New directions for LHC searches

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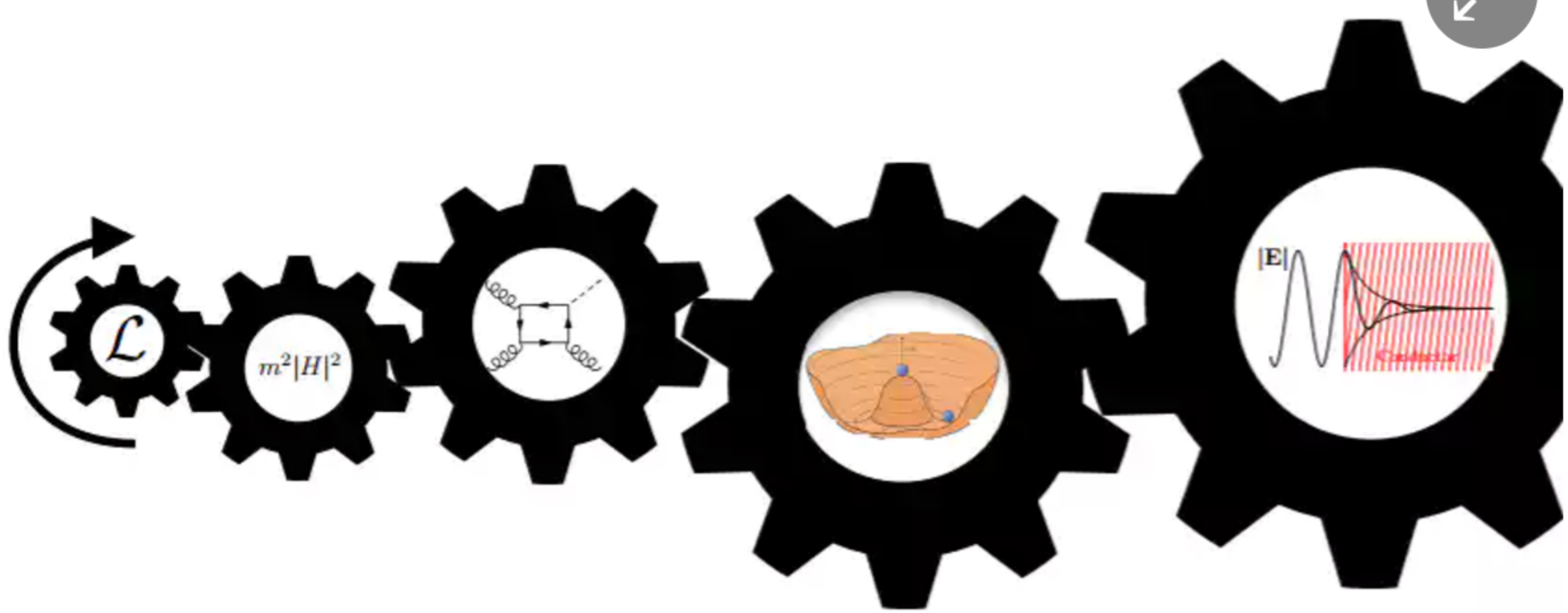
U. Chicago

TeV working group meeting. NanKai University, Tanjin. August 19, 2018

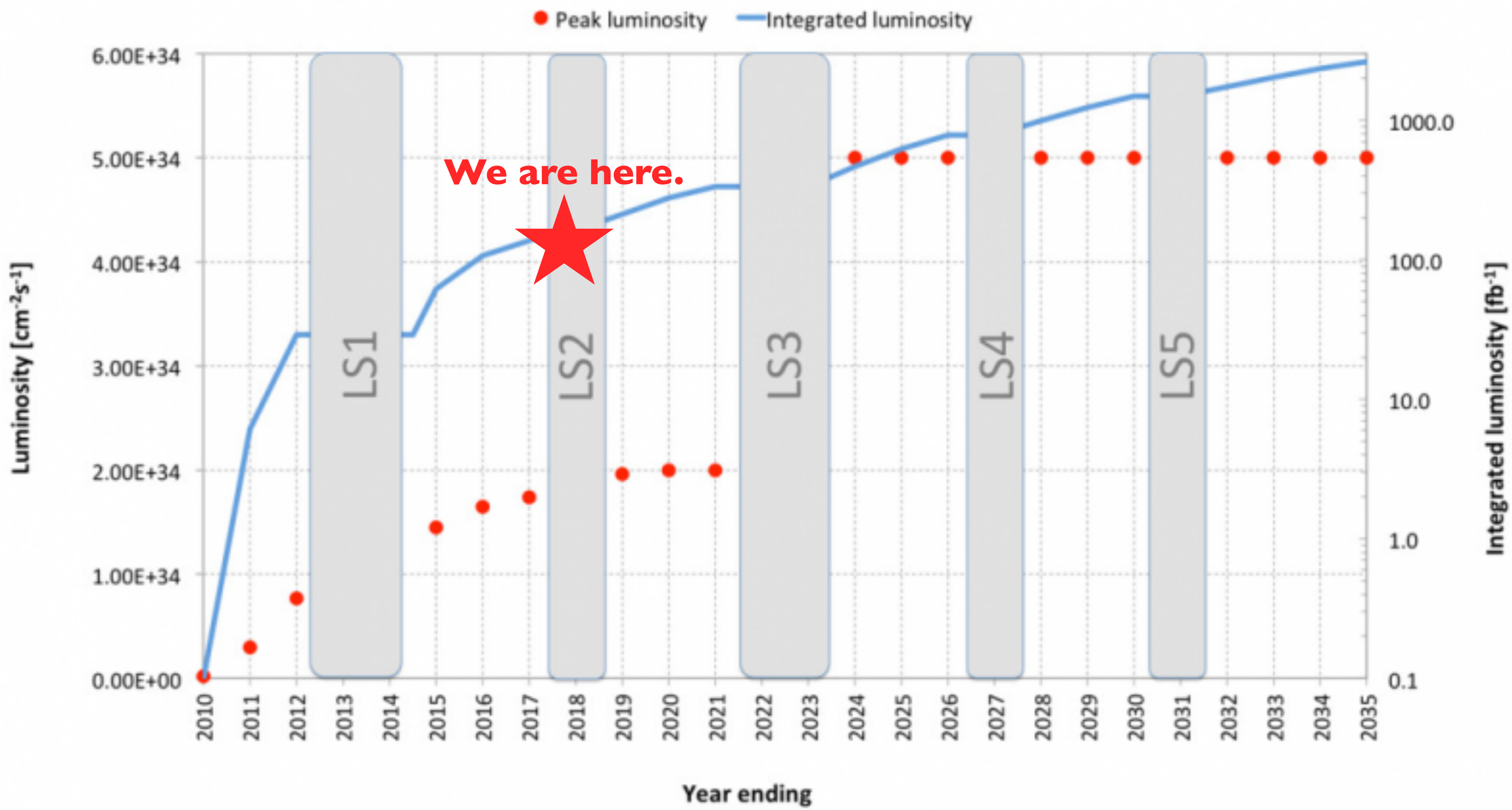
From gravity to the Higgs we're still waiting for new physics

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

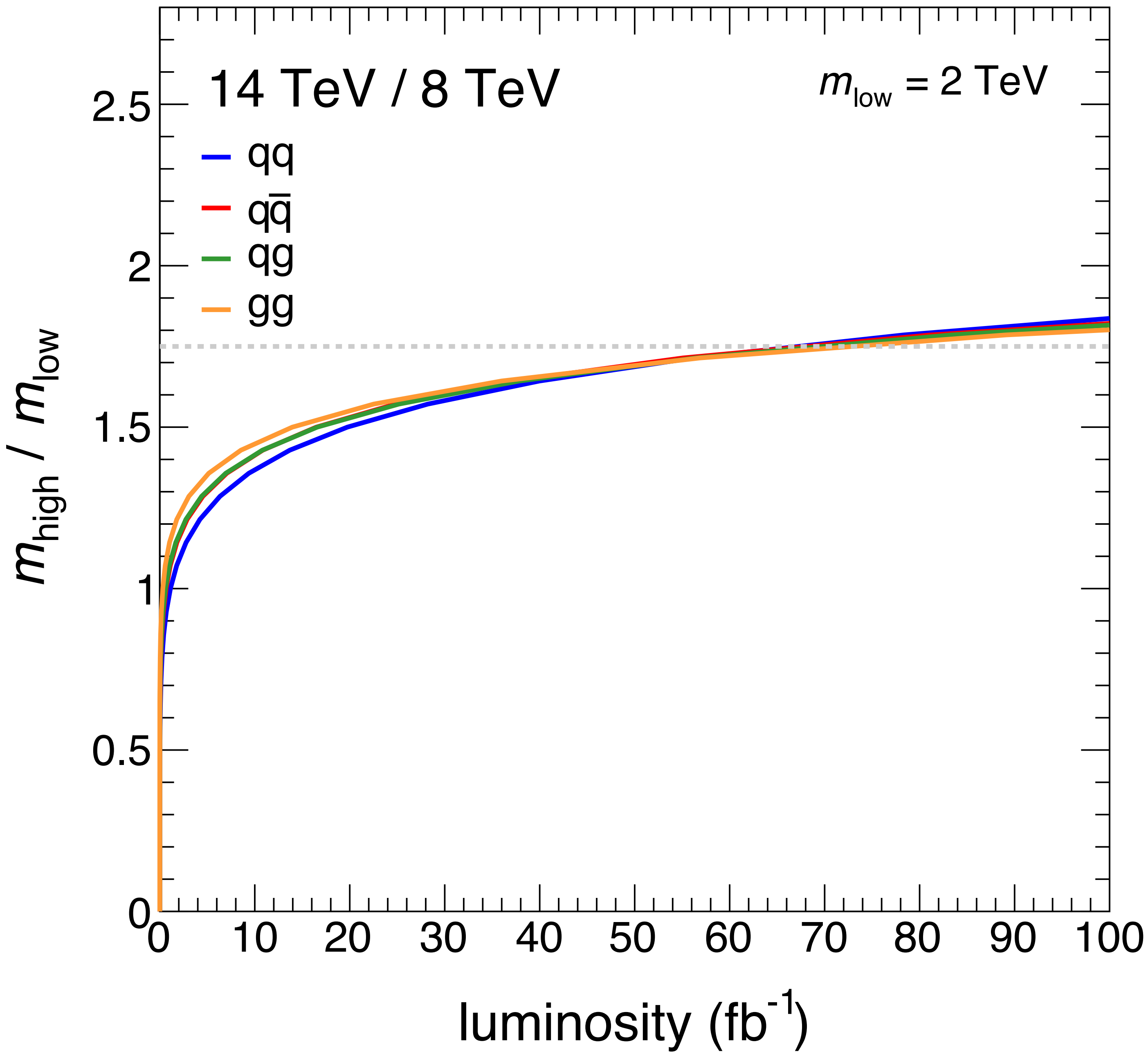


Peak luminosity
Integrated luminosity
We are here.
LS1
LS2
LS3
LS4
LS5
6.00E+34
5.00E+34
4.00E+34
3.00E+34
2.00E+34
1.00E+34
0.00E+00
Luminosity [cm⁻²s⁻¹]
1000.0
100.0
10.0
1.0
0.1
Integrated luminosity [fb⁻¹]
2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028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

LHC is pushing ahead.

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

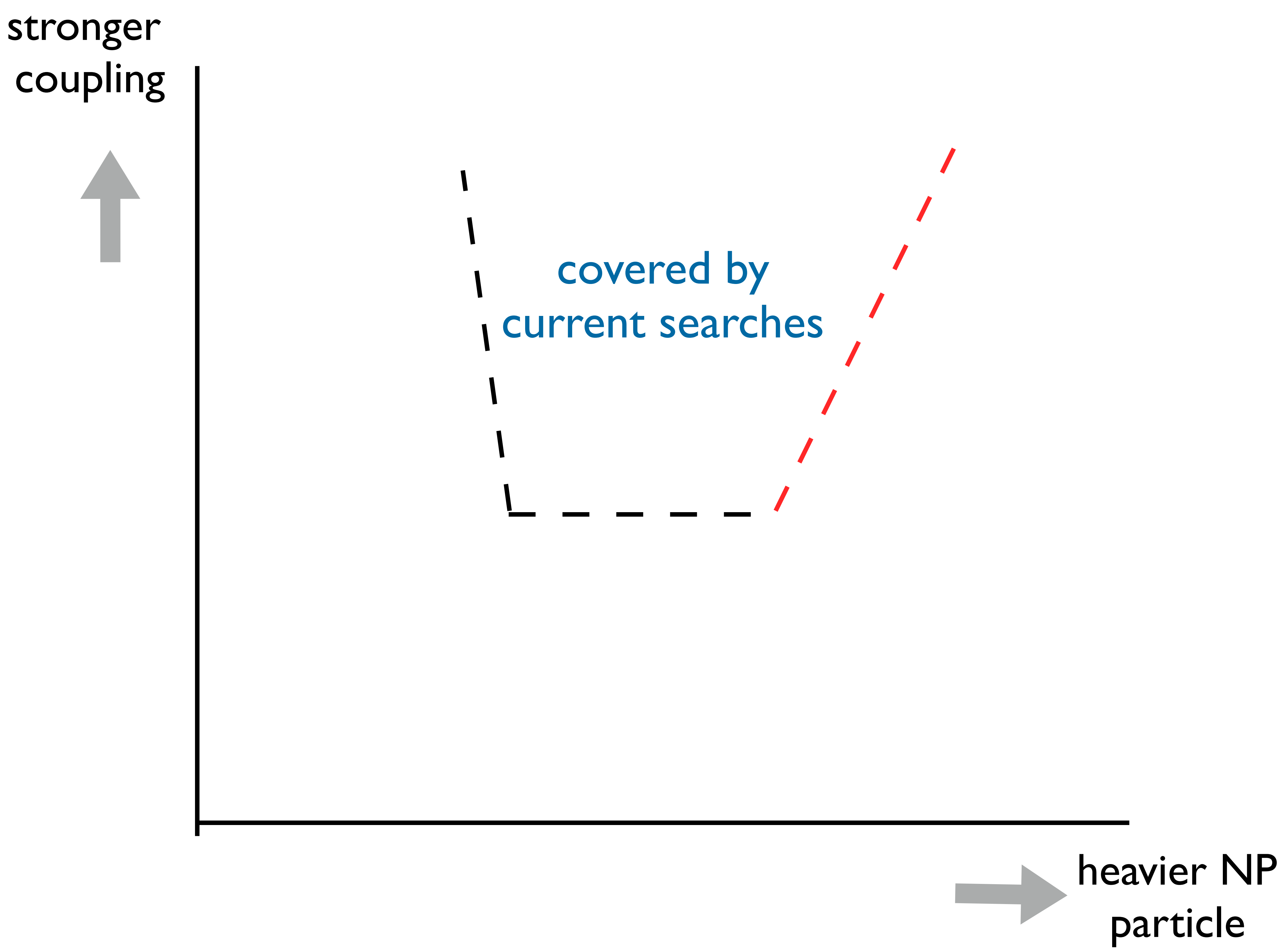
As data accumulates



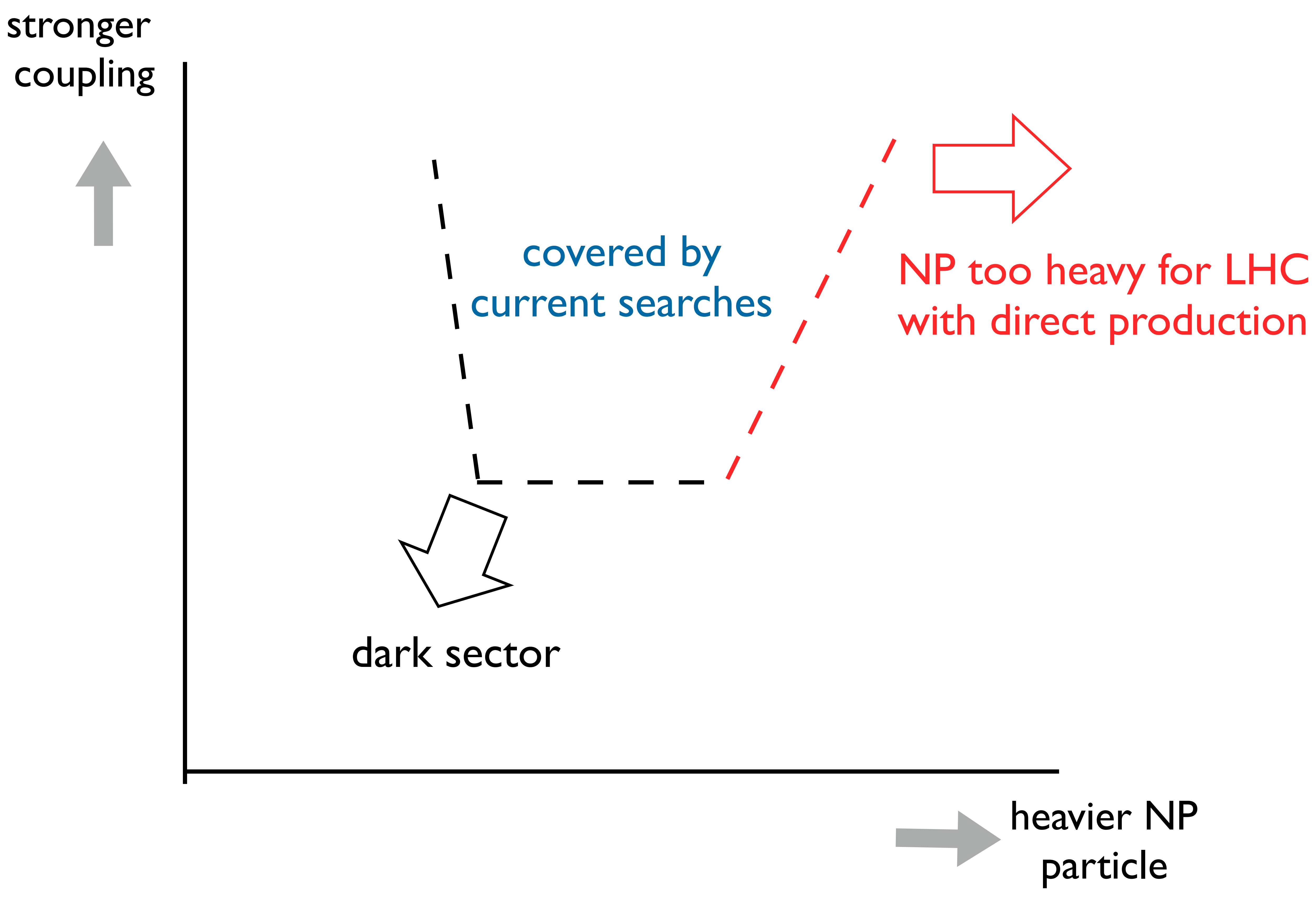
Rapid gain initial 10s-100 fb^{-1}, slow improvements afterwards.

Progress will become slower, harder

New directions?



stronger
coupling
covered by
current searches
heavier NP
particle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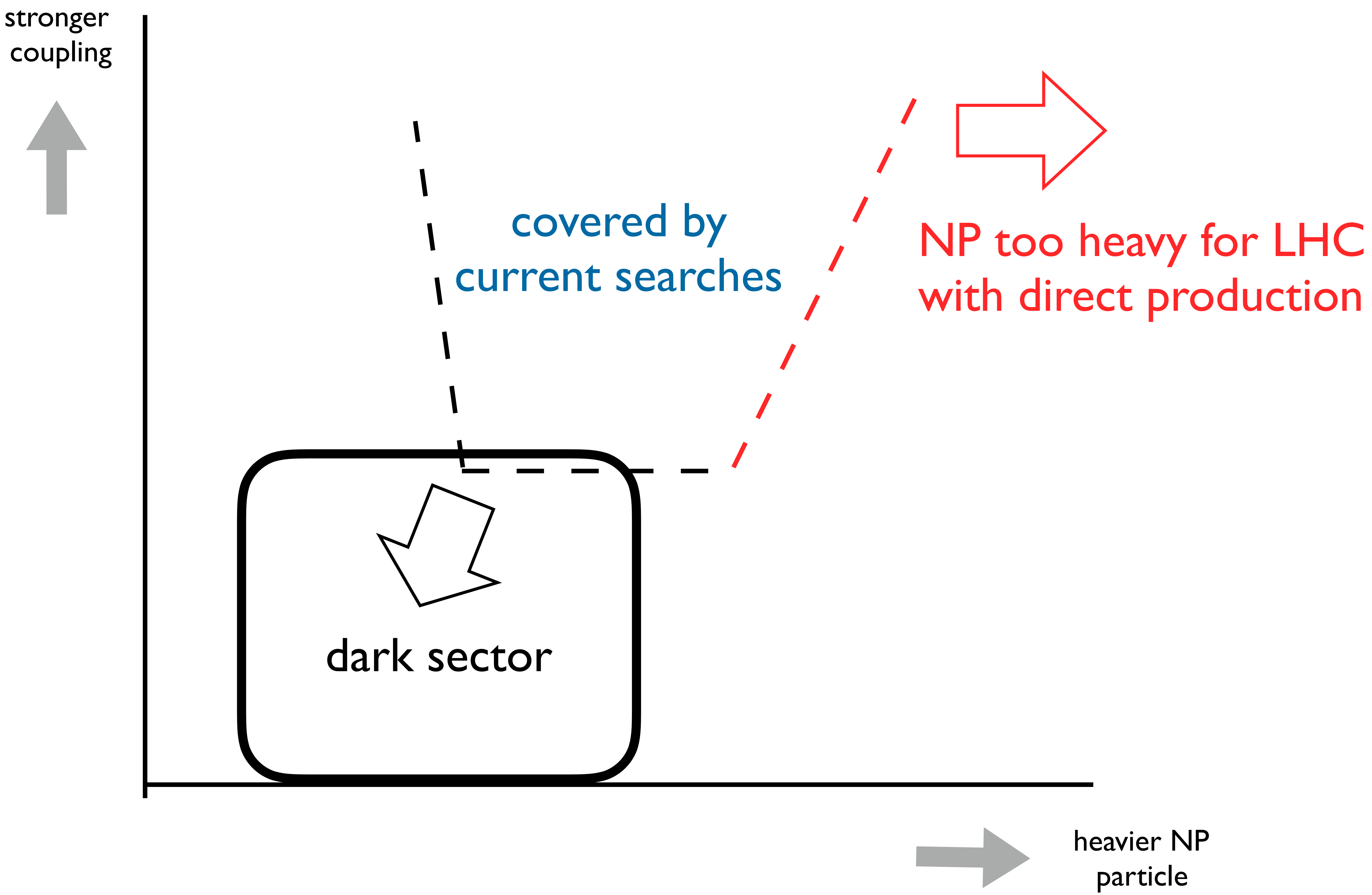
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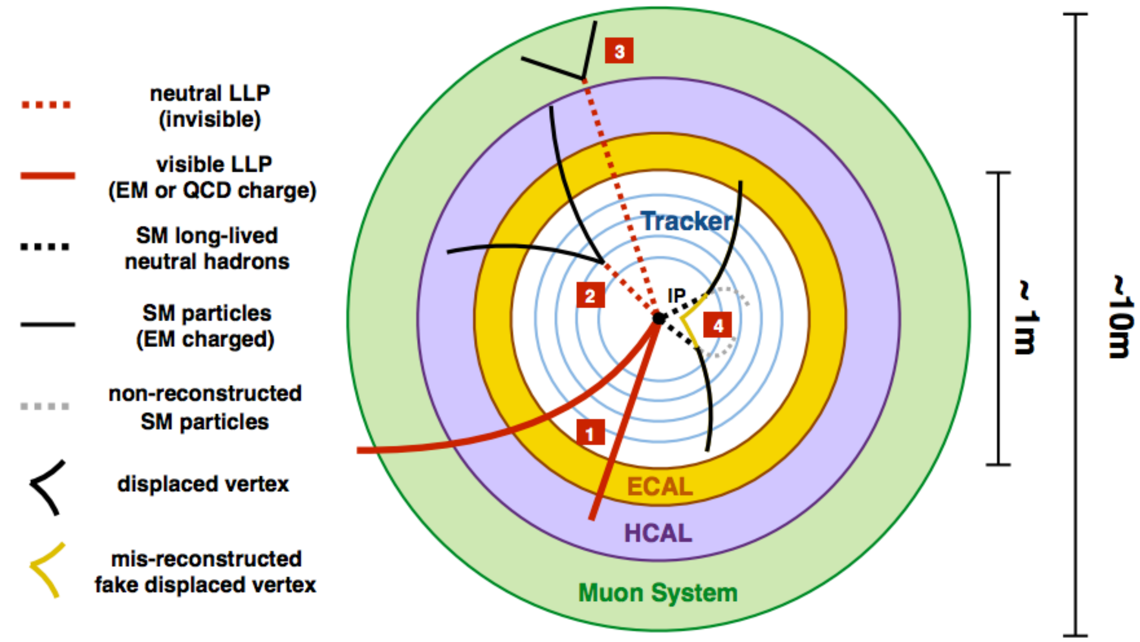
particle

Example: Long Lived particles (LLP)

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

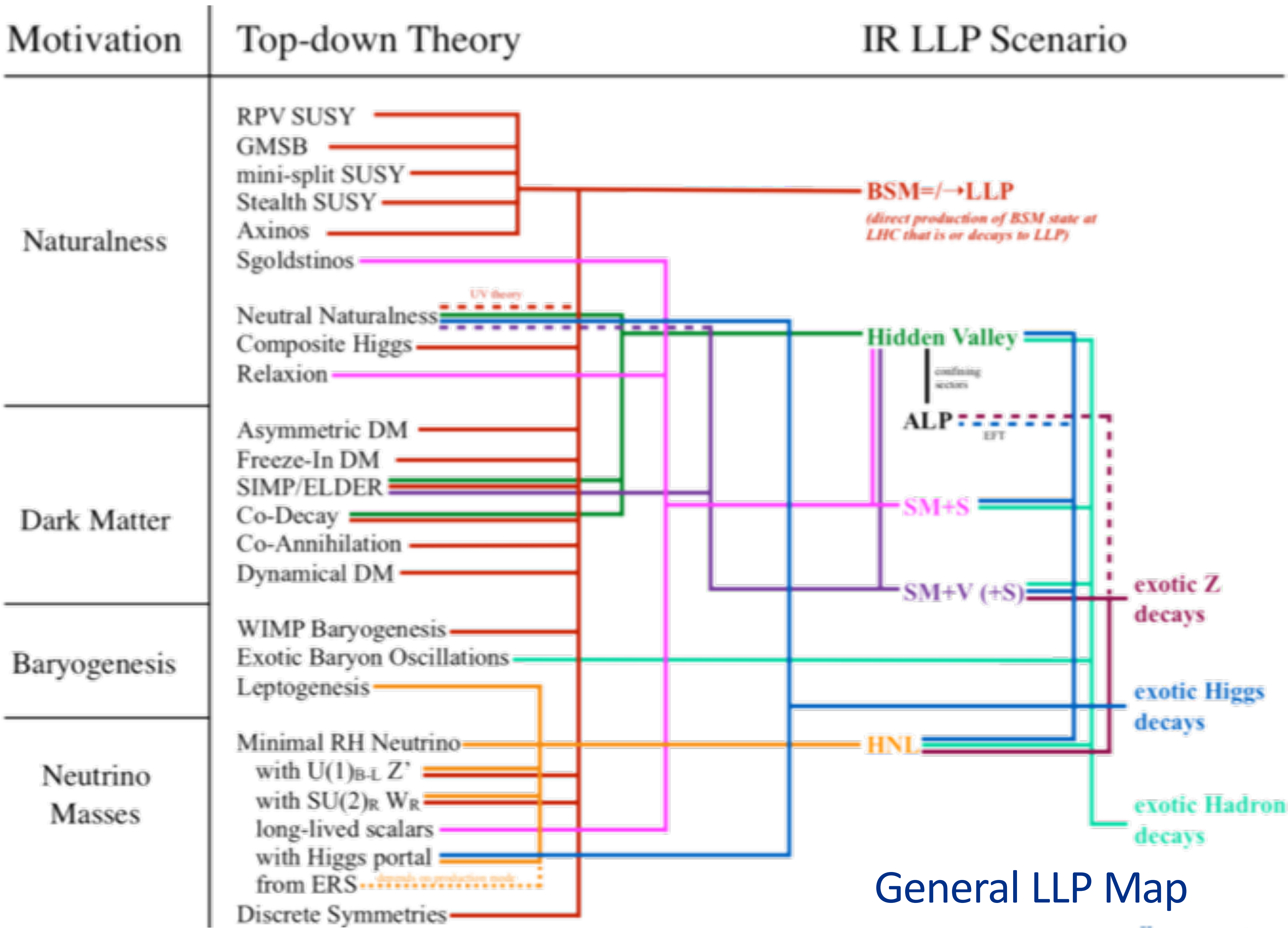
- Displaced-Long lived, soft, kink, … Covered by LHC searches already.



Curtin and Sundrum

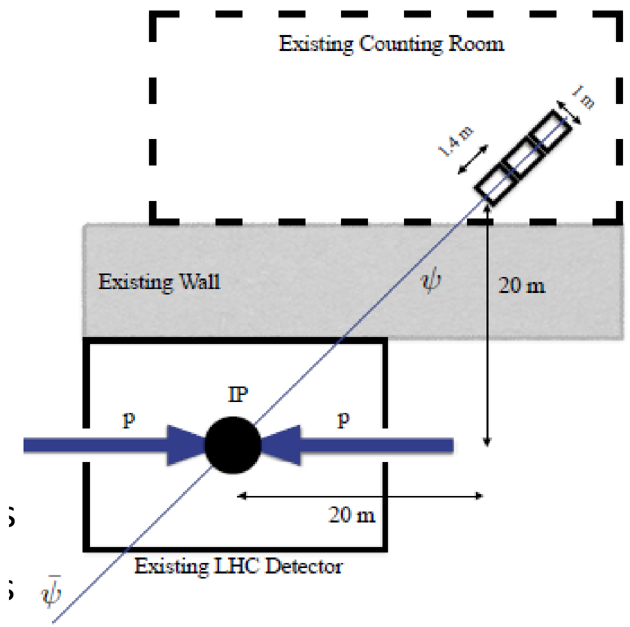
Here, I focus on: decay length >> 10 meters

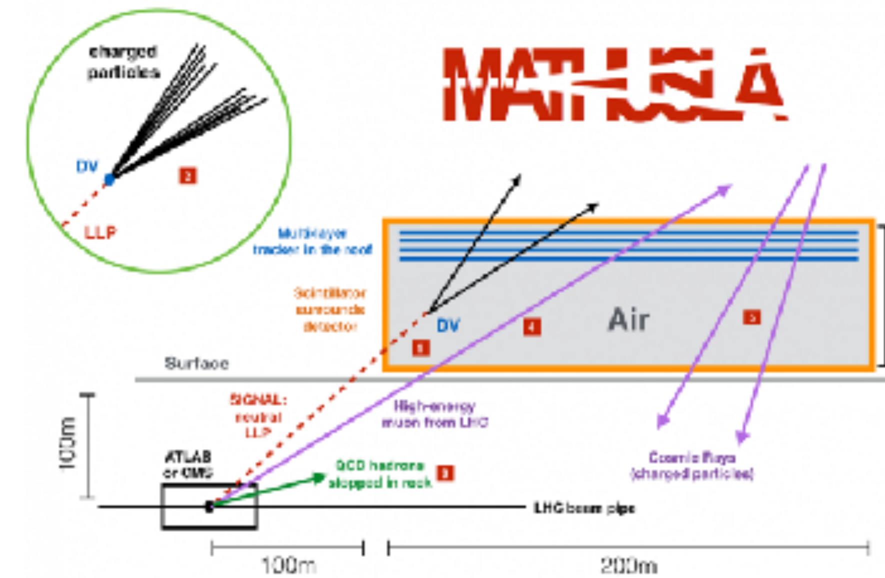
tons of models



General LLP Map

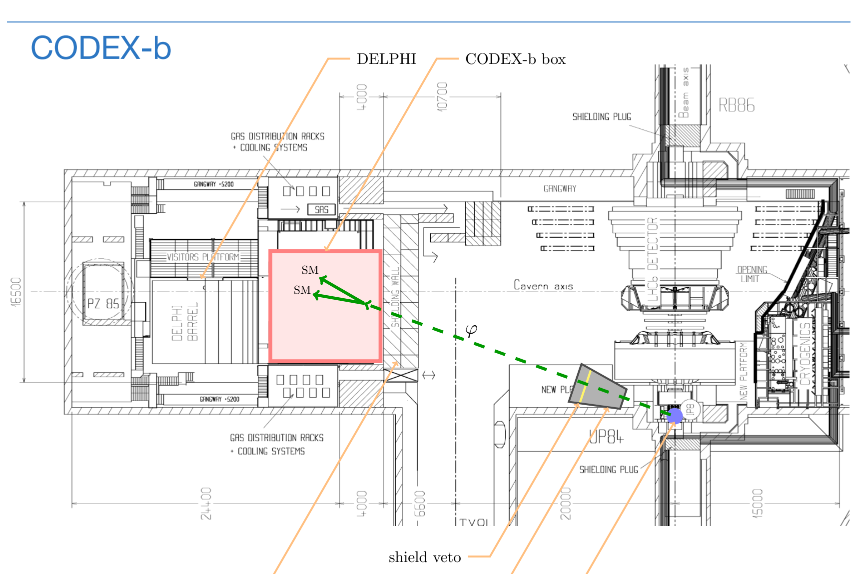
Far detectors

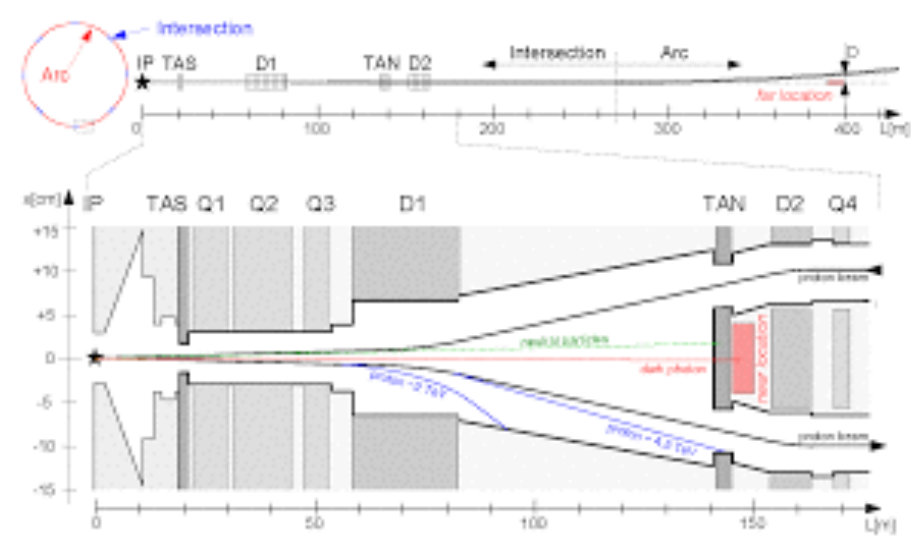




MATHUSLA

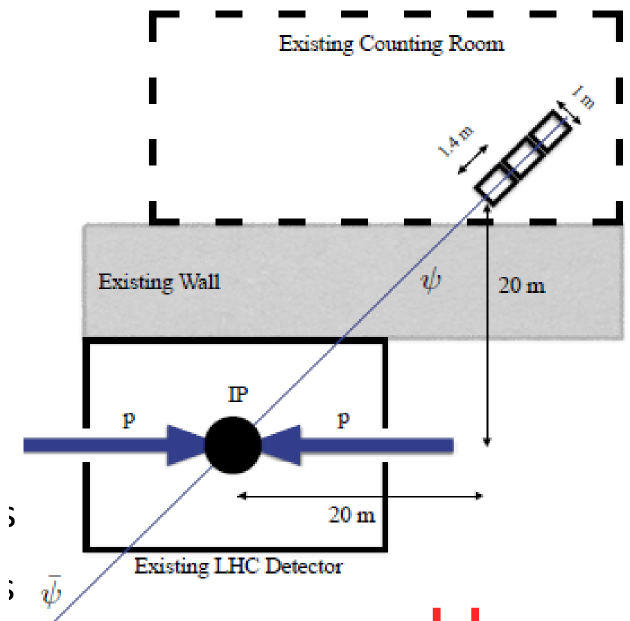
new detectors far
away from the interaction region

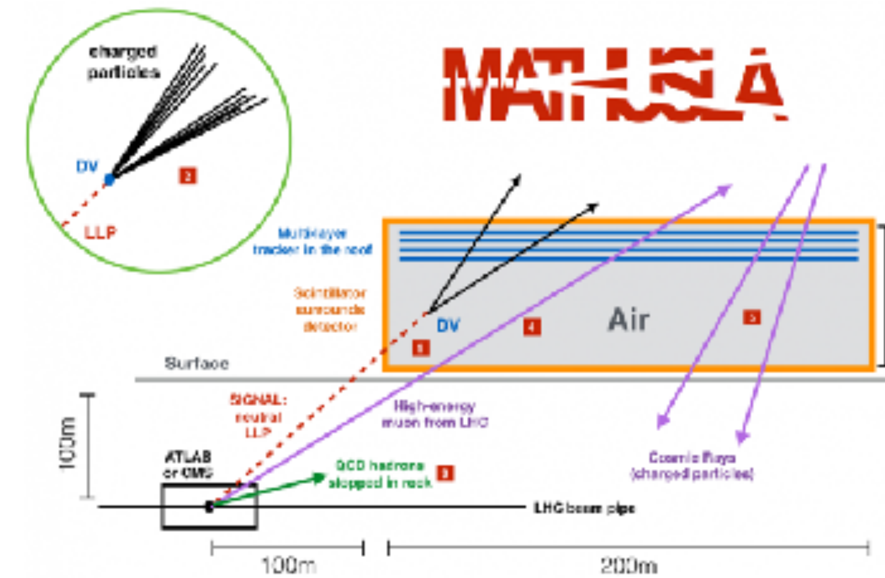




FASER

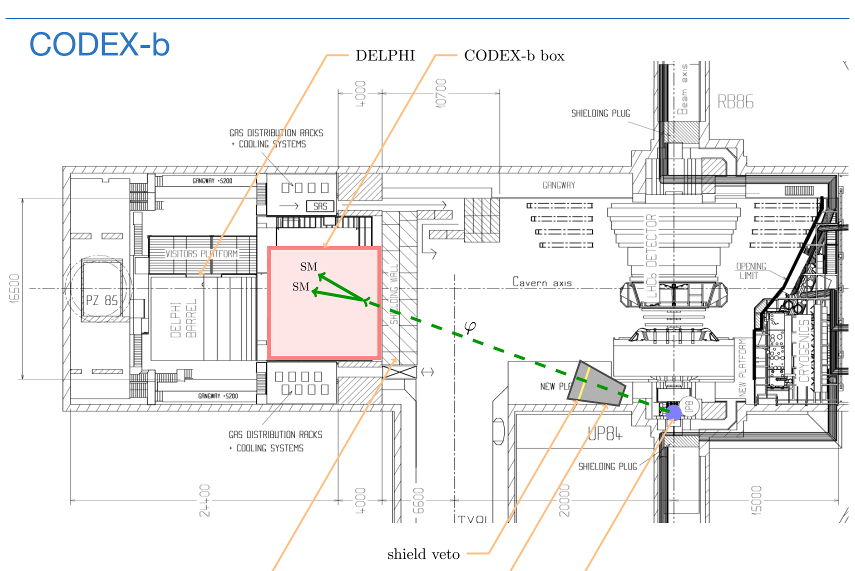
Far detectors

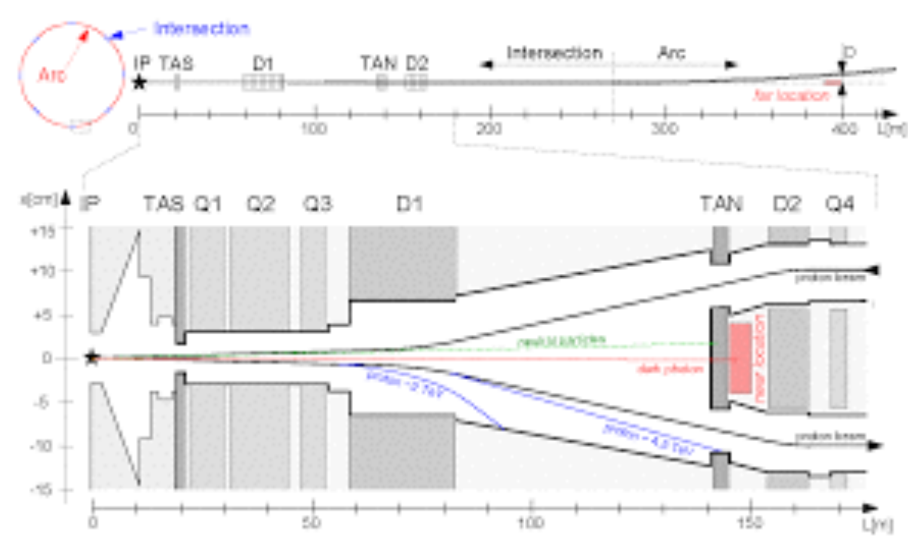




MATHUSLA

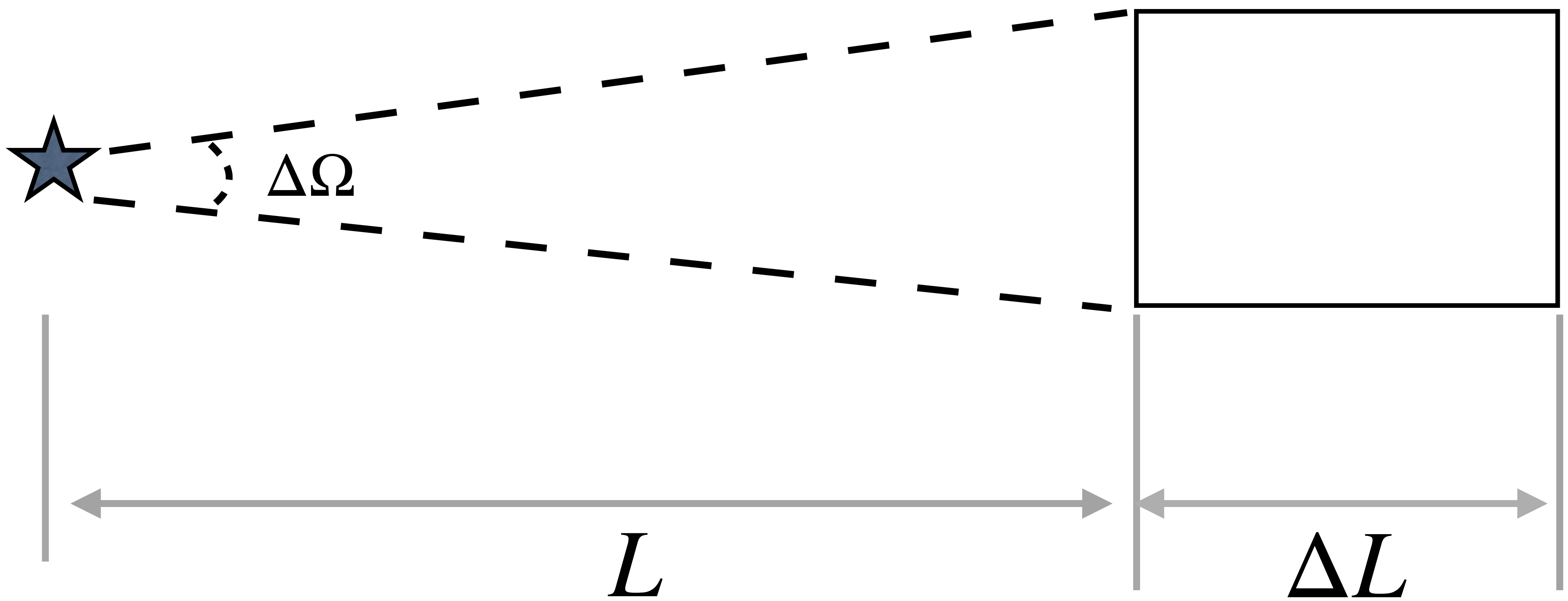
Have we fully optimized LLP searches at the interaction points ATLAS, CMS, LHCb?





FASER

Optimal place to catch LLP



Number of particle decayed within detector volume:

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

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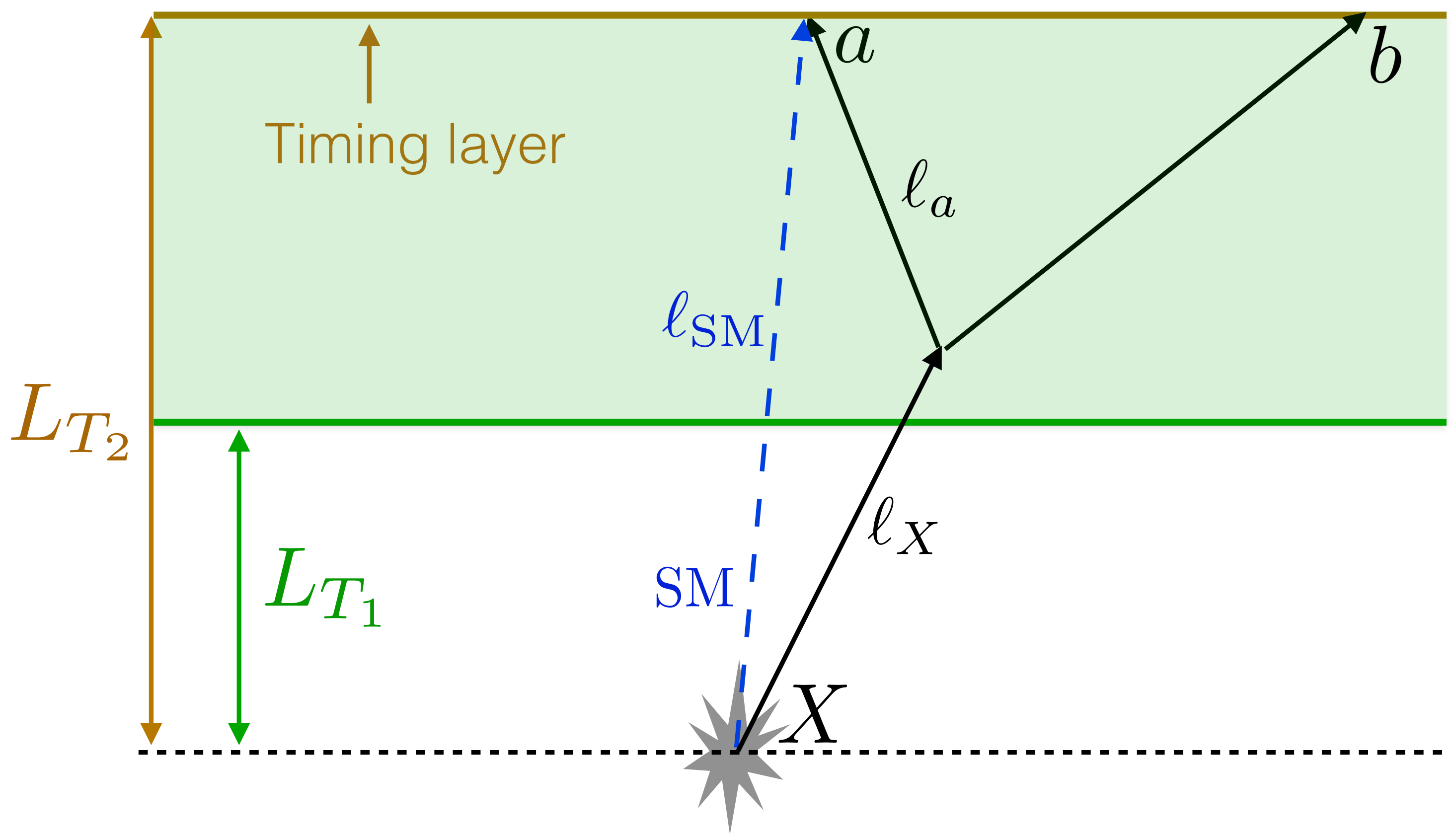
	ATLAS/CMS (LHCb)	Far detectors
$\Delta\Omega$	$\sim 4\pi$	< 0.1
ΔL	$1 - 10$ meters	$1 - 10$ meters
L	$1 - 10$ meters	$10 - 100$ meters

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

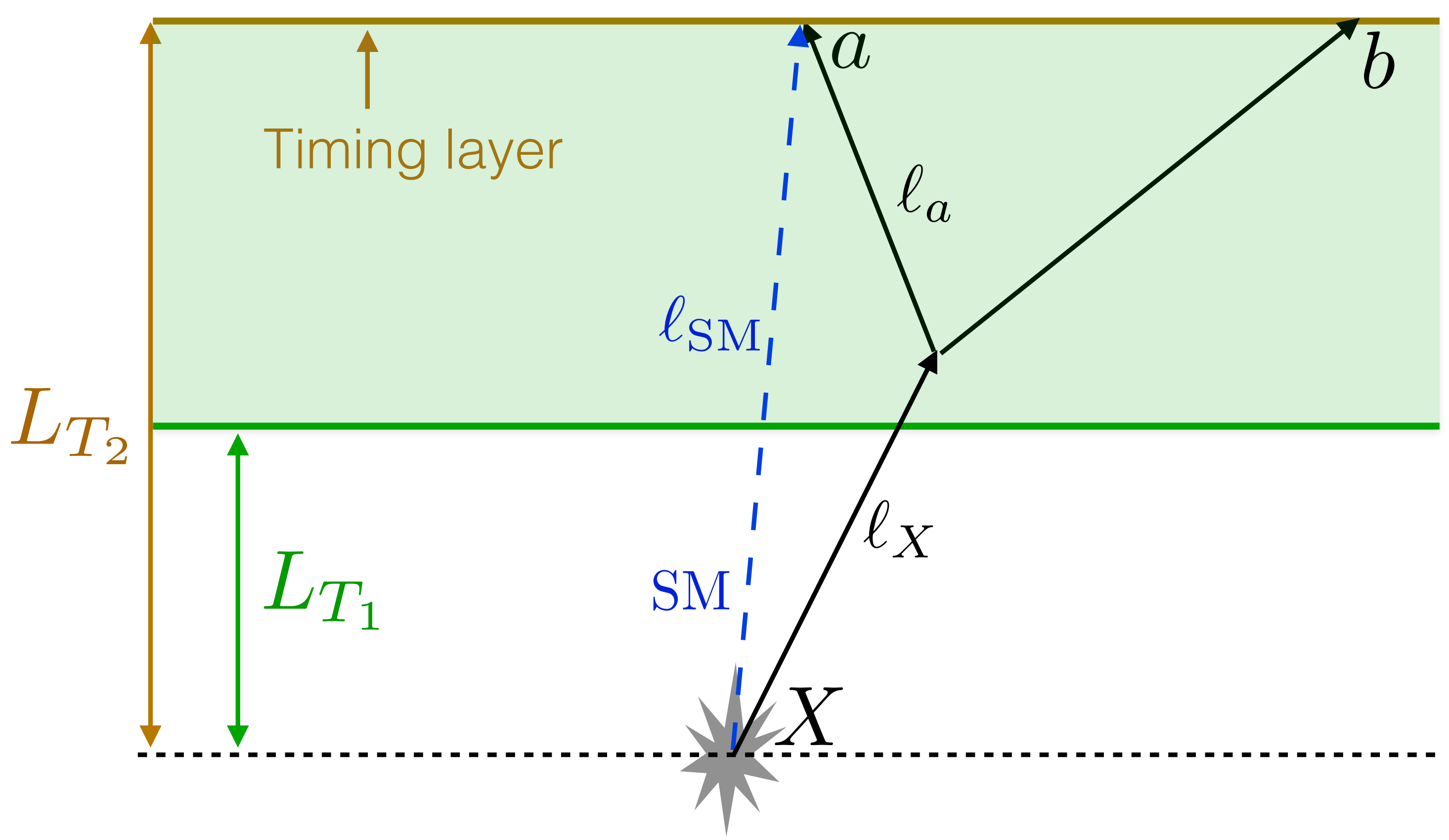


$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{SM}}{\beta_{SM}} \qquad \beta_a \simeq \beta_{SM} \simeq 1$$

Good for massive LLP produced with small or moderate boost

$$\beta_X < 1$$

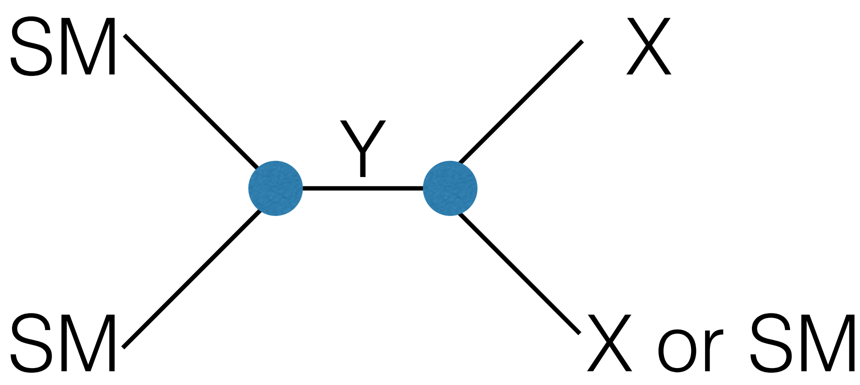
Time delay

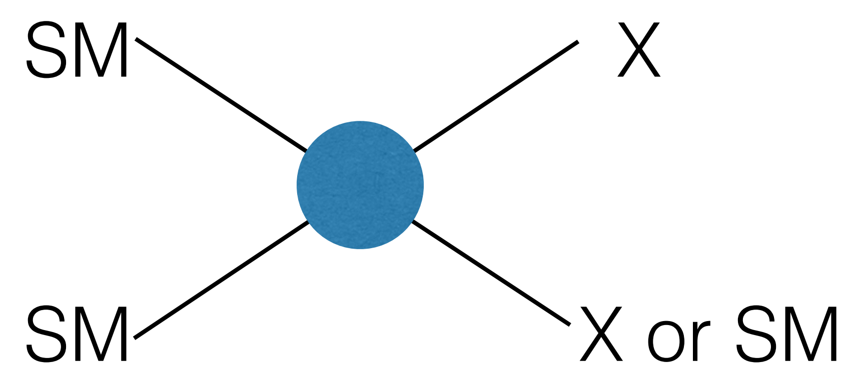


- **timing layers considered here:**
  - **CMS EC search: LT1 = 0.2 m, LT2 = 1.2 m (EC = Electromagnetic Calorimeter)**
    - **Resolution:** $\delta t = 30$ ps
  - **MS search (hypothetical): LT1 = 4.2 m, LT2 = 10.6m (MS = Muon Spectrometer)**
    - **Resolution: don't need to be as good (detail later)**

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: $\gamma \sim 1$

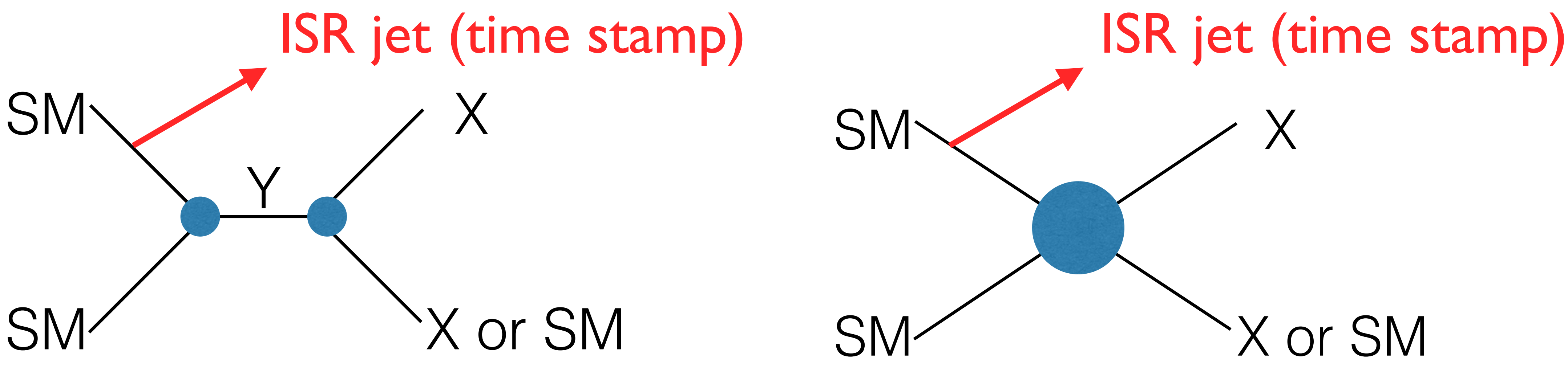
slow moving, sizable Δt

benchmark: SUSY

$X = \text{neutralino}$

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

Signal



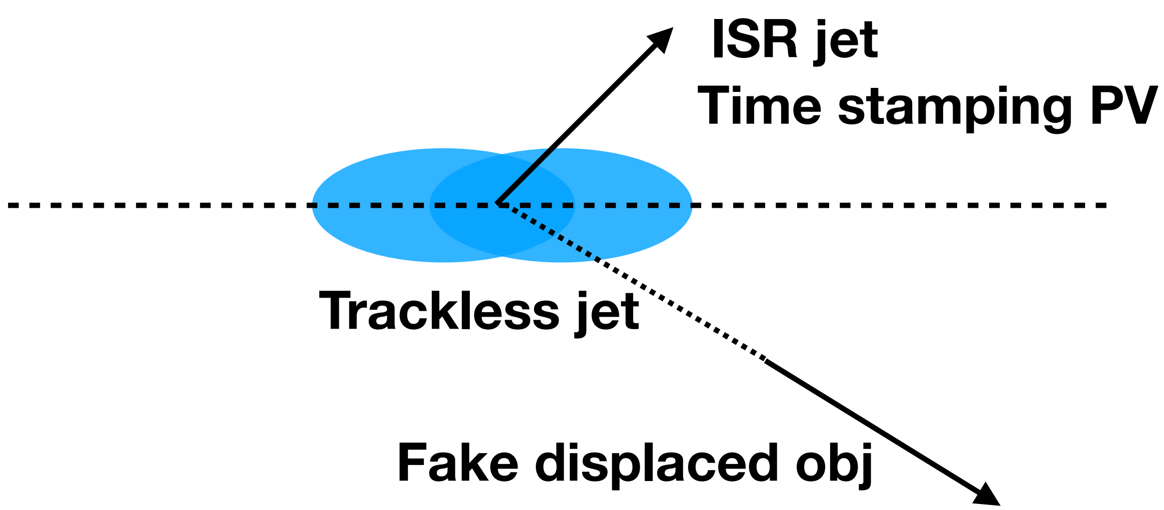
1. ISR jet provides the time for the hard collision

2. LLP decay before reaching timing layer.

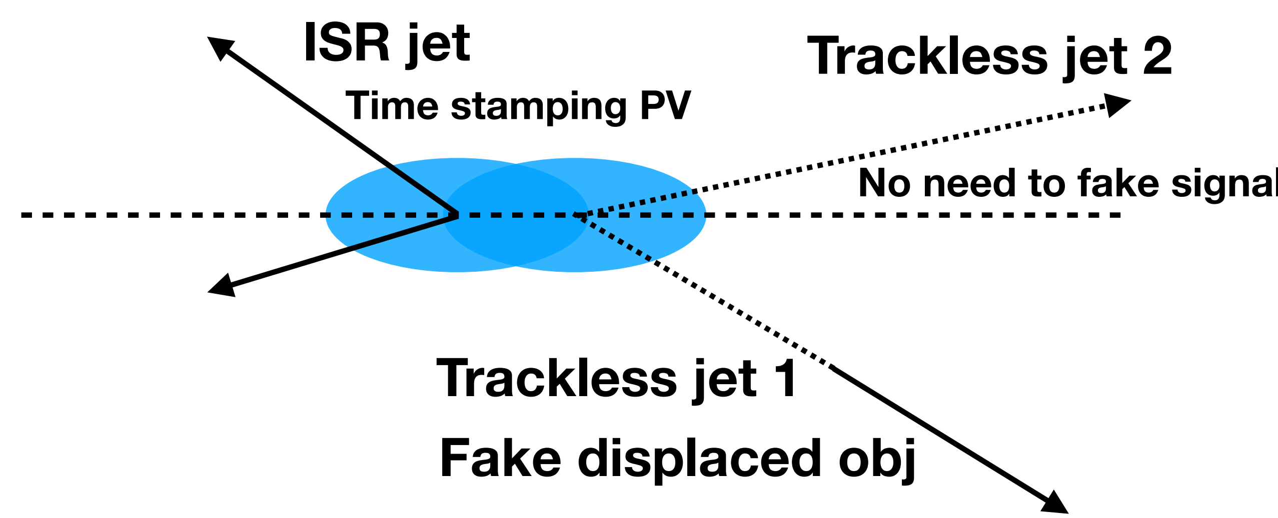
⇨ measurement of Δt

background

Same hard interaction



Pile up

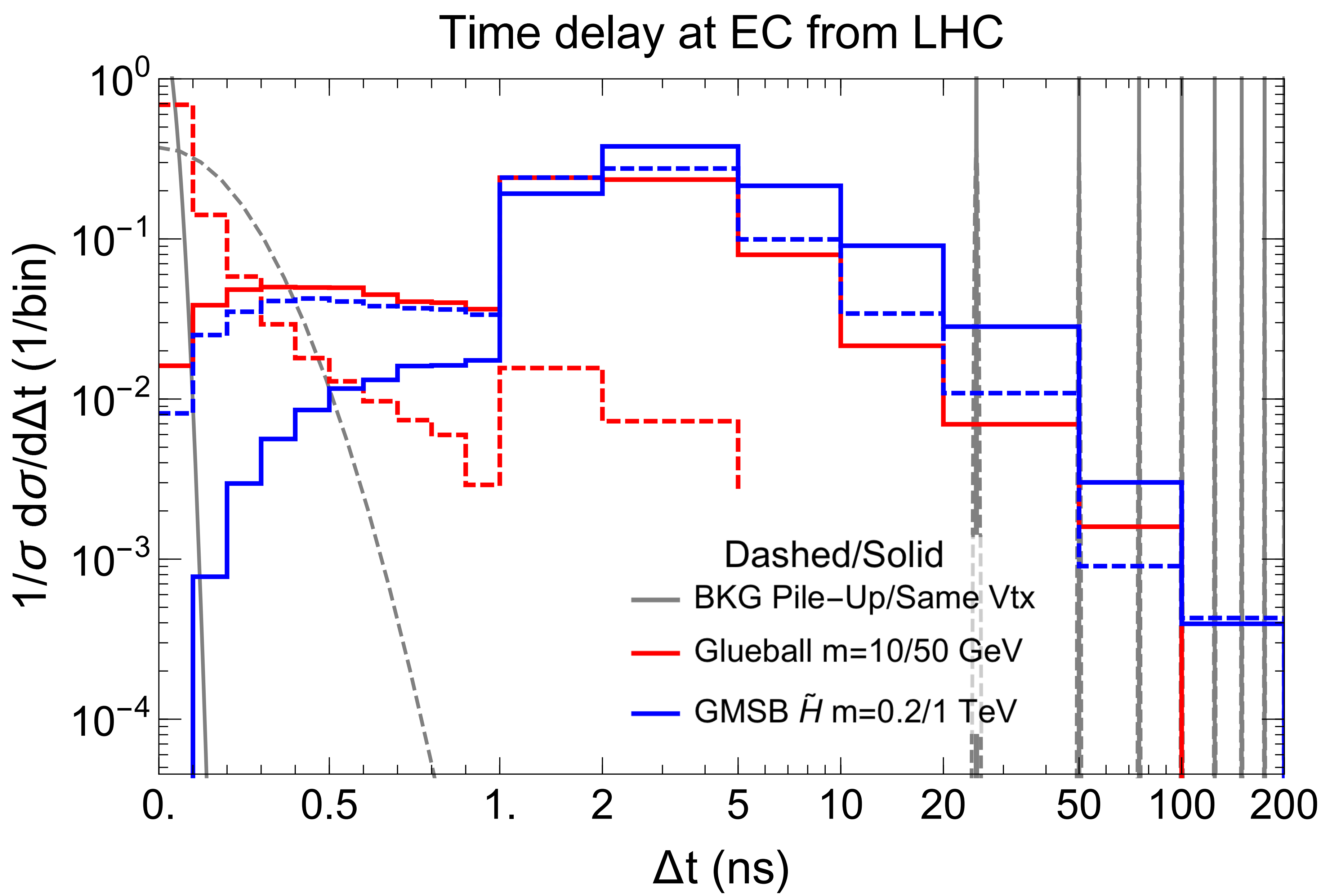


Time delay from
resolution of timing detector.

Time delay from
spread of the proton bunch

$\sim$ **190 ps**

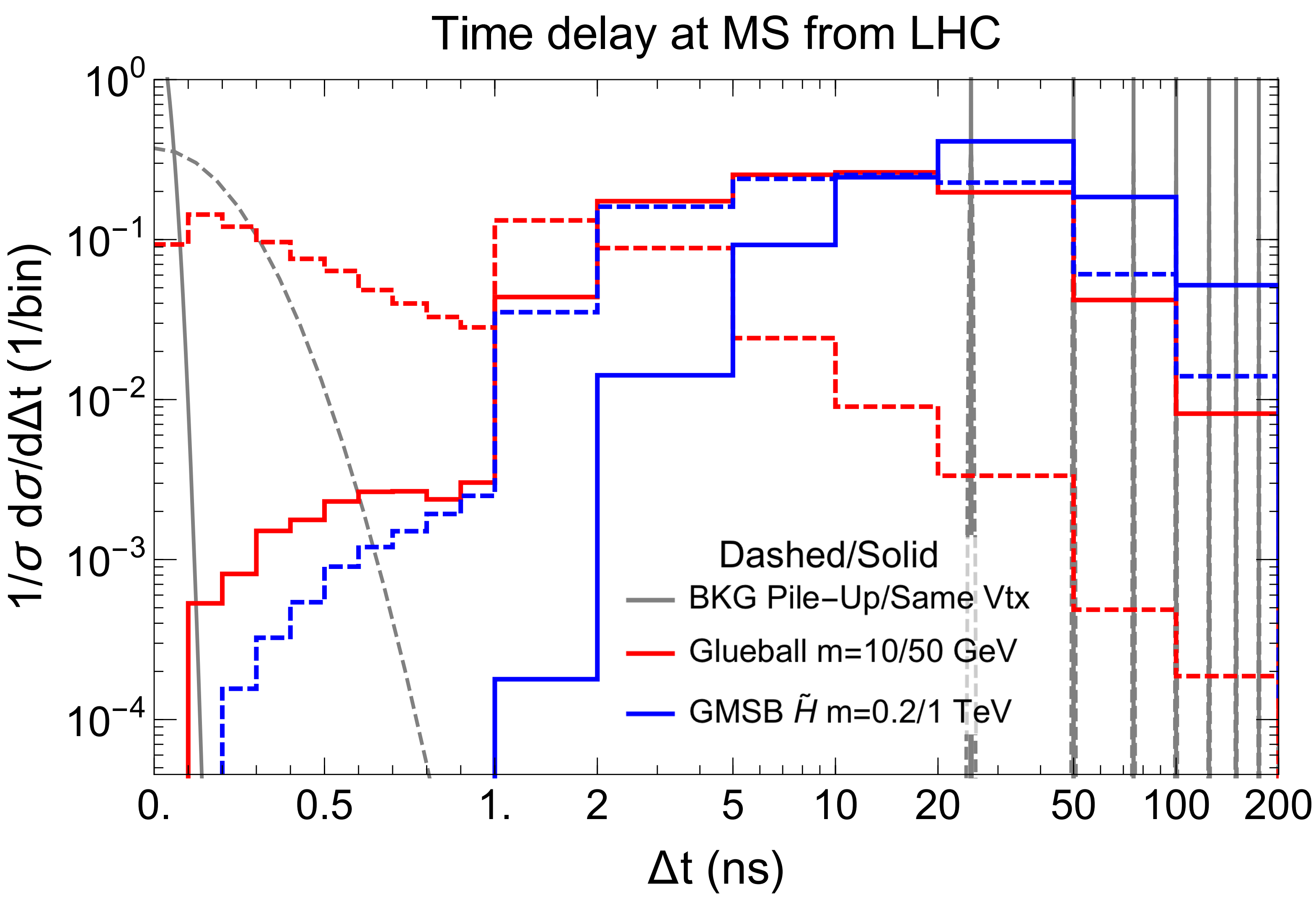
Search based on EC



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

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

Search based on MS



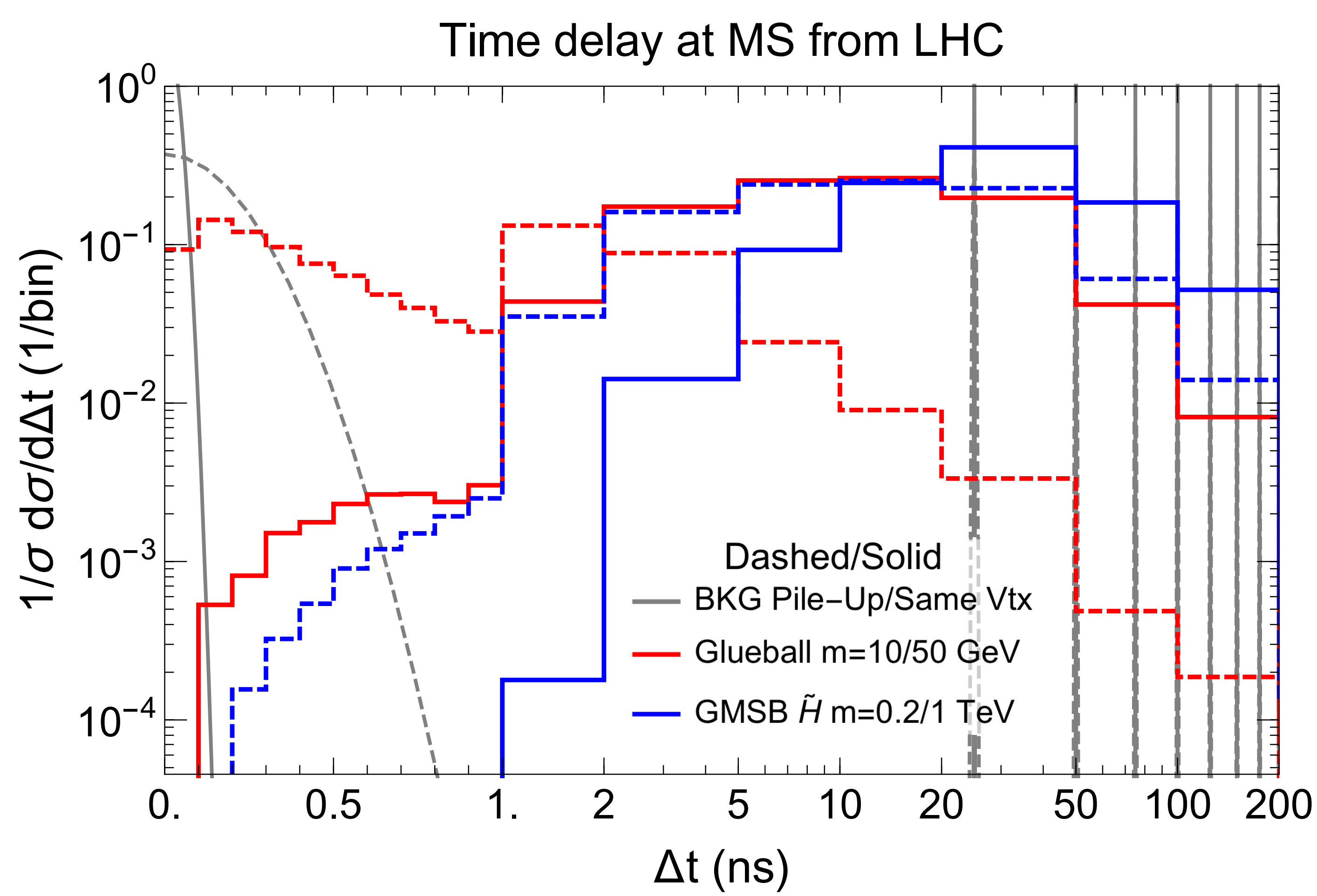
Pile up background smaller, shielded by HCAL etc.

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.

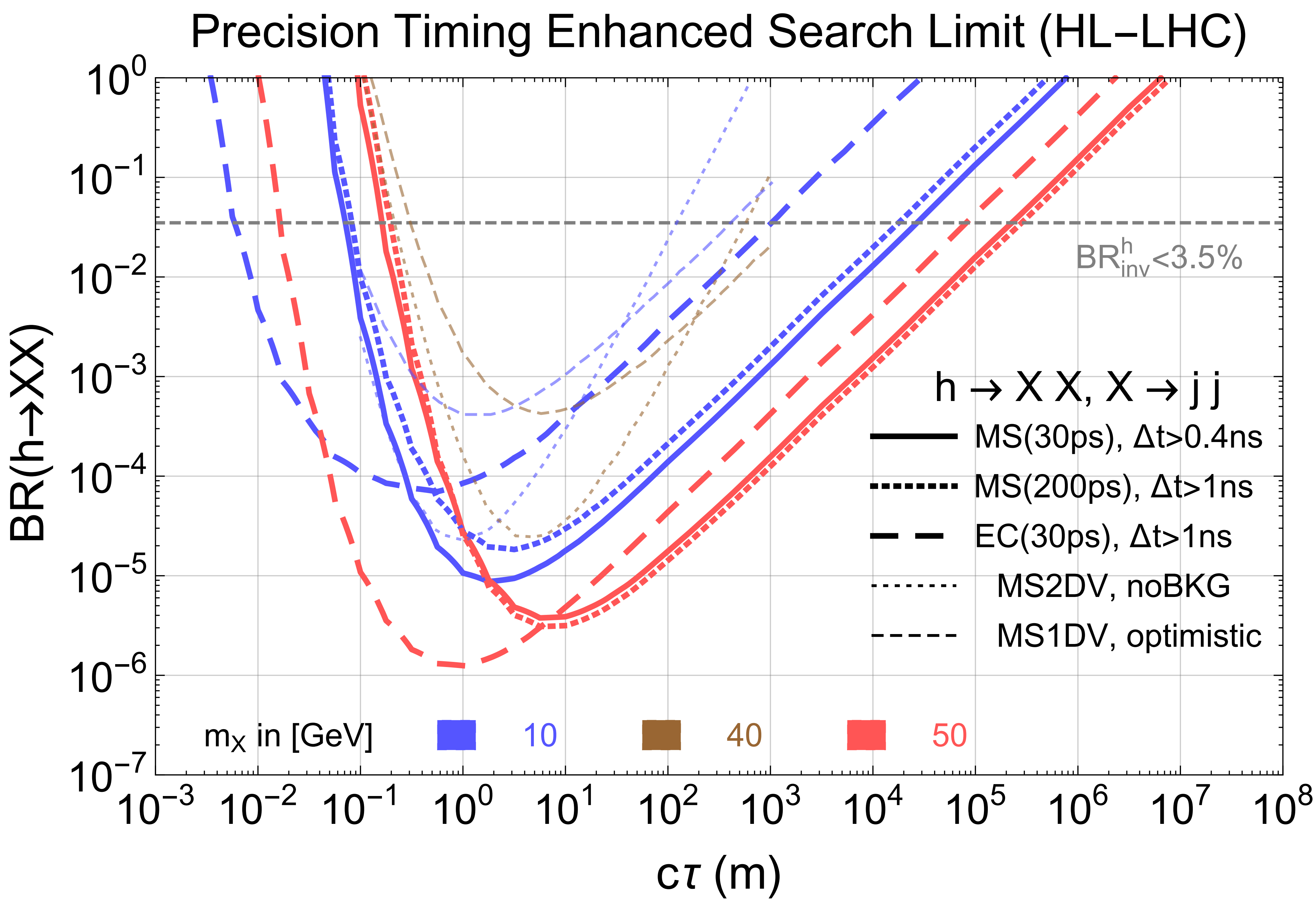
no need for super good timing resolution

$\delta t \sim 200$ ps

will do

Sensitivity to Higgs portal

Jia Liu, Zhen Liu, LTW

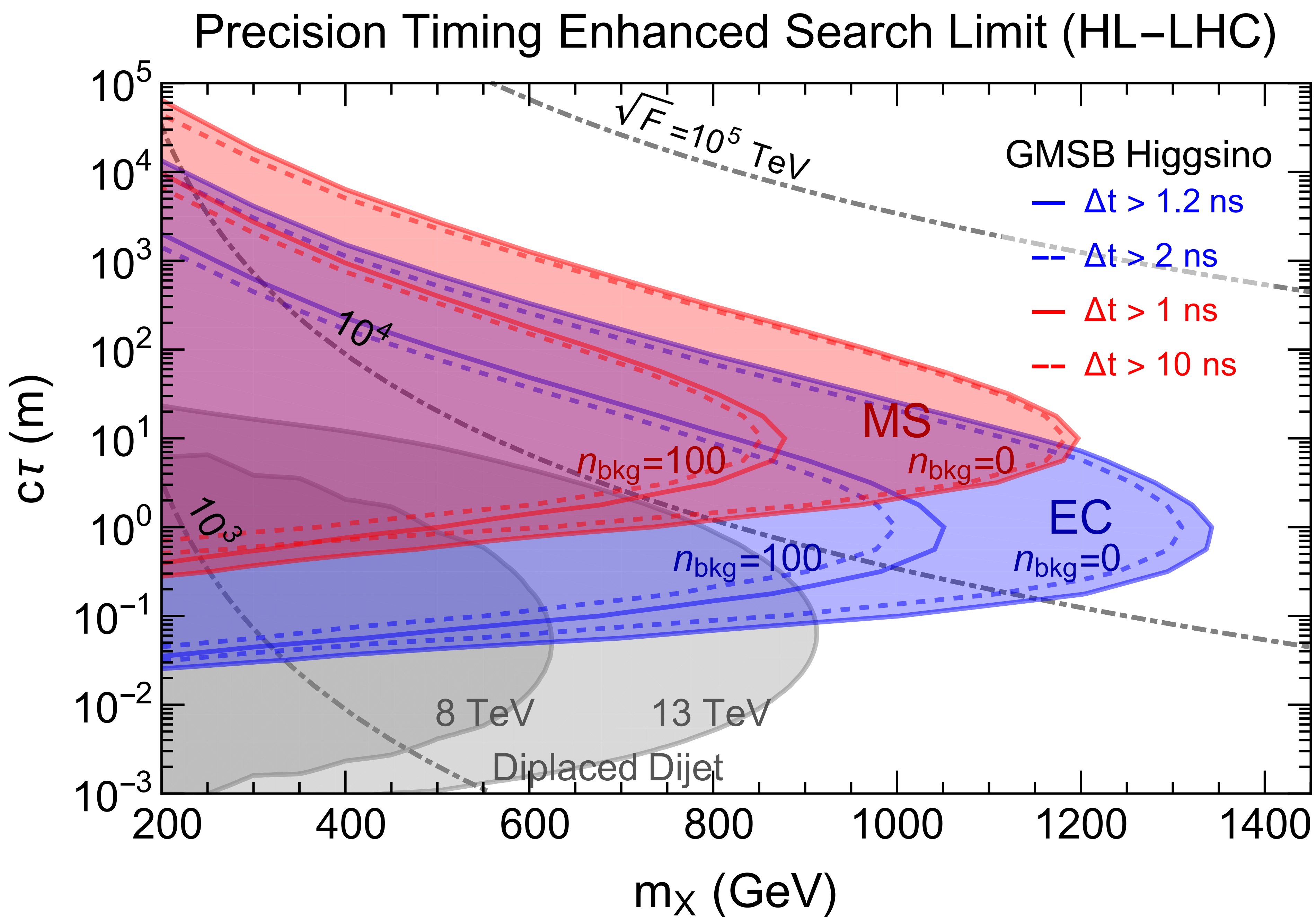


For example, for $\mathrm{BR}(h \to XX) \sim 10^{-3}$

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

Sensitivity to SUSY

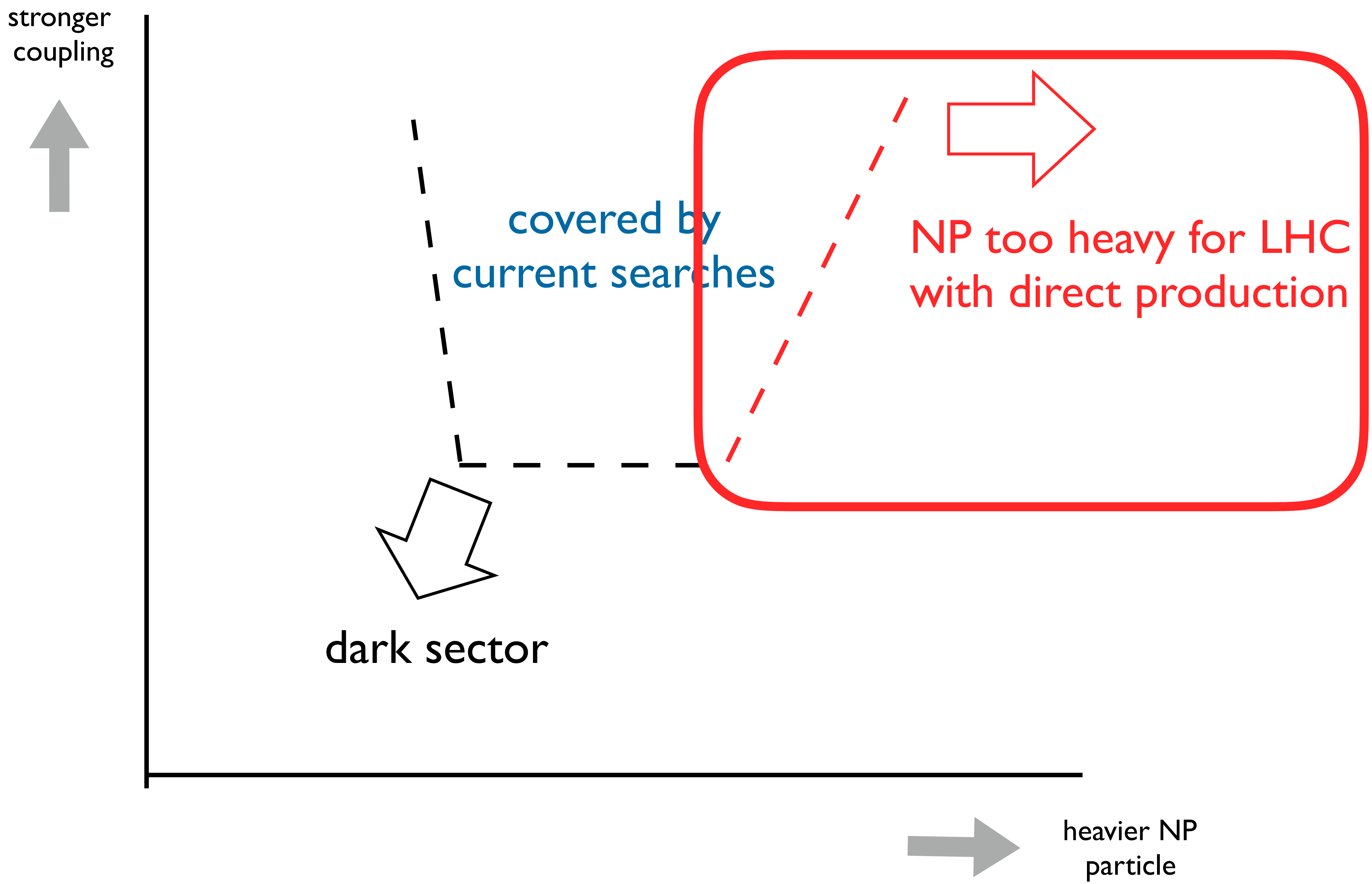
Jia Liu, Zhen Liu, LTW



Slower moving LLP, timing cuts can be further relaxed.

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.



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

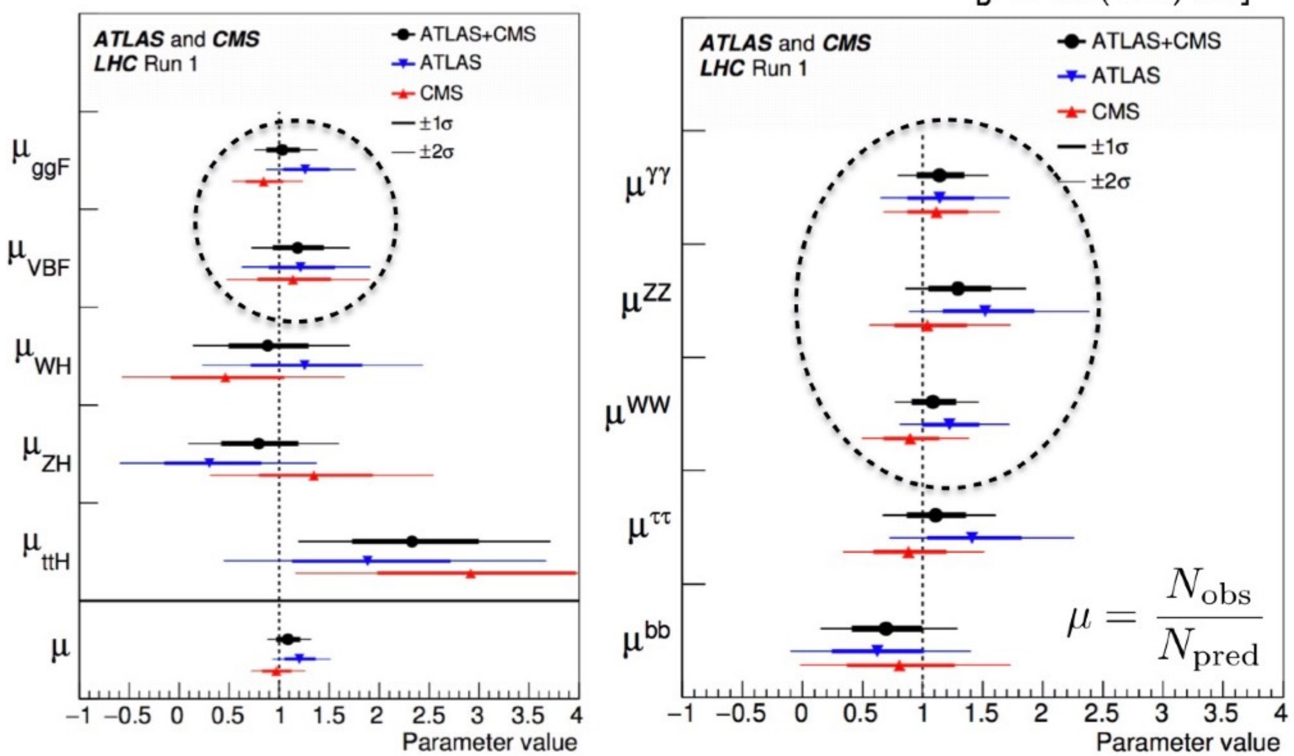
Precision era
at the LHC

Importance of precision measurement

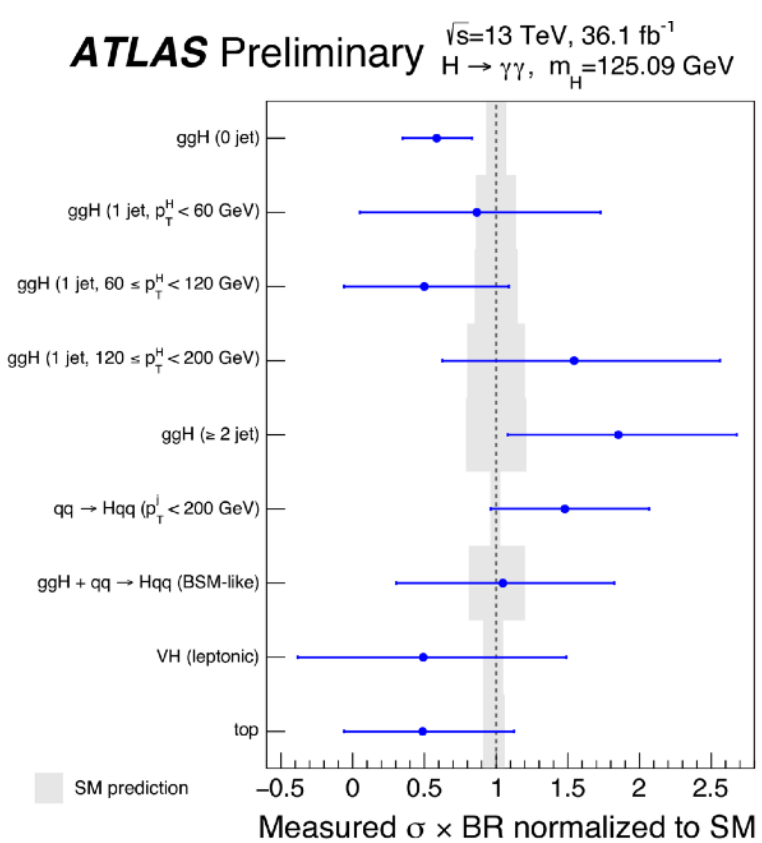
- No clear indication where new physics might be.
  - Precision measurement can give crucial guidance.
- Lots of data still to come
  - Room to improve! Statistics and systematics.
- Will be a important part of the legacy of the LHC.
  - LEP taught us a lot. LHC will do the same.

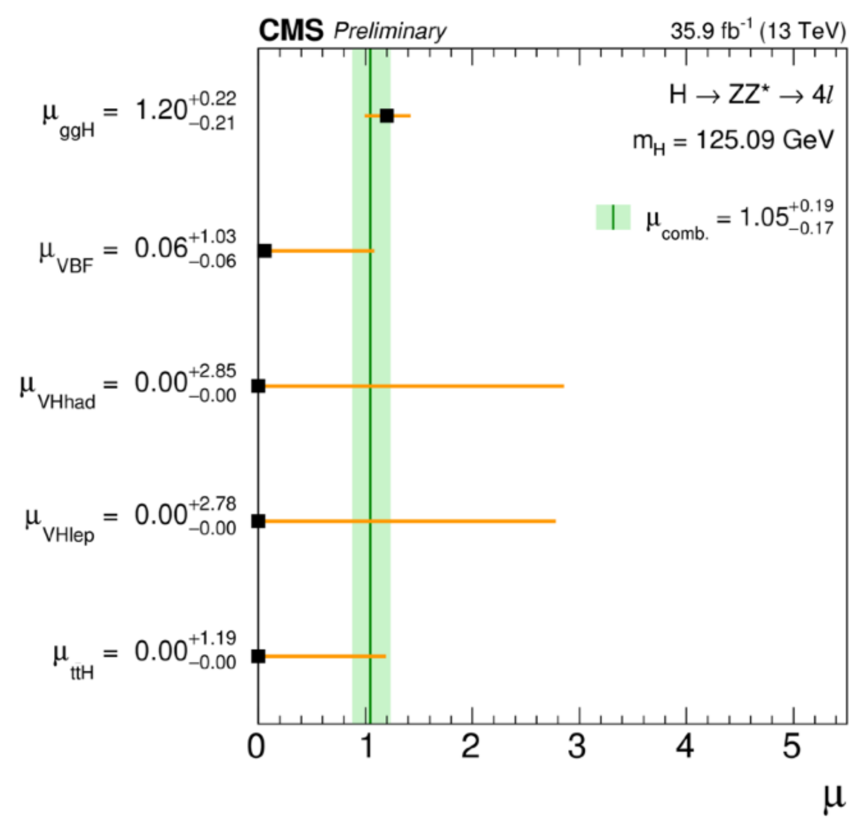
Higgs Standard Model-like

[JHEP 08 (2016) 045]



Agree to about 10-20%





Not entirely surprising

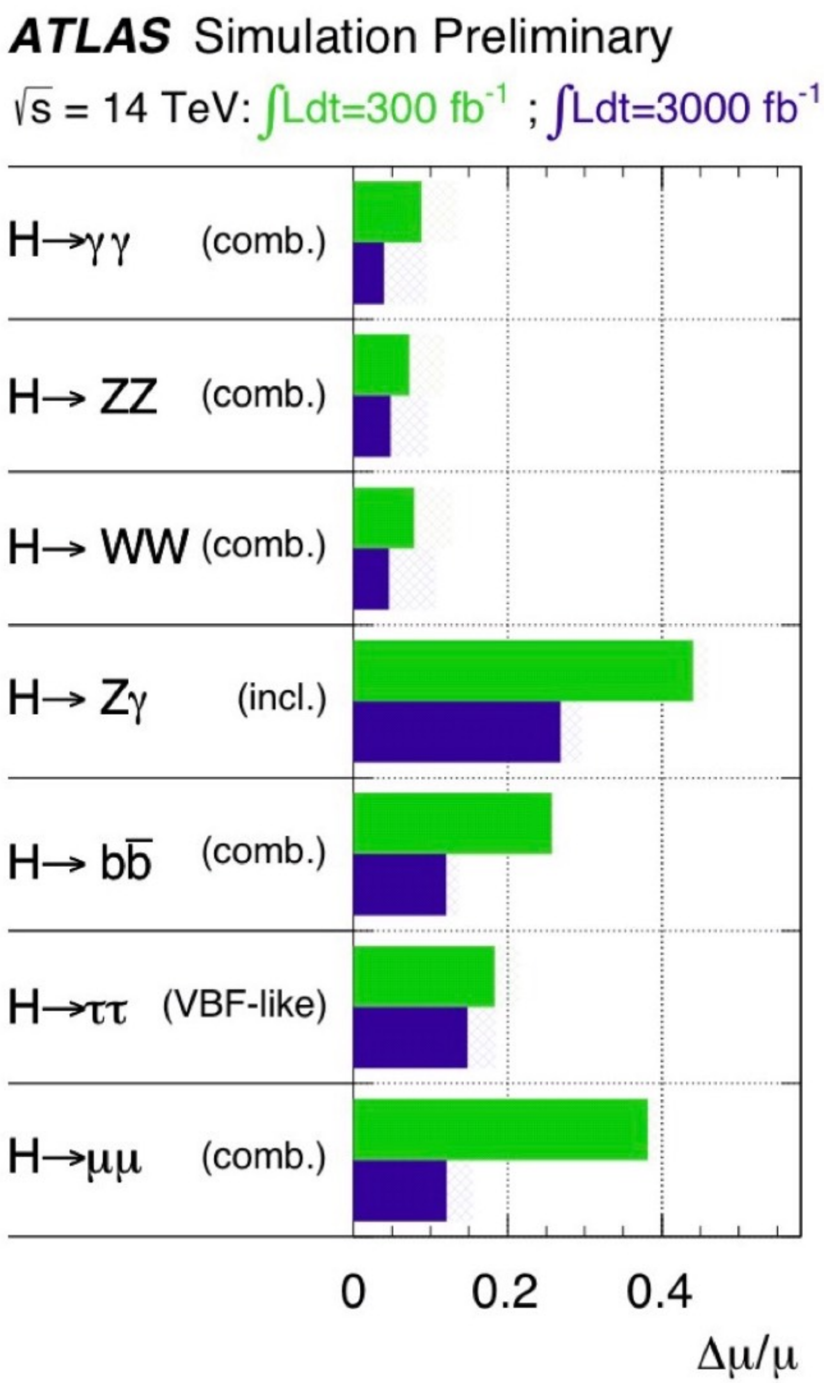
- In general, deviation induced by new physics is of the form

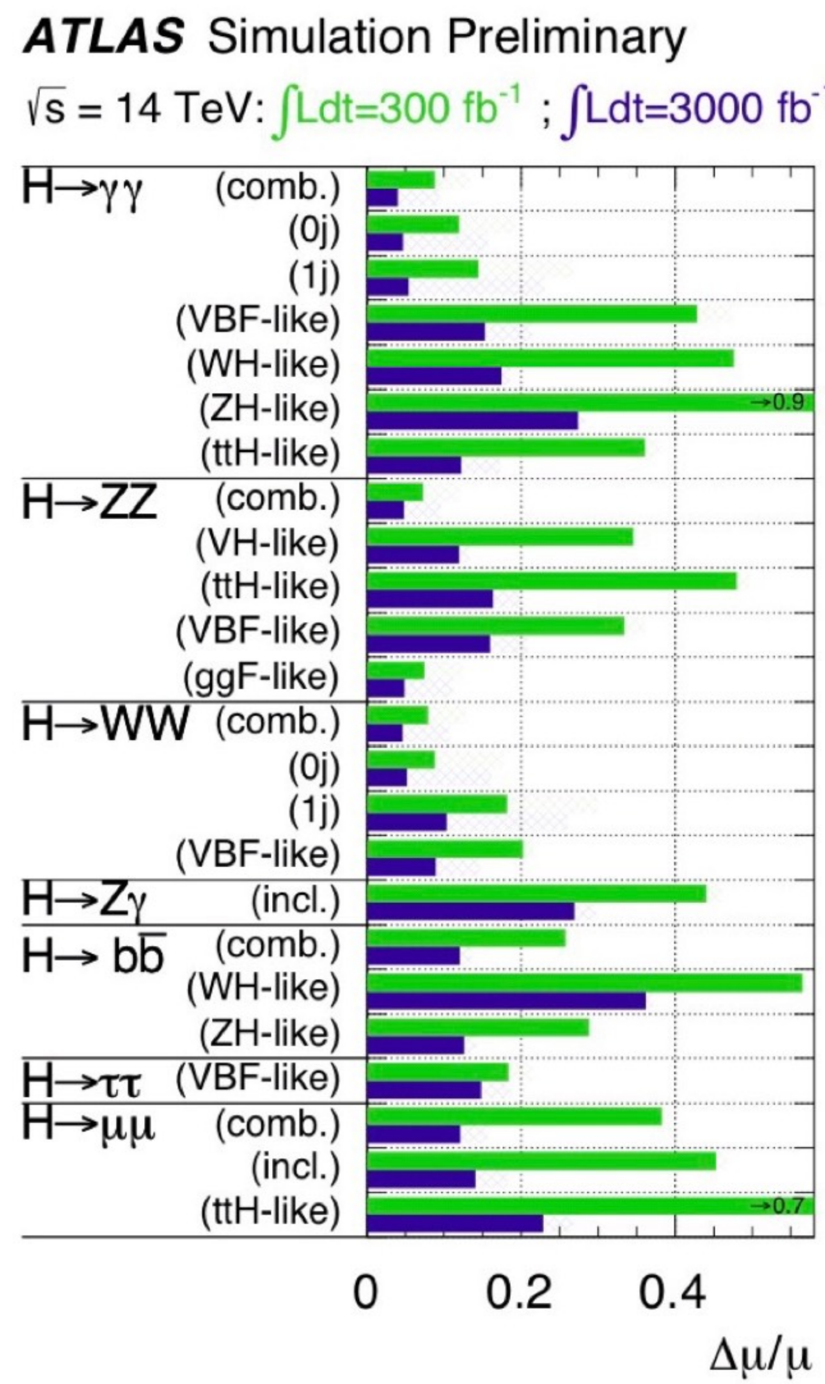
$$\delta \simeq c \frac{v^2}{M_{\rm NP}^2}$$

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.

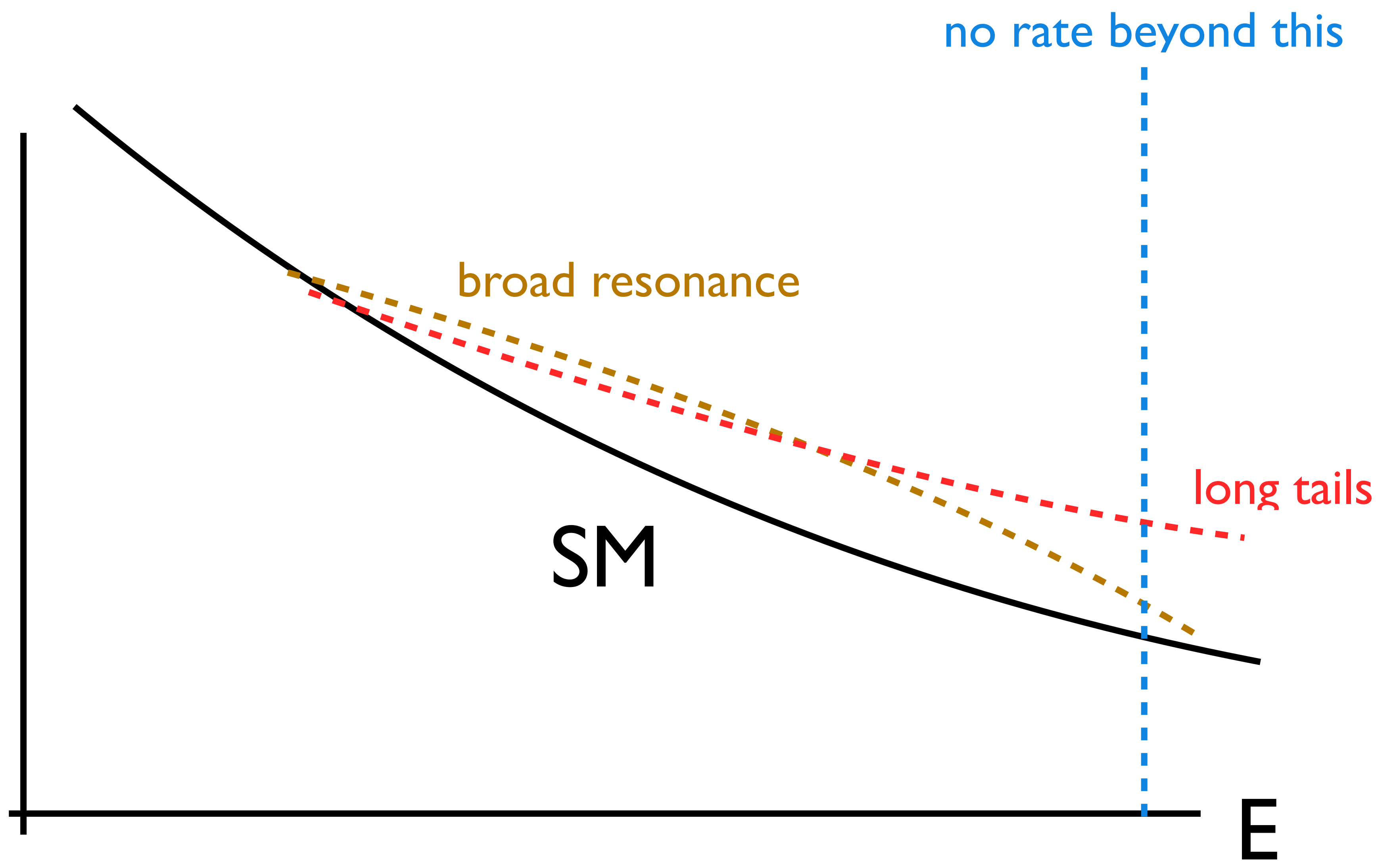
Significant improvement with high lumi





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

Precision measurement with distribution

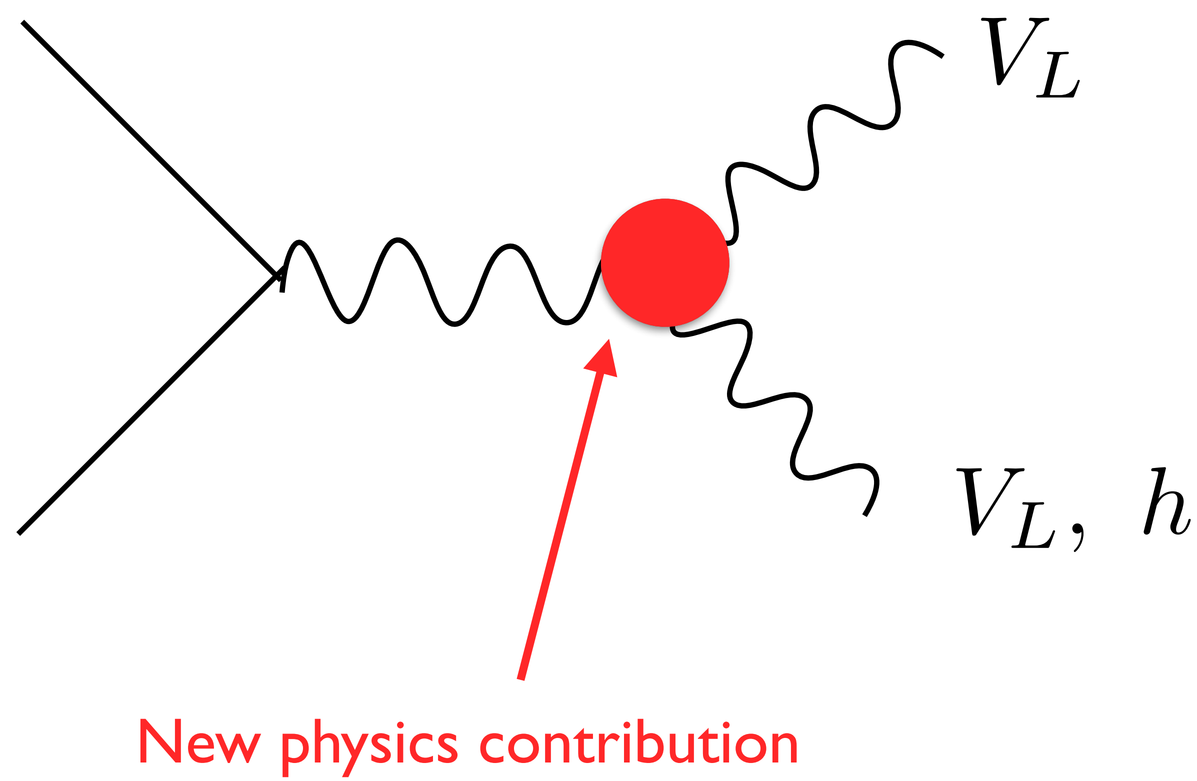


Low S/B, systematic dominated.

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

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

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.

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

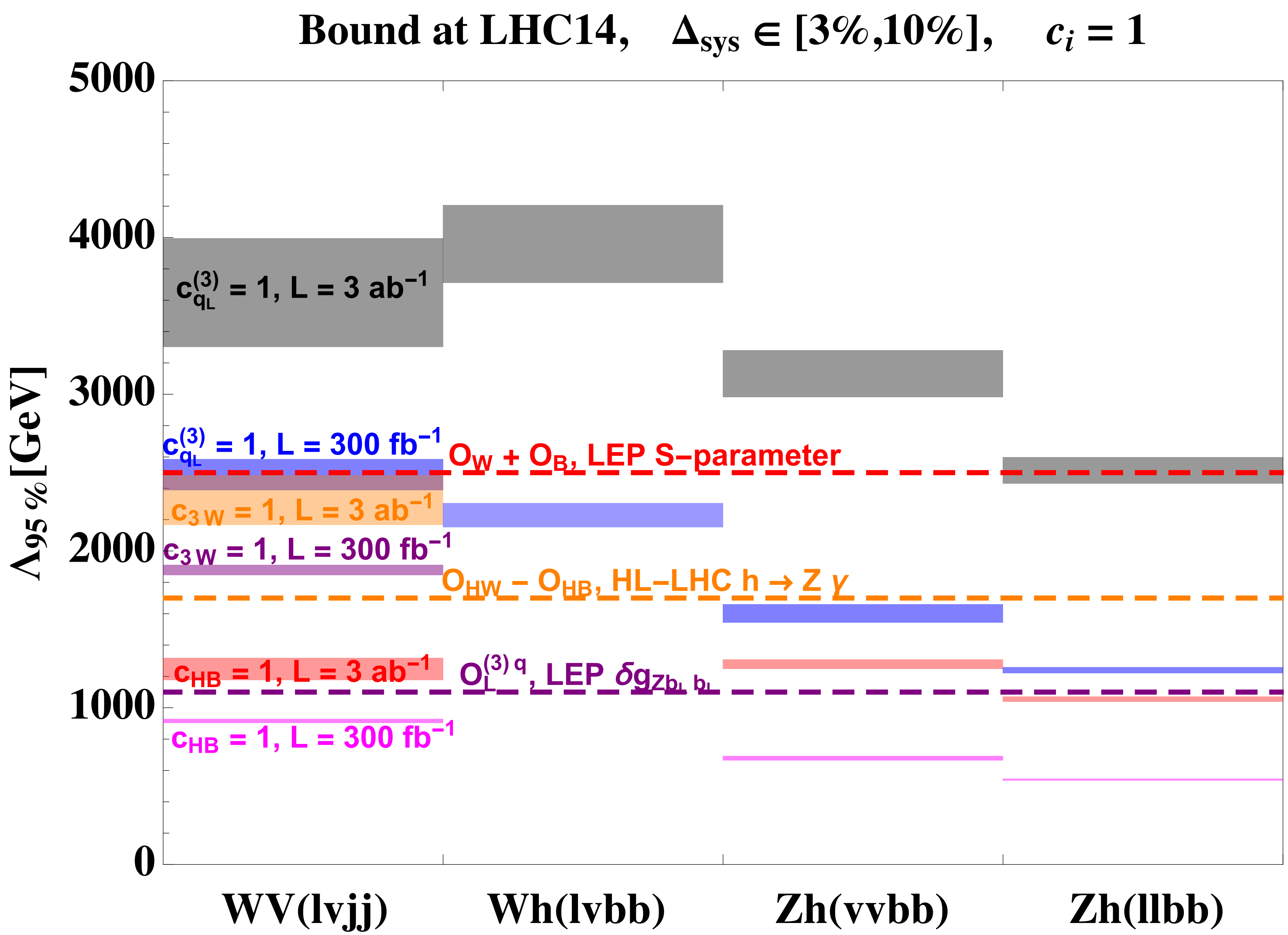
$$\text{LHC @ 8 TeV :} \qquad \sigma_b^{red}/\sigma_{SM}^{Wh} \sim 200 - 10$$

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

Operators: d=6

name	structure	coefficient (power counting)
$\mathcal{O}_H$	$\frac{1}{2}(\partial_\mu \lvert H\rvert^2)^2$	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
$\mathcal{O}_B$	$ig'(H^\dagger \overleftrightarrow{D}^\mu H) D^\nu B_{\mu\nu}$	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	$ig^2(H^\dagger \overleftrightarrow{D}_\mu H)\bar{Q}_L\gamma^\mu Q_L$	$c_q/m_*^2 \times \epsilon_q^2$
$O_L^{q,3}$	$ig^2(H^\dagger\sigma^a \overleftrightarrow{D}_\mu H)\bar{Q}_L\sigma^a\gamma^\mu Q_L$	$c_{q,3}/m_*^2 \times \epsilon_q^2$
O_R^u	$ig^2(H^\dagger \overleftrightarrow{D}_\mu H)\bar{u}_R\gamma^\mu u_R$	$c_u/m_*^2 \times \epsilon_u^2$
O_R^u	$ig^2(H^\dagger \overleftrightarrow{D}_\mu H)\bar{d}_R\gamma^\mu d_R$	$c_d/m_*^2 \times \epsilon_d^2$
O_T	$(H^\dagger \overleftrightarrow{D}_\mu H)^2$	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

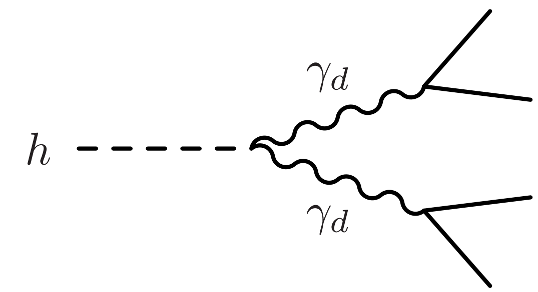
Conclusion

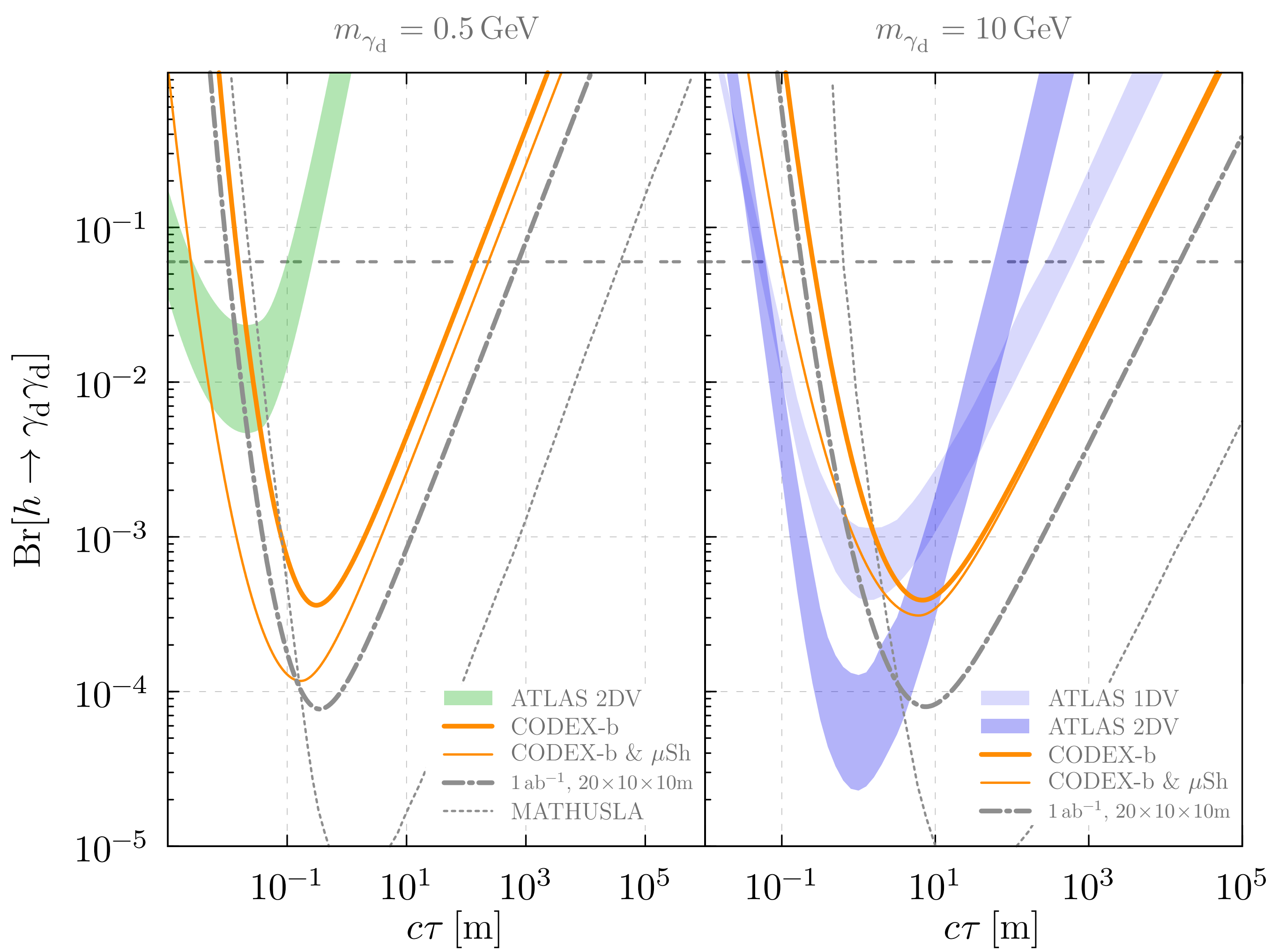
- LHC still has a lot to say.
  - 15+ years of operation, 95+% of data to come.
- Need to think about how to new searches with this data. (In addition to looking else where.)
- I discussed two directions
  - Long lived particles, with timing information.
  - Precision measurement.
- More work (and originality) needed.

extra

Could reach τ≈10⁴⁻⁵ m

Exotic Higgs decays





Application:
Neutral Naturalness
(See back-up material)

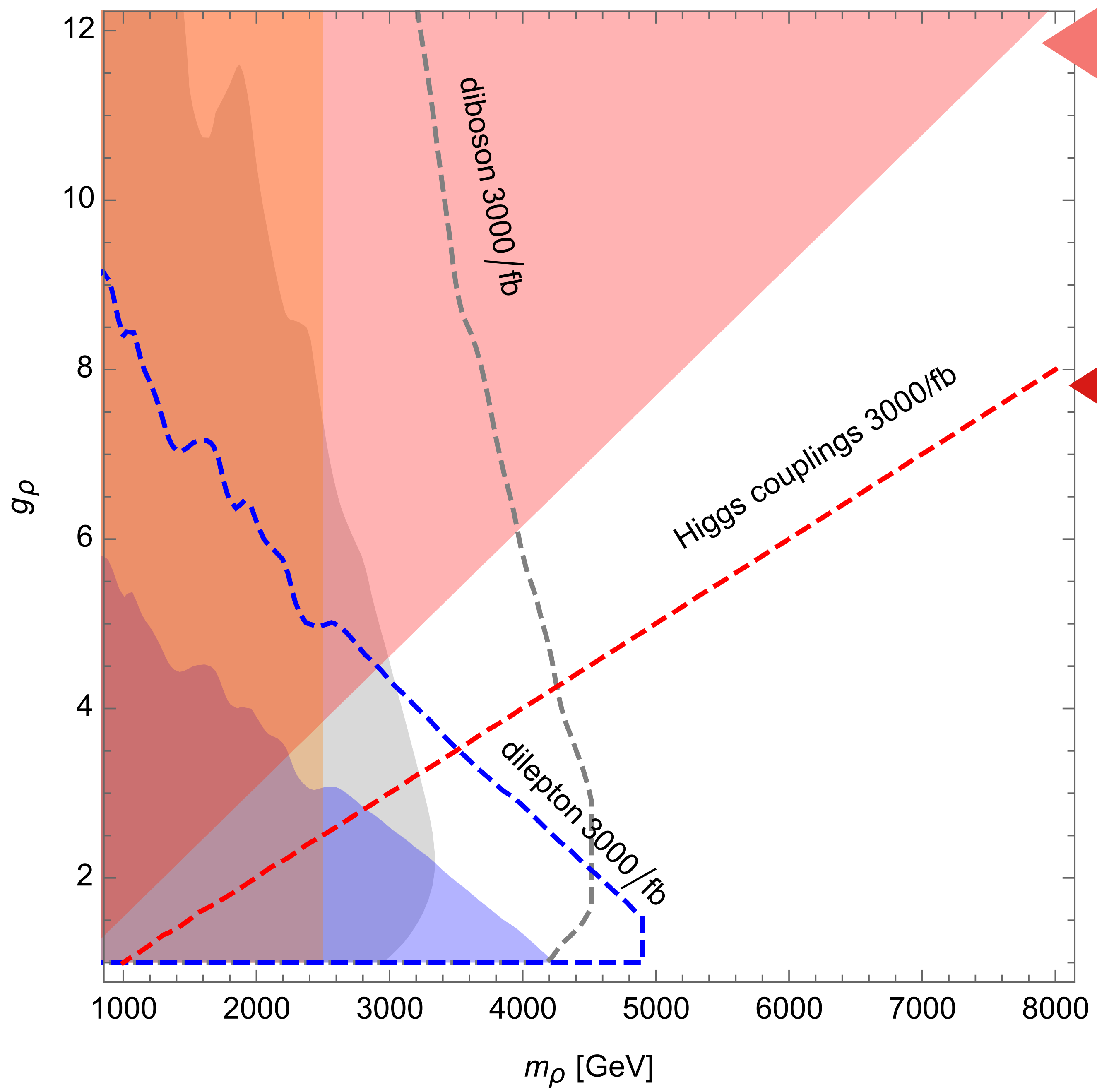
For low masses, ATLAS/CMS are background limited, CODEX-b & MATHUSLA have an edge

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

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

S. Knapen

Higgs coupling vs direct search



Excluded by current Higgs Coupling measurements

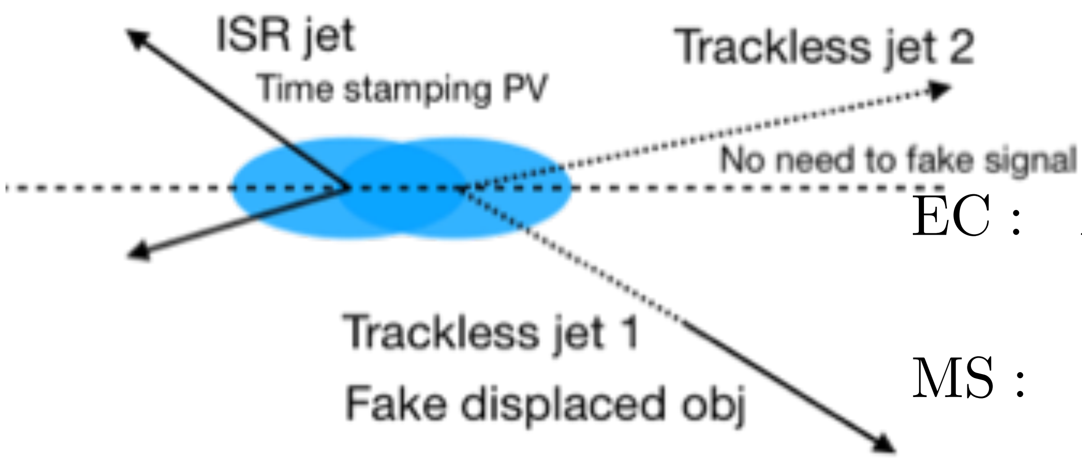
Reach of HL-LHC

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)



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

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

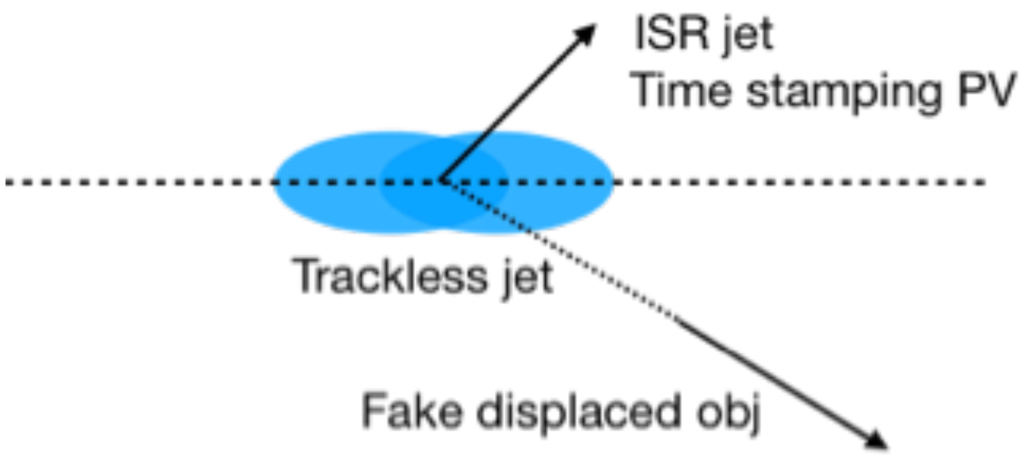
Pile-up BKG: intrinsic resolution ~190 ps
EC (30ps) cut: Δt > 1 ns
BKG(EC-PU) ~ 1.3
MS (30ps) cut: Δt > 0.4 ns
BKG(MS-PU) ~ 0.86

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.
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)



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

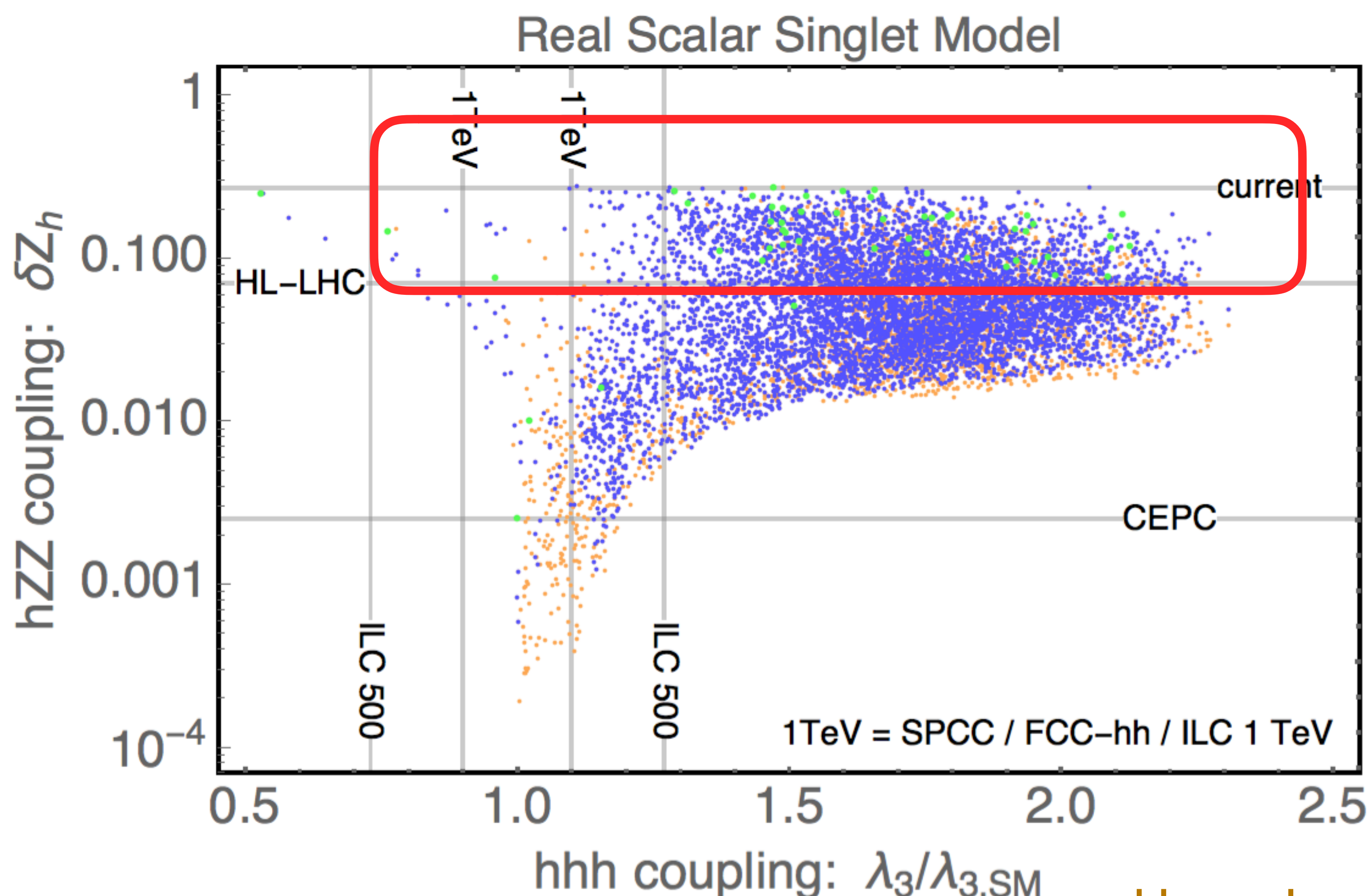
$$\text{EC}: \quad N^{\rm SV}_{\rm bkg} = \sigma_{\rm j}\mathcal{L}_{\rm int}\epsilon^{\rm EC}_{\rm trig}\epsilon^{j,\rm EC}_{\rm fake} \approx 1 \times 10^{11}$$

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

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

Probing EW phase transition



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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