The New-Physics Landscape of HL-LHC

ECFA HL-LHC Workshop
Aix-Les-Bains
Monday 3rd Oct, 2016

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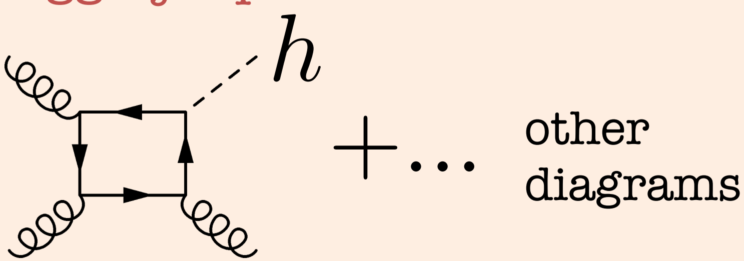
CERN

New Physics at HL-LHC.

HL-LHC would perform many measurements in phase/signal space inaccessible to 300 fb^{-1} LHC.

Higgs Production

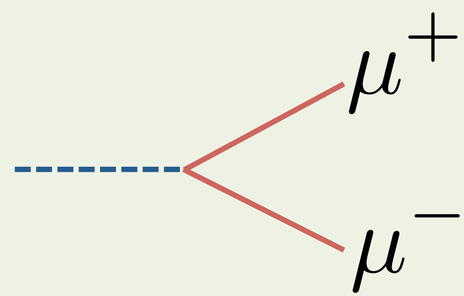
Higgs+jet production



Would occur at Higgs p_T's as large as 1.9 TeV!

Higgs Decays

Higgs coupling to muons



Would be measured to 7%.

Unexplored territory, hence new physics measurements. I'm supposed to talk about another type of new physics...

Goals for this talk.

- Anticipating BSM in coming decades…

Hierarchy problem.

Dark matter.

The unexpected.

- These puzzles have not gone away. Rather, they are more pressing than ever.

- At the time of operation, the HL-LHC will be the only high energy collider equipped to tackle these fundamental questions.

Goals for this talk.

- Anticipating BSM in coming decades…

Hierarchy problem.

Dark matter.

The unexpected.

- Assessing interplay between HL-LHC experiments and theoretical advances…

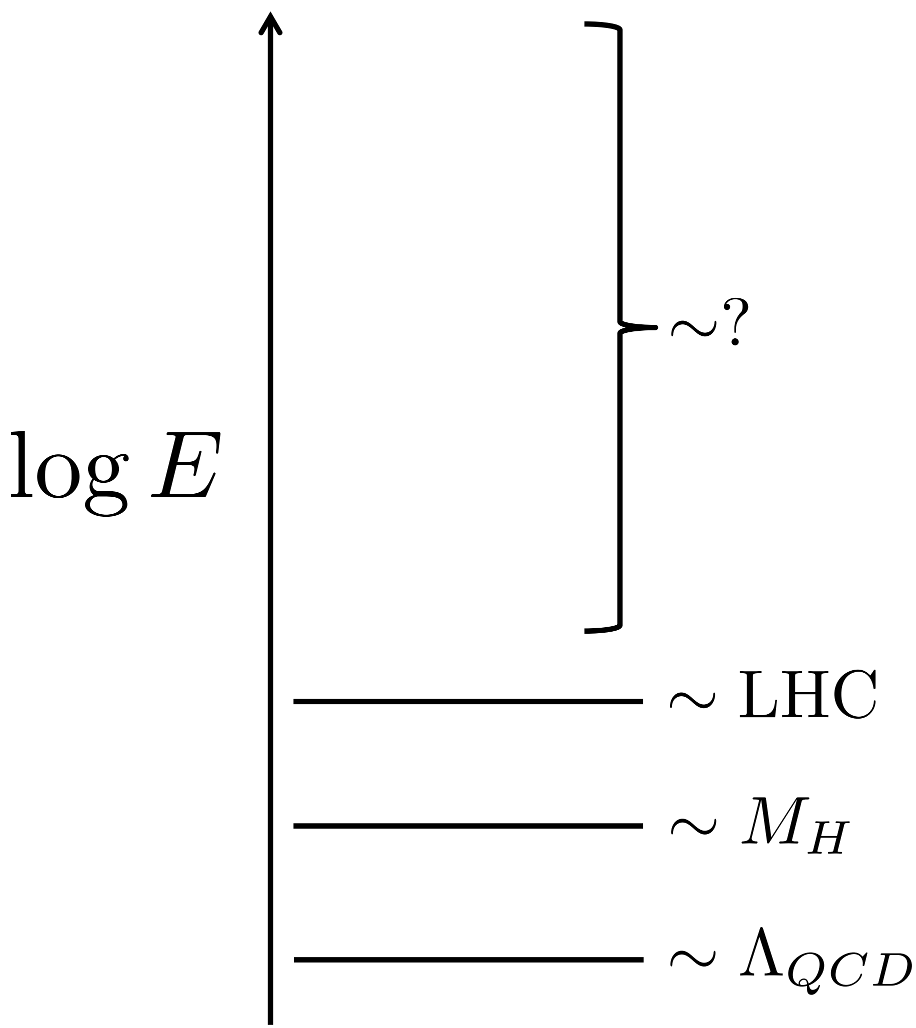
Low BGs/
Rare events.

Soft signals.

Low systematics/
High precision

- Highlighting driving experimental or theory challenges and opportunities.

Looking to the sky.

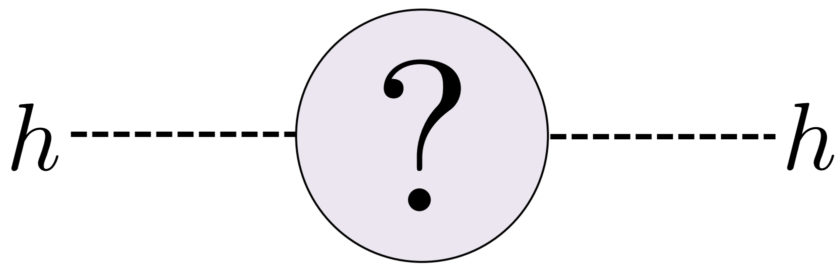


We do not know what new physics lies above, but we have hints...

- Neutrino masses
  $$M_N \gtrsim 10^{10}\ \text{GeV}$$
- Strong CP
  $$M_{\text{PQ}} \gtrsim 10^{10}\ \text{GeV}$$
- Unification?
  $$M_{\text{GUT}} \sim 10^{15}\ \text{GeV}$$
- Quantum gravity
  $$M_P = 2 \times 10^{18}\ \text{GeV}$$
- Hypercharge Landau pole
  $$M_{\Lambda_Y} \gg M_P$$

Looking to the sky.

This has implications at the weak scale...



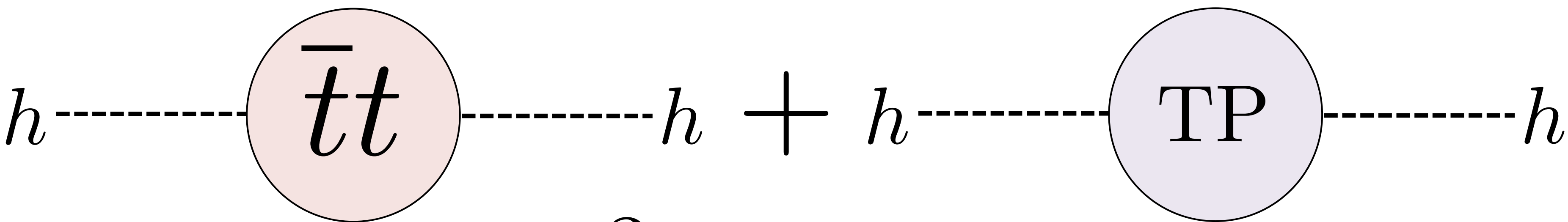
At quantum level, new physics will correct Higgs mass, pulling it up to $m_h \sim \Lambda$.

Should expect $m_H \sim \Lambda$. But I just argued $\Lambda \gg M_W$ so how can we reconcile with

$$m_h = 125 \text{ GeV } ?$$

Generic Expectations

Solutions typically involve a “Top Partner”:



$$\approx \frac{3}{8\pi^2} m_{TP}^2 \log \Lambda$$

If top partner is near the weak scale, Higgs mass corrections logarithmically sensitive to new physics scales, hence naturally light Higgs.

For naturalness expect $m_{TP} \lesssim 400 \text{ GeV}$.

Supersymmetry

Supersymmetry extends SM fields to superfields, thus requiring a top partner:

$$\mathbf{t} = \tilde{t} + \sqrt{2}\theta \cdot t + \theta^2 F_t$$

Top Partner
Stop Squark

Top Quark

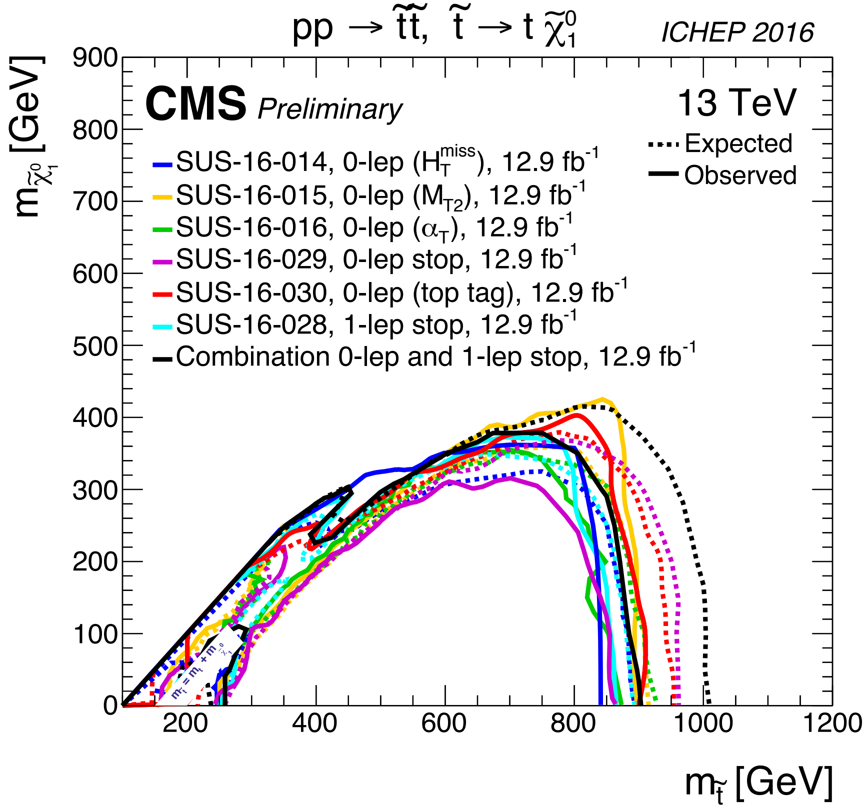
With interactions such as

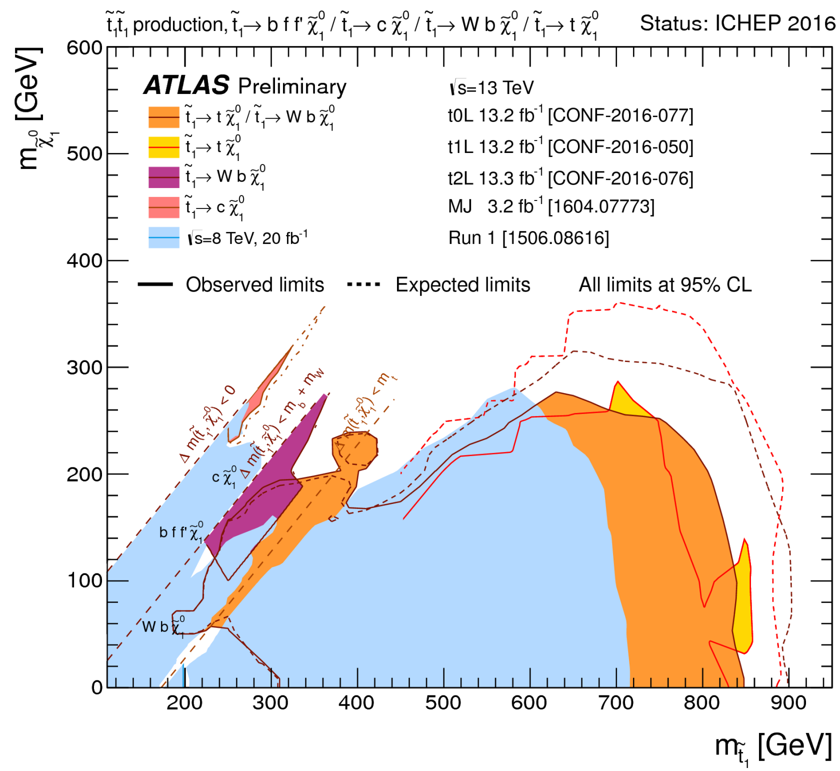
$$\mathcal{L} \sim \lambda_t h t_L t_R + h.c. + \frac{\lambda_t^2}{2} h^2 \left(|\tilde{t}_L|^2 + |\tilde{t}_R|^2 \right)$$

And $\mathcal{L} \sim \tilde{t}^c t \cdot \chi^0$ which enables decays.

Supersymmetry

BSM searches in third generation go right for the jugular of SUSY naturalness:

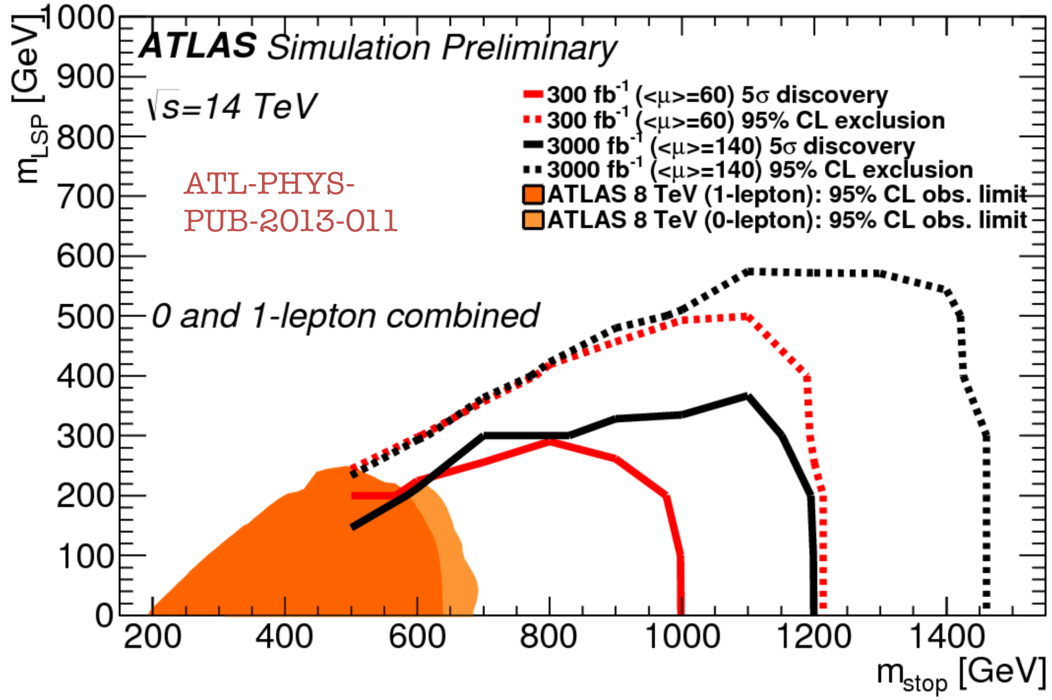




Already considerable pressure on SUSY naturalness…

Supersymmetry

HL-LHC will push the boundaries of natural theories even further:



Theoretical, including scale, uncertainties in modeling of QCD and EW backgrounds is a limiting factor here.

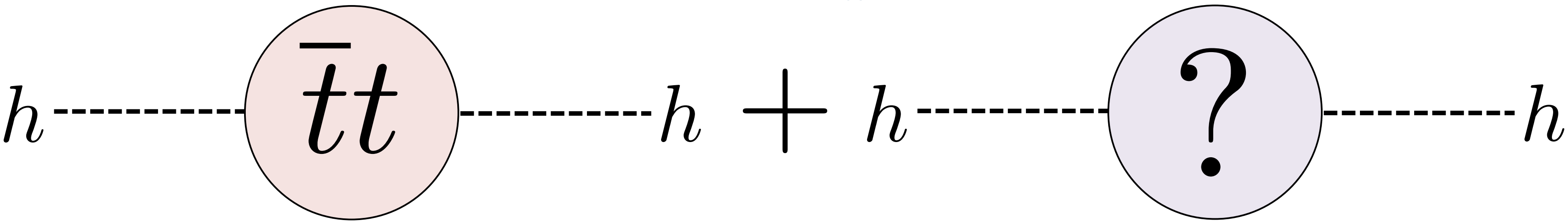
Progress in theoretical SM calculations

Loops. Substructure. Event Gen. Logs.

will be critical to maximize territory explored.

New Ideas in Naturalness

Could there be a hidden "Top Partner"?

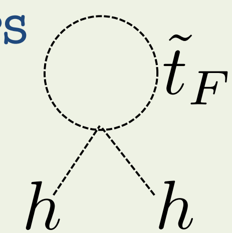


Much attention now to alternative ideas:

Folded SUSY

hep-ph/0609152

Theory where EW-charged uncoloured scalars are top partners



"Folded Stops"

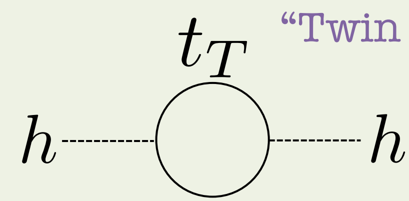
...but they must be charged under new hidden QCD'.

Twin Higgs

hep-ph/0506256

Theory where top partners are SM gauge neutral fermions

"Twin Tops"

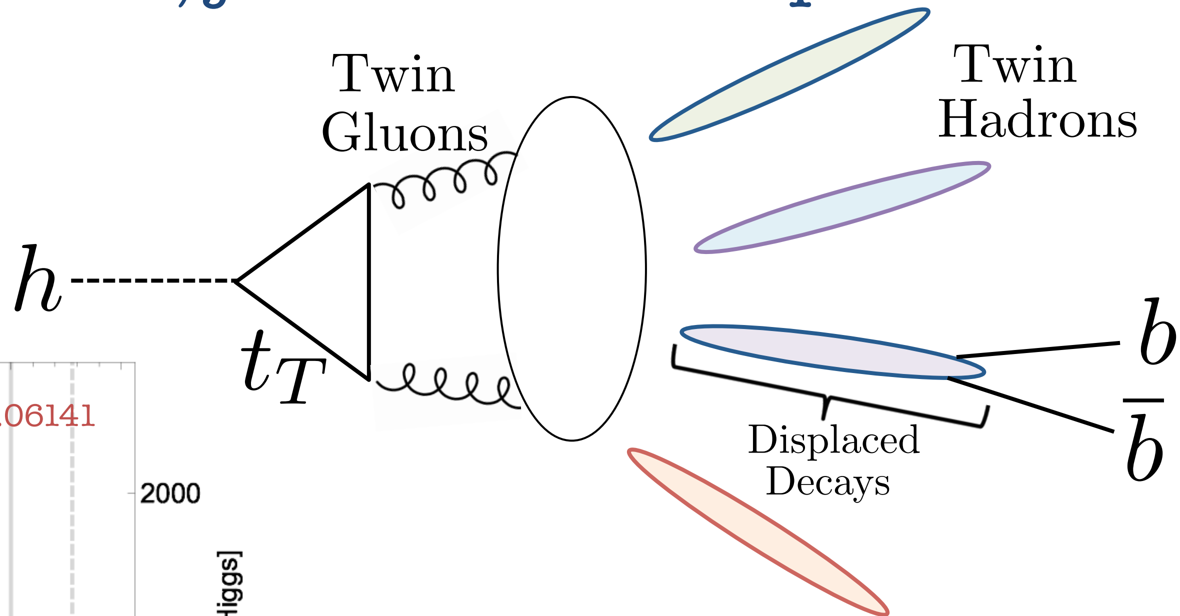


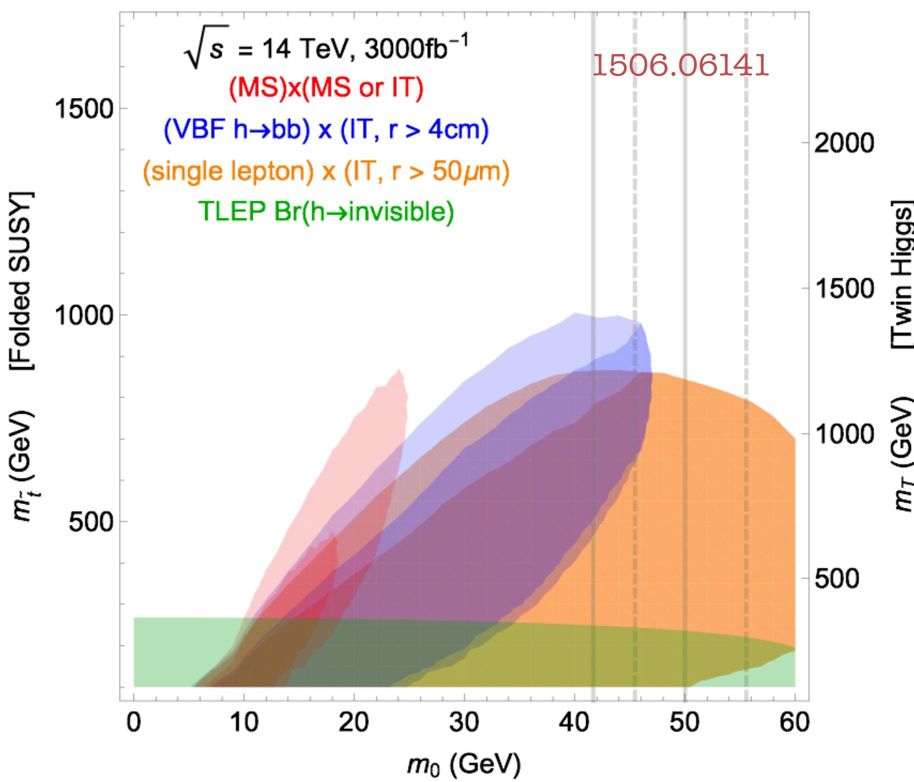
...but they must be charged under new hidden QCD'.

Neutral Naturalness

Naturalness not hidden, just look in new places...

New hidden sector introduces exotic Higgs decays:

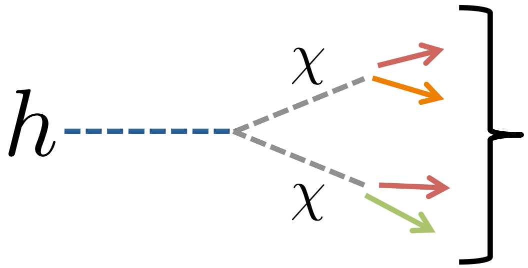




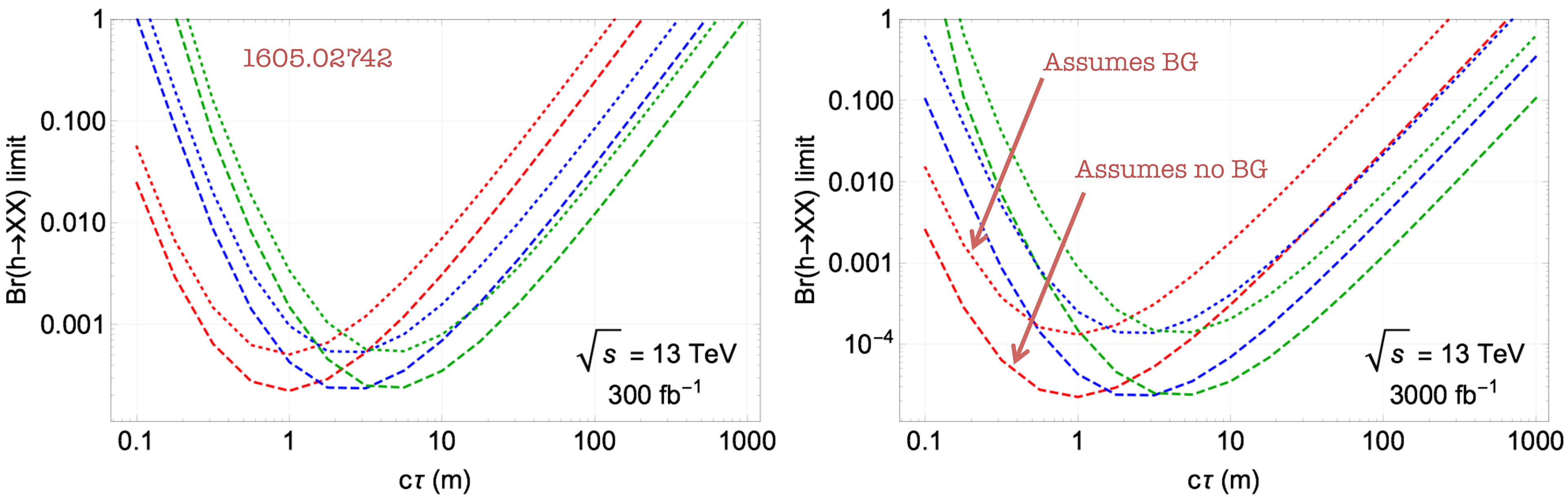
One striking signature these models motivate is displaced vertices, which may also be quite soft.

The Unexpected

Exotic Higgs decays provide a signature “standard candle”



$m_\chi = 10, 25, 40.\ \mathrm{GeV}$



As expected, reach scaling well with luminosity!

The Unexpected

Long-lived particles come up in many models.

Many exciting and creative ideas on the theoretical front…

- …
- Hidden Valleys
- Baryogenesis
- Mini-Split
- Neutrino Masses
- Neutral Naturalness
- RPV
- RHD Neutrinos

The Unexpected

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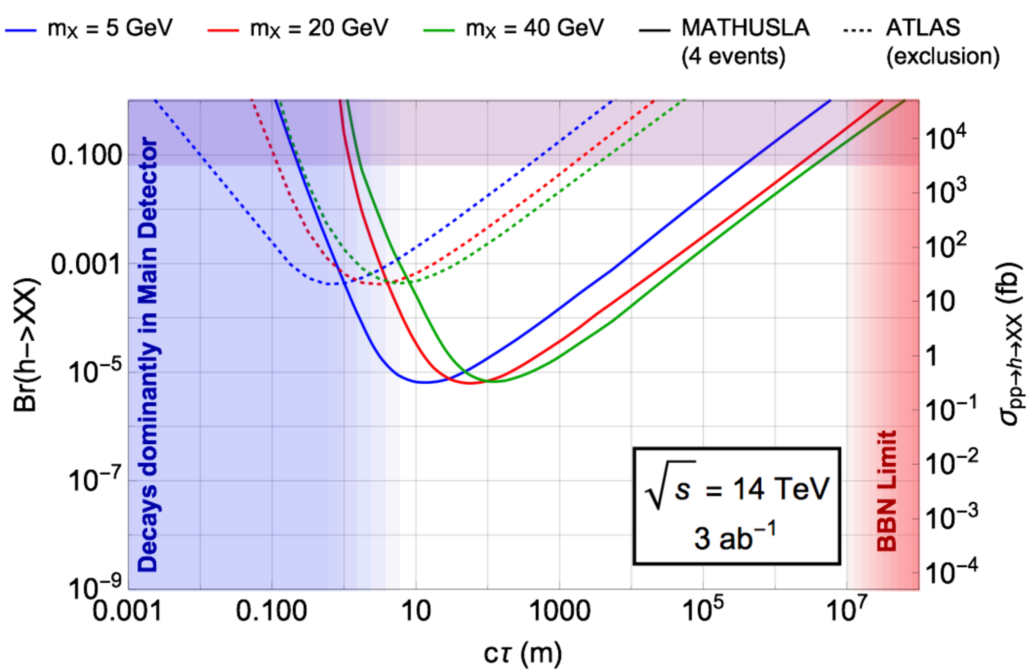
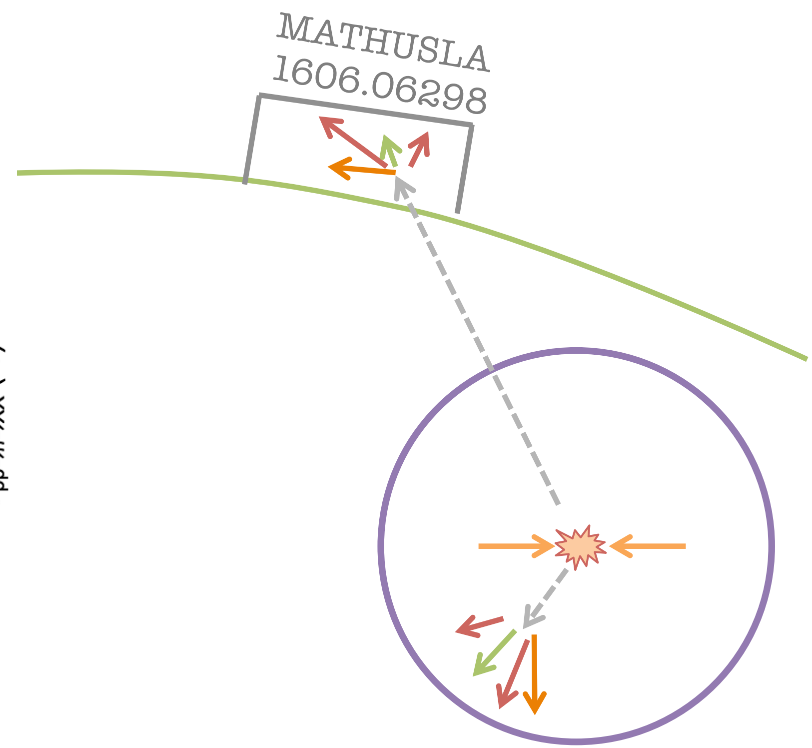
Many exciting and creative ideas on the theoretical front…



Projection based on 1606.06298.

and the detection front…



to extend reach by several orders of magnitude!

Dark Matters

Evidence for dark matter is now overwhelming

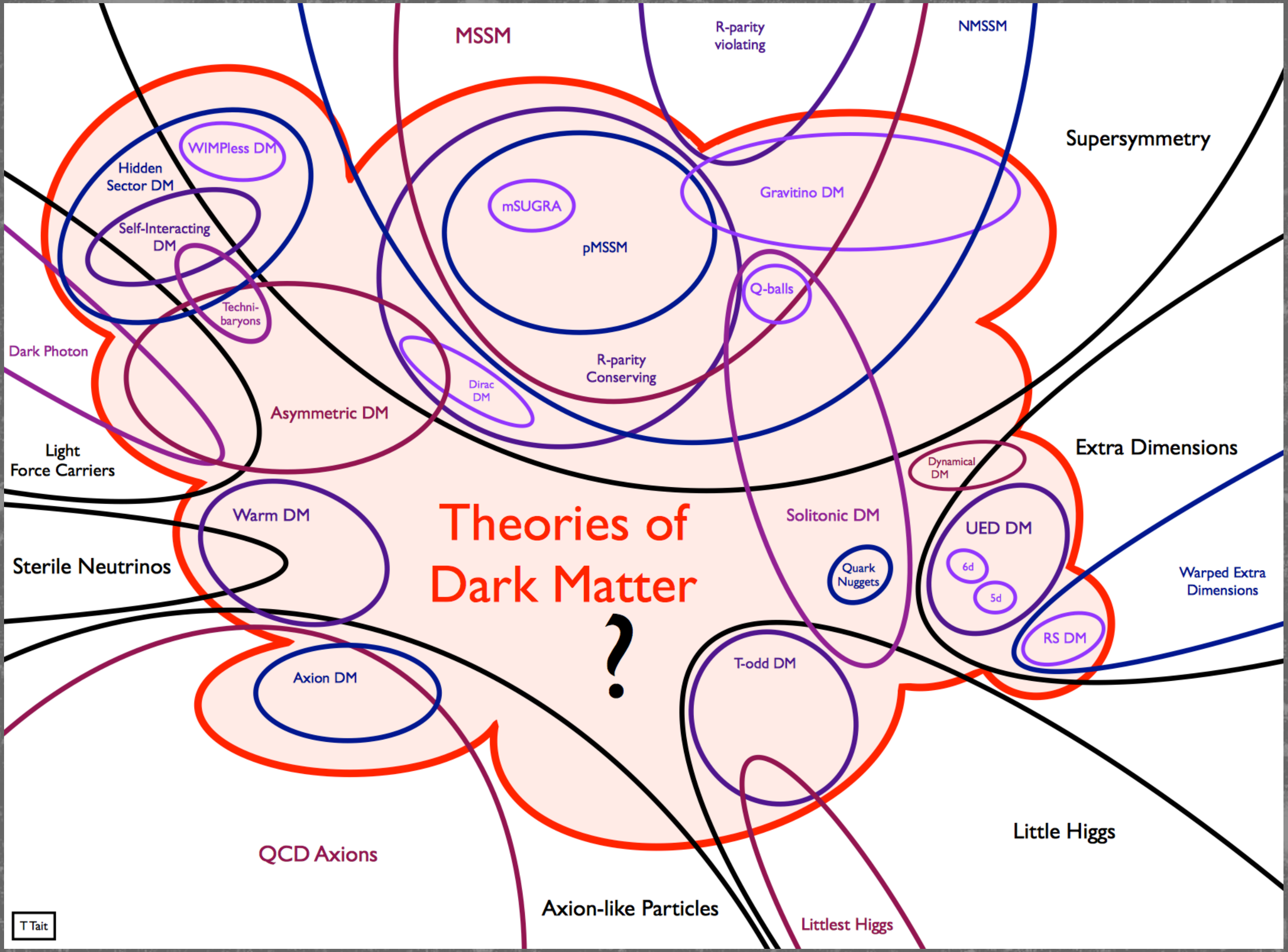
- Rotation curves
- CMB
- Large scale structure
- Velocity dispersions
- Gravitational lensing (Bullet Cluster)
- ....

Yet we have no clue what it is at the particle level!

?

Dark Matters

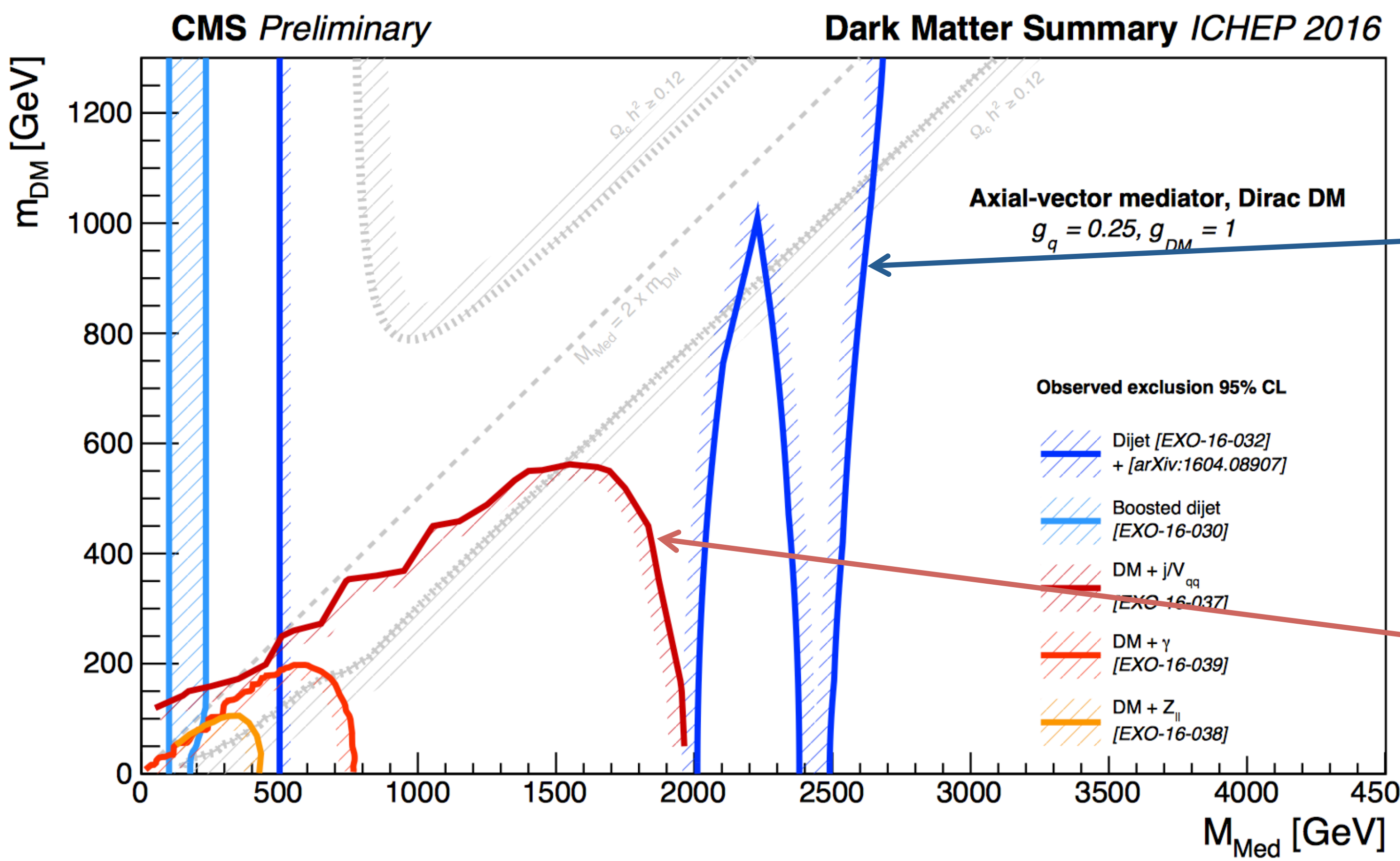
But there are some ideas...

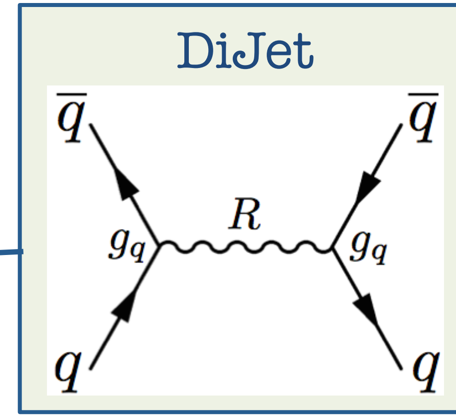


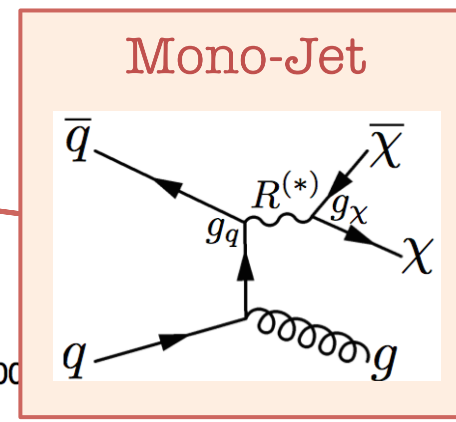
Stolen from slides of Tim Tait

Dark Matter at the HL-LHC

LHC collabs doing a spectacular job in DM hunt…





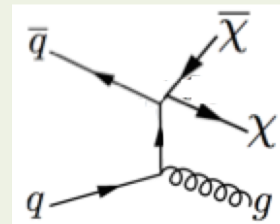


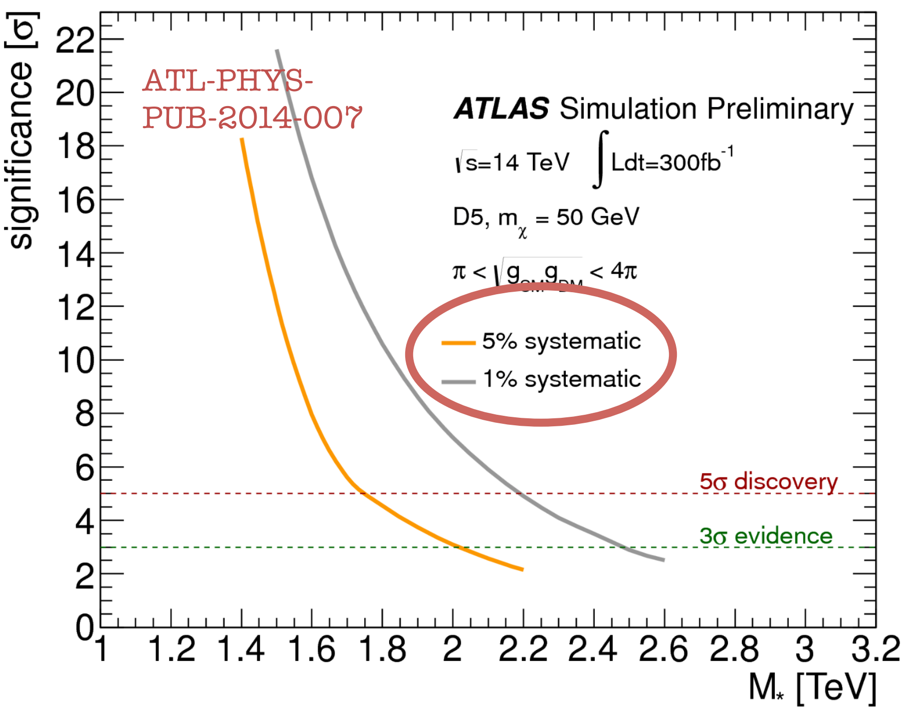
What does the future of these searches look like?

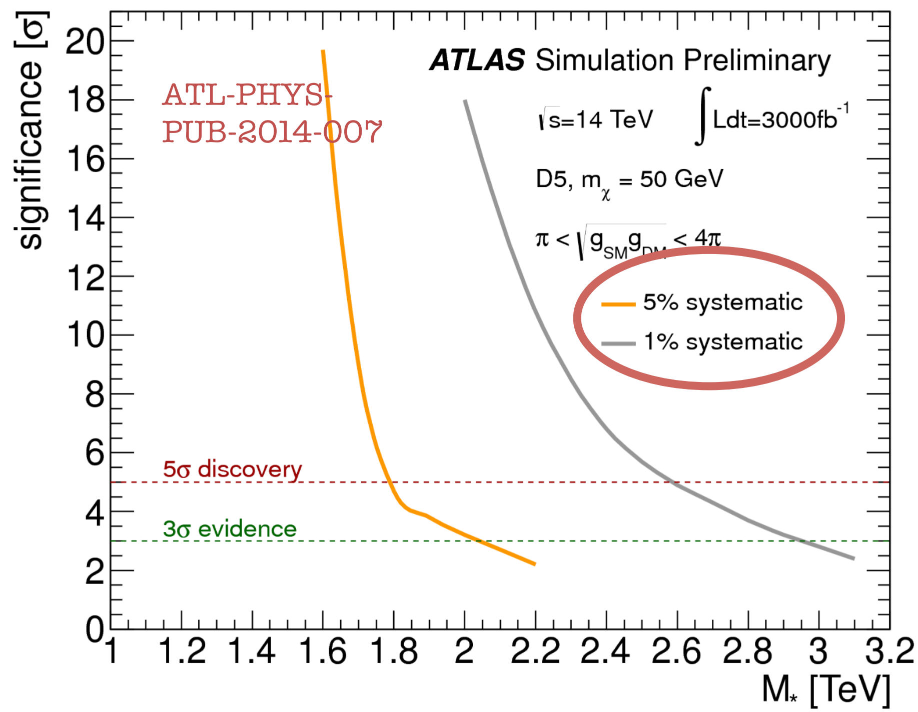
Dark Matter at the HL-LHC

Some old preliminary projections available, using EFT...

$$\mathcal{L}_{\mathrm{Int}} = \frac{\overline{\chi}\gamma^{\mu}\chi\overline{q}\gamma^{\mu}q}{M_*^2}$$







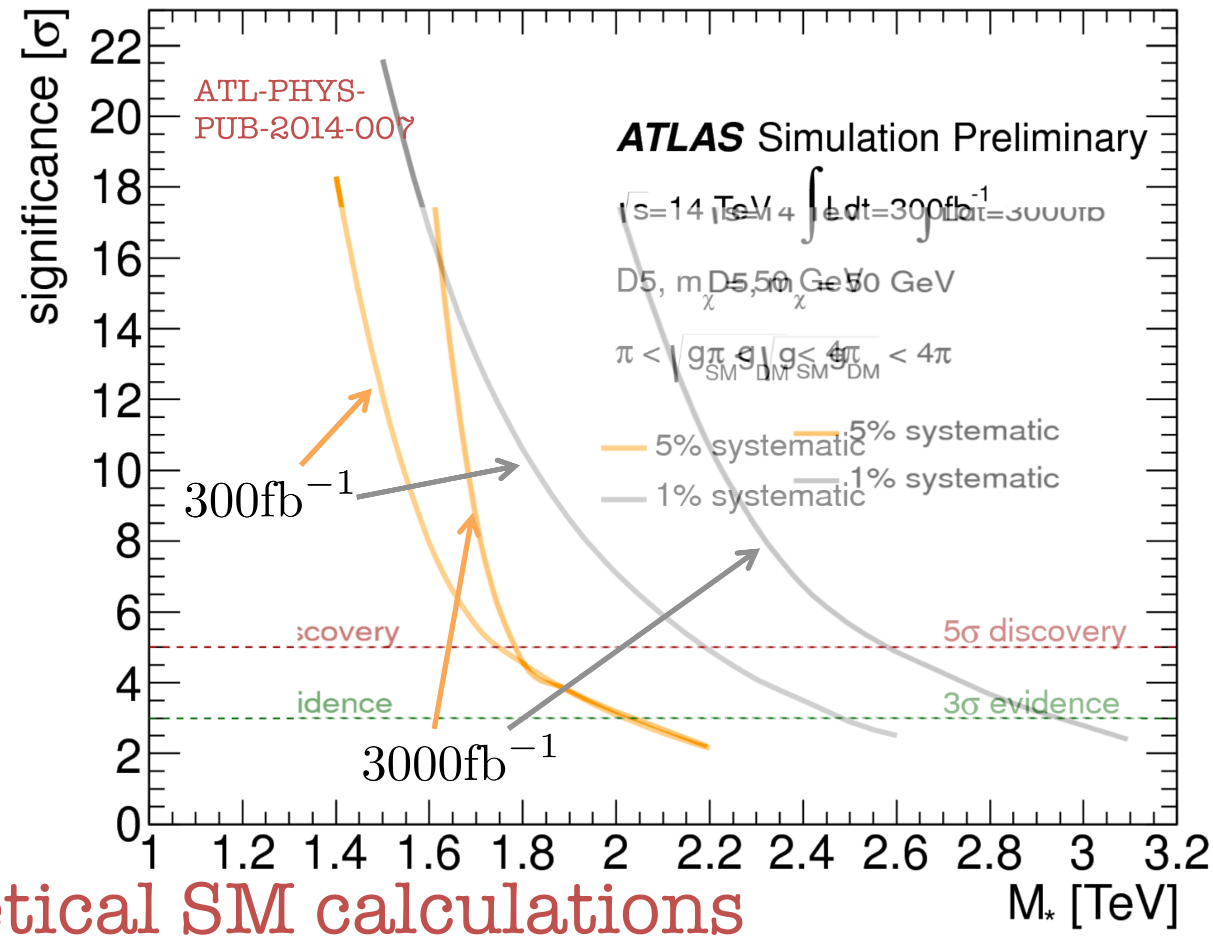
What will the systematics be?

Dark Matter at the HL-LHC

Putting together:

Systematics from electroweak corrections very important.

Can data-driven estimates be further improved?



Progress in theoretical SM calculations

Loops. Substructure. Event Gen. Logs.

will be critical to maximize territory explored.

Dark Matter at the HL-LHC

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Sy…
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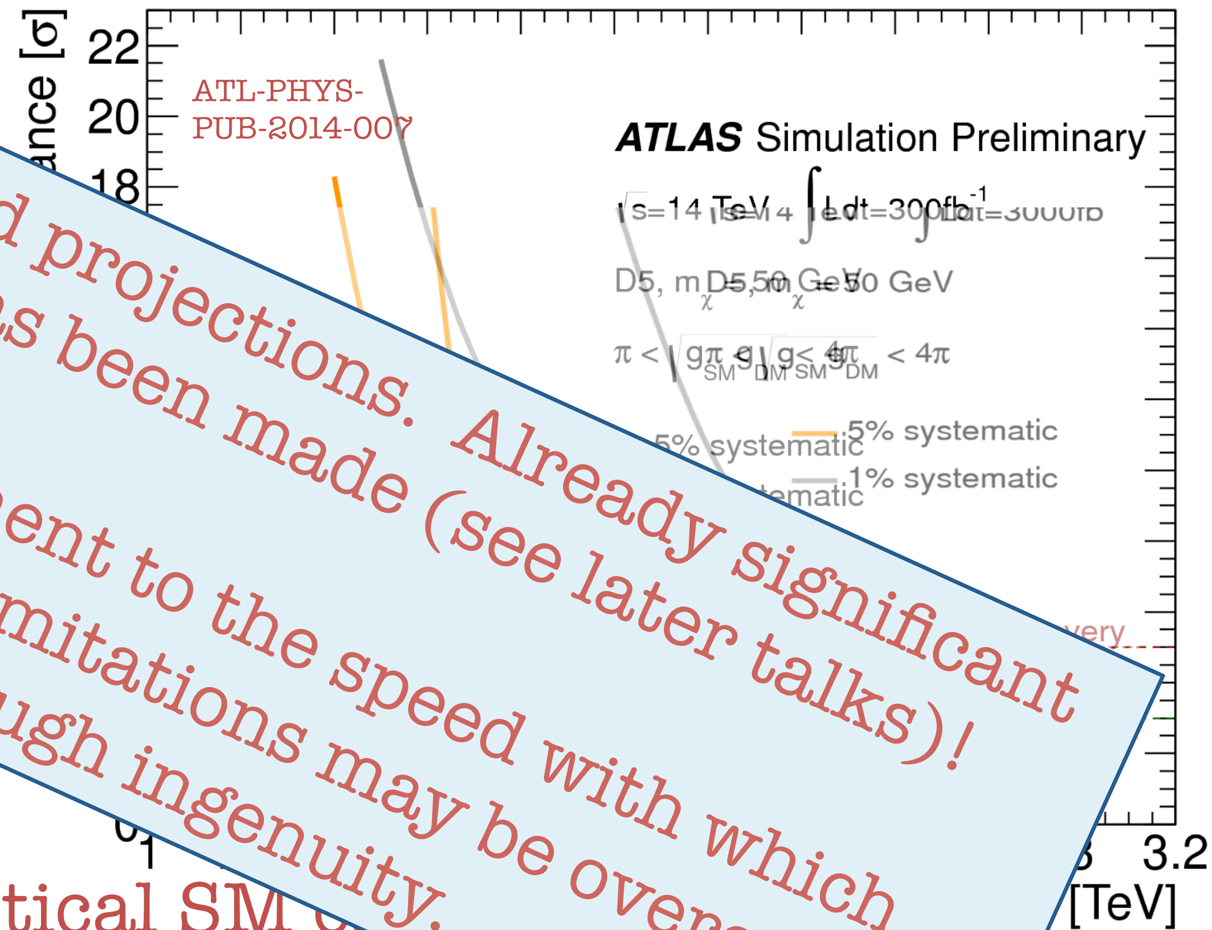
Can data …
estimates be …
improved?



These are old projections. Already significant progress has been made (see later talks)!

This is testament to the speed with which "systematics" limitations may be overcome through ingenuity.

Progress in theoretical SM …

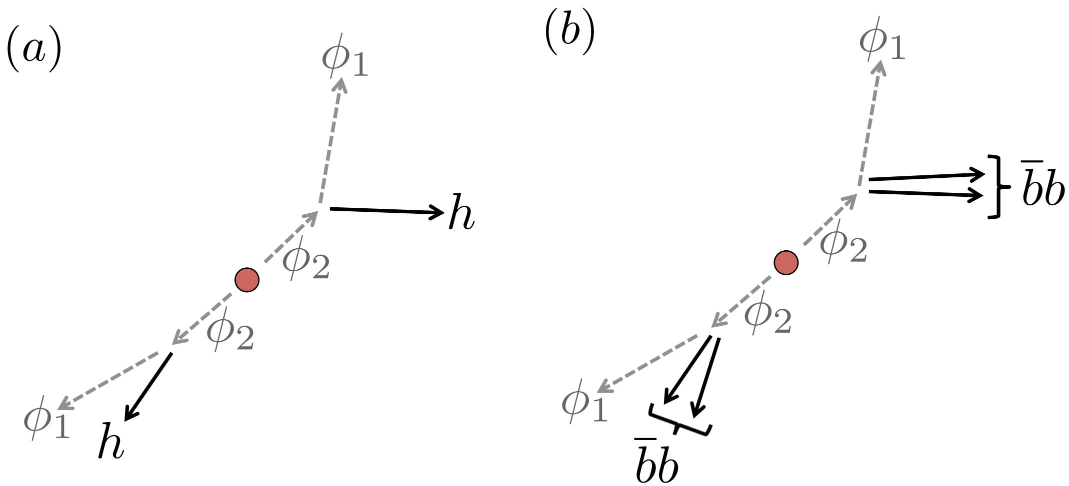
Loops. Substructure. Event Ge… …

will be critical to maximize territory explored.

Dark Matter at HL-LHC

There are generic classes of unexplored scenarios.

An example: $\mathcal{L}_{\mathrm{Int}} \sim \mathcal{O}_{\mathrm{SM}} \times \left(\phi_2^2 + \phi_1^2 + \epsilon\phi_2\phi_1\right)$



Exciting signatures:

- Paired displaced events!
- Soft displaced events.
- Missing energy
- Non-pointing displaced

Clear detector goals:

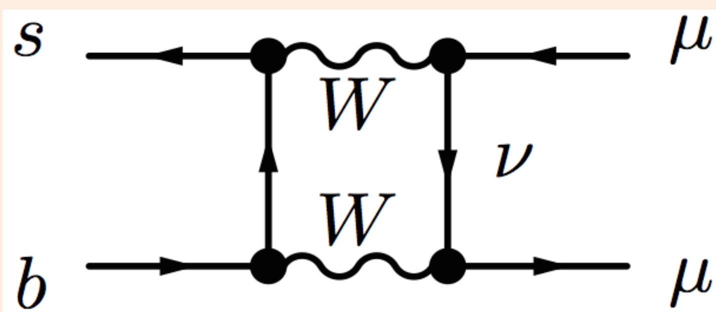
- Triggering
- Tracking
- ???

Numerous unexplored theories that take full advantage of the added integrated luminosity.

Flavour Physics

Fermion mass/mixing pattern demands explanation.

Symmetries of SM suppress certain processes (e.g. GIM). BSM could easily show up. One example



Could new physics (SUSY, Z',...) be hiding in here?

A particularly clean observable:

$$\frac{B^0 \to \mu^+\mu^-}{B^0_s \to \mu^+\mu^-}$$

Theory uncertainties at the level of

$$\delta_{Theory} \sim 5\%$$

However, after HL-LHC with 50 fb^{-1} at LHCb upgrade would have

$$\delta_{Stat} \sim 40\%$$

Every fb^{-1} would count!

LHCb-PUB-2014-040 and talk by Neils Tuning.

No indication for scale of fundamental flavour theory: must reach (indirectly) for all scales.

Not to mention...

Vast programs in...

Higgs Physics
(Salam, Mangano)

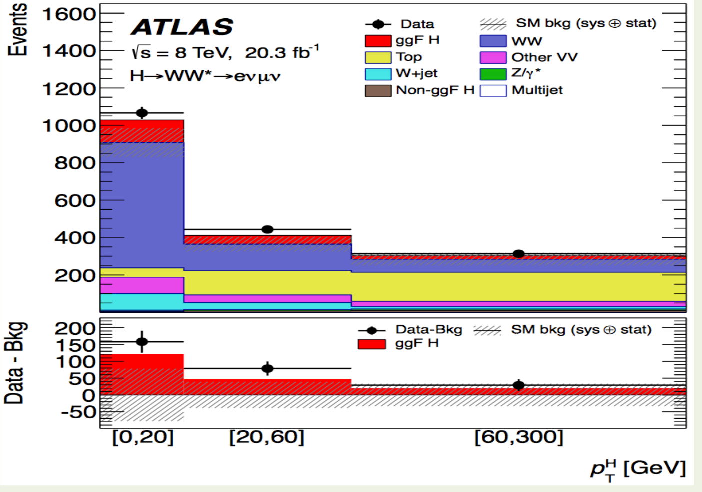
Top Physics
($\sim 10^{10}$ top quarks!!)

EW Sector Physics
(Wulzer)

Power to distributions...

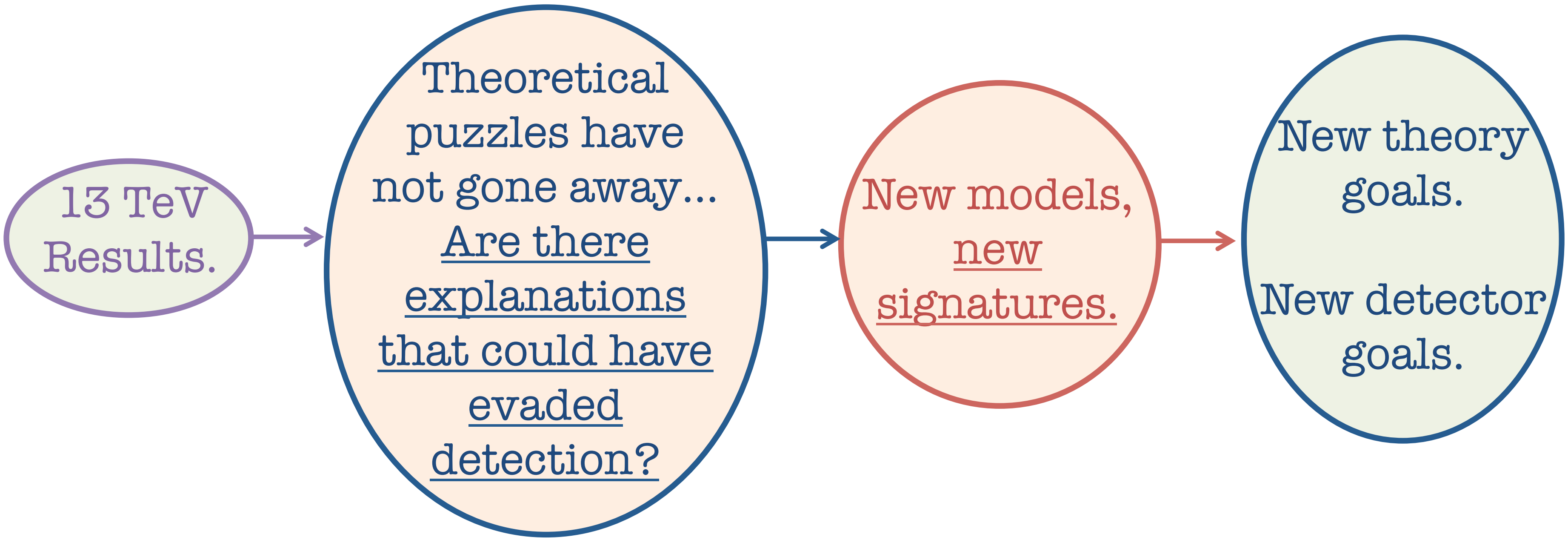
When inclusive measurements turn to exclusive distributions:

- Landscape of uncertainties changes
- New opportunities arise.



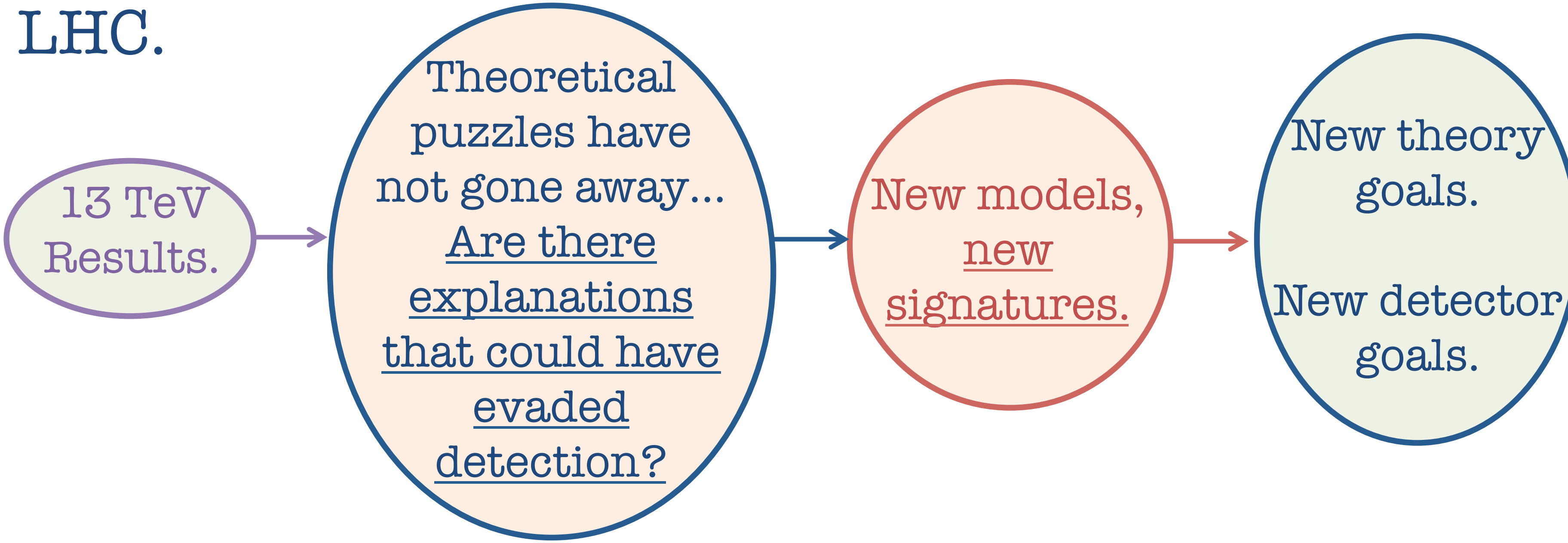
Conclusions.

BSM now is not an extrapolation of BSM pre-LHC.



Conclusions.

Physics at HL-LHC will not be an extrapolation of LHC.



Will need to break new ground on all fronts:

Precision QCD and EW

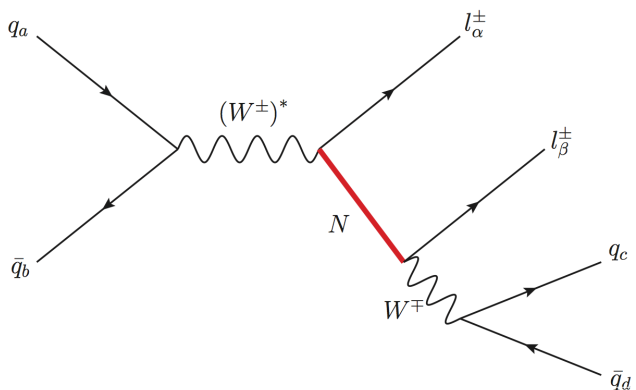
Triggering/tracking

much more...

This will drive progress, to learn all we can about nature at the smallest scales with the HL-LHC.

Neutrino Masses

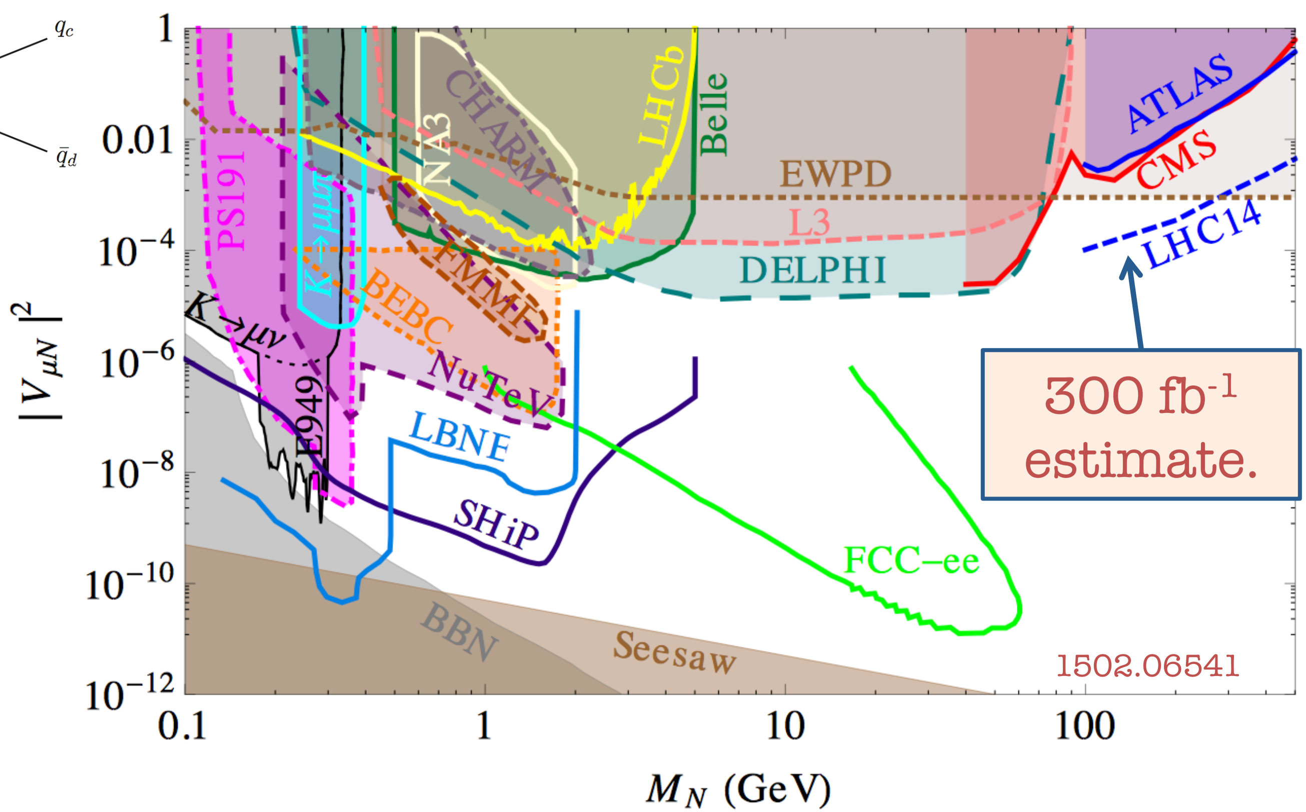
Certain classes of neutrino mass models have RHD neutrinos at weak scale.



Signatures are relatively clean: same-sign leptons+jets.

More generally, new neutral, weakly coupled, fields may show up in the lepton sector.

Signatures rare, with low SM backgrounds.



300 fb^{-1} estimate.