New Physics Searches LHC and beyond

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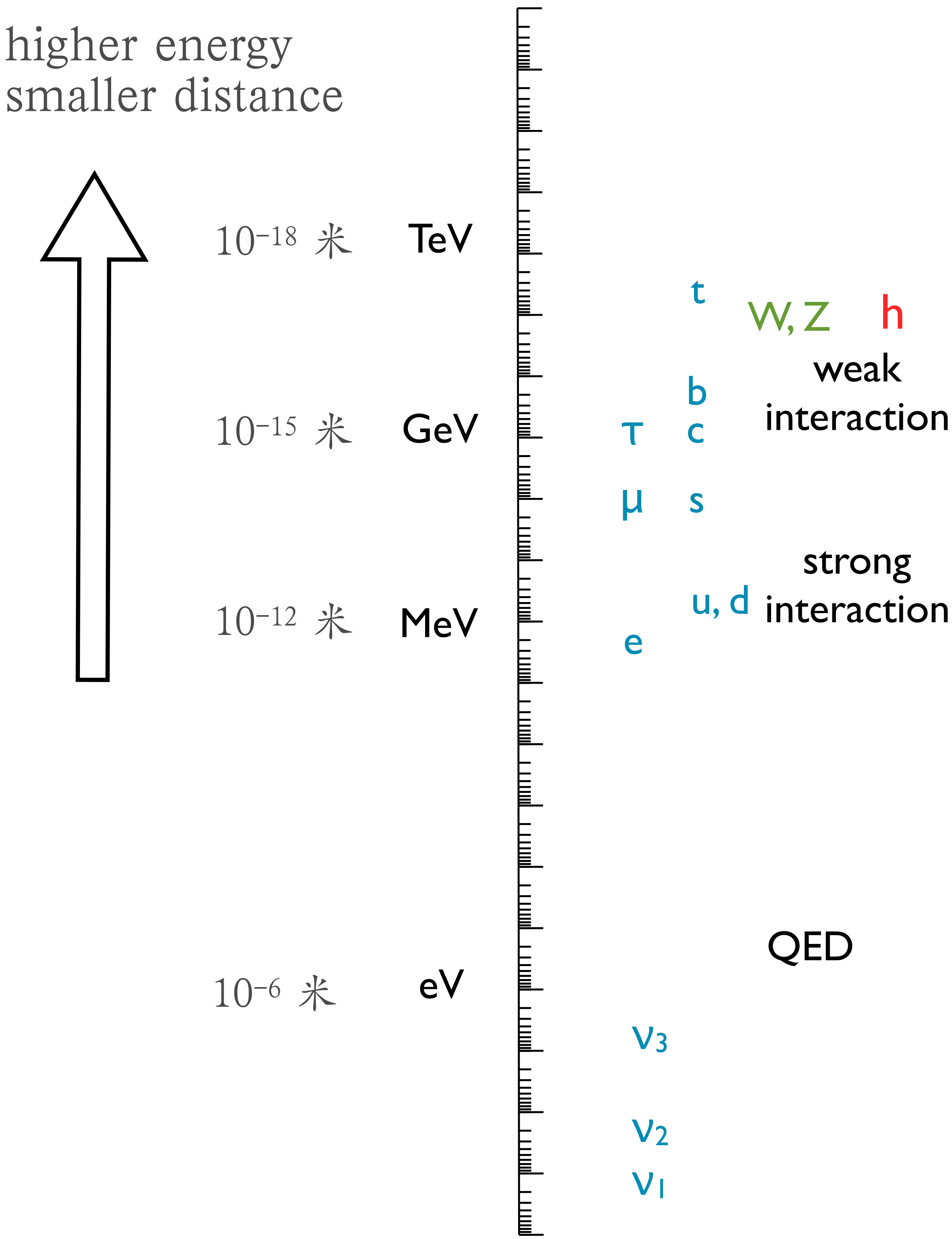
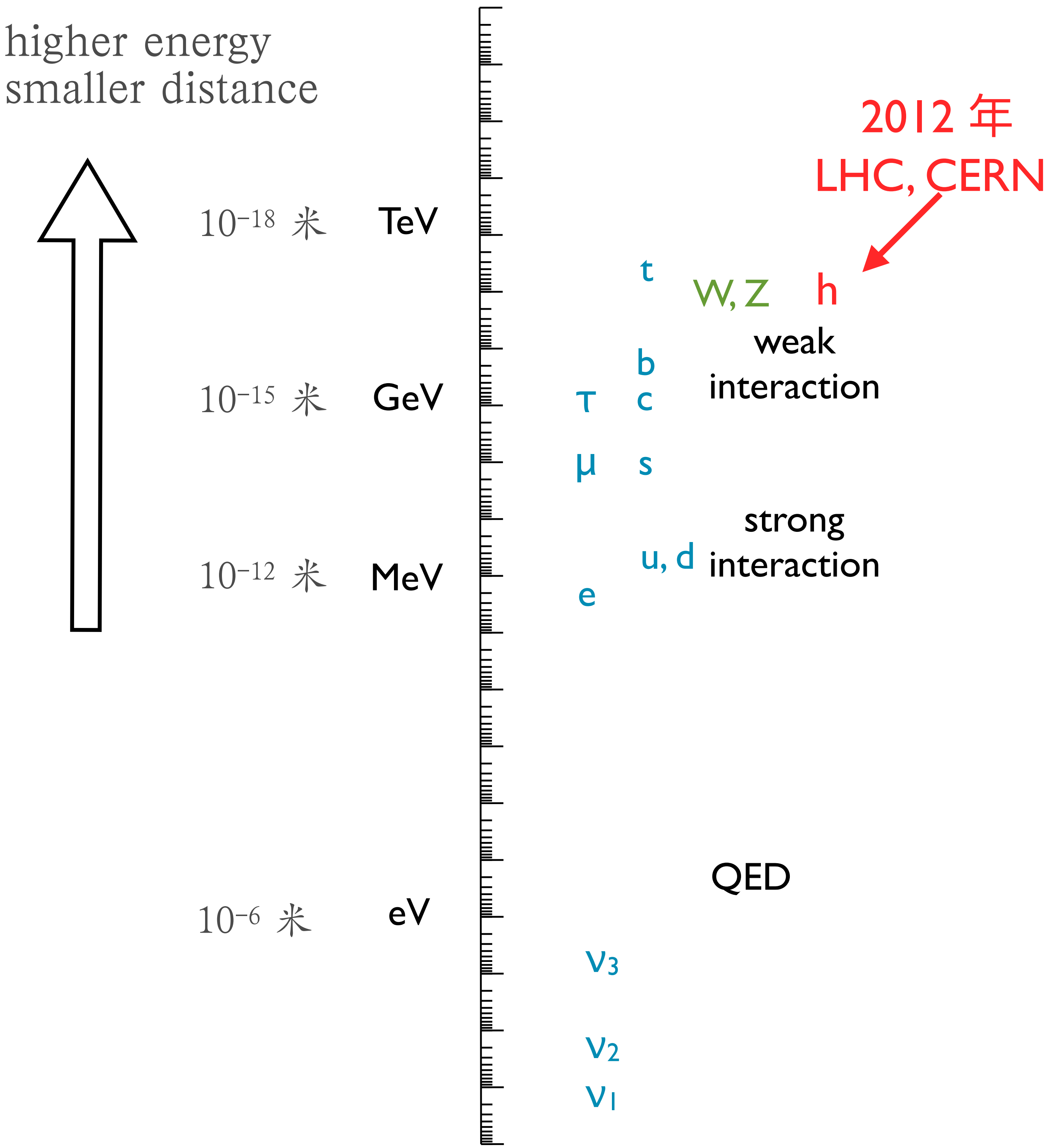
U. Chicago

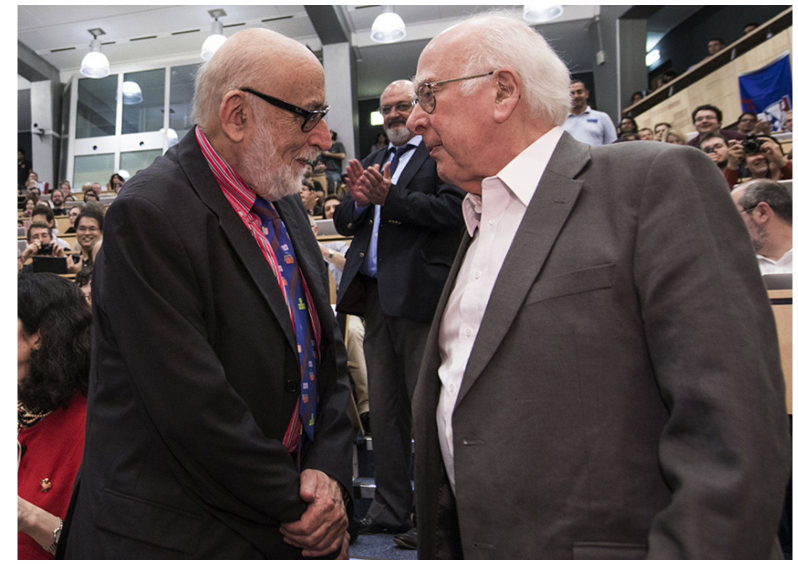
Summer Institute, 2018 Pan Shan, Tianjin

The Standard Model



The discovery of the Higgs boson





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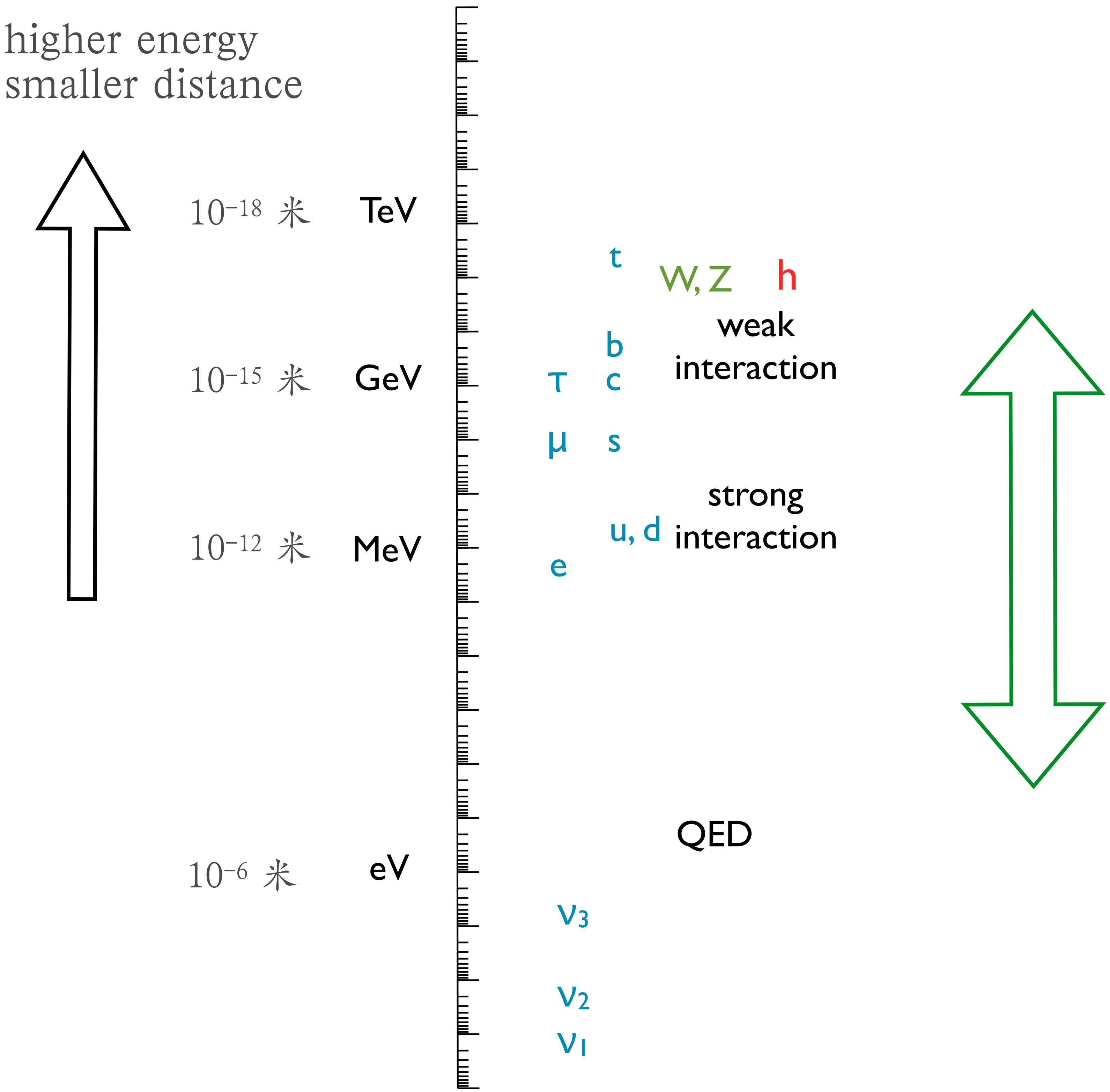
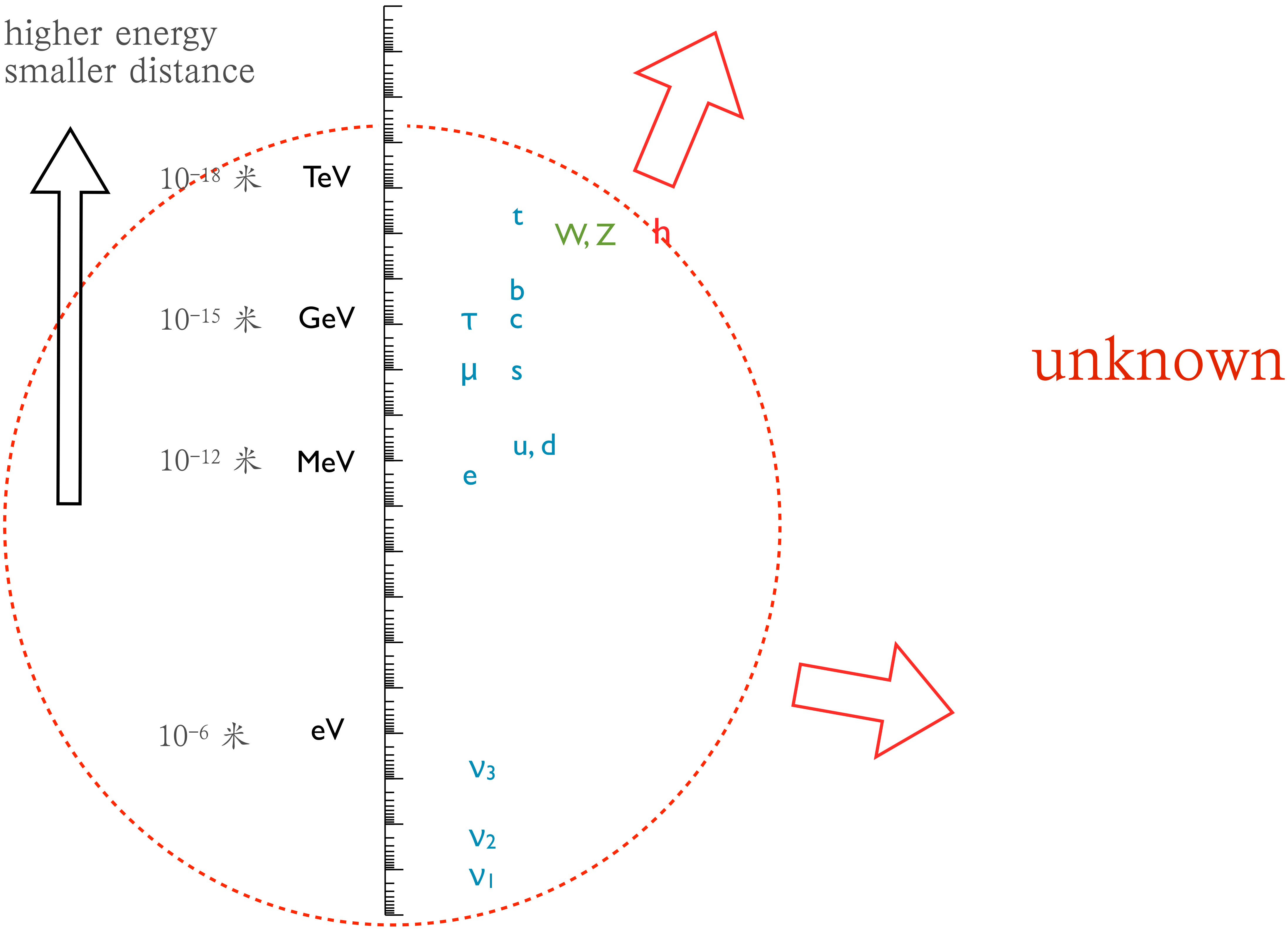


A milestone after a century of amazing progress

Beginning of an new era

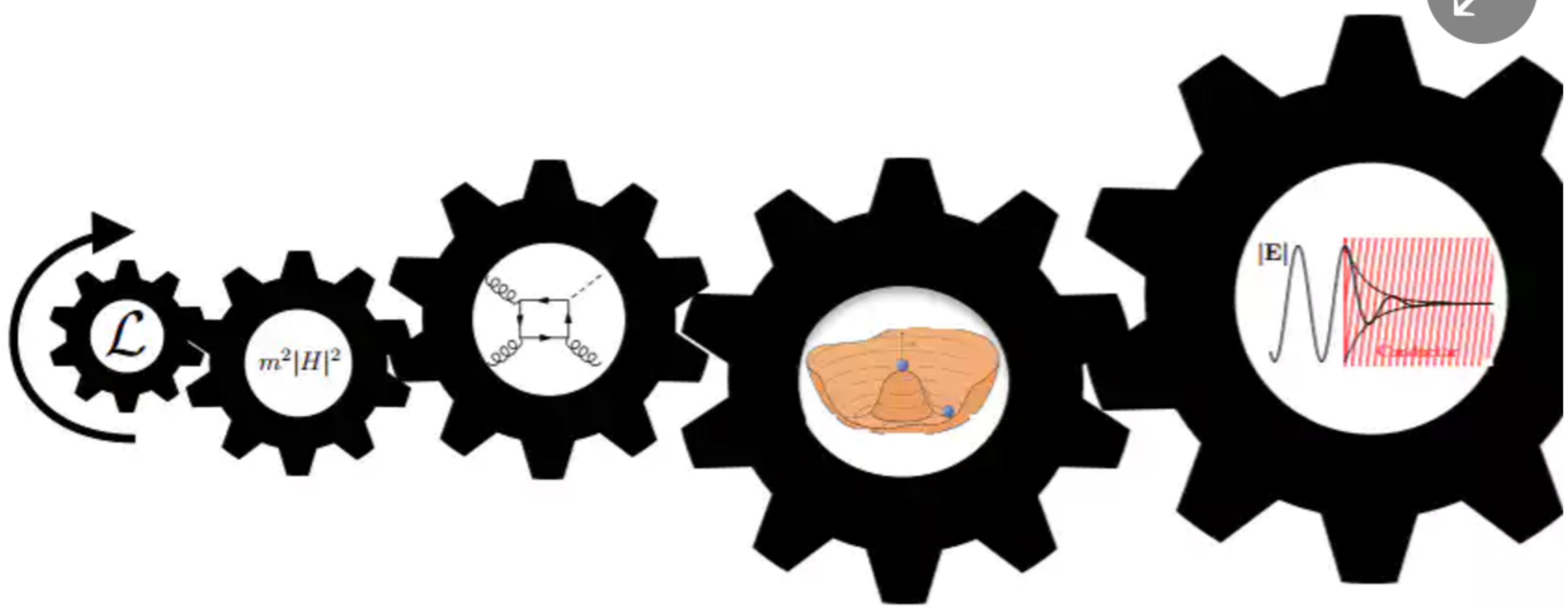


SM: complete yet incomplete

- Complete: could be a consistent theory valid up to the Planck scale.
- Incomplete: many open questions
  - Origin of electroweak scale
  - Dark matter
  - Origin of CP, flavor
  - ...
- Goal of particle physics: answer these questions.
- Colliders (LHC and beyond) will be crucial.

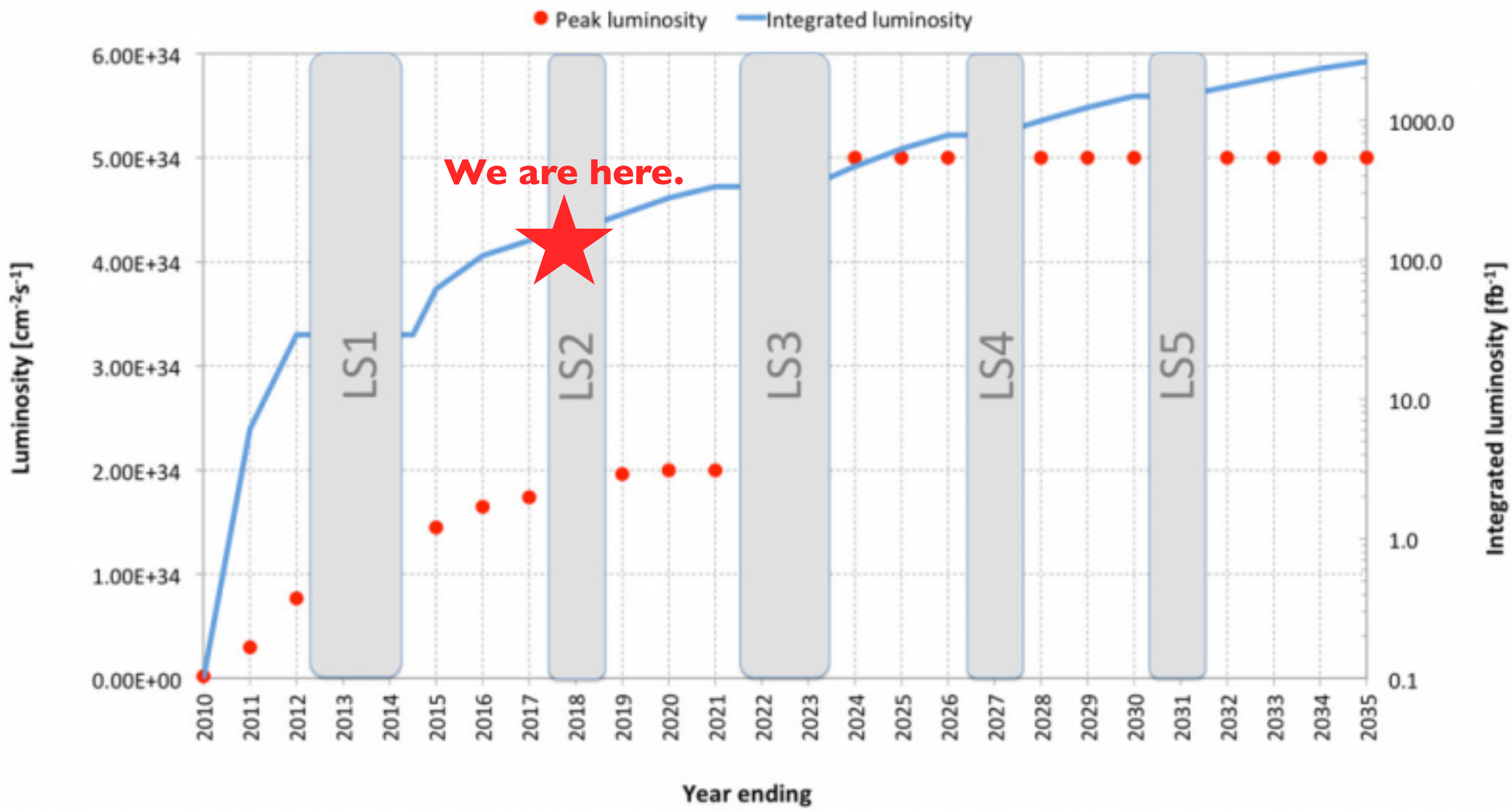
From gravity to the Higgs we're still waiting for new physics

Annual physics jamboree Rencontres de Moriond has a history of revealing exciting results from colliders, and this year new theories and evidence abound



Guardian

Road ahead at the LHC


Peak luminosity
Integrated luminosity
We are here.
LS1
LS2
LS3
LS4
LS5
Luminosity [cm-2s-1]
Integrated luminosity [fb-1]
Year ending
6.00E+34
5.00E+34
4.00E+34
3.00E+34
2.00E+34
1.00E+34
0.00E+00
1000.0
100.0
10.0
1.0
0.1
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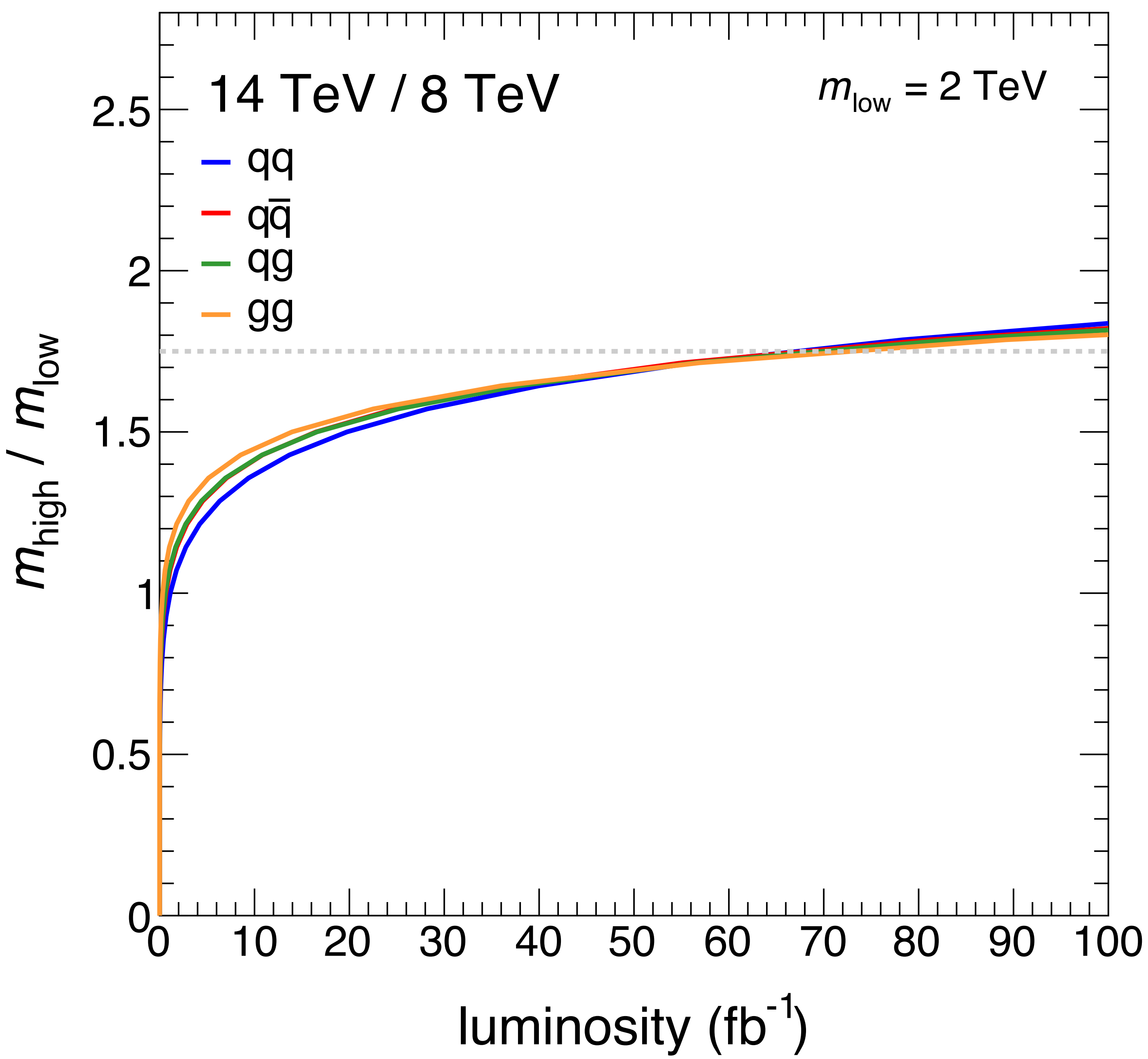
2035

LHC is pushing ahead.

Exp. collaborations are pursuing a broad and comprehensive physics program: SUSY, composite H, extra Dim, etc.

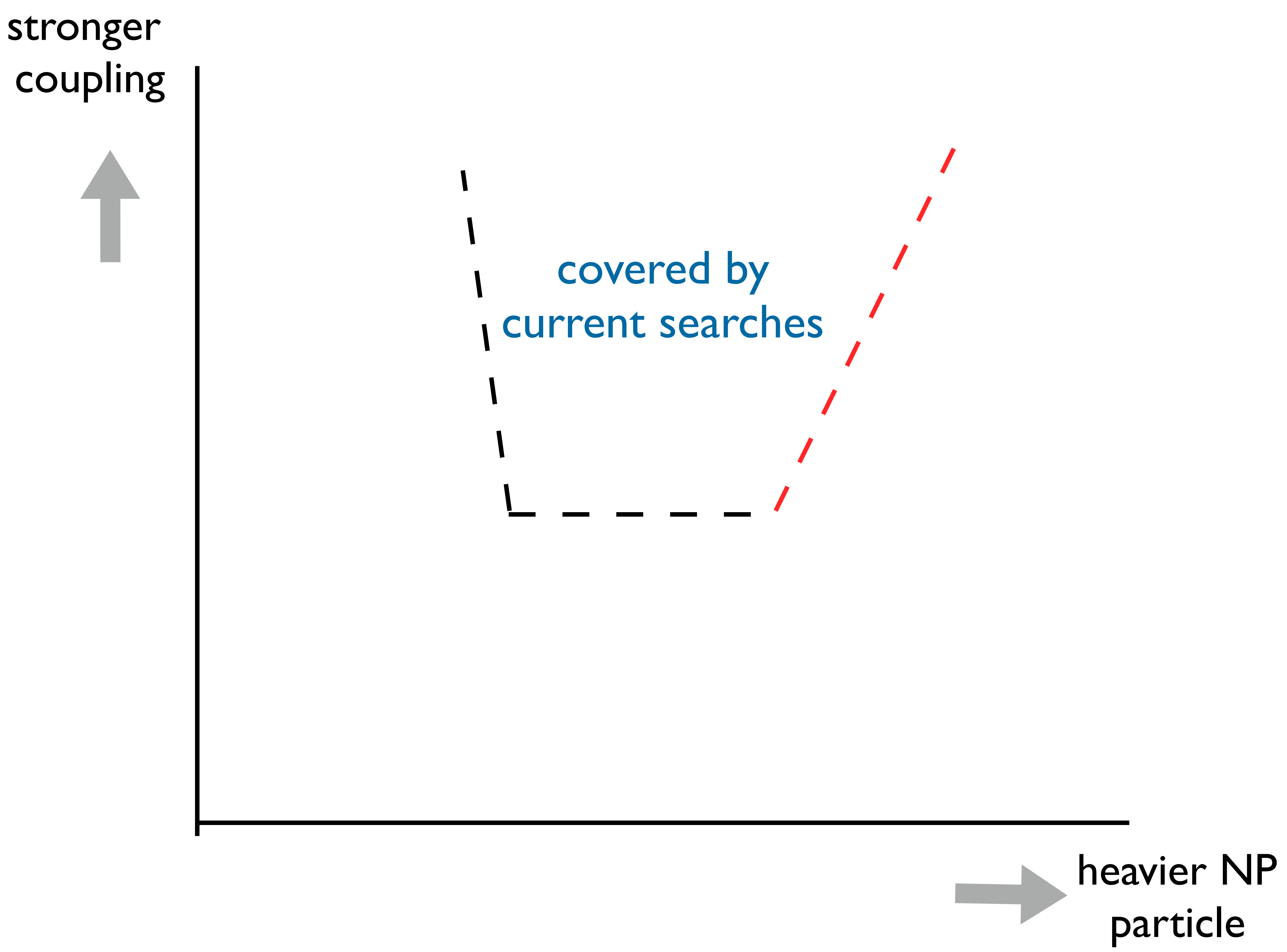
As data accumulates

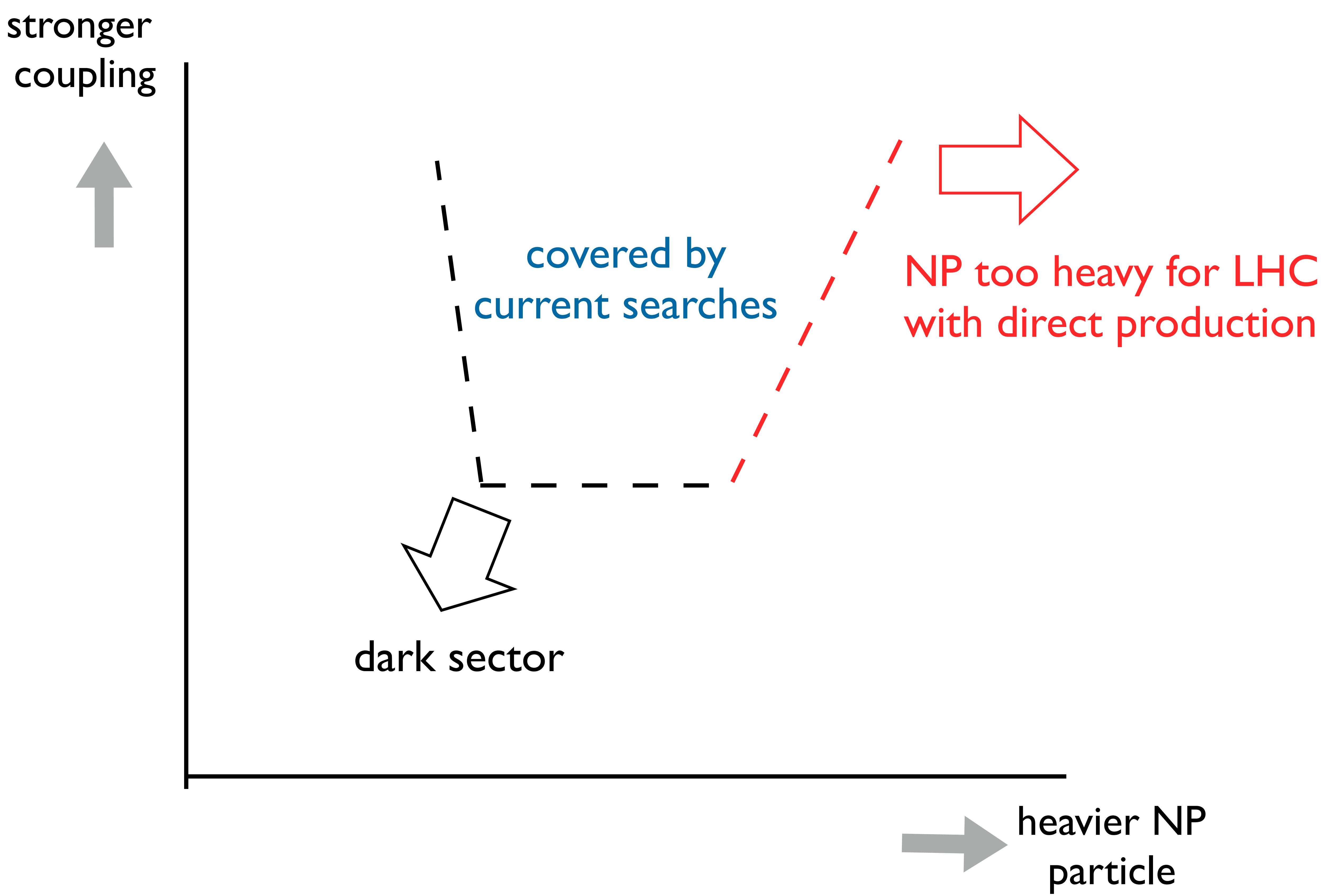


Rapid gain initial 10s-100 fb^{-1}, slow improvements afterwards.

Progress will become slower, harder

New directions?


stronger
coupling
covered by
current searches
heavier NP
particle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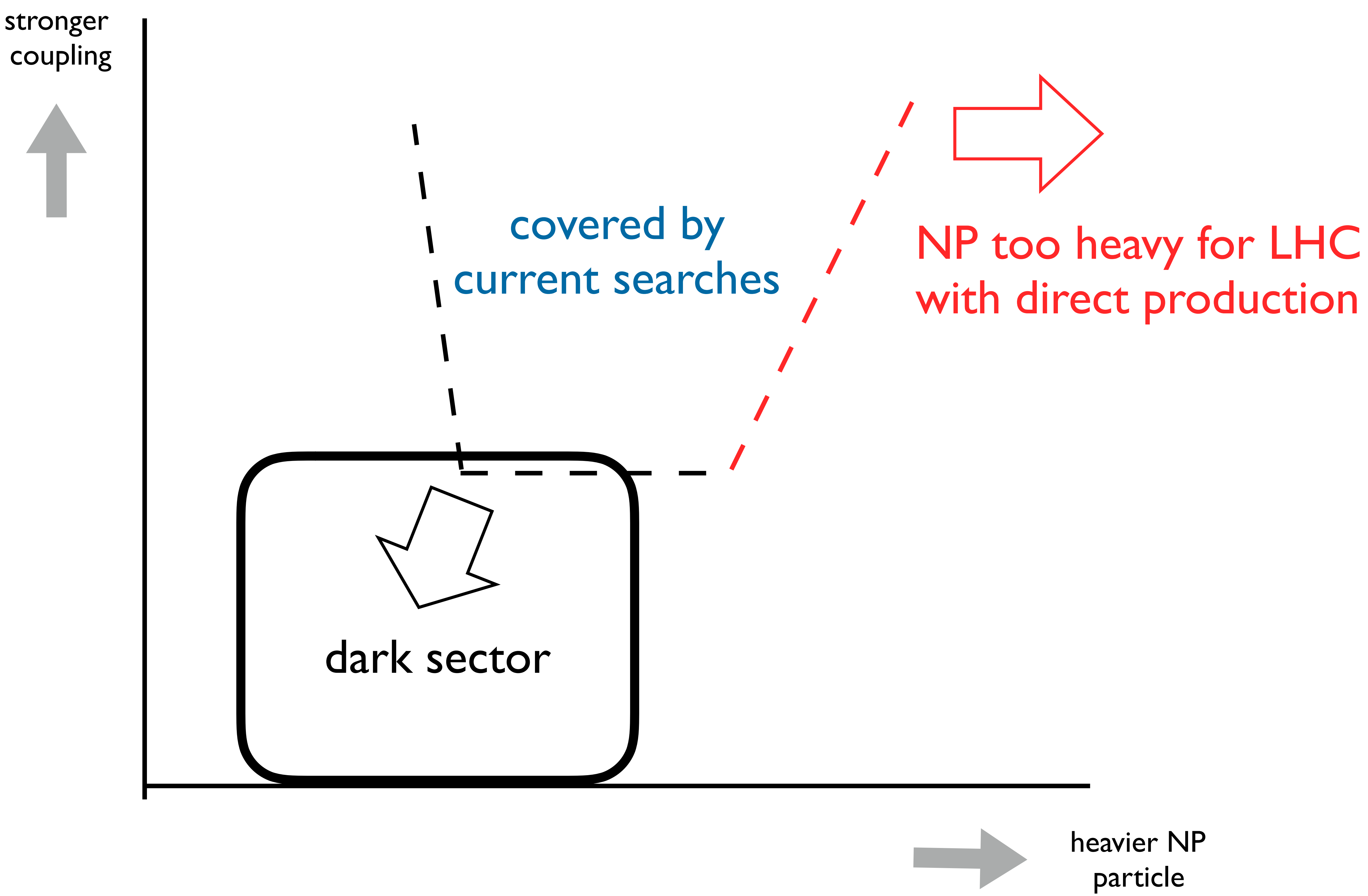
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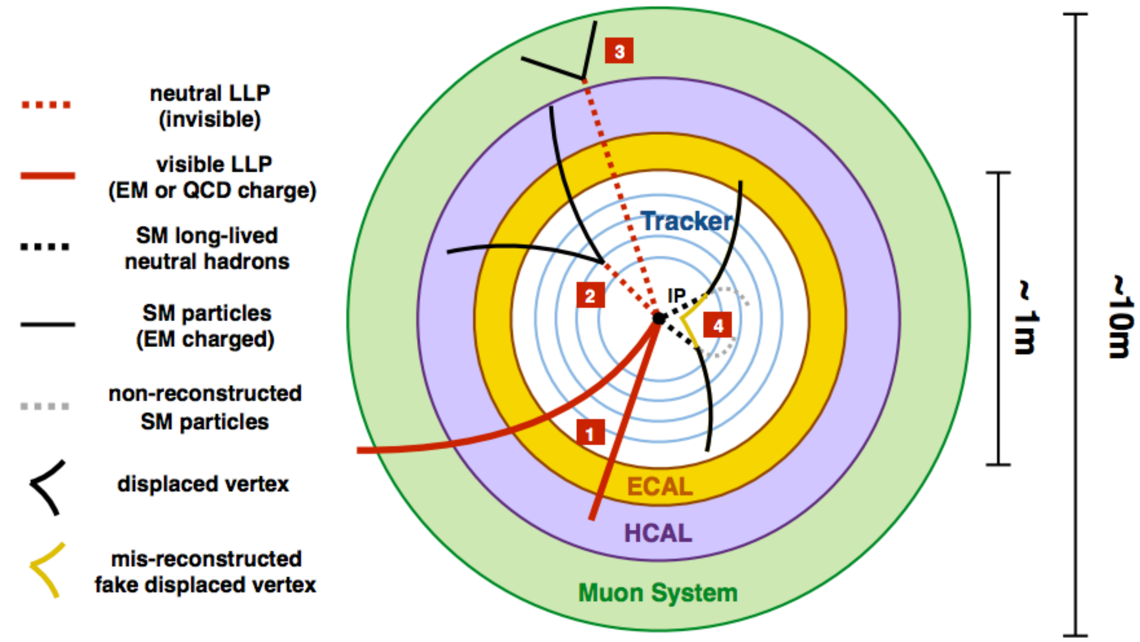
Example: Long Lived particles (LLP)

- Very weakly coupled to the SM.
  - Connection with dark matter, neutrino, etc.

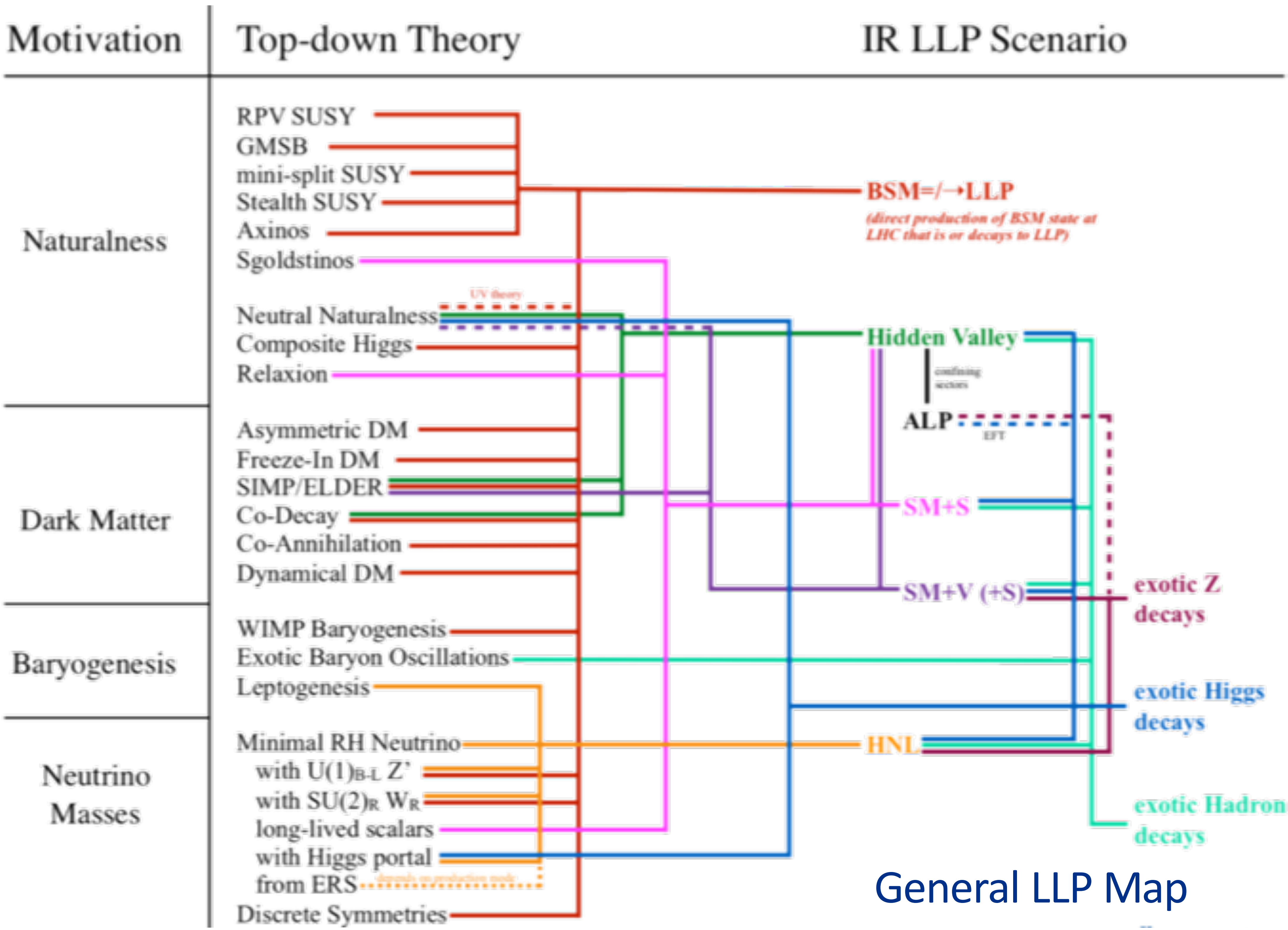
- Displaced-Long lived, soft, kink, ... Covered by LHC searches already.



Curtin and Sundrum

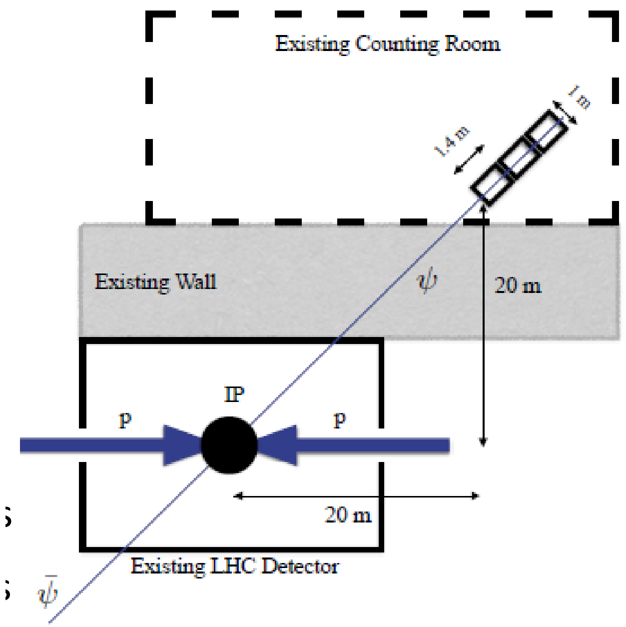
Here, I focus on: decay length >> 10 meters

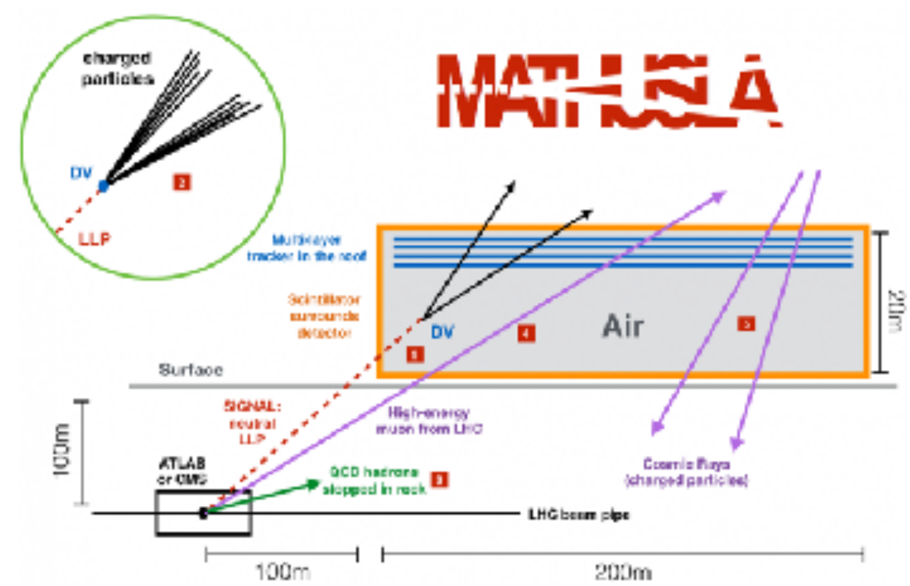
tons of models



General LLP Map

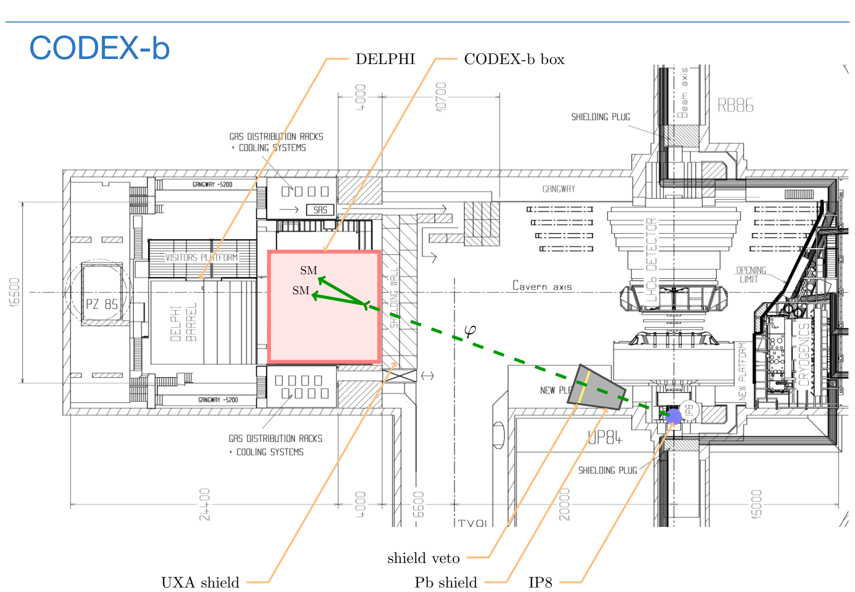
Far detectors

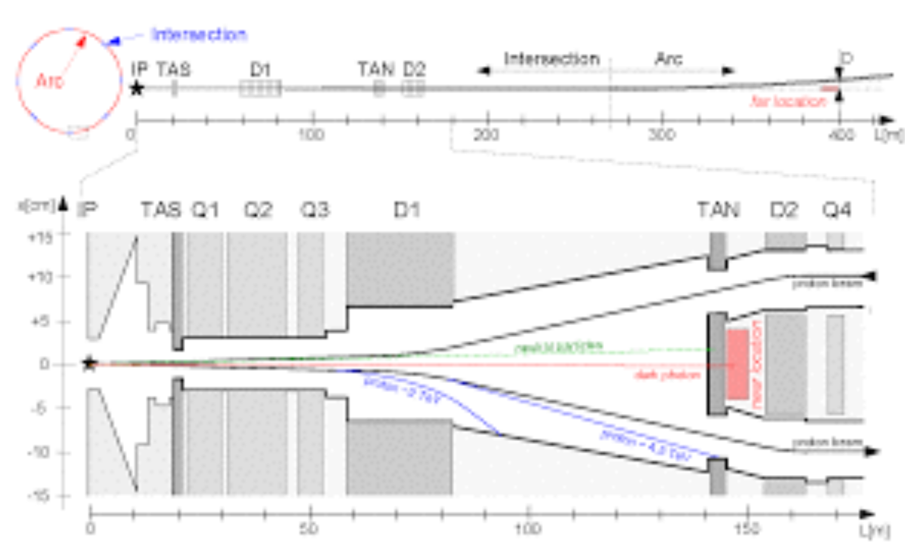




MATHUSLA

new detectors far
away from the interaction region

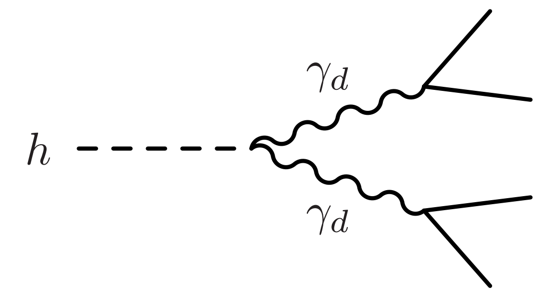


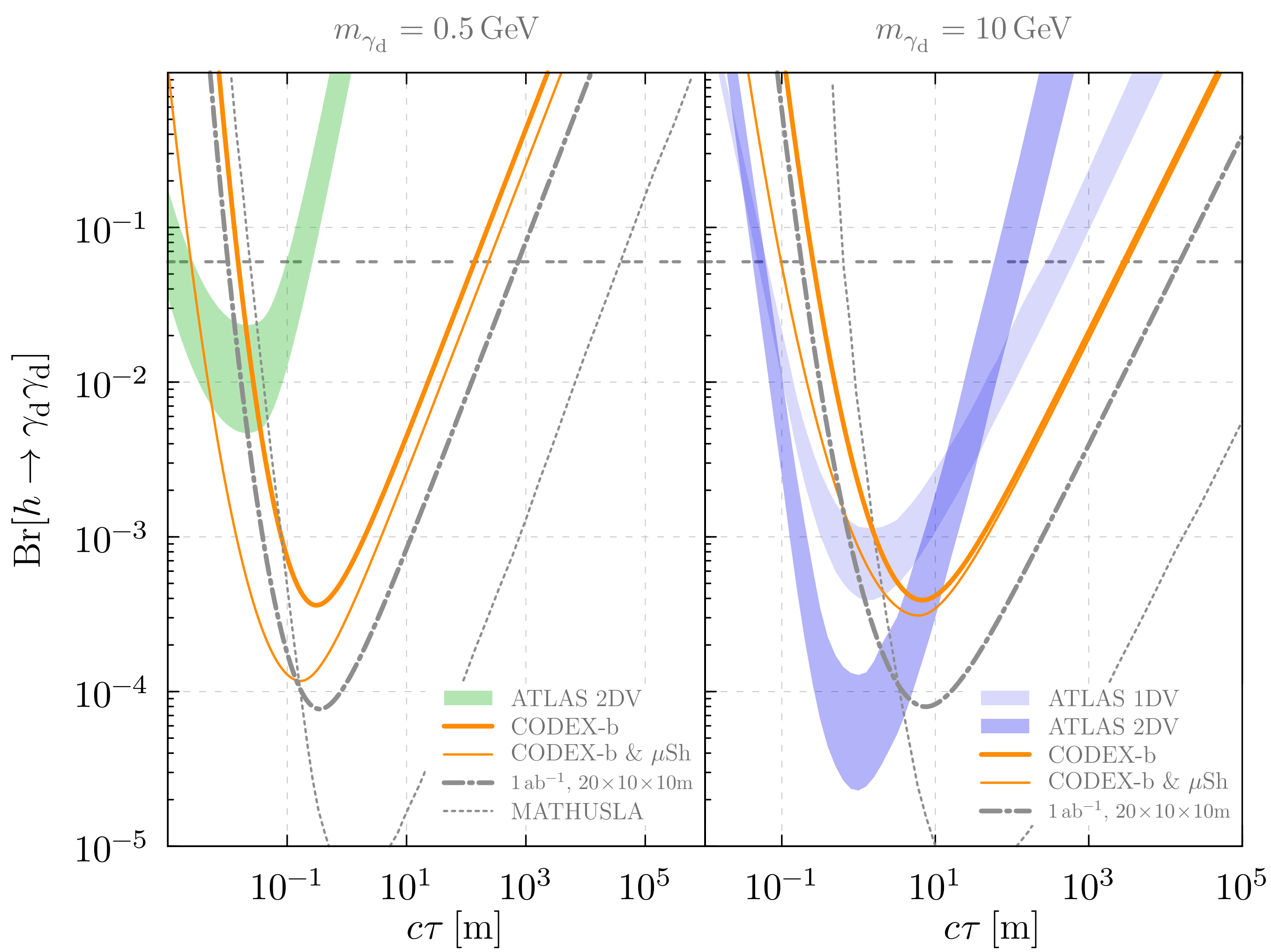


FASER

Could reach τ≈10⁴⁻⁵ m

Exotic Higgs decays





Application:
Neutral Naturalness
(See back-up material)

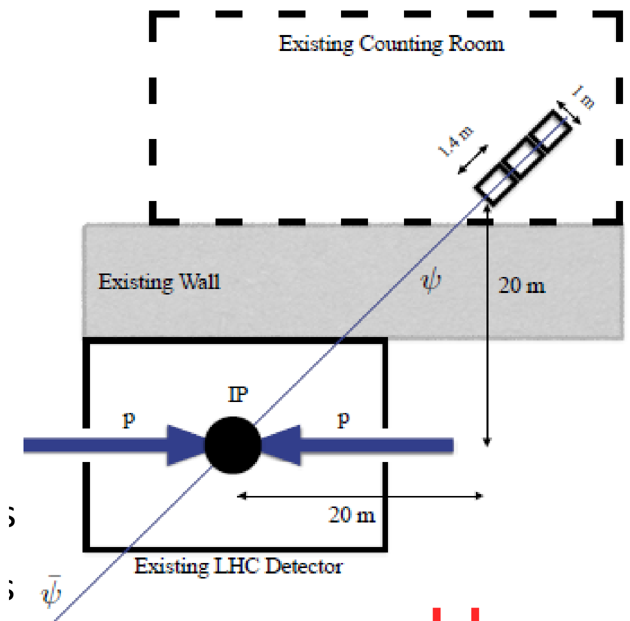
For low masses, ATLAS/CMS are background limited, CODEX-b & MATHUSLA have an edge

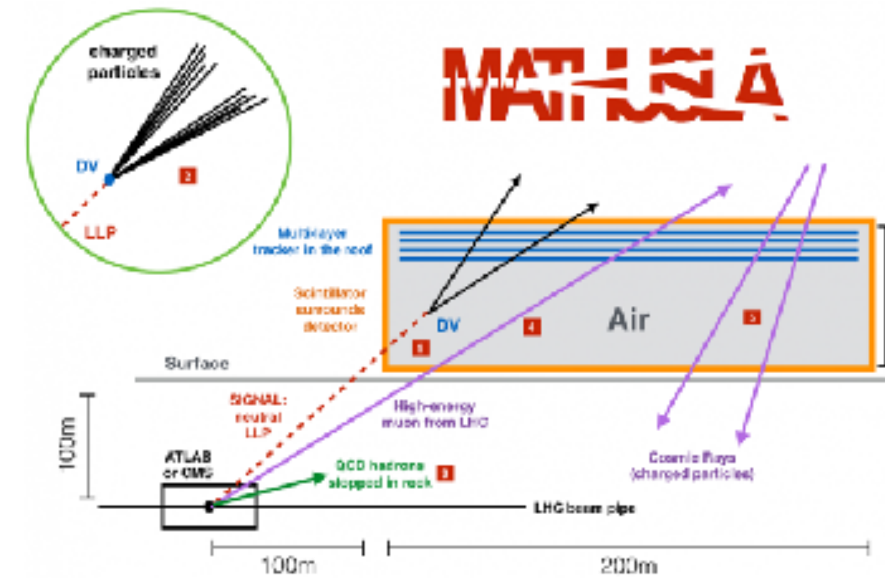
V. Gligorov, SK, M. Papucci, D. Robinson: 1708.02243

ATLAS reach: A. Coccaro, et al.: 1605.02742

S. Knapen

Far detectors

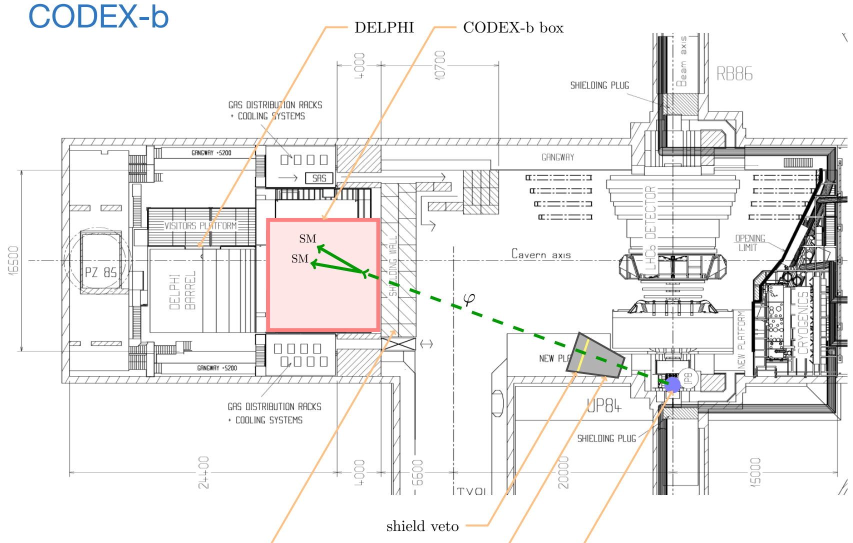


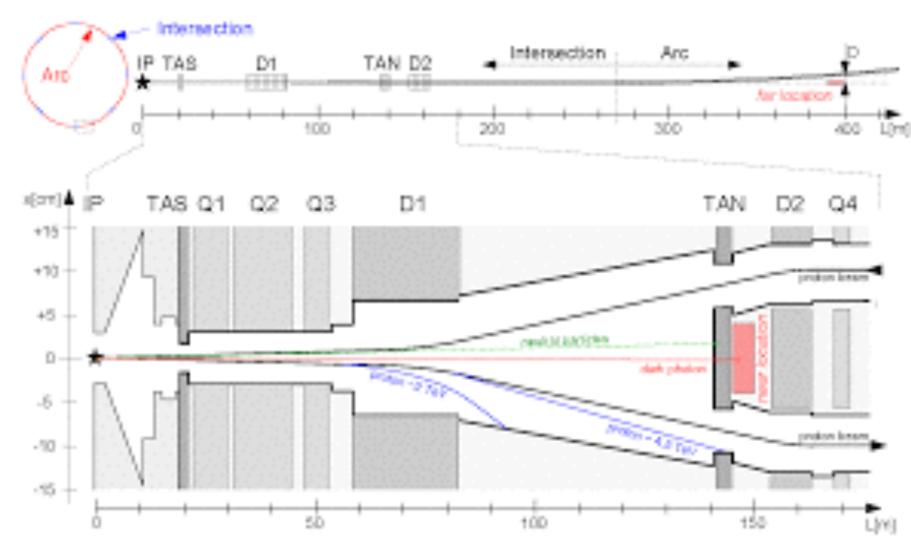


MATHUSLA

Have we fully optimized LLP searches at the interaction points ATLAS, CMS, LHCb?

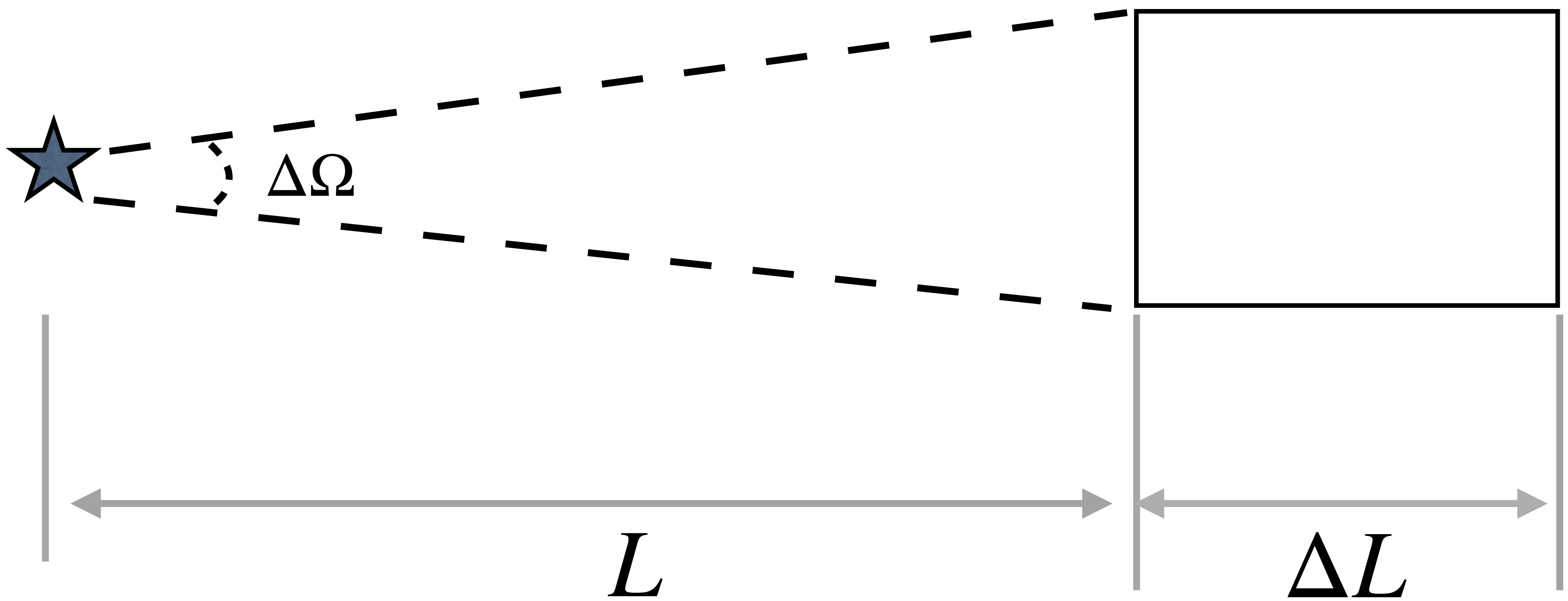
CODEX-b





FASER

Optimal place to catch LLP



Number of particle decayed within detector volume:

$$\#_{\rm in} \simeq \#_{\rm produced} \times \frac{\Delta\Omega}{4\pi} \times \frac{\Delta L}{d} e^{-L/d}$$

$d = \gamma c \tau$ decay length $\quad d \gg \Delta L,\, L$

Very long lived: $d \geq 100\text{s meters}$

Optimal place to catch LLP

Number of particle decayed within detector volume:

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	ATLAS/CMS (LHCb)	Far detectors
$\Delta\Omega$	$\sim 4\pi$	< 0.1
ΔL	$1-10$ meters	$1-10$ meters
L	$1-10$ meters	$10-100$ meters

Optimal place to catch LLP

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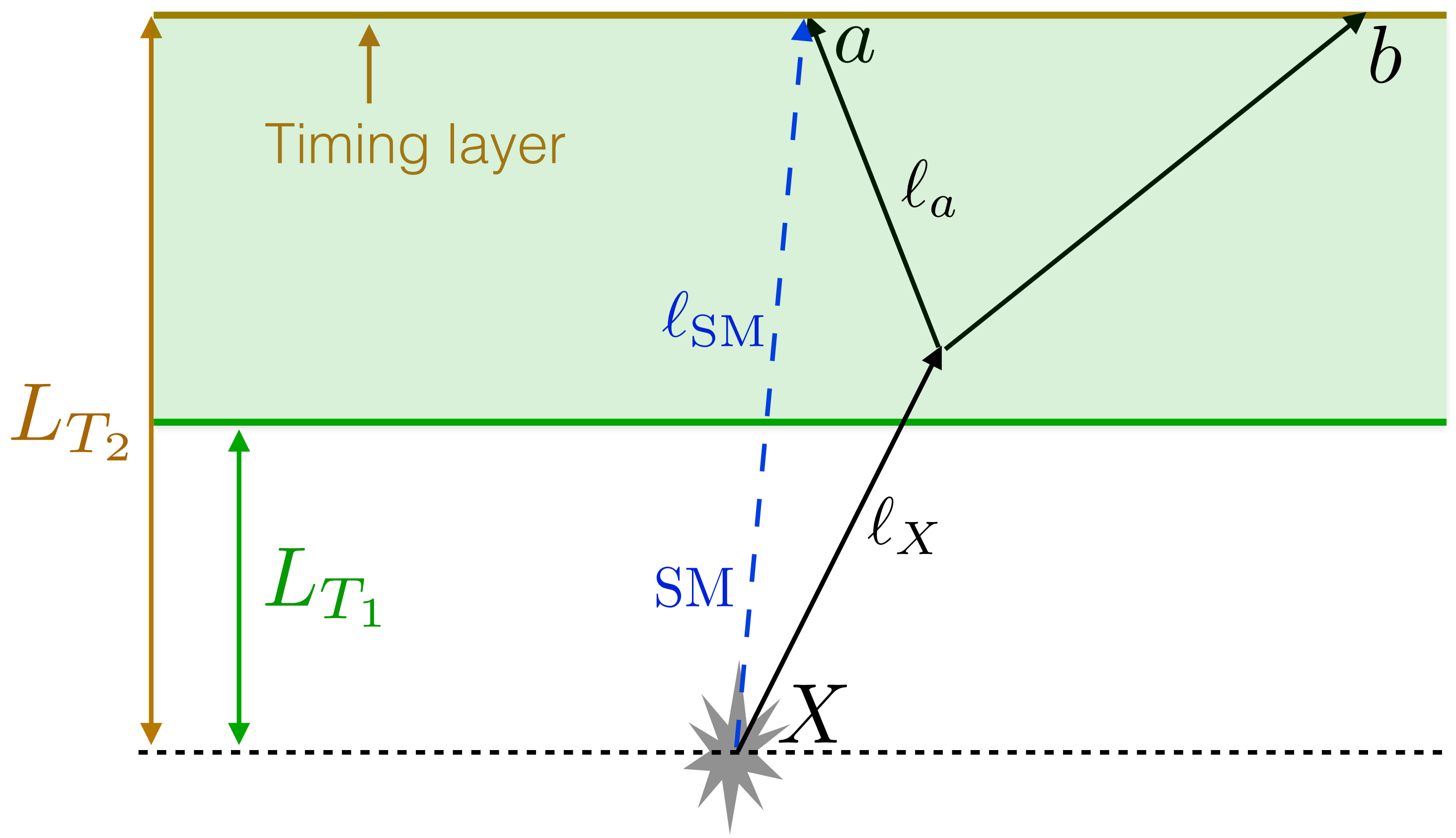
L	$1 - 10$ meters	$10 - 100$ meters

Advantage of far detector?
Far away from interaction point, less background.

We propose to use timing information
Significantly lower background near interaction point.

Time delay



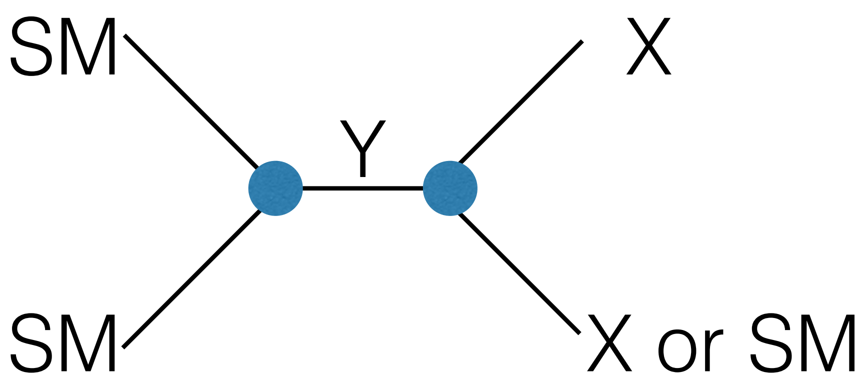
$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}} \qquad \beta_a \simeq \beta_{\rm SM} \simeq 1$$

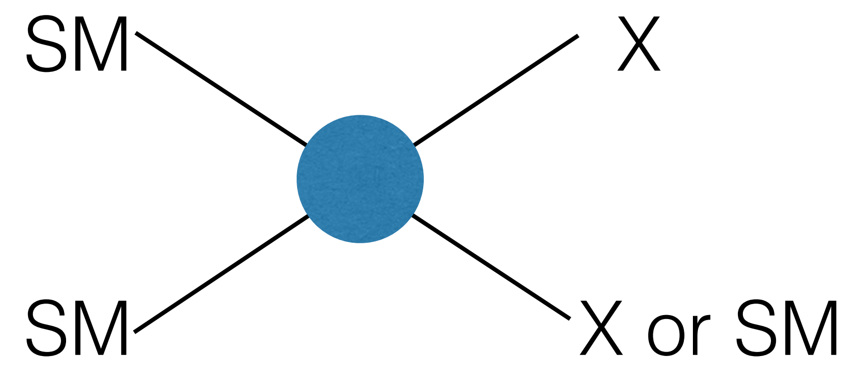
Good for massive LLP produced with small or moderate boost

$$\beta_X < 1$$

Basic topologies

X = LLP





boost: $\gamma \simeq \dfrac{m_Y}{2m_X}$

challenging for $m_X \ll m_Y$

benchmark: Higgs portal

$Y = \text{Higgs}$

$X \to \text{SM}$ Long lived

boost: $\gamma \sim 1$

slow moving, sizable Δt

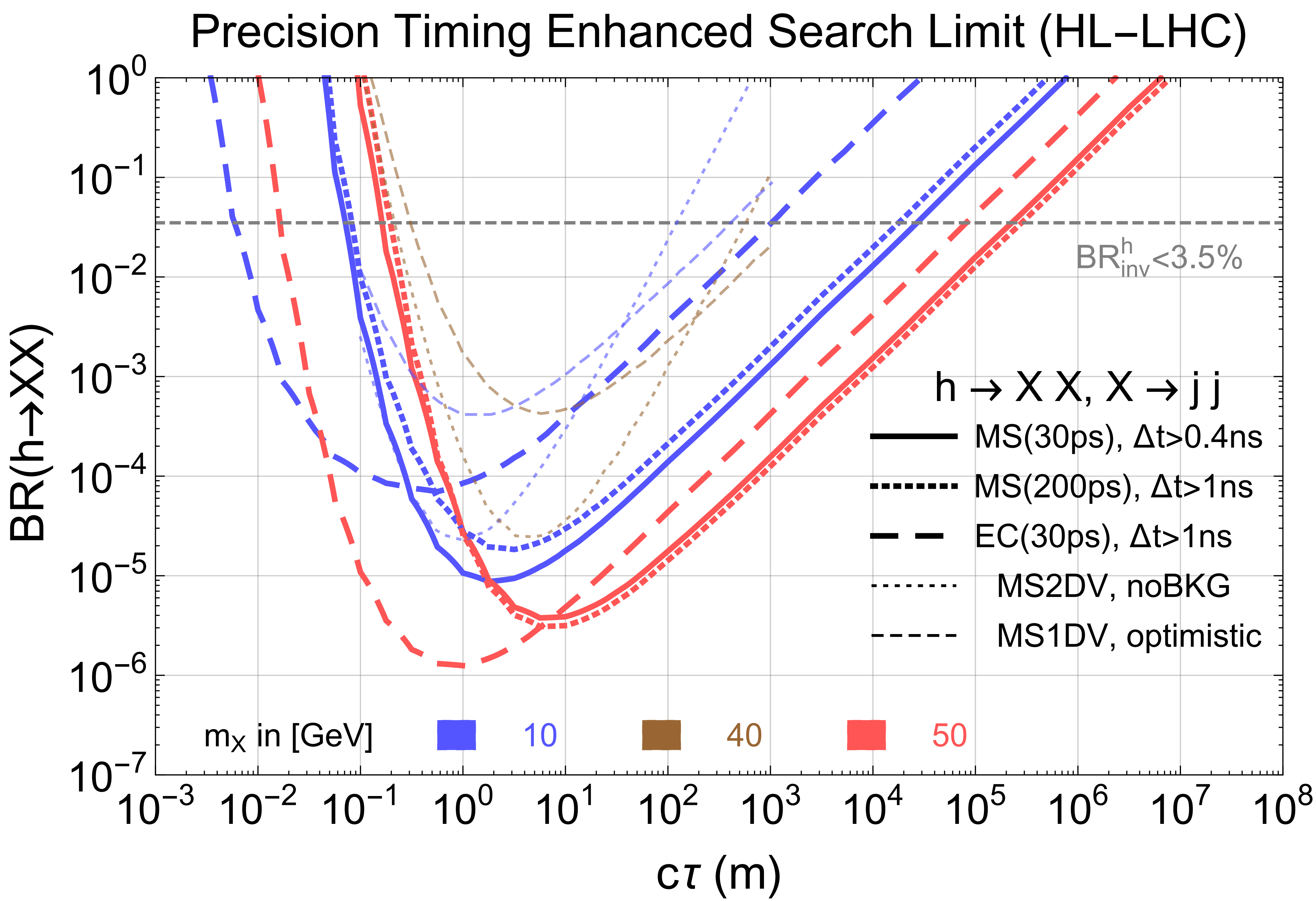
benchmark: SUSY

$X = \text{neutralino}$

$\chi_0 \to \text{gravitino} + \ldots$ Long lived

Sensitivity to Higgs portal

Jia Liu, Zhen Liu, LTW

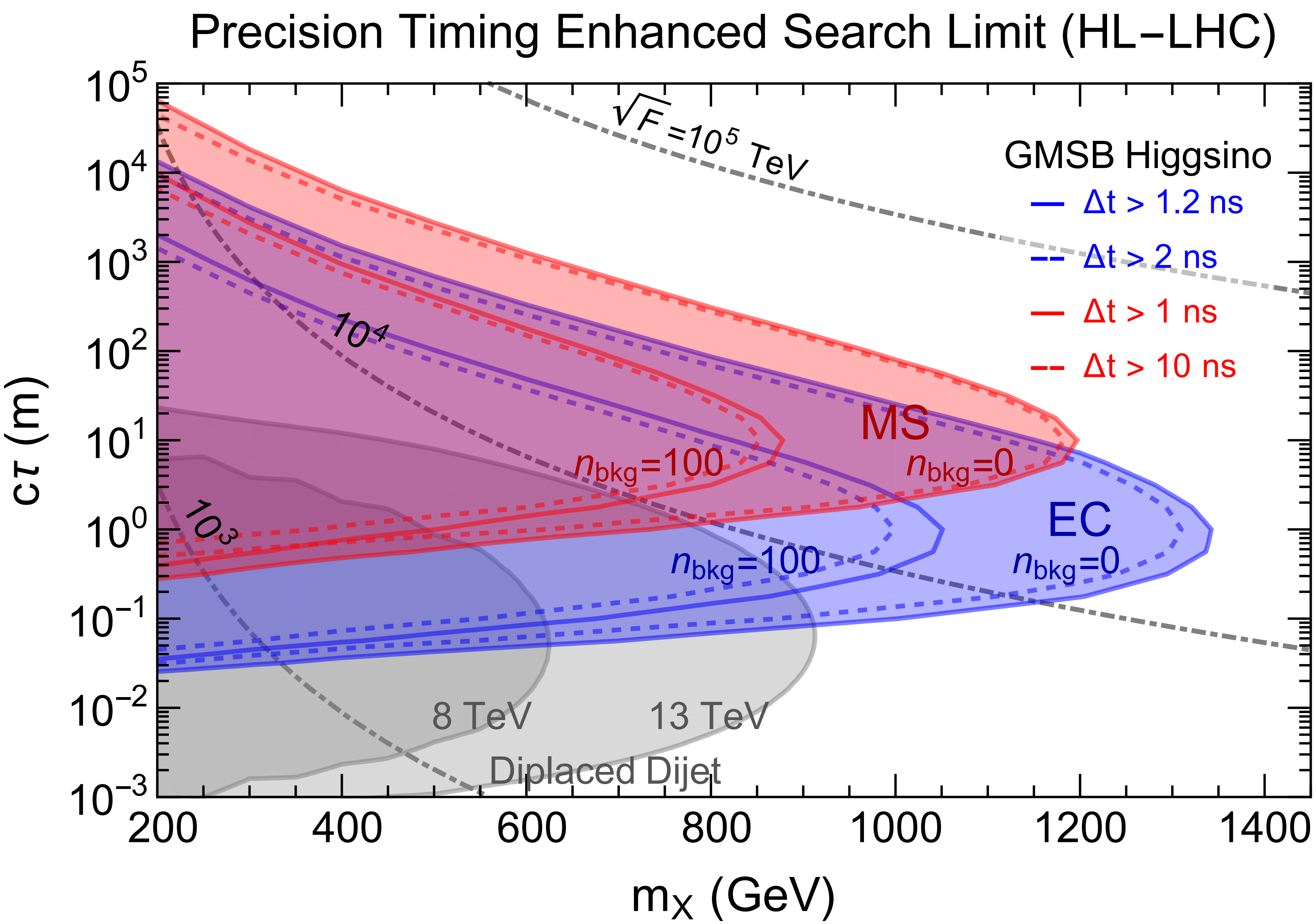


For example, for $\mathrm{BR}(h \to XX) \sim 10^{-3}$

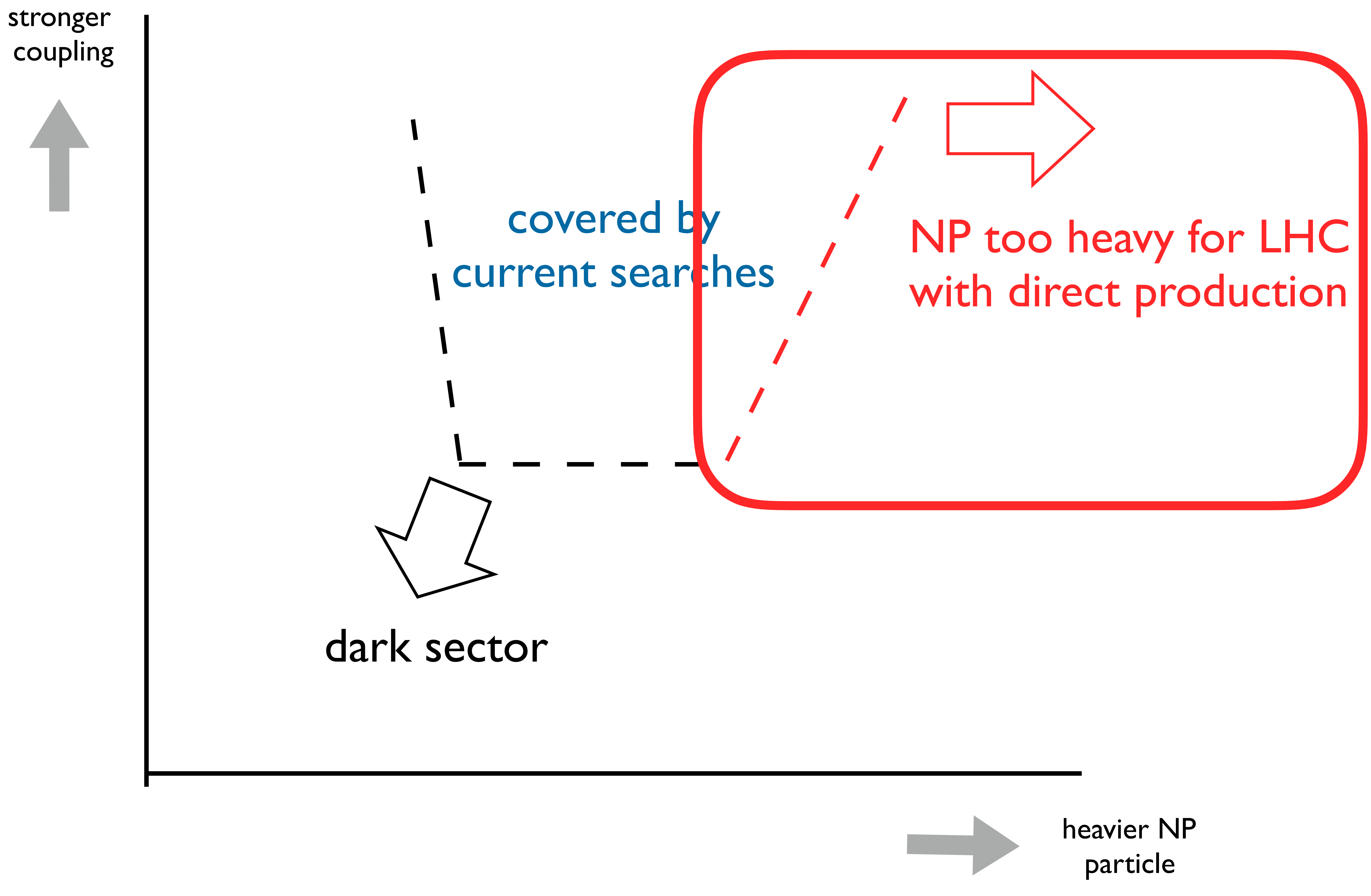
EC(MS) reach can be $c\tau \sim 10^{3}(10^{4})$ meters

Sensitivity to SUSY

Jia Liu, Zhen Liu, LTW



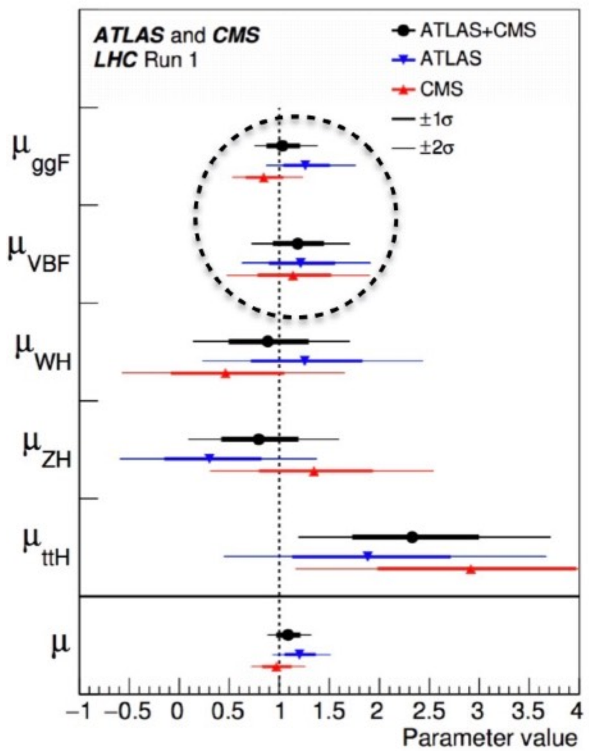
Slower moving LLP, timing cuts can be further relaxed.

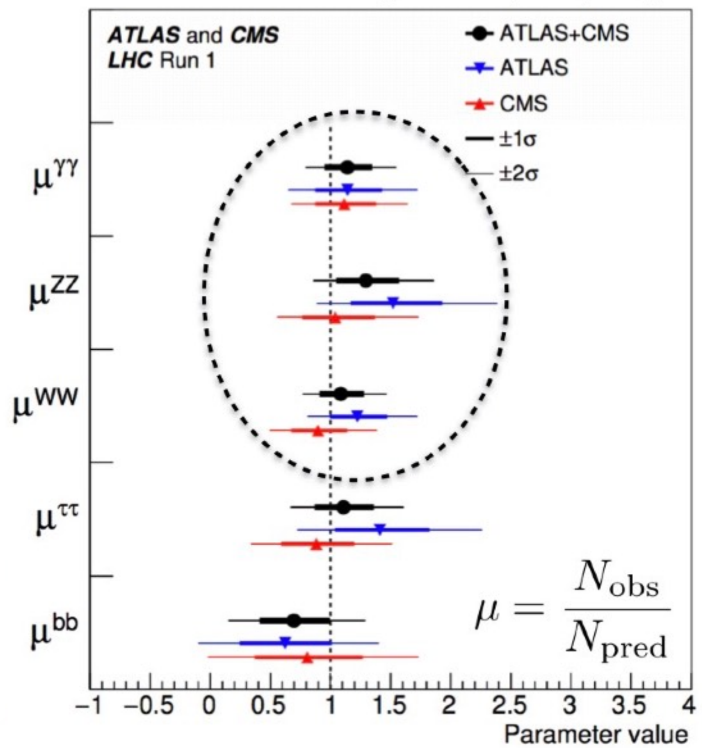

stronger coupling
covered by current searches
NP too heavy for LHC with direct production
dark sector
heavier NP particle

Revealing trace of new physics with precision measurements

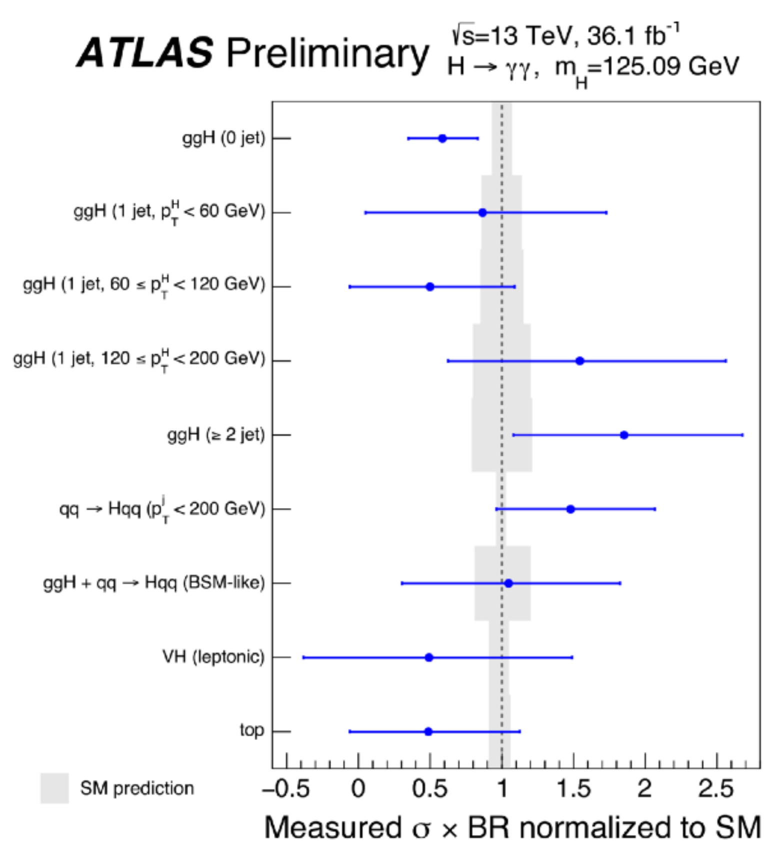
Higgs Standard Model-like

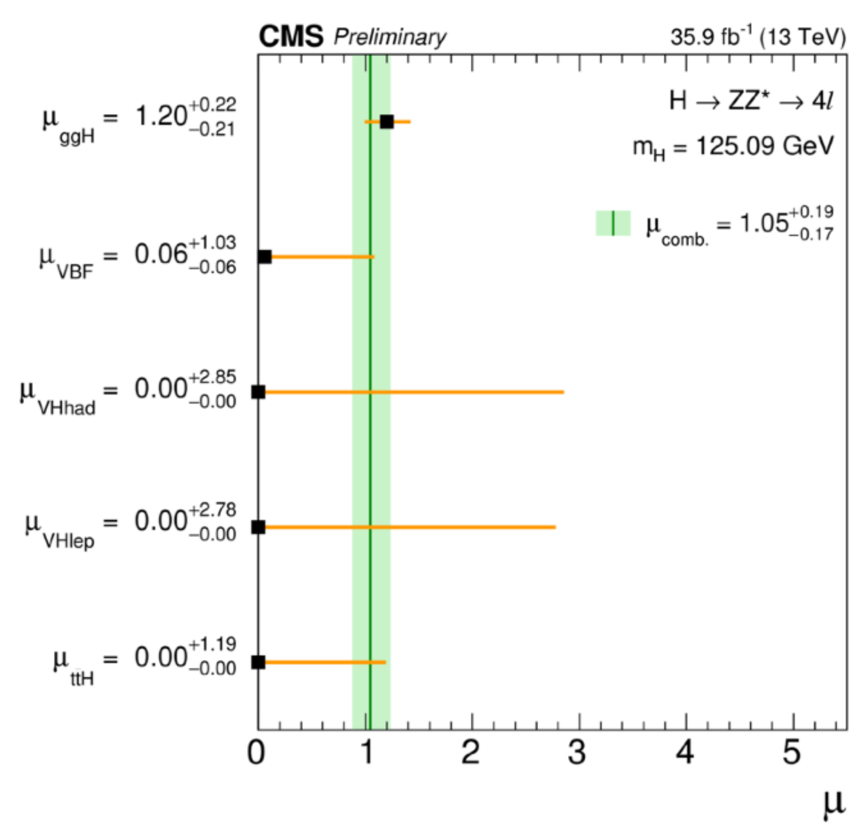
[JHEP 08 (2016) 045]





Agree to about 10-20%





Not entirely surprising

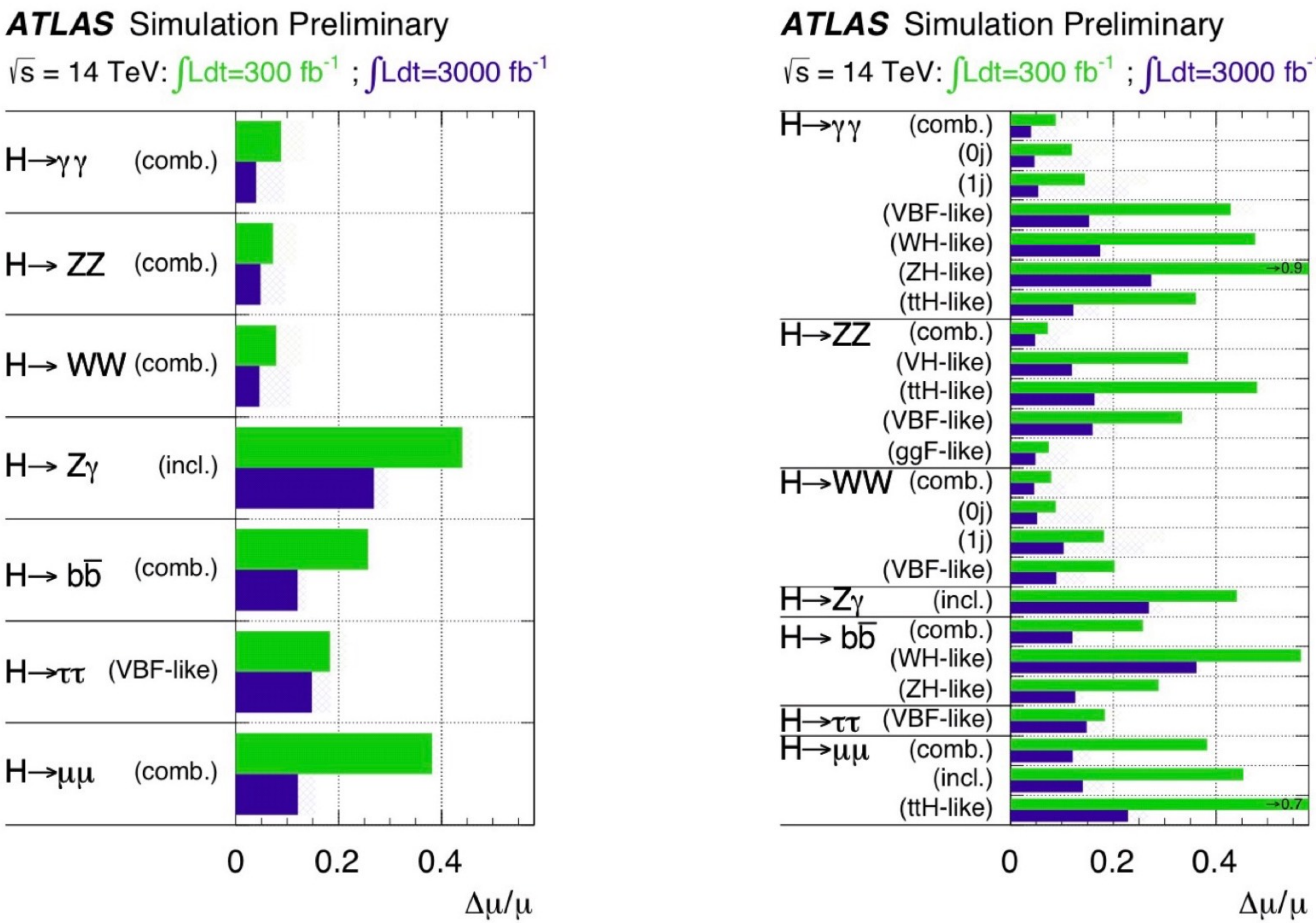
- In general, deviation induced by new physics is of the form

$$\delta \simeq c \frac{v^2}{M_{\rm NP}^2}$$

M_{NP} : mass of new physics
c: O(1) coefficient

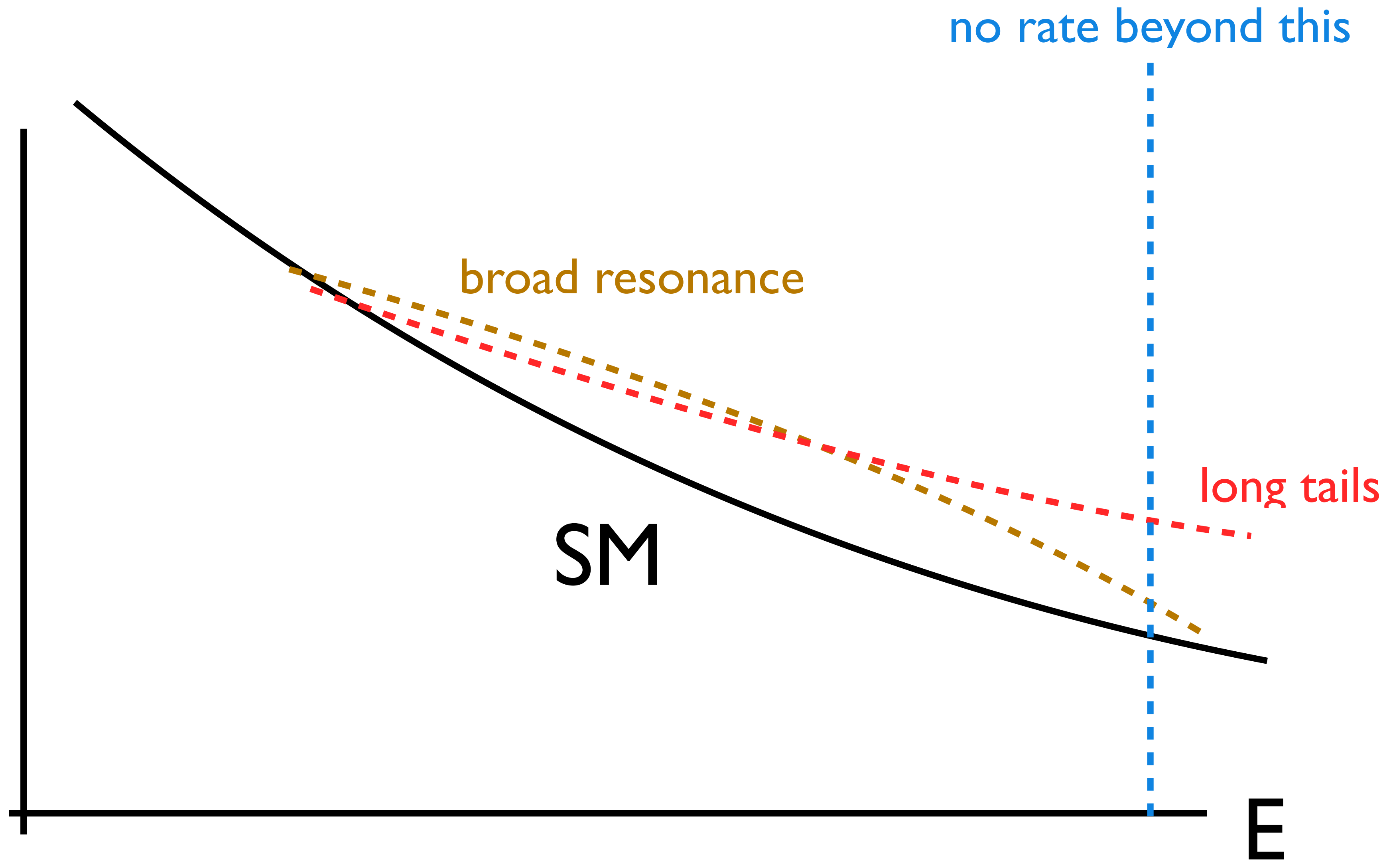
  - Current LHC precision: 10%
    $\Rightarrow$ sensitive to M_{NP} < 500-700 GeV
  - At the same time, direct searches constrain new physics below TeV already.
  - Unlikely to see O(1) deviation.

Significant improvement with high lumi



→ 4-5% on Higgs coupling, reach TeV new physics

Precision measurement with distribution

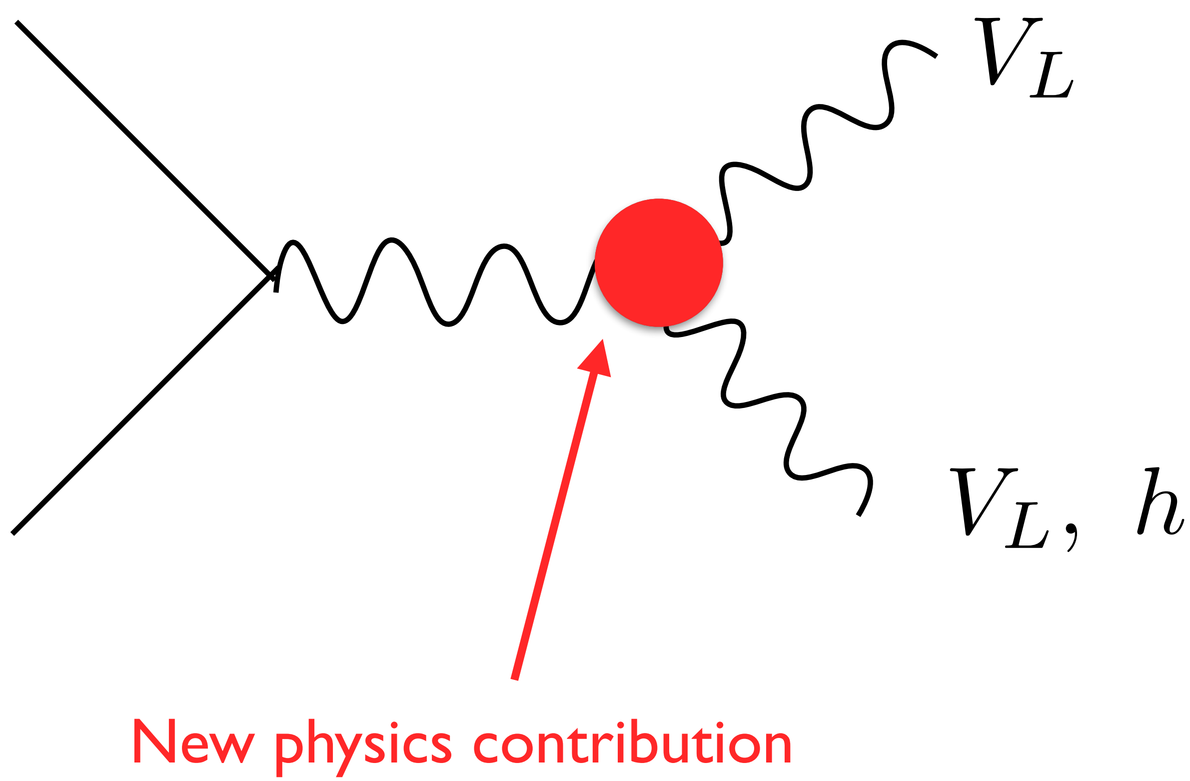


Low S/B, systematic dominated.

Room to improve.

Diboson production at the LHC

$$q\bar{q} \to VV, \quad V = W, Z, h.$$



New physics effect encoded in the non-renormalizable operators:

$$\frac{1}{\Lambda^2}\mathcal{O}$$

Λ : new physics scale

Precision measurement at the LHC possible?

LEP precision tests probe NP about 2 TeV

$$\frac{\delta\sigma}{\sigma_{\rm SM}} \sim \frac{m_W^2}{\Lambda^2} \sim 2\times 10^{-3} \quad \rightarrow \Lambda \geq 2\ {\rm TeV}$$

At LHC, new physics effect grows with energy

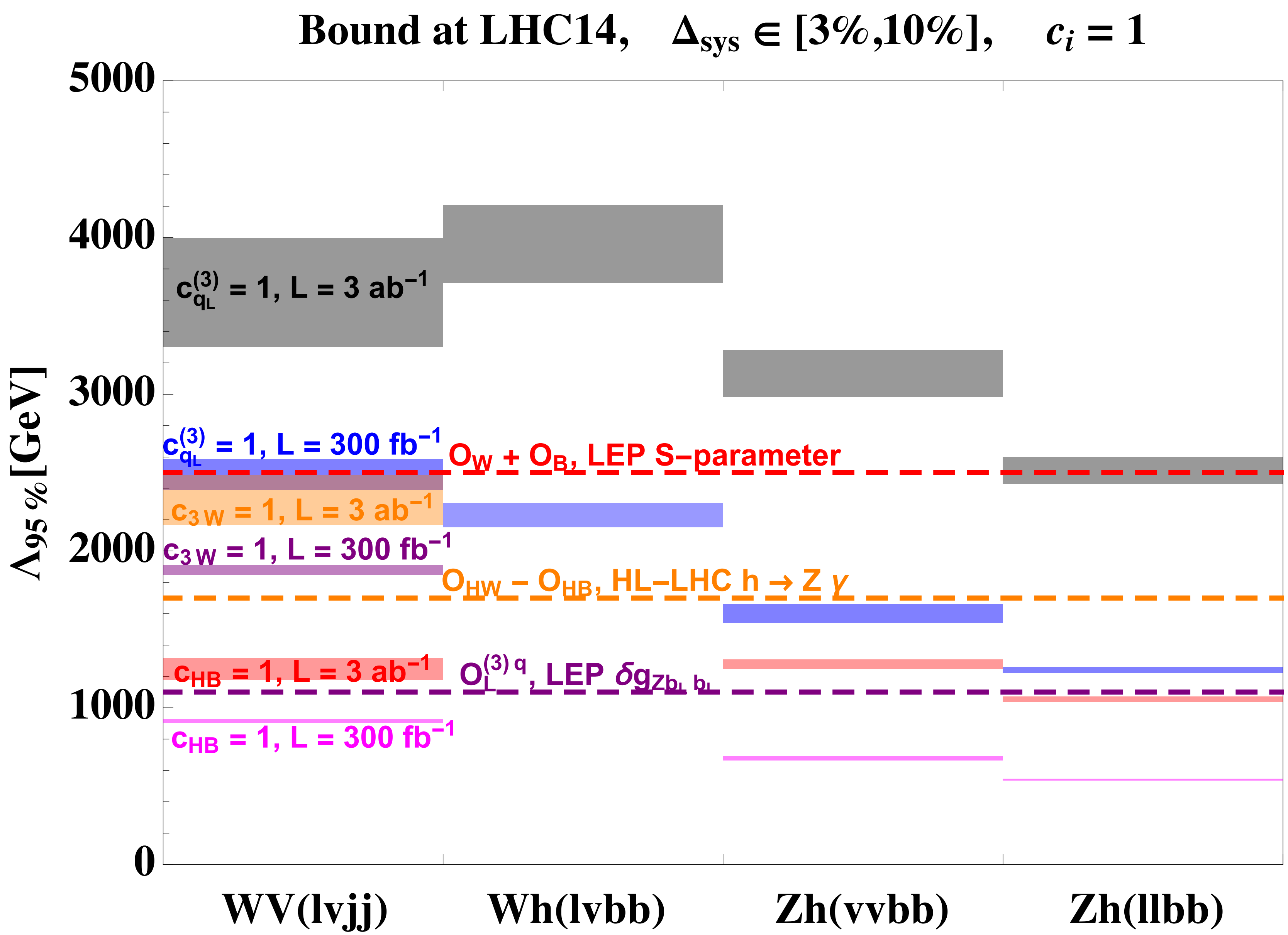
$$\frac{\delta\sigma}{\sigma_{\rm SM}} \sim \frac{E^2}{\Lambda^2} \sim 0.25 \qquad E \sim 1\ {\rm TeV},\ \Lambda \sim 2\ {\rm TeV}$$

LHC needs to make a 20% measurement to beat LEP
LHC has potential.

Operators: d=6

name	structure	coefficient (power counting)
$\mathcal{O}_H$	$\frac{1}{2}\left(\partial_\mu \lvert H\rvert^2\right)^2$	c_H/f^2
$\mathcal{O}_y$	$y\bar{Q}_L H u_R \lvert H\rvert^2$	c_y/f^2
$\mathcal{O}_W$	$ig\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$	c_W/m_*^2
$\mathcal{O}_B$	$ig'\left(H^\dagger \overleftrightarrow{D}^\mu H\right) D^\nu B_{\mu\nu}$	c_B/m_*^2
$\mathcal{O}_{HW}$	$ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$c_{HW}/m_*^2 \times (g_*/4\pi)^2$
$\mathcal{O}_{HB}$	$ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$c_{HB}/m_*^2 \times (g_*/4\pi)^2$
O_L^q	$ig^2\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\bar{Q}_L \gamma^\mu Q_L$	$c_q/m_*^2 \times \epsilon_q^2$
$O_L^{q,3}$	$ig^2\left(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right)\bar{Q}_L \sigma^a \gamma^\mu Q_L$	$c_{q,3}/m_*^2 \times \epsilon_q^2$
O_R^u	$ig^2\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\bar{u}_R \gamma^\mu u_R$	$c_u/m_*^2 \times \epsilon_u^2$
O_R^u	$ig^2\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\bar{d}_R \gamma^\mu d_R$	$c_d/m_*^2 \times \epsilon_d^2$
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	c_T/f^2
$\mathcal{O}_6$	$\lvert H\rvert^6$	λ_3/f^2

Projections



Possible to reach 4 TeV.

D. Liu, LTW

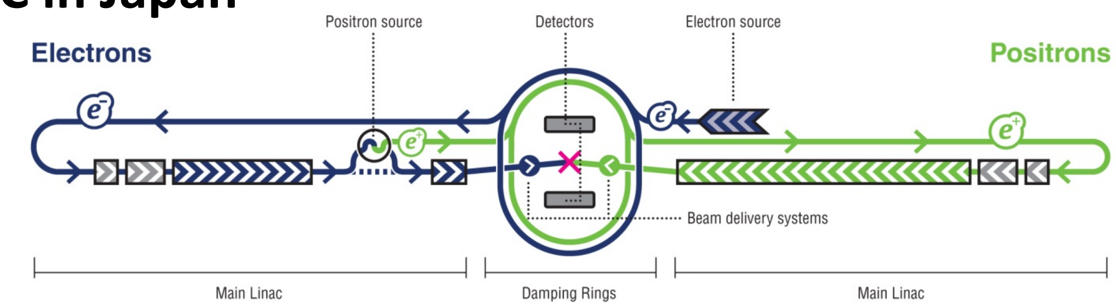
Better than LEP, and many LHC direct searches

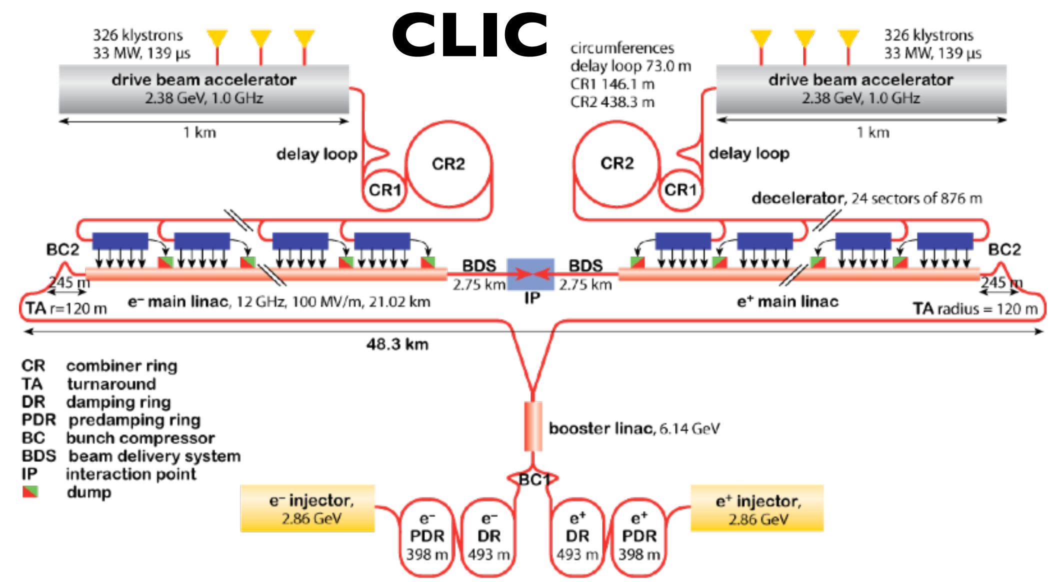
See also: Alioli, Farina, Pappadopulo, Ruderman, Franceschini, Panico, Pomarol, Riva, Wulzer, Azatov, Elias-Miro, Regimuaji, Venturini

Beyond LHC

Future Colliders

ILC in Japan



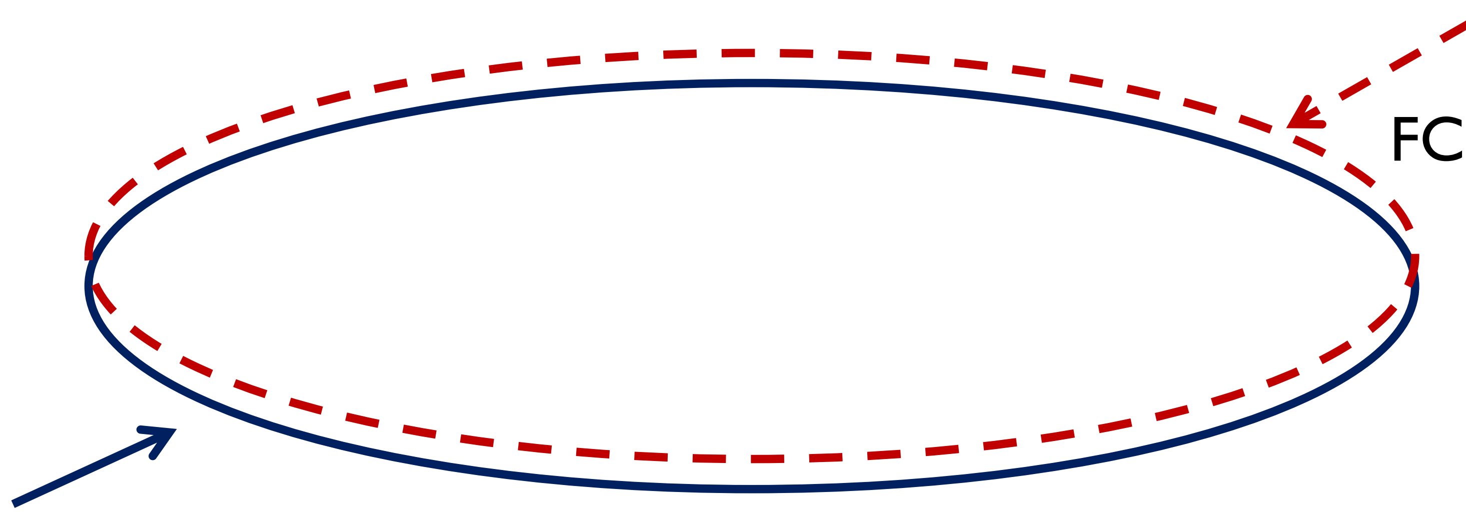


Circular. "Scale up" LEP+LHC

~100 TeV

pp collider

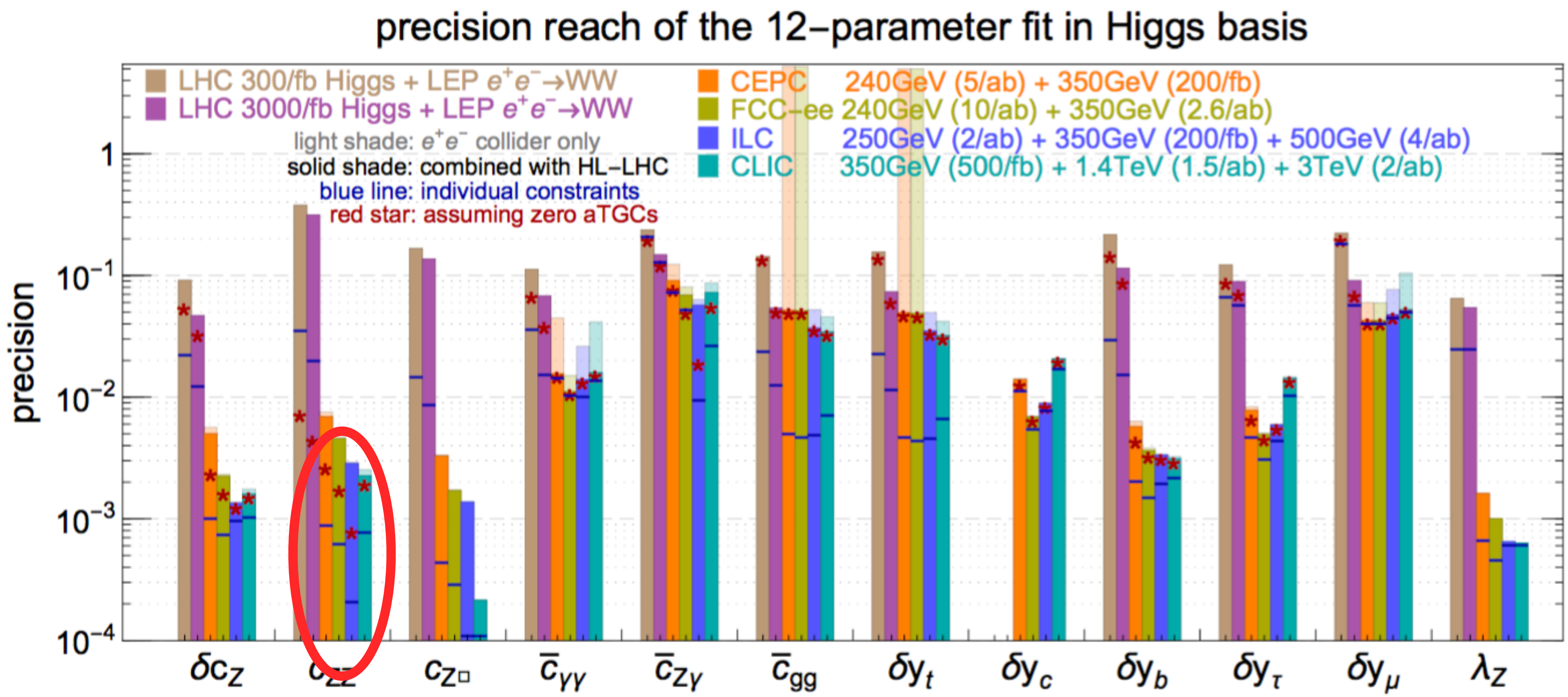
FCC-hh (CERN), SppC(China)



250 GeV **e^-e^+ Higgs Factory**

FCC-ee (CERN), CEPC(China)

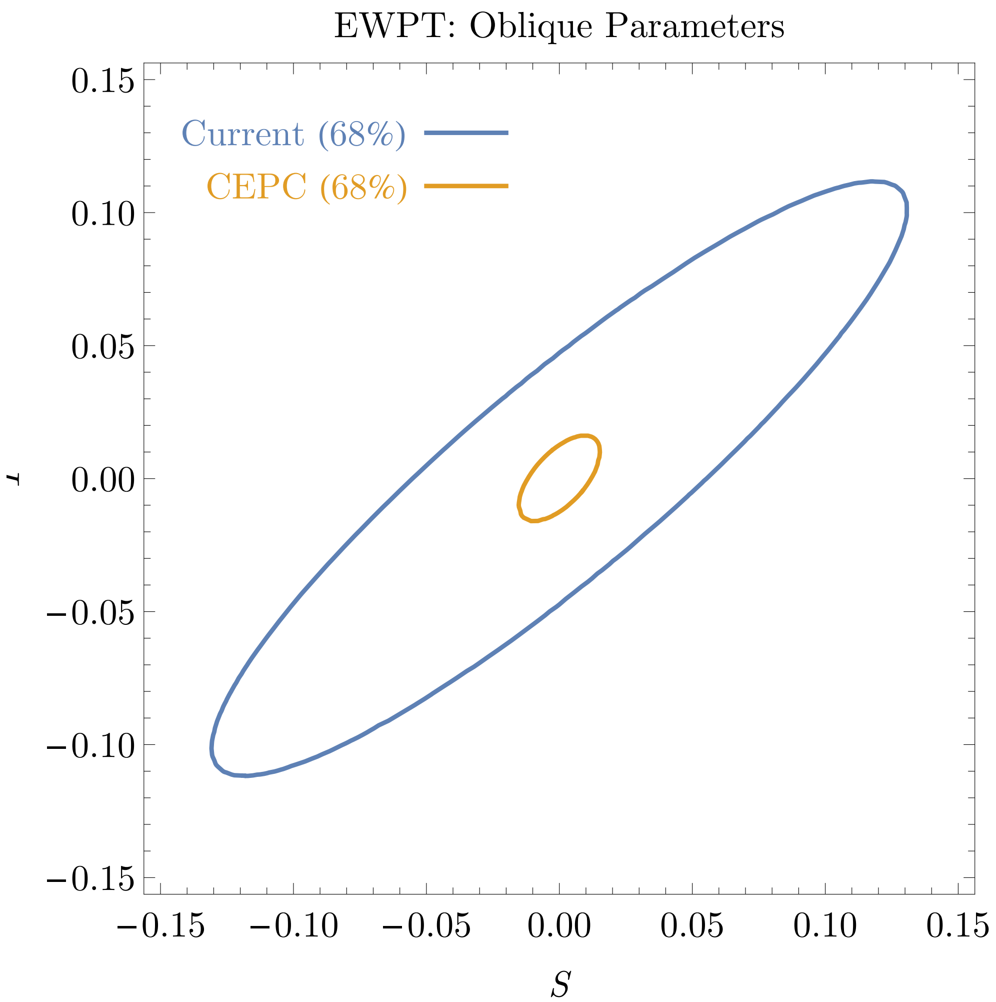
Lepton colliders and precision measurements

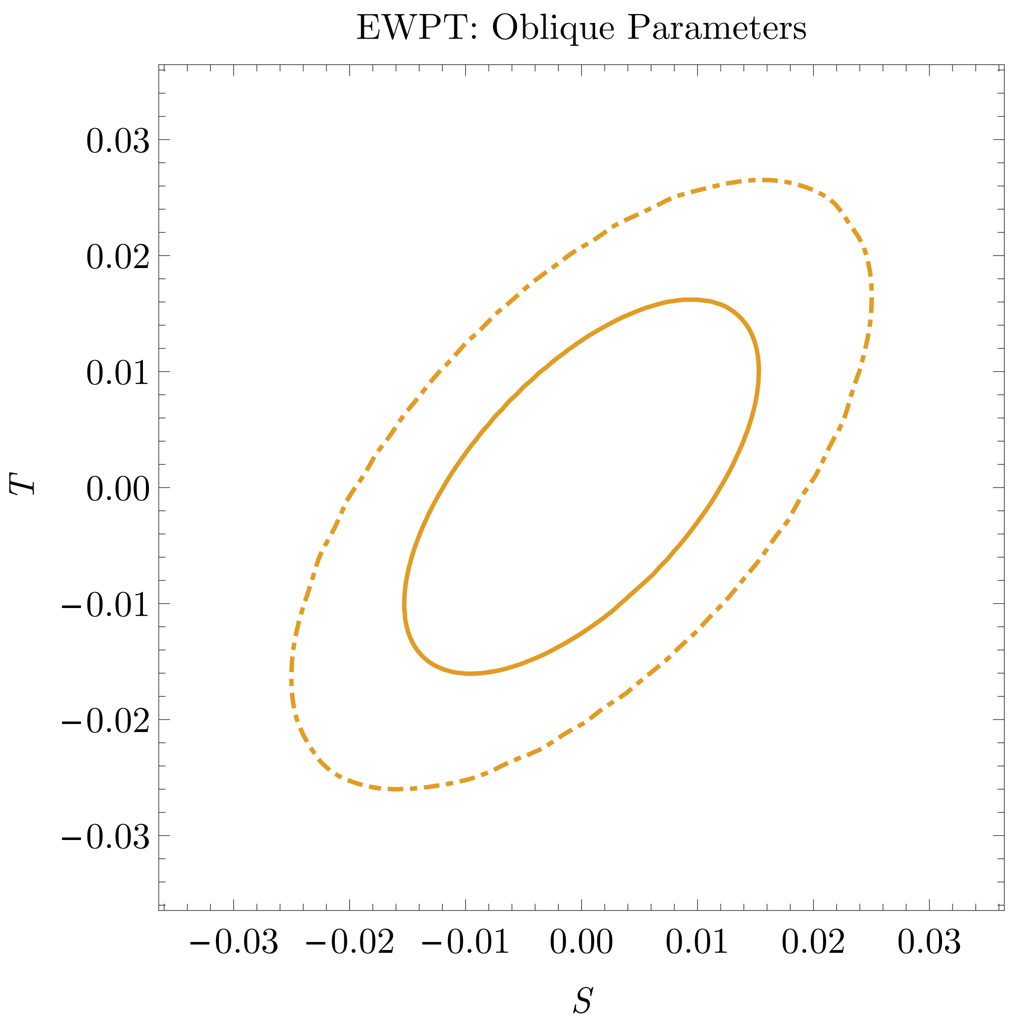


Grojean et al. 1704.02333

Sub percent precision, reach to new physics at multi-TeV scale.
Far beyond the reach of LHC.

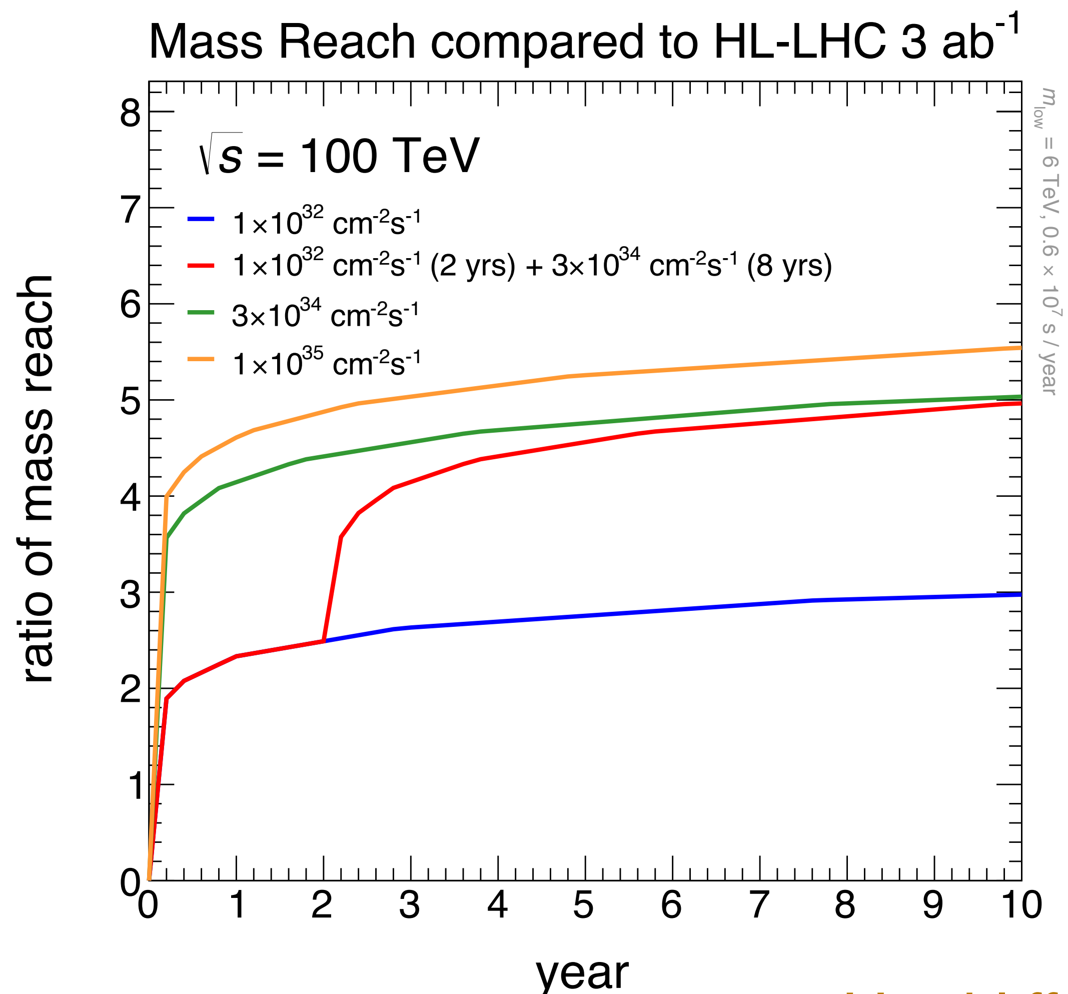
Electroweak precision





FCC can do even better (by a factor of a few)

100-ish TeV pp collider

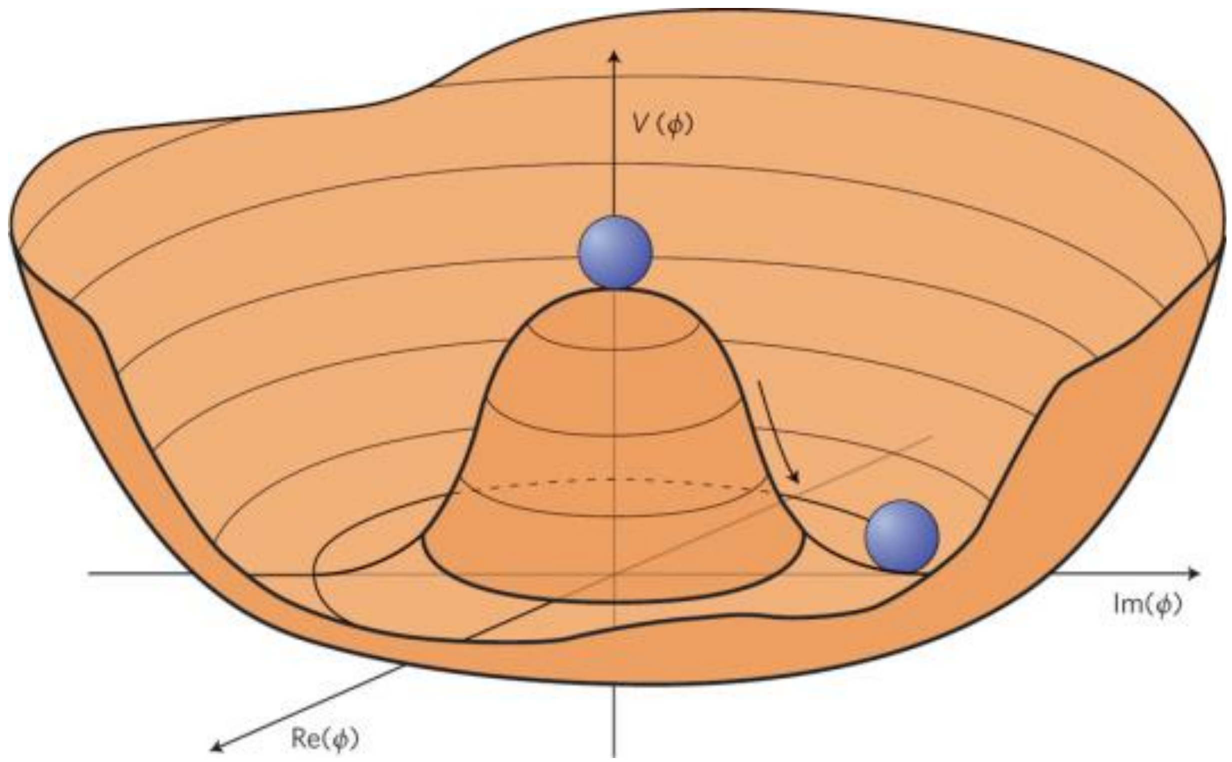


Hinchliffe, Kotwal, Mangano, Quigg, LTW

A factor of at least 5 increase in reach beyond the LHC, with modest luminosity

Electroweak symmetry breaking

"Simple" picture: Mexican hat

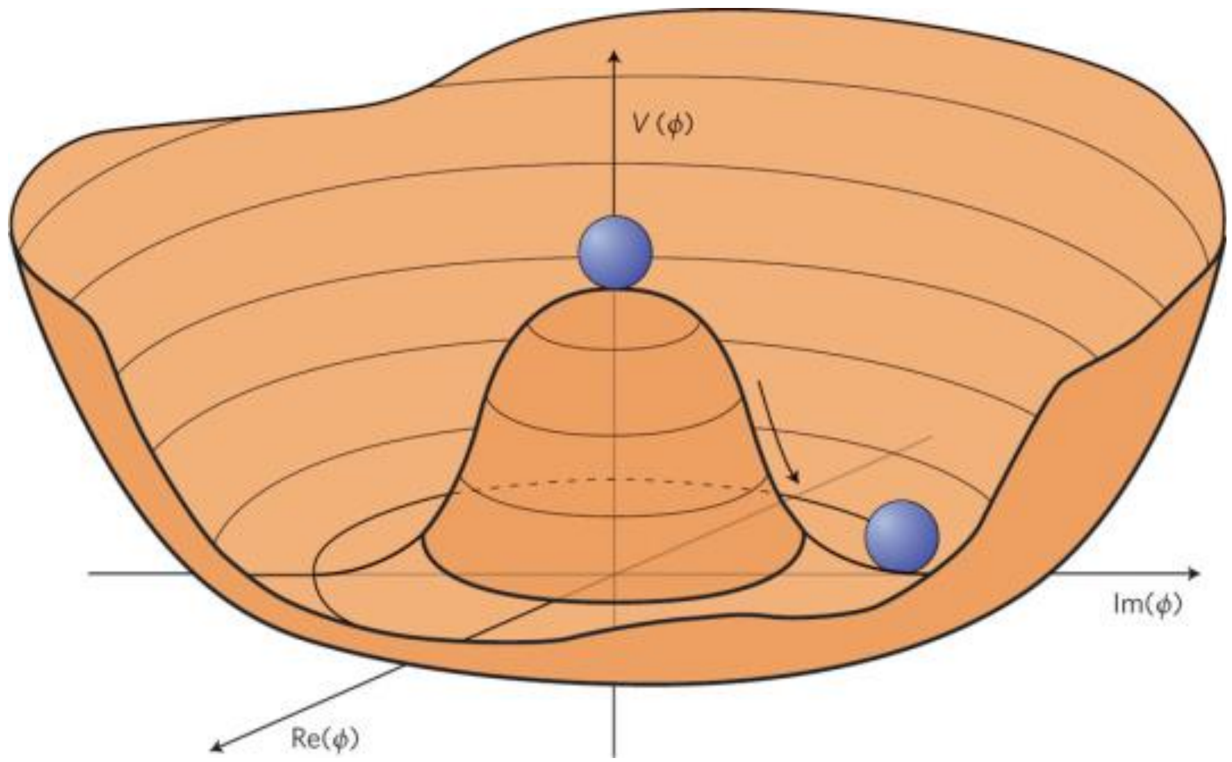


$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

$$\langle h \rangle \equiv v \neq 0 \;\rightarrow\; m_W = g_W \frac{v}{2}$$

Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

"Simple" picture: Mexican hat



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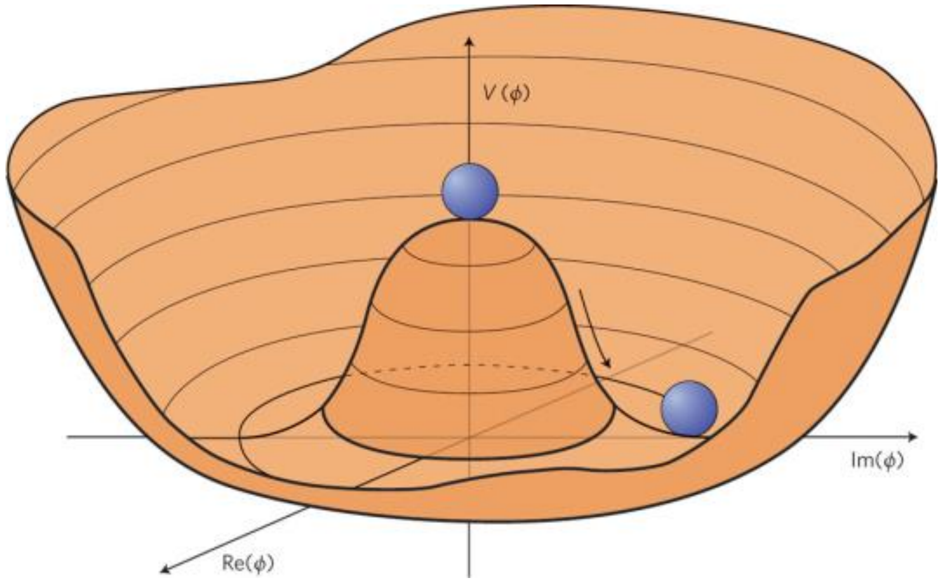
Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

However, this simplicity is deceiving.
Parameters not predicted by theory. Can not be the complete picture.

Mysteries of the electroweak scale.



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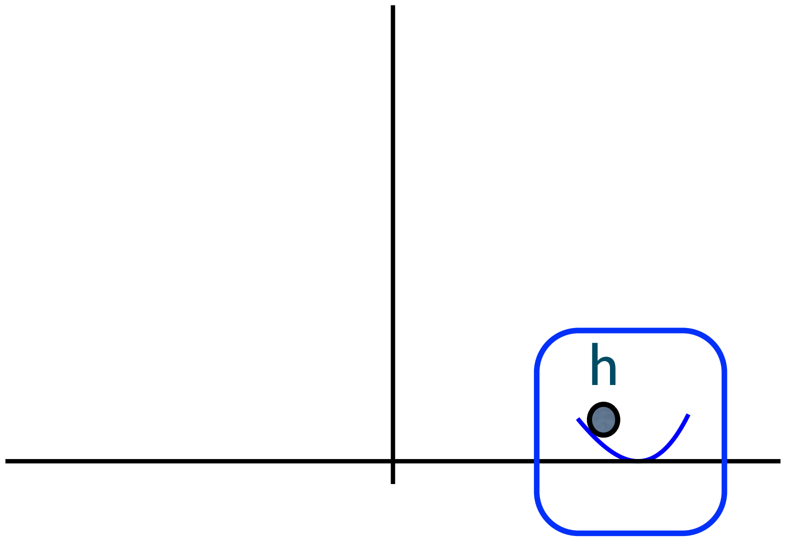
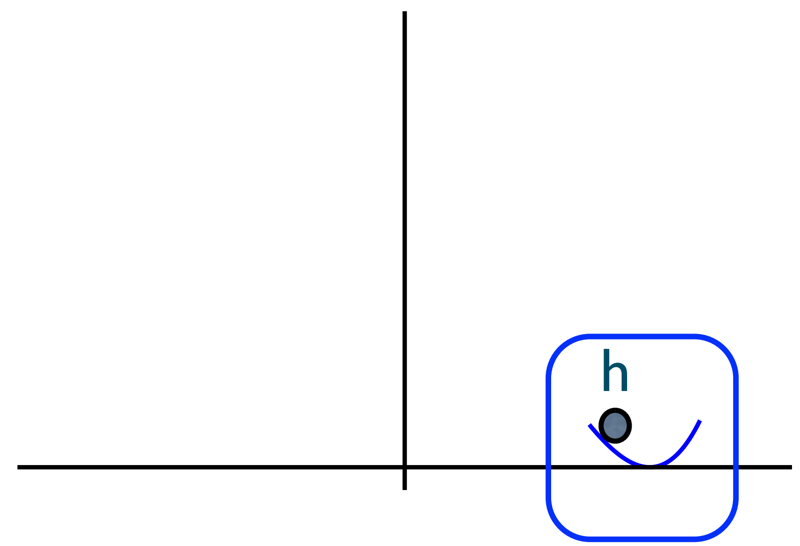


What we know now

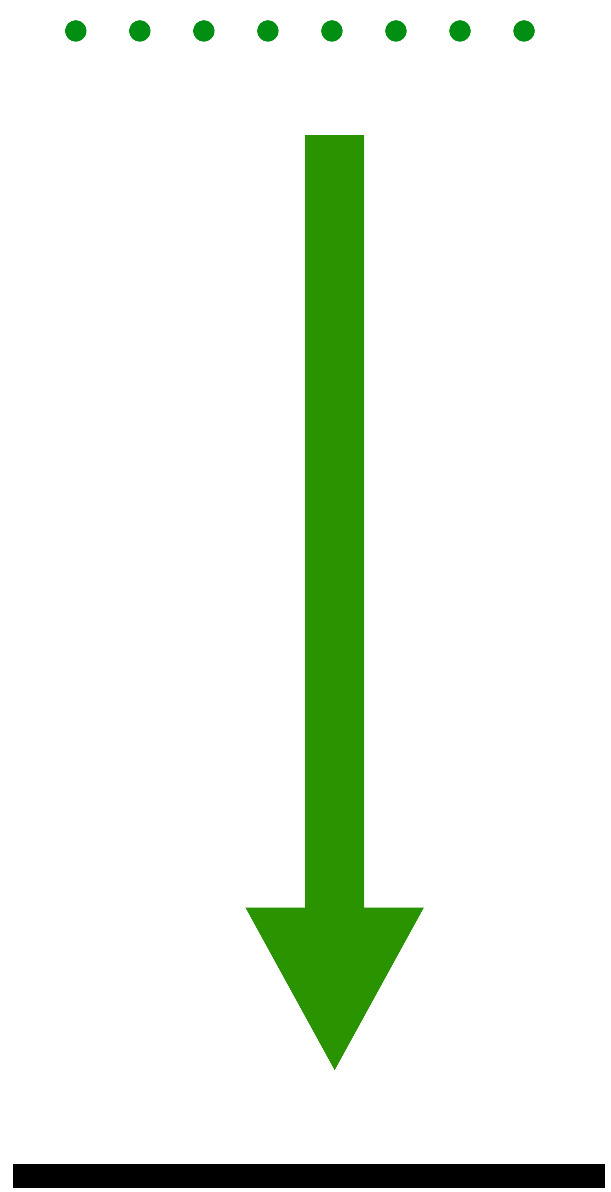
Mysteries of the electroweak scale.



What we know now

- How to predict/calculate Higgs mass? Naturalness
- Full Higgs potential?
  - Order of electroweak phase transition

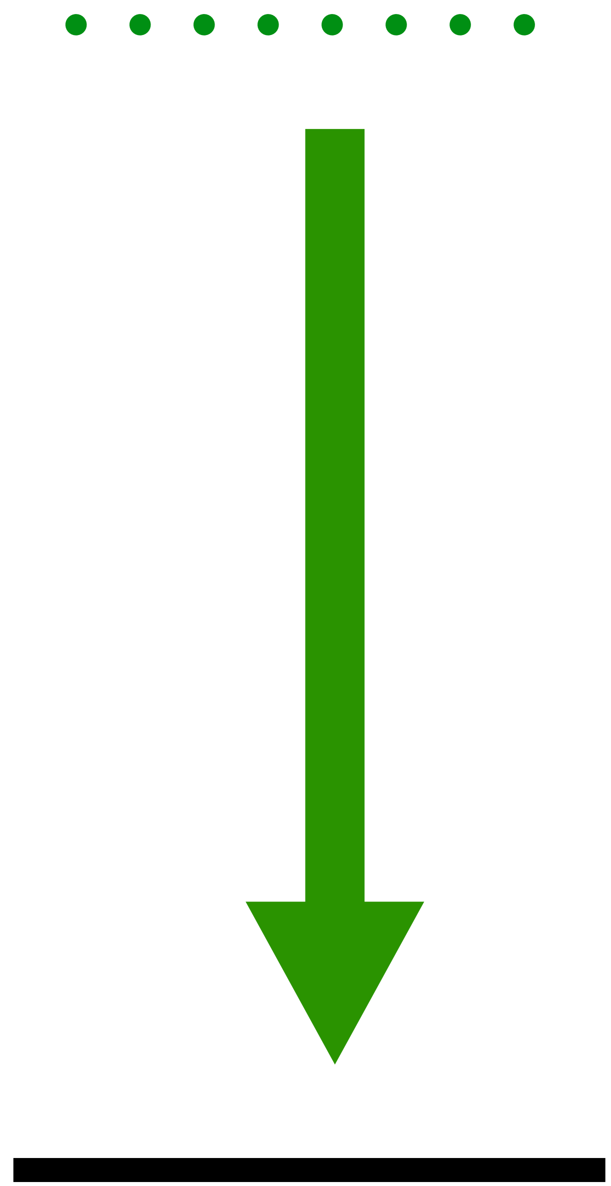
How to predict Higgs mass?



The energy scale of new physics responsible for EWSB

Electroweak scale, 100 GeV.
m_h , m_W …

How to predict Higgs mass?



The energy scale of new physics
responsible for EWSB

What is this energy scale?
$M_{Planck} = 10^{19}$ GeV, …?

If so, why is so different from 100 GeV?
The so called naturalness problem

Electroweak scale, 100 GeV.
m_h , m_W …

Naturalness of electroweak symmetry breaking

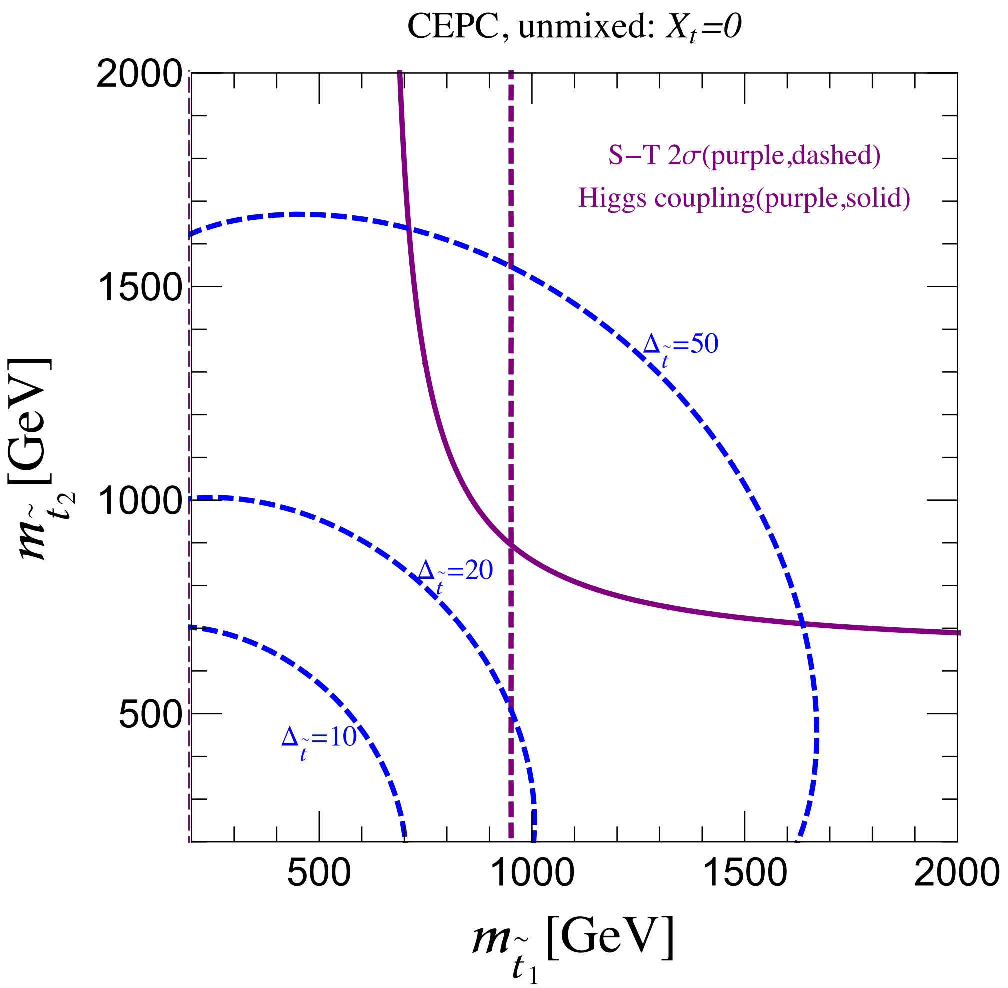
The energy scale of new physics
responsible for EWSB

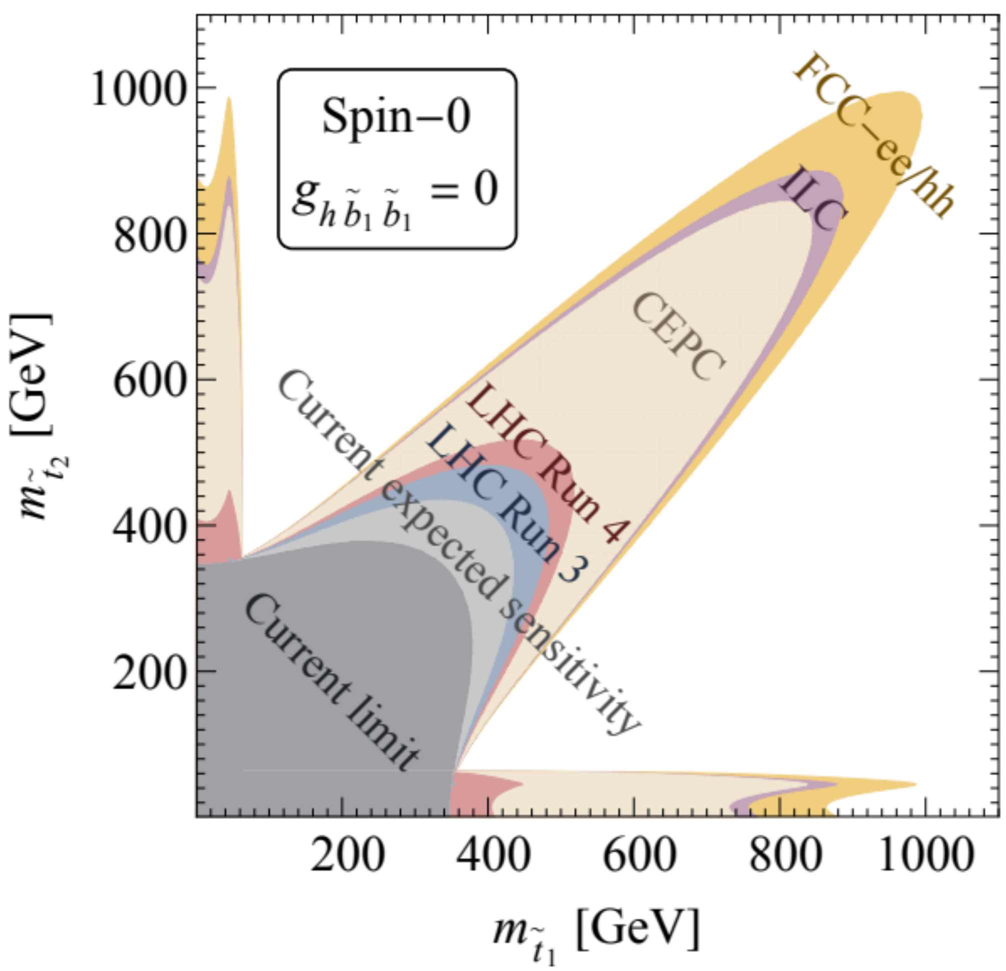
TeV new physics.
Naturalness motivated
Many models, ideas.

Electroweak scale, 100 GeV.
m_h , m_W …

Naturalness in SUSY

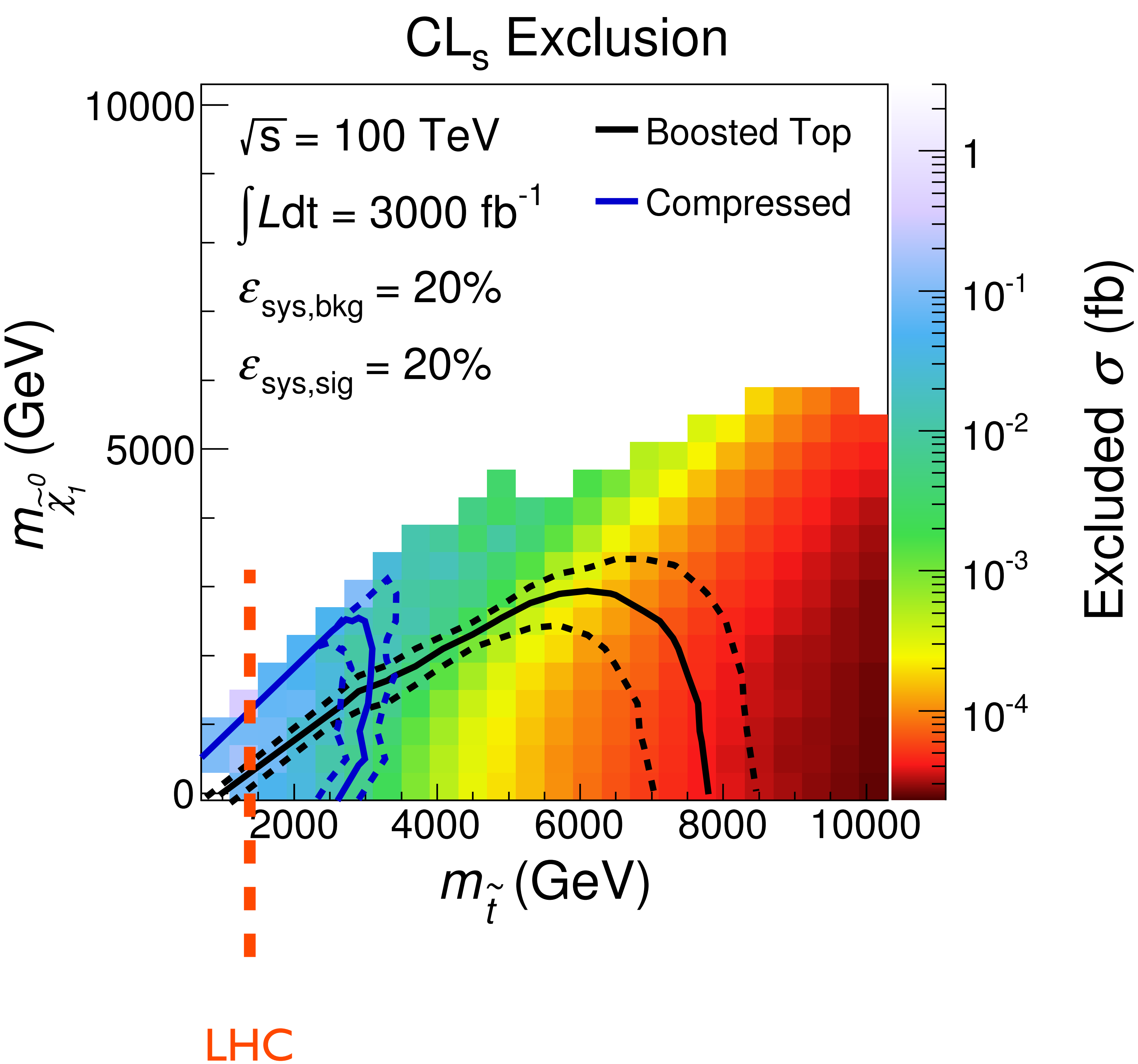
- LHC searches model dependent, many blind spots.



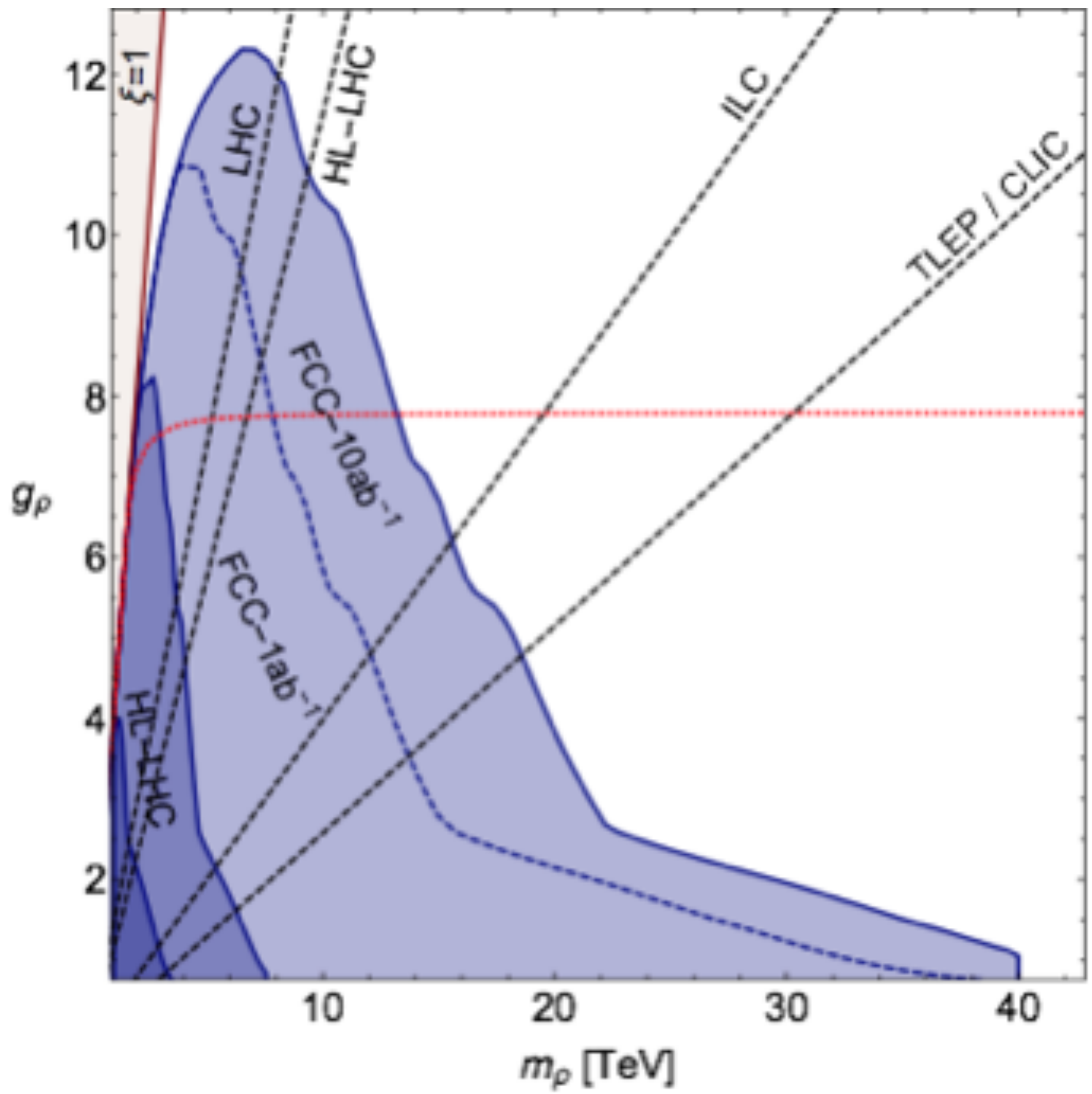


- Testing fine-tuning down to percent level.

Testing naturalness: Supersymmetry



Composite Higgs

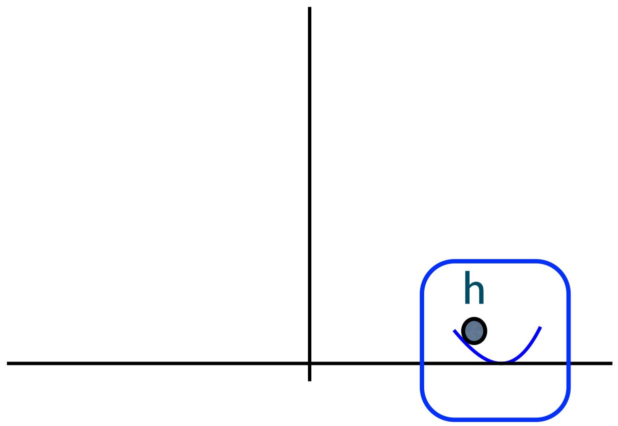


Why is Higgs measurement crucial?

- Naturalness is the most pressing question of EWSB.
  - How should we predict the Higgs mass?
- We may not have the right idea. No confirmation of any of the proposed models.
- Need experiment!
- Fortunately, with Higgs, we know where to look.
- And, the clue to any possible way to address naturalness problem must show up in Higgs coupling measurement.

Mysteries of the electroweak scale.

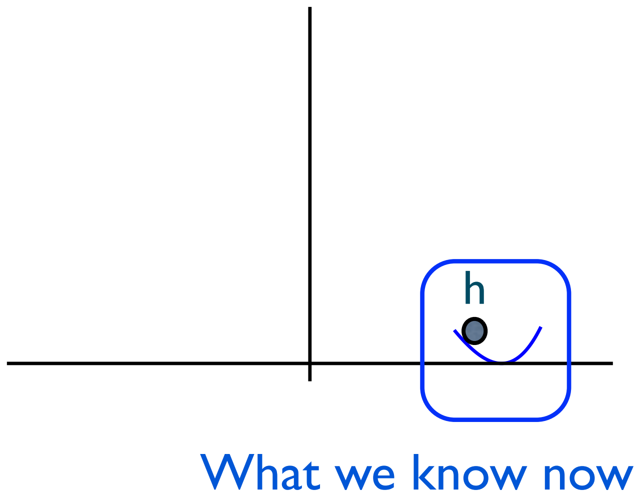
Mysteries of the electroweak scale.



What we know now

- How to predict/calculate Higgs mass?
- What does the rest of the Higgs potential look like? Nature of electroweak phase transition.
- Is it connected to the matter anti-matter asymmetry?

Mysteries of the electroweak scale.

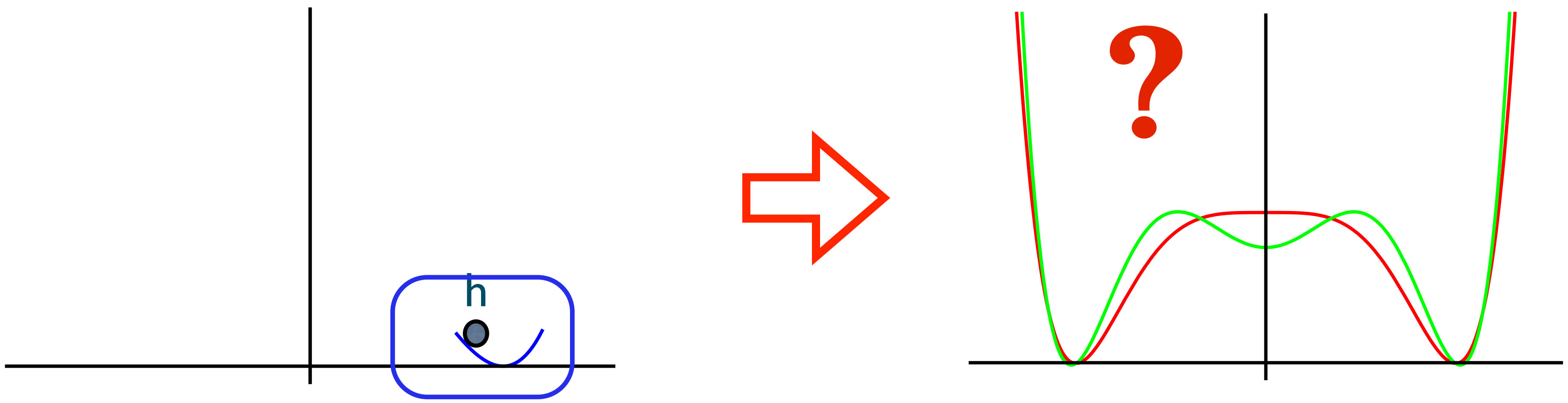


- How to predict/calculate Higgs mass?

- What does the rest of the Higgs potential look like? Nature of electroweak phase transition.

- Is it connected to the matter anti-matter asymmetry?

Nature of EW phase transition



What we know from LHC
LHC upgrades won't go much further

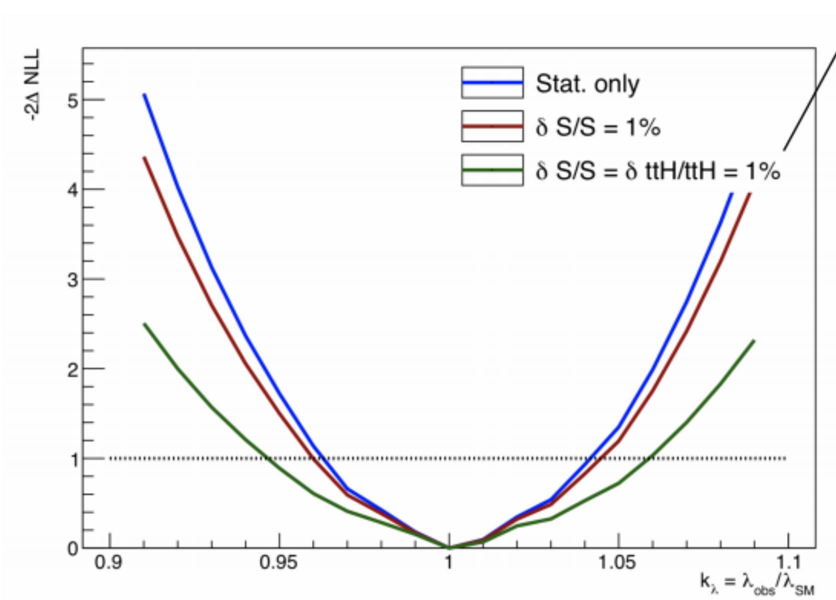
"wiggles" in Higgs potential

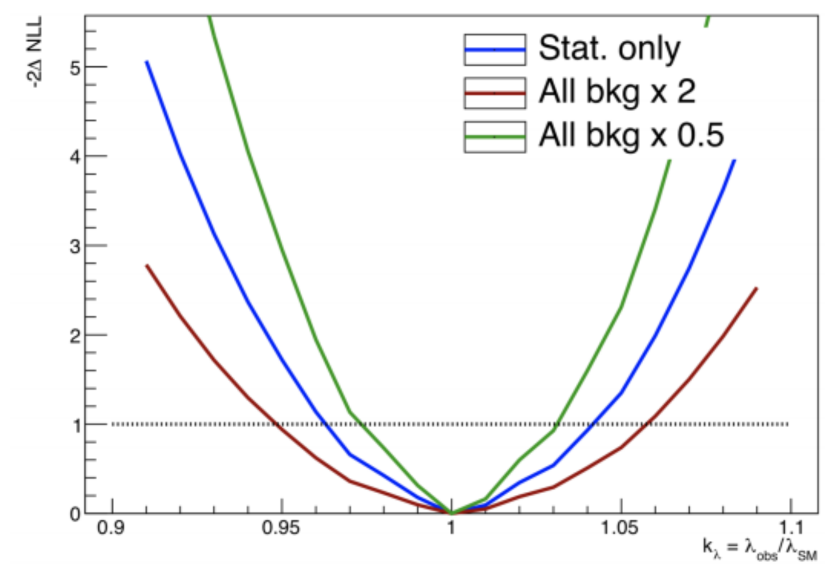
Big difference in triple Higgs coupling

Triple Higgs coupling at 100 TeV collider

Precision on the self-coupling

assuming QCD can be measured from sidebands





nominal background yields:

$\delta\kappa_\lambda(\text{stat}) \approx$ 3.5 %
$\delta\kappa_\lambda(\text{stat + syst}) \approx$ 6 %

varying (0.5x-2x) background yields:

$\delta\kappa_\lambda(\text{stat}) \approx$ 3 - 5 %

Talk by Michele Selvaggi at 2nd FCC physics workshop

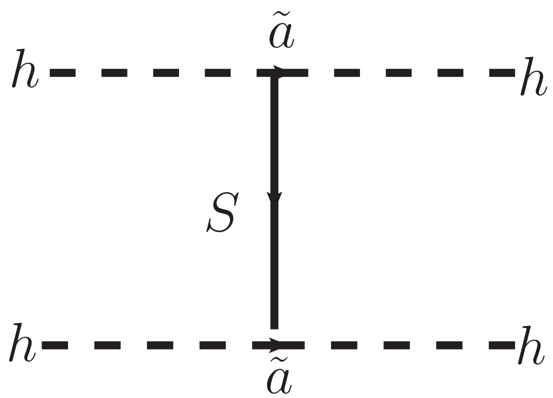
But, there should be more

$$V(h) = \frac{m^2}{2}h^2 + \lambda h^4 + \frac{1}{\Lambda^2}h^6 + \ldots$$

- 1st order EW phase transition means there is new physics close to the weak scale.
- Can be difficult to discover at the LHC.
- Will leave more signature in Higgs coupling.

For example

$$m^2 h^\dagger h + \tilde{\lambda}(h^\dagger h)^2 + m_S^2 S^2 + \tilde{a} S h^\dagger h + \tilde{b} S^3 + \tilde{\kappa} S^2 h^\dagger h + \tilde{h} S^4$$



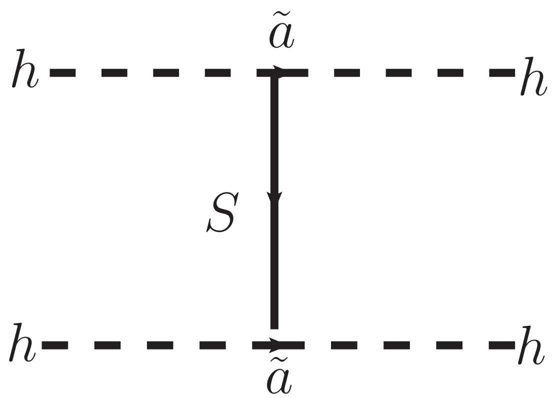
$$\frac{c}{m_S^2}\left(h^\dagger \partial h\right)^2$$

shift in h-Z coupling

$$\delta_{Zh} \sim c\frac{v^2}{m_S^2}$$

For example

$$m^2 h^\dagger h + \tilde{\lambda}(h^\dagger h)^2 + m_S^2 S^2 + \tilde{a} S h^\dagger h + \tilde{b} S^3 + \tilde{\kappa} S^2 h^\dagger h + \tilde{h} S^4$$



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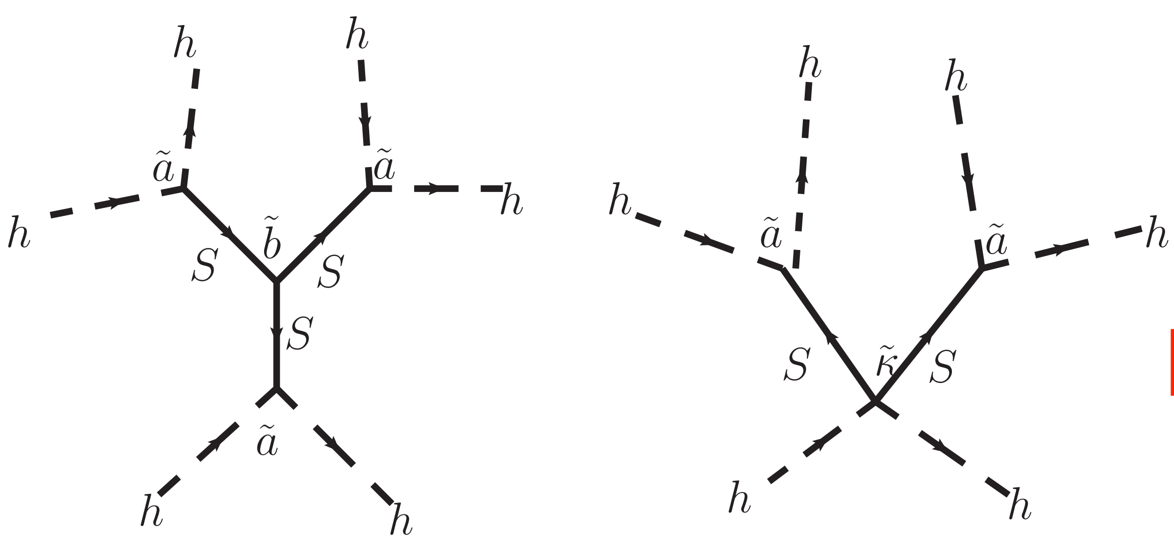
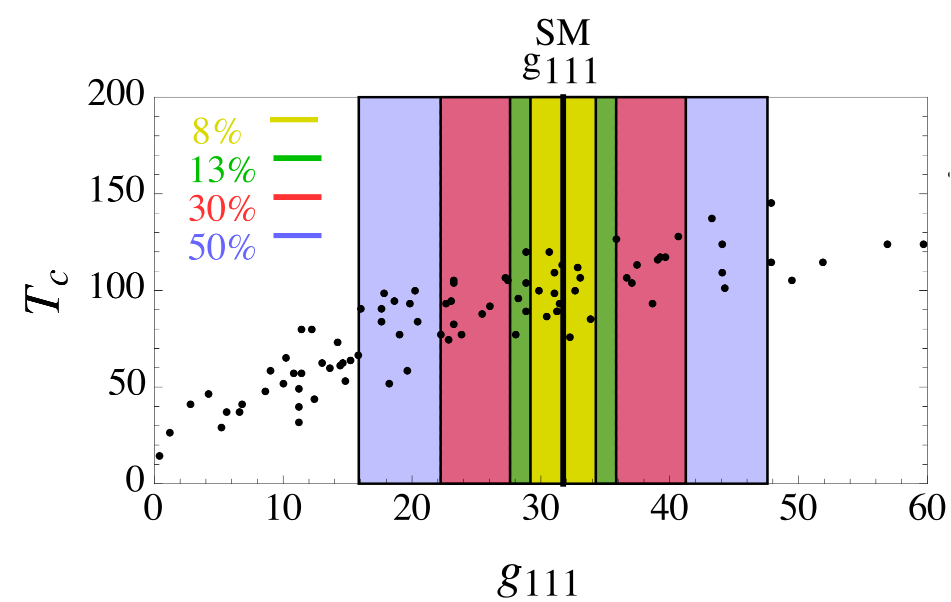
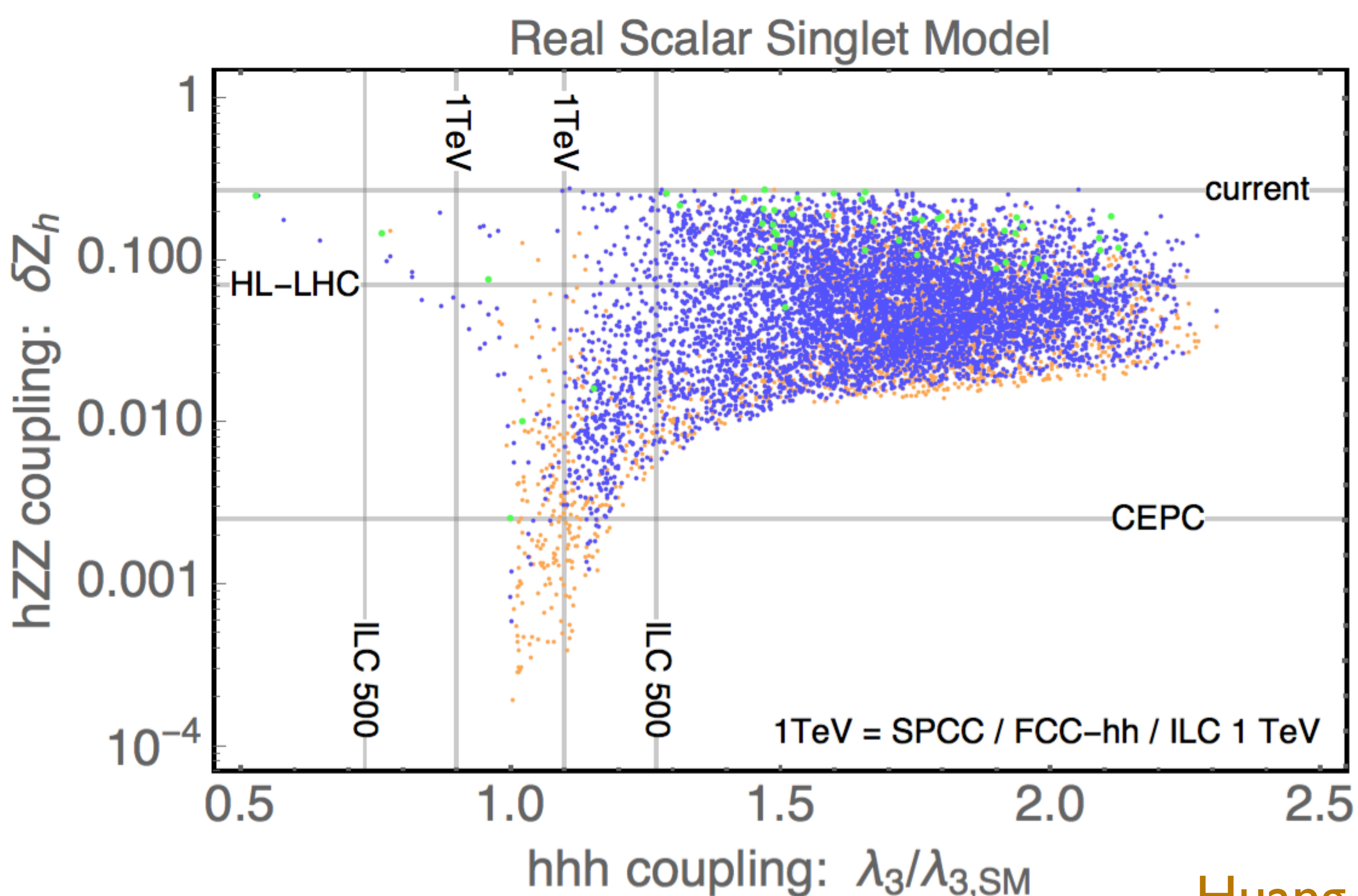




triple Higgs coupling

Probing EWSB at higgs factories



Huang, Long, LTW, 1608.06619

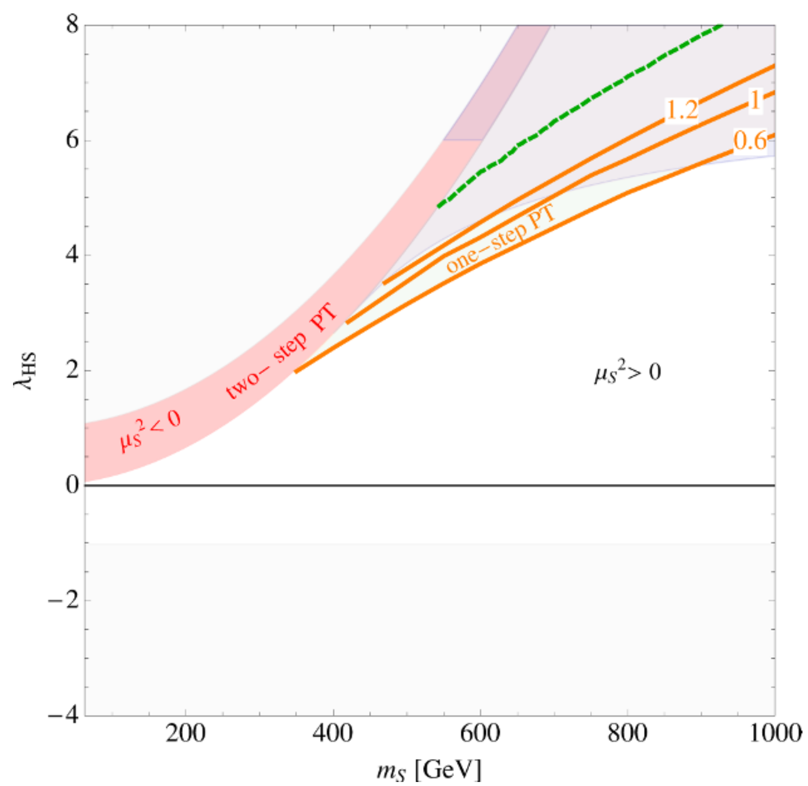
Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = “strongly” first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA

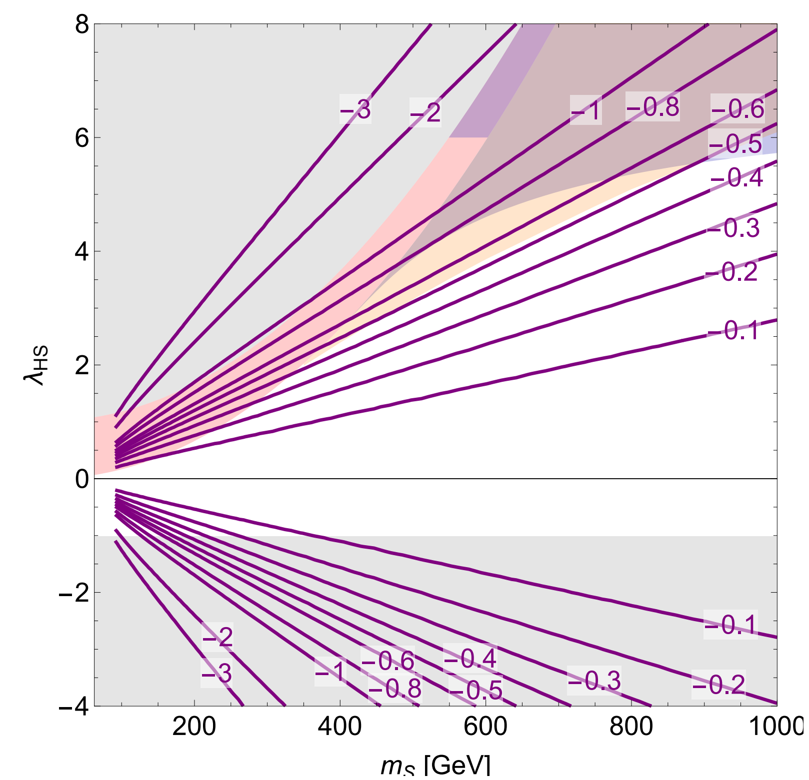
Good coverage in model space

Nightmare scenario:

Meade et al

Singlet model with a Z2 $S \to -S$





h⁶ term generated at 1-loop order

Only marginally visible.

Conclusion

- LHC still has a lot to say.
  - 15+ years of operation, 95+% of data to come.
  - Need to think about how to new searches with this data.
- Beyond the LHC, we need future colliders to address the open questions of the Standard Model.

extra

Late comers will be spotted easily:

	L_{T_2}	L_{T_1}	Trigger	$\epsilon_{\rm trig}$	$\epsilon_{\rm sig}$	$\epsilon^{j}_{\rm fake}$	Ref.
EC	1.17 m	0.2 m	DelayJet	0.5	0.5	10^{-3}	[12]
MS	10.6 m	4.2 m	MS RoI	0.25, 0.5	0.25	5×10^{-9}	[24]

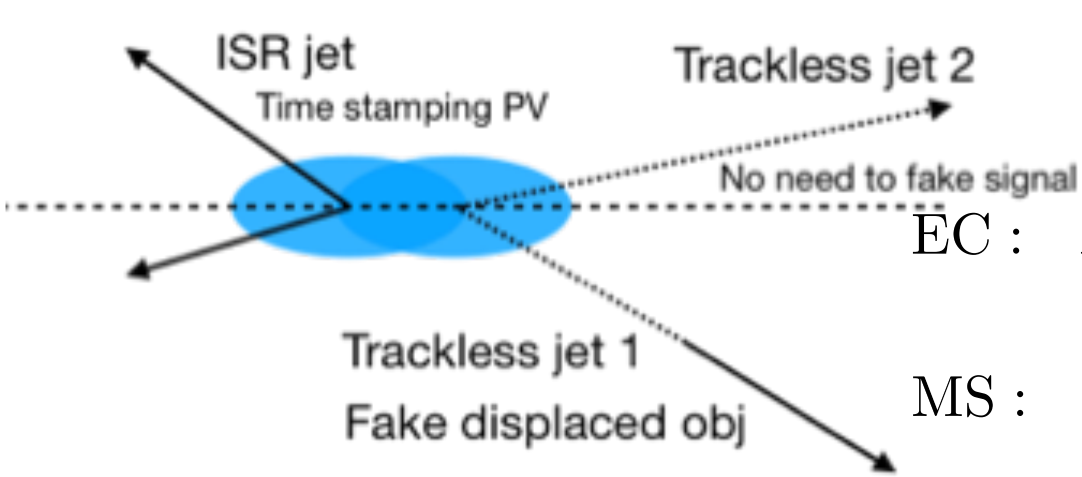
CMS timing module

ATLAS MS LLP search

(without timing)

Pile-Up background, time spread

190 ps (beam property)



$$\text{EC}: \quad N^{\rm PU}_{\rm bkg} = \sigma_{\rm j}\mathcal{L}_{\rm int}\epsilon^{\rm EC}_{\rm trig}\left(\bar{n}_{\rm PU}\frac{\sigma_{\rm j}}{\sigma_{\rm inc}}\epsilon^{j,{\rm EC}}_{\rm fake}f^{j}_{\rm nt}\right) \approx 2\times 10^{7},$$

$$\text{MS}: \quad N^{\rm PU}_{\rm bkg} = \sigma_{\rm j}\mathcal{L}_{\rm int}\epsilon^{\rm MS}_{\rm trig}\left(\bar{n}_{\rm PU}\frac{\sigma_{\rm j}}{\sigma_{\rm inc}}\epsilon^{j,{\rm MS}}_{\rm fake}f^{j}_{\rm nt}\right) \approx 50, \quad (5)$$

Pile-up BKG: intrinsic resolution ~190 ps

EC (30ps) cut: Δt > 1 ns

BKG(EC-PU) ~ 1.3

MS (30ps) cut: Δt > 0.4 ns

BKG(MS-PU) ~ 0.86

The detector time resolution for MS can be downgraded to hundreds of ps

MS (200ps) cut: Δt > 1ns

BKG(MS-PU) << 1

Late comers will be spotted easily:

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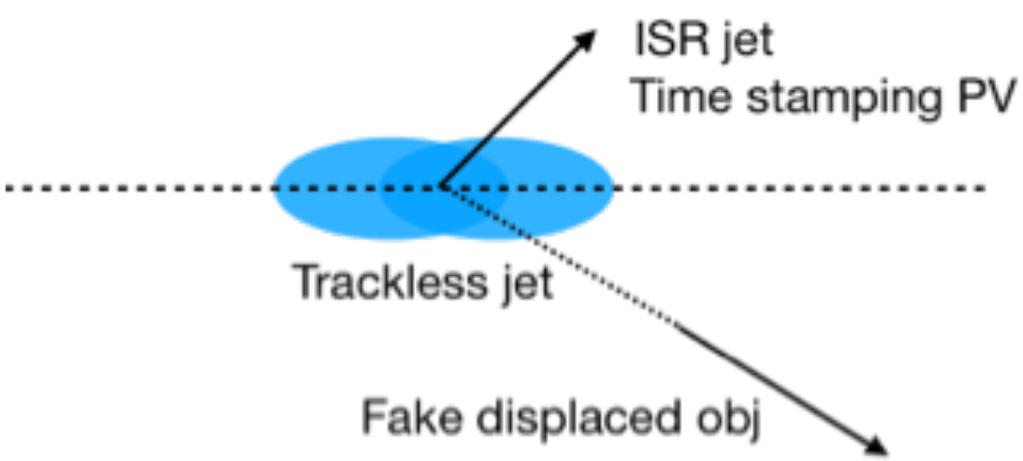


Same-vertex hard scattering background, time spread 30 ps (precision timing)

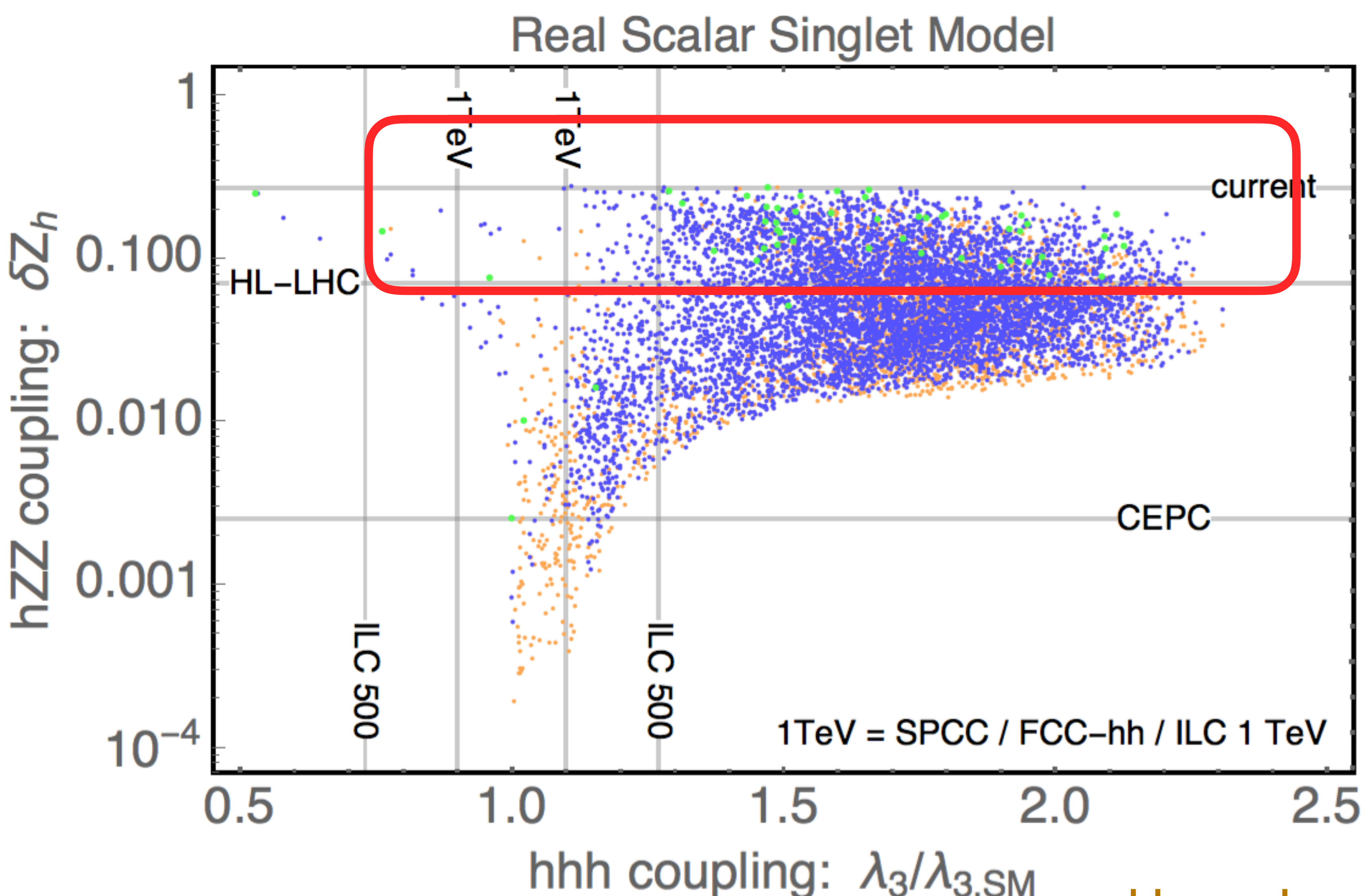
$$\text{EC}: \quad N^{\text{SV}}_{\text{bkg}} = \sigma_{\text{j}} \mathcal{L}_{\text{int}} \epsilon^{\text{EC}}_{\text{trig}} \epsilon^{j,\text{EC}}_{\text{fake}} \approx 1 \times 10^{11}$$

$$\text{MS}: \quad N^{\text{SV}}_{\text{bkg}} = \sigma_{\text{j}} \mathcal{L}_{\text{int}} \epsilon^{\text{MS}}_{\text{trig}} \epsilon^{j,\text{MS}}_{\text{fake}} \approx 4 \times 10^{5},$$

Hard collision BKG: detector time resolution ~30 ps
EC (30ps) cut: Δt > 0.4 ns
MS (30ps) cut: Δt > 1ns
BKG(SV) << 1

The detector time resolution for MS can be downgraded to hundreds of ps
MS (200ps) cut:
Δt > 1ns
BKG(MS-SV) ~ 0.11

Probing EW phase transition



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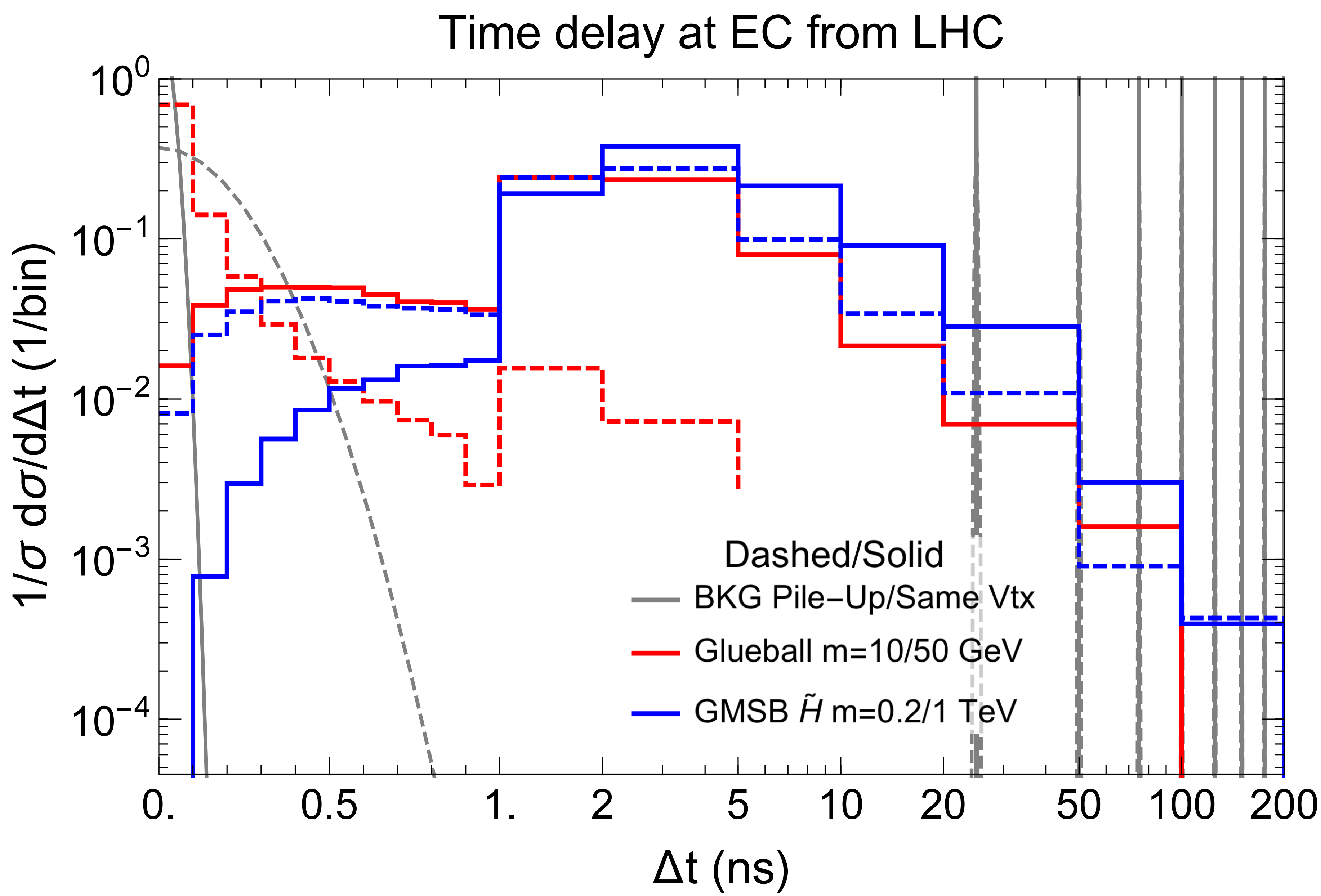
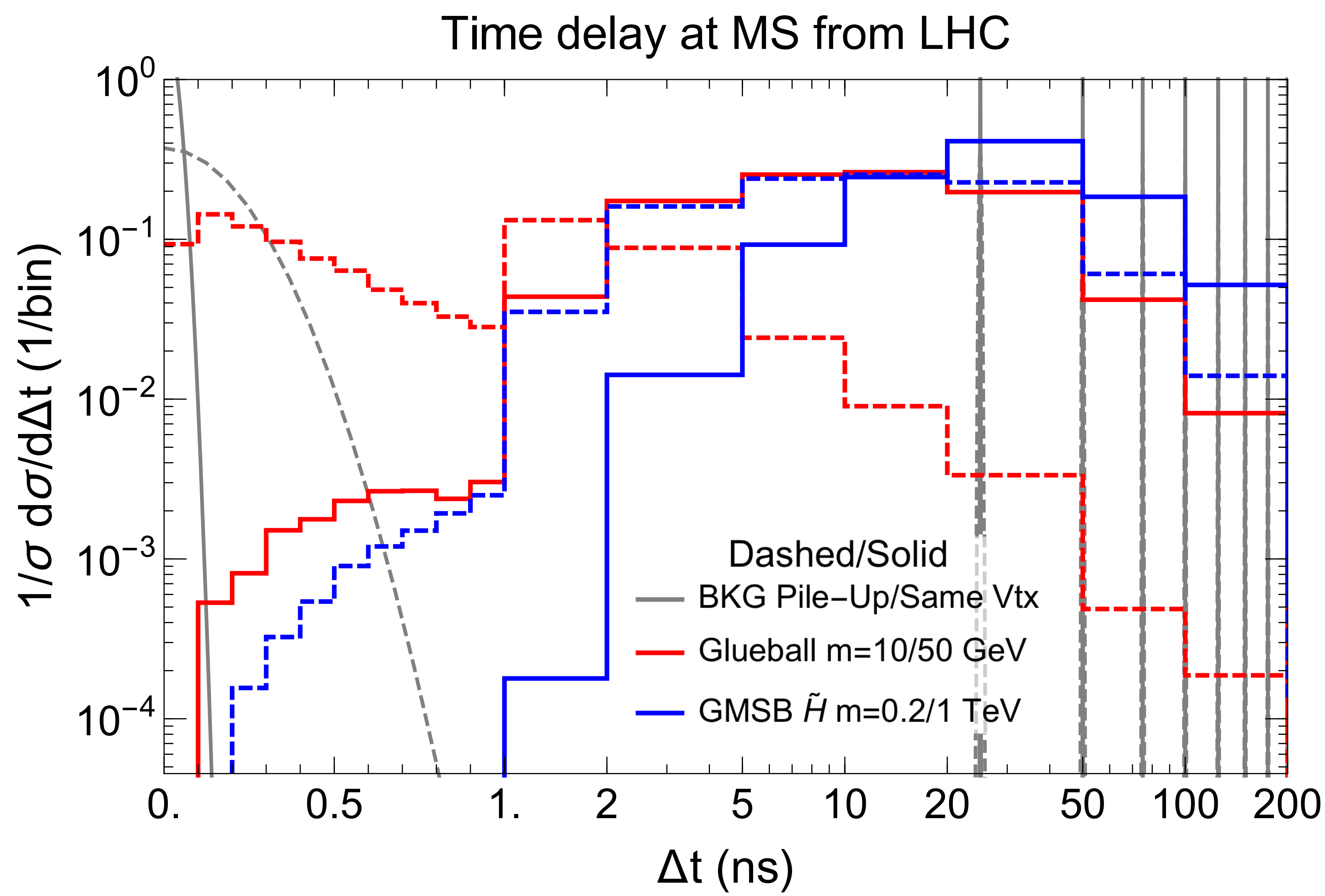
Search based on EC



After timing cut: $\Delta t > 0.8$ ns

Back ground dominated by pile up $\#_{\text{background}} \sim 1$

Search based on MS



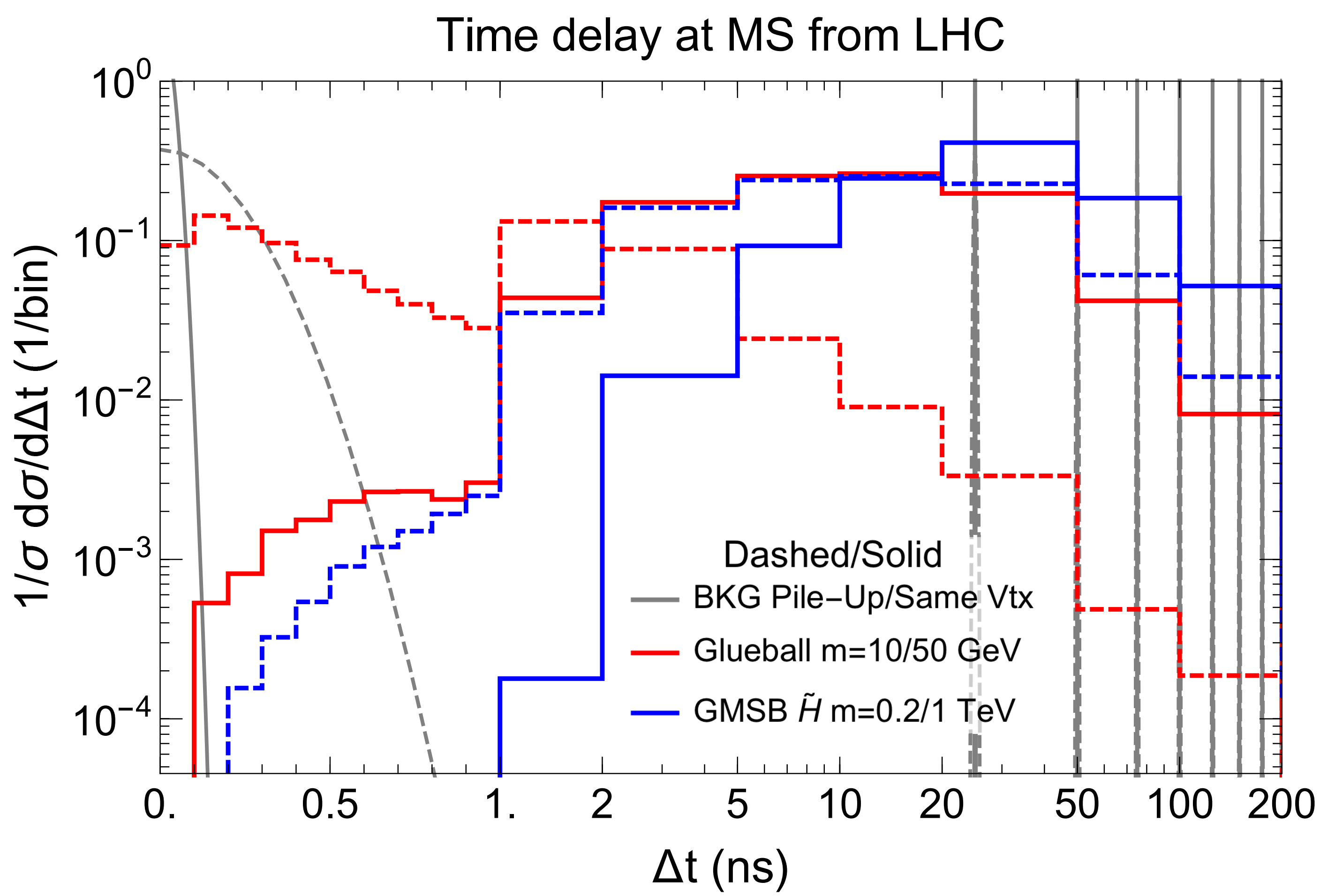
Pile up background smaller, shielded by HCAL etc.

Before timing cut: ~ 50

After timing cut: $\Delta t > 0.4$ ns $\#_{\mathrm{background}} \sim 1$

Further away, larger Δt for signal.

Search based on MS



Pile up background smaller, shielded by HCAL etc.

$\Delta t > 0.4$ ns $\quad \#_{\text{background}} \sim 1$

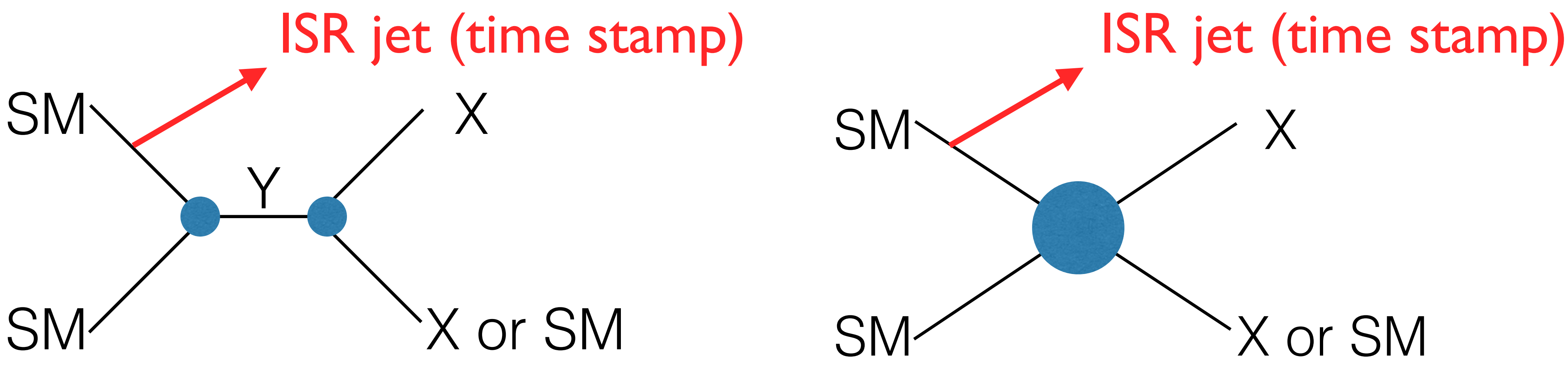
Further away, larger Δt for signal.

no need for super good timing resolution

$\delta t \sim 200$ ps

will do

Signal



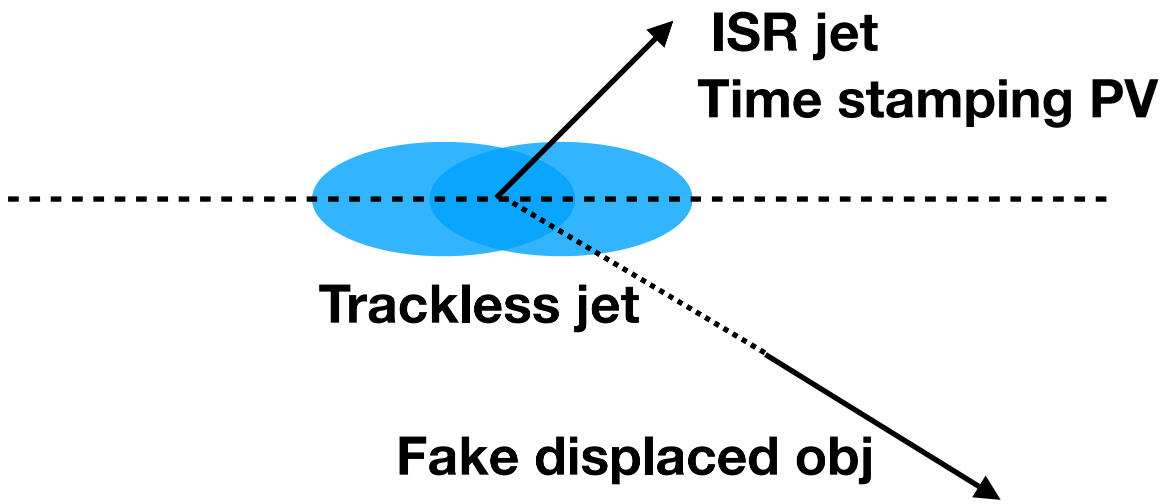
1. ISR jet provides the time for the hard collision

2. LLP decay before reaching timing layer.

⇨ measurement of Δt

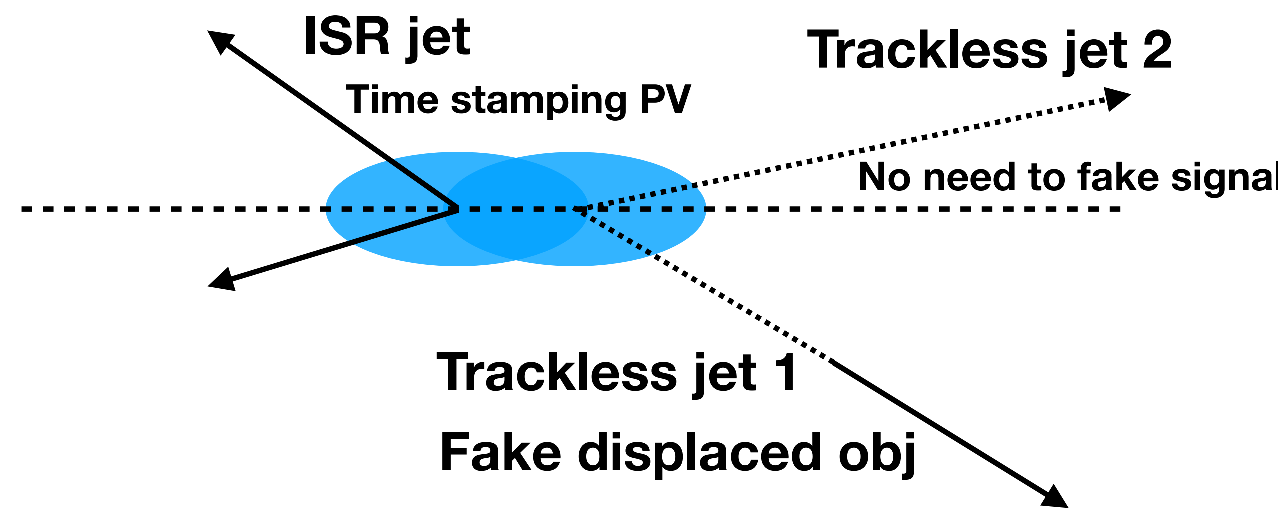
background

Same hard interaction



Time delay from
resolution of timing detector.

Pile up



Time delay from
spread of the proton bunch

$\sim$ 190 ps

Importance of precision measurement

- No clear indication where new physics might be.
  - Precision measurement can give crucial guidance.

- Lots of data still to come
  - Room to improve! Statistics and systematics.

- Will be a important part of the legacy of the LHC.
  - LEP taught us a lot. LHC will do the same.

Summary of LLP searches

- Timing information can significantly improve the reach.
- The result shown are based on generic cuts (ISR+ any delayed decay).
  - Broadly applicable.
  - Further optimization possible for specific decay channel.
- Designing effective triggering strategy is crucial next step.

Precision measurement at the LHC possible?

At LHC, interference with SM crucial

Signal-SM interference

$$\frac{\delta\sigma}{\sigma_{\rm SM}} \sim \frac{E^2}{\Lambda^2} \sim 0.25$$

Without interference

$$\frac{\delta\sigma}{\sigma_{\rm SM}} \sim \frac{E^4}{\Lambda^4} \sim 0.05$$

1. WZ final states, only longitudinal mode useful
2. W/Z+h

Will be challenging

SM WW, WZ processes are dominated by transverse modes

$$\sigma_{SM}^{total}/\sigma_{SM}^{LL} \sim 15 - 50$$

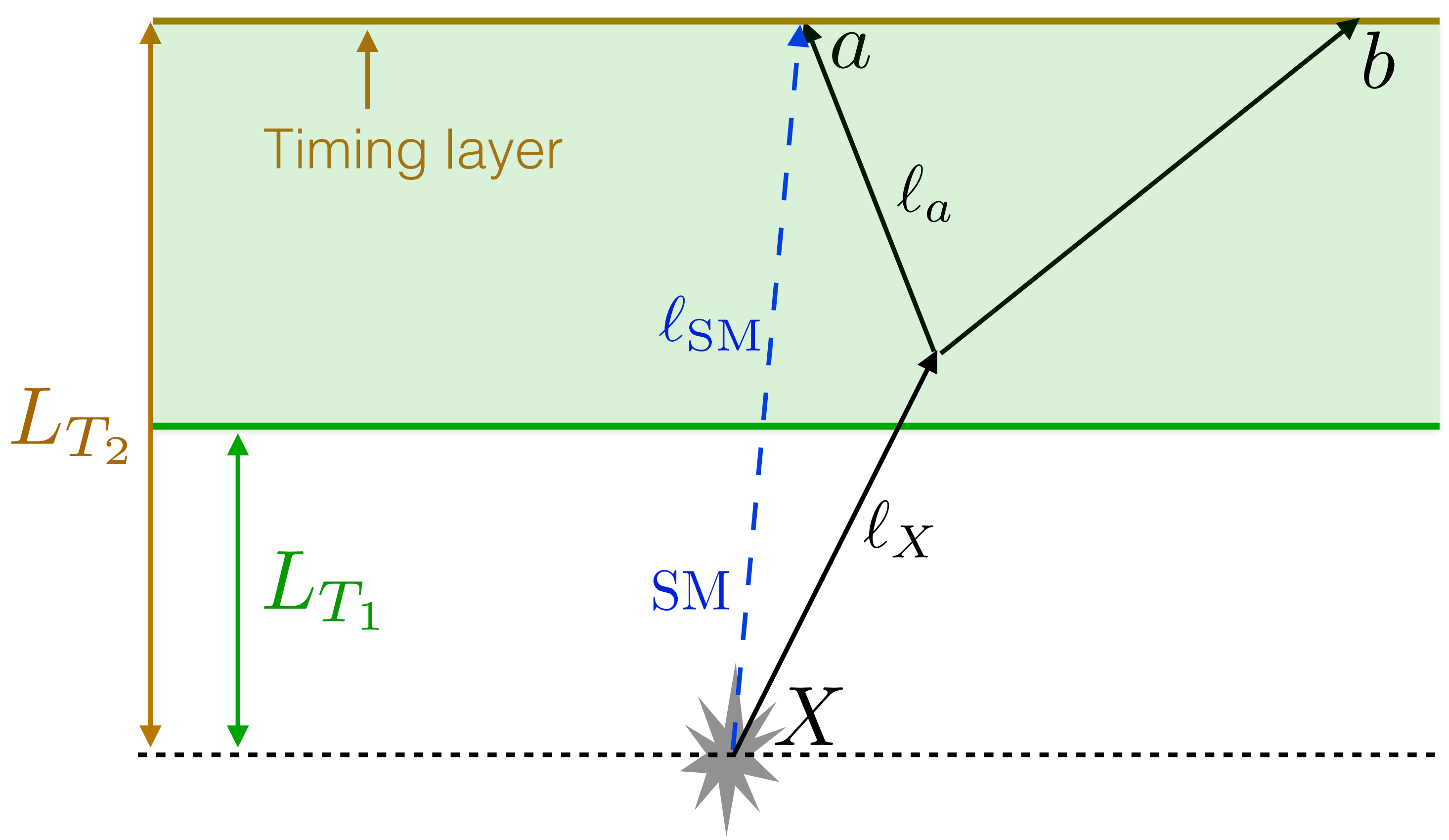
New technique such as polarization tagging of W/Z crucial

Wh/Zh(bb) channels have large reducible background

$$\text{LHC @ 8 TeV :} \qquad \sigma_b^{red}/\sigma_{SM}^{Wh} \sim 200 - 10$$

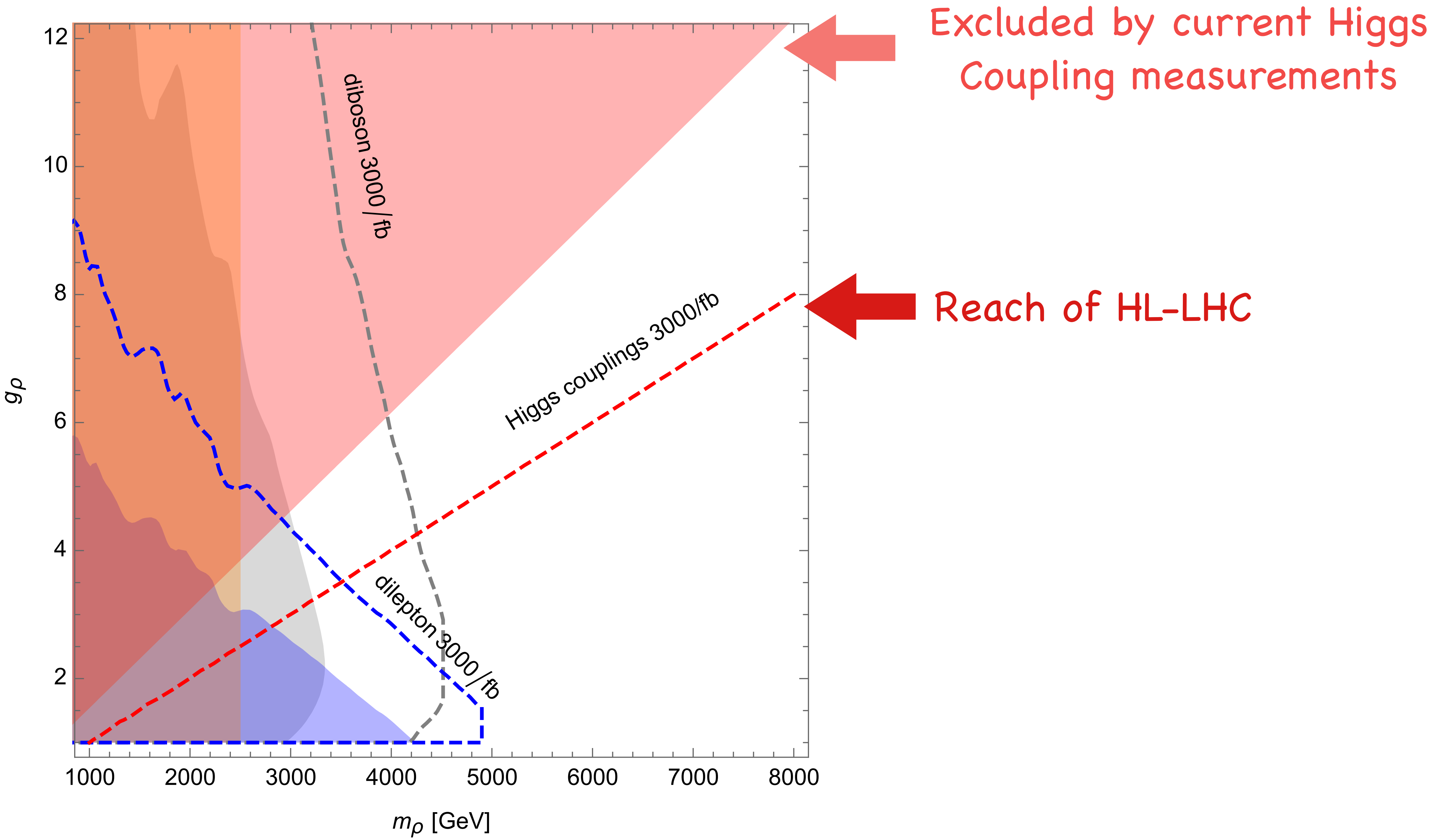
Difficult measurement. Large improvement needed.
Room for developing new techniques

Time delay



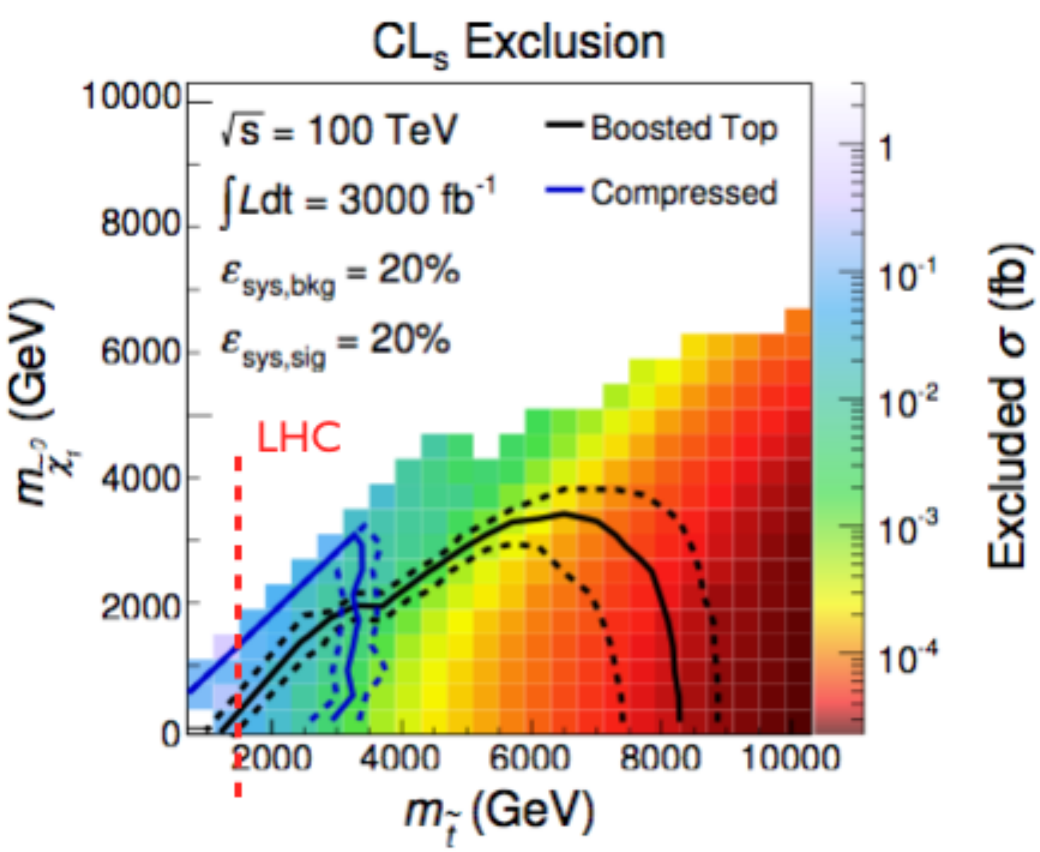
- **timing layers considered here:**
  - **CMS EC search: LT1 = 0.2 m, LT2 = 1.2 m (EC = Electromagnetic Calorimeter)**
    - **Resolution:** $\delta \mathbf{t} = \mathbf{30\ ps}$
  - **MS search (hypothetical): LT1 = 4.2 m, LT2 = 10.6m (MS = Muon Spectrometer)**
    - **Resolution: don't need to be as good (detail later)**

Higgs coupling vs direct search

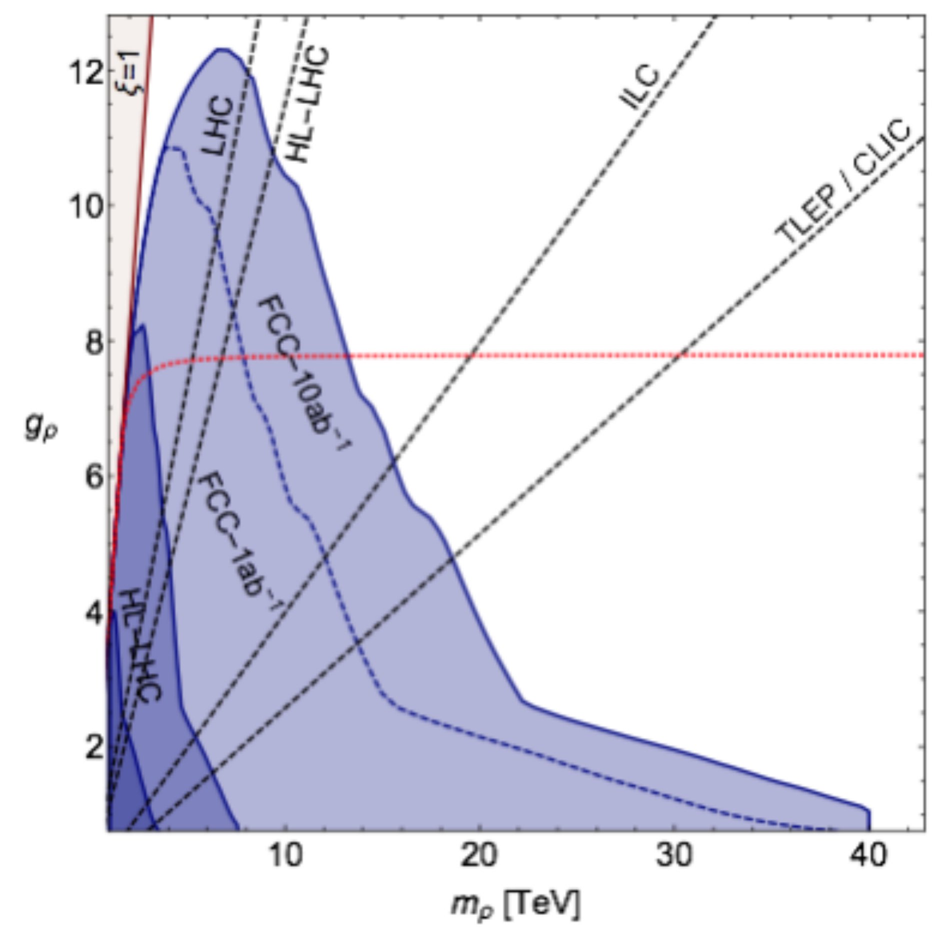


Testing naturalness at 100 TeV pp collider

Cohen et. al., 2014



Pappadopulo, Thamm, Torre, Wulzer, 2014



Fine tuning: $(M_{NP})^{-2}$