The Physics Case for (High Energy) Hadron Colliders

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Horizons in Accelerators, Particle/Nuclear Physics and Laboratory-based Quantum Sensors for HEP/NP
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Current situation

Properties of the observed Higgs boson are so far consistent with SM expectations

LHC also searching for BSM particles in several final states/signal regions

No smoking gun signal of new particle at the LHC and in other experiments

Current situation: new particle search

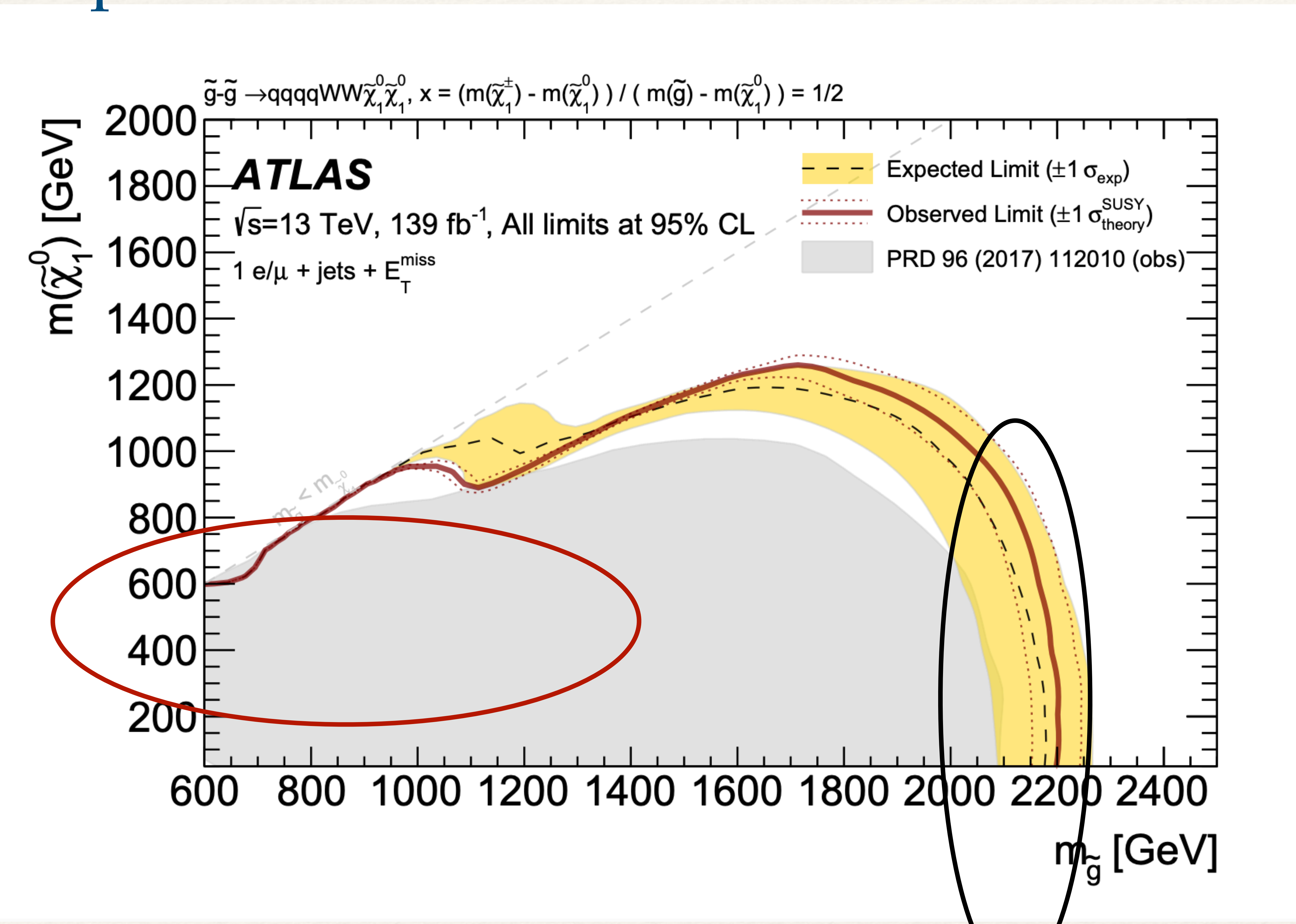
Strong Exclusion limits

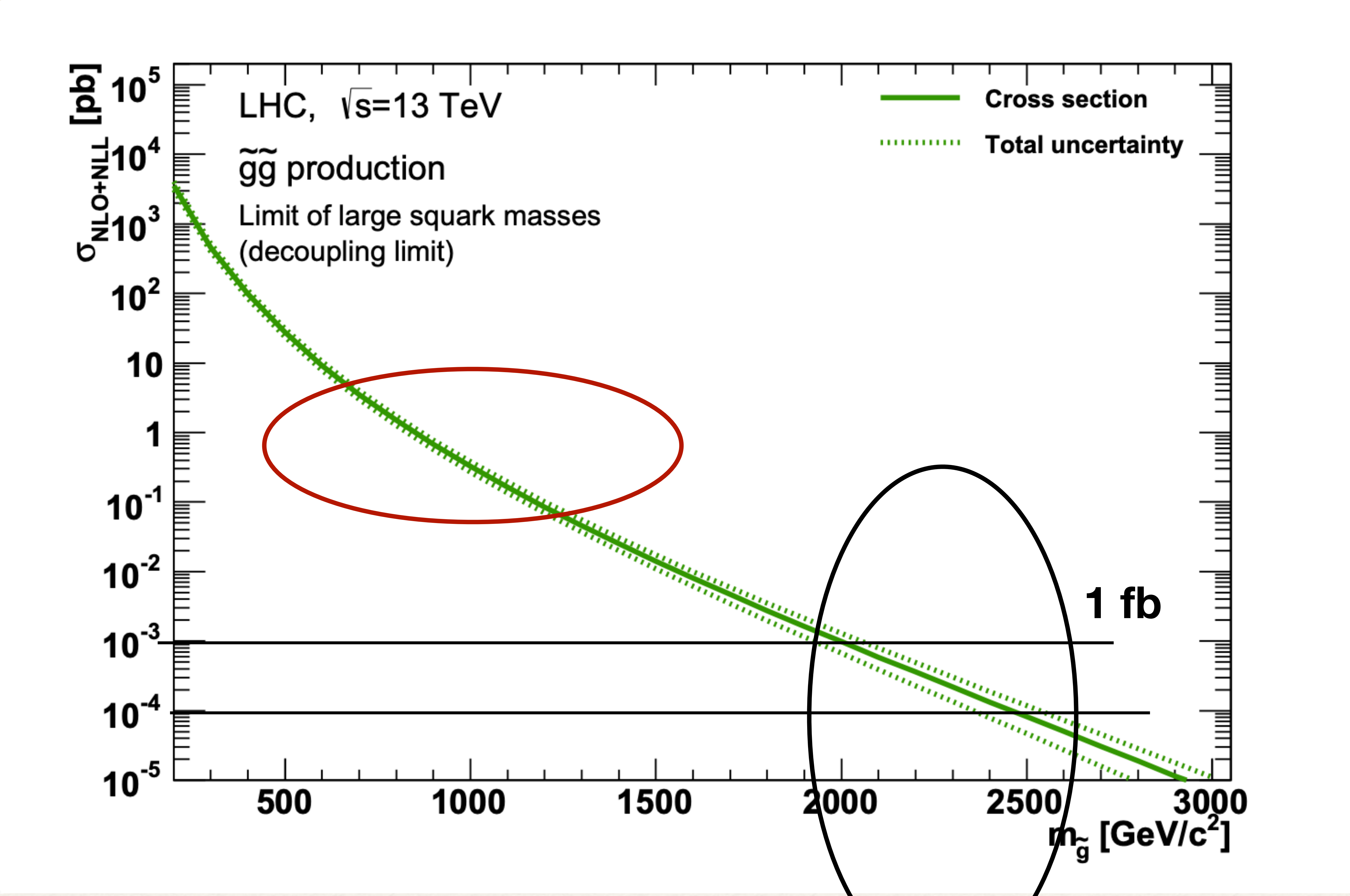
Pair production of gluino (simplified model)

HEP-PH: 1407.5066

Cross section using NLL-fast

Leptonic channel HEP-EX: 2101.01629

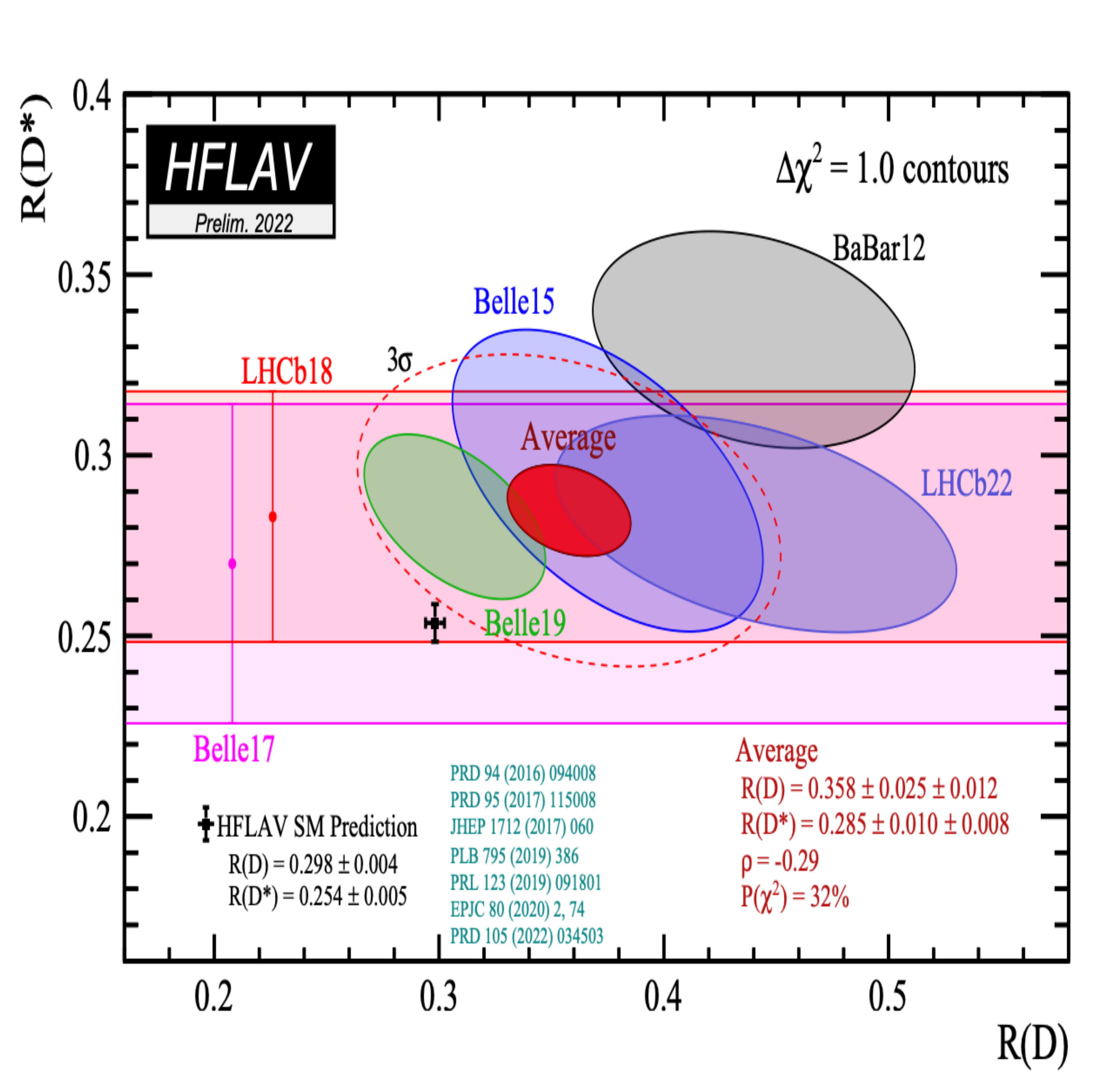


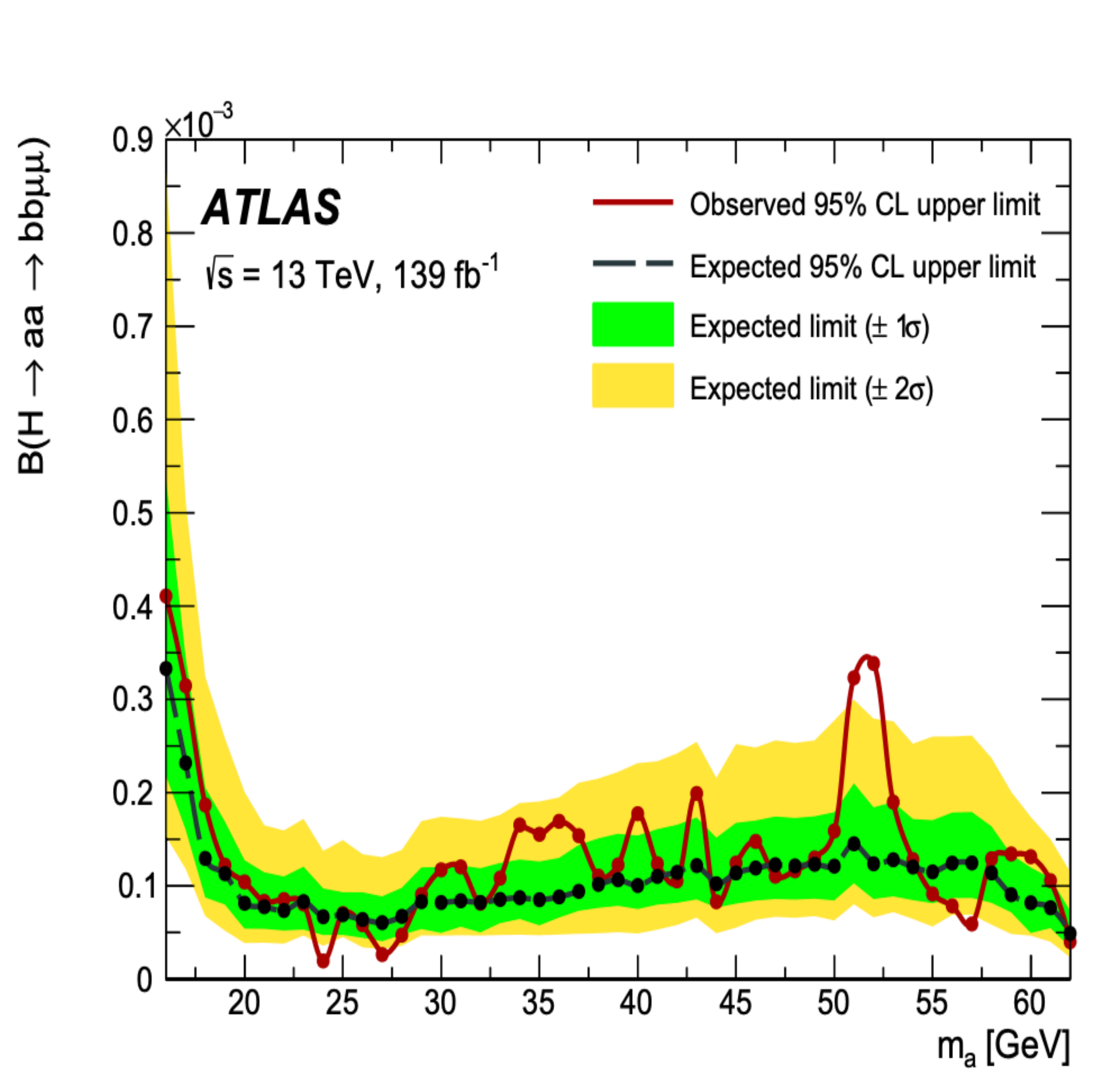


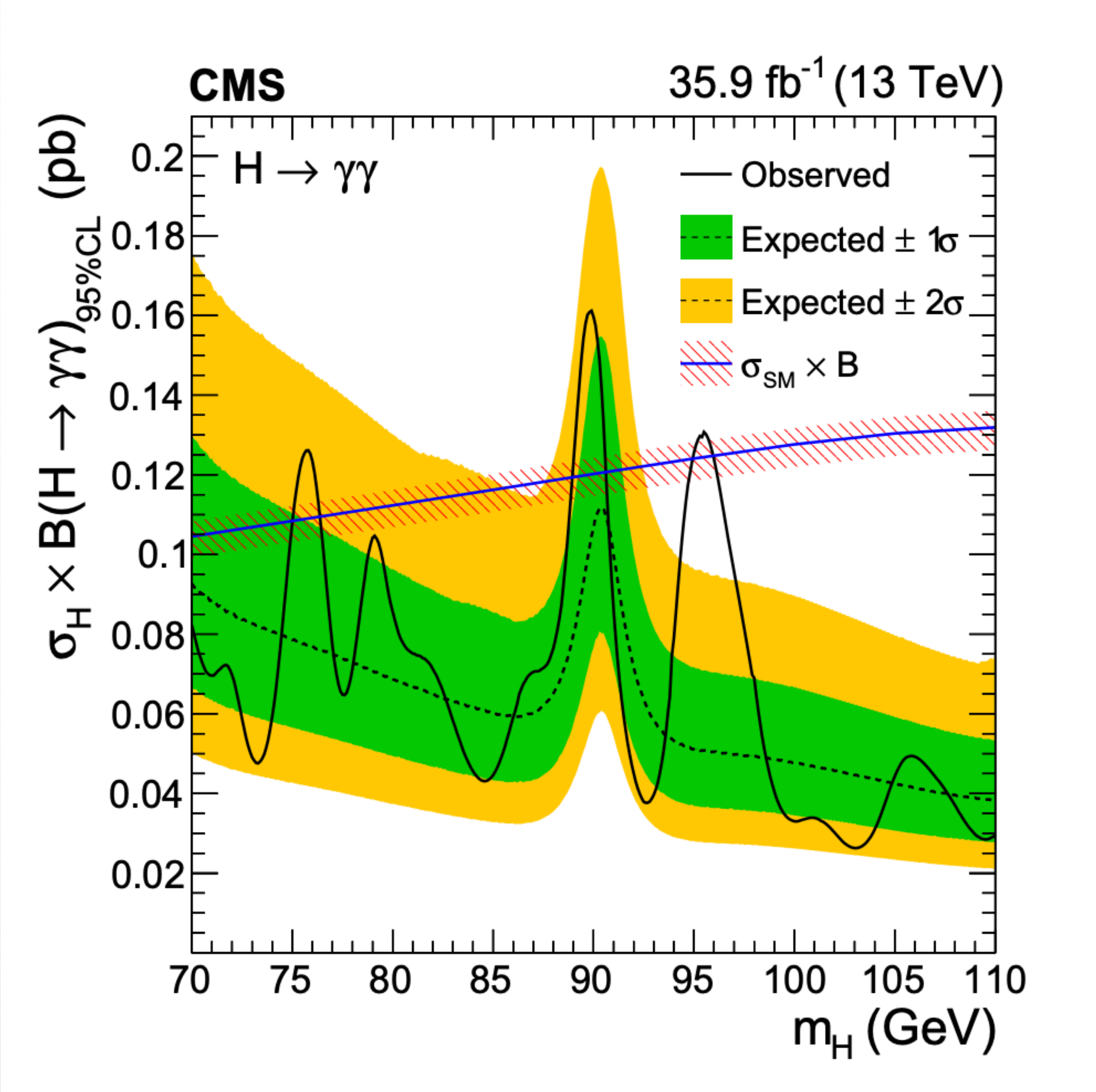
Summary : Degenerate gluino ~ 1TeV , high mass gap limit ~ 2-2.2/2.3 TeV

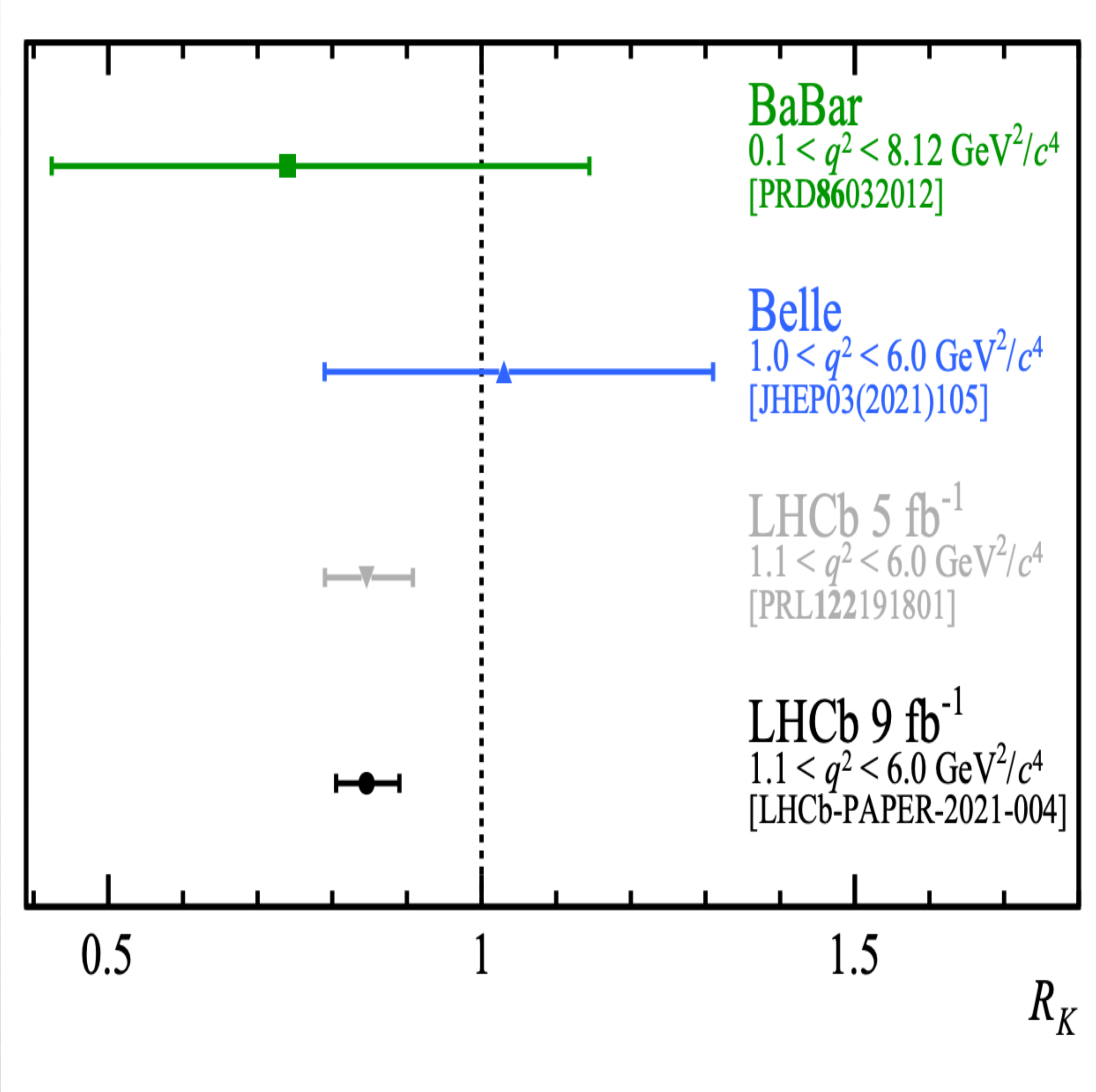
Current situation: Experimental Anomalies

A few Anomalies in experimental results









LINK OF THE LHCB SEMINAR

ATLAS COLLABORATION HEP-EX: 2110.00313

CMS: HEP-EX: 1811.08459

LHCB REPORT HEP-EX: 2103.11769

R(D) R(D*)
3.2 σ

Di-muon + b jets
3.3 σ

Di-photon anomaly
2.8 σ

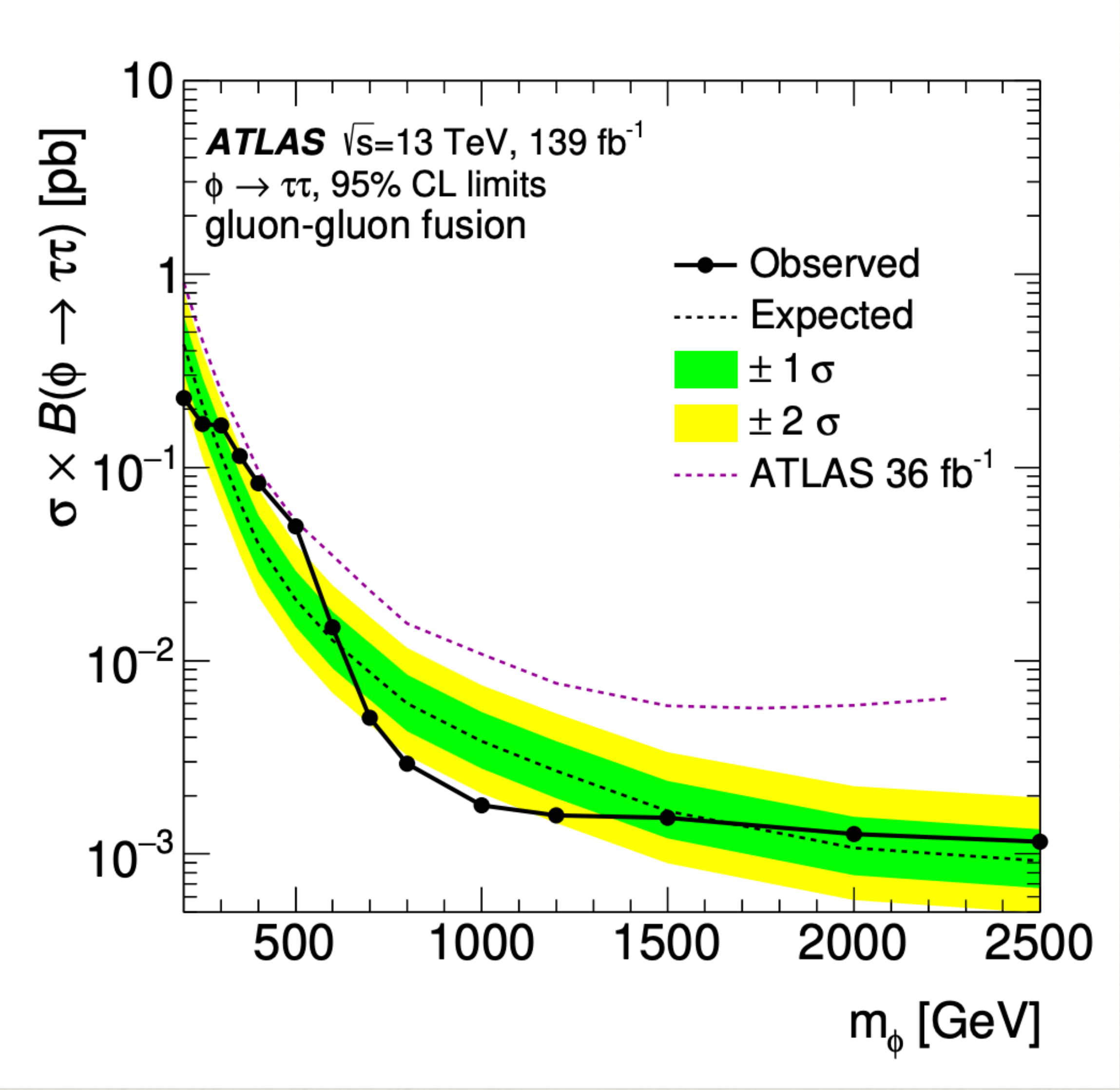
R(K) measurement
3.1 σ

muon magnetic moment, W mass measurements and more ….

Current situation

Better background modelling

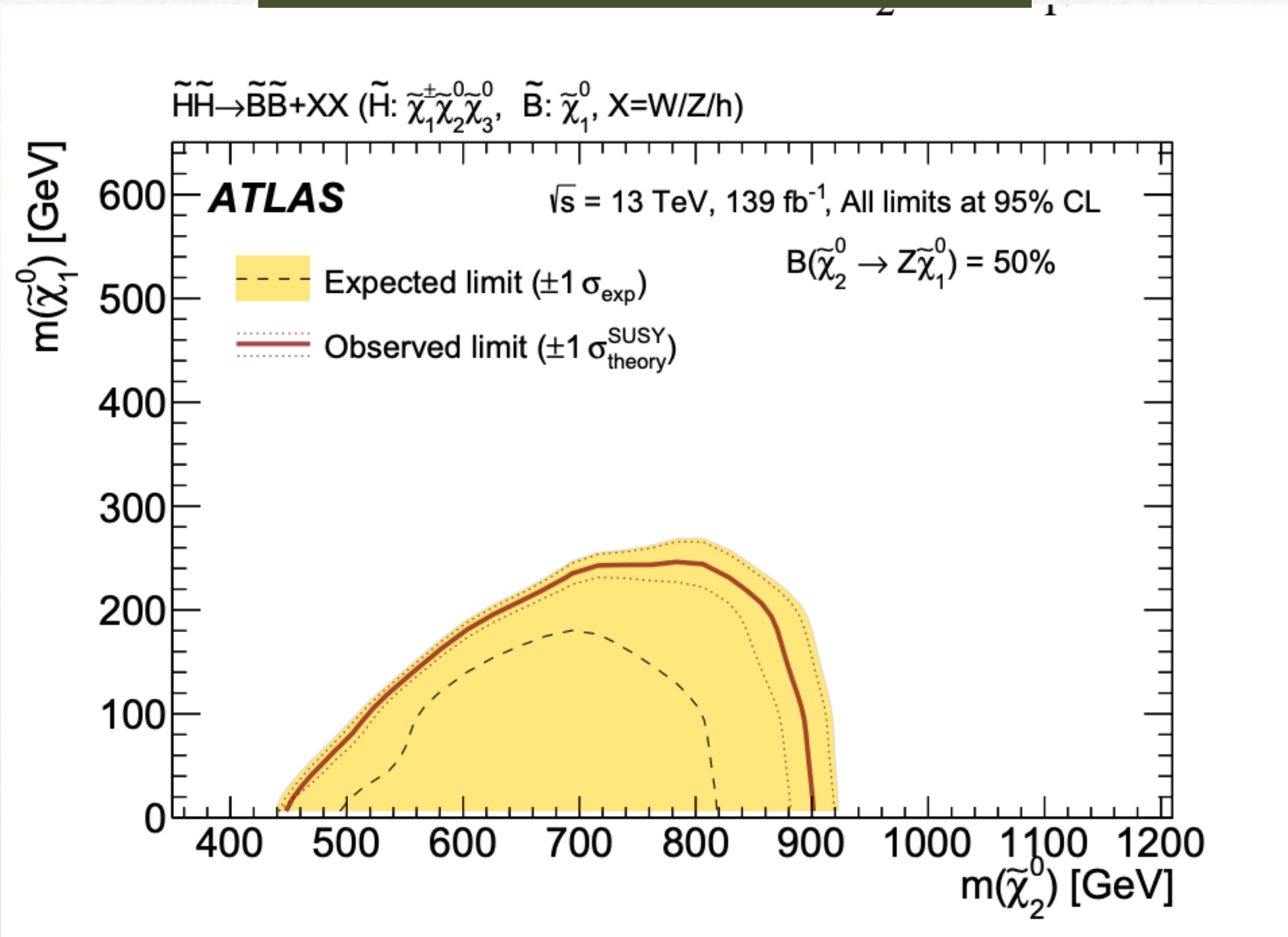
HEP-EX: 2002.12223



Heavy Higgs in tau channel

Better exclusion using New channels

HEP-EX: 2108.07586

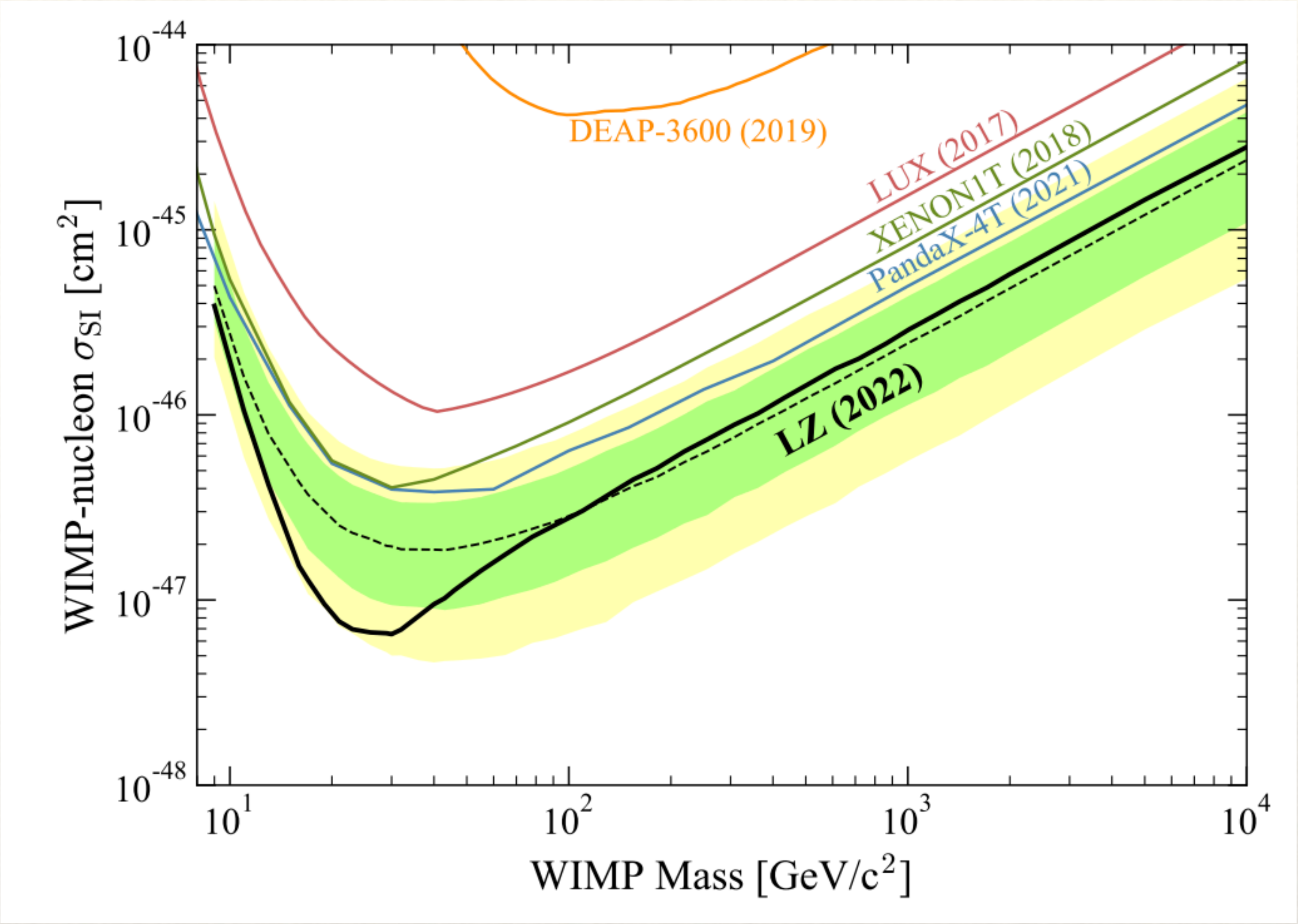


(d) $(\tilde{H}, \tilde{B})$ with $\mathcal{B}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0) = 50\%$

higgsino limit hadronic channel

Complementarity

HEP-EX: 2207.03764



Direct detection limit by LZ collaboration

+ Higgs signal strengths + Flavour data + CMS + ATLAS + Xenon1T

Is the light neutralino thermal dark matter in the MSSM ruled out?
(HEP-PH :2207.06238 BY BARMAN , BELANGER , BB , GODBOLE , SENGUPTA)

Where is new physics hiding ?

TeV scale New physics already ruled out ?

What do we expect next ?

LHC Run3 and HL-LHC

LHC statistics :

Run 1 : 2010-2011	$\sqrt{s} = 7$ TeV	Integrated Luminosity ~ 5 fb^{-1}
2012	$\sqrt{s} = 8$ TeV	Integrated Luminosity ~ 20 fb^{-1}
Run 2: 2015-2018	$\sqrt{s} = 13$ TeV	Integrated Luminosity ~ 140 fb^{-1}
Run 3: 2022 -	$\sqrt{s} = 13.6$ TeV	Integrated Luminosity ~ 200fb^{-1} ?
Run 4: 2026- ?	$\sqrt{s} = 13.6/14??$ TeV	Integrated Luminosity ~ 3000 fb^{-1}

- LHC has collected and analysed about 5% of the full data expected
- Run 3 has started this year and one of the major goals to confirm/exclude anomalous results
- B-parking and Scouting data analysis by CMS and ATLAS analysis should be able to help us understand flavour physics anomalies
- New detector FASER(ForwArd Search Experiment) dedicated for light long-lived particles will take data throughout Run 3

Search limits: Light vs Heavy

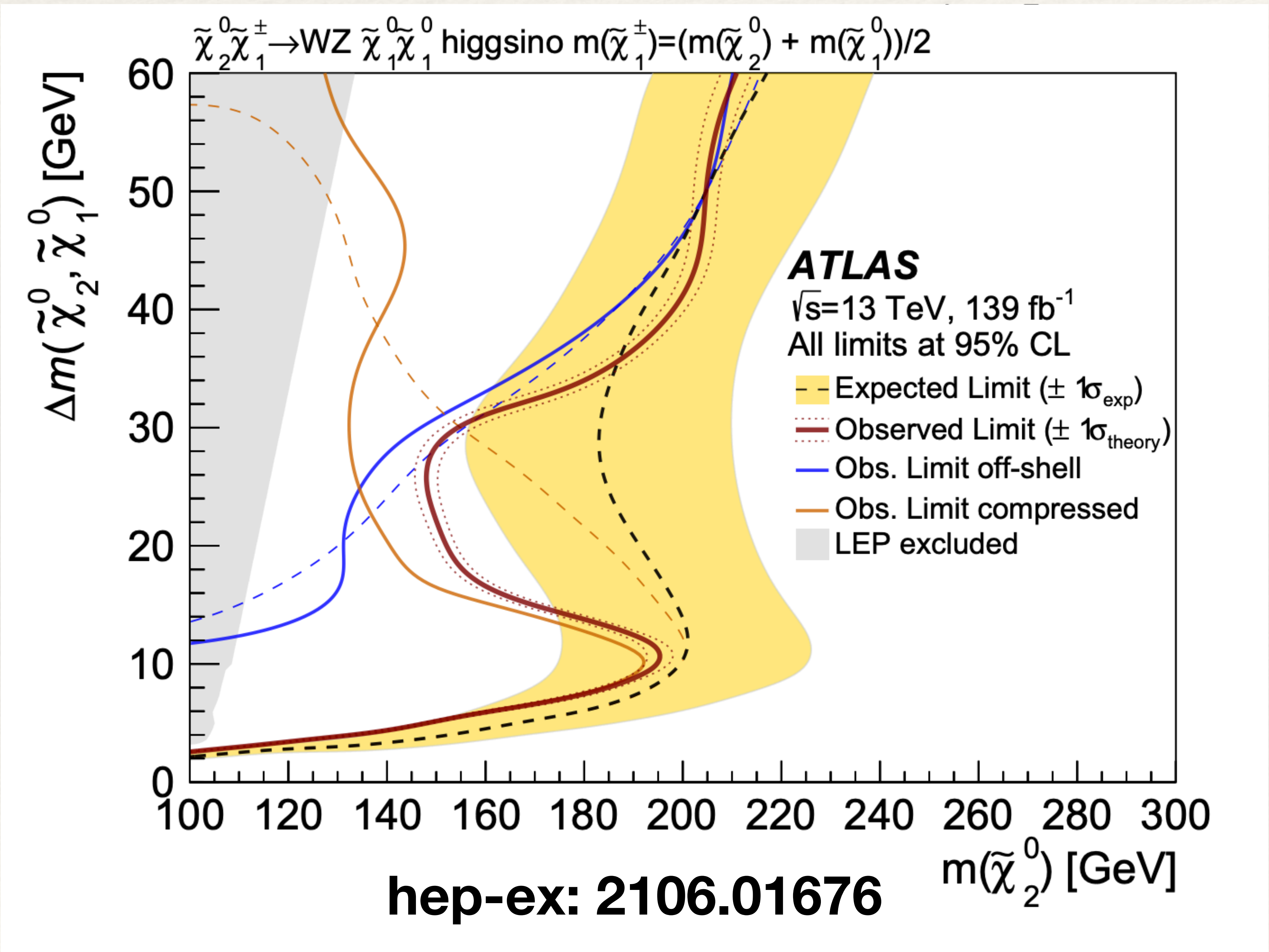
Decay products of heavy particles => generally more energetic compared to particles fromSM processes

Easier to detect => already highly constrained

Limits are almost saturated ==> increase in luminosity will not help improve the limit drastically

Light particle searches ==> high SM backgrounds

$$pp \to h_{125} \to \phi\phi,\ \phi \to \tau\tau$$



Mass limit below 200 GeV

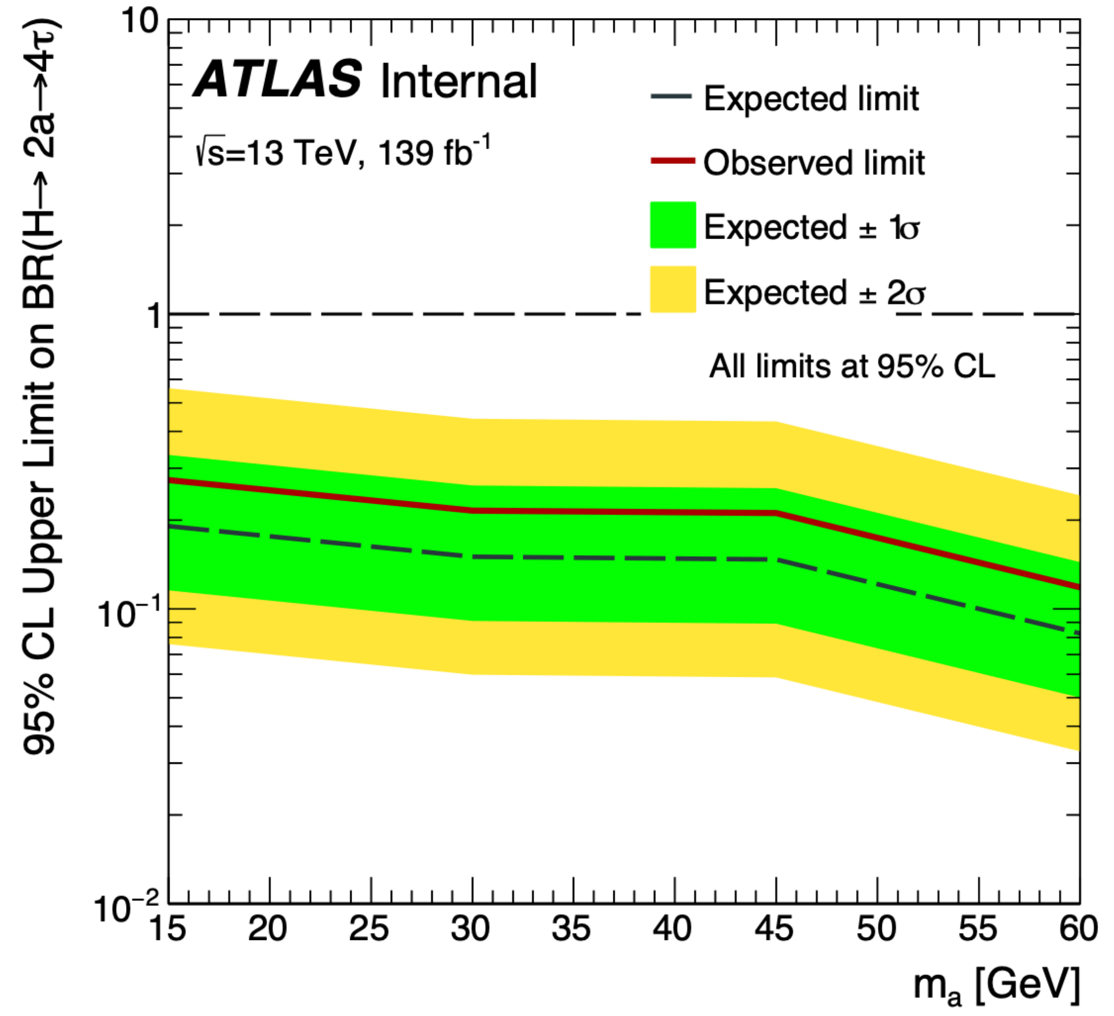


Figure 7.16: The 95% CL upper limit on the branching ratio of $\mathrm{Br}(H \to 2a \to 4\tau)$ in the $\mu\mu$ channel. The expected limit is shown in dashed line and the observed limit is in red solid line.

Thesis of HUACHENG CAI. Link

Branching above 10% Ruled out

HL-LHC sensitivity: $\mathrm{Br}(h \to aa \to 4\tau) \sim$ 0.06% (0.07%), assuming 0% (5%) systematic uncertainty for m_a= 60 GeV

Adhikary, Banerjee, Barman, Batell, BB, Bose, Qian, Spannowsky arXiv: 2211.xxxxx

Unconventional Signatures

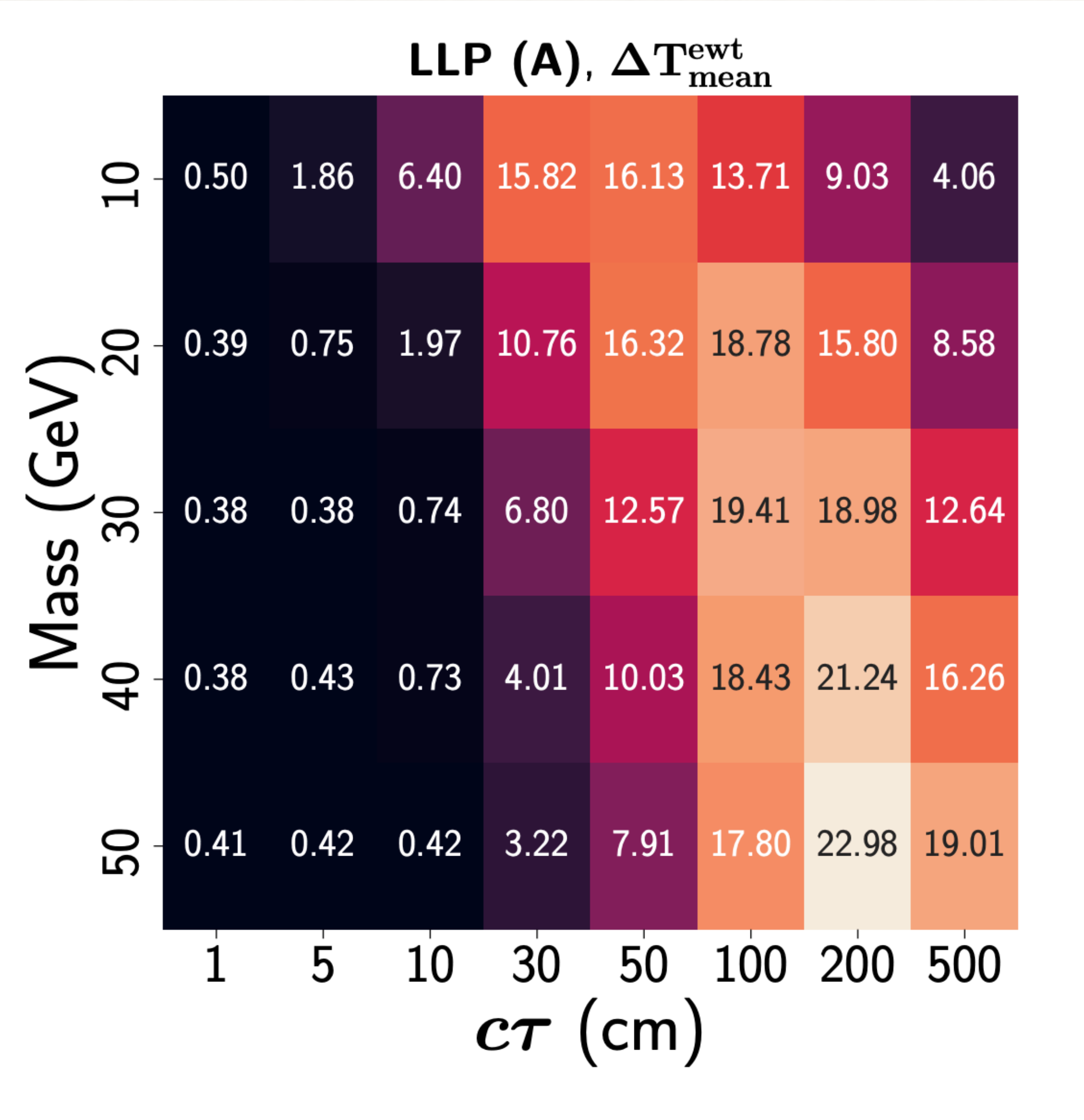
- Addition of timing layers in CMS and ATLAS (Pile-up rejection at HL-LHC)
- Displaced Tracking at L1 and combination of Timing will hugely boost LLP searches
- Inclusion of HGCAL, Possibility of dedicated LLP detectors like CODEX, Mathusla

Consider an example of LLP search: $pp \rightarrow h_{125} \rightarrow \phi_{dark}\phi_{dark}$

BB,GHOSH, SENGUPTA, SOLANKI JHEP 2022

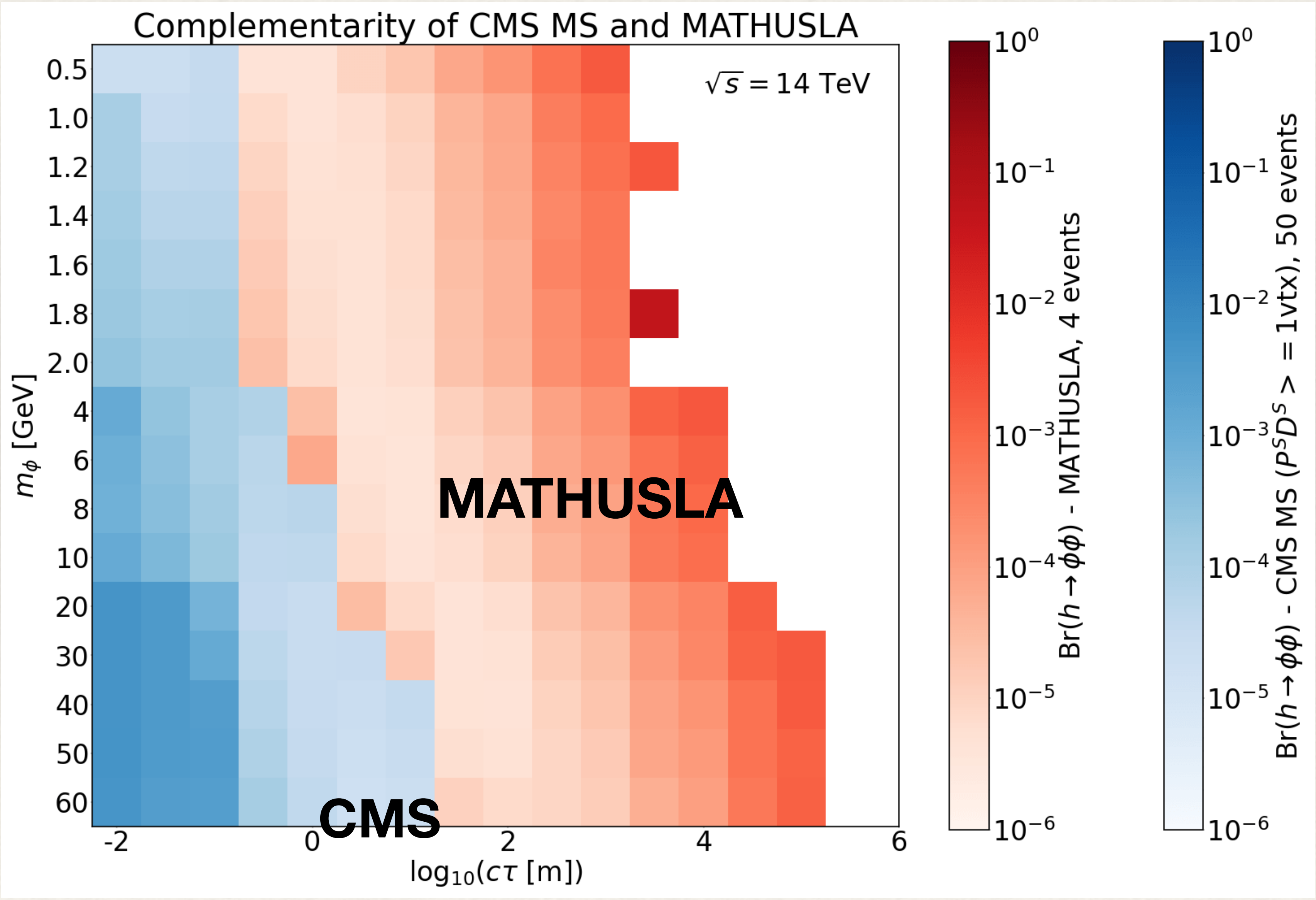
Efficiency Grid

ECAL Timing



HL-LHC sensitivity to $Br(h \rightarrow \phi\phi)$ $\sim 10^{-5}$

BB, MATSUMOTO, SENGUPTA PRD 2022



Complementarity of the CMS analyses using the muon spectrometer and the MATHUSLA LLP detector at 14 TeV with an integrated luminosity of 3000 ifb

HGCAL Study by

LIU, J., LIU, Z., WANG, L.T., WANG, X.P. JHEP11(2020)066

Displaced tracks at L1, combination with timing can potentially improve the sensitivity

BB,GHOSH, SENGUPTA, SOLANKI JHEP 2022 AND BB, MUKHERJEE, SENGUPTA, SOLANKI JHEP 2020

Flavour Physics and Dark Matter detection

BELLE-II :

Collected ~ 400 fb^{-1} data, expected to collect 50 ab^{-1}. Should be able to reach 5 ab^{-1} in 10 years ,
Uncertainties in BELLE on RK and RK* is ~ 25-30% (will be reduced to 10% using 5 ab^{-1}) ,

BELLE-II will also require a few ab^{-1} data to tell us whether RD* anomaly comes from systematic error or statistical

(PTEP 2019 , 12 , 123C01)

BELLE-II : also sensitive to LLP searches: proposal of dedicated LLP detectors.

A. Dark matter detection :

LZ, XENONnt, PANDAX-4T …

B. Dark matter indirect detection:

- Many experiments: Fermi, IceCube, HESS, VERITAS, AMS-02 …..
- Future Experiments : CTA, SWGO, IceCube-Gen2 , AMS-100 ?

DETAILED DISCUSSIONS

IN THE SNOWMASS REPORT :

2209.07426

Summary so far ..

There is always a chance to find the new physics in the near future

Nothing guaranteed !!

Summary so far ..

There is always a chance to find the new physics in the near future

Why do we need high energy hadron collider in future?

Consider three speculative scenarios supporting High Energy hadron collider

Scenario A: Most optimistic

Late discovery of some new heavy particle(X) at the kinematic edge of LHC

Example : Discovery of higgsino-like particle at the HL-LHC, no trace of other SUSY particles

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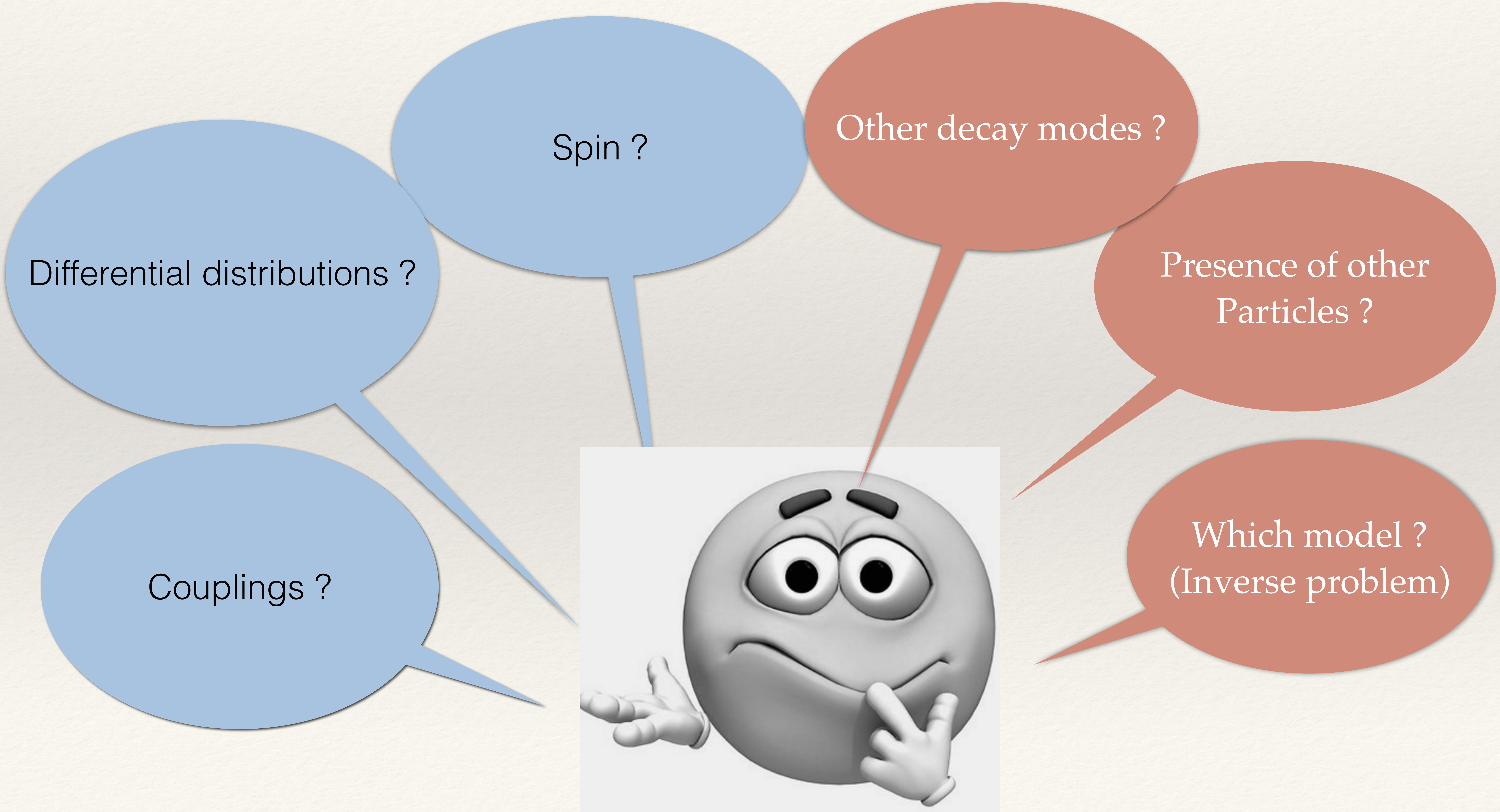
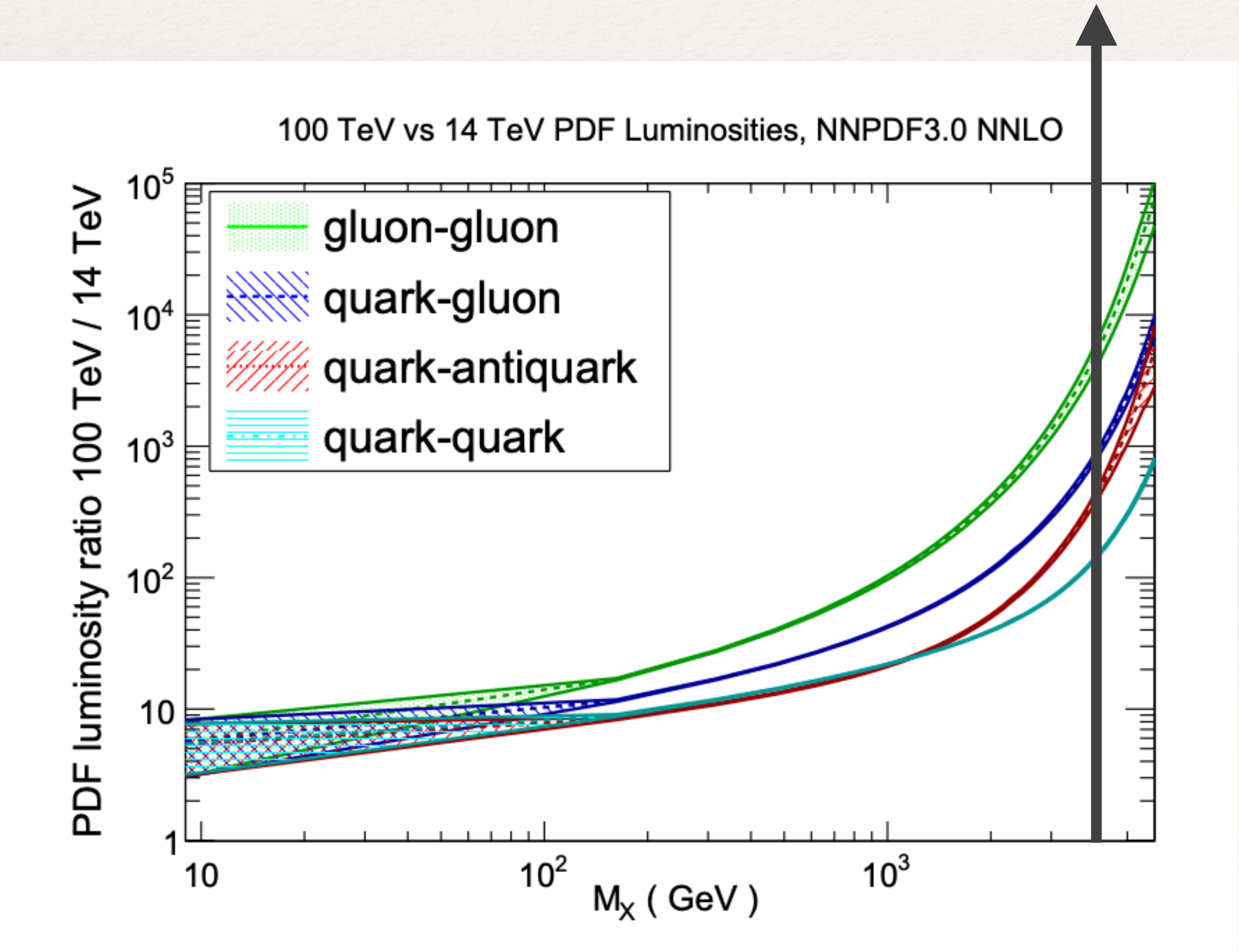


Future Circular Collider(FCC-hh)

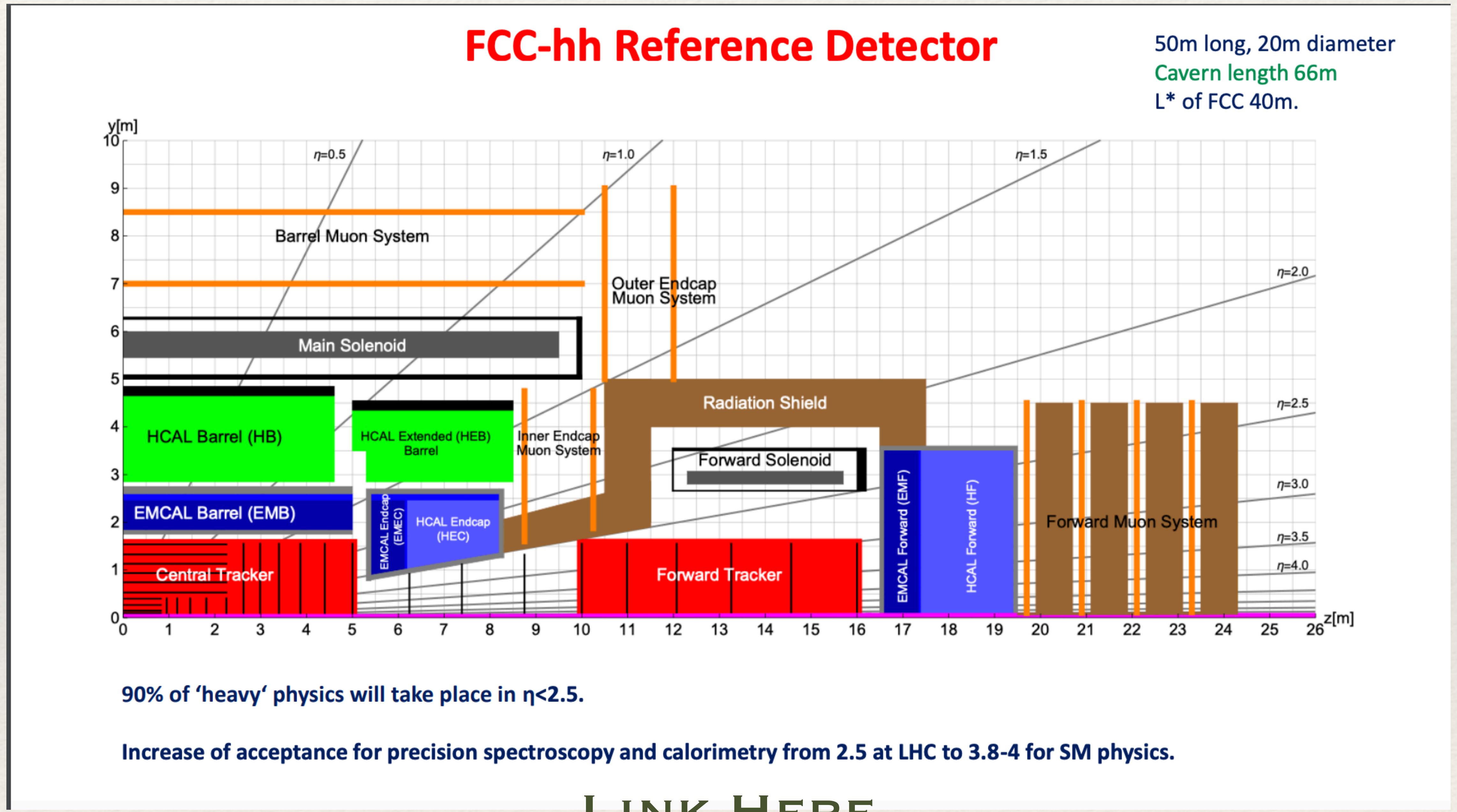
International FCC collaboration has been working on the design for PP collider at the CoM energy 100 TeV

- Conceptual Design Report (CDR) published in 2019
- 25 years of run can accumulate 20k-30k fb^{-1} of data
- 2 main detectors will be placed (combination of results possible)
- For 125 GeV Higgs boson gain ~150 in the ggF channel and ~ 400 in the di-Higgs, ~ 500 in the ttH



Huge gain in the cross section for heavy particle

hep-ph:1607.01831



Link Here

$$\begin{aligned} \textbf{Tracker:} &\quad R \le 1.5\,\text{m}, \quad |Z| \le 5\,\text{m}, \\ \textbf{Barrel + Endcap MS:} &\quad 6\,\text{m} \le R \le 9\,\text{m}, \quad 9\,\text{m} \le |Z| \le 12\,\text{m}, \quad \eta \le 2.5, \\ \boxed{\textbf{Forward MS:} \quad 12\,\text{m} \le |Z| \le 23\,\text{m}, \quad 2.5 \le \eta \le 5.0.} & \end{aligned} \tag{4.1}$$

SUSY

Strong sector : squarks and gluinos(33/100 TeV)

HEP-PH: 1606.00947

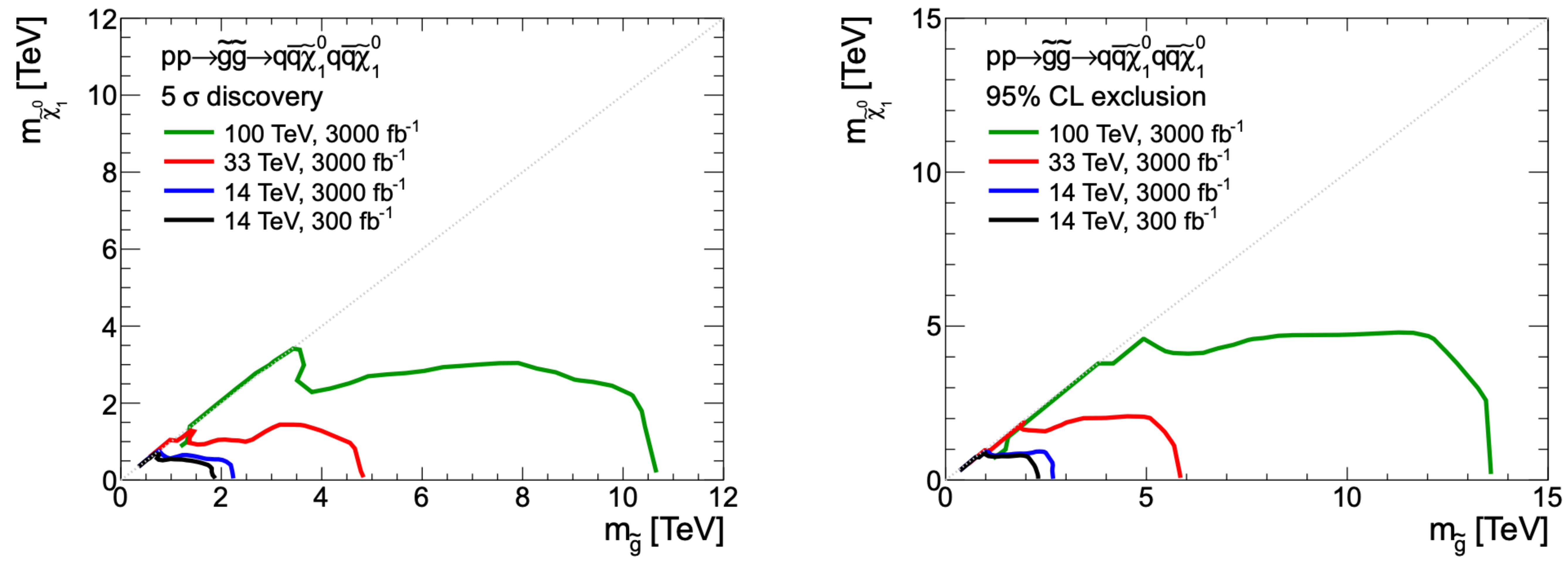


Fig. 13: Results for the gluino-neutralino model with light flavor decays. The left [right] panel shows the 5σ discovery reach [95% CL exclusion] for the four collider scenarios studied here. A 20% systematic uncertainty is assumed and pile-up is not included.

HEP-PH: 1407.5066

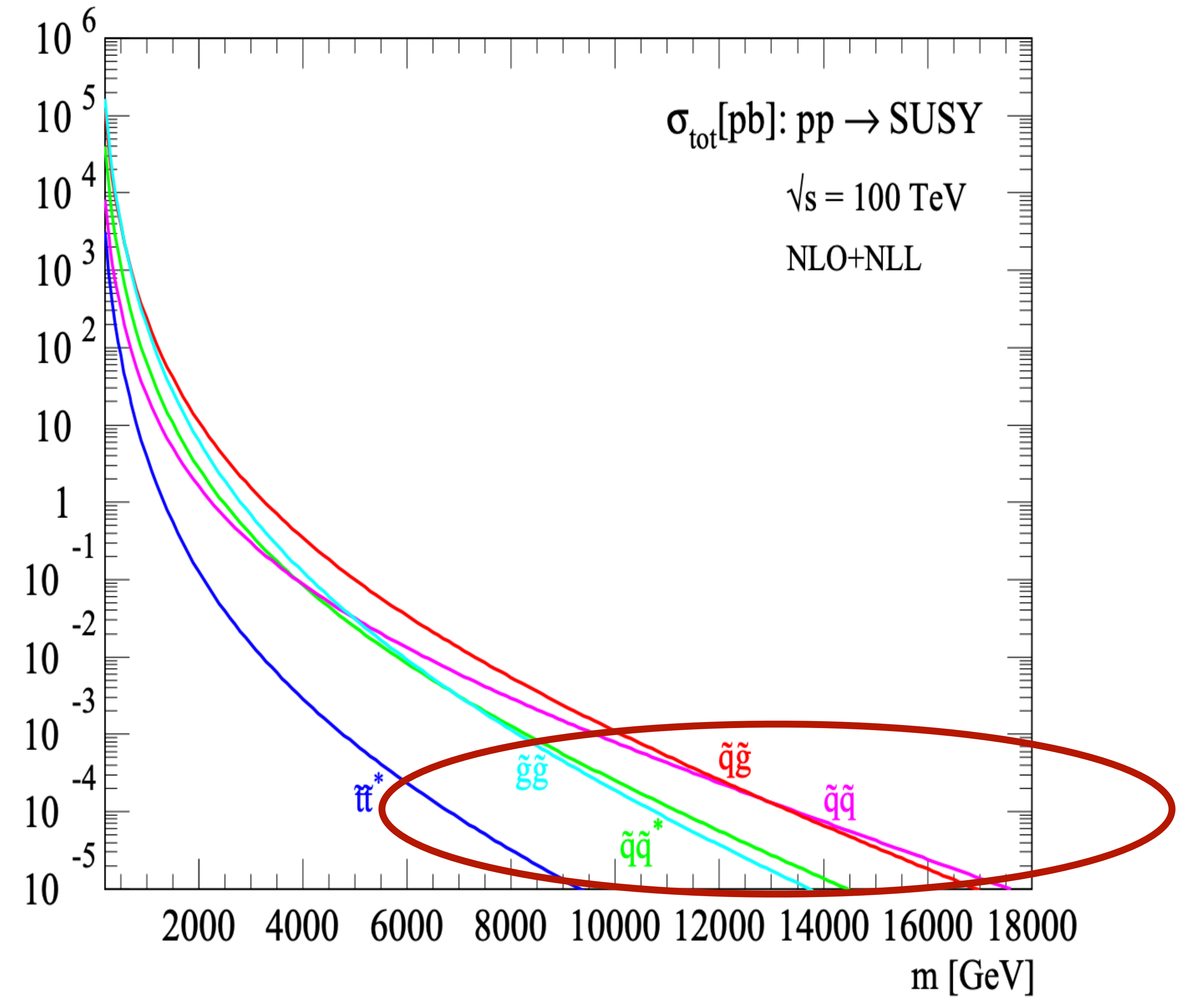


Figure 4: NLO+NLL production cross sections for the case of equal degenerate squark and gluino masses as a function of mass at $\sqrt{s} = 100$ TeV.

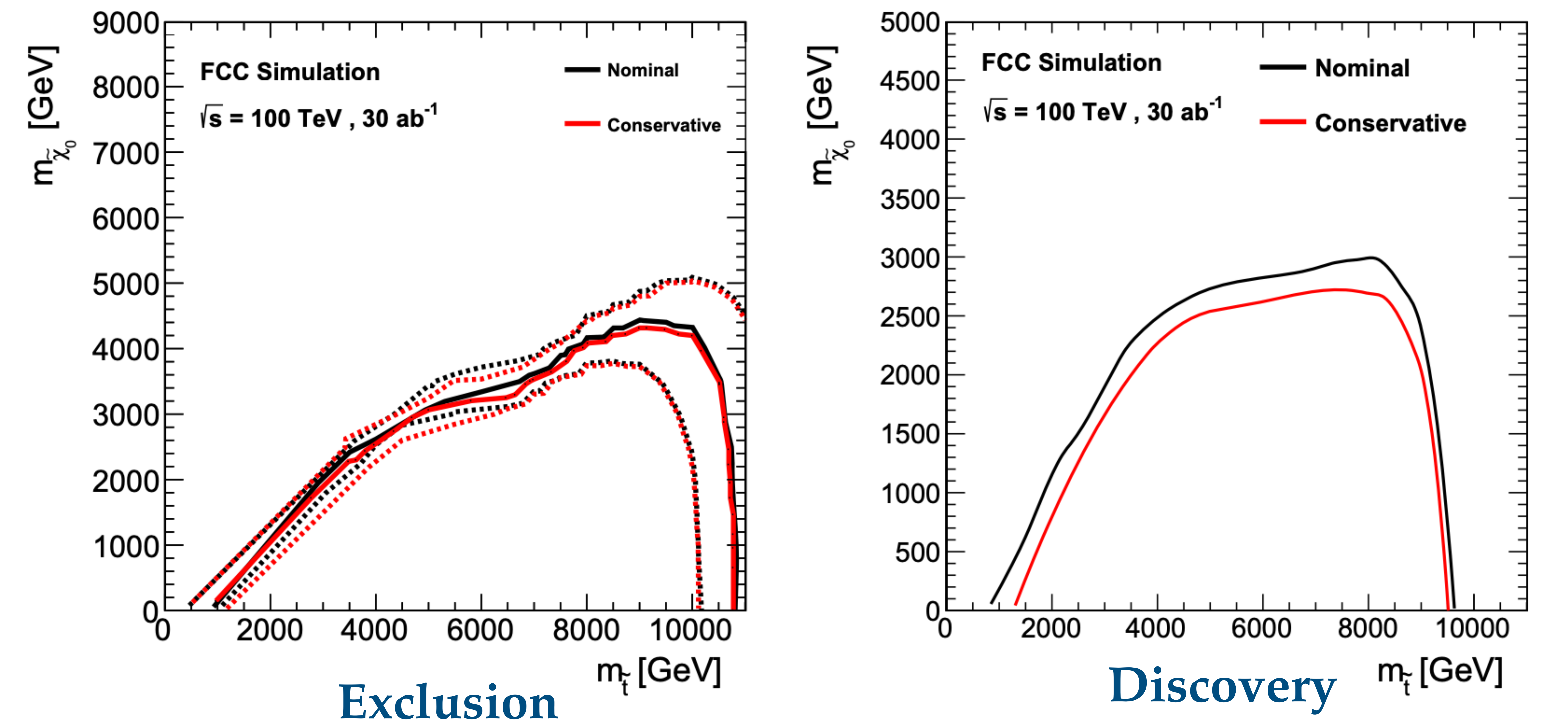
20 percent systematic uncertainty, Integrated Luminosity= 3000 fb^{-1}

100 TeV Collider	33 TeV Collider
Discovery reach ~ 10 TeV	Discovery reach ~ 5 TeV
Exclusion reach ~ 14 TeV	Exclusion reach ~ 6 TeV

SUSY

Stops squarks at 100 TeV

FCC Conceptual Design Report Vol 1 (2018)



$\tilde{t} \to t\chi_0^1$ decay mode considered

High pt jets, at least on b tagged
Jet substructure techniques
At least one top tagged jet
For ultrahigh pt jets track-based substructure used

HEP-PH: 1406.4512,
CERN-ACC-2019-0036

Nominal : 10 % systematic uncertainty
Conservative: 20% systematic uncertainty

BSM Higgs

1504.07617

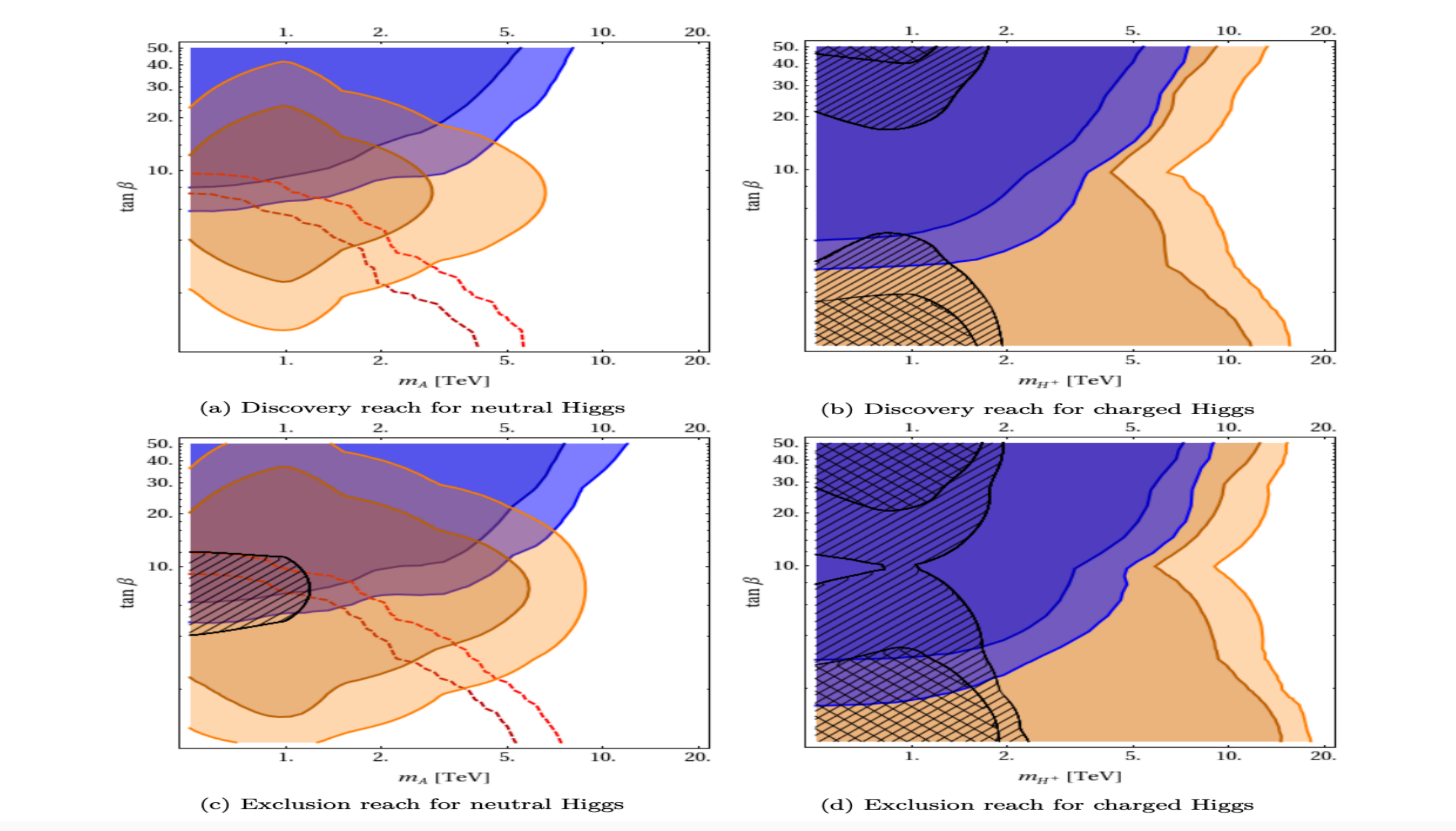
Channels considered

$pp \to bbH/A \to bb\tau\tau/bbtt$

$pp \to H/A \to tt$

$pp \to ttH \to tttt$

$pp \to tbH^{+} \to ttbb, tb\tau\nu$



(a) Discovery reach for neutral Higgs (b) Discovery reach for charged Higgs

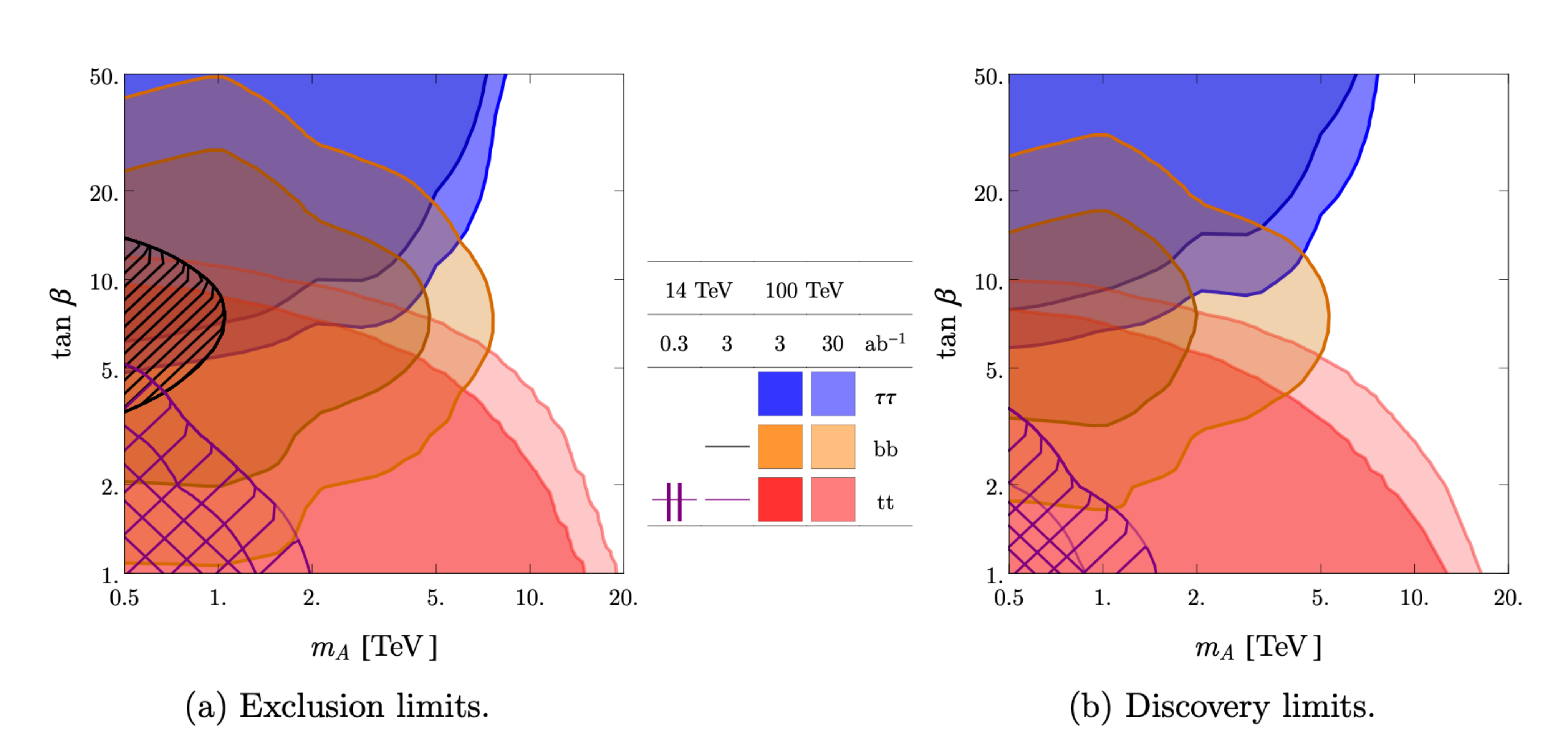
(c) Exclusion reach for neutral Higgs (d) Exclusion reach for charged Higgs

- Limit calculated at the 100 TeV collider assuming a CMS like detector
- Tracker eta coverage up to 3.5
- Assumed luminosity : 3ifb and 30ifb
- Multivariate BDT techniques applied
- BDT based top tagger used

1605.08744

Heavy Higgs production in association with Top quark(s)
Heavy Higgs ->. Top quarks

At least 3 top quarks can produce same-sign Di-lepton + MET final state



(a) Exclusion limits. (b) Discovery limits.

Same sign di-lepton channel

Exclusion range :

tan β range up to 15 and 18 TeV for 3 and 30 ab^{-1}, respectively.

Discovery reach

10 and 15 TeV for the same luminosities.

Associated heavy Higgs production with two bottom quarks and decays to a τ lepton pair channel sensitive to the large tan β range.

Combined results cover the whole tan β range up to ~5TeV.

Light scalar search in the di-Higgs channel also possible at 100 TeV :$pp \to hh, h \to \phi\phi, \phi \to \tau\tau$

5σ discovery at the FCC-hh through the Higgs pair production channel, provided Br(h → aa → 4τ) >~ 1%.

Adhikary, Banerjee, Barman, Batell, BB, Bose, Qian, Spannowsky arXiv: 2211.XXXXX

Scenario B: optimistic

No discovery at the LHC, However breakthrough comes from other experiments (Dark matter, Flavour physics , …)

Examples :

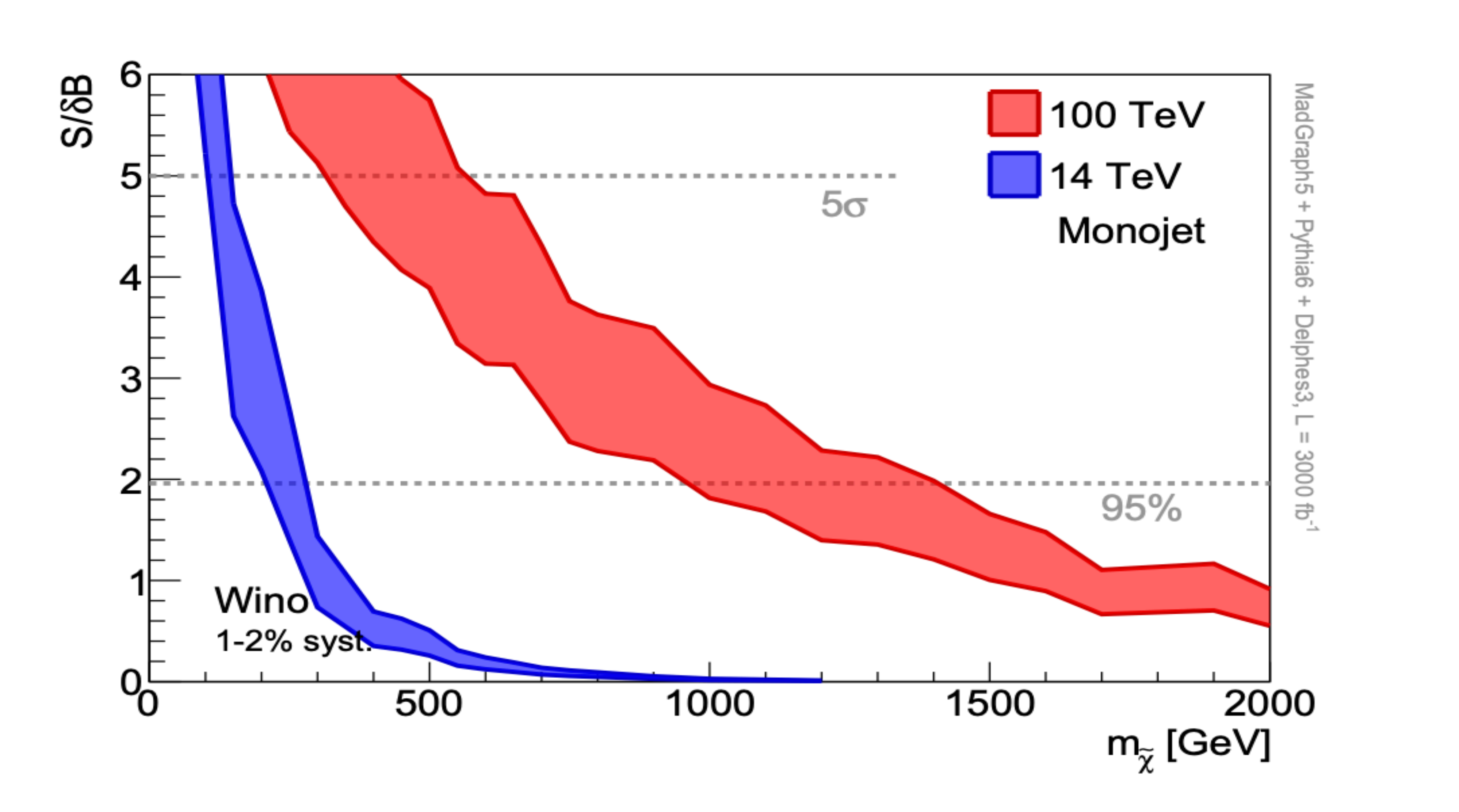
A. Dark matter signal in indirect detection / Direct detection
B. Flavour physics anomaly confirmed , or unified picture emerges from multiple anomalies

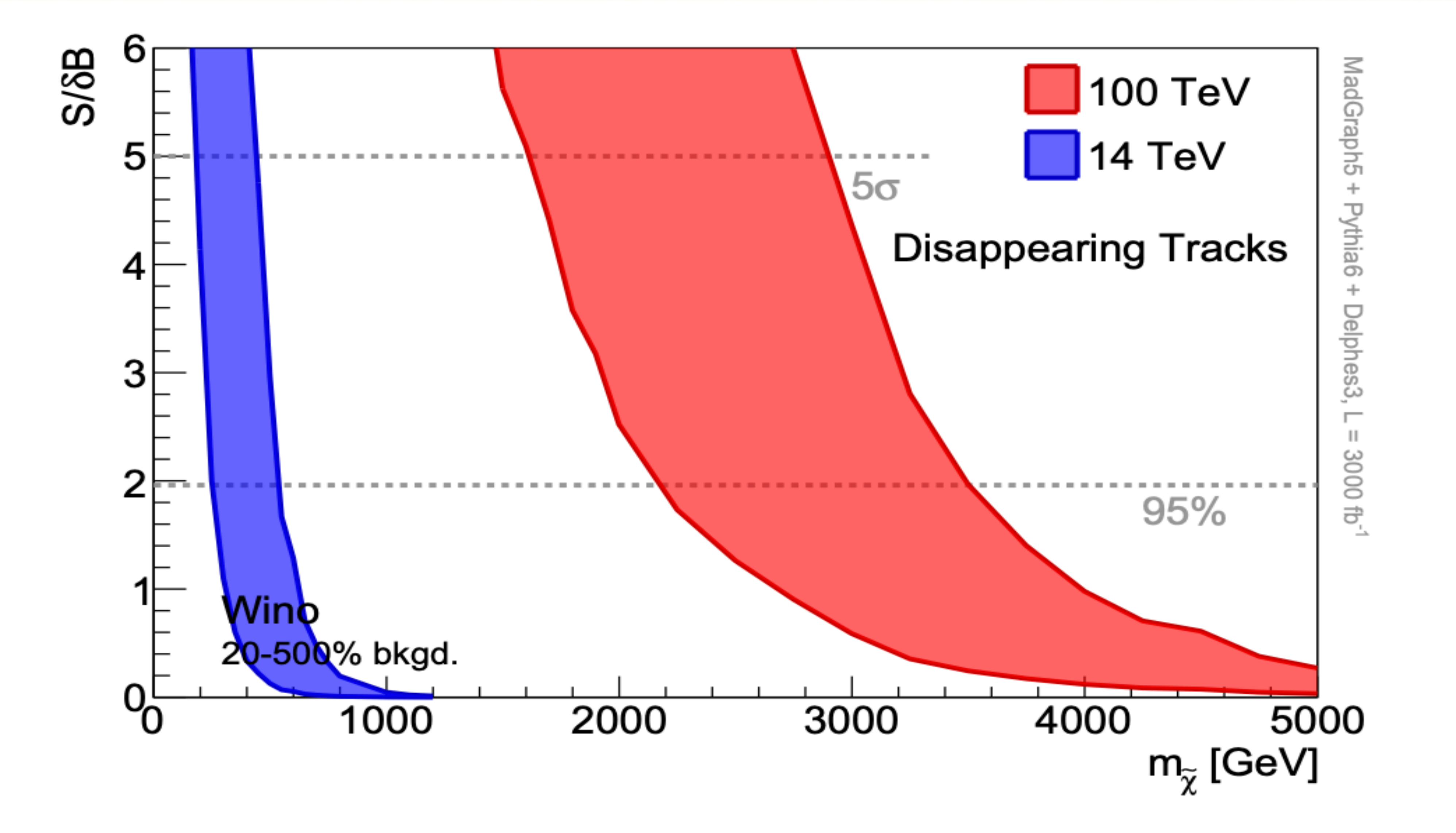
New physics scale may be bounded by the data

Similar story: W/Z discovery from Gargamelle experiment

Dark Matter@ 100 TeV

- FCC-hh will be able to probe huge dark matter parameter space in Mono-X + MET channel.
- Mediator searches will also be improved drastically
- Light DM-Higgs portal models : The Higgs to invisible Branching ratio will probed ~ 10^{-4} (CERN-ACC-2018-0045) .
- Disappearing track search will be sensitive to the full mass range of thermal relic parameter space.





Low and Wang, hep-ph: 1404.0682

Also see Han, Mukhopadhyay and Wang hep-ph: 1805.00015

Resonance searches

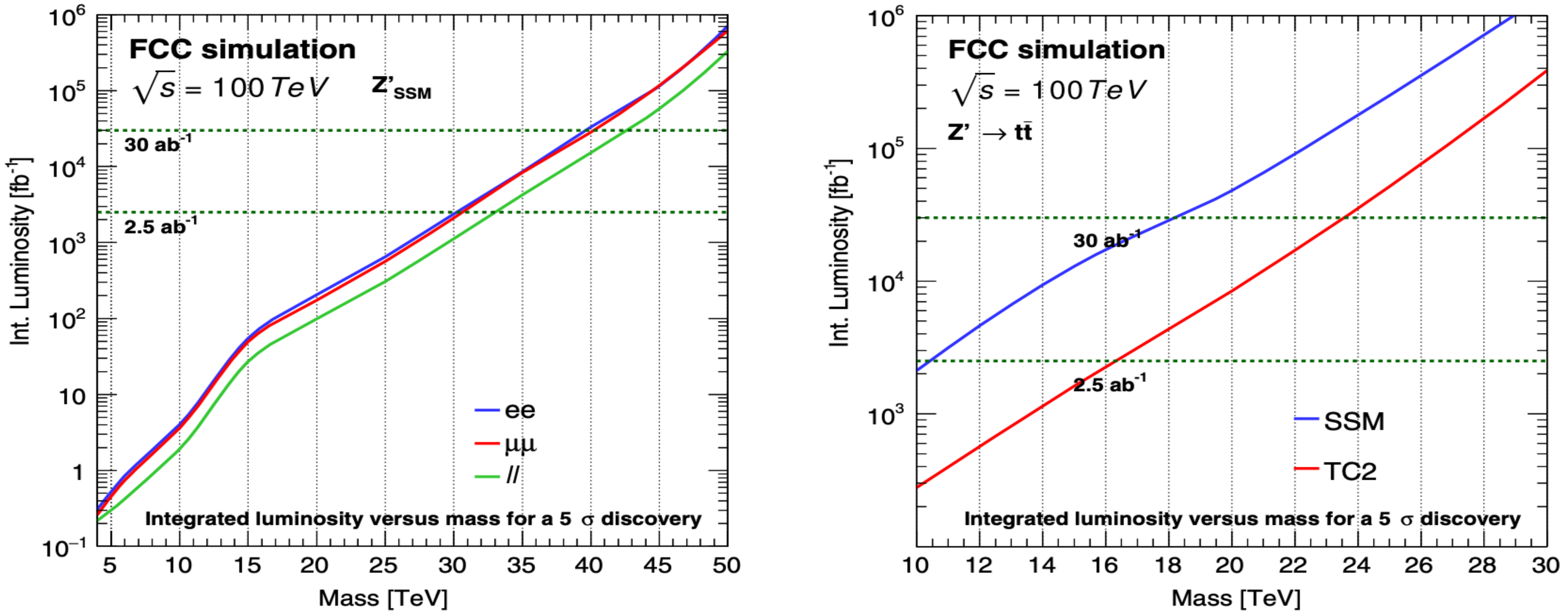


Fig. 1.1. Integrated luminosity required for a 5σ discovery, as a function of the mass, for a Z' gauge boson coupled with SM couplings and decaying to leptons (left) and to $t\bar{t}$ (right).

https://cds.cern.ch/record/2651300/files/CERN-ACC-2018-0058.pdf
https://cds.cern.ch/record/2642473/files/CERN-ACC-2019-0028.pdf

Anomaly motivated heavy resonance searches ==> huge improvement compared to LHC

Delphes study assuming more granular calorimeter compared to LHC

Scenario C: Nightmare Scenario ??

No hint of new physics at the LHC, dark matter, flavour ….

No idea about the scale of the new physics:

Scenario C: Nightmare Scenario ??

No hint of new physics at the LHC, dark matter, flavour ….

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Even in this case future hadron collider will be the best option for new physics searches.

Fcc-hh : will gain both in the energy side and in the luminosity side

Definite goal : Higgs precision, Understand Higgs potential

Not so specific: goals discussed in Scenario A and B

Higgs Physics @ fcc-hh

	$gg \to H$ (Sect 3.1)	VBF (Sect 3.5)	$HW^{\pm}$ (Sect 3.4)	HZ (Sect 3.4)	$t\bar{t}H$ (Sect 3.6)
σ(pb)	802	69	15.7	11.2	32.1
σ(100 TeV)/σ(14 TeV)	16.5	16.1	10.4	11.4	52.3

1606.09408

Huge improvement in statistics

2.4 $10^{10.}$ Higgs from gluon fusion (factor of ~ 180)

FCC-hh

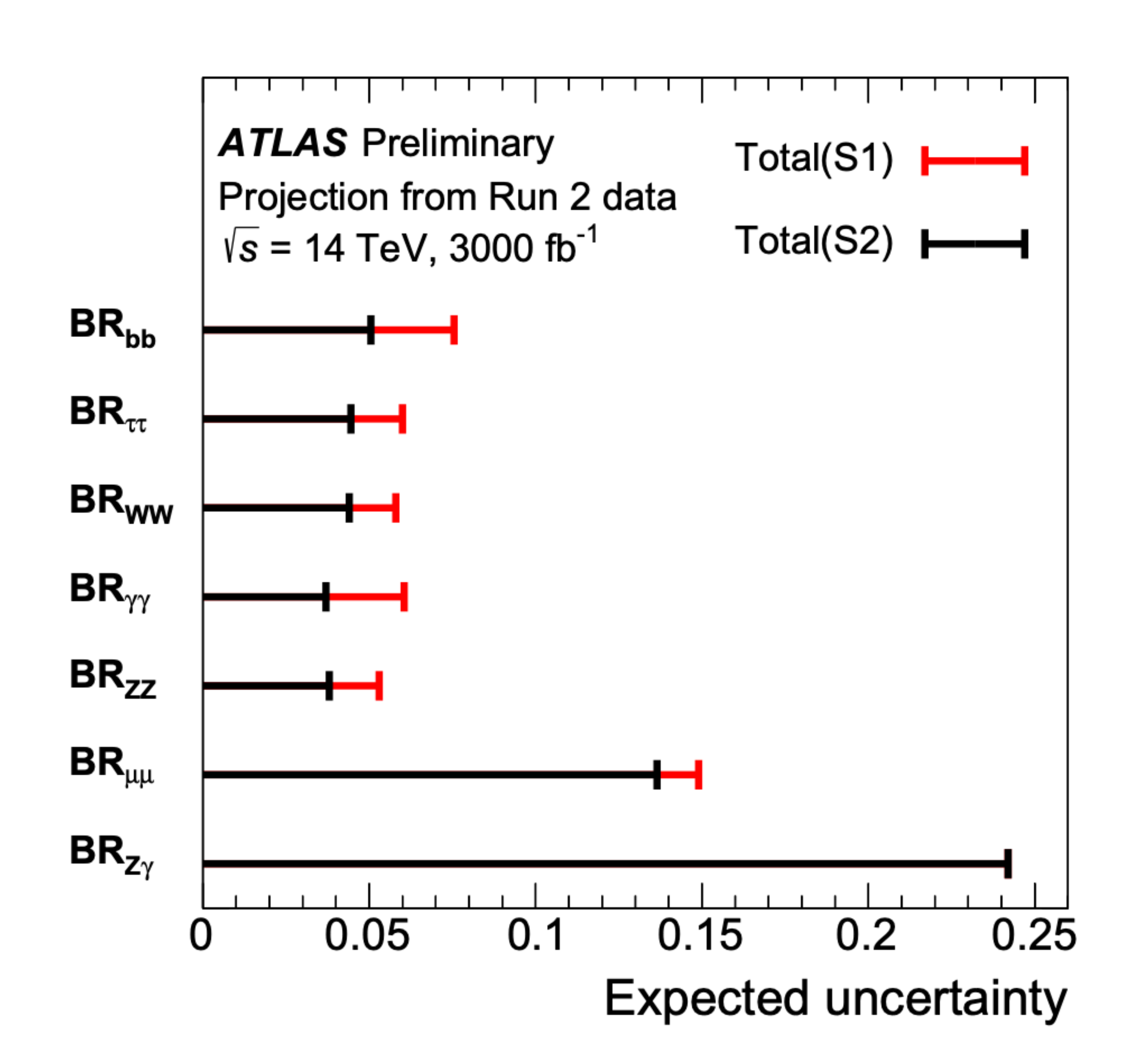
Table 1.2. Target precision for the parameters relative to the measurement of various Higgs decays, ratios thereof, and of the Higgs self-coupling λ.

Observable	Parameter	Precision (stat)	Precision (stat+syst+lumi)
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\to \mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\to 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\to \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$\mu = \sigma(\mathrm{HH}) \times \mathrm{B}(\mathrm{H}\to\gamma\gamma)\mathrm{B}(\mathrm{H}\to b\bar{b})$	$\delta\lambda/\lambda$	5%	7.0%
$R = \mathrm{B}(\mathrm{H}\to\mu\mu)/\mathrm{B}(\mathrm{H}\to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = \mathrm{B}(\mathrm{H}\to\mu\mu\gamma)/\mathrm{B}(\mathrm{H}\to\mu\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(t\bar{t}\mathrm{H}) \times \mathrm{B}(\mathrm{H}\to b\bar{b})/\sigma(t\bar{t}\mathrm{Z}) \times \mathrm{B}(\mathrm{Z}\to b\bar{b})$	$\delta R/R$	1.05%	1.9%
$B(\mathrm{H}\to$ invisible)	B@95%CL	1×10^{-4}	2.5×10^{-4}

Notes. Notice that Lagrangian couplings have a precision that is typically half that of what

https://cds.cern.ch/record/2651300/files/CERN-ACC-2018-0058.pdf

HL-LHC



ATL-PHYS-PUB-2018-054

Higgs pair Production at future hadron collider

- BSM effects could affect the measurement of Higgs self-coupling λ
- HL-LHC will not be able to measure λ very precisely (statistically limited sample)
- Future hh collider will provide the unique opportunity

- **27 TeV studies in different channels (XGBOOST)**
- **Adhikary, BB and Barman JHEP 12 (2020) 179**

Channel	Statistical Significance
$b\bar{b}\gamma\gamma$	9.5-12.5
$b\bar{b}\tau\tau$	~5
$b\bar{b}WW^*$	~2.75
$\gamma\gamma WW^*$	~2
$b\bar{b}ZZ^*$	1+1

- Many dedicated studies available for FCC-hh (30 times enhancement in cross section)
- **Yao(1308.6302); Fuks,Kim and Lee, PRD 93 (2016) 3; Papaefstathiou, PRD 91 (2015) 11; Barr et.al., JHEP 02 (2015) 016; Banerjee et.al, Eur.Phys.J.C 78 (2018) 4, 322; Borgonovi et.al., CERN-ACC-2018-0045; Blas et.al., JHEP 139(2020); Mangano, Ortona,Selvaggi 2004.03505 + many more ...**
- λ can be measured with a few percent precision (significance dominated by bb$\gamma\gamma$ channel)

Top quark physics

- Top quark cross section at 100 TeV FCC-hh is ~ 30 nb (more than 30 times larger than at 14 TeV LHC) ==> Rare decay modes of top quark can be studied easily)
- $t \to hq$ or $t \to q\gamma$ decay modes are extremely suppressed in the SM (HEP-PH: 0409342)
- New physics can enhance such rare decay modes (HEP-PH: 9705341,1311.2028)

FCC-hh Projection (Delphes studies):

$Br(t \to c\gamma) \sim 2\ 10^{-7}$ $Br(t \to ch) \sim 4\ 10^{-5}$ (FCC STUDY GROUP:1812.00902)

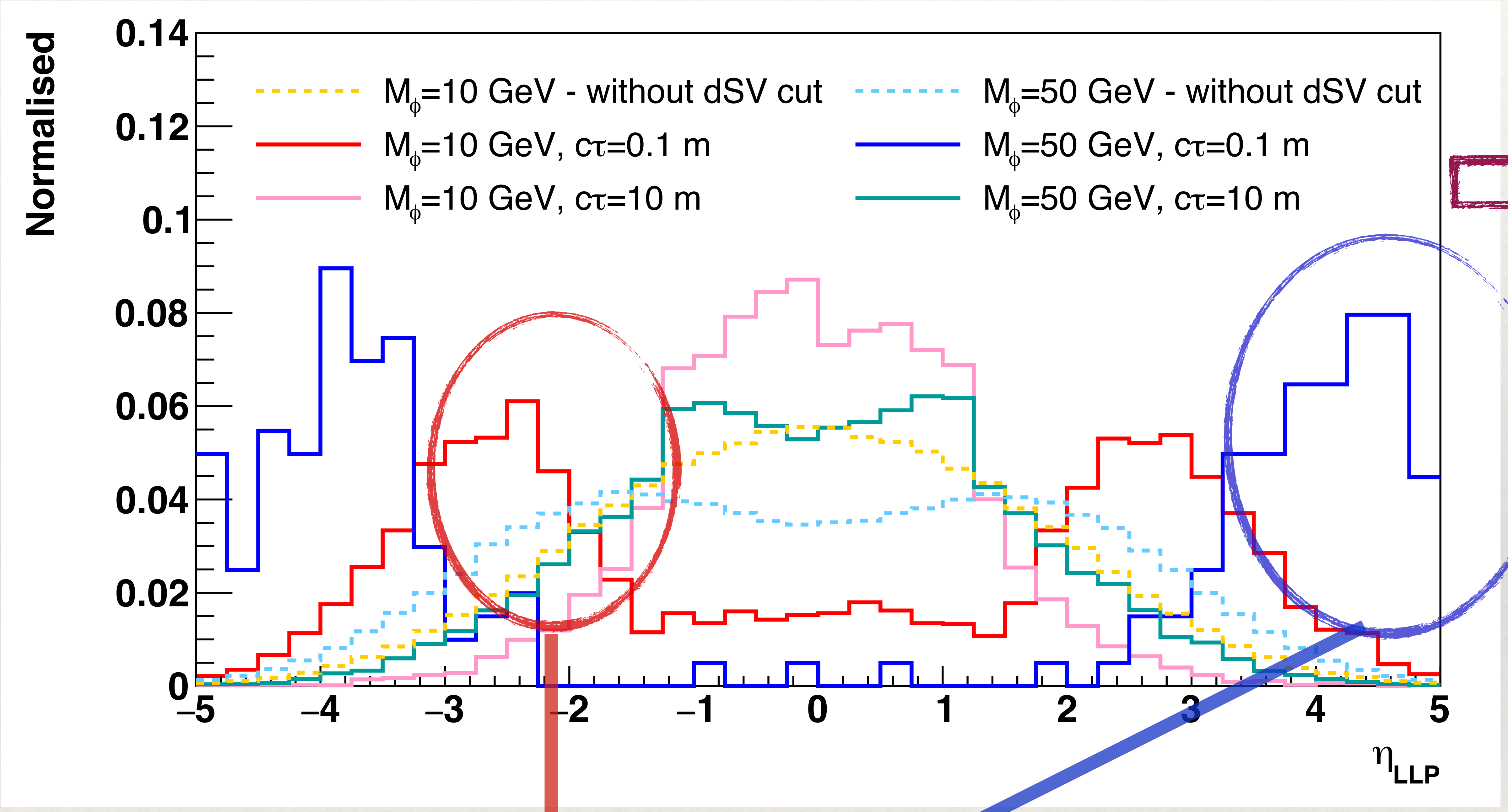
Current precision (ATLAS 13 TeV 36 fb^{-1}): $Br(t \to ch) \sim 1.6\ 10^{-3}$

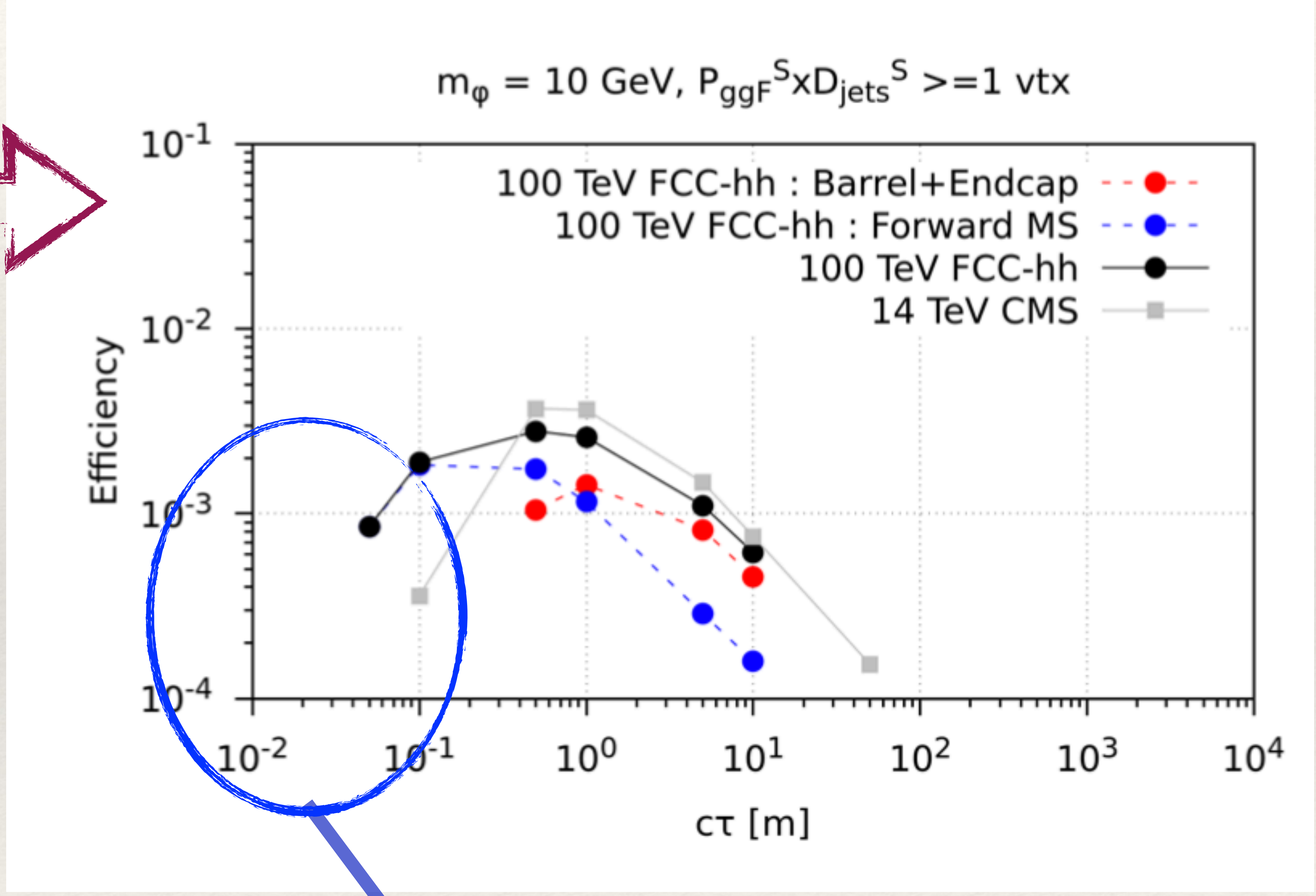
- **Huge enhancement in the 4 top cross section** $\sigma_{t\bar{t}t\bar{t}} \sim 5000$ **fb at** 100 **TeV** (1607.01831) ($\sigma_{t\bar{t}t\bar{t}} \sim 12$ **fb at** 14 **TeV**)

Extra capabilities of Future Collider

Role of forward Muon spectrometer for light LLP searches

BB, Matsumoto, Sengupta PRD 2022





LLPs more in forward direction for lower $c\tau$ when decay is restricted within MS

Forward MS increases sensitivity to lower decay lengths

Dedicated LLP Detector at FCC-hh(DELIGHT)

Advantage: The collider, as well as the detectors, are not yet constructed, possible to optimise the position as well as the size of the detector to maximise its sensitivity, rather than finding empty spaces near the various IPs to place and fit the LLP detectors for the HL-LHC experiment.

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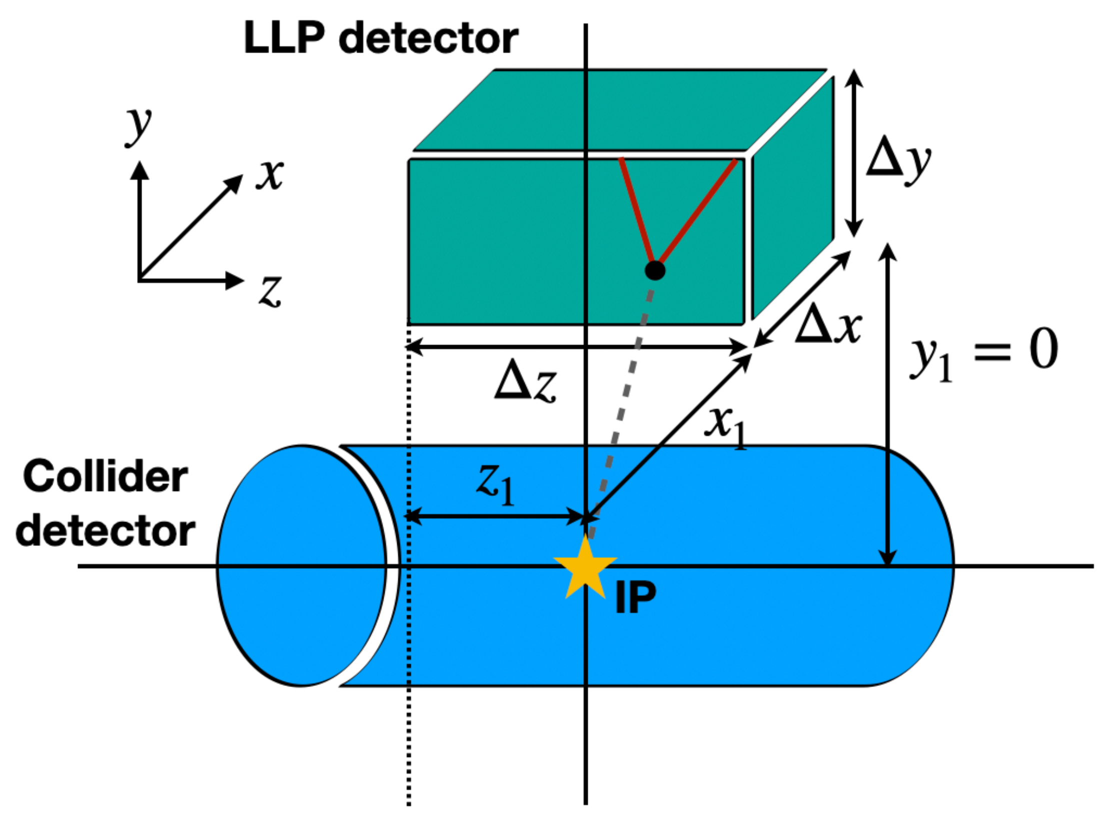
Advantage: The collider, as well as the detectors, are not yet constructed, possible to optimise the position as well as the size of the detector to maximise its sensitivity, rather than finding empty spaces near the various IPs to place and fit the LLP detectors for the HL-LHC experiment.

We here propose three designs of a dedicated LLP detector DELIGHT (Detector for long-lived particles at high energy of 100 TeV), a box-type detector in the periphery of the FCC-hh collider

A position starting at around 25 m in the x-direction around $\eta = 0$ region can be kept empty for placing a dedicated LLP detector.



DELIGHT (A): The same as the dimensions of the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 25 \times 100 \times 100\,\mathrm{m}^3$.

DELIGHT (B): Four times bigger than the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 100 \times 100 \times 100\,\mathrm{m}^3$.

DELIGHT (C): The same decay volume as the MATHUSLA detector with different dimensions, i.e. $\Delta x \times \Delta y \times \Delta z = 200 \times 50 \times 50\,\mathrm{m}^3$.

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LLP detectors for FCC-ee is proposed here : 2011.01005

DELIGHT (A)

DELIGHT (A): The same as the dimensions of the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 25 \times 100 \times 100\,\mathrm{m}^3$.

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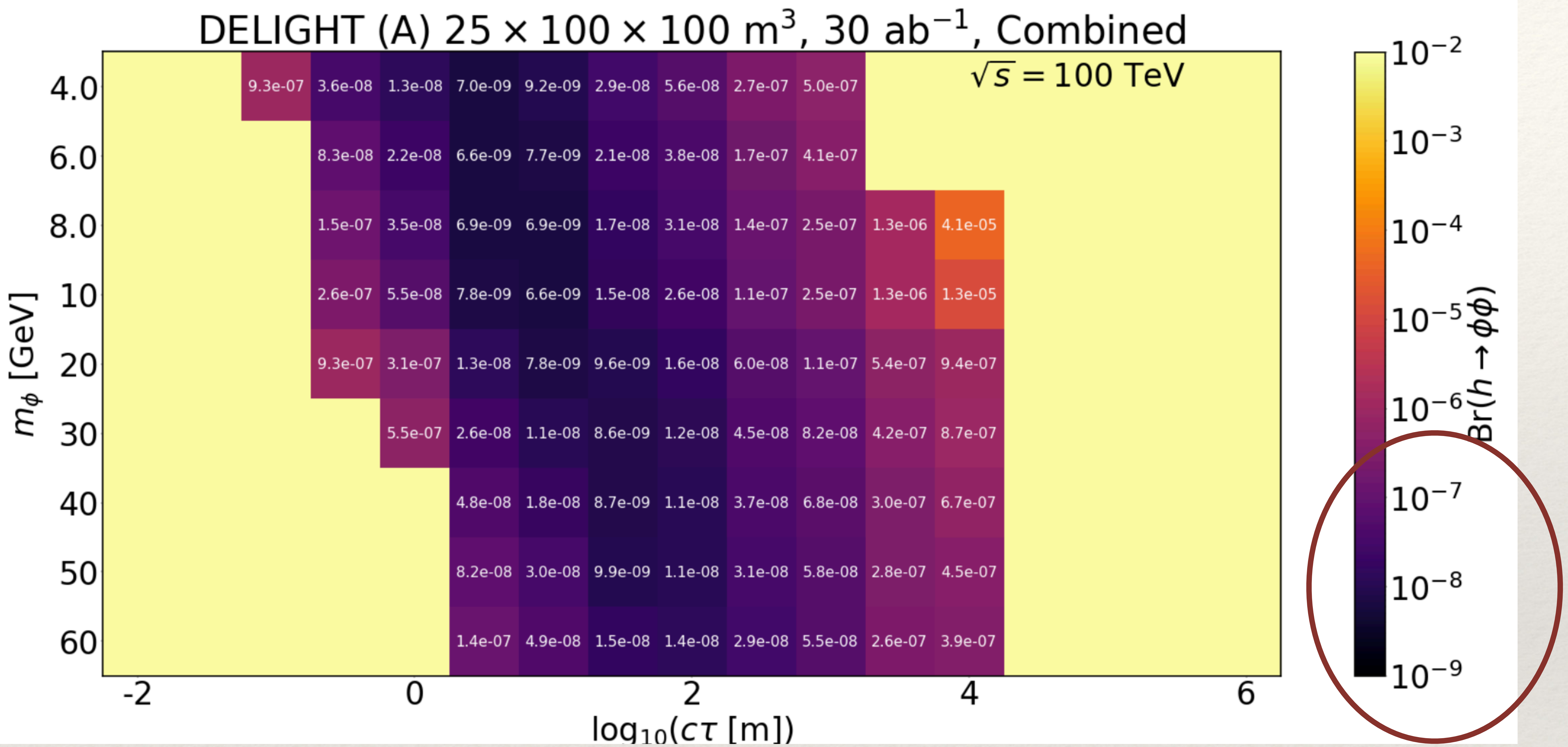

DELIGHT(A) vs MATHUSLA: an improvement by a factor of ~ 540,

around ~ 150 from increased cross-section and integrated luminosity,

another factor of ~ 3–4 is gained by moving the detector close to the IP.

Central position of the detector can benefit light LLPs.

DELIGHT (C)

DELIGHT (C): The same decay volume as the MATHUSLA detector with different dimensions, i.e. $\Delta x \times \Delta y \times \Delta z = 200 \times 50 \times 50\,\mathrm{m}^3$.

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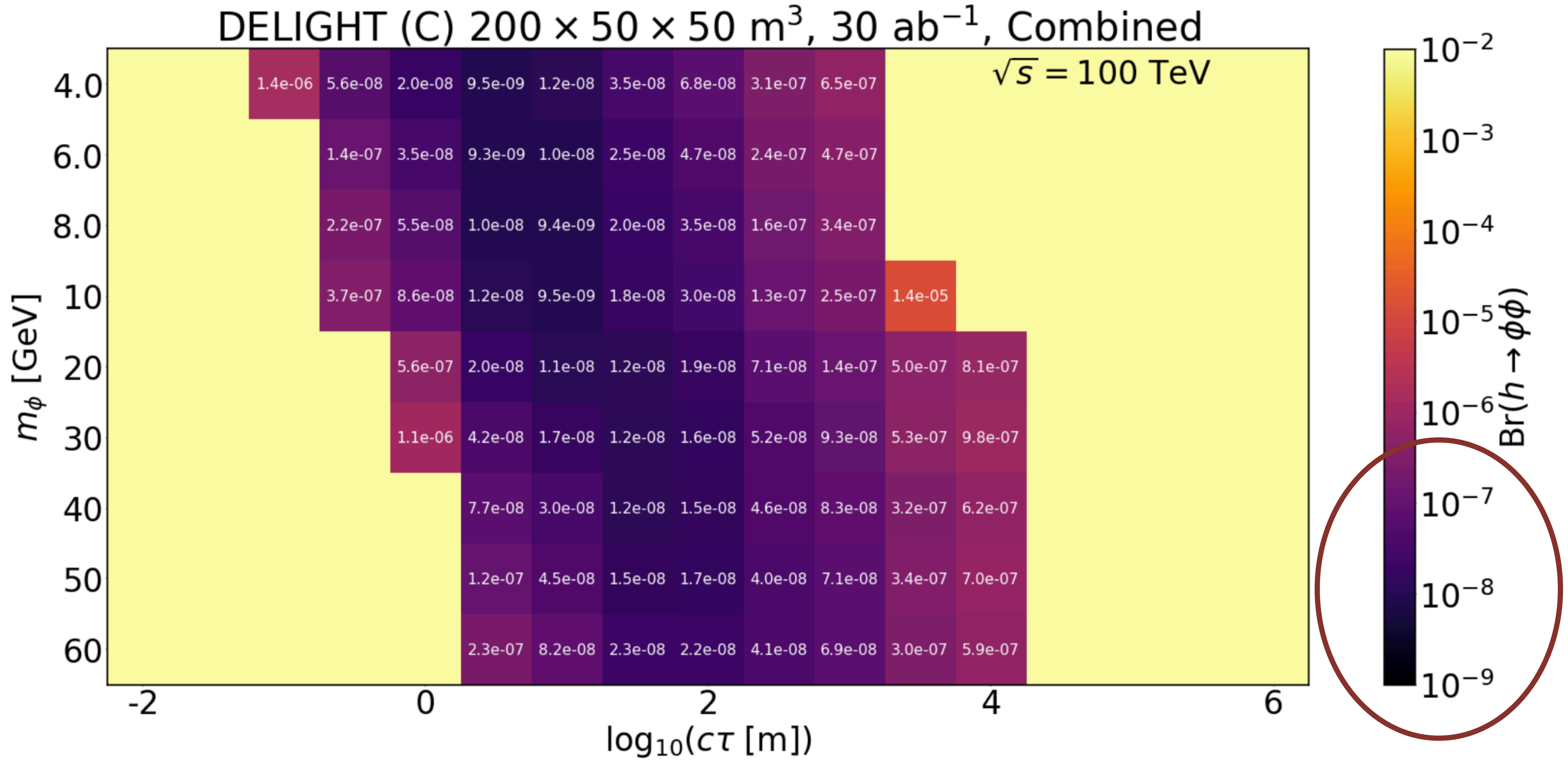

DELIGHT (A) vs DELIGHT(C): have the same decay volumes, lower $\Delta\eta\times\Delta\phi$ coverage, limits slightly weaker (factor of around 0.8 – 0.9), may have better shielding from cosmic rays, tunnel like structure might be useful for other LLP models (needs more detailed analysis) .

Challenges

- Pile up will be increased from 140-200 to ~500-1000 !
- Average distance between vertices at around z=0 is 100 μm in space and 0.4 ps in time. (Pile up ~ 140-200 for HL-LHC: average distance is 1 mm in space and 3 ps in time)
- Excellent spatial and timing resolution required for pileup mitigation.
- Some of the projected results for FCC-hh crucially depend on this factor
- Advanced detectors and algorithm will be required to keep the resolutions (Example : Di-photon invariant mass resolution for Higgs identification), and efficiencies (b/tau tagging, ultra relativistic top tagging etc.) , at par with the LHC
- Search sensitivity of higgsino search using disappearing jet will crucially depend on the number of pixel layers in the tracker (Saito, Sawada,Terashi and Asai, EPJC(2019) 79:469)

Challenges

$$pp \to h_{125} \to \phi_{dark}\phi_{dark}$$

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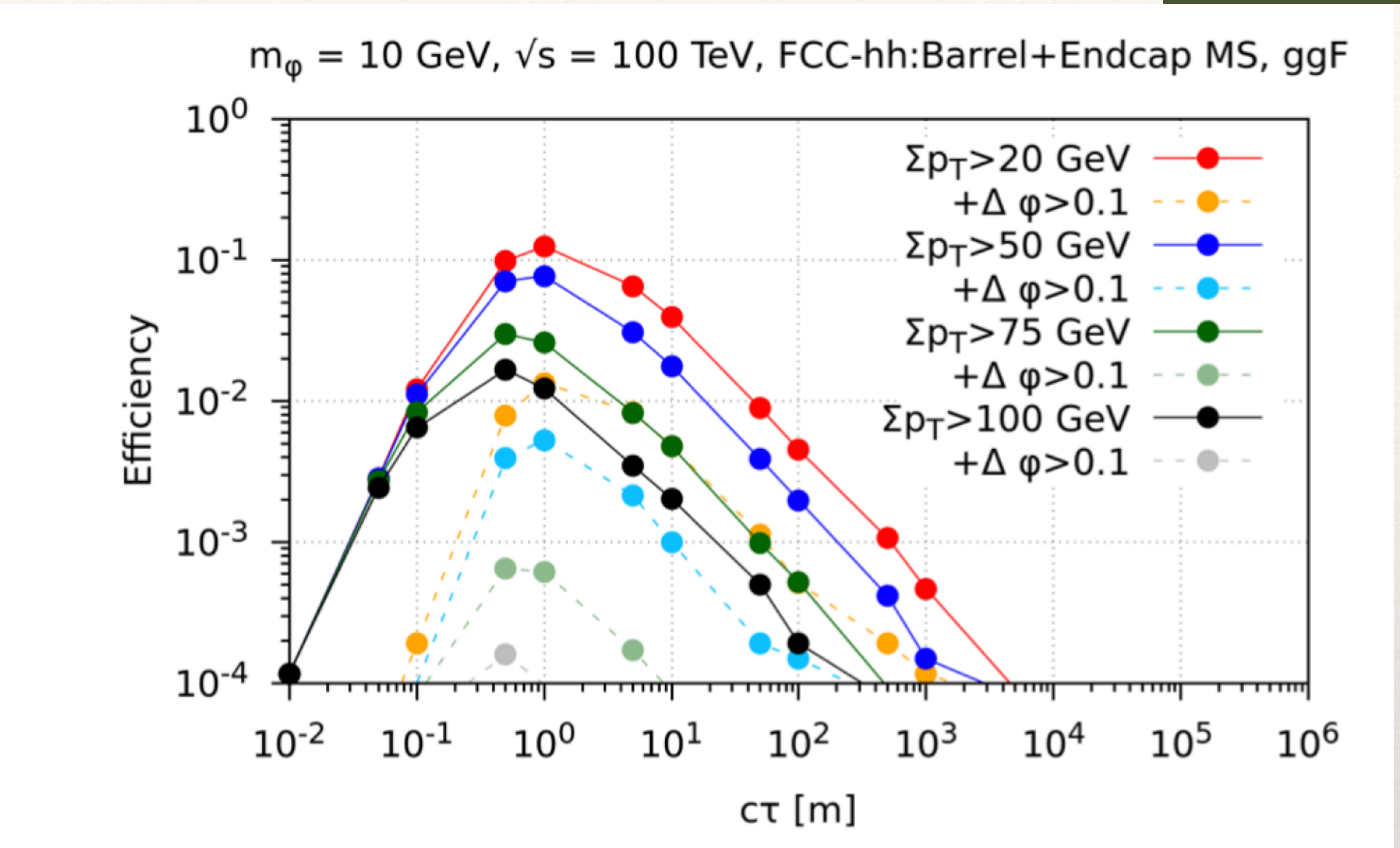


We need to increase the energy threshold for 100 TeV Collider = > angular separation among decay products reduced

Creates problem in identifying the signal and background rejection

Similar problem encountered in ultra high-pt top quark tagging from multi-TeV particle decays

Summary

Future hadron colliders offer rich physics

- High mass searches (inaccessible to LHC or electron positron collider)
- Increase in luminosity and cross section enable us to probe rare processes
- Higgs physics : Higgs precision study, parameters of the Higgs potential etc., ..
- New facilities (dedicated to specific scenarios like DELIGHT for LLPs), Fixed target experiment (1706.07667) can be incorporated.

Electron-Positron vs Hadron collider ? => situation dependent

In case of no-discovery in the recent future=> hadron collider will still be a better choice for physics studies

We need to start now …hope for the best (scenario-A and B) and prepare for the worst(scenario-C)

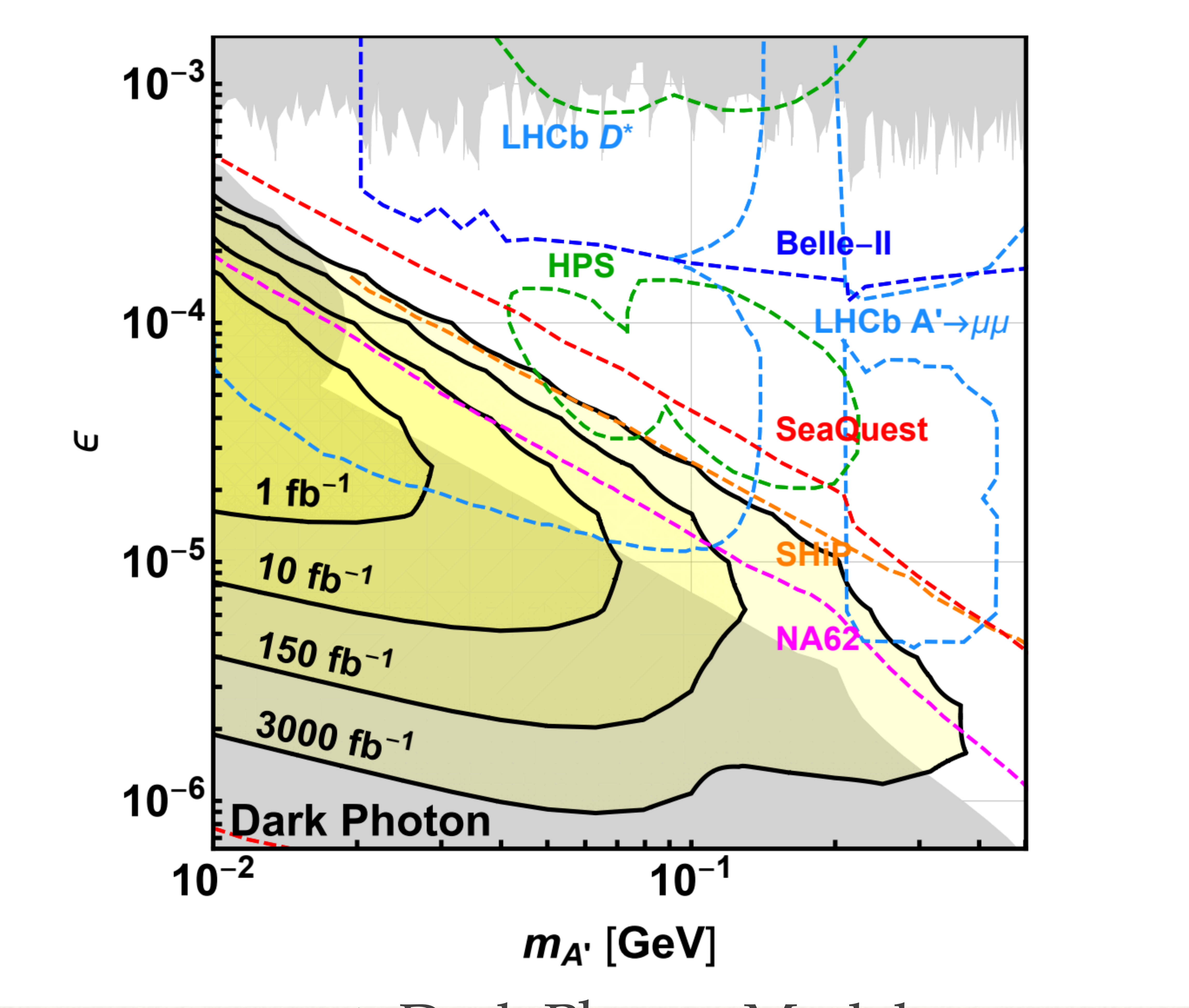
Thank you

Extra Slides

FASER

- ForwArd Search Experiment dedicated for light long-lived particles
- Placed 480 m downstream of the ATLAS detector interaction point
- FASER will take data throughout Run 3 (about 150 ifb data)
- It also has neutrino program
- FASER II proposal for HL-LHC

HTTPS://ARXIV.ORG/PDF/2207.11427.PDF



- Dark Photon Model

Some discussions on LLP detector DELIGHT

- 100 TeV collider will have very high luminosity => a distance of 25 m might not seem enough to provide a background free environment.

- Still in the designing phase => significant shielding may be placed as well as active veto to reject backgrounds. It can be placed deep inside the ground to suppress cosmic ray backgrounds.

- Current RPC technology should provide adequate sensitivity => future technology can further improve the sensitivity.

- Presence of calorimeter can extend sensitivity to LLP decays to photons, and other neutral particles.

- The detector can be integrated with one of the detectors => coordinated triggers can be developed