New directions for LHC searches

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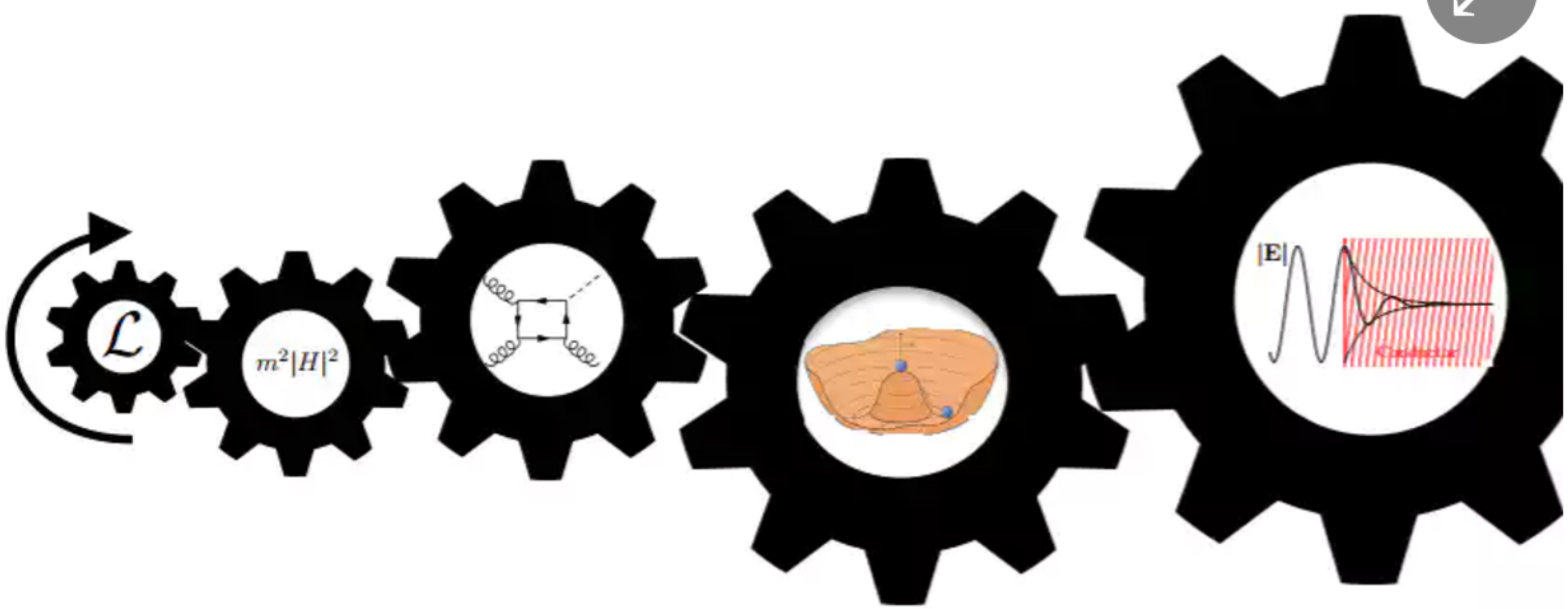
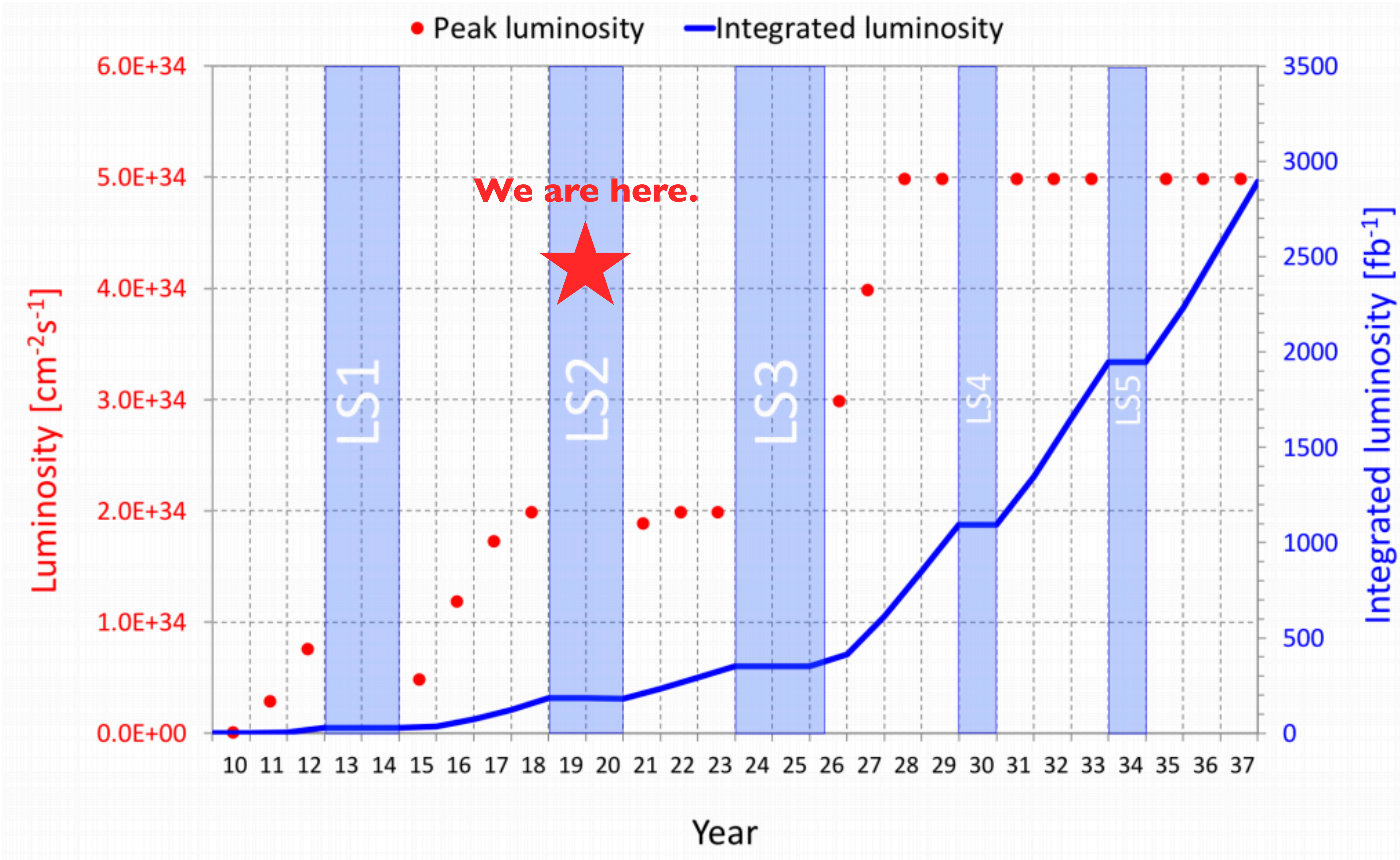
From gravity to the Higgs we're still waiting for new physics

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

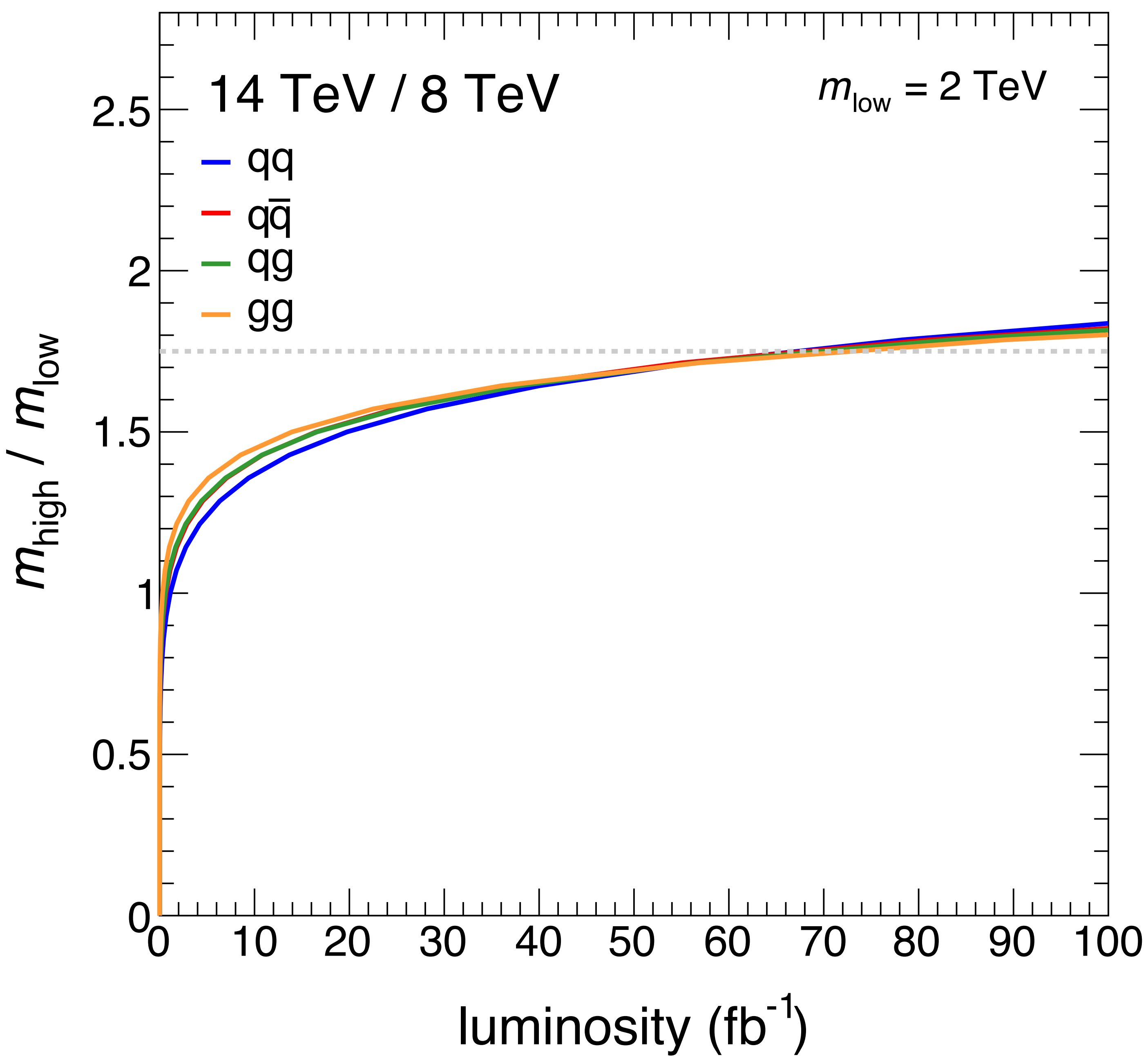


Peak luminosity
Integrated luminosity
We are here.
LS1
LS2
LS3
LS4
LS5
6.0E+34
5.0E+34
4.0E+34
3.0E+34
2.0E+34
1.0E+34
0.0E+00
Luminosity [cm-2s-1]
3500
3000
2500
2000
1500
1000
500
0
Integrated luminosity [fb-1]
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
Year

LHC is pushing ahead.

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

As data accumulates



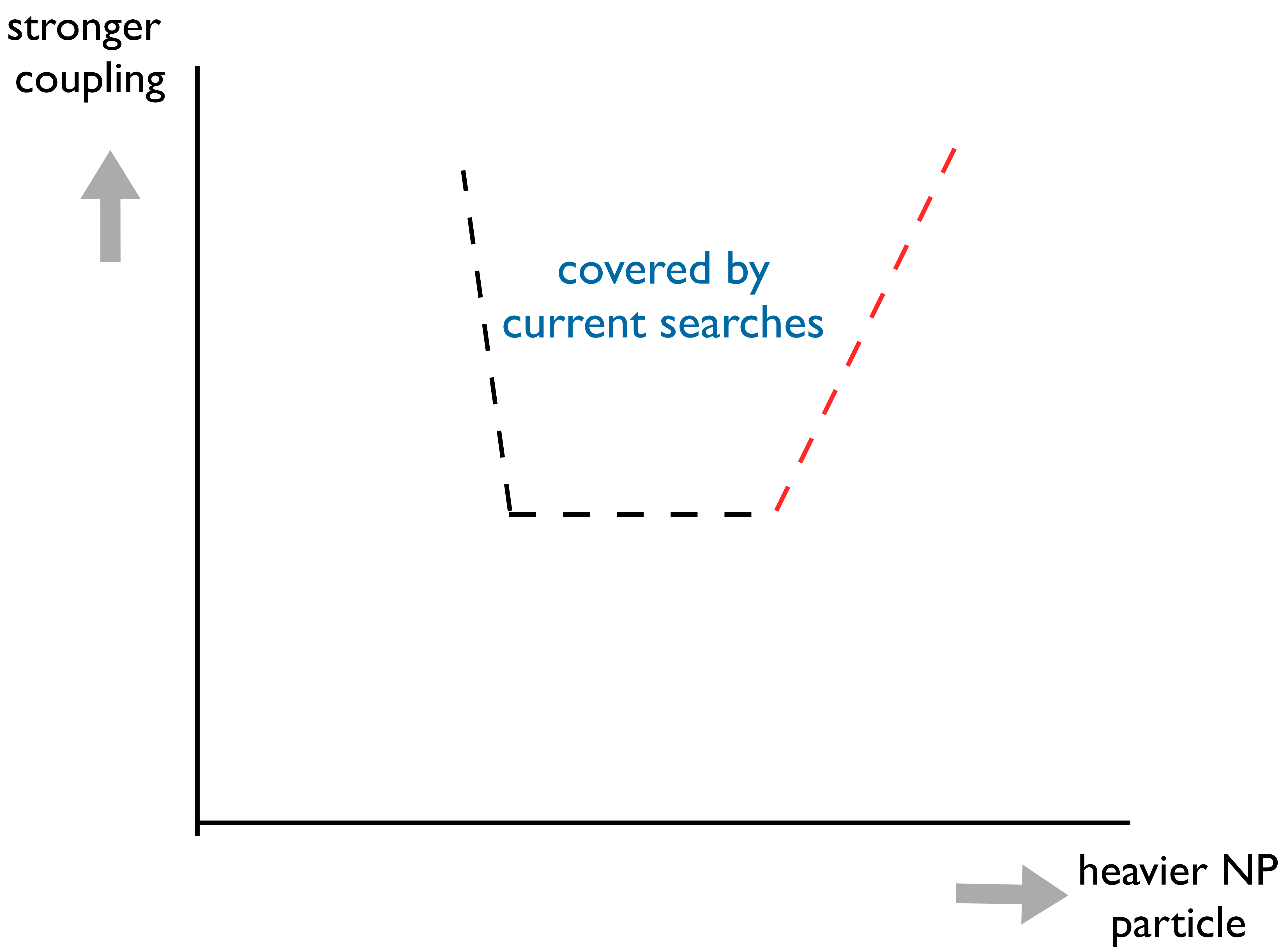
Rapid gain initial 10s-100 fb^{-1}, slow improvements afterwards.

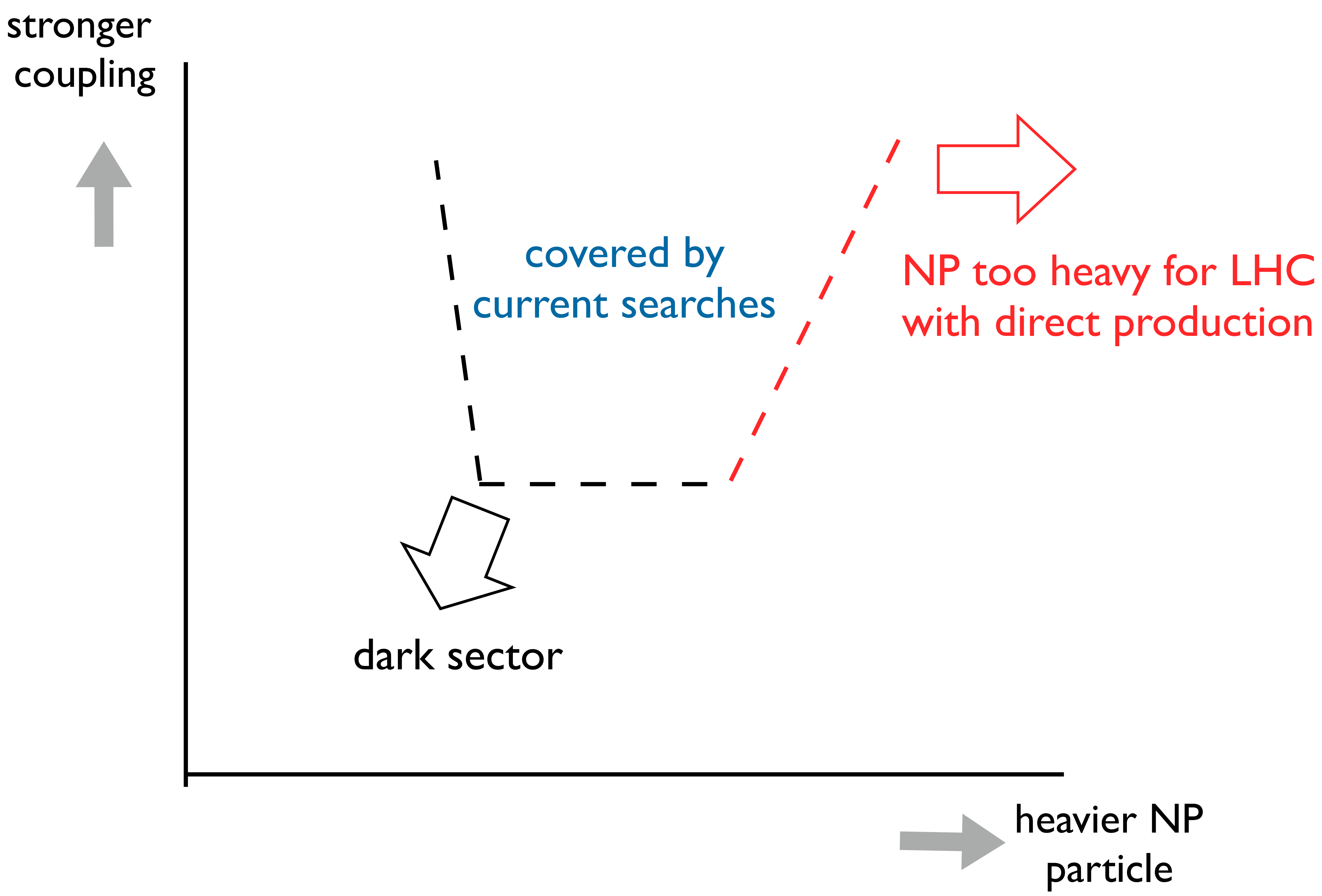
Progress will become slower, harder

New directions

The potential of a lot of data

- Very rare signal
  - E.g. dark sector, rare decays, ...
- Data can help with reducing systematics
  - Precision measurements.


stronger
coupling
covered by
current searches
heavier NP
particle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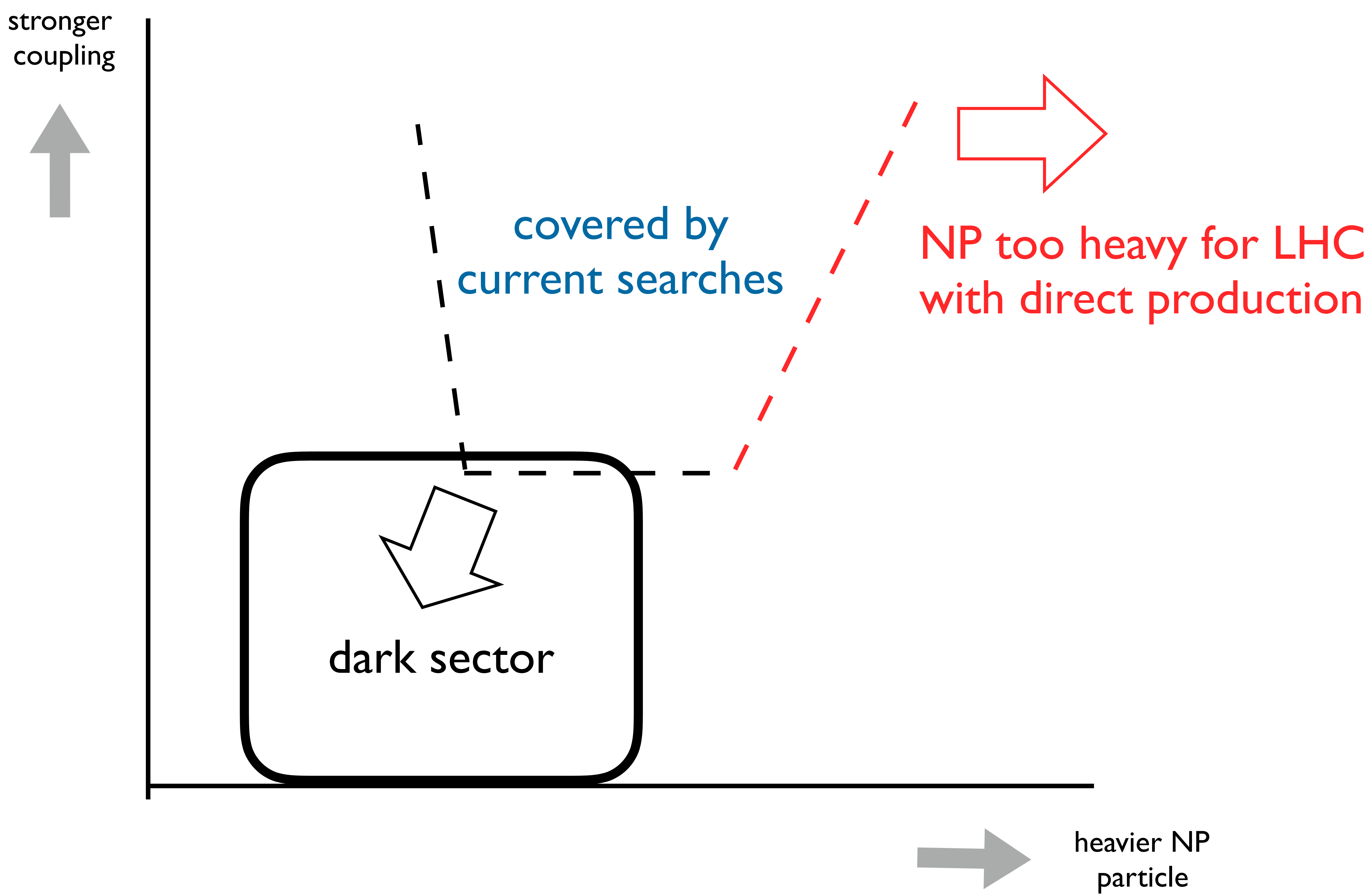
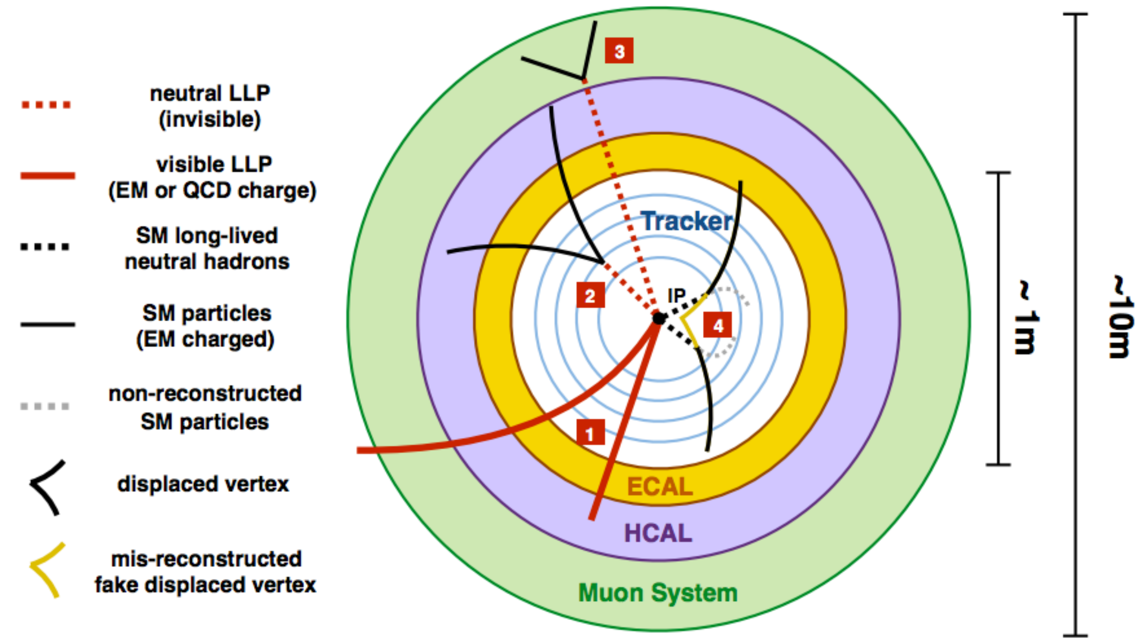

stronger
coupling
covered by
current searches
NP too heavy for LHC
with direct production
dark sector
heavier NP
particle

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.

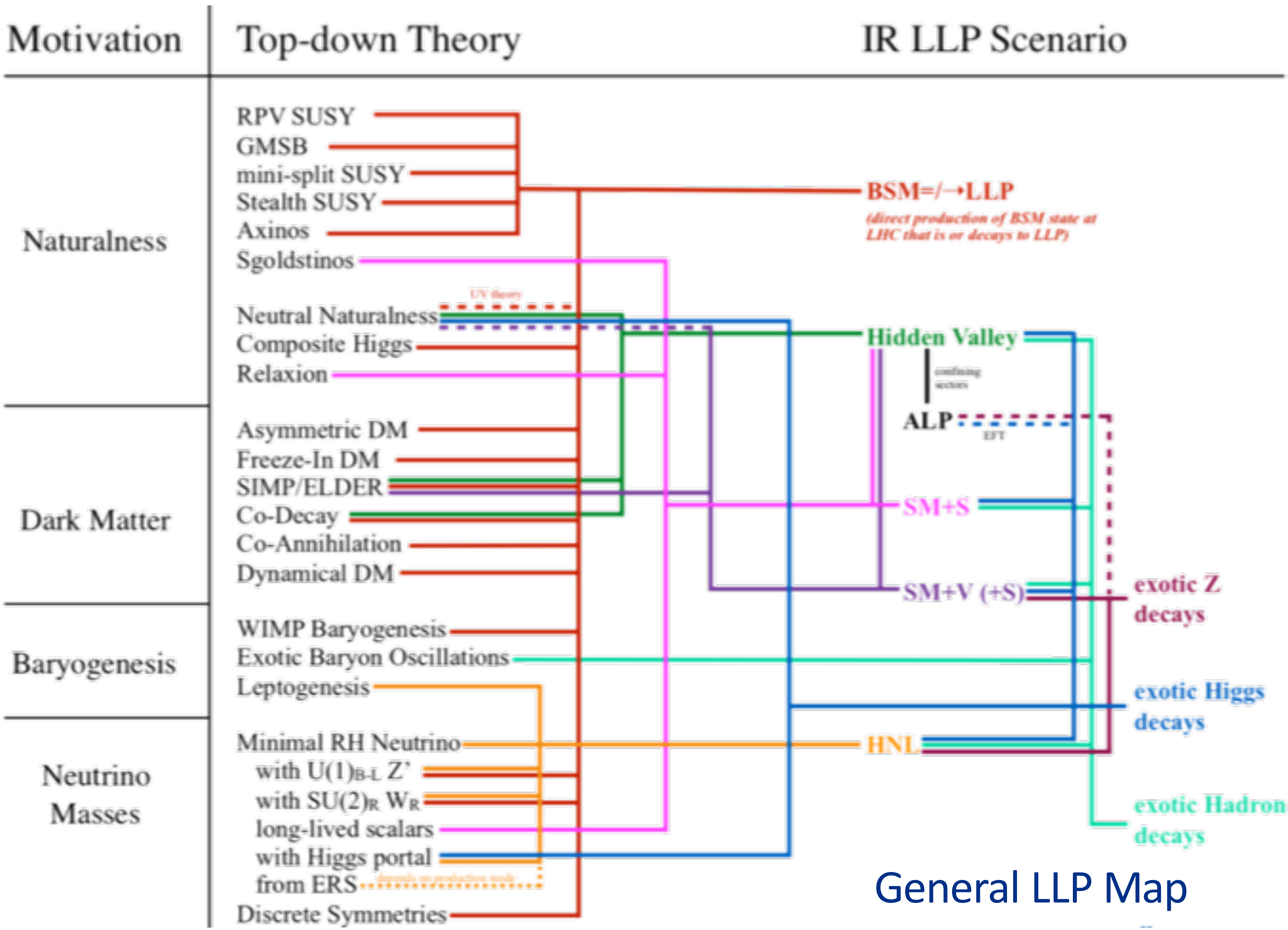


Curtin and Sundrum

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

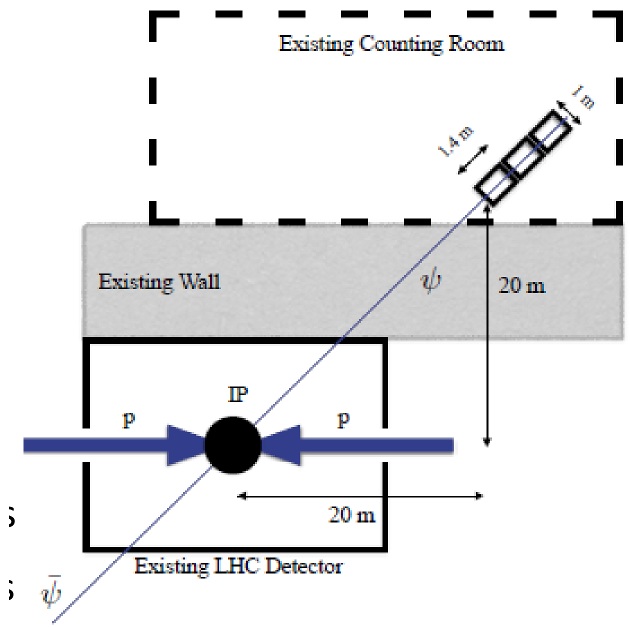
Generic constraint from cosmology: $\tau < 0.1$ s

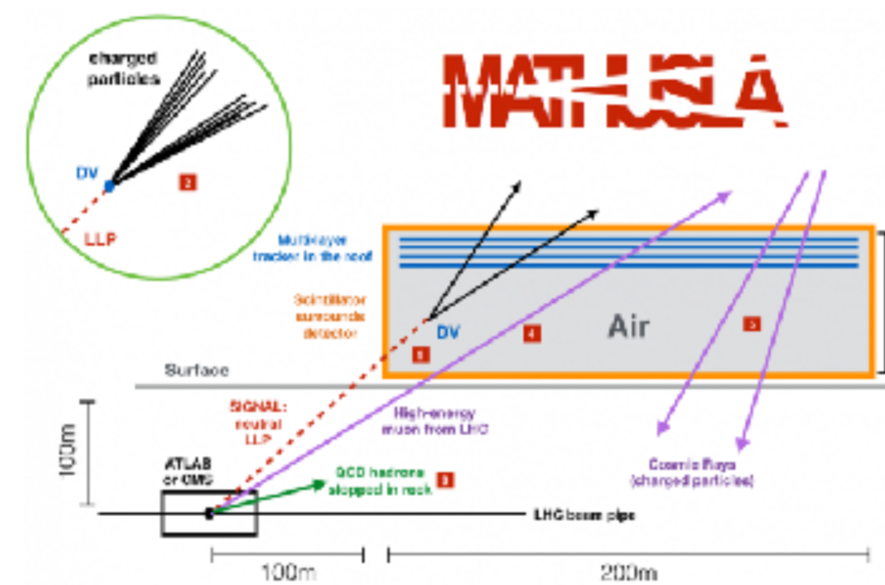
tons of models



General LLP Map

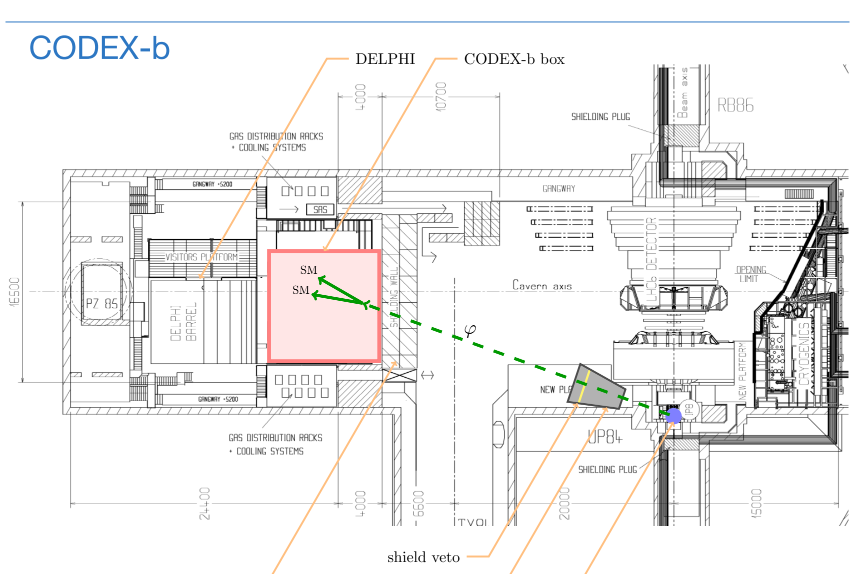
Far detectors

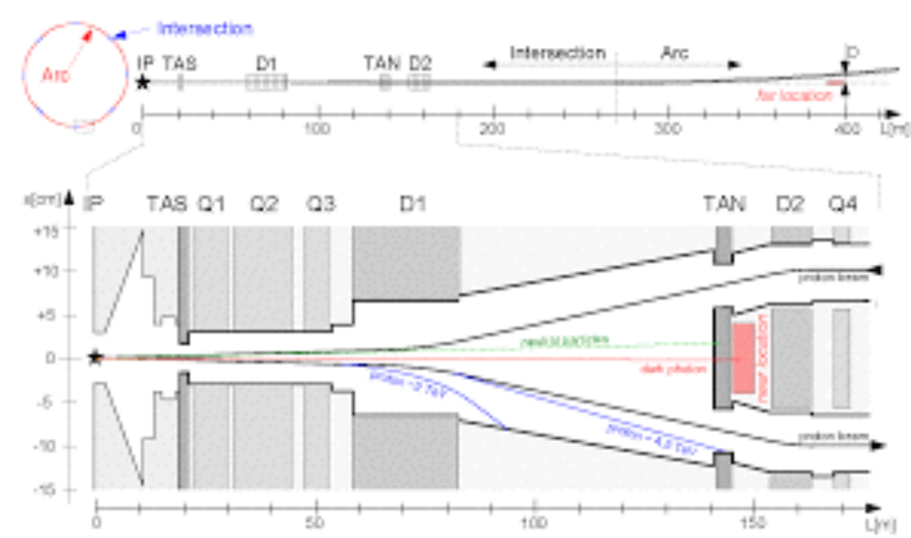




MATHUSLA

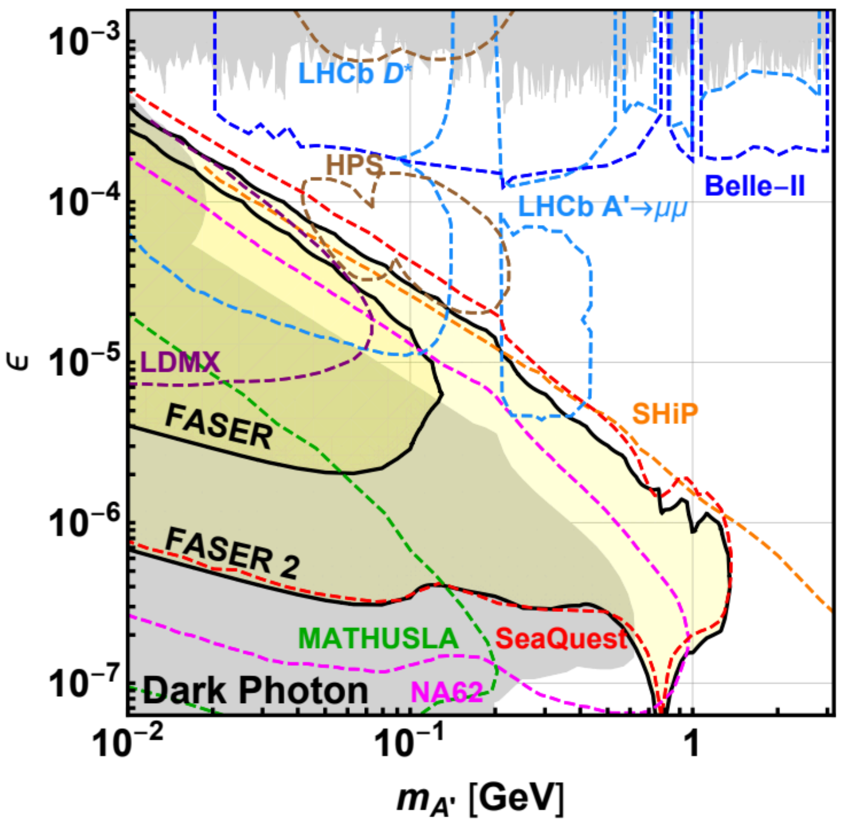
new detectors far
away from the interaction region

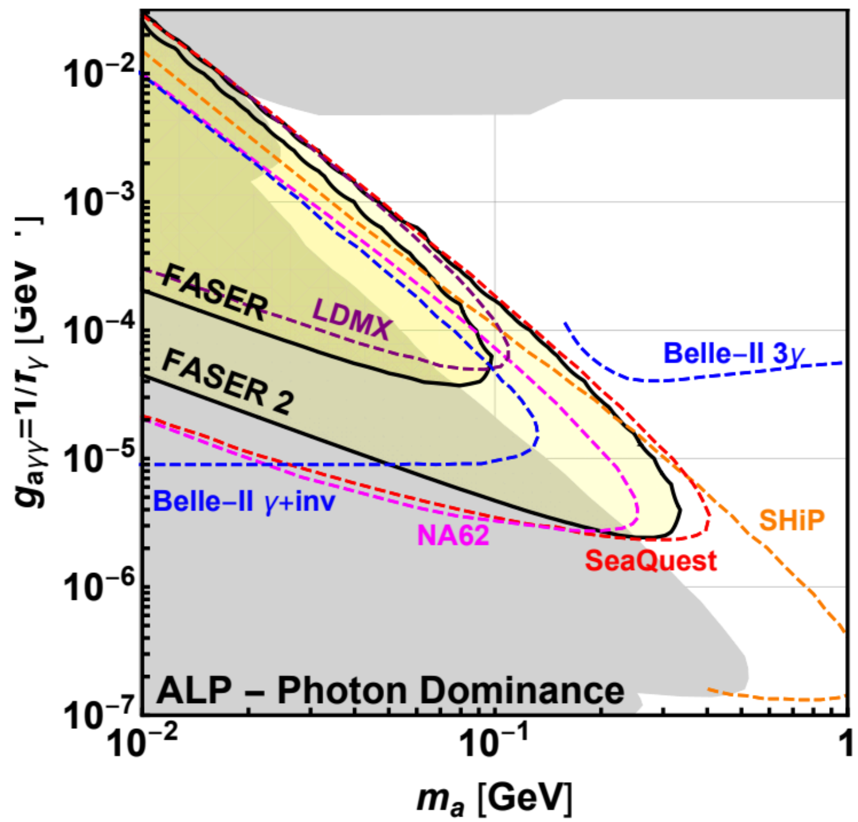


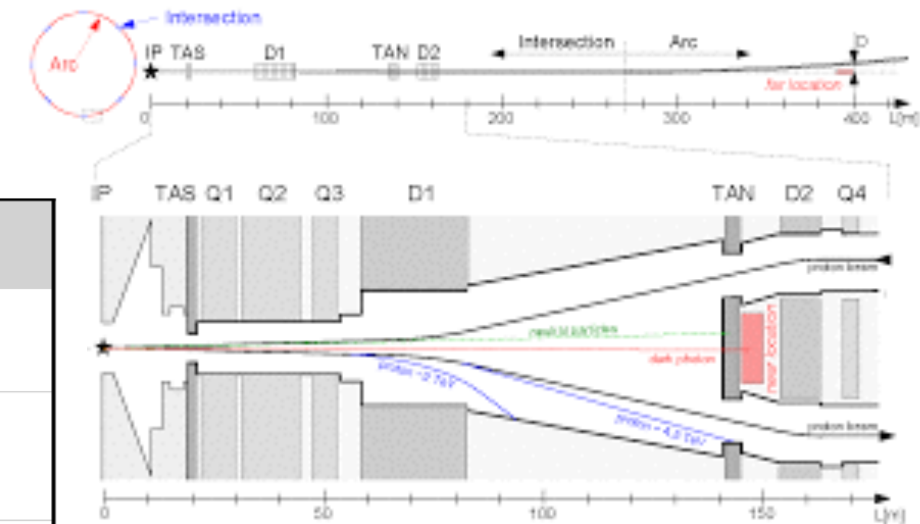


FASER

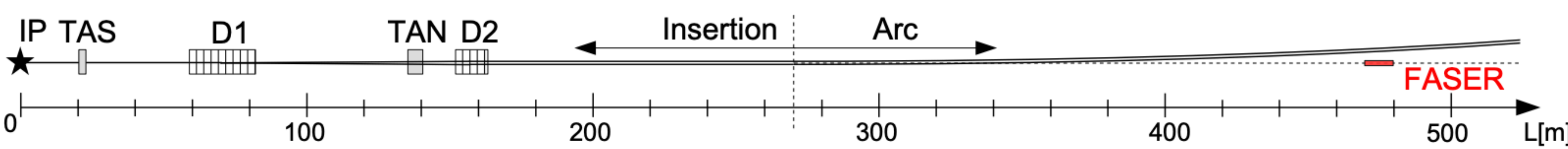
Far detectors

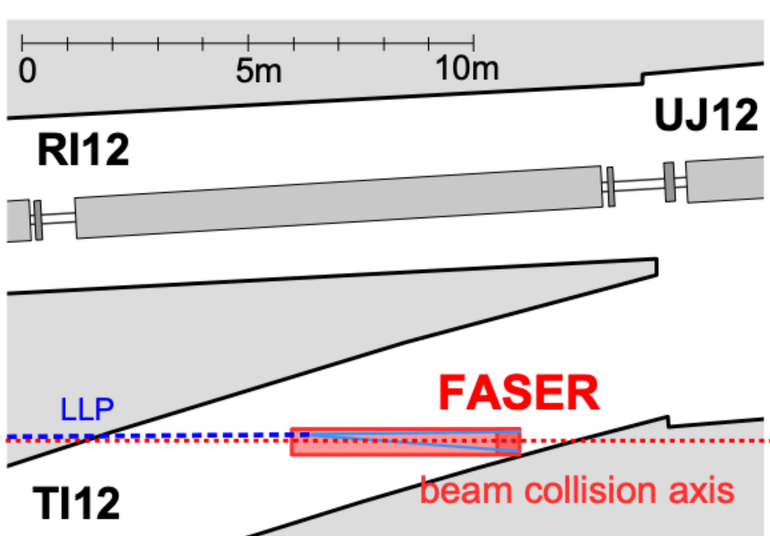


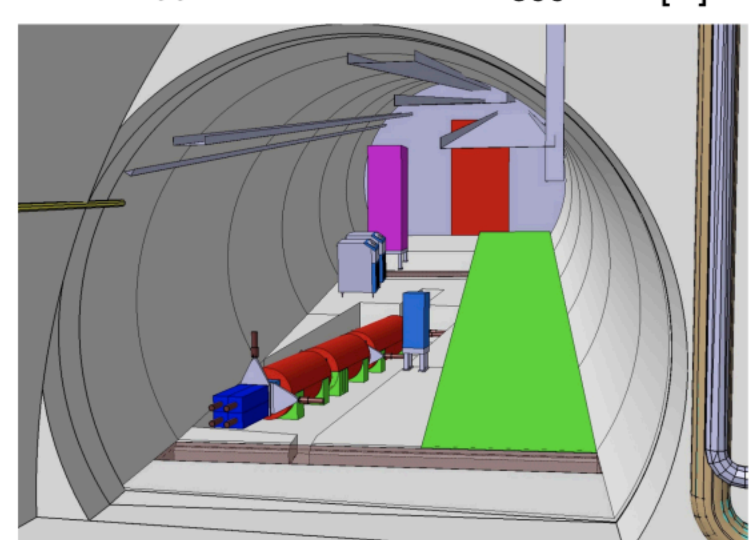




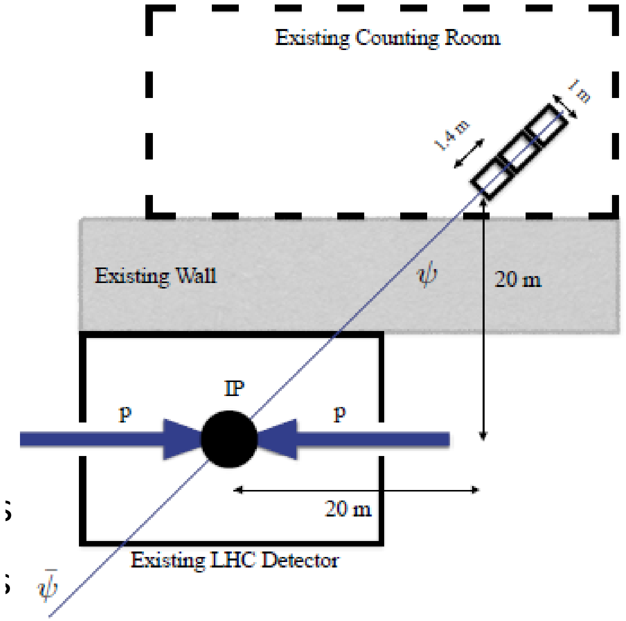
FASER

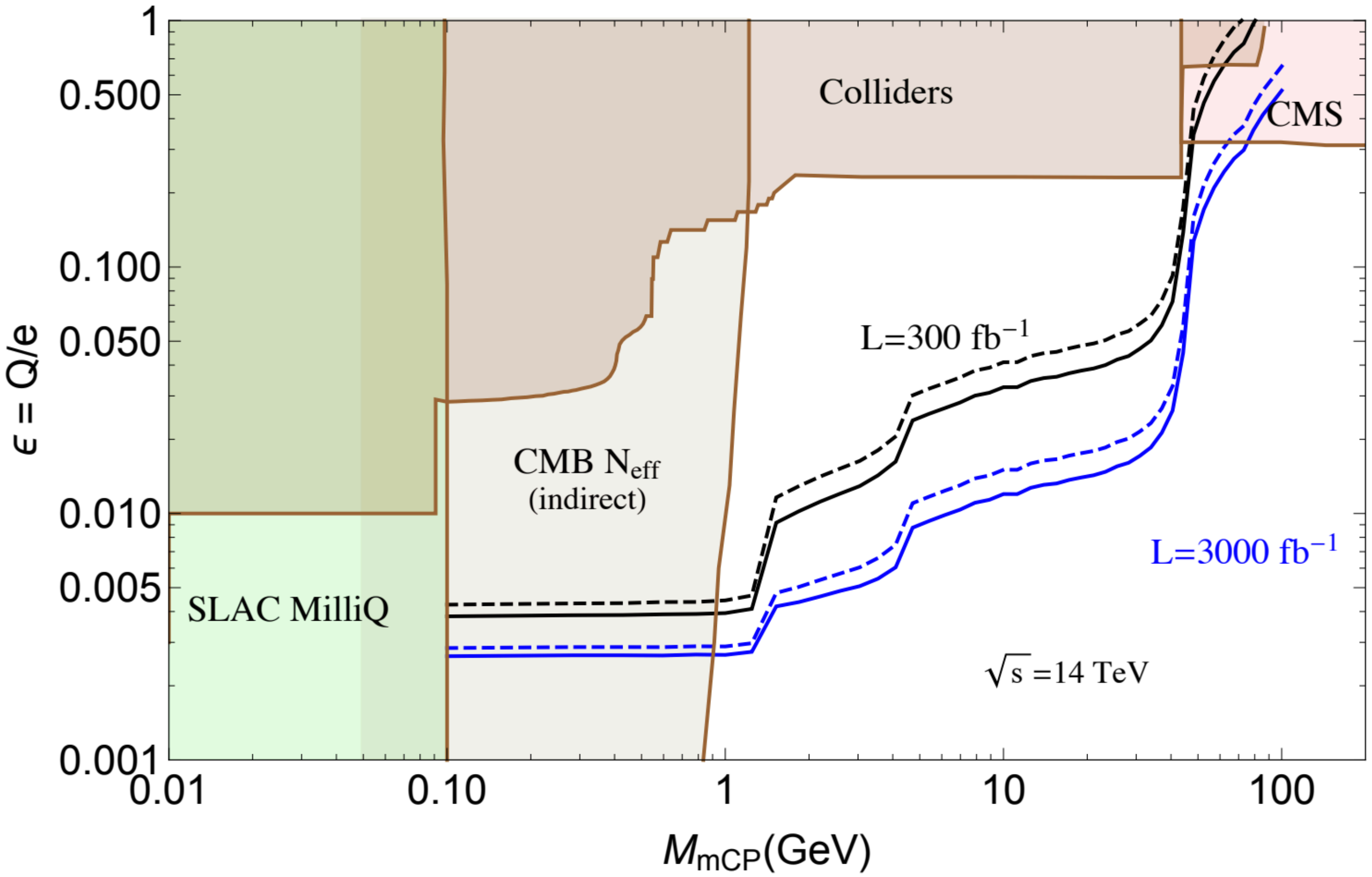






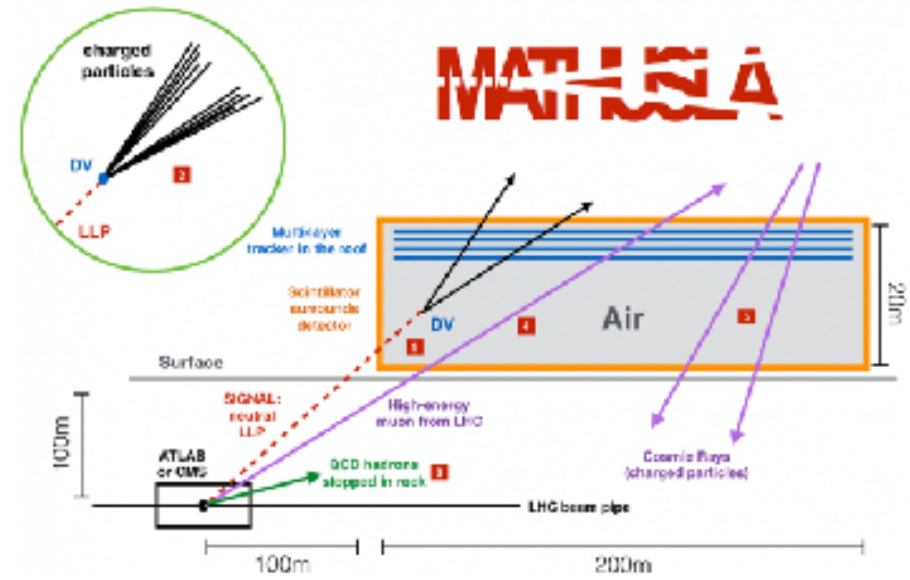
Far detectors



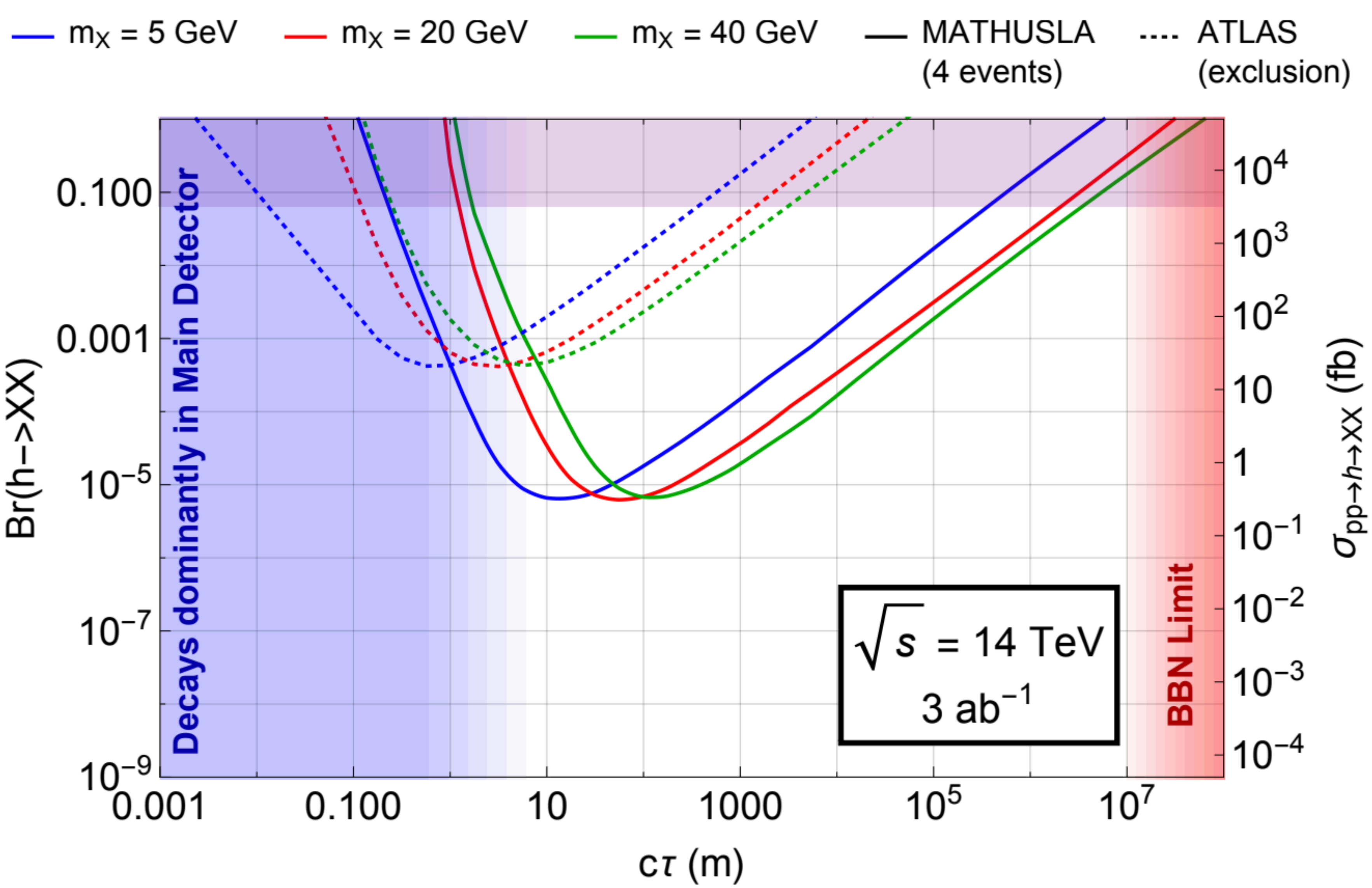


Far detectors

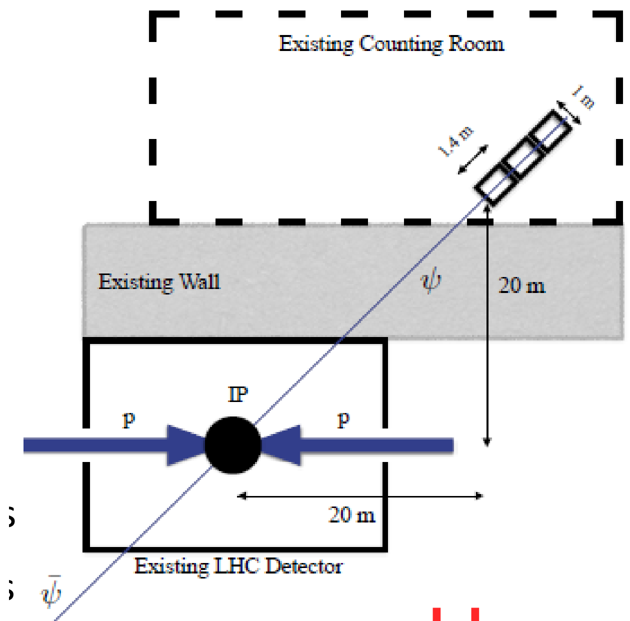
claim: zero background

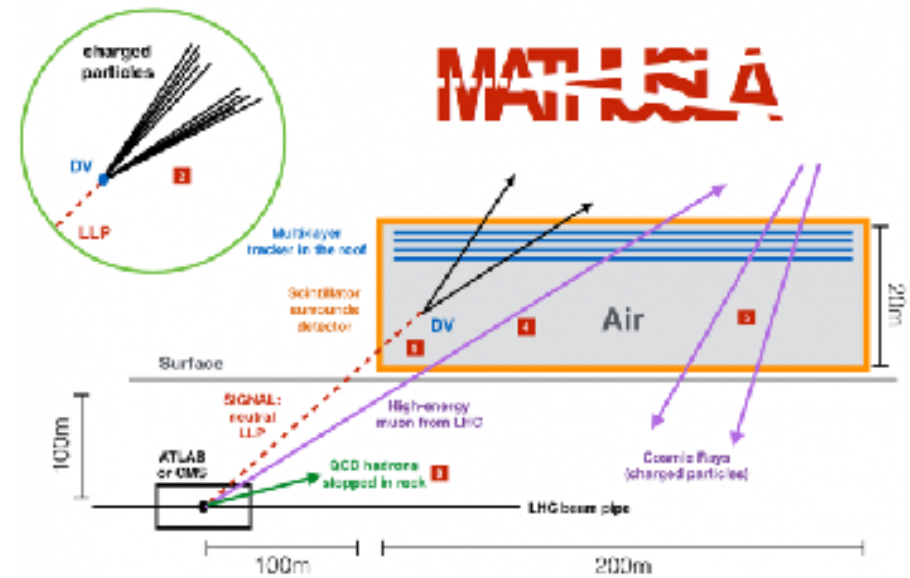


MATHUSLA



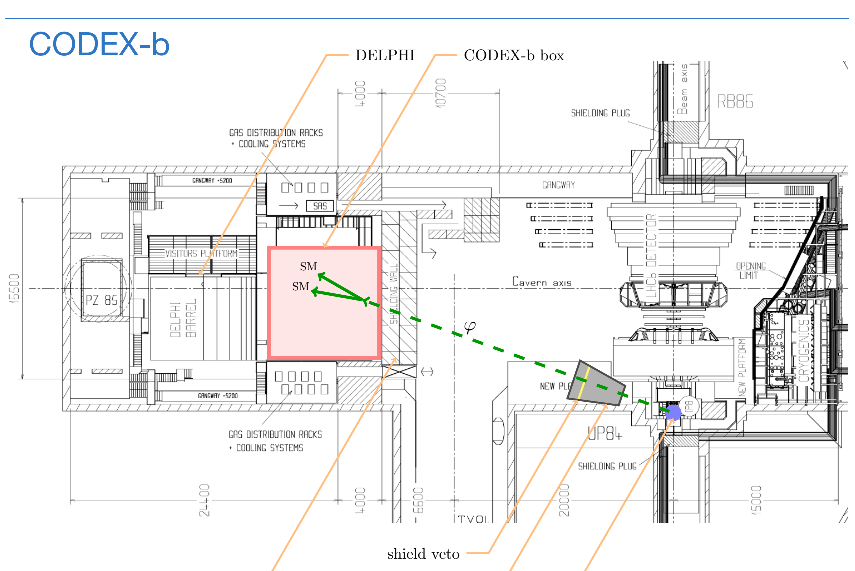
Far detectors

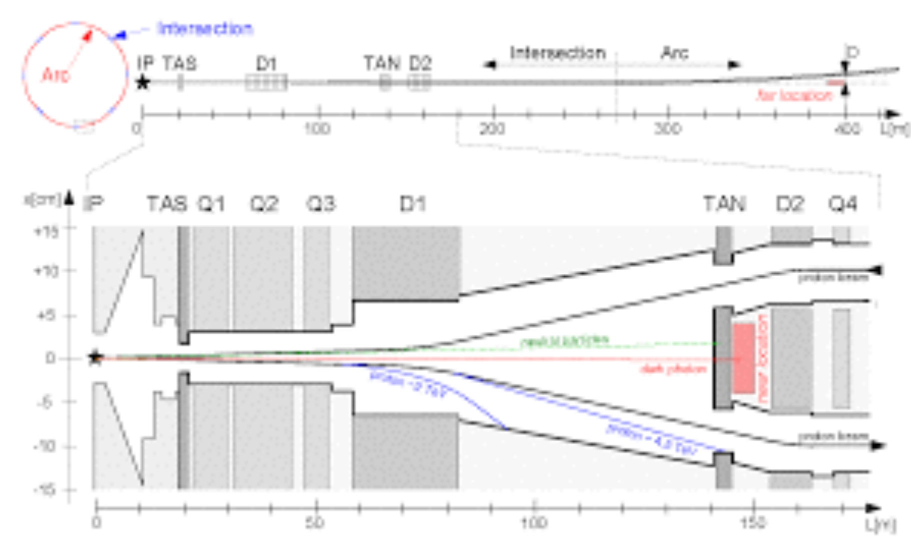




MATHUSLA

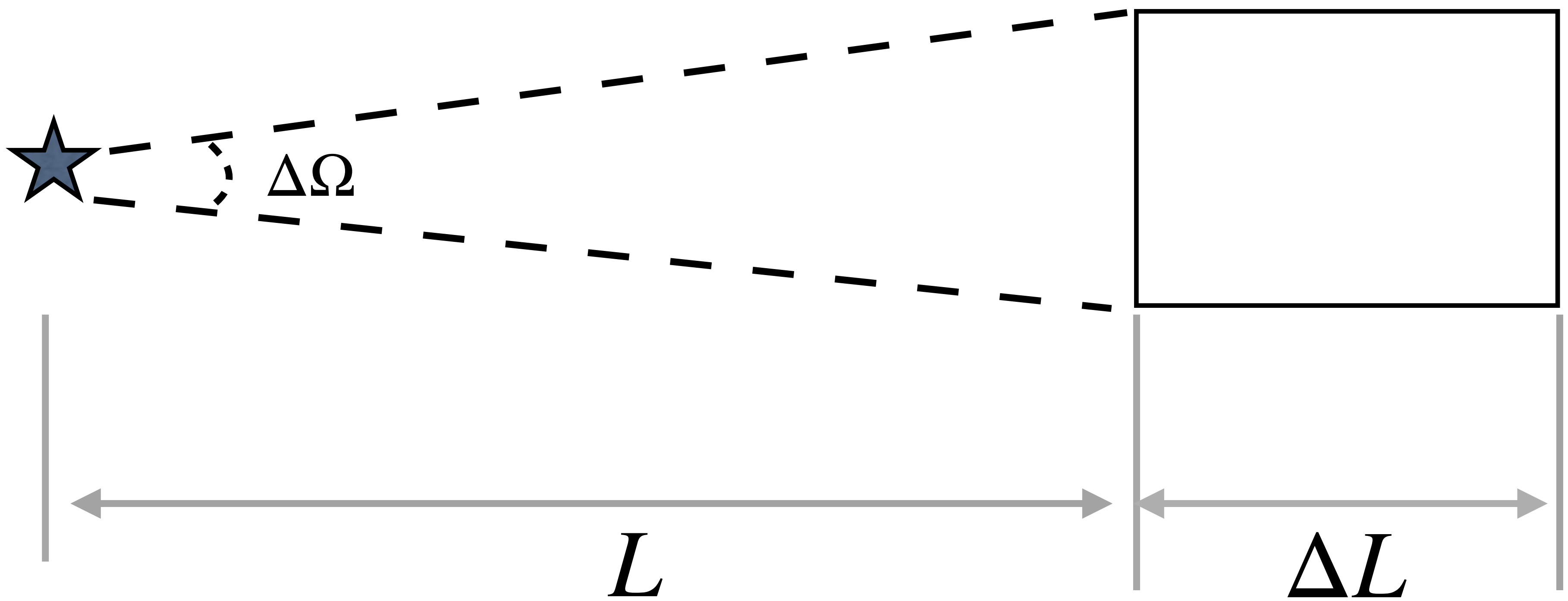
Have we fully optimized LLP searches at the interaction points ATLAS, CMS, LHCb?





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

Number of particle decayed within detector volume:

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

	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

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

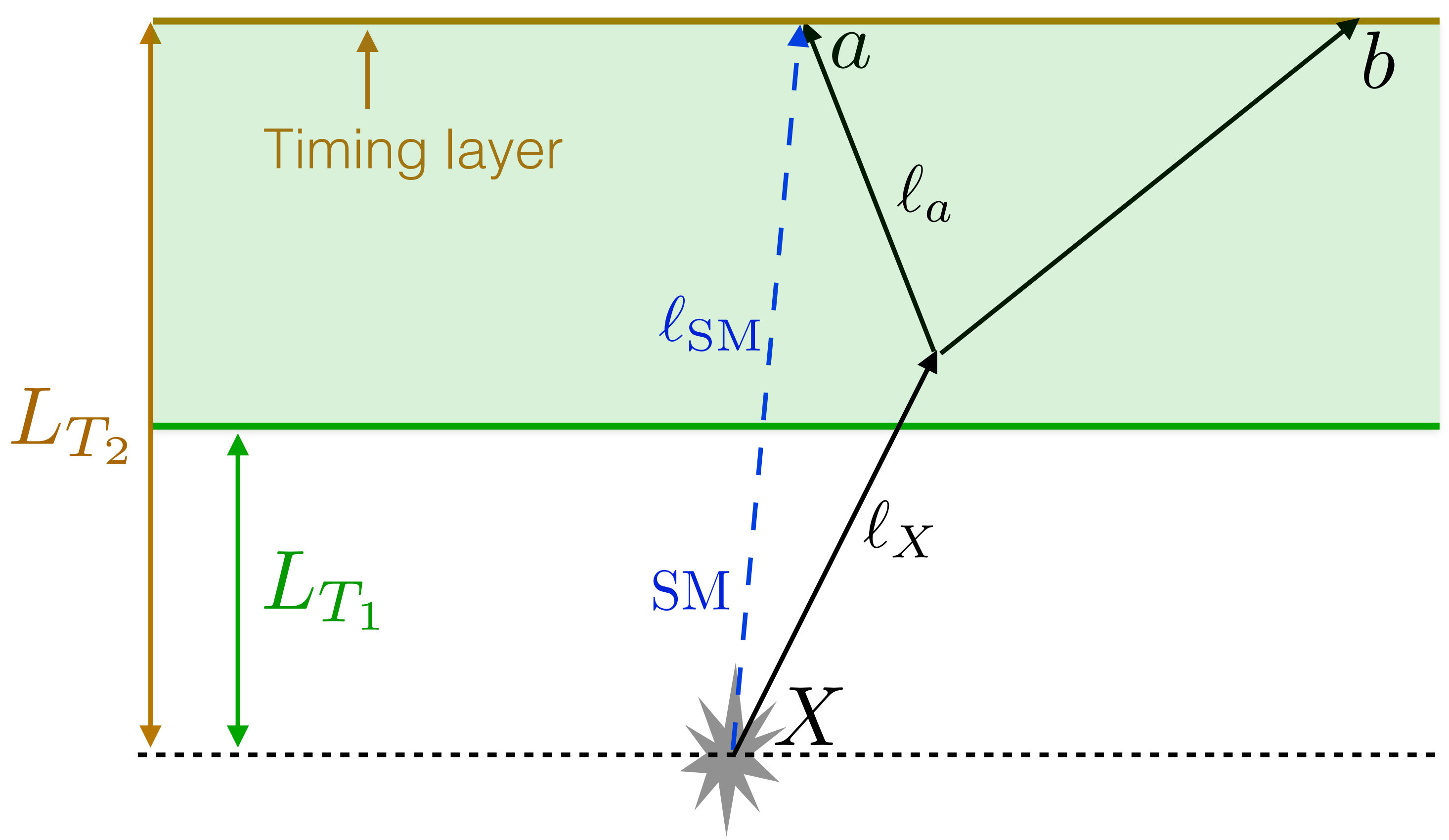
	ATLAS/CMS (LHCb)	Far detectors
$\Delta\Omega$	$\sim 4\pi$	< 0.1
ΔL	$1 - 10$ meters	$1 - 10$ meters
L	$1 - 10$ meters	$10 - 100$ meters

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

Room for new ideas: suppression bkgd near interaction point.

We played with one: using timing information

Time delay

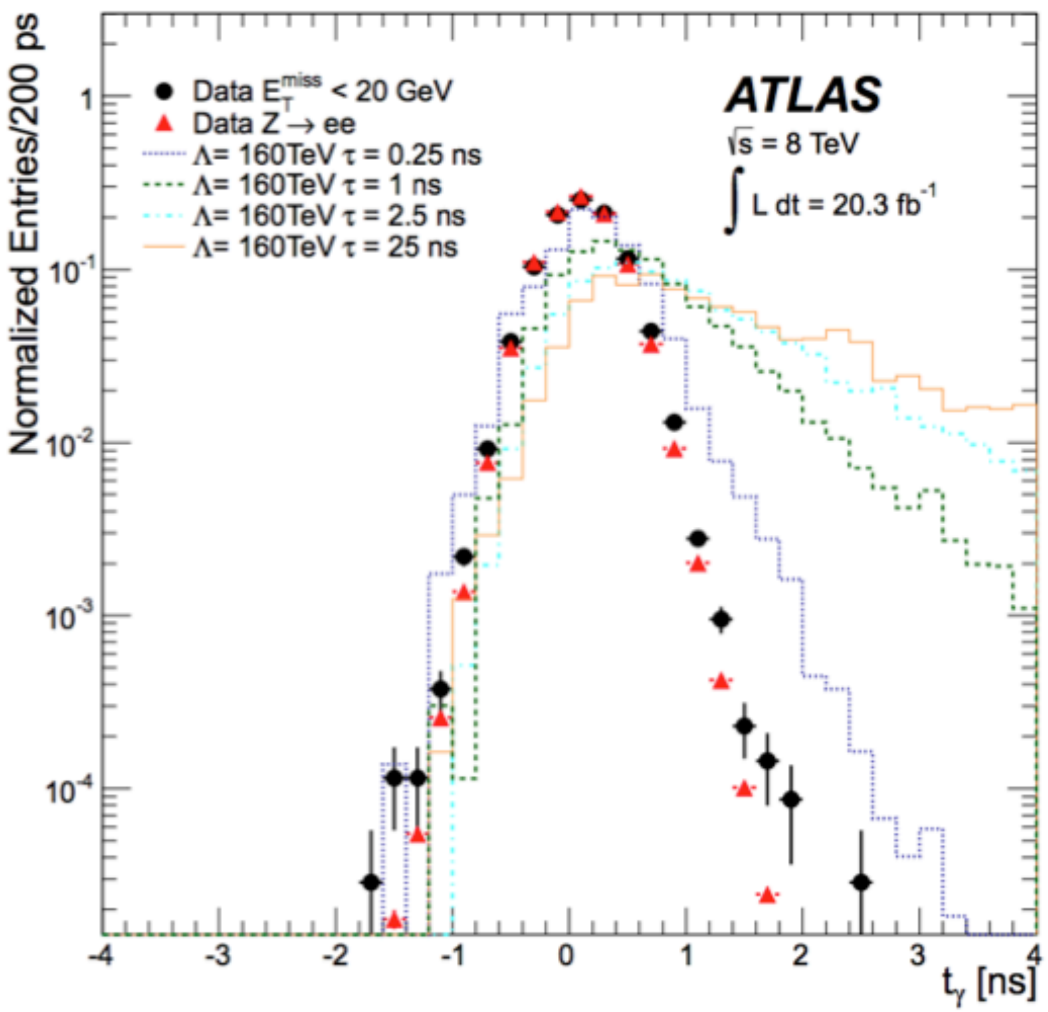


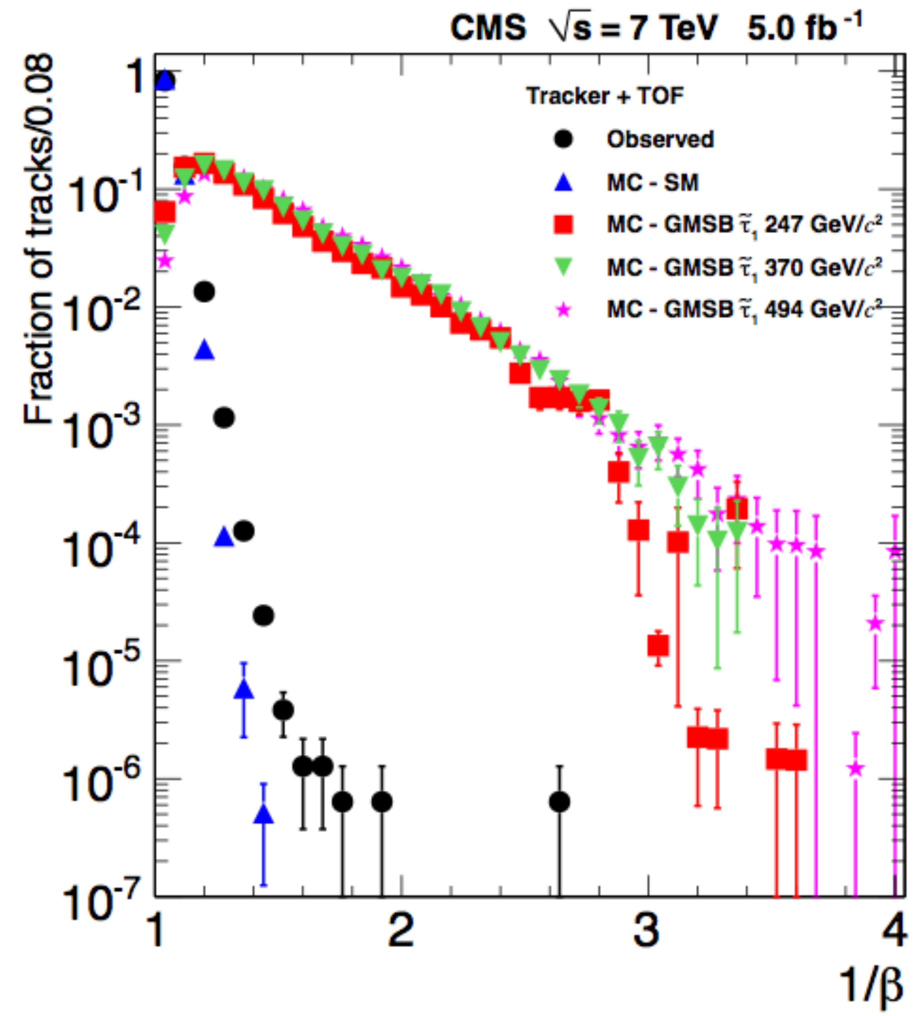
$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}} \qquad \beta_a \simeq \beta_{\rm SM} \simeq 1$$

Good for massive LLP produced with small or moderate boost

$$\beta_X < 1$$

Some timing info has been used

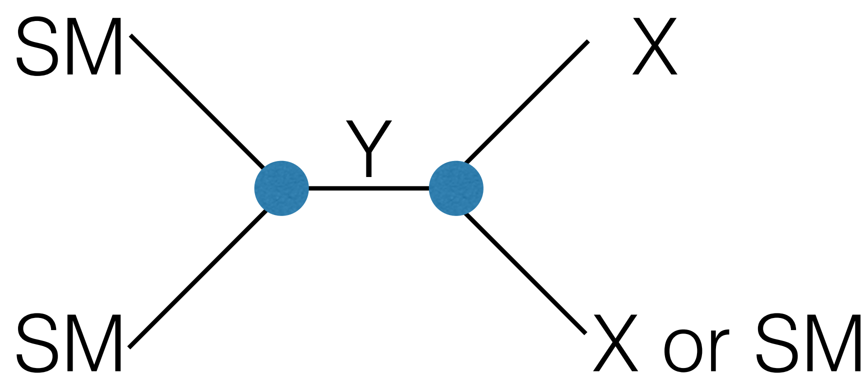


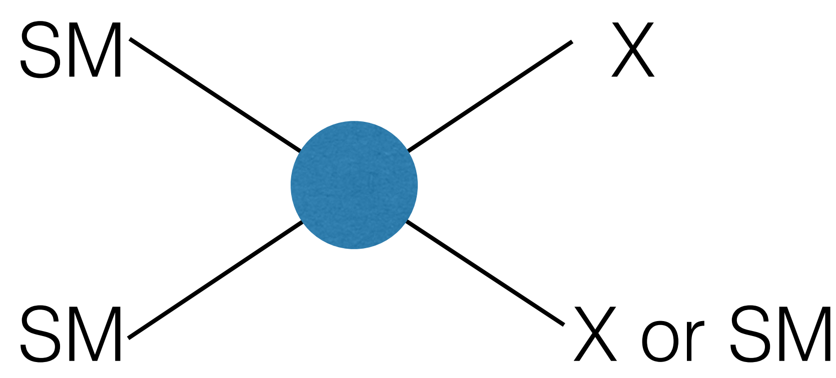


We hope to initiate more comprehensive studies, stimulate new ideas, broader application

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: $\gamma \sim 1$

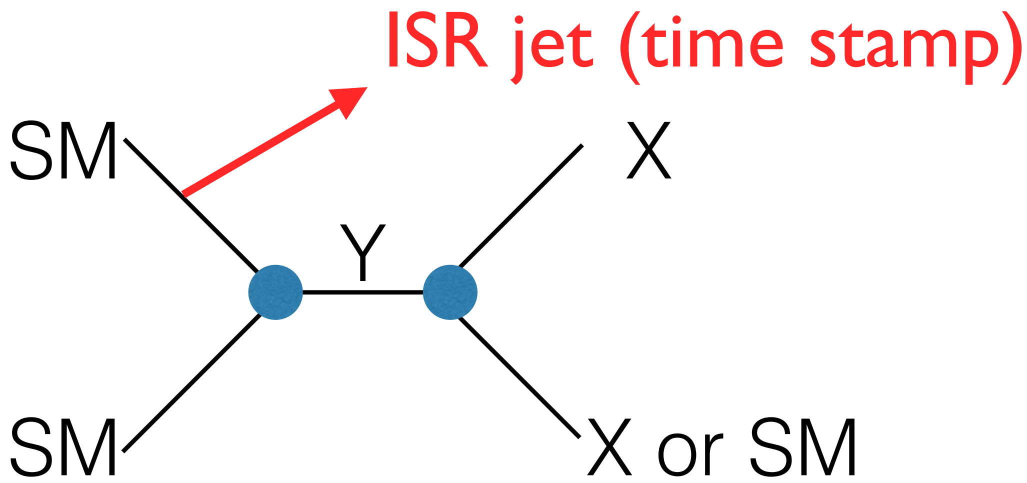
slow moving, sizable Δt

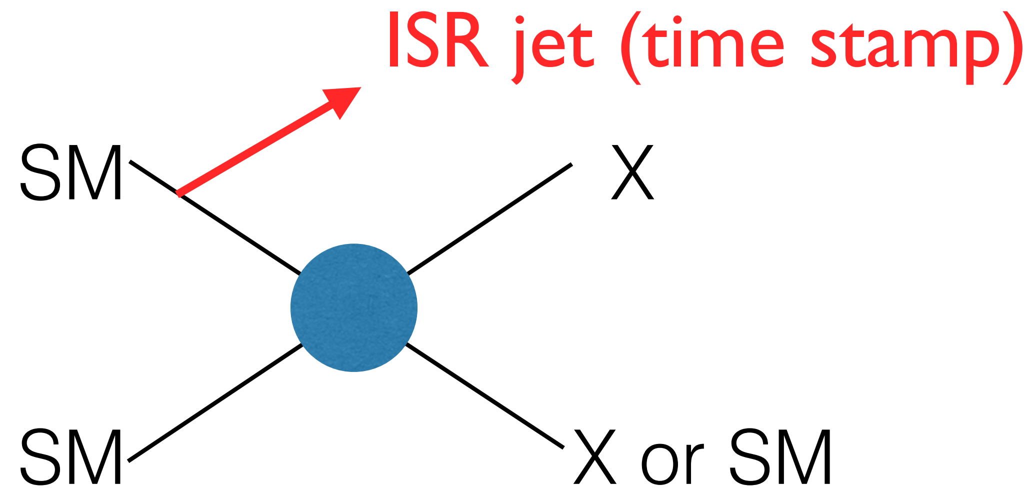
benchmark: SUSY

$X = \text{neutralino}$

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

Signal





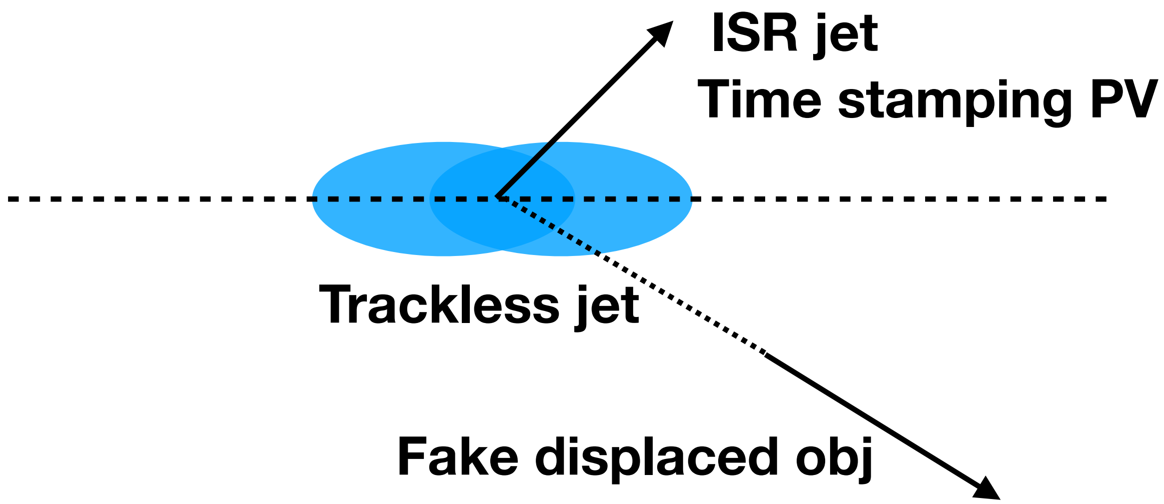
1. ISR jet provides the time for the hard collision

2. LLP decay before reaching timing layer.

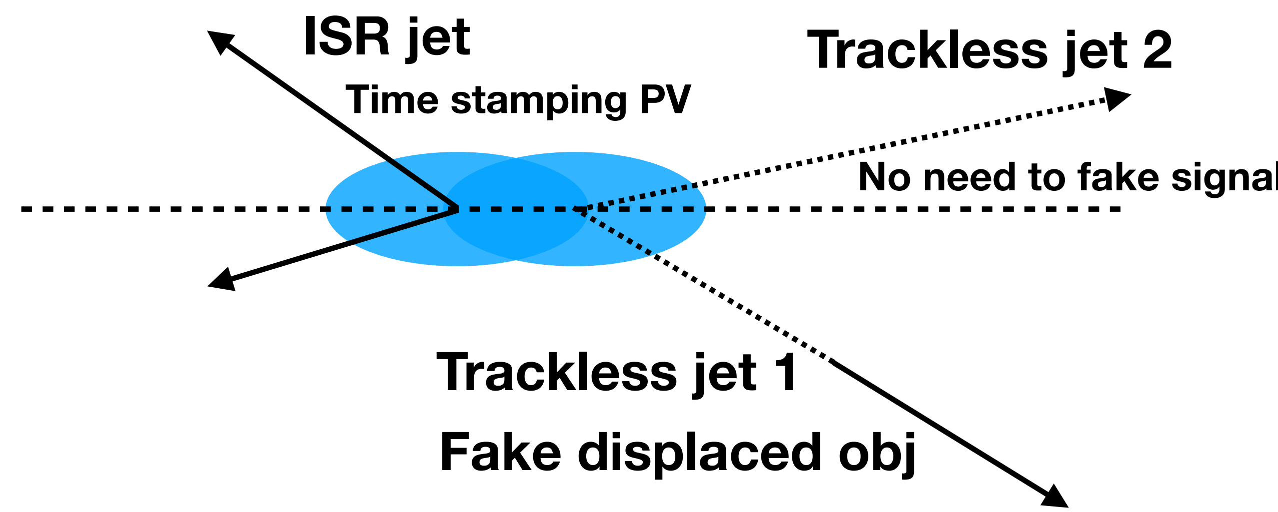
⇨ measurement of Δt

“physics” background

Same hard interaction



Pile up

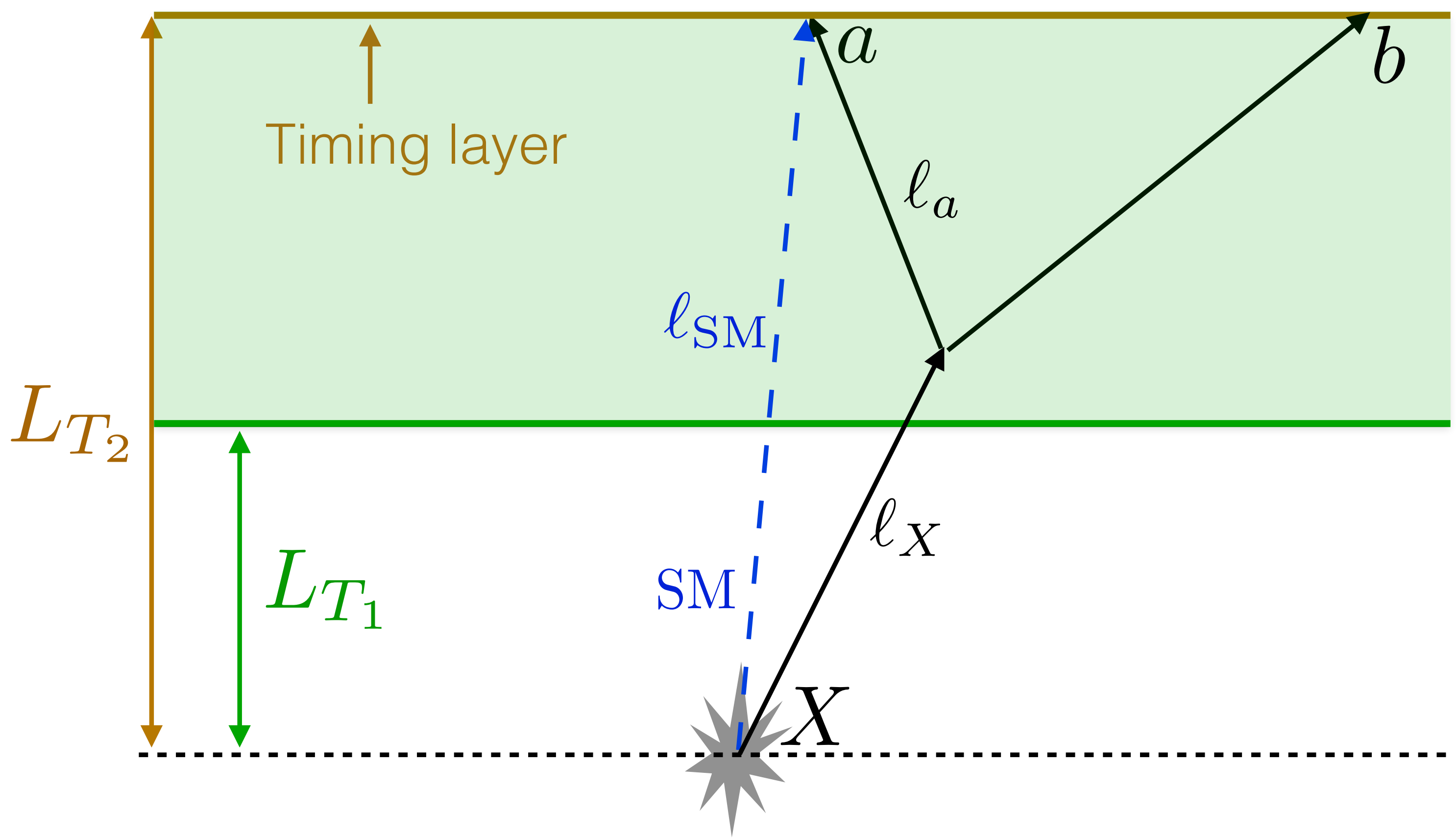


Time delay from
resolution of timing detector.

Time delay from
spread of the proton bunch

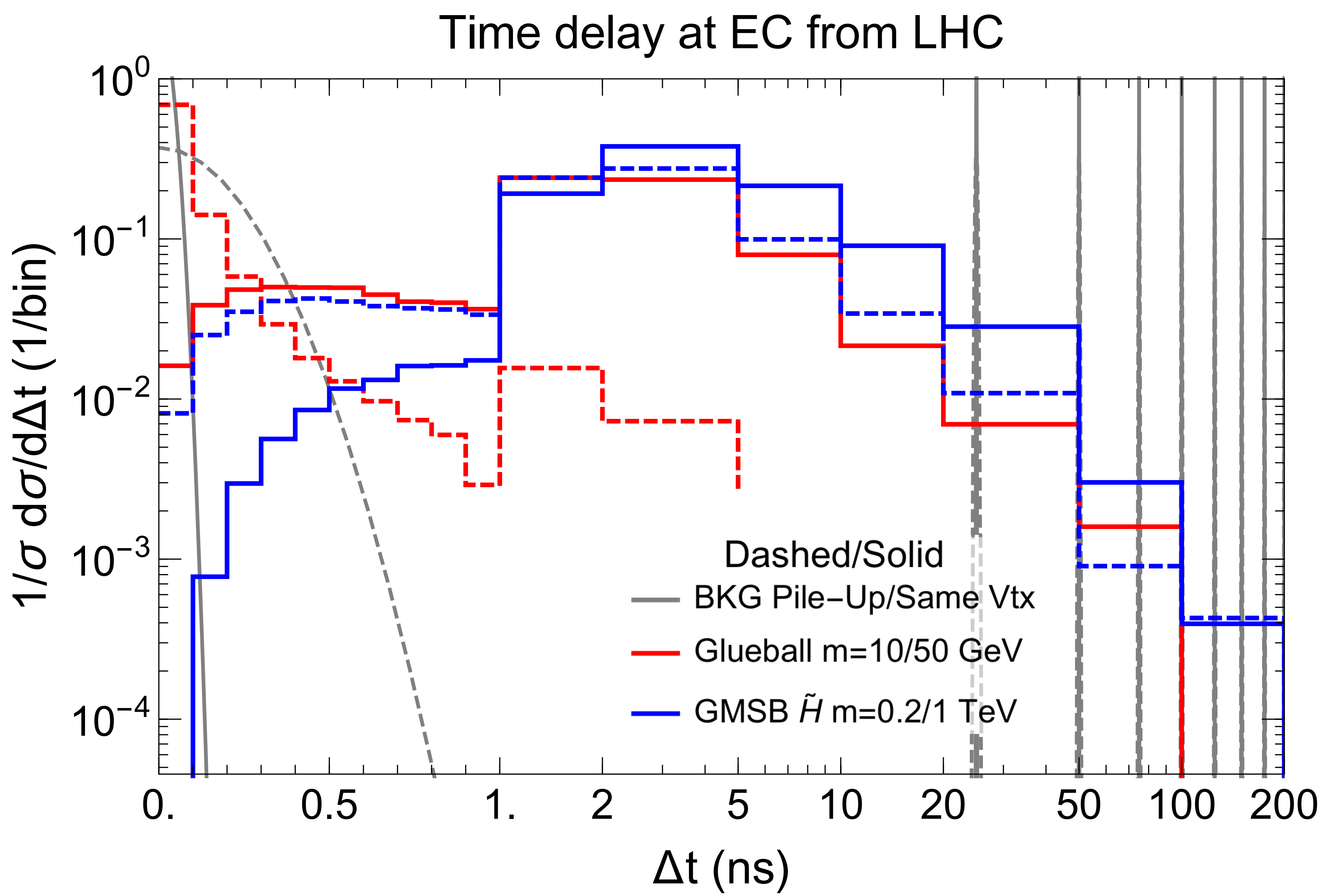
$\sim$ **190 ps**

Examples:



- **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)**

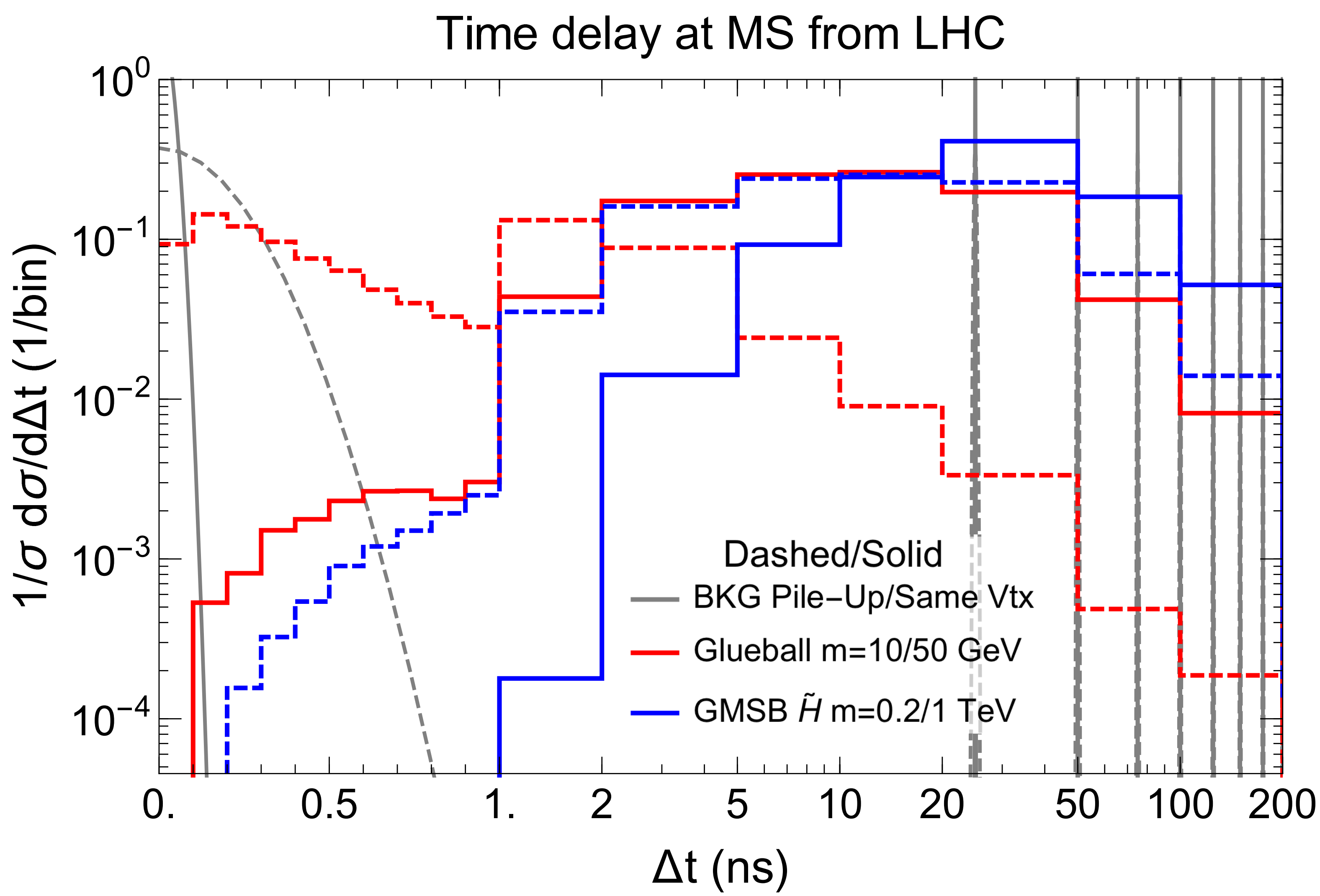
Search based on EC



After timing cut: $\Delta t > 1$ ns

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

Search based on MS



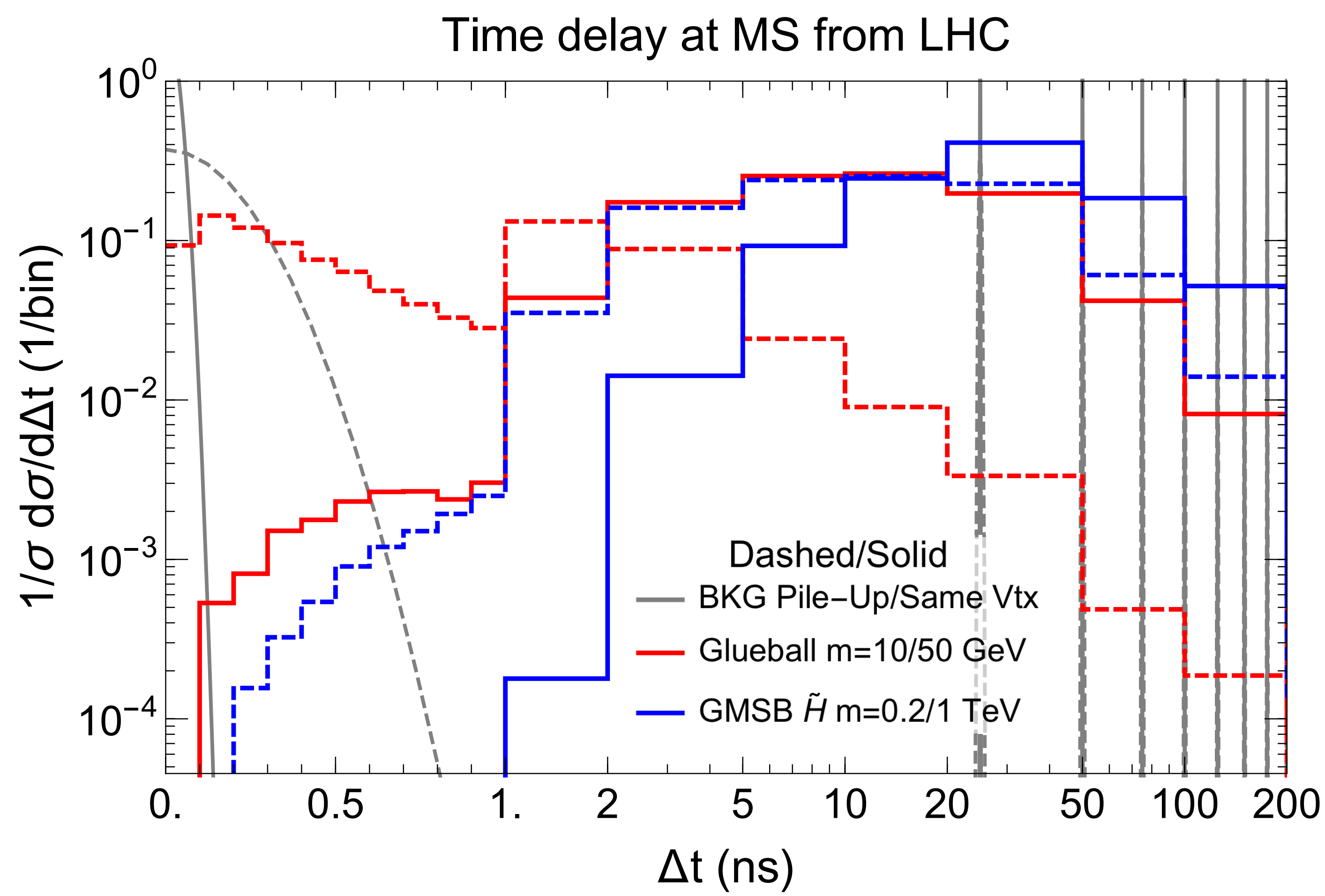
Pile up background smaller, shielded by HCAL etc.

Before timing cut: ~ 50

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

Further away, larger Δt for signal.

Search based on MS



Pile up background smaller, shielded by HCAL etc.

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

Further away, larger Δt for signal.

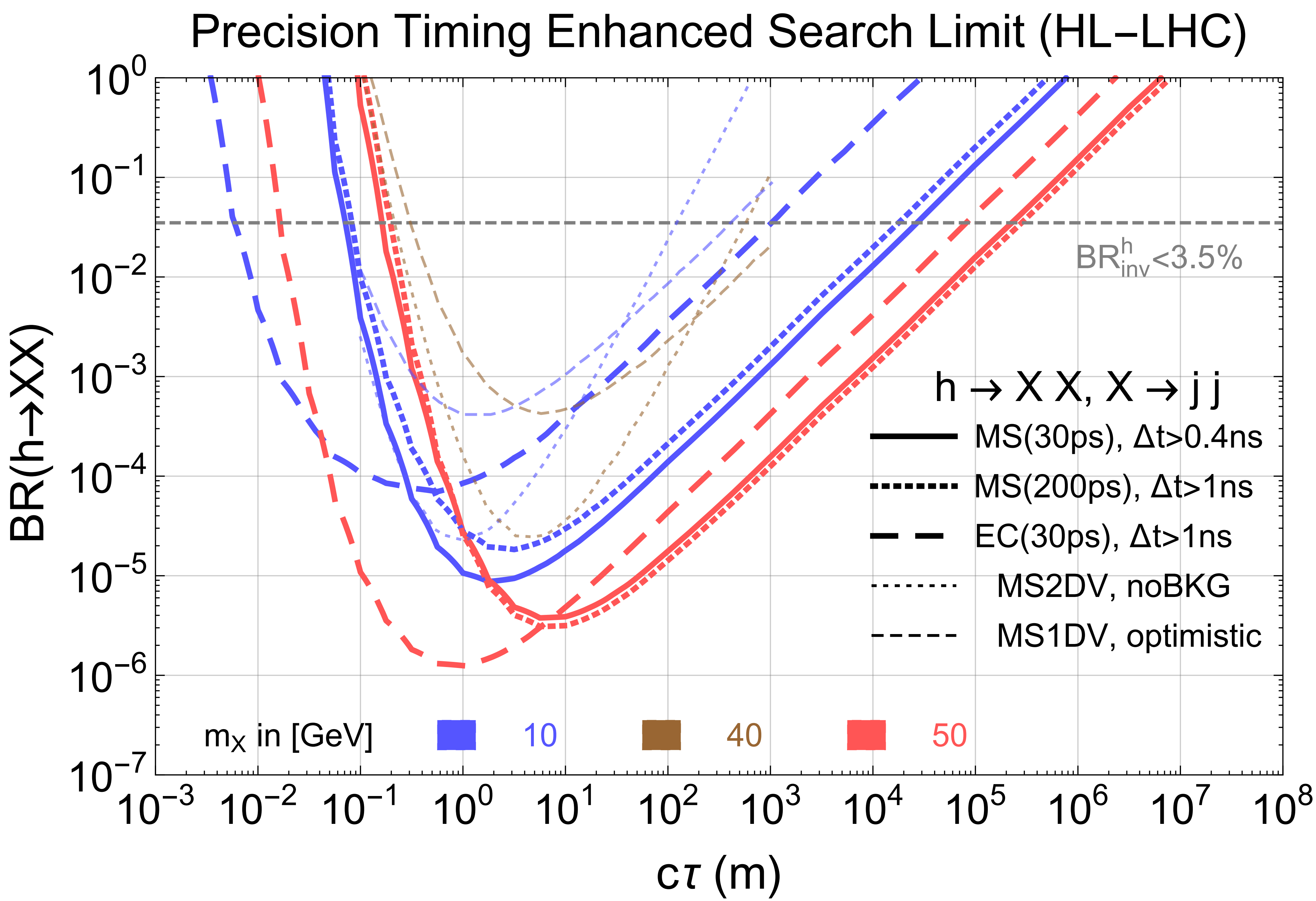
no need for super good timing resolution

$\delta t \sim 200$ ps

will do

Sensitivity to Higgs portal

Jia Liu, Zhen Liu, LTW

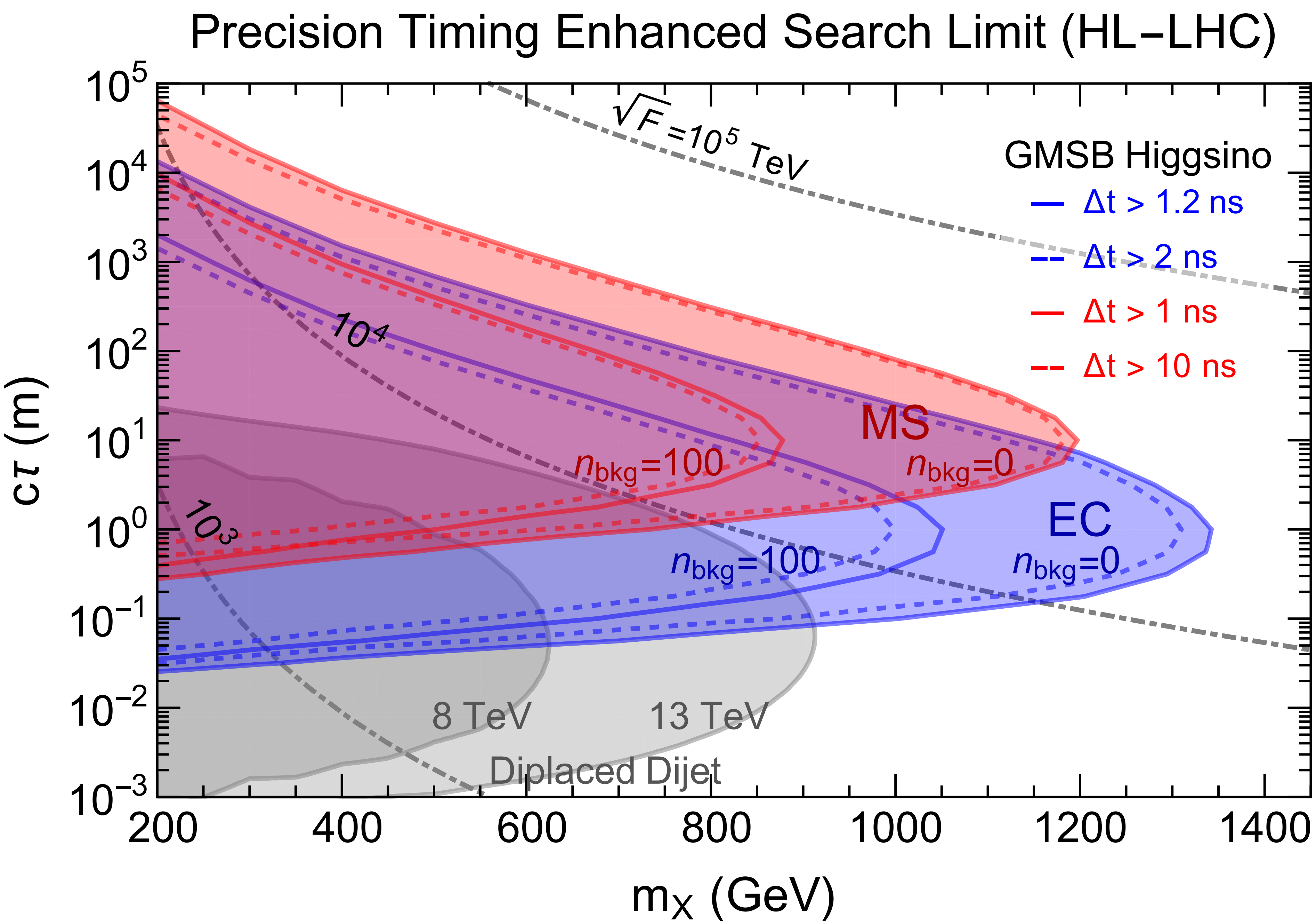


For example, for $\mathrm{BR}(h \to XX) \sim 10^{-3}$

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

Sensitivity to SUSY

Jia Liu, Zhen Liu, LTW



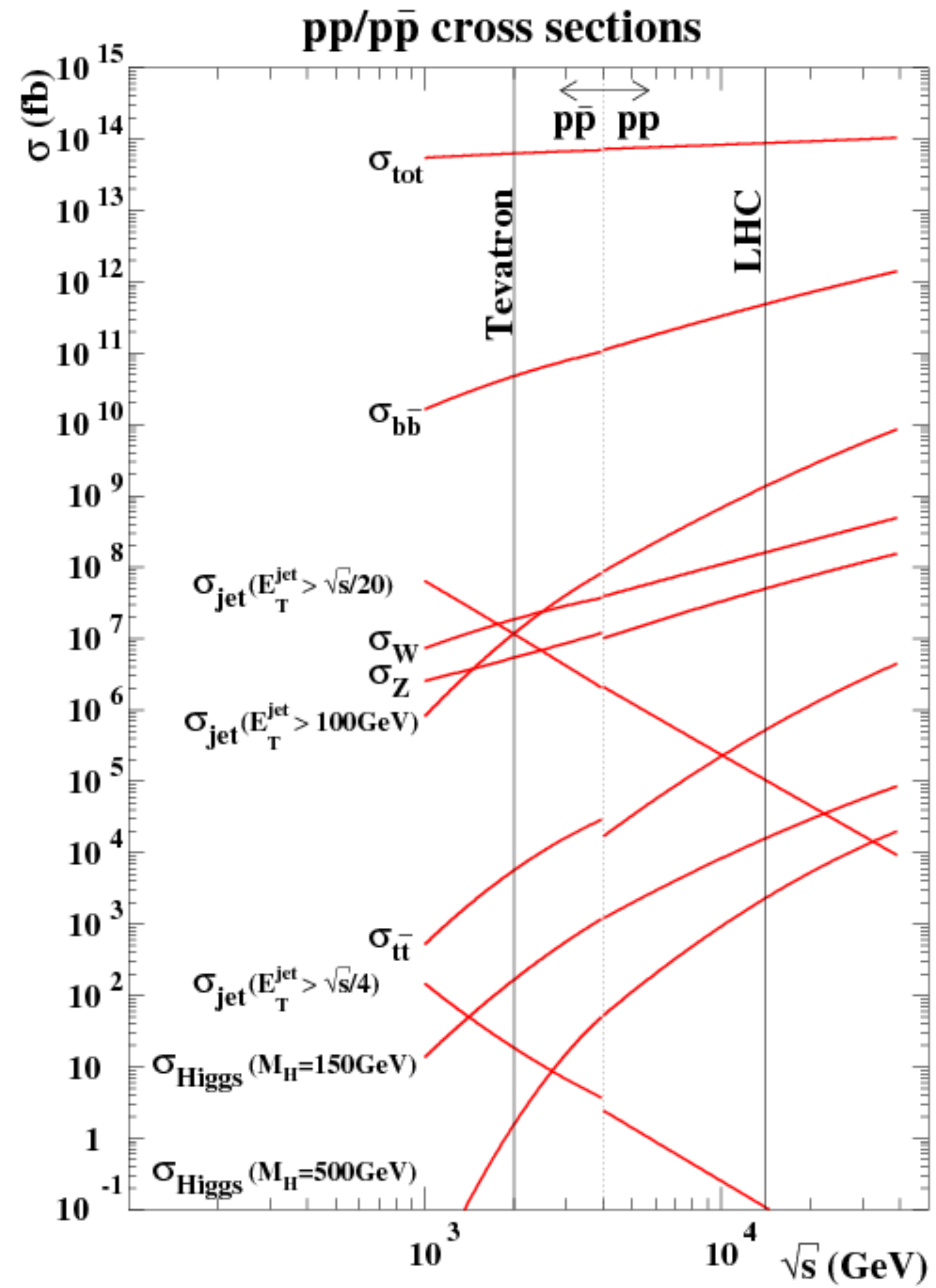
Slower moving LLP, timing cuts can be further relaxed.

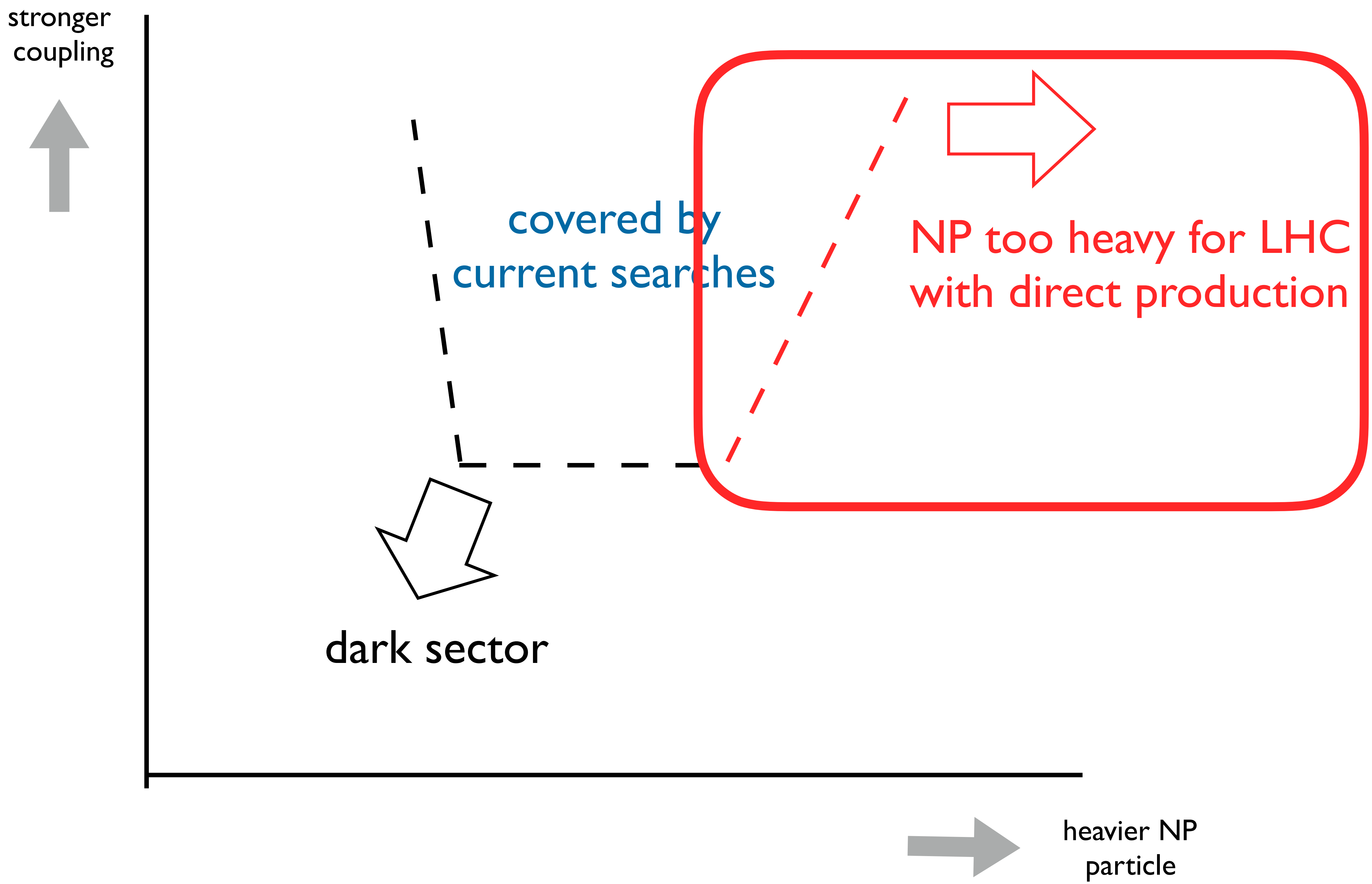
New directions and ideas

- Apply timing to current LLP searches should already help.
  - e.g. muon-RoI based searches
- Removing the ISR jet for MS searches.
  - Higher rate. Larger Δt = 1 ns cut, don't need precise hard collision time.
- High granularity, better pointing and vertexing
  - Would be at least as useful as timing.
  - HGCAL, MS RPC upgrade.
- Using timing info with the calorimeters, HGTD.

Other rare processes

- Rare W, Z, top decays.
  - Sensitive to very rare and distinct signals.
- More attention needed.

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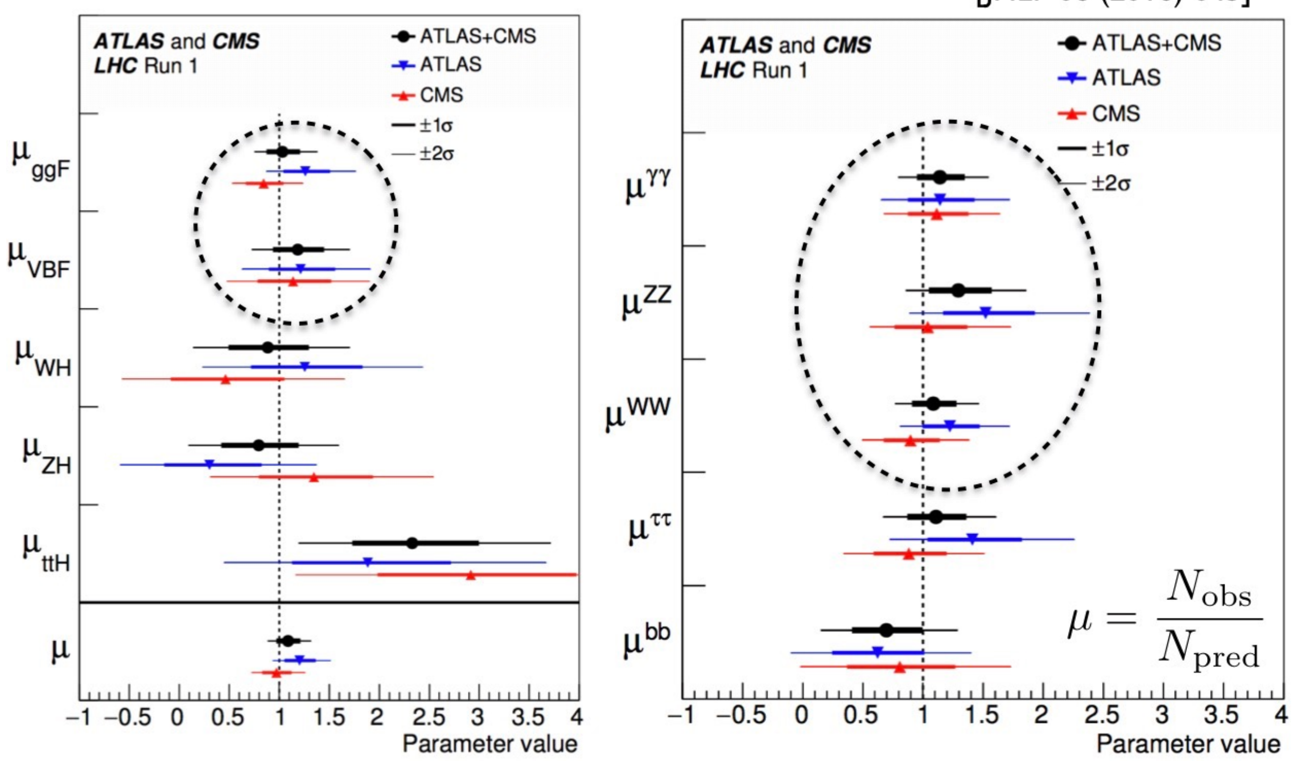
Precision measurements at the LHC

Importance of precision measurement

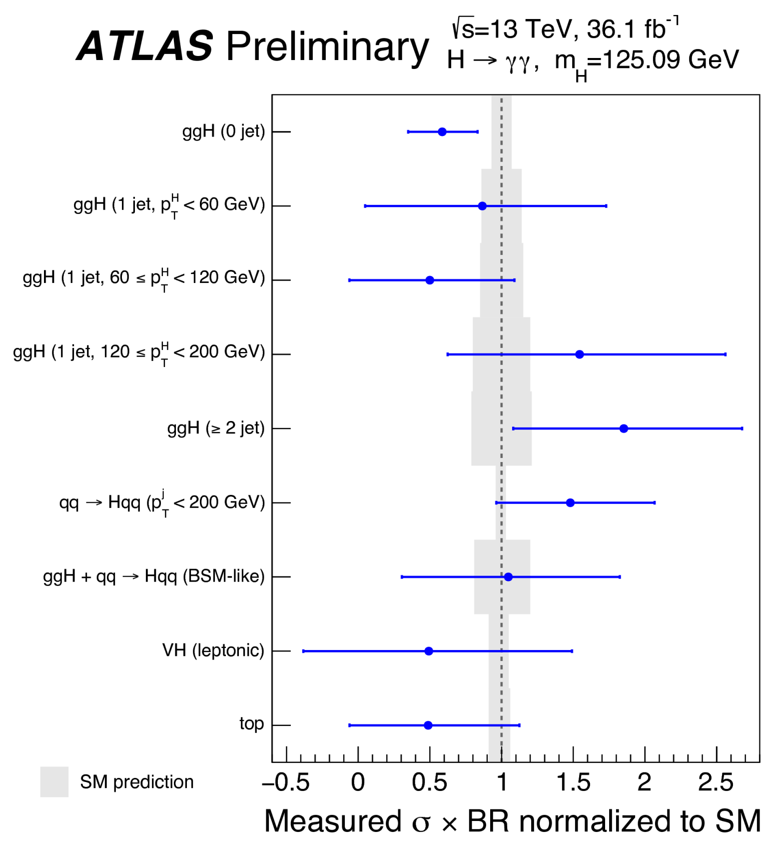
- No clear indication where new physics might be.
  - Precision measurement can give crucial guidance.
- Lots of data still to come
  - Room to improve! Statistics and systematics.
- Will be a important part of the legacy of the LHC.
  - LEP taught us a lot. LHC will do the same.

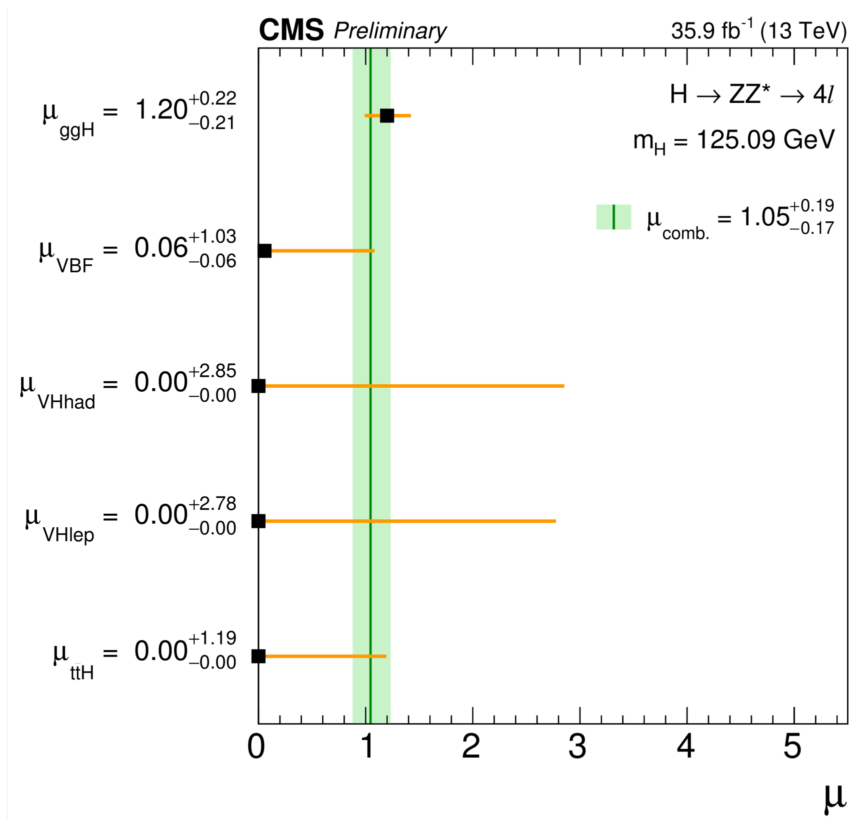
Higgs Standard Model-like

[JHEP 08 (2016) 045]



Agree to about 10-20%





Not entirely surprising

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

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

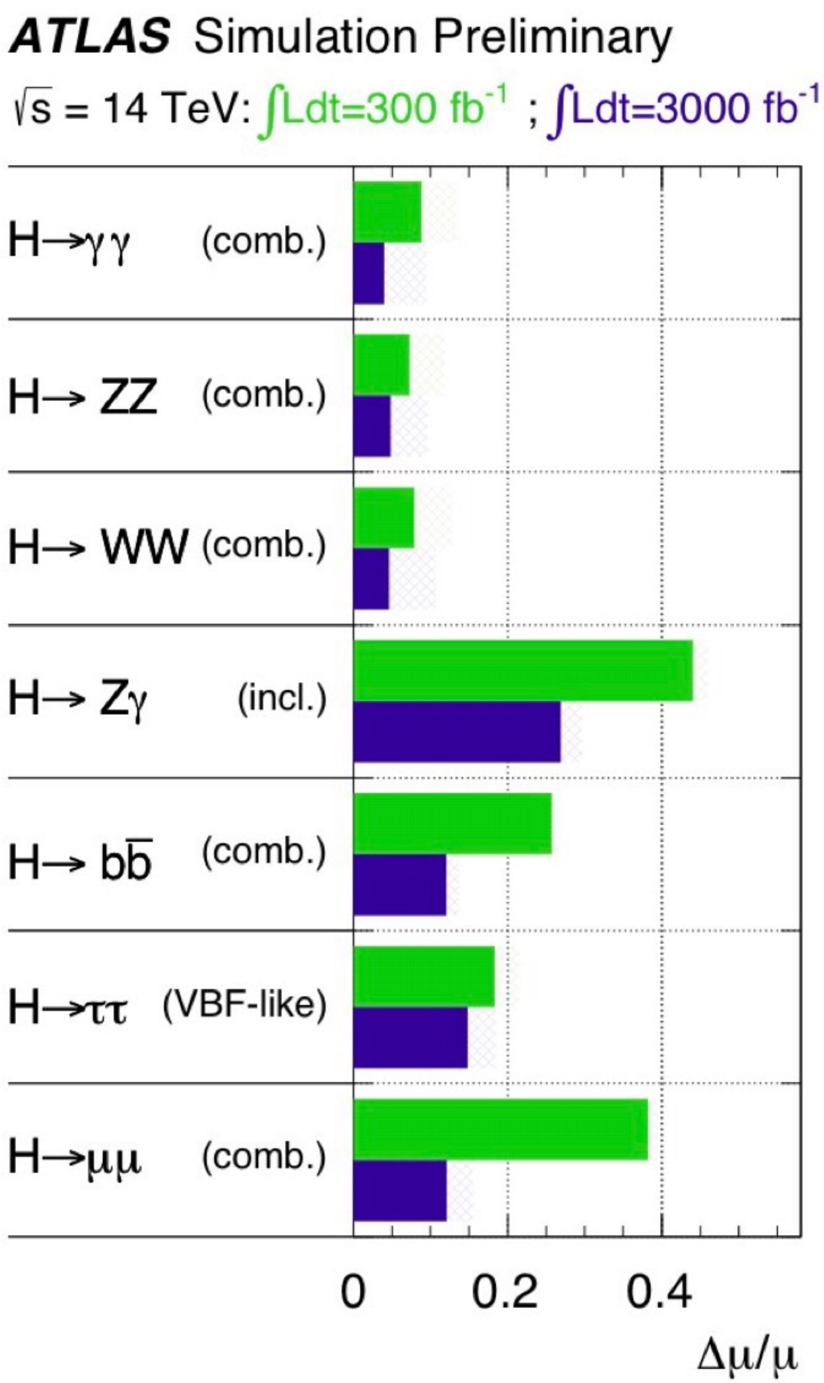
M_{NP} : mass of new physics
c: $O(1)$ coefficient

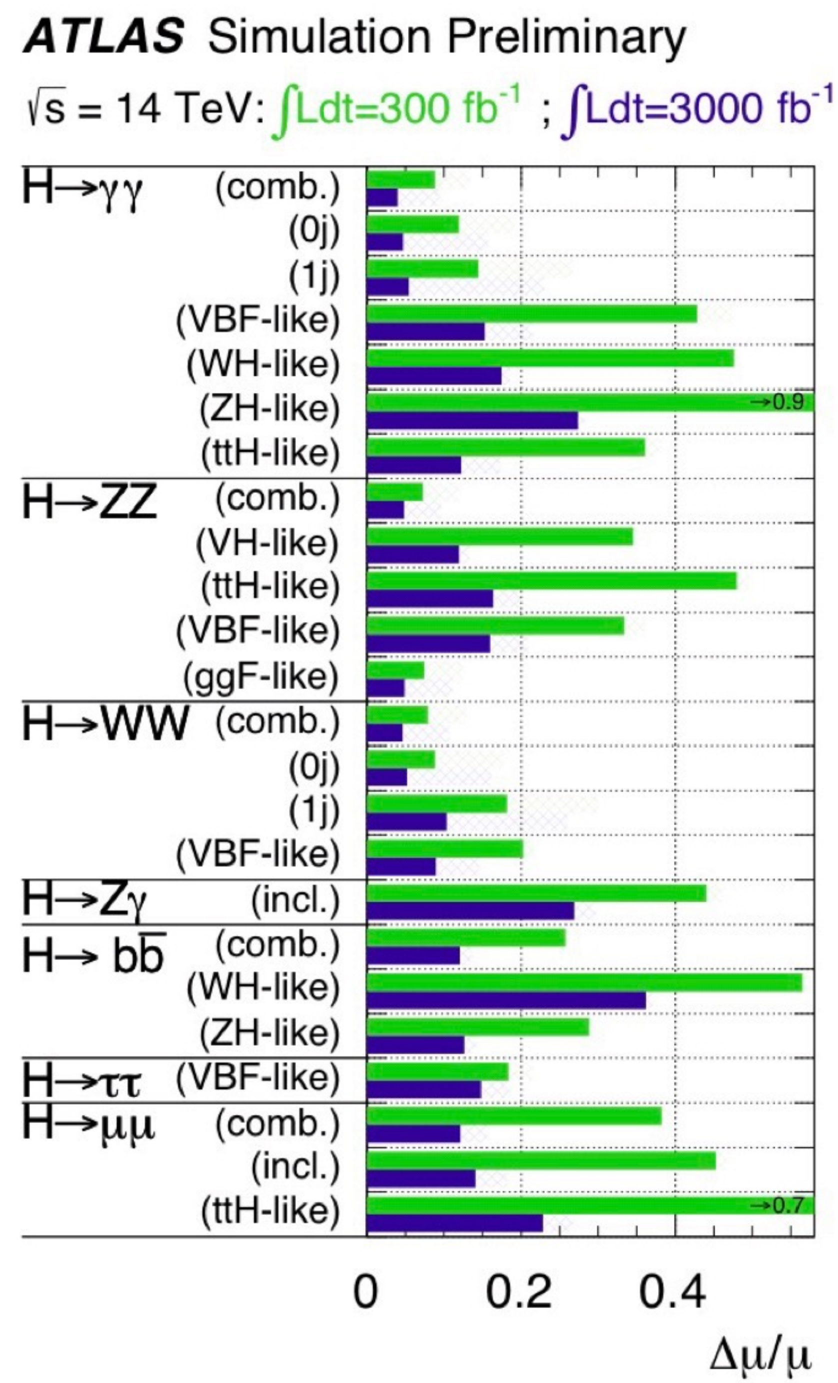
- Current LHC precision: 10%
  $\Rightarrow$ sensitive to M_{NP} < 500-700 GeV

- At the same time, direct searches constrain new physics below TeV already.

- Unlikely to see O(1) deviation.

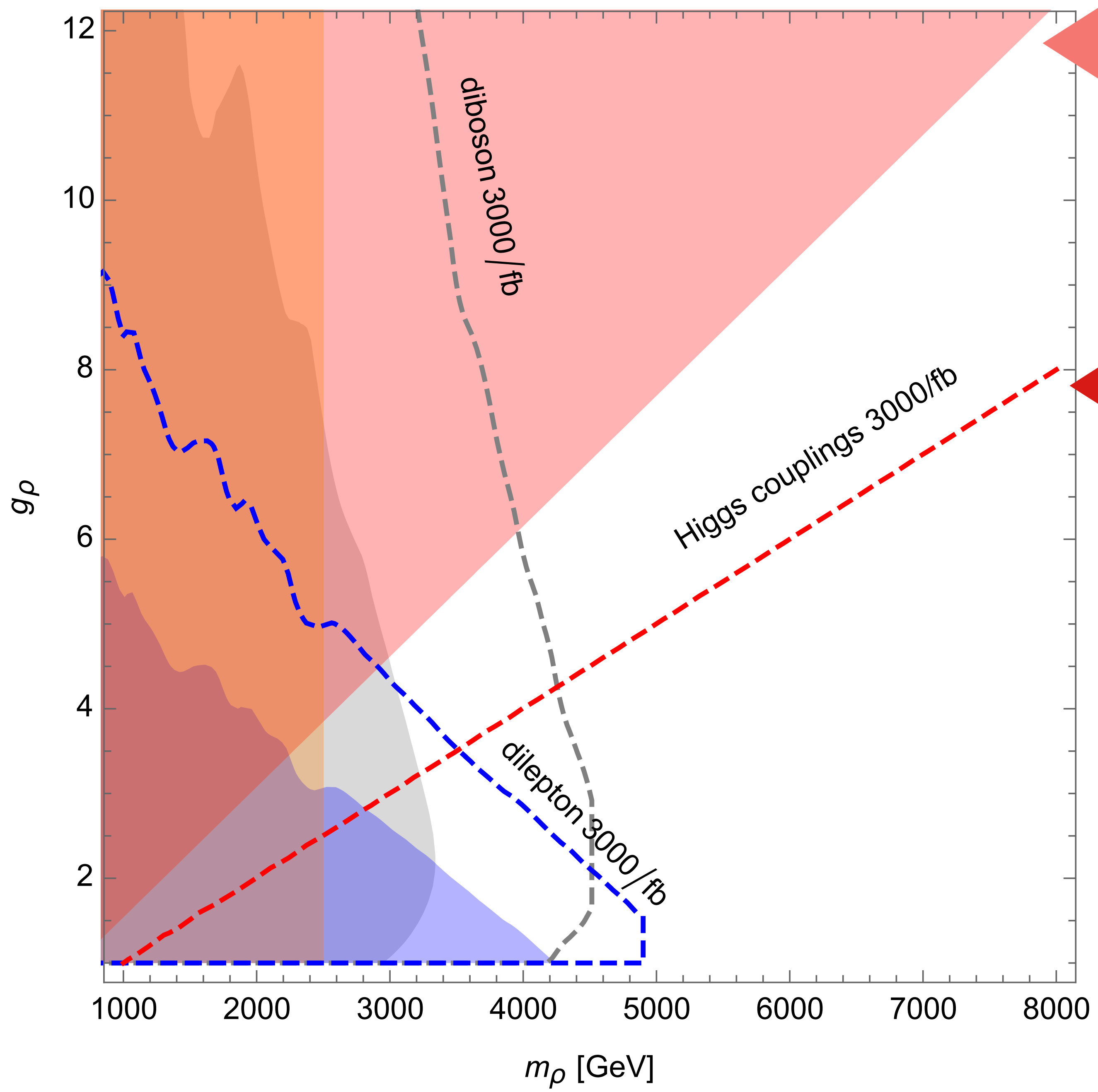
Significant improvement with high lumi





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

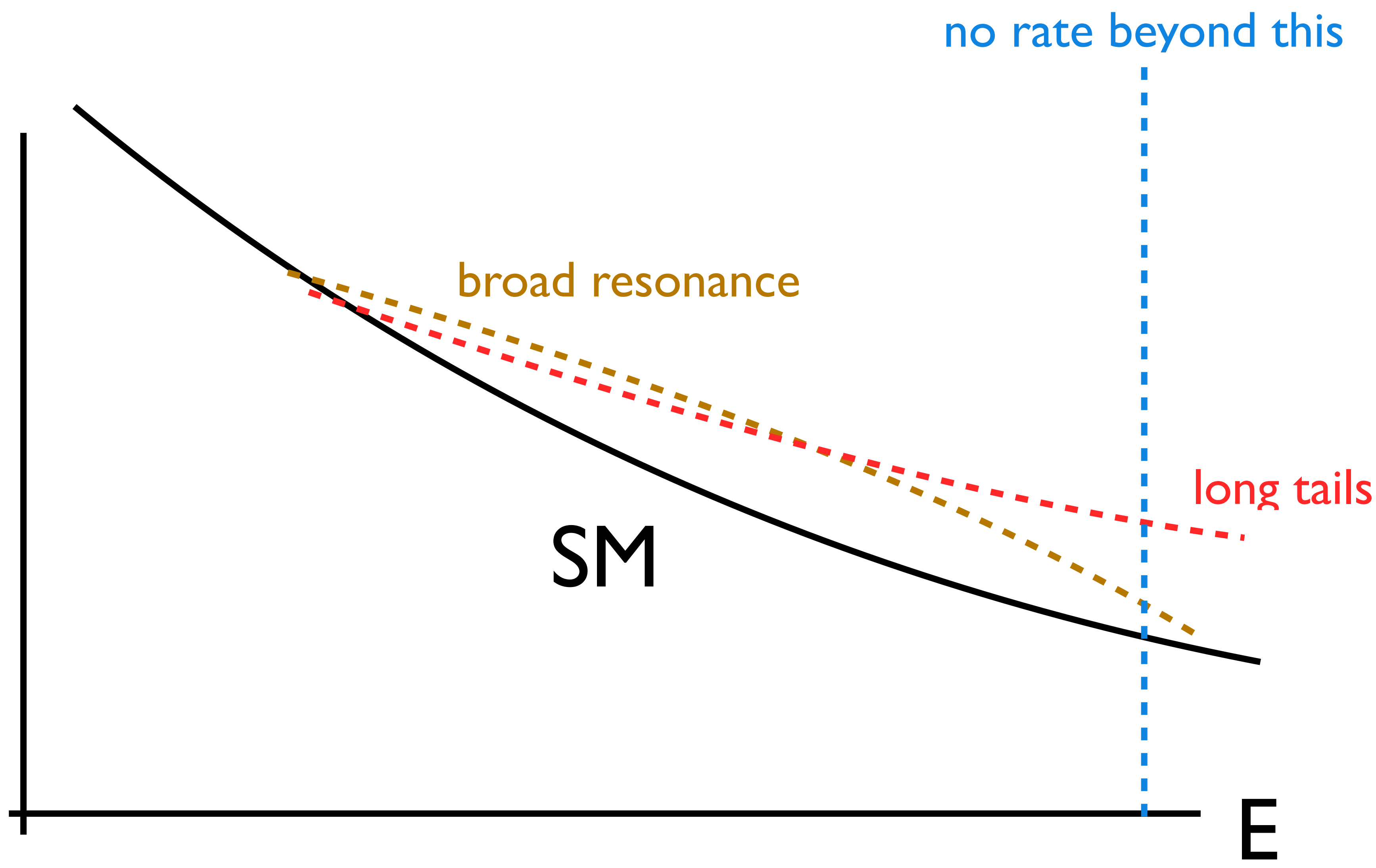
Higgs coupling vs direct search



Excluded by current Higgs Coupling measurements

Reach of HL-LHC

Precision measurement with distribution

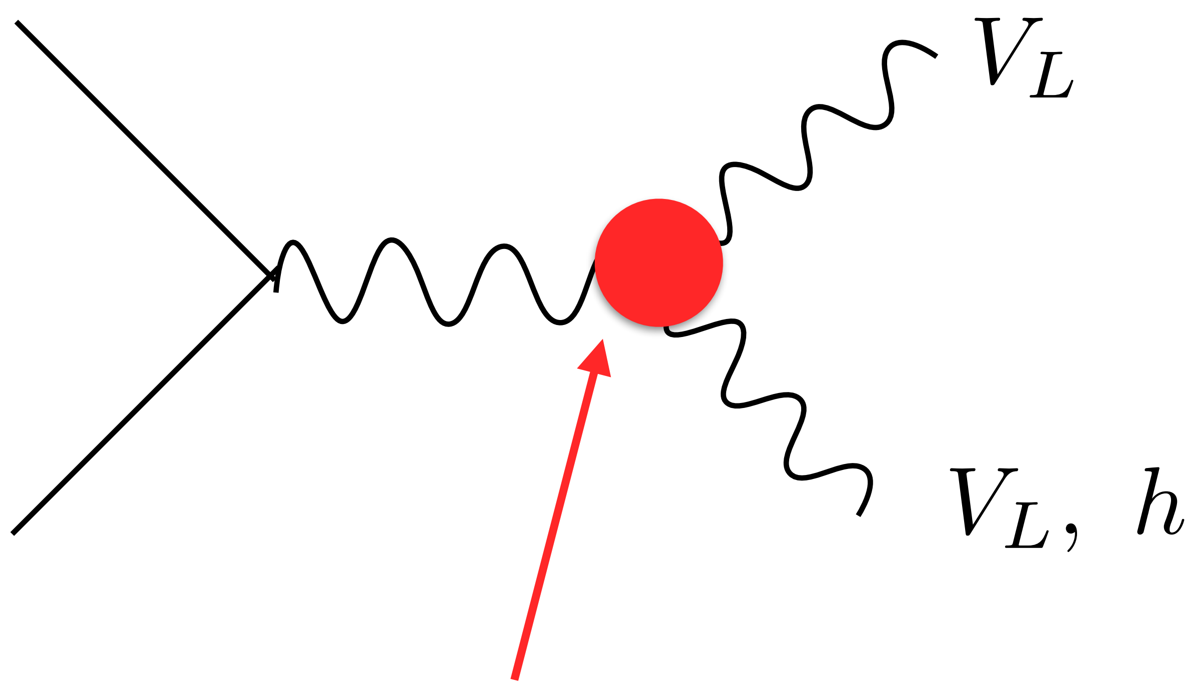


Low S/B, systematic dominated.

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

Helicity structure at LHC

$$f_L \bar{f}_R \to W^+ W^-$$

(h_{W^+}, h_{W^-})	SM	$\mathcal{O}_W$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_B$	$\mathcal{O}_{3W}$	$\mathcal{O}_{TWW}$
$(\pm, \mp)$	1	0	0	0	0	0	$\frac{E^4}{\Lambda^4}$
$(0,0)$	1	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	0	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$
$(0,\pm), (\pm, 0)$	$\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^4}{\Lambda^4}\frac{m_W}{E}$
$(\pm, \pm)$	$\frac{m_W^2}{E^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	0	0	$\frac{E^2}{\Lambda^2}$	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$

$$f_R \bar{f}_L \to W^+ W^-$$

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$(\pm, \mp)$	0	0	0	0	0	0	$\frac{E^4}{\Lambda^4}$
$(0,0)$	1	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	0	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$
$(0,\pm), (\pm, 0)$	$\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{m_W^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^4}{\Lambda^4}\frac{m_W}{E}$
$(\pm, \pm)$	$\frac{m_W^2}{E^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	0	0	$\frac{m_W^2}{\Lambda^2}$	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$

growing with energy

- Whether interference or not depends on polarization of WW. Polarization differentiation can be crucial.

- Need large SM piece to interfere with. Longitudinal (0,0) most promising.

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

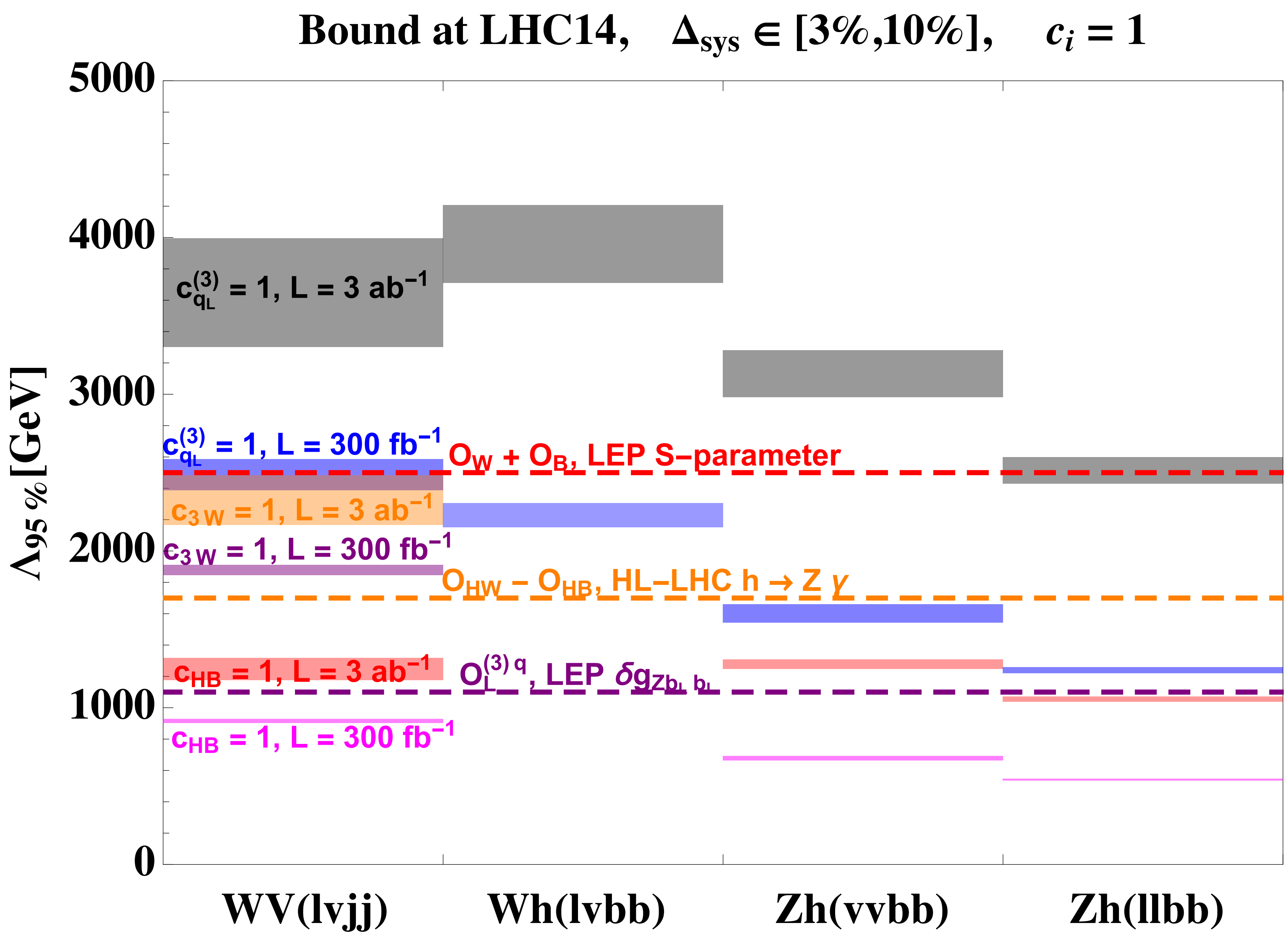
$$\text{LHC @ 8 TeV :} \qquad \sigma_b^{red}/\sigma_{SM}^{Wh} \sim 200-10$$

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



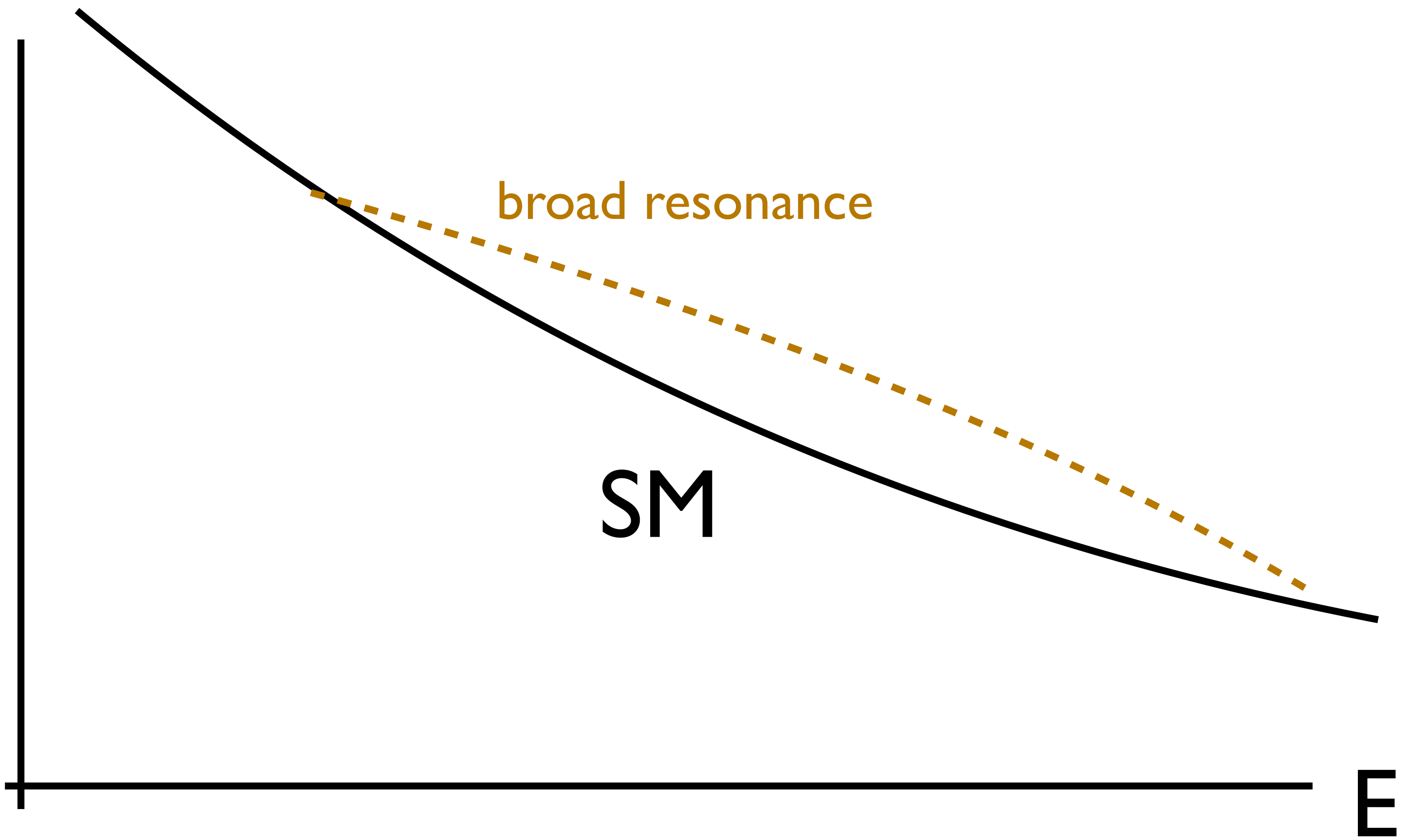
Possible to reach 4 TeV.

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

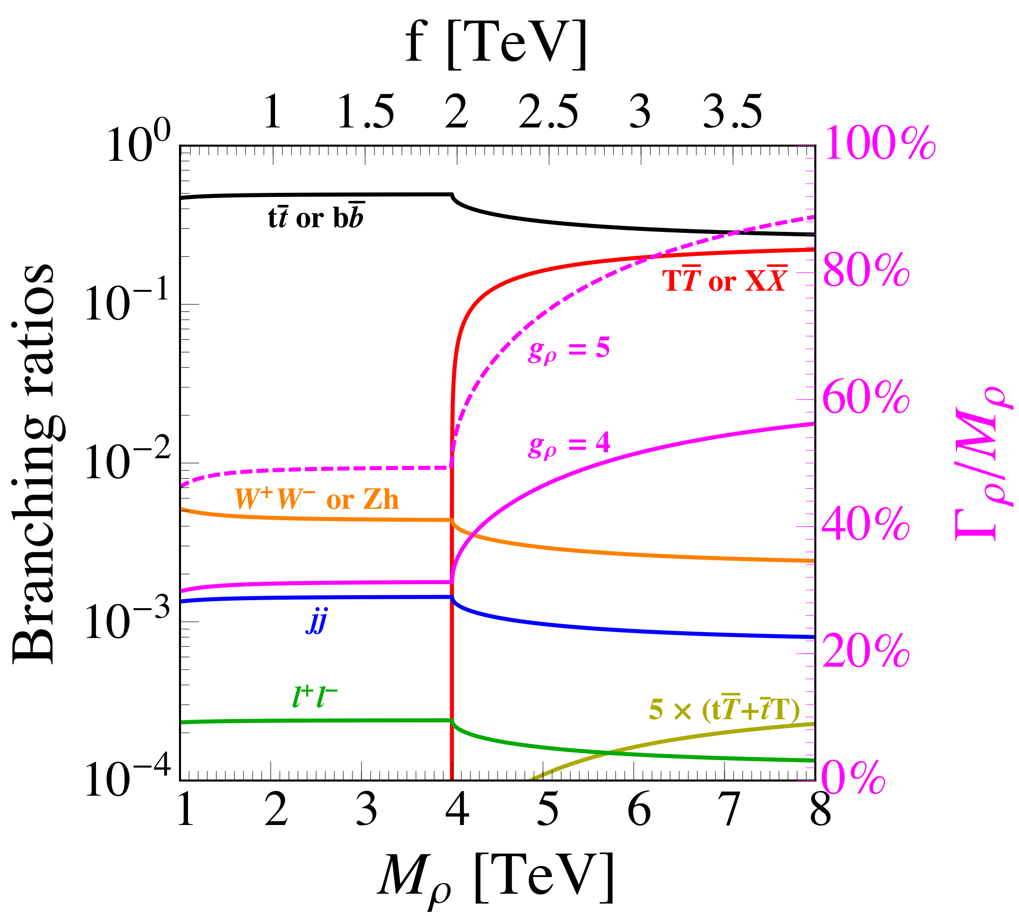
Broad resonances

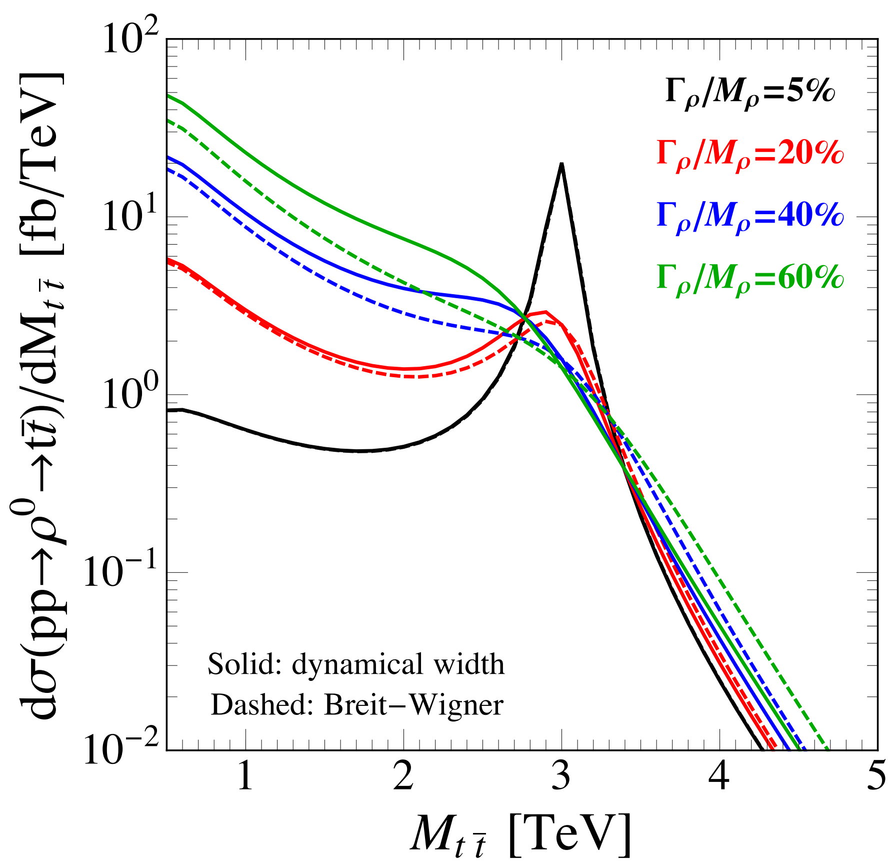


Low S/B, systematic dominated.

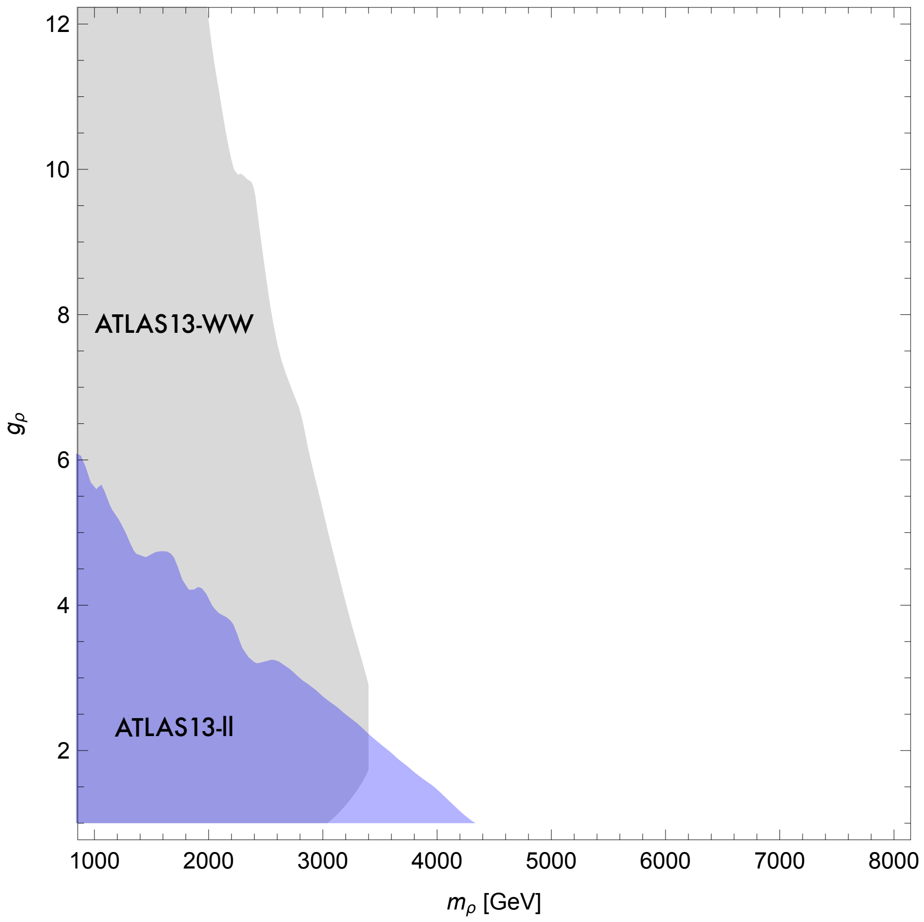
Broad composite resonance

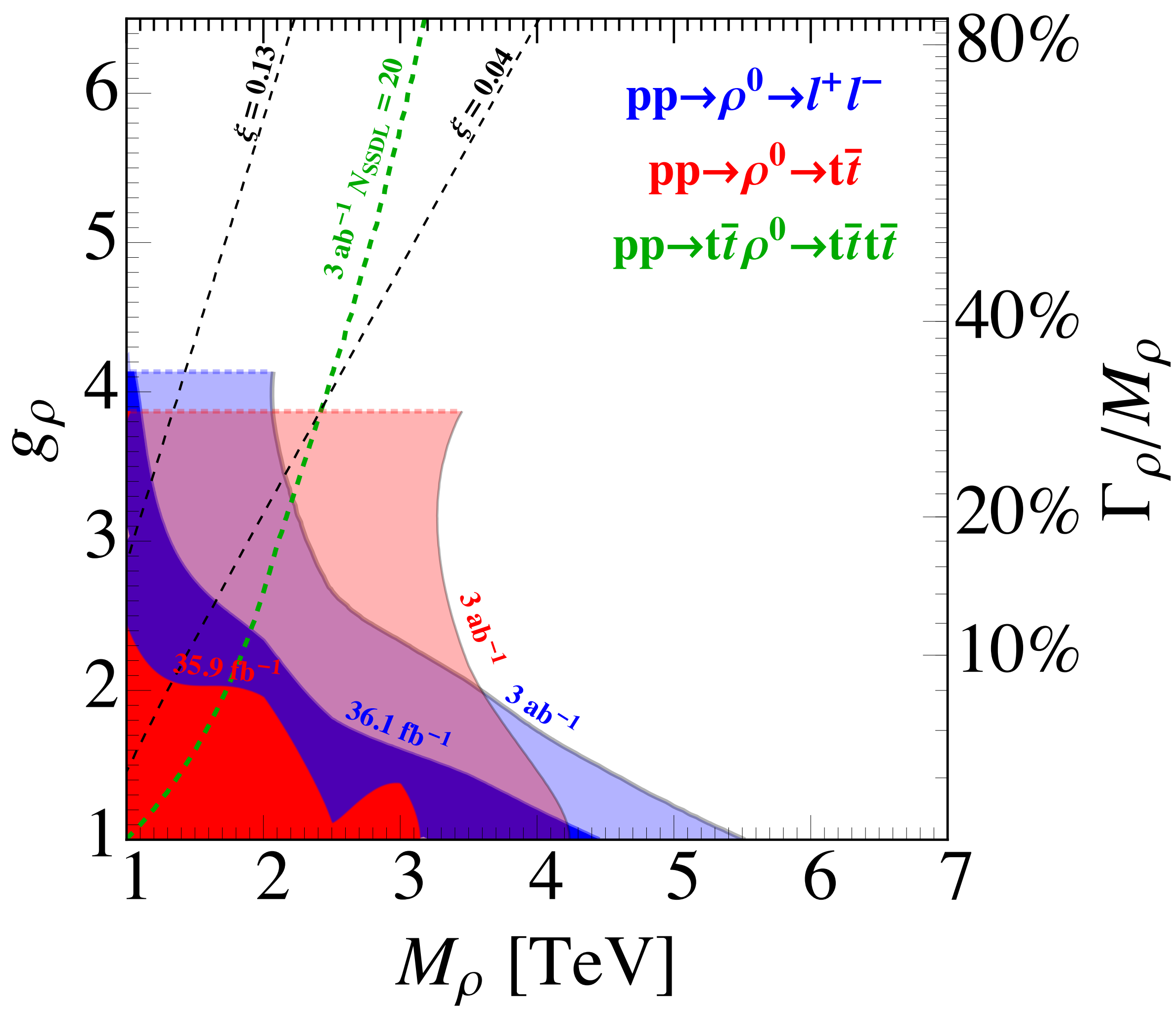
D. Liu, LTW, K. Xie





Significantly altering searches





Need new studies for searching for very broad resonances.

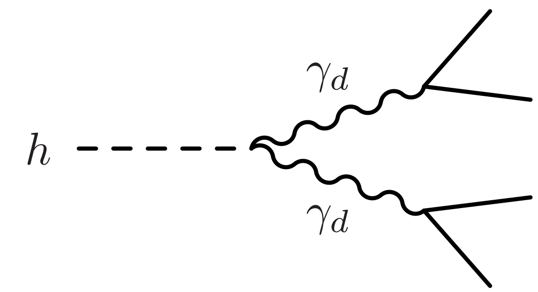
Conclusion

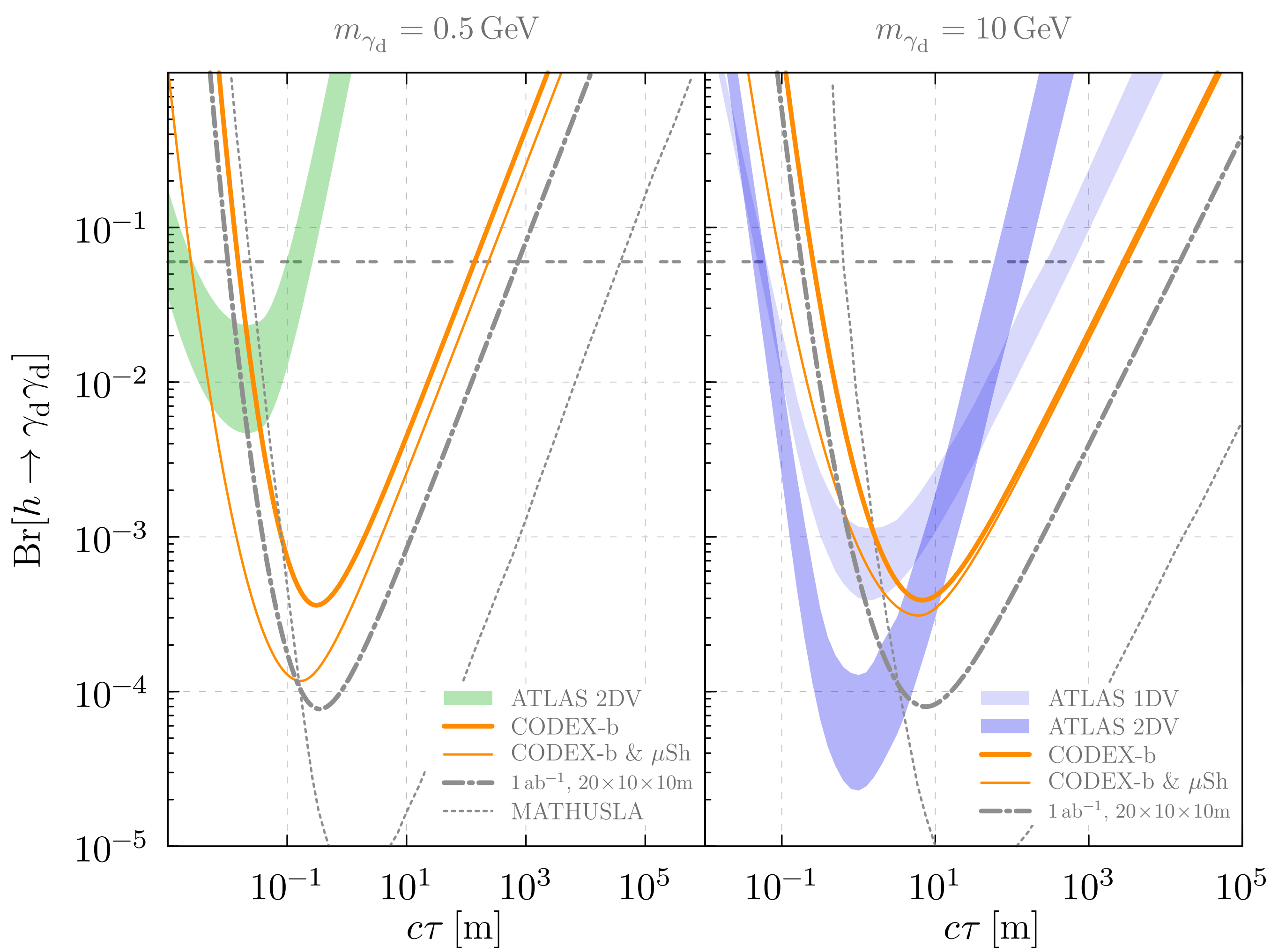
- LHC still has a lot to say.
  - 15+ years of operation, 95+% of data to come.
- Need to think about how to new searches with this data. (In addition to looking else where.)
- I discussed two directions
  - Long lived particles, with timing information.
  - Precision measurement.
- More work (and originality)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

extra

Could reach τ≈10^{4-5} m

Exotic Higgs decays





Application:
Neutral Naturalness
(See back-up material)

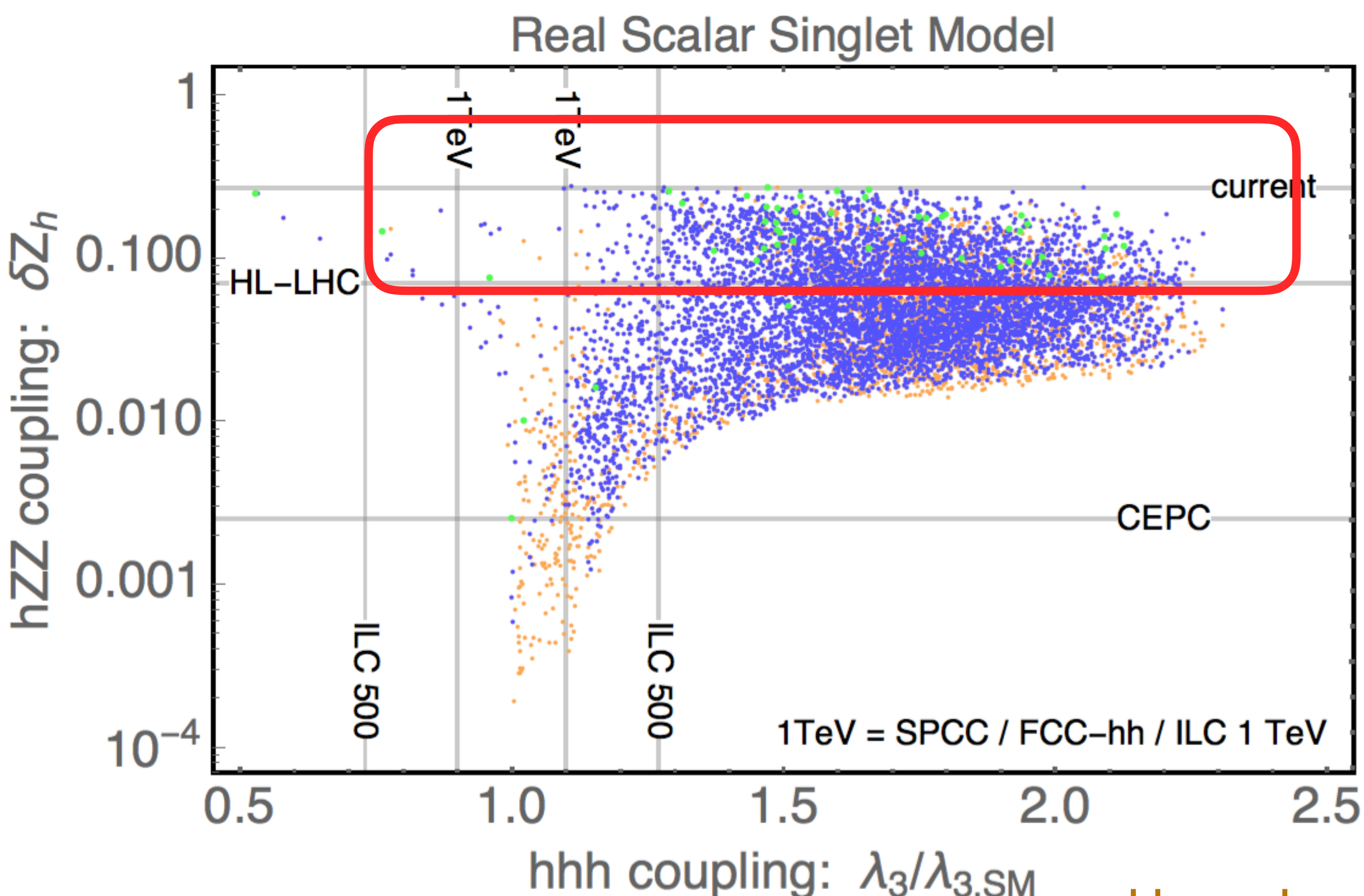
For low masses, ATLAS/CMS are background limited, CODEX-b & MATHUSLA have an edge

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

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

S. Knapen

Probing EW phase transition

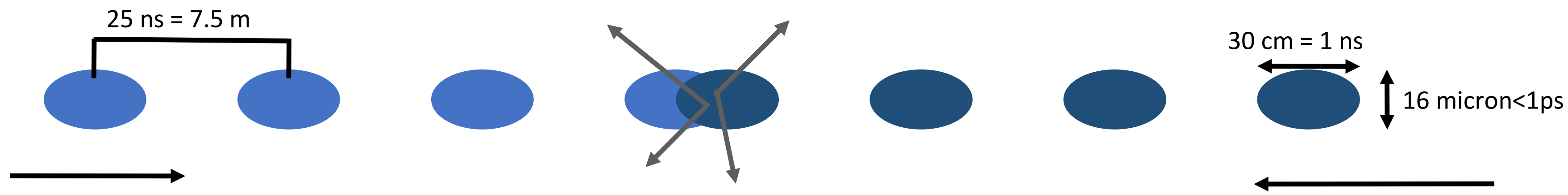


Huang, Long, LTW, 1608.06619

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

Detector with timing information

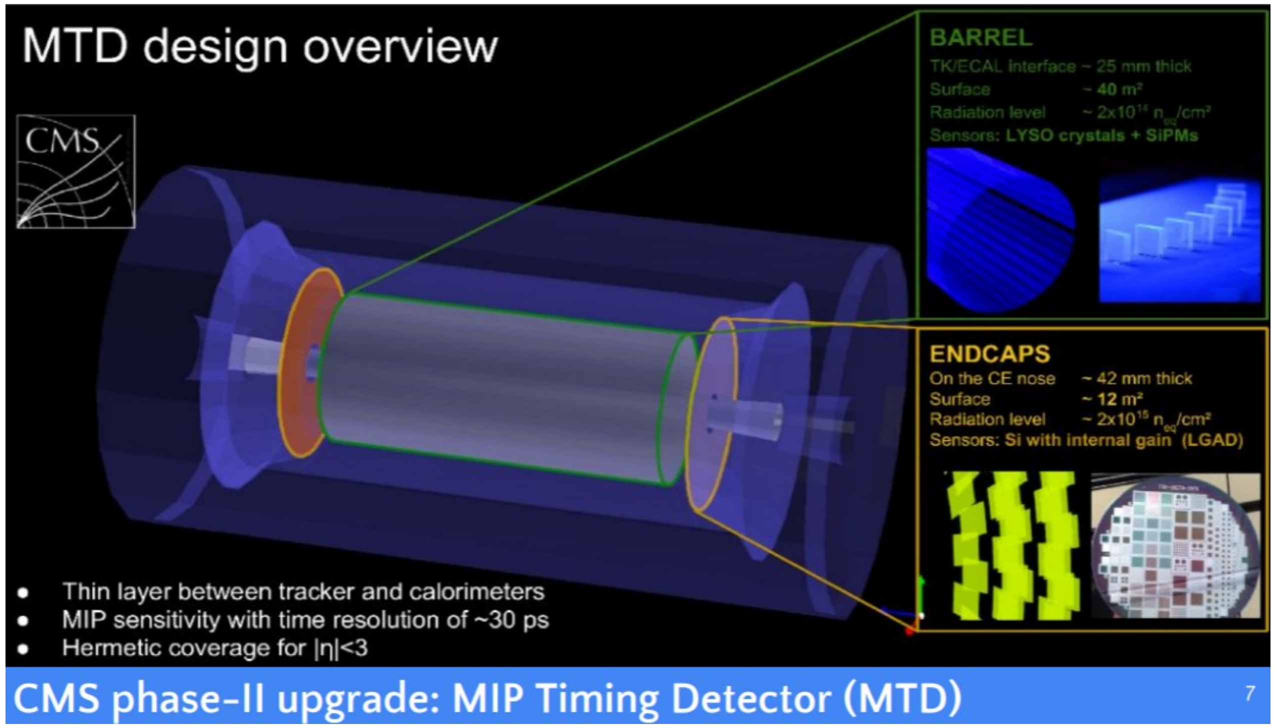
- Detector needs timing information to record event



CMS Phase-II upgrade:
MIP Timing Detector(MTD)
both barrel and endcap

With 30 ps timing resolution, enable 4d reconstruction

Aim for reducing pile-up



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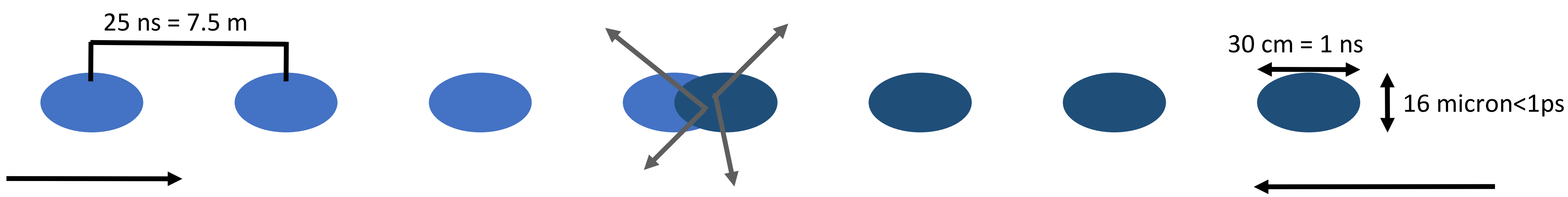

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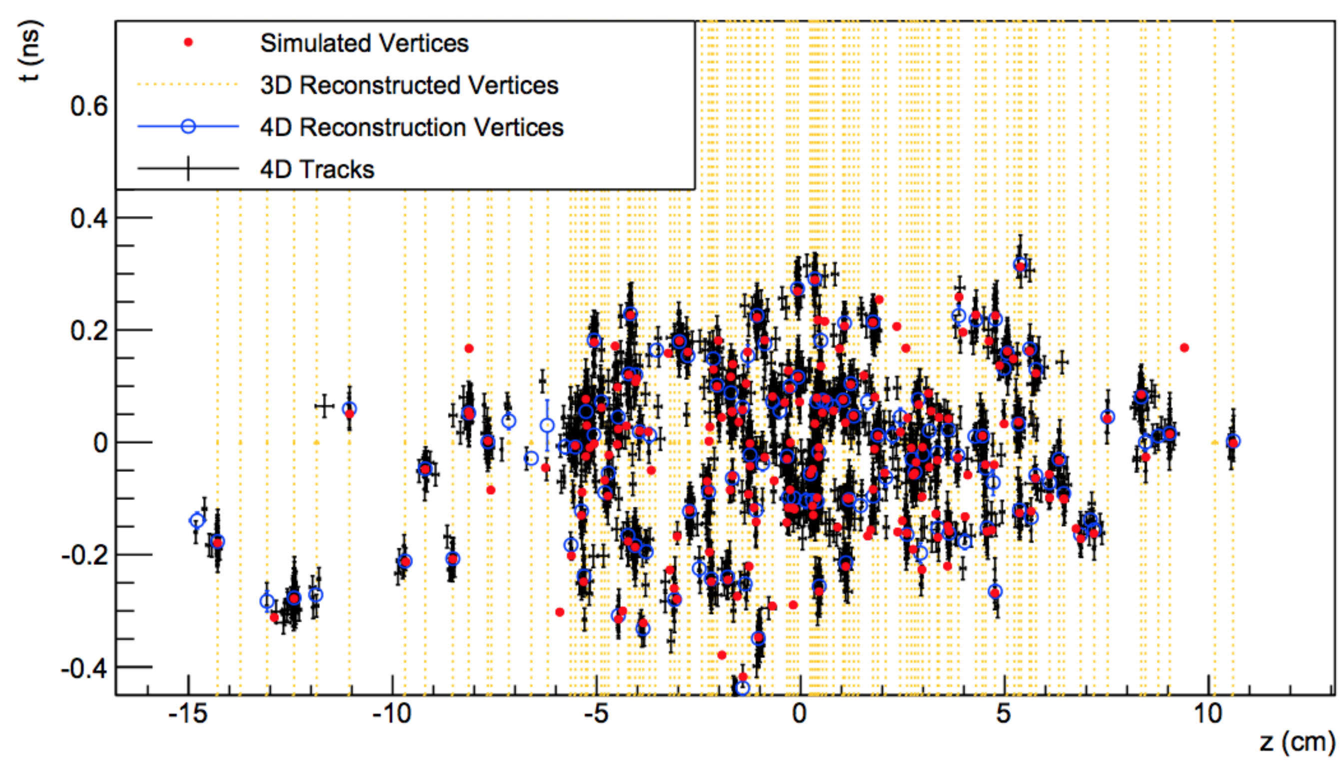
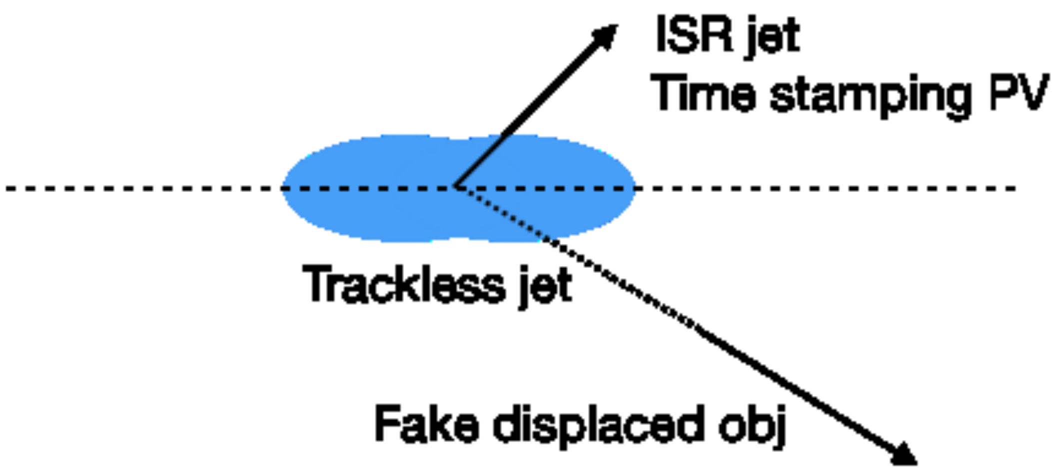


Late comers will be spotted easily:

	L_{T_2}	L_{T_1}	Trigger	ϵ_{trig}	ϵ_{sig}	$\epsilon^{j}_{\text{fake}}$
MTD	1.17 m	0.2 m	DelayJet	0.5	0.5	10^{-3}
MS	10.6 m	4.2 m	MS RoI	0.25, 0.5	0.25	5×10^{-9}

CMS MTD $|\eta| < 3.0$
ATLAS MS LLP search
(without timing)



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

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

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

Late comers will be spotted easily:

	L_{T_2}	L_{T_1}	Trigger	$\epsilon_{\rm trig}$	$\epsilon_{\rm sig}$	$\epsilon^j_{\rm fake}$
MTD	1.17 m	0.2 m	DelayJet	0.5	0.5	10^{-3}
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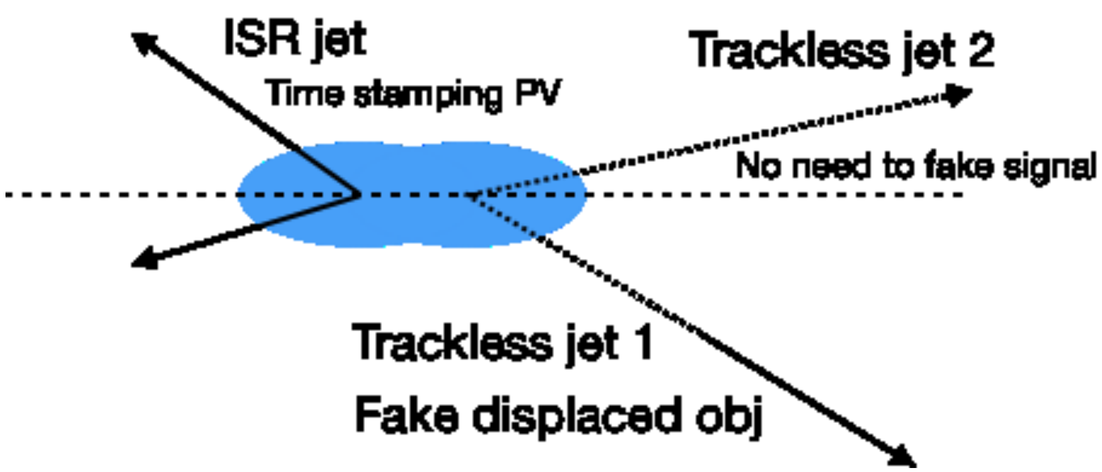
ATLAS MS LLP search

(without timing)



Pile-Up background, time spread

190 ps (beam property)

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

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

Pile-up BKG: intrinsic resolution ~190 ps

MTD (30ps) cut: Δt > 1 ns

BKG(MTD-PU) ~ 1.3

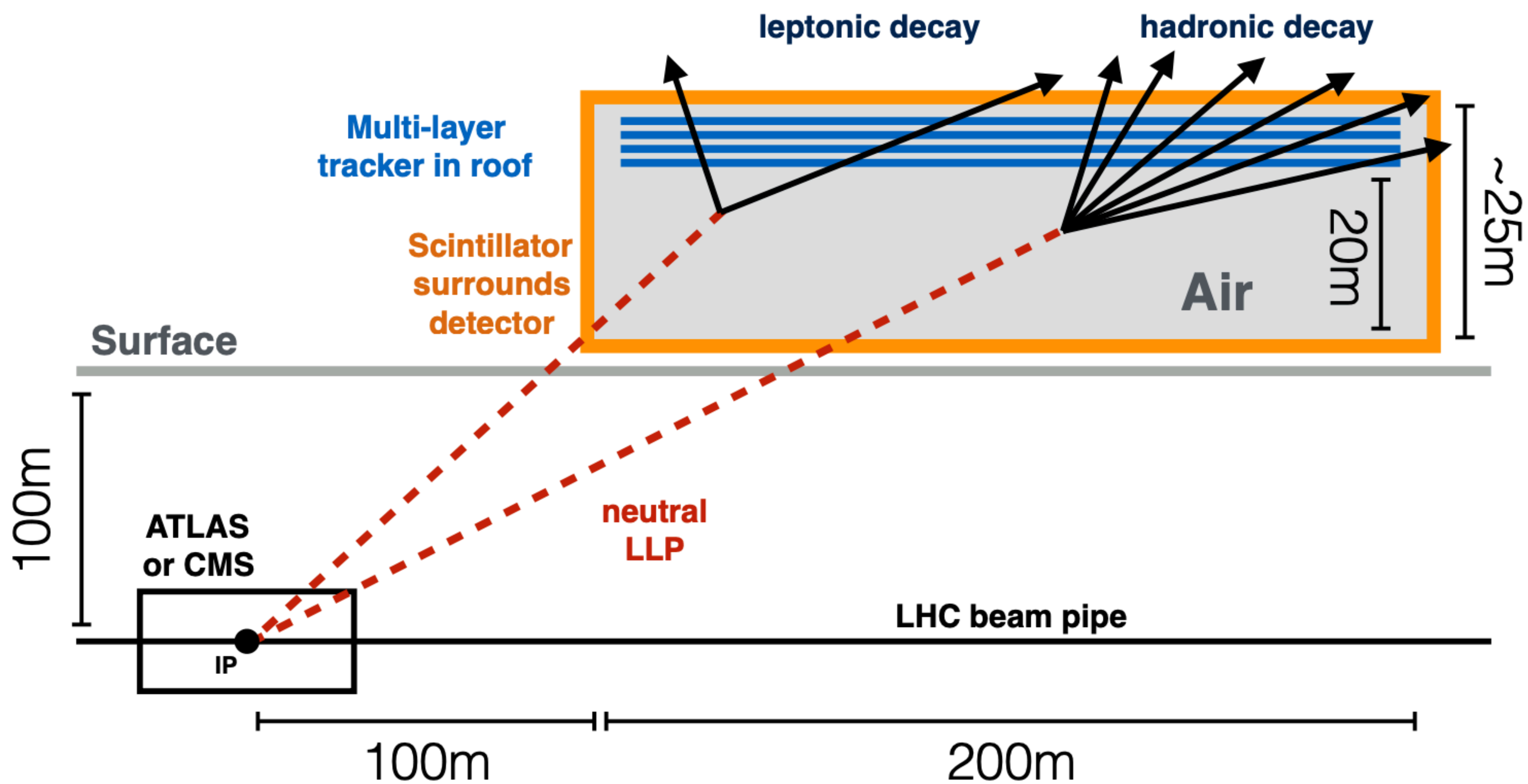
MS (30ps) cut: Δt > 0.4 ns

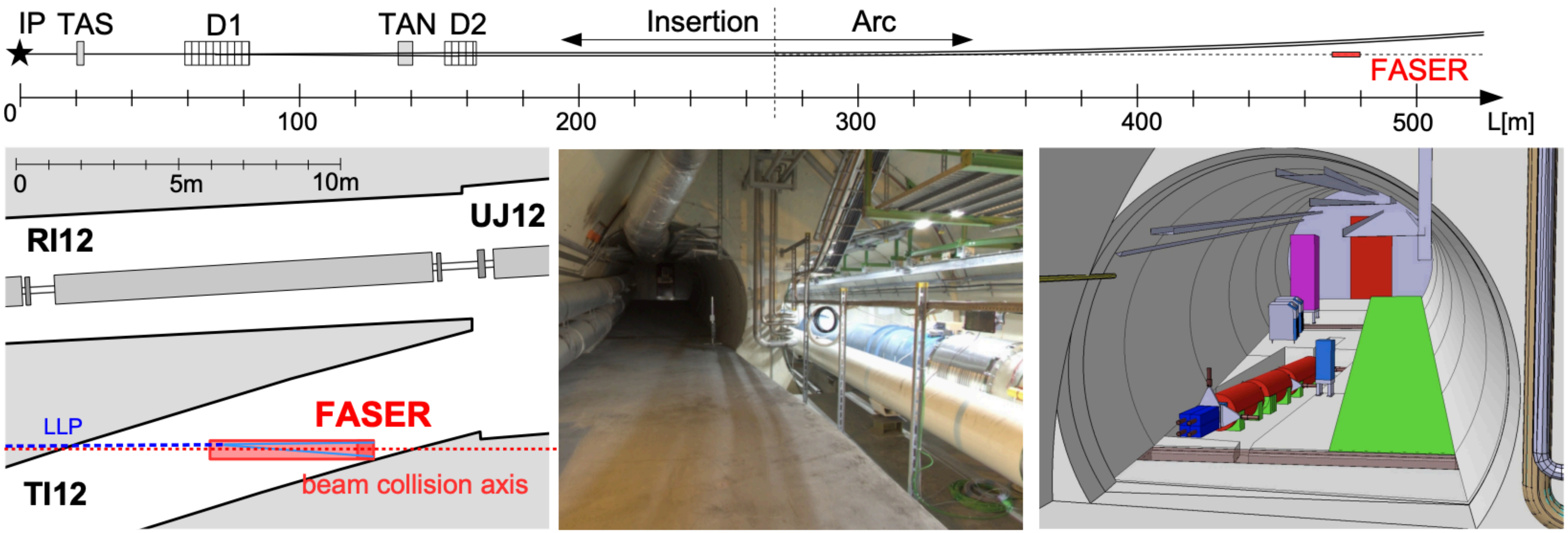
BKG(MS-PU) ~ 0.86

The detector time resolution for MS can be hundreds of ps, even ns

MS (200ps) cut: Δt > 1ns

BKG(MS-PU) << 1


leptonic decay
hadronic decay
Multi-layer
tracker in roof
Scintillator
surrounds
detector
Air
20m
~25m
Surface
100m
ATLAS
or CMS
neutral
LLP
LHC beam pipe
IP
100m
200m



IP TAS
D1
TAN D2
Insertion
Arc
FASER
0
100
200
300
400
500
L[m]
0
5m
10m
UJ12
RI12
LLP
FASER
TI12
beam collision axis

An informal discussion this coming week

March 5. 16:00 - 19:00 CET

https://indico.cern.ch/event/793591/timetable/
#20190305