Searches for new physics towards the European Strategy 2020

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"UK inputs to EU strategy" meeting, *IPPP Durham*
April 17th 2018

A premise

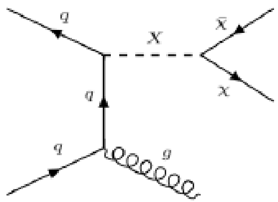
- I have been asked to review the expected reach of HL-LHC and prospects beyond that in the context of BSM searches
  - which projects would enable better reach, what are potential developments, experimental possibilities (beyond HL-LHC), possible choices for the strategy and UK inputs
- A very broad remit!
- I will give my (personal) view as experimentalist at collider, with an eye to what our theory community suggest us to do to answer the major open questions …

- **What's the origin of Dark matter / energy ?**
- **What's the origin of baryon asymmetry in the universe?**
- **What's the origin of neutrino masses?**
- **What's the origin of EW symmetry breaking?**
- **What's the origin of the flavour structure of the SM?**
- **What's the solution to the hierarchy problem?**
- **..**

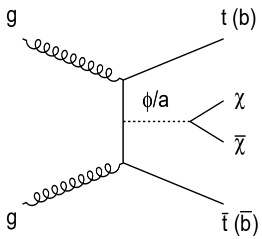
DM, DE and some of the above in other talks at this meeting – although…

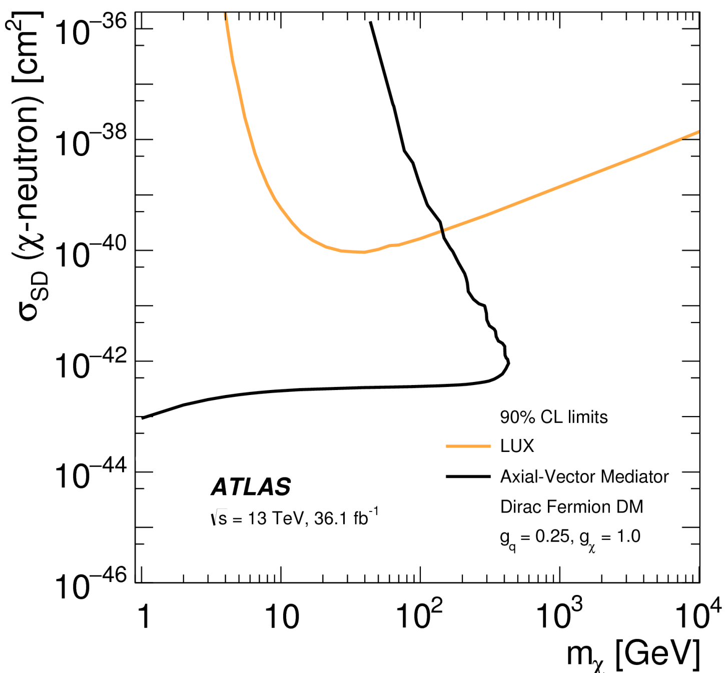
1 slide of DM at colliders

- Just two examples to show the complementarities with DM direct detection experiments

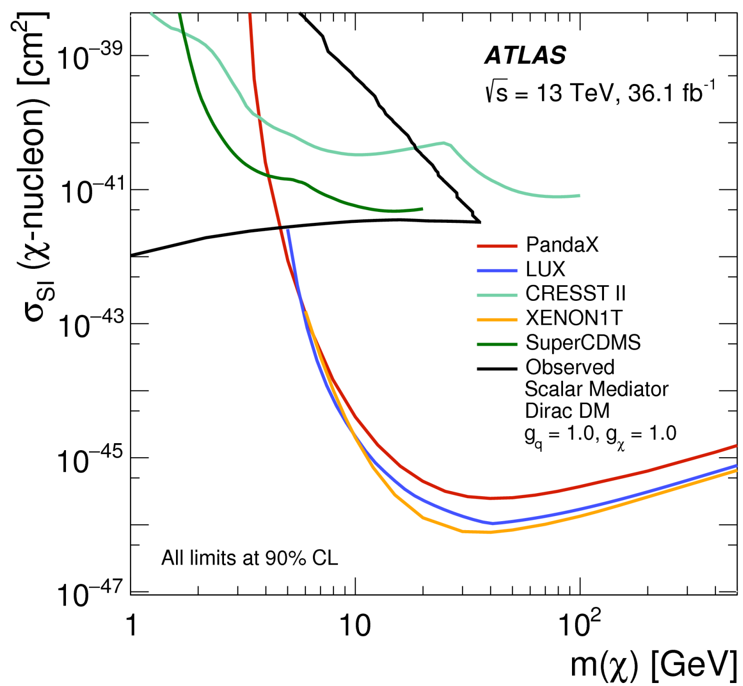


Assumptions needed
But complementarities clear





spin-dependent DM-neutron scattering cross section plane



spin-independent DM–nucleon cross-section

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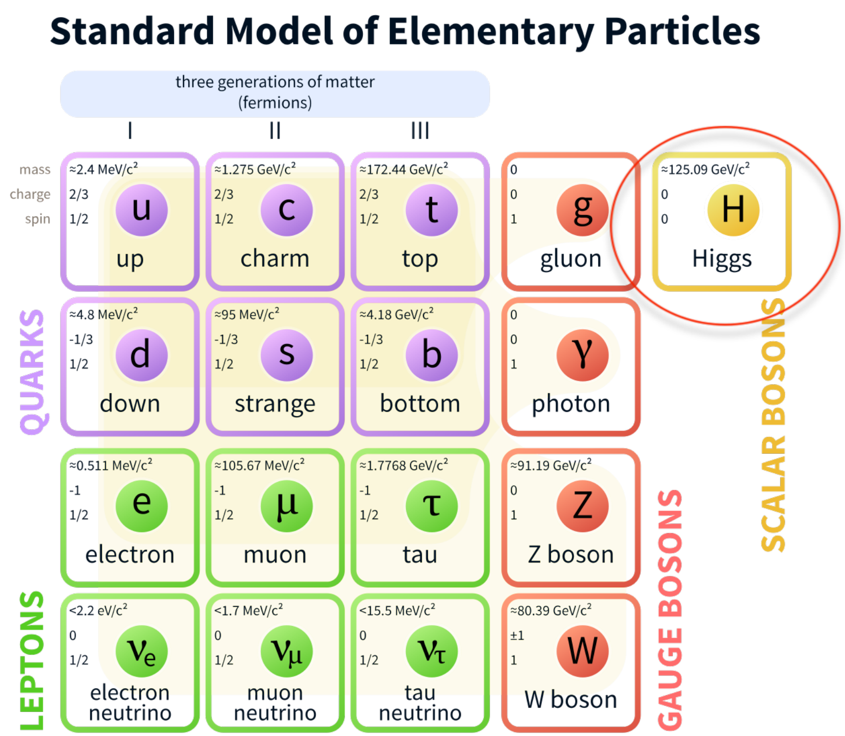
"there is no experiment nor facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can ***guarantee discoveries*** beyond the SM, and ***answers*** to the big questions of the field" (M.Mangano, 98th ECFA, November 2015)

Searching for new physics: what



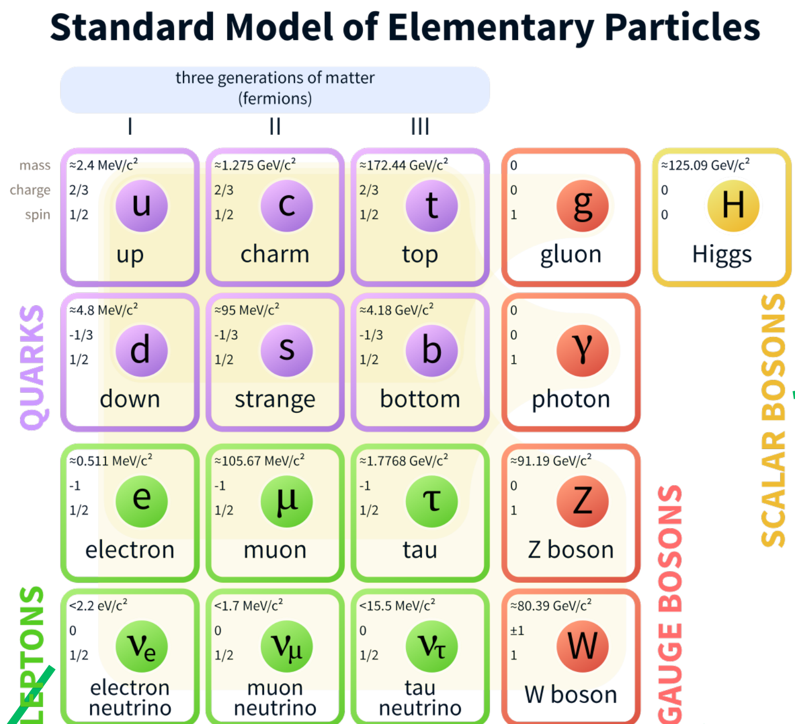
2010: clear guidance for the LHC: EWSB and the **Higgs boson**, and we discovered it…

Today: Evidence of NP BSM (Dark Universe, neutrinos, baryogenesis..)

… but not of **where/what** BSM is !

→ arguments as naturalness/tuning possibly pushed to boundaries
→ precision tests perfectly healthy (so far), no need for NP at the EW scale

Searching for new physics: what



Non minimal Higgs sector

- Exotics / Rare / Invisible decays
- Higgs as portal to DM
- Extended: Two-Higgs-Doublet Models, MSSM, NMSSM and r
- Charged Scalars
- Composite Higgs

In Victoria's talk

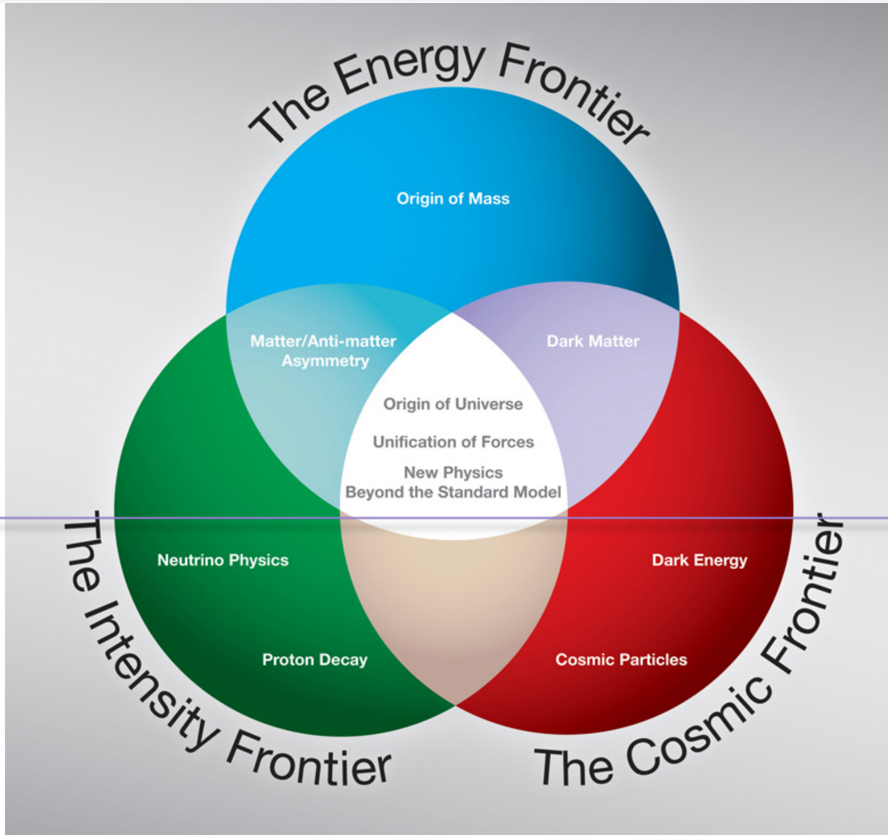
"Exotics": referred to a large variety of theories and models

- Heavy vector bosons, vector-like quarks, excited quarks, non-SUSY Dark-Matter models, lepto-quarks, dark/ hidden sectors and more
- **The unknown!**

SUSY, SUSY-inspired

- many variants and kind (MSSM, NMSSM, R-parity conservation or violation..)
- mostly heavy super-partners, prompt or long-lived, several Higgs bosons

Searching for new physics: where



- LHC (and future pp colliders) offer a unique place where to look directly for new particles:
  - possibility to search for excesses in number of events in a plethora of kinematic regions and for resonances from new heavy particles
    [The main focus of this talk]
  - perform precision measurements of SM parameters → Each deviation could be an hint of new physics!
    [not really covered here]

- Other colliders/experiments give alternative but fundamental opportunities:
  - hidden sector particles (NA62), precision measurements leading to loop-induced deviations (g-2, EDM); LFV experiments (m2e, m3e); BC experiments for ALPs. @ colliders: EWK SUSY, Higgs precision (ee), LQ and contact interactions (ep), and more

Why colliders

- As for today, we need to plan future facilities to
  - access a WIDE and BROAD exploration potential → target well justified BSM scenarios but also have sensitivity to the unknown
  - guarantee flexibility → if (indirect) hints of NP arise somewhere, need to be able to re-direct efforts
  - guarantee deliverables → if not a discovery, precision measurements!
  - have the potential to provide conclusive and quantitative answers to the relevant questions

Physics at Colliders fulfill all of the above conditions so it is mandatory to guarantee a continuous progression in this direction with sufficient complementarity

PAST

Tevatron/HERA/LEP → LHC → HL-LHC → Again pp/(ep)/ee ?

(fermiscale) (Terascale) (multi-Terascale)

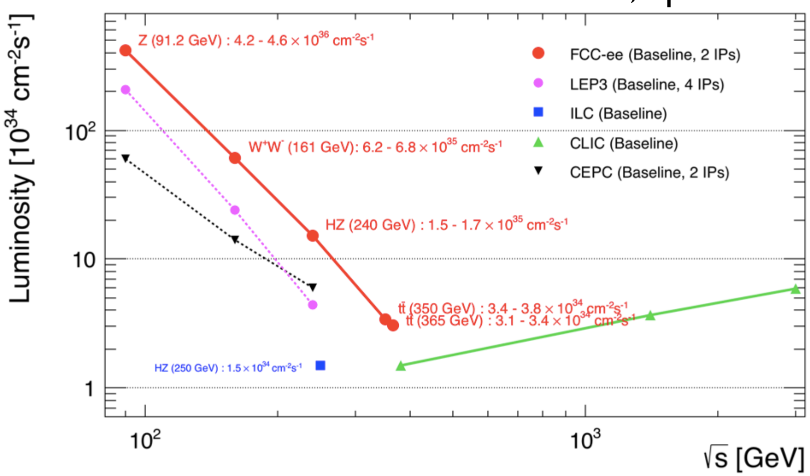
PRESENT

FUTURE

Which colliders: proposals made

- **Proton-proton**
  - **HL-LHC → 14 TeV com energy, 2025-2038, up to 4000/fb**
  - **HE-LHC** → 27 TeV com energy, beyond 2038
  - **FCC-hh** → 100 TeV com energy, beyond 2045 (so far, after FCC-ee), up to 30/ab
- **Electron-positron**
  - Linear collider:
    - ILC → $E_{cm} \approx$ 500 GeV with staging at 250 GeV, Lumi ~1.8×10^{34} $cm^{-2}s^{-1}$
    - CLIC → three stages $E_{cm} \approx$ 380 GeV, 1.5 TeV and 3 TeV for 500/fb, 1.5/ab and 3/ab respectively, data taking after HL-LHC for ~ 20 yrs
  - Circular collider:
    - CepC → At least two stages, $E_{cm} \approx$ 91 and 240 GeV, 2IP, data-taking 2030-2040 [Upgradable to pp collision 50-100 TeV, with ep and HI option)
    - FCC-ee → 2IP, beyond 2045, Operation model foresees, 5 different stages and lumi

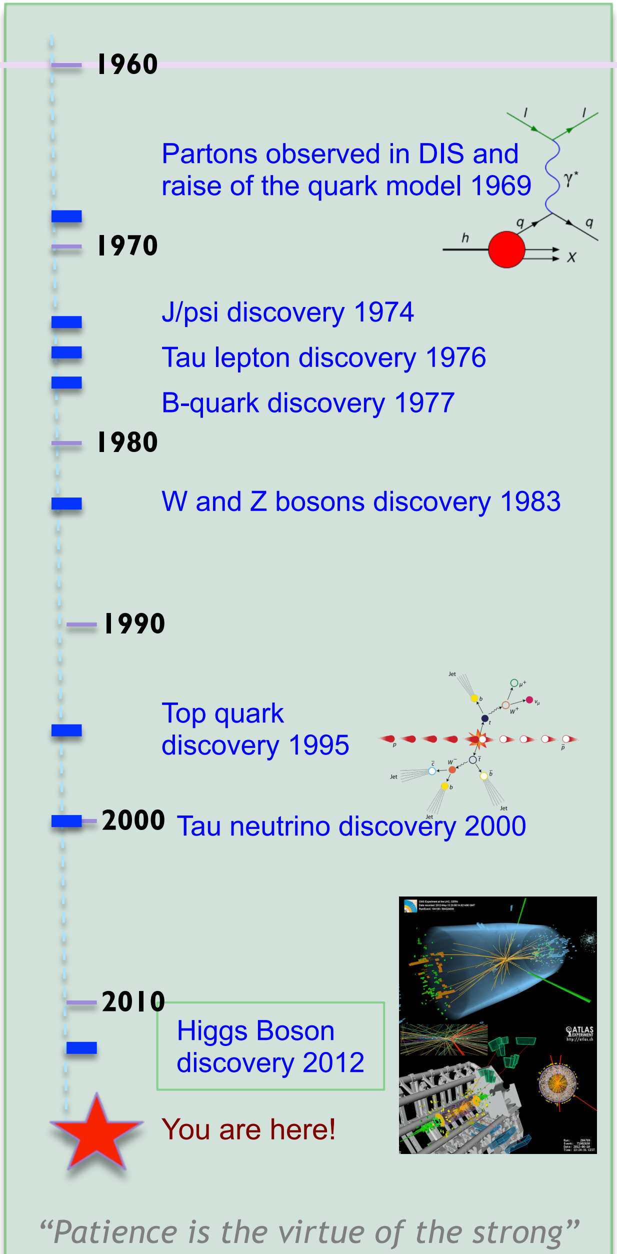
FCC Amsterdam, April 2018



- **Electron-proton**
  - LHeC → E_e = 60 GeV, p from LHC, up to 1/ab, running at the same time as HL-LHC
  - HE-LHeC → upgrade in parallel to HL-LHC
  - FCC-eh → E_e = 60 GeV vs 50 TeV, up to 3/ab

benchmark routes @ colliders

- At the LHC, hundreds of searches for new physics are on-going targeting many models proposed in the past thirty years.
  - Leaving no stones unturned, searching for direct signs of NP or carrying out precision measurements which might be an indirect sign of it
- HL-LHC physics studies are being finalized
  - Yellow report in preparation for EU strategy
  - Include also HE-LHC prospects studies
- **This is not a review talk**, rather a discussion about goals, synergies
  - Will illustrate what data might tell us at the end of HL-LHC and which directions we could take depending on the outcome
  - **Consider some benchmark routes**
    - **New heavy resonances** and high p_T physics
    - **Supersymmetry**
    - **Long-lived particles and their role in hidden/ dark sectors, sterile neutrinos**



New resonances (and high p_T searches)

Where high luminosity and high center of mass energy help the most

- Sensitive to many BSM scenarios
  Heavy higgses (A/H), Extra-dimensions, new gauge bosons… without mentioning the role of dijet searches for DM (see dedicated talk)
- Consider <u>all relevant combinations</u> of final state objects
- Example of flexibility/synergy: strong focus on 3^{rd} generation: can help explaining anomalies in B-sector and beyond
  Leptoquarks, Z’, W’

Anomalies on the market (from LHCb)

- B-physics anomalies could be explained by LQ-like or Z'-like mediators
  - TeV-scale and 3rd generation favored
- LQ could also explain g-2

Quark level transition $b \to c\ell\bar{\nu}$

R_D, R_{D^*}: combined $\sim 4\sigma$ deviation

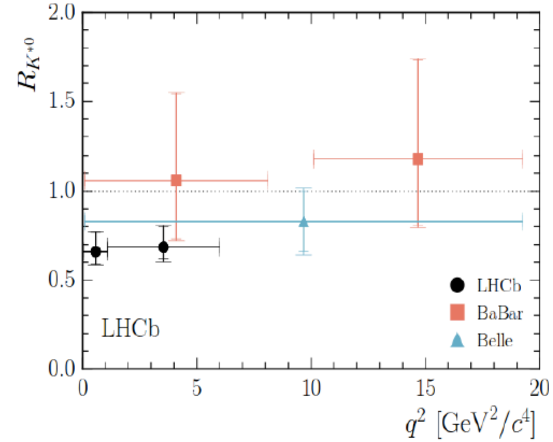
$$R^{\tau/\ell}_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$$

Quark level transition $b \to s\ell\bar{\ell}$

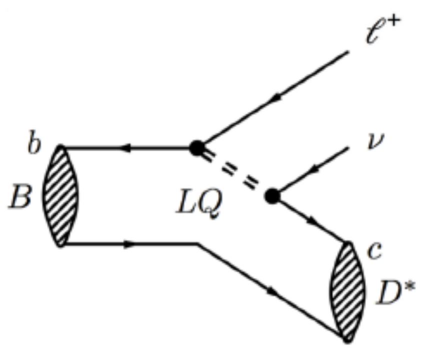
R_K, R_{K^*}: $\sim 2.5\ \sigma$ deviation (LHCb)

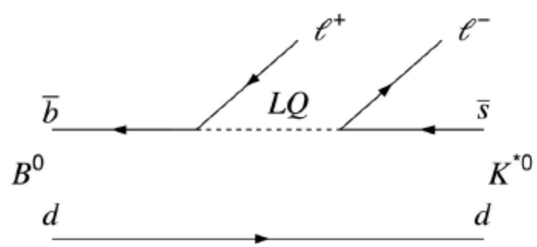
$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$

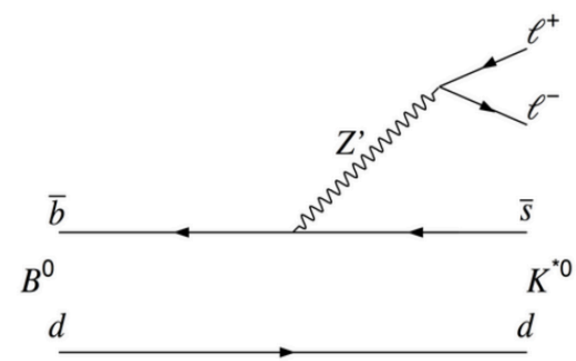
$B^0 \to K^{*0}\mu^+\mu-$ angular analysis:
$3.4\ \sigma$ deviation (LHCb)



Possible new contribution in the $b \to s\ell\ell$ transition in BSM scenarios involving Z'

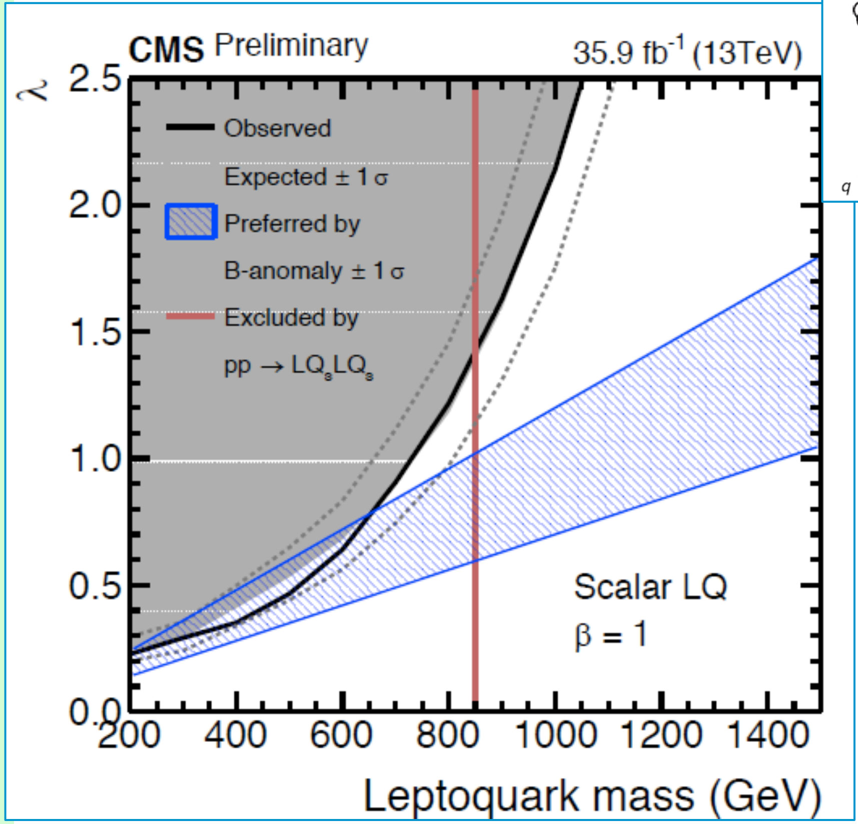


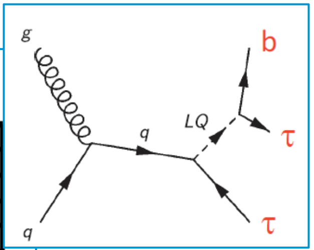




LQ: → τ + b and beyond

- Projections for HL-LHC not yet available, but likely to cover part of the interesting phase-space regions
  - ~2.9-3 TeV in mass, according to back-of the envelope extrapolations





Pure 3G (scalar) LQ are not the only option:

→ Mixed generation LQ models have also been proposed to explain LFV anomalies

→ Left-, right- handed muons-top coupling could explain g-2 (arXiv:1612.06858)

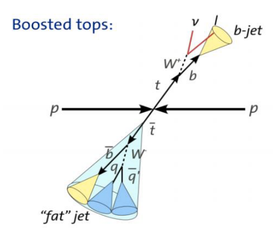
(e.g. see A. Crivellin talk at Moriond 2018)

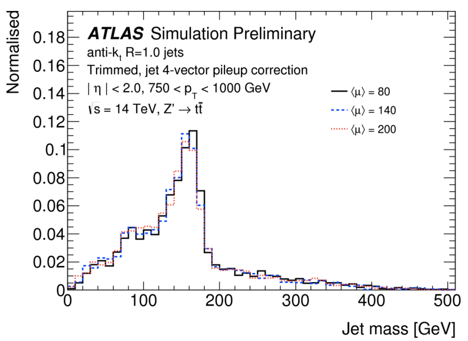
→ More to be done by ATLAS/CMS HL-LHC

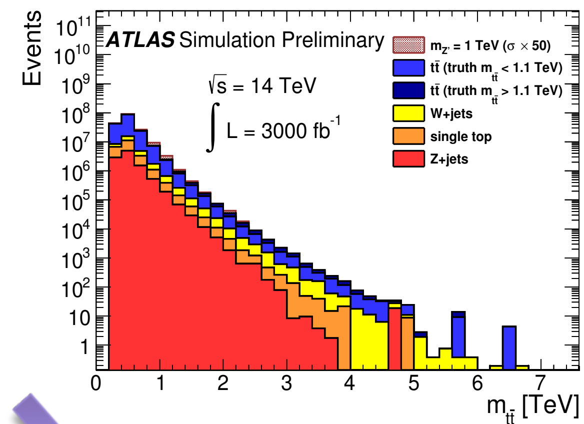
Reach with HL-LHC: Z' →ttbar

ATL-PHYS-PUB-2017-002

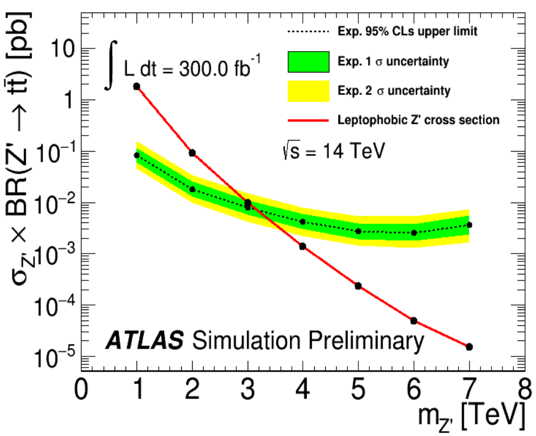
- ATLAS → full analysis
  - Resolved and **boosted**
  - Large **R-jets** considered



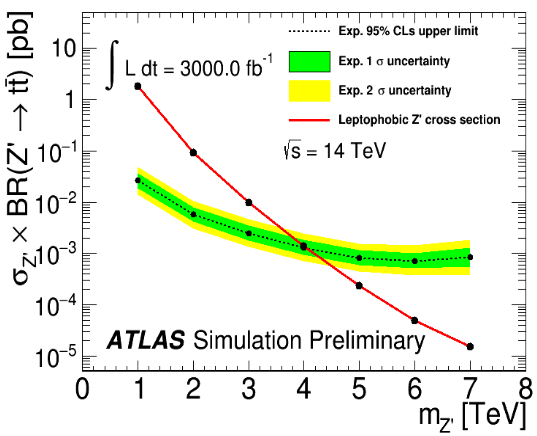




(b) Resolved Muon Channel.



(a) Upper cross section limits for 300 fb^{-1}.



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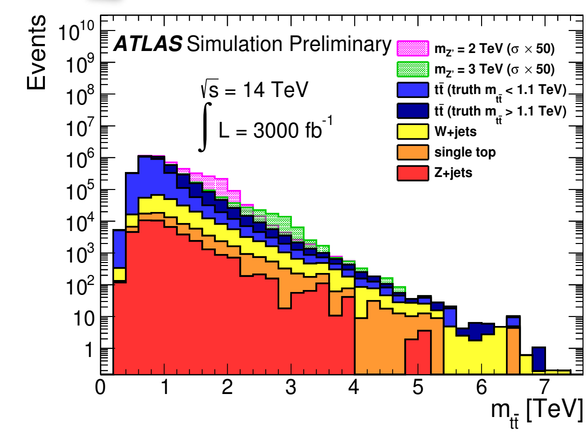


(d) Boosted Muon Channel.

Reach: beyond 4 TeV (1 TeV gained with HL-LHC)

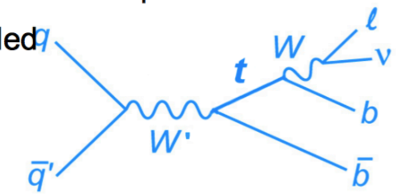
For Z→ee, exclusion up to 6.4 TeV, discovery reach ~ 5.9 TeV

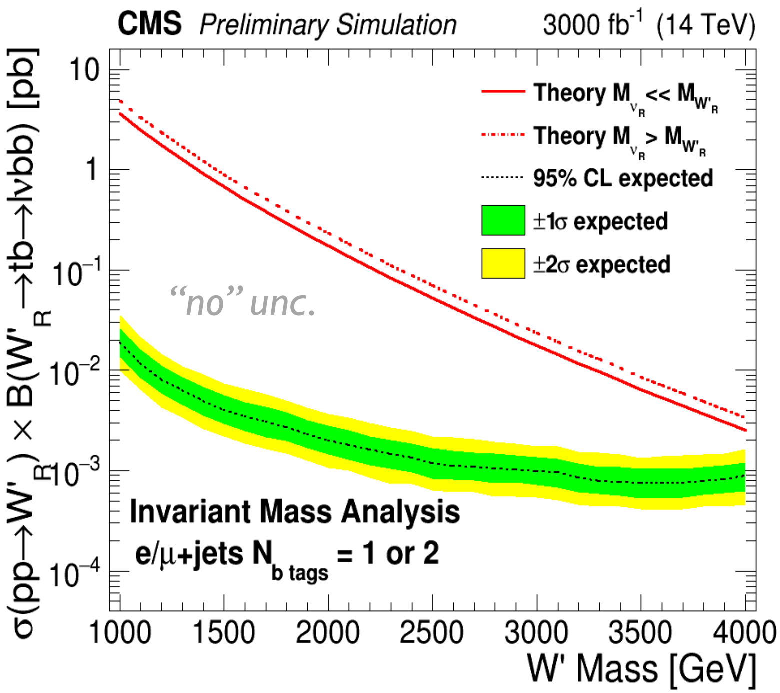
Reach with HL-LHC: W'→tb

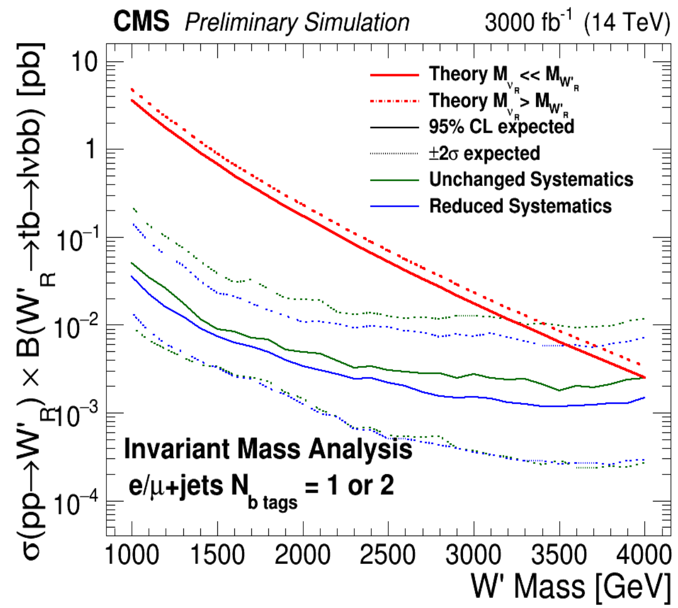
- Projections performed – assuming NWA using 2015 and 2016 analyses

Three possibilities for the evolution of systematic uncertainties with integrated luminosity are considered

- (Flat) All systematic uncertainties are assumed to remain unchanged
- (Scaled) All systematic uncertainties are assumed to improve
- (None) No systematic uncertainties are included







Again, dependence on assumptions on uncertainties

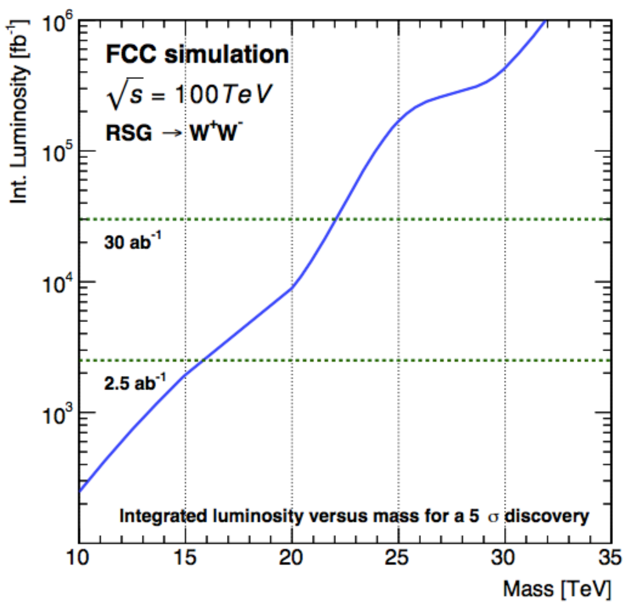
CMS DP016_064

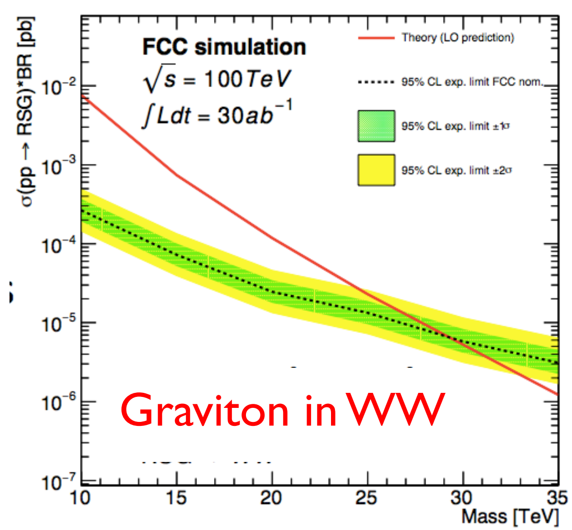
Reach: beyond 4 TeV
For W' in eν and μν → reach up to 7 TeV

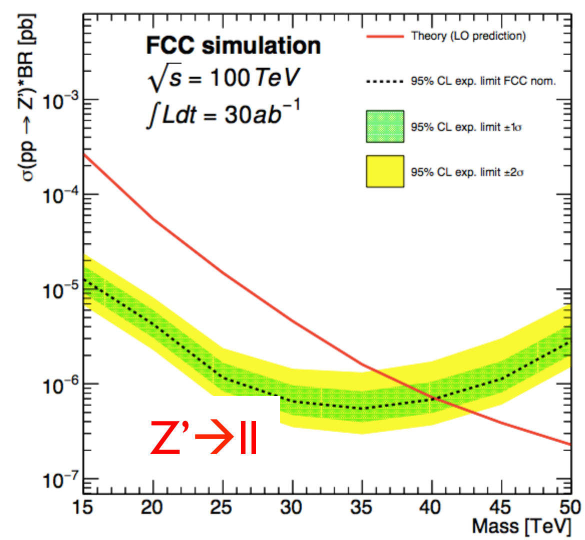
The (far) future

On the optimistic side: if deviations are observed in Run 3, HL-LHC will allow to study new physics properties with high statistics in characteristic distributions, e.g. A_{FB}. On LQ, depending on mixture and mass, studies could be also possible at e-p (limited by com energy)

- Clearly, the higher c.o.m. energy, the better
  - If nothing is found by HL-LHC, only option for direct observation
  - @100 TeV collider would increase the reach of **a factor 10** with full dataset (30/ab) [question: to discover an m=6-10 TeV new particle produced via gluon-fusion, do we wait for FCC-hh or is HE-LHC enough? What do we need?]



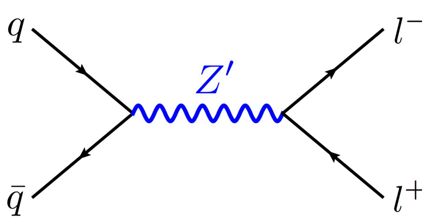


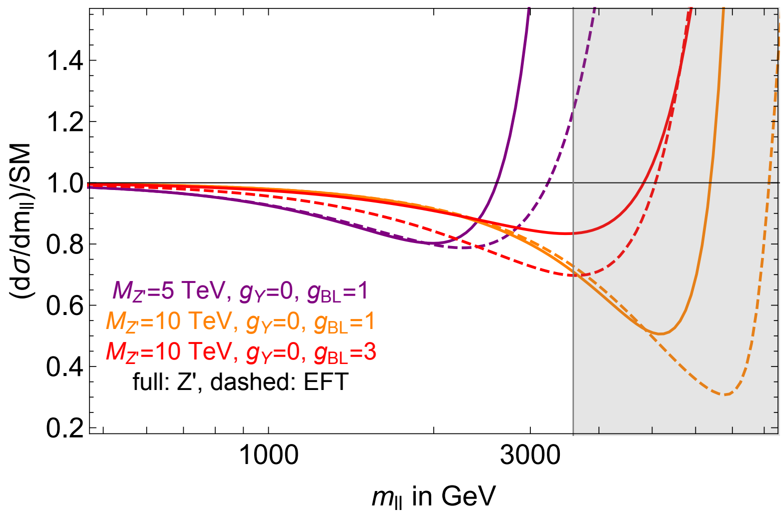


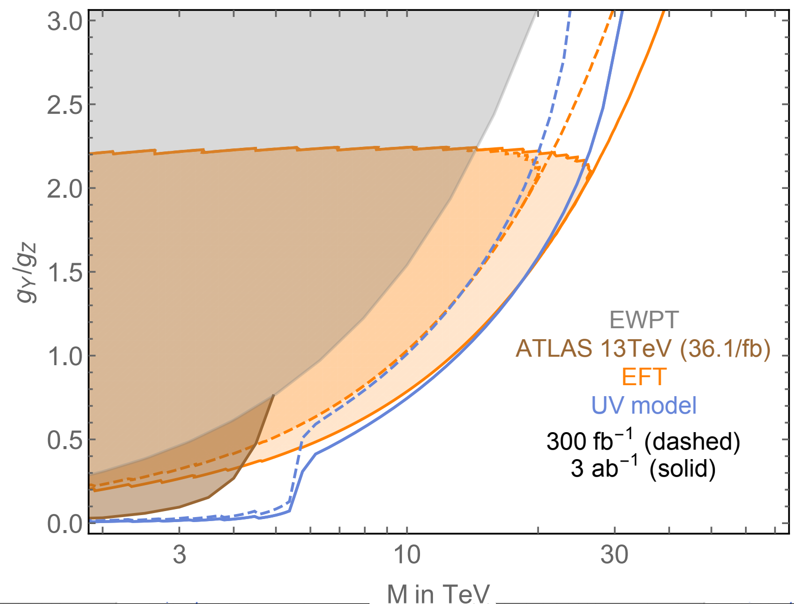
Indirect constraints on Z'

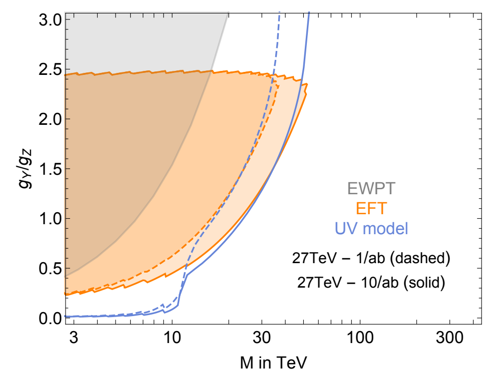
- If mZ'>>5 TeV, main contributions from interference effects modifying DY
- The precision of e^+e^- colliders help but LHC (and HL-LHC) can do a lot

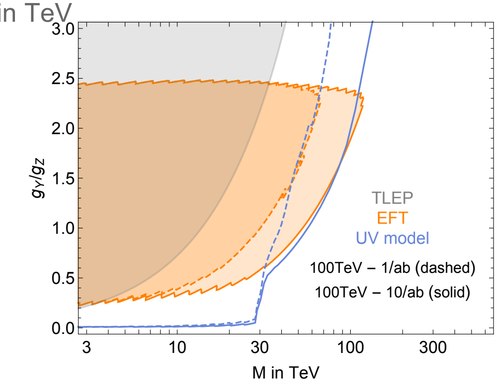
Alioli, Farina, Pappadopulo, JTR, Phys. Rev. Lett. **120**, no. 10, 101801 (2018)





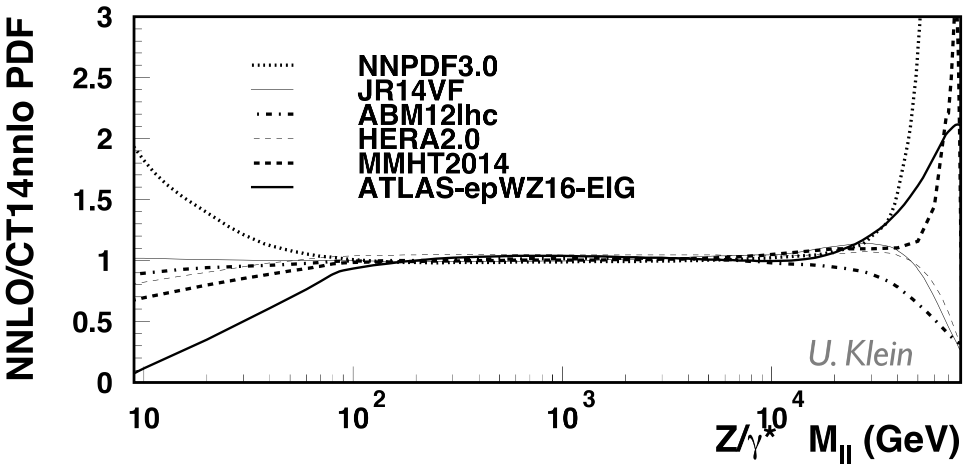






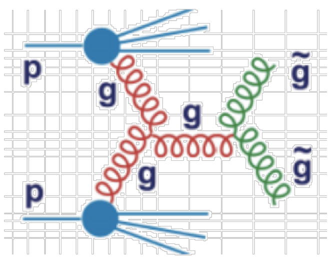
A comment on high p_T / mass searches

- Already at HL-LHC, limitations arise from difficulties to identify high p_T / boosted objects, but also from modeling of SM processes



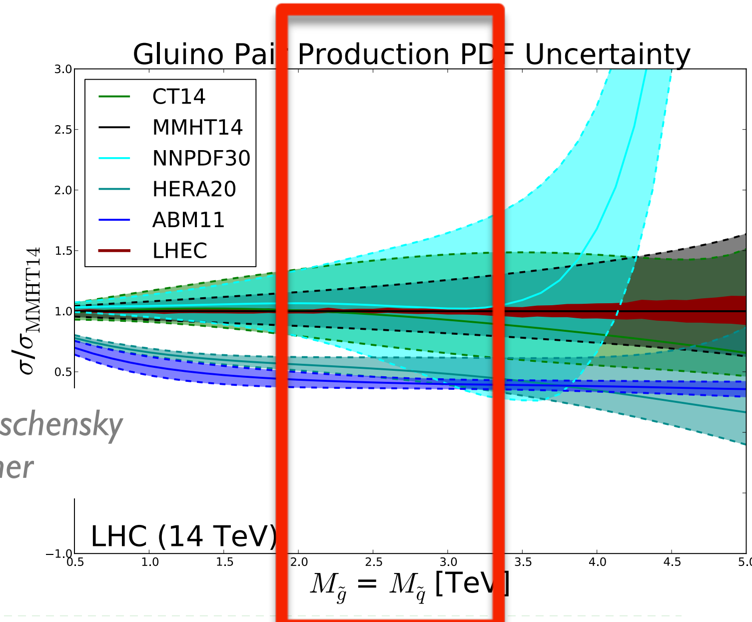
"Troubles" at low and high x

LHeC (and then FCC-eh) can improve low and high M(ll) and M(lv) precision for searches for new physics



Impact on PDF unc for any gluon-gluon production at relative high x

Christoph Borschensky
Michael Kramer



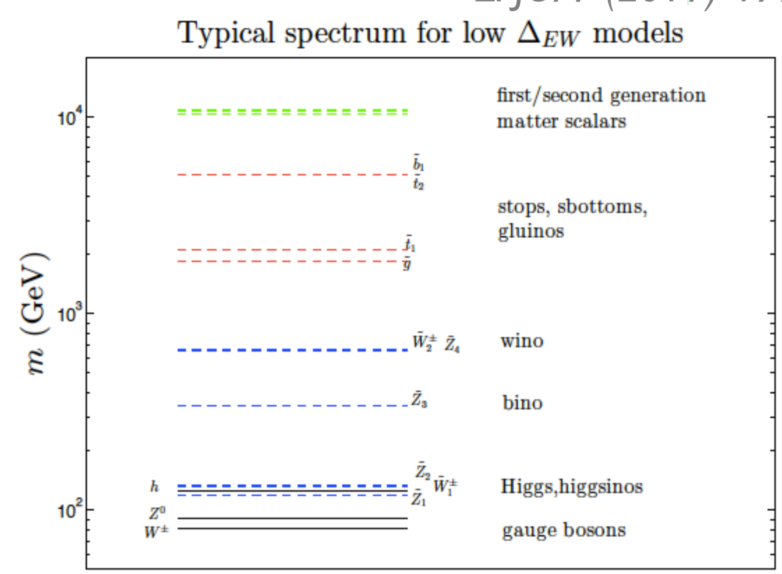
Supersymmetry

Lot of interesting consequences, theoretically sound, predictive framework, what about naturalness ?

- Current LHC: m(gluino)>2 TeV, m(stop)>1 TeV
- compare: Barbieri-Giudice 3% naturalness:
  → m(gluino)<~1000 GeV; m(t1)<~500 GeV
- LHC limits way beyond naturalness bounds
  → is SUSY unnatural? Is SUSY dead? **NO**
  (and it's not me saying that …)

Using electroweak fine-tuning (Δ_{EW}), SUSY is natural (**3-10%**) with: gluinos up to 5-6 TeV, stop up to 2-3 TeV, squarks up to 10-20 TeV, + need low μ_H ~ 100-300 GeV

EPJC77 (2017) 499



H. Baer, FNAL HL/HE-LHC workshop

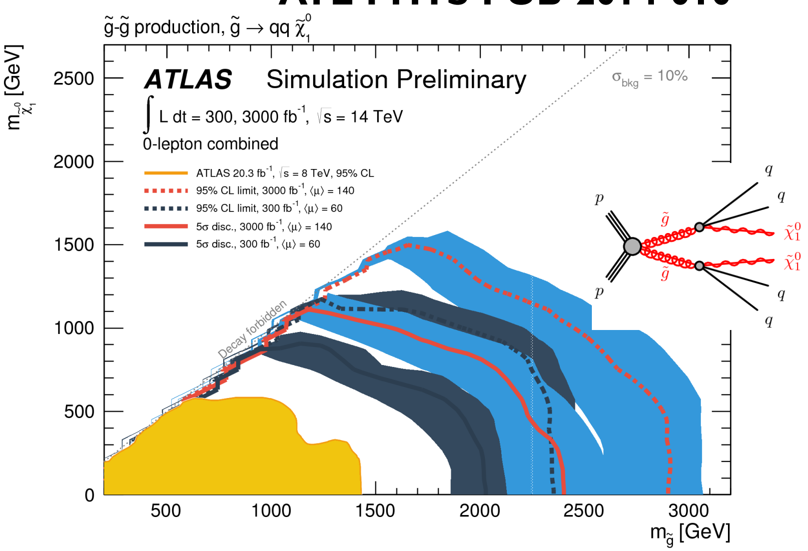
higgsino is LSP, higgsino-like WIMP~100-300 GeV thermally under-produced as DM candidate: augment with e.g. axion

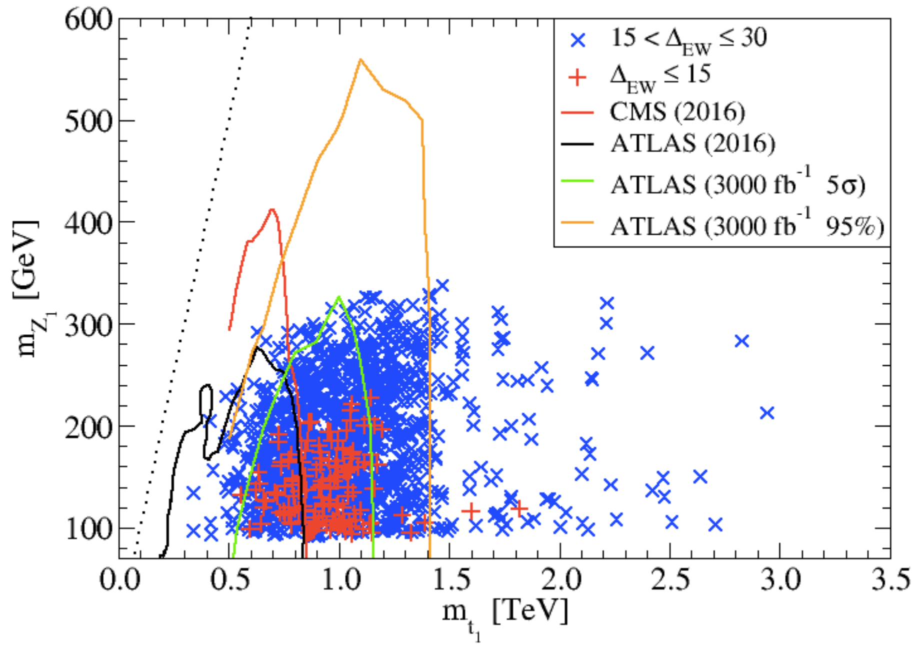
SUSY @ HL-LHC: strong sector

- In strong production, can push the reach to much higher masses
  - Question: is this sufficient to exclude natural SUSY? Probably not
- With HL-LHC, gain several hundred GeV in discovery potential for pair-produced gluinos or squarks (including stop).

Baer et al., EPJC77 (2017) 499

- **ATL-PHYS-PUB-2014-010**





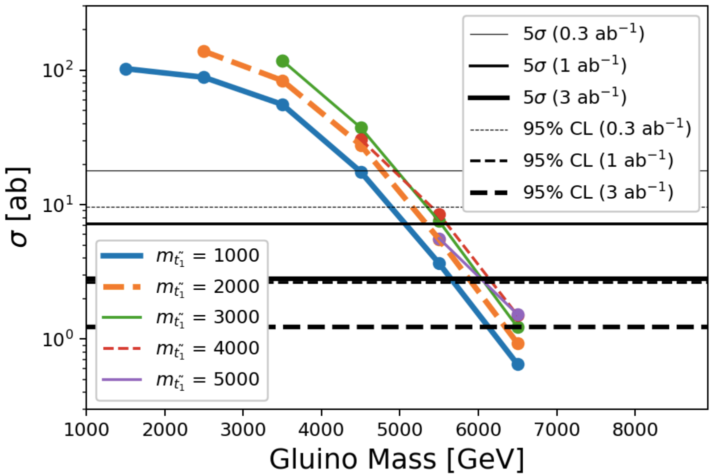
Large uncertainties from PDF → improvements expected with LHC data and, possibly, new facilities (LHeC)

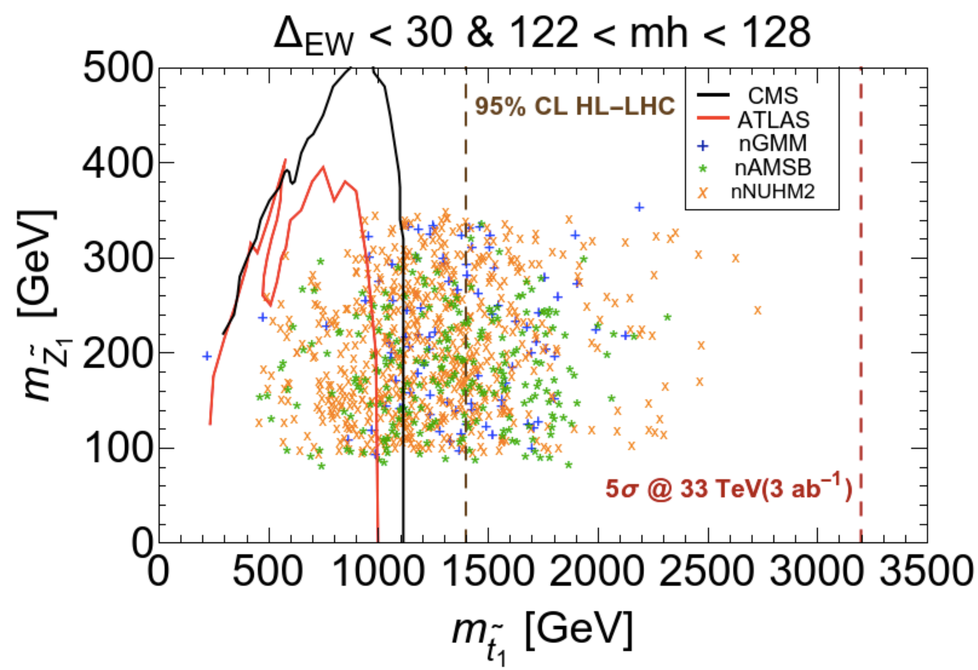
Analyses being re-assessed:
Exp. gluino reach up to 3 TeV

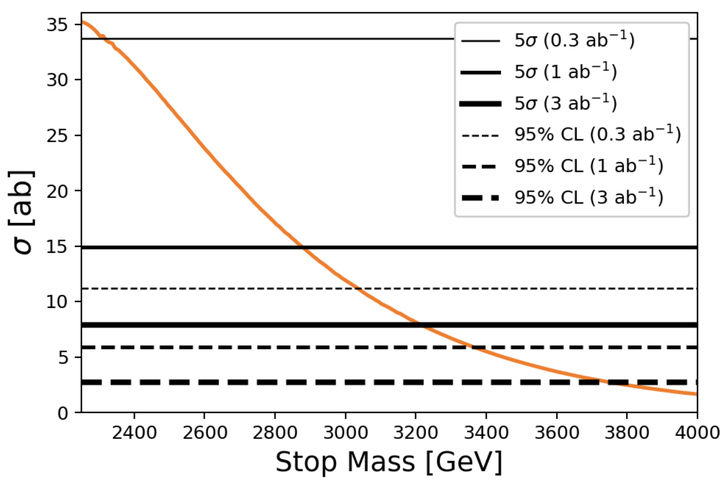
M(stop) can range up to 3 TeV with little cost to naturalness. **HL-LHC Stop reach: 1.4-1.5 TeV (1.9 TeV with new analyses, but for compressed scenarios ~ 700 GeV)**

Expected reach with HE-LHC in strong sector

HB, Barger, Gainer, Huang, Savoy, Serce, Tata, PRD96 (2017) 115008





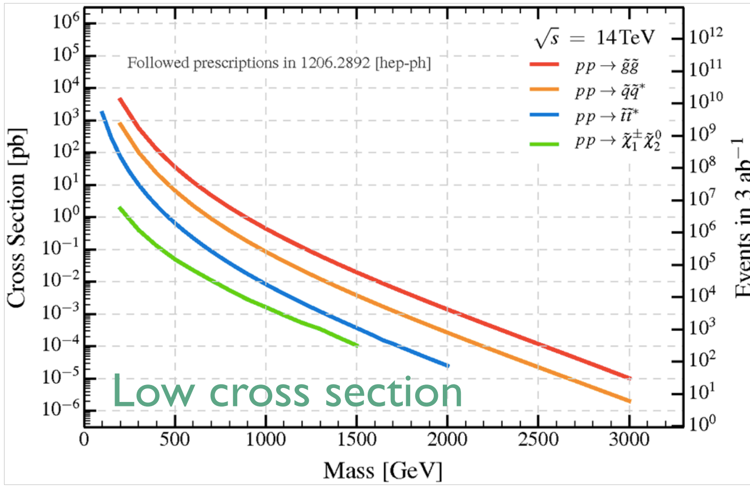


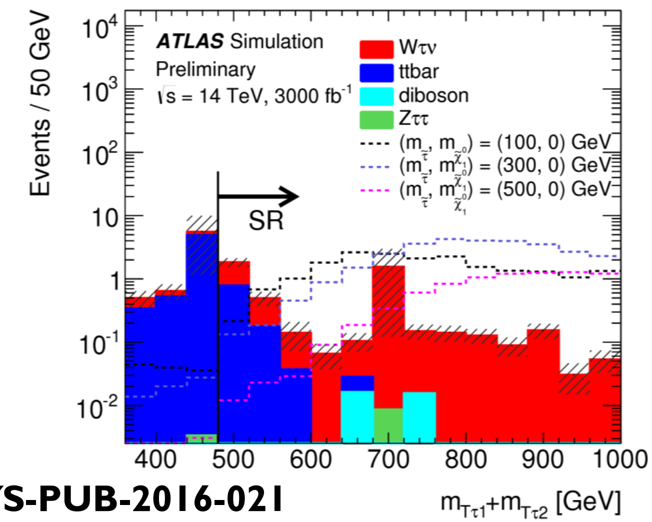
@ HE-LHC reach extends to m(gl)~6 TeV; m(t1)~3-3.8 TeV

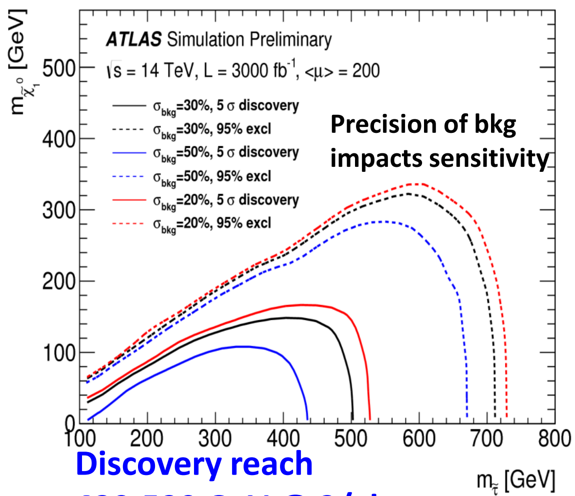
Stringent constraints on SUSY natural models

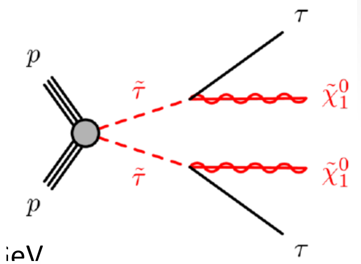
SUSY@ HL-LHC: EWK sector

- EWK SUSY fundamental e.g. for DM
- HL-LHC dataset has the potential to increase the sensitivity to EWK SUSY enormously
- HE-LHC at 27 TeV can lead to a ~2x increase of signal xs for sub-TeV EKW-inos
  - But unclear if it is really an advantage
- Sensitivity strongly depends on EWK-inos composition and consequent decay
- Slepton production also very challenging
  - E.g. current LHC stau results DO NOT provide constraints







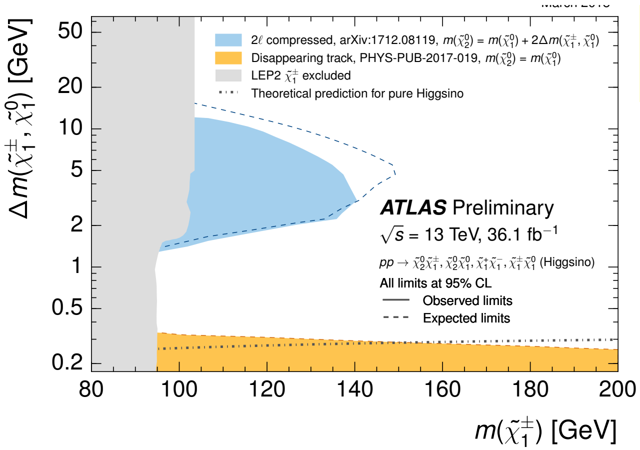


ATL-PHYS-PUB-2016-021

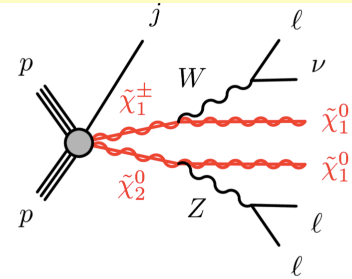
Discovery reach
430-520 GeV @ 3/ab depending on bkg

SUSY@ HL-LHC: EWK sector (II)

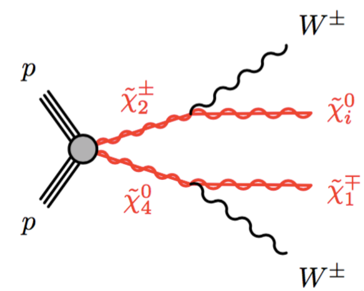
- SUSY higgsino-like scenarios also difficult (and very relevant for DM)
  - Low x-section, compressed → decay products are soft/invisible (for prompt production)



little sensitivity at the LHC for higgsino scenarios → new ideas coming in!



Search for events with Higgsinos produced in association with an ISR jet

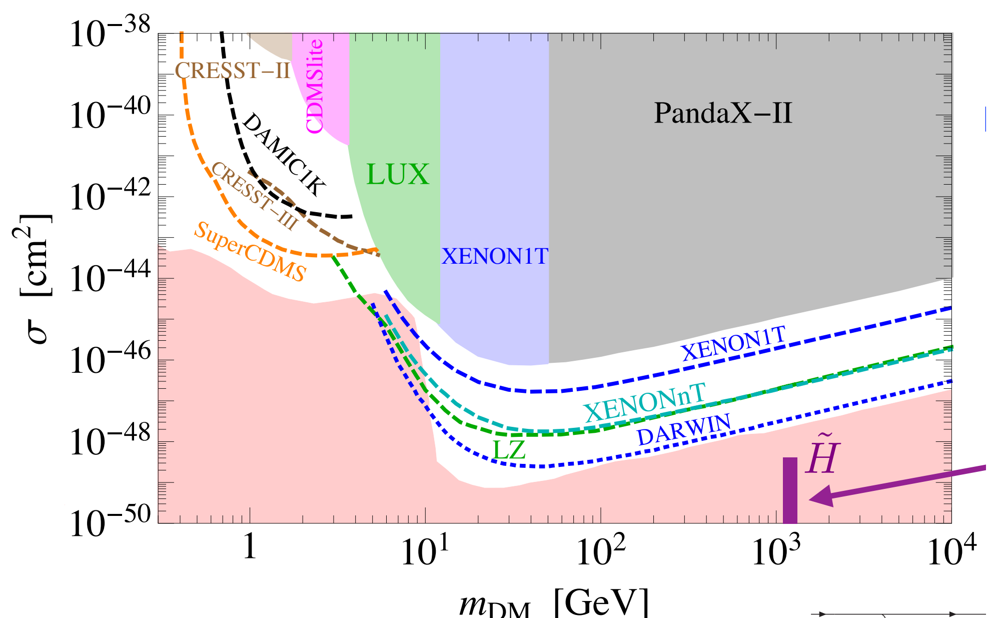


Profit of additional charginos and neutralinos

- And if you wonder about higgsino-DM and direct detection …

  ~ 1 TeV: maximum mass for the Higgsinos such that their relic abundance is at most Ω_{DM}

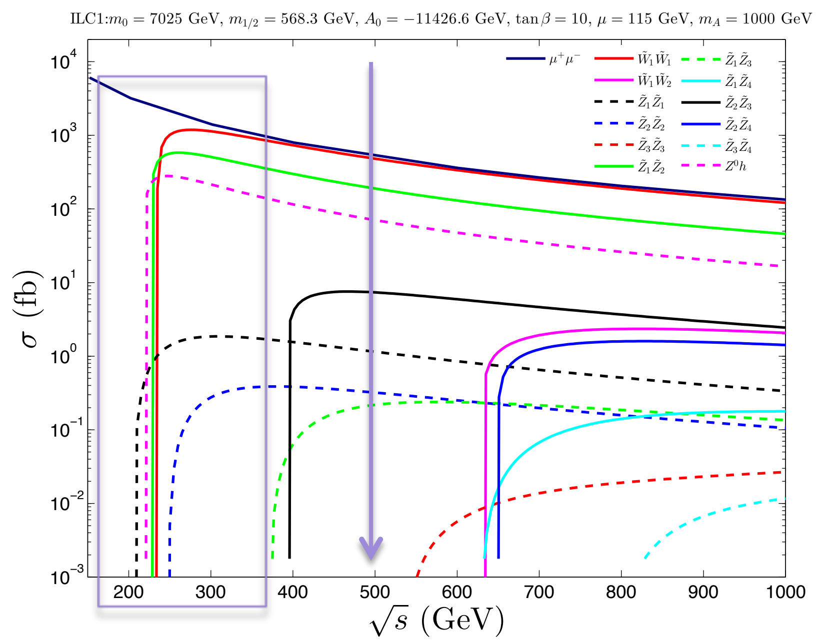
  J. Ruderman, FCC week Amsterdam (April 2018)



potential @ electron-positron machines

- Sensitive to EWK processes and useful to target compressed scenarios
- Caveat: **depends on the center of of mass energy**

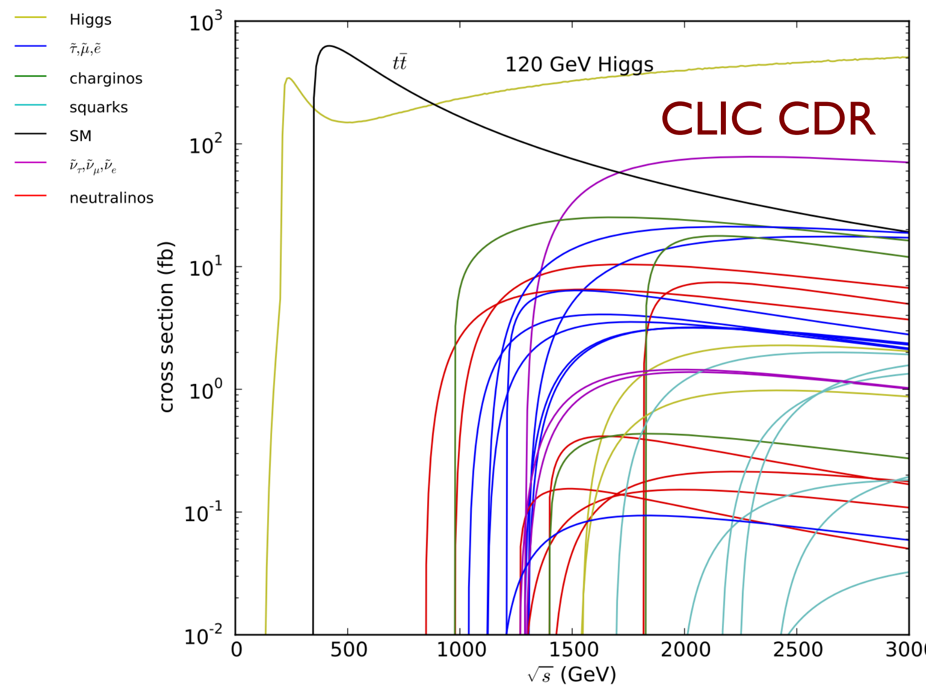
Sparticle σ for unpolarized beams at e+e- for ILC benchmark but also for FCC-ee



arXiV:1404.7510

High cross section for $\chi^{\pm}_1$ and χ_0 production and sleptons: clean environment to access very compressed scenarios

Sparticle σ at e+e- for one CLIC benchmark point



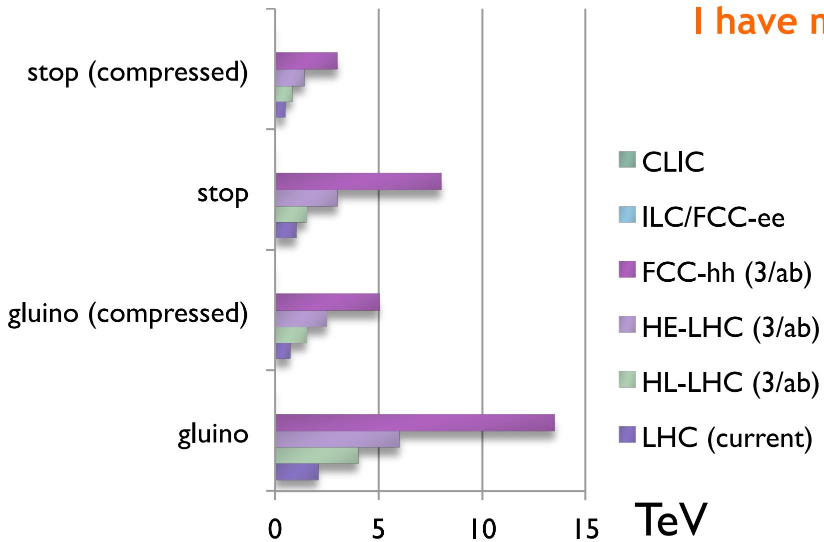
Cross-section for higgsinos too low also for CLIC?

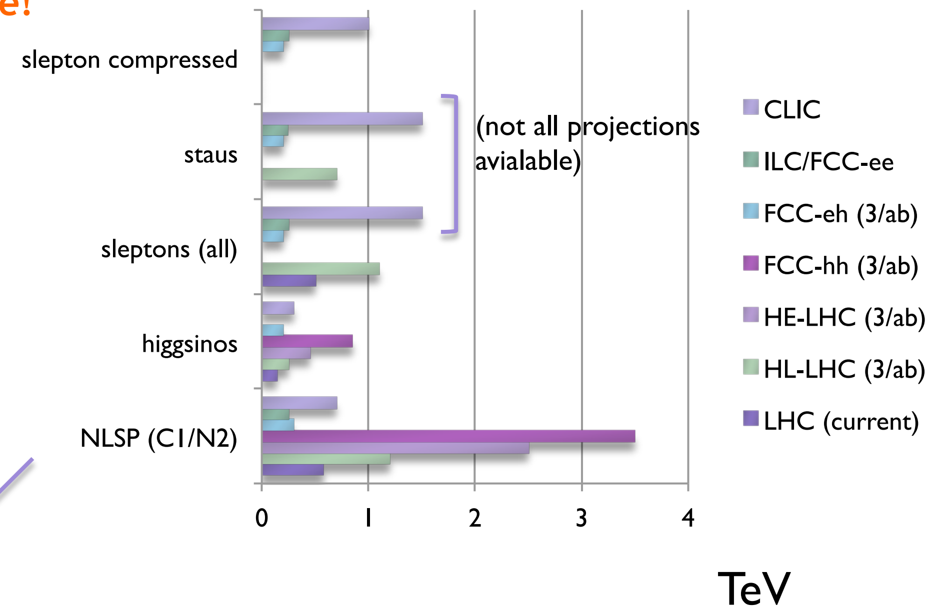
arXiV:1801.05192

Sensitivity for sleptons and charg/neut up to ~√s/2

In a snapshot

CAUTION: Crude approximations/extrapolations I have made!



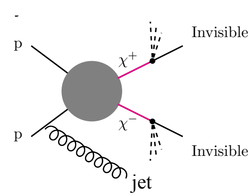


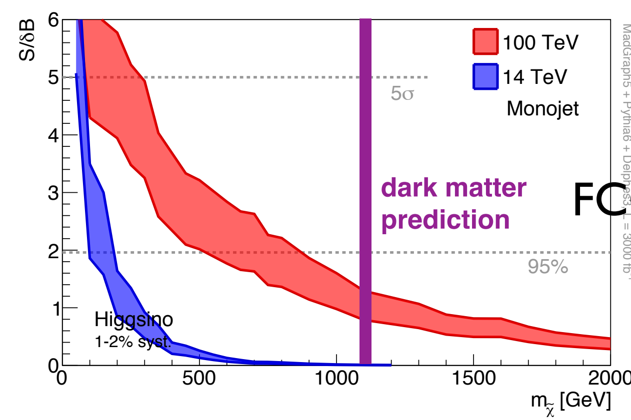
- Sleptons projections not yet available everywhere. Potential at ILC and CLIC (not for higgsinos).
- using mono-jet signatures
  - A signature relevant for many

  NP models (DM-oriented)

  Sensitivity also for FCC-eh (lower)

  → **1 TeC boundary reached only by FCC-hh**

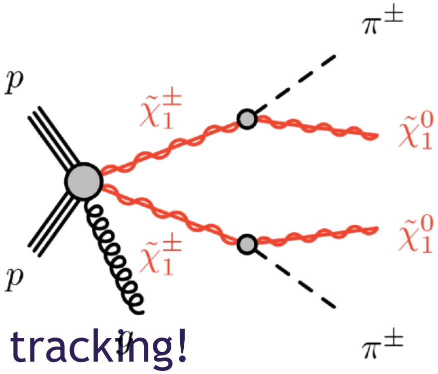


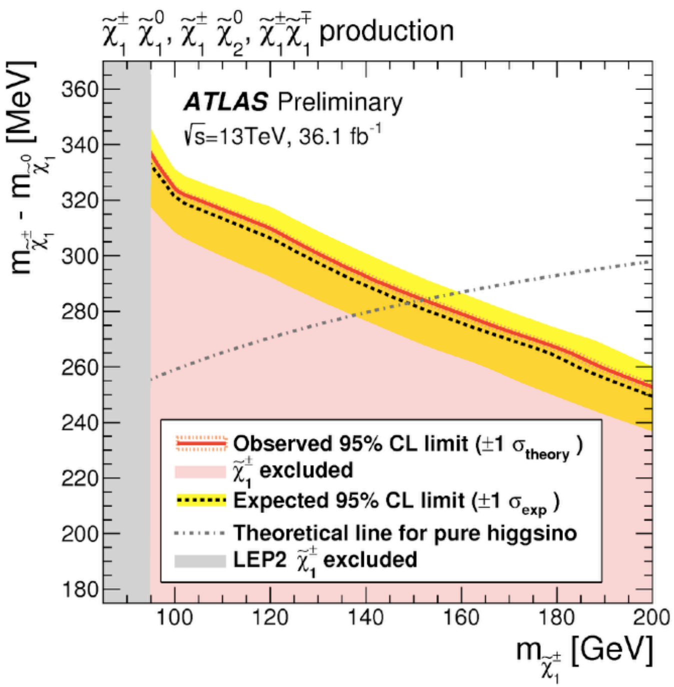


FCC-hh

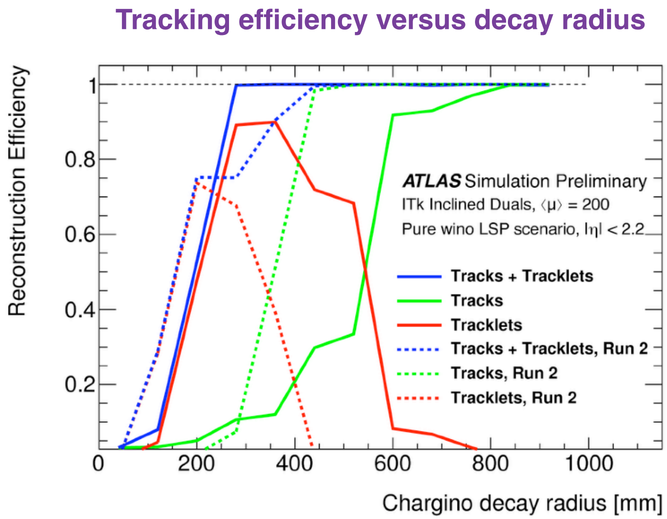
Long-lived higgsinos

- If DM(charg-neut) ~ 200 MeV, higgsinos might be long-lived
- charged particle with lifetime ~10 ps - 10 ns which decays to "invisible"
  - pure higgsino case: ~0.05 ns (wino: 0.2 ns)
- Studies for HL-LHC are in progress
  - Current results promising, but challenging – need excellent tracking!





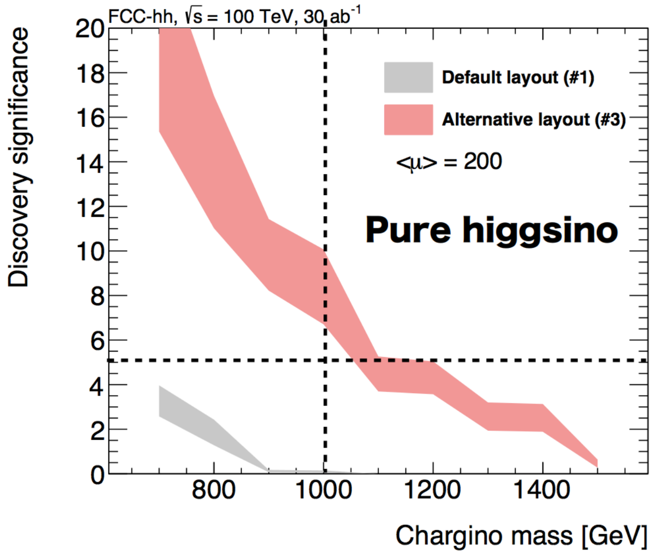
@HL-LHC: expect to exclude up to 250 GeV for pure higgsino (τ = 0.05 ns)



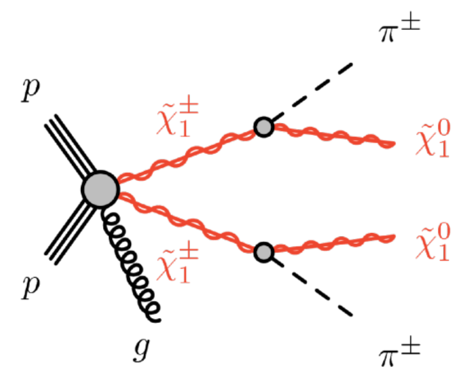
Long-lived higgsinos: long term future?

- At FCC-hh, sensitivity will depend on the bkg (very high PU)

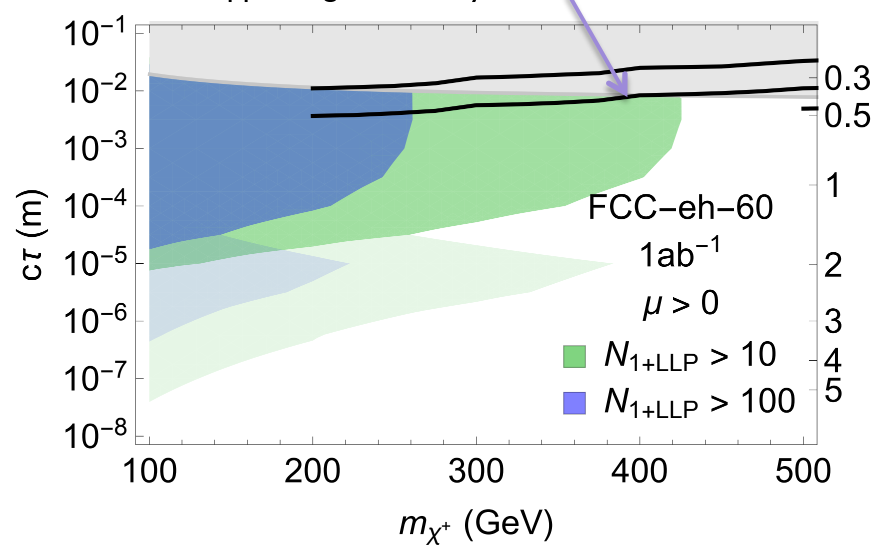
FCC week, Amsterdam 2018



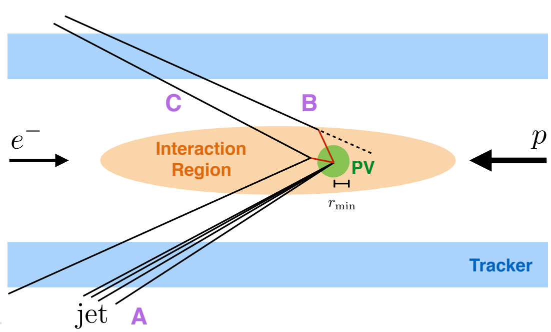
Maybe optimistic on Pile Up



HL-LHC and FCC-hh bound from disappearing track analyses



- Also possible at FCC-eh: advantage from low bkg and low PU



Curtin, Deshpande, Fischer, Zurita arXiV: 1712.07135

Long-lived particle, dark sectors and sterile neutrinos

LLP → Hot topic of the past 2-3 years

Not only for the higgsinos…

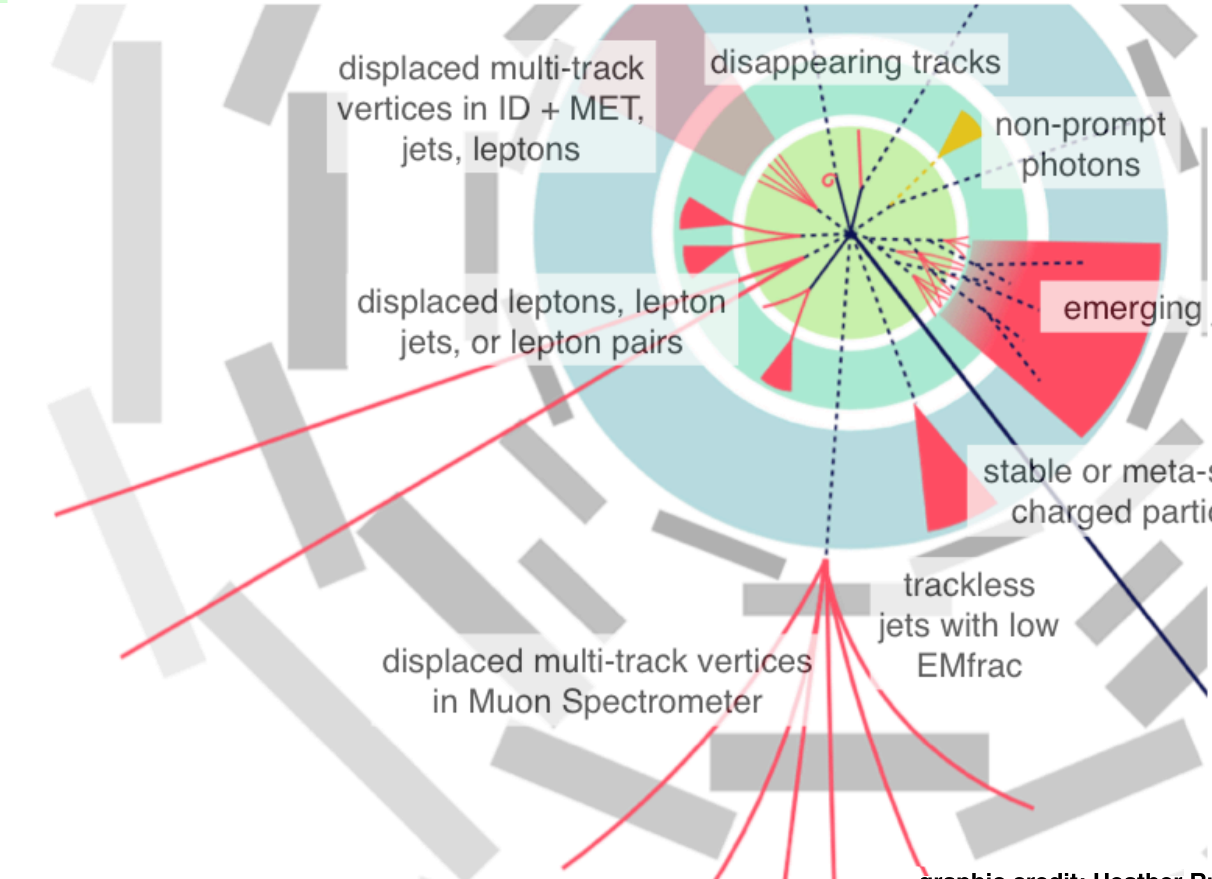
Great discovery potential: many NP models predict LLPs

- small couplings: RPV decays, dark sector coupling
- small mass-splittings: degenerate next-LSP
- heavy messengers, split SUSY, hidden valley

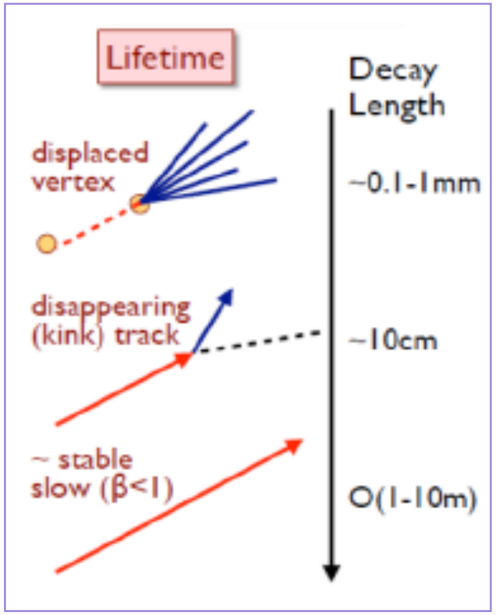
Signature space quite complex → joined exp/theory efforts to review all modes

Long-lived particles

- Particles decaying non-promptly are one of the major targets of HL-LHC experiments and beyond



graphic credit: Heather Russell



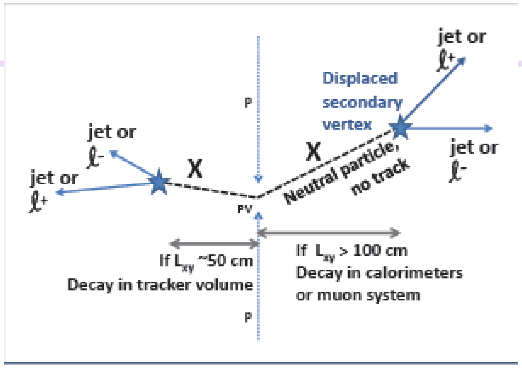
Synergy among ATLAS, CMS and LHCb experiments

- Target complementary lifetimes and mass ranges

A few examples

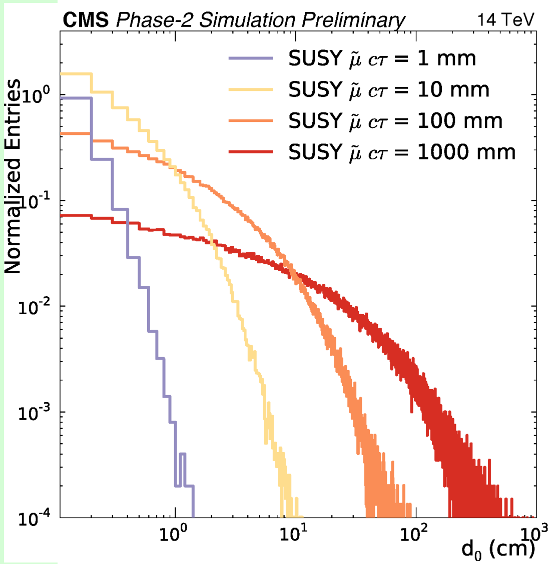
Displaced muons

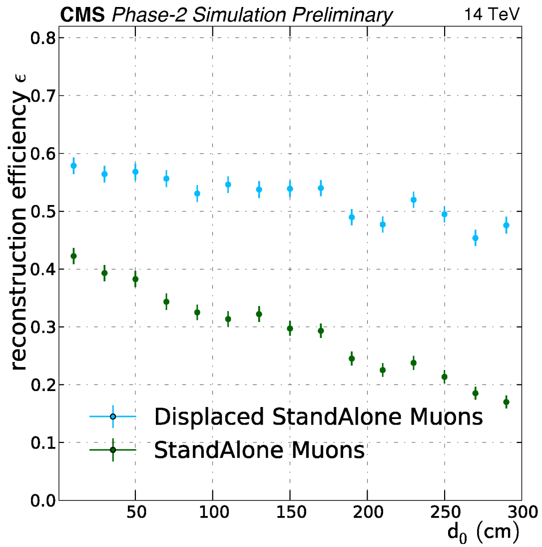
- New studies from CMS on SUSY:
  - **Smuons**

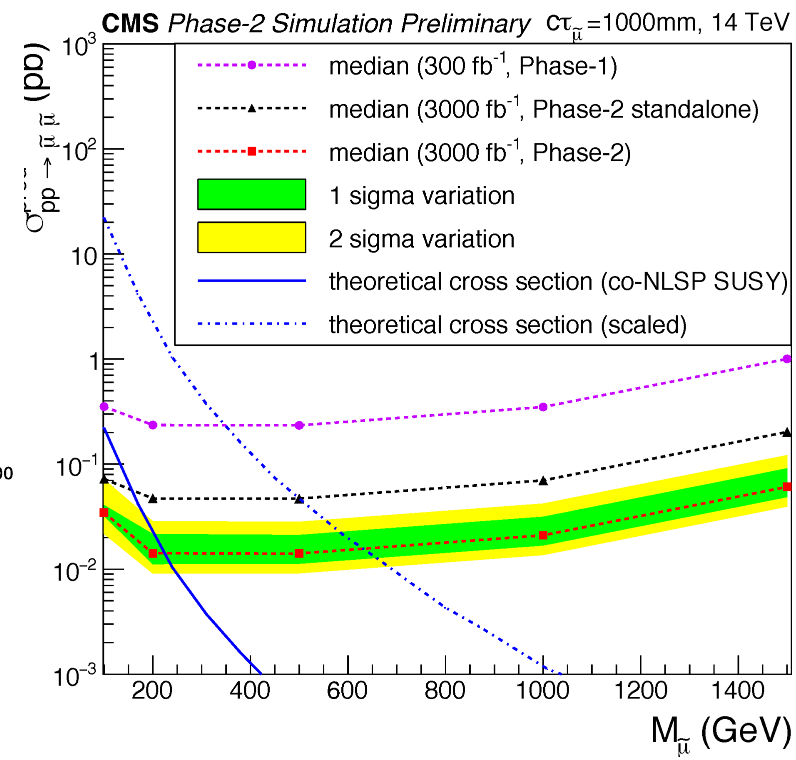


$$\tilde{\mu} \rightarrow \mu + X$$

CMS TDR (NEW)







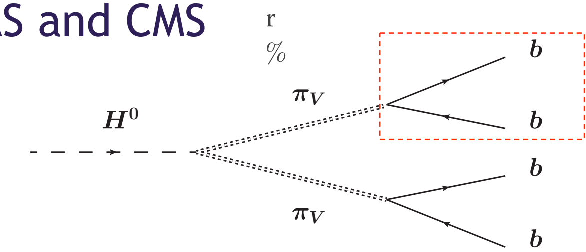
Experimental challenge:

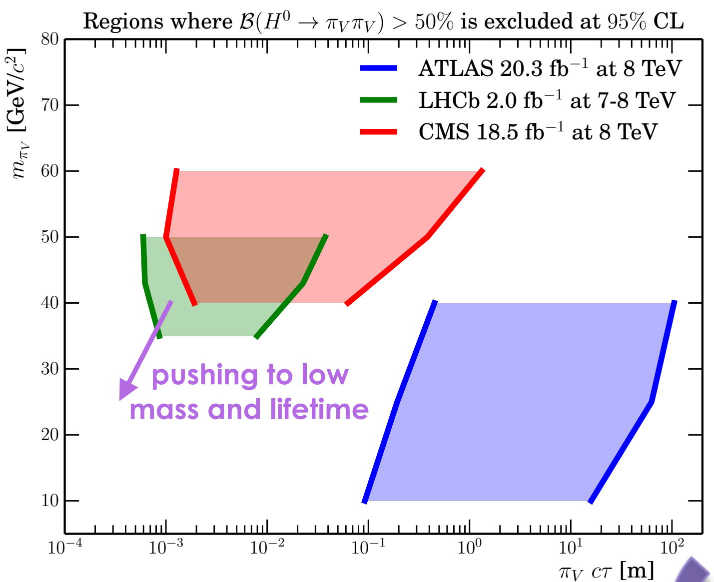
→ trigger displaced signatures
→ Vertex constrains reduce efficiency
→ Dedicated algorithms needed for displaced muons to recover efficiency

Quite an improvement in sensitivity!

Displaced jets

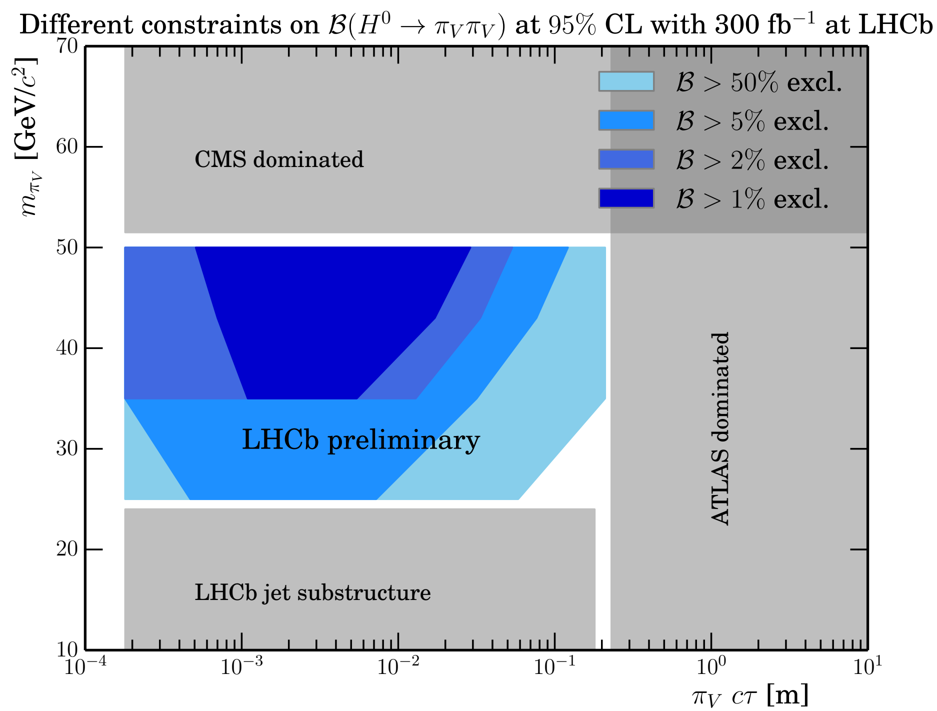
- Aim to exploit at best the complementarities among detectors
  - LHCb sensitive to lighter mass and low τ wrt ATLAS and CMS
- E.g. hidden valley dark pions from Higgs





extrapolation to 300 fb^{-1}

(E Dell'Occo, FNAL workshop 4-6 April 2018)



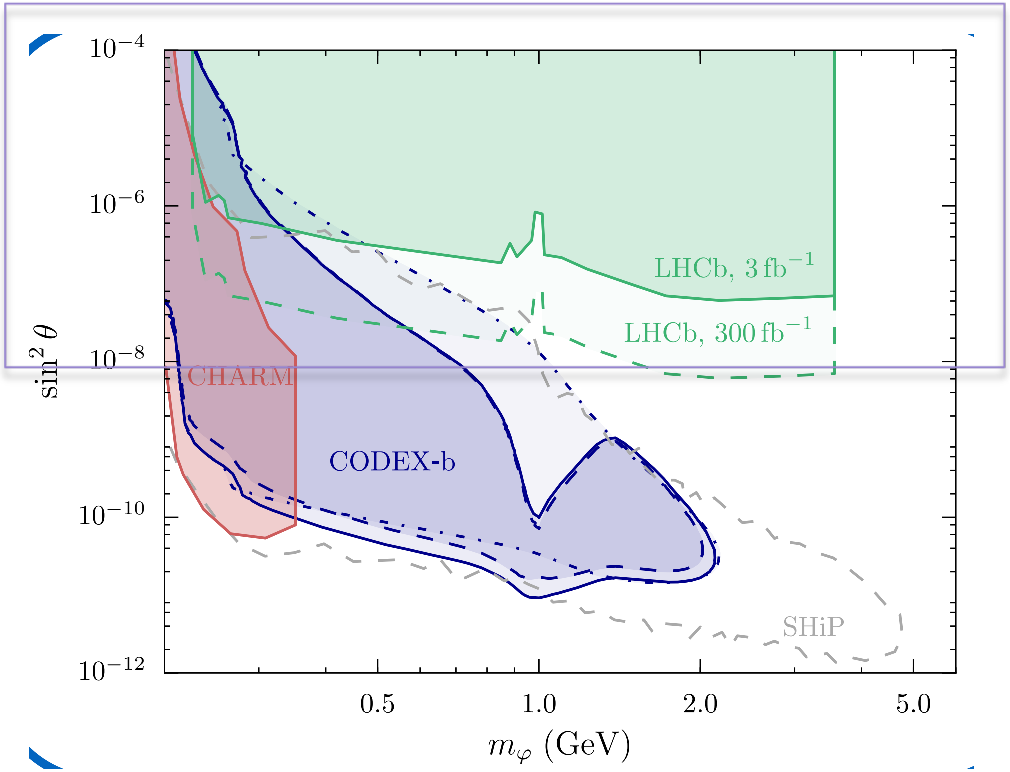
For short-lifetimes, this could be complemented by CepC !

LLP and Dark sectors

- **Higgs-portal models**
  - B and exotic decays
    - φ = light CP-even scalar mixing with the higgs
  - Projections promising !
  - Additional gain from proposal for a new detector (**CodeX-b**)

Significant extension of LHCb coverage

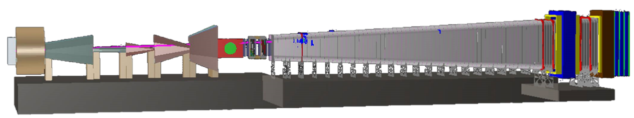
arXiv:1708.09395



Relation between Dark sector and Long-lived particle have led to many new ideas for new detectors and experiments
→ big interplay with so-called PBC experiments

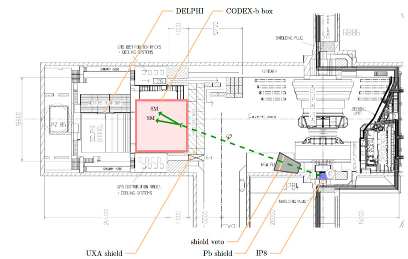
LLP and Dark sectors: PBC proposals

SHIP



Alekhin et al. (2015)

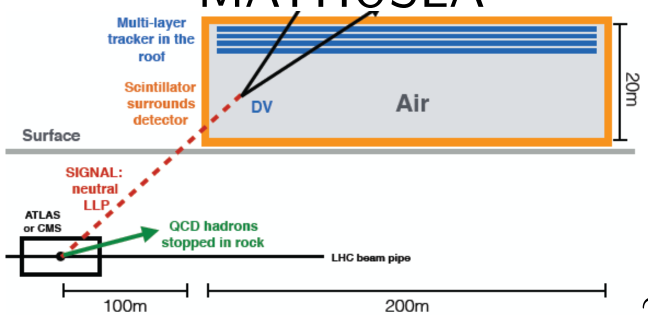
CODEX-b



$\sim 1000\ \mathrm{m}^3$

Gligorov, Knapen, Papucci, Robinson (2016)

MATHUSLA

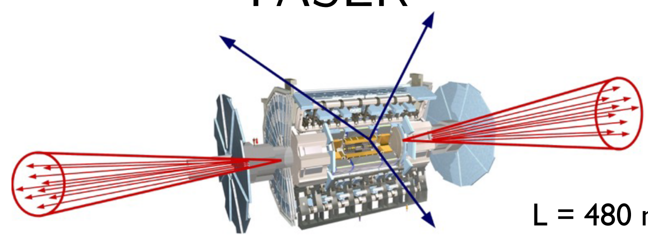


$2 \times 10^5\ \mathrm{m}^3$ ∼1 IKEA

Chou, Curtin & Lubatti (2016)

Curtin & Peskin (2017)

FASER



L = 480 m downstream from ATLAS/CMS IP

$\sim 1\ \mathrm{m}^3 \sim 5\mu$IKEAs

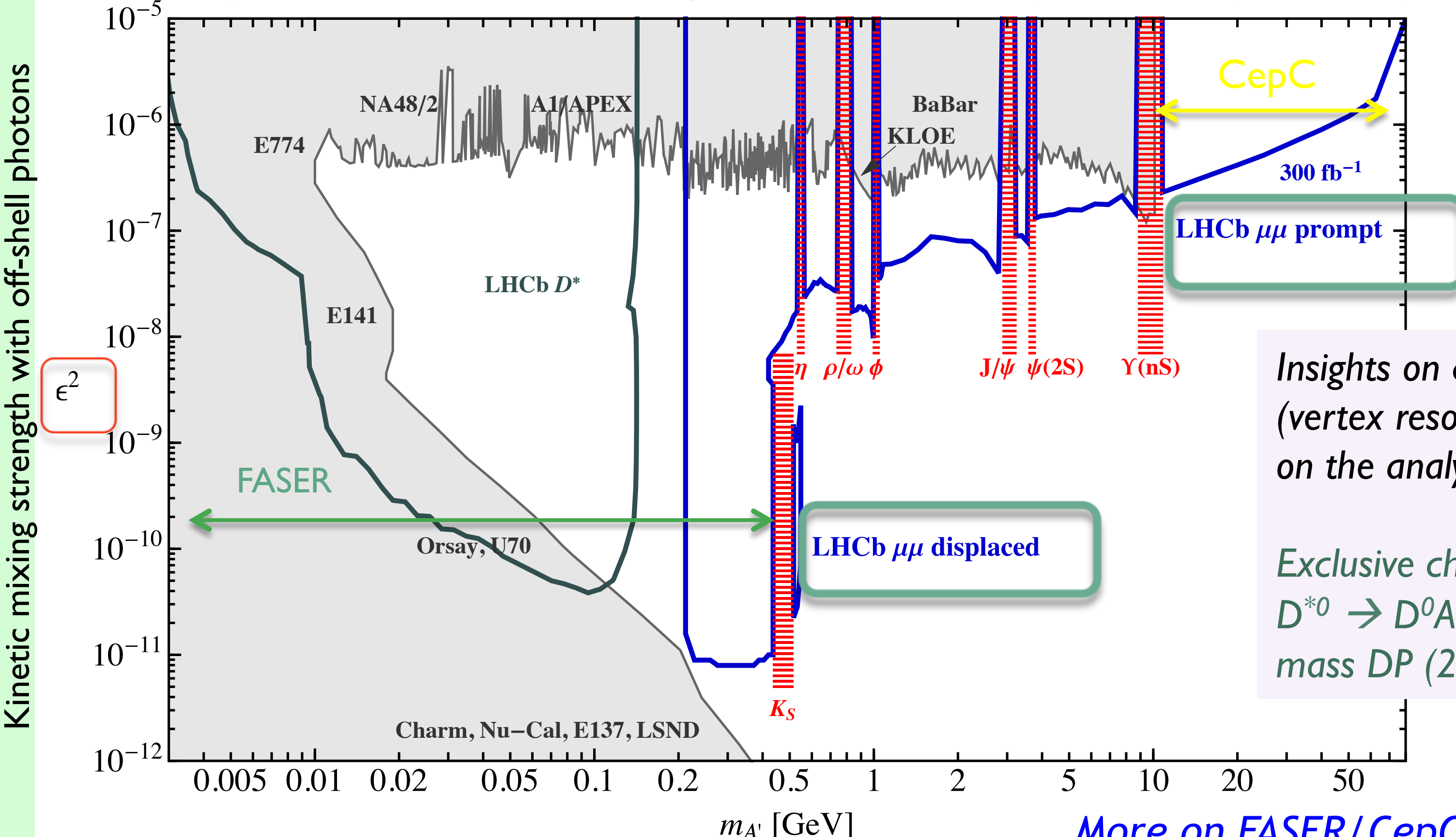
Feng, Galon, Kling & Trojanowski (2017)

Credits: I. Galon at FNAL workshop on HL/HE-LHC (4-6 April 2018)

Target complementary life-time and kinematic regions (forward and central, short and long)
Note: CepC and FCC could incorporate the basic of these experiments from the beginning

Dark photons @ HL-LHC

- Dedicated worldwide effort to search for dark photons
- E.g., can exploit the A'→μμ mode: at LHCb – impressive prospects:
  - curves assume Run 3 performance with more luminosity [*triggerless detector readout in Run 3 will have a huge impact on low-mass BSM searches, including dark photons*]
  - Magnet chambers would help with soft A' decays to e+e- (efficiency and/or resolution).



e.g. 1603.08926

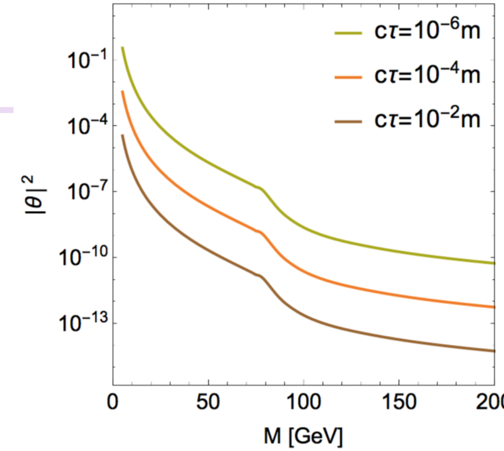
Insights on detector implications (vertex resolution, VELO size) and on the analysis in dedicated talk

Exclusive charm decay mode $D^{*0} \to D^0A'(ee)$ suitable for low-mass DP ($2m_e$-142 MeV)

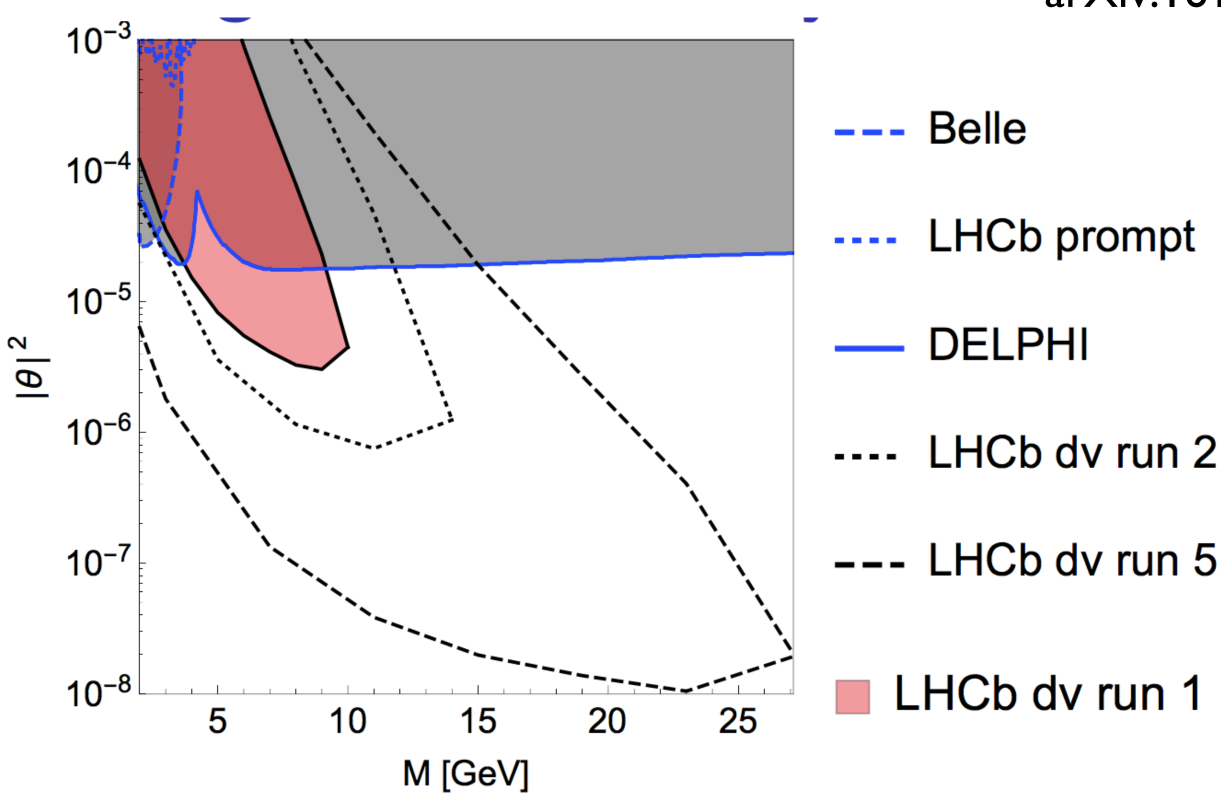
More on FASER/CepC impact in back-up

LLP and heavy sterile neutrinos

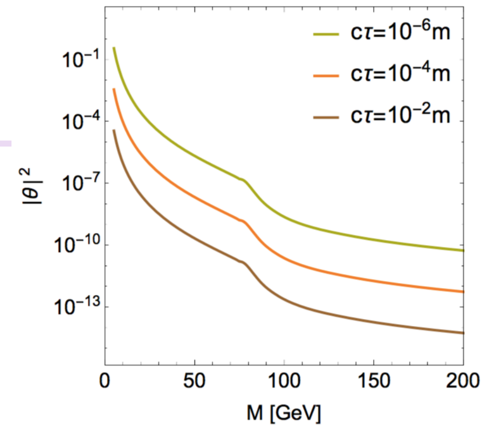
- Low-scale type I seesaw with sterile neutrinos
  - heavy neutrino mass eigenstates with M ~ vEW
  - Neutrino mixing $|\theta_\alpha|, \alpha=e,\mu,\tau \Rightarrow$ Weak current production.
  - Present constraints: $|\theta_e| \leq 10^{-3}$, can be long-lived
- Projections (LHCb)



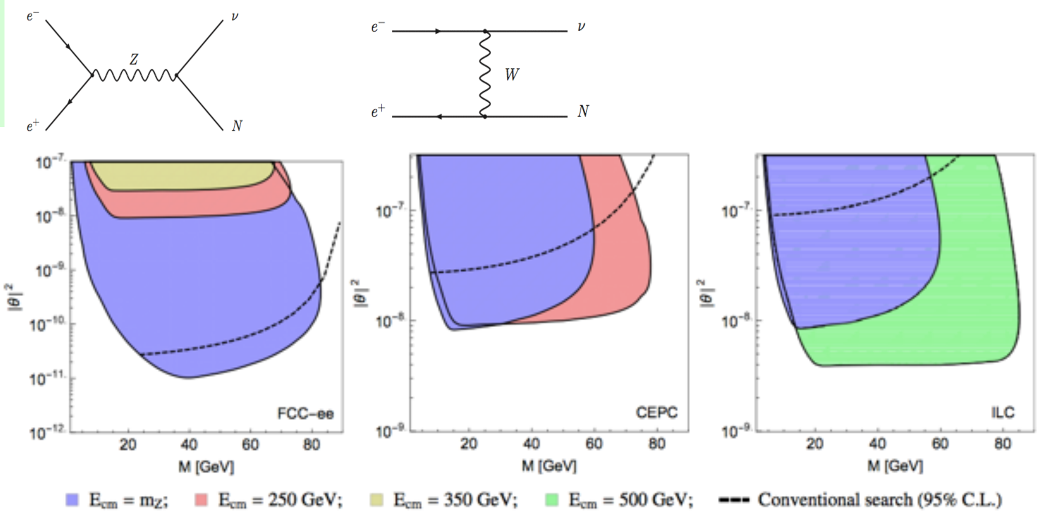
arXiv:1612.00945

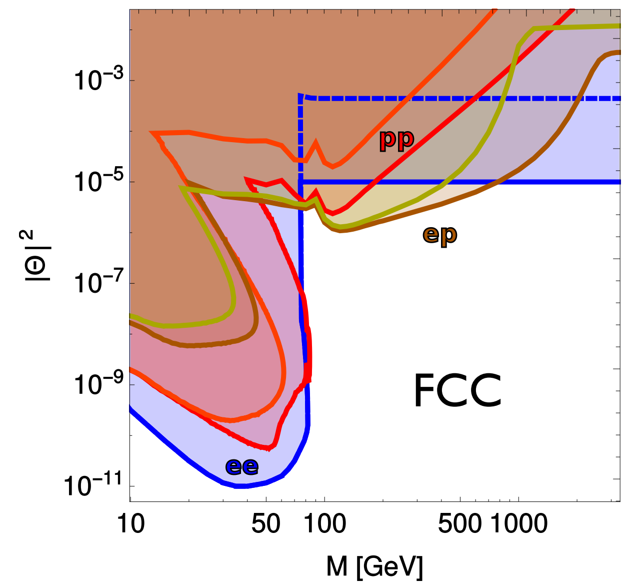


LLP and heavy sterile neutrinos



- Low-scale type I seesaw with sterile neutrinos
  - heavy neutrino mass eigenstates with M ~ vEW
  - Neutrino mixing $|\theta_\alpha|, \alpha = e, \mu, \tau \Rightarrow$ Weak current production.
  - Present constraints: $|\theta_e| \leq 10^{-3}$, can be long-lived
- Potential at e-e colliders, complementarities of FCC-hh, eh, ee





A long way before constraining the full mass/mixing ranges

A good news worth further investigation: Heavy neutrino-antineutrino oscillations could be resolvable and hh and eh

Fischer, Cazzato, arXiV: 1709.03797

Summary

- In the past years, experiments have focused on the completion of the detector proposals and optimization of performance
  - Lot of benchmark studies have been carried out, with continued efforts to evaluate the prospects of BSM searches in parallel to data analyses
  - New ideas are being explored
    - Never underestimate physicists ingenuity ☺ We did not find NP yet, but pushed the boundaries well beyond initial projections
- There is huge potential also in terms of complementarities:
  - Push for a synergic approach across HL-LHC experiments i.e. in NP scenarios characterized by long-lived particles and dark sectors
  - Work to fully exploit the HL-LHC potential also considering new detectors/ facilities (e.g. for long-lived particles)

Lot of exciting physics can be done at HL-LHC and 'around', and a great physics case is being developed

- For the **long-term and UK strategy ….**

Some points for discussion

- At the moment, it is not possible to define a preferred direction
  - Direct searches limited by kinematic reach, indirect searches limited (e.g.) by precisions → not a unique recipe
- Directions: HARD until we see some deviations from SM predictions!
  - Not necessarily at LHC, could be on any other related field (cosmo, neutrino…)
    - Correlations LHC/non-LHC signals could be pursued, hints of DM candidates and more could indicate the scale
- A proton-proton machine provides a wide range for exploration of NP
  - **My take:** the potential of HE-LHC is huge for new particles up to ~10+ TeV with large datasets. FCC-hh is great, but far away in time (after FCC-ee)
    - We should ask ourselves how long should we wait to reach (ie) 40 TeV in Z'?
    - Help in improving SM predictions could come from additional e-p option (also for HL-LHC)
    - Unfortunately, won't be able to constrain higgsinos up to 1 TeV without FCC-hh (?)
  - HE-LHC pp (+ep) running at the same time of a e+e- machine in 25-30 yrs from now?
    - Lot of advantages also for retaining expertise, develop detector technology, FCC-hh later ?

PAST

Tevatron/HERA/LEP → LHC → HL-LHC *(ep?)* → HE-LHC/(ep)/ee(CepC?,ILC)

(fermiscale) (Terascale) (multi-Terascale)

PRESENT

FUTURE ?

Some points for discussion

- An e+e- machine provides high precision
  - Precision vs energy → preference largely depends on the NP model
  - Low center-of-mass energy:
    - "blind" to most open NP scenarios in terms of direct detection (CepC, but also ILC and FCC-ee in its first phases)
    - Sufficient for indirect constrains (EFT) and some of the dark sectors
  - High center-of-mass energy:
    - Certainly higher potential (e.g. SUSY @ ILC-500 and CLIC)
    - Yet not conclusive for most NP models
  - **My take:** e+e- is great for precision measurements and higgs physics; for most of BSM scenarios does not provide conclusive results
    - CepC enough for indirect fits, ILC and FCC-ee would be great for EWK SUSY
    - CLIC clearly superior in terms of NP reach for some NP models – not enough anyway?

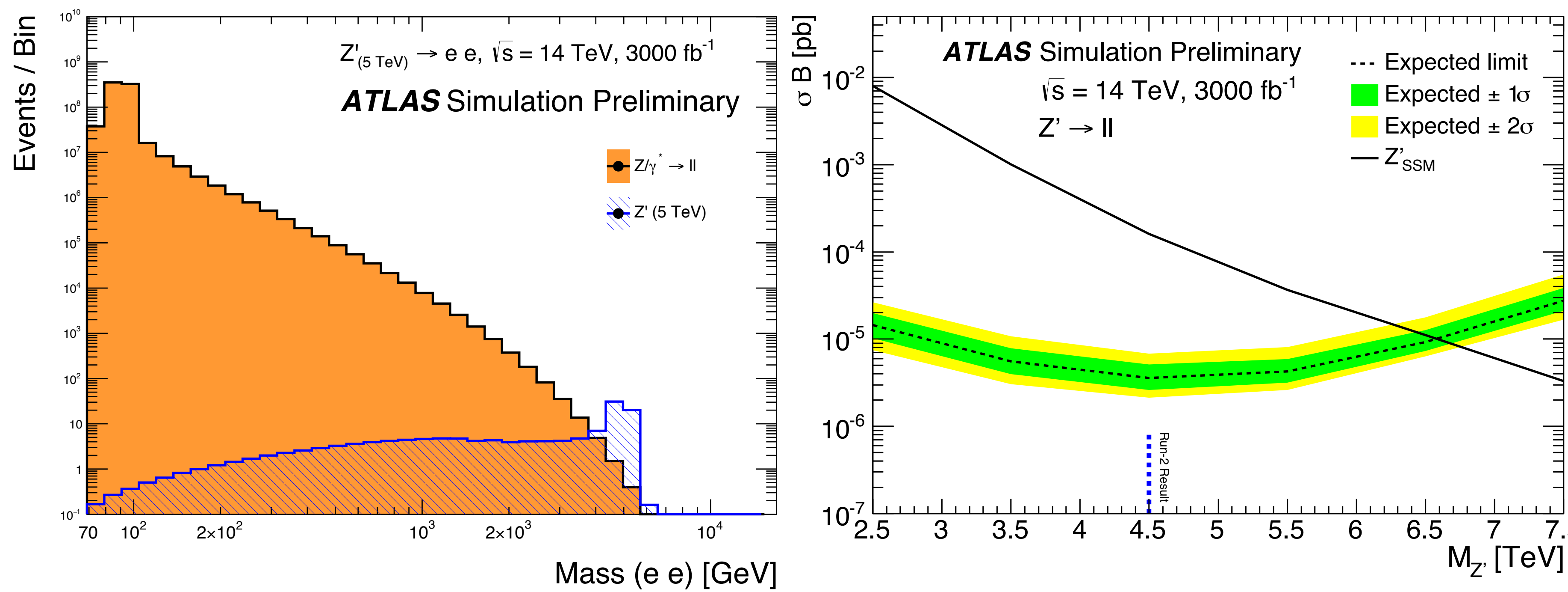
- Potential for long-lived particles to be retained as much as possible
  - Invest more for future facilities / experiments complementing LHC and embed what we have learned in future facilities

Back up

Reach with HL-LHC: Z'→ee (ATLAS)

- LAr calorimeter has a direct impact on the ee invariant mass resolution
- Consider Sequential SM Z' as benchmark
- 2 electrons with p_T>25 GeV
  - exclusion up to to 6.4 TeV, discovery reach ~ **5.9 TeV**

ATLAS TDR



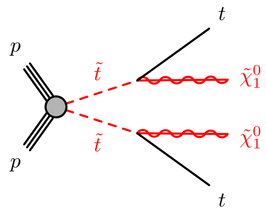
- Constraints are about 200 GeV more stringent than for muons, thanks to the resolution for high p_T electron

SUSY @ HL-LHC: challenging scenarios (stop)

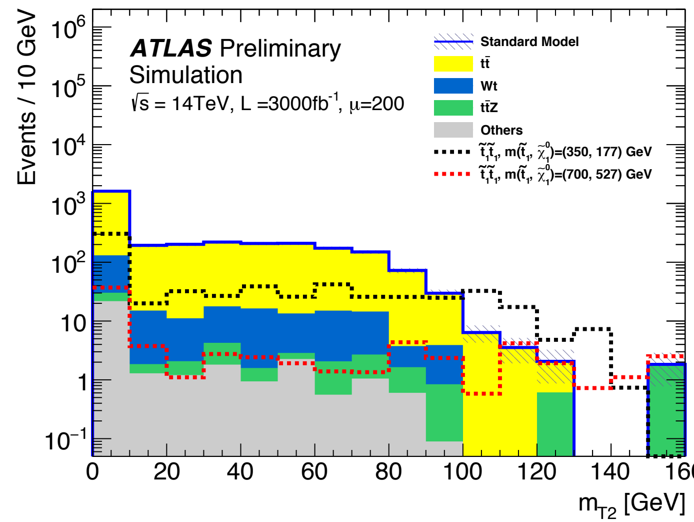
ATL-PHYS-PUB-2016-022

- Target compressed scenarios and use ISR jets
- m_{T2} as discriminating quantity, 2l + 2b + MET
  - Not simple to target those!

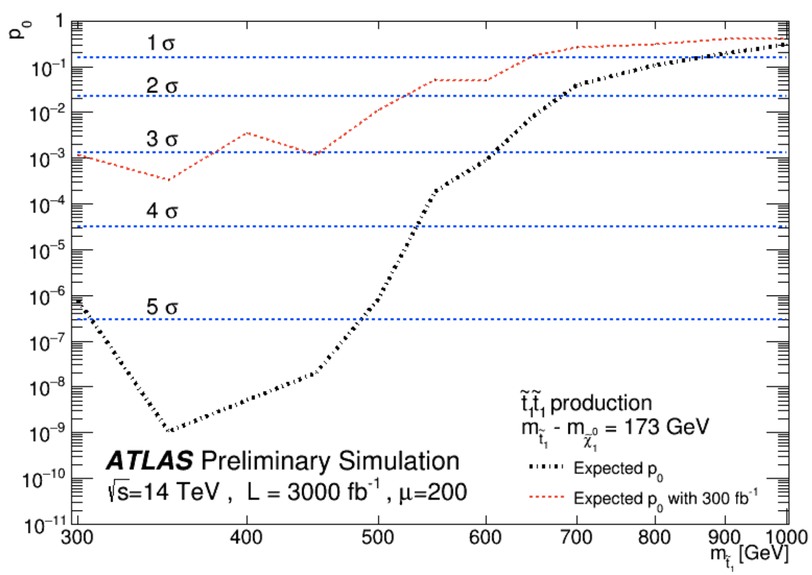
$$(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}) \cong m_t$$

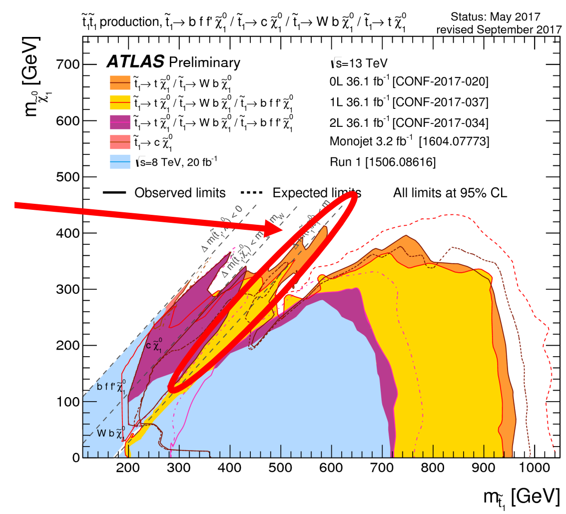


$m_{\ell\ell}$ [GeV] (SF lepton pairs only)	$81.2 < m_{\ell\ell} < 101.2$
$\min\{\Delta\phi(\text{jet}_{\text{ISR}}, E_T^{\text{miss}})\}$	> 0.4
$\Delta\phi(\text{jet}_{\text{ISR1}}, E_T^{\text{miss}})$	> 2
$R_{\ell\ell}$	> 6
E_T^{miss} [GeV]	> 350
Leading ISR jet p_T [GeV]	> 300
m_{T2} [GeV]	> 100



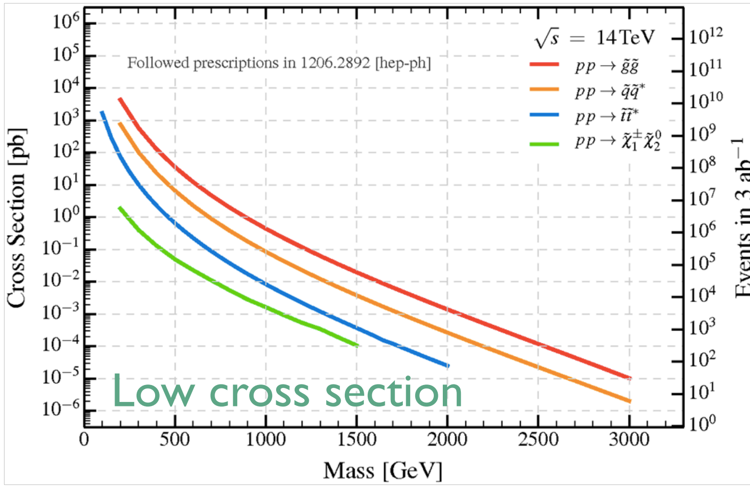
Cut-and-count, optimized for discovery



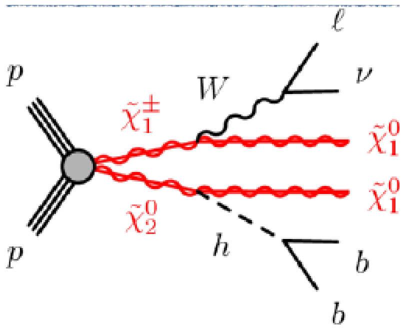


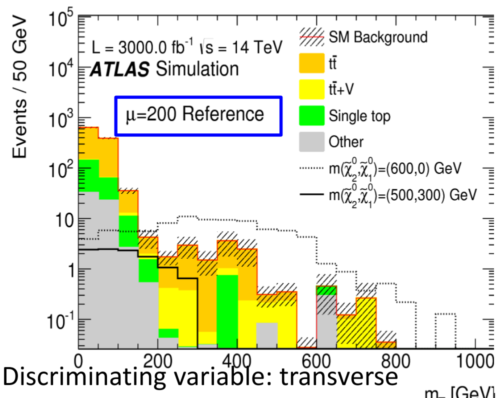
SUSY@ HL-LHC: EWK sector

- HL-LHC dataset has the potential to increase the sensitivity to EWK SUSY enormously
- HE-LHC at 27 TeV can lead to a ~2x increase of signal xs for sub-TeV EKW-inos
  - But unclear if it is really an advantage
- Sensitivity strongly depends on EWK-inos composition and consequent decay



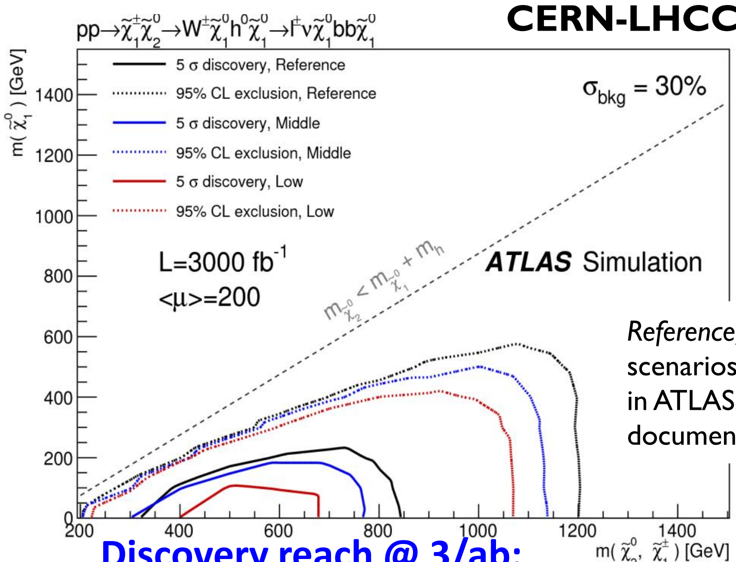
Very challenging:





Discriminating variable: transverse lepton mass m_T

CERN-LHCC-2015-020



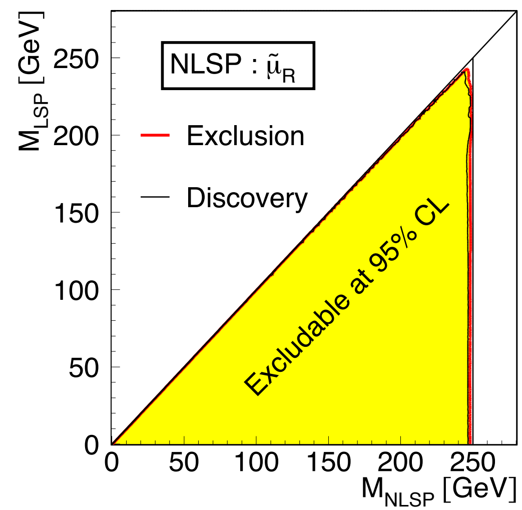
Reference, middle, low – scenarios considered in ATLAS scoping document

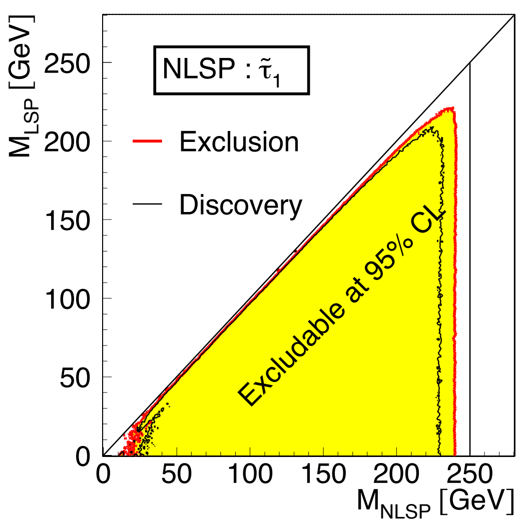
Results depend on the PU conditions as well as on the approach

Discovery reach @ 3/ab: 850 GeV reference detector

SUSY @ electron-positron machines (II)

Sleptons @ ILC (500 GeV)

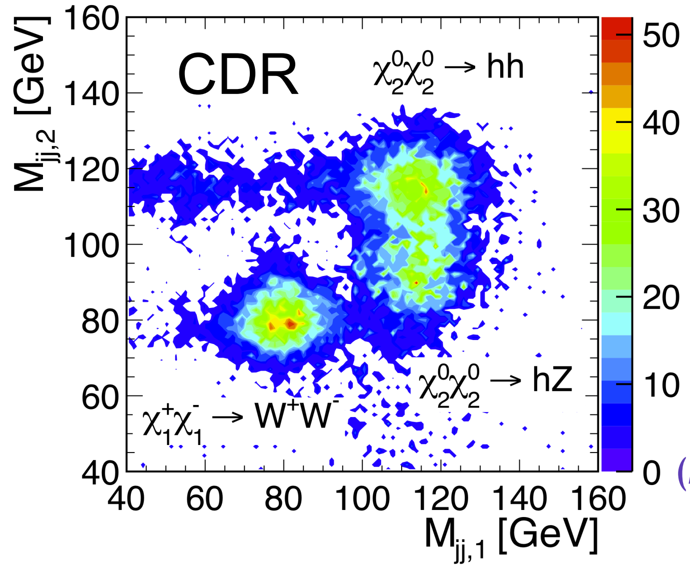




arXiV:1307.5248

Chargino/neut @ CLIC (Stage 2: 1.5 TeV)

$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+W^-$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow hh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow Zh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0$$



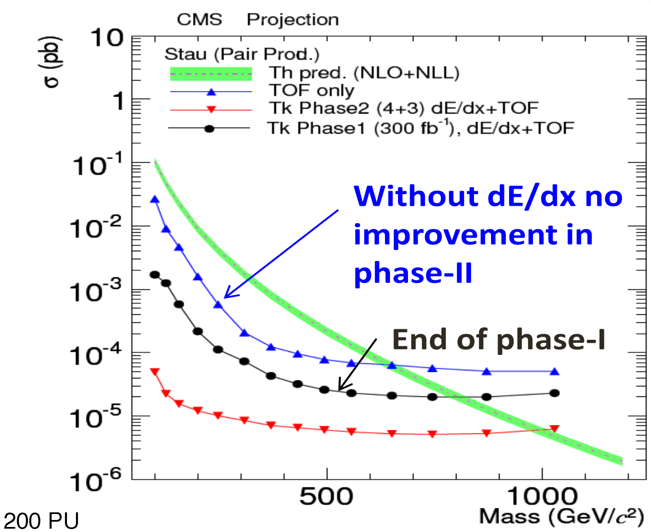
Precision on the measured chargino/ neutralino masses (few hundred GeV): 1 - 1.5%

(M(charg/neut2)=487 GeV)

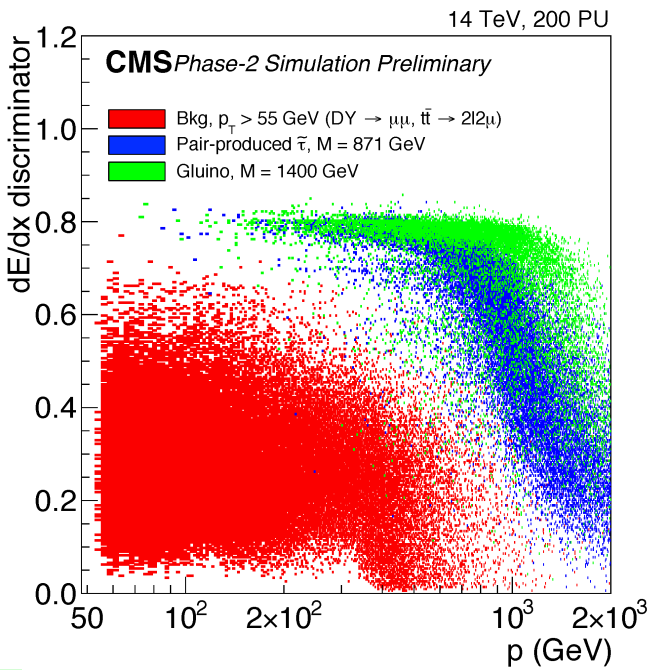
Similar studies in progress for circular colliders

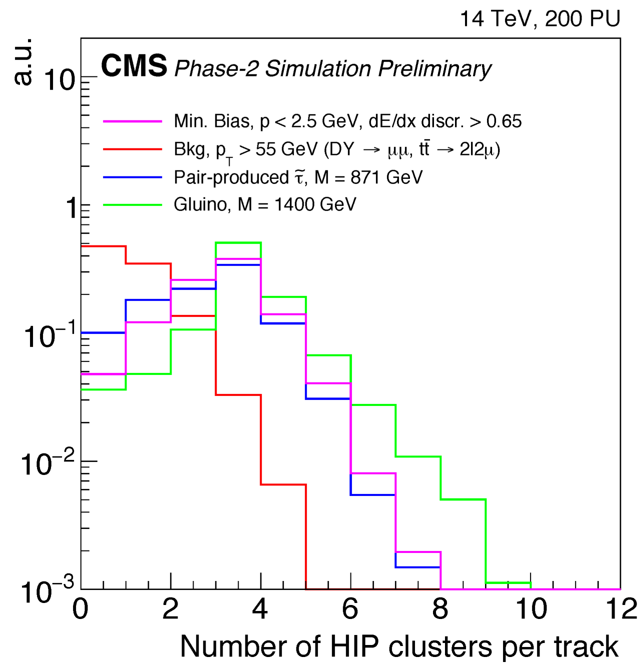
Heavy Stable charged particles

- Dedicated studies showed the need to keep good dE/dx capabilities



- New 200 PU studies:
  - consider stau and gluinos models
  - pT>55 GeV tracks, show also N of high threshold clusters with HI particle

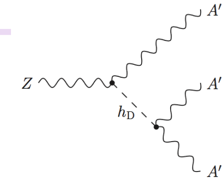




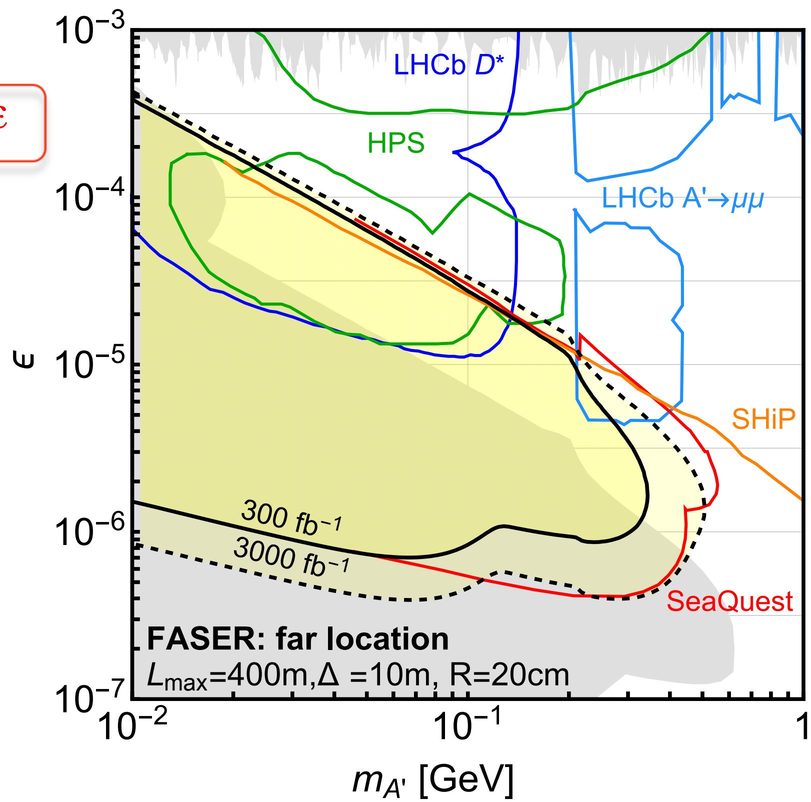
Additional CMS studies on performance for Heavy stable charged particle via muon system also available *(more in dedicated talk)*

CMS TDR (NEW)

Dark photons: future potential



- FASER predictions



I. Galon at FNAL workshop on HL/HE-LHC (4-6 April 2018)

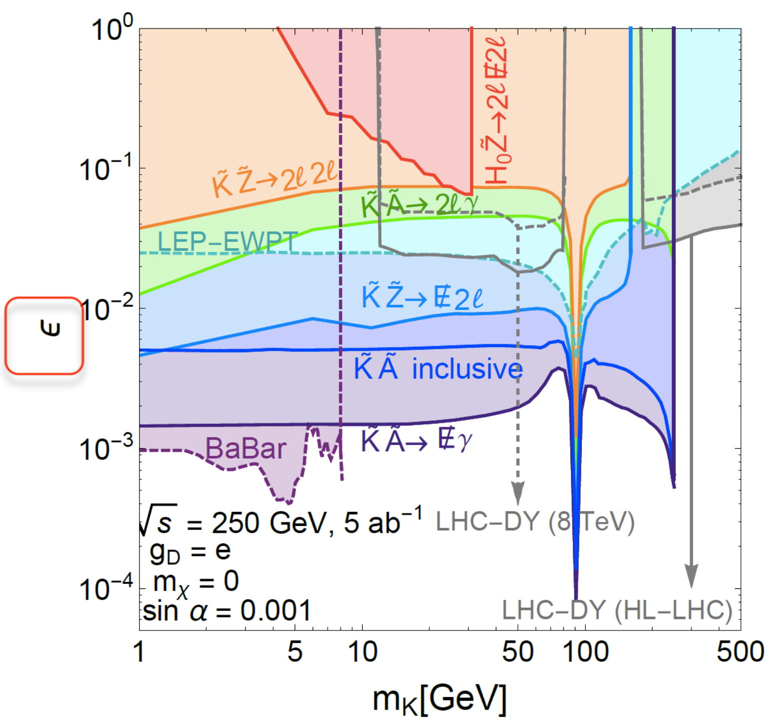
- CepC potential

$e^+e^- \to \tilde{Z}H_0$ Study $\tilde{Z} \to \ell\ell$ and semi-visible $H_0 \to (\ell\ell)_Z\chi\chi$

$e^+e^- \to \tilde{Z}\tilde{K}$ Study $\tilde{Z} \to \ell\ell$ and $\tilde{K} \to \bar{\chi}\chi$ or $\ell\ell$

$e^+e^- \to \gamma\tilde{K}$ Study $\tilde{K}$ inclusive decays, and exclusive $\tilde{K} \to \bar{\chi}\chi$ or $\ell\ell$

$e^+e^- \to \tilde{Z}S$ Study $\tilde{Z} \to \ell\ell$ and $S \to 4\chi$

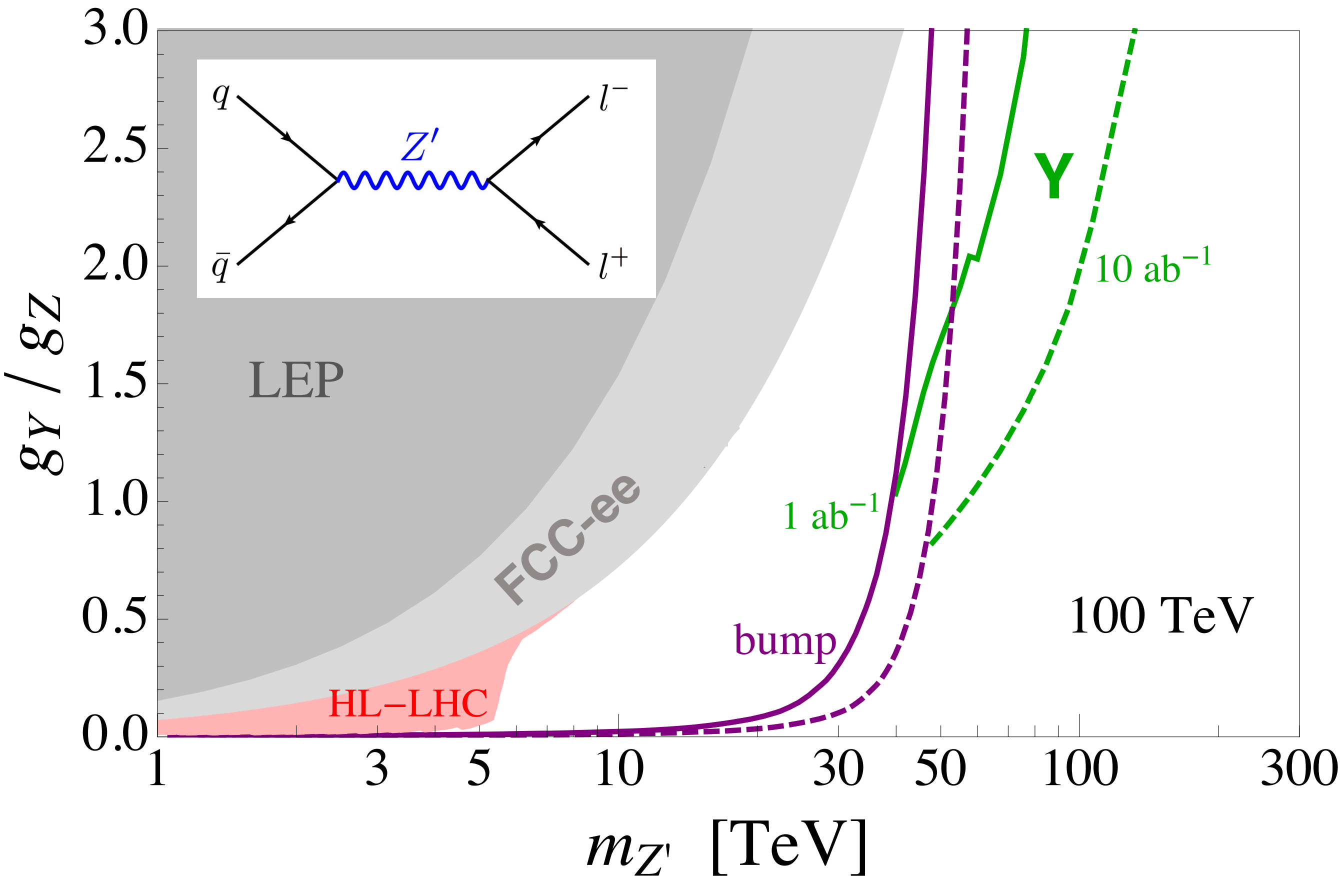


Felix Yu – Dark Sectors at CEPC

Indirect constraints on Z'

- If mZ'>>5 TeV, main contributions from interference effects modifying DY
- The precision of e^+e^- colliders help but LHC (and HL-LHC) can do a lot

Alioli, Farina, Pappadopulo, JTR, Phys. Rev. Lett. **120**, no. 10, 101801 (2018)



Similar Cost for 3 of the 4

ILC (250 GeV)

	ILC	
CoM. Energy	250	500
Site Length	~21	31
Luminosity	0.82	1.8
AC Power	129	163
Value Cost in TDR	TBD	7.98

($5 - 6B?)

CLIC (380 GeV)

380 GeV centre-of-mass energy.

	Value [MCHF of December 2010]
	1245
	974
	2038
	132
	2112
ure	216
	6690

CEPC (100 km)

总价（万元） 100公里
3606984.81
2323610.85
250227.56
32635.00
1000511.40

($5.5B)

- No cost available for FCC-ee at this moment