Direct searches for new physics
status and prospects on the experimental side

Monica D'Onofrio (University of Liverpool)

[WG3, with Keith Ulmer, Xabier Cid, Riccardo Torre, Patrick Fox]

On behalf of the LHCb, ATLAS and CMS collaborations

Workshop on the physics of the HL-LHC and prospects on HE-LHC – Geneva

October 30th 2017

Searches for new physics at (HL-)LHC

- 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
- In this talk, a number of HL-LHC studies from ATLAS, CMS and LHCb are reported as well as prospects for new searches which benefit of the larger 14 TeV dataset and of the new detectors
  - **Supersymmetry**
  - **Dark Matter and its nature**
  - **Long-lived particles and hidden/dark sectors**
  - **New heavy resonances**

Continuing benchmark analyses and developing new strategies: *A lot on-going but also a lot to be done! We expect to* ***consolidate*** *and* ***widen*** *the HL-LHC studies at this workshop with new ideas, exploitation of synergy among WGs and experiments*

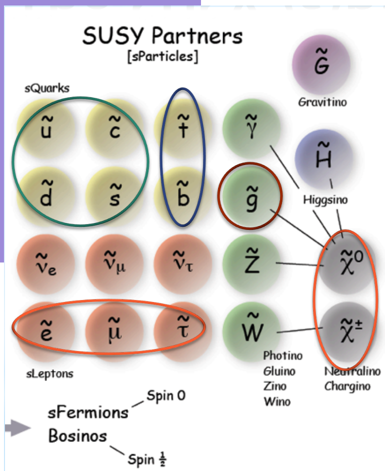
more on prospects for HE-LHC in WG3 intro later (R. Torre et al.)

Foreword: methodologies

- Experiments use different approaches to perform analyses:
  - **Method 1 - truth + smearing (ATLAS):** truth-level events overlaid with jets (full sim) from pileup library, reconstruct particles (electrons, muons, jets, MET) from truth +overlay and smear their energy and pT using appropriate smearing functions
    - Cross checked with some of the 'real' data analyses
  - **Method 2 - Full analysis with parameterized detector performance (CMS):** use DELPHES with up-to-date phase-2 detector performance (tracking, vertexing, timing, dedicated PUPPI jet algorithms, increased acceptance, performance of new detectors)
    - Analysis steps (cuts) guided by present analysis. Limited optimization for HL-LHC conditions. Cross checks with present analysis.
  - **Method 3: projections (mostly CMS and LHCb)**
    - Existing signal and background samples (simulated at 13 TeV) scaled to higher luminosity and sqrt(s)=14 TeV. Analysis steps (cuts) from present analyses.
    - Three scenarios for systematics: (1) keep present systematics (2) Improved by a fixed factor (3) no systematics, only statistics
- Each approach has pros and cons and results might be very different depending on the assumptions (e.g. on systematic uncertainties, detector performances, contributions from rare background)

This and more in dedicated talk (K. Ulmer et al. tomorrow)

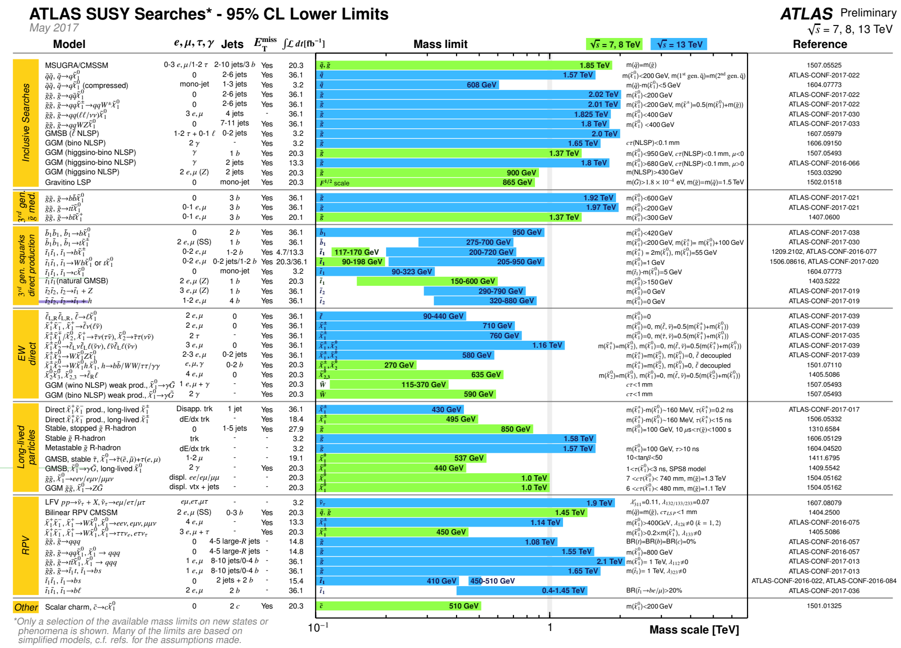
Supersymmetry

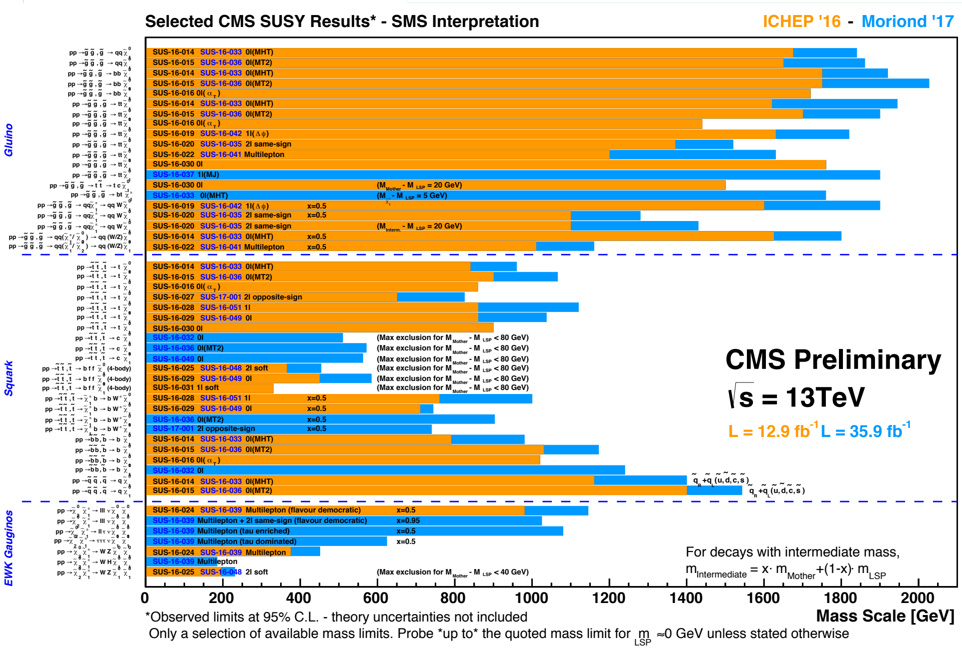


Strong production
(gluinos, squarks)

EWK production
(charginos, neutralinos, sleptons)

Role of R-parity: impact on expected phenomenology





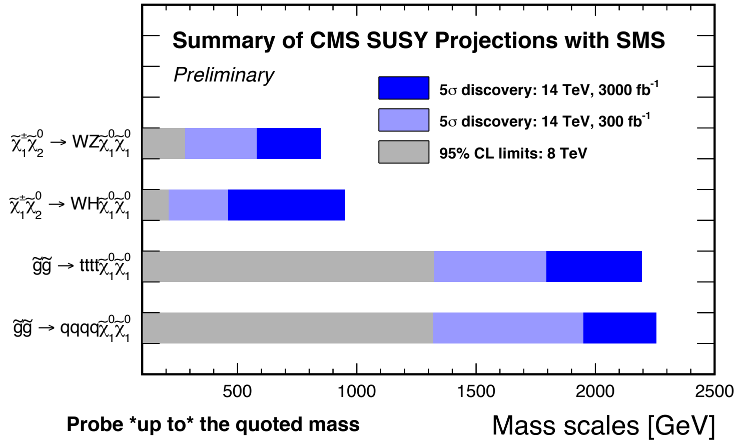
A VERY wide range of processes investigated at the LHC now

@HL-LHC: target high masses but also challenging scenarios/processes

A few examples – details and more in dedicated talks in parallel sessions

SUSY@ HL-LHC

- Can push the reach to much higher masses

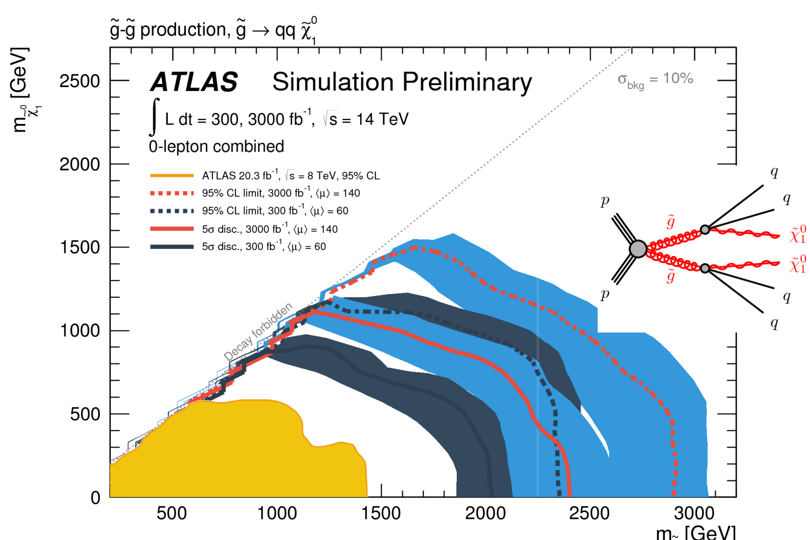


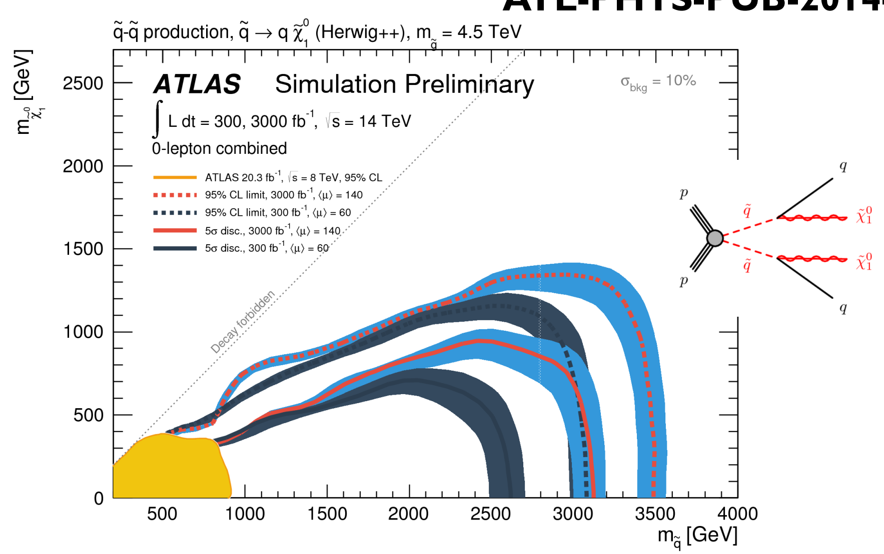
CMS PAS SUS-14-012

Gain several hundred GeV in discovery potential for pair-produced gluinos or squarks.
Even more for chargino and neutralinos

Comprehensive studies carried out since 2012 by ATLAS (truth-smearing analyses) and CMS (projections)

ATL-PHYS-PUB-2014-010

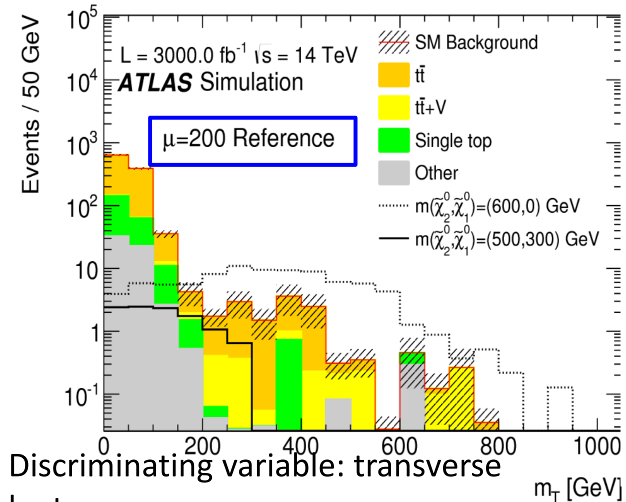




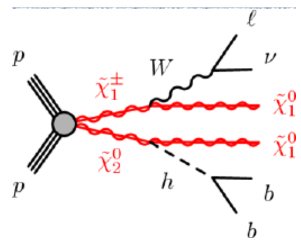
Large uncertainties from PDF → improvements expected with LHC data and, possibly, new facilities (LHeC)

SUSY@ HL-LHC: challenging scenarios (I)

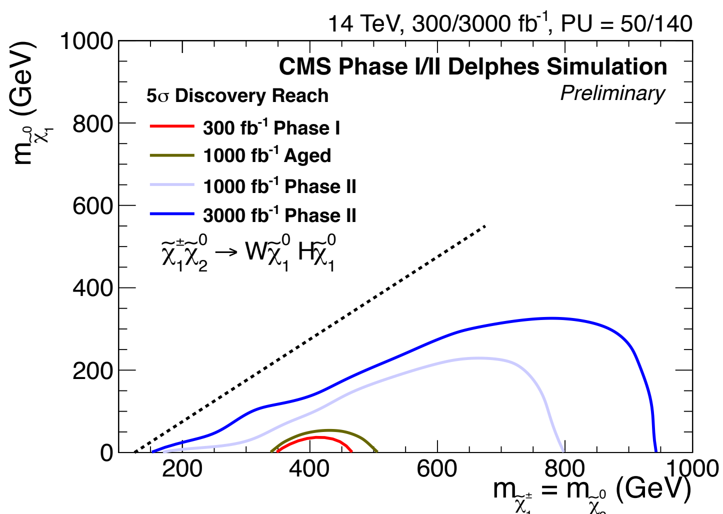
- **Electroweak SUSY: chargino-neutralino**
  - Most challenging: neutralino2 in higgs + LSP
  - New detectors will improve performances a lot
  - Results depend on the PU conditions as well as on the approach (projections vs analyses vs optimal/conservative conditions)



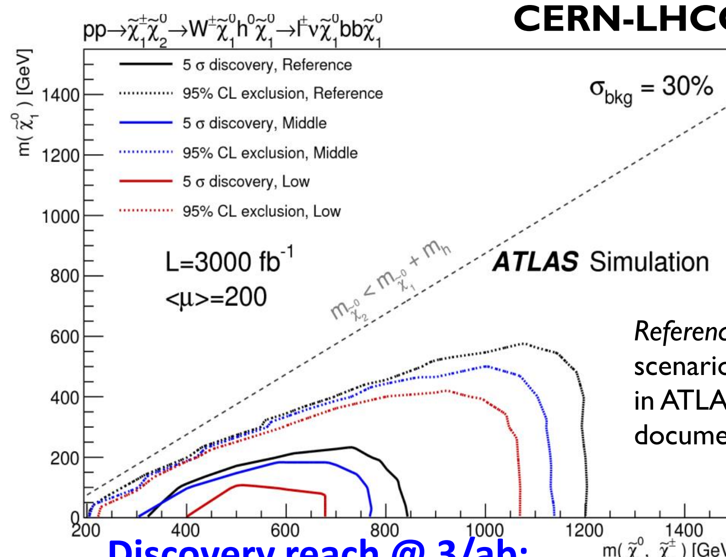
Discriminating variable: transverse lepton mass m_T



CERN-LHCC-2015-020



CMS Technical Proposal



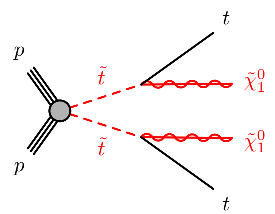
Reference, middle, low – scenarios considered in ATLAS scoping document

Discovery reach @ 3/ab: 850 GeV reference detector

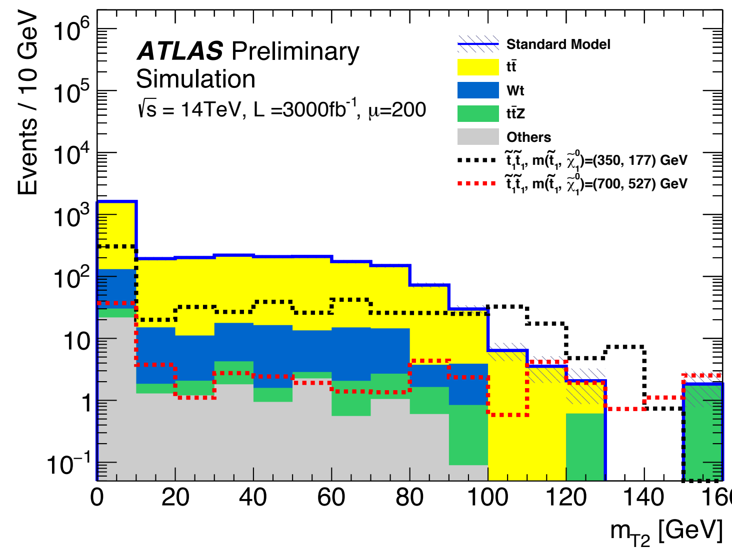
SUSY @ HL-LHC: challenging scenarios (II)

- **Third generation squarks** — **ATL-PHYS-PUB-2016-022**
  - Target compressed scenarios and use ISR jets
  - m_{T2} as discriminating quantity, 2l + 2b + MET

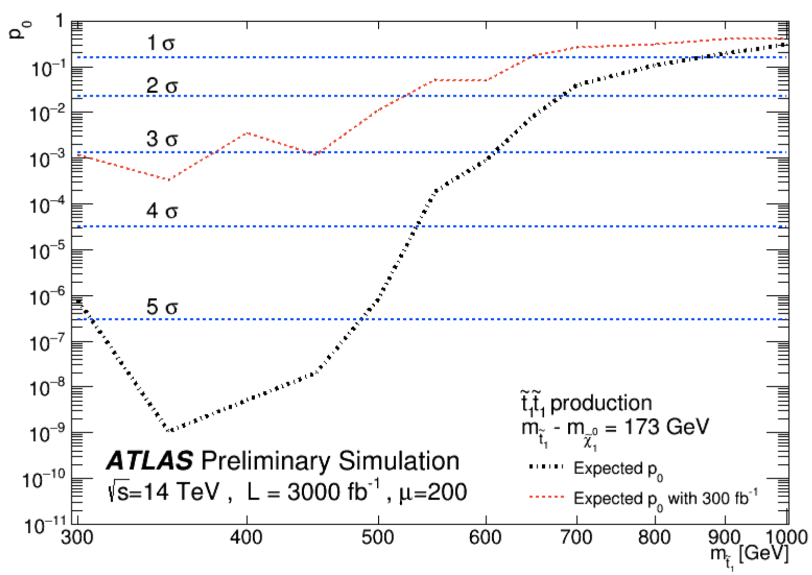
$$(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}) \cong m_t$$

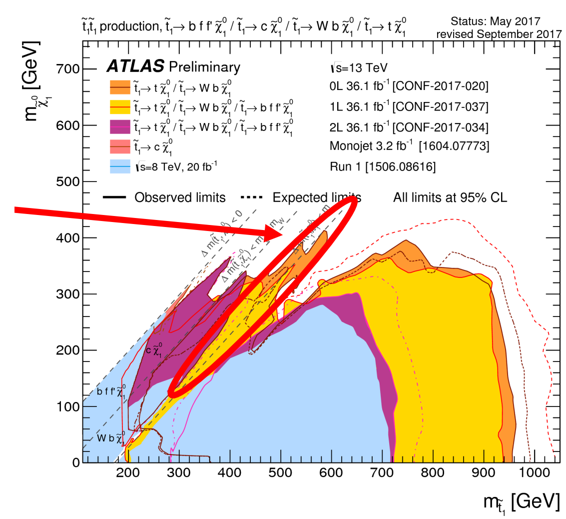


$m_{\ell\ell}$ [GeV] (SF lepton pairs only)	$81.2 < m_{\ell\ell} < 101.2$
$\min\{\Delta\phi(\mathrm{jet}_{\mathrm{ISR}}, E_T^{\mathrm{miss}})\}$	> 0.4
$\Delta\phi(\mathrm{jet}_{\mathrm{ISR1}}, E_T^{\mathrm{miss}})$	> 2
$R_{\ell\ell}$	> 6
E_T^{miss} [GeV]	> 350
Leading ISR jet p_T [GeV]	> 300
m_{T2} [GeV]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



Cut-and-count, optimized for discovery





SUSY @ HL-LHC: challenging scenarios (III)

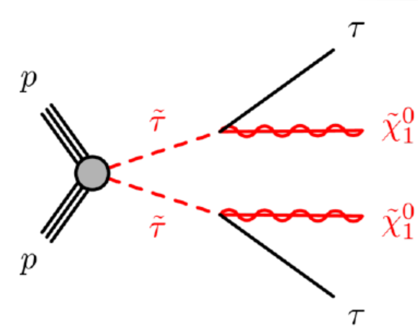
- **Electroweak SUSY: di-stau production**

ATL-PHYS-PUB-2016-021

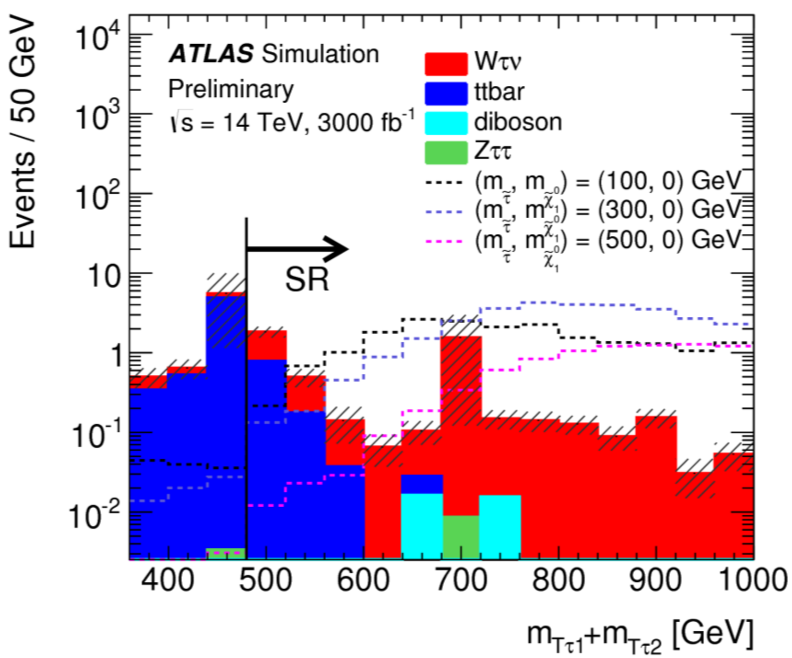
Current LHC results → no exclusion aside for one scenario (m_stau = 100 GeV, LSP massless)

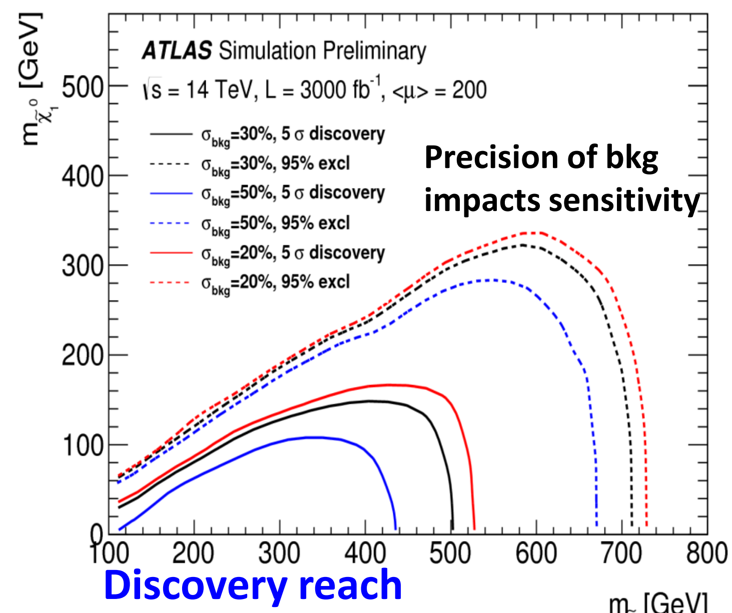
Signature:
- 2 tau jets (hadronically decaying tau)
- Large MET

Main background: W+jets, ttbar



Define signal region (SR) in $m_T(\tau 1) + m_T(\tau 2)$



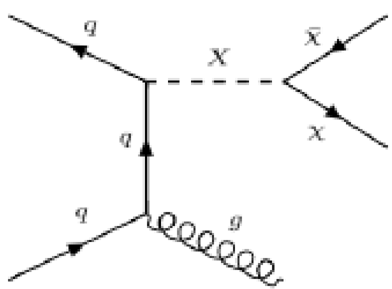


Discovery reach

430-520 GeV @ 3/ab depending on bkg

Dark Matter searches

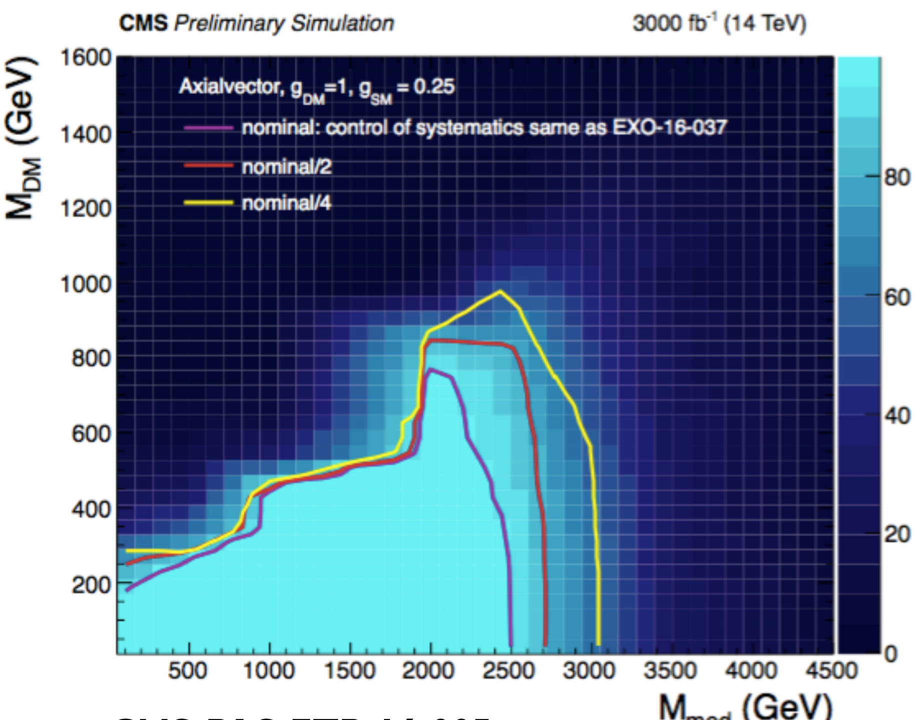
- Searches for SUSY RPC scenarios are also indirect searches for DM (LSP)
- Other general (EFT → simplified) models considered
- Comprehensive re-assessment of current efforts for HL-LHC not yet done [analyses are often systematics limited, experimental sources hard to estimate, theoretical uncertainties might be conservative]
- Classic jet + MET



Spin-1 mediator, axialvector
$g_{SM} = 0.25$, $g_{DM} = 1$

Systematic scenarios considered:
(a) Nominal = same level of unc. as now (b) reduced by 2 (c) reduced by 4.
[most relevant uncertainty: knowledge of MET at high ET]

Projections - Axialvector

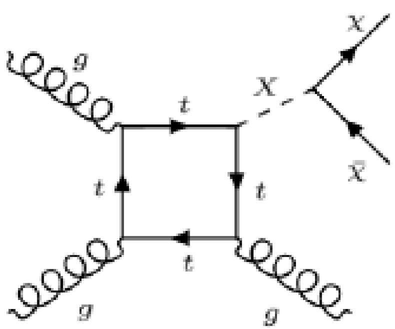


CMS-PAS-FTR-16-005

Dark Matter searches (II)

BSM parallel session:
All experiments talk: A. Magnan

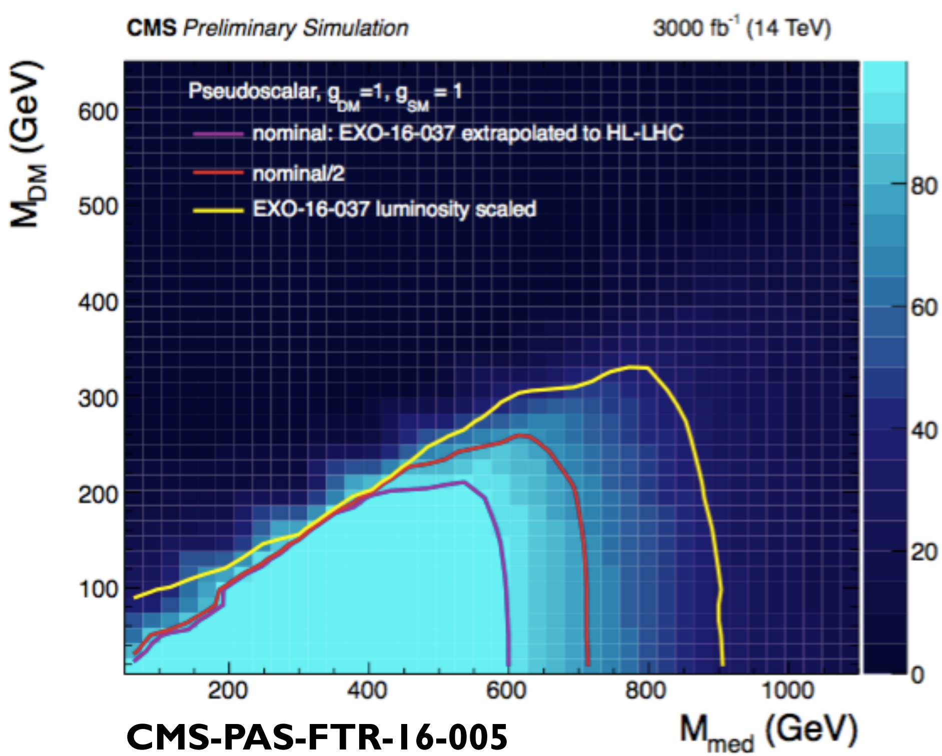
- Searches for SUSY RPC scenarios are also indirect searches for DM (LSP)
- Other general (EFT → simplified) models considered
- Comprehensive re-assessment of current efforts for HL-LHC not yet done [analyses are often systematics limited, experimental sources hard to estimate, theoretical uncertainties might be conservative]
- Classic jet + MET



Spin-0 mediator, pseudoscalar
$g_{SM} = 1, g_{DM} = 1$

Different systematic scenarios again considered
(a) Nominal = same level of unc. as now (b) reduced by 2 (c) pure scaling of lumi

Projections - Pseudoscalar



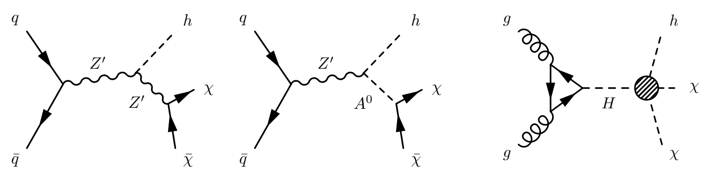
CMS-PAS-FTR-16-005

Dark Matter: more to be explored!

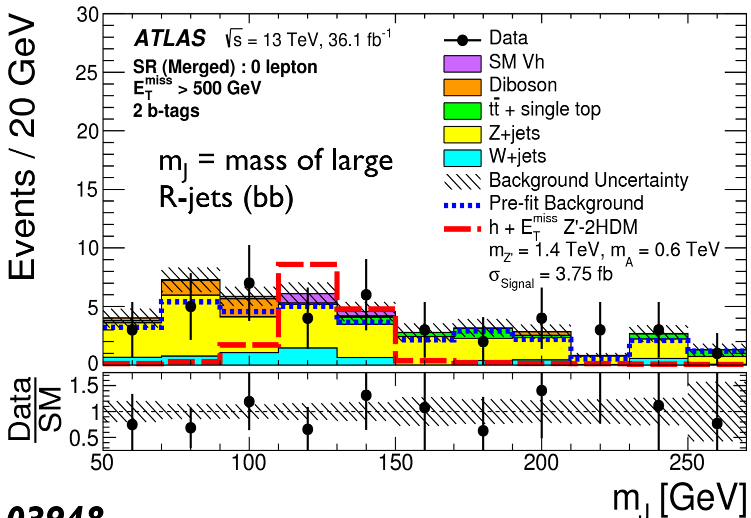
- Many more DM scenarios are actively pursued by ATLAS, CMS and LHCb with 13 TeV data → yet to be fully considered for HL-LHC. Examples:
  - **@ATLAS/CMS:** Mono-photon, Mono-W/Z/Higgs; mono-top;
  - Knowledge of high-MET tails and boosted objects reconstruction very relevant

Higgs in bb+ E_T^{Miss}

Z' model Z'/2HDM model Heavy scalar model



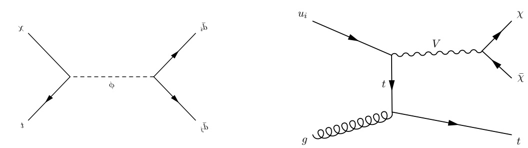
Higgs: *e.g.* in bb final states

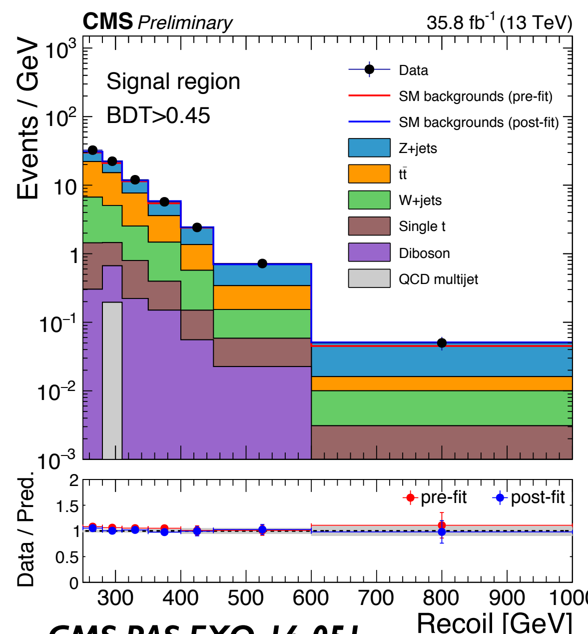


1706.03948

top + E_T^{Miss}

Heavy scalar FCNC



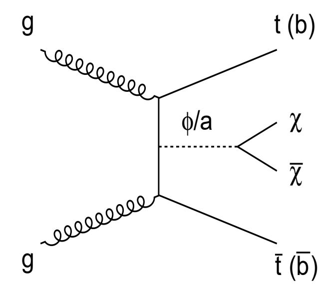


CMS PAS EXO-16-051

Dark Matter: more to be explored!

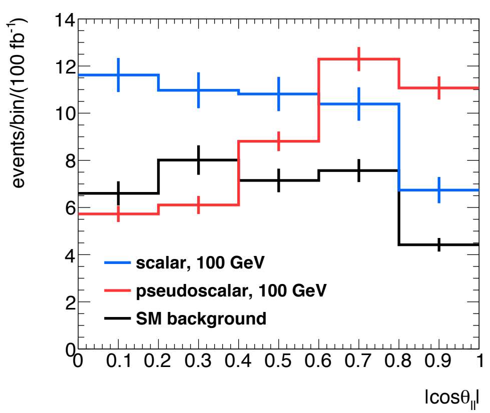
- Many more DM scenarios are actively pursued by ATLAS, CMS and LHCb with 13 TeV data → yet to be fully considered for HL-LHC. Examples:

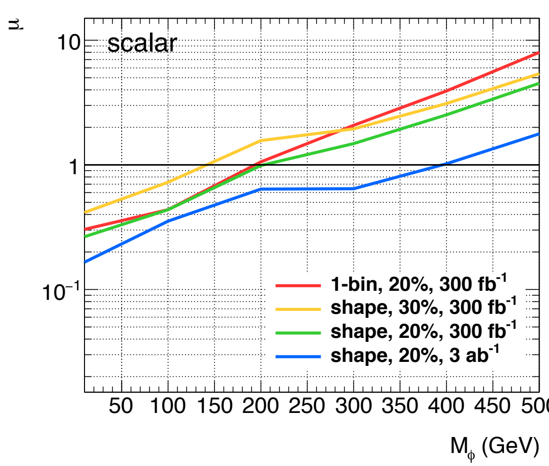
  - **DM + bb**: b-jets might be **forward (|η|>2.4)**, analysis could benefit from extended tracking [in progress **@ATLAS/CMS**]

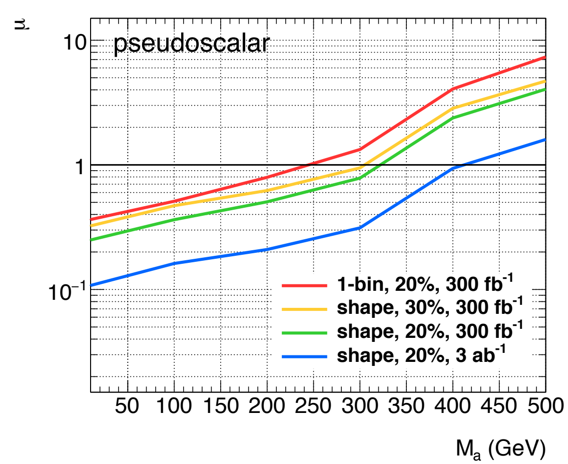


  - **DM +ttbar**: several studies on-going (more in Uli's talk in parallel session)
    - **@ATLAS/CMS:** Exploit angular correlations of leptons from top decays (2l+2b+MET signatures)
    - Clear improvements with larger HL-LHC dataset

arXiV:1611.09841v2







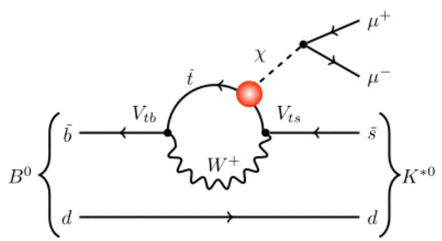
Dark Matter: more to be explored!

- Many more DM scenarios are actively pursued by ATLAS, CMS and LHCb with 13 TeV data → yet to be fully considered for HL-LHC. Examples:
  - **Axion-like Dark Matter**

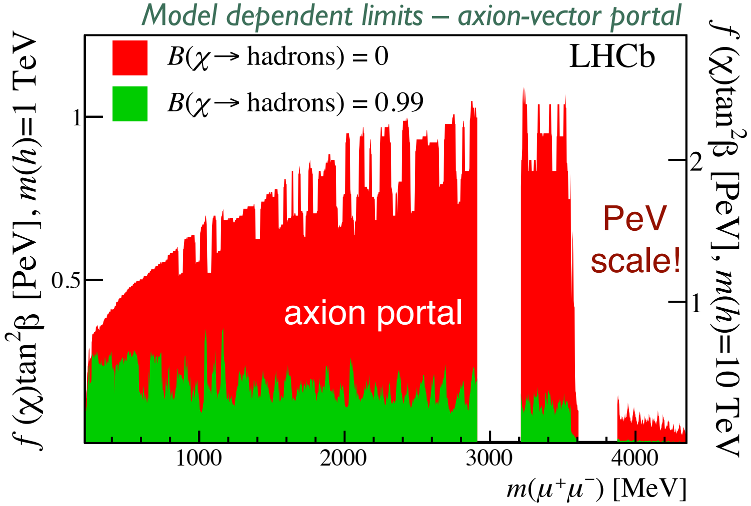
@LHCb: Axion-top couplings constrained measurements of di-muon spectrum

B→K*μ+μ-

PRL 115(2015)161802



Model dependent limits – axion-vector portal

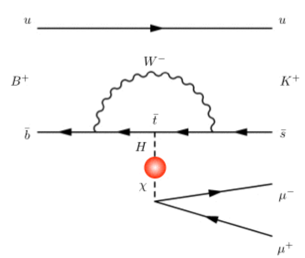


  - **The dark sector: Higgs-portals**

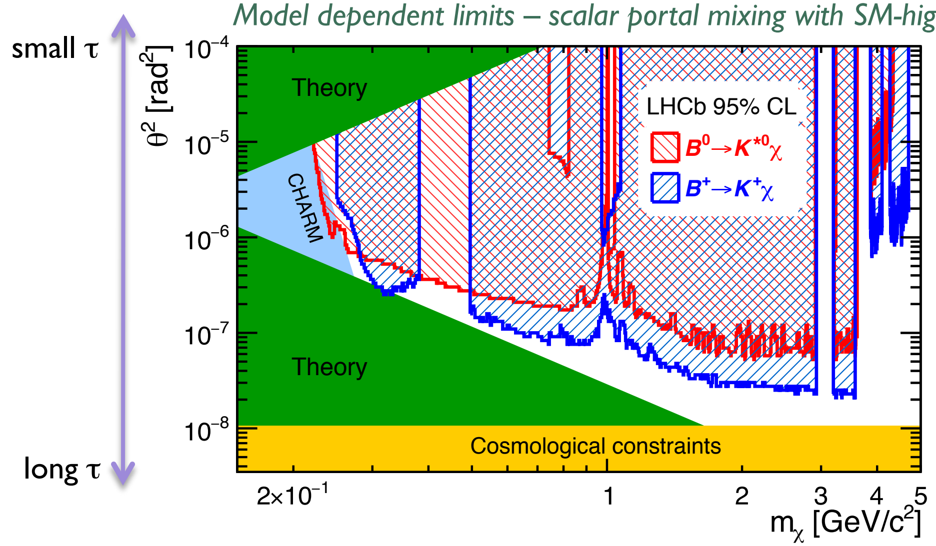
@LHCb Severe constraints already!

$$B^+ \to K^+\chi(\mu^+\mu^-)$$

PRD 95(2017)071101



Model dependent limits – scalar portal mixing with SM-higgs



Constraints in parameter space of the inflation models: mixing angle vs mass

Dark Matter: more to be explored!

BSM parallel session: LHCb and more - M. Borsato

- Many more DM scenarios are actively pursued by ATLAS, CMS and LHCb with 13 TeV data → yet to be fully considered for HL-LHC. Examples:
  - **Axion-like Dark Matter**

@LHCb: Axion-top couplings constrained measurements of di-muon spectrum

$B \to K^* \mu^+ \mu^-$

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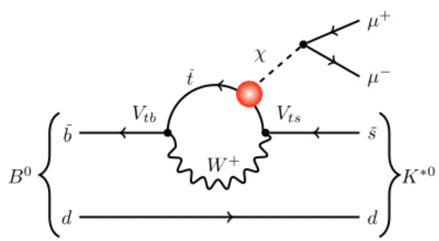
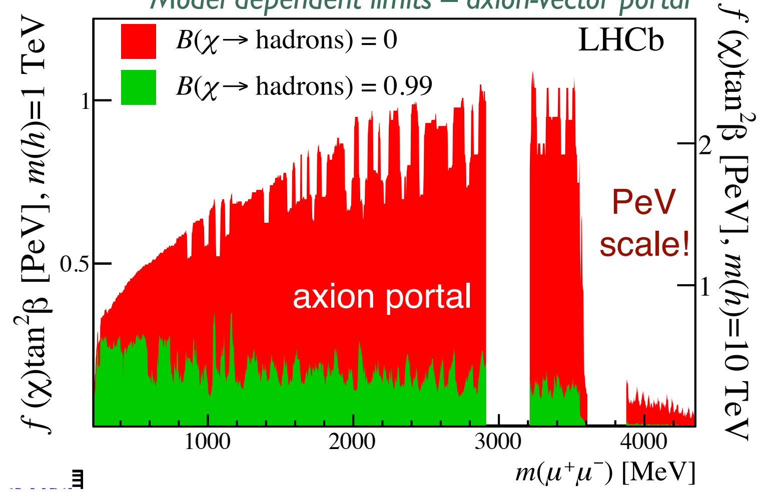


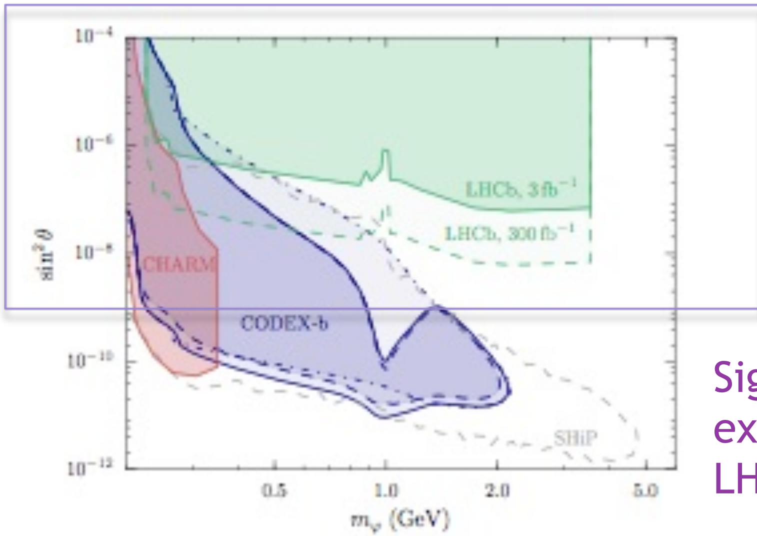
Model dependent limits – axion-vector portal



  - **The dark sector: Higgs-portals**
    - with exotic decays
    - Projections promising !

Will hear more on CODEX-b etc on dedicated talk (D. Curtin)

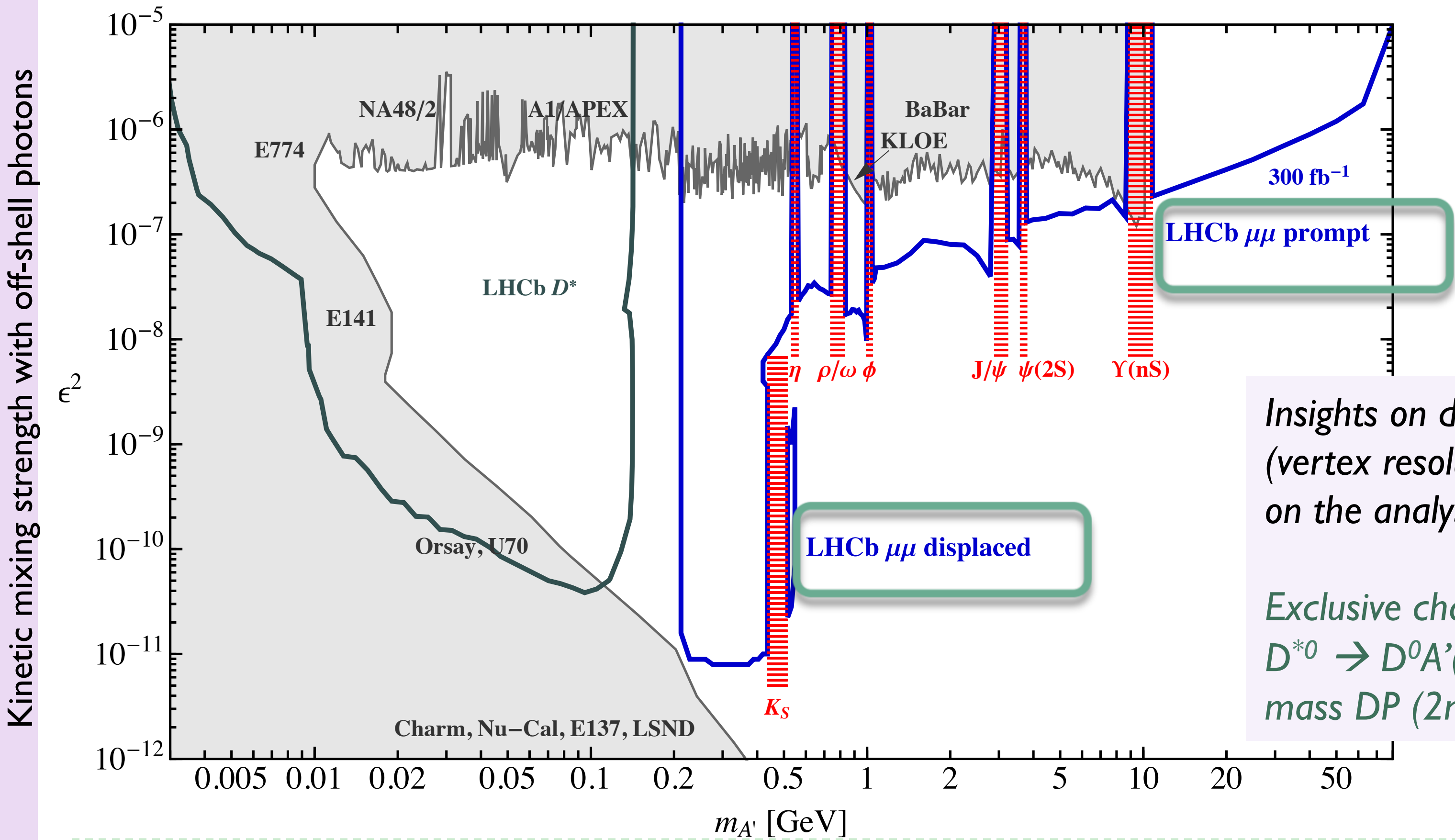
arXiv:1708.09395



Significant extension of LHCb coverage

Dark photons

- 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

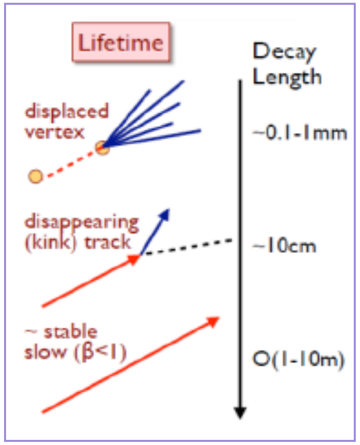
Insights on detector implications (vertex resolution, VELO size) and on the analysis in dedicated talk

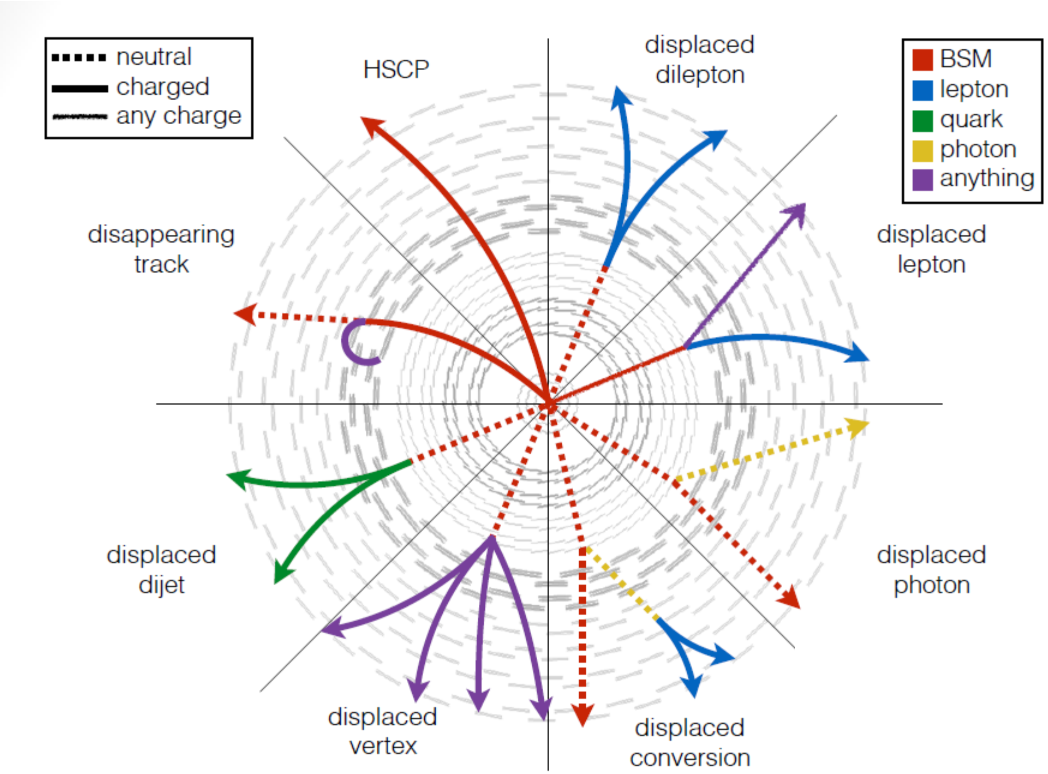
Exclusive charm decay mode $D^{*0} \rightarrow D^0A'(ee)$ suitable for low-mass DP ($2m_e$-142 MeV)

Long-lived particles

BSM parallel session:
ATLAS talk: S. Pagan Riso
CMS talk: J. Alimena; LHCb talk: C. Sierra

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





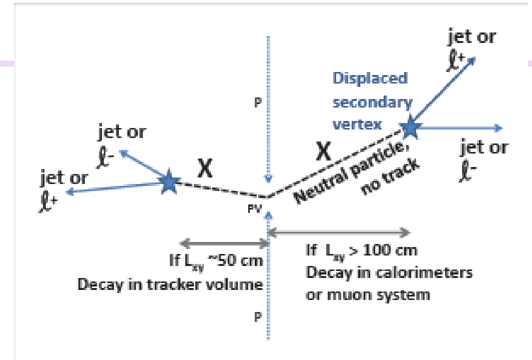
Synergy among ATLAS, CMS and LHCb experiments

- Target complementary lifetimes and mass ranges
- Use different 'signatures'

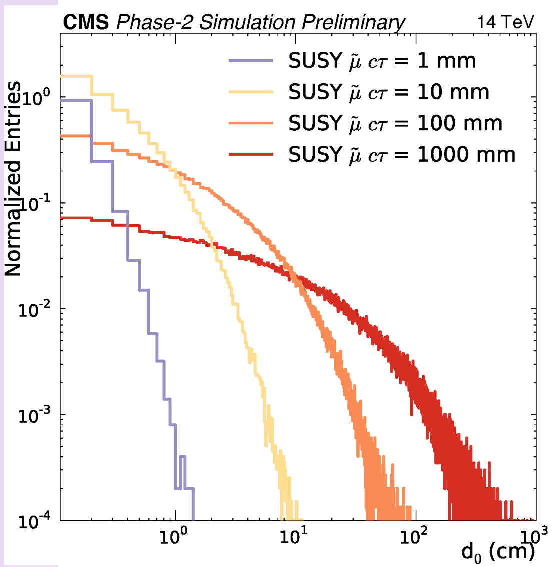
A few examples here, more in dedicated talks

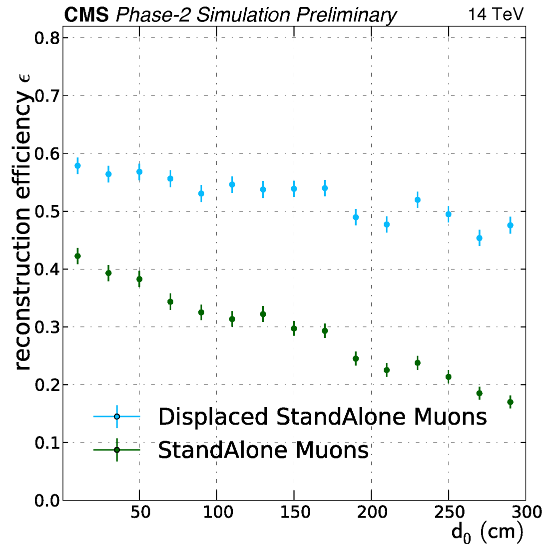
Displaced muons

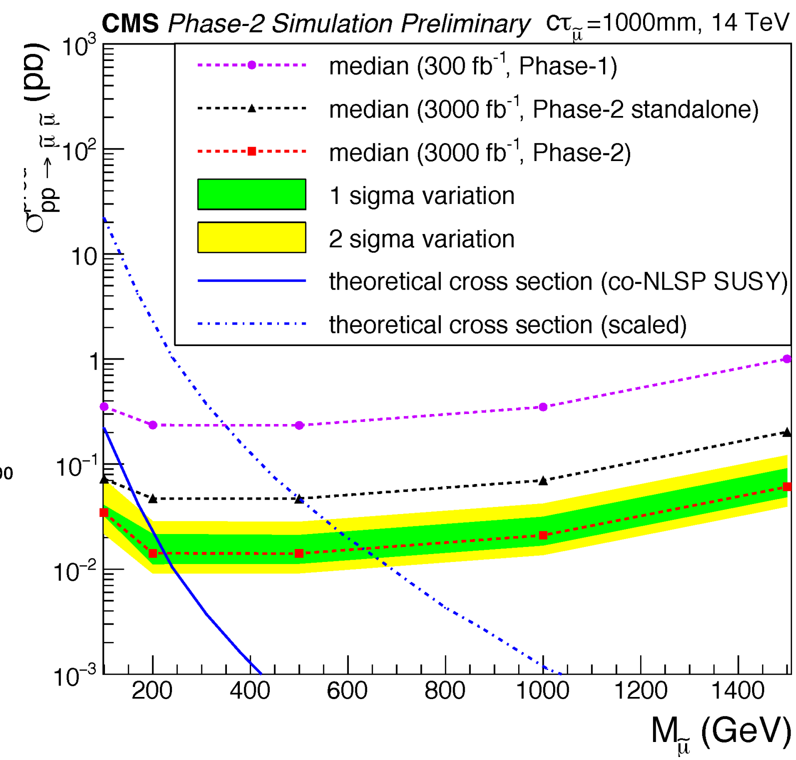
- Examples already shown for LHCb
- New studies from CMS on SUSY:
  - Smuons $\tilde{\mu} \rightarrow \mu + X$



CMS TDR (NEW)







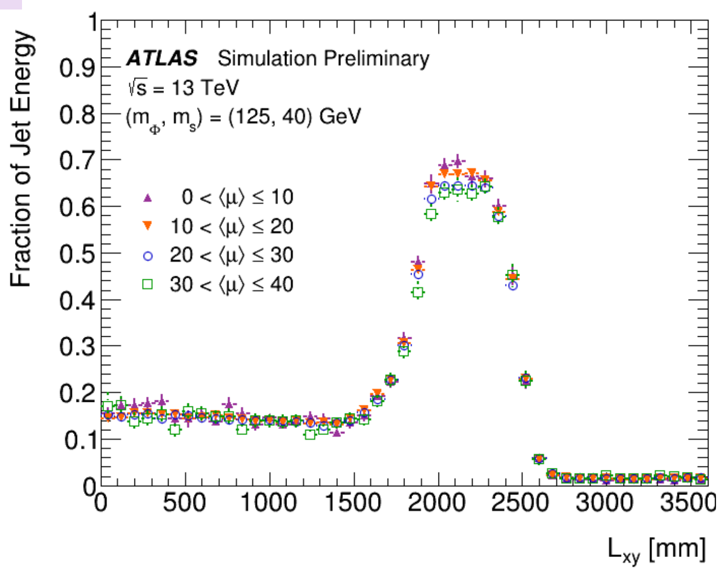
Experimental challenge:

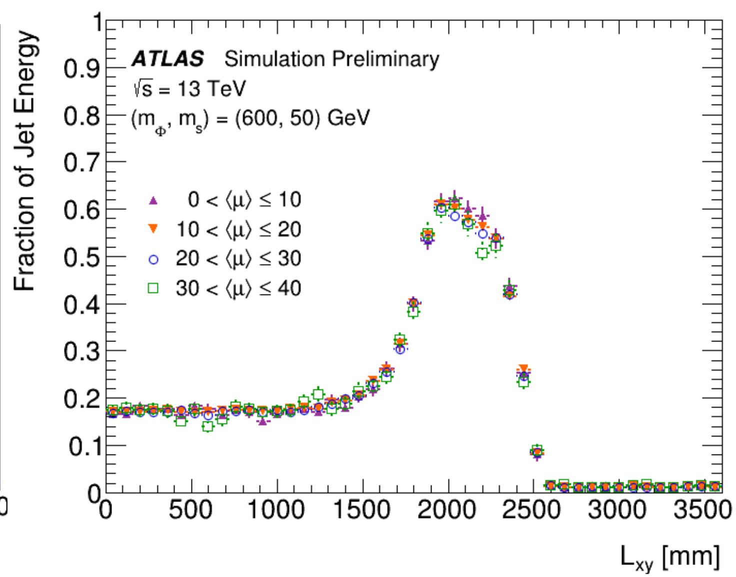
→ trigger displaced signatures
→ Vertex constrains reduce efficiency
→ Dedicated algorithms needed for displaced muons to recover efficiency

Quite an improvement in sensitivity!

Displaced jets

- Great potential → relevant for neutral LLPs decaying within the hadronic calorimeter:
  - Jets have several properties that are uncommon in jets originating at the interaction point.
- New studies using ATLAS Tile-calorimeter information
  - Use dedicated triggers, test a simple hidden-sector model with neutral particle ϕ weakly coupled to SM particles



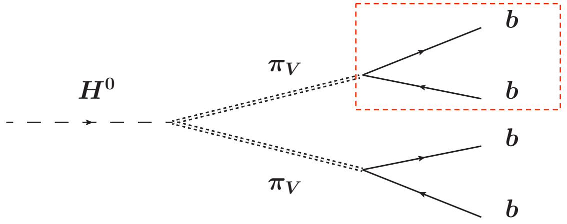


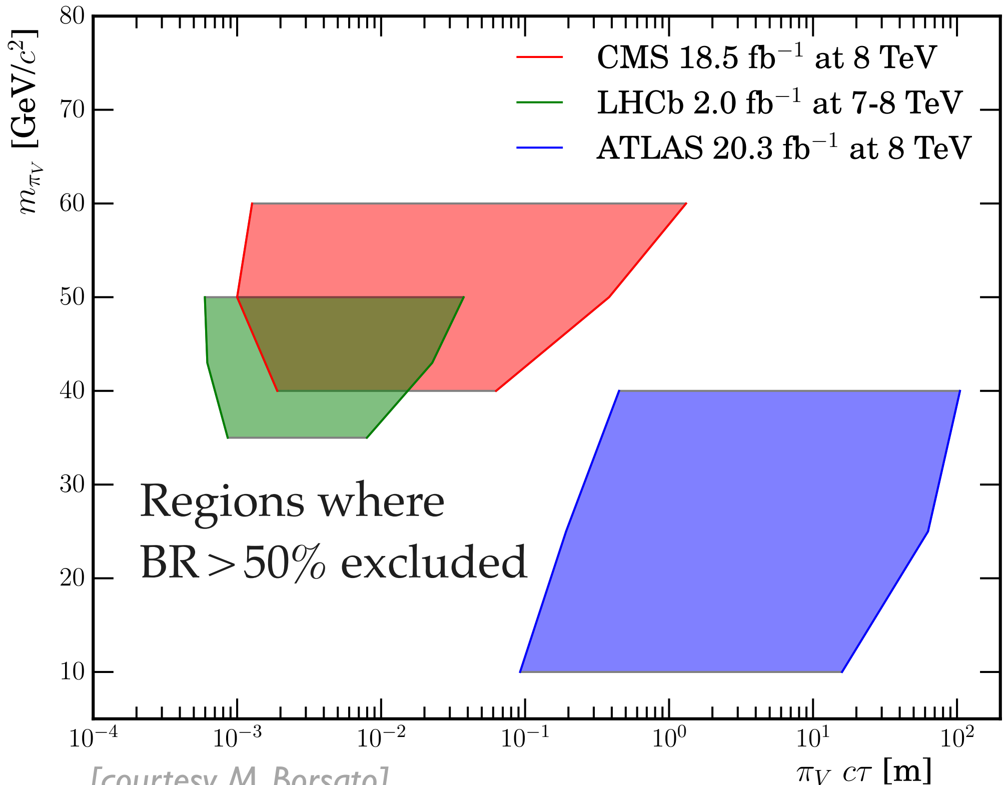
fraction of total jet energy at the EM-scale deposited by the LLPs produced

ATLAS TDR (NEW)

LLP → dijets: complementarities

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



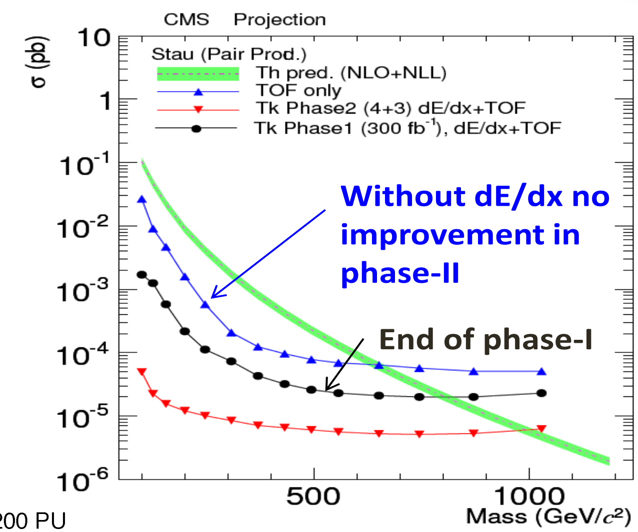


[courtesy M. Borsato]

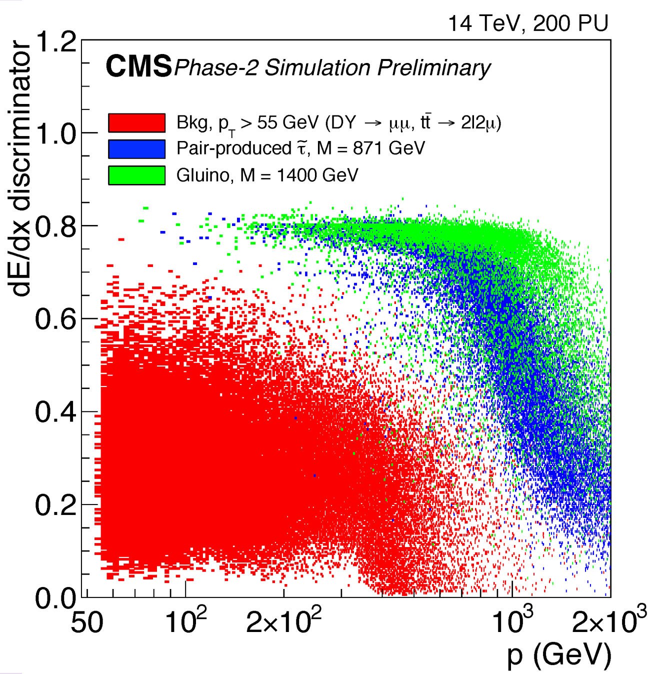
Similar complementarities expected at HL-LHC

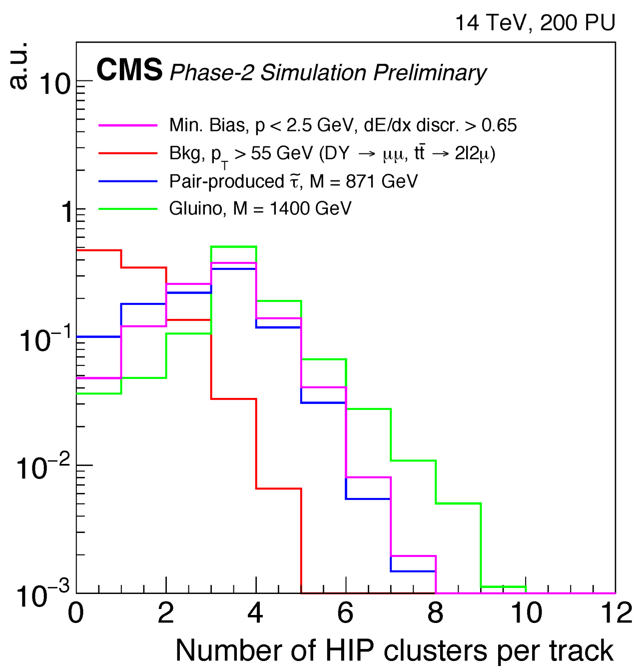
Heavy Stable charged particles

- 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)

back from 'exotics' to classic New resonances

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

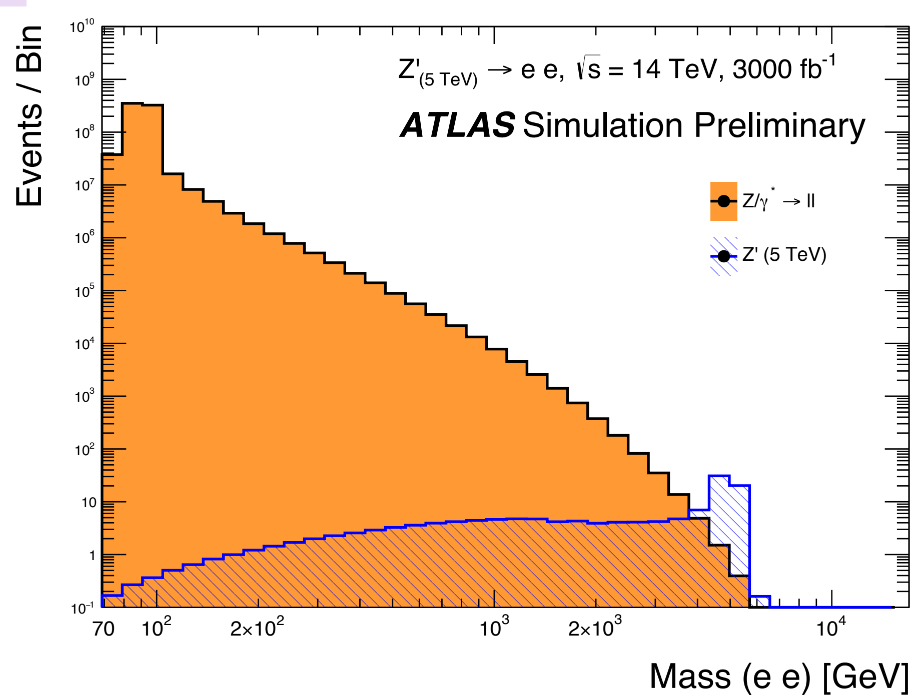
- Sensitive to many BSM scenarios
  Heavy higgses (A/H) – as seen already, Extra-dimensions, new gauge bosons…
- Consider all relevant combinations of final state objects – work in progress but some interesting results already available

More on heavy higgs in two dedicated parallel session talks

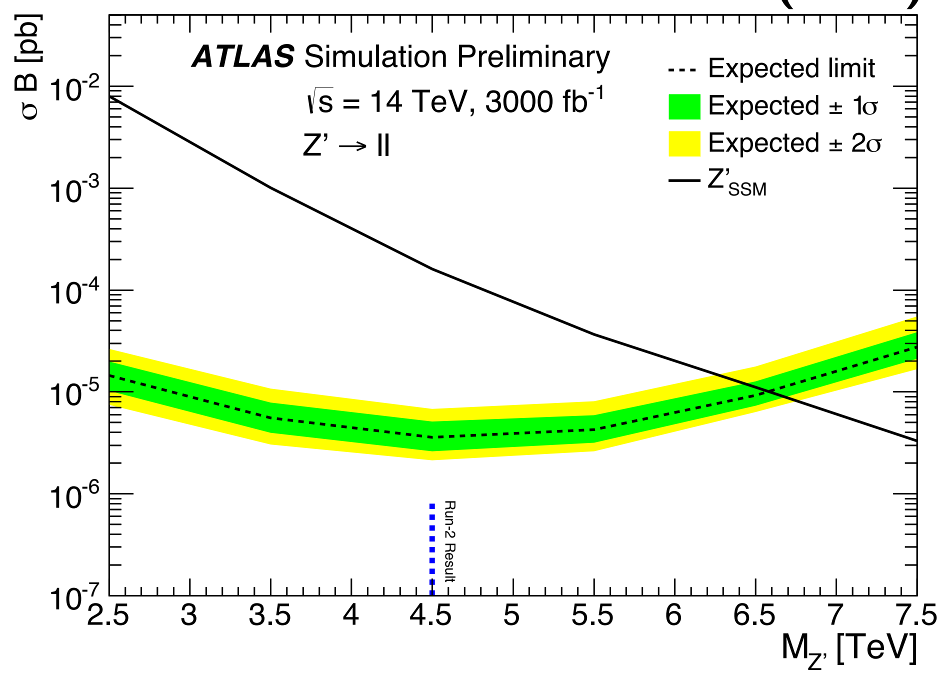
New from ATLAS: Z'→ee

BSM-Higgs parallel session:
Talk 1: S.Willocq
Talk 2: K. Hoepfner

- LAr calorimeter has a direct impact on the dielectron invariant mass resolution
- Consider Sequential SM Z' as benchmark
- 2 electrons with pT>25 GeV
  - Results: exclusion up to to 6.4 TeV, discovery reach ~ 5.9 TeV → more than 2 TeV better than current results!



ATLAS TDR (NEW)



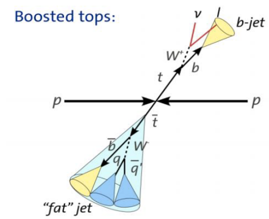
- Constraints are about 200 GeV more stringent than for muons, thanks to the resolution for high pT electron

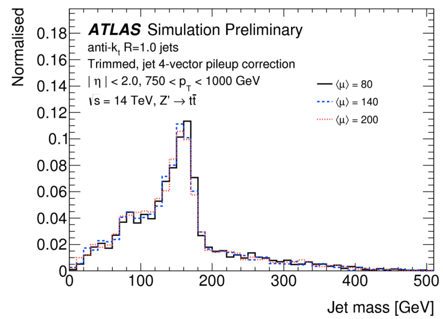
Z' →ttbar

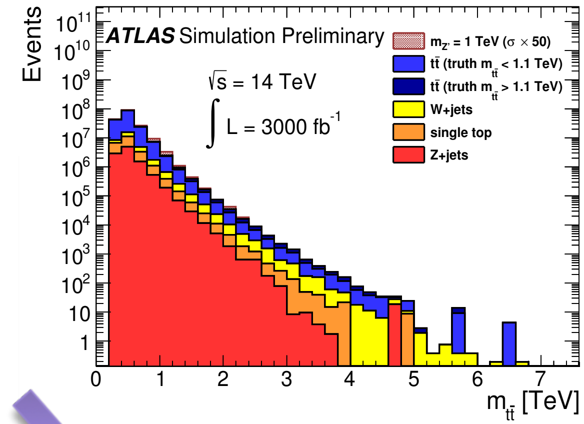
ATL-PHYS-PUB-2017-002

top-pairs resonance search

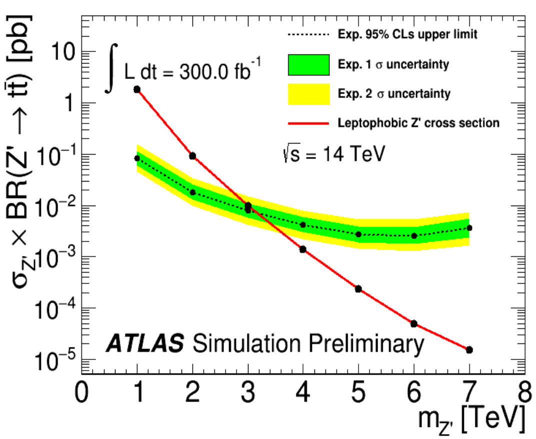
- CMS → projections
  - Either with equal uncertainties or improved wrt current analysis
  - O(4 TeV) exclusions as well
- ATLAS → full analysis
  - Resolved and **boosted**
  - Large **R-jets** considered



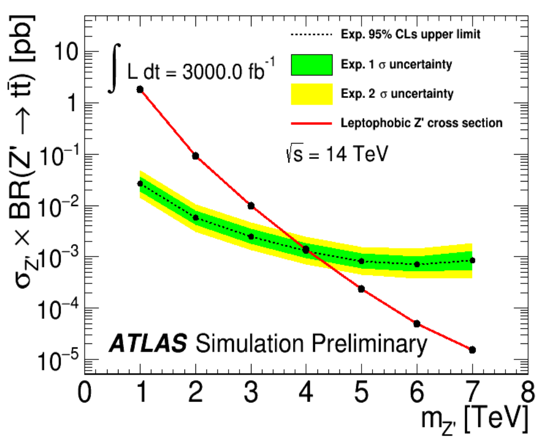




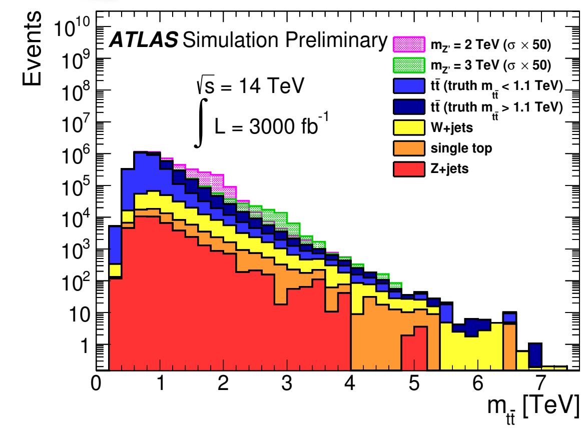
(b) Resolved Muon Channel.



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



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



(d) Boosted Muon Channel.

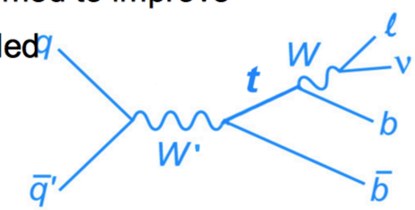
1 TeV gained with HL-LHC!

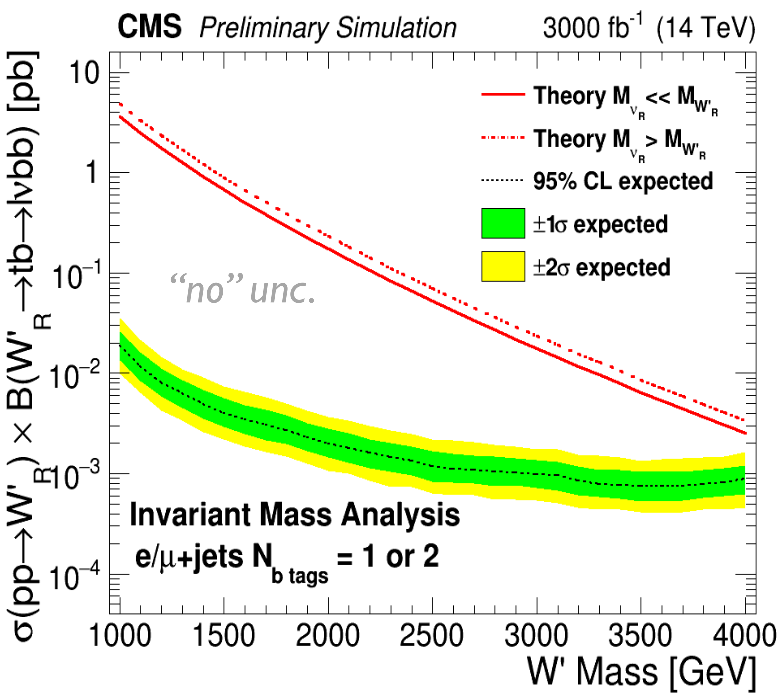
W'→tb

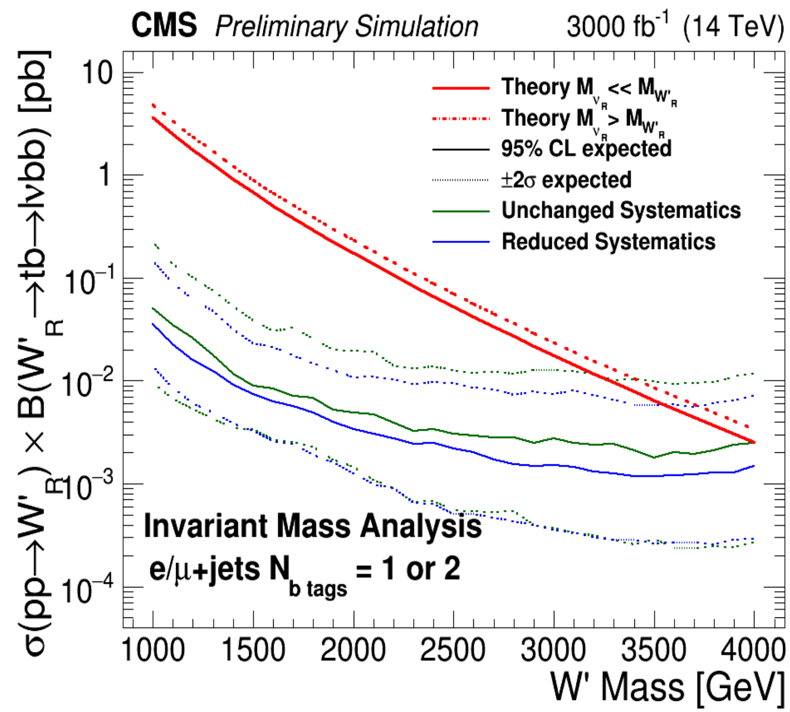
- Projections performed – assuming NWA using 2015 and 2016 analyses

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







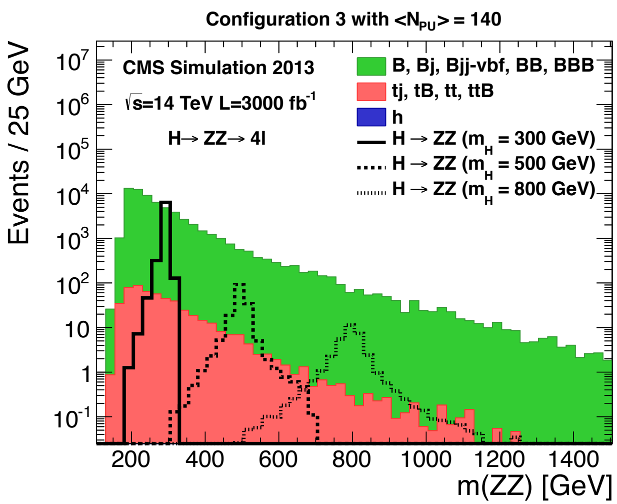
Again, dependence on assumptions on uncertainties

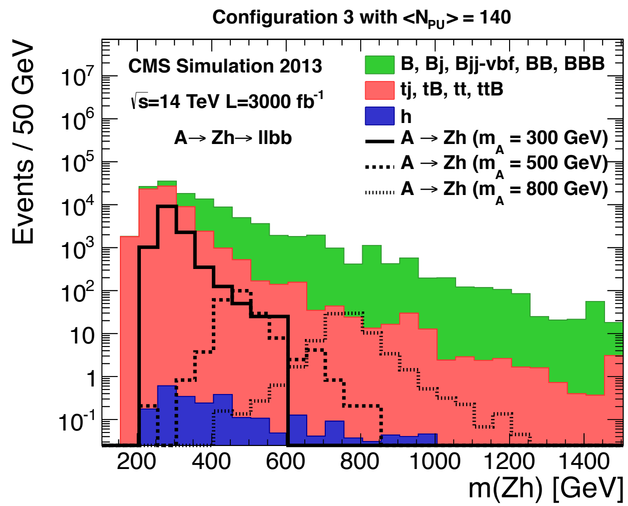
CMS DP016_064

Prospects: heavy higgs

- Past and recent results on heavy higgs resonance searches.
  - H→ZZ (4 lepton) and A→Zh (2l+2b) (CMS)

CMS PAS FTR-13-024





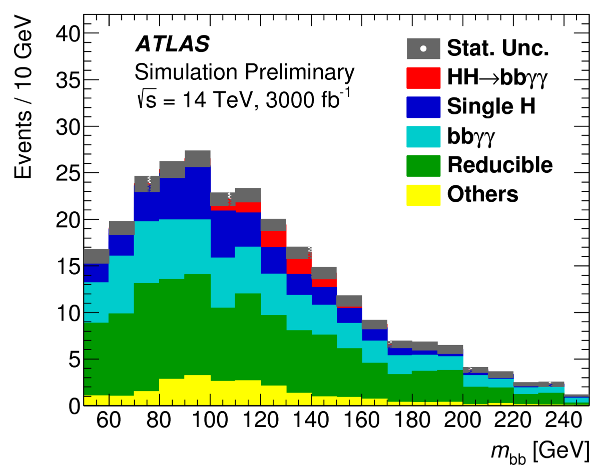
Can constrain 2HDM models

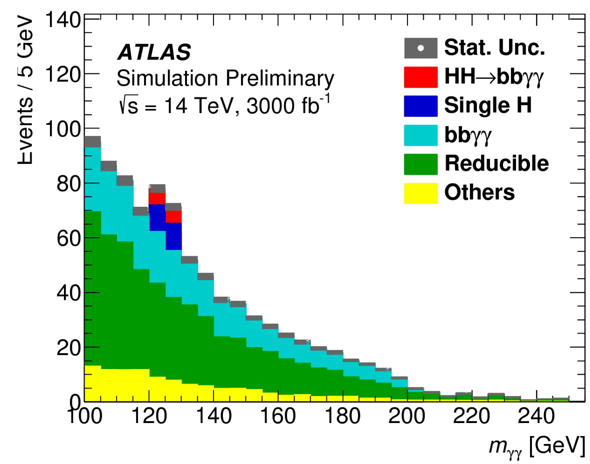
- Di-higgs

(although here shown non-resonant) (ATLAS)

ATLAS TDR (NEW)

h→bb and h→γγ





Much more being investigated based on the expected performance of the detectors

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 and hopefully we will get more at this workshop!
- Analyses have been carried out using different approaches (projections / truth-smearing / DELPHES) or assumptions (PU, modeling uncertainties, treatment of rare backgrounds)
  - For the YR, we should ensure a **coherent set of approaches**
- 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, for dark matter and dark sectors in general
  - Work to fully exploit the HL-LHC potential also considering new detectors/facilities

→ Plans and intro of WG3 activities in the next session

→ Have a look at the BSM and BSM-joint sessions

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

BSM and joint agendas

Tuesday

11:00 → 13:00 BSM WG: session 1 — 503-1-001 - Council Chamber — Join

- 11:00 **Theoretical overview of Supersymmetry at the energy frontiers**
  Speaker: Tilman Plehn (Heidelberg University)
- 11:20 **Search for Long-lived particles at ATLAS**
  Speaker: Simone Pagan Griso (Lawrence Berkeley National Lab. (US))
- 11:40 **Search for Long-Lived particles at CMS**
  Speaker: Juliette Alimena (Ohio State University (US))
- 12:00 **Searches for Long-lived particles at LHCb**
  Speaker: Carlos Vazquez Sierra (Nikhef National institute for subatomic physics (NL))
- 12:20 **New proposals for long-lived particle studies**
  Speaker: David Curtin (University of Maryland)
- 12:40 **challenges and needs for BSM searches: experimentalists perspective**
  Speaker: Keith Ulmer (University of Colorado, Boulder (US))

14:00 → 16:00 Joint session: Higgs, flavour and BSM — 500-1-001 -

- 14:00 **Higgs, light Yukawas, and FC couplings**
  Speaker: Fady Bishara (University of Oxford (GB))
- 14:30 **Light Yukawa Couplings: experimental searches**
  Speaker: Oscar Augusto De Aguiar Francisco (CERN)
- 15:00 **Physics potential for the e-p collider: Higgs, BSM and flavour**
  Speaker: Uta Klein (University of Liverpool (GB))
- 15:20 **Flavour anomaly inputs for high pT measurements**
  Speaker: Admir Greljo (University of Mainz)
- 15:45 **Discussion on Flavour anomalies after high lumi**
  Speaker: Tevong You
  The Case for Future Hadron Colliders From $B\to K^{(*)}\mu^+\mu^-$ $B\to K^{(*)}\mu^+\mu^-$ Decays

16:30 → 18:40 Joint session: Higgs and BSM — 500-1-001

- 16:30 **Searches for heavy resonances in bosonic final states**
  Speaker: Stephane Yves G Willocq (University of Massachusetts (US))
- 16:50 **Searches for heavy resonances in fermionic final states**
  Speaker: Kerstin Hoepfner (Rheinisch Westfaelische Tech. Hoch. (DE))
- 17:10 **Experimental DM searches and higgs implications**
  Speaker: Anne-Marie Magnan (Imperial College (GB))
- 17:30 **High mass dileptons dijets EWPT**
  Speaker: Marco Farina (Rutgers University)
- 17:55 **Dibosons studies (theory)**
  Speaker: Andrea Wulzer (CERN)
- 18:20 **Additional scalars in the Higgs sector**
  Speaker: Matthew Philip Mcculloough (CERN)

Wednesday

09:00 → 10:35 BSM WG: session 2 — 222-R-001

- 09:00 **Dark Photons and other Exotic Searches**
  Speaker: Martino Borsato (Universidade de Santiago de Compostela (ES))
- 09:20 **Searches for SUSY and other non-resonant signatures from ATLAS**
  Speaker: Federico Meloni (Universitaet Bern (CH))
- 09:40 **Searches for SUSY and other non-resonant signatures from CMS**
  Speaker: Giovanni Zevi Della Porta (Univ. of California San Diego (US))
- 10:00 **Dark Matter at the LHC**
  Speakers: Uli Haisch , Ulrich Andreas Haisch
- 10:20 **Axion-like particles**
  Speaker: Diego Redigolo

11:00 → 13:00 BSM WG: session 3 — 222-R-001 — Joi

- 11:00 **Resonances in Composite Theories**
  Speaker: Andrea Thamm (CERN)
- 11:20 **Neutral Naturalness**
  Speaker: Andrea Tesi
- 11:40 **R-parity Violating Models**
  Speakers: Dr. Manuel E. Krauss (Bonn University) , Manuel Krauss (Bayerische Julius Max. Universitaet Wuerzburg (DE))
- 12:00 **Discussion of submitted abstracts and other ideas**
  Speaker: All

+ Posters (Monday evening)
+ Abstracts and teaser slides to be discussed on Wednesday morning!