The diphoton excess as a gravity mediator of Dark Matter

Veronica Sanz (Sussex)

IC HEP seminar, May 2016

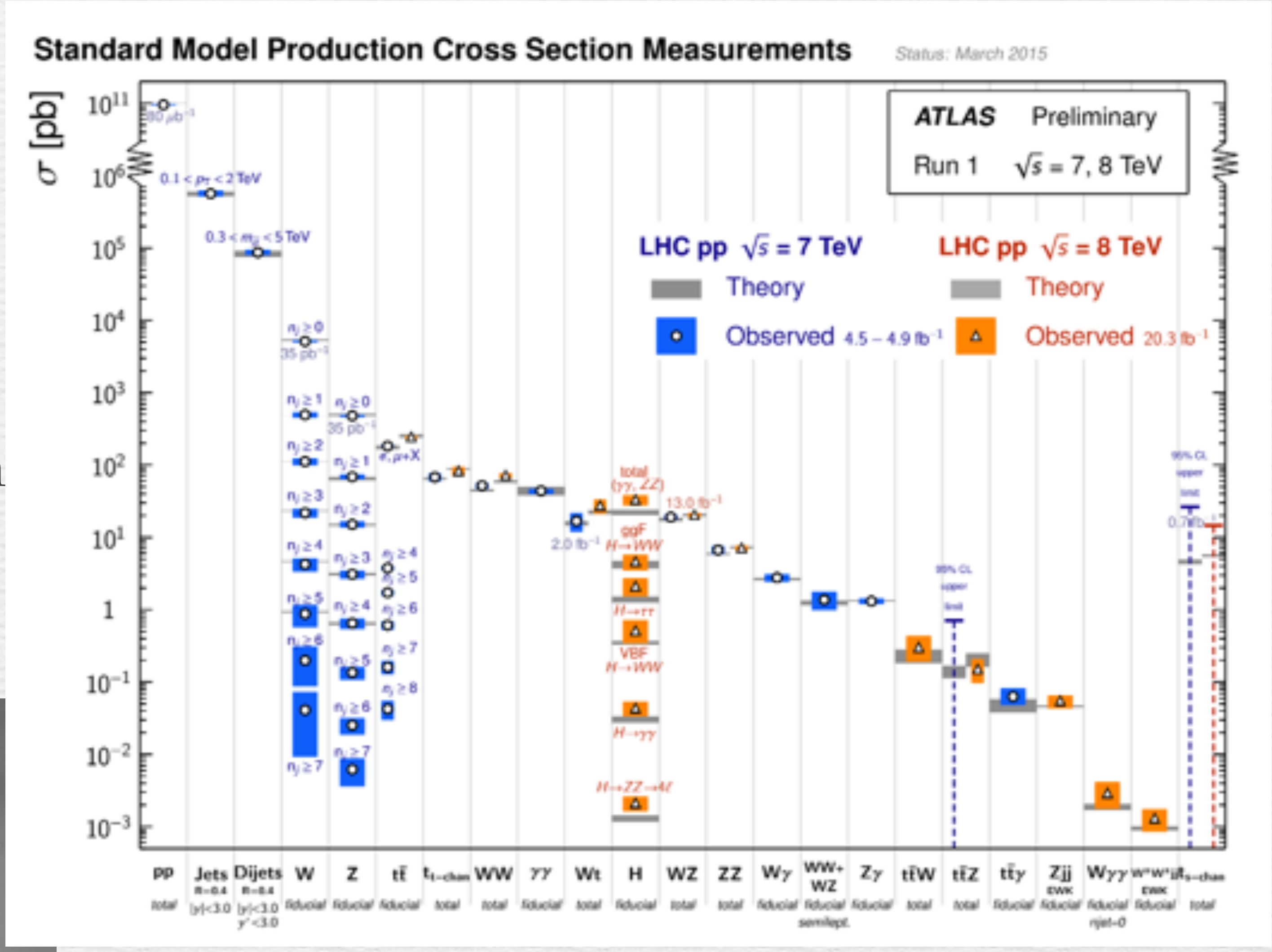
Outline

- Challenges for Run2
- The diphoton excess
- Models for the diphoton
- A spin-two candidate
- The excess and DM
- Conclusions

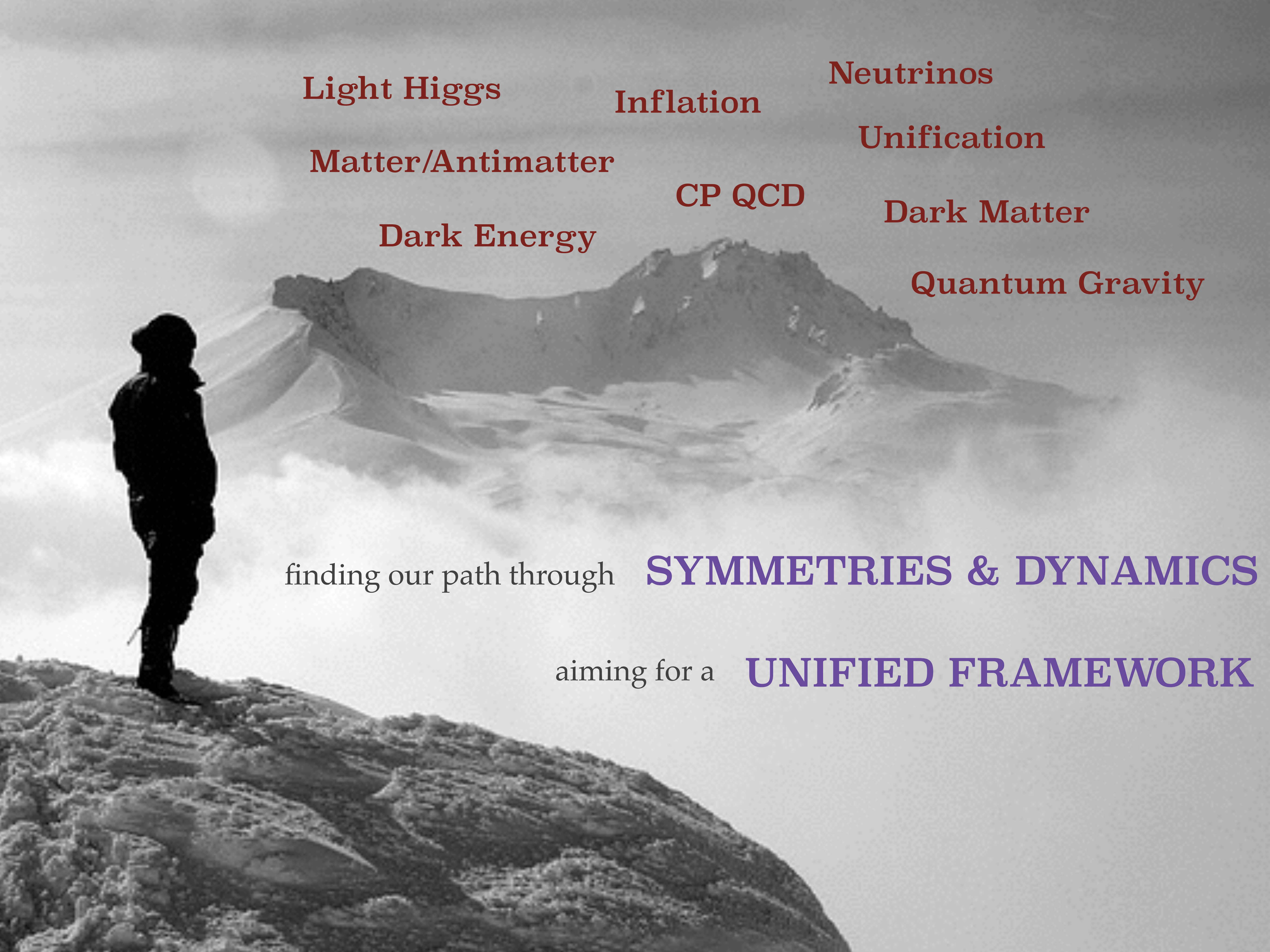
Challenges

Standard Model of Particle Physics

Predictive, successful paradigm
being tested to higher and higher precision
at the LHC



Based on QFT, symmetries
(global/gauge) and consistent
ways to break them
Foundation from which we
develop theories beyond the SM


Light Higgs
Inflation
Neutrinos
Unification
Matter/Antimatter
CP QCD
Dark Matter
Dark Energy
Quantum Gravity
finding our path through SYMMETRIES & DYNAMICS
aiming for a UNIFIED FRAMEWORK

Example of a unified framework: Supersymmetry

Unifies concept of bosons and fermions

Light scalar bosons

Candidates for Dark Matter

Unification of strong/EM/weak forces

Matter/Antimatter asymmetry

Component of Quantum Gravity

New mechanisms
Inflation, Neutrinos and Dark Energy

The discovery of SUSY at LHC first step to understand many aspects of Nature

Run2 more lumi and energy
foundation more precise, better ways of testing the Standard Model

't Hooft, Veltman, Weinberg…

e.g. top coupling to the Higgs

e.g. total rates to differential distributions

H+jets, VV distributions, shower models

Run2 more lumi and energy
foundation more precise, better ways of testing the Standard Model

Enthusiasm and dedication of the community

ground-breaking discovery
challenges our understanding of Nature
new particles, new principles

e.g. SUSY particles, hidden sector, QG effects, quasi-conformal strong dynamics…

This is not just wishful thinking
we *know* the SM is not the ultimate theory

Evidence

Dark Universe Neutrinos Baryogenesis

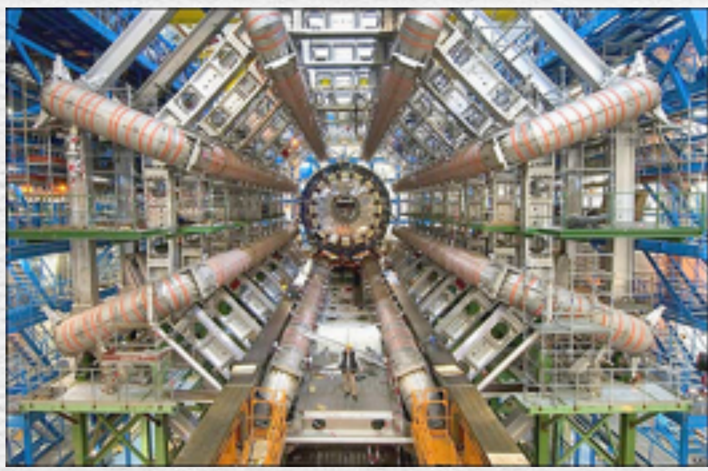
Run2 has the **potential** to shed light on the origin
of these observations
and on theoretical conundrums (e.g. naturalness)

Unique opportunity
Dark Matter

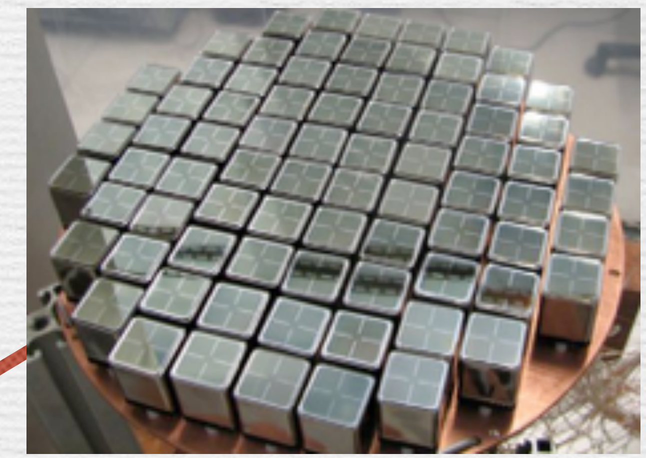
THEORY

Discrete symmetries
Dynamical stability
self-interactions
Link to Higgs…

COLLIDERS

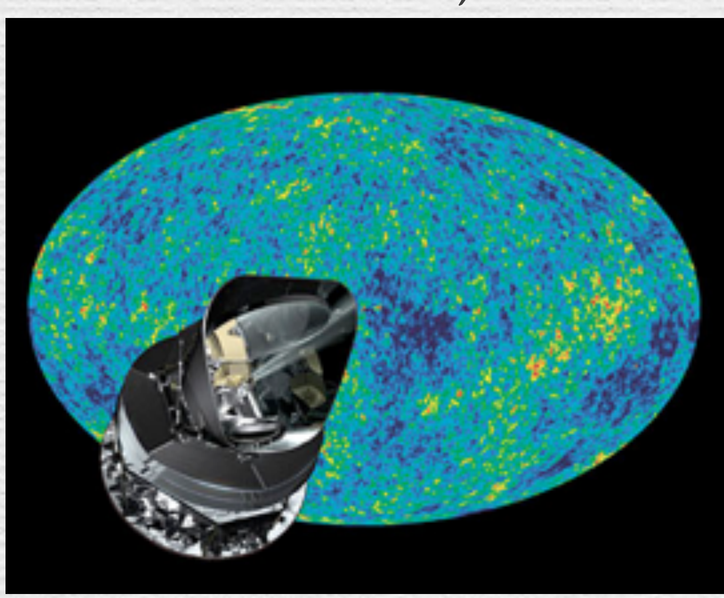


DIRECT DETECTION

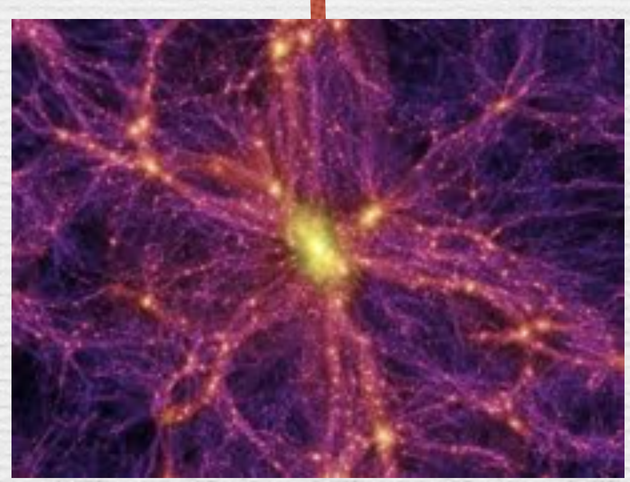


DARK MATTER

CMB: relic, tilt



INDIRECT DETECTION



SIMULATIONS

The diphoton excess

What is it?

An excess in a channel with two photons at an invariant mass of about 750 GeV

scalar, e.g. more Higgses

tensor, e.g. spin-two graviton

What we knew before Dec 2015

Run 1: CMS already a (less significant) excess, ATLAS did not show above 600 GeV

Dec 2015

excess in both ATLAS and CMS Run2 data

Moriond 2016

ATLAS and CMS results for s=0 & s=2
narrow and wide

ATLAS analysis note public

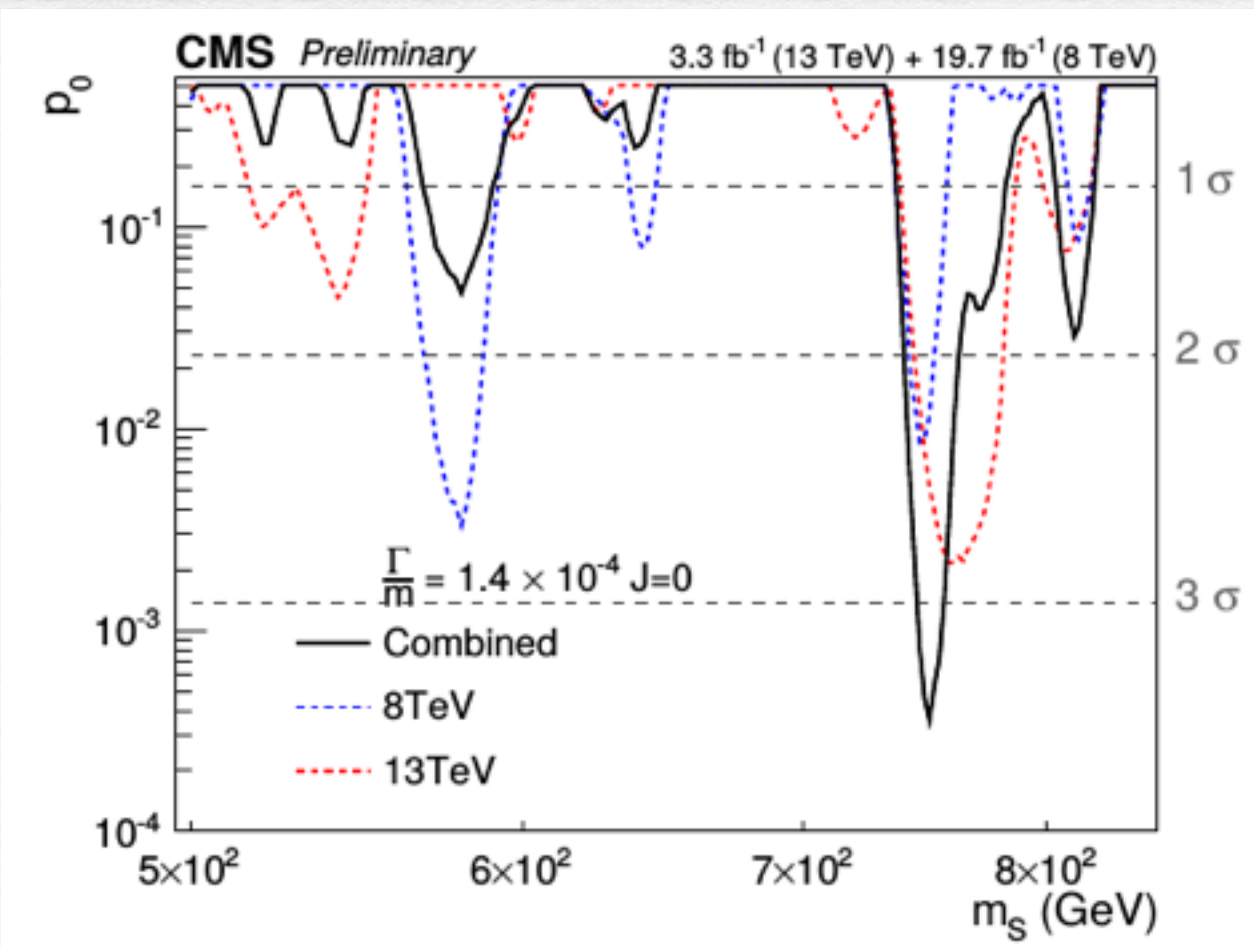
CMS update including improvements
in mass resolution and 0T data-set

Significance

ex. interpreted as a gluon-fusion narrow scalar
(similar results for spin-two)

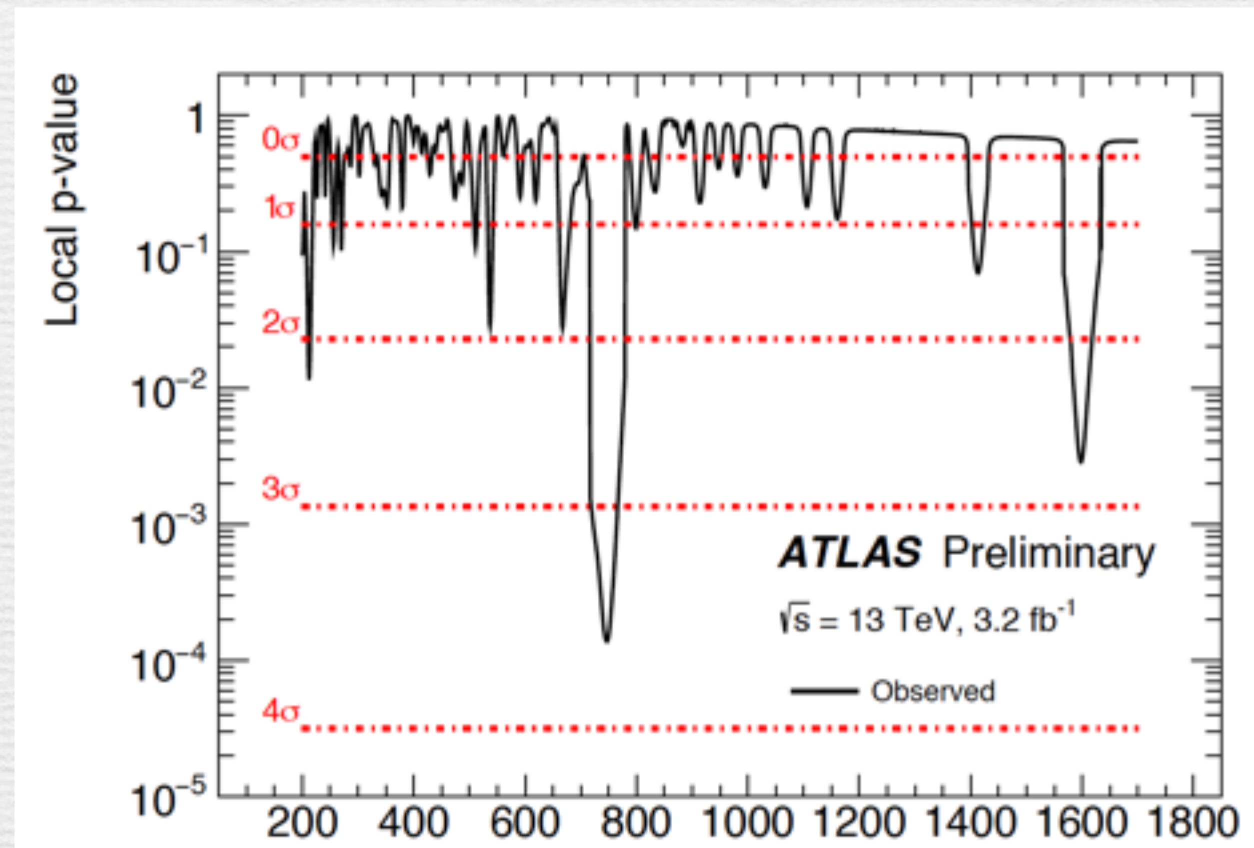
CMS

3.4



ATLAS

3.6

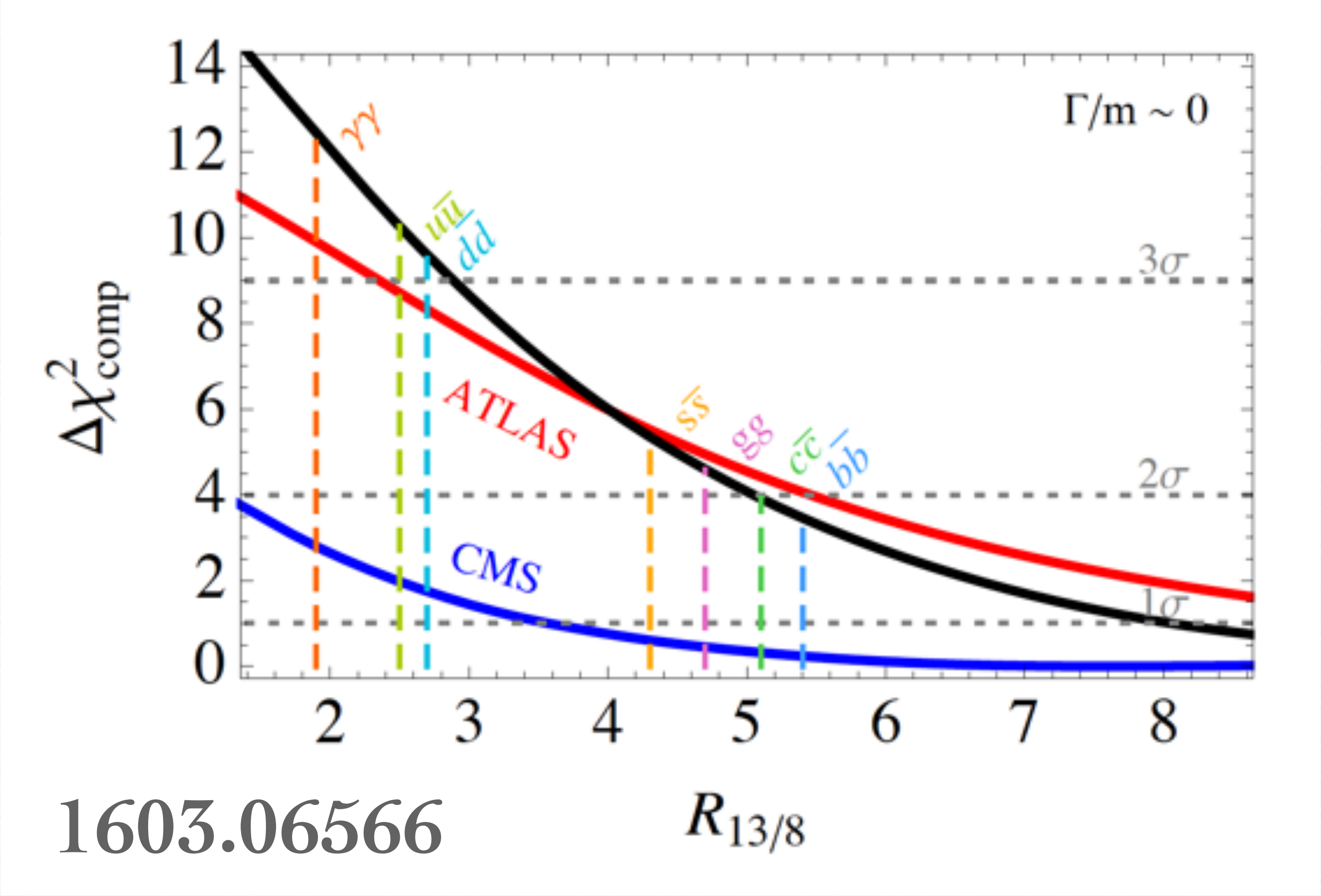


no Run1 combination

(remember LEE should be taken only once)

Production

Kick from 8 to 13 TeV
from non-valence quarks or gluons



sizeable cross section & narrow resonance

indicates gluon-initiated

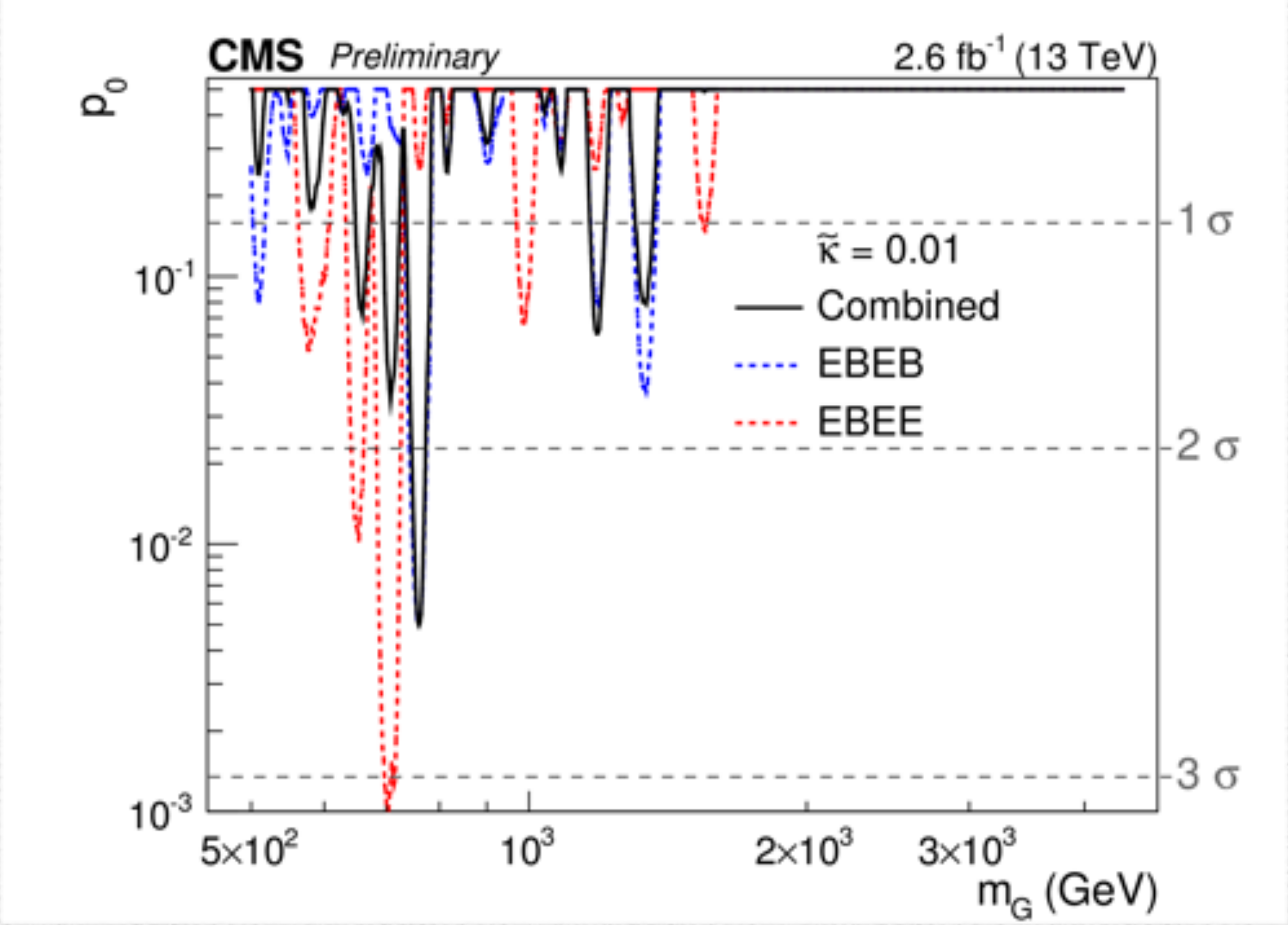
but other productions, incl diphoton still an option

Kinematics

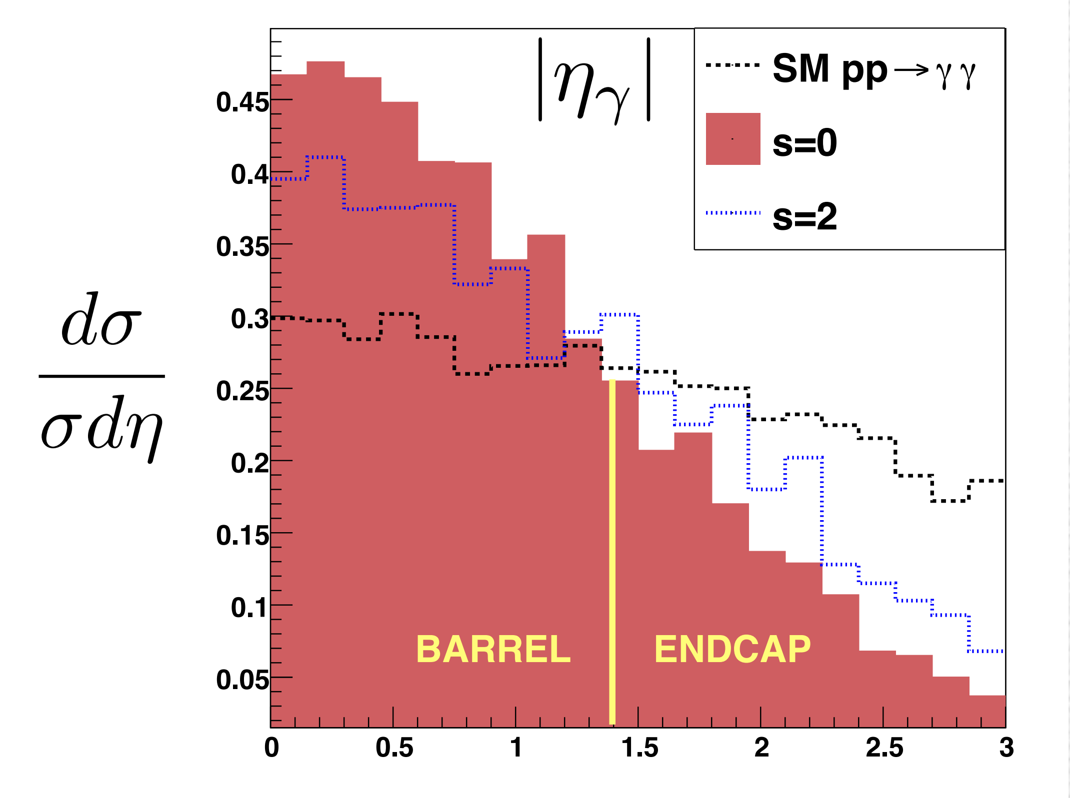
where are the photons? EBEB vs EBEE

Initially (Dec), it looked as if kinematics were funny

CMS



but s=0 and 2 are not so different



Han, Lee, Park, VS.

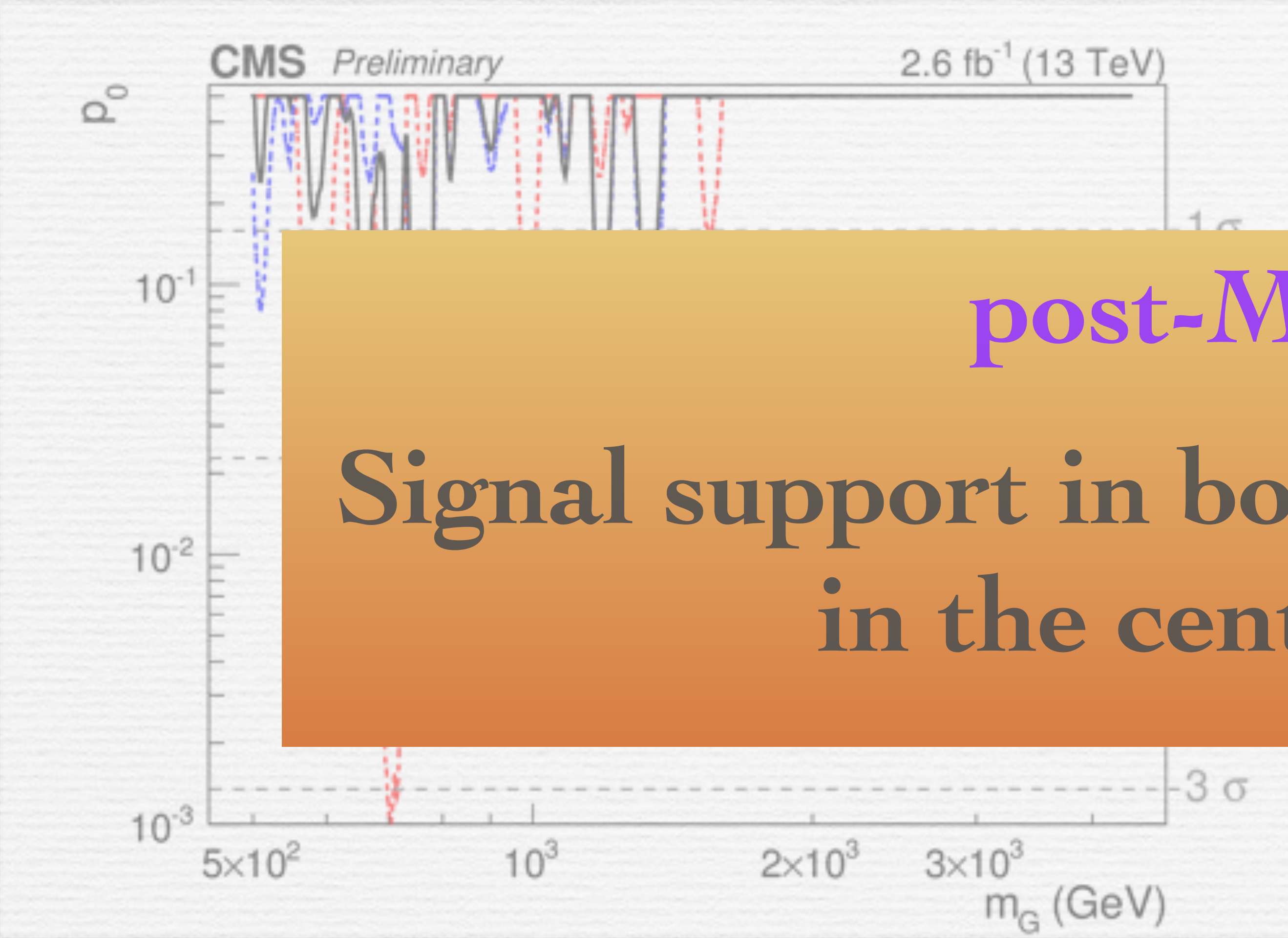
but we didn't have ATLAS to compare with

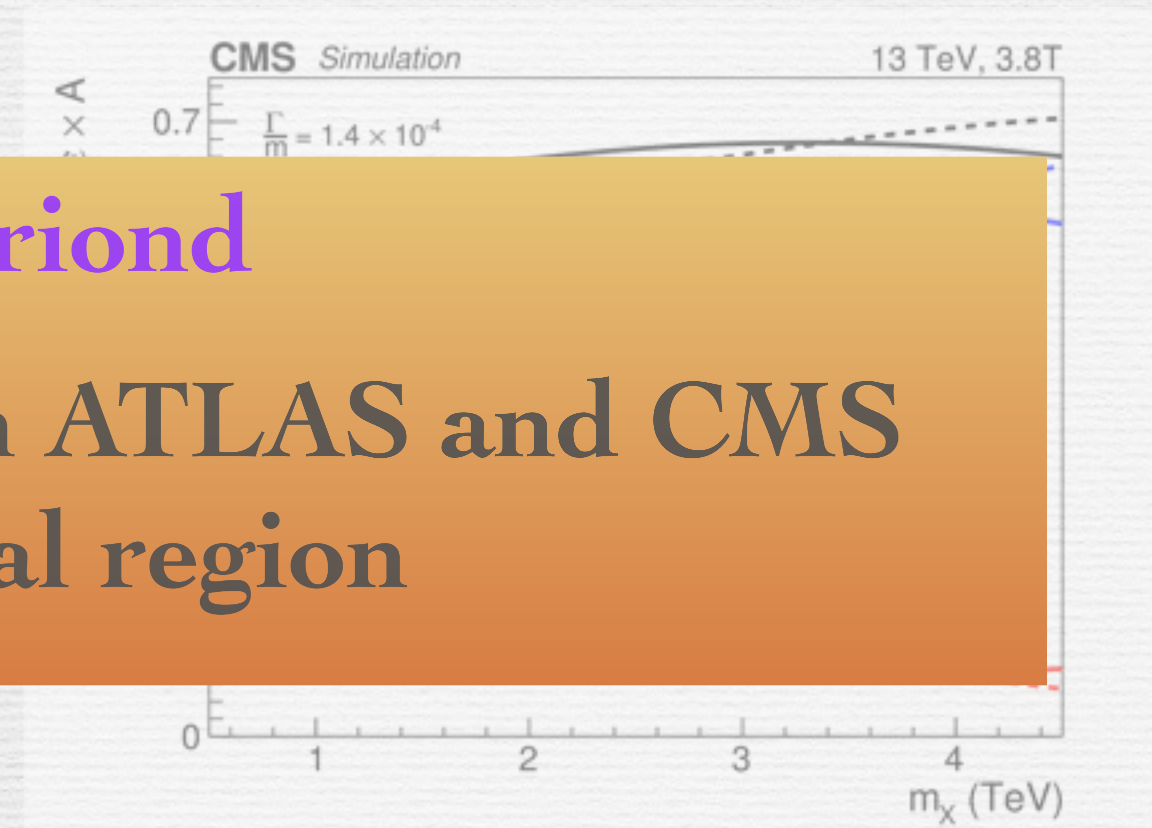
Kinematics

where are the photons? EBEB vs EBEE

Initially (Dec), it looked as if kinematics were funny

CMS





post-Moriond

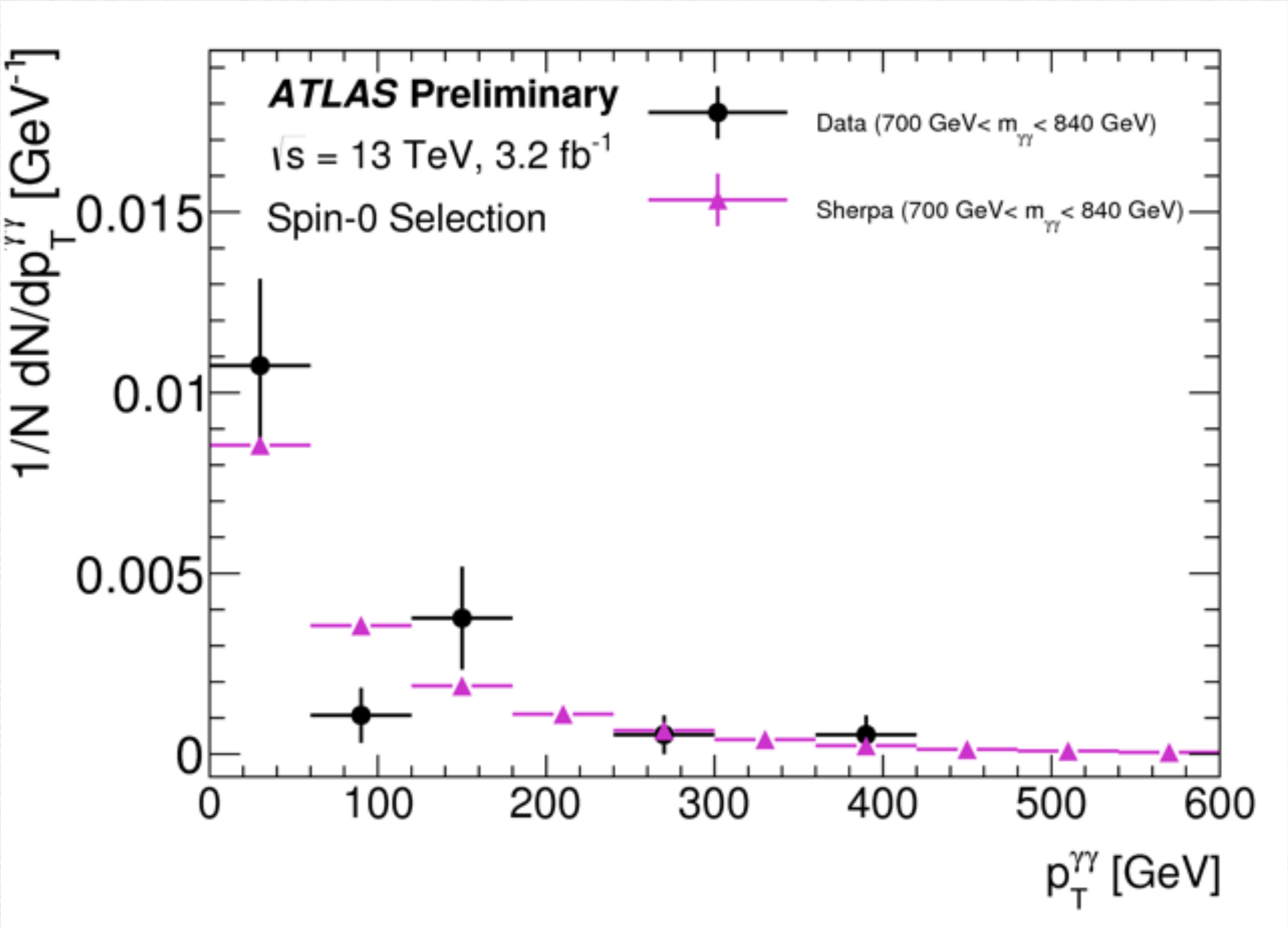
Signal support in both ATLAS and CMS in the central region

but we didn't have ATLAS to compare with

Kinematics

Is this excess coming along other objects?

1. It doesn't recoil (much)



Kinematics

Is this excess coming along other objects?

2. No electrons or muons

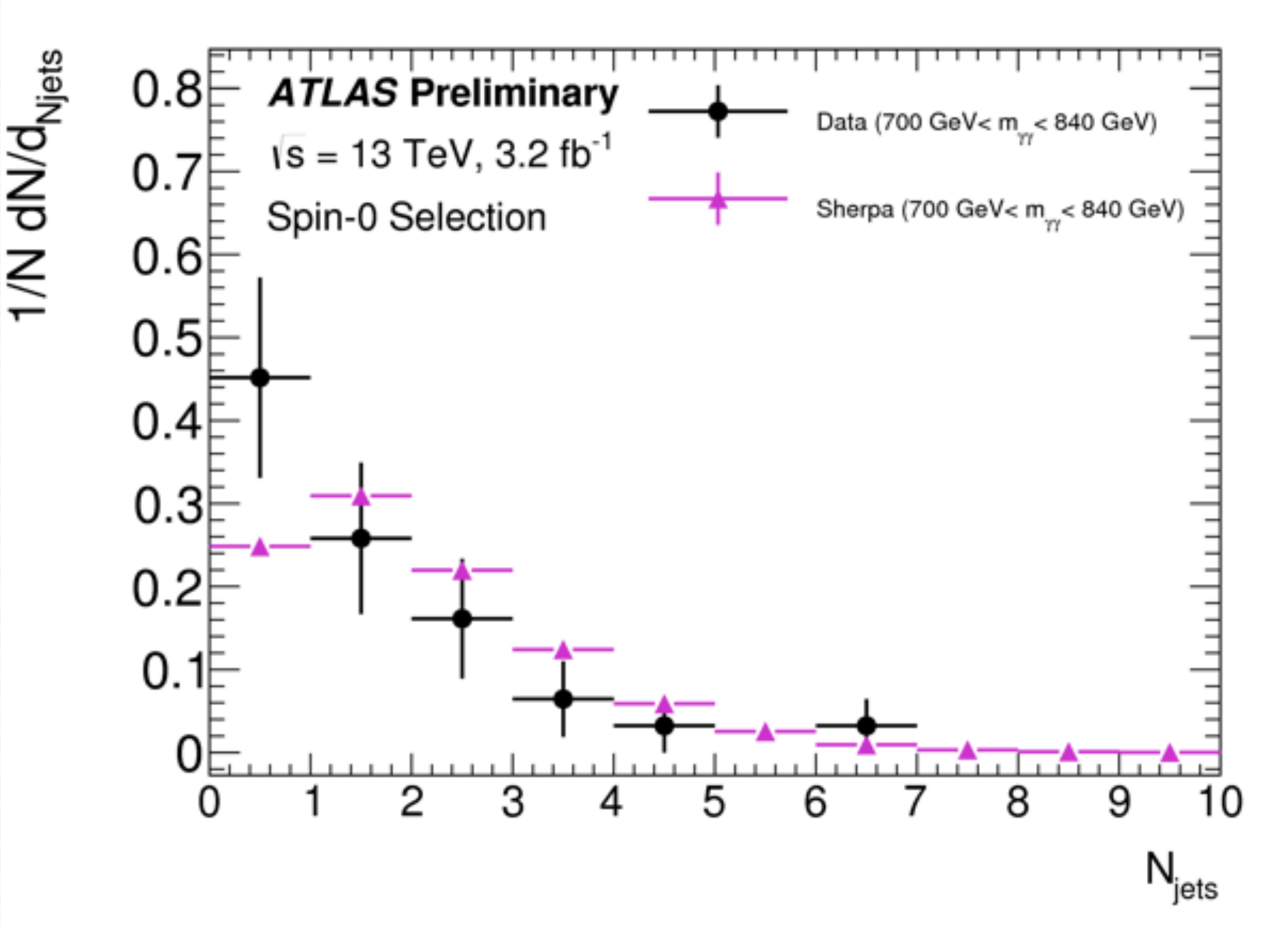
e.g. from ATLAS analysis

"In addition, no electron or muon candidates have been found, with $p_T > 10$ GeV and $|\eta| < 2.$ (electrons) or 2.7 (muons) in the events with invariant masses between 700 GeV and 840 GeV.

Kinematics

Is this excess coming along other objects?

3. No high-pT jets



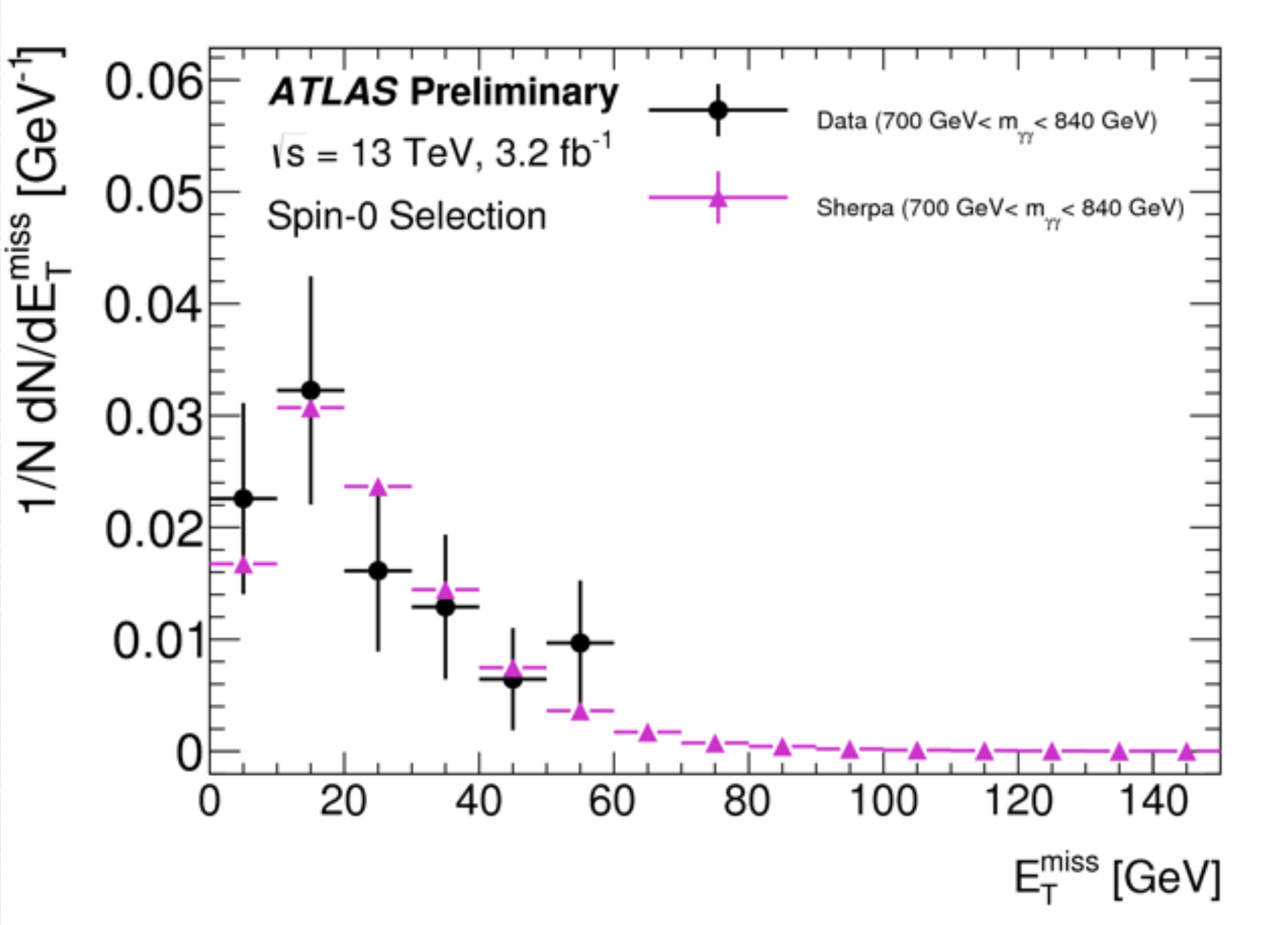
jet anti-kT 0.4
pT> 25, eta< 4.4

disfavours bb, VBF
and photon fusion

Kinematics

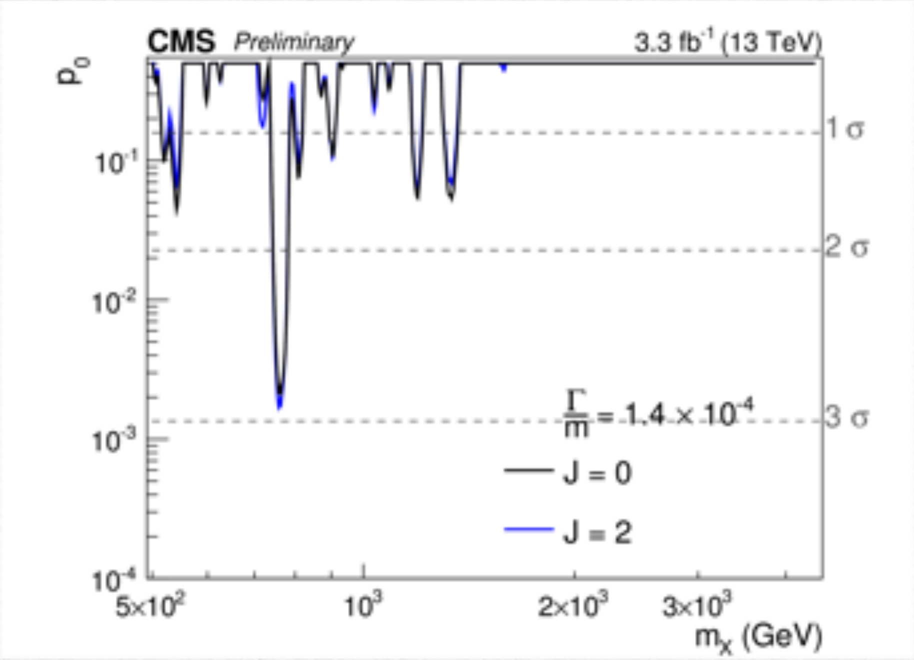
Is this excess coming along other objects?

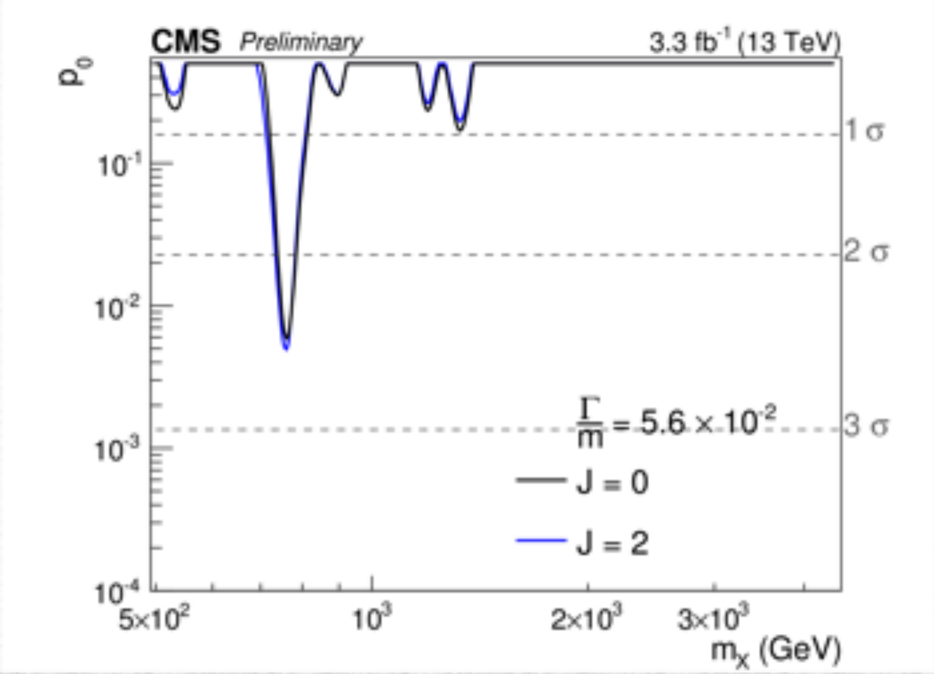
4. No MET



Kinematics
Narrow or wide?

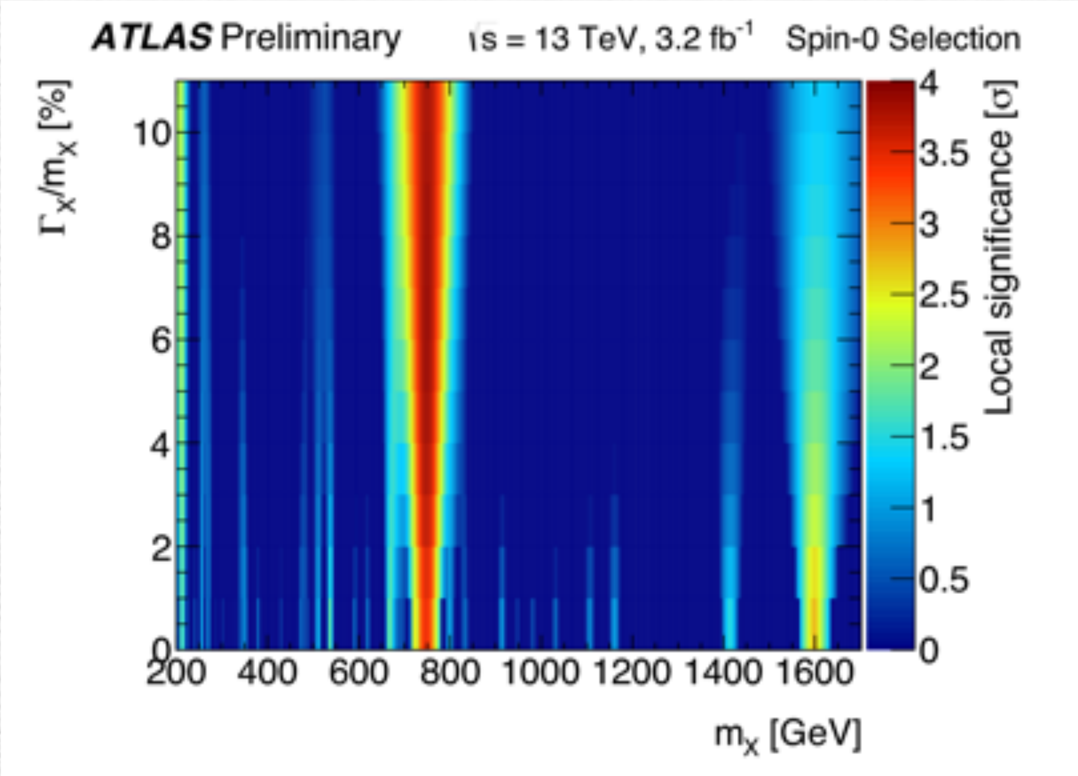
CMS
prefers narrow





ATLAS

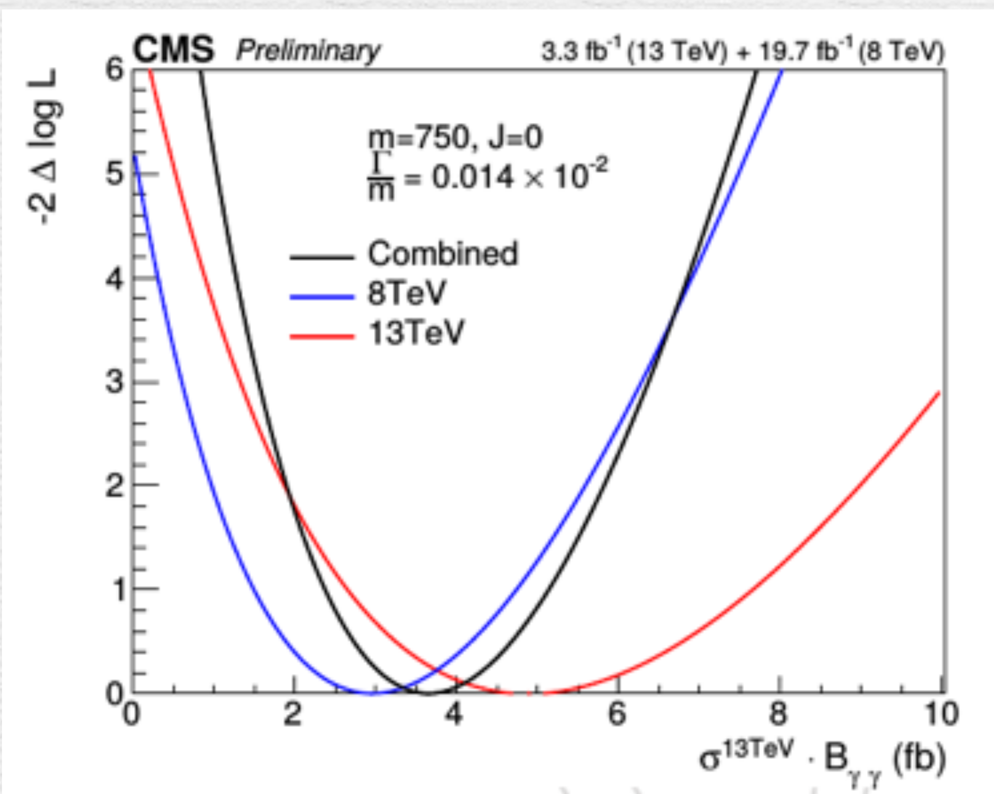
slight preference wide
(0.3 sigma)

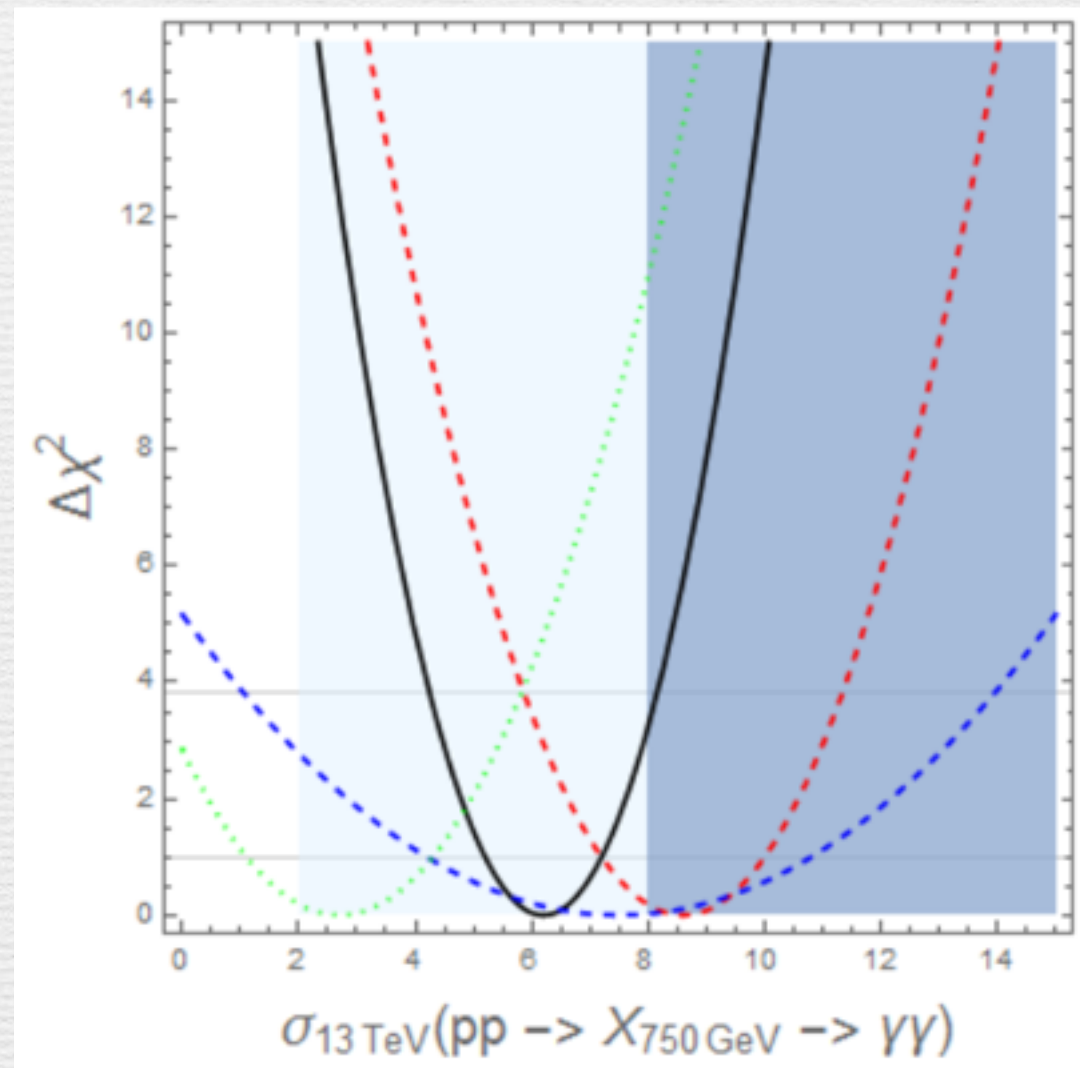


overall
no preference for wide

Signal strength

compatibility? Run1 vs Run 2
and CMS vs ATLAS





Ellis et al.
1512.05327
CMS1
CMS2
ATLAS2

theorists combination in Dec

6.2 ± 1.0 (fb) (local)

Other final states

light Higgs into diphotons is not like the 750 GeV

Higgs below the threshold of WW, ZZ, suppressed BRs

A heavy resonance in two photons?

it couples to SM gauge interactions we expect

WW, ZZ and Zgamma (and hh)

Model-independent prediction:

diphotons means there must be at least one non-zero BR(Z-gamma) and/or BR(ZZ)

$$g_{\gamma\gamma} = c_1 \alpha_1 c_W^2 + c_2 \alpha_2 s_W^2$$

→

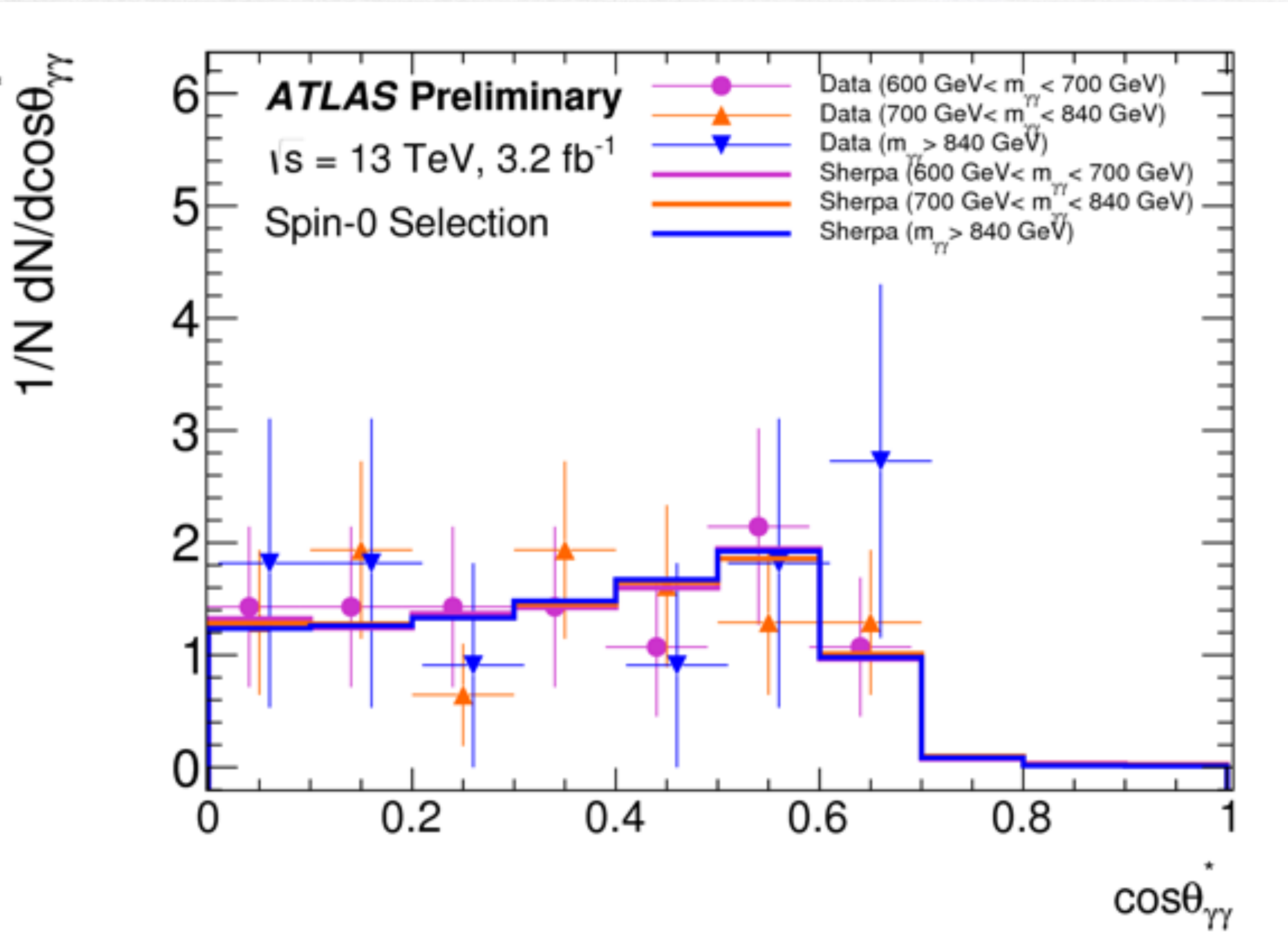
$$g_{z\gamma} = (c_1 \alpha_1 - c_2 \alpha_2) s_{2W}$$

$$g_{zz} = c_1 \alpha_1 s_W^2 + c_2 \alpha_2 c_W^2$$

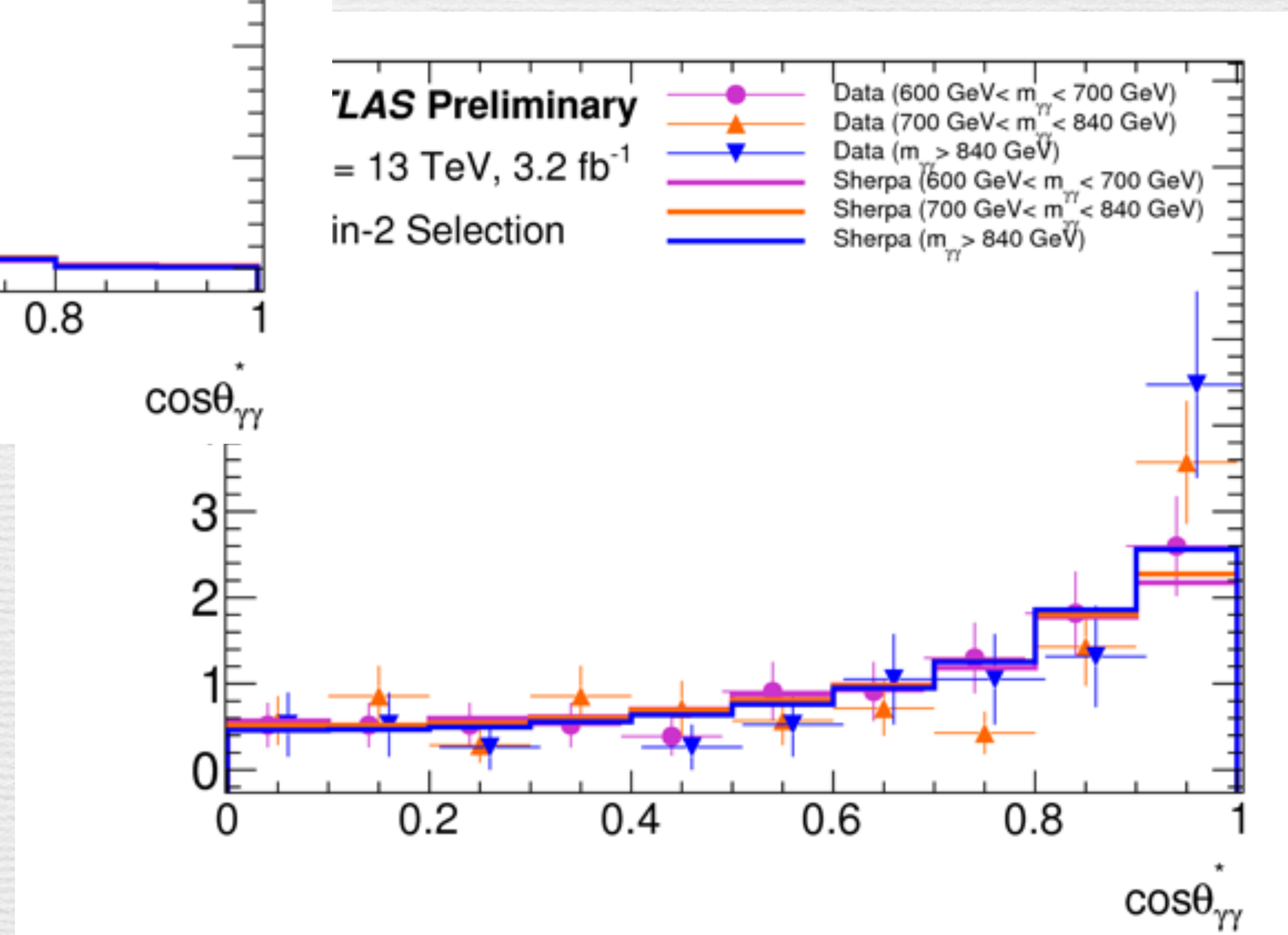
non-zero coupling to photons → coupling to ZZ and/or Zphoton

No, VS, Setford. 1512.0

Spin



spin-0 vs spin-2
both compatible



Models for the diphoton

Many papers written (~300 today)
Some model-independent,
most model-building

Spin

J=0

A new scalar

Would this be the end of anthropics?

Spin

J=0

A new scalar

Hooray SUSY!?

MSSM or NMSSM
will not do
compatibility with other
searches, dof,
perturbativity and tuning

non-minimal
or threshold effects

Spin

J=0

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MSSM or NMSSM
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or threshold effects

Composite dynamics?

glueball of new strong force
or a pseudo-Goldstone boson

link to

e.g.
see-saw composite Higgs
Dark Matter, Baryogenesis

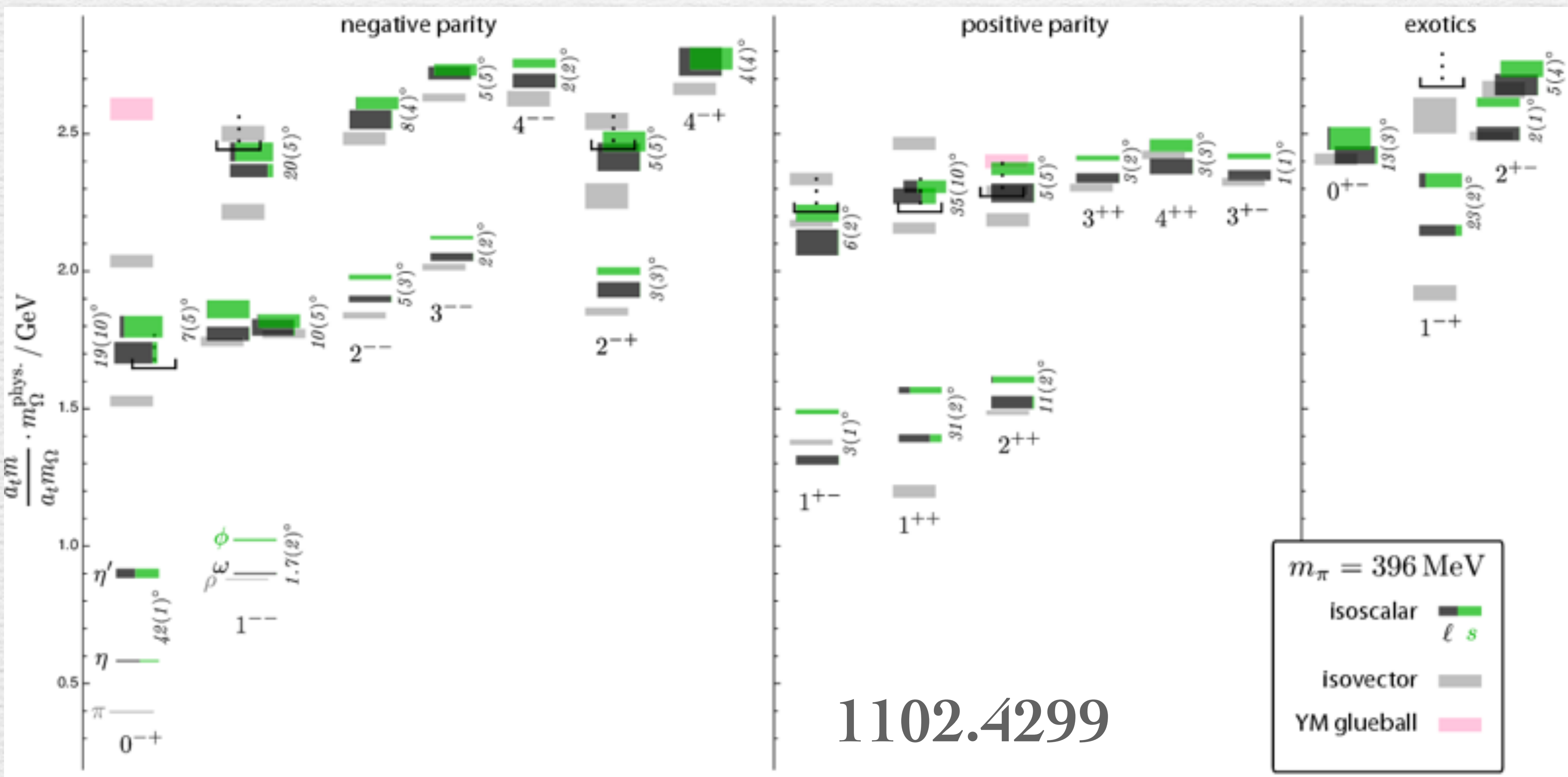
No, VS, Setford.1512.05700

Spin

J=2

A kind of

Important hurdle is EWPTs



Spin

J=2

Experimental interpretations neglect this problem,
theorists use AdS/CFT to find succesful models

recent progress

1603.06980, 1603.08250

& in composite Higgs

Dillon, VS. 1603.09550

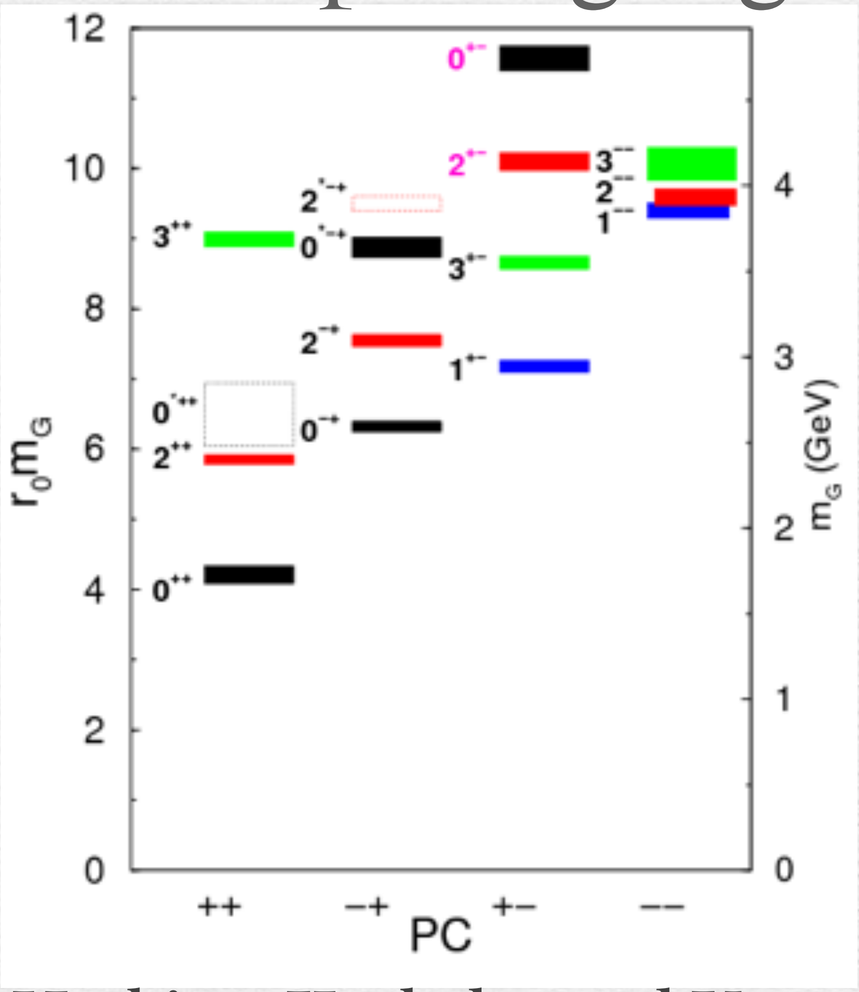
Spin

J=2

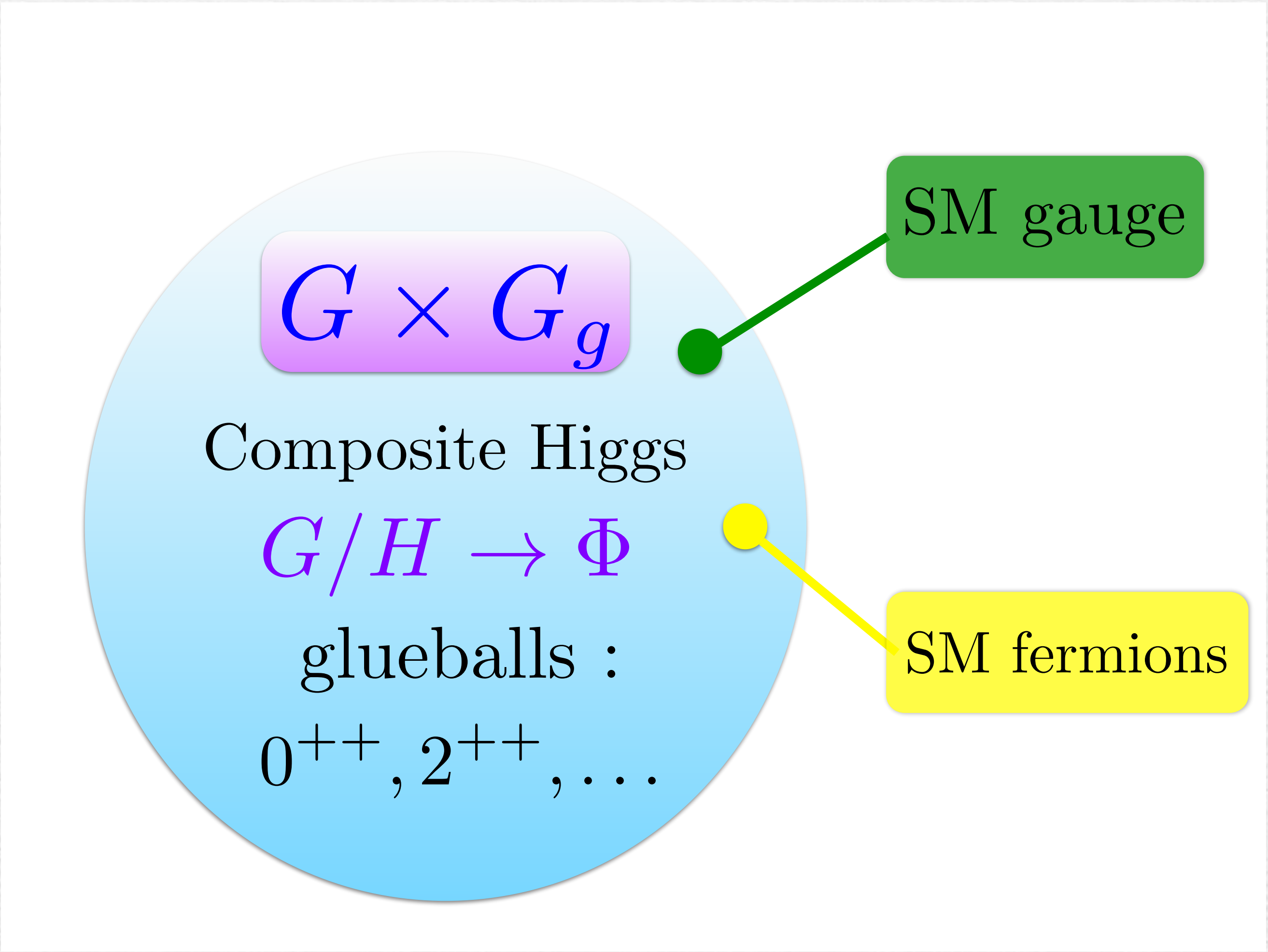
A kind of

aka

lattice pure-gauge



Mathieu, Kochelev and Vento 0810.4453



VS. 1603.05574, 1507.03553

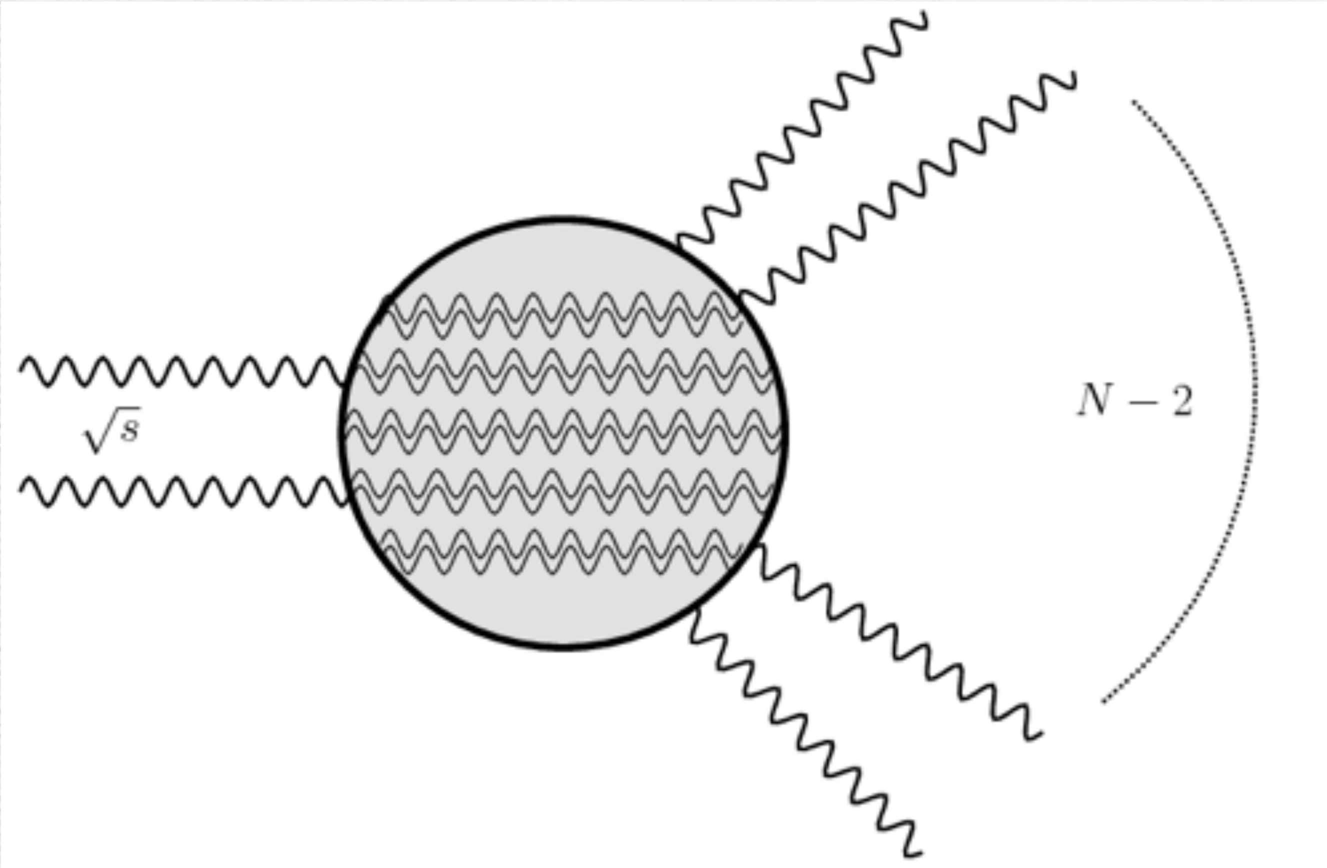
Spin

J=2

A kind of

aka

aka



Dvali et al.

lightest QBH
1->2 dominates

KK-graviton and

KK-graviton vs an

Guimaraes, Fok, Lewis VS.
1203.2917

i.e. massive spin-2 resonance = smoking gun of extra-dimensions?

KK-graviton vs an

Guimaraes, Fok, Lewis VS.
1203.2917

i.e. massive spin-2 resonance = smoking gun of extra-dimensions?

G
KK-graviton

$\hat{G}$
glueball/QBH

KK-graviton vs an

Guimaraes, Fok, Lewis VS.
1203.2917

i.e. massive spin-2 resonance = smoking gun of extra-dimensions?

G	$\hat{G}$
KK-graviton	glueball/QBH

propagation

KK-graviton vs an

Guimaraes, Fok, Lewis VS.
1203.2917

i.e. massive spin-2 resonance = smoking gun of extra-dimensions?

	G KK-graviton	$\hat{G}$ glueball/QBH
propagation	Pauli-Fierz	Pauli-Fierz

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interactions		

KK-graviton vs an

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i.e. massive spin-2 resonance = smoking gun of extra-dimensions?

	G KK-graviton	$\hat{G}$ glueball/QBH
propagation	Pauli-Fierz	Pauli-Fierz
interactions	$\frac{c_i}{M} G_{\mu\nu} T^{\mu\nu}_{i,SM}$	?

c_i overlap G with fields i and $M \sim$ TeV

KK-graviton vs an

Guimaraes, Fok, Lewis VS.
1203.2917

$\hat{G}$ couplings?

KK-graviton vs an

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$\hat{G}$ couplings?

Lorentz and gauge → no dimension-4

KK-graviton vs an

Guimaraes, Fok, Lewis VS.
1203.2917

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flavour and CP invariant → dimension-5 same as in $T_{\mu\nu}$

KK-graviton vs an

Guimaraes, Fok, Lewis VS.
1203.2917

$\hat{G}$ couplings?

Lorentz and gauge → no dimension-4

flavour and CP invariant → dimension-5 same as in $T_{\mu\nu}$

e.g. couplings to gauge bosons

$$\mathcal{L}^V_{\rm KK} = -\frac{1}{\Lambda}G^{\mu\nu}\Big[c_{\gamma\gamma}\left(\frac{1}{4}g_{\mu\nu}A^{\lambda\rho}A_{\lambda\rho} - A_{\mu\lambda}A^{\lambda}{}_{\nu}\right) + c_{Z\gamma}\left(\frac{1}{4}g_{\mu\nu}A^{\lambda\rho}Z_{\lambda\rho} - A_{\mu\lambda}Z^{\lambda}{}_{\nu}\right)$$
$$+c_{ZZ}\left(\frac{1}{4}g_{\mu\nu}Z^{\lambda\rho}Z_{\lambda\rho} - Z_{\mu\lambda}Z^{\lambda}{}_{\nu}\right) + c_{WW}\left(\frac{1}{4}g_{\mu\nu}W^{\lambda\rho}W_{\lambda\rho} - W_{\mu\lambda}W^{\lambda}{}_{\nu}\right)$$
$$+c_{gg}\left(\frac{1}{4}g_{\mu\nu}G^{\lambda\rho}G_{\lambda\rho} - G_{\mu\lambda}G^{\lambda}{}_{\nu}\right)\Big]$$

KK-graviton vs an

Guimaraes, Fok, Lewis VS.
1203.2917

$\hat{G}$ couplings?

Lorentz and gauge → no dimension-4

flavour and CP invariant → dimension-5 same as in $T_{\mu\nu}$

$\hat{G}$ couples like G

same spin determination

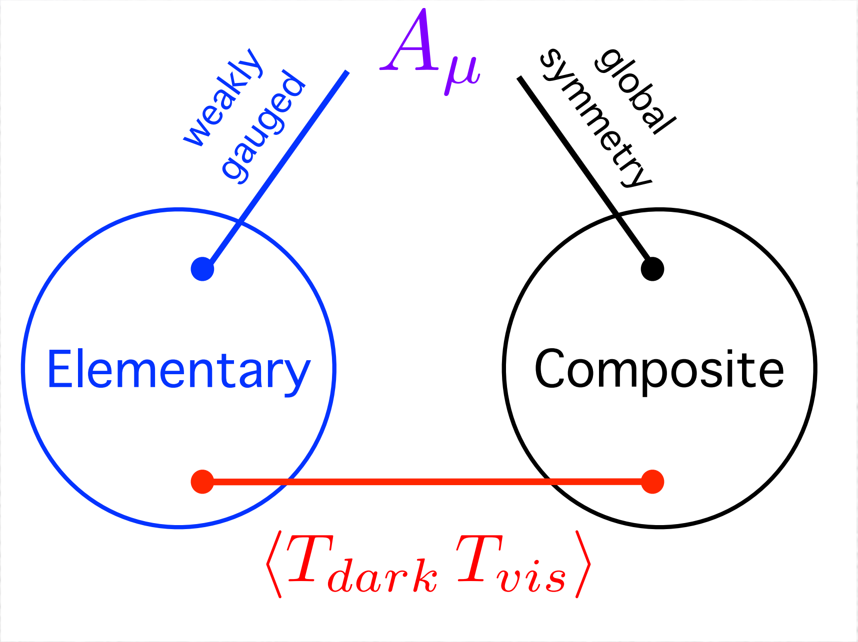
How do we distinguish them?
non-trivial question

The diphoton

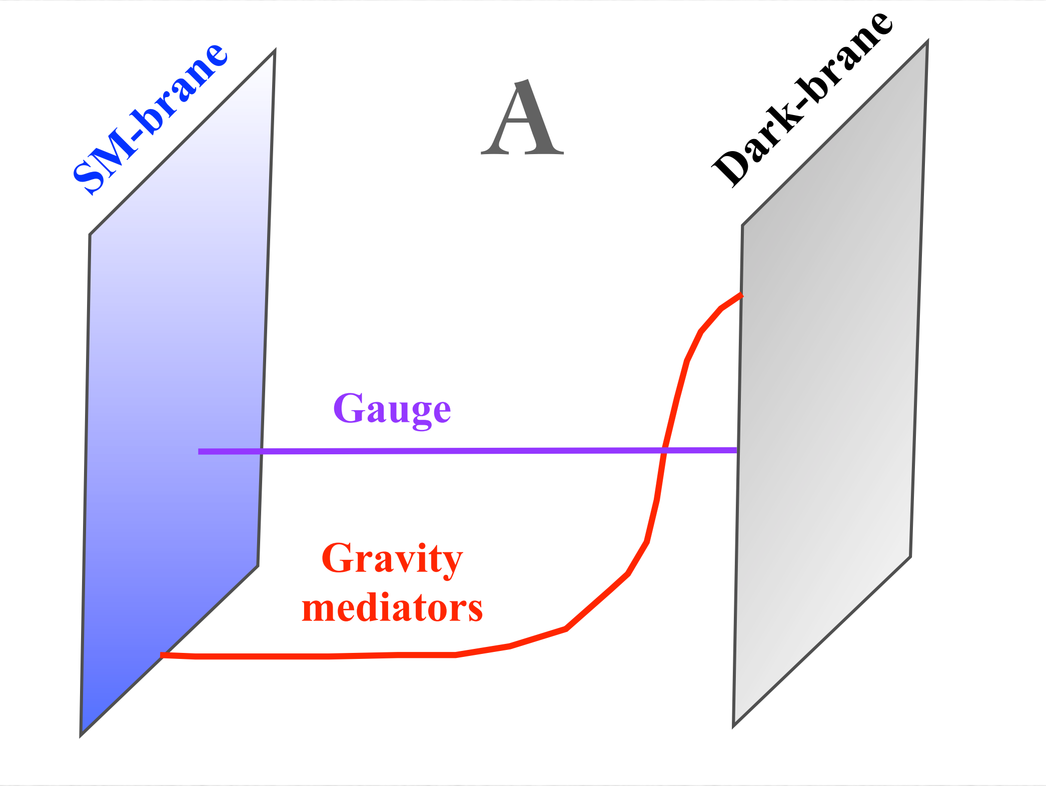
From now on:

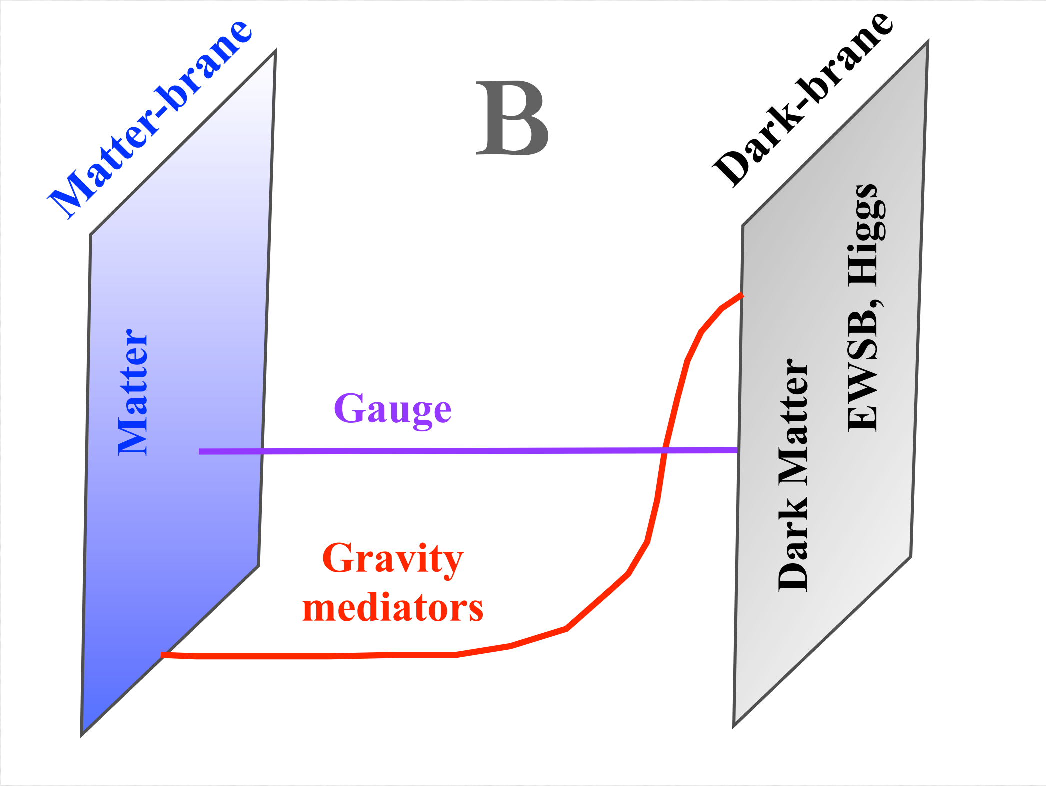
calculations in

different 4D theories



holographic to different bulk configurations





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Production/decay of KK

- Production cross section for gg→G

$\sqrt{s}$=8 TeV	$\sqrt{s}$=13 TeV	$\sigma_{13\text{TeV}}/\sigma_{8\text{TeV}}$	$\Gamma_{G\to gg}$
105 fb	465 fb	4.4	0.015 GeV

Λ=3 TeV and $c_3 = 0.1$

- Invisible decay rates

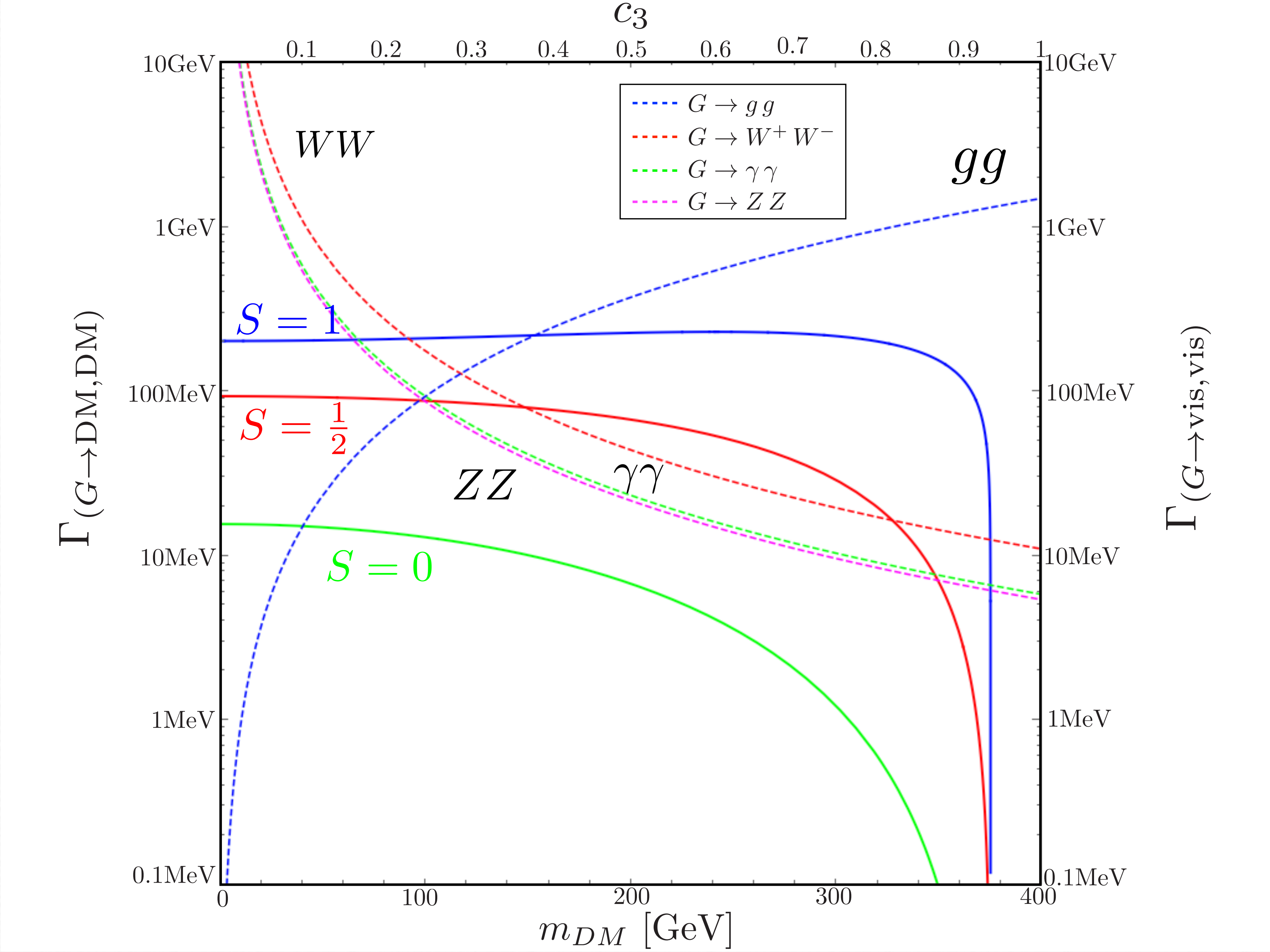
$$\Gamma(\gamma\gamma) = \frac{c_{\gamma\gamma}^2 m_G^3}{80\pi\Lambda^2},$$
$$\Gamma(Z\gamma) = \frac{c_{Z\gamma}^2 m_G^3}{160\pi\Lambda^2}\left(1-\frac{m_Z^2}{m_G^2}\right)^3\left(1+\frac{m_Z^2}{2m_G^2}+\frac{m_Z^4}{6m_G^4}\right),$$
$$\Gamma(ZZ) = \frac{c_{ZZ}^2 m_G^3}{80\pi\Lambda^2}\left(1-\frac{4m_Z^2}{m_G^2}\right)^{\frac{1}{2}}\left(1-\frac{3m_Z^2}{m_G^2}+\frac{6m_Z^4}{m_G^4}\right),$$
$$\Gamma(WW) = \frac{c_{WW}^2 m_G^3}{160\pi\Lambda^2}\left(1-\frac{4m_W^2}{m_G^2}\right)^{\frac{1}{2}}\left(1-\frac{3m_W^2}{m_G^2}+\frac{6m_W^4}{m_G^4}\right),$$
$$\Gamma(gg) = \frac{c_{gg}^2 m_G^3}{10\pi\Lambda^2}.$$

phase space suppressed

$$\Gamma(SS) = \frac{N_f c_S^2 m_G^3}{960\pi\Lambda^2}\left(1-\frac{4m_S^2}{m_G^2}\right)^{\frac{5}{2}},$$
$$\Gamma(\chi\bar{\chi}) = \frac{N_f c_\chi^2 m_G^3}{160\pi\Lambda^2}\left(1-\frac{4m_\chi^2}{m_G^2}\right)^{\frac{3}{2}}\left(1+\frac{8}{3}\frac{m_\chi^2}{m_G^2}\right),$$
$$\Gamma(XX) = \frac{N_f c_X^2 m_G^3}{960\pi\Lambda^2}\left(1-\frac{4m_X^2}{m_G^2}\right)^{\frac{1}{2}}\left(13+\frac{56m_X^2}{m_G^2}+\frac{48m_X^4}{m_G^4}\right).$$

scalar, fermion, vector DM

Henceforth, $c_1 = c_2$: no Zγ decay.



diphoton signal rates imposed;

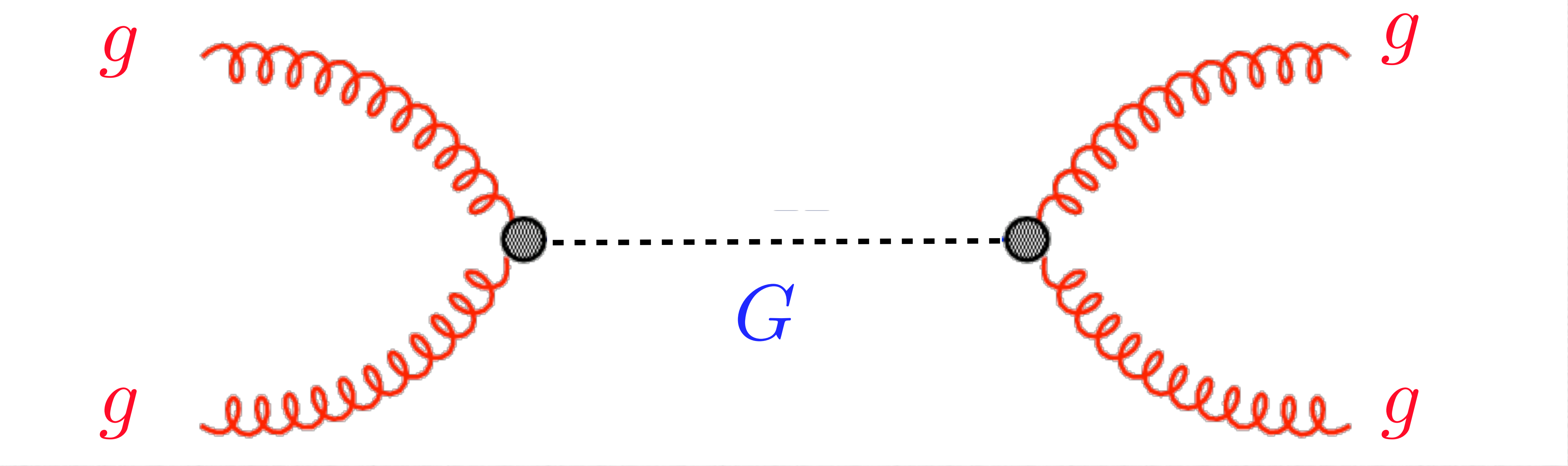
$$\Lambda = 3\,\mathrm{TeV},\ m_G = 750\,\mathrm{GeV}$$

$c_X = 1$: Invisible decay rate is subdominant.

Vector DM is the largest.

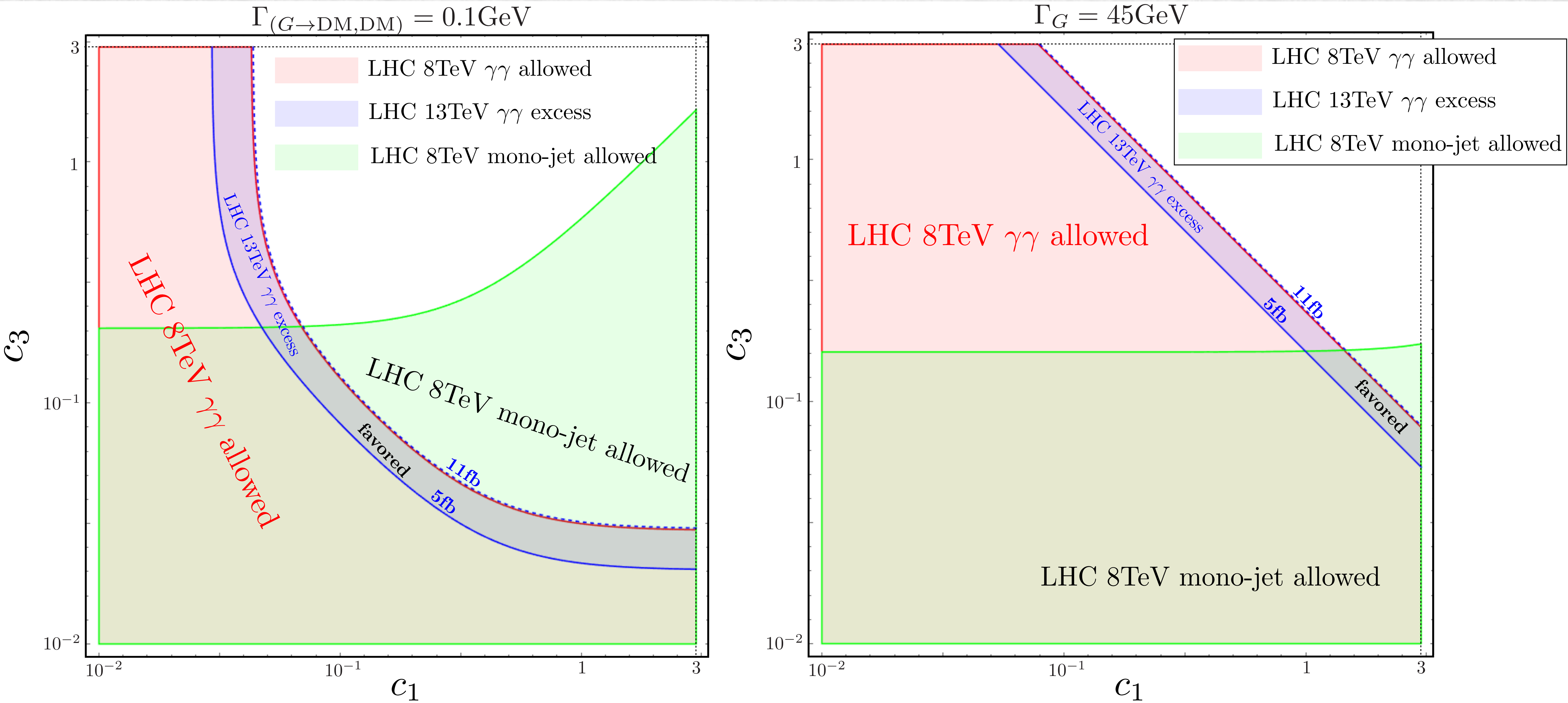
Bounds on KK graviton

Channels	$\sqrt{s}$=8 TeV	$\sqrt{s}$=13 TeV
$WW(lvjj)$	$\lesssim$ 68 fb [10]	$\lesssim$ 259 fb [11]
$ZZ(lljj)$	$\lesssim$ 37 fb [12]	$\lesssim$ 151 fb [13]
$\gamma\gamma$	$\lesssim$ 2.4 fb [14]	$\lesssim$ 11 fb
dijet	14 pb[1] [15]	-
Monojet	$\lesssim$ 270 fb [16]	-

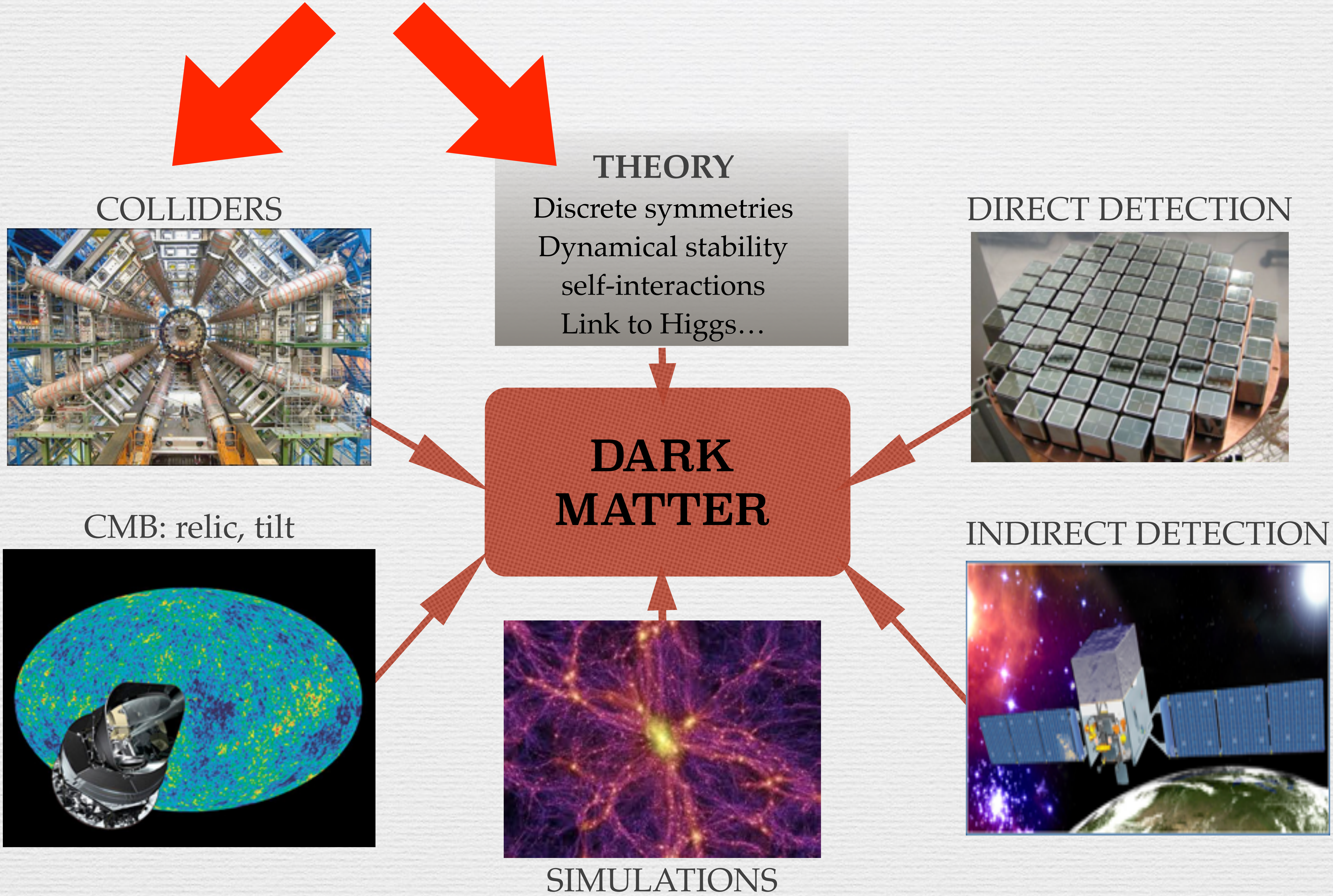


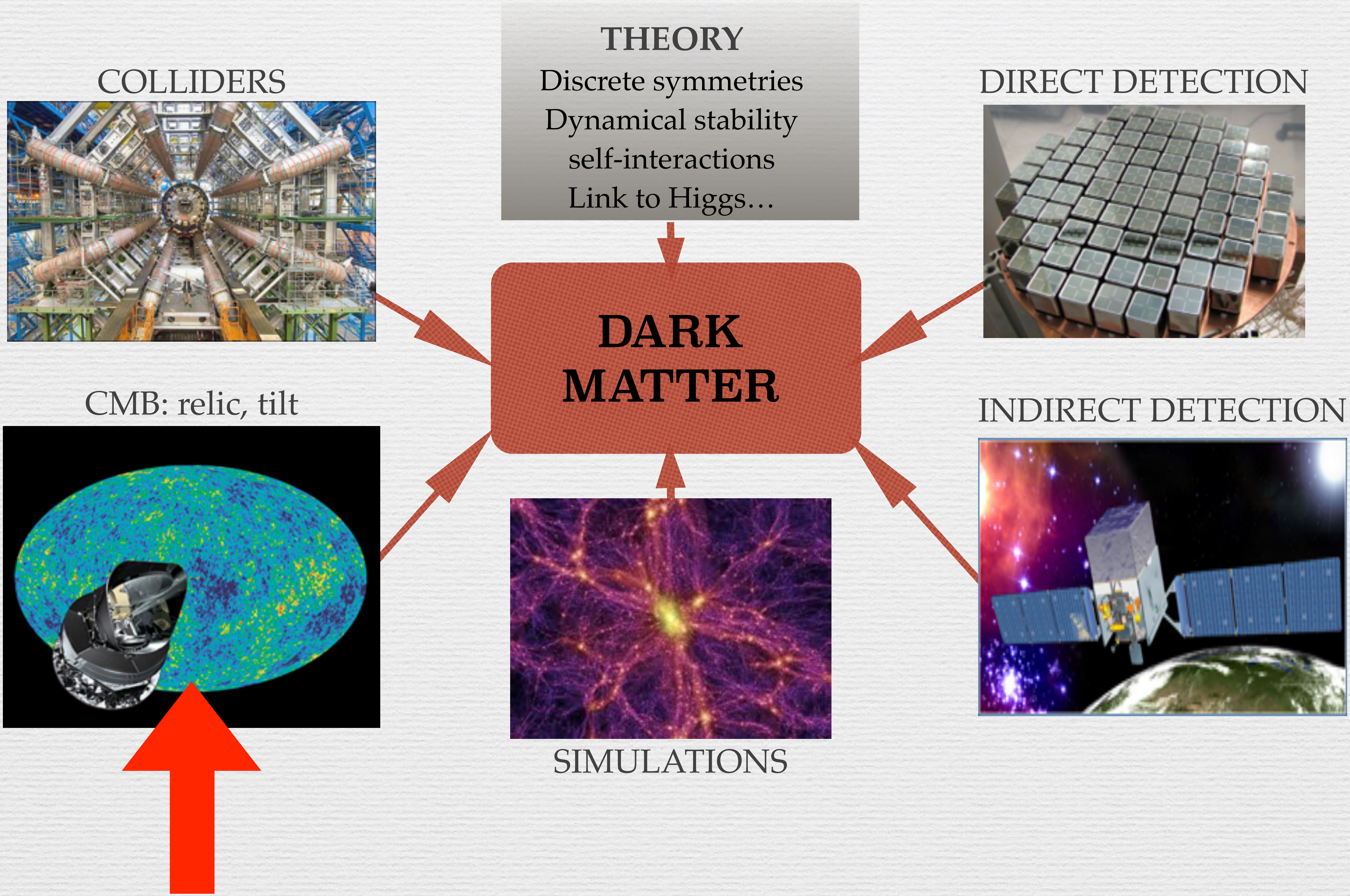
Invisible decay & mono-jet

$$c_{gg} \times c_{\gamma\gamma} = 0.16 \left(\frac{\sigma_{pp\to\gamma\gamma}}{8\,\text{fb}}\right)^{1/2} \left(\frac{\Lambda}{3\,\text{TeV}}\right)^{2} \left(\frac{45\,\text{GeV}}{\Gamma_G}\right)^{1/2}.$$



KK graviton as DM mediator


THEORY
Discrete symmetries
Dynamical stability
self-interactions
Link to Higgs…
COLLIDERS
DIRECT DETECTION
DARK MATTER
CMB: relic, tilt
INDIRECT DETECTION
SIMULATIONS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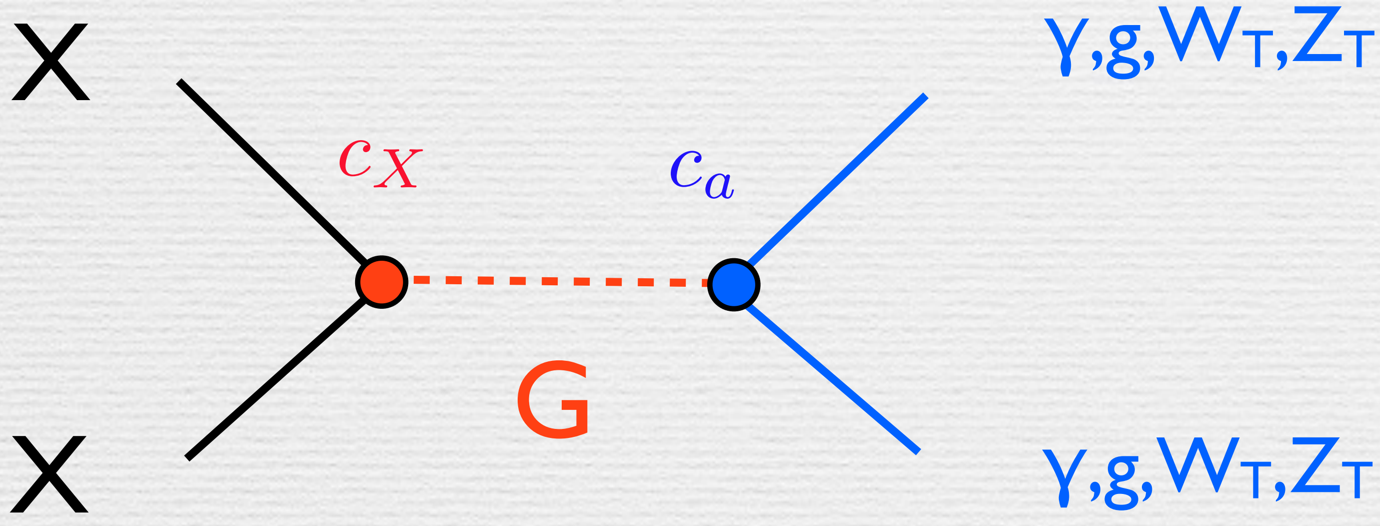
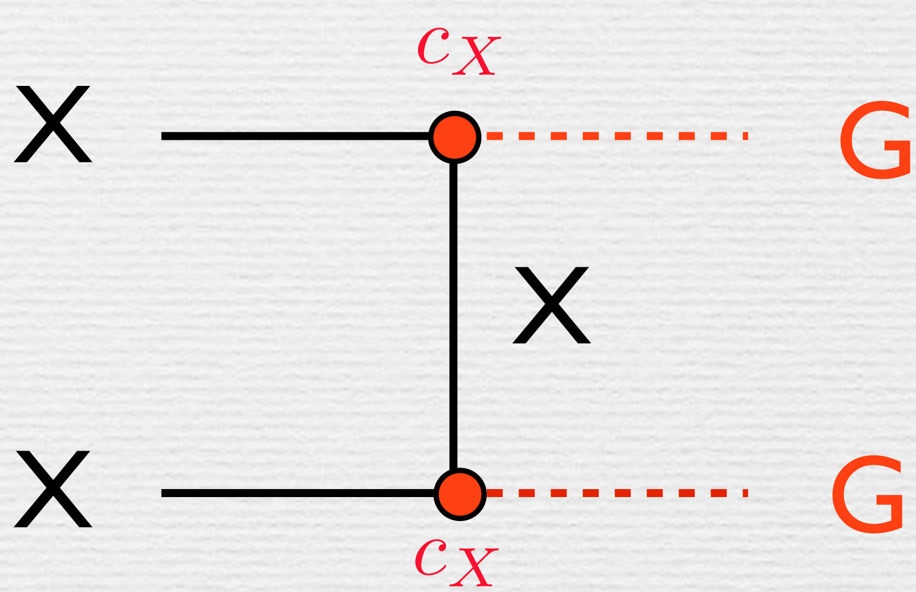
SIMULATIONS

DM annihilation

[HML, M.Park, V. Sanz, 2013, 2014]



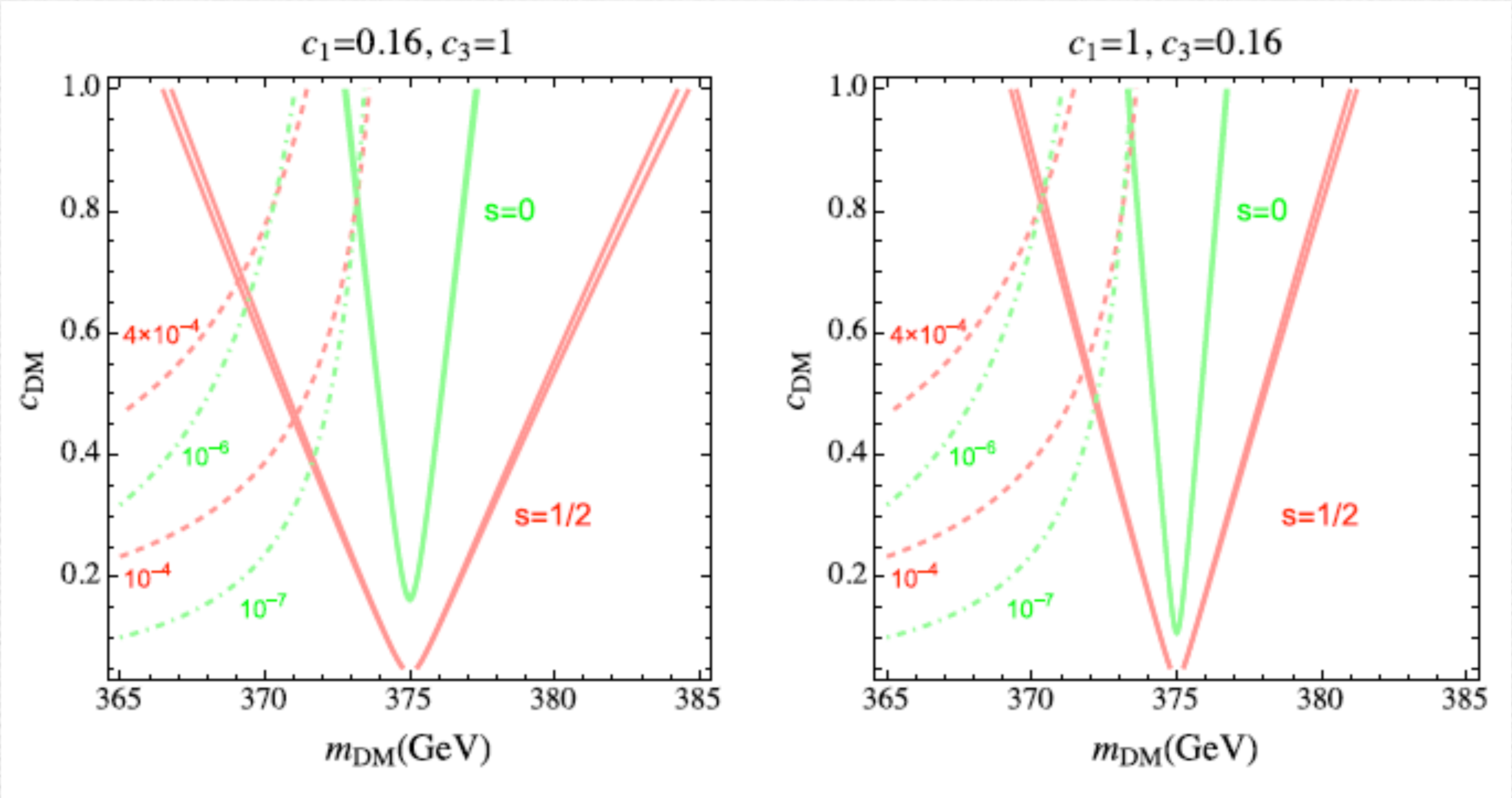


$$(\sigma v)_s \sim v^n \frac{c_X^2 c_a^2 m_X^2}{\Lambda^4}\left(\frac{m_X}{m_G}\right)^4$$

$$(\sigma v)_t \sim \frac{c_X^4 m_X^2}{\Lambda^4}\left(\frac{m_X}{m_G}\right)^8$$

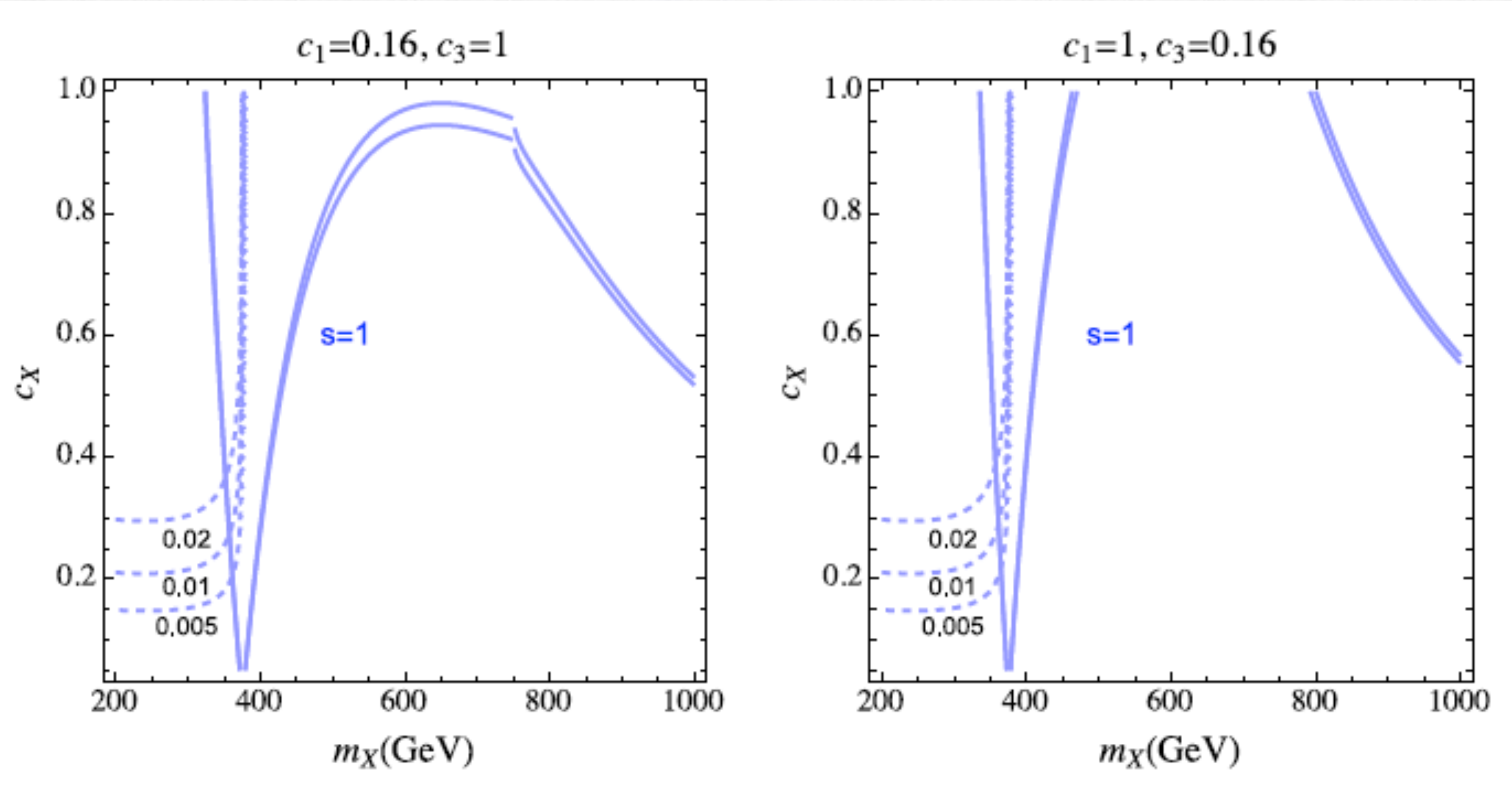
channels	DM mass	X (s=0)	X (s=1/2)	X (s=1)
s-channel	$m_{DM} < m_W$	d-wave	p-wave	s-wave
s-channel	$m_{DM} > m_W$	s-wave	p-wave	s-wave
t-channel	$m_{DM} > m_G$	s-wave	s-wave	s-wave

Scalar and fermion DM



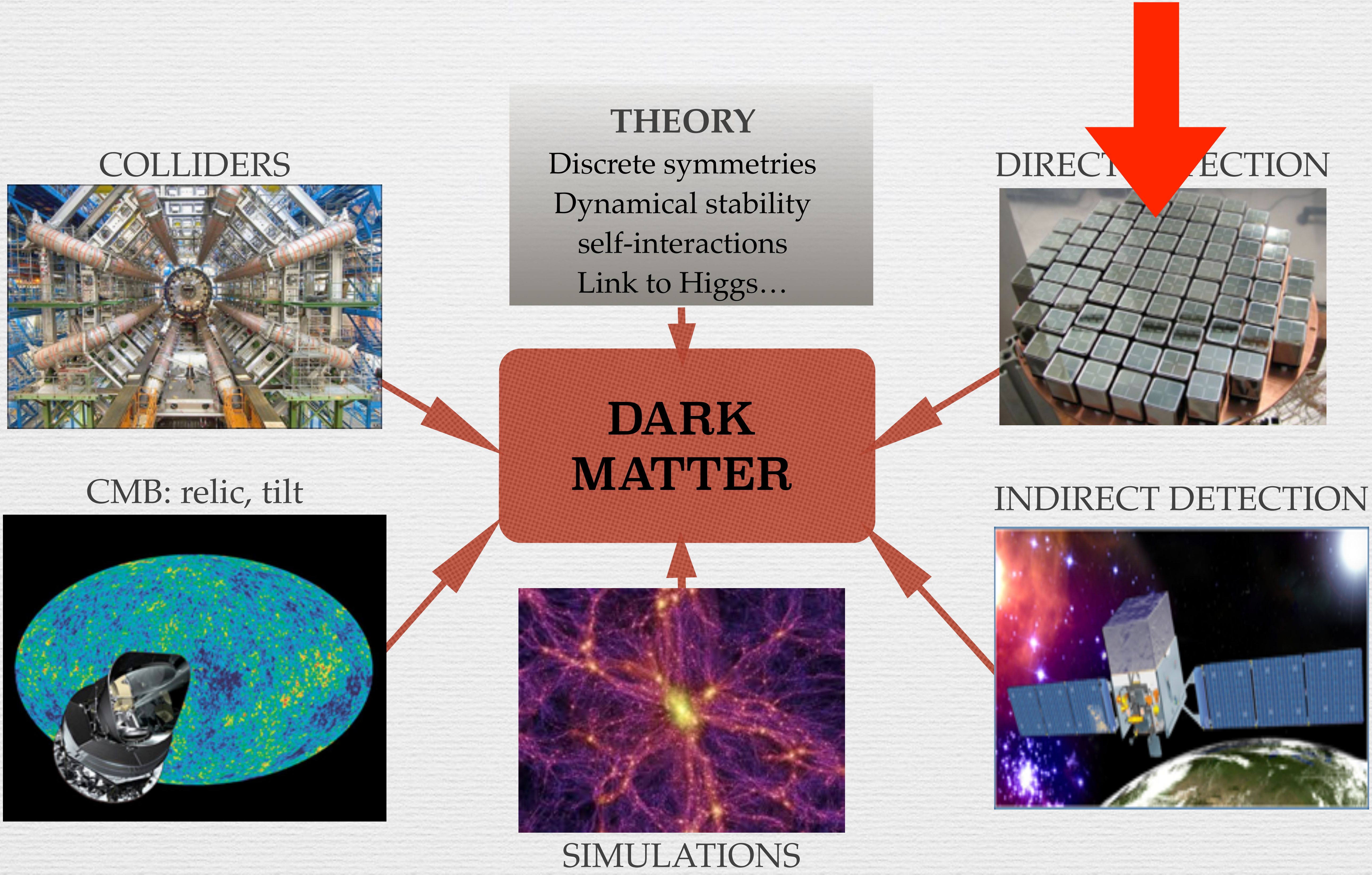
- Correct relic density is obtained near resonance, due to velocity-suppressed annihilation.
- Invisible decay rates (given in unit of GeV) are small in the region of correct relic density.

Vector DM



- Correct relic density can be obtained even away from resonance, due to s-wave annihilation.

- Invisible decay rate is larger than the cases with other spins, but is still small.

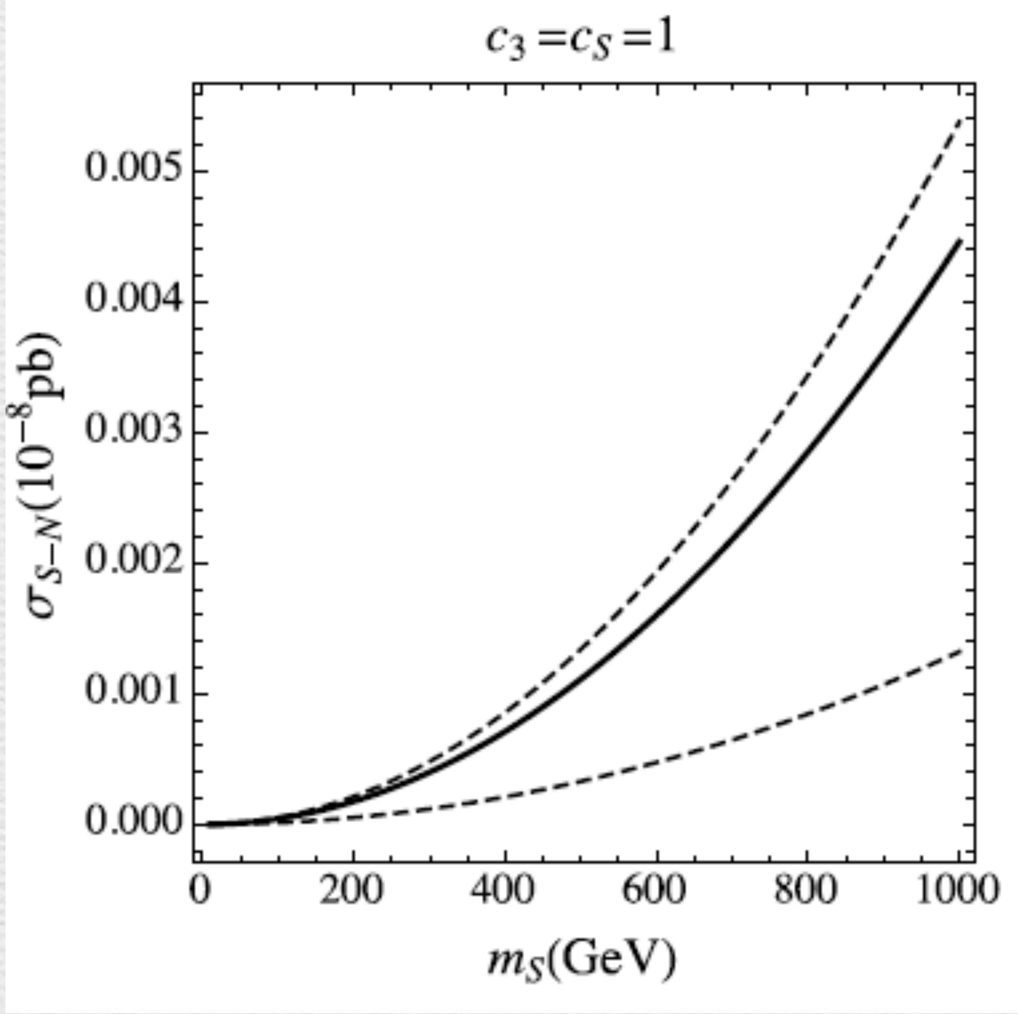

THEORY
Discrete symmetries
Dynamical stability
self-interactions
Link to Higgs…
COLLIDERS
DIREC
ECTION
DARK MATTER
CMB: relic, tilt
INDIRECT DETECTION
SIMULATIONS

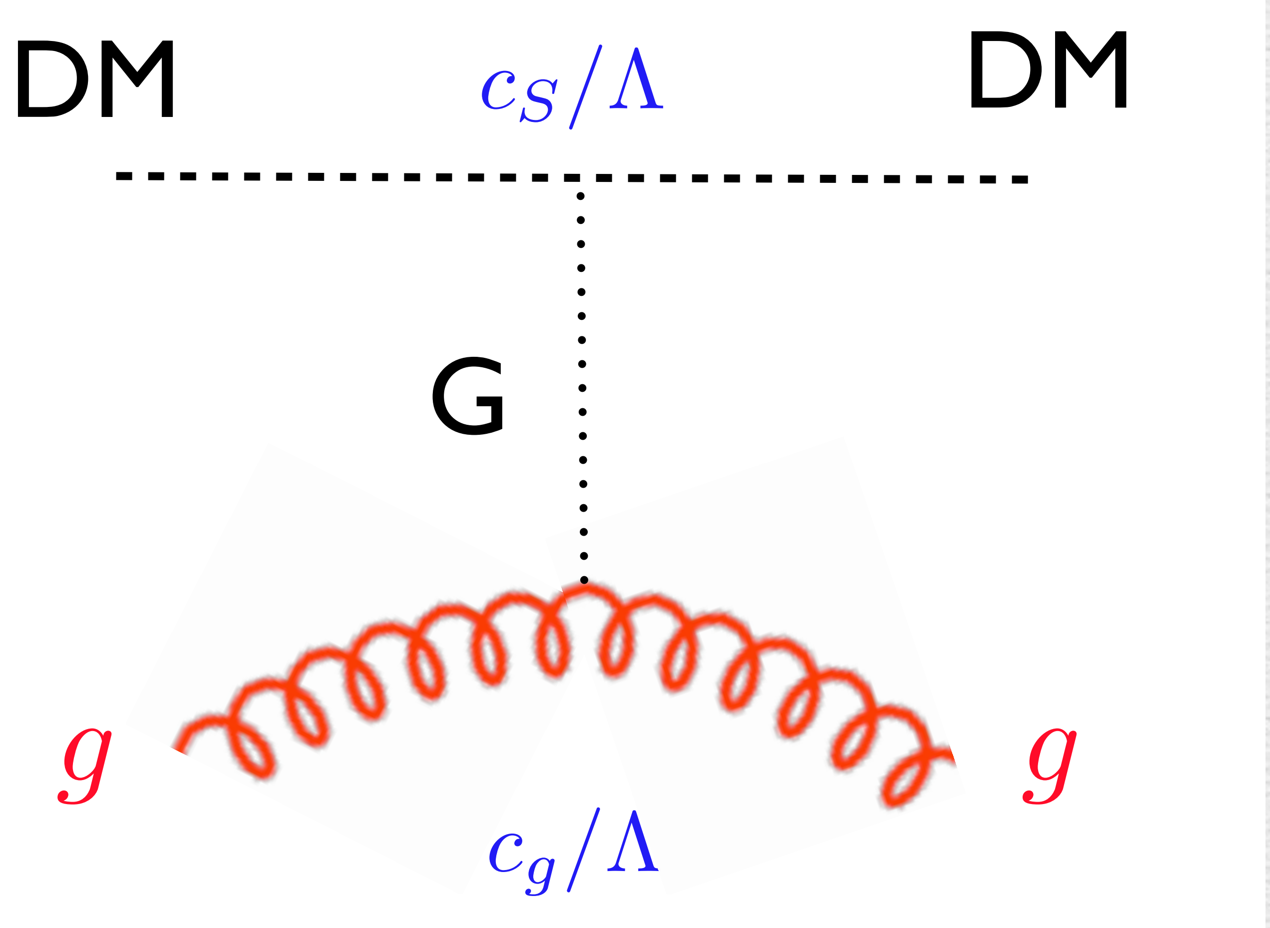
Direct detection

- Gluon coupling is unconstrained by direct detection.

$$\mathcal{L}_{S-N} = \xi_g \, S^2 G_{\mu\nu} G^{\mu\nu}, \;\; \xi_g = \frac{c_S c_g}{6\Lambda^2} \frac{m_S^2}{m_G^2},$$

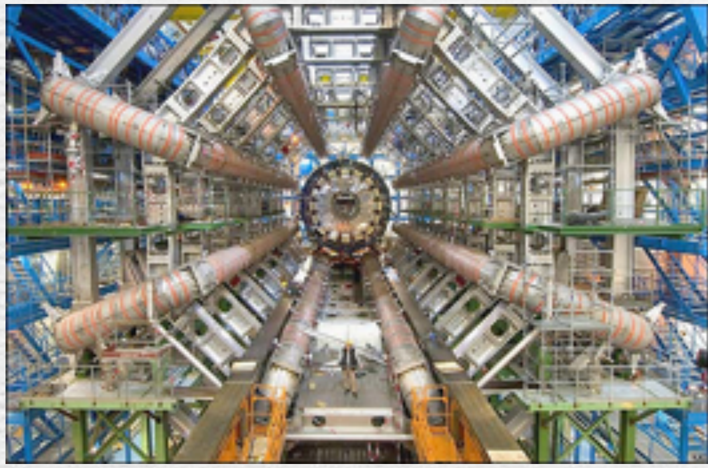
$$\sigma_{S-N} = \frac{\mu^2}{\pi m_S^2}\left(\frac{8\pi}{9\alpha_S}\right)^2 m_N^2 \xi_g^2 f_{TG}^2, \quad f_{TG} = \frac{1}{m_N}\langle N|\frac{-9\alpha_S}{8\pi} G_{\mu\nu}G^{\mu\nu}|N\rangle$$
$$= 0.472 - 0.952(\mathrm{MILC}).$$



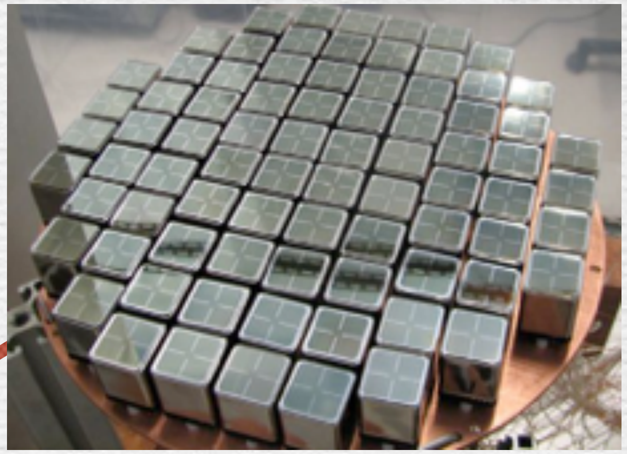


THEORY
Discrete symmetries
Dynamical stability
self-interactions
Link to Higgs…

COLLIDERS

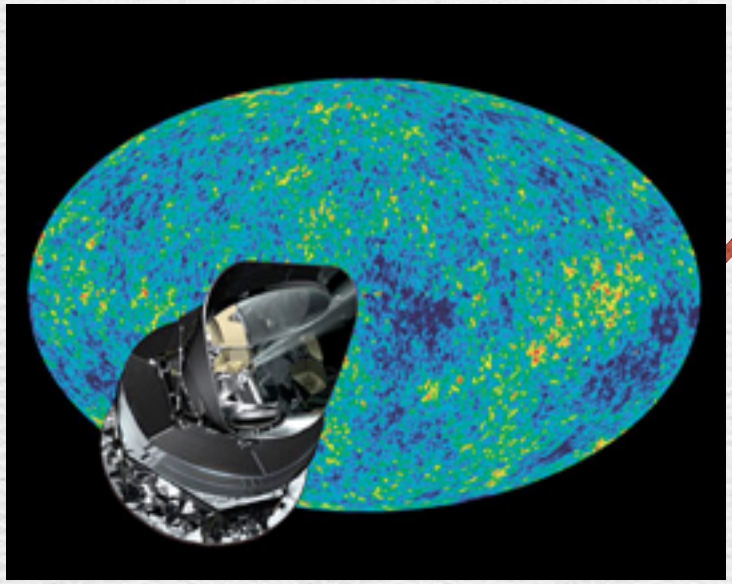


DIRECT DETECTION



DARK MATTER

CMB: relic, tilt



INDIRECT DETECTION

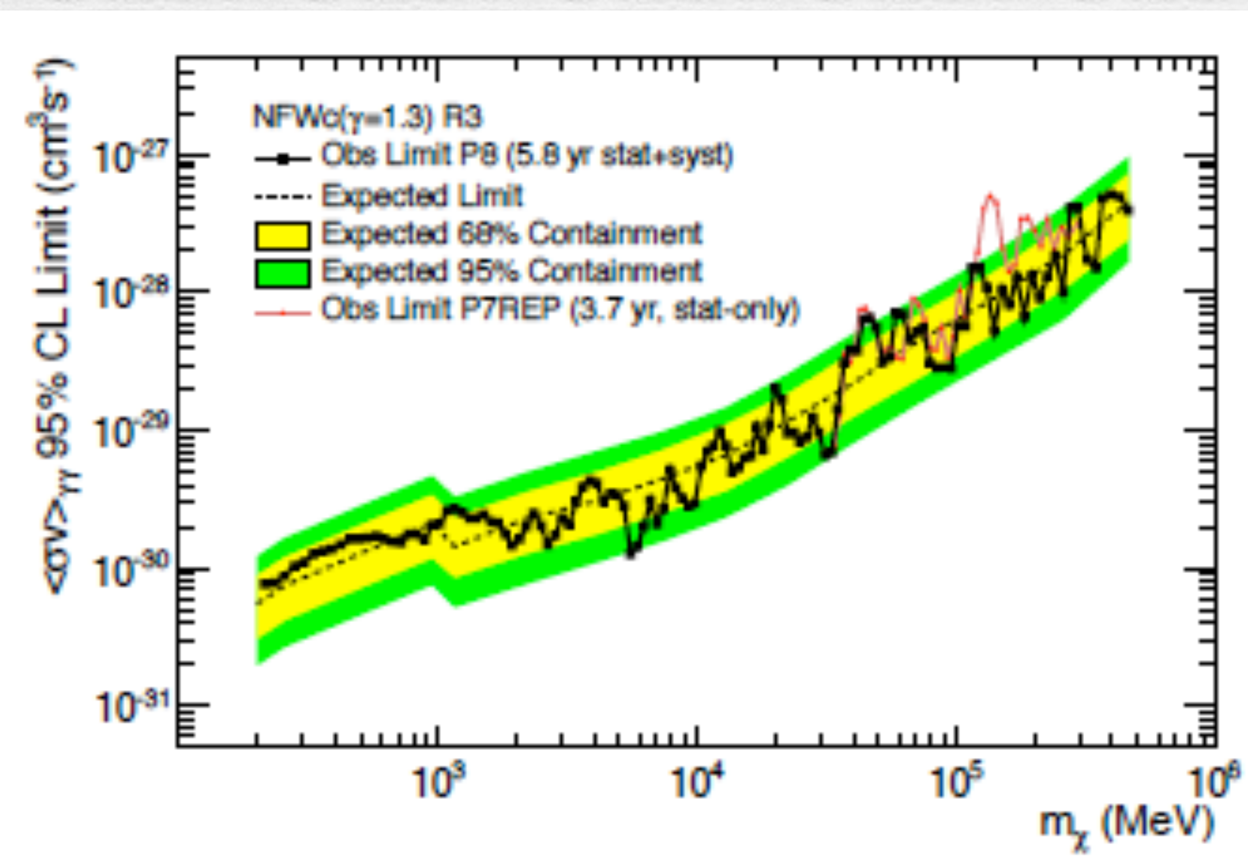
SIMULATIONS

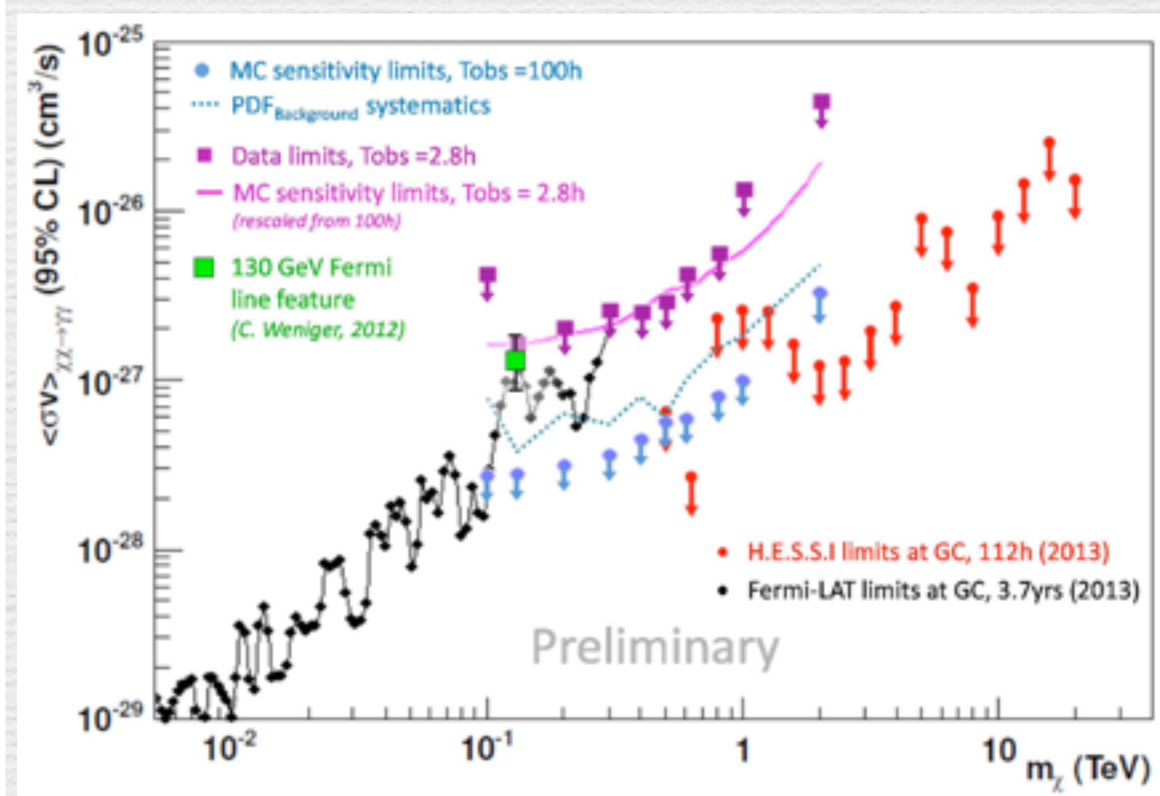
Indirect detection - lines

- Spectral gamma-ray line (Fermi-LAT, HESS, CTA, etc):

  $\gamma\gamma$, GG$\rightarrow$ $\gamma\gamma\gamma\gamma$ channels (vector DM)

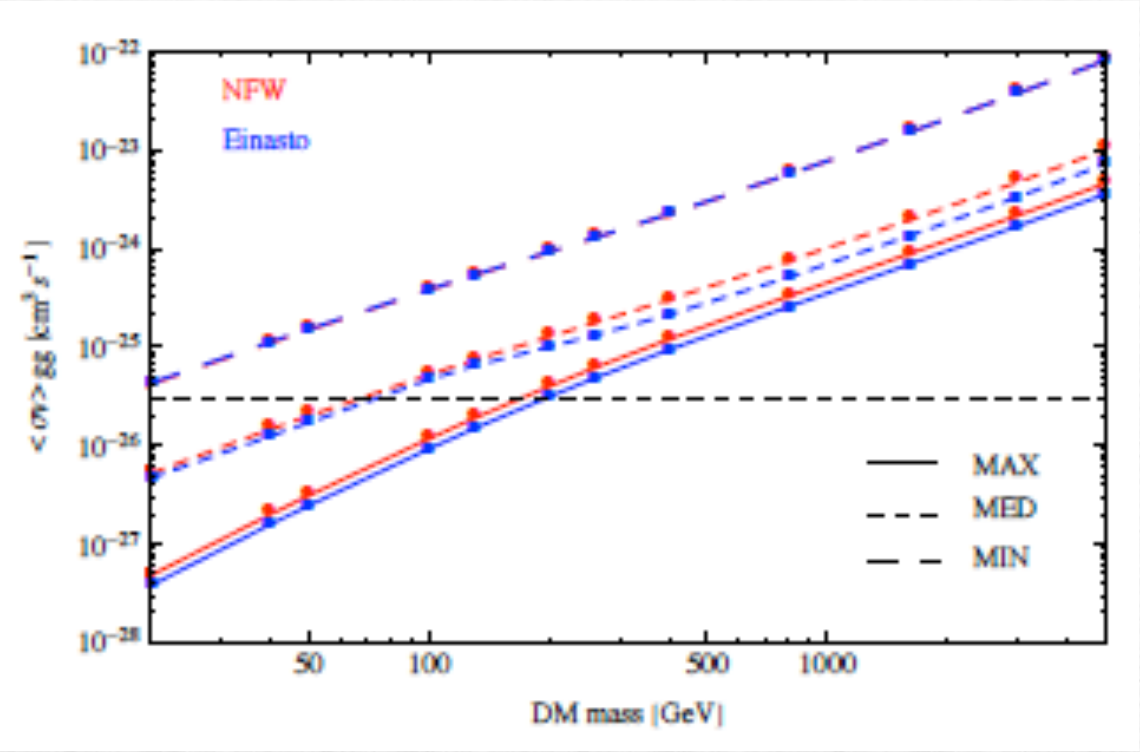
- BR of DM annihilation into a photon pair less than 1% of thermal cross section for DM mass ~ a few 100GeV.

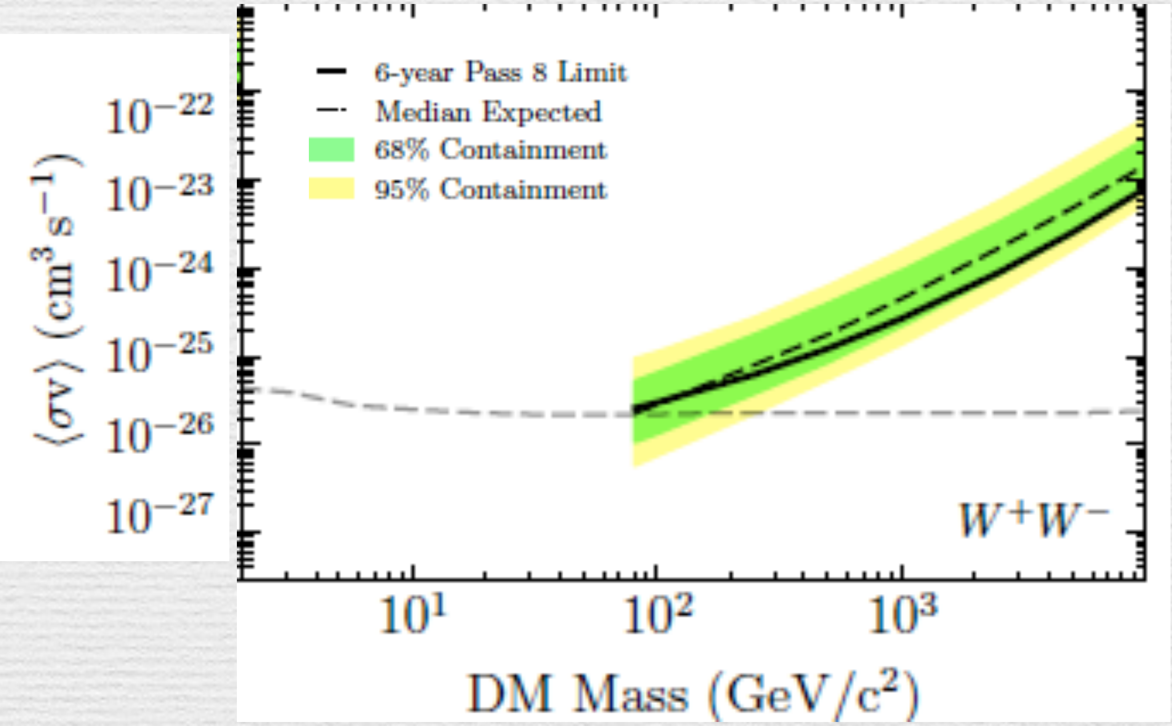




Indirect detection -

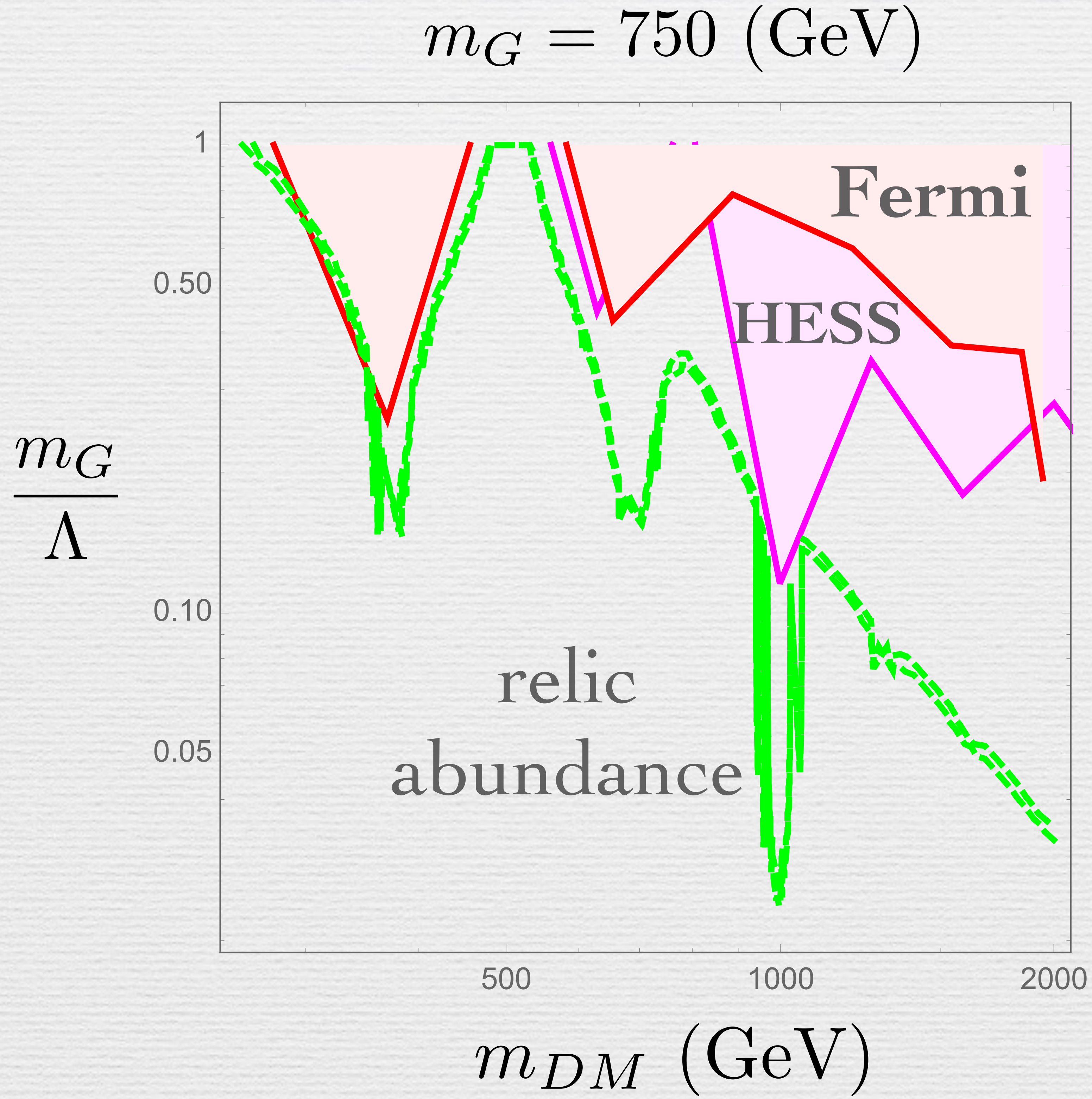
- Continuum gamma-ray (Fermi-LAT dwarf galaxies):
  WW, ZZ channels (scalar & vector DM)
- Anti-proton (PAMELA, AMS-02): gg channel (vector DM)
- Bounds from Anti-proton & Fermi dwarf galaxies constrain thermal cross section for gg & WW.





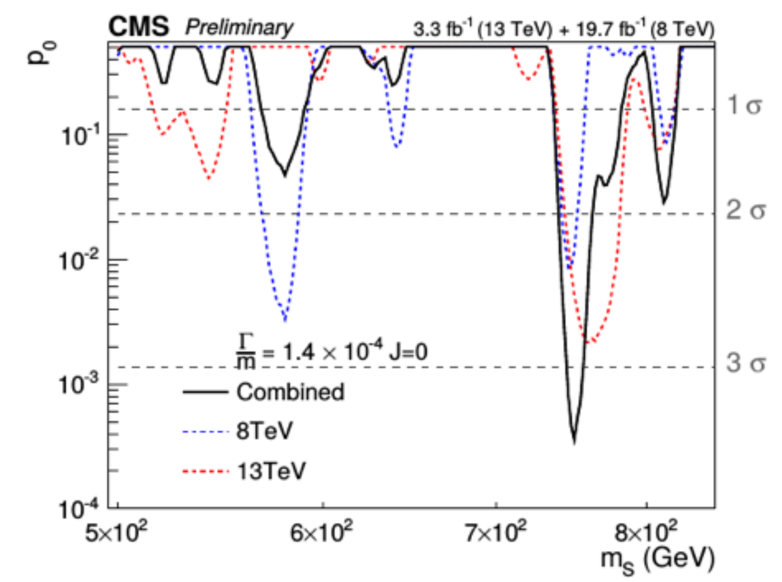
[Chu, Hambye, Scarna, Tytgat, 2012]

Indirect detection

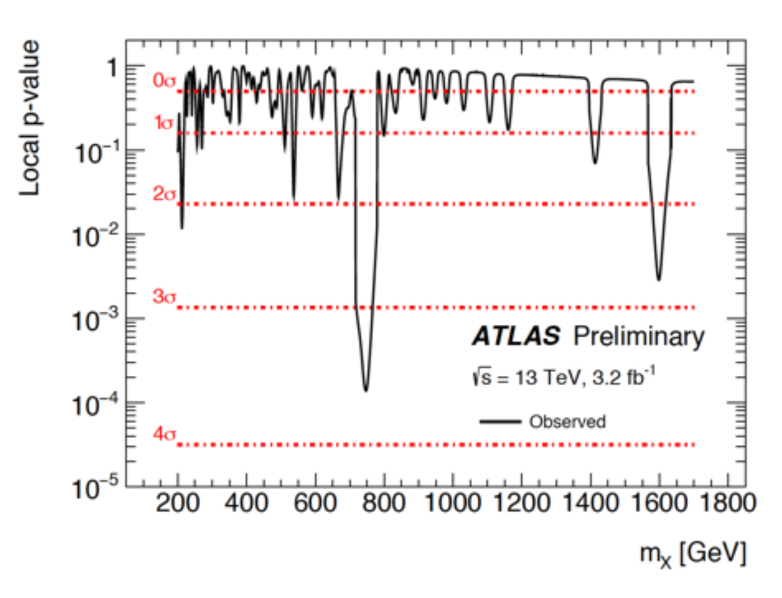


Conclusions

- Two excesses at roughly 3.5sigma at 750 GeV and cross section ~5 fb. Width and spin still TBD. Excess doesn't come with high-pT objects. Most compatible with gluon-fusion



- Models of spin-zero:
  standard SUSY.
  standard AdS/CFT techniques required



- Spin-two would probe
  graviton/Quantum Black Holes
  diphoton resonance common origin:
  correlations with DD/ID.

Whatever this is, making sense of naturalness, Dark Universe and model-building techniques is a challenge for theorists.
300 papers in ~ 4 months, we are up to it!