Searches for new physics towards the European Strategy 2020

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University of Liverpool

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

A premise

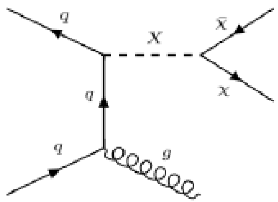
- I have been asked to review the expected reach of HL-LHC and prospects beyond that in the context of BSM searches
  - which projects would enable better reach, what are potential developments, experimental possibilities (beyond HL-LHC), possible choices for the strategy and UK inputs
- A very broad 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?**
- **..**

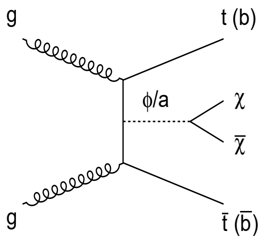
DM, DE and some of the above in other talks at this meeting – although…

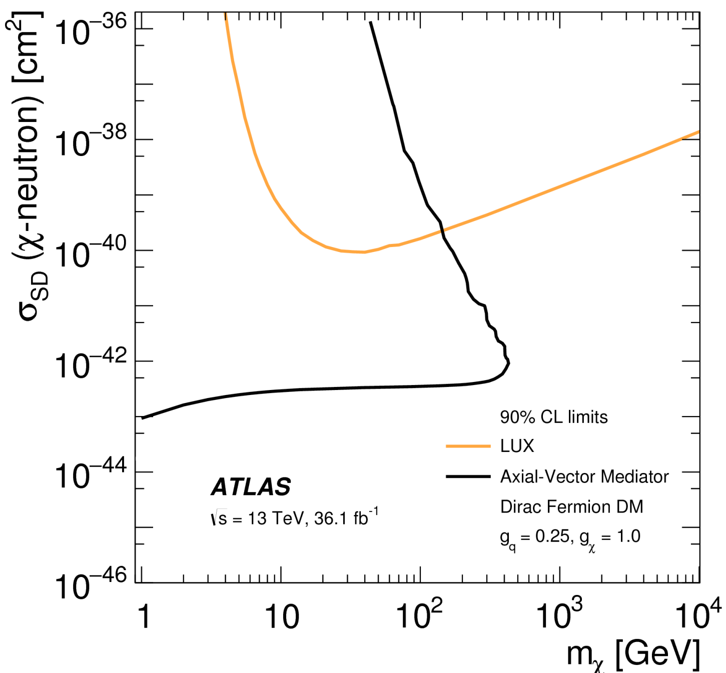
1 slide of DM at colliders

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

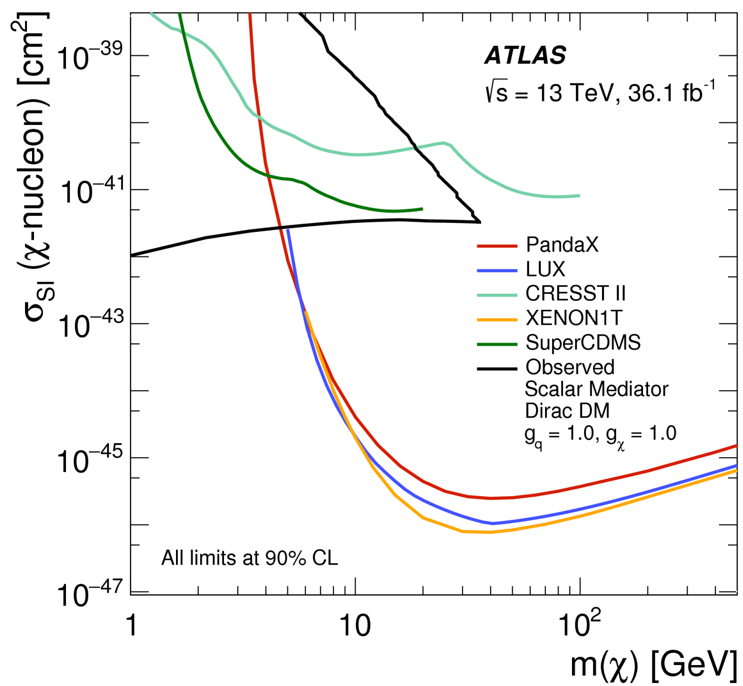


Assumptions needed
But complementarities clear





spin-dependent DM-neutron scattering cross section plane



spin-independent DM--nucleon cross-section

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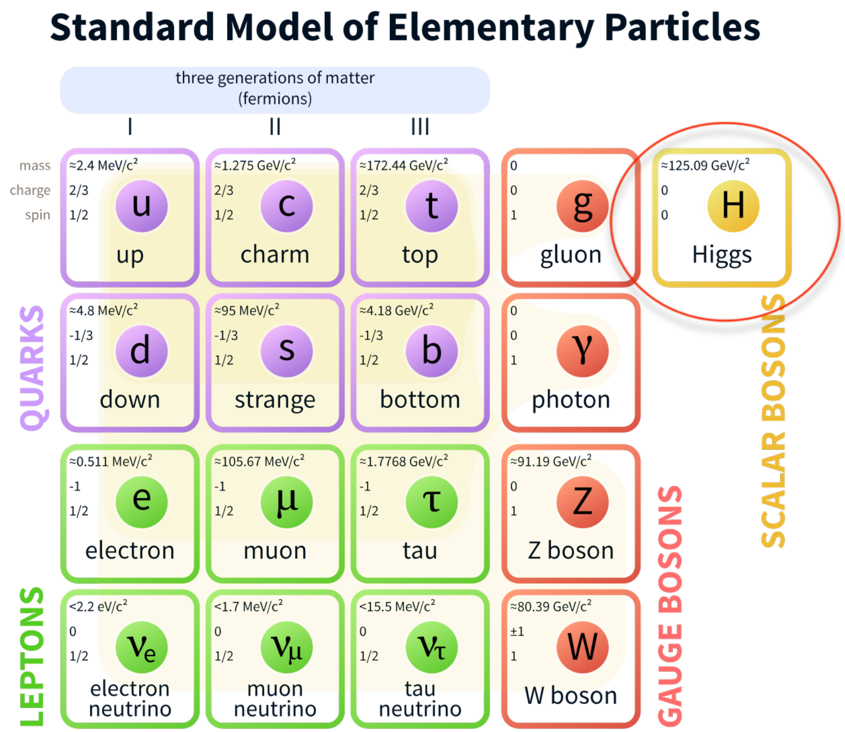
> “there is no experiment nor facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can ***guarantee discoveries*** beyond the SM, and ***answers*** to the big questions of the field” (M.Mangano, 98th ECFA, November 2015)

Searching for new physics: what



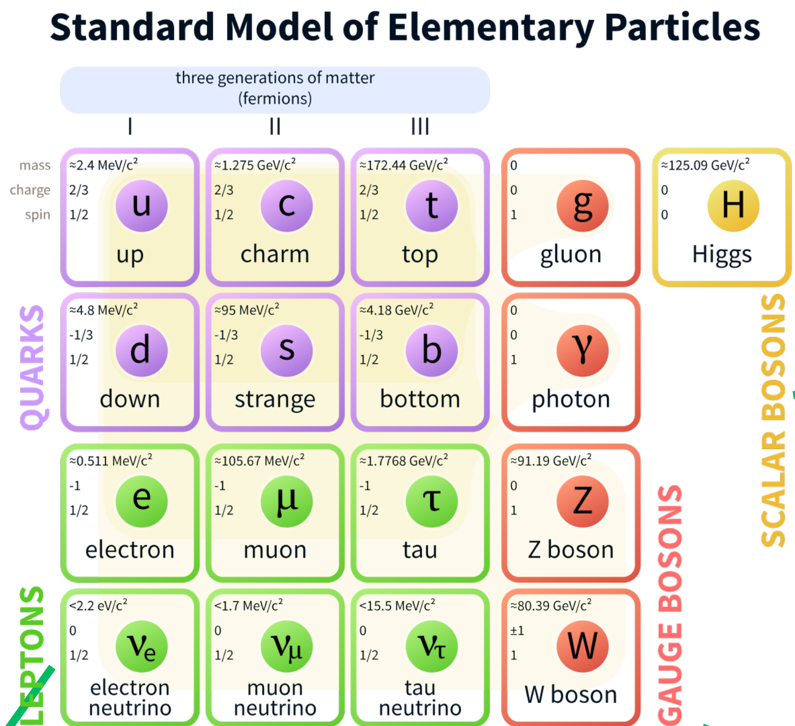
2010: clear guidance for the LHC: EWSB and the **Higgs boson**, and we discovered it…

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

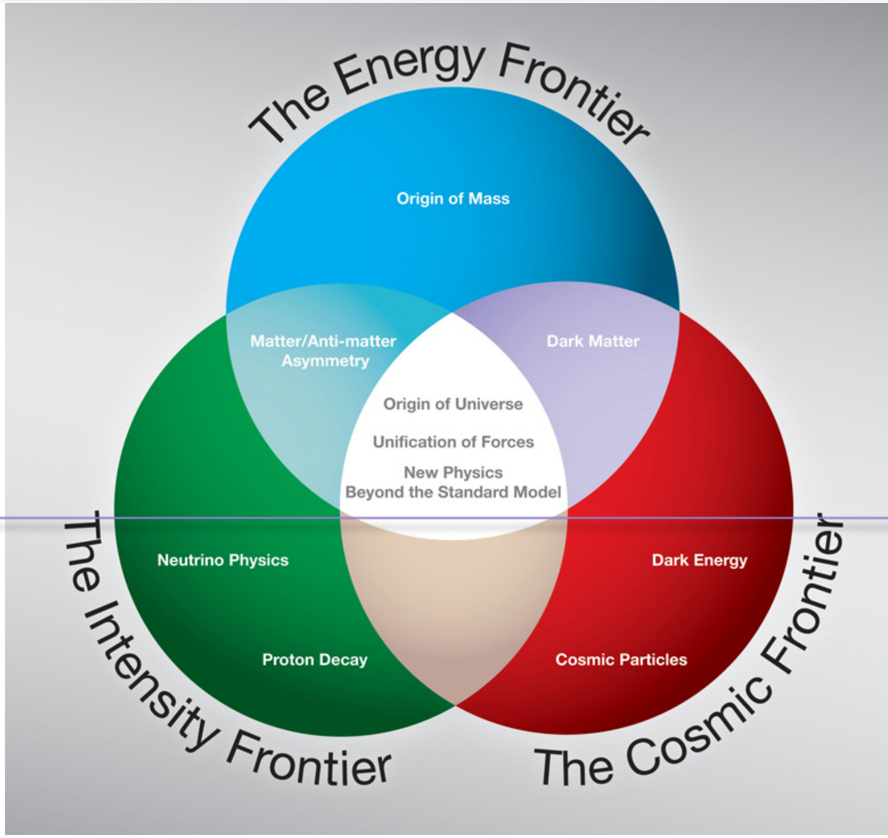
"Exotics": referred to a large variety of theories and models

- 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)

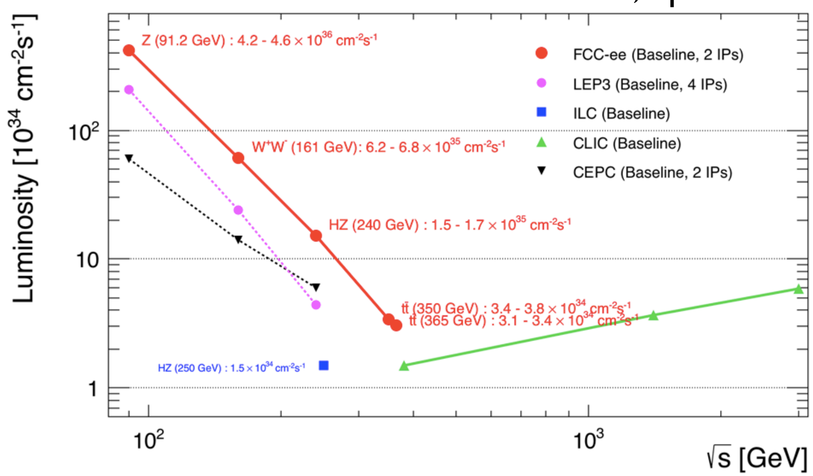
PRESENT

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



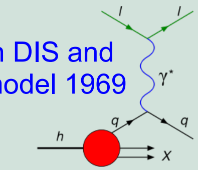
- **Electron-proton**
  - LHeC → E_e = 60 GeV, p from LHC, up to 1/ab, running at the same time as HL-LHC
  - HE-LHeC → upgrade in parallel to HL-LHC
  - FCC-eh → E_e = 60 GeV vs 50 TeV, up to 3/ab

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**

1960

Partons observed in DIS and raise of the quark model 1969



1970

J/psi discovery 1974

Tau lepton discovery 1976

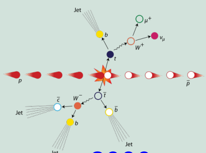
B-quark discovery 1977

1980

W and Z bosons discovery 1983

1990

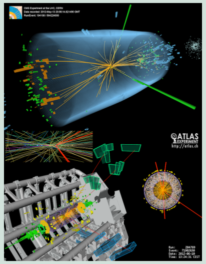
Top quark discovery 1995



2000 Tau neutrino discovery 2000

2010

Higgs Boson discovery 2012



You are here!

"Patience is the virtue of the strong"

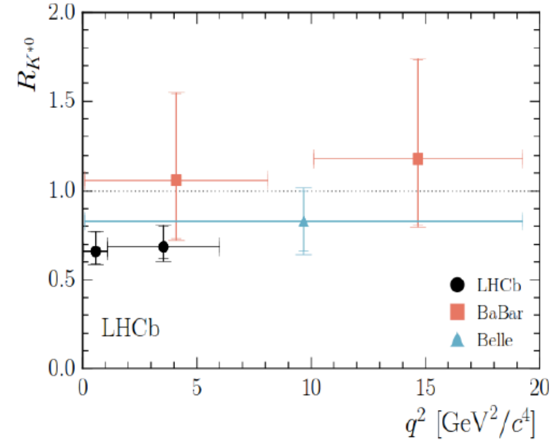
New resonances (and high p_T searches)

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 all relevant combinations of final state objects
- Example of flexibility/synergy: strong focus on 3rd 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

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

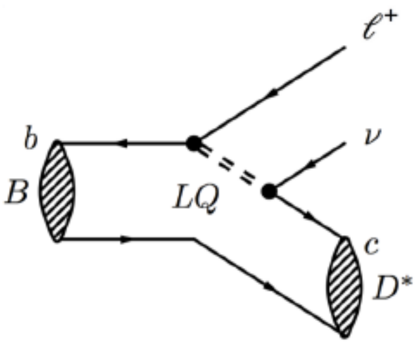
Quark level transition $b \to s\ell\bar{\ell}$

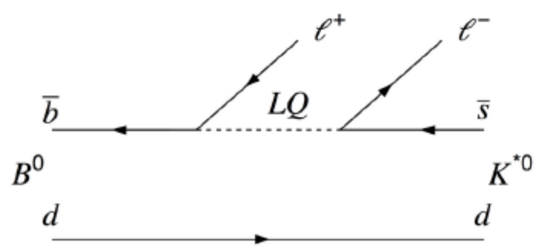
R_K, R_{K*}: $\sim 2.5\ \sigma$ deviation (LHCb)

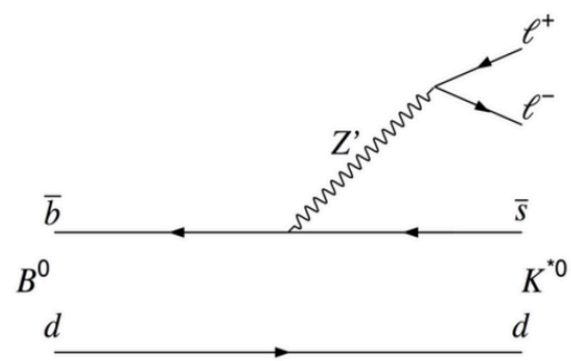
$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$

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

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

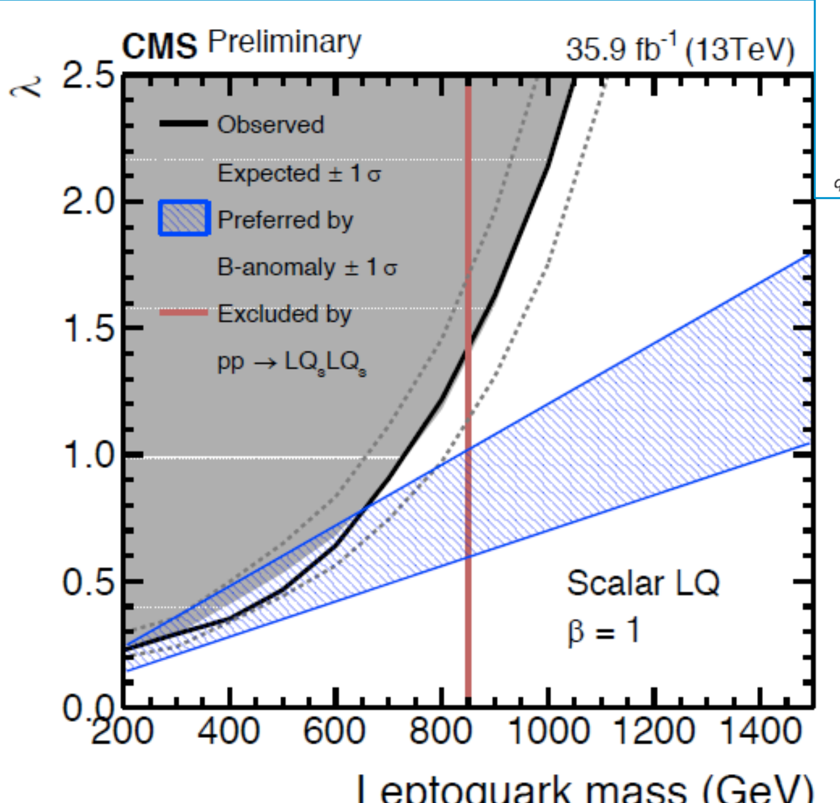


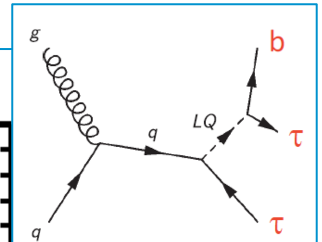




LQ: → τ + b and beyond

- 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

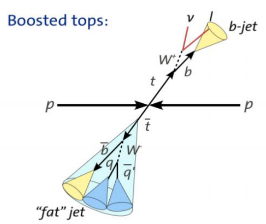
→ Left-, right- handed muons-top coupling could explain g-2 (arXiv:1612.06858)
(e.g. see A. Crivellin talk at Moriond 2018)

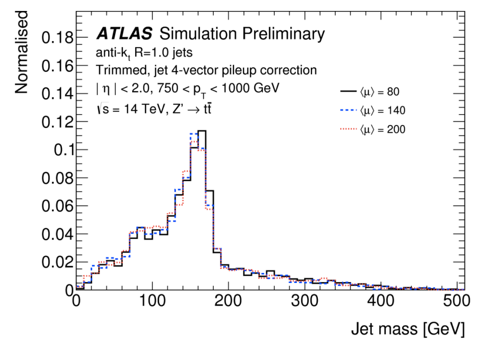
→ More to be done by ATLAS/CMS HL-LHC

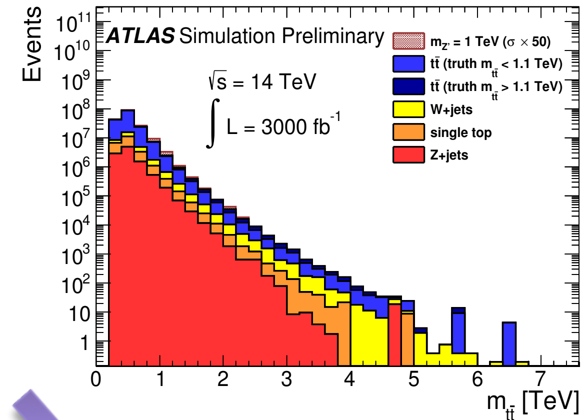
Reach with HL-LHC: Z' →ttbar

ATL-PHYS-PUB-2017-002

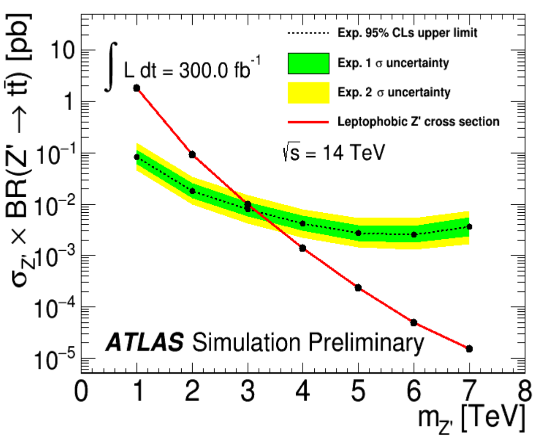
- ATLAS → full analysis
  - Resolved and **boosted**
  - Large **R-jets** considered



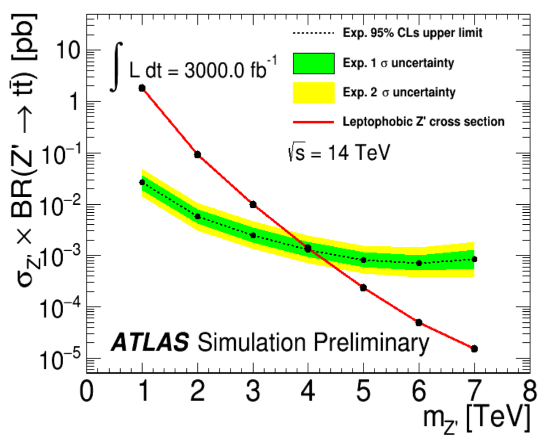




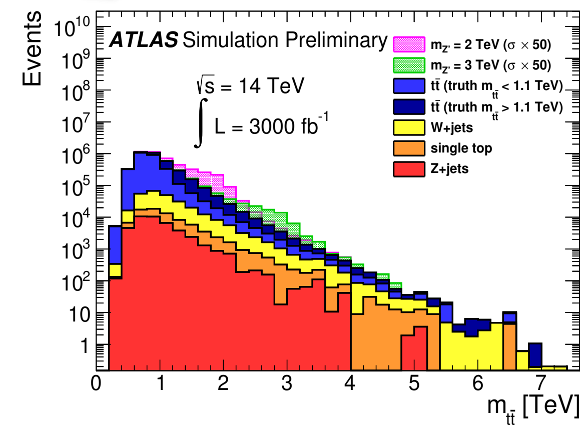
(b) Resolved Muon Channel.



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



(b) Upper cross section limits for 3000 fb^{-1}.



(d) Boosted Muon Channel.

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

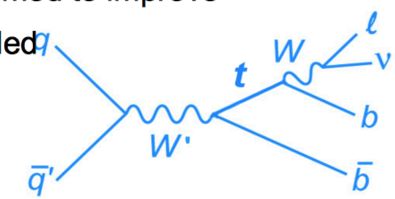
For Z→ee, exclusion up to 6.4 TeV, discovery reach ~ 5.9 TeV

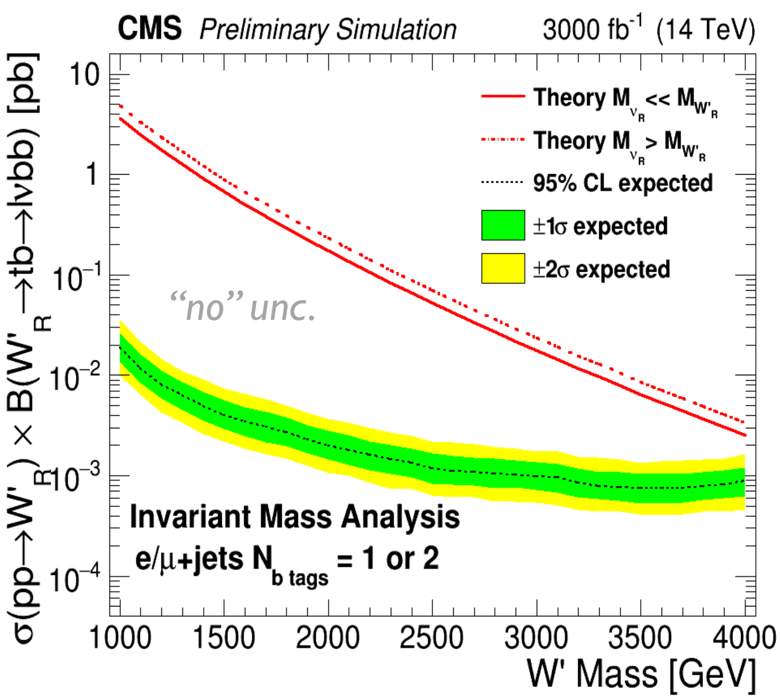
Reach with HL-LHC: W'→tb

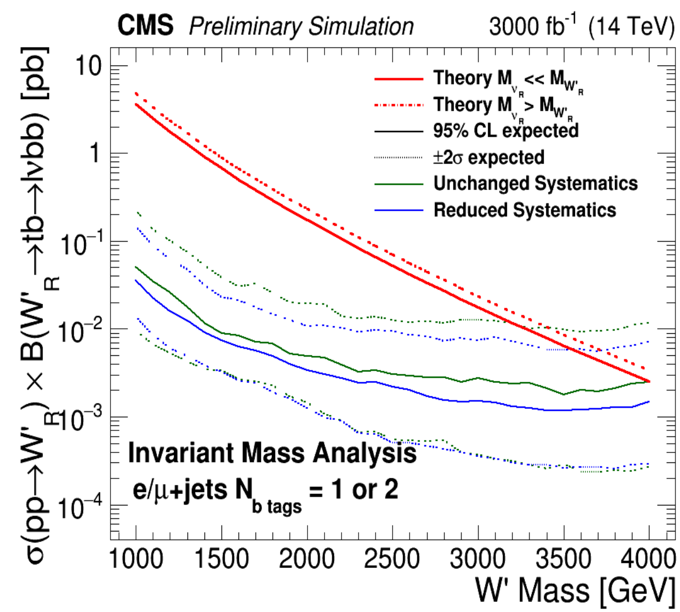
- Projections performed – assuming NWA using 2015 and 2016 analyses

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

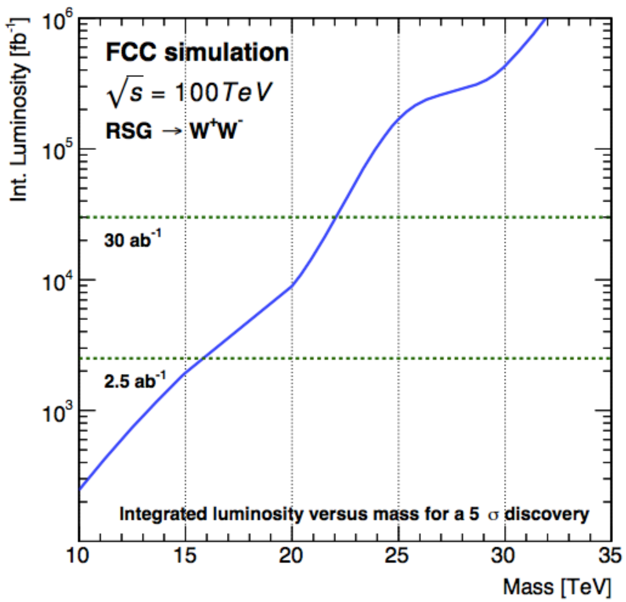
CMS DP016_064

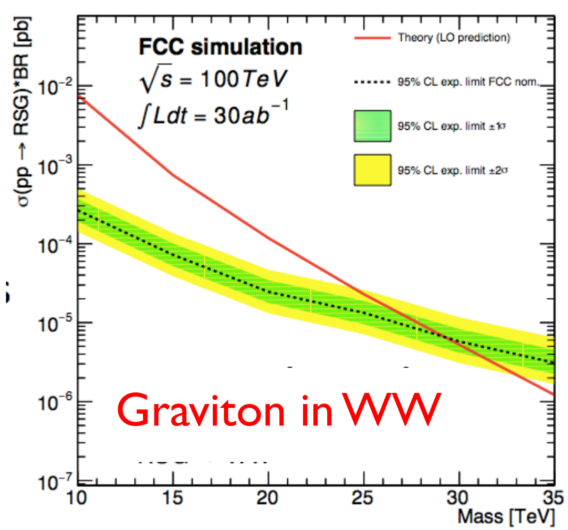
Reach: beyond 4 TeV
For W' in eν and μν → reach up to 7 TeV

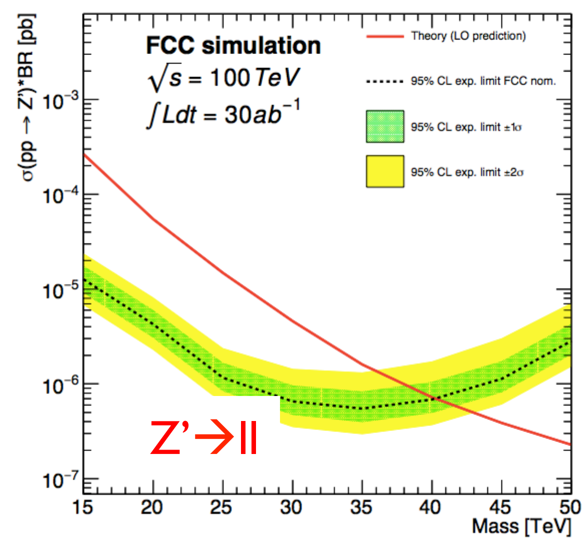
The (far) future

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?]



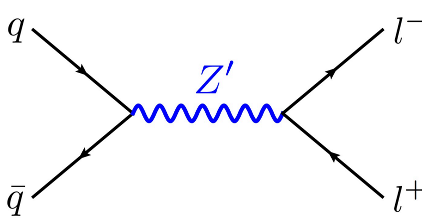


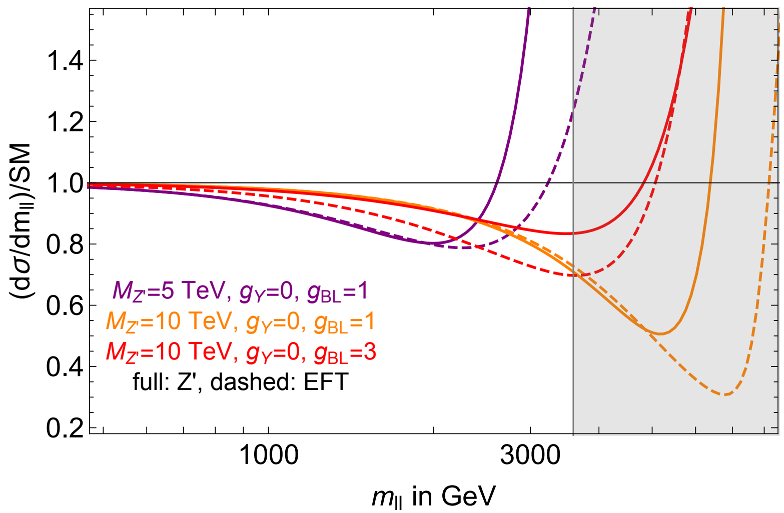


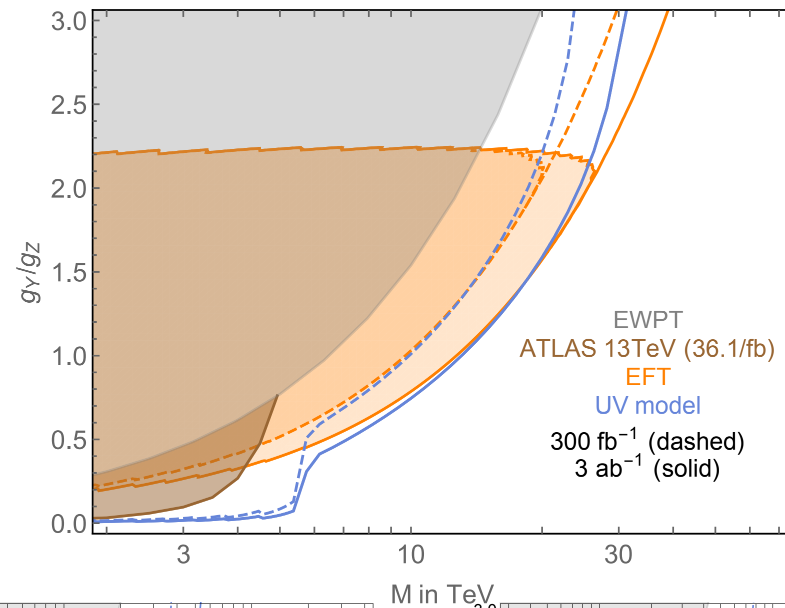
Indirect constraints on Z’

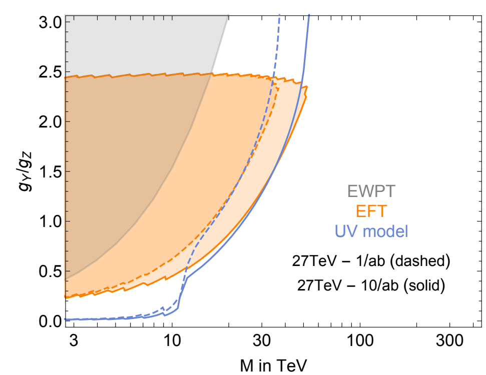
- If mZ’>>5 TeV, main contributions from interference effects modifying DY
- The precision of e^+e^- colliders help but LHC (and HL-LHC) can do a lot

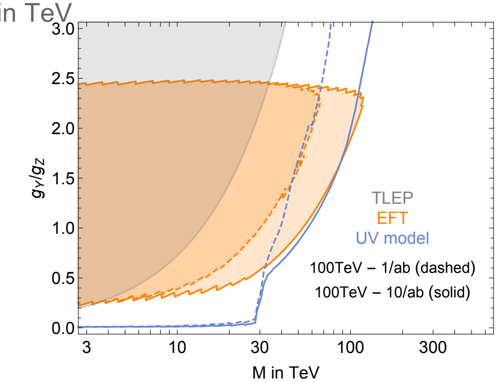
Alioli, Farina, Pappadopulo, JTR, Phys. Rev. Lett. **120**, no. 10, 101801 (2018)





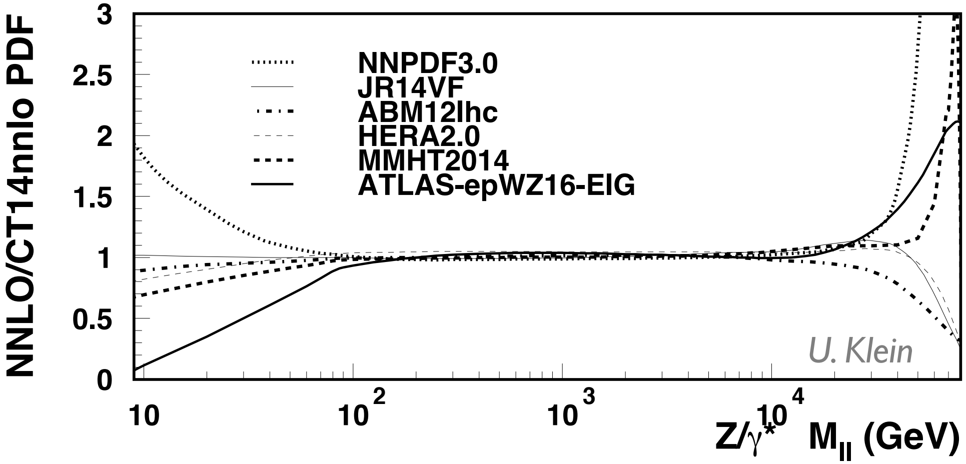






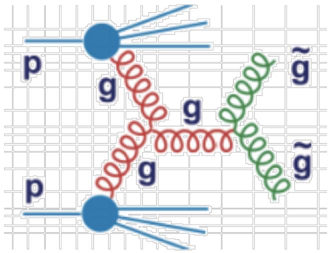
A comment on high p_T / mass searches

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



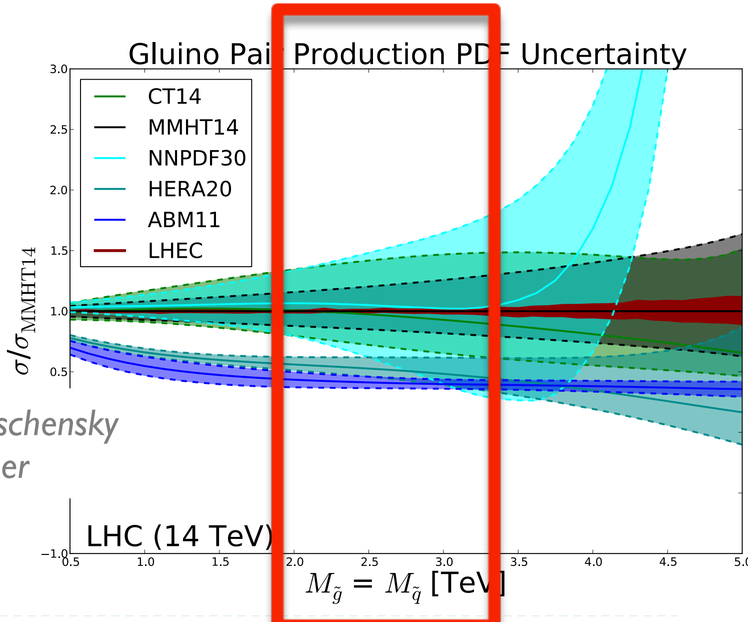
"Troubles" at low and high x

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



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

Christoph Borschensky
Michael Kramer



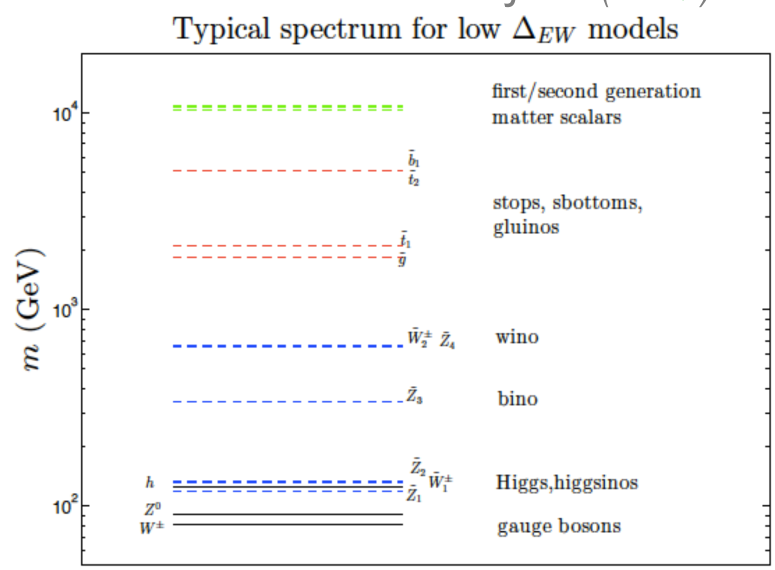
Supersymmetry

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

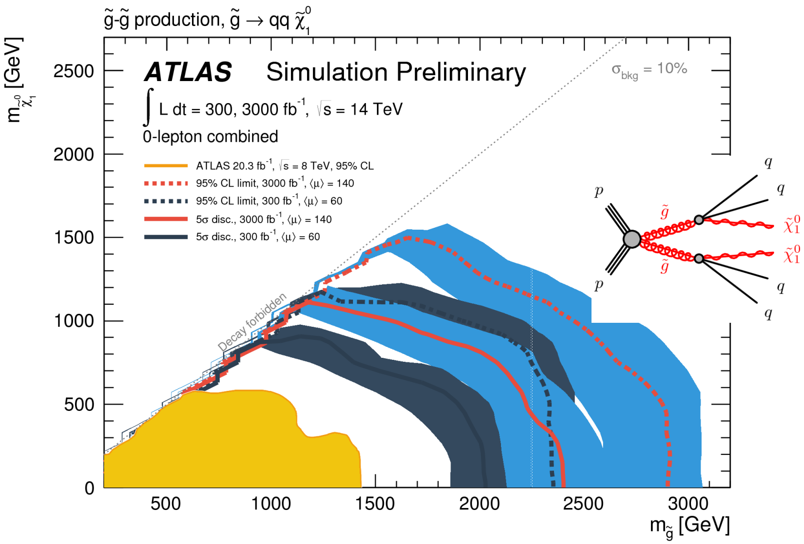
higgsino is LSP, higgsino-like WIMP~100-300 GeV thermally under-produced as DM candidate: augment with e.g. axion

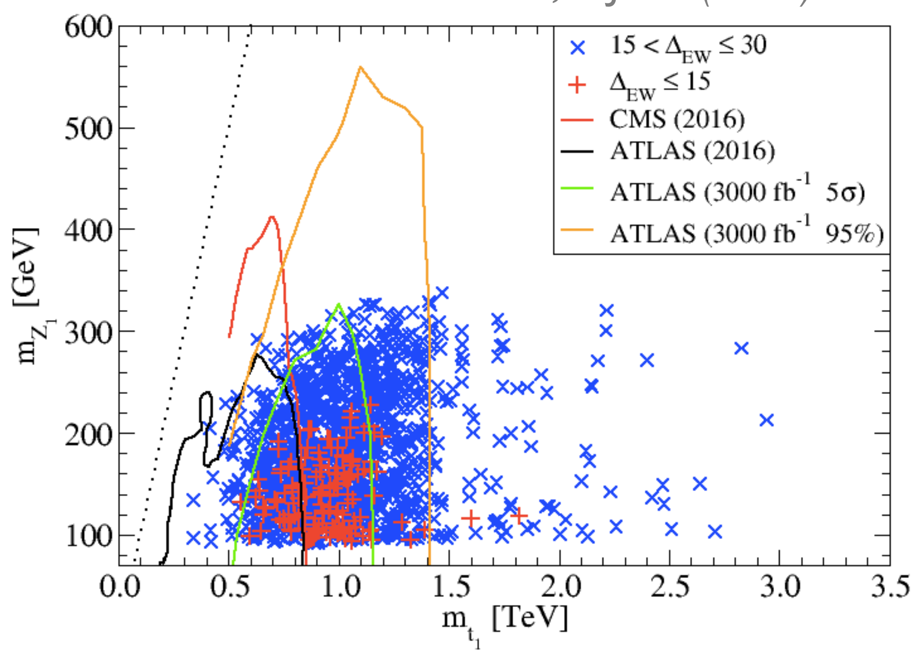
SUSY @ HL-LHC: strong sector

- 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**





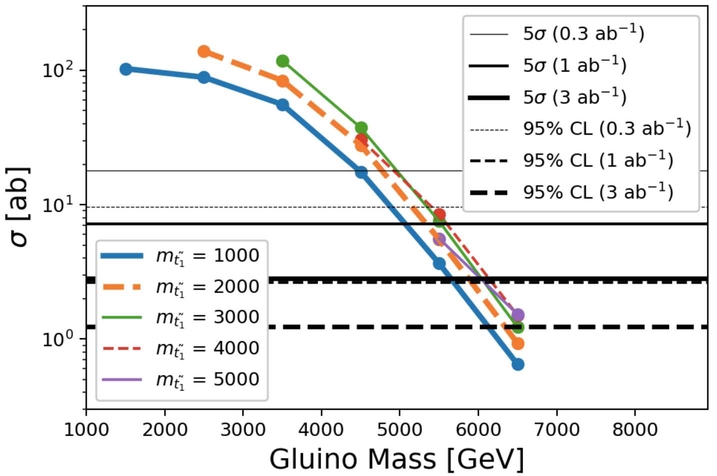
Large uncertainties from PDF → improvements expected with LHC data and, possibly, new facilities (LHeC)

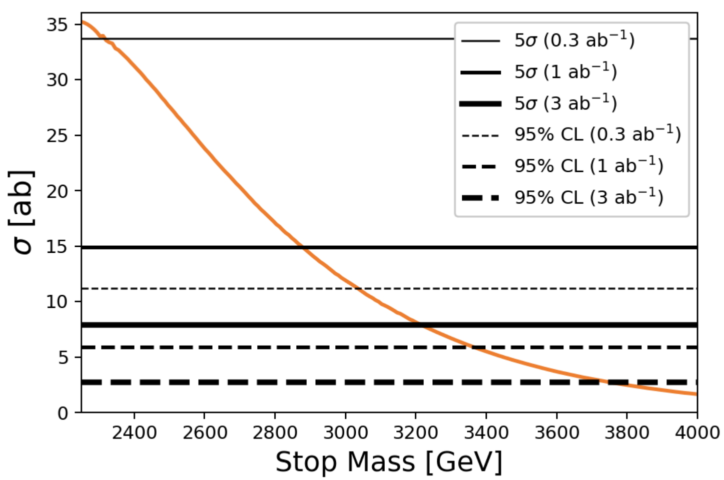
Analyses being re-assessed:
Exp. gluino reach up to 3 TeV

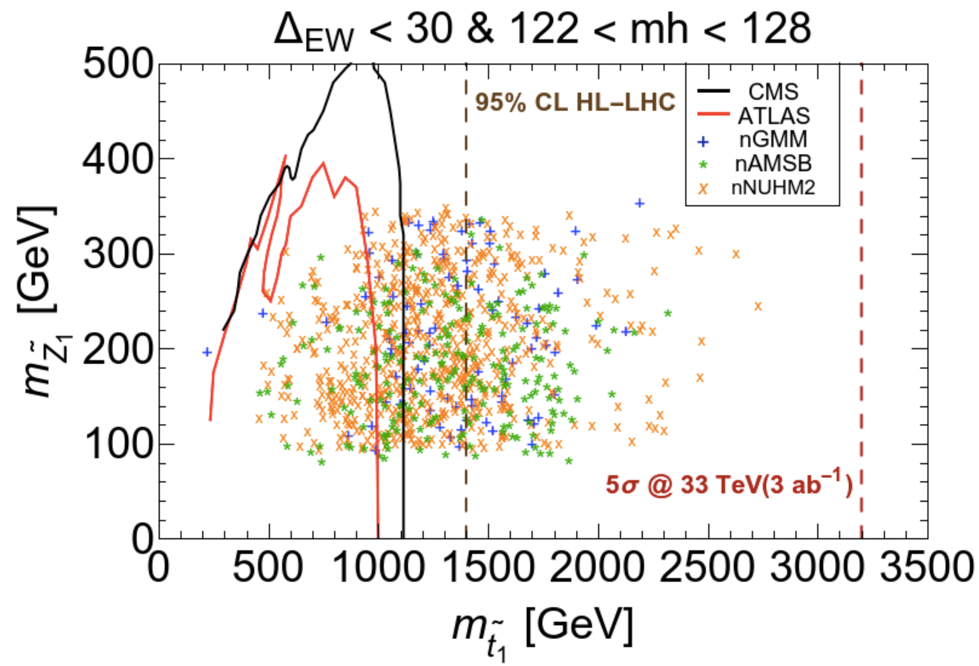
M(stop) can range up to 3 TeV with little cost to naturalness. **HL-LHC Stop reach: 1.4-1.5 TeV (1.9 TeV with new analyses,** **but for compressed scenarios ~ 700 GeV)**

Expected reach with HE-LHC in strong sector

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





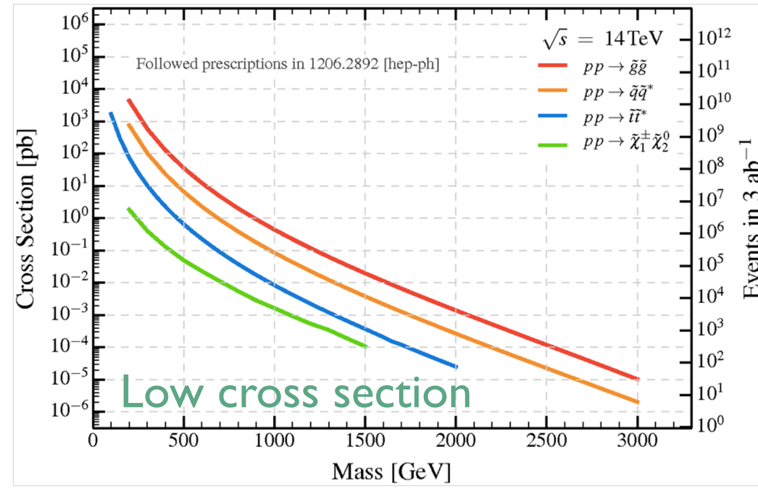


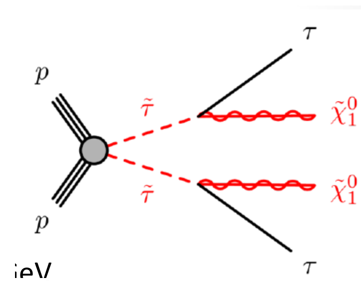
@ HE-LHC reach extends to m(gl)~6 TeV; m(t1)~3-3.8 TeV

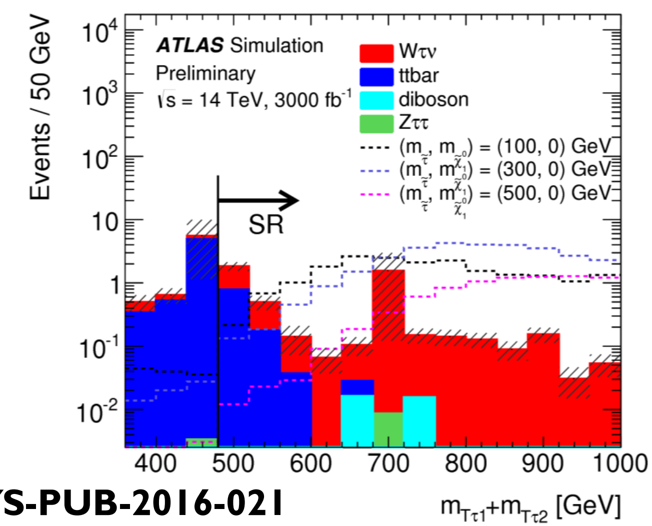
Stringent constraints on SUSY natural models

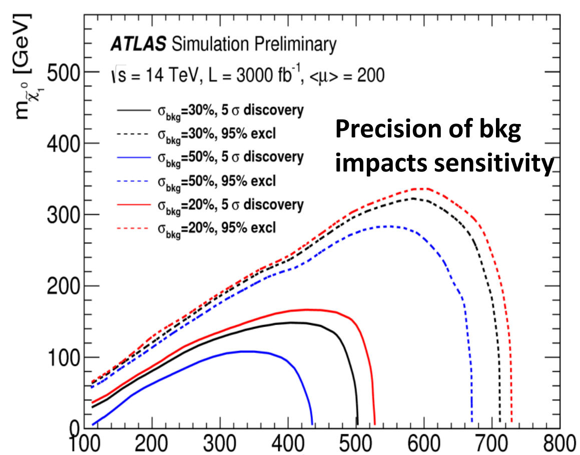
SUSY@ HL-LHC: EWK sector

- 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







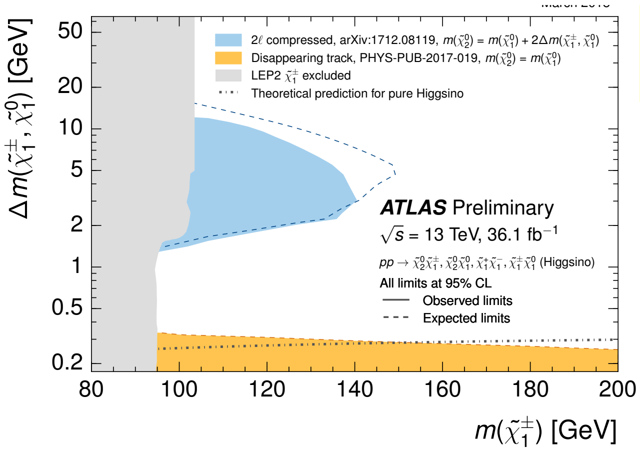


Discovery reach
430-520 GeV @ 3/ab depending on bkg

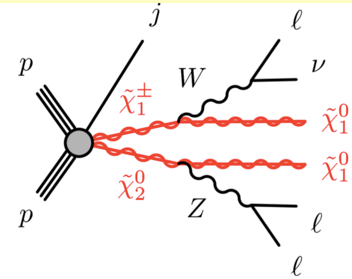
ATL-PHYS-PUB-2016-021

SUSY@ HL-LHC: EWK sector (II)

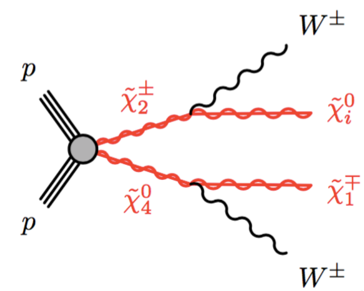
- SUSY higgsino-like scenarios also difficult (and very relevant for DM)
  - Low x-section, compressed → decay products are soft/invisible (for prompt production)



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



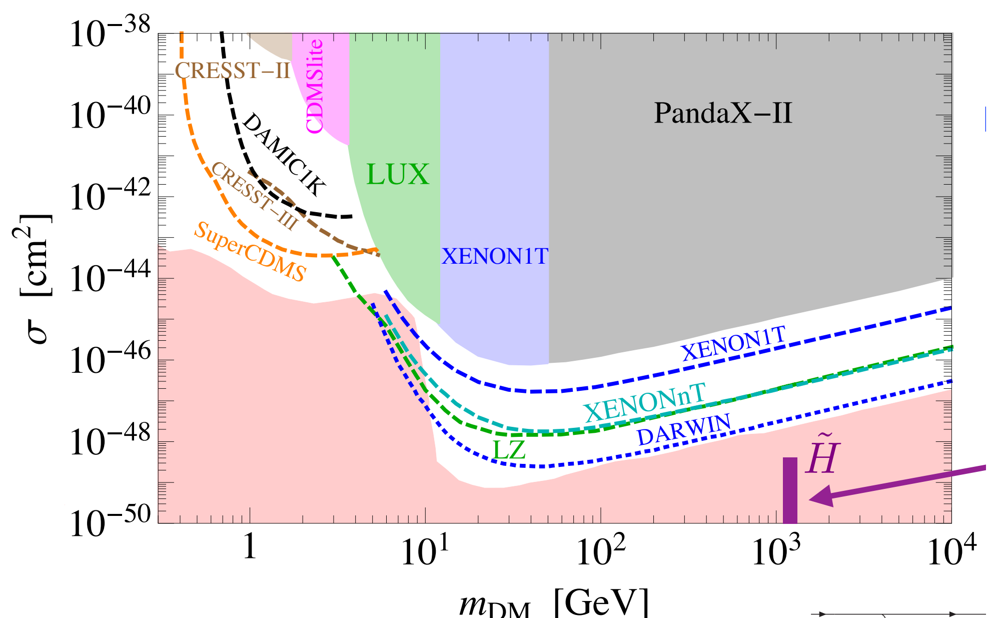
Search for events with Higgsinos produced in association with an ISR jet



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}

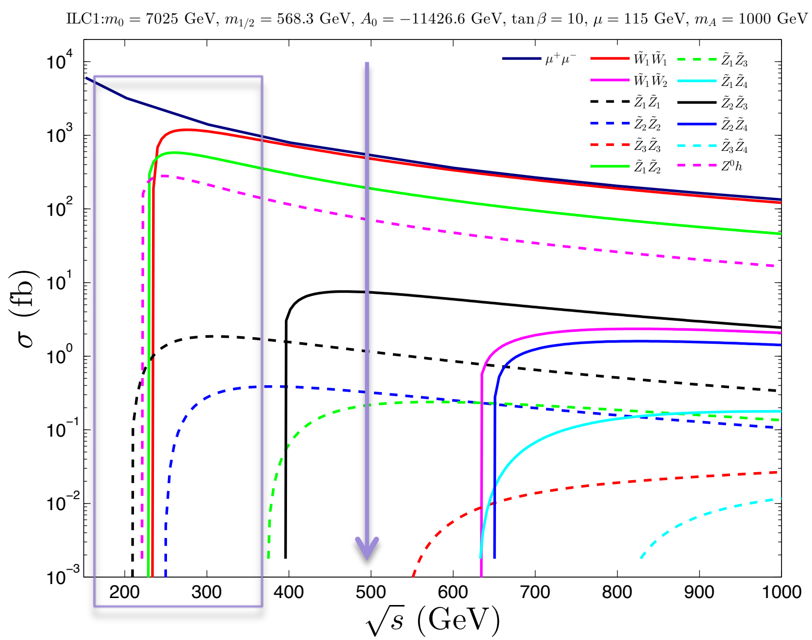


J. Ruderman, FCC week Amsterdam (April 2018)

potential @ electron-positron machines

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

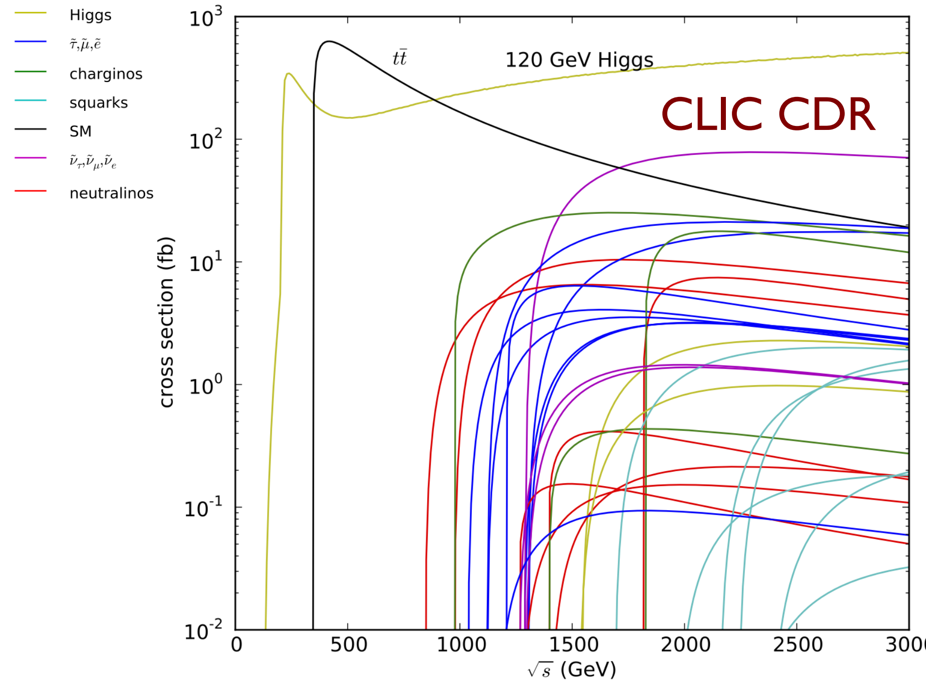
Sparticle σ for unpolarized beams at e+e- for ILC benchmark but also for FCC-ee



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



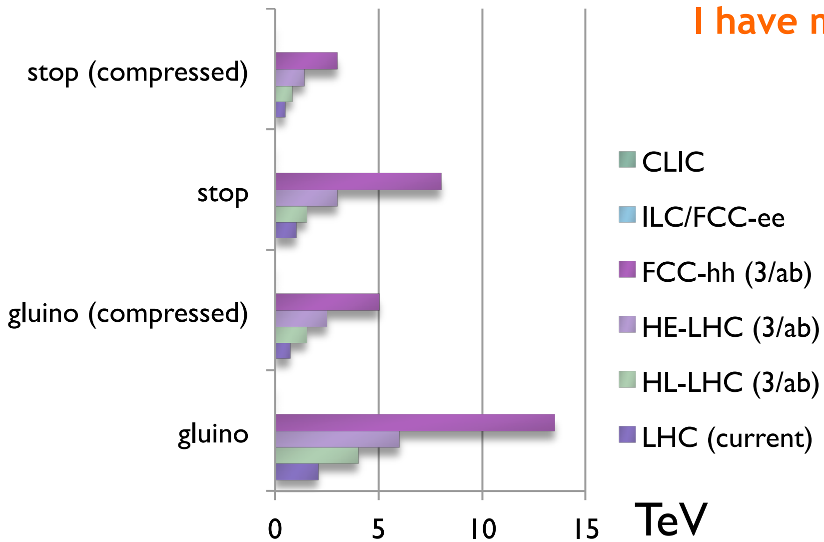
Cross-section for higgsinos too low also for CLIC?

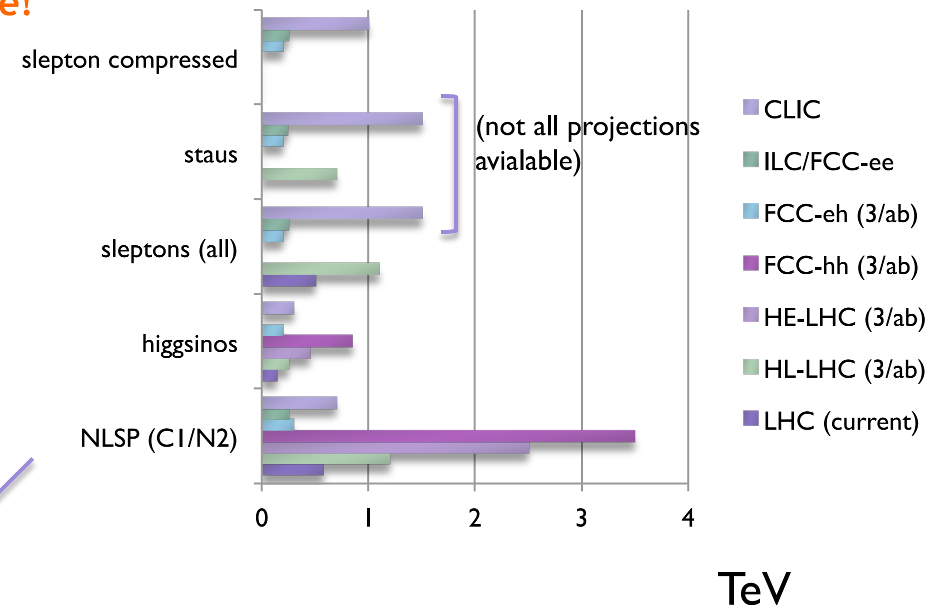
arXiV:1801.05192

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

In a snapshot

CAUTION: Crude approximations/extrapolations I have made!



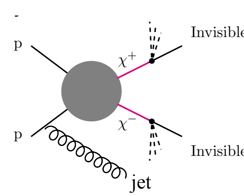


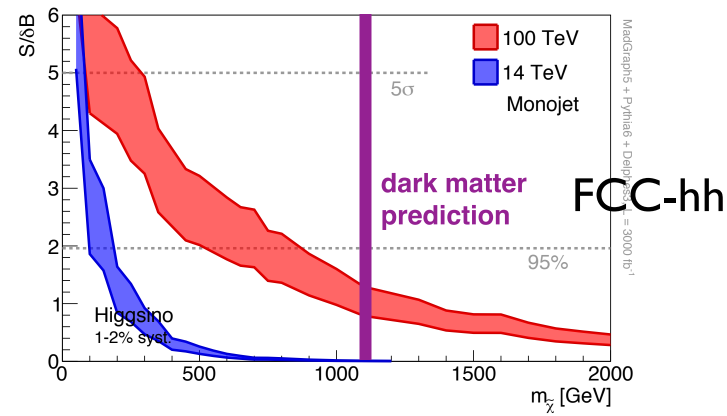
- Sleptons projections not yet available everywhere. Potential at ILC and CLIC (not for higgsinos).
- using mono-jet signatures
  - A signature relevant for many

NP models (DM-oriented)

Sensitivity also for FCC-eh (lower)

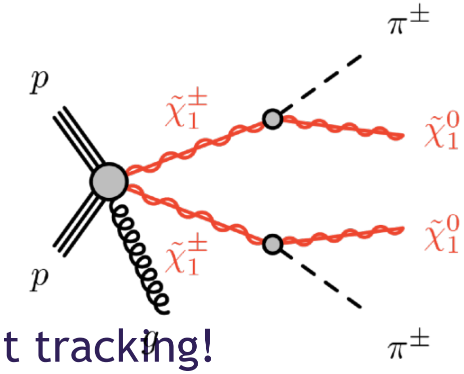
→ **1 TeC boundary reached only by FCC-hh**

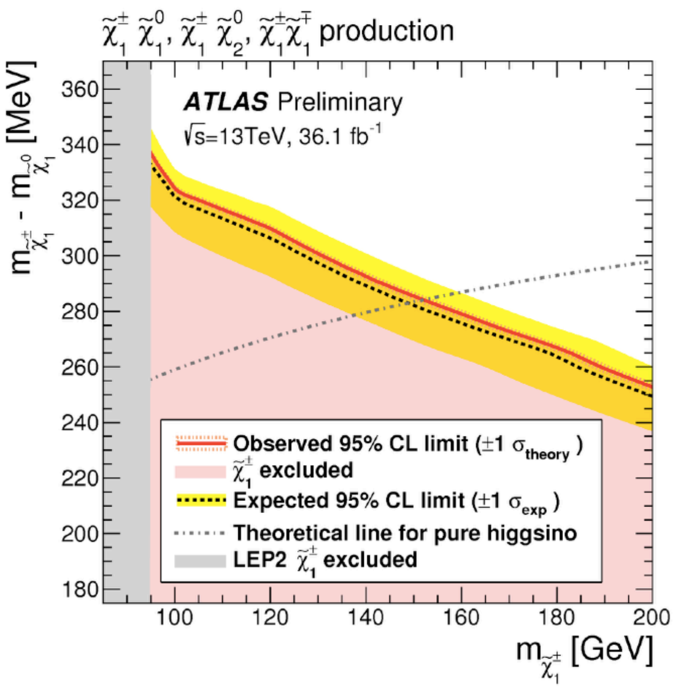




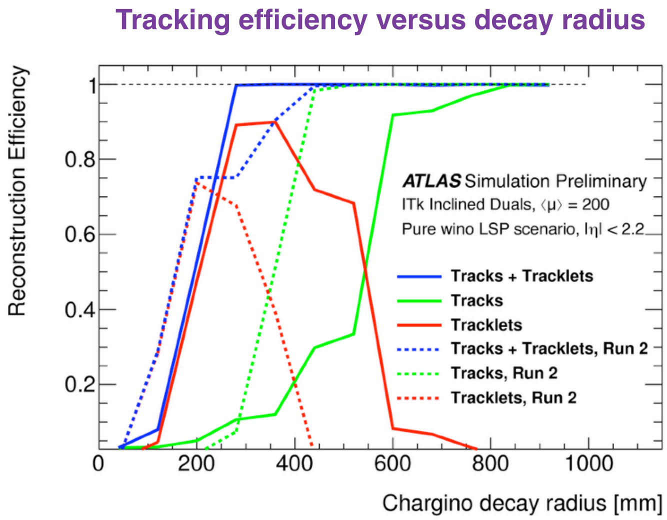
Long-lived higgsinos

- 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!



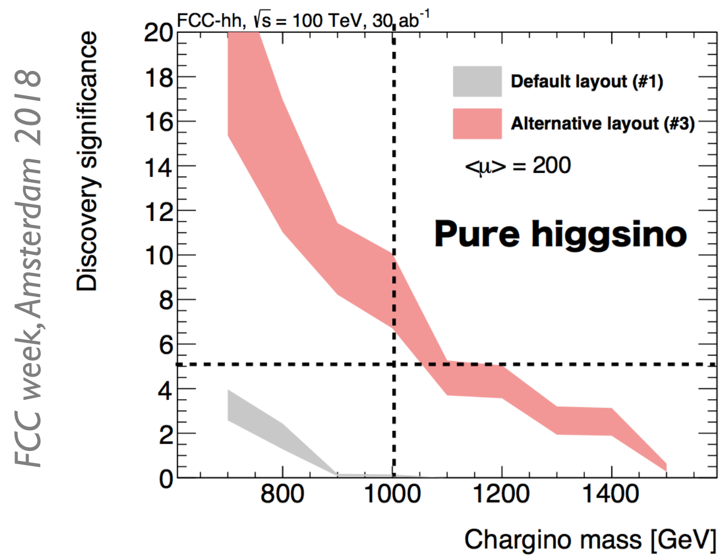


@HL-LHC: expect to exclude up to 250 GeV for pure higgsino (τ = 0.05 ns)

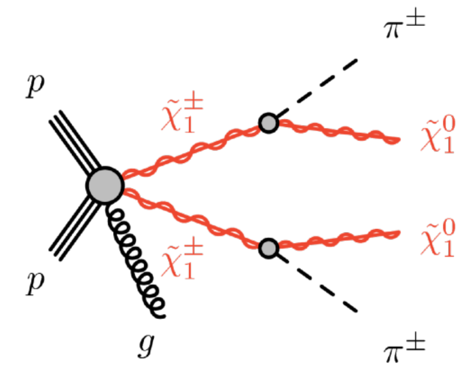


Long-lived higgsinos: long term future?

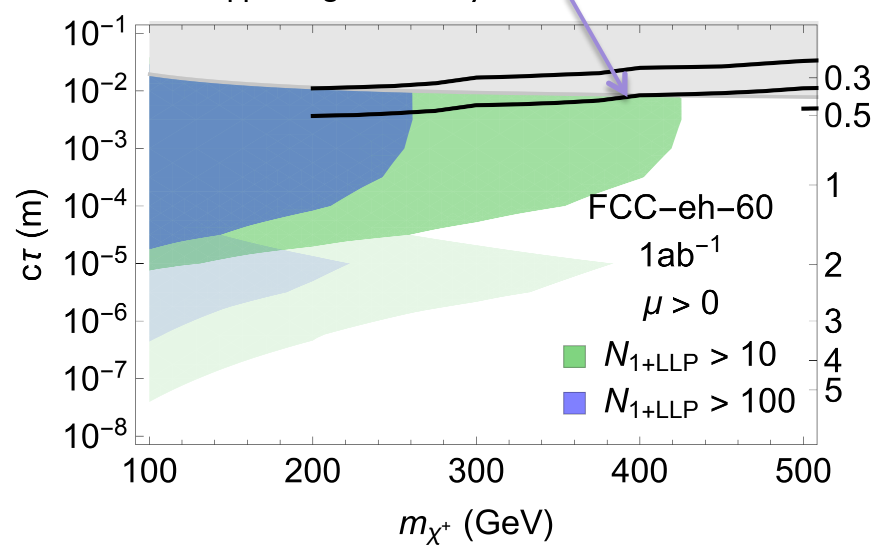
- At FCC-hh, sensitivity will depend on the bkg (very high PU)



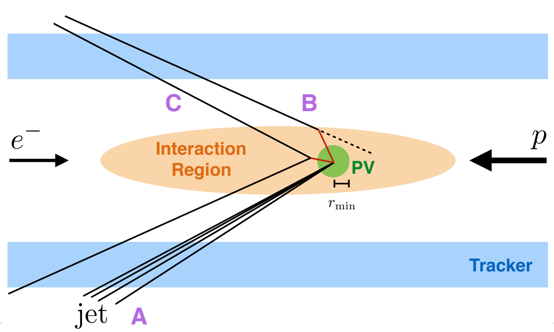
Maybe optimistic on Pile Up



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…

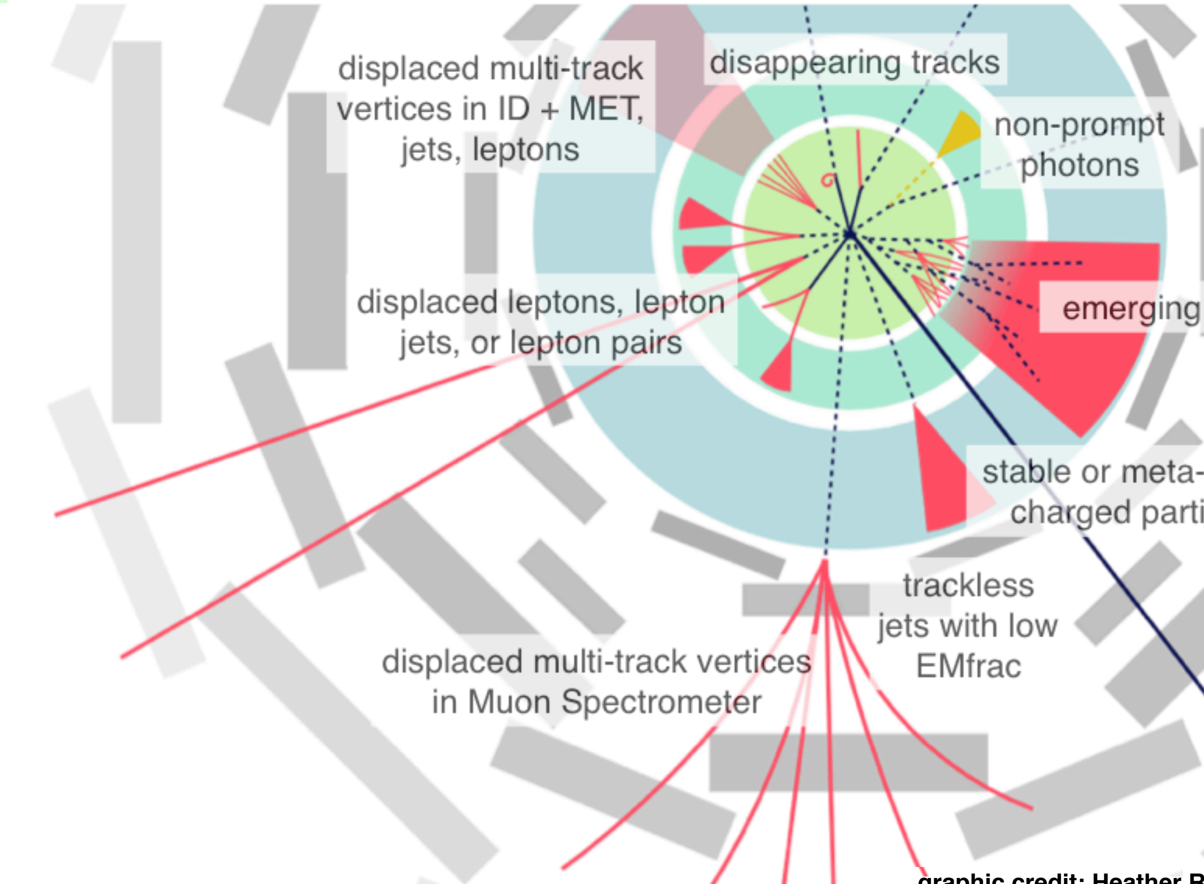
Great discovery potential: many NP models predict LLPs

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

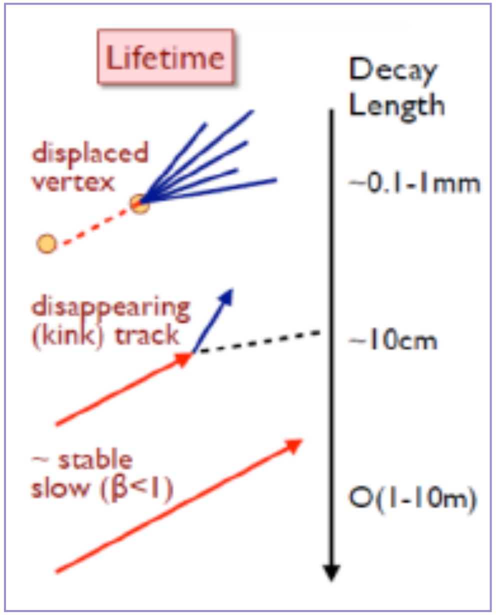
Signature space quite complex → joined exp/theory efforts to review all modes

Long-lived particles

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



graphic credit: Heather Russell



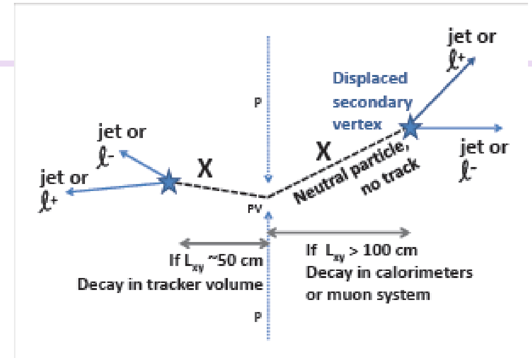
Synergy among ATLAS, CMS and LHCb experiments
- Target complementary lifetimes and mass ranges

A few examples

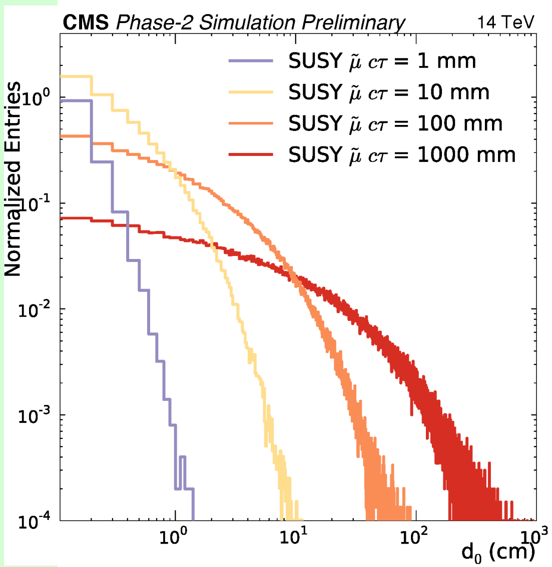
Displaced muons

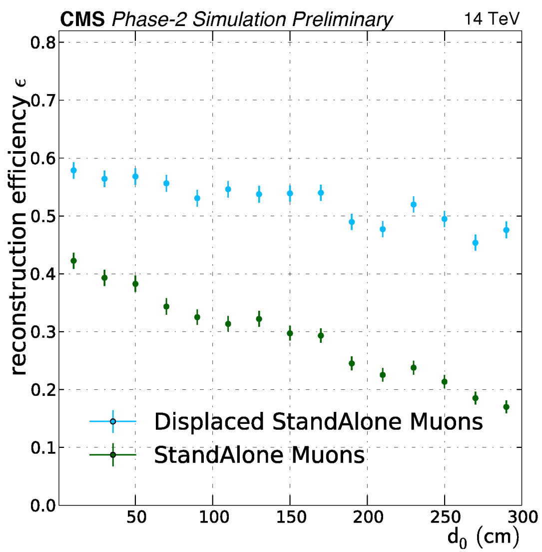
- New studies from CMS on SUSY:
  - Smuons

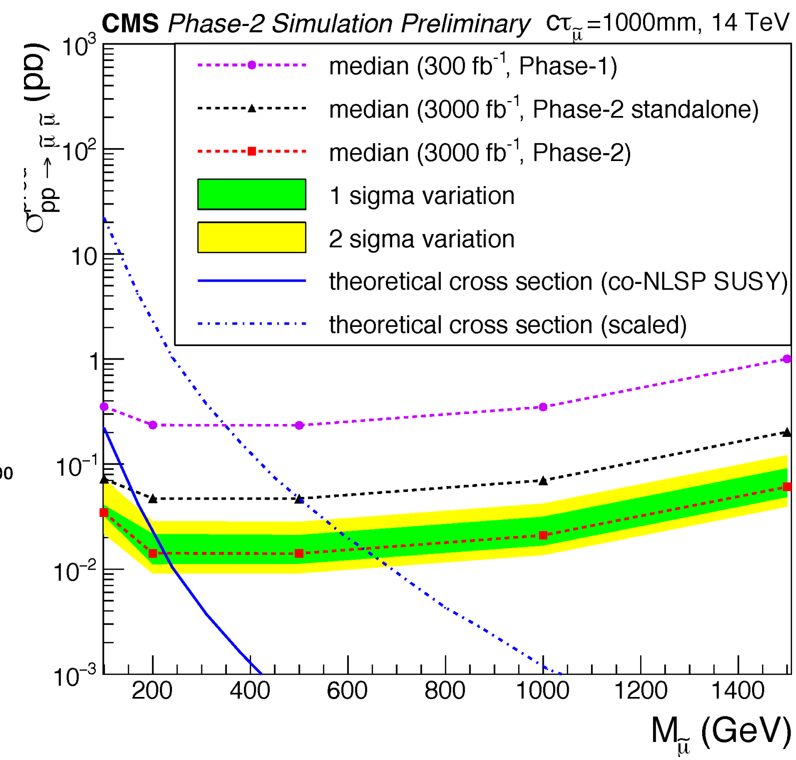
$$\tilde{\mu} \rightarrow \mu + X$$



CMS TDR (NEW)







Experimental challenge:

→ trigger displaced signatures

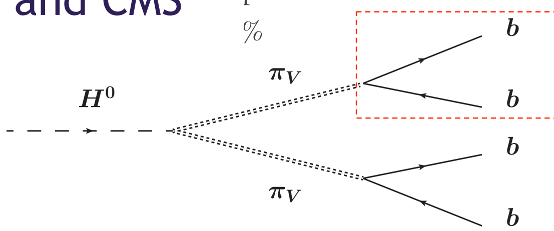
→ Vertex constrains reduce efficiency

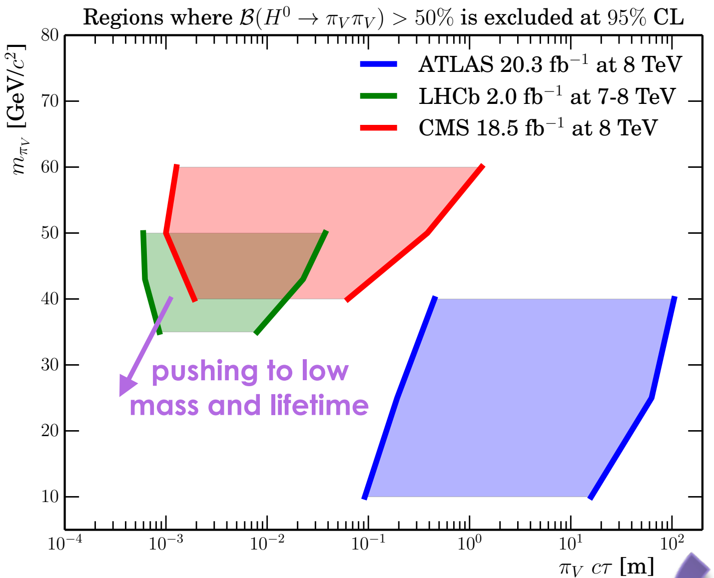
→ Dedicated algorithms needed for displaced muons to recover efficiency

Quite an improvement in sensitivity!

Displaced jets

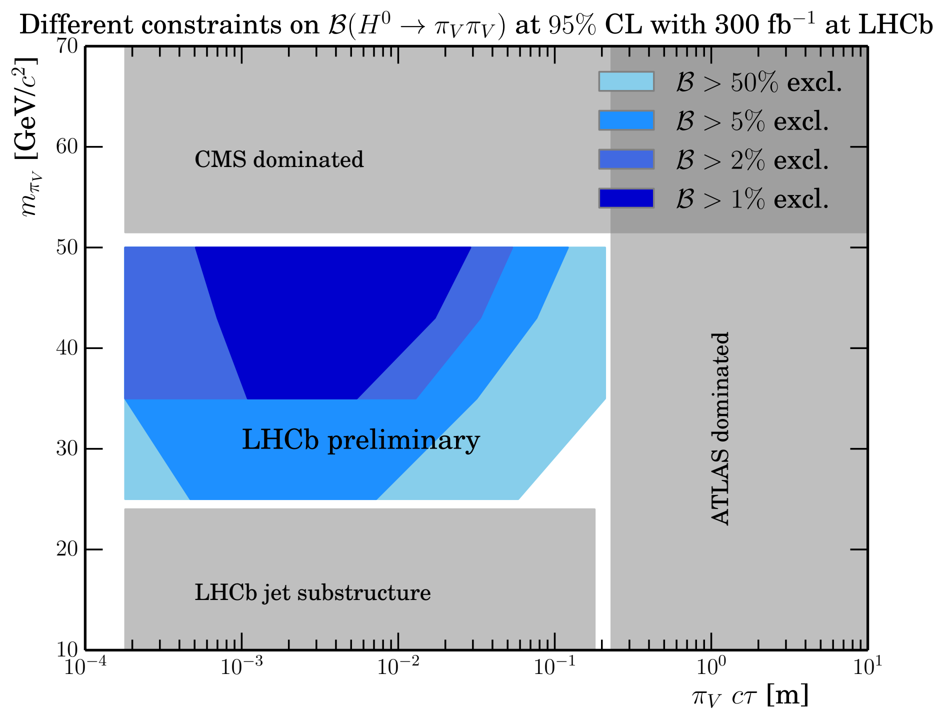
- Aim to exploit at best the complementarities among detectors
  - LHCb sensitive to lighter mass and low τ wrt ATLAS and CMS
- E.g. hidden valley dark pions from Higgs





extrapolation to 300 fb^{-1}

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



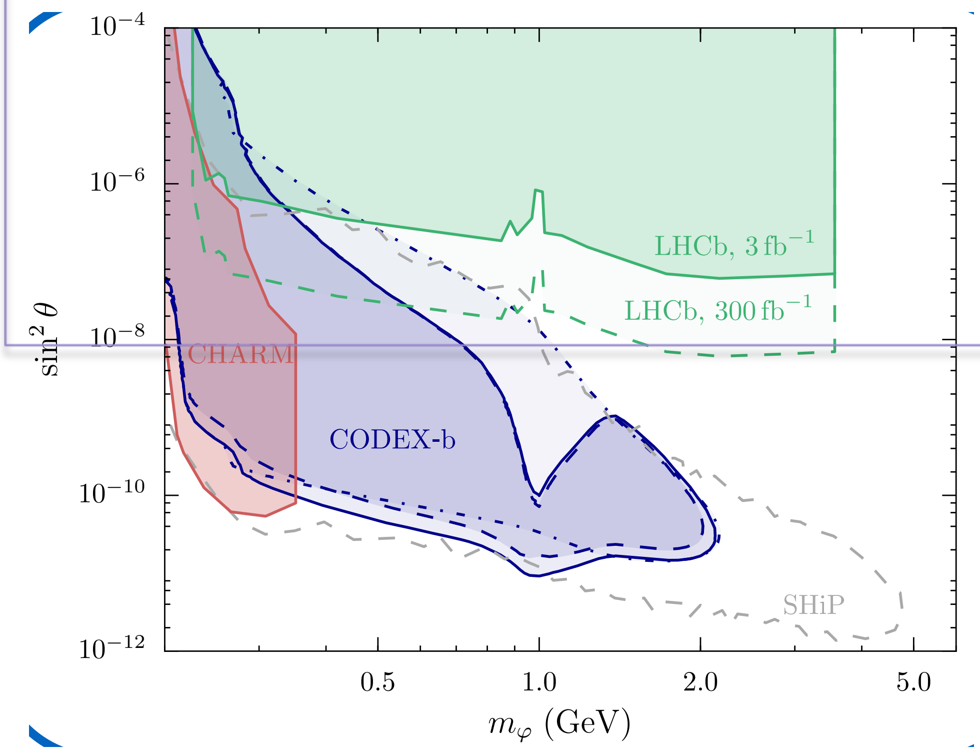
For short-lifetimes, this could be complemented by CepC !

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

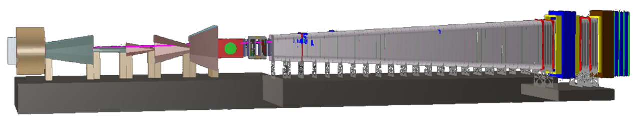
arXiv:1708.09395



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

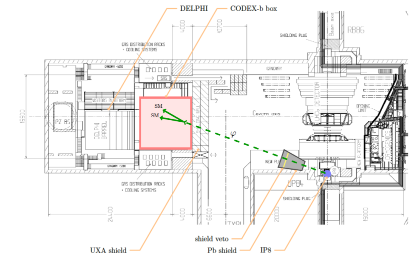
LLP and Dark sectors: PBC proposals

SHIP



Alekhin et al. (2015)

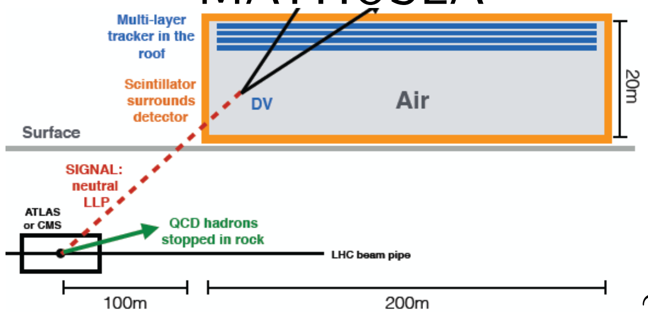
CODEX-b



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

Gligorov, Knapen, Papucci, Robinson (2016)

MATHUSLA



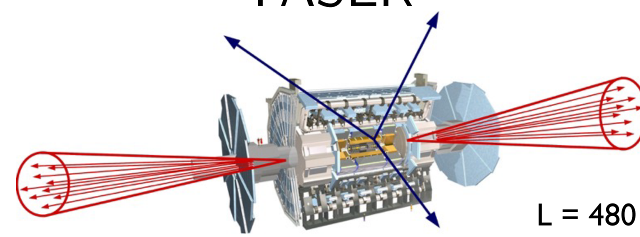
$\sim$

$2 \times 10^5\ \mathrm{m}^3$ ~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)

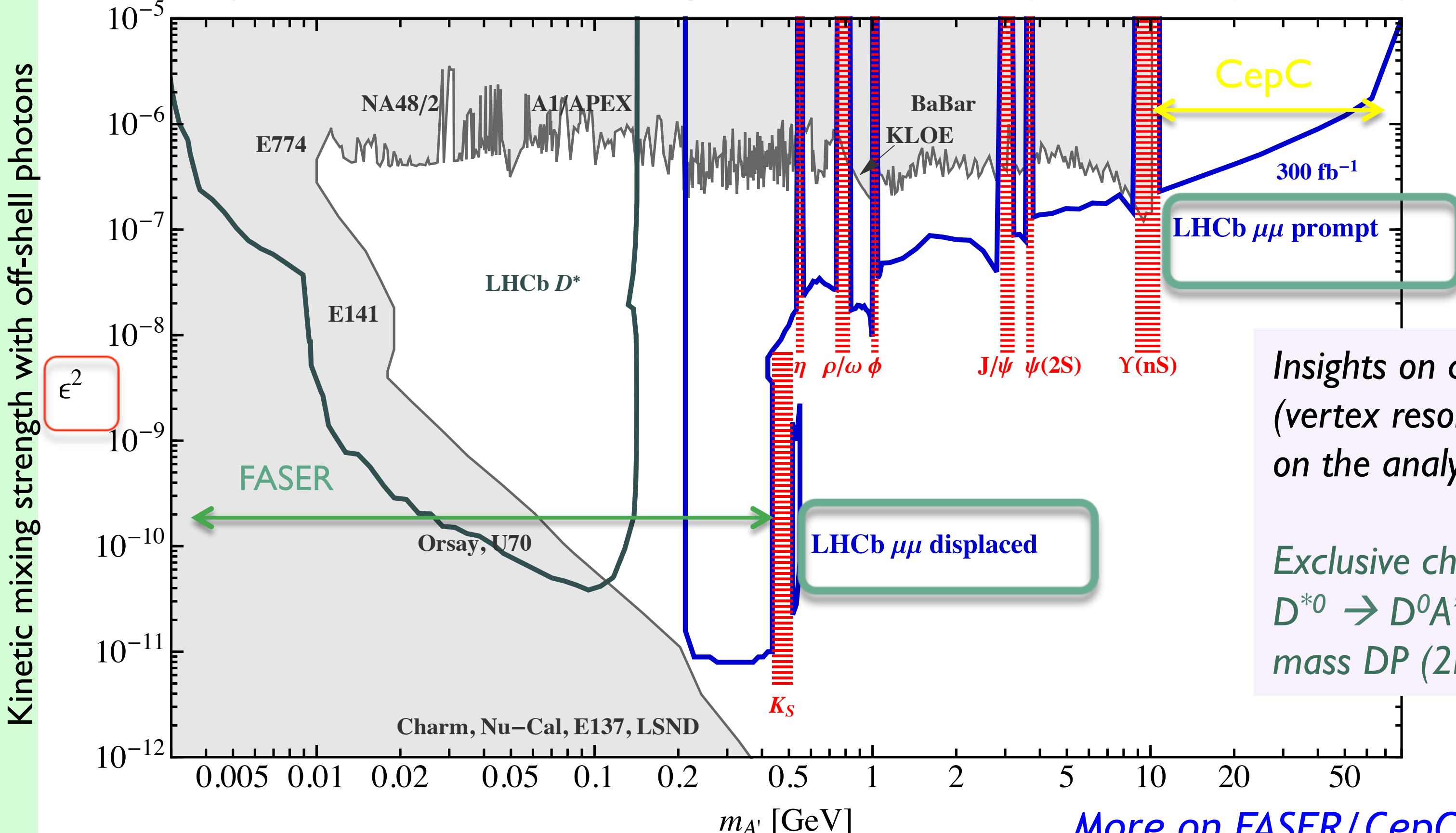
Credits: I. Galon at FNAL workshop on HL/HE-LHC (4-6 April 2018)

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

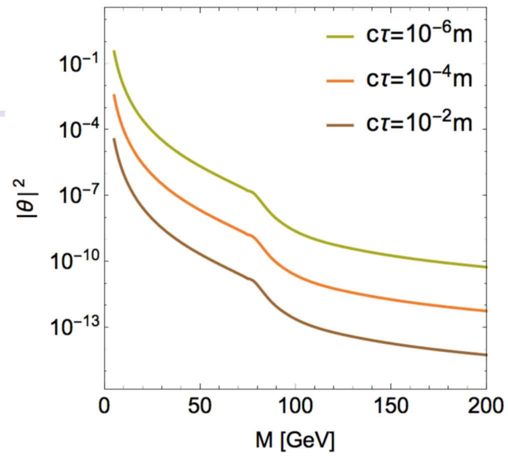
Insights on detector implications (vertex resolution, VELO size) and on the analysis in dedicated talk

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

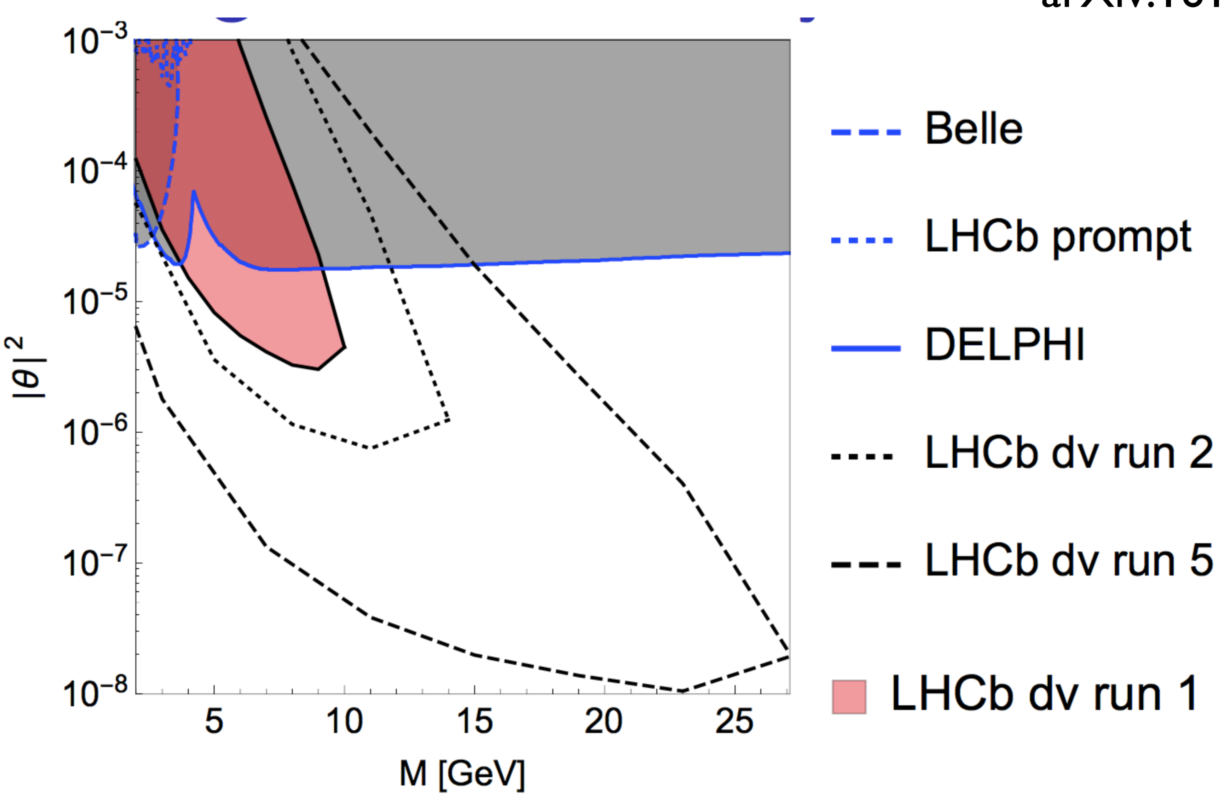
More on FASER/CepC impact in back-up

LLP and heavy sterile neutrinos

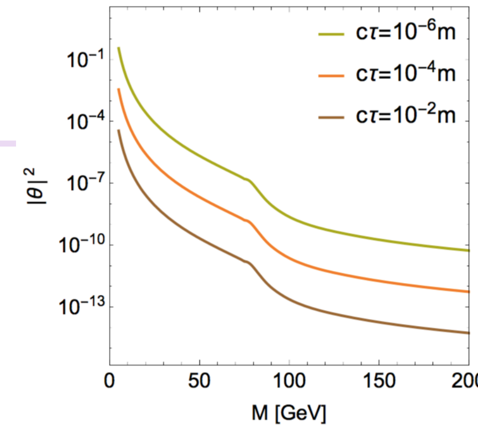
- Low-scale type I seesaw with sterile neutrinos
  - heavy neutrino mass eigenstates with M ~ vEW
  - Neutrino mixing $|\theta_\alpha|, \alpha=e,\mu,\tau \Rightarrow$ Weak current production.
  - Present constraints: $|\theta_e| \leq 10^{-3}$, can be long-lived
- Projections (LHCb)



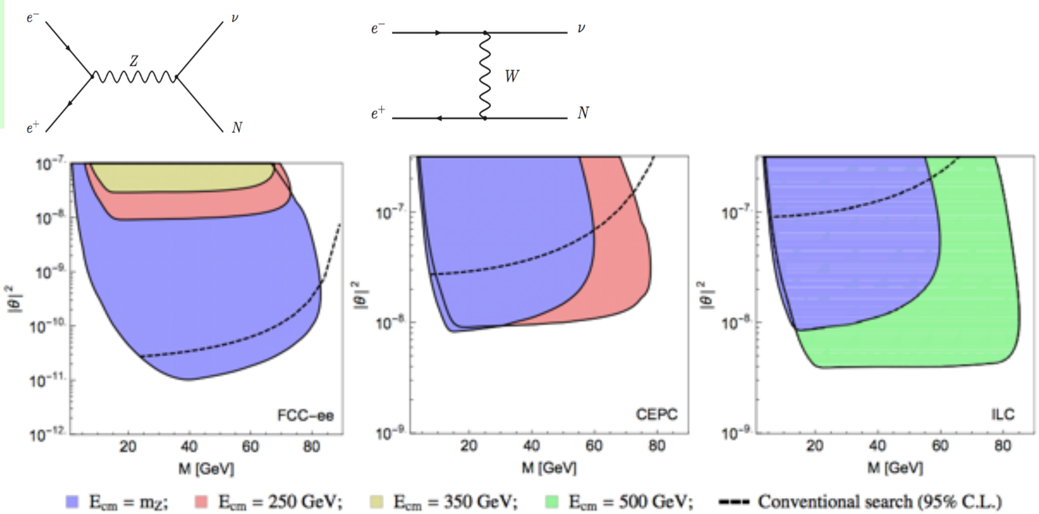
arXiv:1612.00945

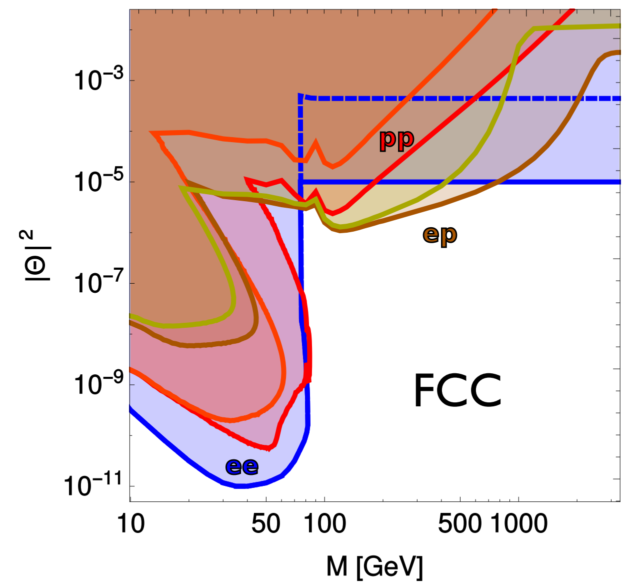


LLP and heavy sterile neutrinos



- 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?

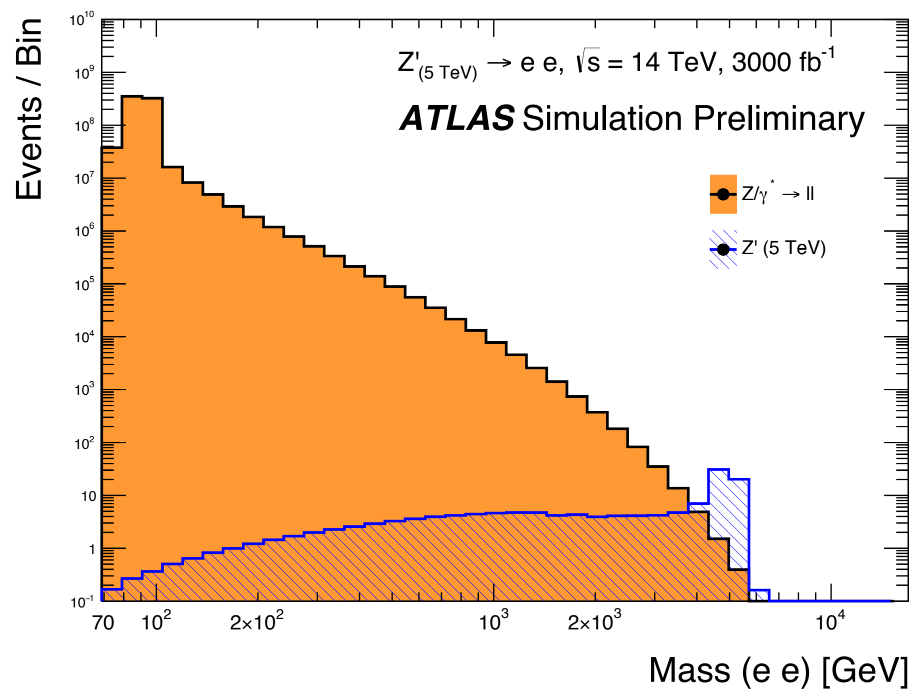
- Potential for long-lived particles to be retained as much as possible
  - Invest more for future facilities / experiments complementing LHC and embed what we have learned in future facilities

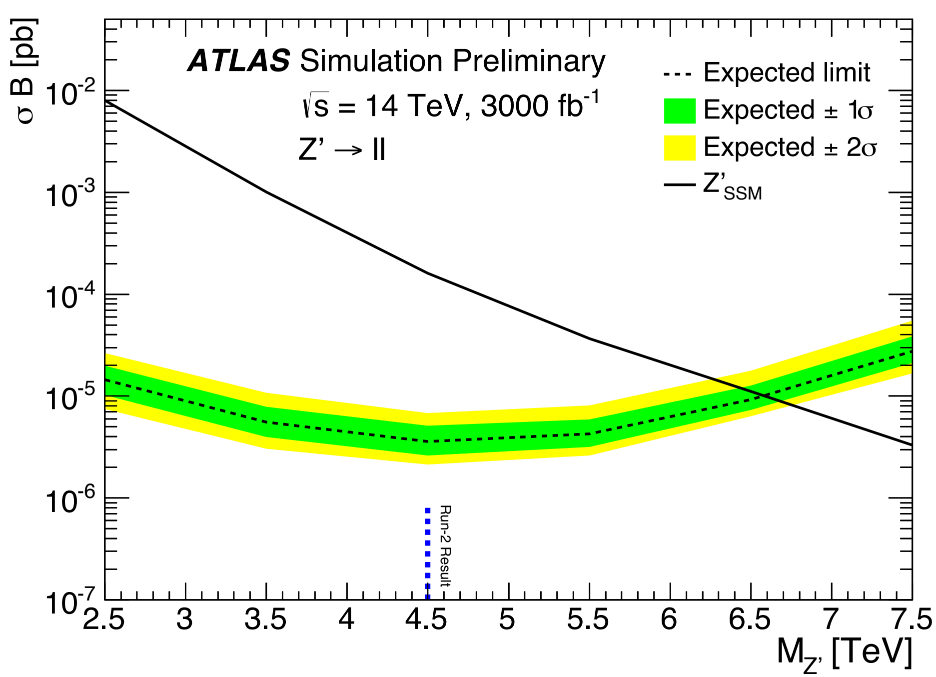
Back up

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





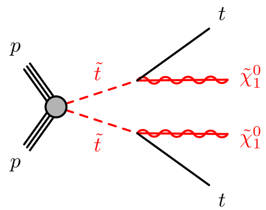
- Constraints are about 200 GeV more stringent than for muons, thanks to the resolution for high p_T electron

SUSY @ HL-LHC: challenging scenarios (stop)

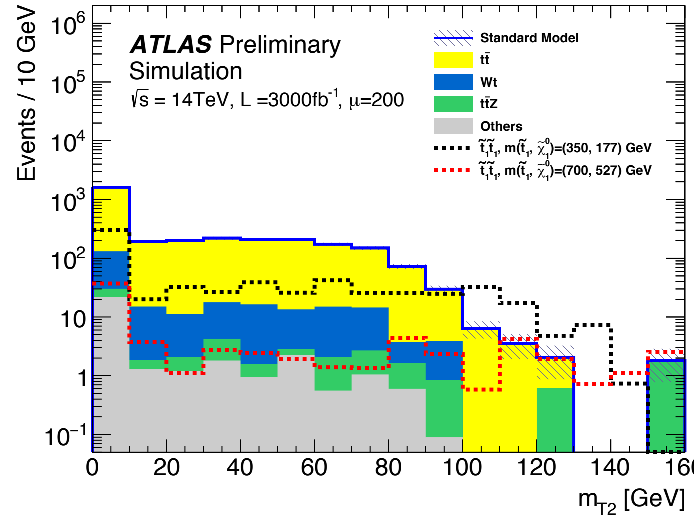
ATL-PHYS-PUB-2016-022

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

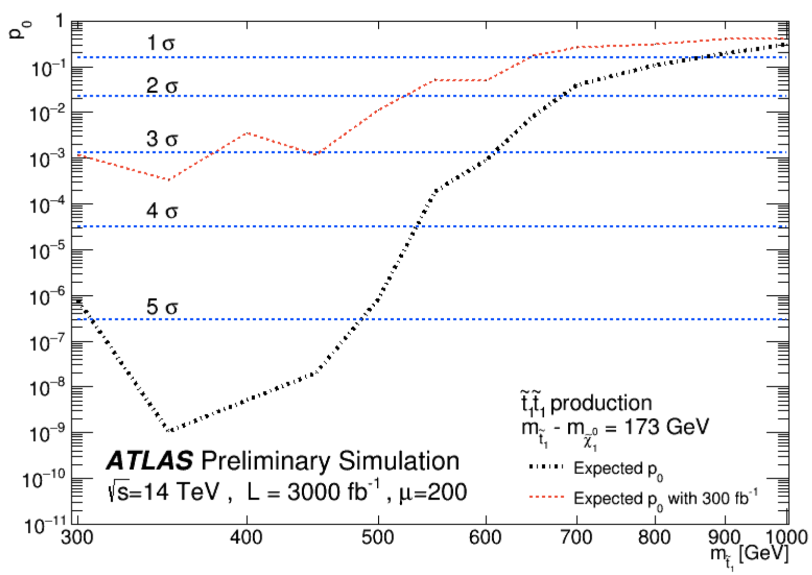
$$(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}) \cong m_t$$

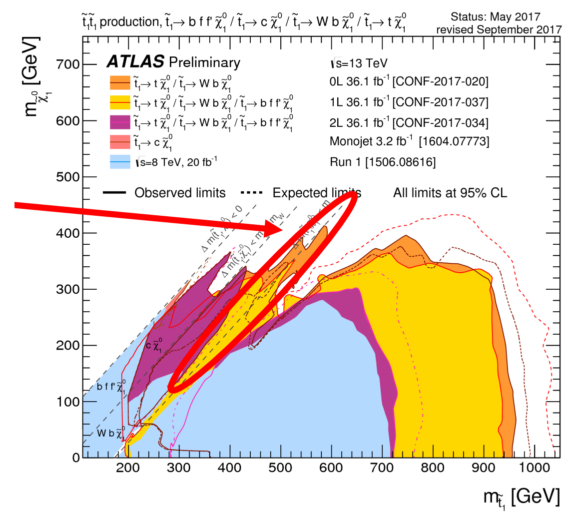


$m_{\ell\ell}$ [GeV] (SF lepton pairs only)	$81.2 < m_{\ell\ell} < 101.2$
$\min\{\Delta\phi(\text{jet}_{\text{ISR}}, E_T^{\text{miss}})\}$	> 0.4
$\Delta\phi(\text{jet}_{\text{ISR1}}, E_T^{\text{miss}})$	> 2
$R_{\ell\ell}$	> 6
E_T^{miss} [GeV]	> 350
Leading ISR jet p_T [GeV]	> 300
m_{T2} [GeV]	> 100



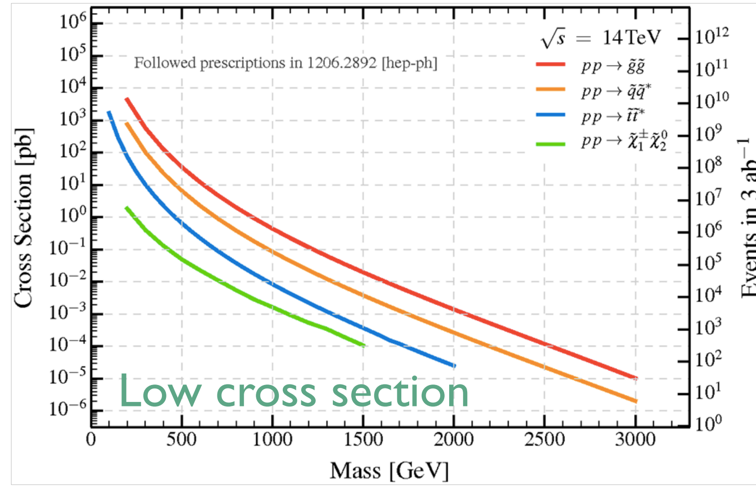
Cut-and-count, optimized for discovery



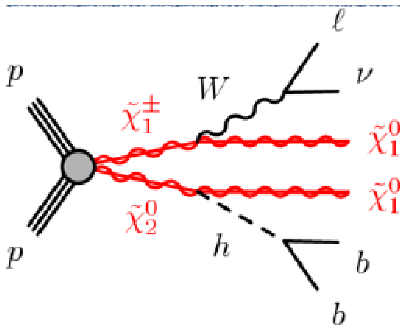


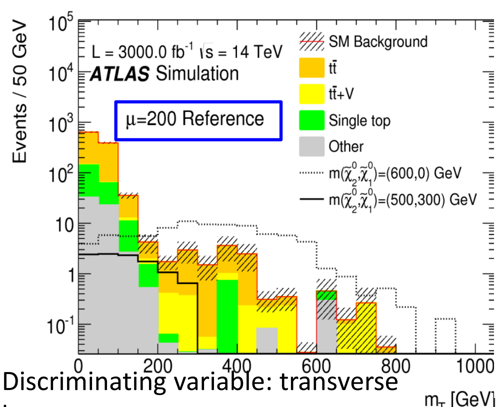
SUSY@ HL-LHC: EWK sector

- 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



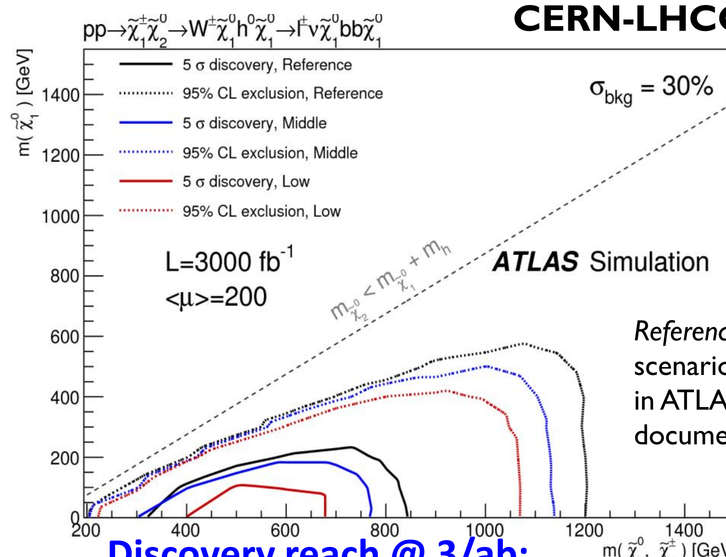
Very challenging:





Discriminating variable: transverse lepton mass m_T

CERN-LHCC-2015-020



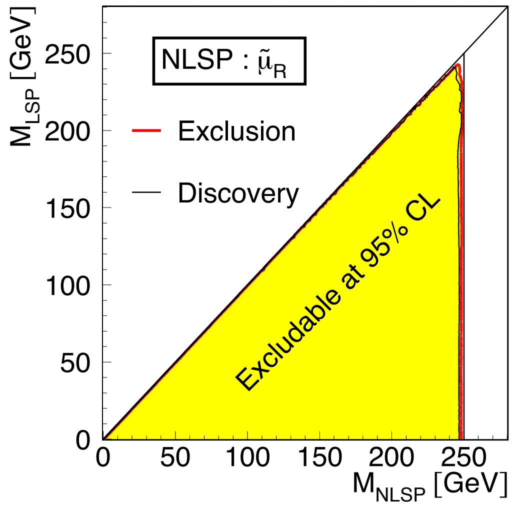
Reference, middle, low – scenarios considered in ATLAS scoping document

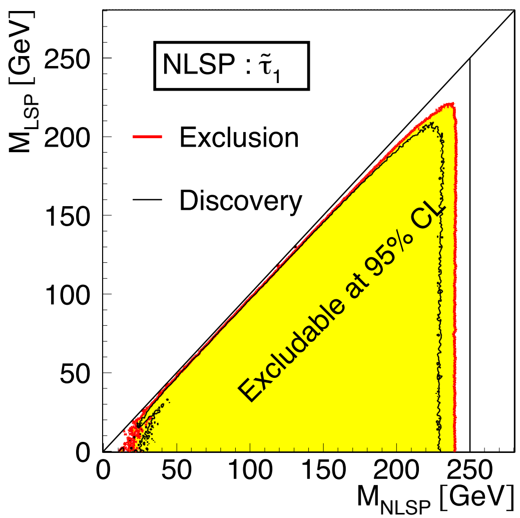
Discovery reach @ 3/ab: 850 GeV reference detector

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

SUSY @ electron-positron machines (II)

Sleptons @ ILC (500 GeV)





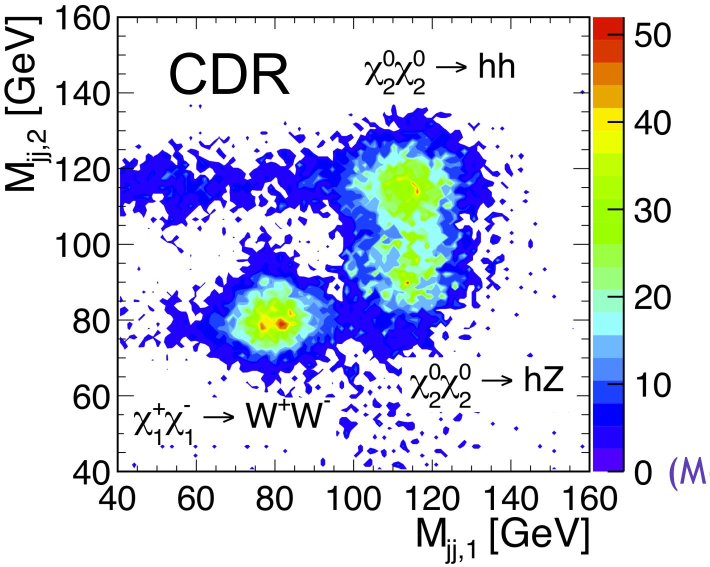
arXiV:1307.5248

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

$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+W^-$$

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

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



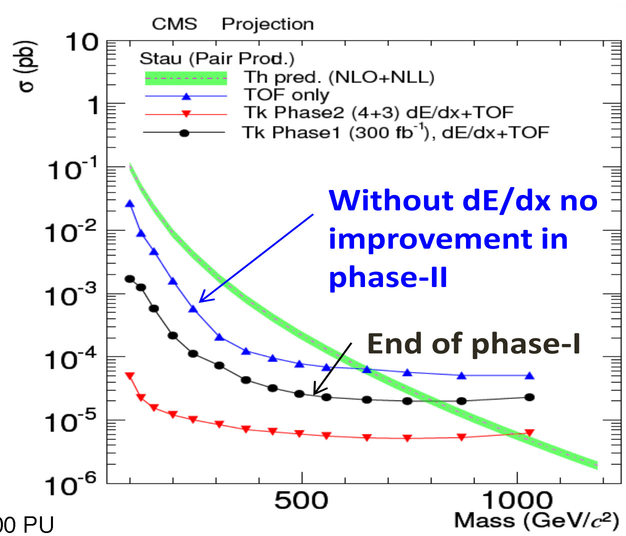
Precision on the measured chargino/ neutralino masses (few hundred GeV): 1 - 1.5%

(M(charg/neut2)=487 GeV)

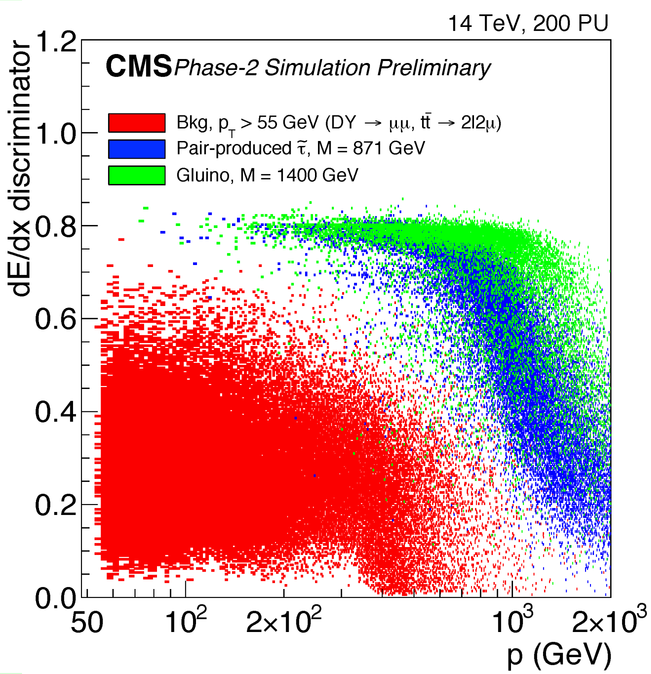
Similar studies in progress for circular colliders

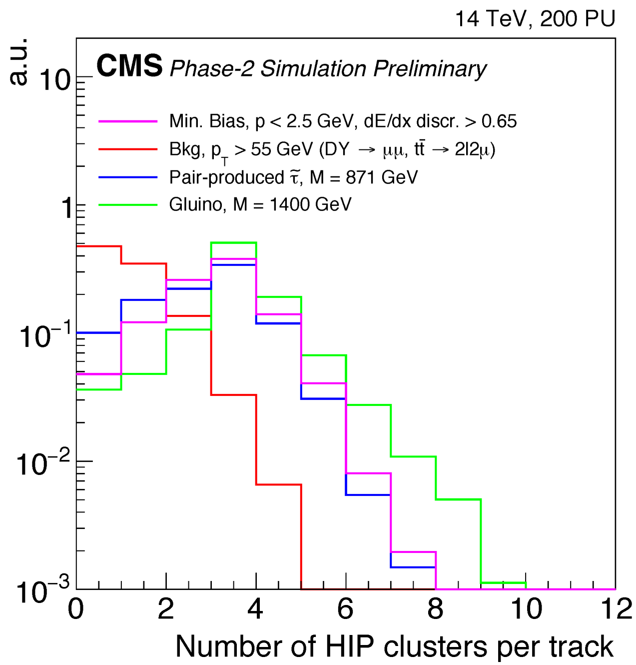
Heavy Stable charged particles

- 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

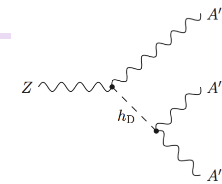




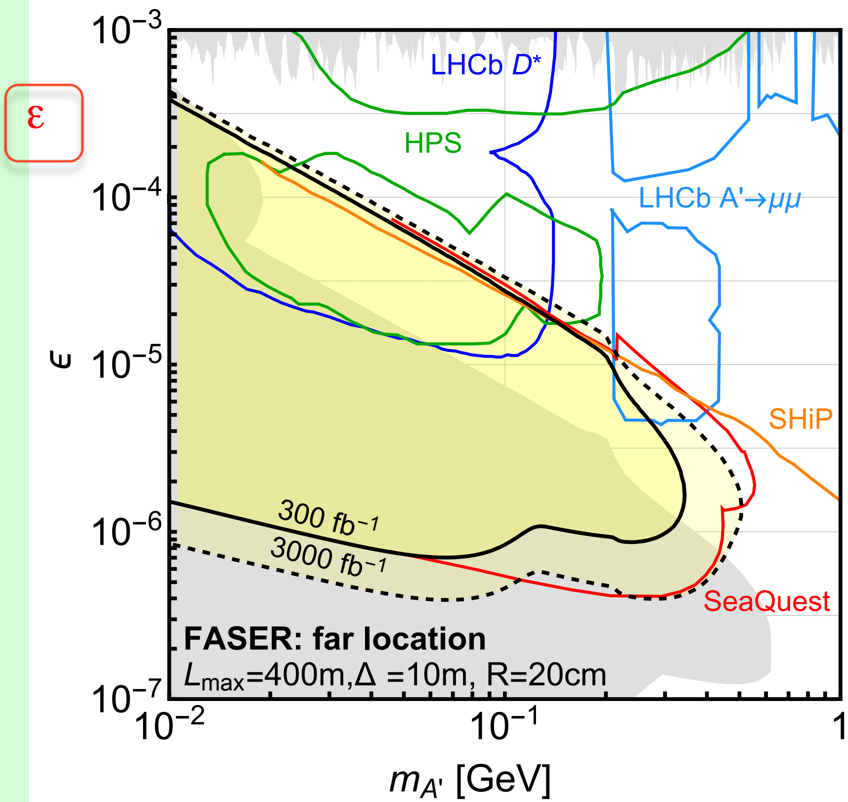
Additional CMS studies on performance for Heavy stable charged particle via muon system also available *(more in dedicated talk)*

CMS TDR (NEW)

Dark photons: future potential



FASER predictions



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

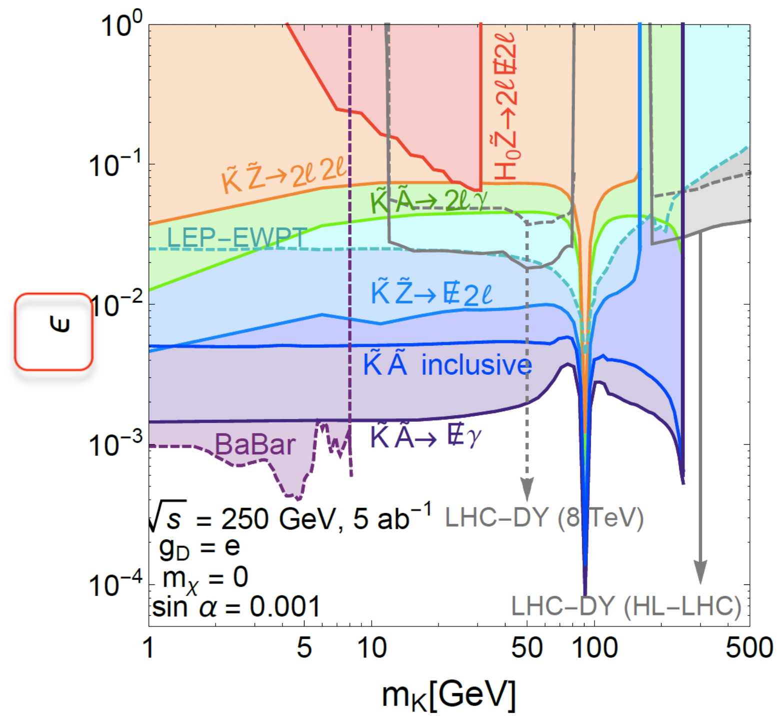
CepC potential

$e^+e^- \to \tilde{Z}H_0$ 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 $S \to 4\chi$

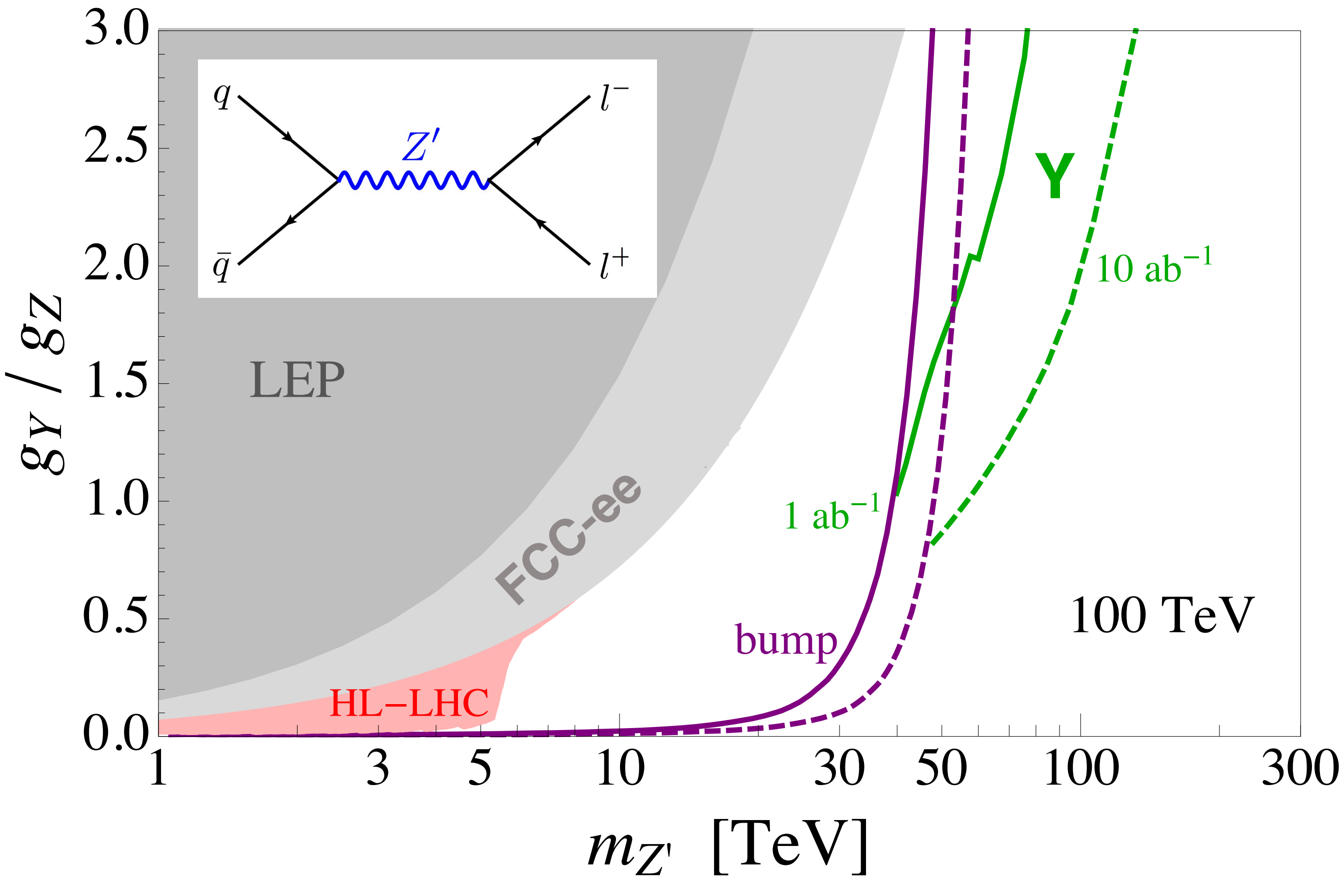


Felix Yu – Dark Sectors at CEPC

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