THE EXPERIMENTAL WAY

Raffaele Tito D’Agnolo - CEA IPhT Saclay and ENS Paris

Higgs Mass Squared

$$m_h^2 |H|^2$$

WEAK FORCE, STRUCTURE OF NUCLEI, COMPLEX CHEMISTRY, …

SYMMETRY-BASED ESTIMATE

$$m_h^2 \sim \frac{y_t^2 M_{\rm Pl}^2}{16\pi^2}$$

Symmetry~10^{34} Experiment

$$m_h^2 = 0$$

Special

Planck

New Symmetry

SM

$$m_h^2 \sim \frac{y_t^2 M_S^2}{16\pi^2}$$

Planck

M_S — New Symmetry

SM

$$m_h^2 |H|^2$$

We have been looking for answers at energies close to mh for more than **40 years**

Higgs Boson

and we have not found them

As a consequence we have gone wild theoretically

Ultralight DM

[Arkani-Hamed, RTD, Kim, '20], [RTD, Teresi, '21]

Axion-Like

[Graham, Rajendran, Kaplan, '15], [RTD, Teresi, '21], [Chatrchyan, Servant '23]

…

Only EW

[Arvanitaki, Dimopoulos, Gorbenko, Huang, Van Tilburg '16], [Arkani-Hamed, RTD, Kim, '20], [Chacko, Goh, Harnik, '05]

…

Fifth Forces

[Arkani-Hamed, RTD, Kim, '20]

CMB Signals

[Arkani-Hamed, Cohen, RTD, Kim, Pinner, '16]

No Signals

[Dvali, Vilenkin '03], [Dvali '04], [Geller, Hochberg, Kuflik,'18], [Giudice, McCullough, You, '21], [Agrawal, Barr, Donoghue, Seckel '97],

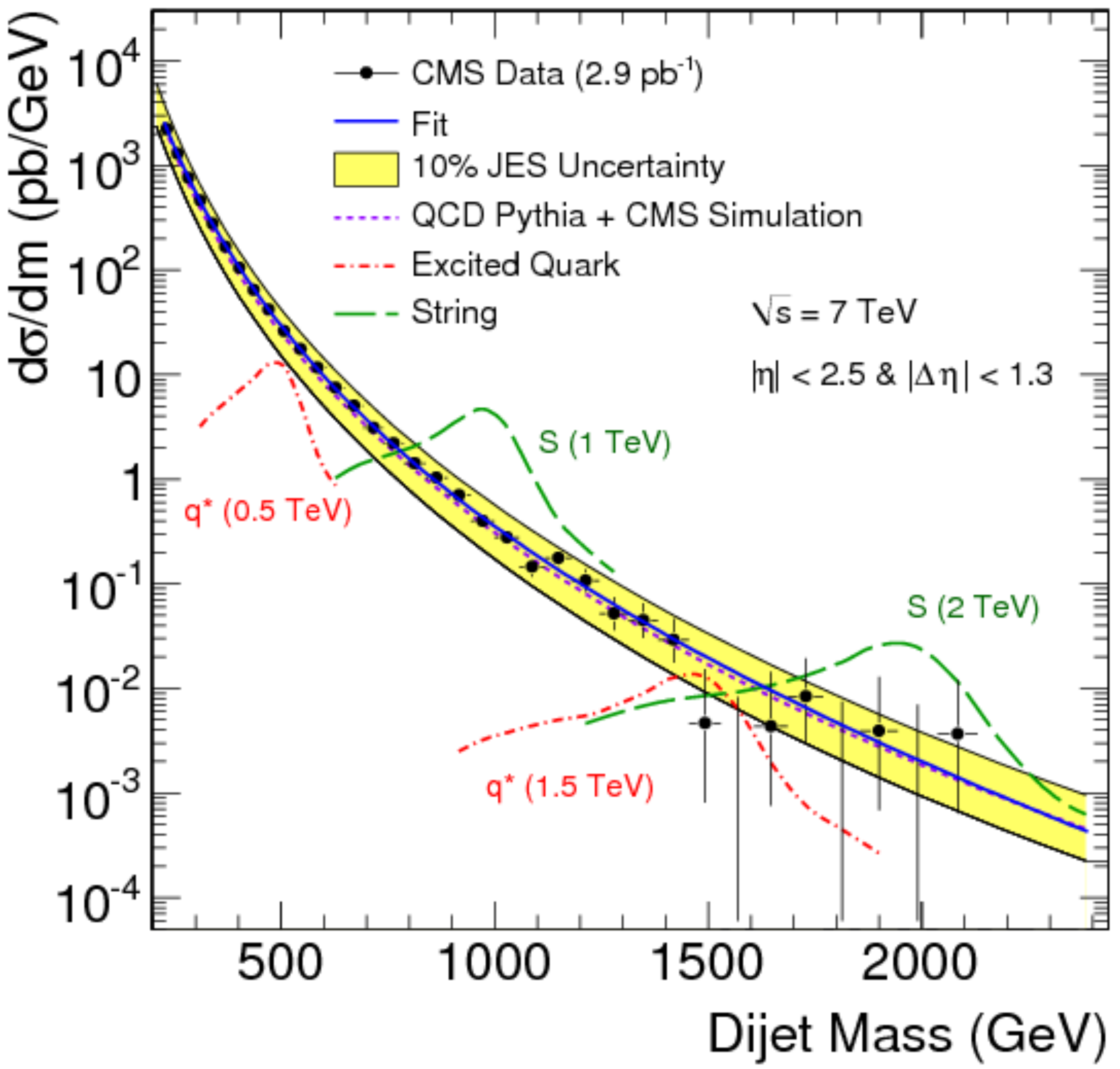
…

Neutron EDM

[RTD, Teresi, '21]

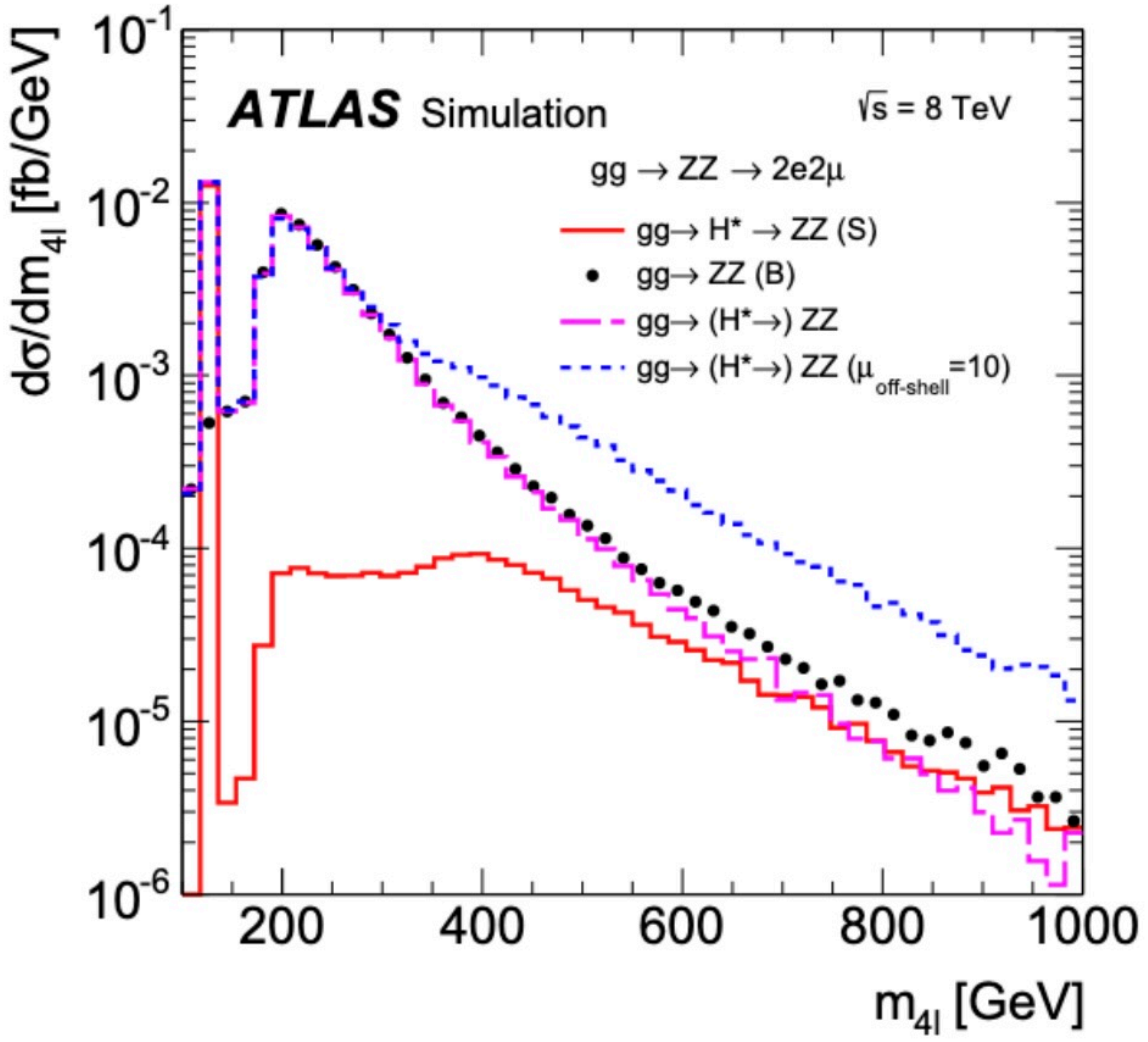
But there is still a lot that we have not done experimentally

Bumps



CMS Data (2.9 pb^{-1})
Fit
10% JES Uncertainty
QCD Pythia + CMS Simulation
Excited Quark
String
$\sqrt{s}$ = 7 TeV
$|\eta|$ < 2.5 & $|\Delta\eta|$ < 1.3
S (1 TeV)
S (2 TeV)
q* (0.5 TeV)
q* (1.5 TeV)
dσ/dm (pb/GeV)
Dijet Mass (GeV)

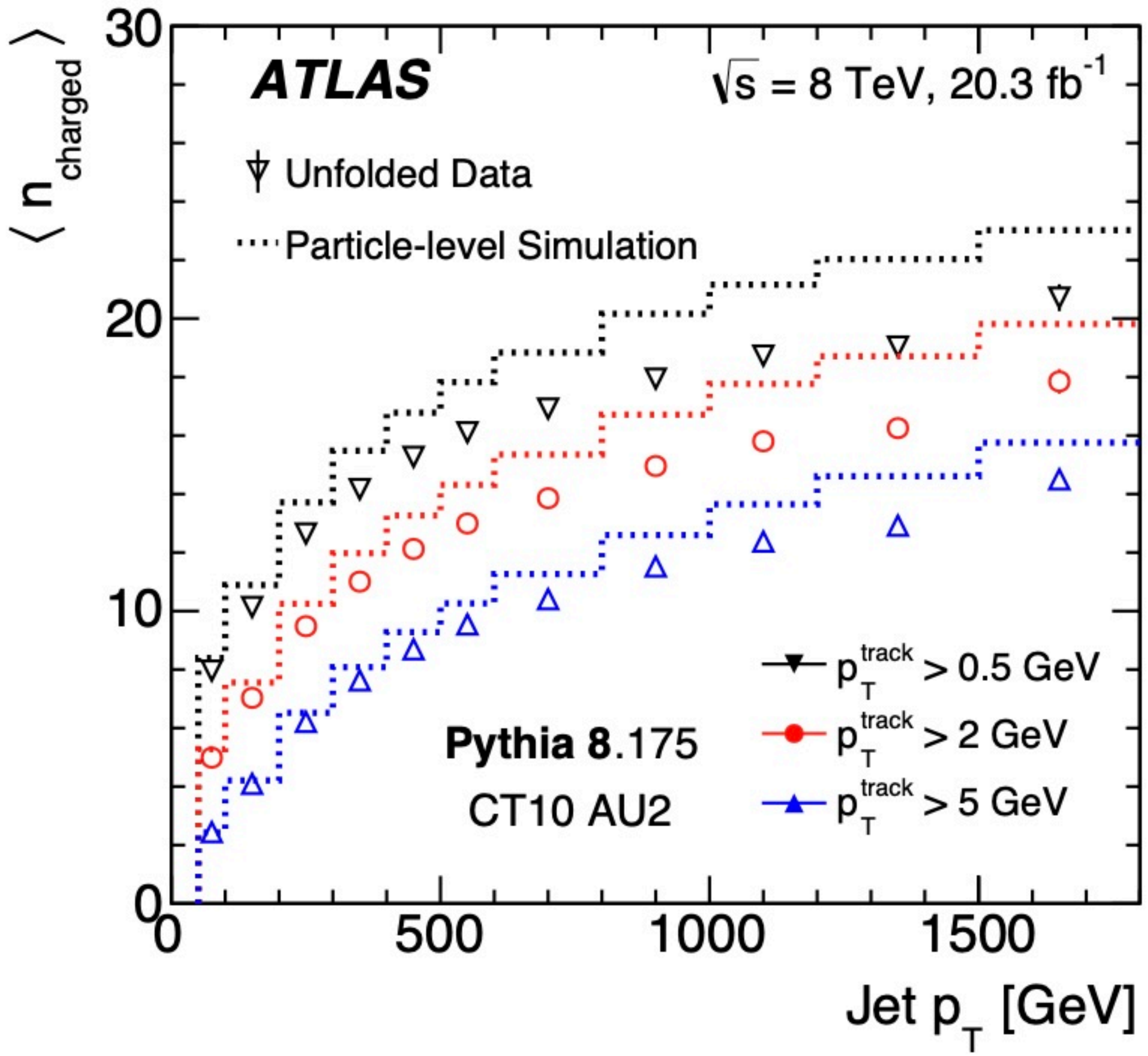
Tails

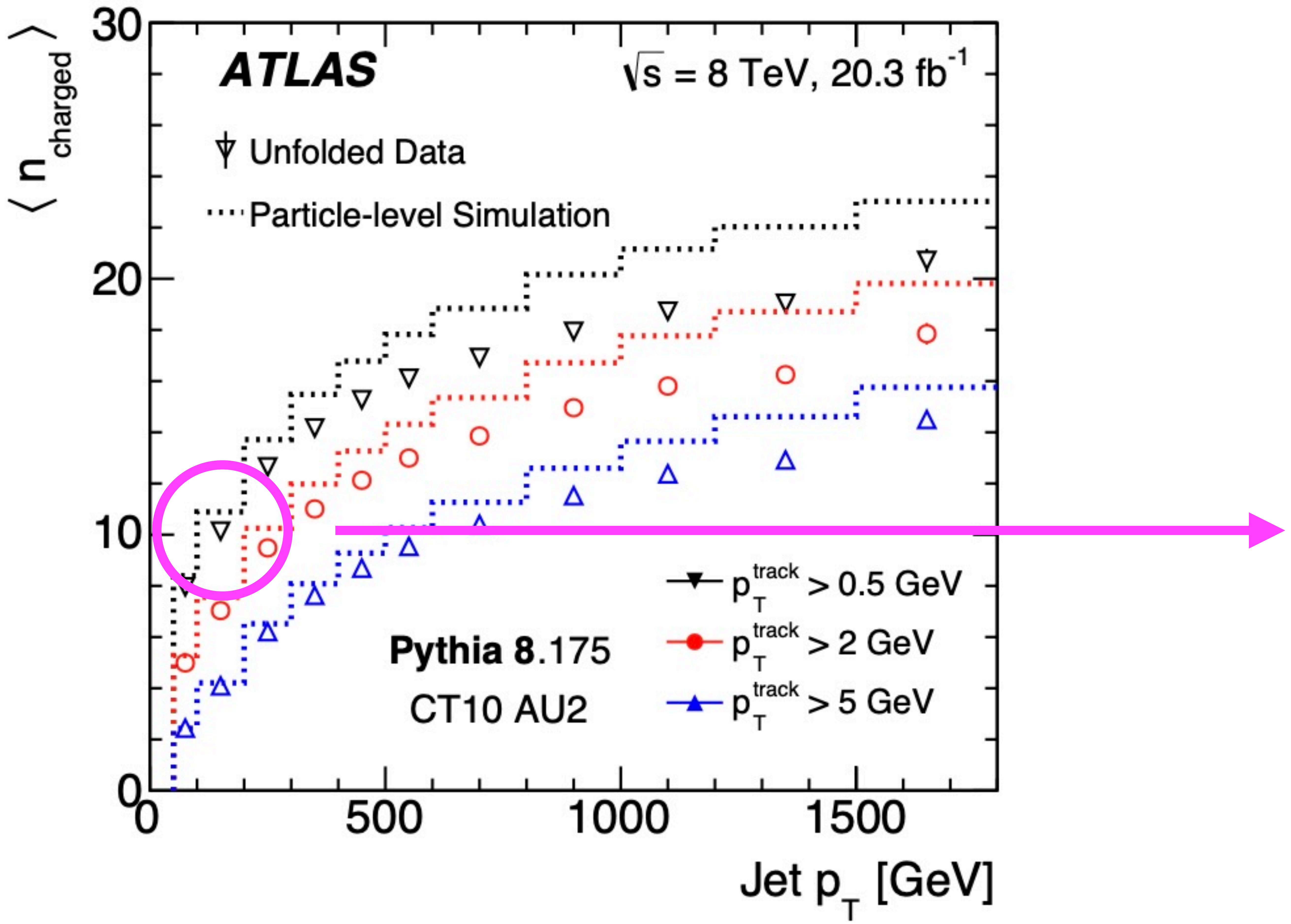


ATLAS Simulation
$\sqrt{s}$ = 8 TeV
gg → ZZ → 2e2μ
gg→ H* → ZZ (S)
gg→ ZZ (B)
gg→ (H*→) ZZ
gg→ (H*→) ZZ ($\mu_{off-shell}$=10)
$d\sigma/dm_{4l}$ [fb/GeV]
m_{4l} [GeV]

Could there still be **HUGE** signals hiding in collider data?

40 SIGMA SIGNALS AND WHERE TO FIND THEM


ATLAS
√s = 8 TeV, 20.3 fb⁻¹
Unfolded Data
Particle-level Simulation
Pythia 8.175
CT10 AU2
p_T^track > 0.5 GeV
p_T^track > 2 GeV
p_T^track > 5 GeV
⟨n_charged⟩
Jet p_T [GeV]
0
10
20
30
0
500
1000
1500



Roughly ~ 10 charged tracks in a 100 GeV jet

Dijet event

~ 20 x 4 = **80**

kinematical variables

$$\sim N^{80}$$

Possible signals

$$N > 1$$

But unknown

$$\sim N^{80}$$

And this does not even include:

1) All particles from Pile Up

2) The growth at 13 TeV

3) All the hits in the tracker from tracks that don't look "normal"

$$\sim N^{80}$$

And this does not even include:

1) All particles from Pile Up

2) The growth at 13 TeV

3) All the hits in the tracker from tracks that don't look "normal"

$$\sim N^{10^4}$$

And this does not even include:

1) All particles from Pile Up

2) The growth at 13 TeV

3) All the hits in the tracker from tracks that don't look "normal"

THE DREAM

Raw data = Hits in tracker and muon system + energy deposits in the calorimeters

THE DREAM

Raw data → Dr. Black Box

THE DREAM

Raw data $\longrightarrow$ Dr. Black Box $\longrightarrow$ New Physics?

THE PROBLEMS

Raw data →

Old Physics →

Dr. Black Box

→ New Physics?

Raw data →

Old Physics →

Look-elsewhere effect

→ New Physics?

LOOK-ELSEWHERE EFFECT

Number of observables

$$D \gg 1$$

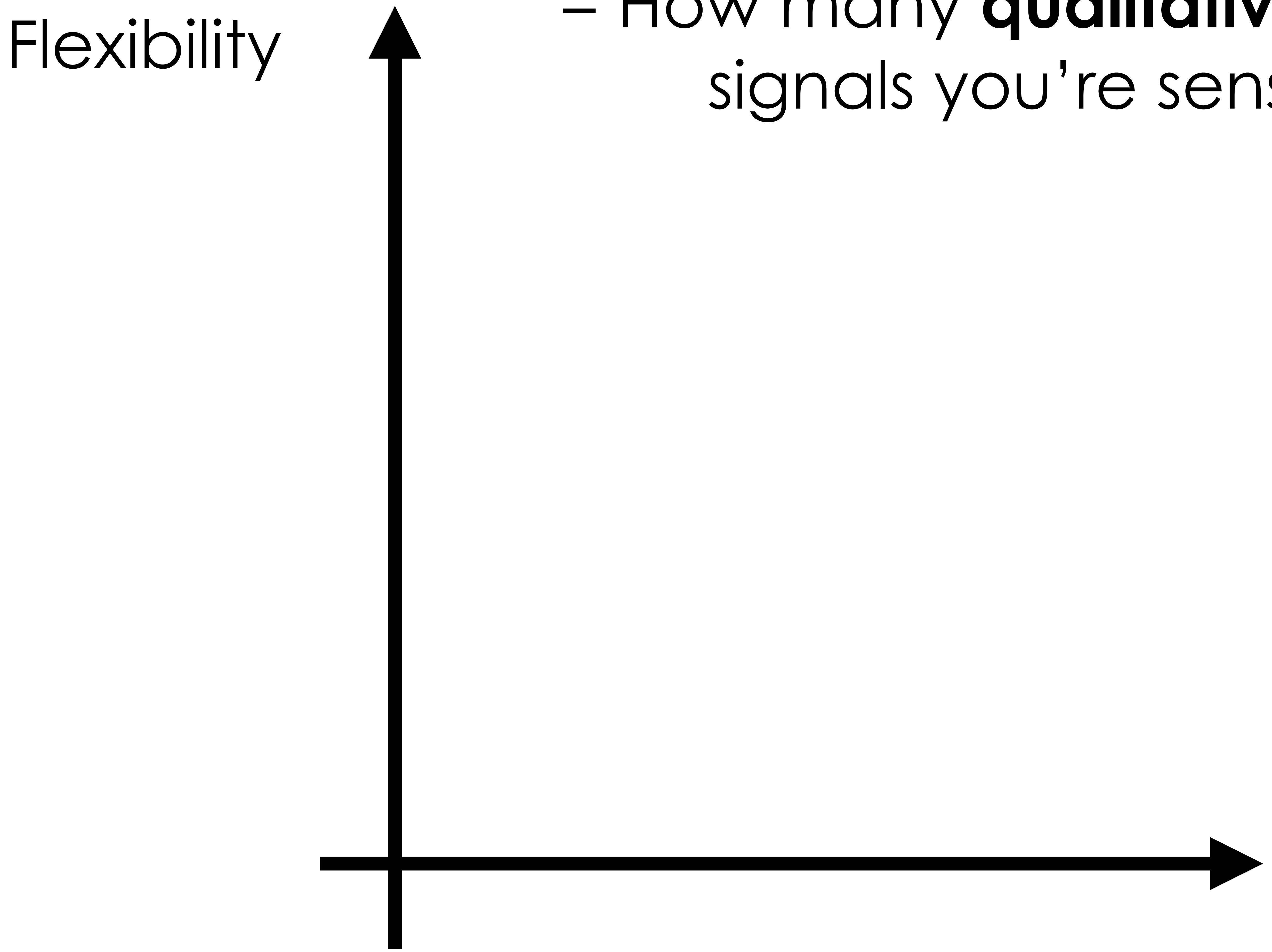
Number of signals

$$N^D$$

Significance of observation

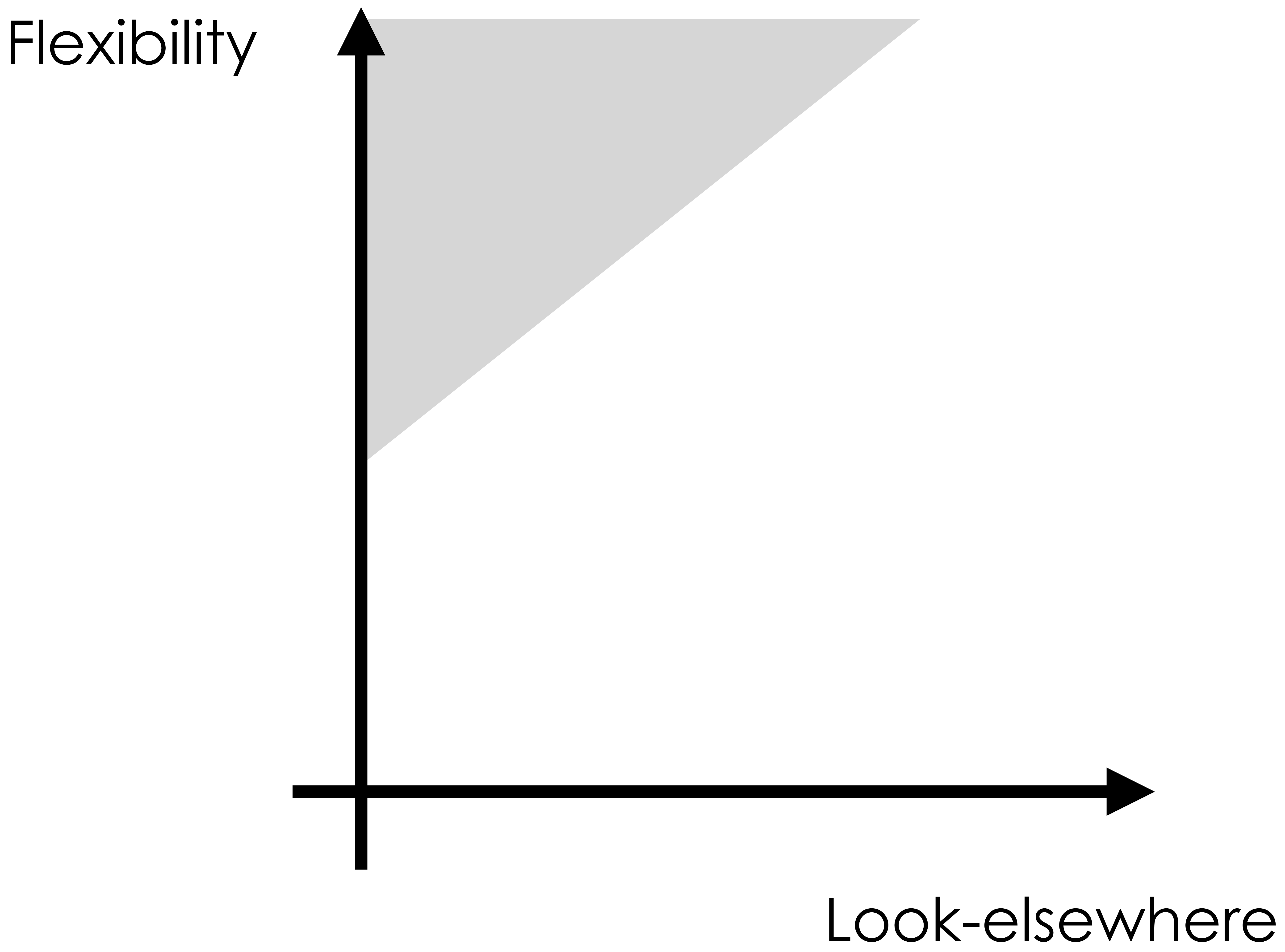
$$p_{\text{global}} = p_{\text{local}} \times N^D$$

LOOK-ELSEWHERE EFFECT

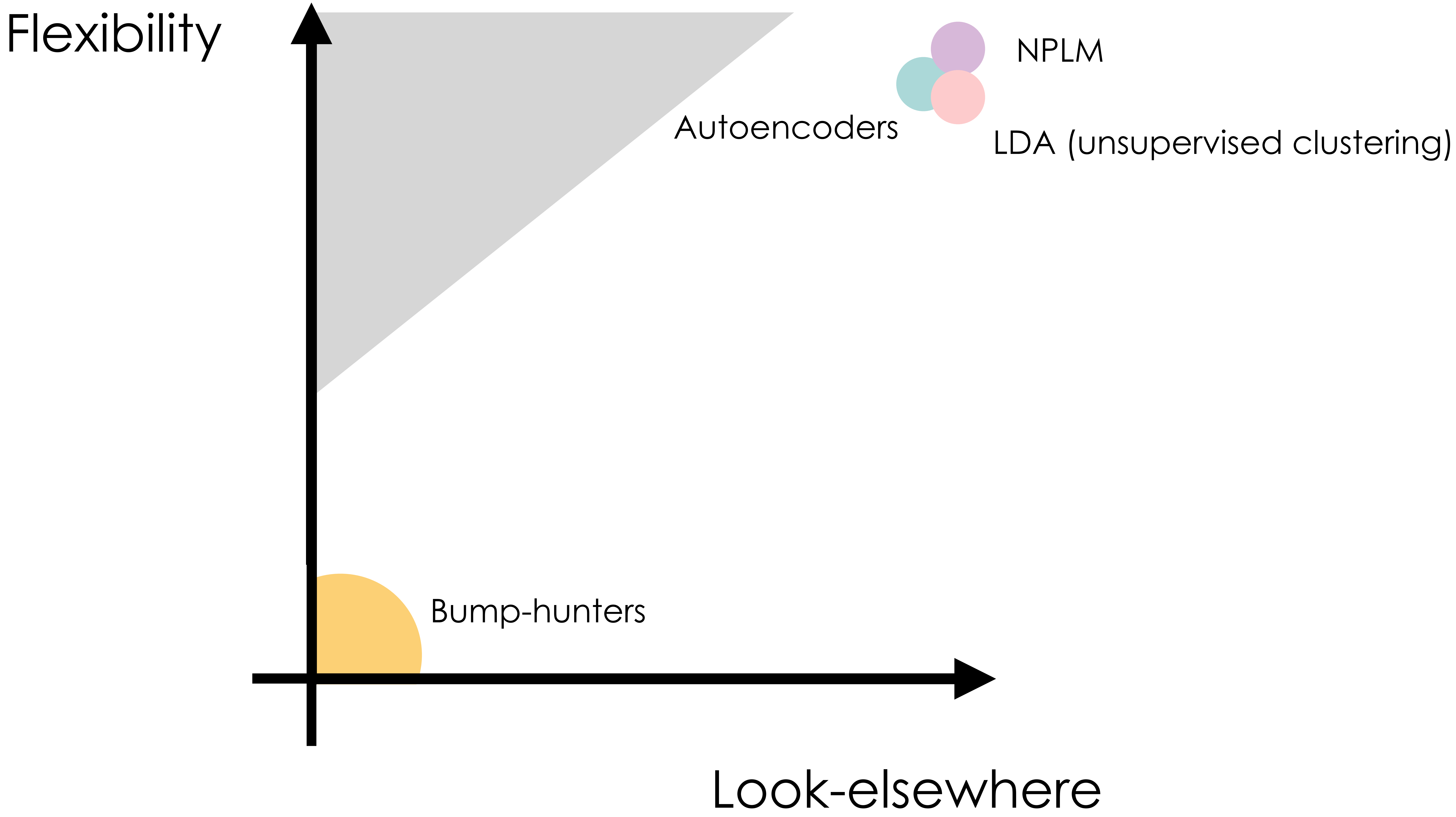


= How many **qualitatively different** signals you're sensitive to

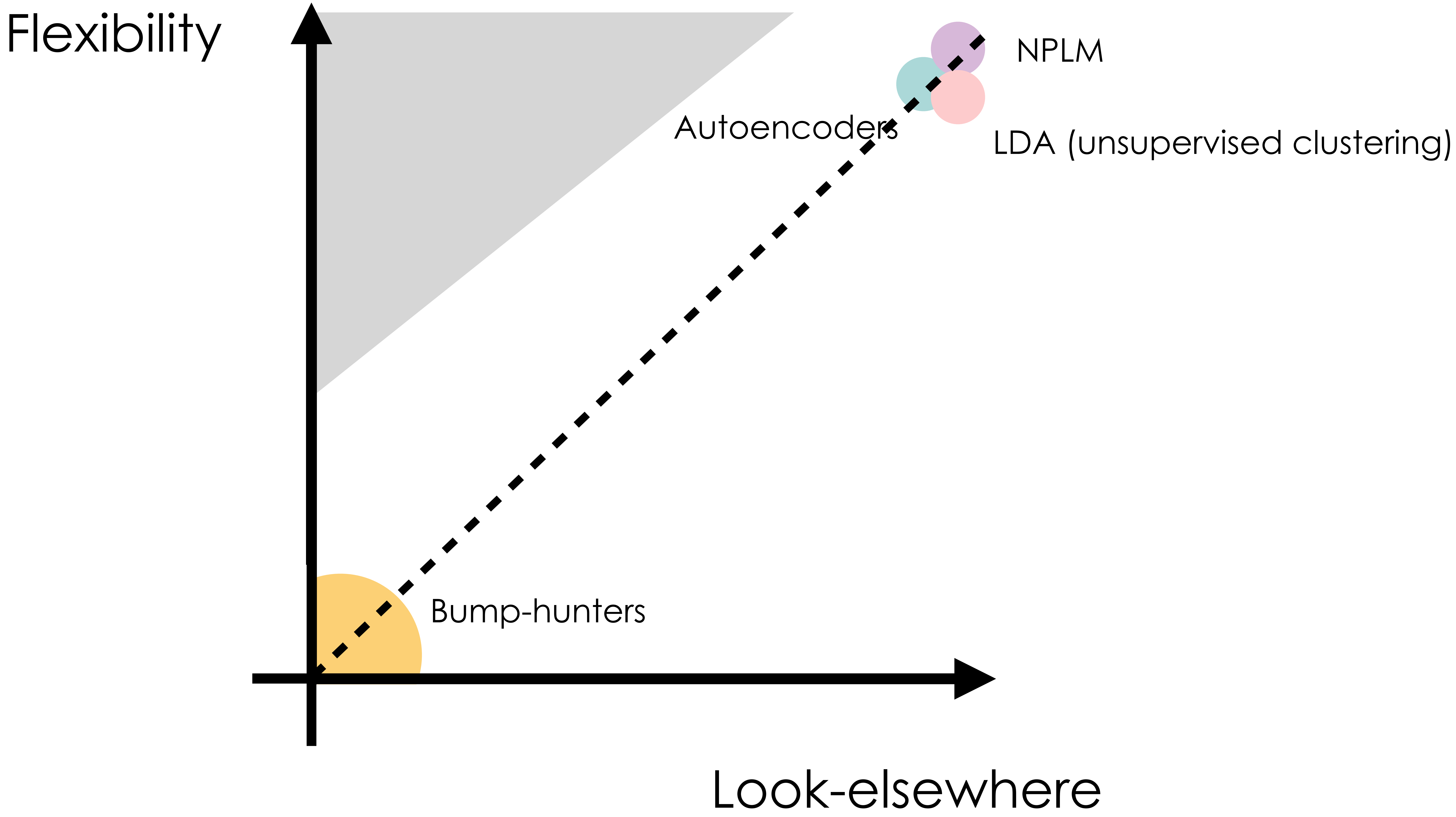
LOOK-ELSEWHERE EFFECT



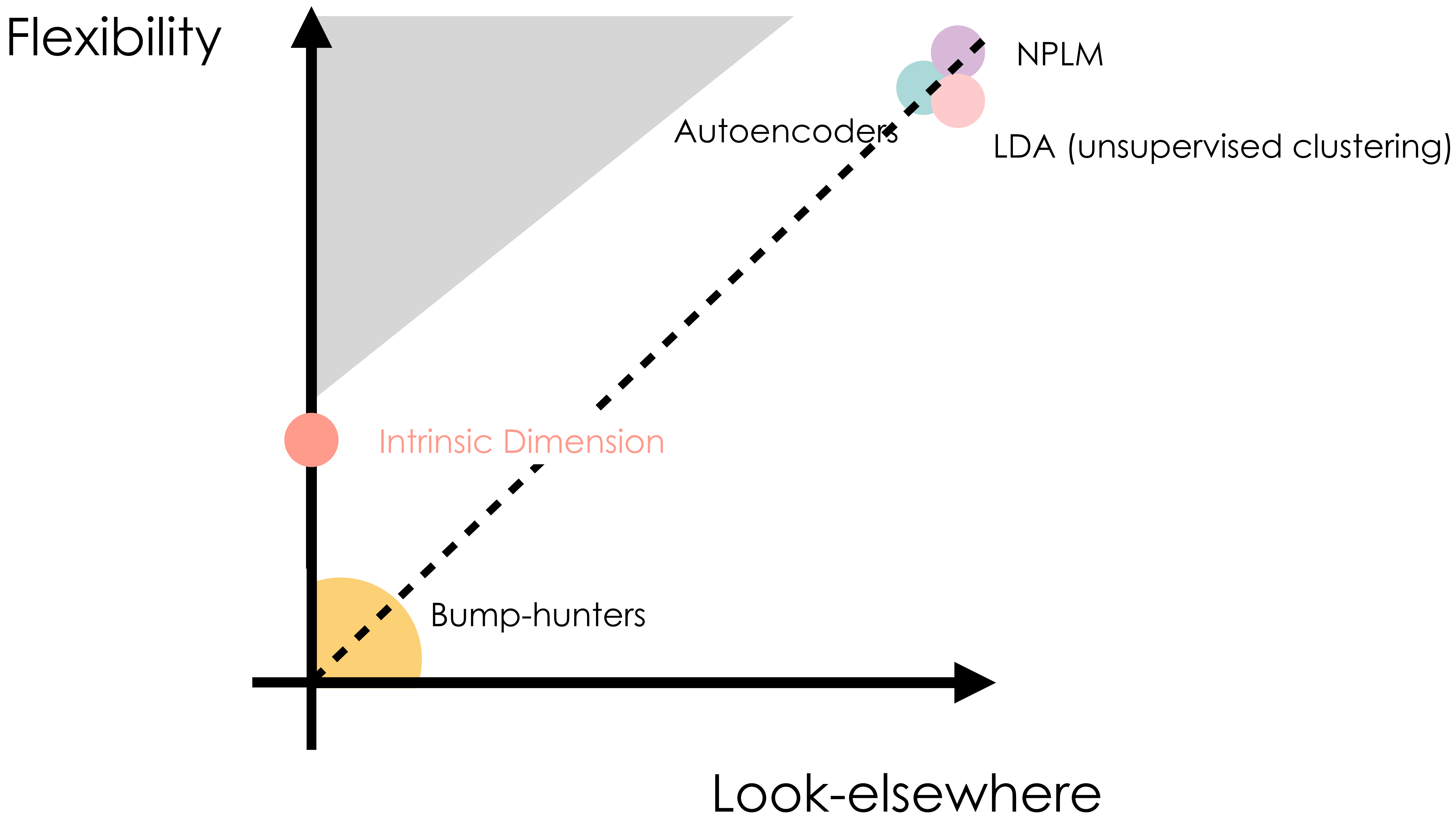
LOOK-ELSEWHERE EFFECT



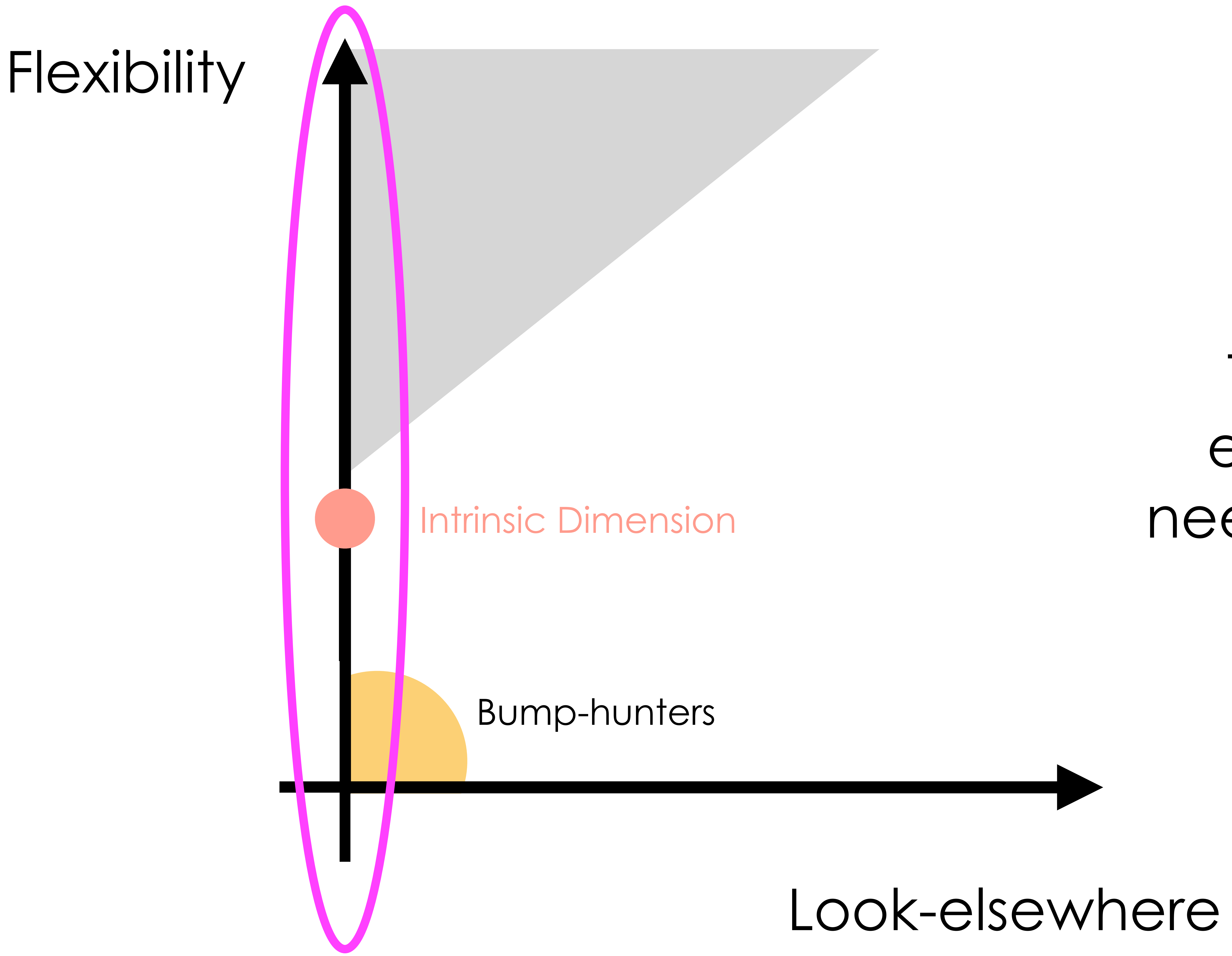
LOOK-ELSEWHERE EFFECT



LOOK-ELSEWHERE EFFECT



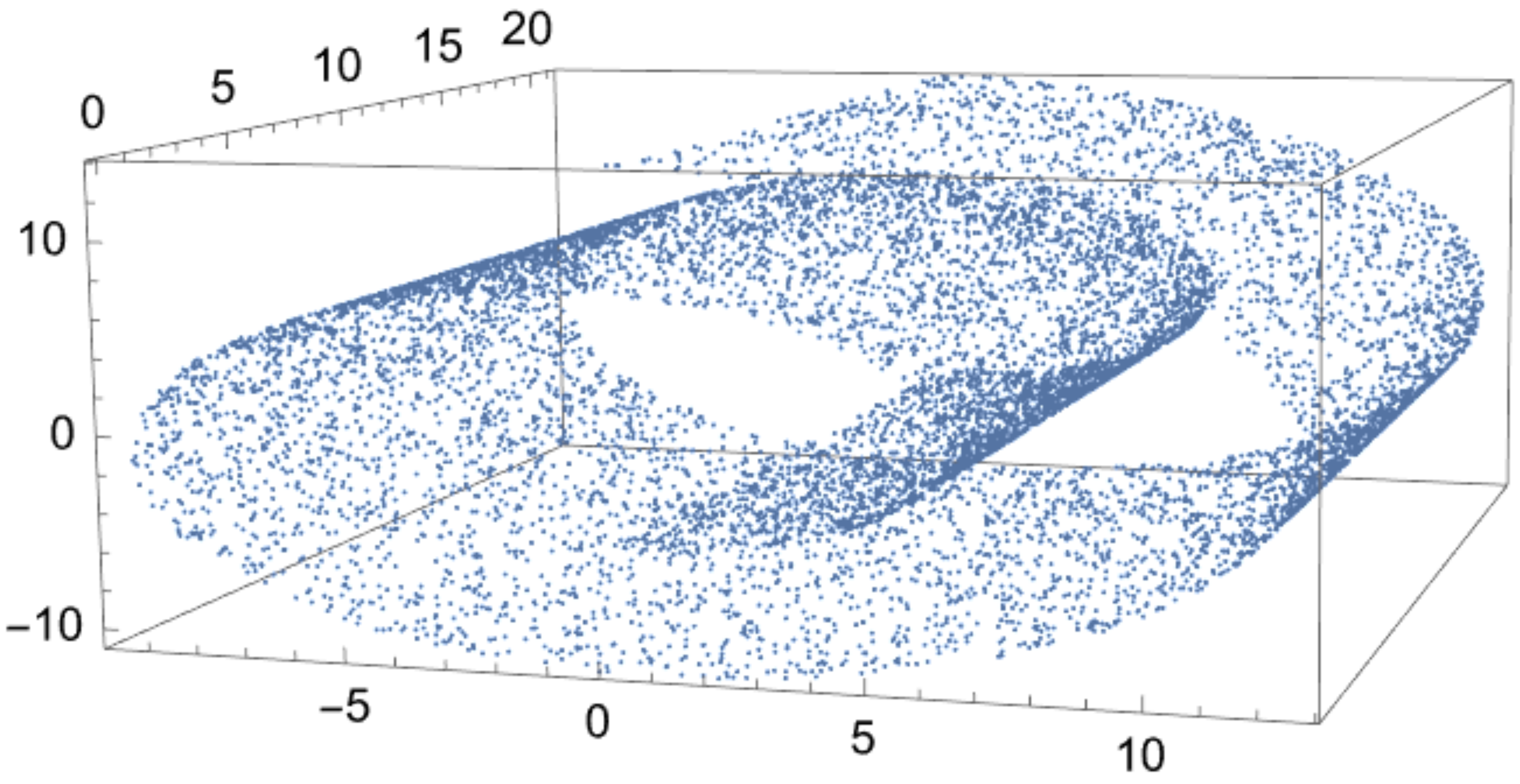
LOOK-ELSEWHERE EFFECT



To avoid a big look-elsewhere effect you need an analysis strategy independent of D

THE INTRINSIC DIMENSION OF COLLIDER EVENTS

INTRINSIC DIMENSION



Can you tell that D=2 just from the data?

INTRINSIC DIMENSION

r_i = Distance between reference point and its i-th nearest neighbor

INTRINSIC DIMENSION

$$\mu_{ij} \equiv \frac{r_j}{r_i}$$

INTRINSIC DIMENSION

$$\mu_{ij} \equiv \frac{r_j}{r_i} \longrightarrow$$

Under mild assumptions

the PDF can be derived analytically

INTRINSIC DIMENSION

$$\mu_{ij} \equiv \frac{r_j}{r_i} \quad \longrightarrow \quad f(\mu_{ij}) = \frac{D(\mu_{ij}^D - 1)^{j-i-1} \mu_{ij}^{-D(j-1)-1}}{B(j-i, i)}$$

INTRINSIC DIMENSION

1. Compute μ_{ij} for every point in your dataset
2. Use all values of μ_{ij} to compute its PDF
3. Fit for the intrinsic dimension

WHY?

1. First thing to do before any analysis

2. First thing to do before building any autoencoder

WHY?

3. As you vary i and j you are exploring non-trivial features of the kinematics

WHY?

$r_i =$ Earth Mover's Distance

[Komiske, Metodiev, Thaler '19]

3. As you vary i and j you are exploring non-trivial features of the kinematics

WHY?

3. As you vary i and j you are exploring non-trivial features of the kinematics

4. What is the dimension of a jet?

THE INTRINSIC DIMENSION AND NEW PHYSICS

[RTD, A. GLIOTI, G. RIGO, A. VALENTI, In preparation]

PRELIMINARY RESULTS

1. Test it on qualitative different signals

2. Check that the significance remains stable as we increase D

3. Test it at large D

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Robustness, systematics, ...

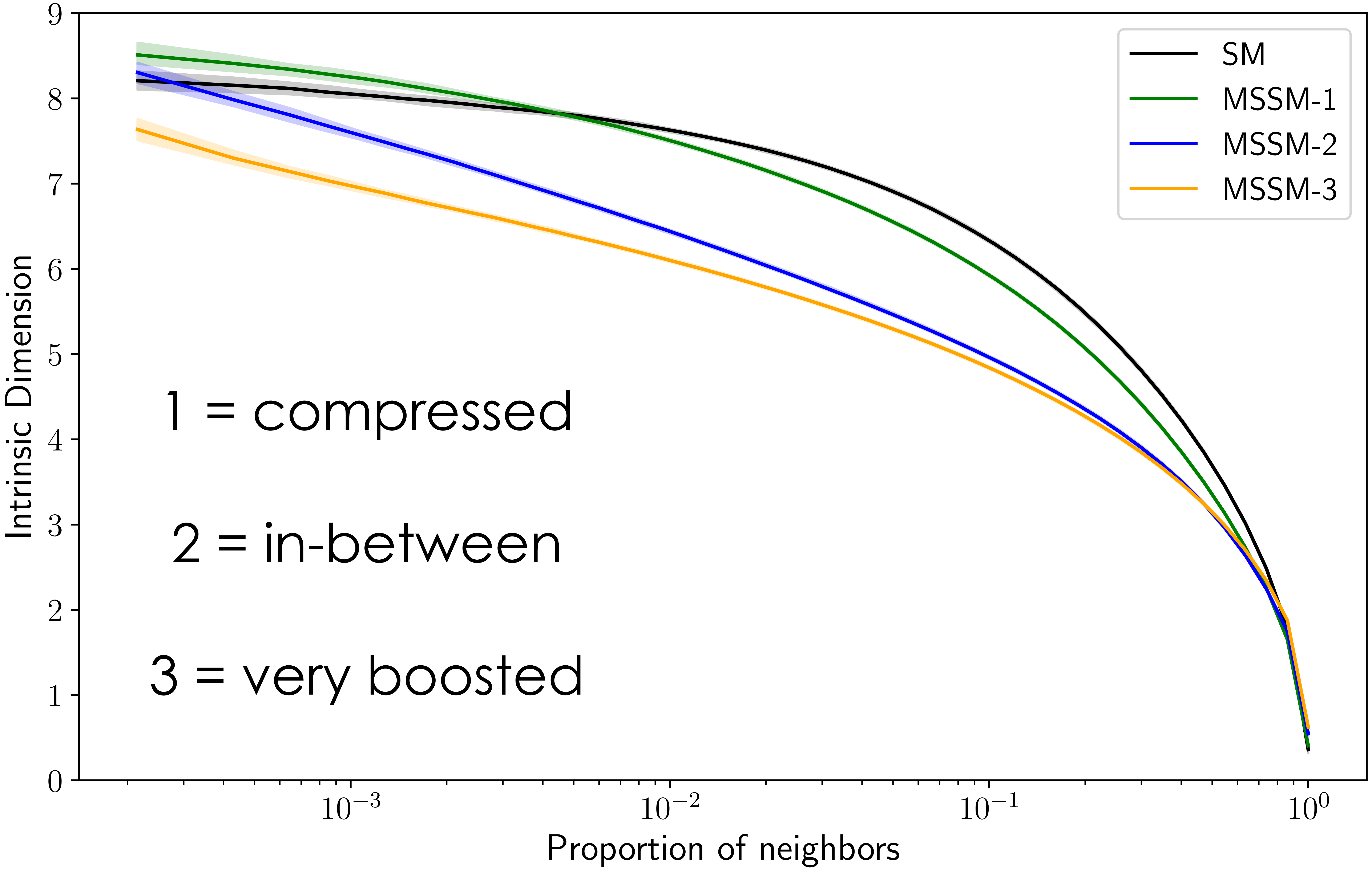

ALL VERY PRELIMINARY!

SIGNAL 1

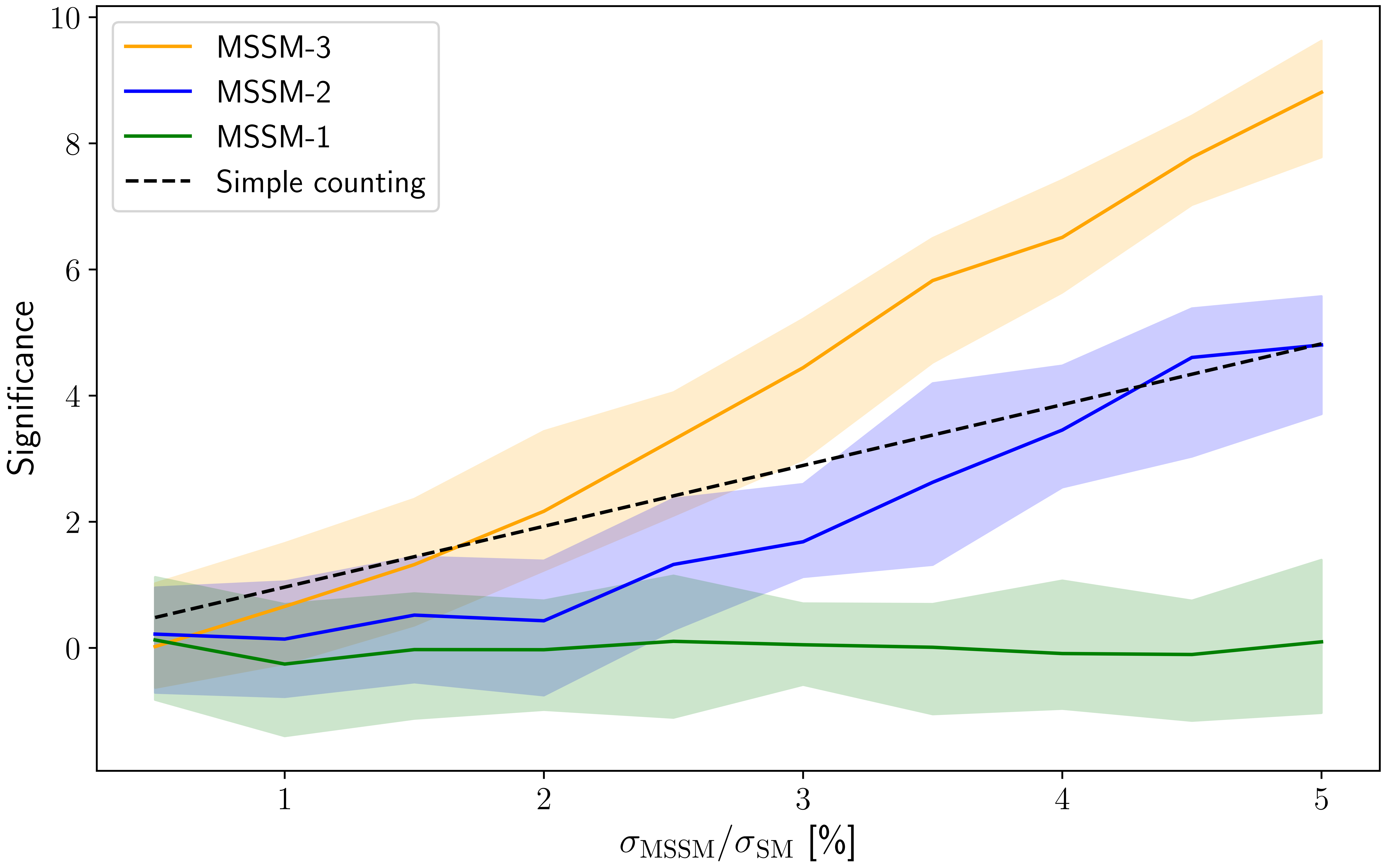
SM: $$pp \to W^+ Z \to \mu^+ \mu^- e^+ \nu_e$$

SIGNAL: $$pp \to \chi^+ \chi_2^0 \to W^+ Z \chi^0 \chi^0 \to \mu^+ \mu^- e^+ \nu_e \chi^0 \chi^0$$

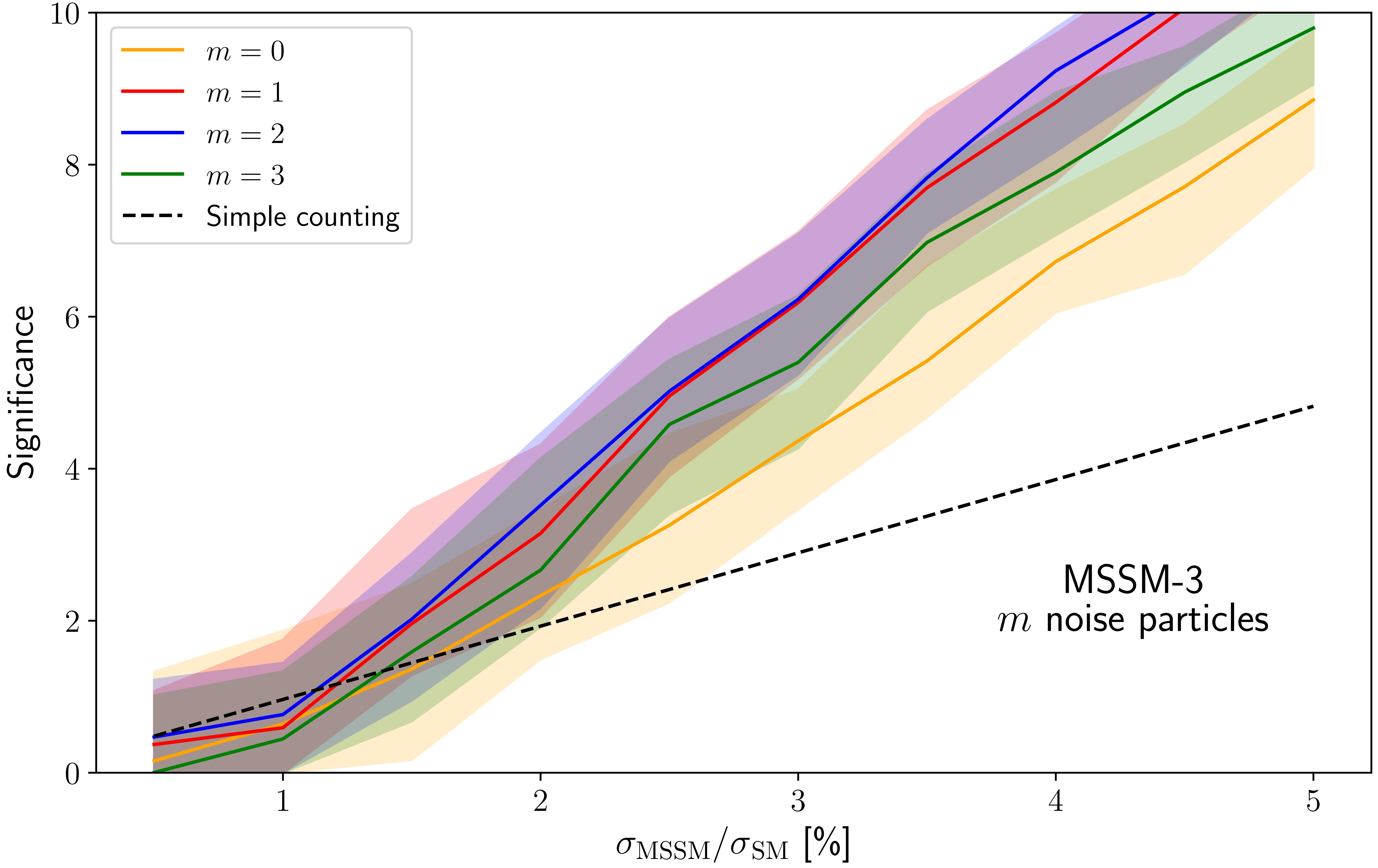
PRELIMINARY RESULTS, SIGNAL 1



PRELIMINARY RESULTS, SIGNAL 1



PRELIMINARY RESULTS, SIGNAL 1

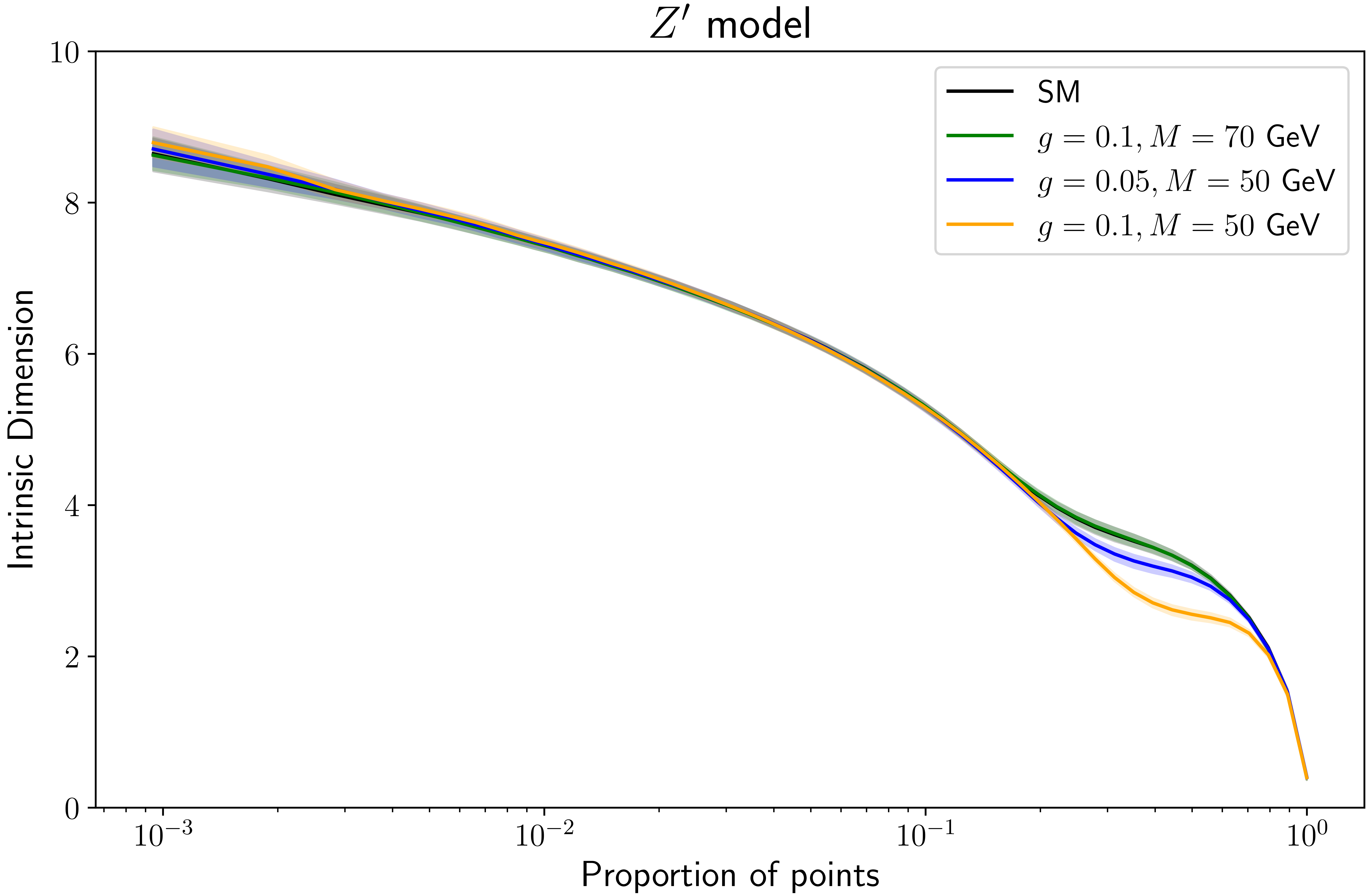


SIGNAL 2

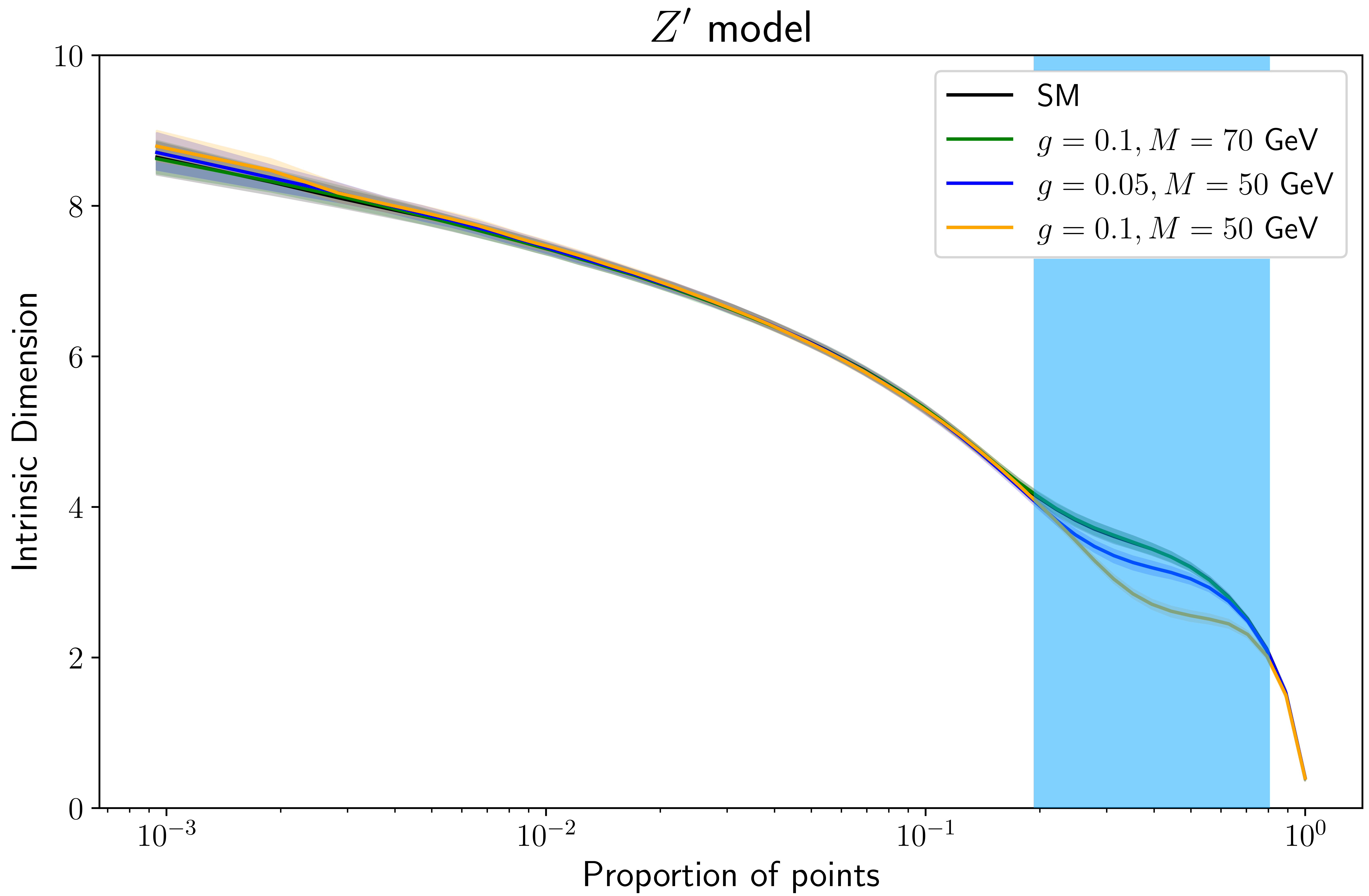
SM: $pp \to ZZ \to 4\mu$

SIGNAL: $pp \to Z \to \mu^+\mu^- Z_{L_\mu - L_\tau} \to 4\mu$

PRELIMINARY RESULTS, SIGNAL 2

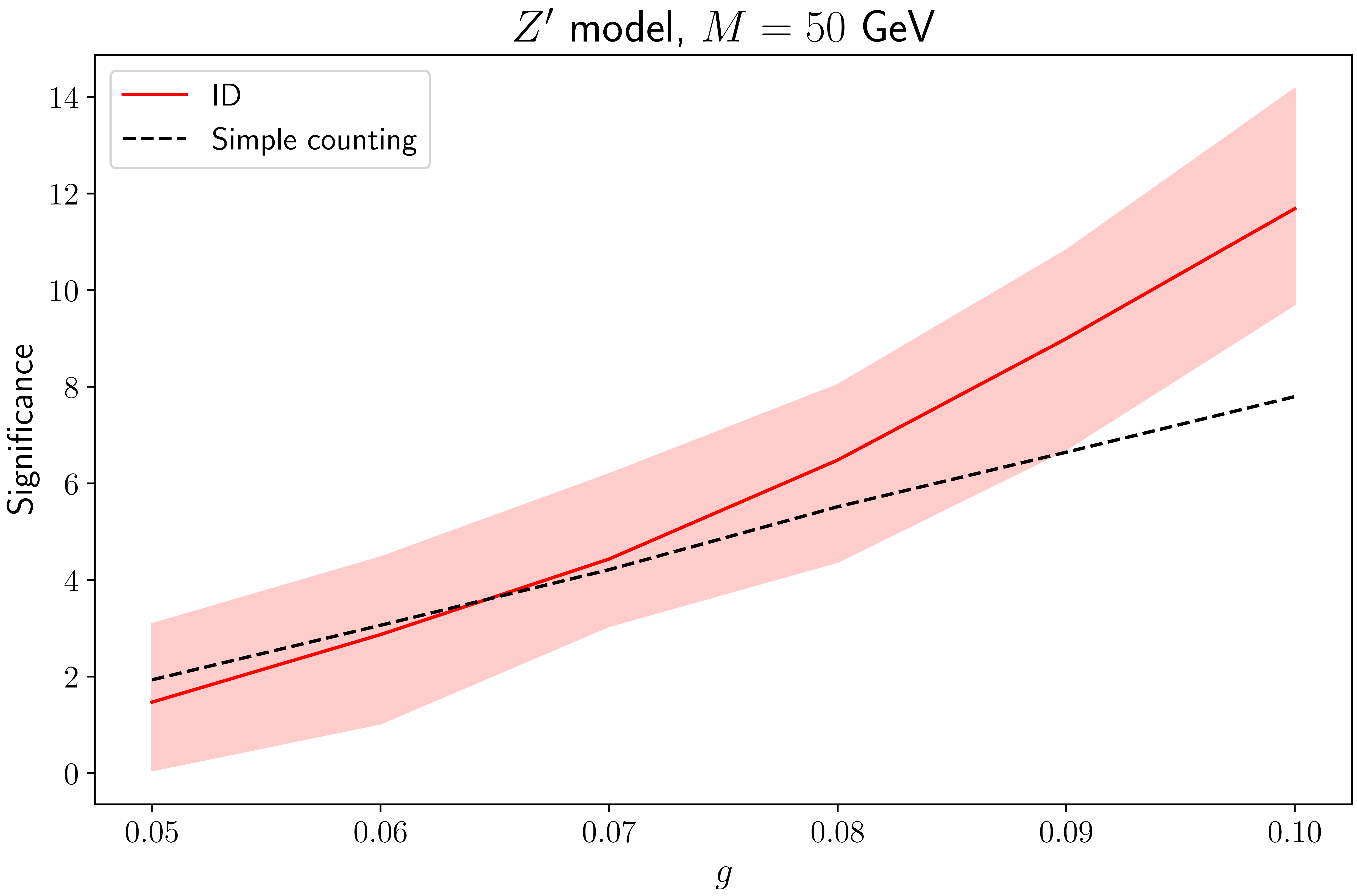


PRELIMINARY RESULTS, SIGNAL 2



$r \in [m_Z, 2m_Z]$

PRELIMINARY RESULTS, SIGNAL 2



SIGNAL 3

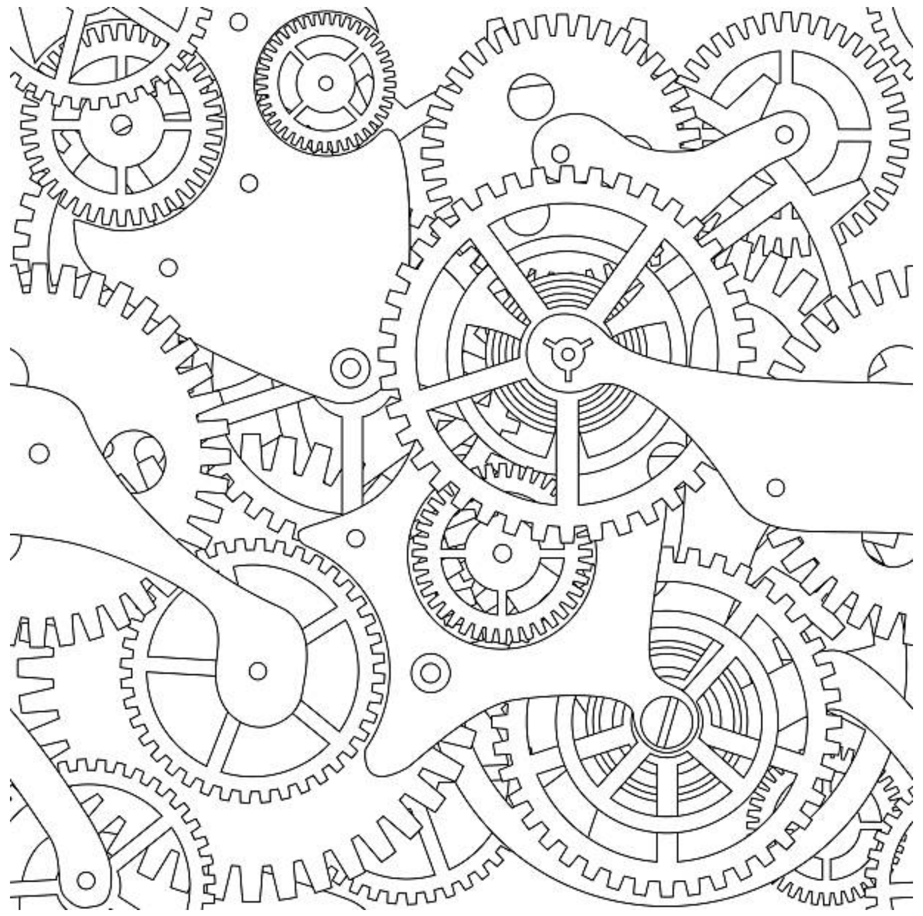
$$pp \to WZ \to \mu^+\mu^- jj$$

~ 100 particles per event

D = 400

SIGNAL 3

$$pp \to WZ \to \mu^+\mu^- jj$$



In progress, but looking promising

SO FAR WE HAVE IGNORED ONE PROBLEM

Raw data →

Old Physics →

Dr. Black Box

→ New Physics?

OLD PHYSICS

1. Use it on final states where the MC has been tested to death

2. Test for time variations in LHC data (DQM)

3. Test the exact and approximate symmetries of the Standard Model (CP, Lepton flavor, Lorentz, …)

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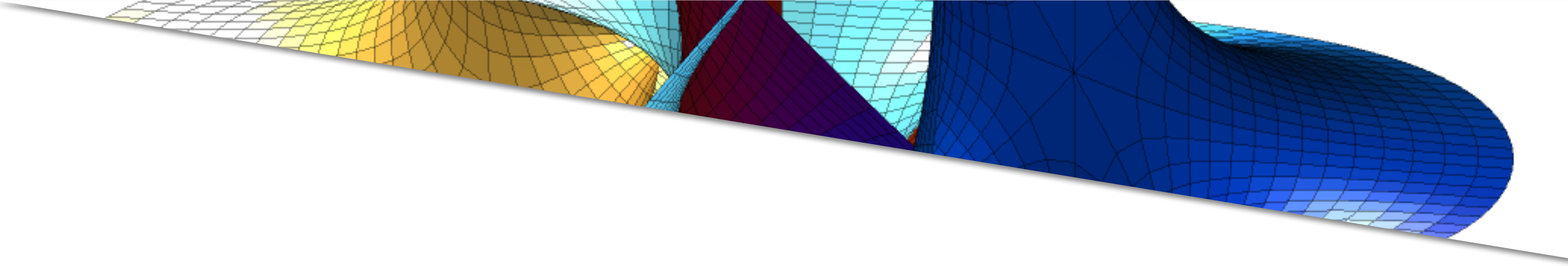


SAMPLE 1

All events with 1 electron

SAMPLE 2

All events with 1 muon

SOME MORE THEORY MOTIVATION FOR COLLIDERS

[Arkani-Hamed, RTD, Kim, '20]

Does anything change in Nature as we vary the Higgs mass squared?

$$\frac{d\log f(\langle h\rangle)}{d\log\langle h\rangle} = O(1)$$

Most relevant phenomenologically:

Physics coupled to the Higgs with

$$m \lesssim v$$

One trigger = **Many solutions** to the hierarchy problem

$$G\widetilde{G}$$

$$H_1 H_2$$

$$F\widetilde{F}$$

A BSM TRIGGER

[Arkani-Hamed, RTD, Kim, ’20]

$$\boxed{H_1 H_2}$$

Protected by the **Z2 symmetry**

$$\boxed{H_1 H_2 \to -H_1 H_2}$$

H1H2 **without Z2** first considered as ‘paleo’-trigger in: [Espinosa, Grojean,Panico, Pomarol, Pujolas ’15], [Dvali, Vilenkin ’01]. Today these models require **two coincidences of scales to be alive at the LHC**.

TYPE-0 2HDM

[Arkani-Hamed, RTD, Kim, '20]

$$\boxed{m_{A,H^\pm}^2 \sim \lambda v^2, \quad \lambda \lesssim 2}$$

$$\boxed{m_H^2 \sim \lambda_1 v_1^2 \leq m_h^2 = (125\ \mathrm{GeV})^2}$$

TYPE-0 2HDM
[Arkani-Hamed, RTD, Kim, '20]

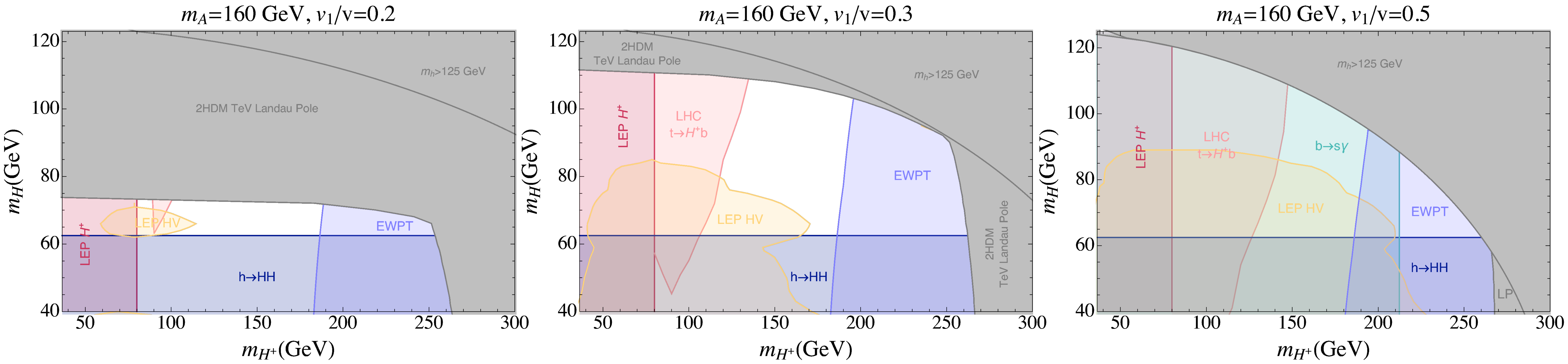
For quarks and leptons we choose the **phenomenologically safest Z2 charge assignments**

$$H_2 \to -H_2, \quad (qu^c) \to -(qu^c), \quad (qd^c) \to -(qd^c), \quad (le^c) \to -(le^c)$$

This gives

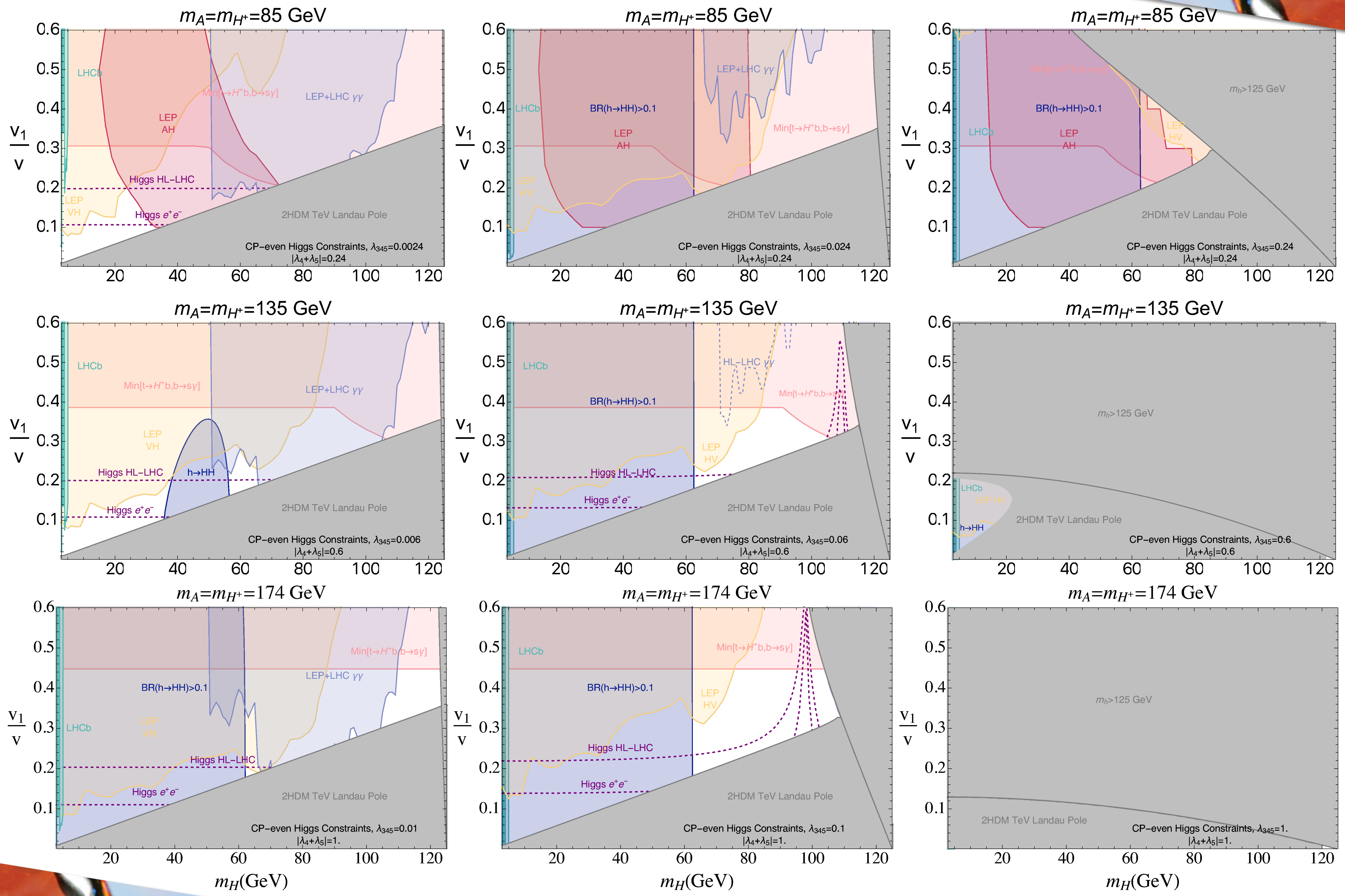
$$\boxed{V_Y = Y_u q H_2 u^c + Y_d q H_2^\dagger d^c + Y_e l H_2^\dagger e^c}$$

TYPE-0 2HDM
[Arkani-Hamed, RTD, Kim, '20]



Sharp target for HL-LHC and FCC
which **can't be decoupled**!
(See also the next slide)

TYPE-0 2HDM



$m_A=m_{H^+}$=85 GeV
$m_A=m_{H^+}$=135 GeV
$m_A=m_{H^+}$=174 GeV
$\frac{v_1}{v}$
m_H(GeV)
LHCb
LEP AH
LEP VH
LEP HV
LEP+LHC $\gamma\gamma$
HL-LHC $\gamma\gamma$
Min[t→H^+b,b→sγ]
Higgs HL-LHC
Higgs e^+e^-
BR(h→HH)>0.1
h→HH
m_h>125 GeV
2HDM TeV Landau Pole
CP-even Higgs Constraints, λ_{345}=0.0024
CP-even Higgs Constraints, λ_{345}=0.024
CP-even Higgs Constraints, λ_{345}=0.24
$|\lambda_4+\lambda_5|$=0.24
CP-even Higgs Constraints, λ_{345}=0.006
CP-even Higgs Constraints, λ_{345}=0.06
CP-even Higgs Constraints, λ_{345}=0.6
$|\lambda_4+\lambda_5|$=0.6
CP-even Higgs Constraints, λ_{345}=0.01
CP-even Higgs Constraints, λ_{345}=0.1
CP-even Higgs Constraints, λ_{345}=1.
$|\lambda_4+\lambda_5|$=1.

New vector-like leptons

+

Dark confining gauge group

$$\mathcal{L} \supset -m_L L L^c - m_N N N^c - y L H N^c - y^c L^c H N + \text{h.c.} - \frac{\phi}{32\pi^2 f} F\widetilde{F}$$

CONCLUSION

1. What is going on with the Higgs mass? **We don't know**

2. We have been creative theoretically, but maybe it's still not enough

3. We have been conservative experimentally, and it's time to go wild

BACKUP

SIGNAL BENCHMARKS

- MSSM-1: N1 = 150 GeV, N2/chi1+ = 250 GeV
- MSSM-2: N1 = 150 GeV, N2/chi1+ = 500 GeV
- MSSM-3: N1 = 150 GeV, N2/chi1+ = 1000 GeV

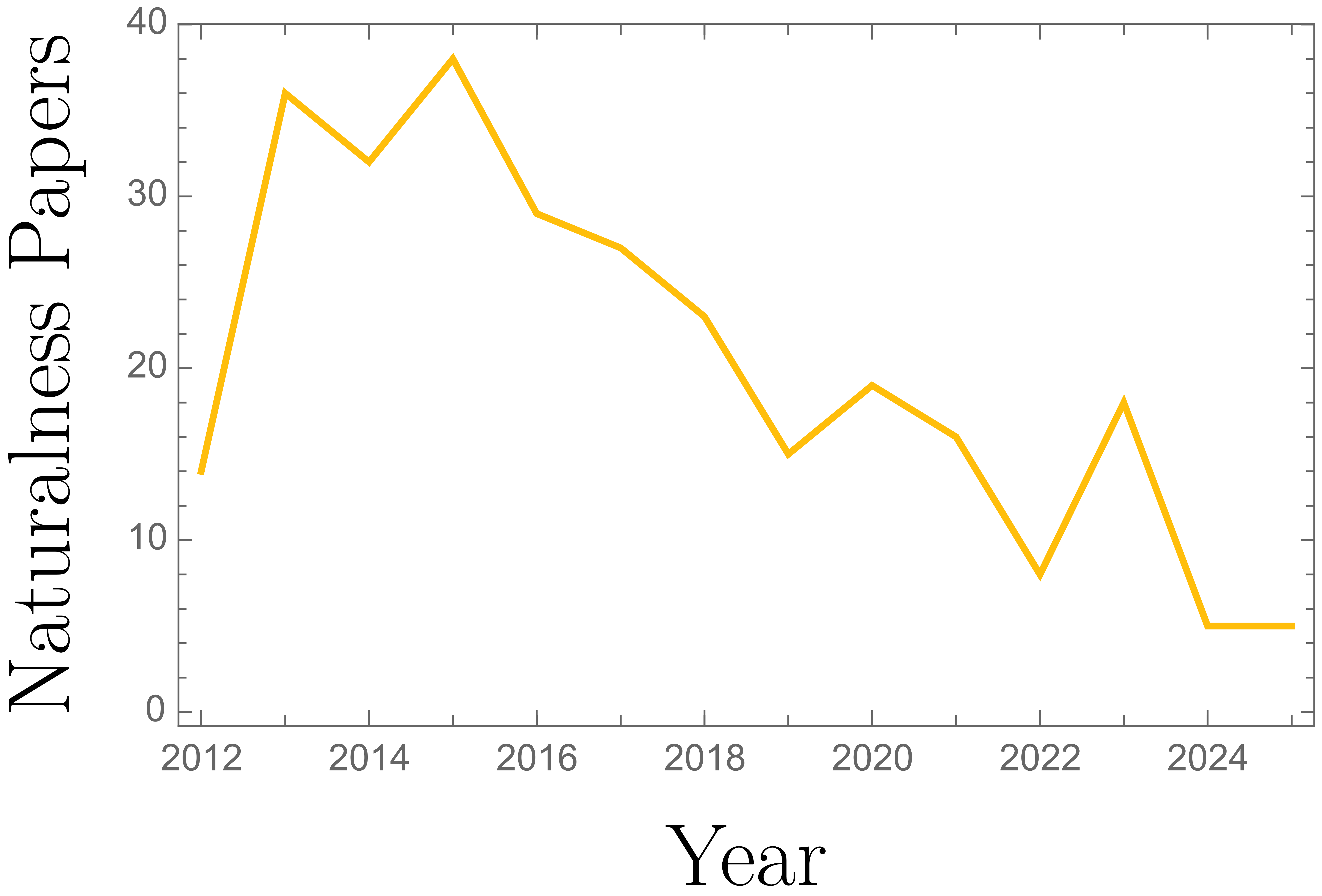
WHY THE HIGGS MASS?

1. Symmetry plus a bit of tuning
2. There is no mass scale beyond the SM [1305.6939]
3. The Higgs mass is an input
4. UV/IR Mixing [1909.01365]
5. Swampland on steroids
6. There is a landscape
7. ...

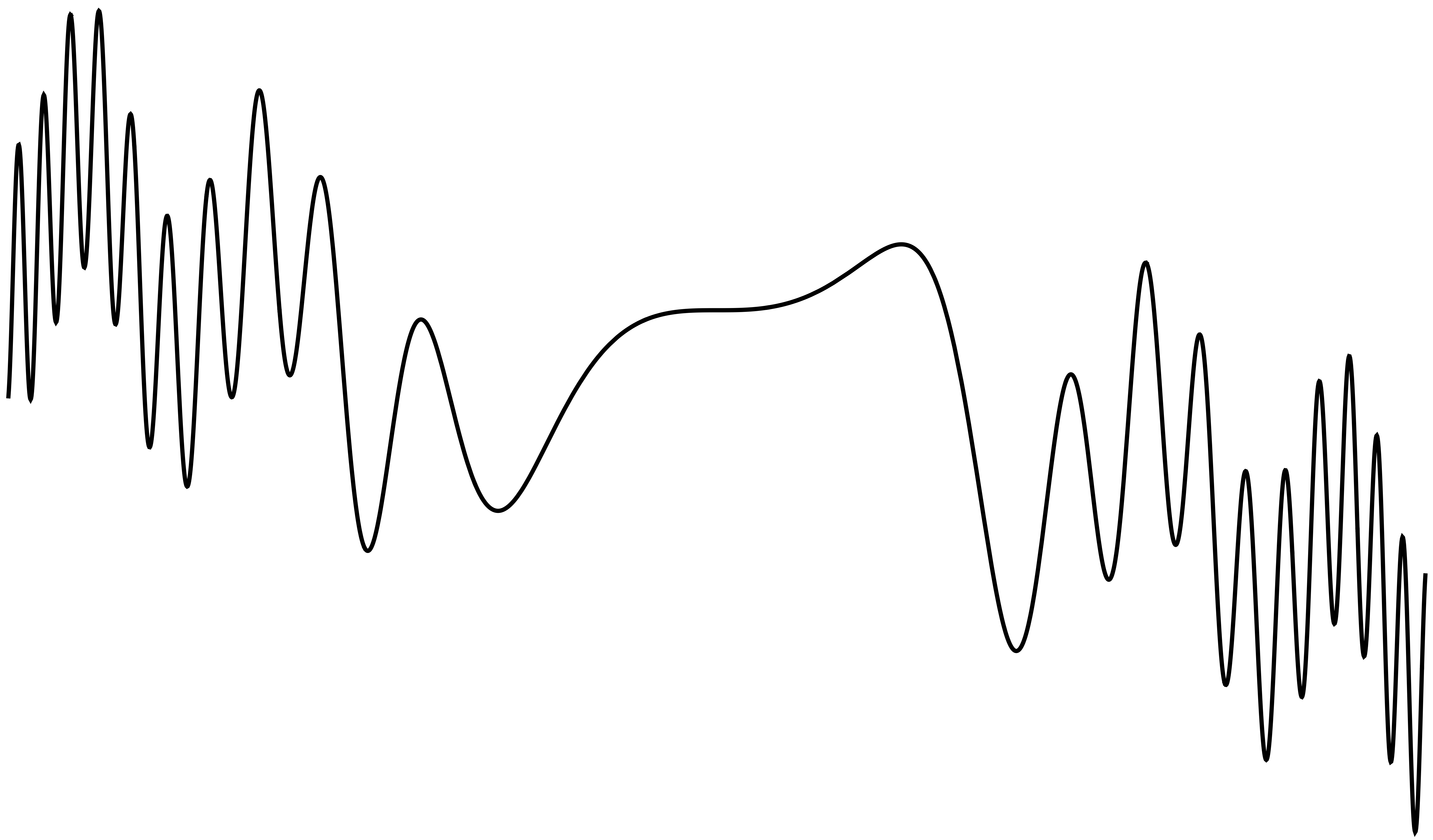
LES HOUCHES POLL '23

1. Symmetry plus a bit of tuning 95%
2. There is no mass scale beyond the SM [1305.6939]
3. The Higgs mass is an input
4. UV/IR Mixing [1909.01365]
5. Swampland on steroids
6. There is a landscape
7. 5% ...

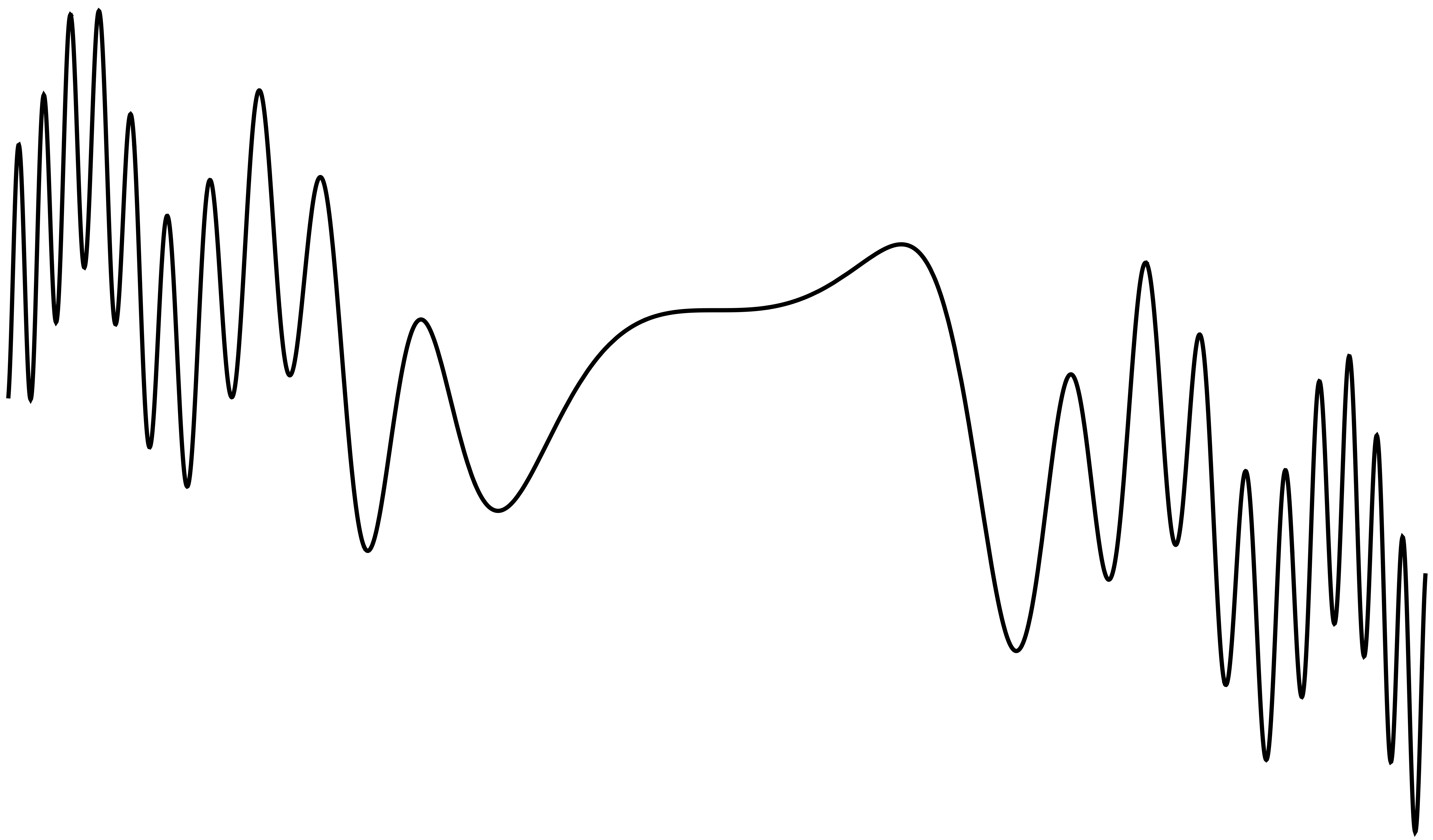
From Inspire HEP



LANDSCAPES AT COLLIDERS



Currently our most concrete explanation for the cosmological constant

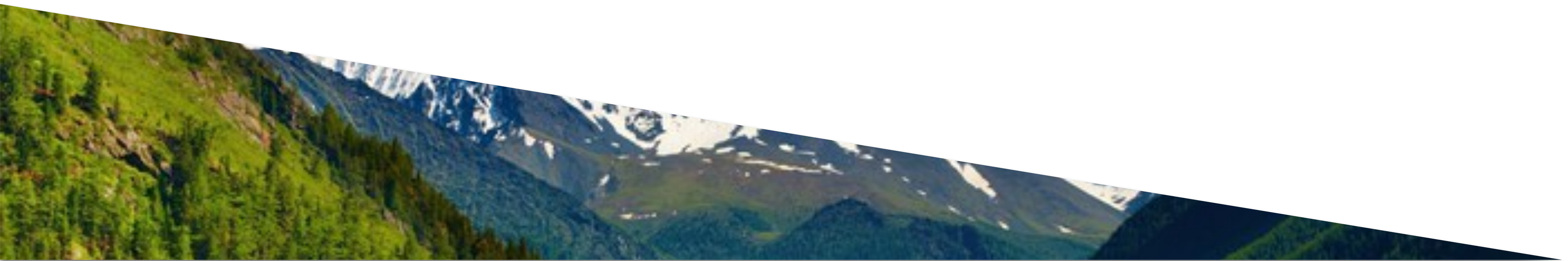


Where are the minima?

They could all be at the Planck scale

M_{Pl}

H



They could all be at the Planck scale, however…

$M_{\rm Pl}$

H

$\phi_1, \phi_2, \ldots, \phi_N$

They could all be at the Planck scale, however…

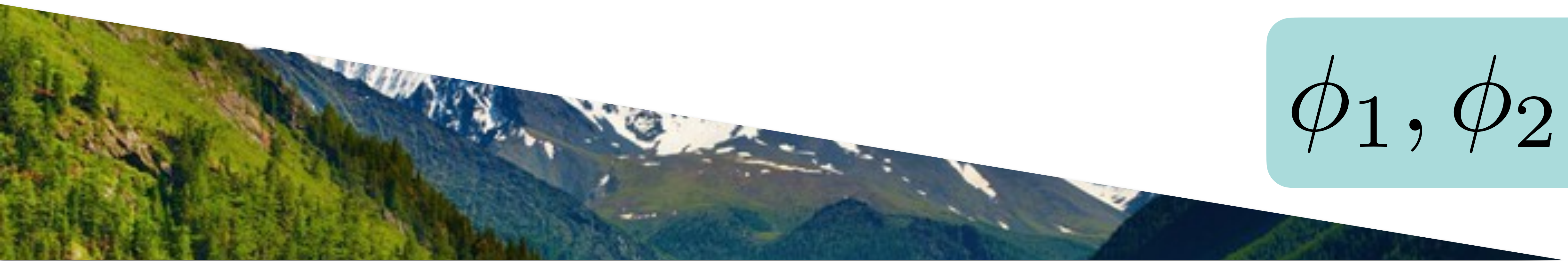
M_{Pl}

H

$\phi_1, \phi_2, \ldots, \phi_N$

Weak Scale as a Trigger

N. Arkani-Hamed, RTD, H. Kim



They could all be at the Planck scale, however…

M_{Pl}

H

$\phi_1, \phi_2, \ldots, \phi_N$

In preparation

RTD, M. Ettengruber, L. Wang