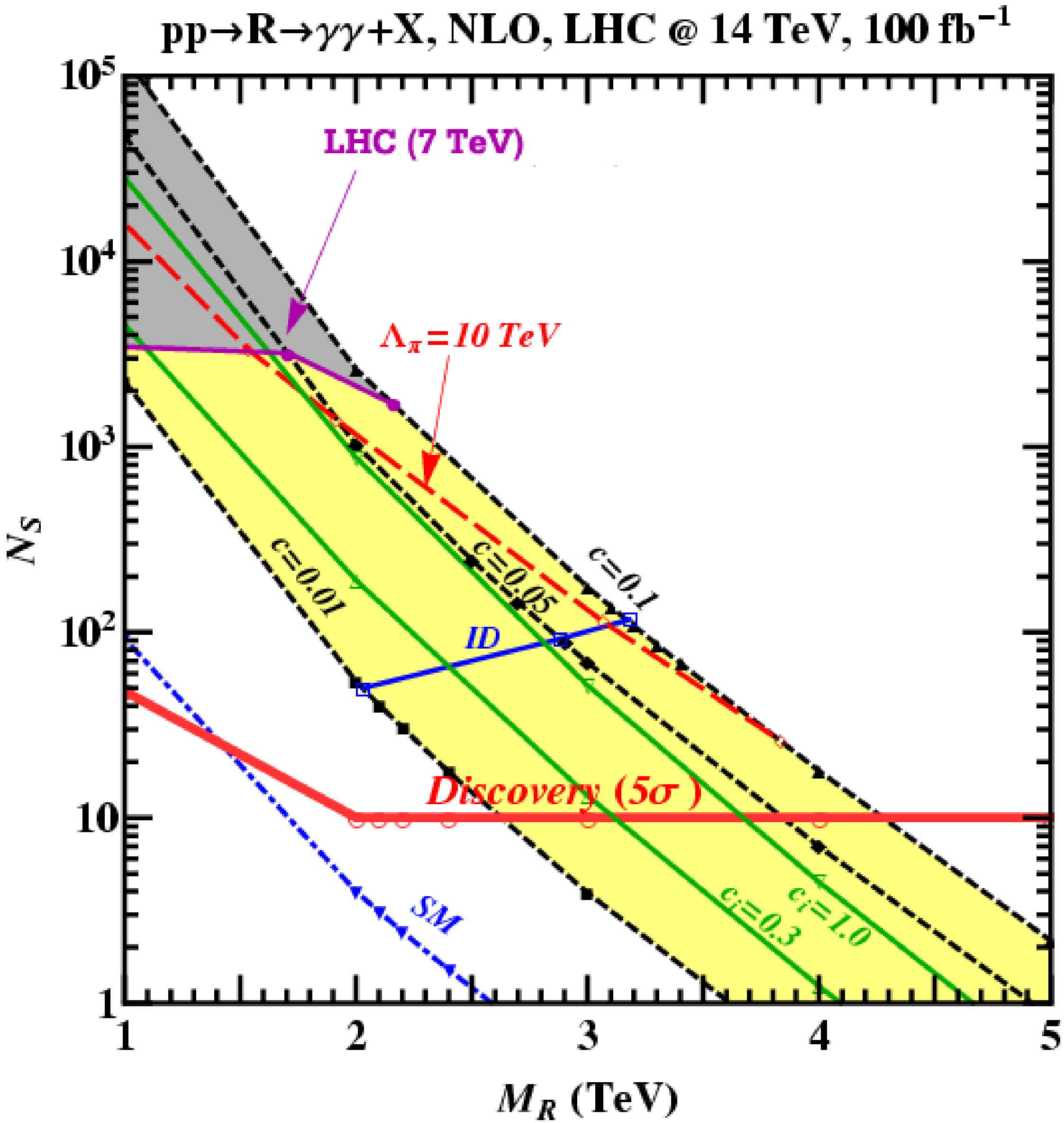
- Assume observed peak due to Spin-2 Graviton exchange with given c, M_G.
- One wants to exclude Spin-0 scalar exchange for all couplings c_i and same $M_S=M_G$.
- "Distance" between models: $\Delta A_{CE} = A_{CE}^G - A_{CE}^S$
- Compare ΔA_{CE} with uncertainty δA_{CE} :
- Statistical uncertainty

$$\delta A_{CE} = \sqrt{\frac{1-\left(A_{CE}^G\right)^2}{N_{min}}}; \quad N_{evts} = \varepsilon_{\gamma\gamma} L\, \sigma(G\gamma\gamma)$$

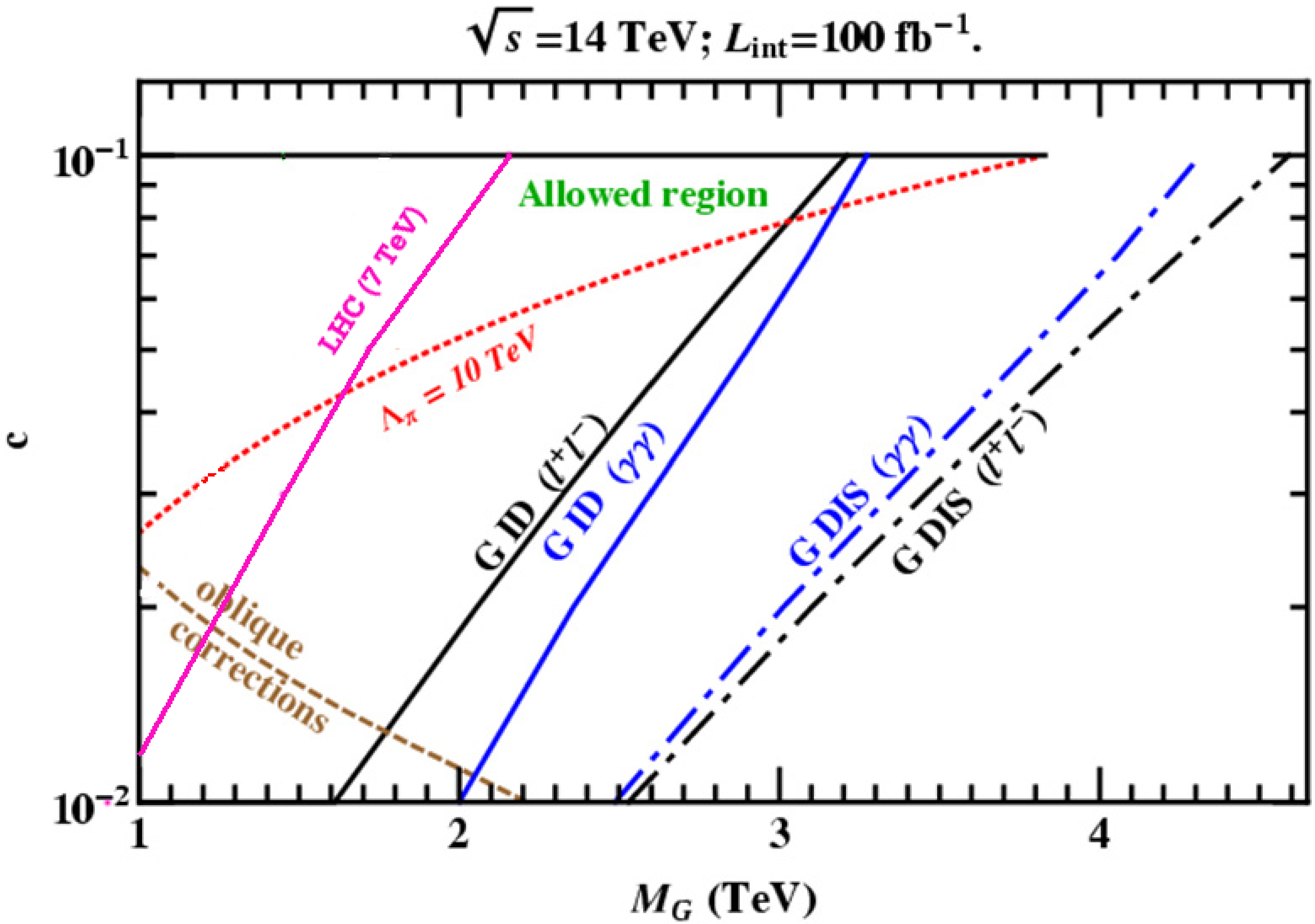
efficiency ($\varepsilon_{\gamma\gamma}$), luminosity ($L$)

- Condition $\Delta A_{CE} = \zeta\, \delta A_{CE}$ determined N_{min}; $\zeta^2 = 3.84$ (95% CL)
- Simple-minded χ^2- like analysis: $\chi^2 = \left(\frac{\Delta A_{CE}^G}{\delta A_{CE}}\right)^2$
- $\chi^2 \geq \chi^2_{CL}$ determines ID reach on G in (c, M_G) plane

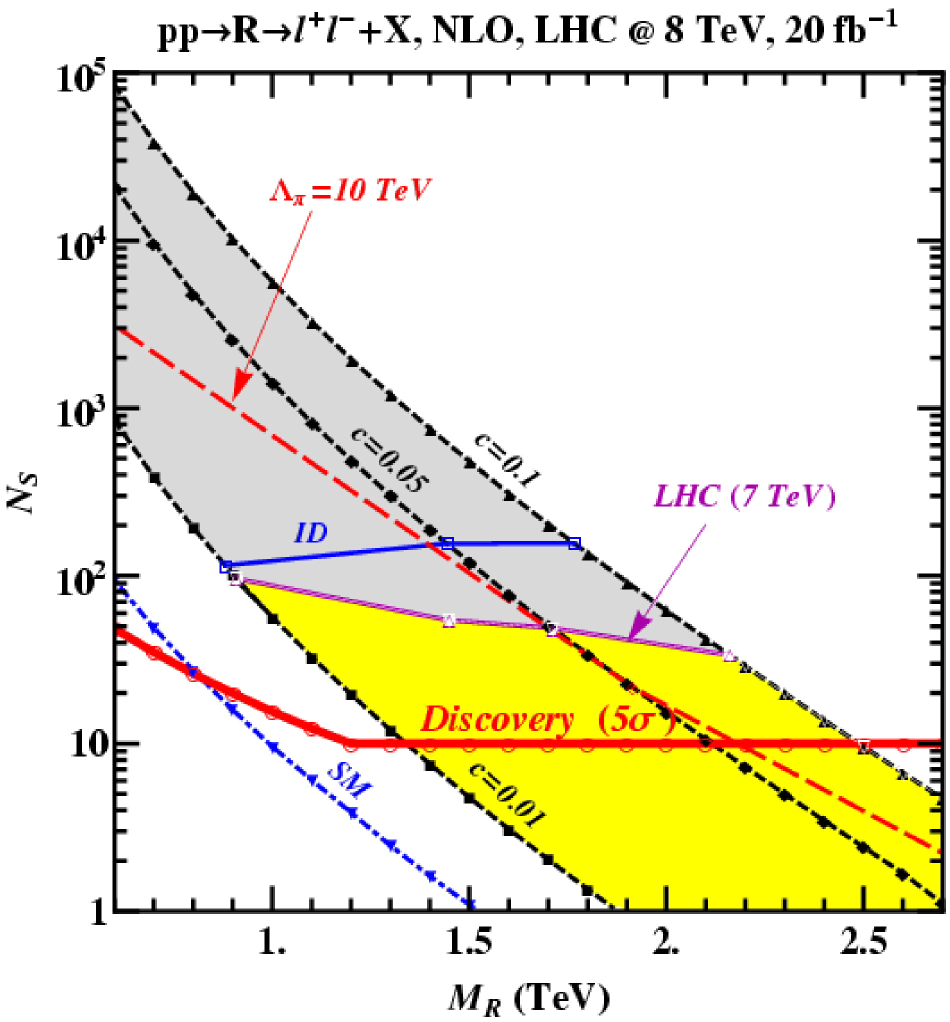
Diphotons. High energy/luminosity case.

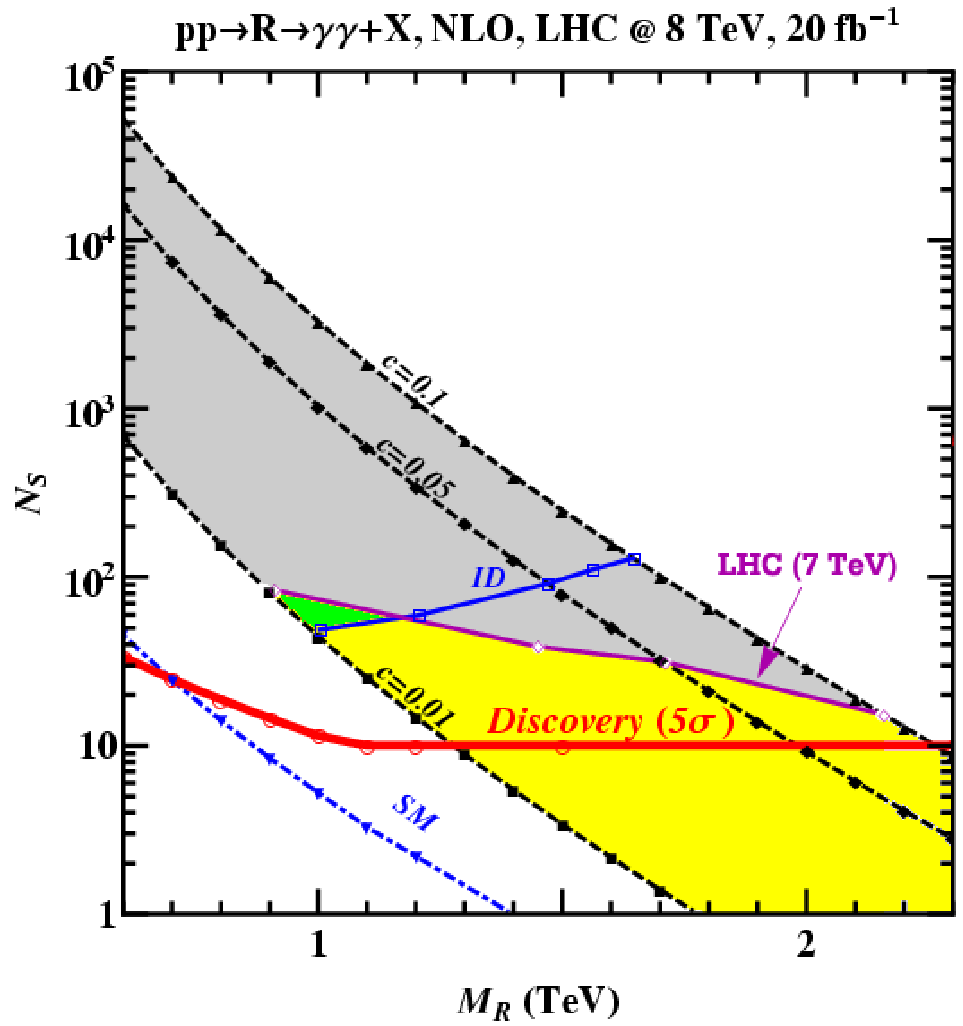


Results for spin-2 identification



Dileptons vs. diphotons 8 TeV, 20 fb^{-1}





Summary of results (Disc. 5σ; ID 95% CL)

- Discovery & Identification of RS diphoton:

$\sqrt{s}, \mathcal{L}_{\text{int}}$	14 TeV, 100 fb^{-1}		7 TeV, 10 fb^{-1}	
$k/\overline{M}_{\text{Pl}}$	Dis	ID	Dis	ID
0.01	2.6	2.0	1.2	~0.9
0.05	3.8	2.9	1.8	1.4
0.1	4.2	3.2	2.0	Excl.

- Comparison at equal # of events – distinctive ang. distributions.
- NLO substantial effects: RS *K-factor* = 1.5; S *K-factor* ≈ 3 but angular distributions not upset
- Current limits on c & M_G ➔ at LHC 7 TeV, L=10 fb^{-1}
- Full LHC 14 TeV, L=100 fb^{-1} may be needed for A_{CE} ang. Analysis
- DY dilept., diphot. evts ➔ complementary information on RS G.

 Work in progress