BSM searches at colliders long term prospects

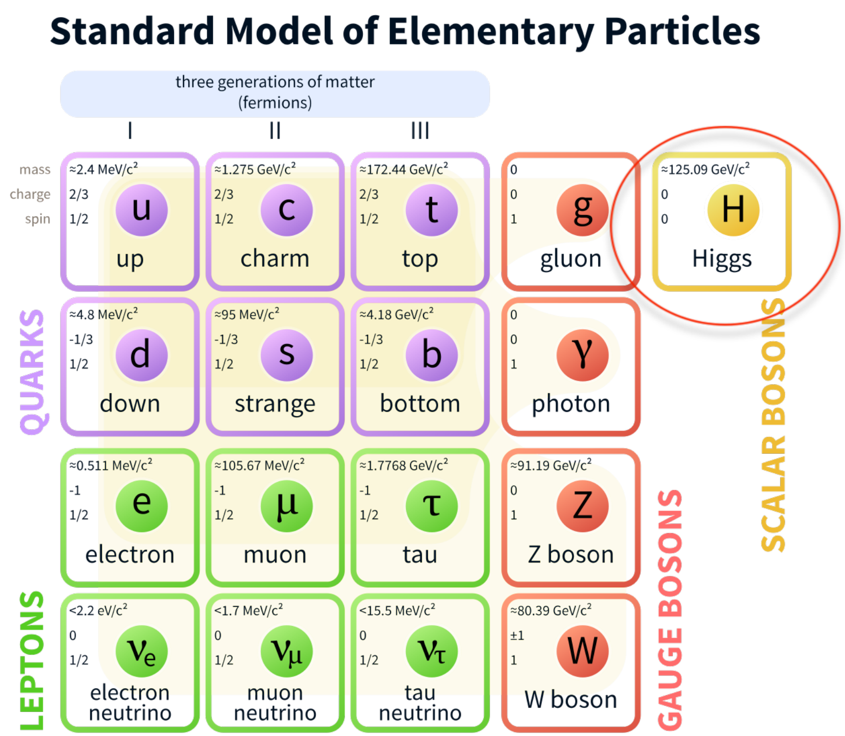
Monica D'Onofrio
University of Liverpool

"Pushing the boundaries of energy and intensity frontiers"

IPPP Durham

July 3rd 2018

Searching for new physics: what



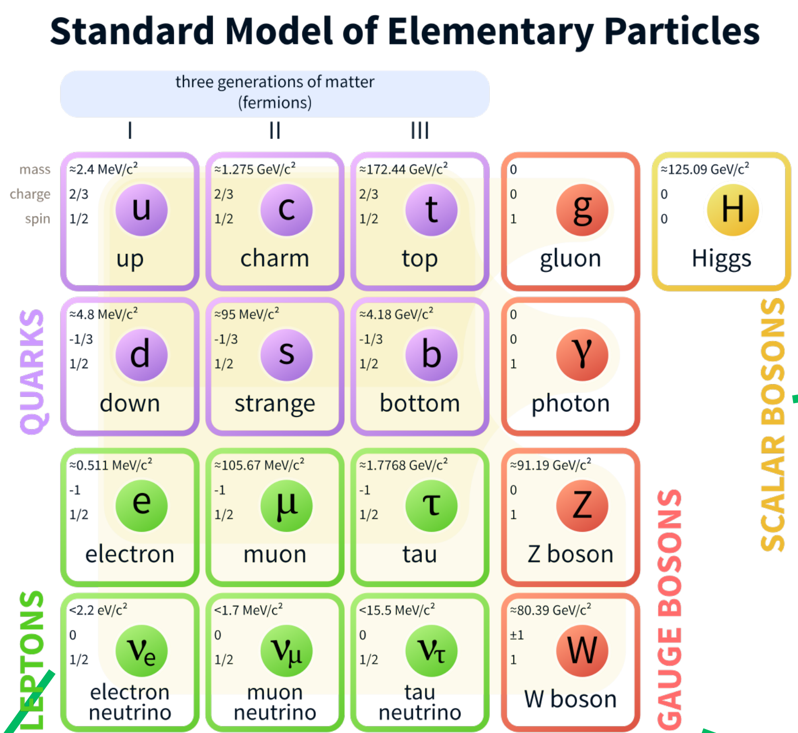
2010: clear guidance for the LHC: EWSB and the **Higgs boson**, and we discovered it…

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 more
- Charged Scalars
- Composite Higgs

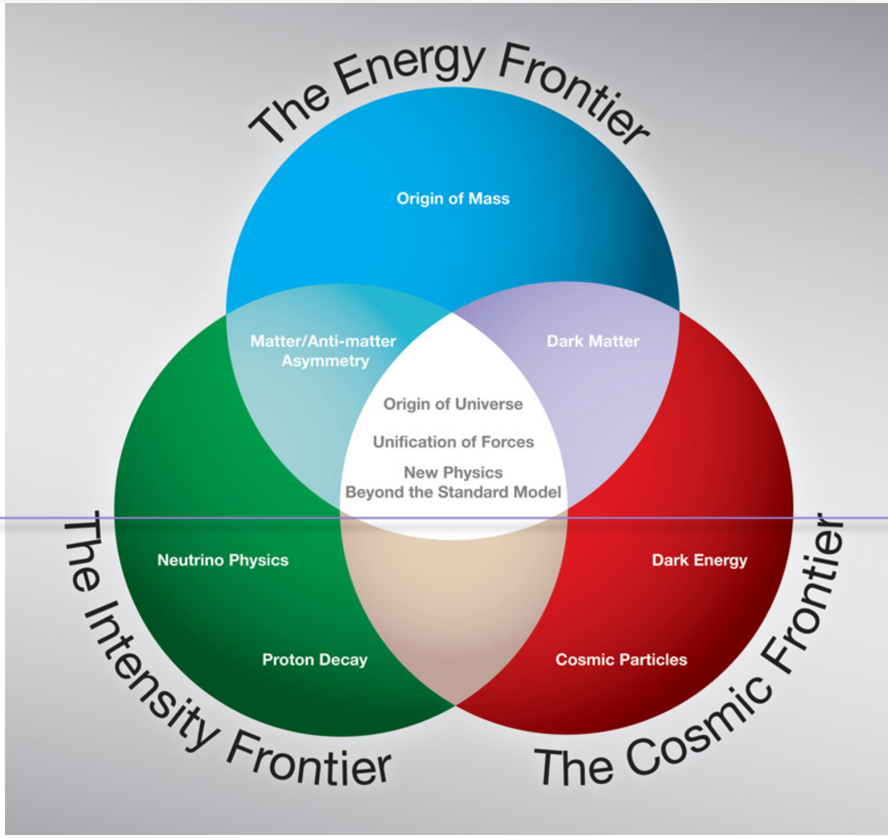
"Exotics": referred to a large variety of theories and models

- 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

- 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

HL-LHC

- 14 TeV com energy, 2025-2038, up to 3000 or 4000/fb (300/fb for LHCb)
  - The only one really approved, on which most studies have been made
- ATLAS, CMS and LHCb detectors upgrade well on-going
- Start time 2025
- Yellow Report for EU strategy expected in December 2018 summarize studies and projections by experiments and theory community on SM&Top, Higgs, BSM, Heavy Flavor and Heavy Ions
- WG3 (=BSM) has more than 80 contributions foreseen
  - Half and half between experiments and theorists

Section 1: Intro and review
Section 2: SUSY
Section 3: DM
Section 4: LLP
Section 5: Dark sectors
Sections 6 and 7: Resonances, VLQ (to be decided on possible merging)
Section 8: Flavor-related and Miscellanea

HE projections studies also included

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHEWG3

Conveners: MD (ATLAS) Keith Ulmer (CMS), Xabier Vidal (LHCb), Riccardo Torre (TH), Paddy Fox (TH)

Status of WG3 document so far

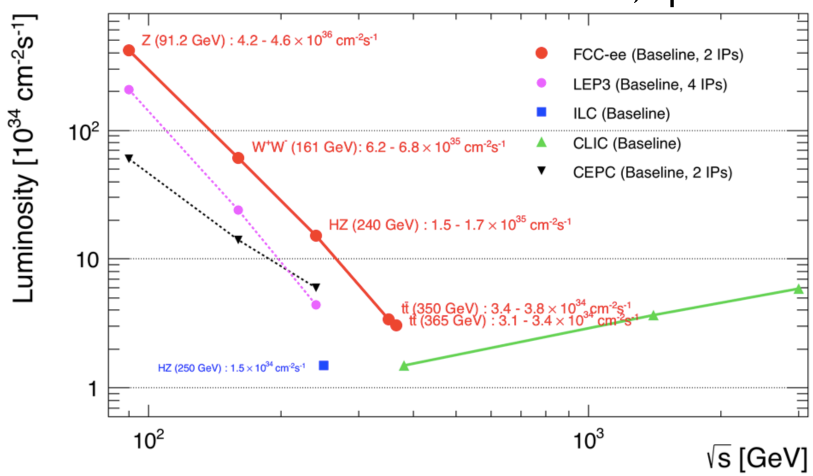
- 113 pages, theoretical contributions only, experimental results in preparation for september
  https://www.overleaf.com/14722141bbfgfvqrrvbp#/56185127/

Contents

Other (future?) "colliders"

- **Proton-proton**
  - 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,
    - 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



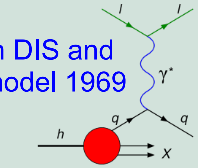
- **Electron-proton**
  - LHeC → E_e = 60 GeV, p from LHC, up to 1/ab, running at the same time as HL-LHC
  - HE-LHeC → upgrade in parallel to HL-LHC
  - FCC-eh → E_e = 60 GeV vs 50 TeV, up to 3/ab

outline

- At the LHC, hundreds of searches for new physics are on-going targeting many models proposed in the past thirty years.
- HL LHC studies on-going
- **This is not a review talk**, rather a discussion about goals and synergies
  - Will illustrate what data might tell us at the end of HL-LHC and complementarities with other facilities (e.g. e+e-, e-p)
  - **Consider some benchmark routes**
    - **New heavy resonances** and high p_T physics
    - **Supersymmetry**
    - **Dark matter**
    - **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

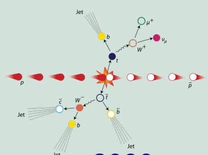
B-quark discovery 1977

1980

W and Z bosons discovery 1983

1990

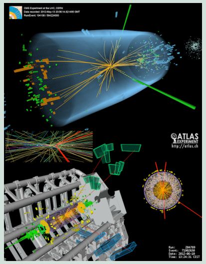
Top quark discovery 1995



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)

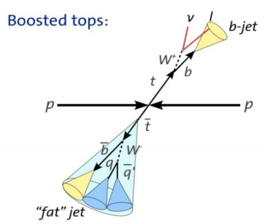
Where high luminosity and high center of mass energy help the most

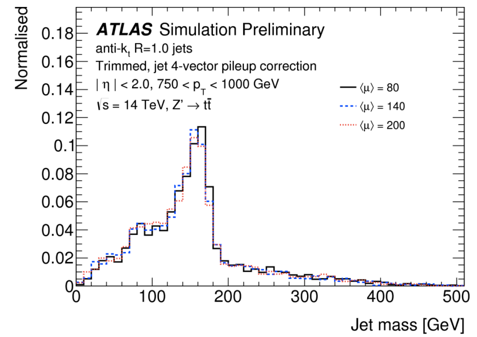
- Sensitive to many BSM scenarios
  Heavy higgses (A/H), Extra-dimensions, new gauge bosons… without mentioning the role of dijet searches for DM
- Consider all relevant combinations of final state objects
- Example of flexibility/synergy: strong focus on 3rd generation: can help explaining anomalies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

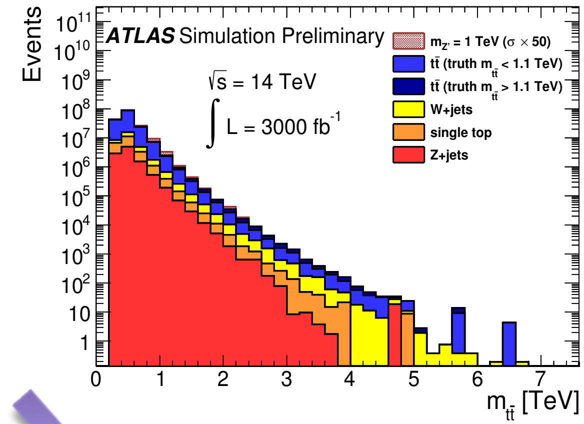
Reach with HL-LHC: Z' →ttbar

ATL-PHYS-PUB-2017-002

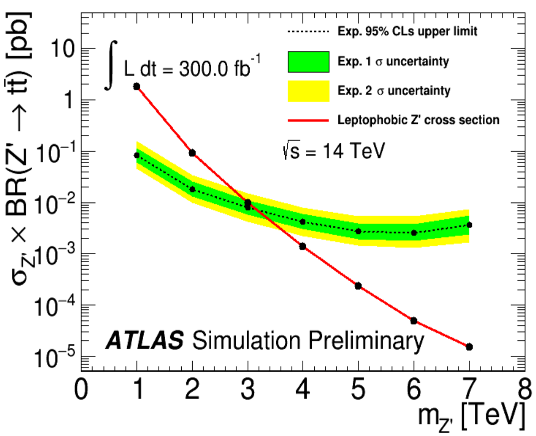
- Resolved and **boosted top systems**
- Large **R-jets** considered



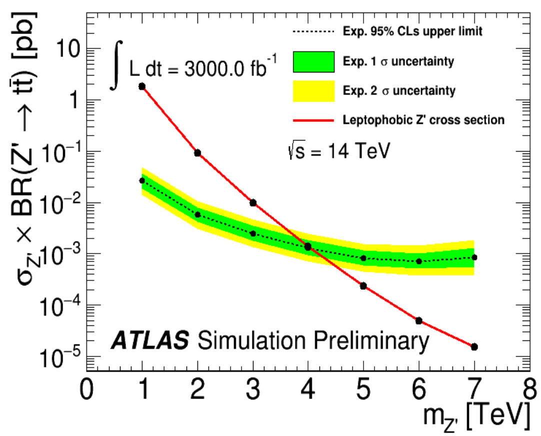




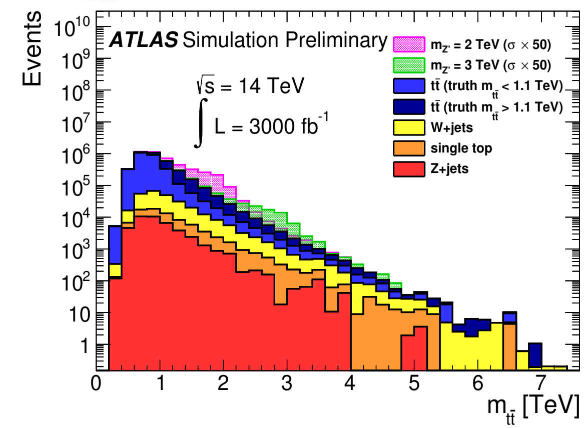
(b) Resolved Muon Channel.



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



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



(d) Boosted Muon Channel.

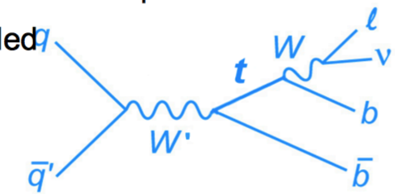
Reach: beyond 4 TeV (1 TeV gained with HL-LHC)

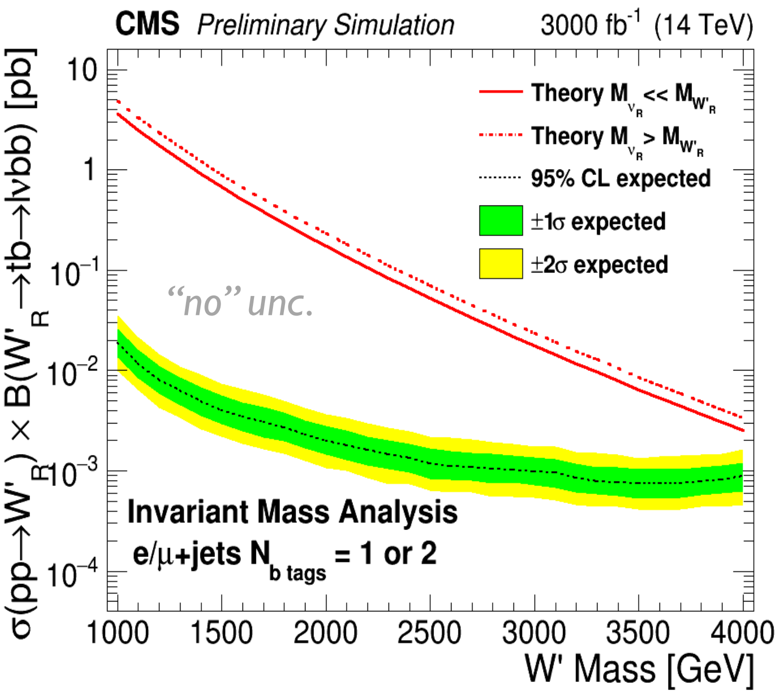
Reach with HL-LHC: W'→tb

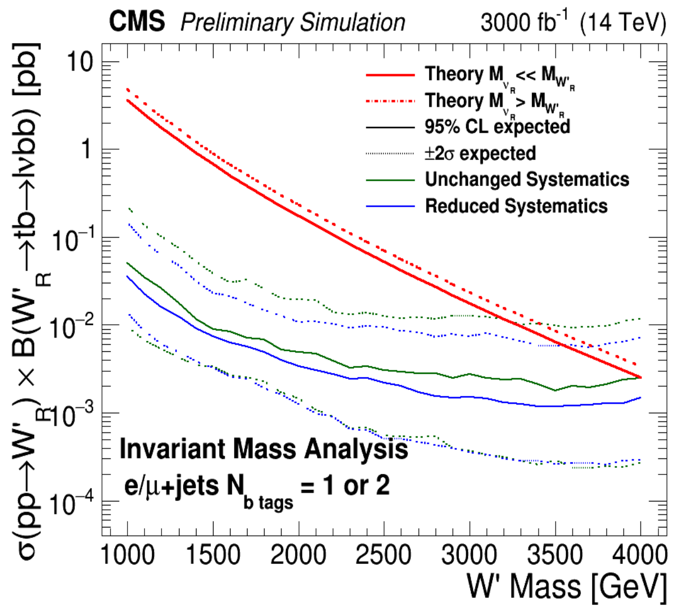
- Projections performed – assuming NWA using 2015 and 2016 analyses

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

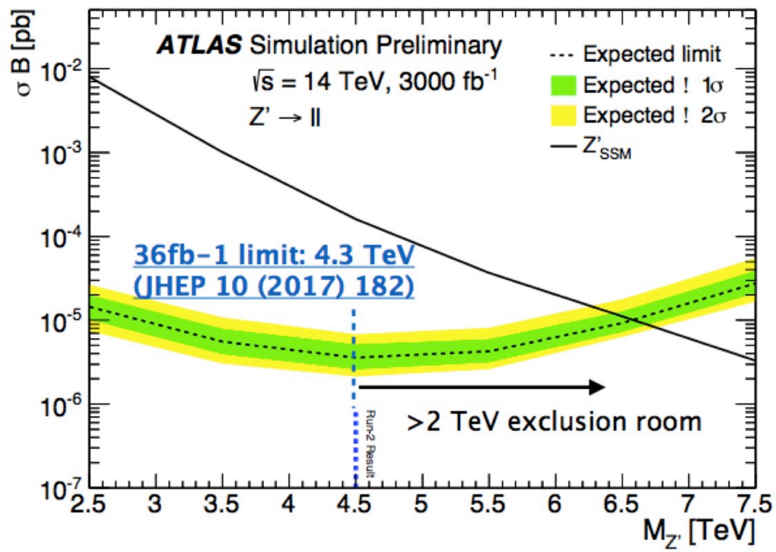
Reach: beyond 4 TeV
For W' in eν and μν → reach up to 7 TeV

Reach with HL-LHC: Z'→ll

ATLAS and CMS update for Yellow Report in progress

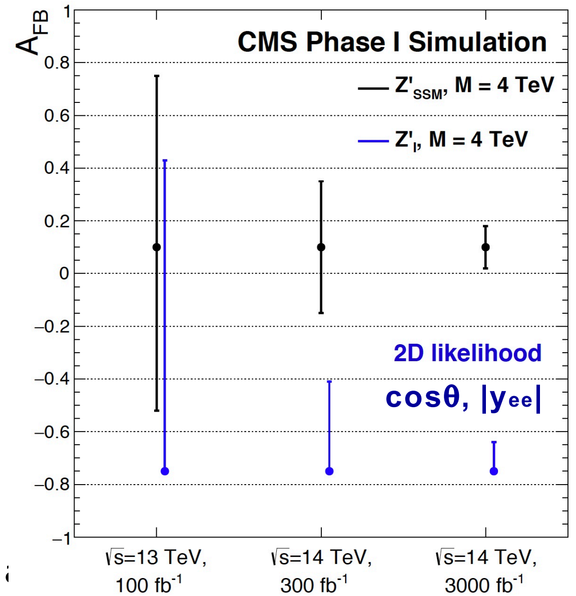
- ATLAS
  - Search in the ee and μμ final states using MC truth + smearing
  - Exclusion limits shown in LAr TDR
  - Also plans for property studies

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



- CMS (CMS-PAS-EXO-14-007)
  - Study ee final state
  - Existing full sim property study using A_{FB} in 2014

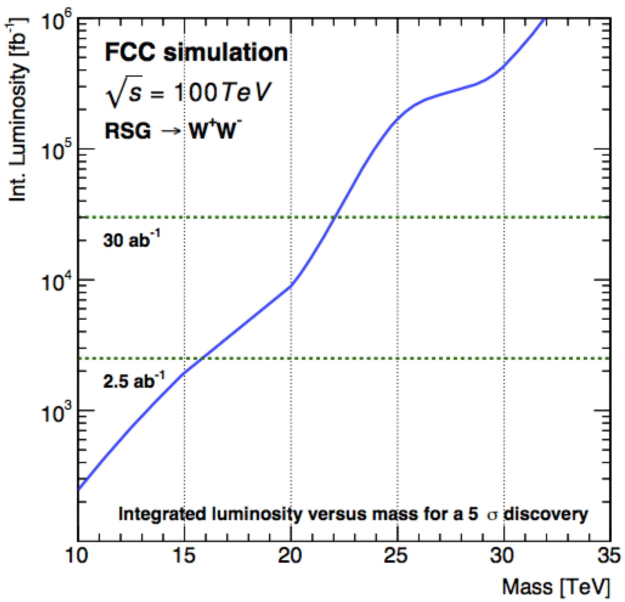
→ updates on the possibility to characterize signals being followed up by ATLAS and CMS and for HE-LHC

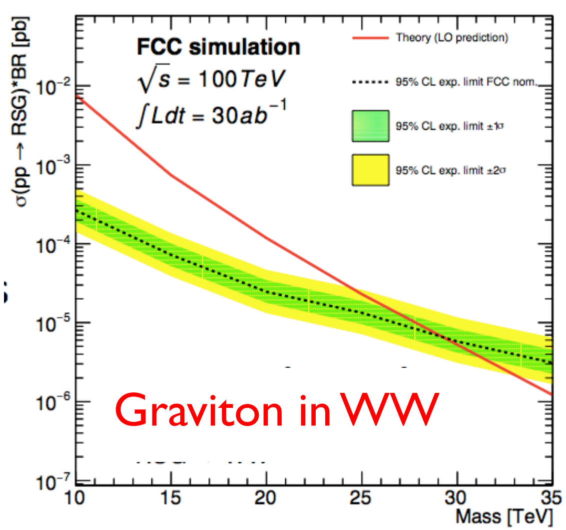


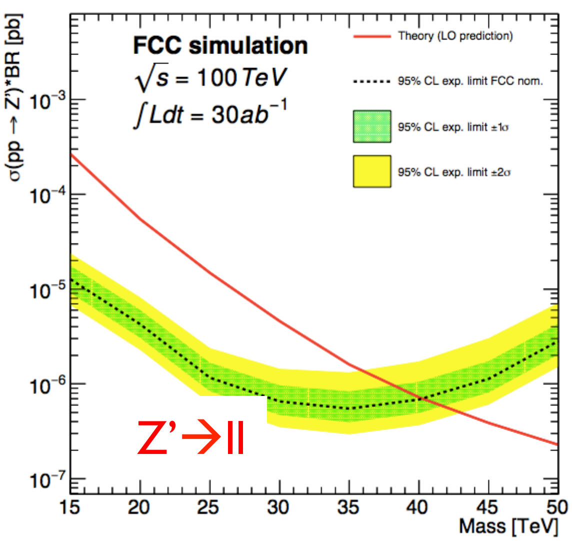
The (far) future

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}.

- 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?]



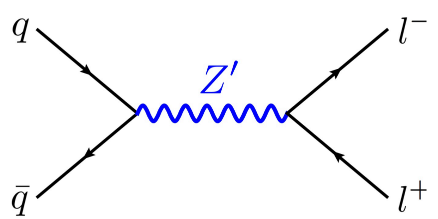


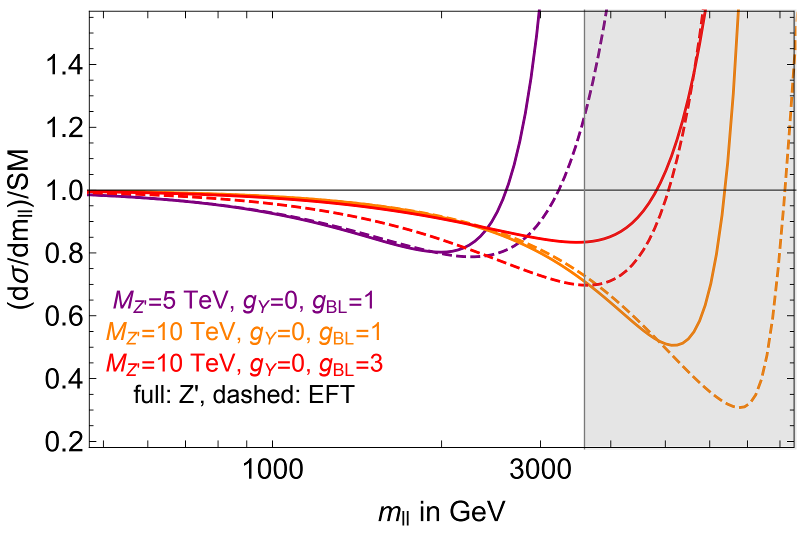


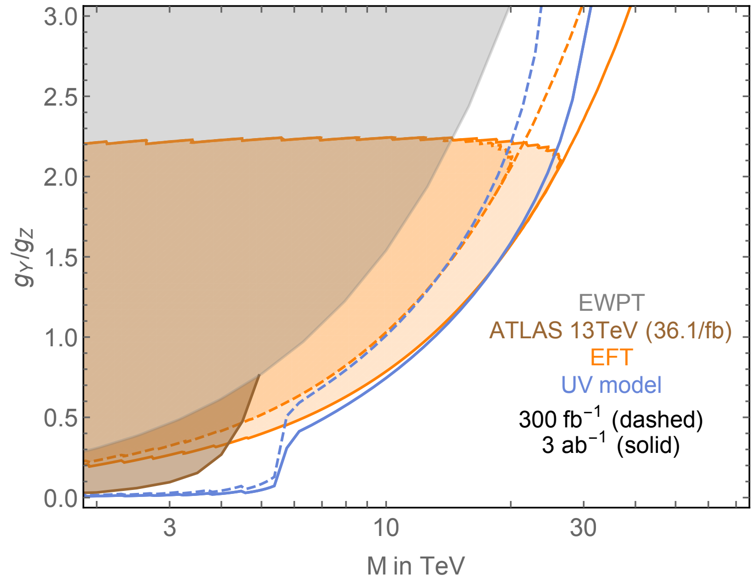
Indirect constraints on Z'

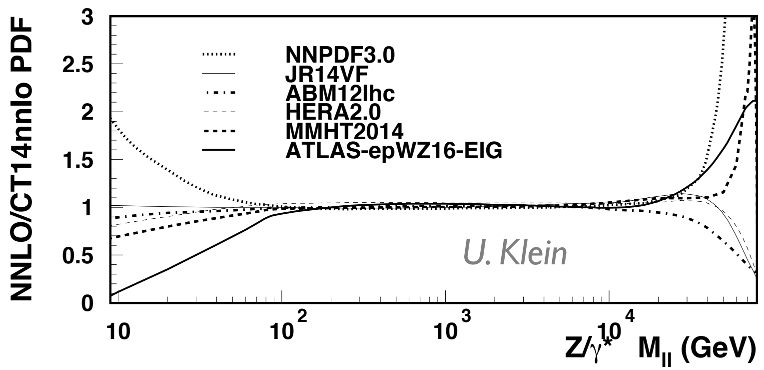
- If mZ'>>5 TeV, main contributions from interference effects modifying DY
- HL-LHC can do a lot → but need very precise predictions of SM DY – again PDF!

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







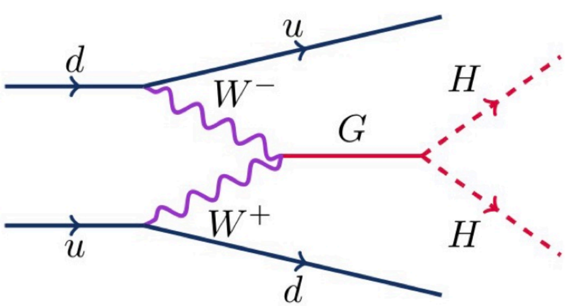


Effects of PDF might be extremely important

Other resonances: di-higgs

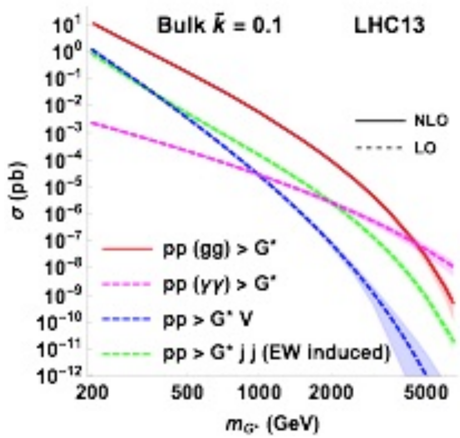
New from CMS for Yellow Report

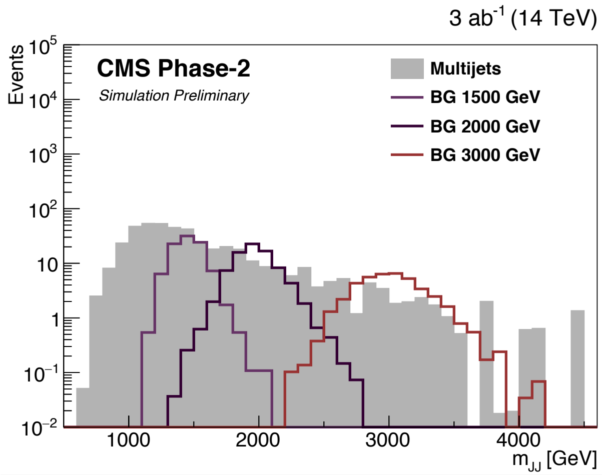
- NP in the higgs sector can manifest in various ways
  - E.g.: heavy particles decaying into higgs
  - Very recent result from CMS released for the HL-LHC Yellow Report

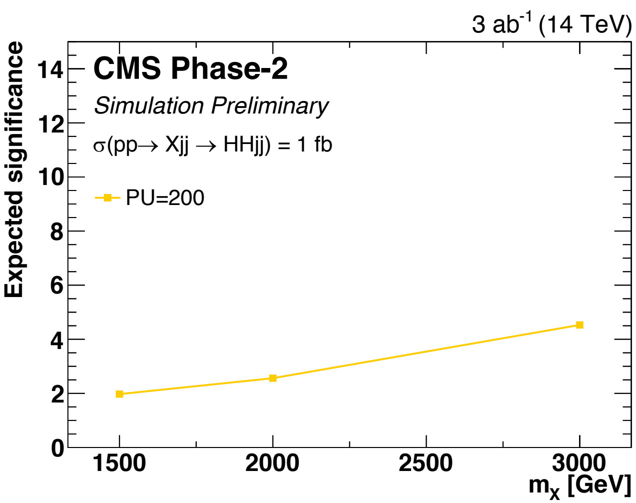


VBF signatures: very good potential at HL-LHC

Search for di-higgs resonance in the 4b channel
→ Substructure + boosted b-tagging helps to suppress large QCD multijets background.
→ Bump-hunt on mJJ (J = Large R jet from h→bb)







Follow the anomalies ?

- 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 $\rightarrow c\ell\bar{\nu}$

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

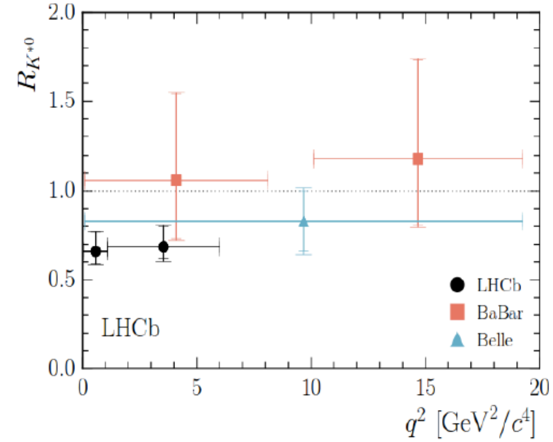
$$R^{\tau/\ell}_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$$

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

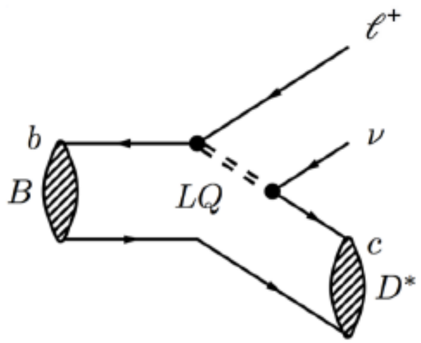
R_K, R_{K^*}: $\sim 2.5\ \sigma$ deviation (LHCb)

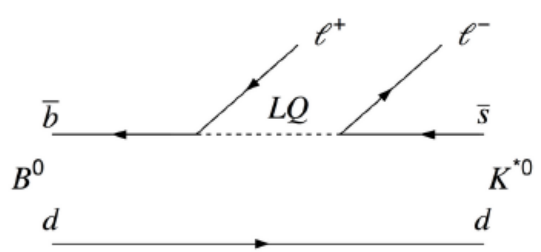
$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$

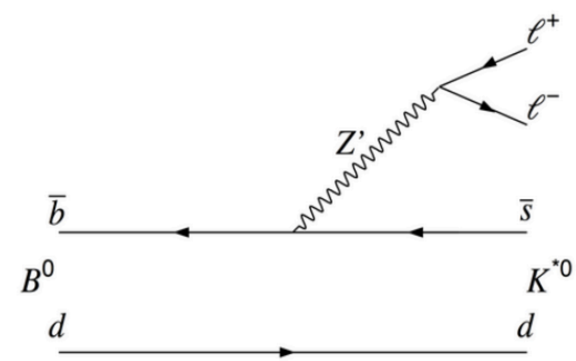
$B^0 \rightarrow K^{*0}\mu^+\mu-$ angular analysis:
3.4 σ deviation (LHCb)



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



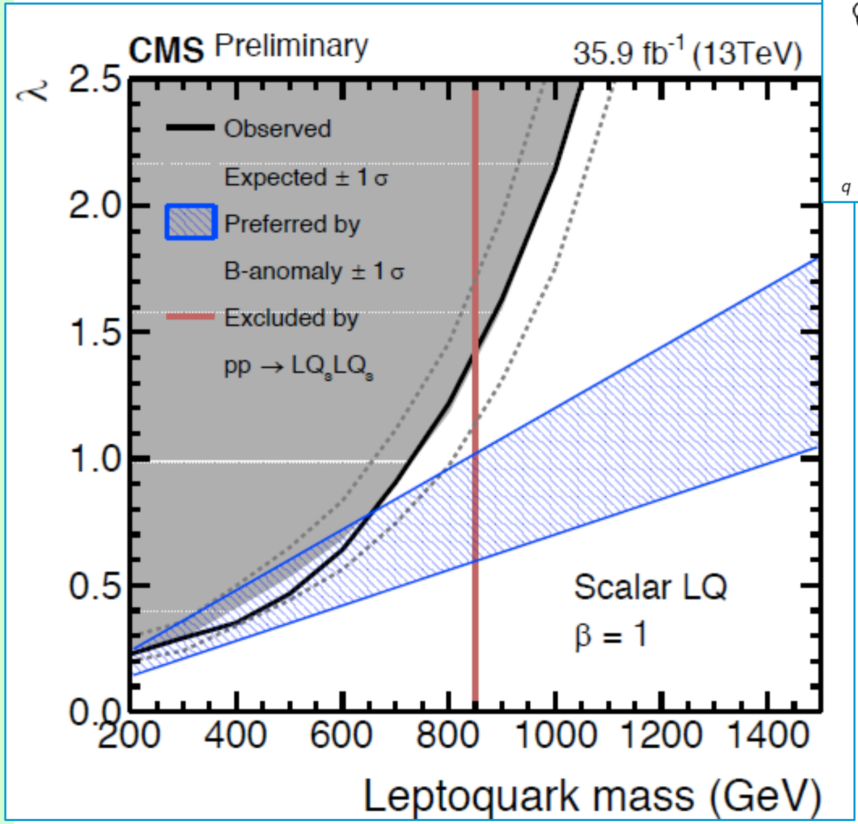


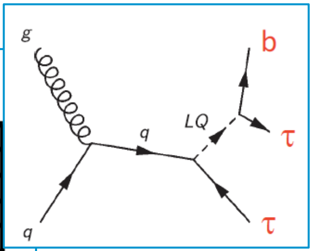


LQ: → τ + b and beyond

ATLAS and CMS update for Yellow Report in progress

- 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)

→**CMS HL-LHC studies and projections expected for September**

Note: depending on mixture and mass, studies could be also possible at e-p (limited by c.o.m energy)

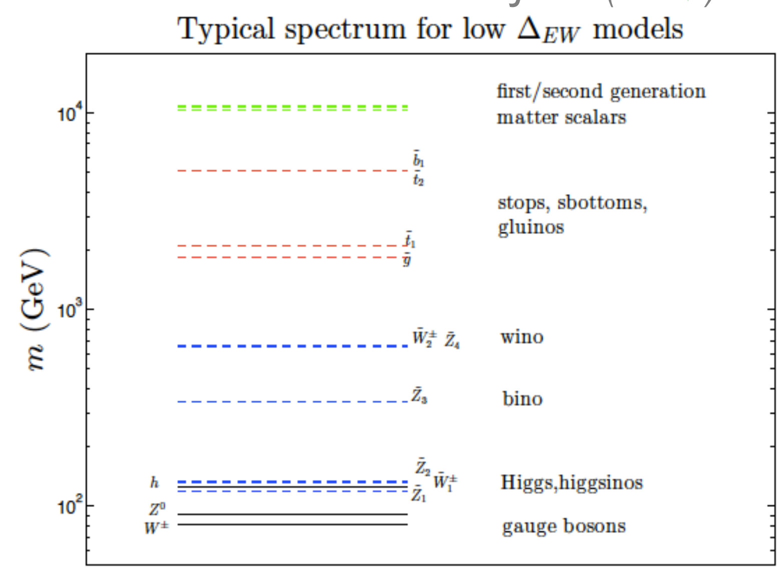
Supersymmetry

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

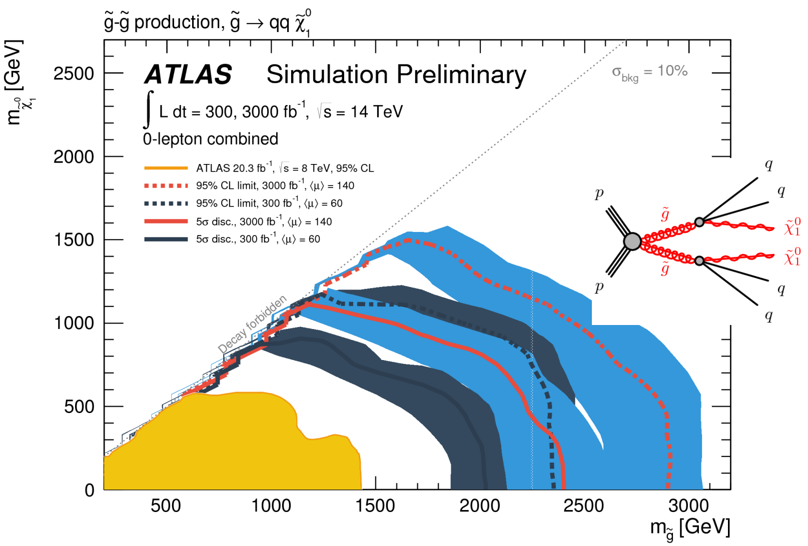
SUSY @ HL-LHC: strong sector

ATLAS update for Yellow Report in progress

- 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).

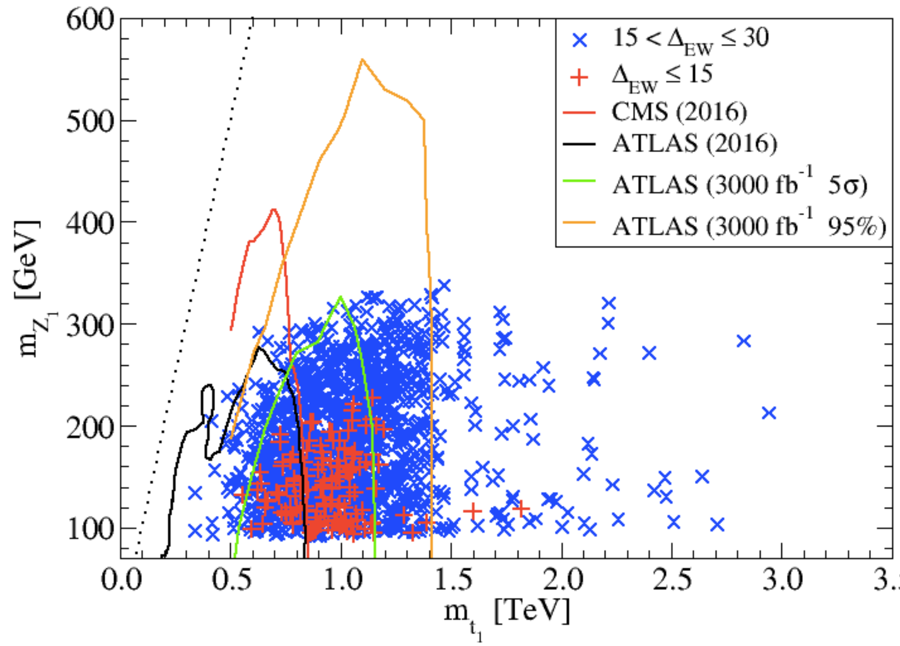
Baer et al., EPJC77 (2017) 499

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



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

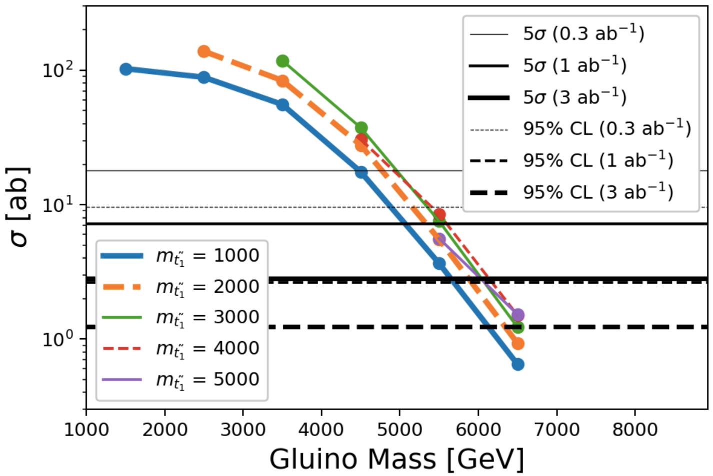
Analyses being re-assessed:
Exp. gluino reach up to 3 TeV

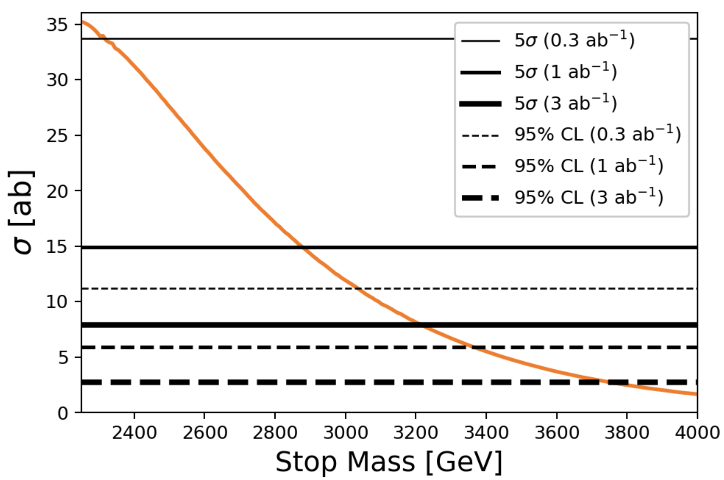


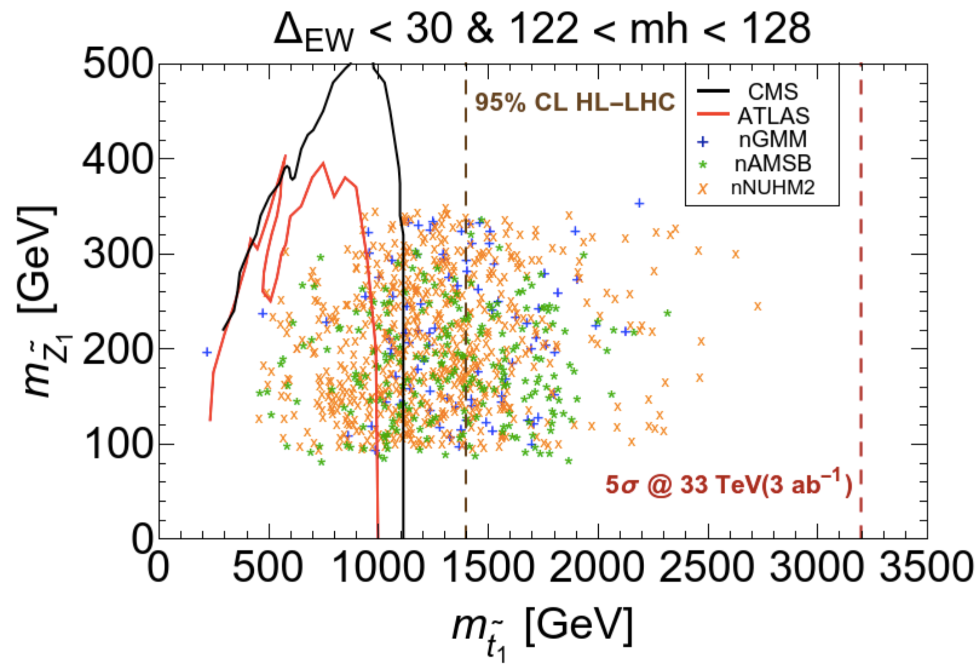
M(stop) can range up to 3 TeV with little cost to naturalness. **HL-LHC Stop reach: 1.4-1.5 TeV (1.9 TeV with new analyses,** **but for compressed scenarios ~ 700 GeV)**

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

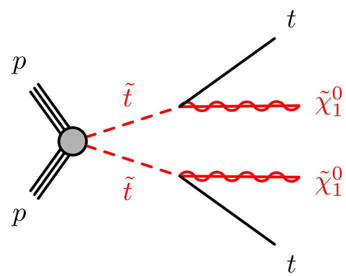
Stringent constraints on SUSY natural models

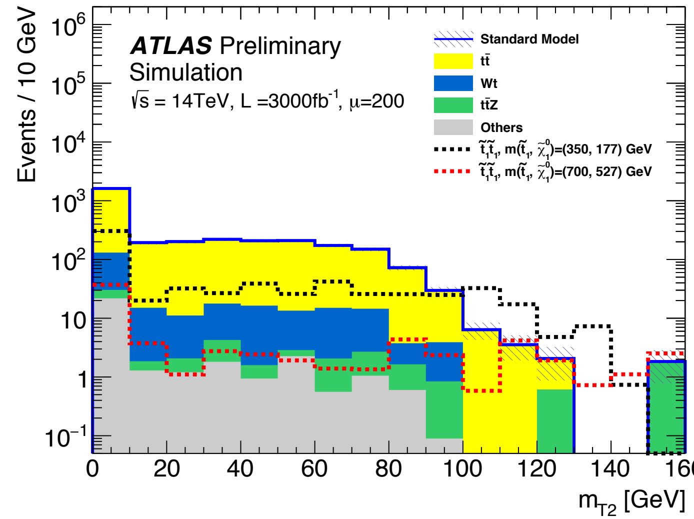
SUSY @ HL-LHC: challenging scenarios (stop)

ATL-PHYS-PUB-2016-022

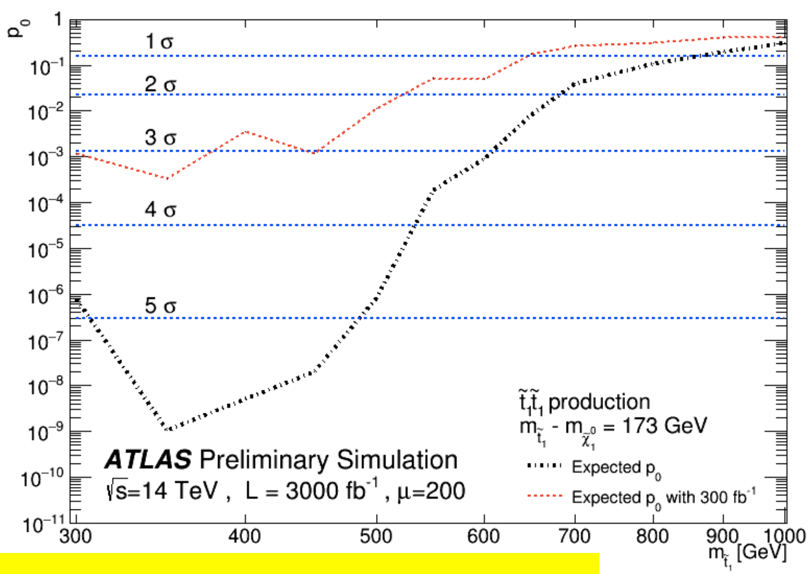
- Target compressed scenarios and use ISR jets
- m_{T2} as discriminating quantity, 2l + 2b + MET
  - Not simple to target those!

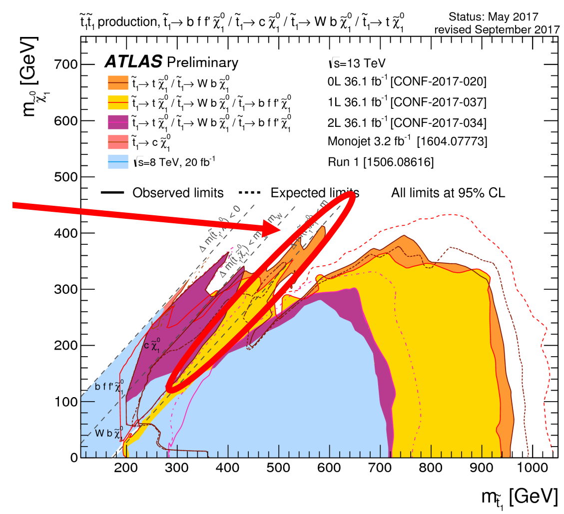
$$\boxed{(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}) \cong m_t}$$





Cut-and-count, optimized for discovery



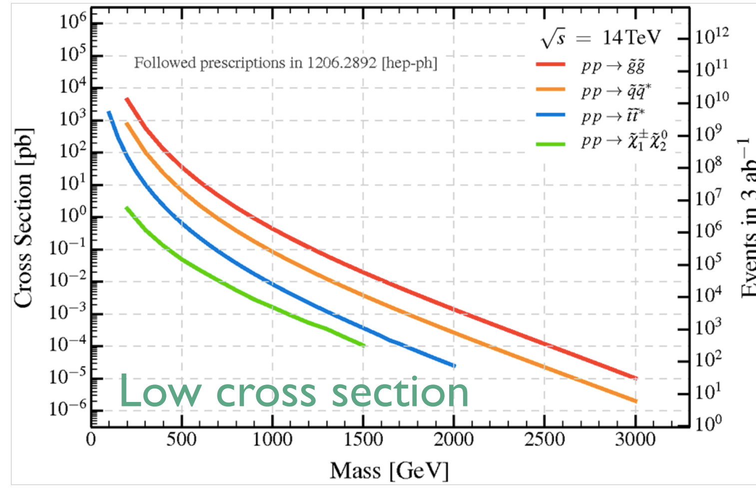


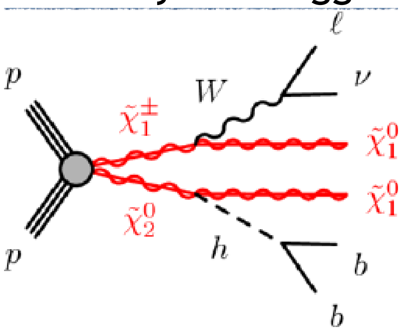
ATLAS update on stops in progress

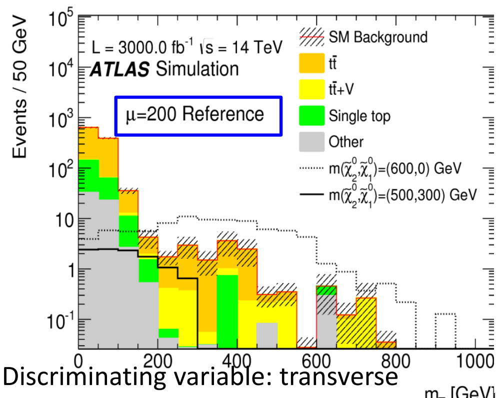
SUSY@ HL-LHC: EWK sector

ATLAS and CMS update for Yellow Report in progress

- 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
- Decays via higgs very challenging

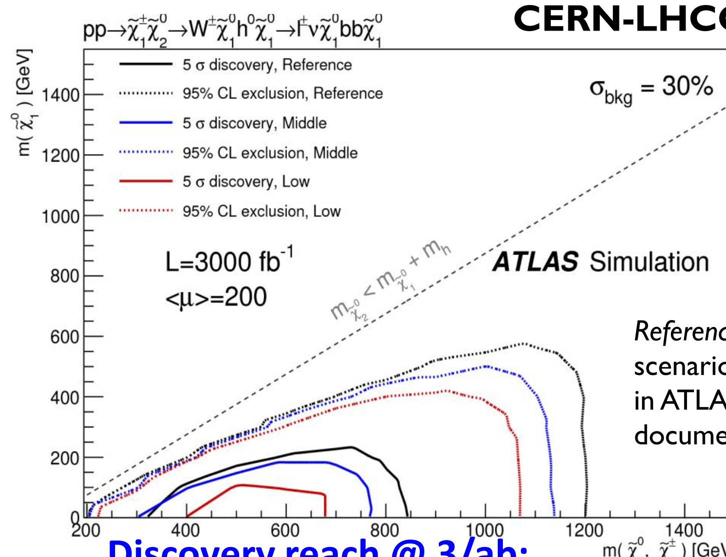






Discriminating variable: transverse lepton mass m_T

CERN-LHCC-2015-020



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

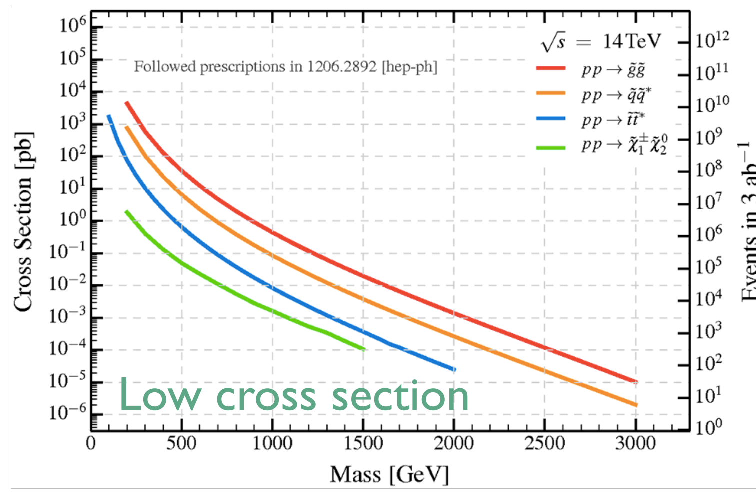
Results depend on the PU conditions as well as on the approach

Discovery reach @ 3/ab: 850 GeV reference detector

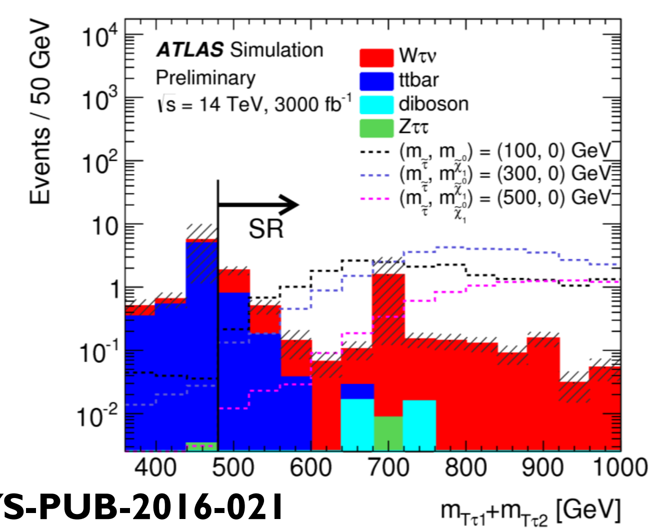
SUSY@ HL-LHC: EWK sector (II)

ATLAS and CMS update for Yellow Report in progress

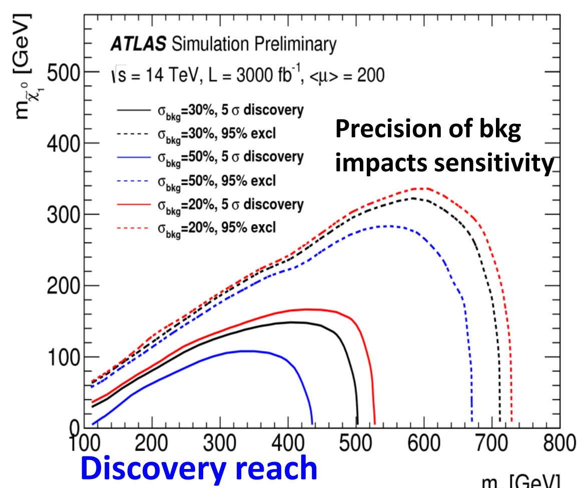
- EWK SUSY fundamental e.g. for DM
- HL-LHC dataset has the potential to increase the sensitivity to EWK SUSY enormously
- HE-LHC at 27 TeV can lead to a ~2x increase of signal xs for sub-TeV EKW-inos
  - But unclear if it is really an advantage
- Sensitivity strongly depends on EWK-inos composition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



Low cross section



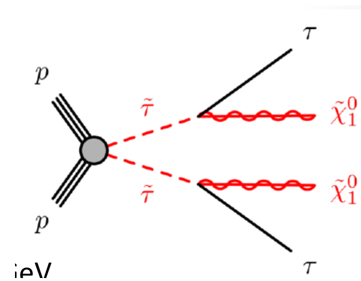
ATL-PHYS-PUB-2016-021



Precision of bkg impacts sensitivity

Discovery reach

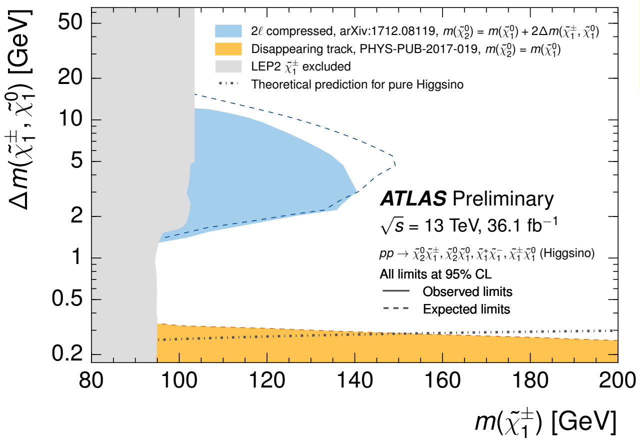
430-520 GeV @ 3/ab depending on bkg



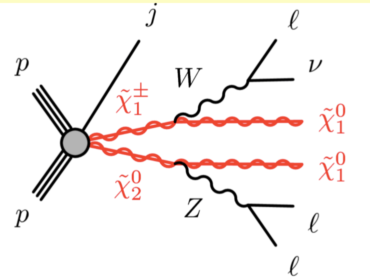
SUSY@ HL-LHC: EWK sector (III)

ATLAS update for Yellow Report in progress

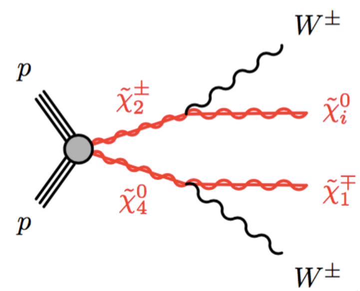
- SUSY higgsino-like scenarios also difficult (and very relevant for DM)
  - Low x-section, compressed → decay products are soft/invisible (for prompt production)



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



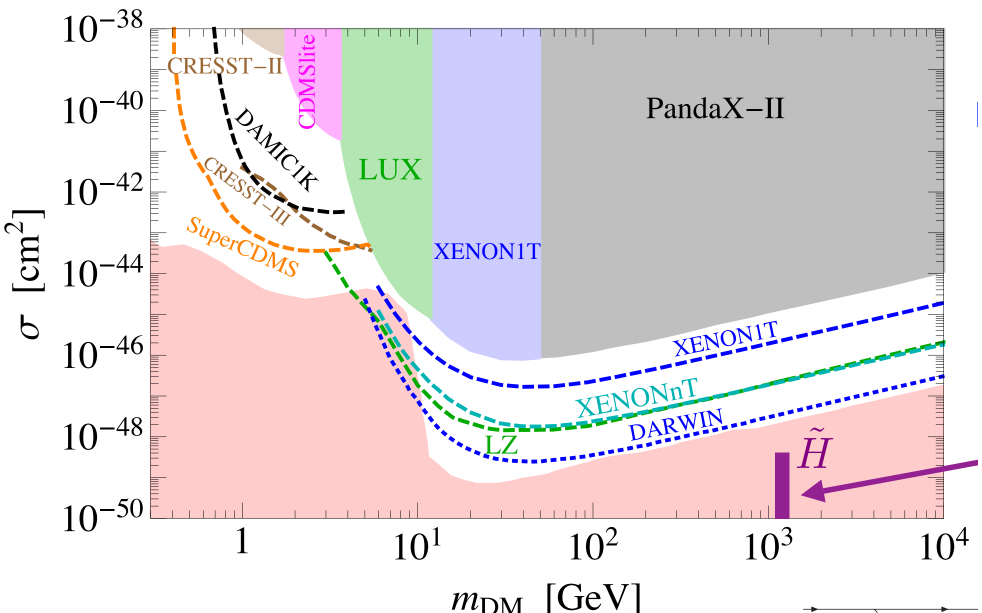
Search for events with Higgsinos produced in association with an ISR jet



Profit of additional charginos and neutralinos

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

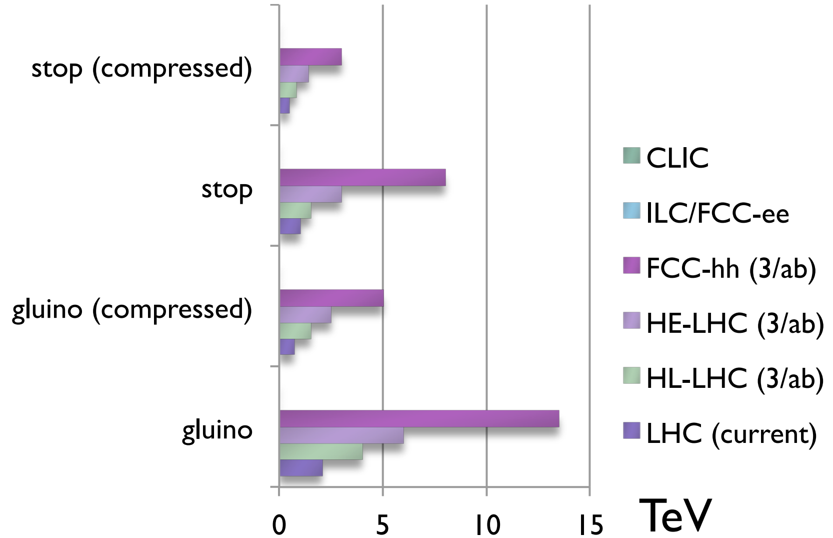
~ 1 TeV: maximum mass for the Higgsinos such that their relic abundance is at most Ω_{DM}

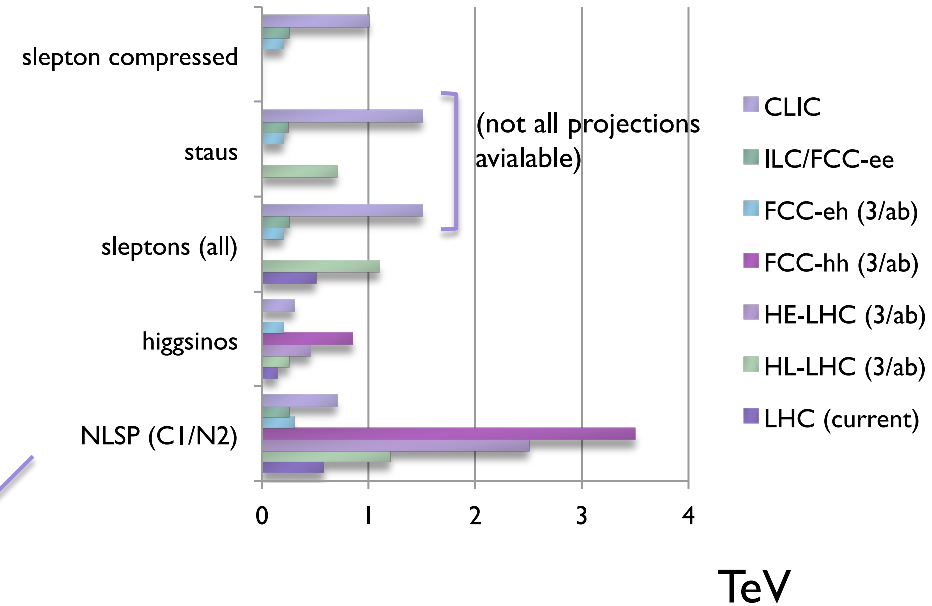


J. Ruderman, FCC week Amsterdam (April 2018)

A brief outlook on SUSY reach

CAUTION: Crude approximations/extrapolations I have made!

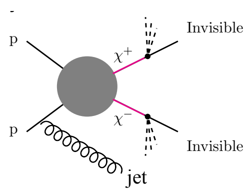


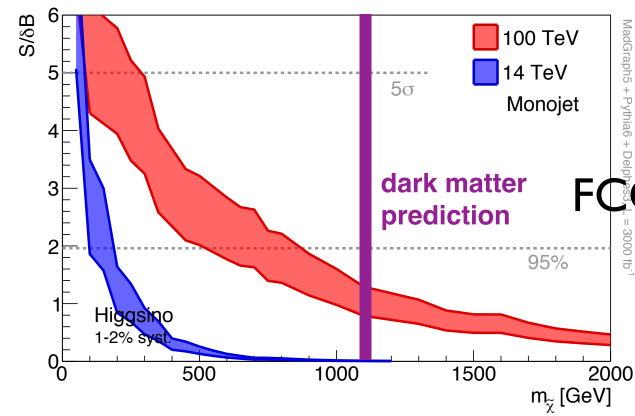


- Sleptons projections not yet available everywhere. Potential at ILC and CLIC (not for higgsinos).
- using mono-jet signatures
  - A signature relevant for many

NP models (DM-oriented)

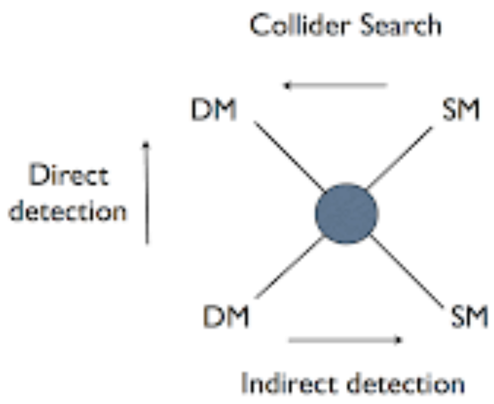
→ **1 TeC boundary reached only by FCC-hh**





FCC-hh

dark matter candidates

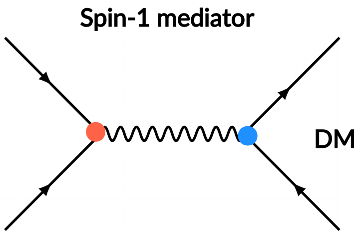


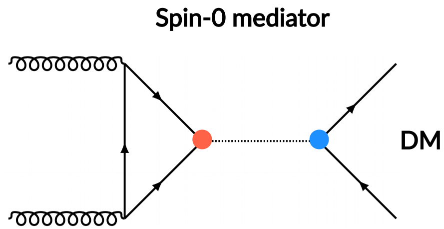
Most wanted after the higgs!

Foreseen by full theories as SUSY but nowdays searched under ‘simplified models’ assumptions

Complementarities with non-collider experiments to be exploited more

Dark matter searches at HL-LHC (I)



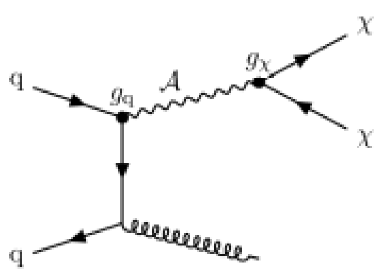


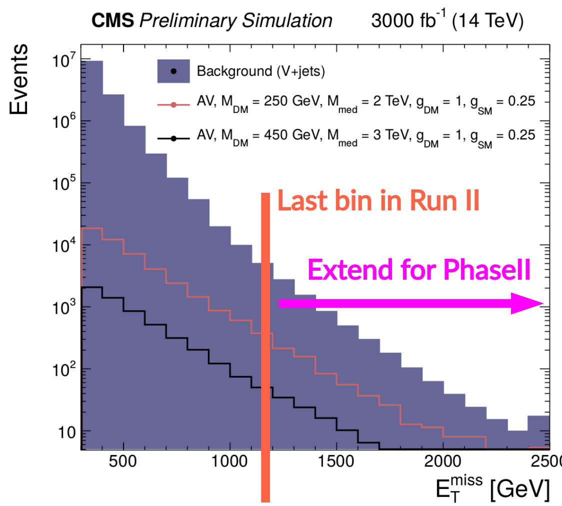
Strategy: Search for associated production with one of many SM tags: Jet, photon, Z, single/double top, b, H

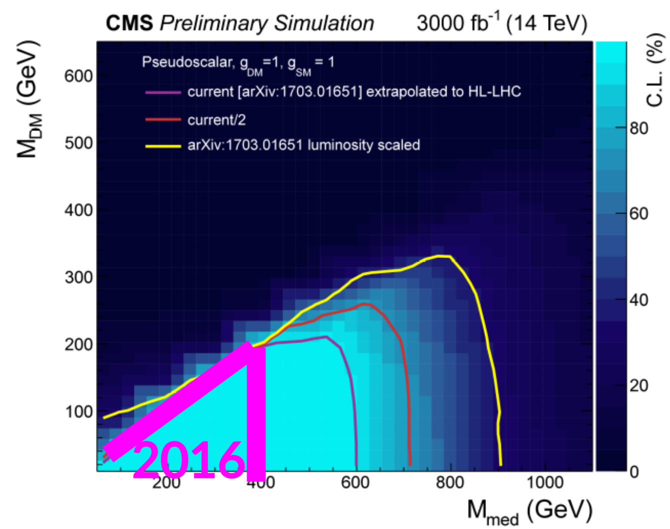
Simplified models with few free parameters:

m_{med}, m_{DM}, med-quark coupling, med-DM coupling

The classic: **monojet**

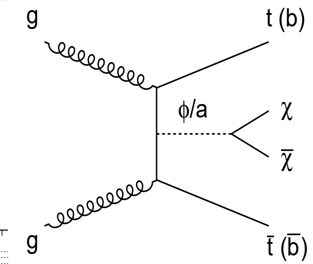






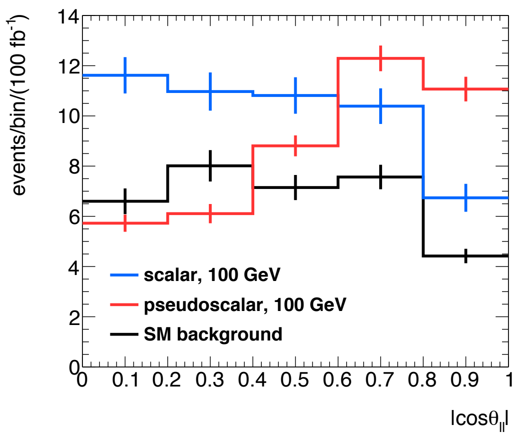
Dark matter searches at HL-LHC (II)

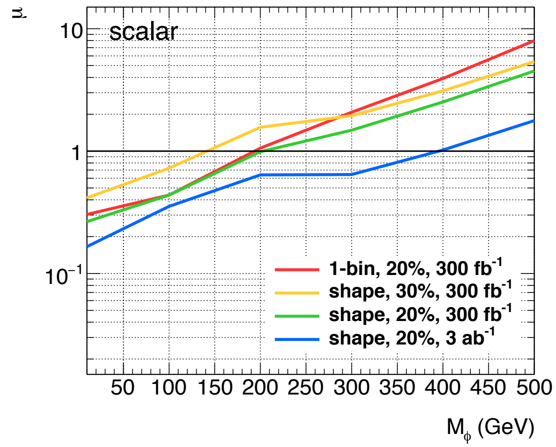
ATLAS and CMS update for Yellow Report in progress

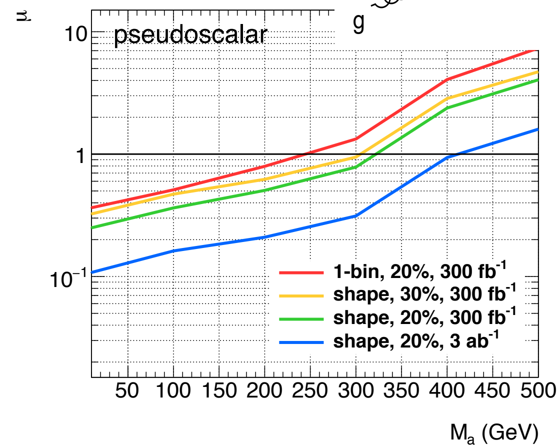


- **DM + heavy flavor:** great potential, lot of studies in progress (CMS, ATLAS, theory)

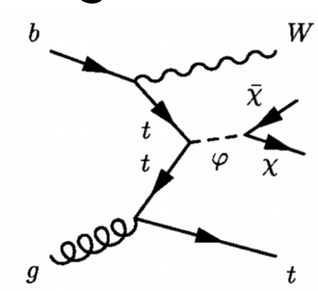
arXiV:1611.09841v2

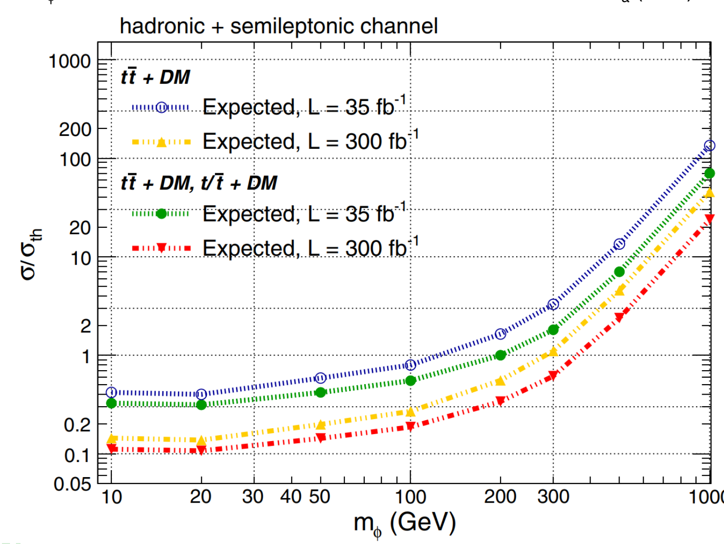






- Also including **DM + single-top**
  - E.g.:



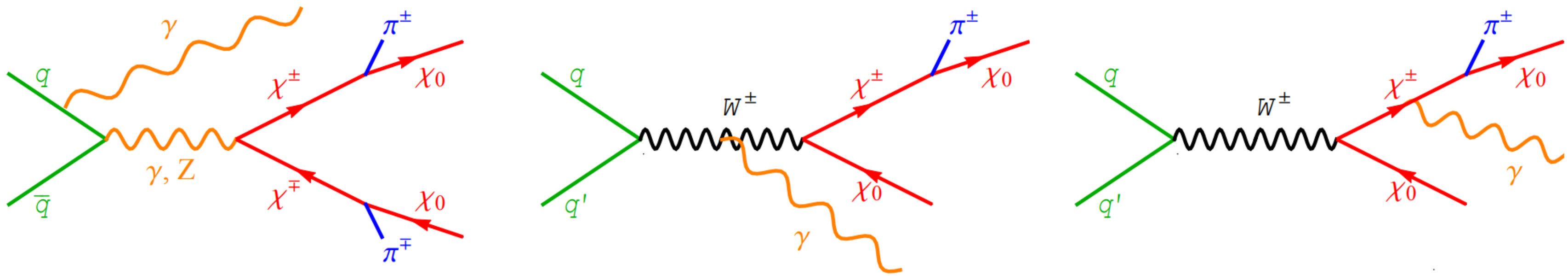


Forward tracking will increase sensitivity to DM+HF

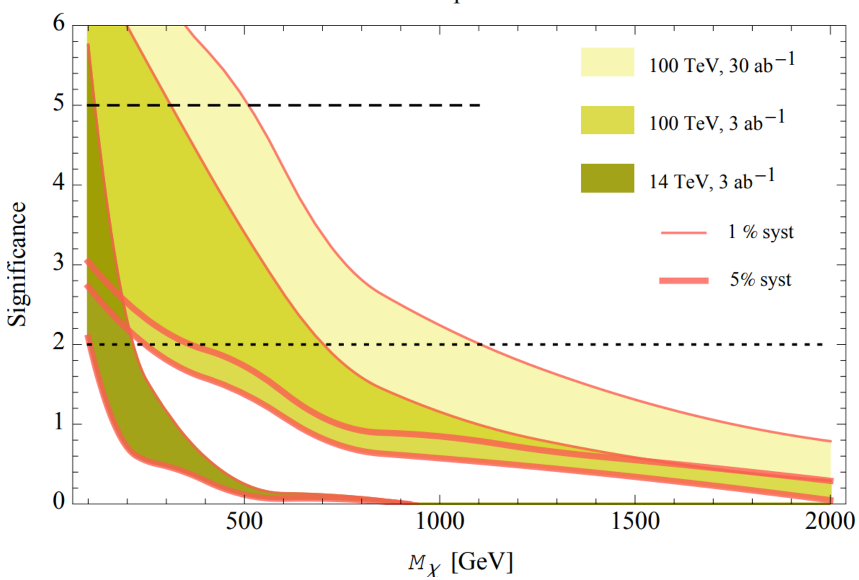
Dark Matter searches at HL-LHC (III)

ATLAS update for Yellow Report in progress

- Can also target models with pure wino DM.
- Studied using various signatures (monojet, disappearing tracks, photons, VBF…)
- **Monophoton**:



Monophoton



Monophoton: γ radiation not just ISR

ATLAS projections ongoing

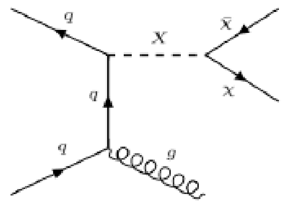
Rescaling Run-II results

Monophoton: ≈ 300 GeV reach if syst small

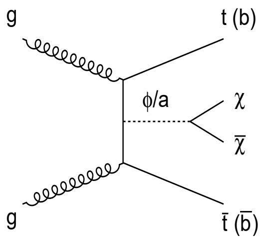
VBF: ≈ 100-150 GeV reach
(for comparison, also under study)

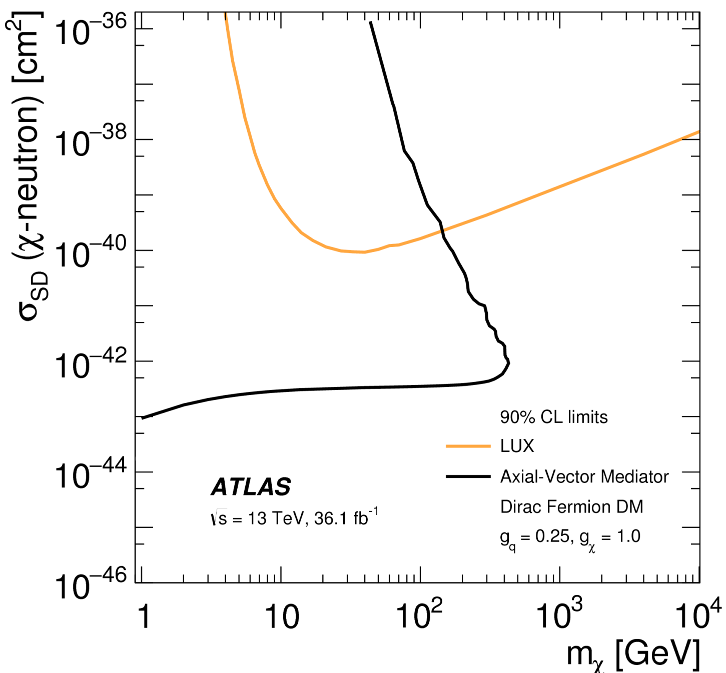
Complementarities

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

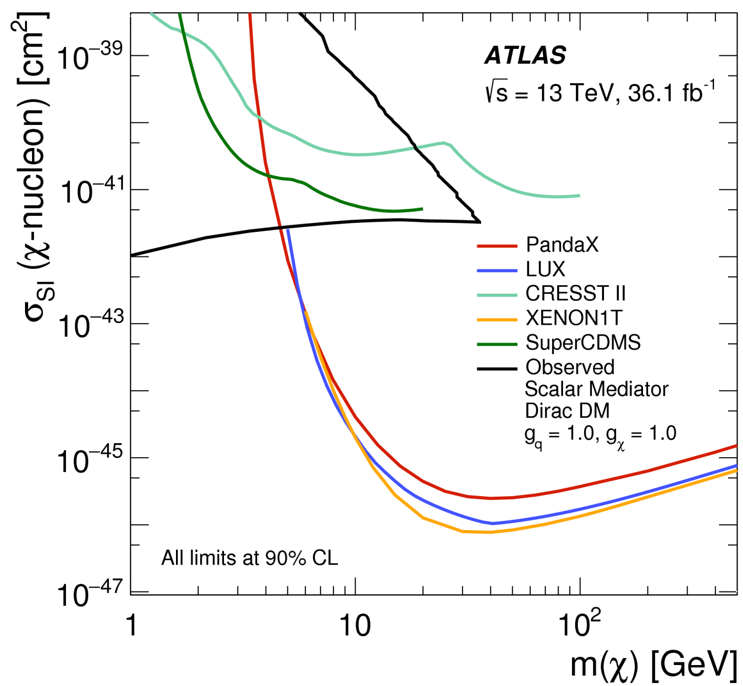


Assumptions needed
But complementarities clear





spin-dependent DM-neutron scattering cross section plane



spin-independent DM–nucleon cross-section

Long-lived particle, dark sectors and sterile neutrinos

LLP → Hot topic of the past 2-3 years

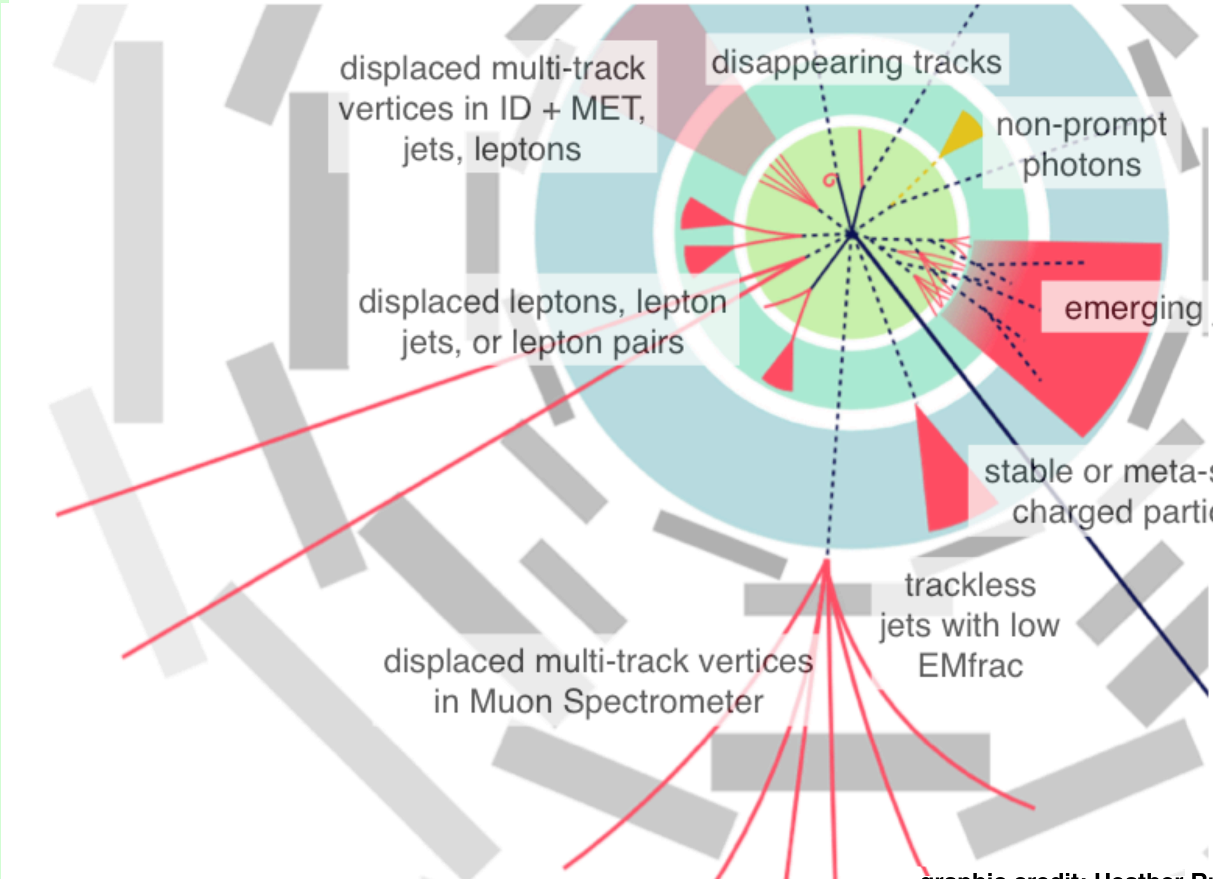
Great discovery potential: many NP models predict LLPs

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

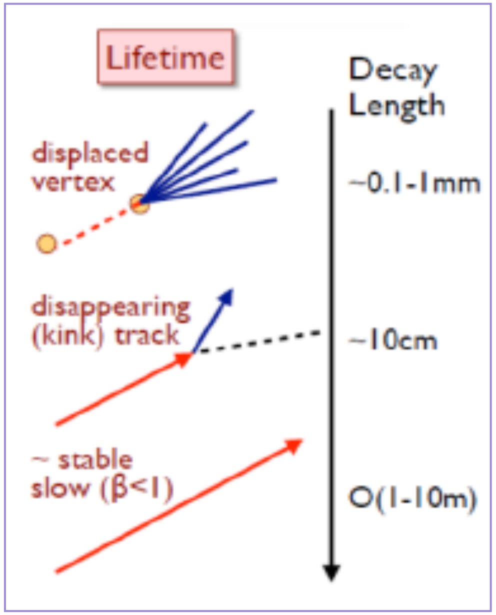
Signature space quite complex → joined exp/theory efforts to review all modes

Long-lived particles

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



graphic credit: Heather Russell



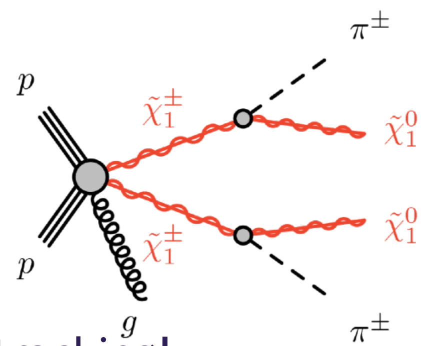
Synergy among ATLAS, CMS and LHCb experiments
- Target complementary lifetimes and mass ranges

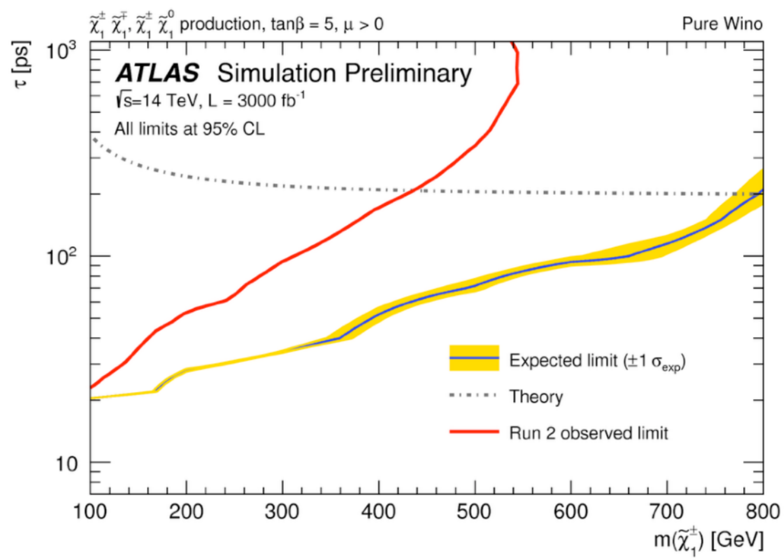
A few examples

Long-lived higgsinos

ATLAS and CMS update for Yellow Report in progress

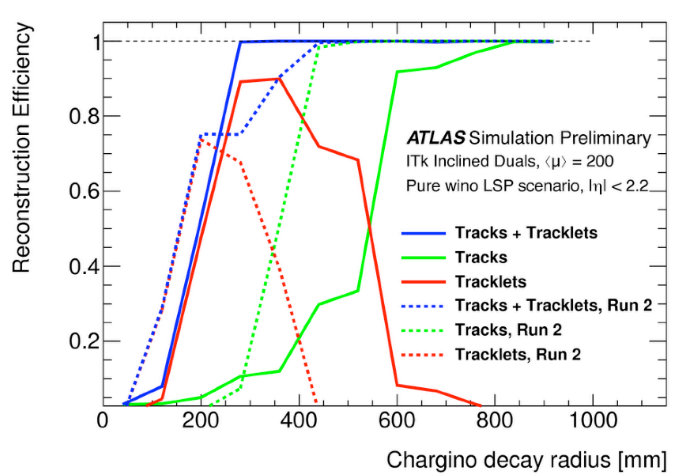
- If DM(charg-neut) ~ 200 MeV, higgsinos might be long-lived
- charged particle with lifetime ~10 ps - 10 ns which decays to "invisible"
  - pure higgsino case: ~0.05 ns (wino: 0.2 ns)
- Studies for HL-LHC are in progress
  - Current results promising, but challenging – need excellent tracking!
  - Results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





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

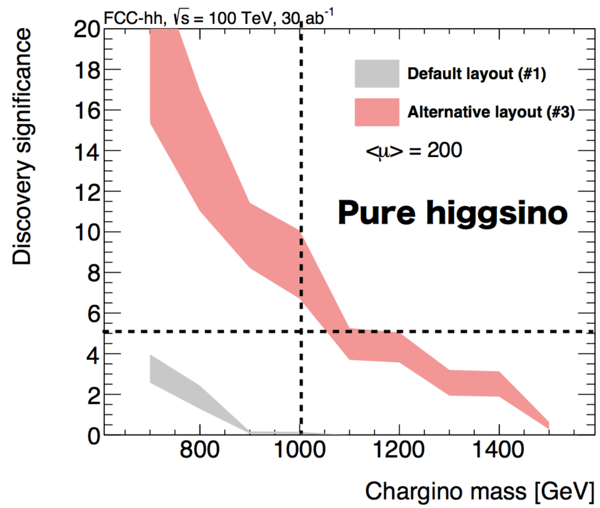
Tracking efficiency versus decay radius



Long-lived higgsinos: long term future?

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

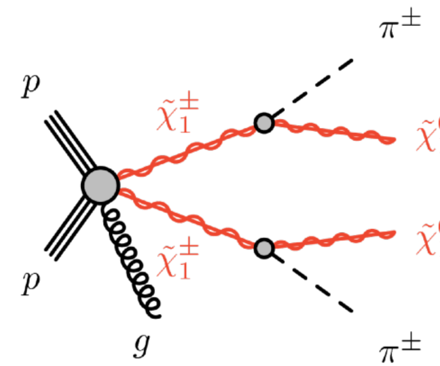
FCC week, Amsterdam 2018



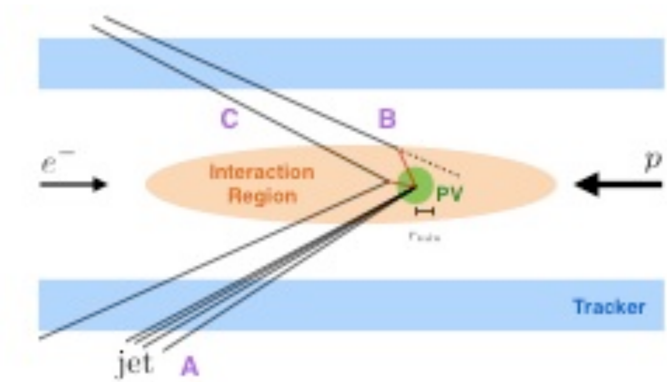
HL-LHC and FCC-hh bound from disappearing track analyses

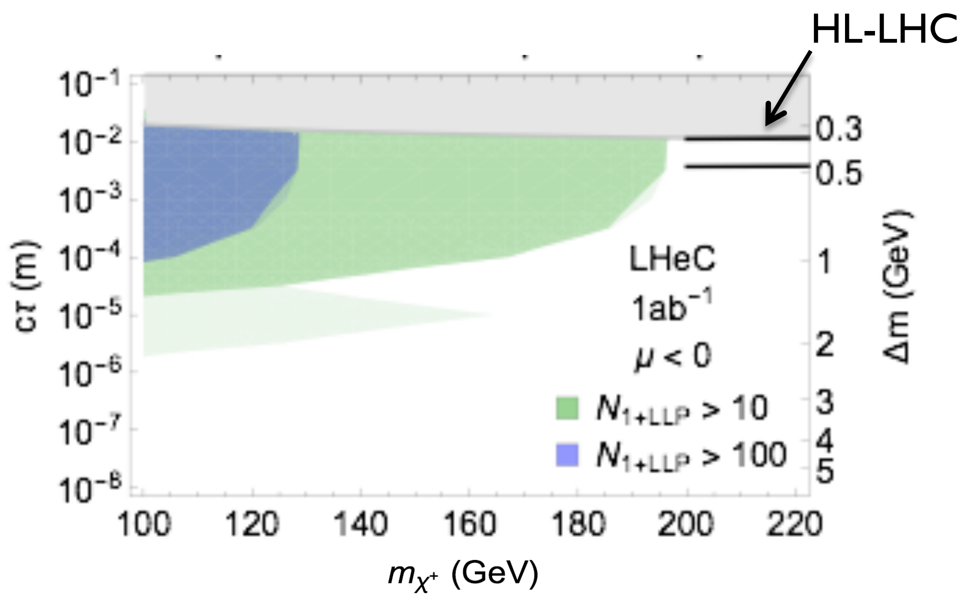
Maybe optimistic on Pile Up

Only sensitive to cτ>10^{-2}



- Also possible at ep-colliders: advantage from low bkg and low PU





Curtin, Deshpande, Fischer, Zurita arXiV: 1712.07135

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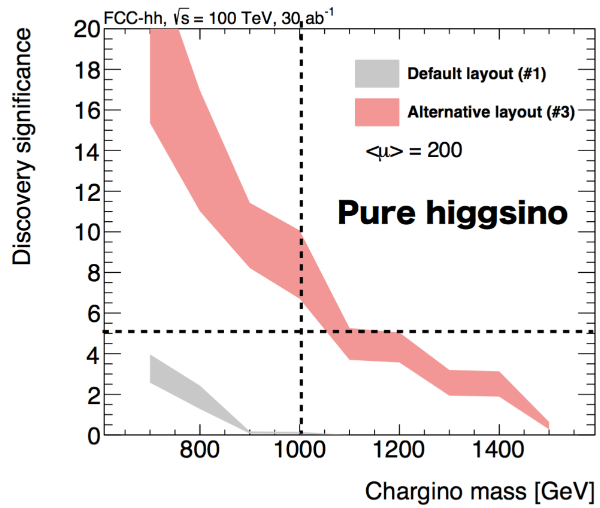
FCC week, Amsterdam 2018



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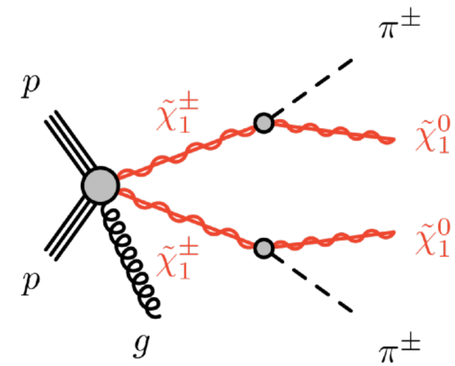

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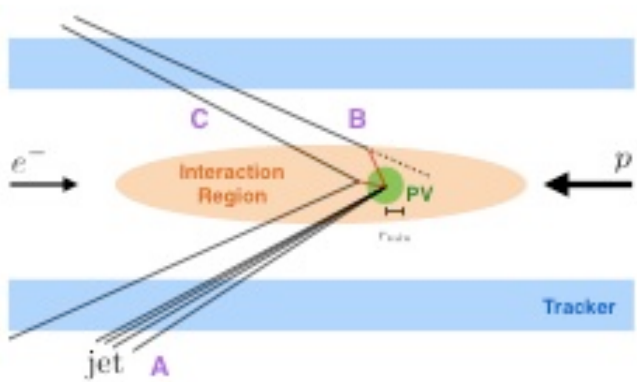
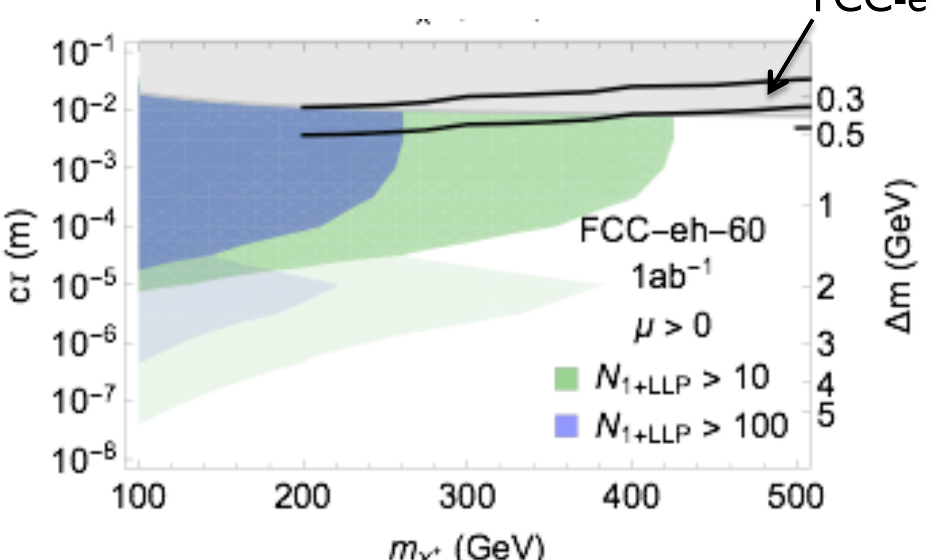
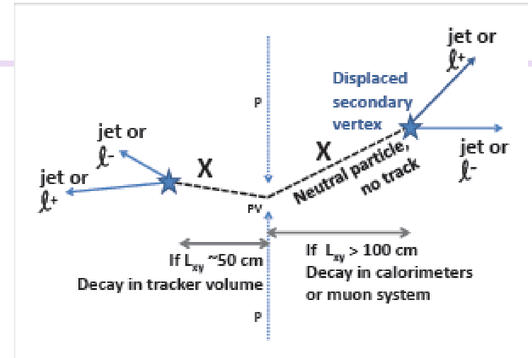




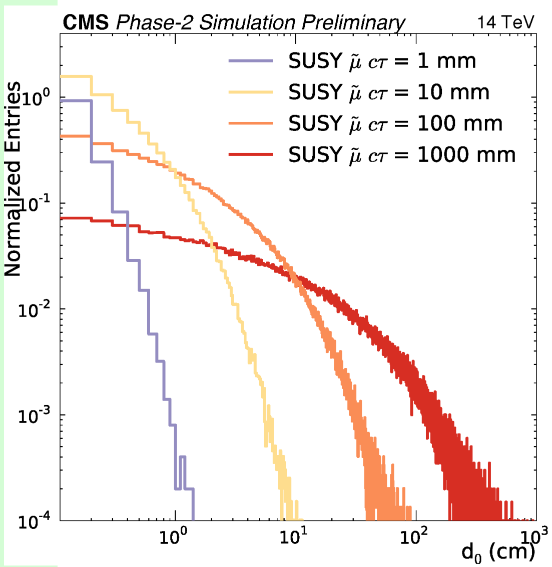
Curtin, Deshpande, Fischer, Zurita arXiV: 1712.07135

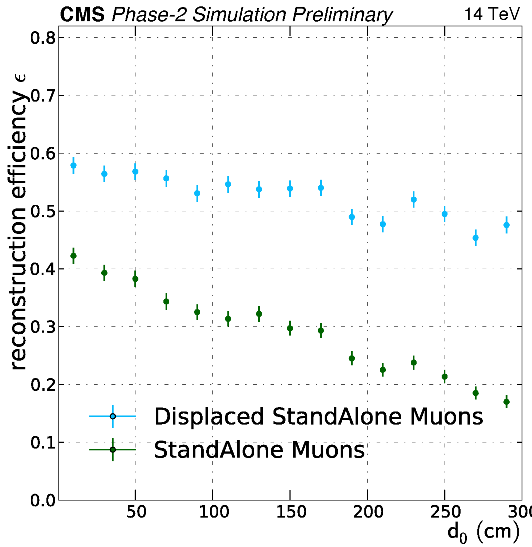
Displaced muons

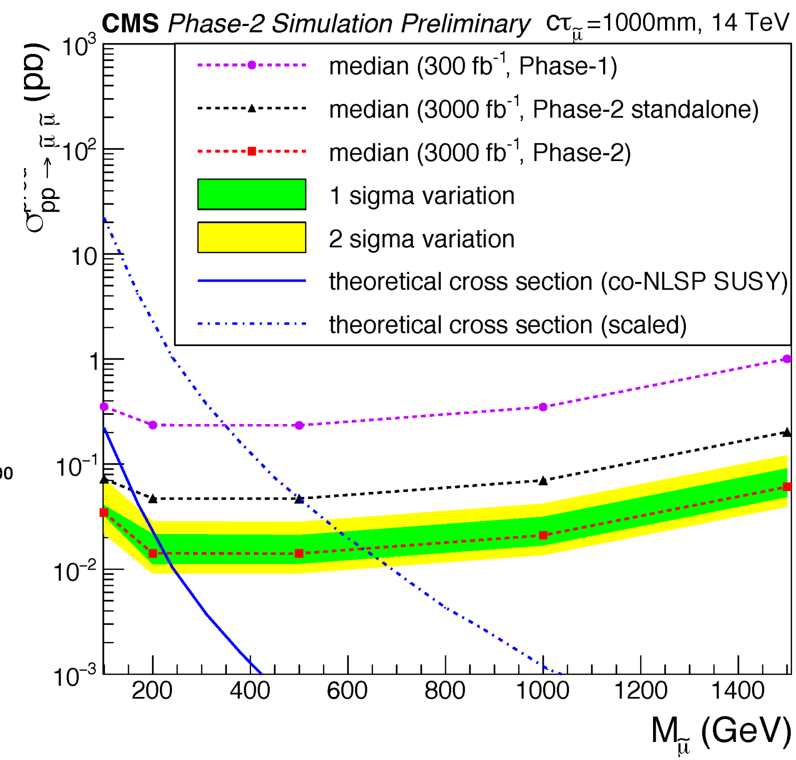
- **New studies from CMS**:
  - Smuons $\tilde{\mu} \to \mu + X$



CMS TDR (NEW)







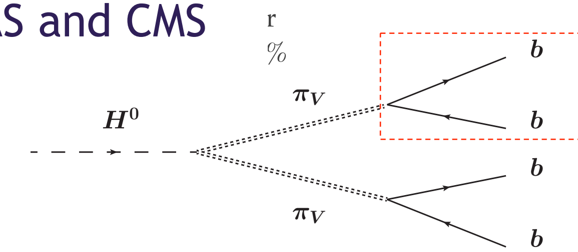
Experimental challenge:

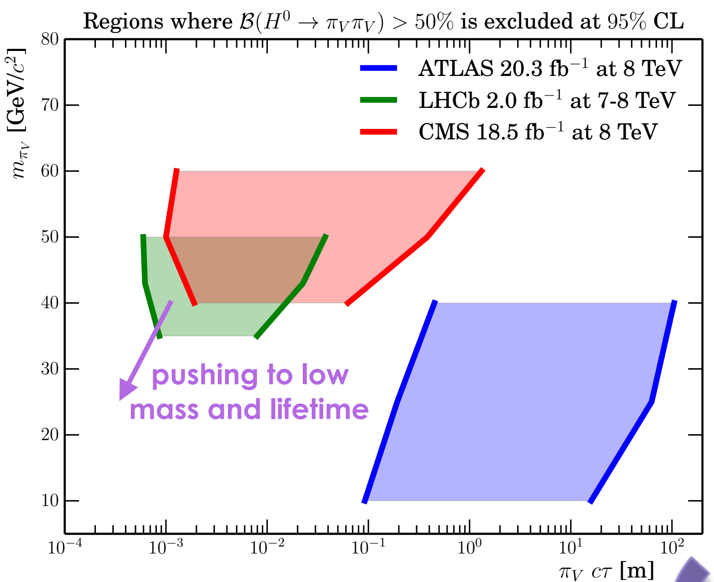
→ trigger displaced signatures
→ Vertex constrains reduce efficiency
→ Dedicated algorithms needed for displaced muons to recover efficiency

Quite an improvement in sensitivity!

Displaced jets

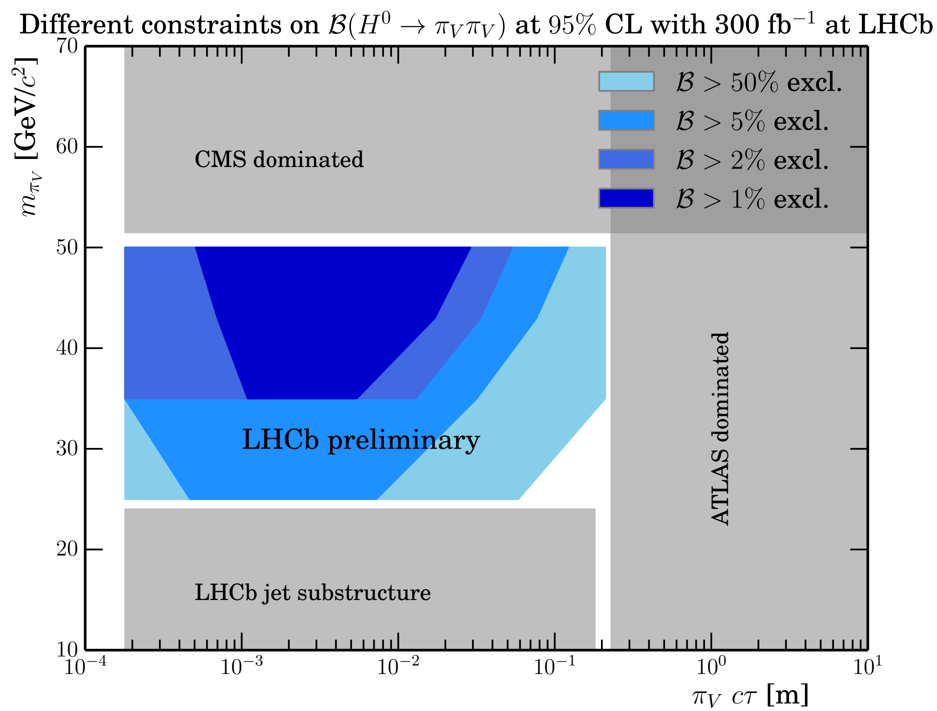
- Aim to exploit at best the complementarities among detectors
  - LHCb sensitive to lighter mass and low τ wrt ATLAS and CMS
- E.g. hidden valley dark pions from Higgs





extrapolation to 300 fb^{-1}

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



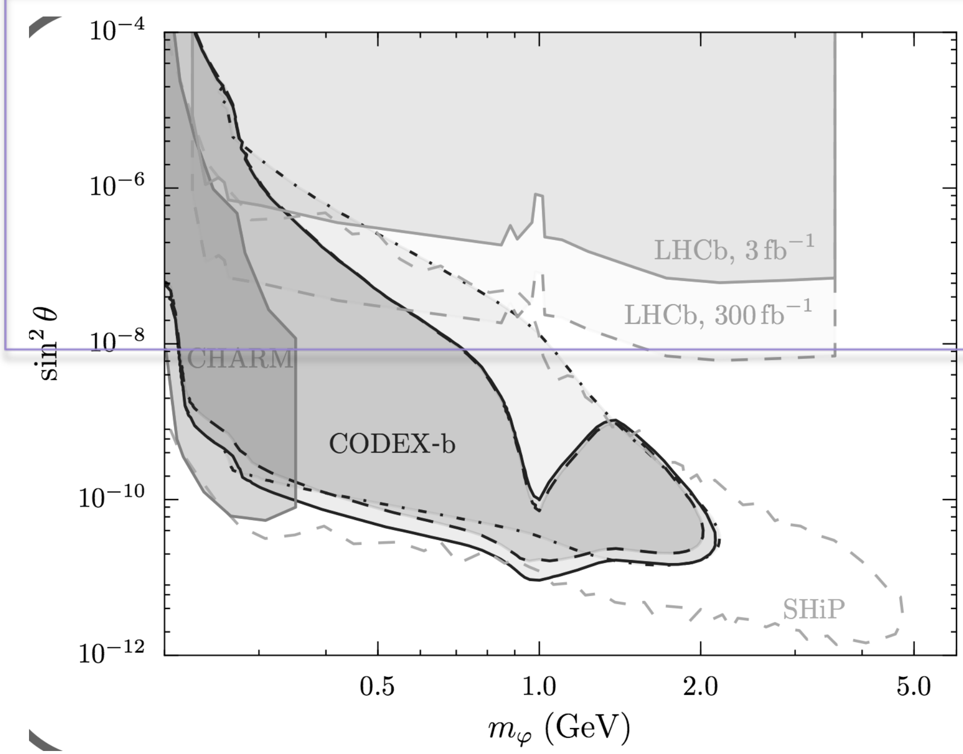
For short-lifetimes, this could be complemented by CepC !

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

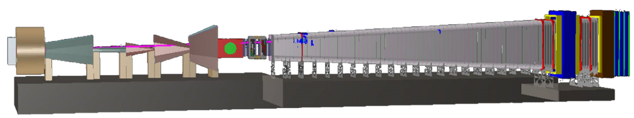
arXiv:1708.09395



Relation between Dark sector and Long-lived particle have led to many new ideas for new detectors and experiments
→ big interplay with Physics Beyond collider experiments

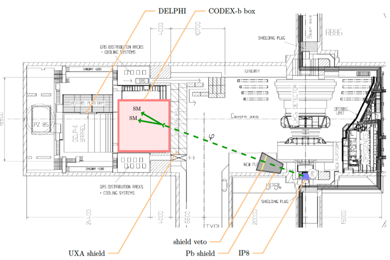
LLP and Dark sectors: PBC proposals

SHIP



Alekhin et al. (2015)

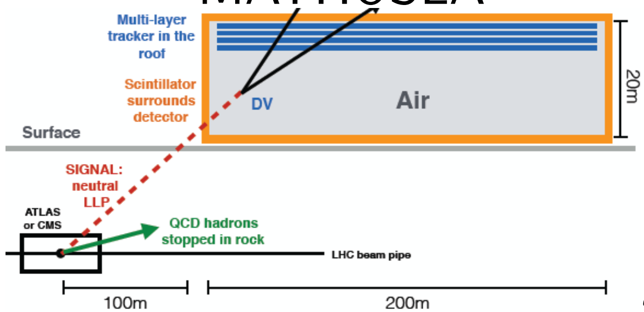
CODEX-b



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

Gligorov, Knapen, Papucci, Robinson (2016)

MATHUSLA



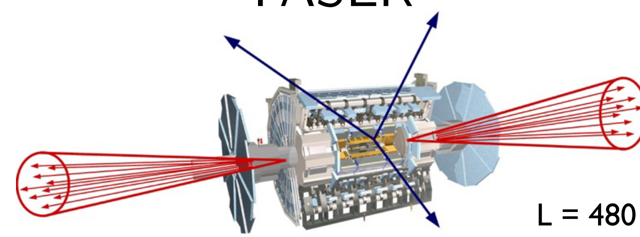
$\sim$

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

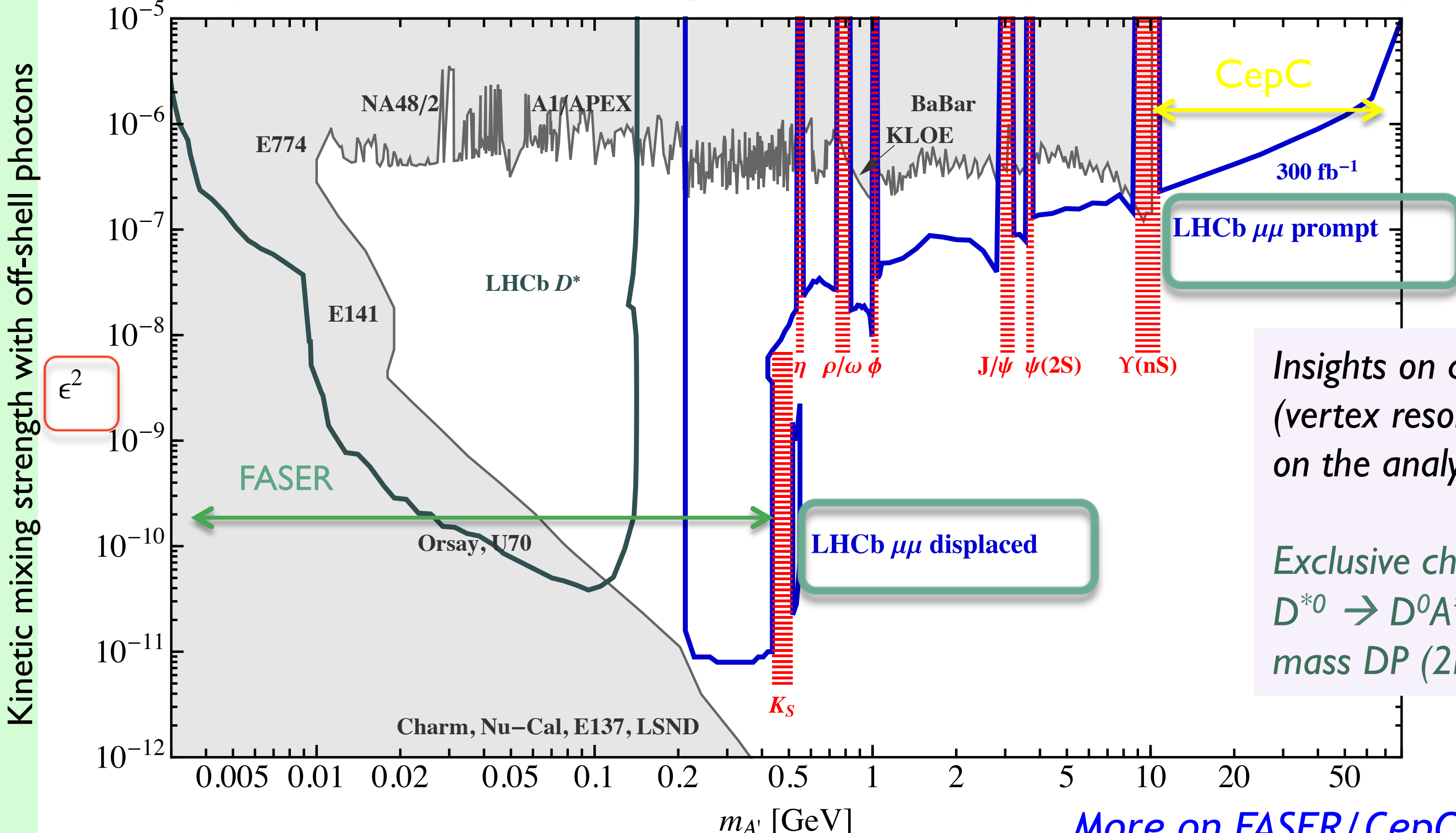
Credits: I. Galon at FNAL workshop on HL/HE-LHC (4-6 April 2018)

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

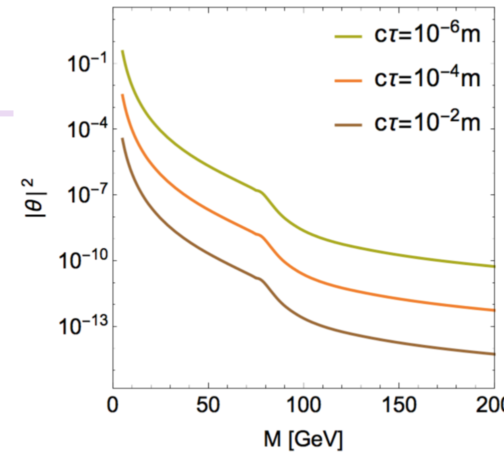
Insights on detector implications (vertex resolution, VELO size) and on the analysis in dedicated talk

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

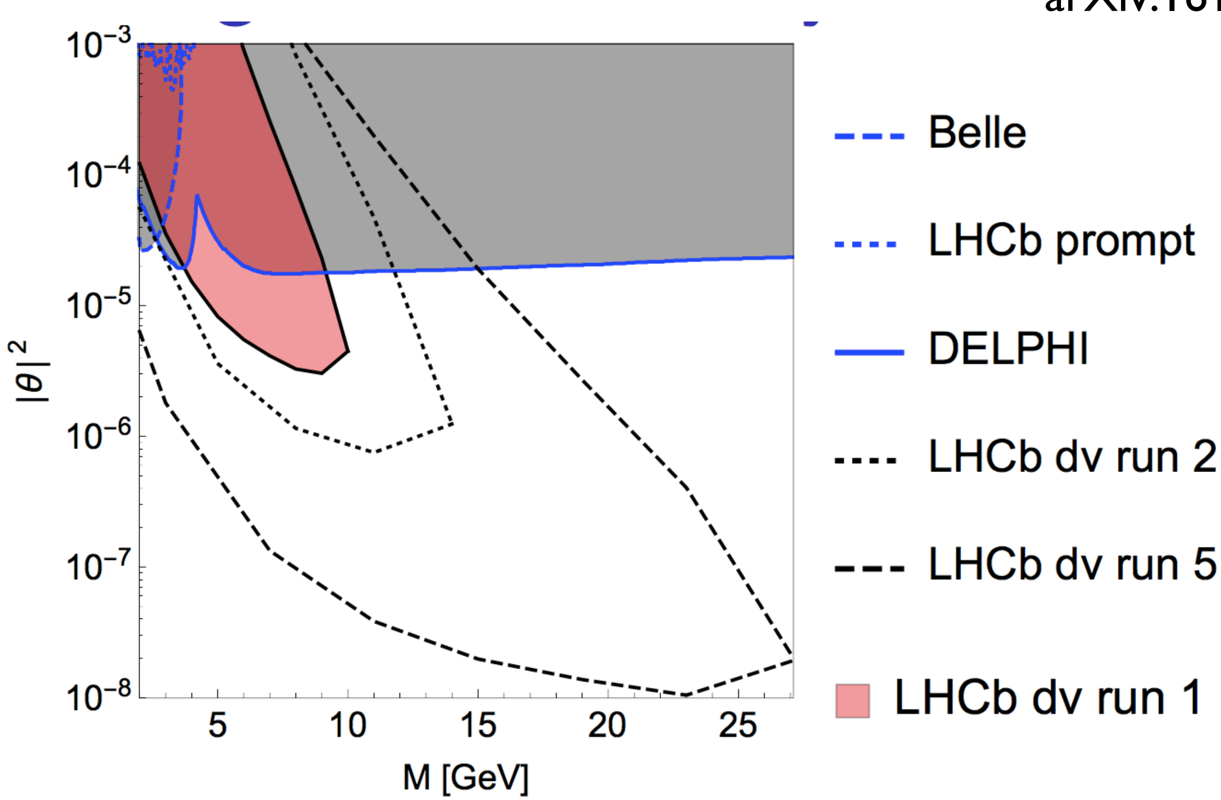
LLP and heavy sterile neutrinos

- 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

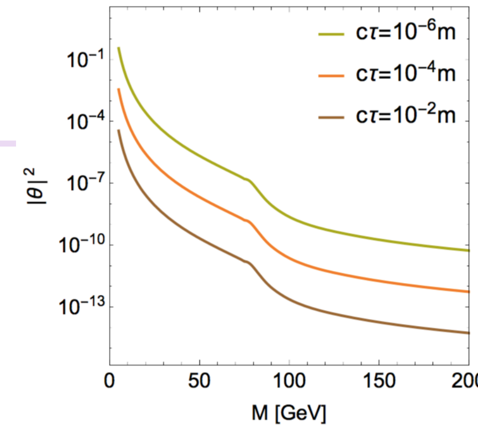


arXiv:1612.00945

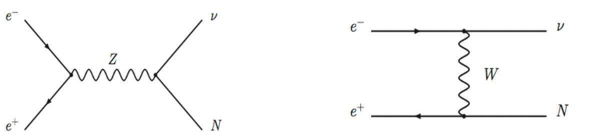
- Projections (LHCb)

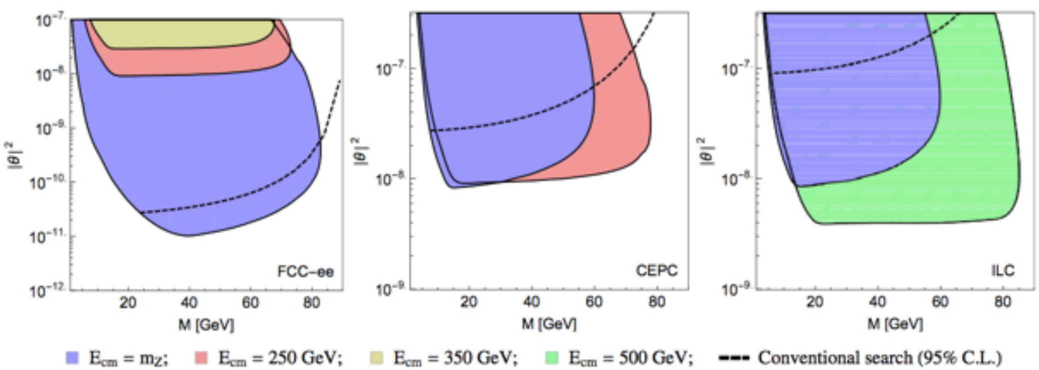


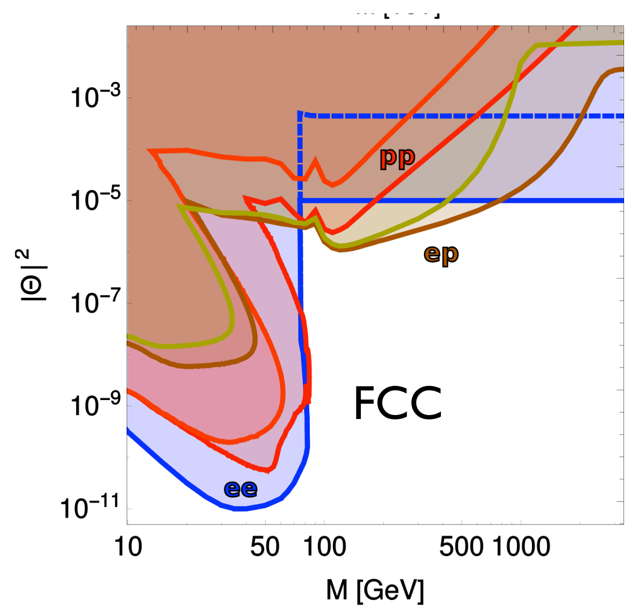
LLP and heavy sterile neutrinos



- Low-scale type I seesaw with sterile neutrinos
  - heavy neutrino mass eigenstates with M ~ vEW
  - Neutrino mixing $|\theta_\alpha|$,α=e,μ,τ ⇒ 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)
    - In YR WG3, more than 80 contributions being finalized

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

Outlook

- 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
- **Is that enough ?**

PAST

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

(fermiscale) (Terascale) (multi-Terascale)

PRESENT

FUTURE ?

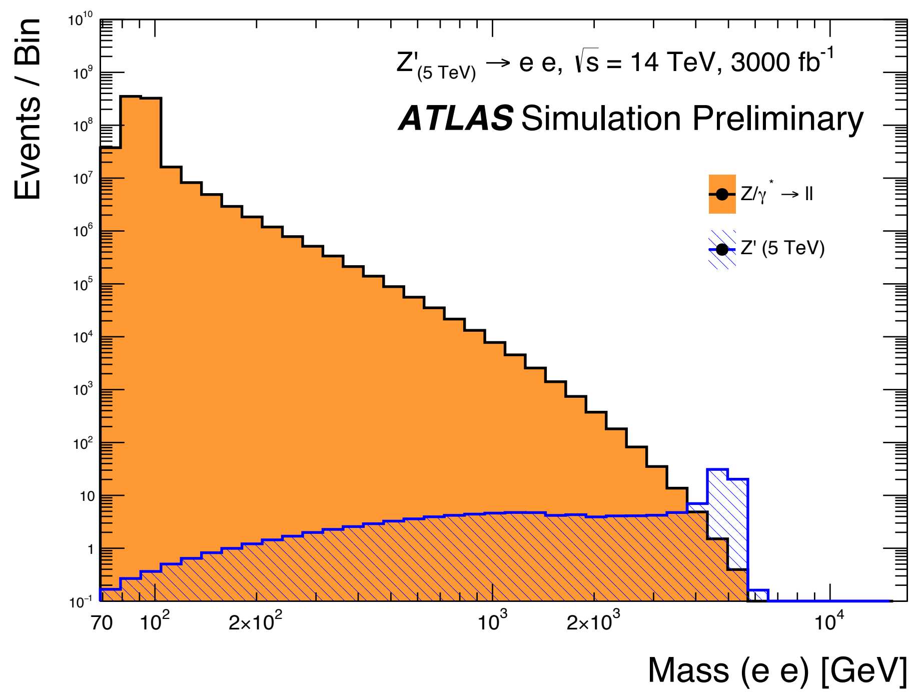
"there is no experiment nor facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can ***guarantee discoveries*** beyond the SM, and ***answers*** to the big questions of the field" (98th ECFA, November 2015)

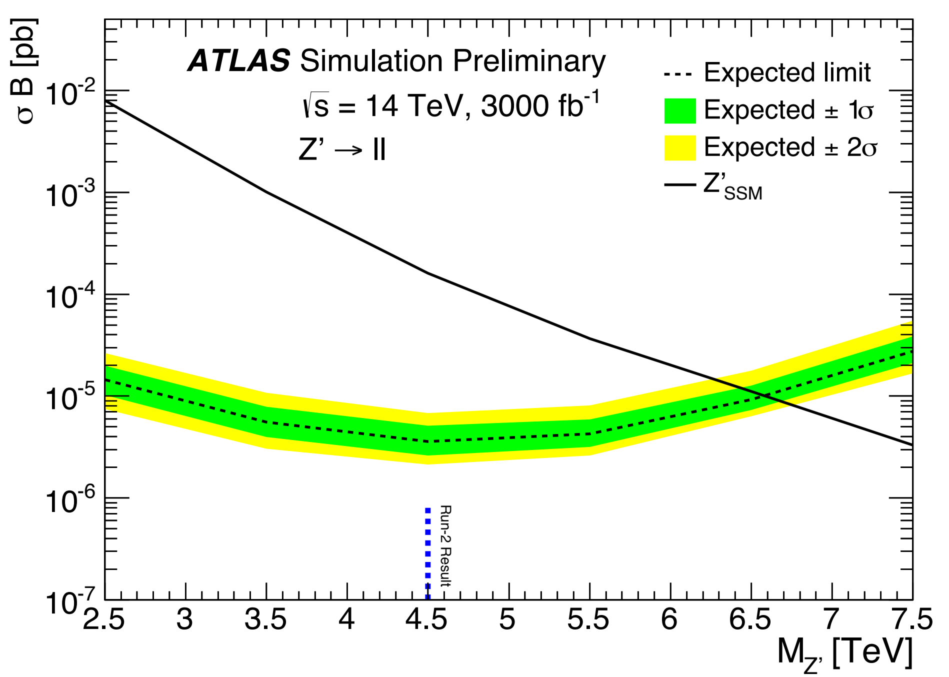
Back up

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

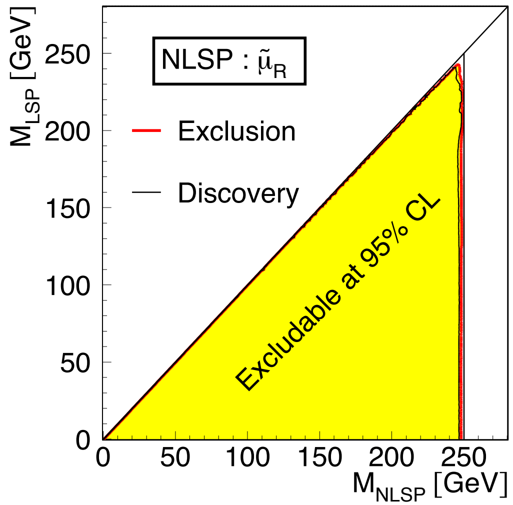


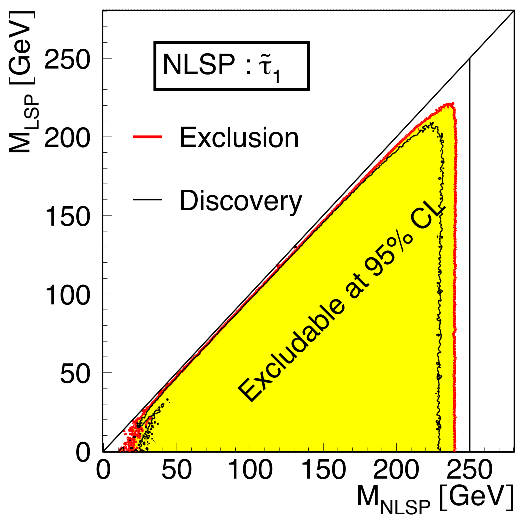


- Constraints are about 200 GeV more stringent than for muons, thanks to the resolution for high p_T electron

SUSY @ electron-positron machines (II)

Sleptons @ ILC (500 GeV)

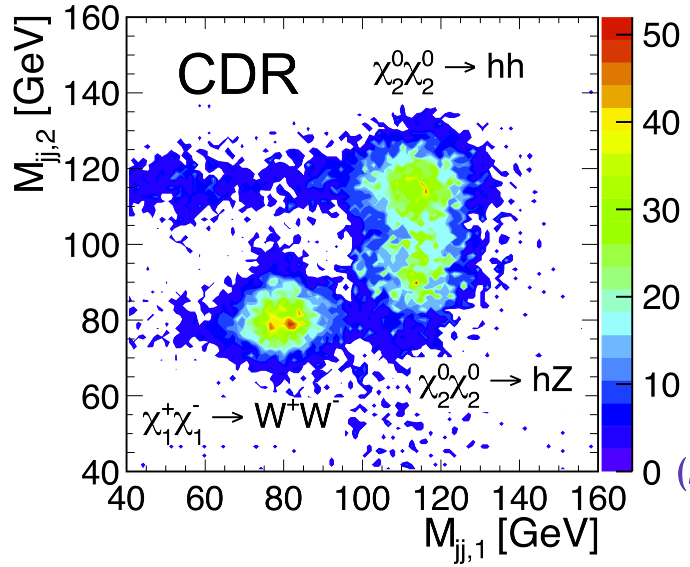




arXiV:1307.5248

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

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



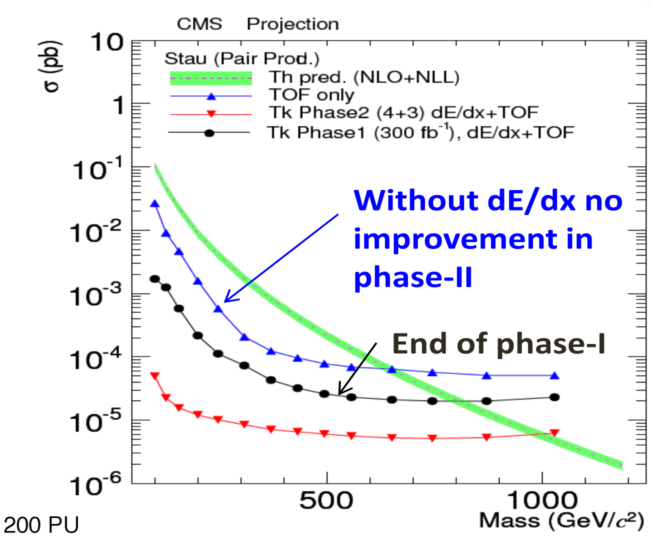
Precision on the measured chargino/neutralino masses (few hundred GeV): 1 - 1.5%

(M(charg/neut2)=487 GeV)

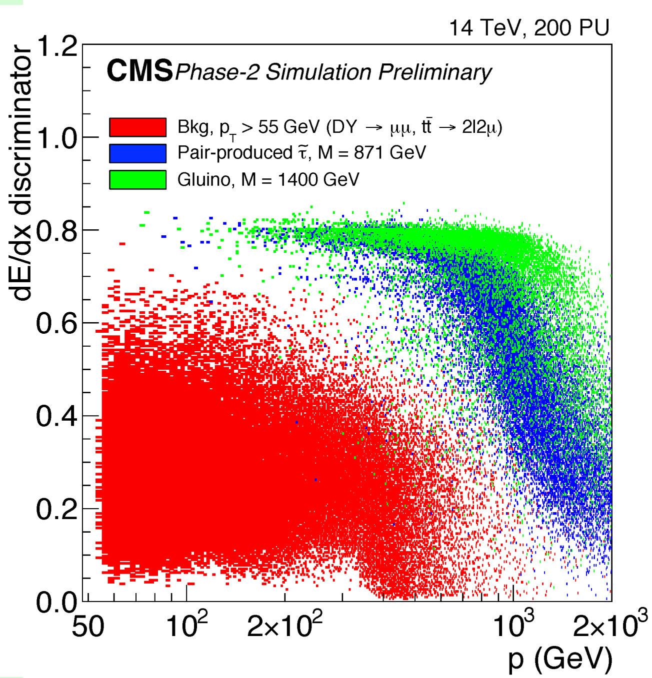
Similar studies in progress for circular colliders

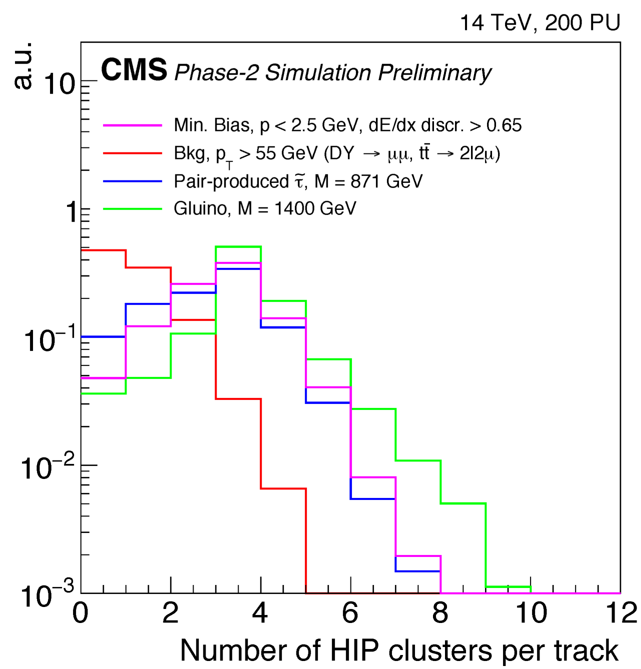
Heavy Stable charged particles

- 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





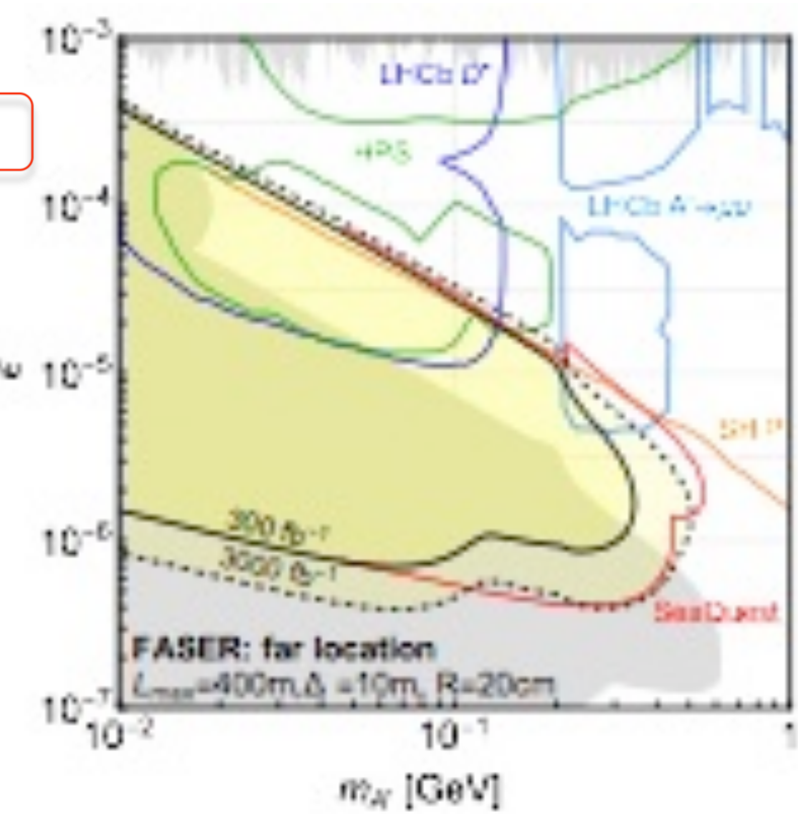
Additional CMS studies on performance for Heavy stable charged particle via muon system also available *(more in dedicated talk)*

CMS TDR (NEW)

Dark photons: future potential

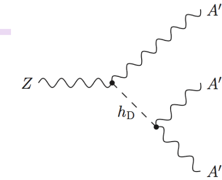
- FASER predictions

ε



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

- CepC potential



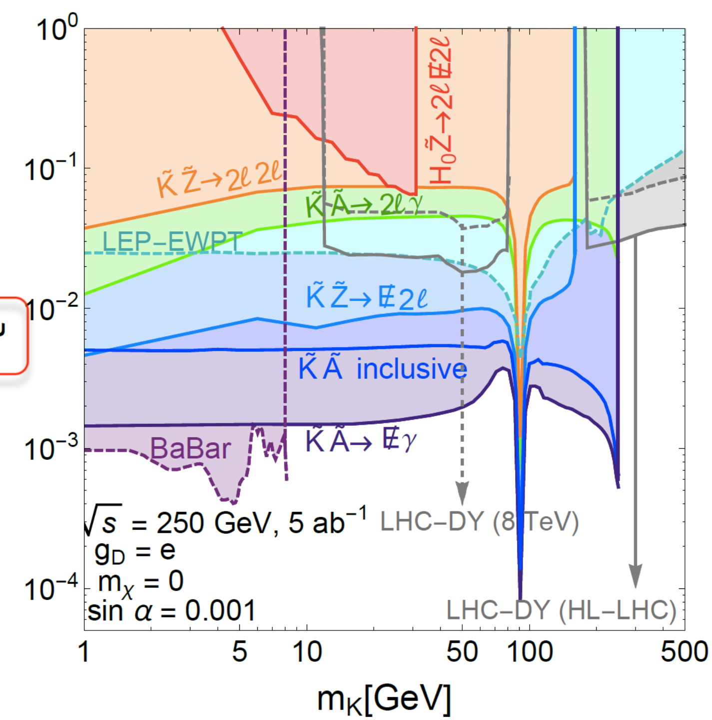
$e^+e^- \to \tilde{Z}H_0$ Study $\tilde{Z} \to \ell\ell$ and semi-visible $H_0 \to (\ell\ell)_Z\chi\chi$

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

ε

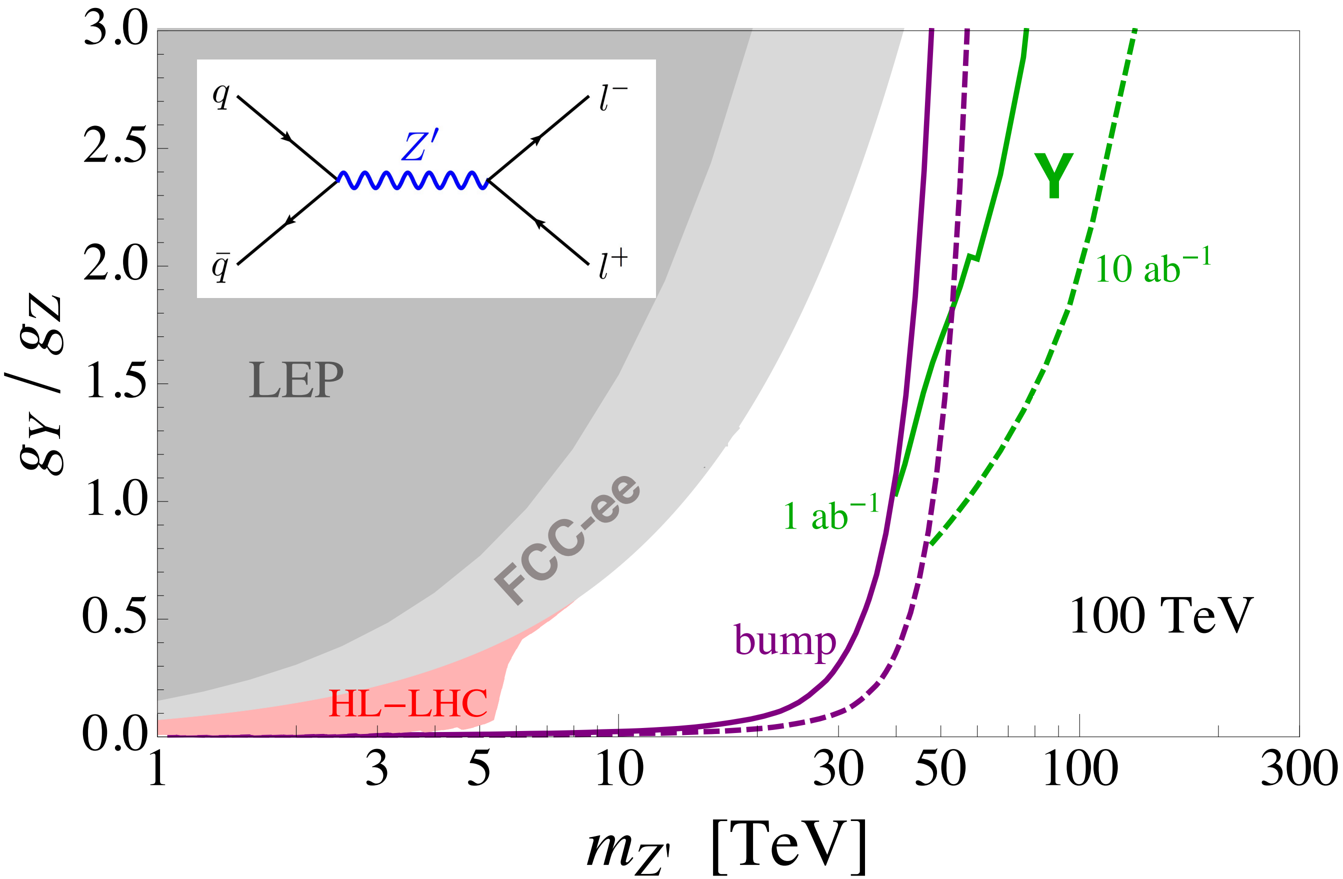


Felix Yu – Dark Sectors at CEPC

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

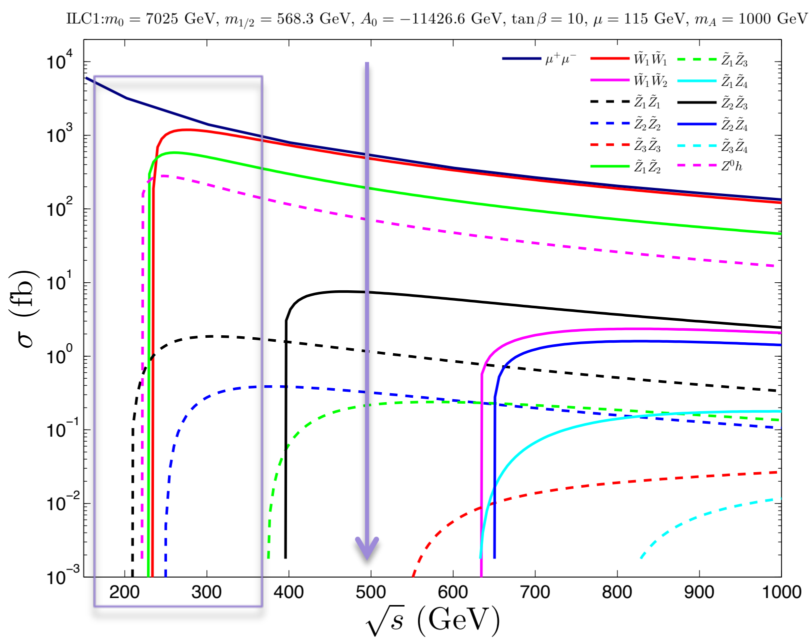
Alioli, Farina, Pappadopulo, JTR, Phys. Rev. Lett. **120**, no. 10, 101801 (2018)



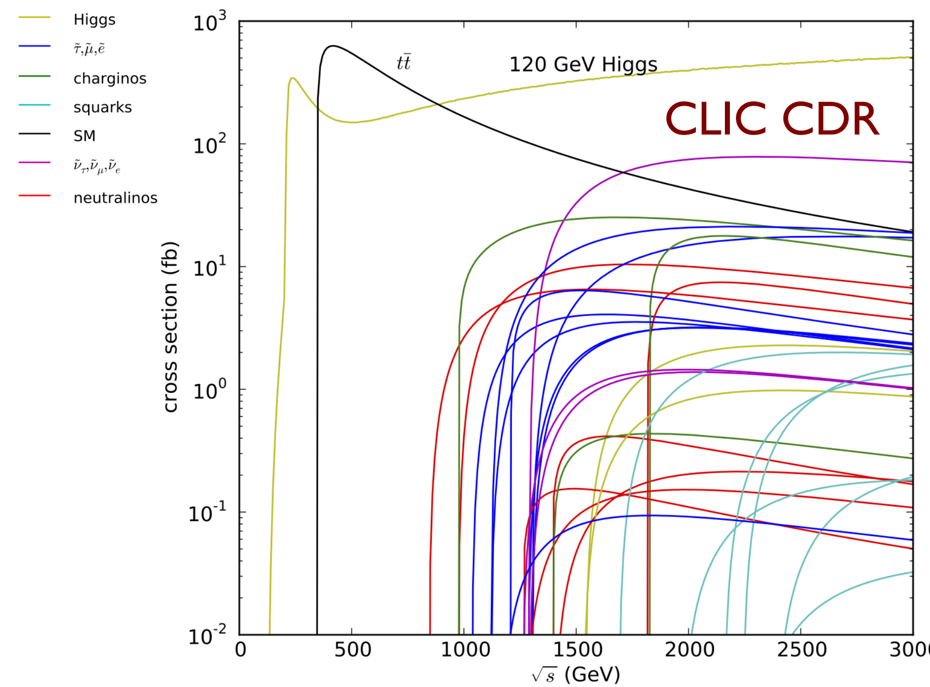
potential @ electron-positron machines

- 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



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



arXiV:1404.7510

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

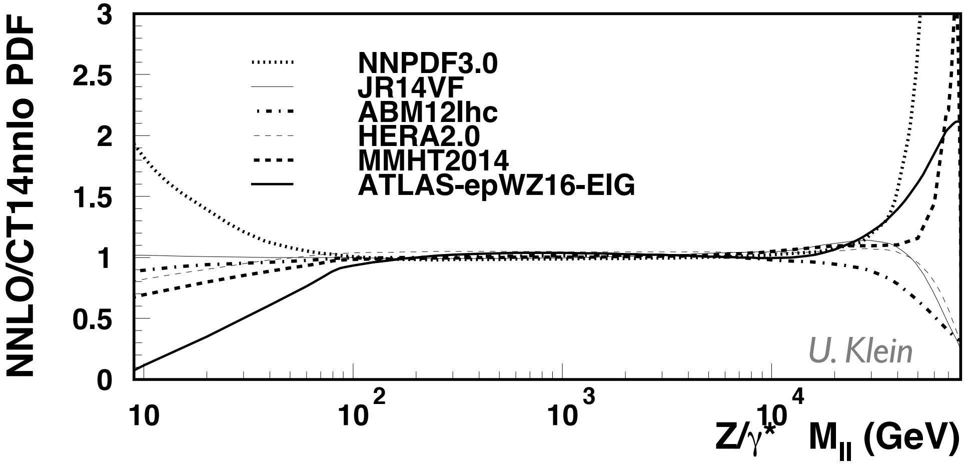
Cross-section for higgsinos too low also for CLIC?

arXiV:1801.05192

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

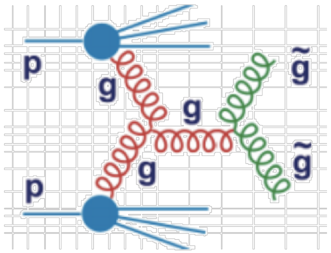
A comment on high p_T / mass searches

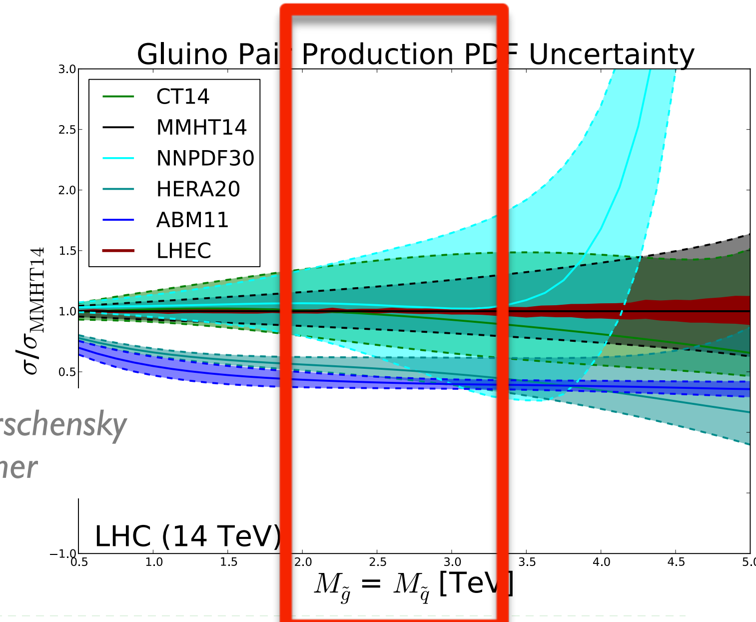
- Already at HL-LHC, limitations arise from difficulties to identify high p_T / boosted objects, but also from modeling of SM processes



"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



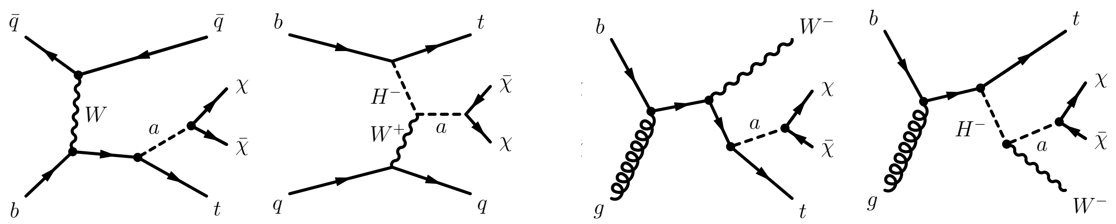


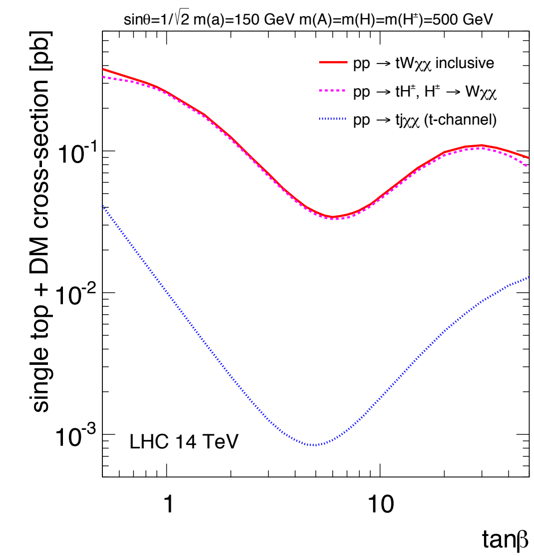
Impact on PDF unc for any gluon-gluon production at relative high x

Christoph Borschensky
Michael Kramer

more for DM in Wt+MET final states

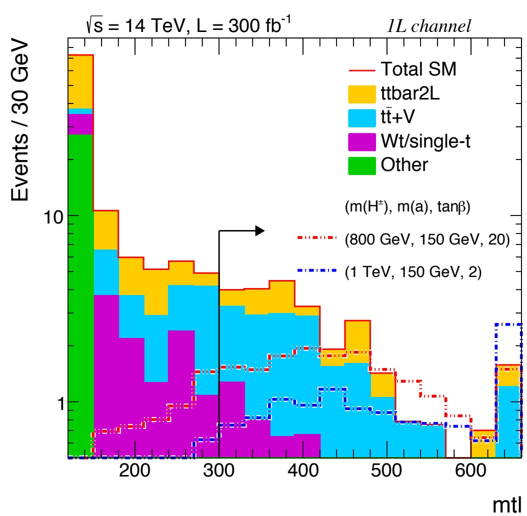
- Modified 2HDMa models lead to Wt+MET signatures

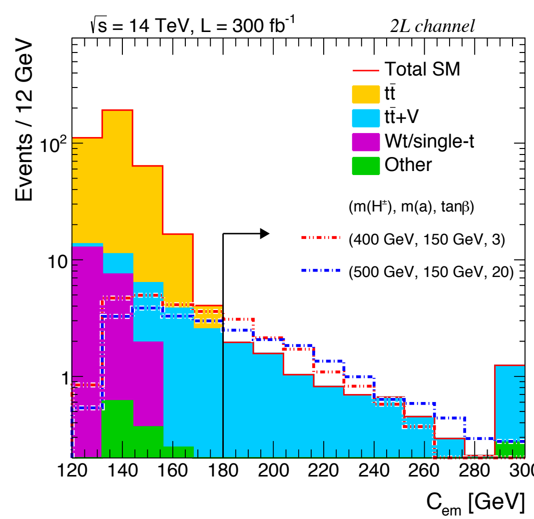


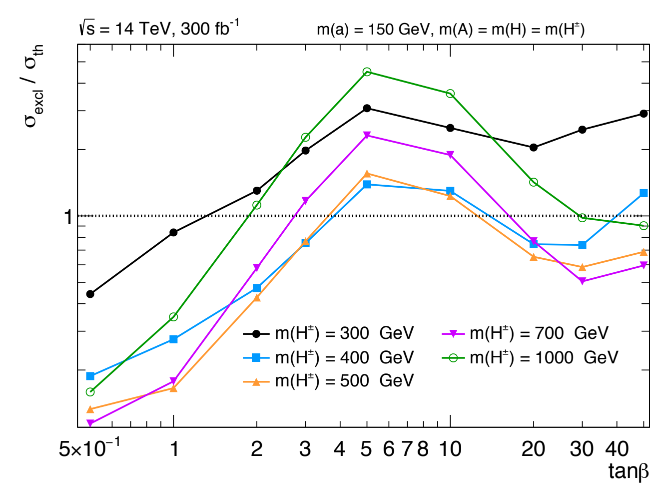


Studies in **1712.03874** performed using 1L and 2L channels

$$C_{\rm em} \equiv m_{\rm T2} + 0.2 \cdot E_{\rm T}^{\rm miss}$$

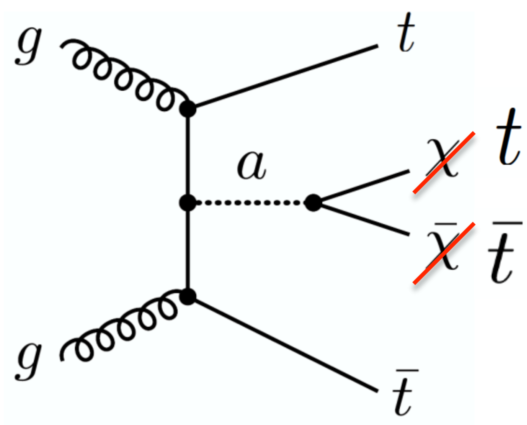




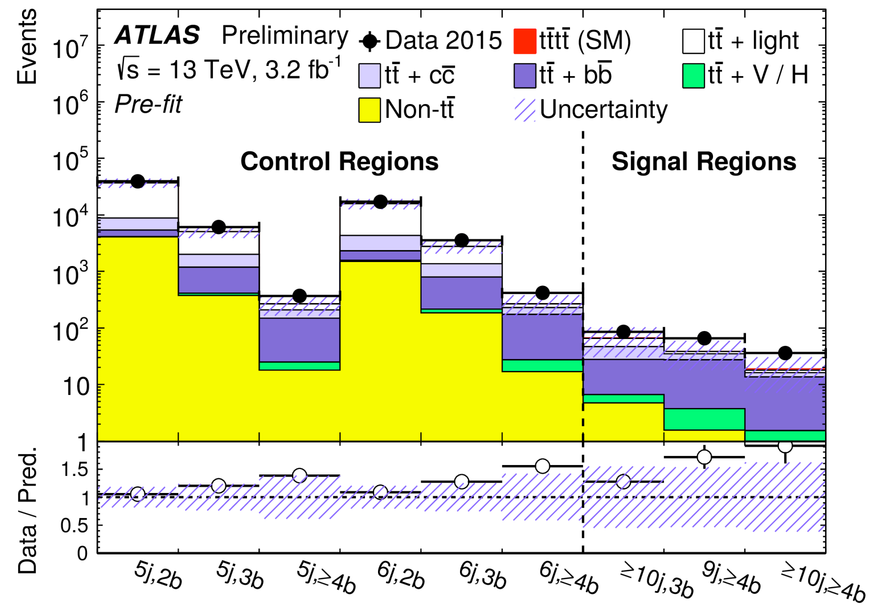


DM with 2HDM+a models

- One more final states being considered: 4-top



Analysis for Run 2 released with 3.2/fb



Look for final state with at least one lepton, multi-bjets and MET

Scan various sets of parameters:
- e.g. scan in m(a) for benchmark values of m_H

ttbar+bb main background
Difficult to model with MC but we can assume a better understanding of this process at HL-LHC!