Searching for a new world

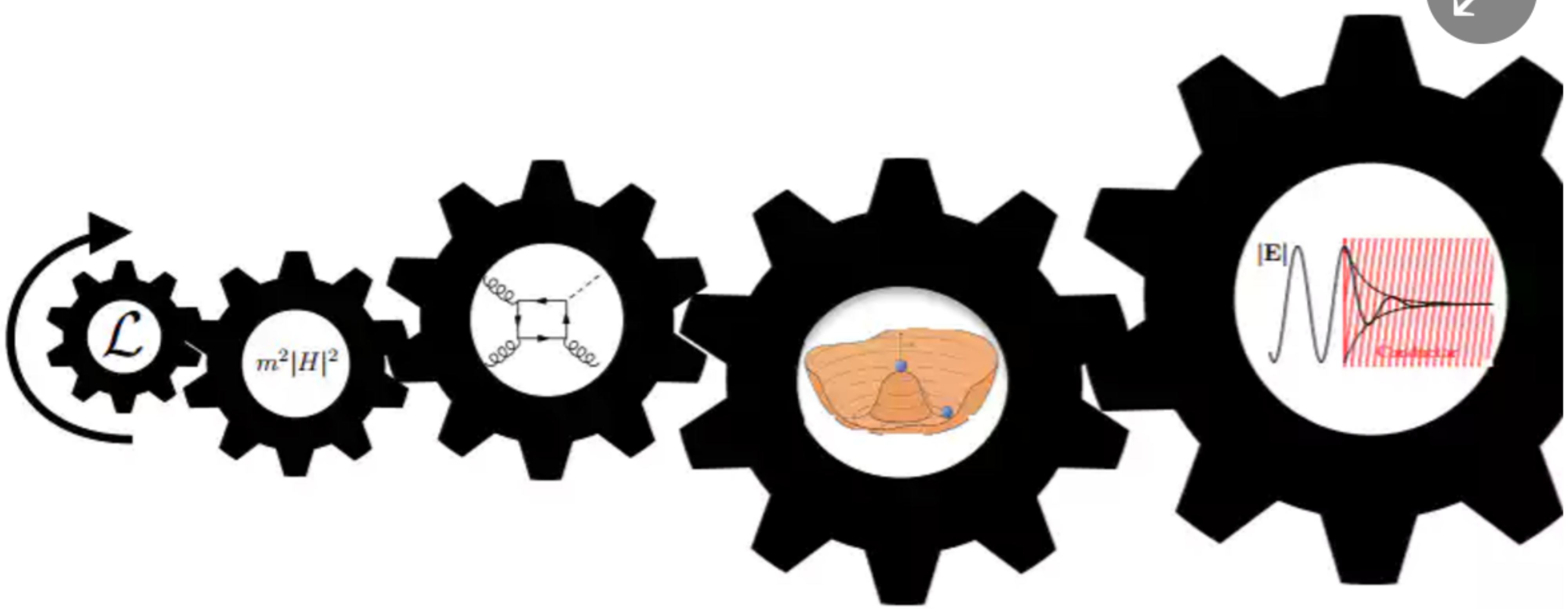
New Physics at the LHC and beyond

LianTao Wang
U. Chicago

FeynRules/Madgraph School. Nov. 19, 2018. USTC HeFei.

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

SM: complete yet incomplete

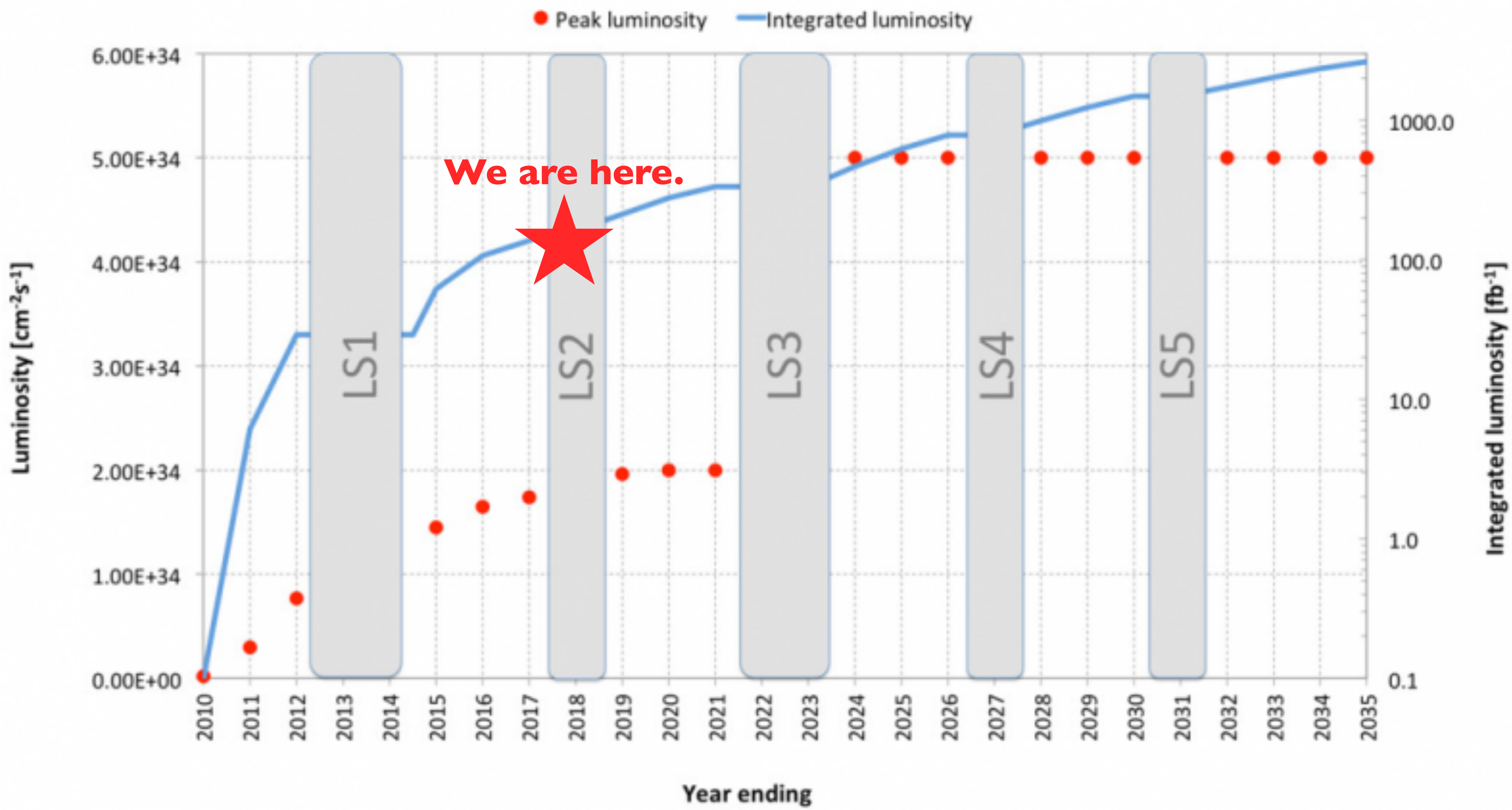
- Complete: could be a consistent theory valid up to the Planck scale.

- Incomplete: many open questions
  - Origin of electroweak scale
  - Dark matter
  - Origin of CP, flavor
  - Matter anti-matter asymmetry
  - ...

- Goal of particle physics: answer these questions.

- Colliders (LHC and beyond) will be crucial.

Road ahead
at the LHC

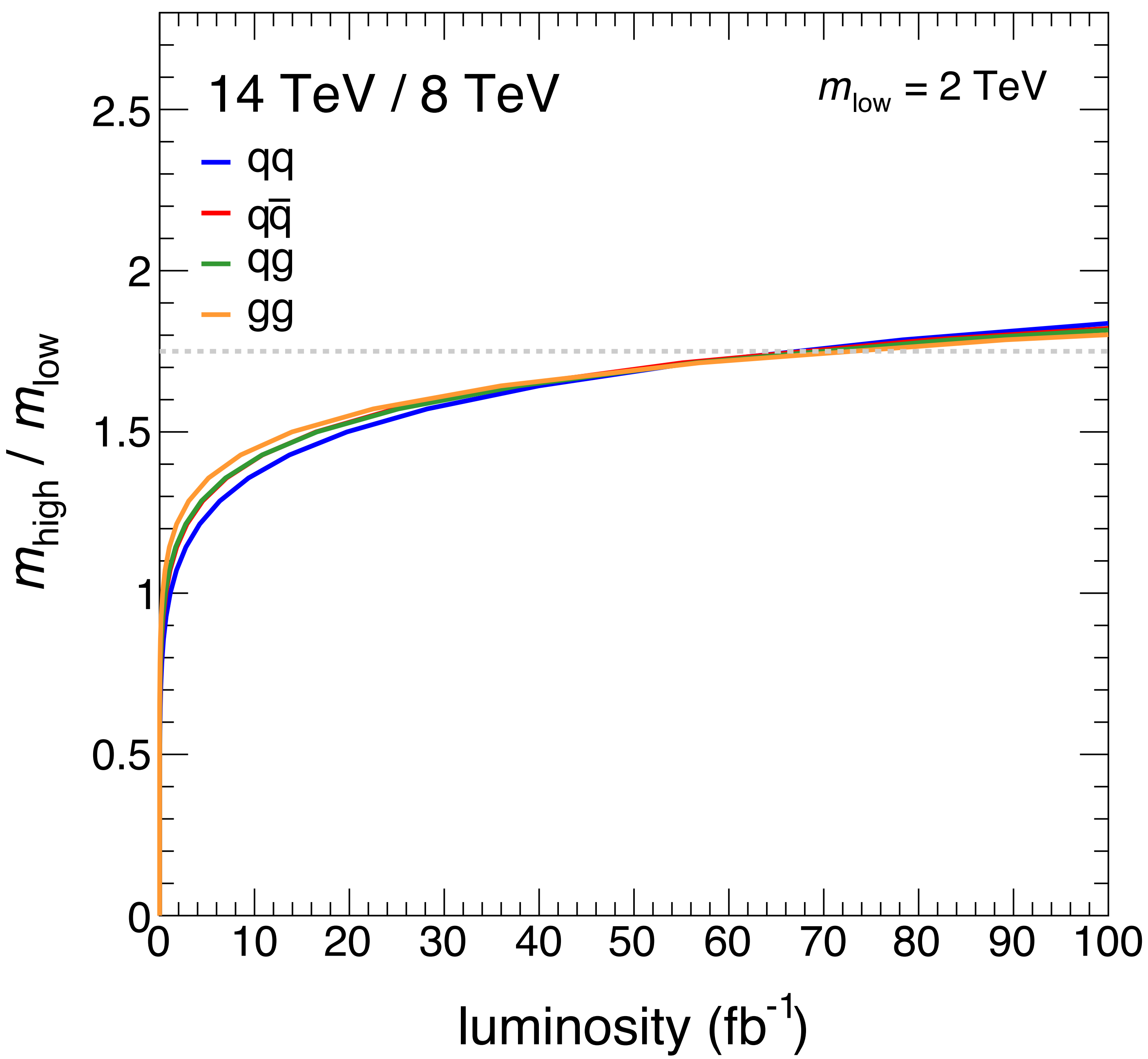


Peak luminosity
Integrated luminosity
We are here.
Luminosity [cm-2s-1]
Integrated luminosity [fb-1]
Year ending
LS1
LS2
LS3
LS4
LS5
6.00E+34
5.00E+34
4.00E+34
3.00E+34
2.00E+34
1.00E+34
0.00E+00
1000.0
100.0
10.0
1.0
0.1
2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035

LHC is pushing ahead.

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

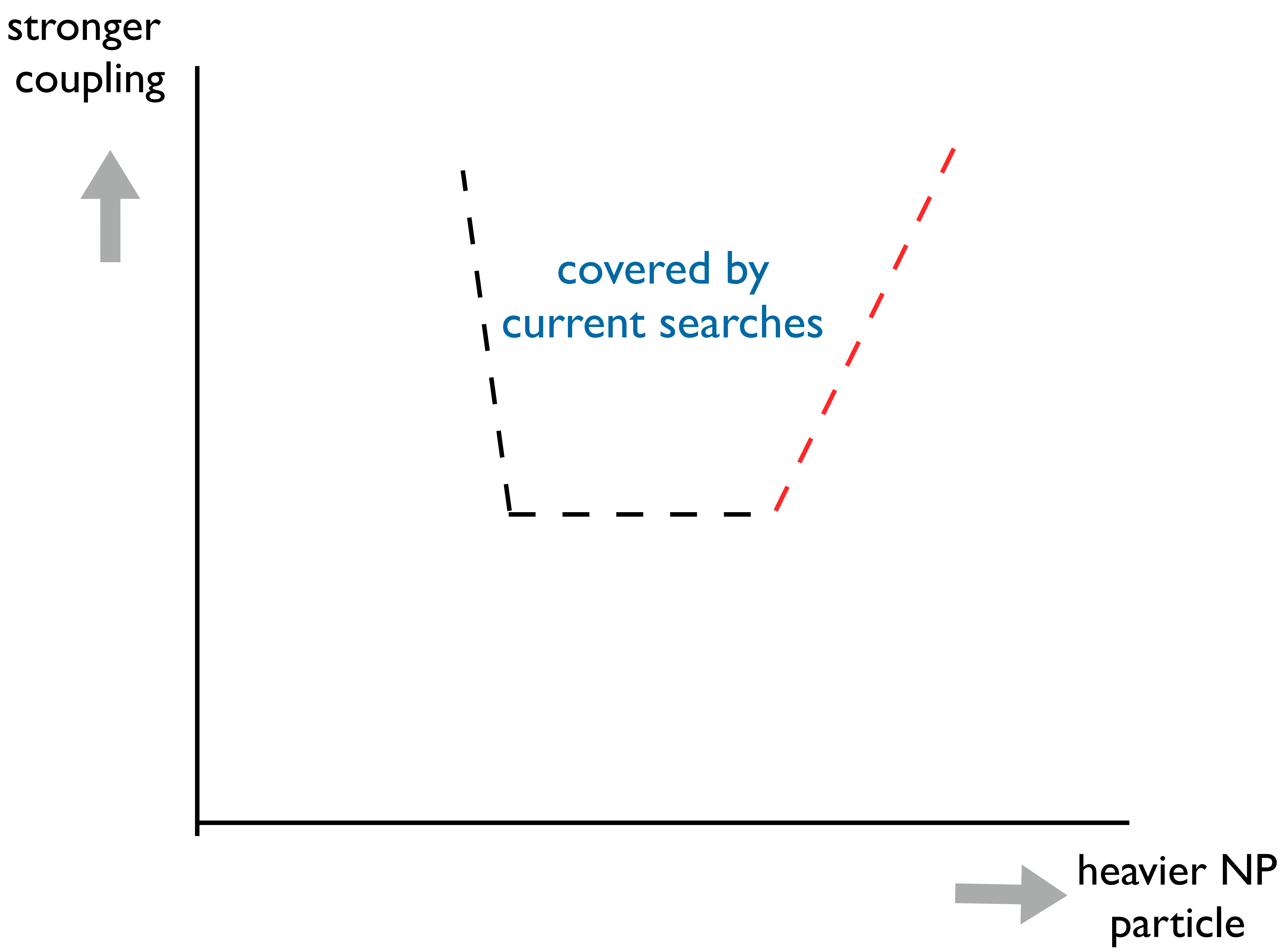
As data accumulates



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

Progress will become slower, harder

New directions?


stronger
coupling
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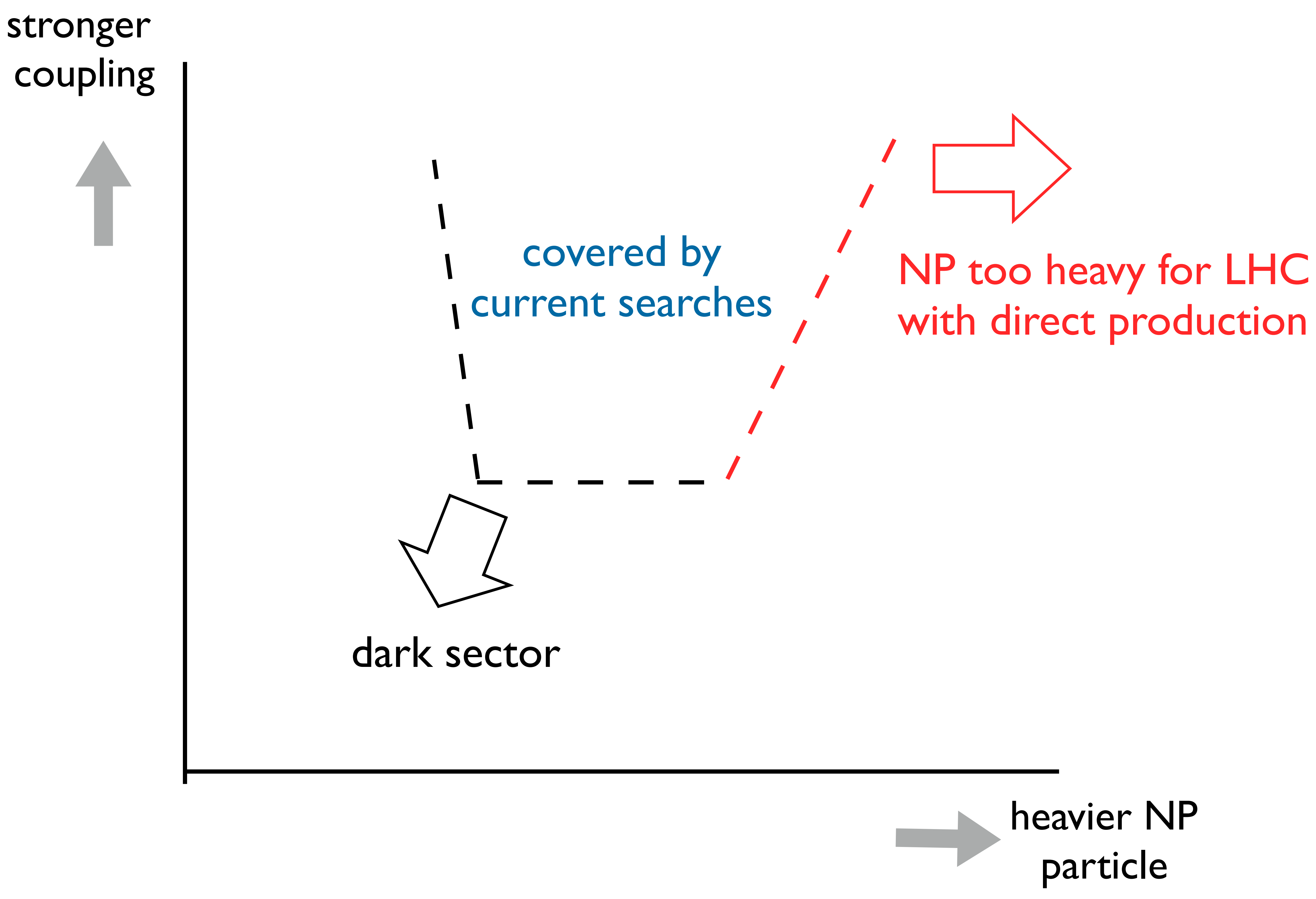
particle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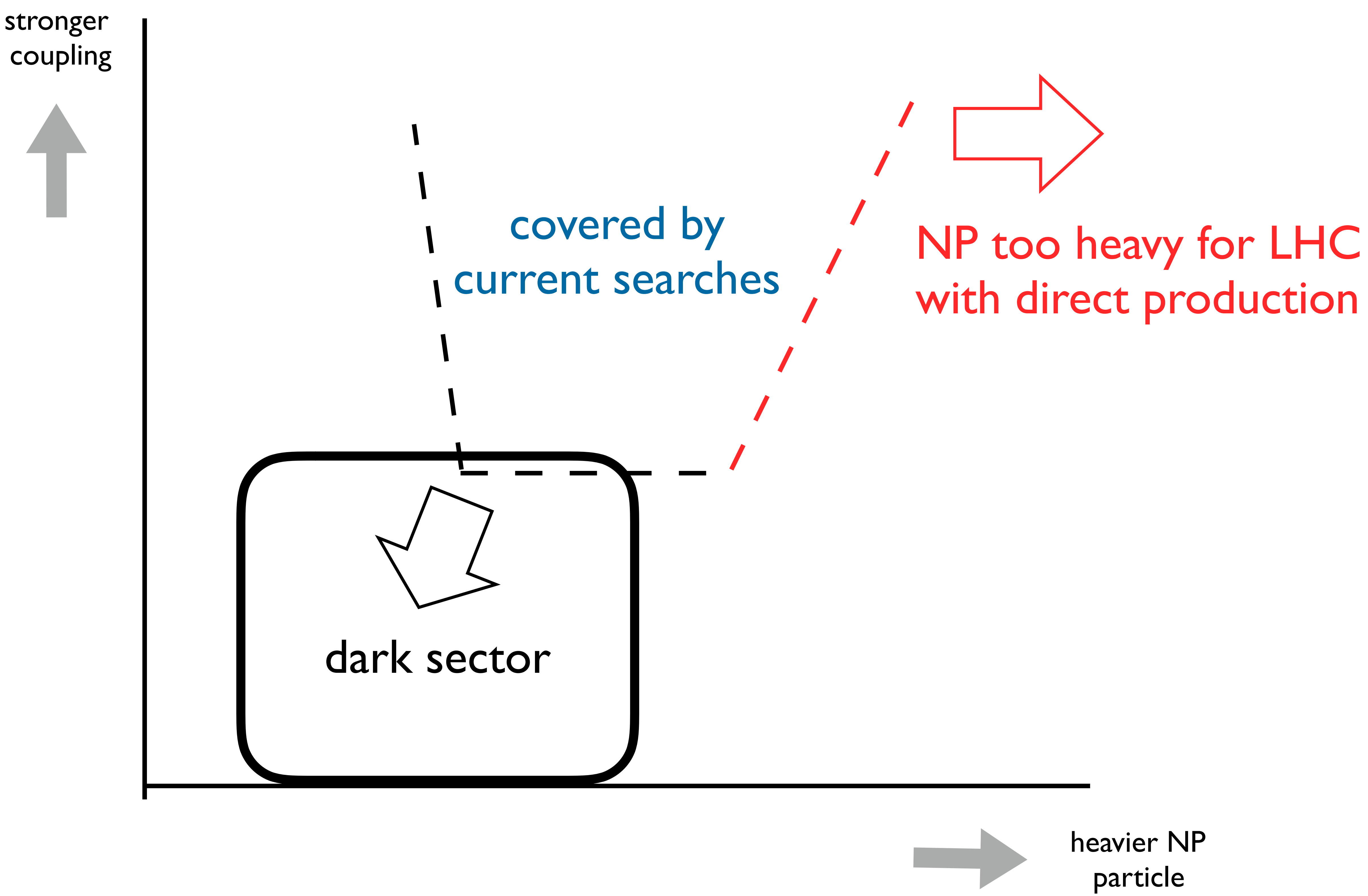
stronger coupling
covered by current searches
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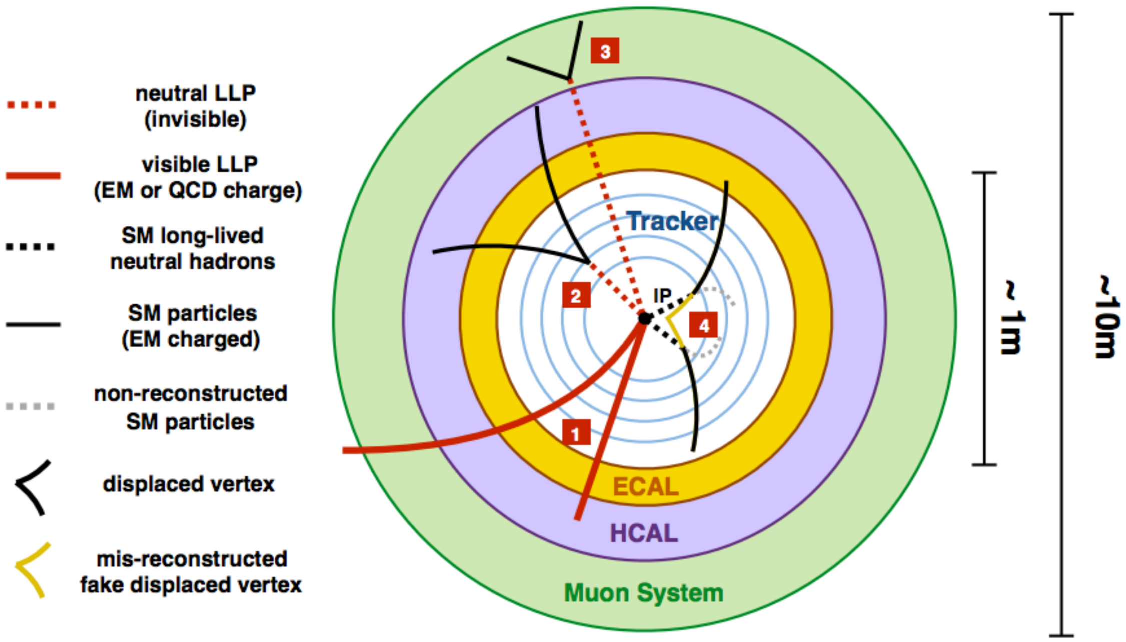
heavier NP particle

Example: Long Lived particles (LLP)

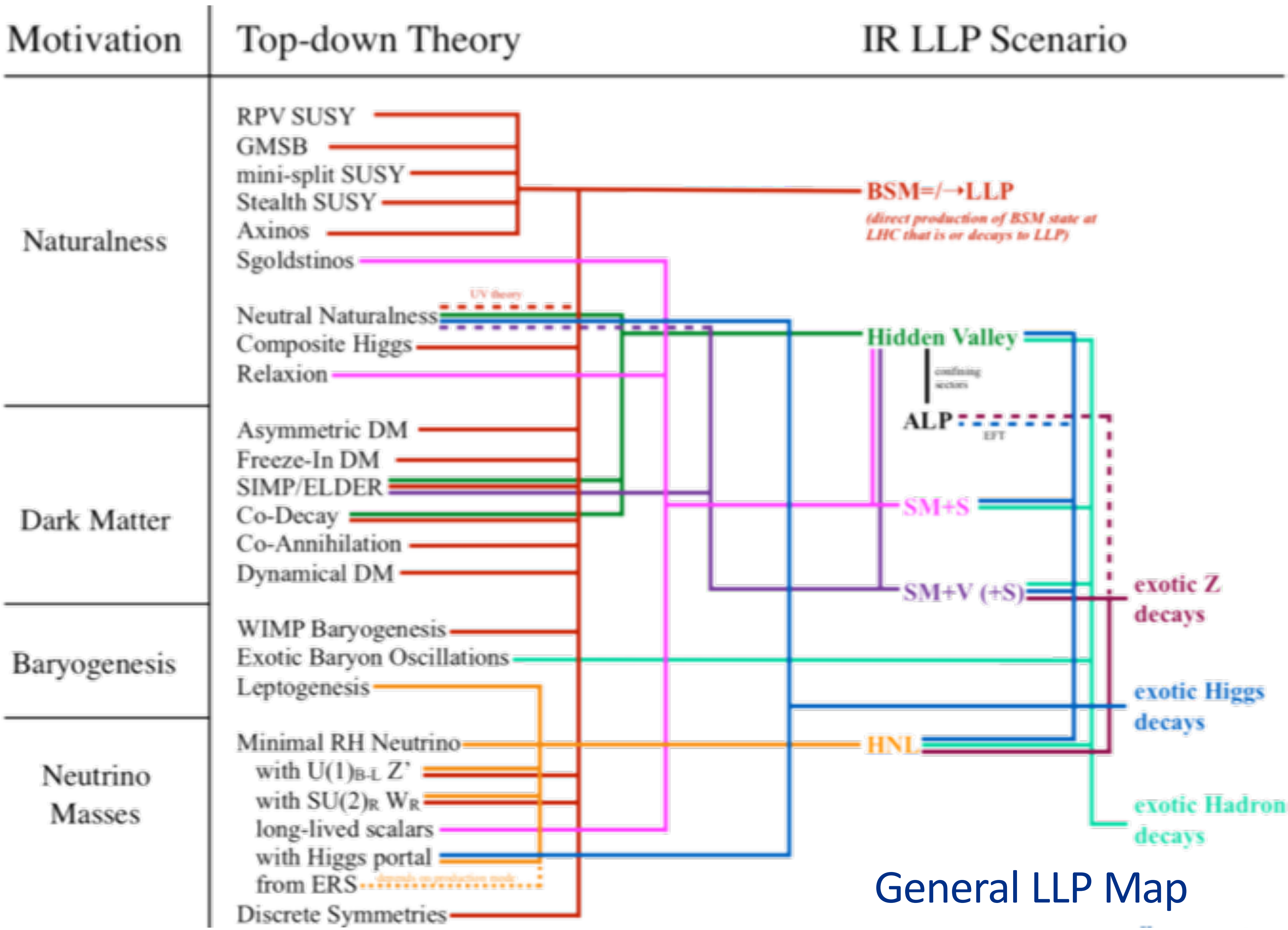
- Very weakly coupled to the SM.
  - Connection with dark matter, neutrino, etc. τ
- Displaced-Long lived, soft, kink, Covered by LHC searches already.
- Cosmological constraints from BBN: $\tau < 0.1$ sec (10^7 m)



Curtin and Sundrum

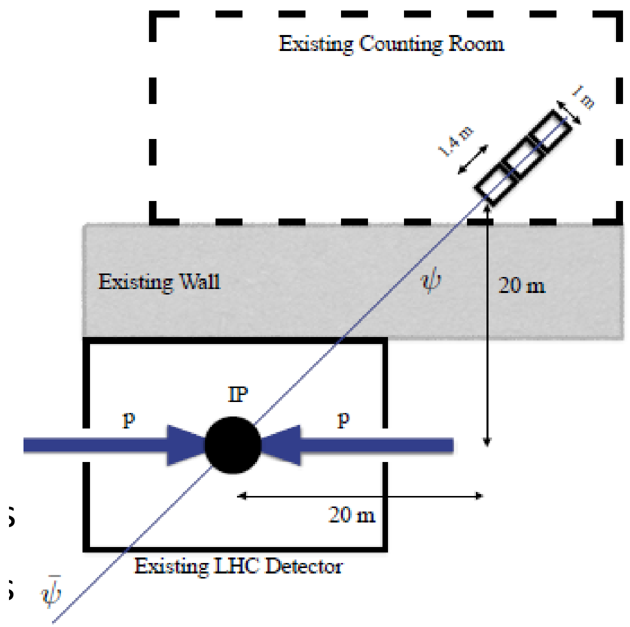
Here, I focus on: decay length >> 10 meters

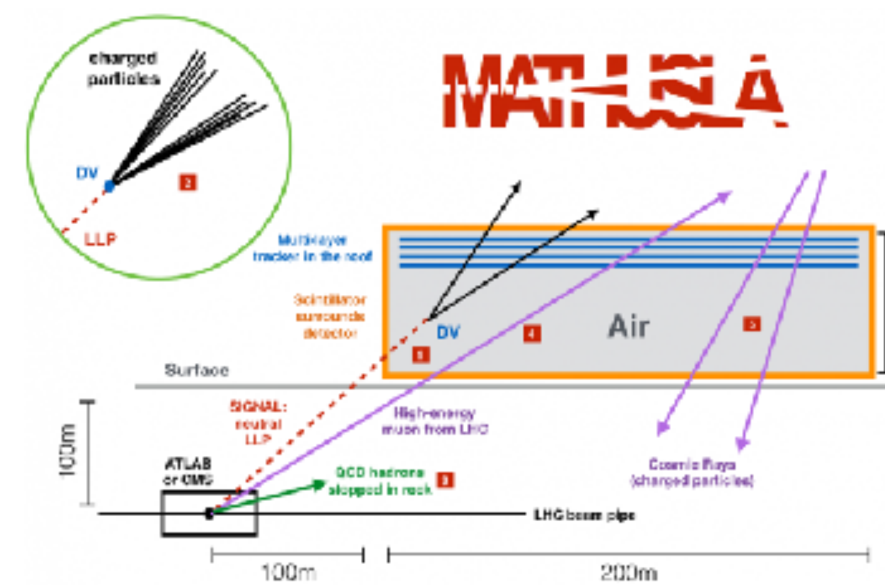
tons of models



General LLP Map

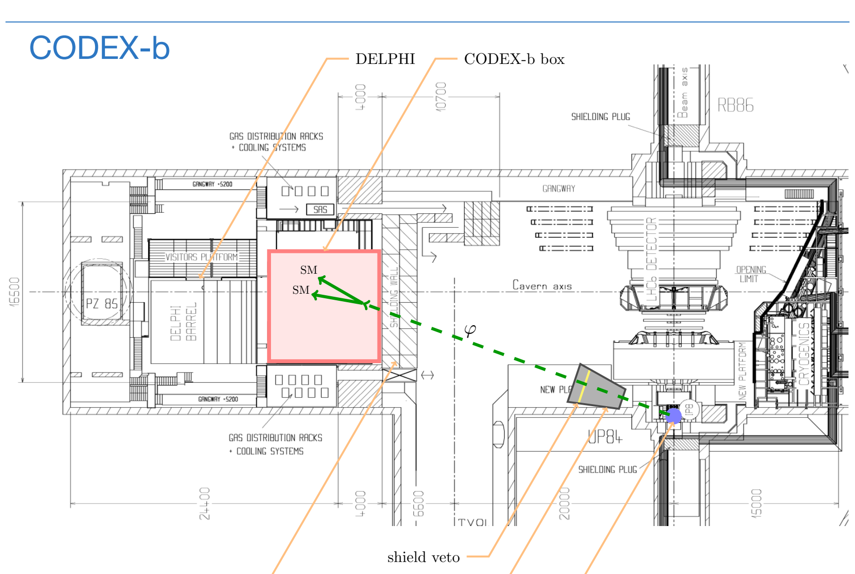
Far detectors

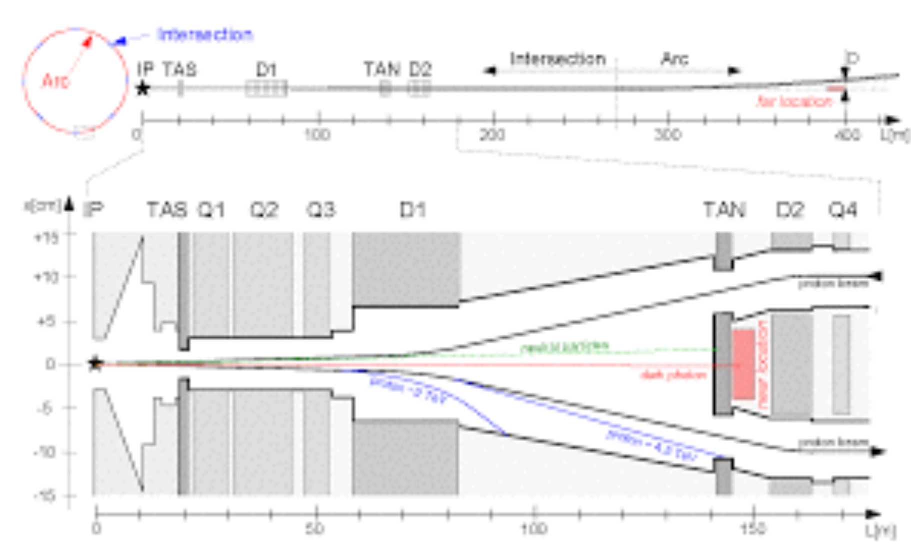




MATHUSLA

new detectors far
away from the interaction region

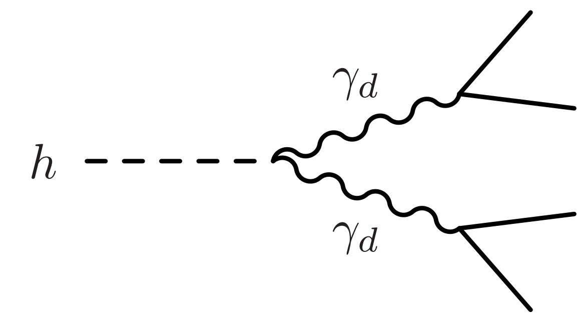


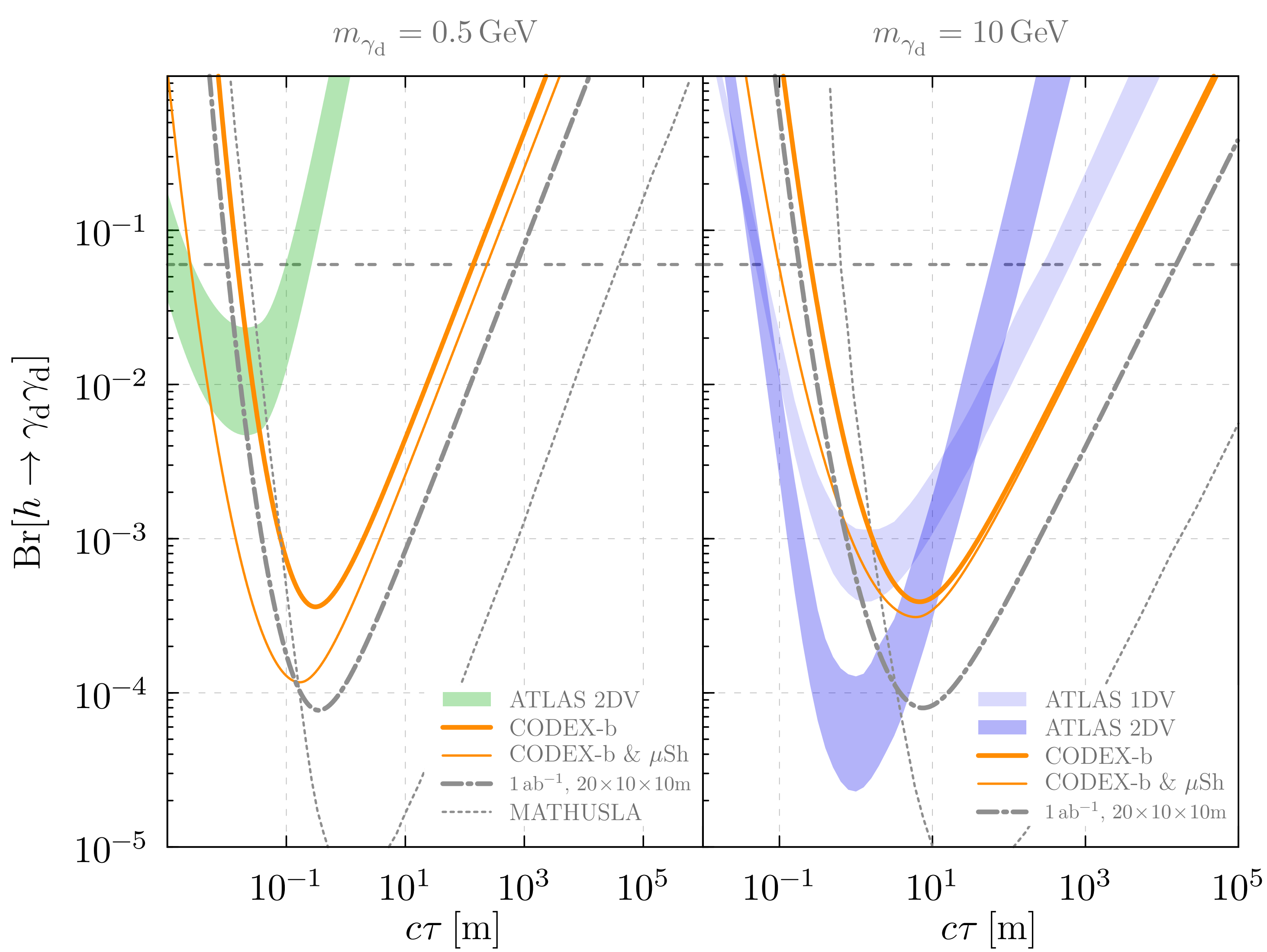


FASER

Could reach τ≈10$^{4-5}$ m

Exotic Higgs decays





Application:
Neutral Naturalness
(See back-up material)

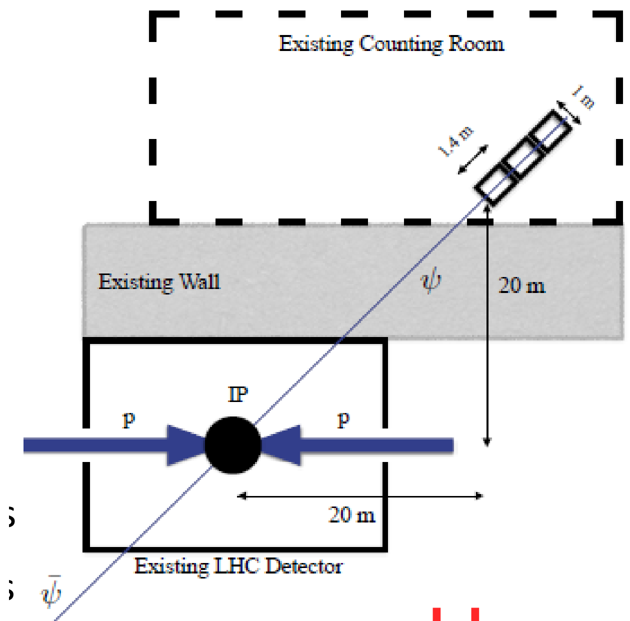
For low masses, ATLAS/CMS are background limited, CODEX-b & MATHUSLA have an edge

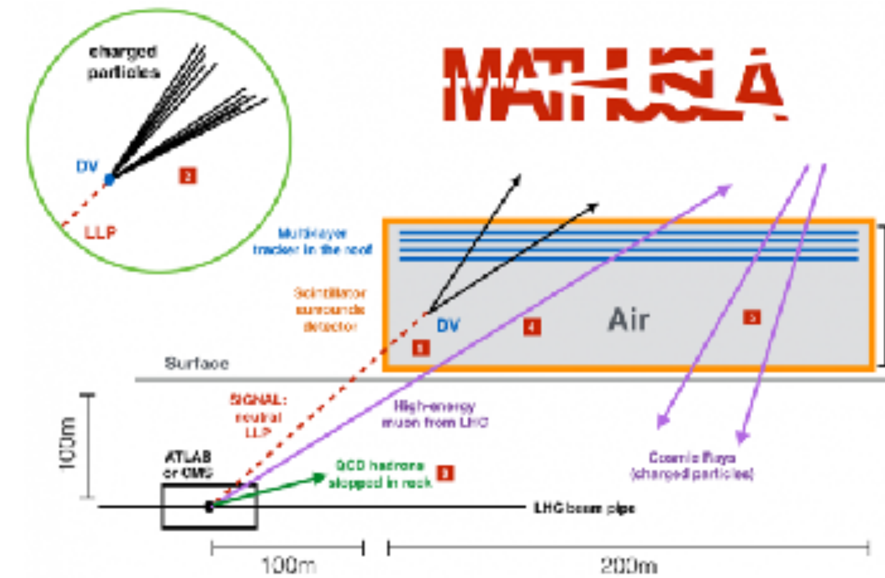
V. Gligorov, SK, M. Papucci, D. Robinson: 1708.02243

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

S. Knapen

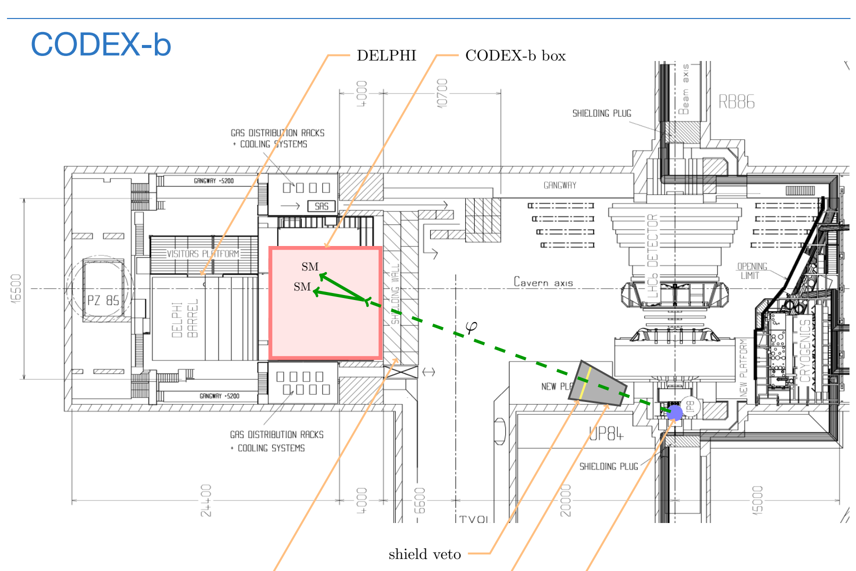
Far detectors

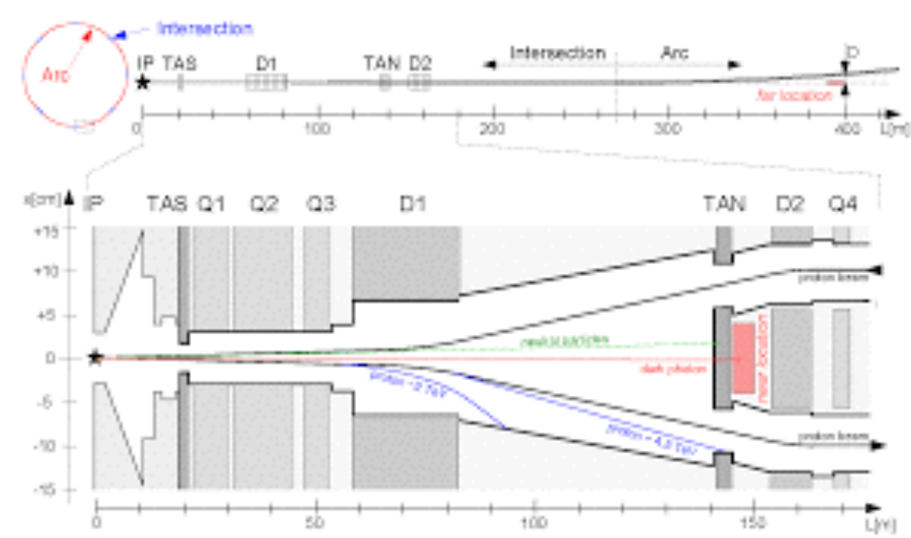




MATHUSLA

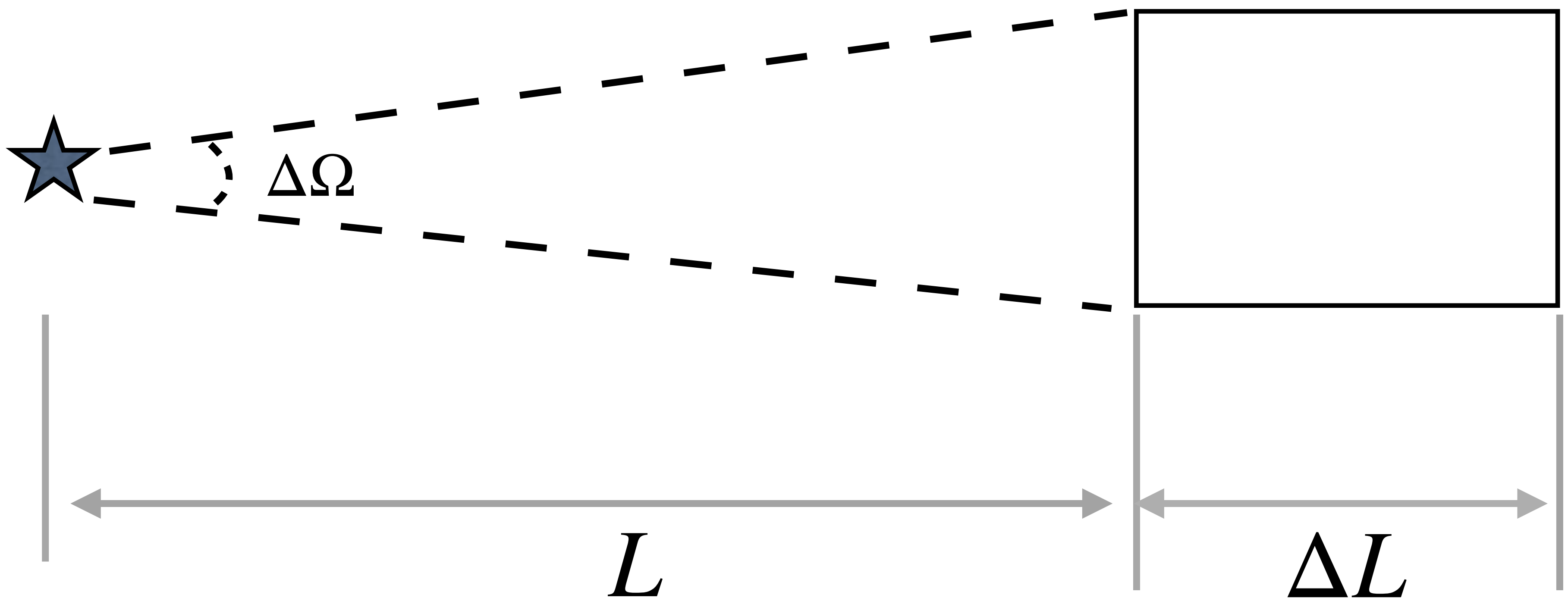
Have we fully optimized LLP searches at the interaction points ATLAS, CMS, LHCb?





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

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$$\#_{\text{in}} \simeq \#_{\text{produced}} \times \frac{\Delta\Omega}{4\pi} \times \frac{\Delta L}{d} e^{-L/d} \qquad d = \gamma c \tau$$

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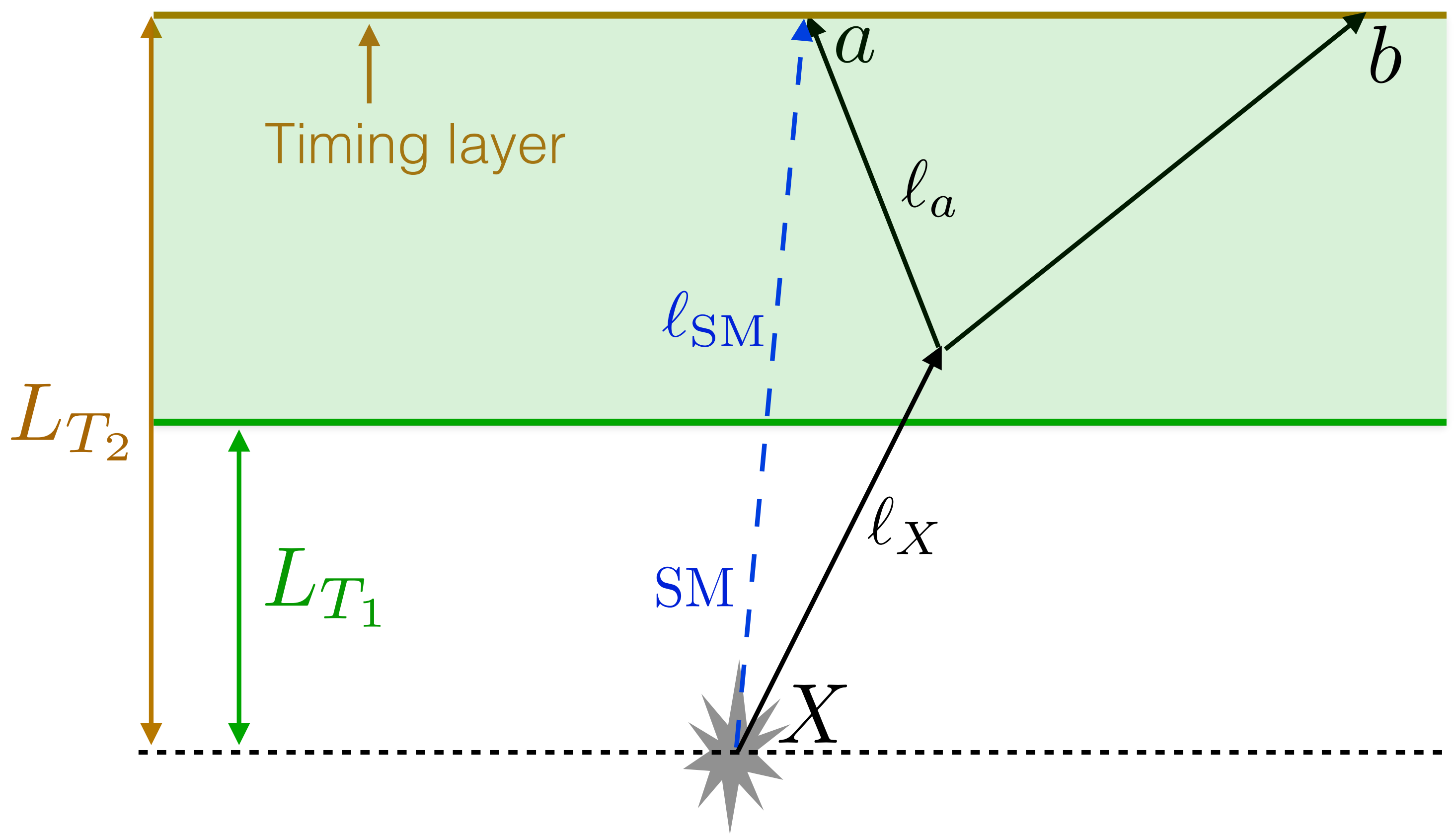
Advantage of far detector?
Far away from interaction point, less background.

New proposal: use timing information
Significantly lower background near interaction point.

Time delay



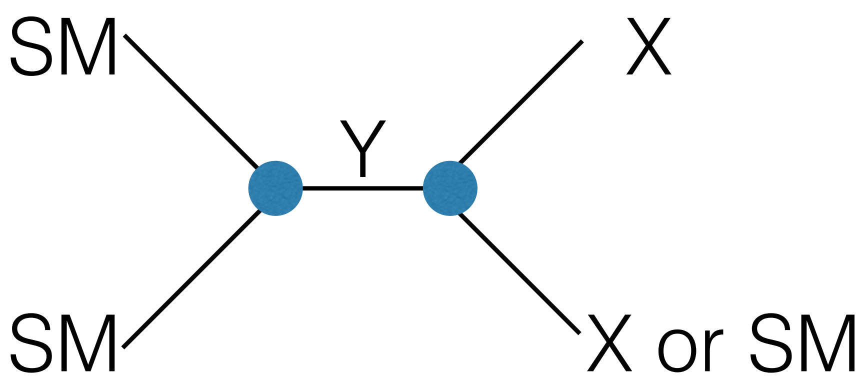
$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}} \qquad \beta_a \simeq \beta_{\rm SM} \simeq 1$$

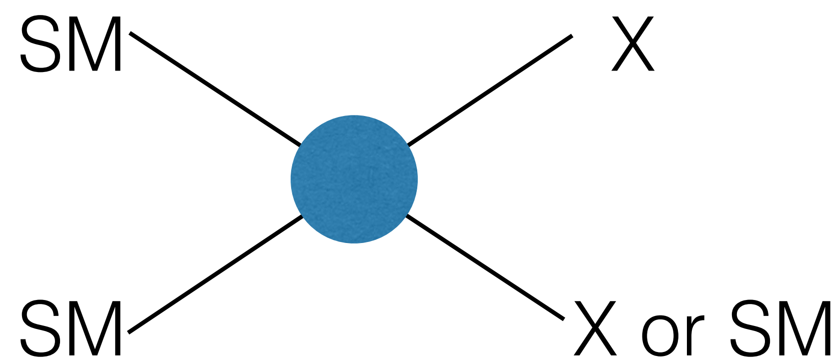
Good for massive LLP produced with small or moderate boost

$$\beta_X < 1$$

Basic topologies

X = LLP





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

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

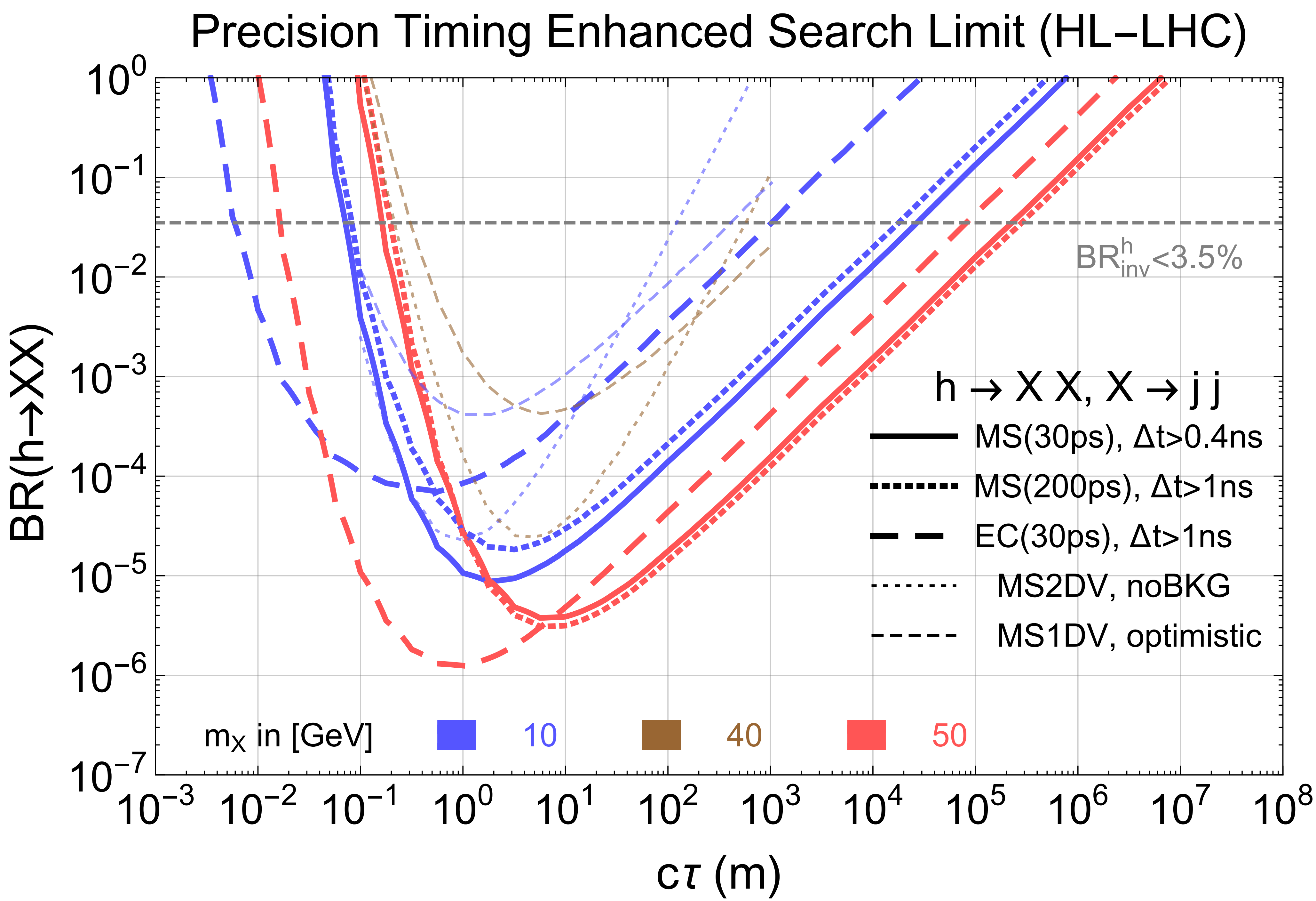
benchmark: SUSY

$X = \text{neutralino}$

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

Sensitivity to Higgs portal

Jia Liu, Zhen Liu, LTW

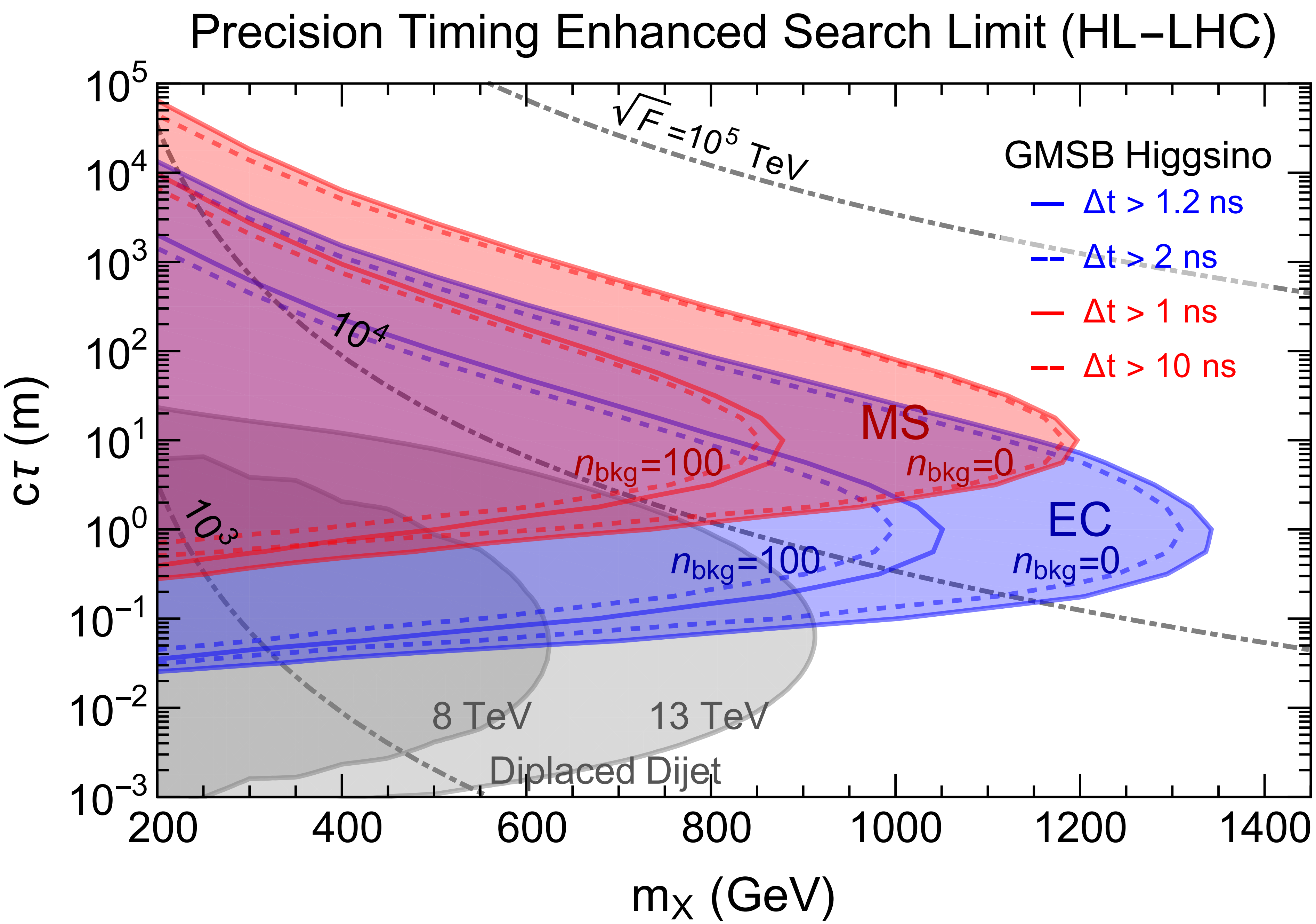


For example, for $\mathrm{BR}(h \to XX) \sim 10^{-3}$

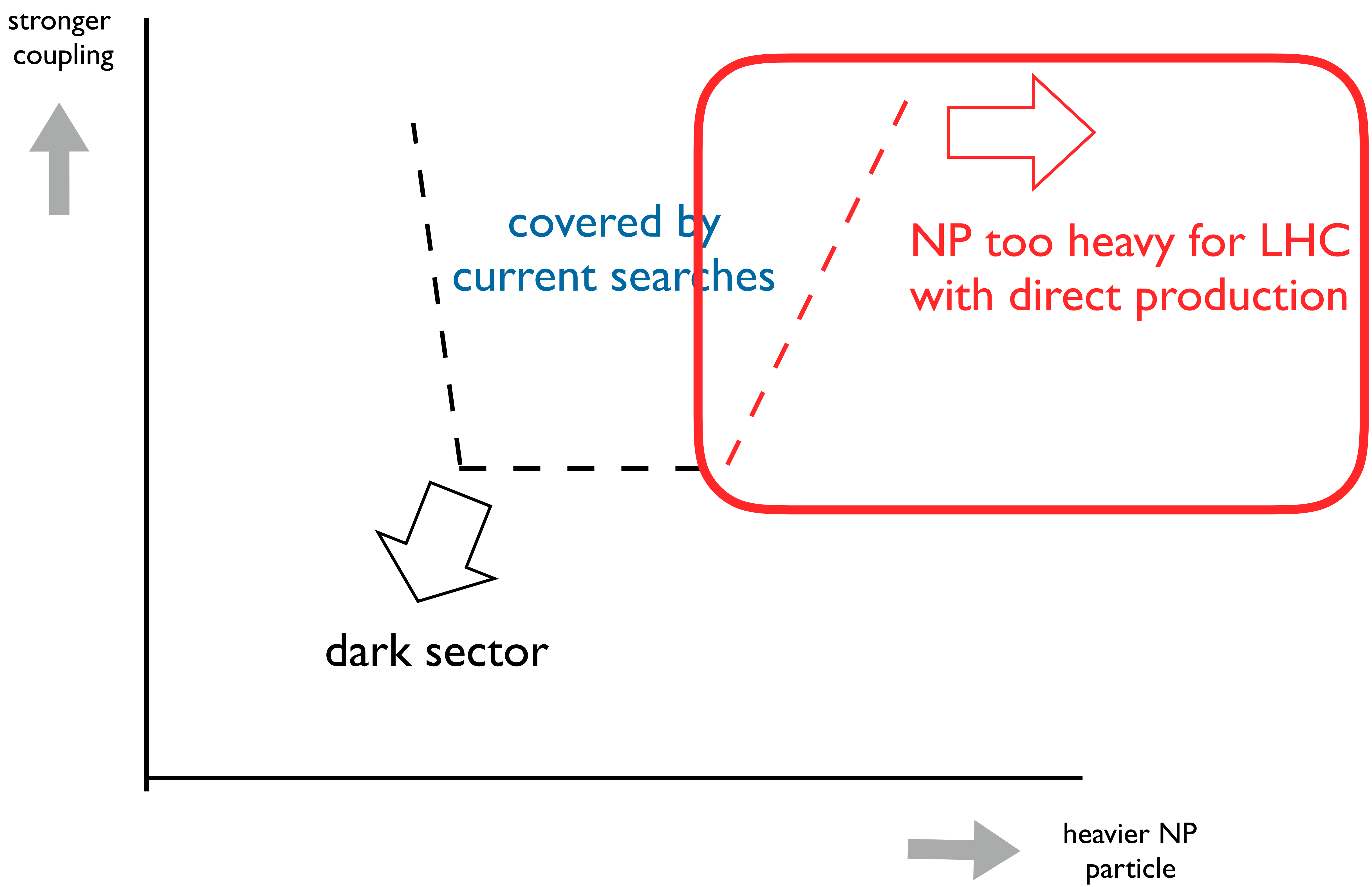
EC(MS) reach can be $c\tau \sim 10^3(10^4)$ meters

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
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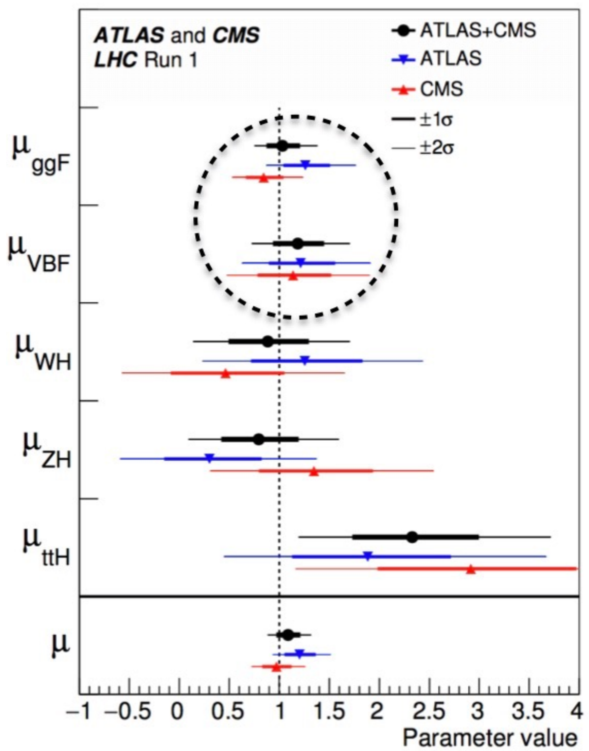
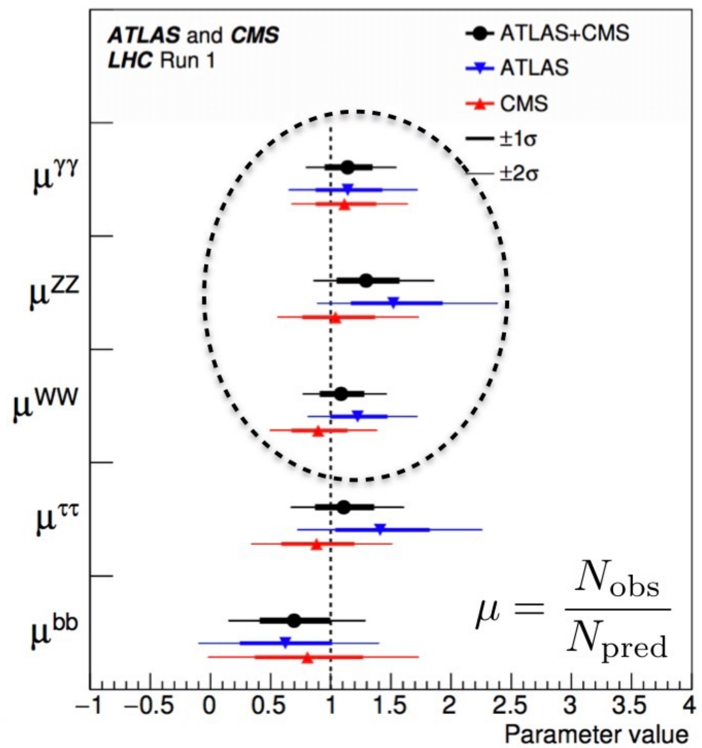
Revealing trace of new physics with precision measurements

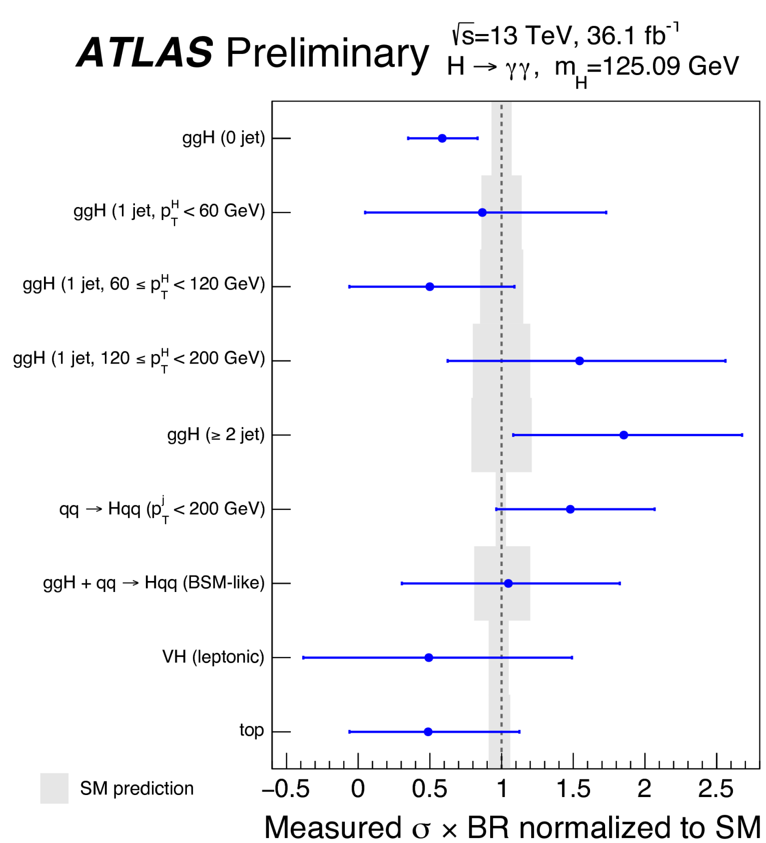
Higgs Standard Model-like

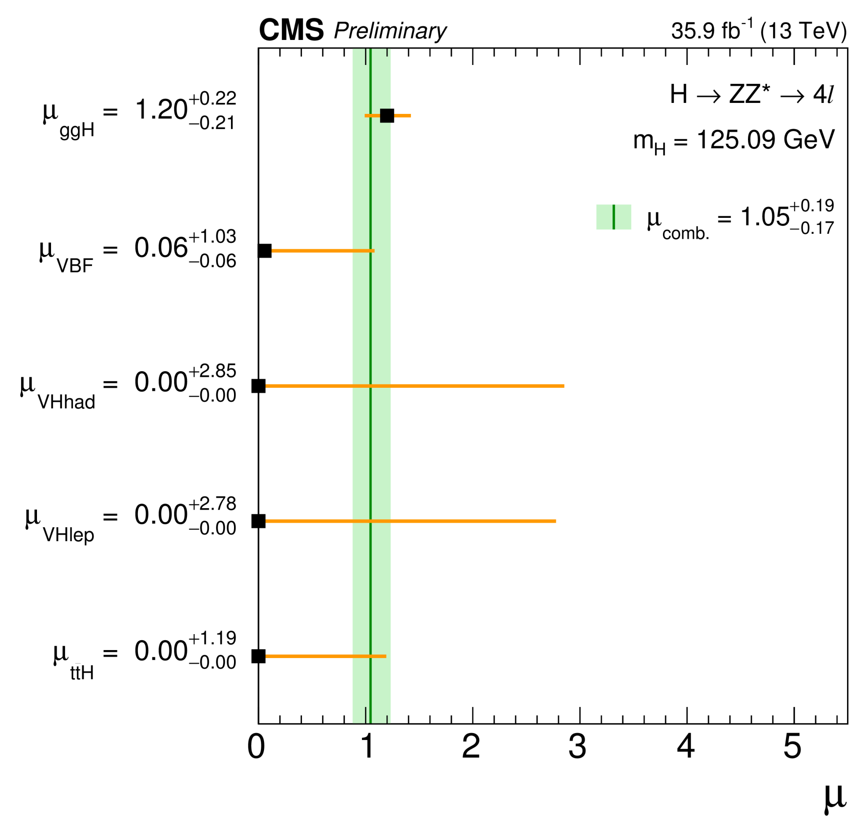
[JHEP 08 (2016) 045]





Agree to about 10-20%





Not entirely surprising

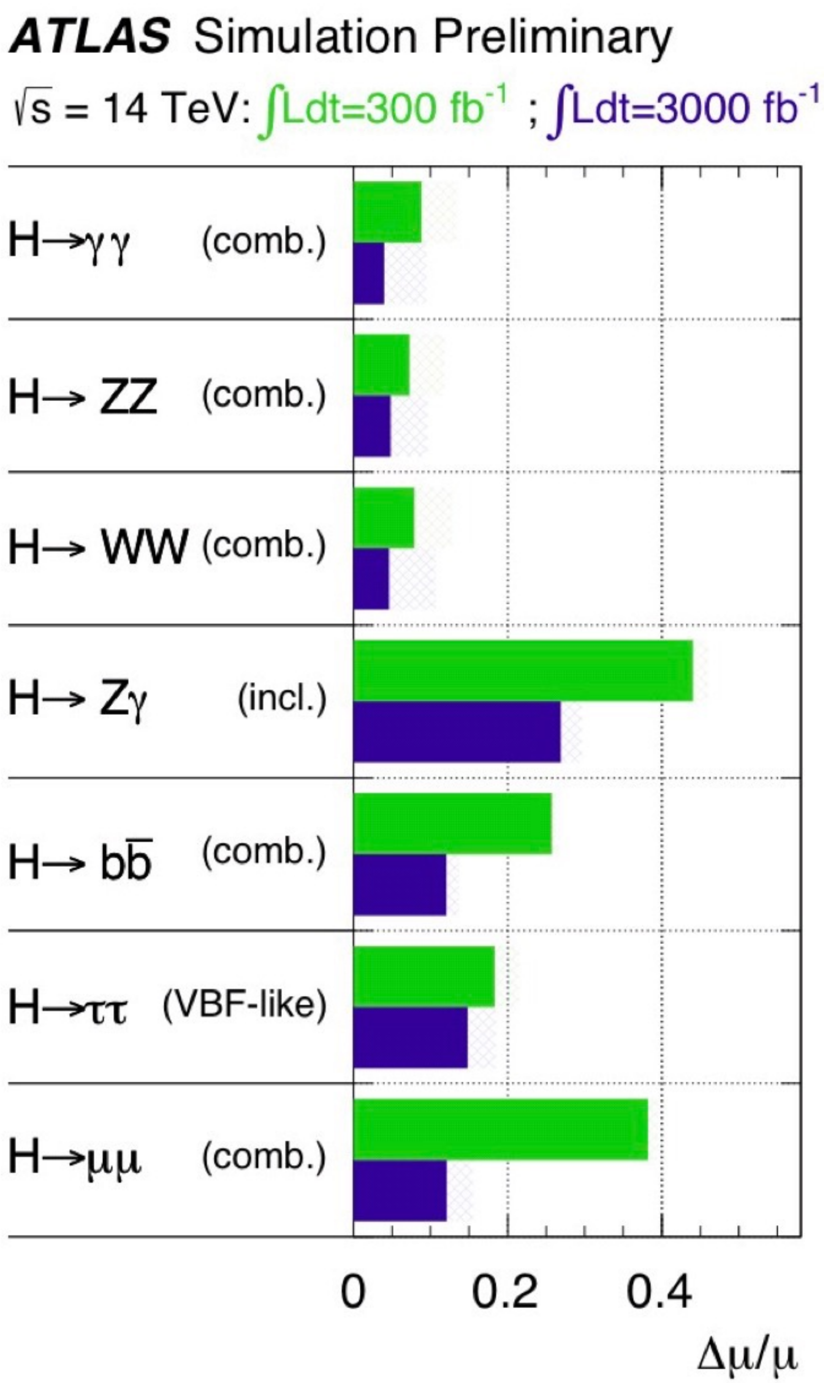
- In general, deviation induced by new physics is of the form

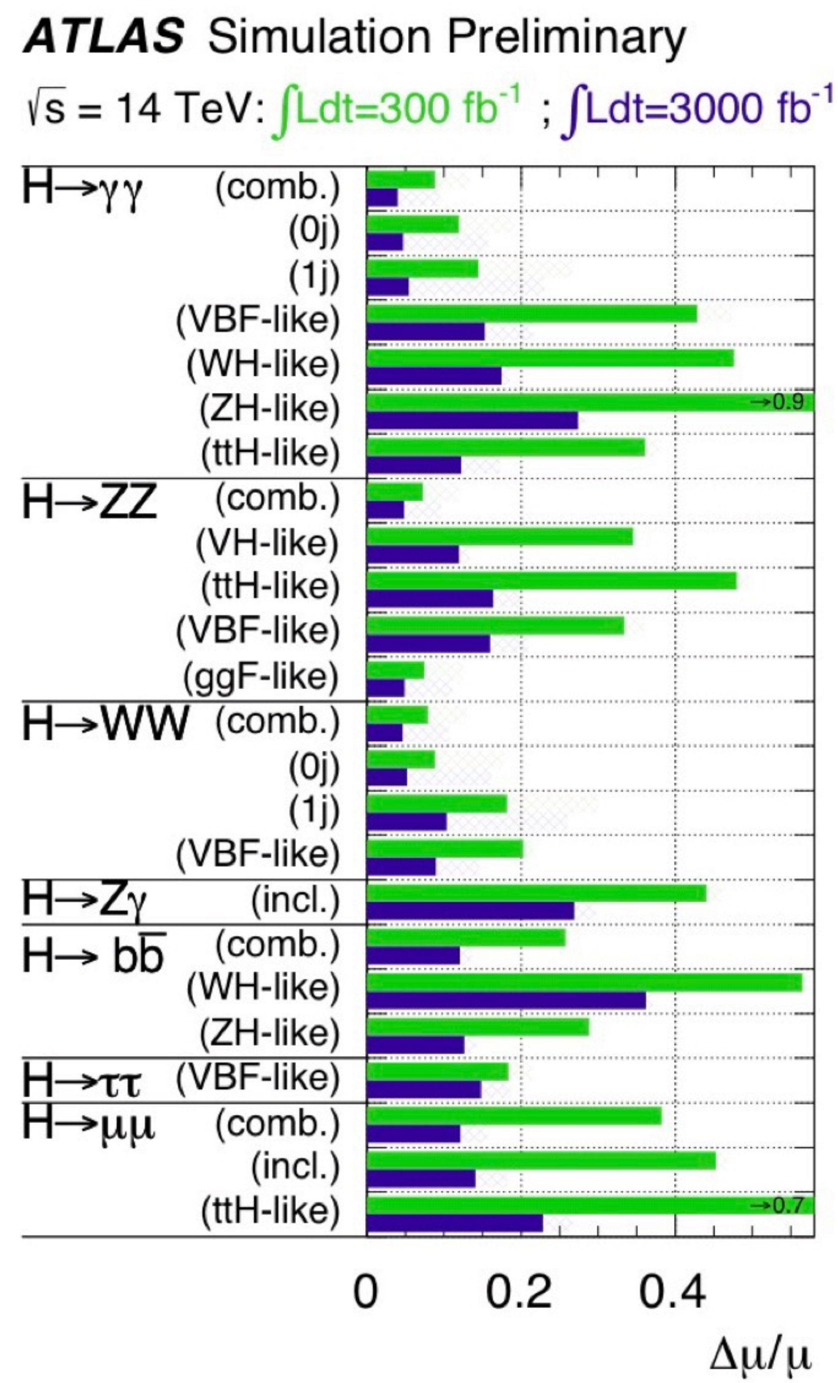
$$\delta \simeq c \frac{v^2}{M_{\mathrm{NP}}^2}$$

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.

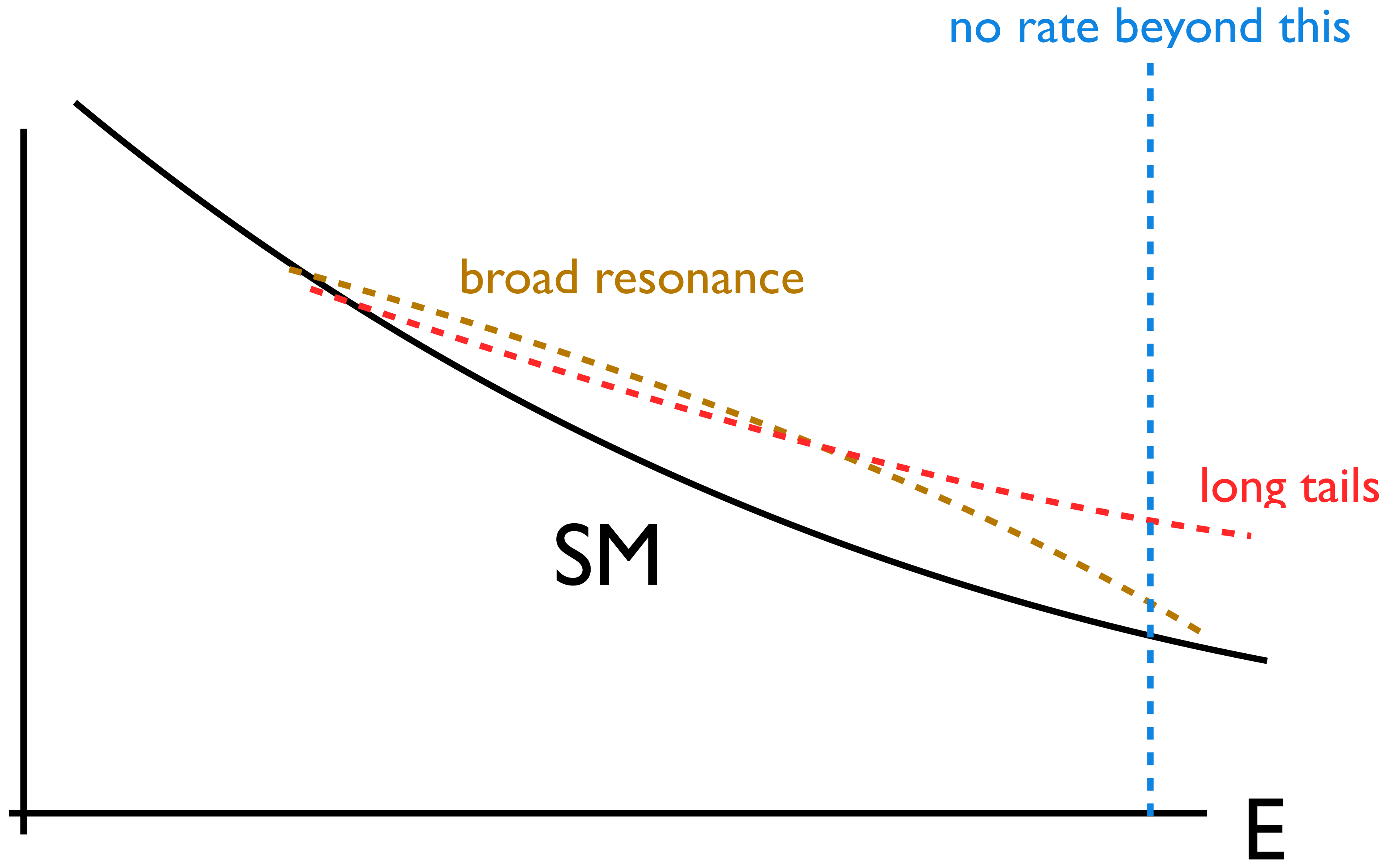
Significant improvement with high lumi





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

Precision measurement with distribution

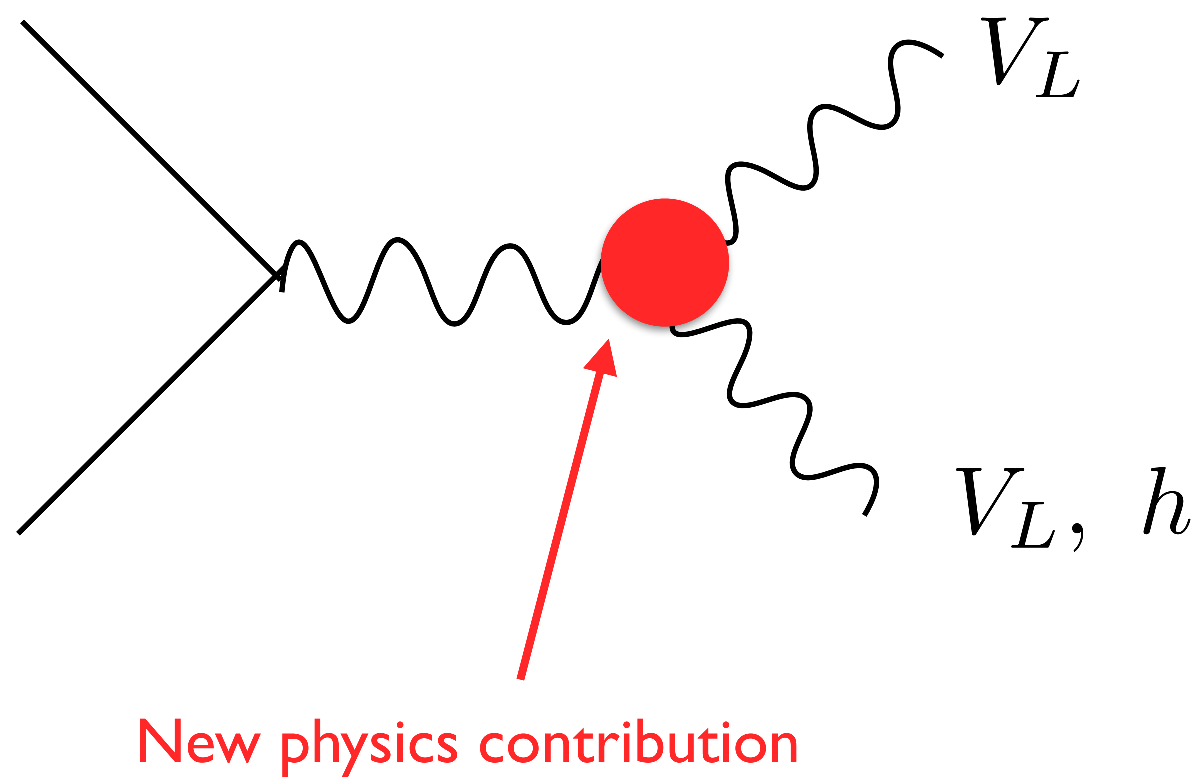


Low S/B, systematic dominated.

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

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

At LHC, new physics effect grows with energy

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

LHC needs to make a 20% measurement to beat LEP

LHC has potential.

Picking final state important

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

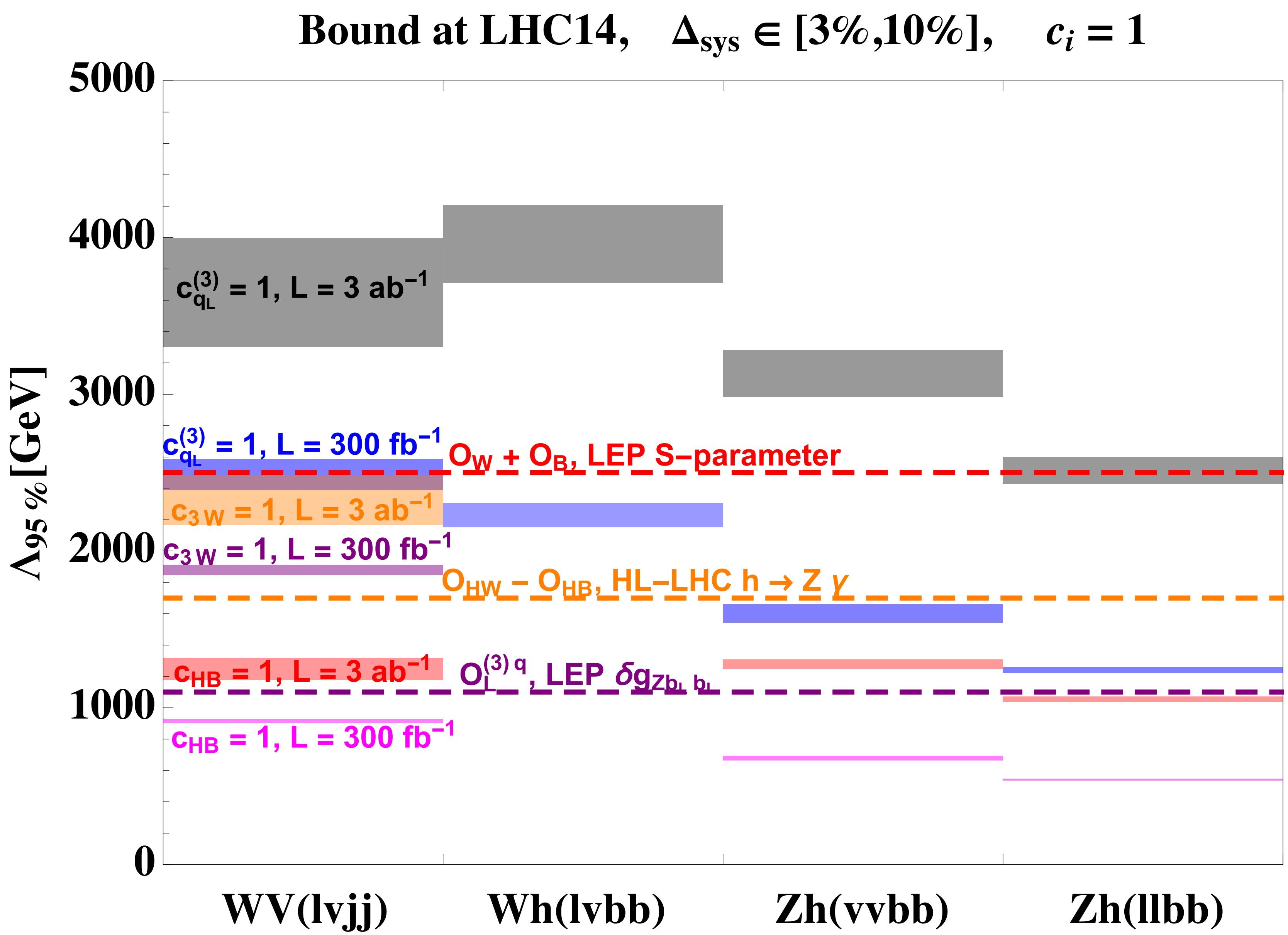
LHC @ 8 TeV : $\sigma_b^{red}/\sigma_{SM}^{Wh} \sim 200 - 10$

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

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^q_L	$ig^2\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\bar{Q}_L\gamma^\mu Q_L$	$c_q/m_*^2 \times \epsilon_q^2$
$O^{q,3}_L$	$ig^2\left(H^\dagger\sigma^a \overleftrightarrow{D}_\mu H\right)\bar{Q}_L\sigma^a\gamma^\mu Q_L$	$c_{q,3}/m_*^2 \times \epsilon_q^2$
O^u_R	$ig^2\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\bar{u}_R\gamma^\mu u_R$	$c_u/m_*^2 \times \epsilon_u^2$
O^u_R	$ig^2\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\bar{d}_R\gamma^\mu d_R$	$c_d/m_*^2 \times \epsilon_d^2$
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

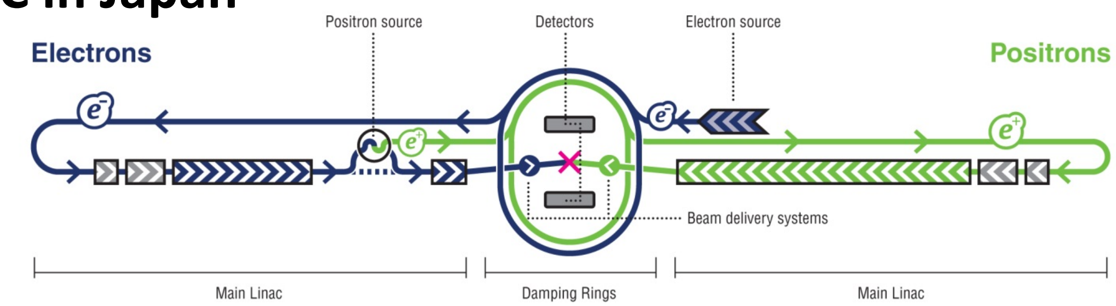
Better than LEP, and many LHC direct searches

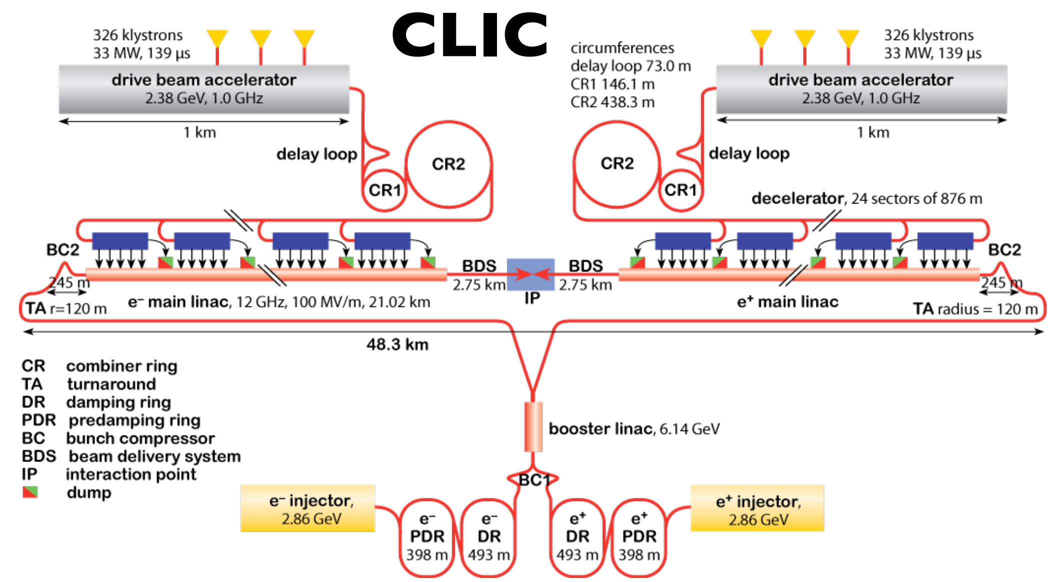
See also: Alioli, Farina, Pappadopulo, Ruderman, Franceschini, Panico, Pomarol, Riva, Wulzer, Azatov, Elias-Miro, Regimuaji, Venturini

Beyond LHC

Future Colliders

ILC in Japan



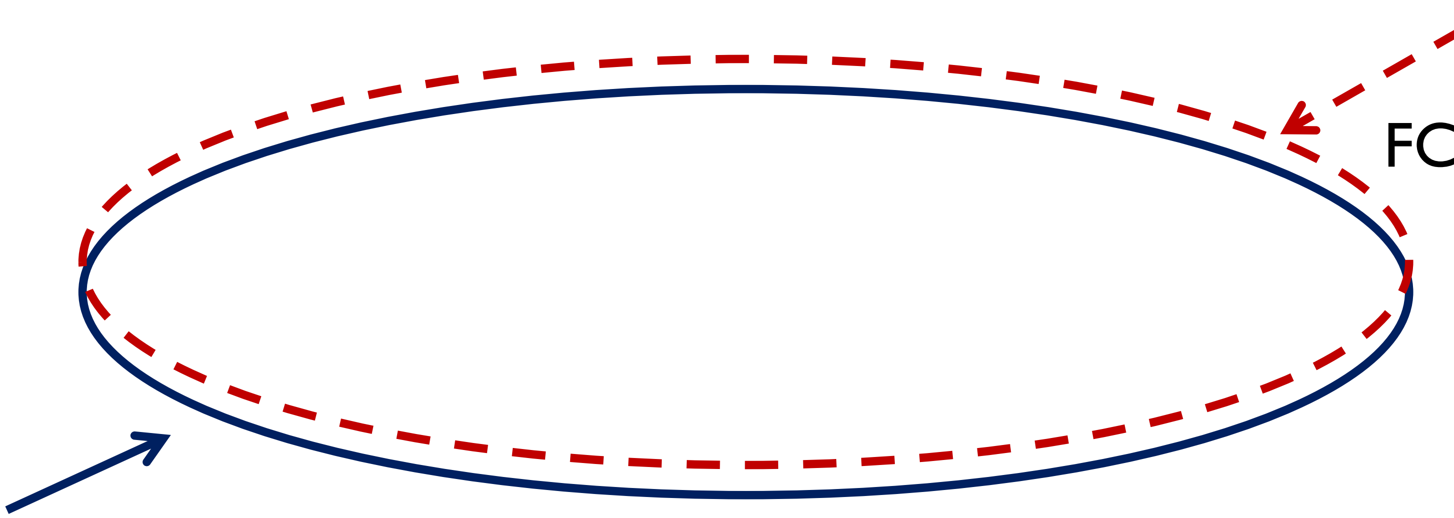


Circular. "Scale up" LEP+LHC

~100 TeV

pp collider

FCC-hh (CERN), SppC(China)



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

FCC-ee (CERN), CEPC(China)

Ambitious program

FCC-ee:

FCC-ee possible operation model

working point	luminosity/IP [10^{34} cm^{-2}s^{-1}]	total luminosity (2 IPs)/ yr	physics goal	run time [years]
Z first 2 years	100	26 ab^{-1}/year	**150 ab^{-1}**	**4**
Z later	200	52 ab^{-1}/year		
W	32	8.3 ab^{-1}/year	**10 ab^{-1}**	**1**
H	7.0	1.8 ab^{-1}/year	**5 ab^{-1}**	**3**
machine modification for RF installation & rearrangement: **1 year**				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	**0.2 ab^{-1}**	**1**
top later (365 GeV)	1.5	0.38 ab^{-1}/year	**1.5 ab^{-1}**	**4**

$$\sim 10^6 \text{ Higgses}, \ \sim 10^{13} \text{ Zs}, \ldots$$

13 yr run plan: Higgs=3, Z=4, top=5, W=1

CEPC Operation Plan

Particle type	Energy (c.m.) (GeV)	Luminosity per IP (10^{34} $cm^{-2}s^{-1}$)	Luminosity per year (ab^{-1}, 2 IPs)	Years	Total luminosity (ab^{-1}, 2 IPs)	Total number of particles
H	240	3	0.8	**7**	5.6	1×10^6
Z	91	32	8	**2**	16	7×10^{11}
W	160	10	2.6	**1**	2.6	8×10^6

CEPC yearly run time assumption:

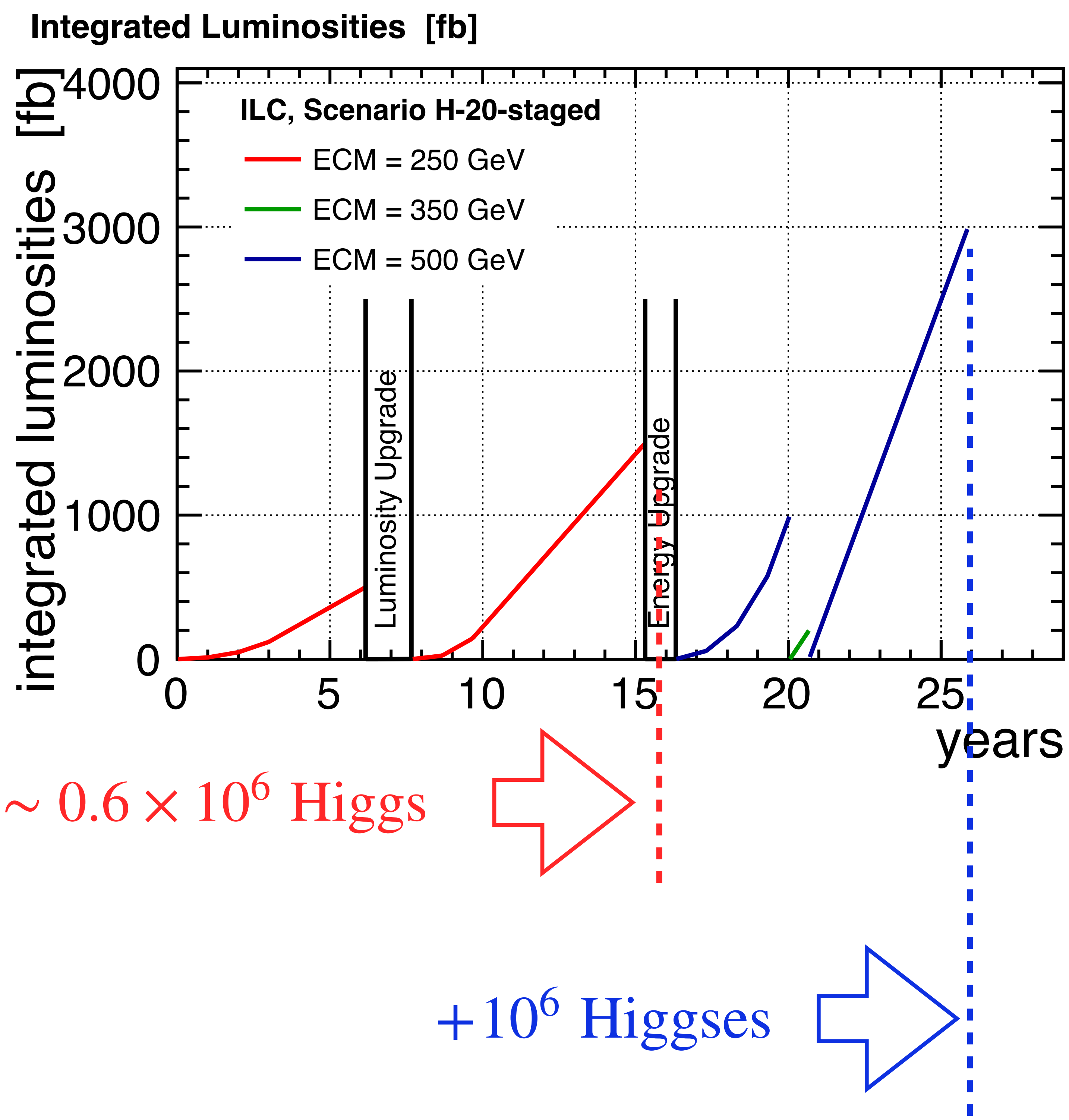
- Operation – 8 months, or 250 days, or 6,000 hrs
- Physics (60%) – 5 months, or 150 days, or **3,600 hrs**, or 1.3 Snowmass Unit.

Currently, no plan to scan the ttbar threshold.

CEPC

staging scheme	physics focus
7 year at Higgs ~1M events 240 GeV (initial stage)	H indir. BSM
2 years at Z upto 10^{12} events 1 year at WW ~20M events	Z, W EW Physics

ILC run plan



No Z-pole or WW run planned

What precision should we aim for?

- In precision measurements, we are going after deviations of the form

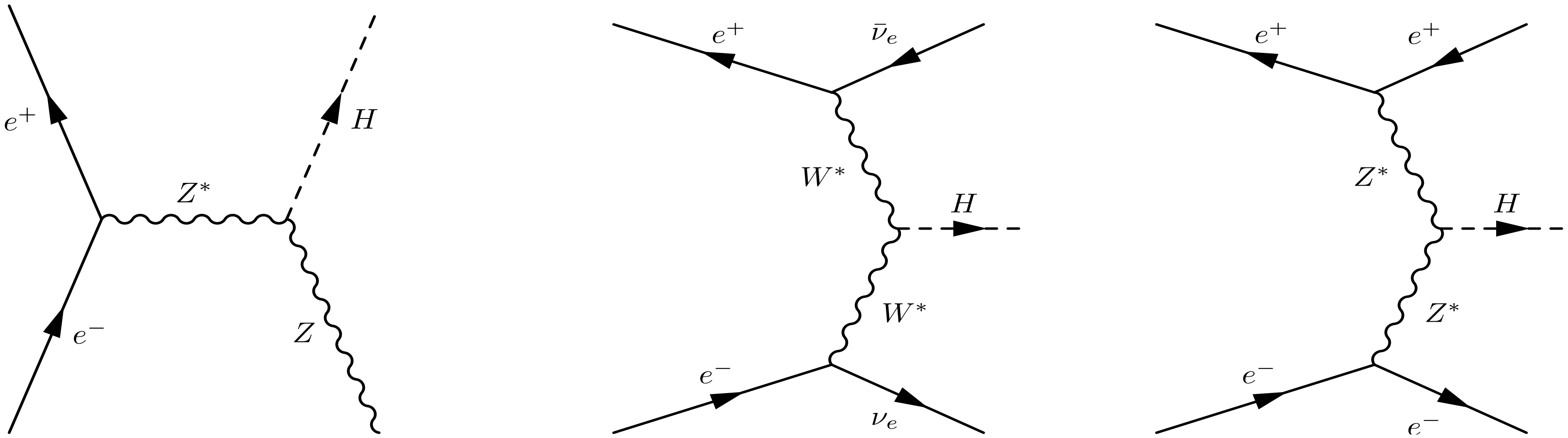
$$\delta \simeq c \frac{v^2}{M_{\rm NP}^2}$$

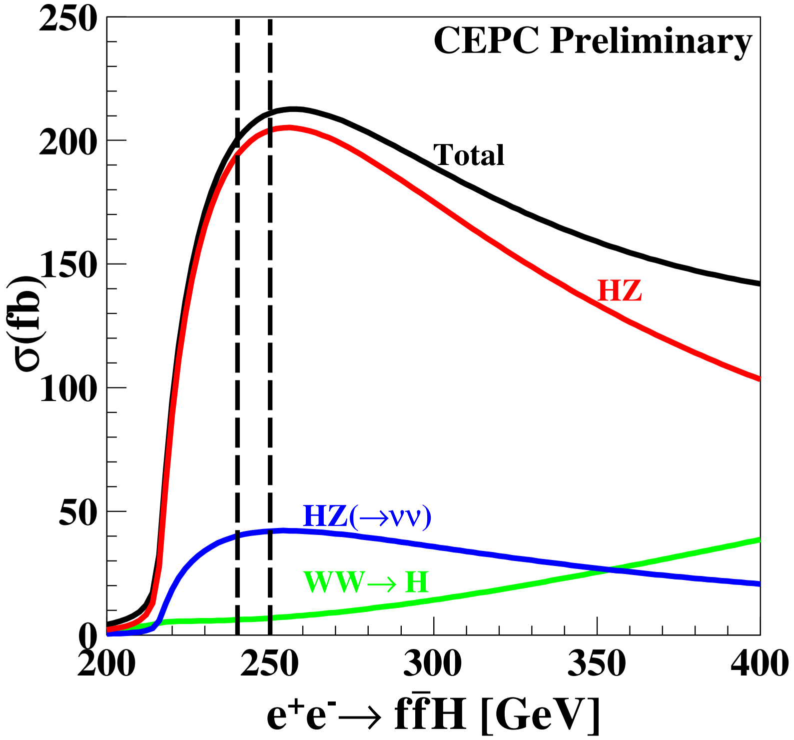
M_{NP} : mass of new physics
c: $O(1)$ coefficient

- Take the Higgs coupling.
  - LHC precision: 5-10% $\Rightarrow$ sensitive to M_{NP} < TeV

- To go beyond the LHC, need 1% or less precision.

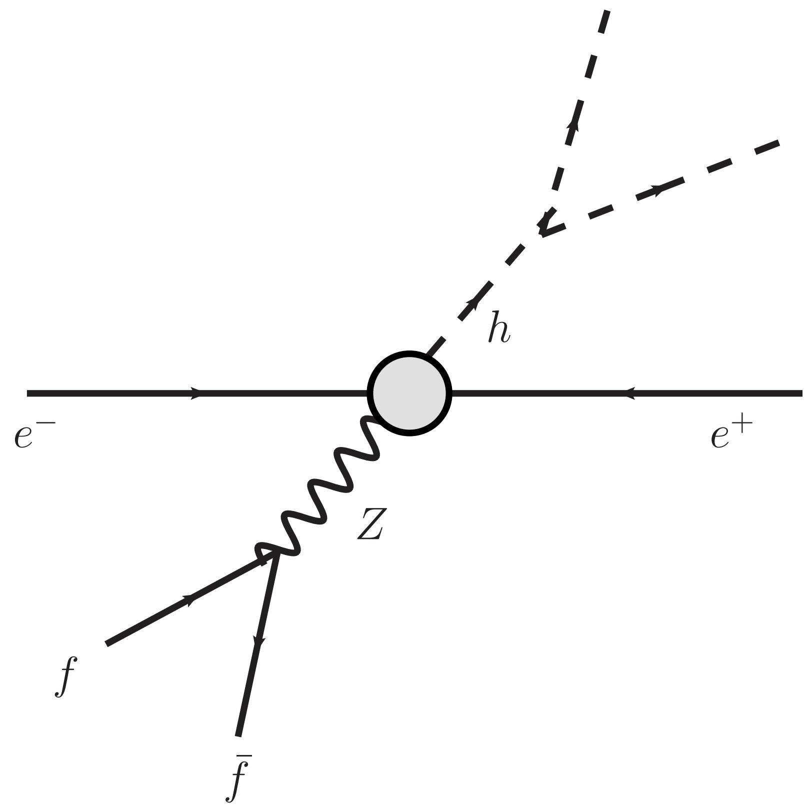
Higgs factory processes

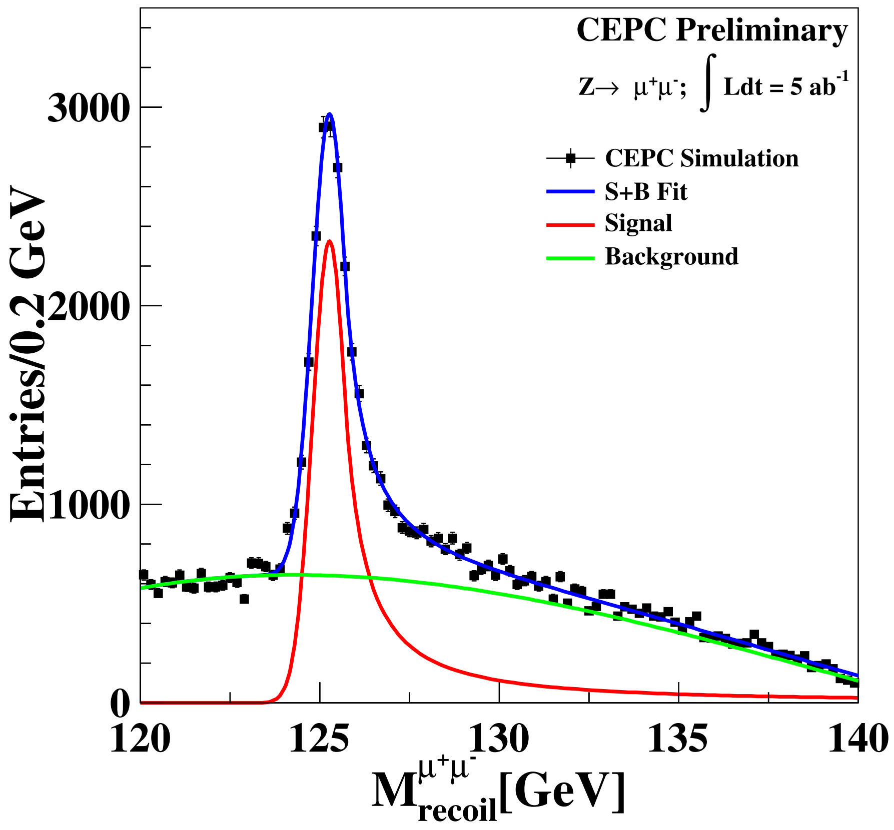




Process	Cross section	Nevents in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\nu H$	6.72	3.36×10^4
$e^+e^- \to eeH$	0.63	3.15×10^3
Total	219	1.10×10^6

Zh cross section





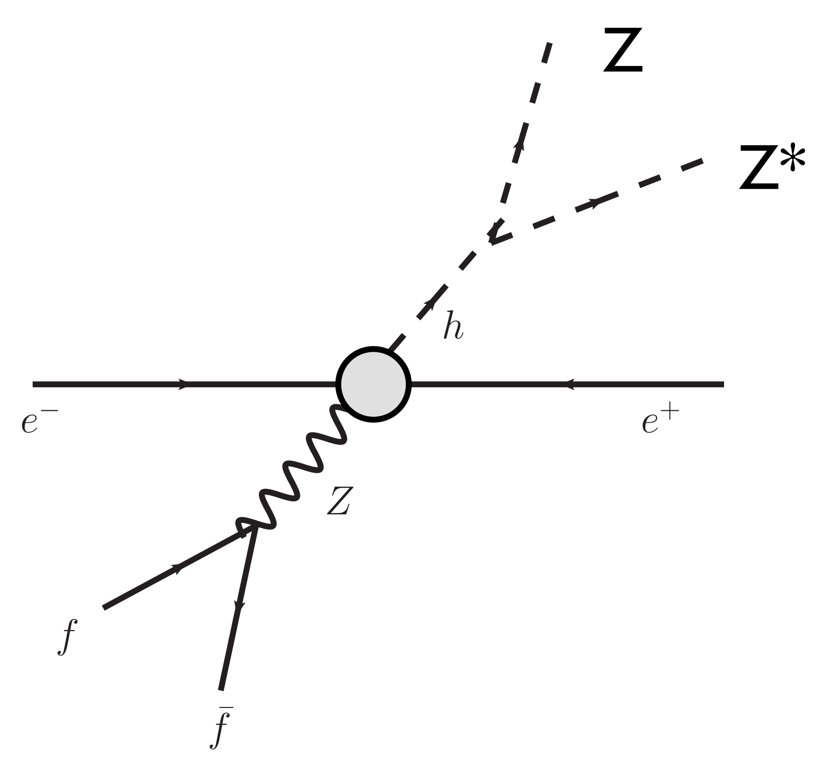
$$M_{\rm recoil}^2 = (\sqrt{s} - E_{ff})^2 - p_{ff}^2 = s - 2E_{ff}\sqrt{s} + m_{ff}^2$$

Can use recoil mass to identify Zh process, independent of Higgs decay

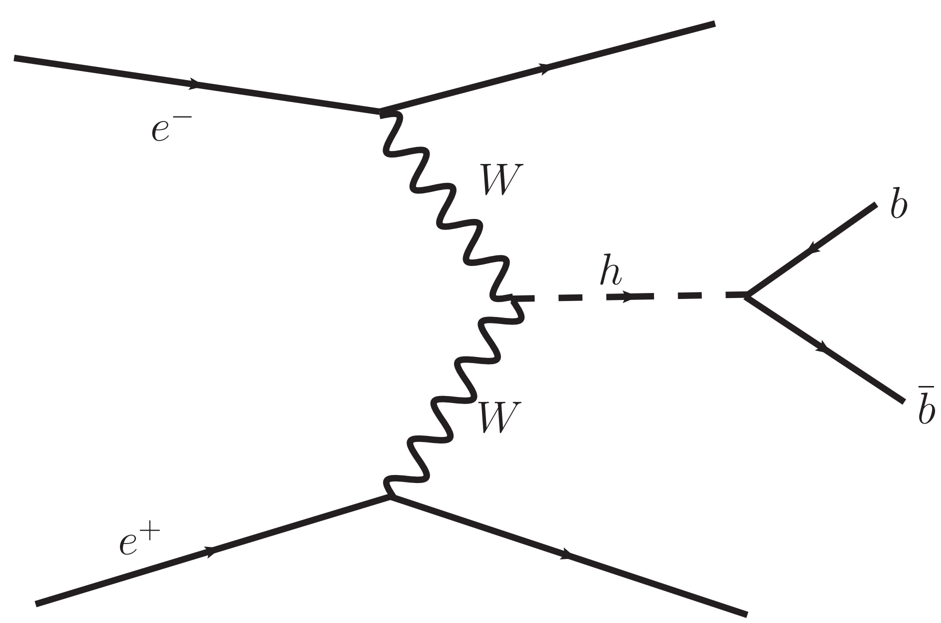
⇒ inclusive measurement of Zh cross section

Higgs width.

Unique capability of lepton colliders.



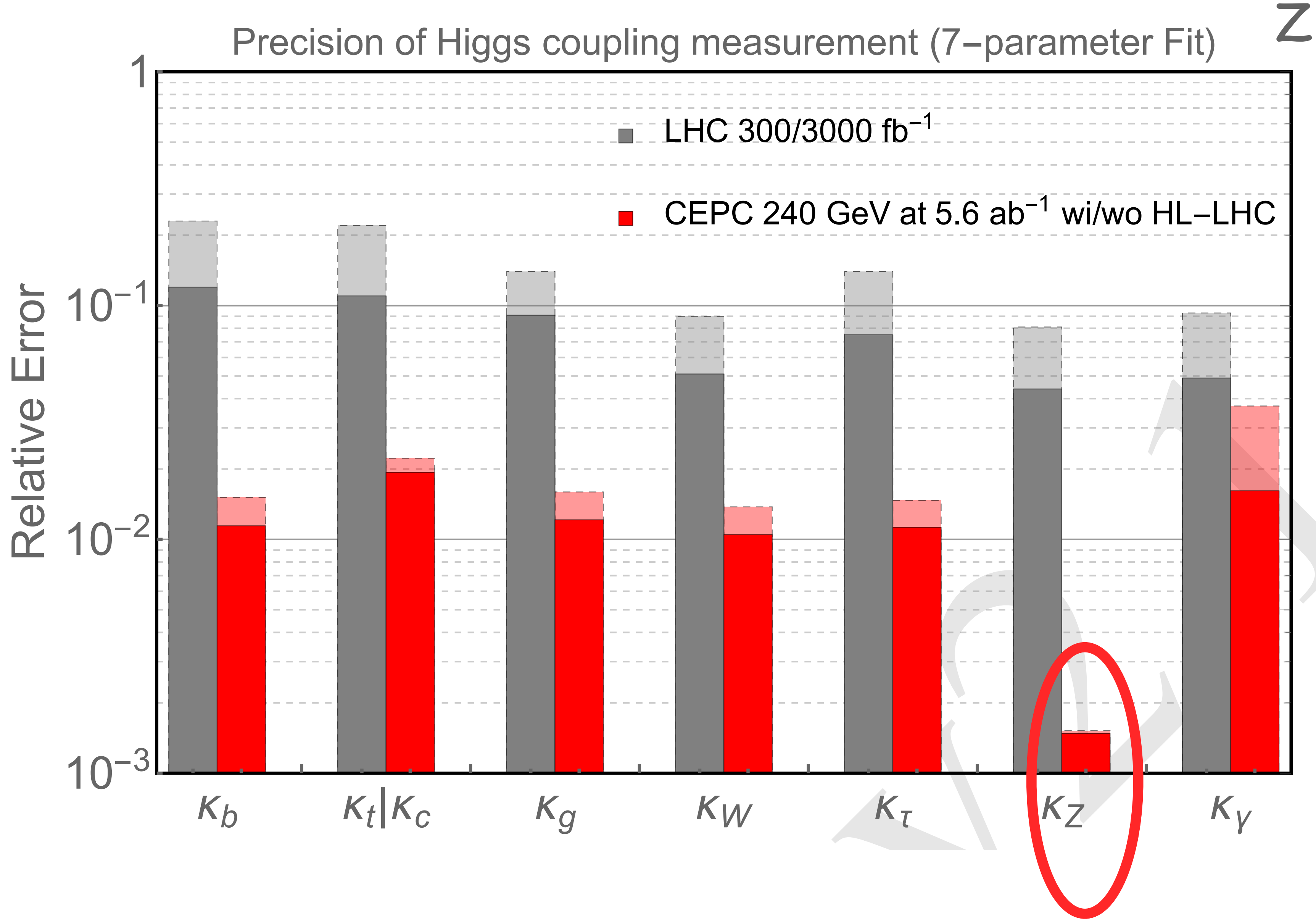
$$\Gamma_H \propto \frac{\Gamma(H \to ZZ^*)}{\mathrm{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H \to ZZ^*)}$$



$$\Gamma_H \propto \frac{\Gamma(H \to bb)}{\mathrm{BR}(H \to bb)} \propto \frac{\sigma(\nu\nu H \to \nu\nu bb)}{\mathrm{BR}(H \to bb) \cdot \mathrm{BR}(H \to WW^*)}$$

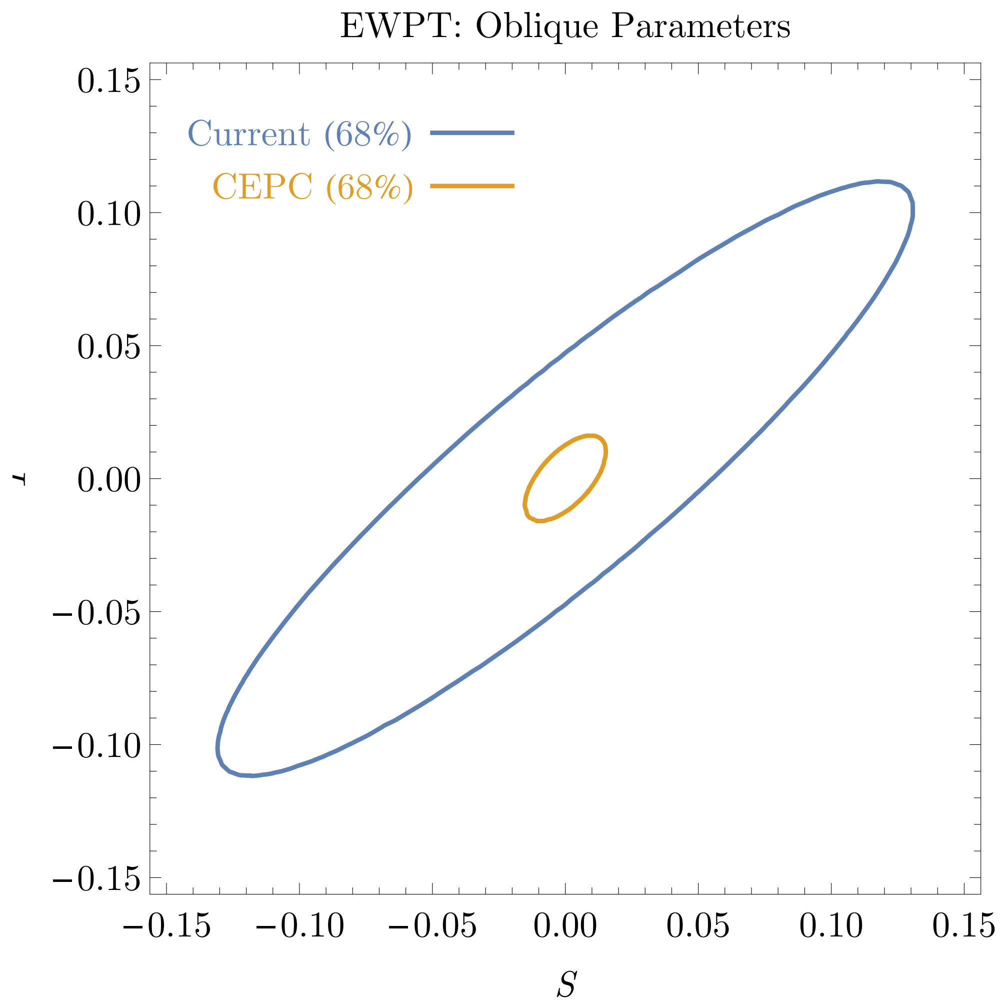
CEPC can do very well

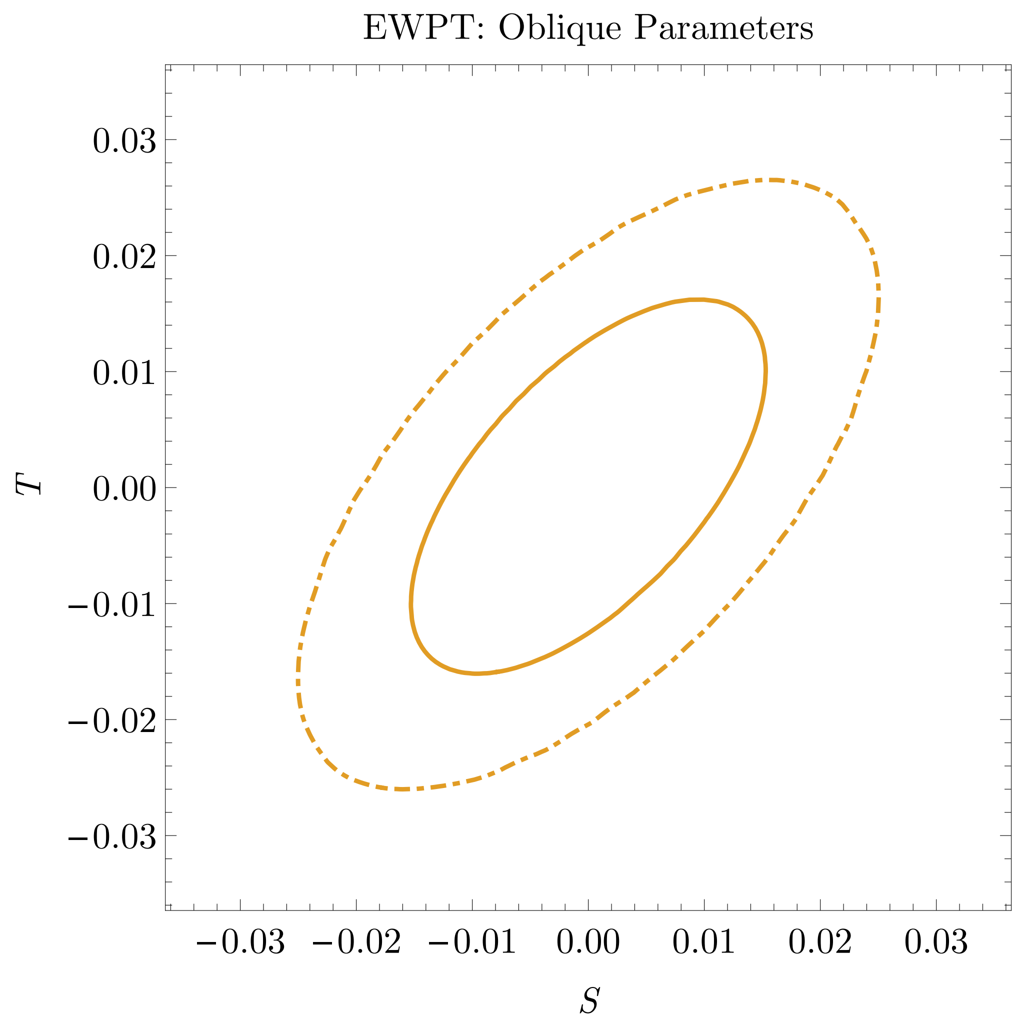
Zhen Liu



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

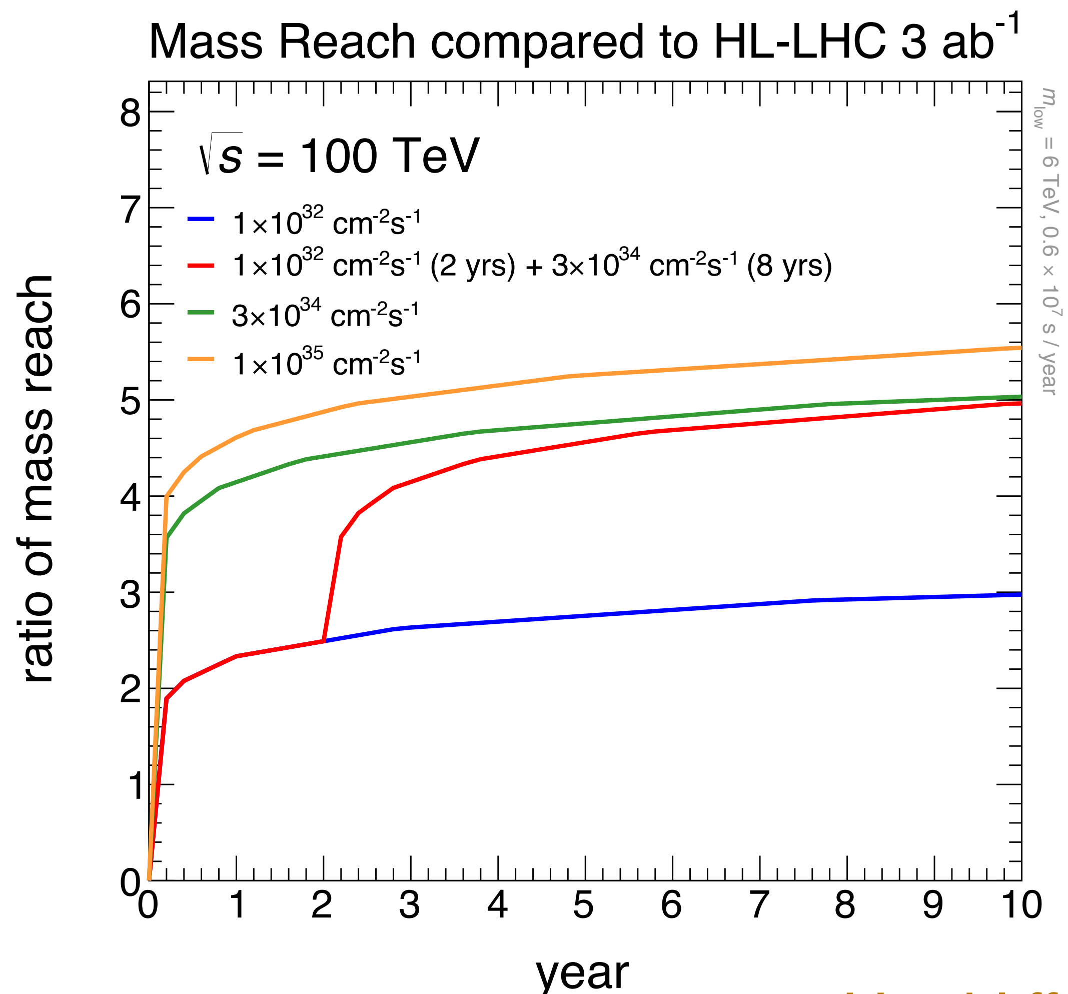
Electroweak precision





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

100-ish TeV pp collider

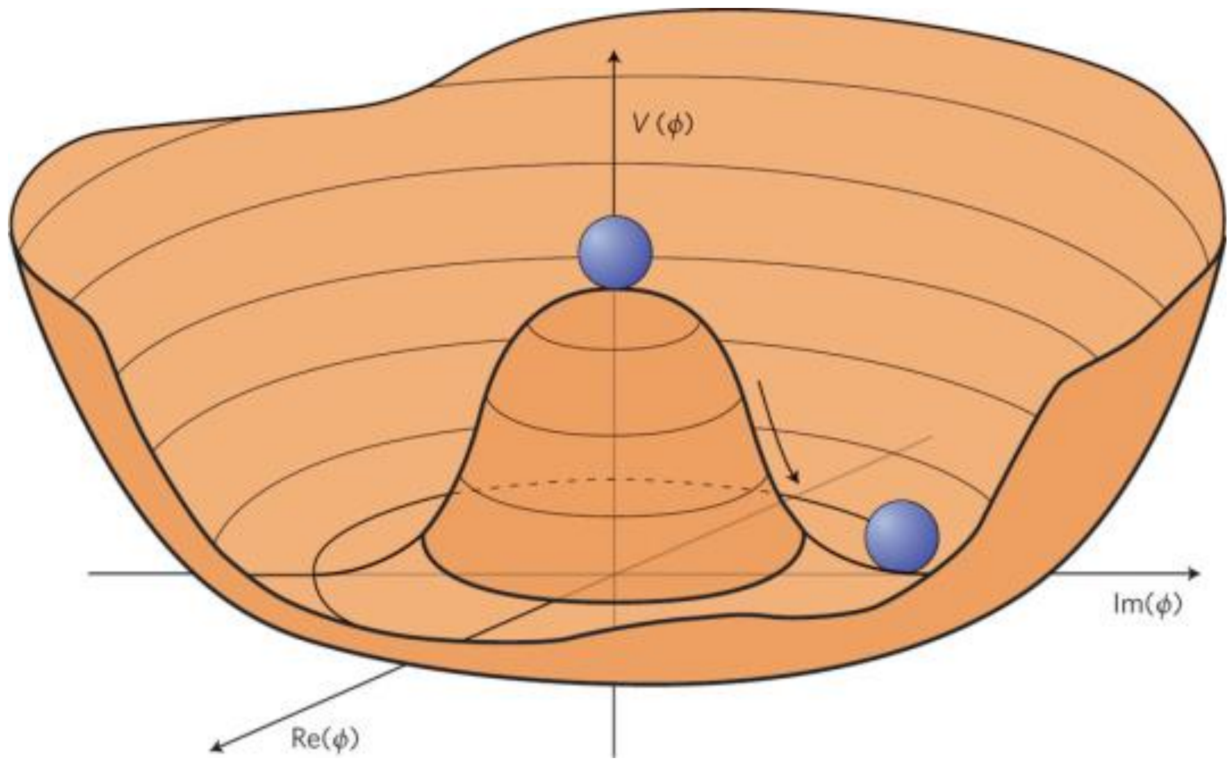


Hinchliffe, Kotwal, Mangano, Quigg, LTW

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

Electroweak symmetry breaking

“Simple” picture: Mexican hat

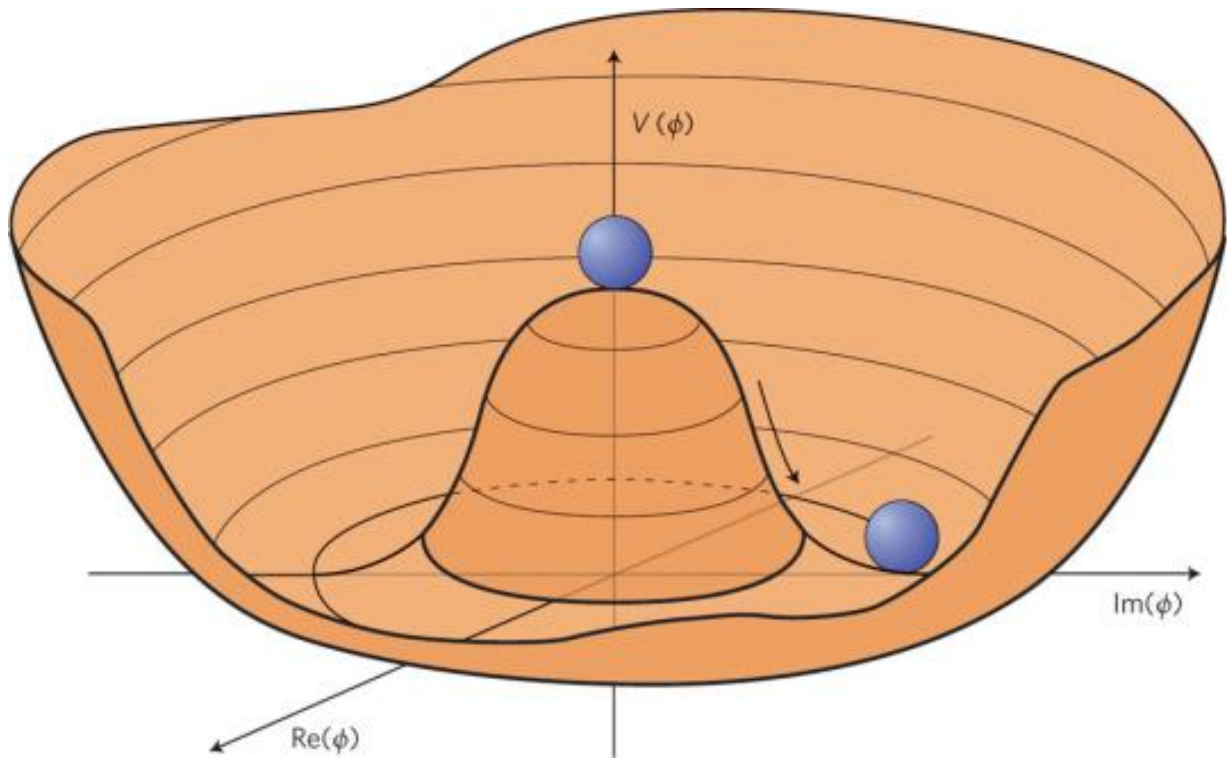


$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

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

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

"Simple" picture: Mexican hat



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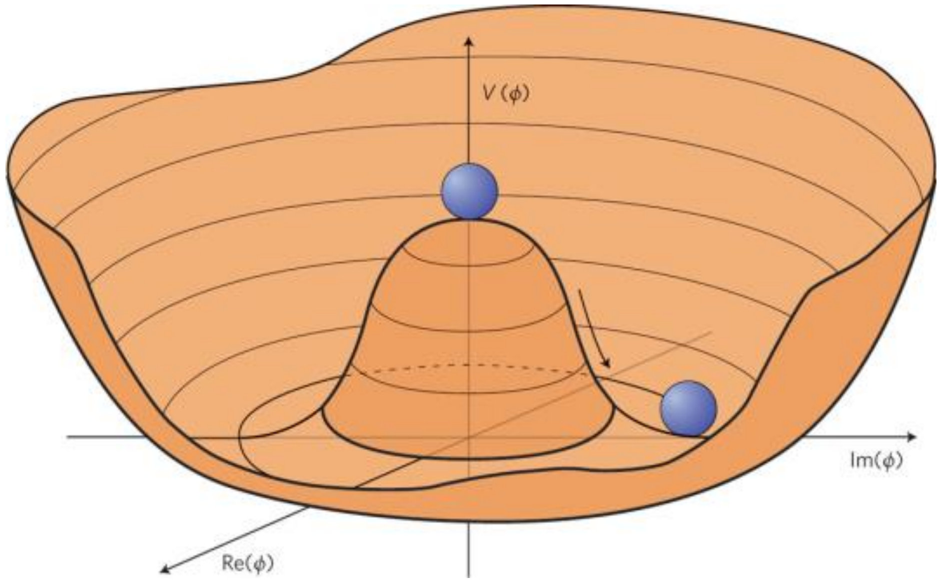
$$\langle h \rangle \equiv v \neq 0 \;\rightarrow\; m_W = g_W \frac{v}{2}$$

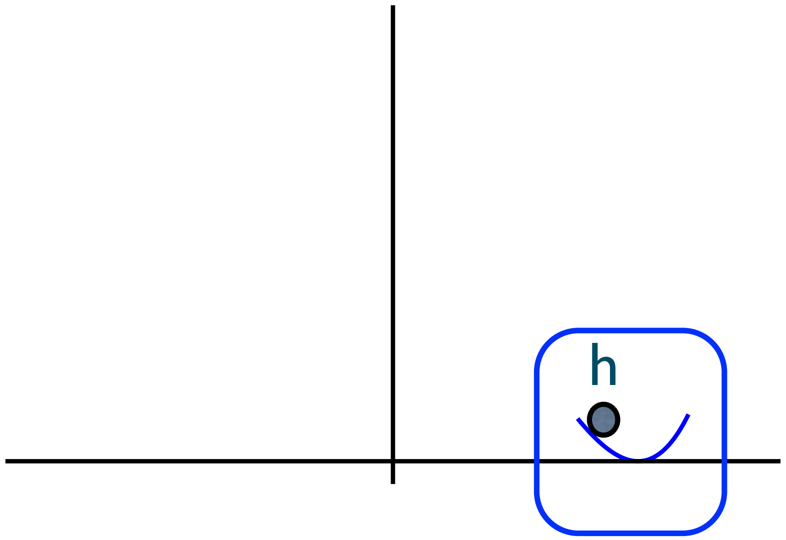
Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

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

Mysteries of the electroweak scale.

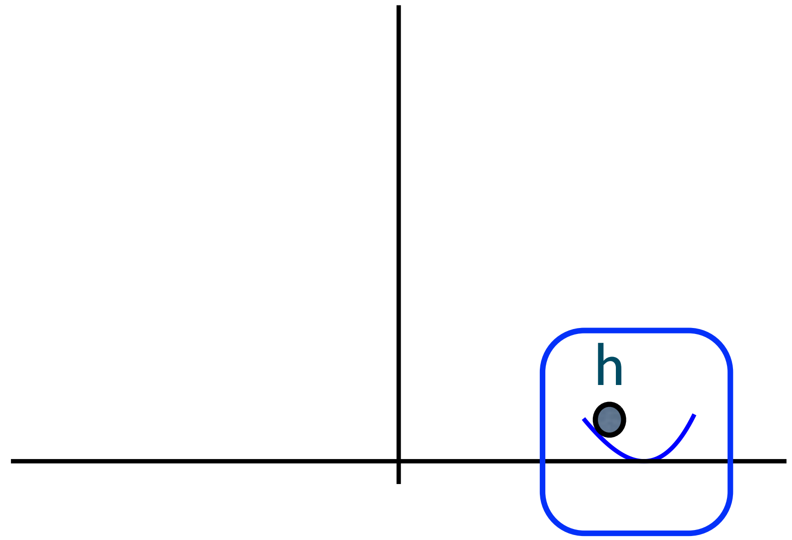


Mysteries of the electroweak scale.



What we know now

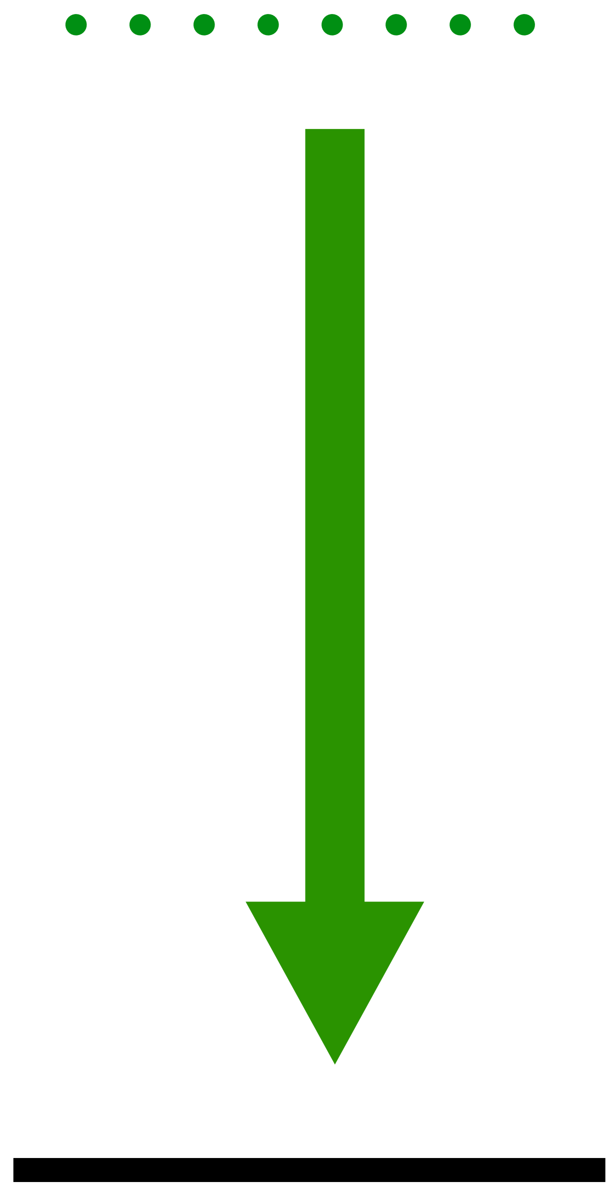
Mysteries of the electroweak scale.



What we know now

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

How to predict Higgs mass?

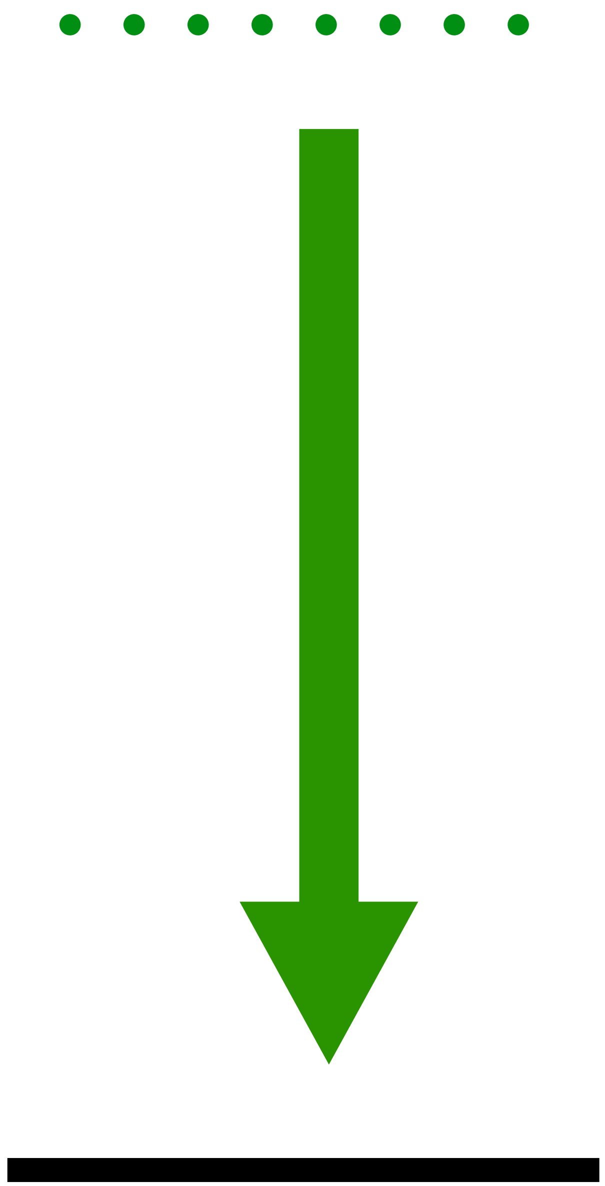


The energy scale of new physics responsible for EWSB

Electroweak scale, 100 GeV.

m_h , m_W …

How to predict Higgs mass?



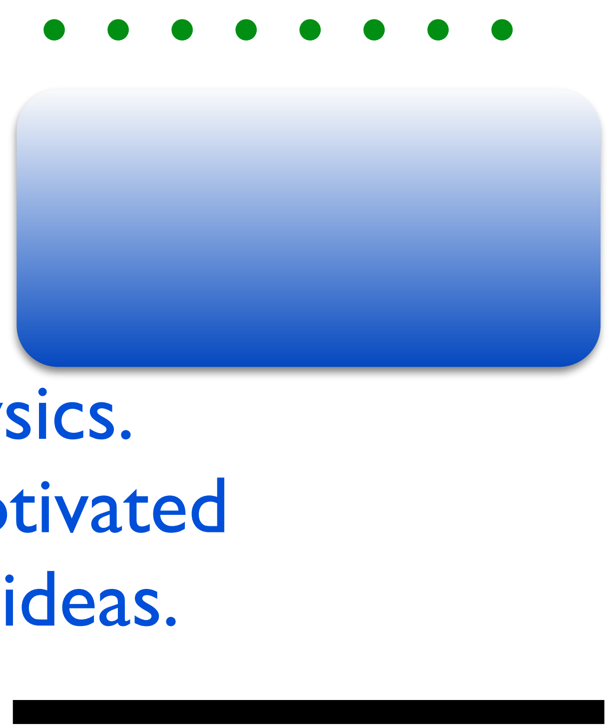
The energy scale of new physics responsible for EWSB

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.

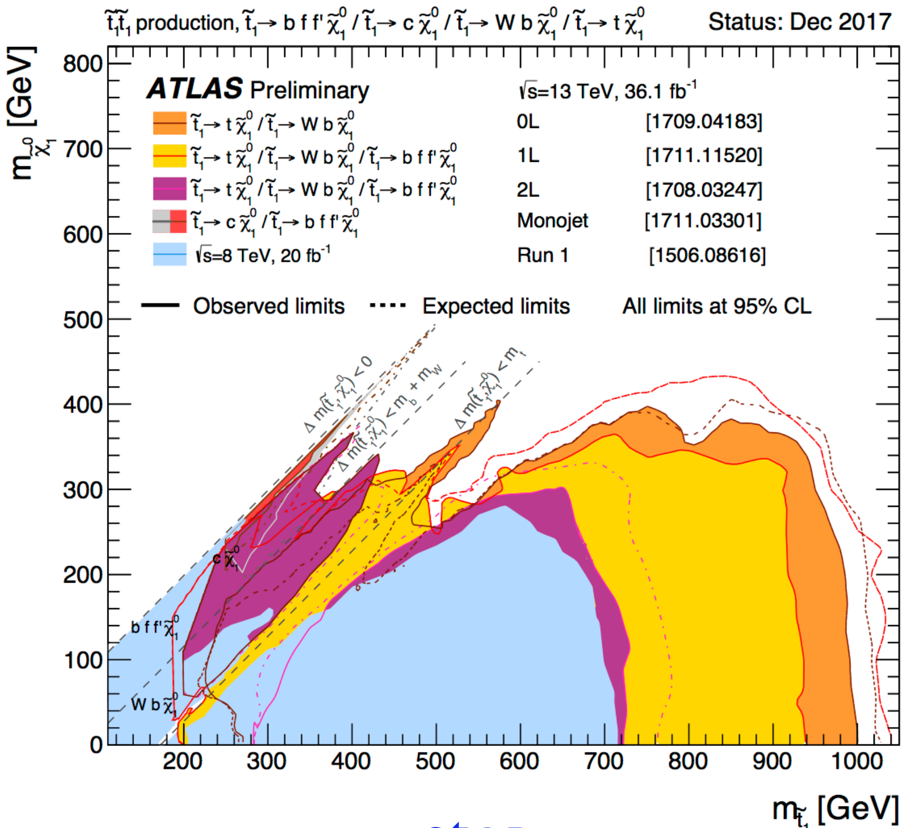
Electroweak scale, 100 GeV.
m_h , m_W …

Models

- "conventional"
  - Supersymmetry (SUSY), Composite Higgs, ...
  - A bit uncomfortable, still viable.

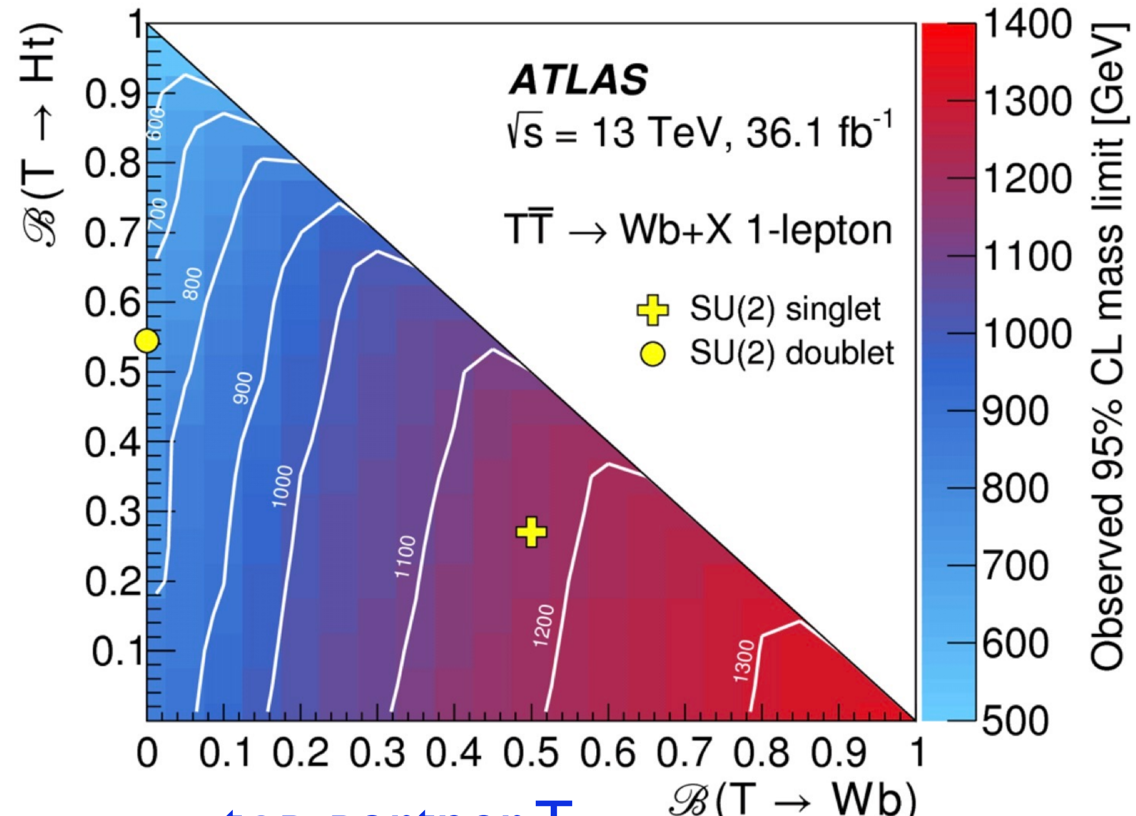
All eyes on these searches

Supersymmetry



stop

Composite Higgs



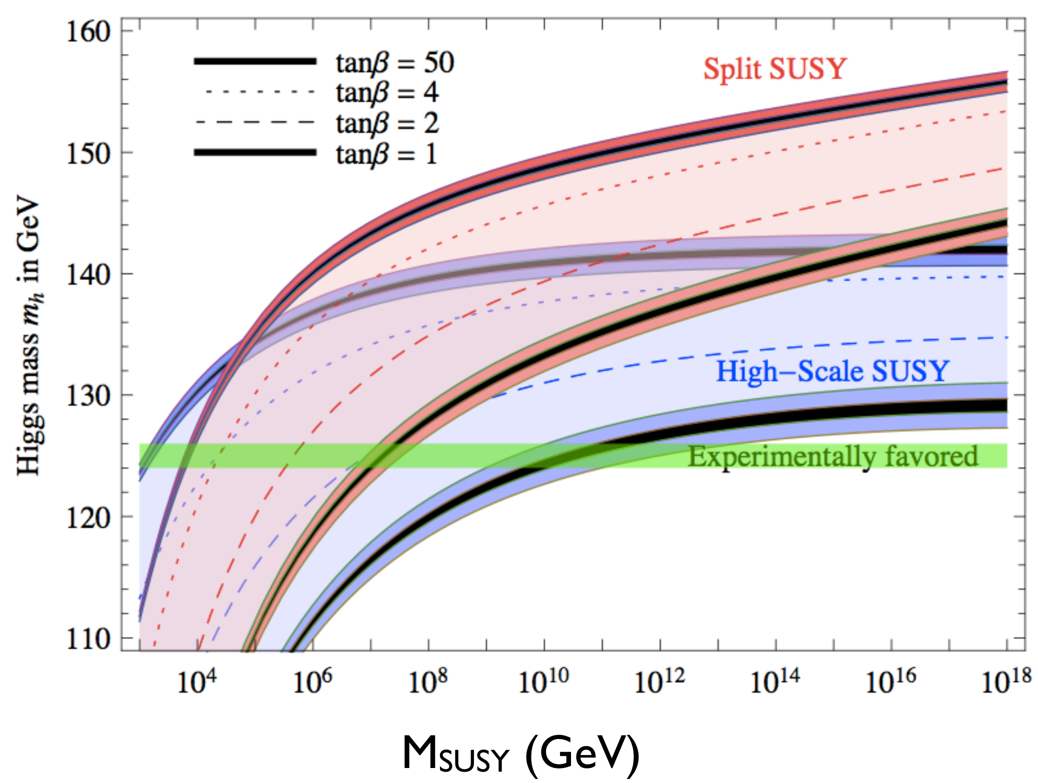
top partner, T

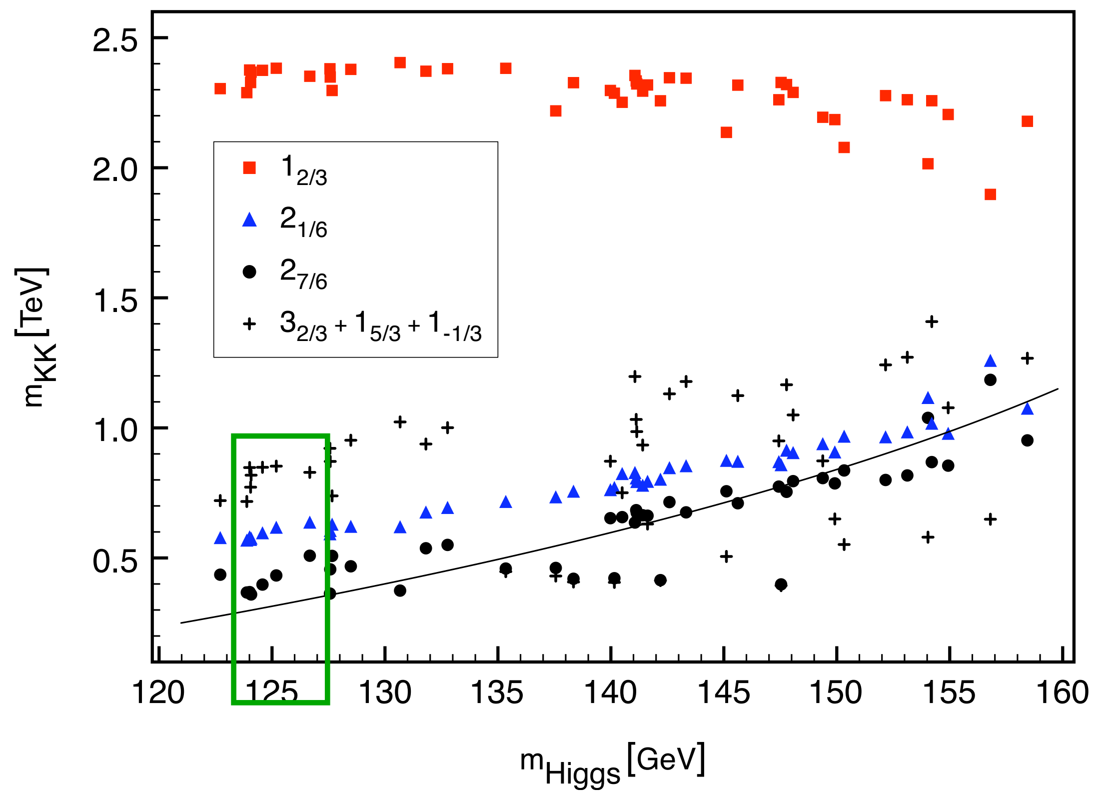
fine-tuning = comparison: $\frac{1}{16\pi^2} m_{\rm T}^2 \quad vs \quad m_h^2 = (125 \text{ GeV})^2$

current limit: $m_{\rm T} \sim 1 \text{ TeV}$

My view: not a big problem yet.

A confusing picture for Higgs mass





Supersymmetry
Stop too heavy to be natural

Composite top partner
too light, excluded

Such conclusions too simplistic, "work around" available.
A bit uncomfortable, yes. Not time to give up just yet.

Models

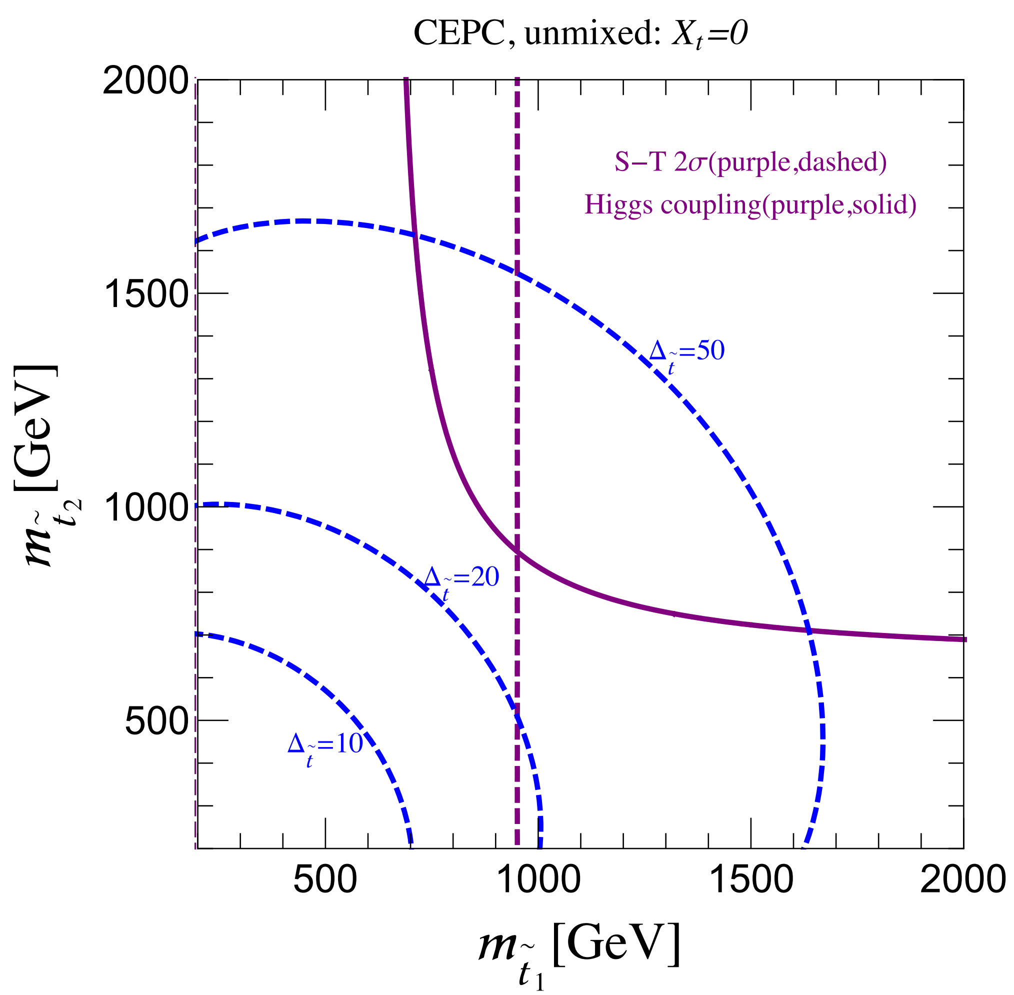
- "conventional"
  - Supersymmetry (SUSY), Composite Higgs, …
  - A bit uncomfortable, still viable.

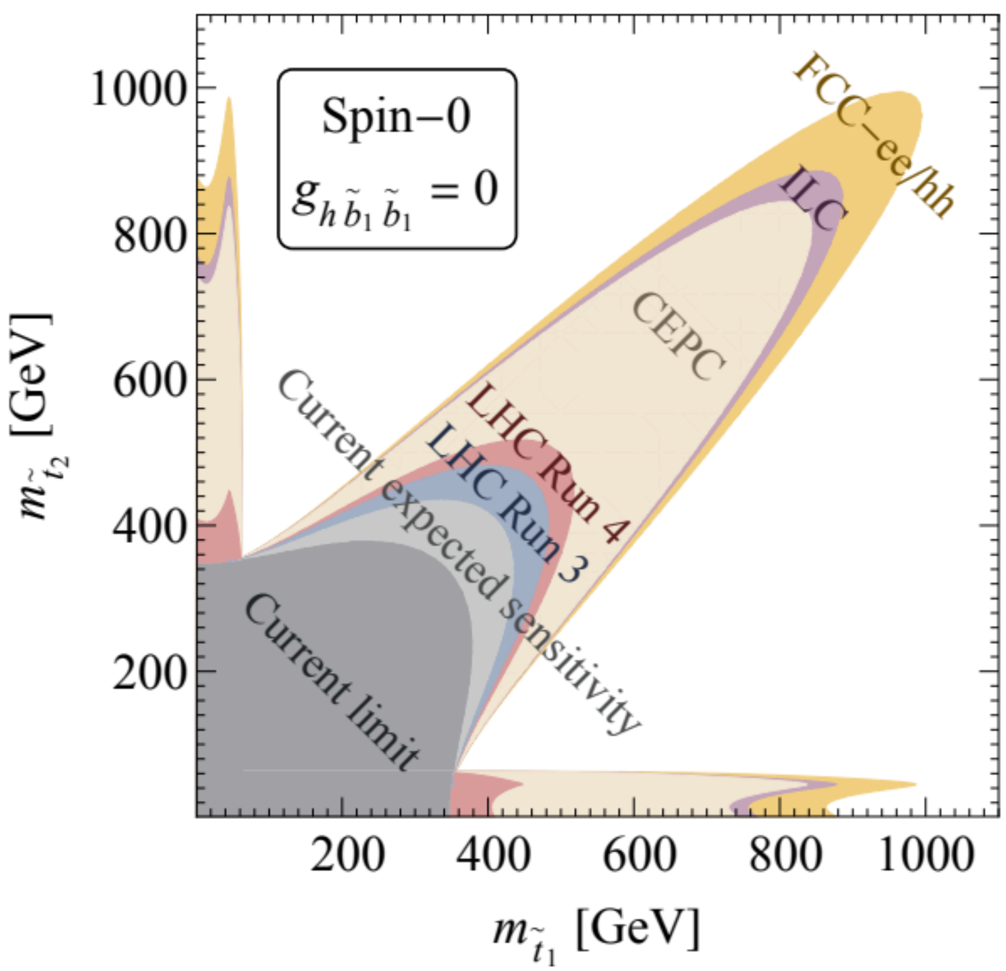
Models

- New attempts
  - Neutral naturalness, N-naturalness, relaxion…
  - None of these is in terribly good shape. But interesting, could develop into something better.
- Why so many models?
  - Because the situation is confusing.
- Future Colliders crucial in testing them.

Naturalness in SUSY

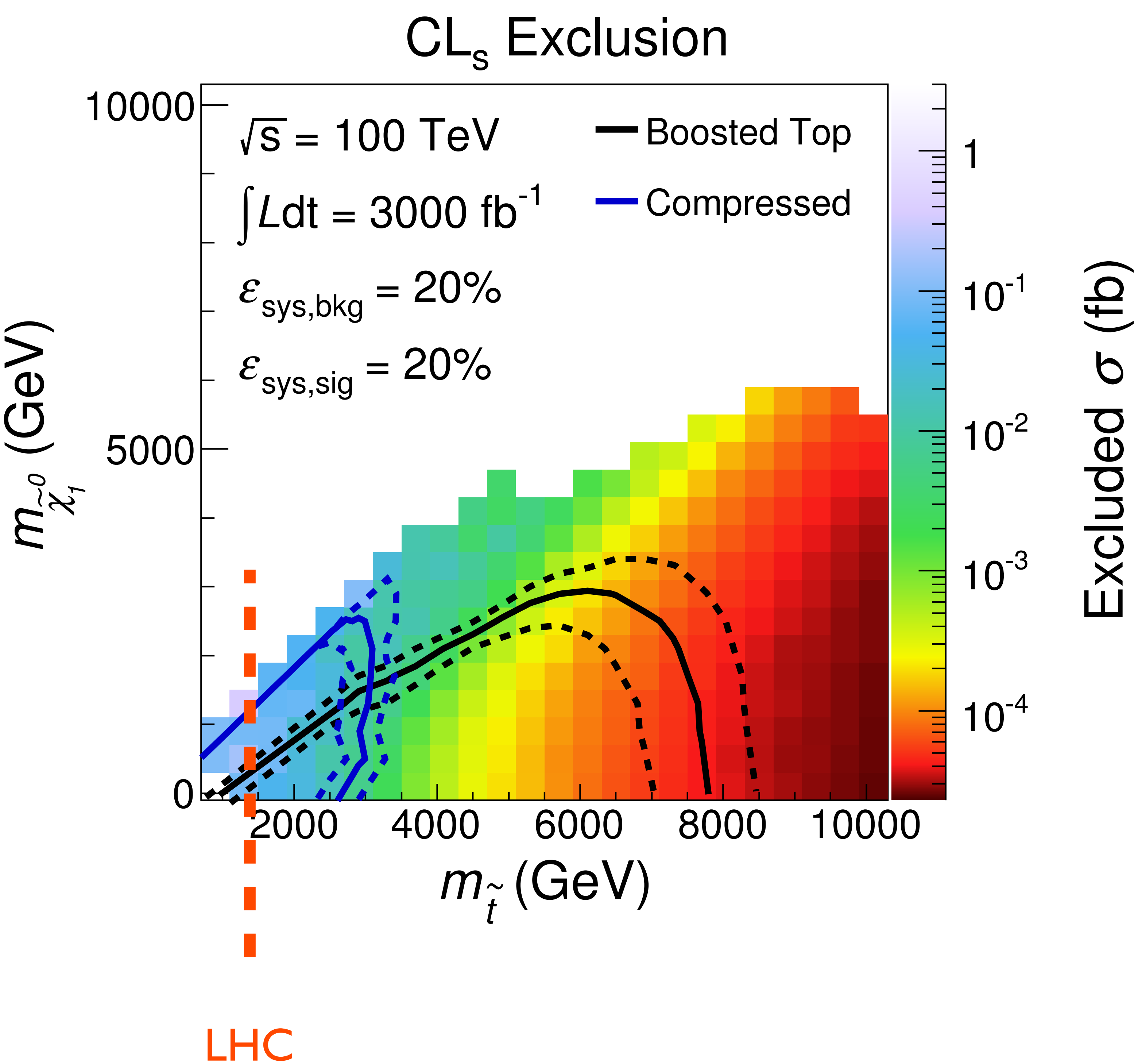
- LHC searches model dependent, many blind spots.



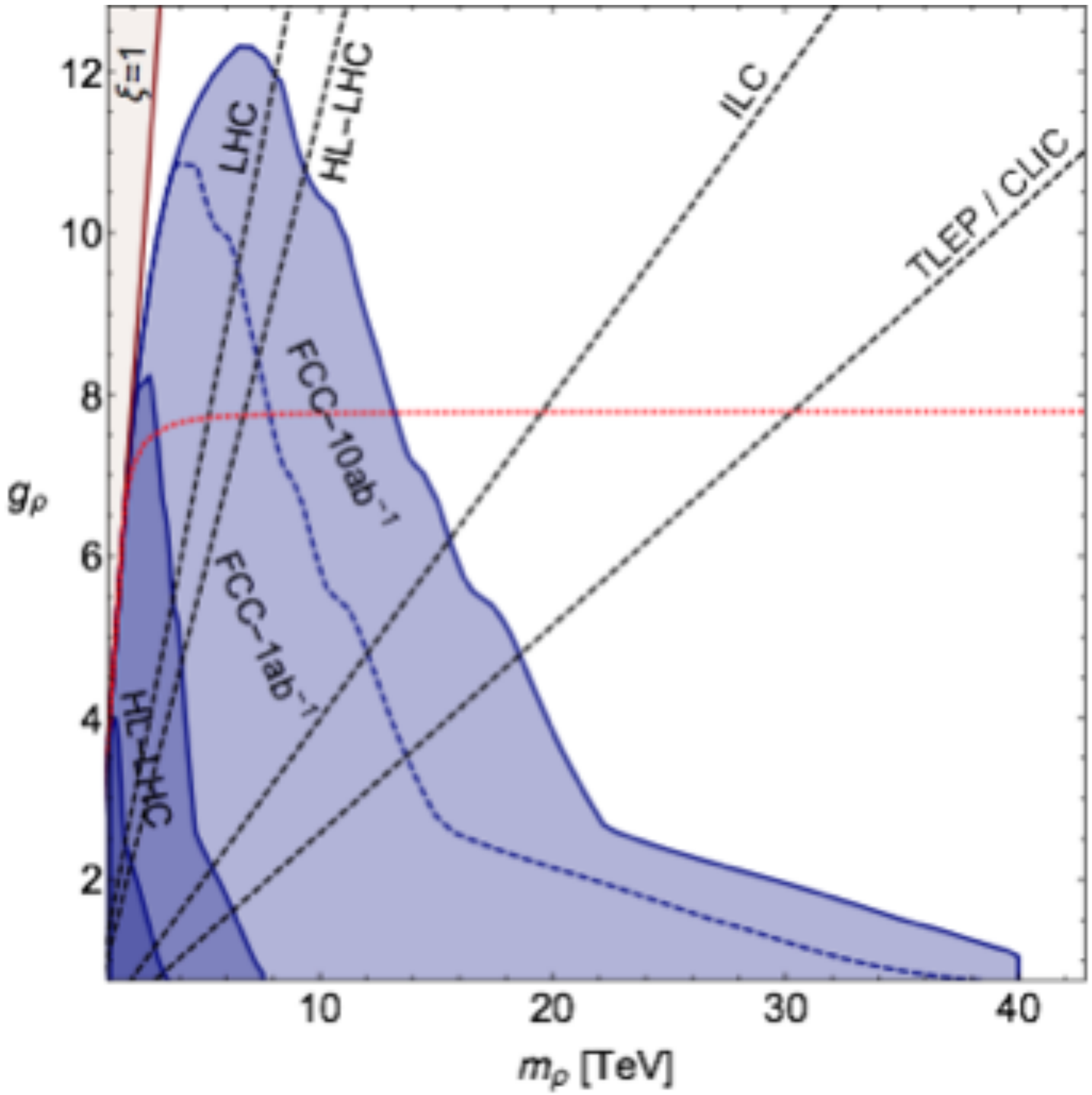


- Testing fine-tuning down to percent level.

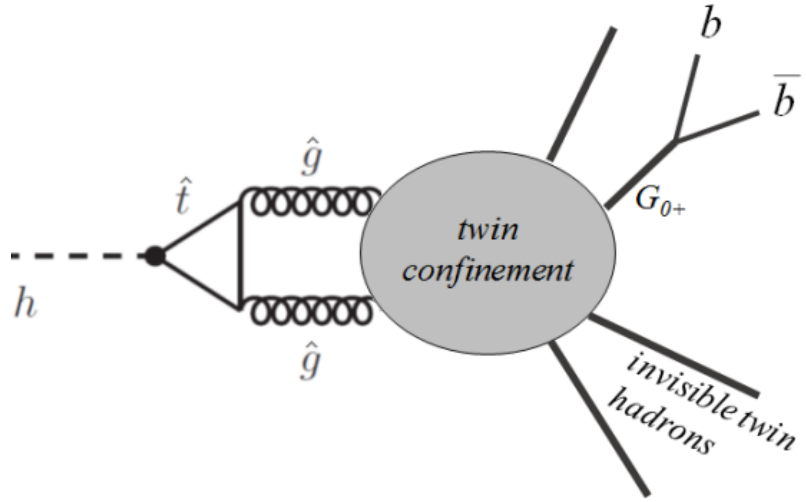
Testing naturalness: Supersymmetry



Composite Higgs



Neutral naturalness: "twin"



Chacko, Goh, Harnik

Craig, Katz, Strassler, Sundrum

UV completion with composite Higgs:
Low, Tesi, and LTW

Top partner T not colored.
Higgs decay through hidden world and back

Neutral naturalness: "twin"

Chacko, Goh, Harnik

Craig, Katz, Strassler, Sundrum

UV completion with composite Higgs:
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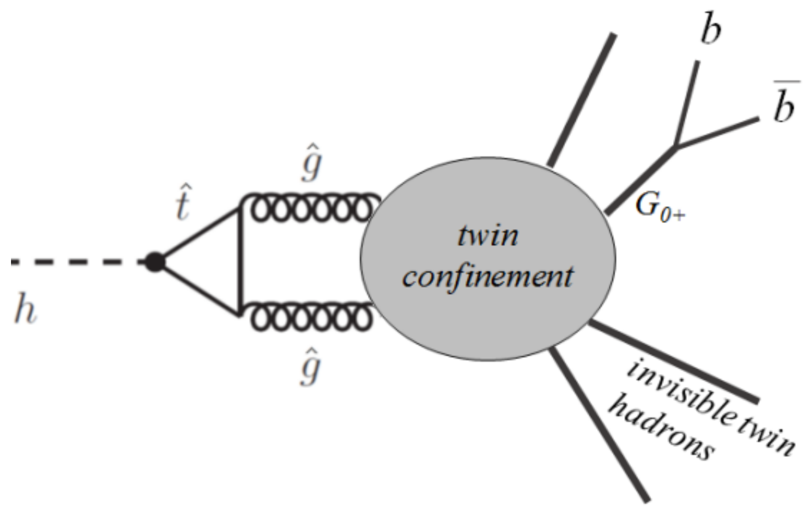
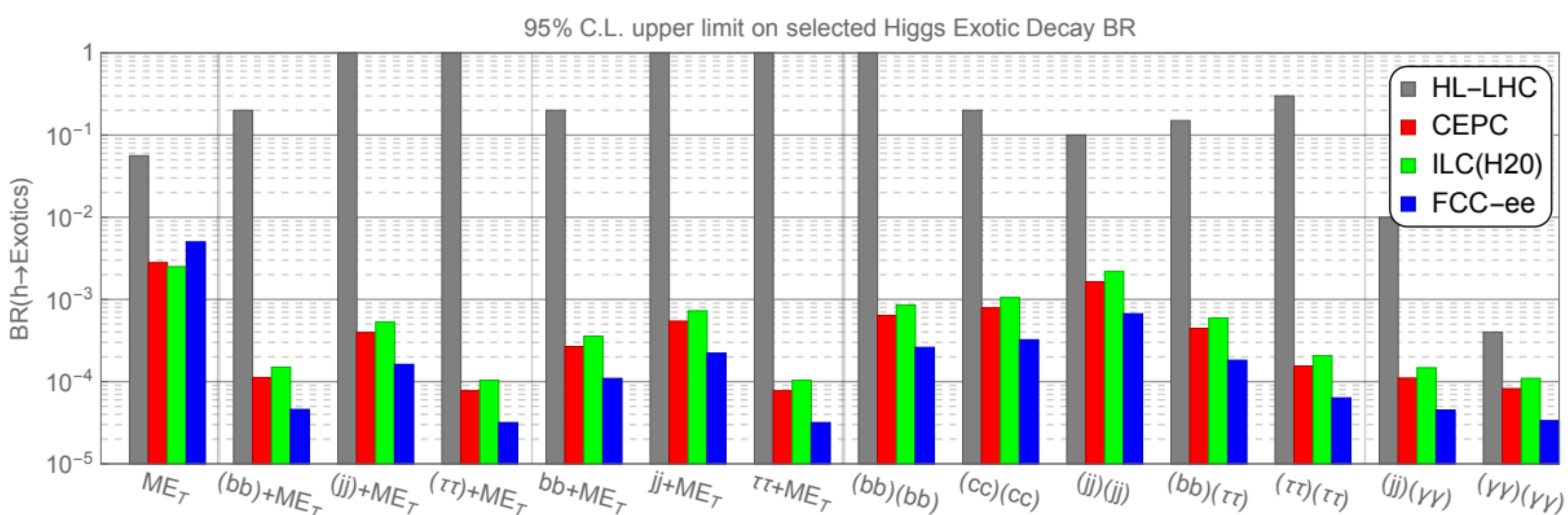


Top partner T not colored.
Higgs decay through hidden world and back

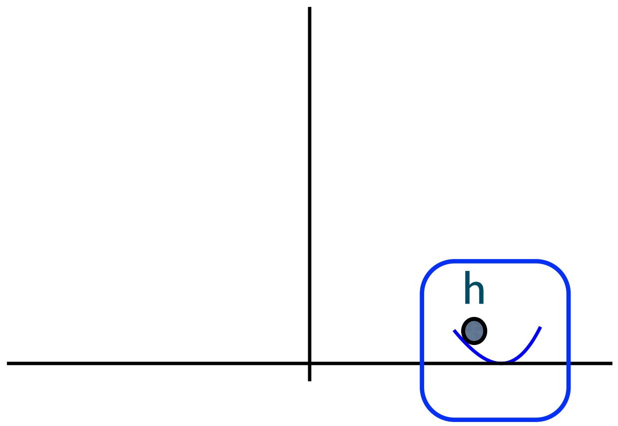


Zhang, Liu, LTW

– Can be tested at LHC and Higgs factories.

Mysteries of the electroweak scale.

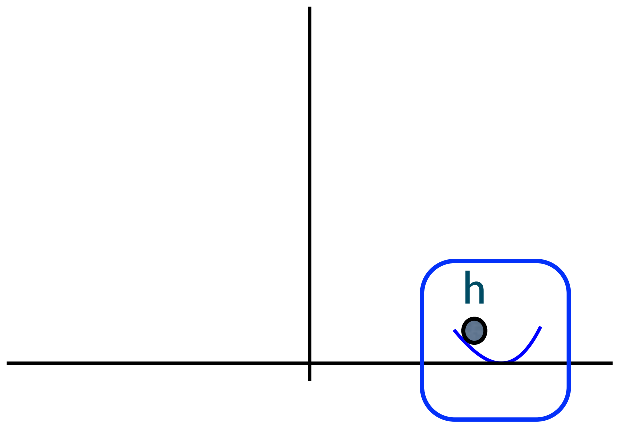
Mysteries of the electroweak scale.



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.



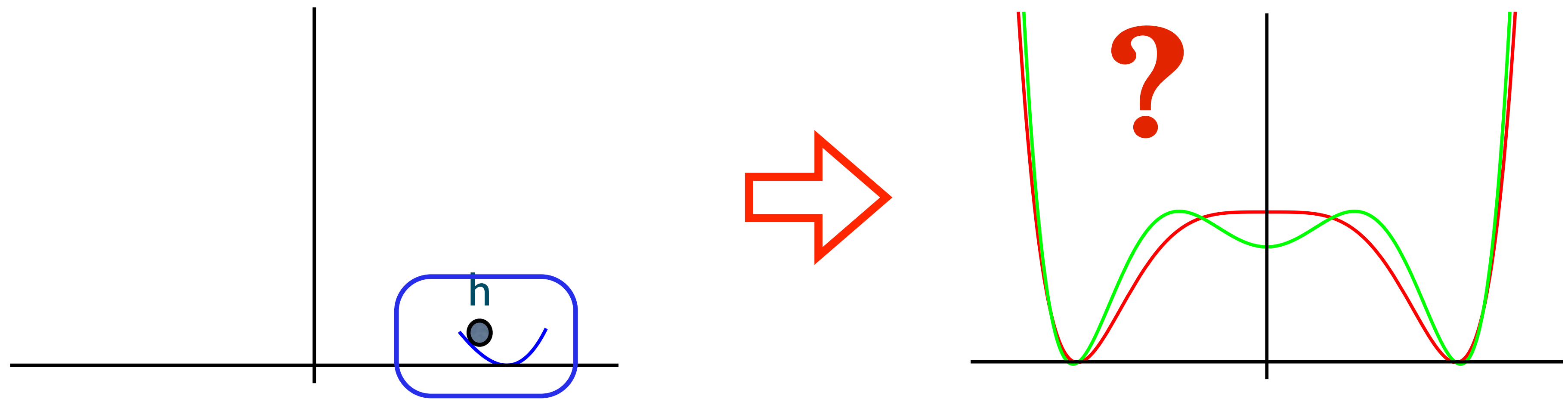
What we know now

- 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?

Nature of EW phase transition



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

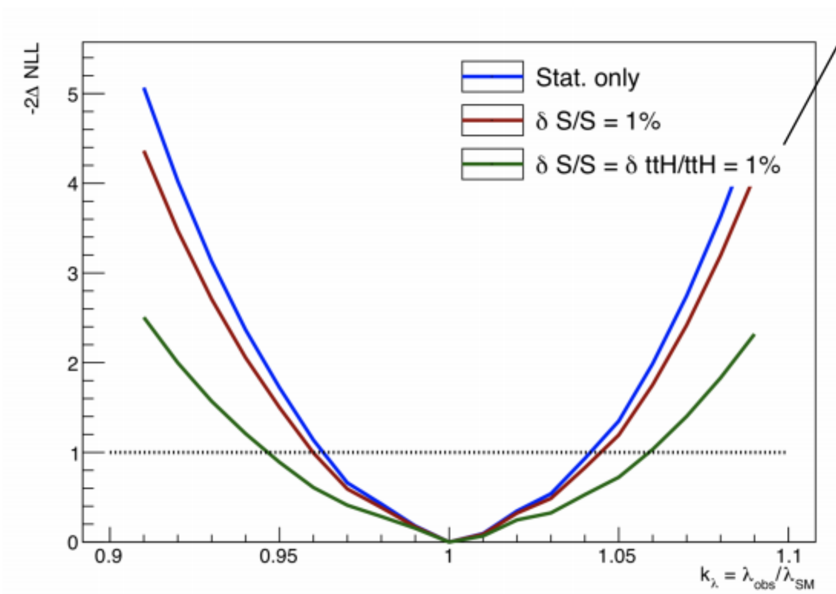
"wiggles" in Higgs potential

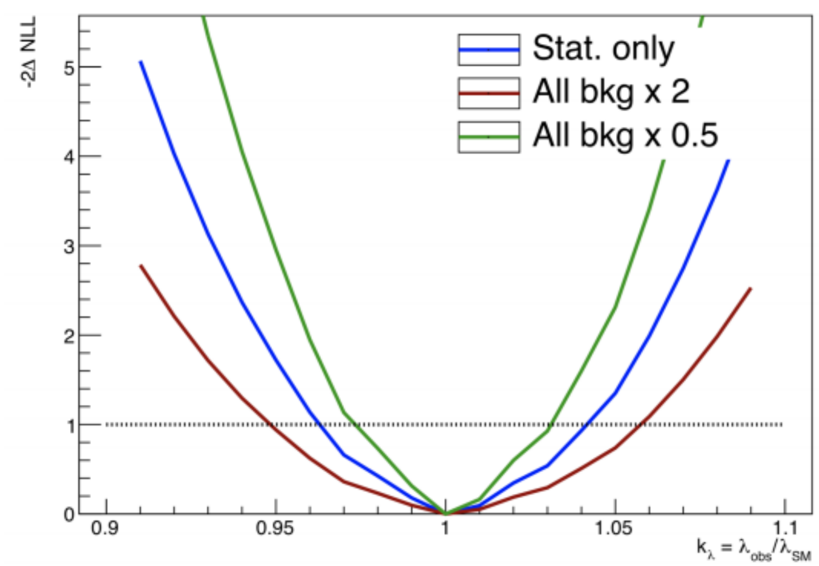
Big difference in triple Higgs coupling

Triple Higgs coupling at 100 TeV collider

Precision on the self-coupling

assuming QCD can be measured from sidebands





nominal background yields:

$\delta\kappa_\lambda$(stat) ≈ 3.5 %
$\delta\kappa_\lambda$(stat + syst) ≈ 6 %

varying (0.5x-2x) background yields:

$\delta\kappa_\lambda$(stat) ≈ 3 - 5 %

Talk by Michele Selvaggi at 2nd FCC physics workshop

But, there should be more

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

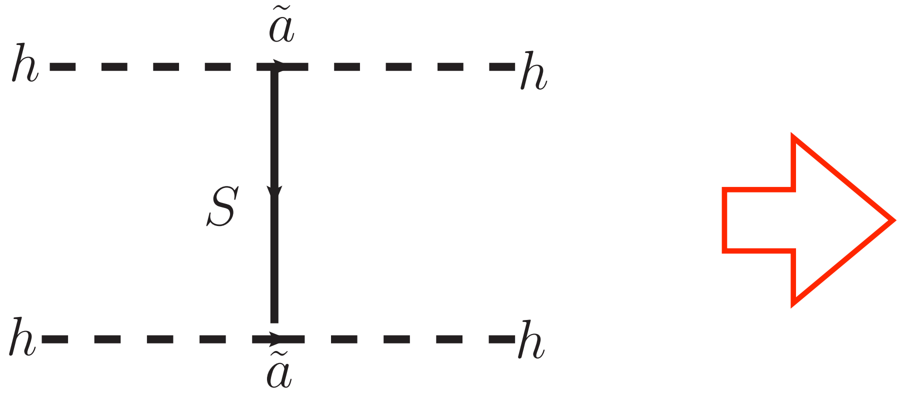
- 1st order EW phase transition means there is new physics close to the weak scale.

- Can be difficult to discover at the LHC.

- Will leave more signature in Higgs coupling.

For example

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



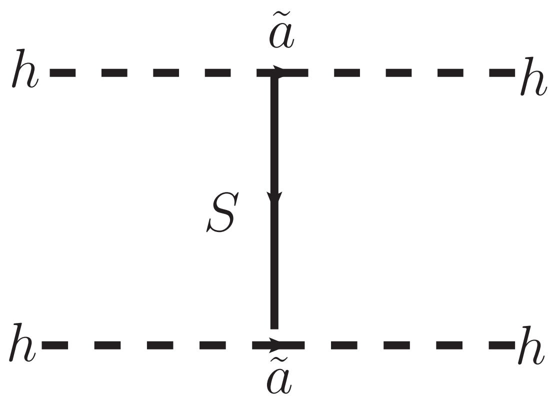
$$\frac{c}{m_S^2}\left(h^\dagger \partial h\right)^2$$

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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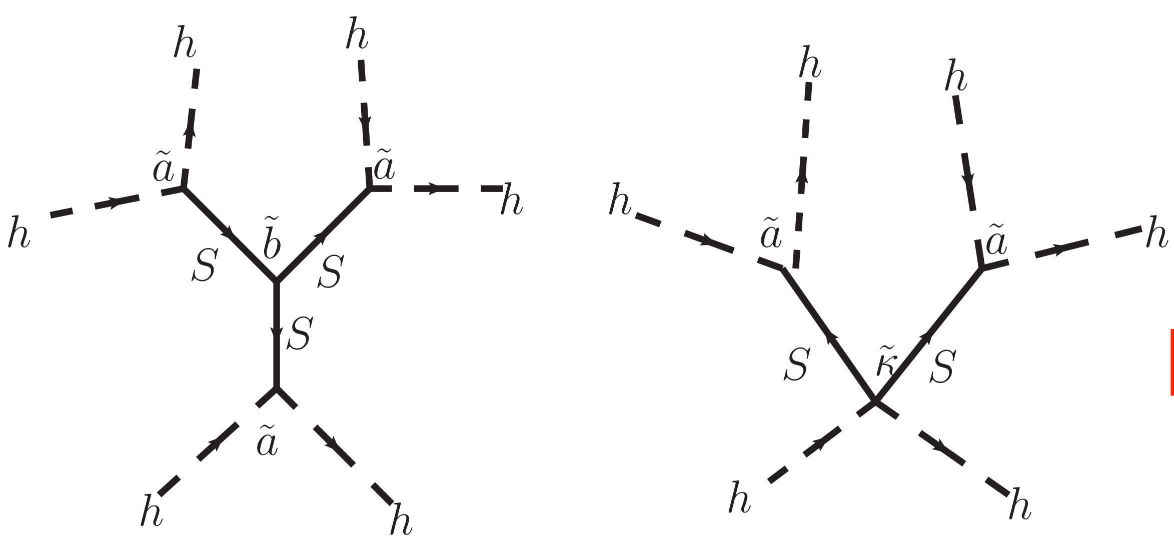
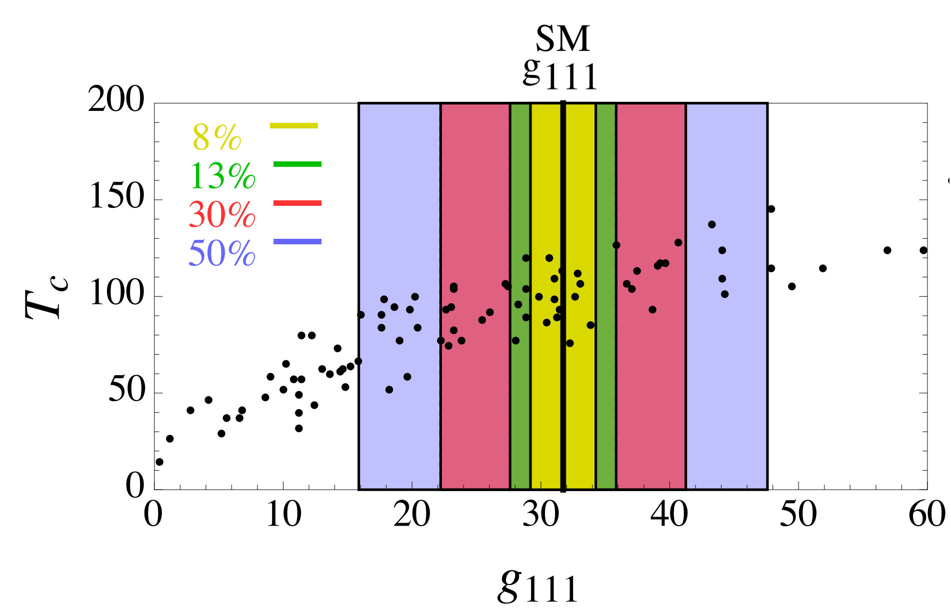
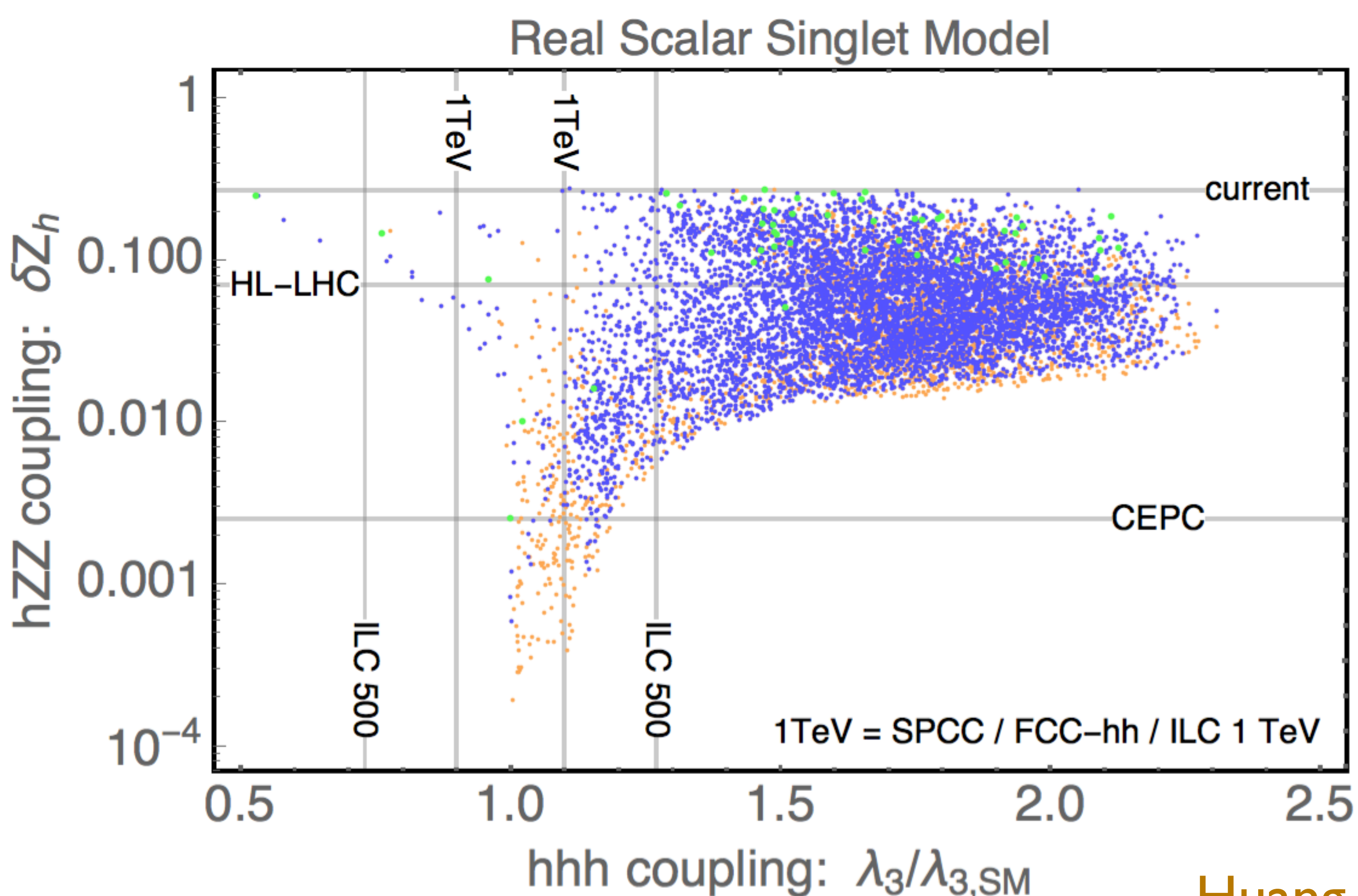




triple Higgs coupling

Probing EWSB at higgs factories

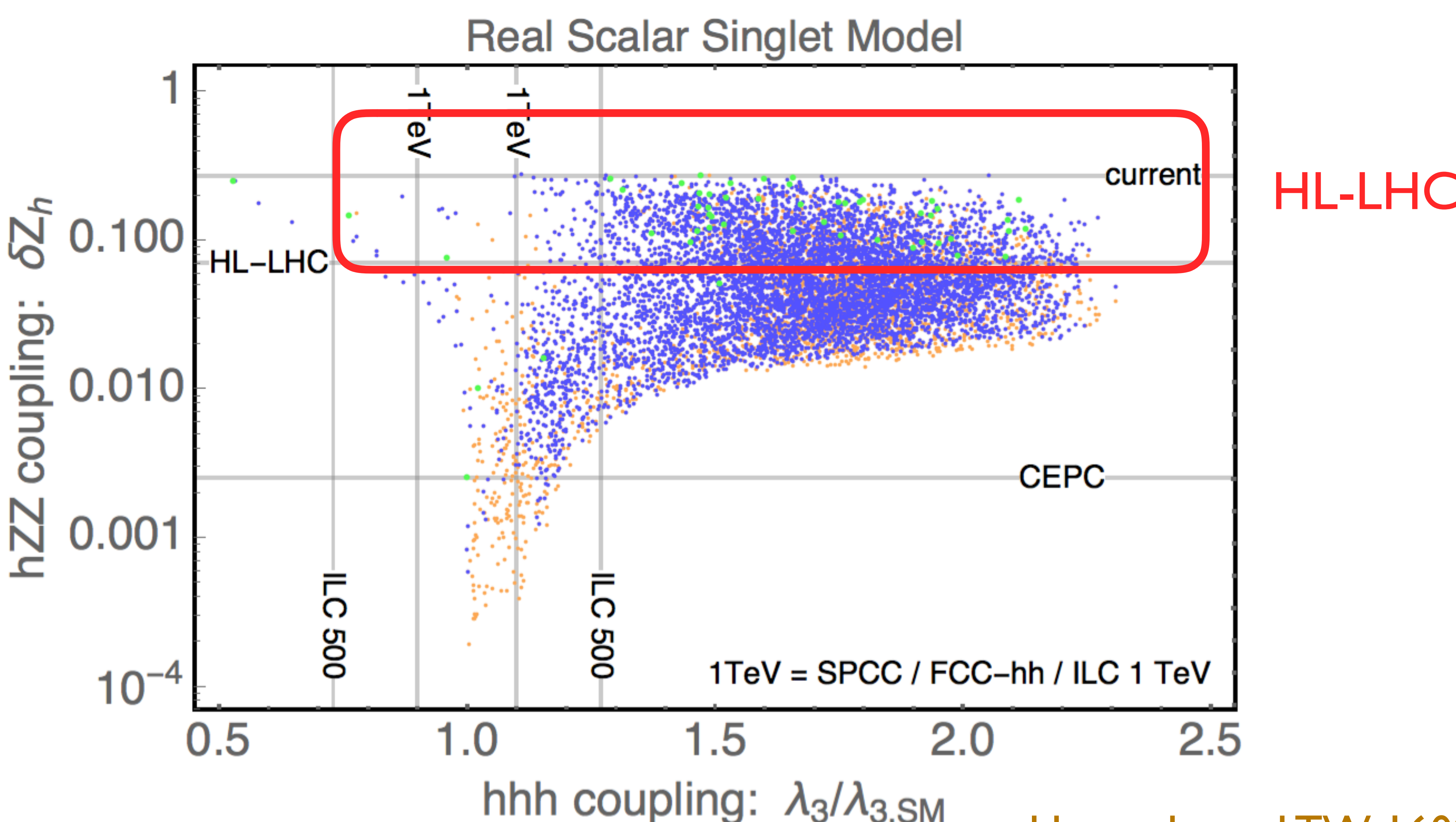


Huang, Long, LTW, 1608.06619

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

Probing EW phase transition



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Green = very strongly 1PT, could detect GWs at eLISA

Conclusion

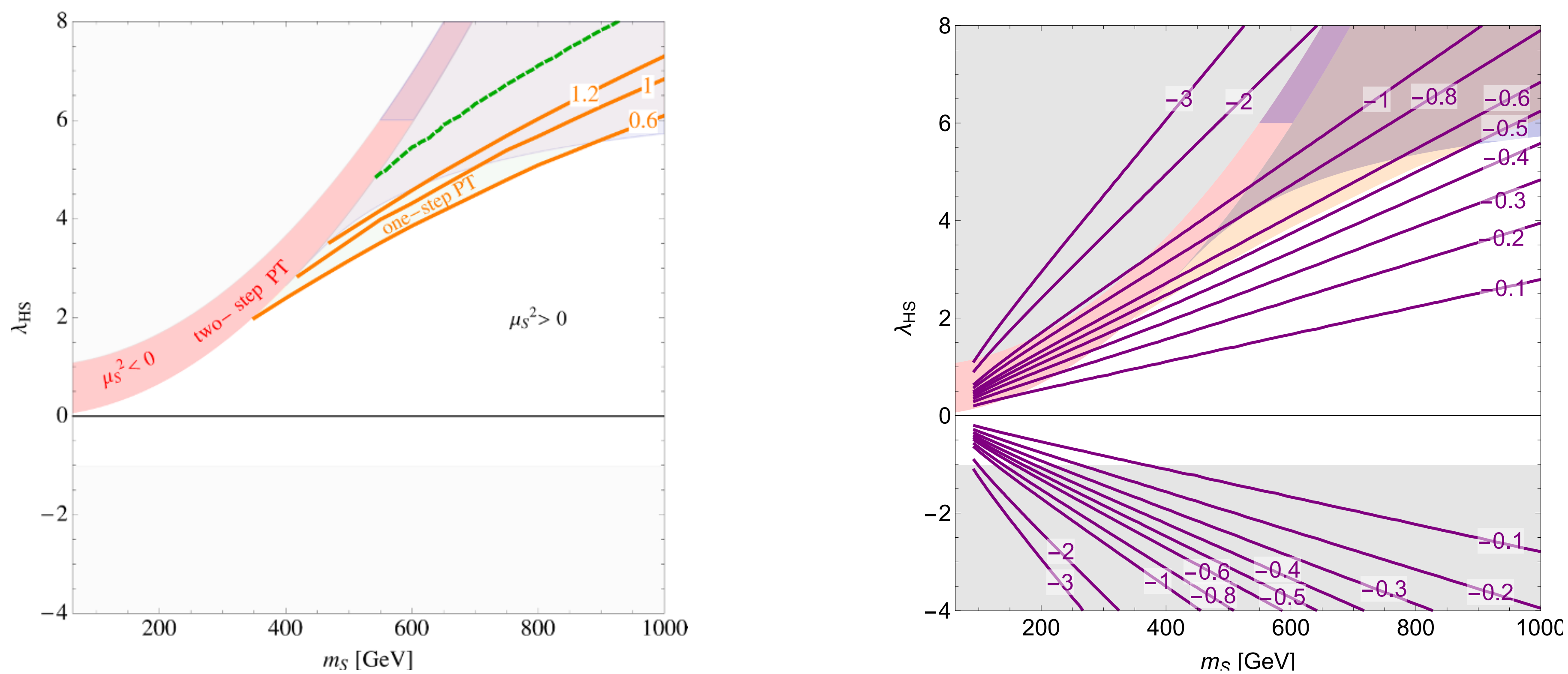
- LHC still has a lot to say.
  - 15+ years of operation, 95+% of data to come.
  - Need to think about how to new searches with this data.

- Beyond the LHC, we need future colliders to address the open questions of the Standard Model.

extra

Nightmare scenario: Meade et al

Singlet model with a Z_2 $\quad S \rightarrow -S$



h^6 term generated at 1-loop order

Only marginally visible.

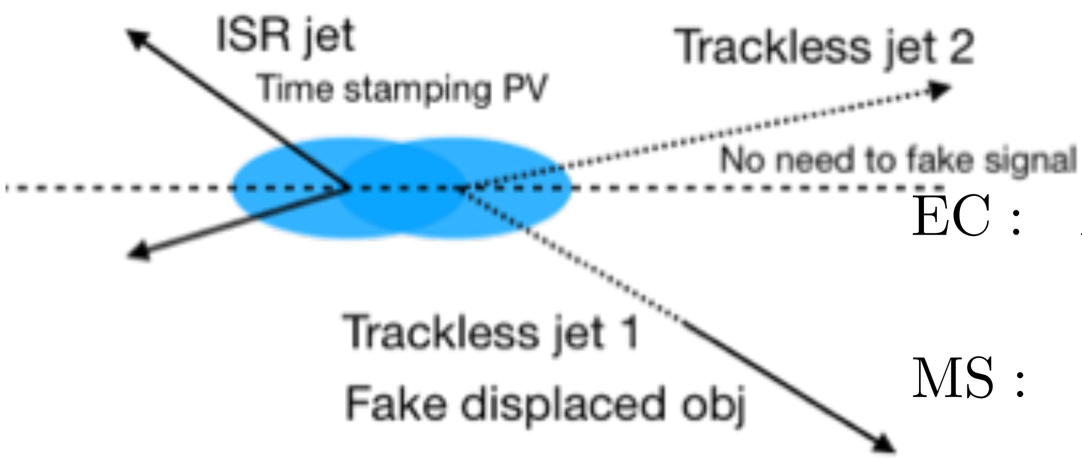
Late comers will be spotted easily:

	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)

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

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

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:

	L_{T_2}	L_{T_1}	Trigger	$\epsilon_{\rm trig}$	$\epsilon_{\rm sig}$	$\epsilon^{j}_{\rm fake}$	Ref.
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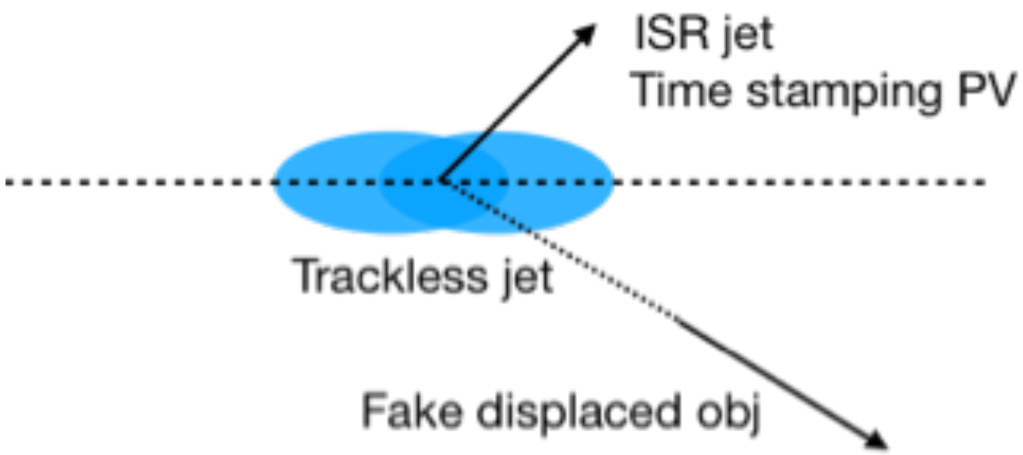


Same-vertex hard scattering background, time spread 30 ps (precision timing)

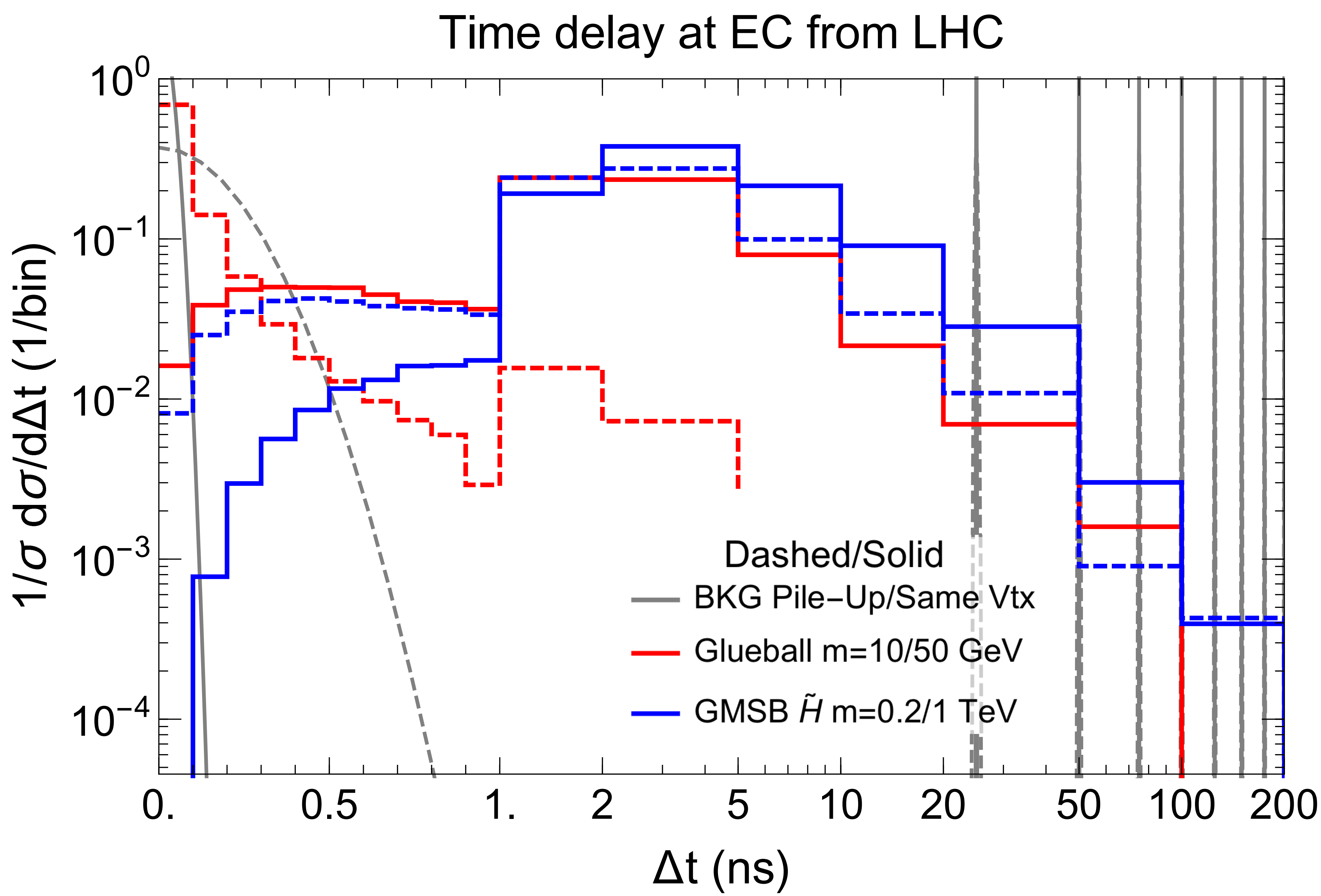
$$\text{EC}: \quad N^{\rm SV}_{\rm bkg} = \sigma_{\rm j} \mathcal{L}_{\rm int} \epsilon^{\rm EC}_{\rm trig} \epsilon^{j,\rm EC}_{\rm fake} \approx 1 \times 10^{11}$$

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

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

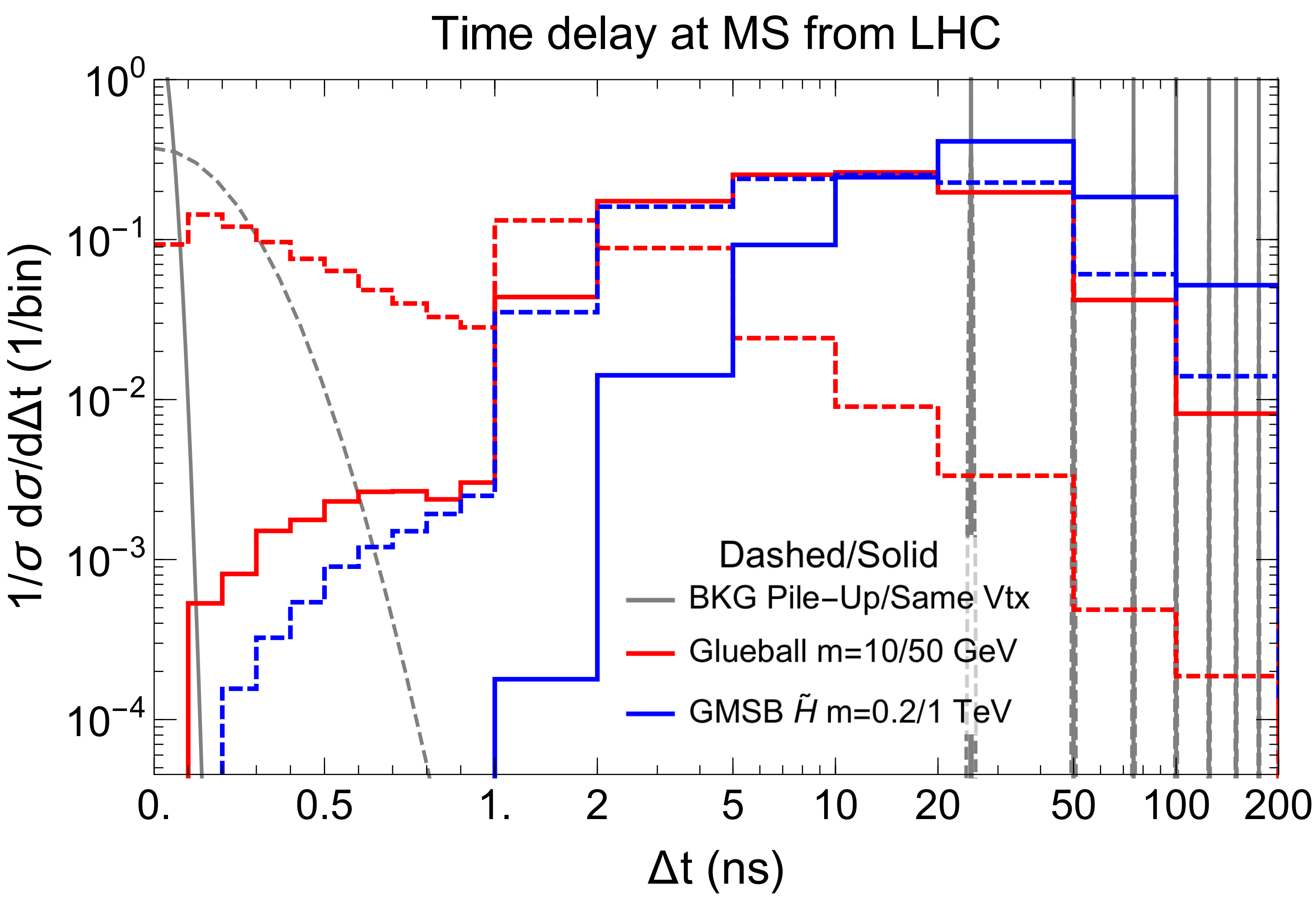
Search based on EC



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

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

Search based on MS



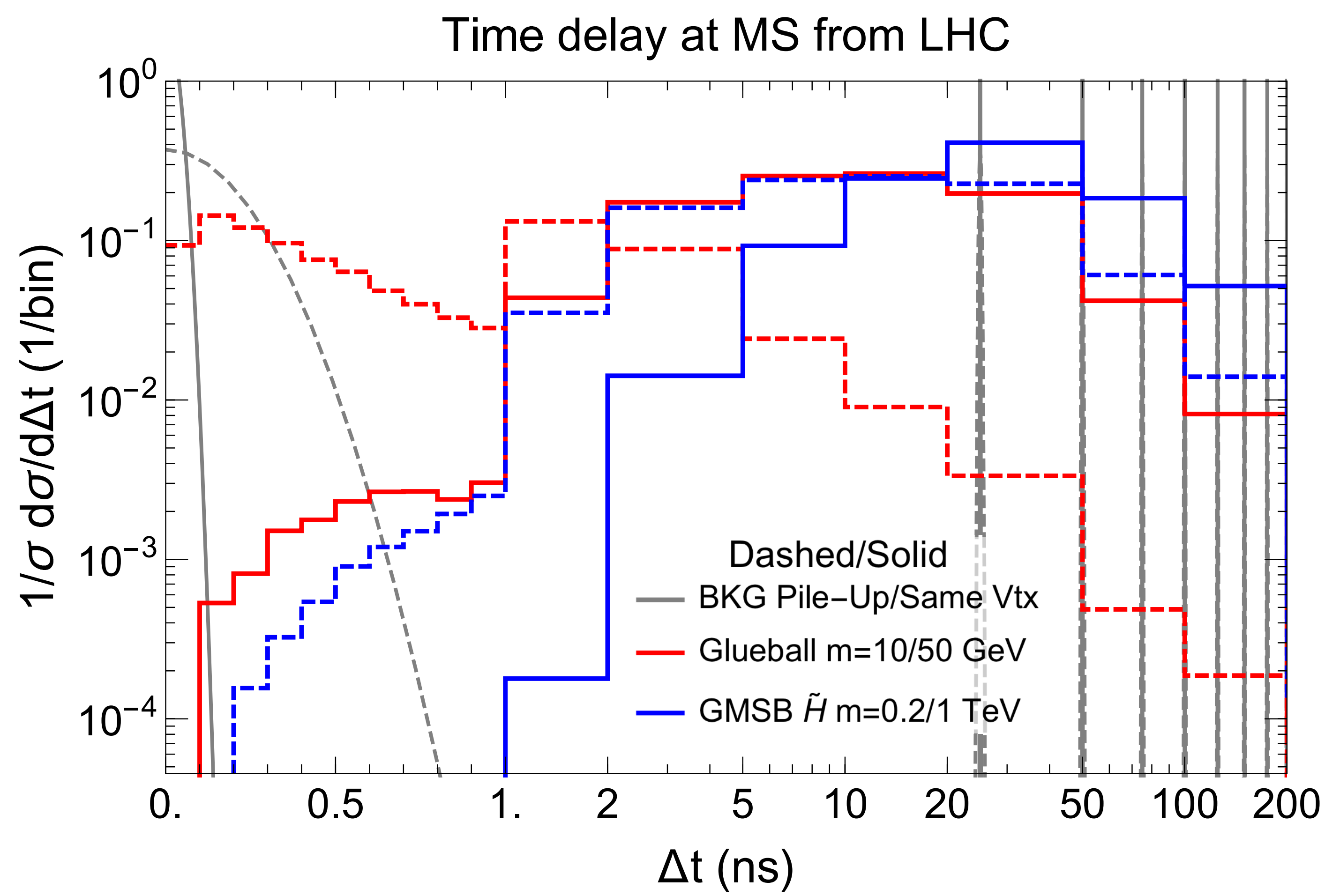
Pile up background smaller, shielded by HCAL etc.

Before timing cut: ~ 50

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

Further away, larger Δt for signal.

Search based on MS



Pile up background smaller, shielded by HCAL etc.

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

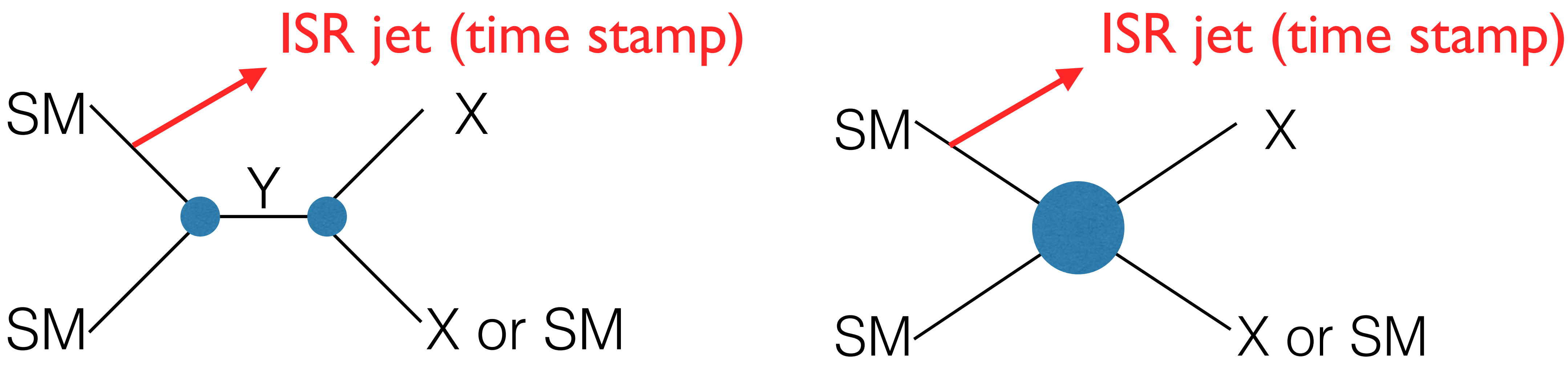
Further away, larger Δt for signal.

no need for super good timing resolution

$\delta t \sim 200$ ps

will do

Signal



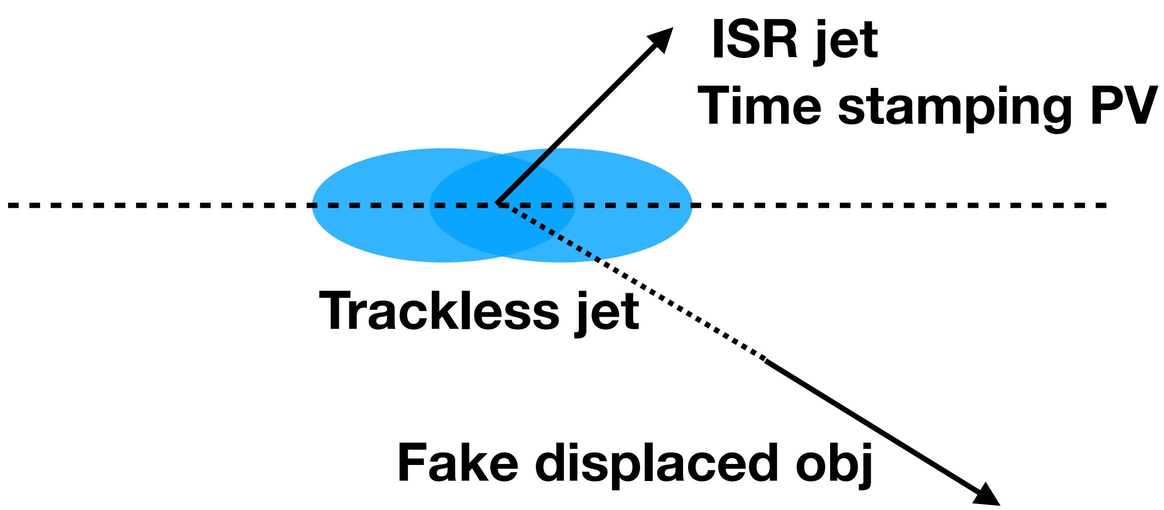
1. ISR jet provides the time for the hard collision

2. LLP decay before reaching timing layer.

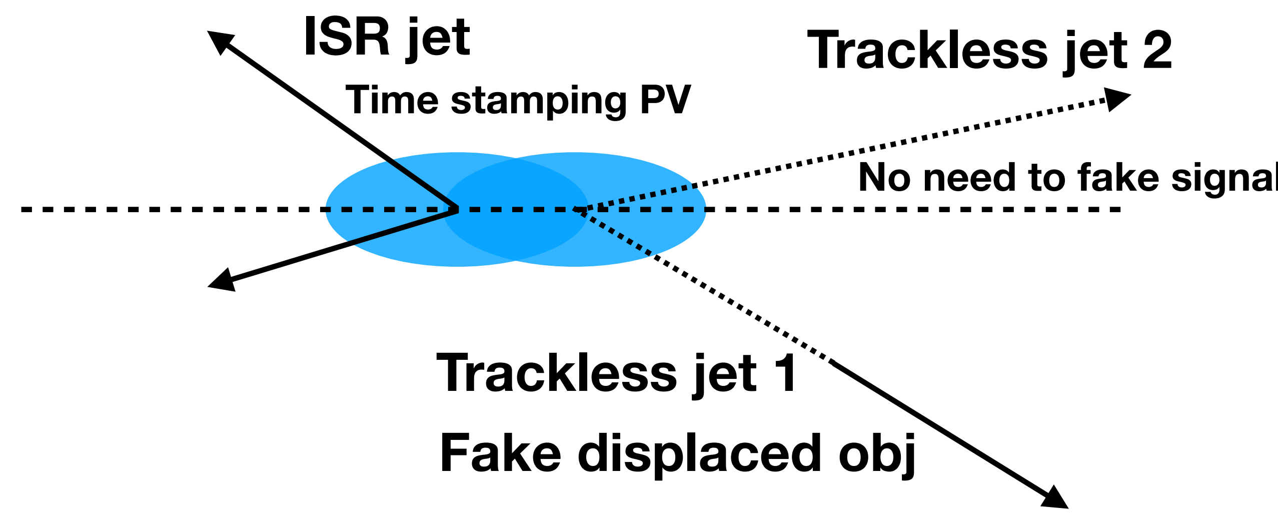
⇨ measurement of Δt

background

Same hard interaction



Pile up



Time delay from
resolution of timing detector.

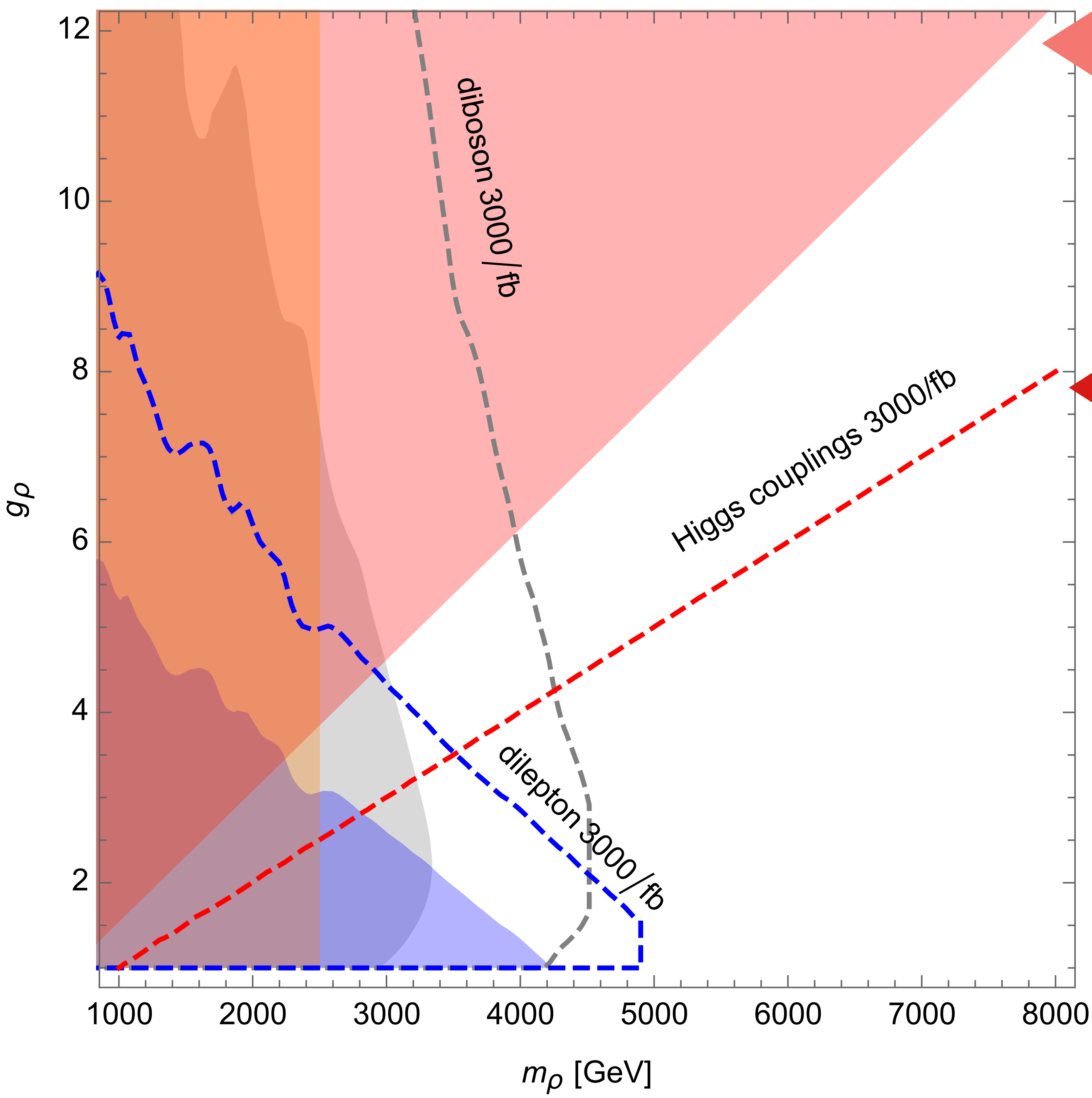
Time delay from
spread of the proton bunch

$\sim$ **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.

Higgs coupling vs direct search

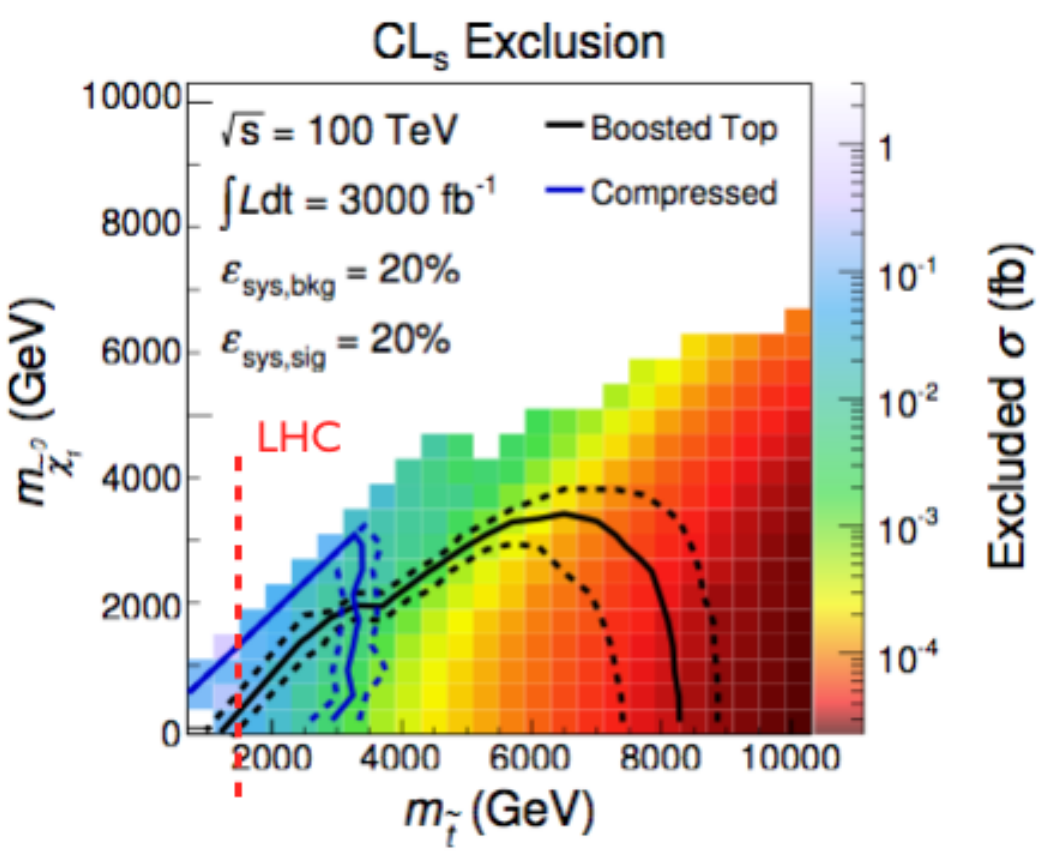


Excluded by current Higgs Coupling measurements

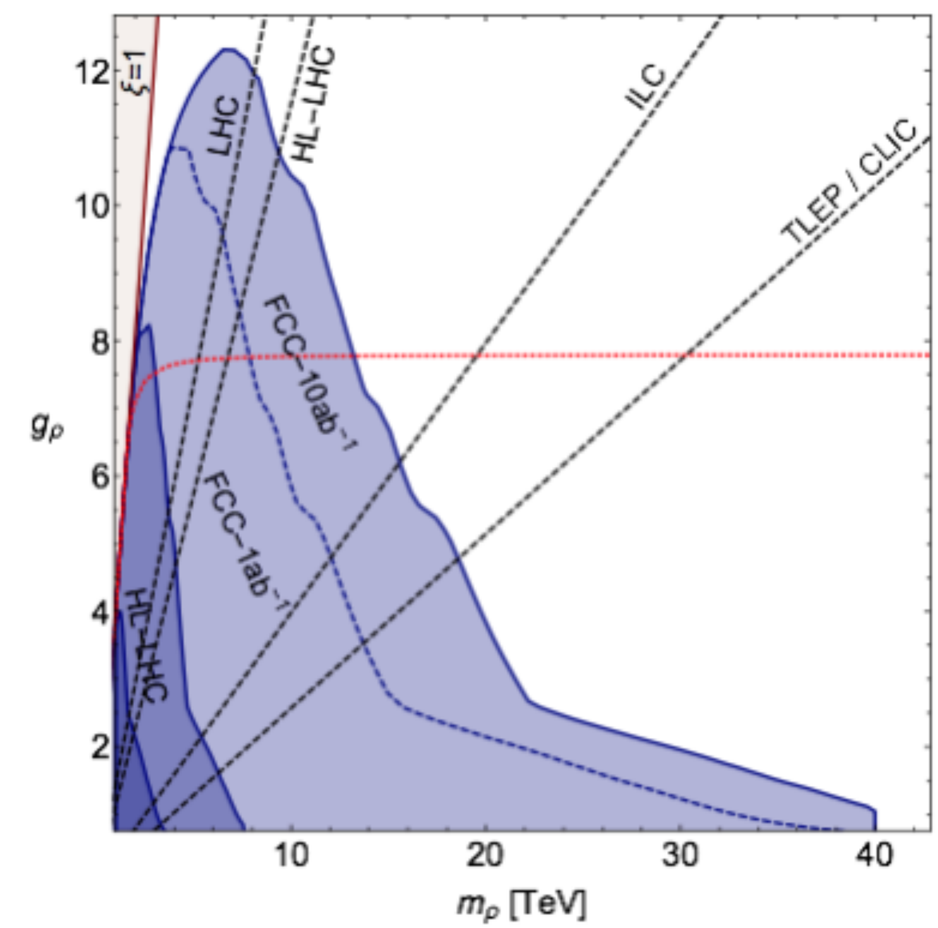
Reach of HL-LHC

Testing naturalness at 100 TeV pp collider

Cohen et. al., 2014



Pappadopulo, Thamm, Torre, Wulzer, 2014



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

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.