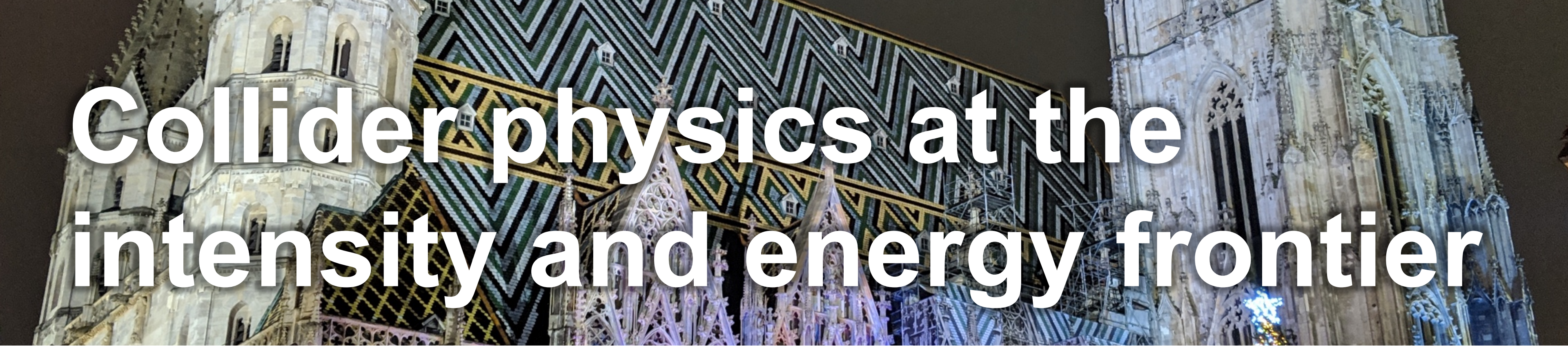


Collider physics at the intensity and energy frontier

The HL-LHC and beyond

Federico Meloni (DESY),
on behalf of the ATLAS and CMS collaborations

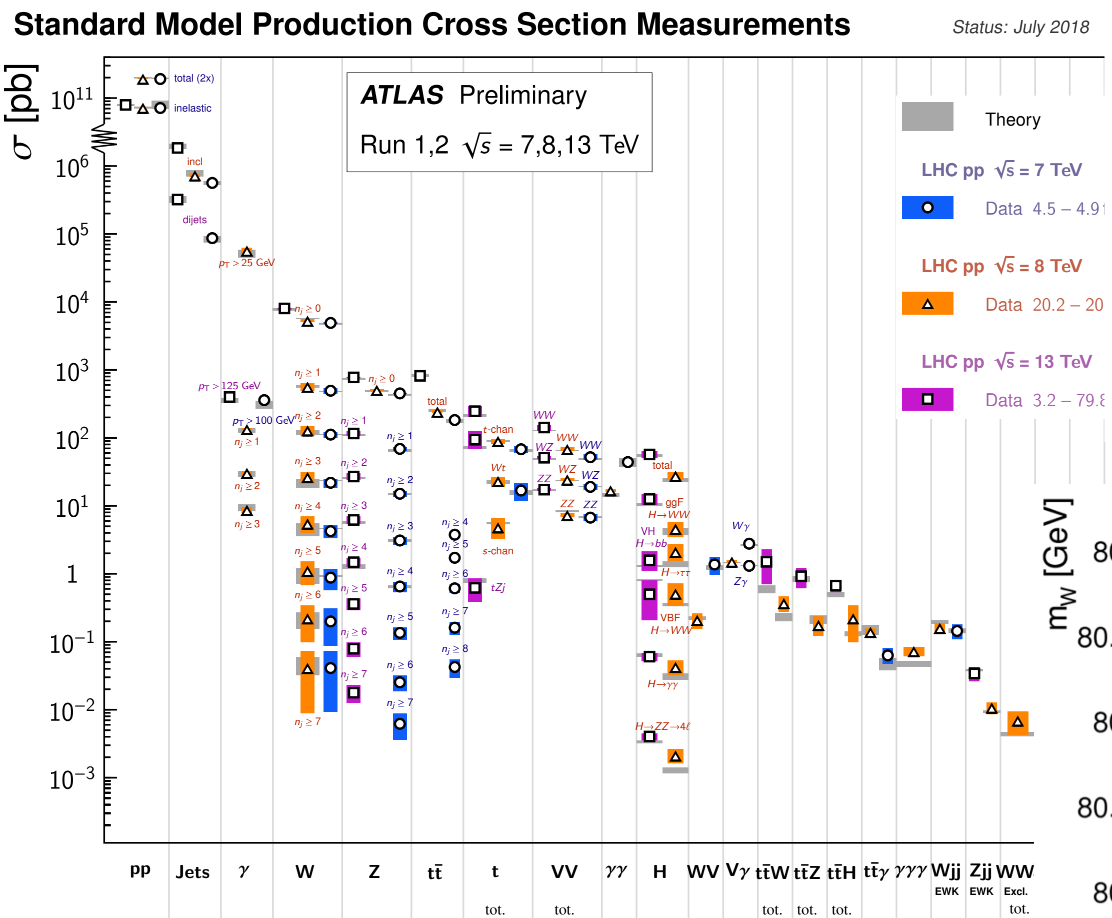
28 November 2018
DISCRETE 2018, Vienna

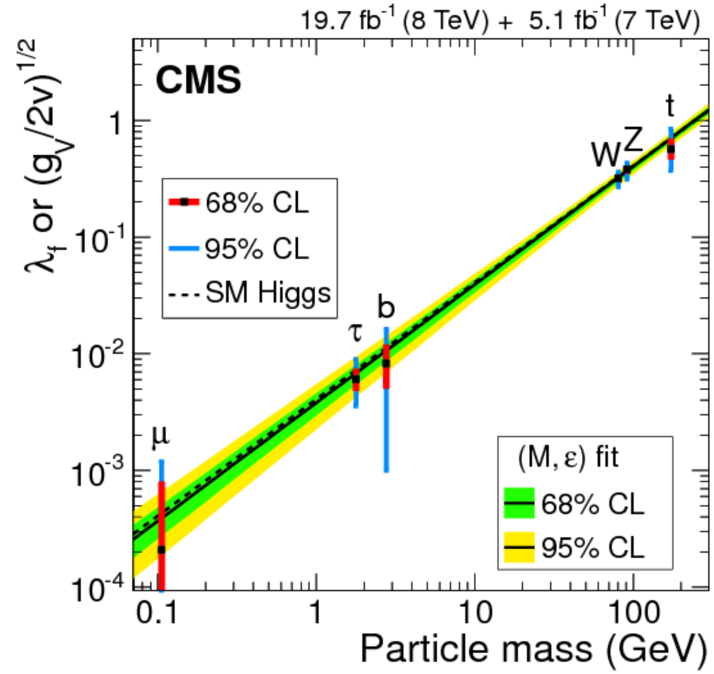
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

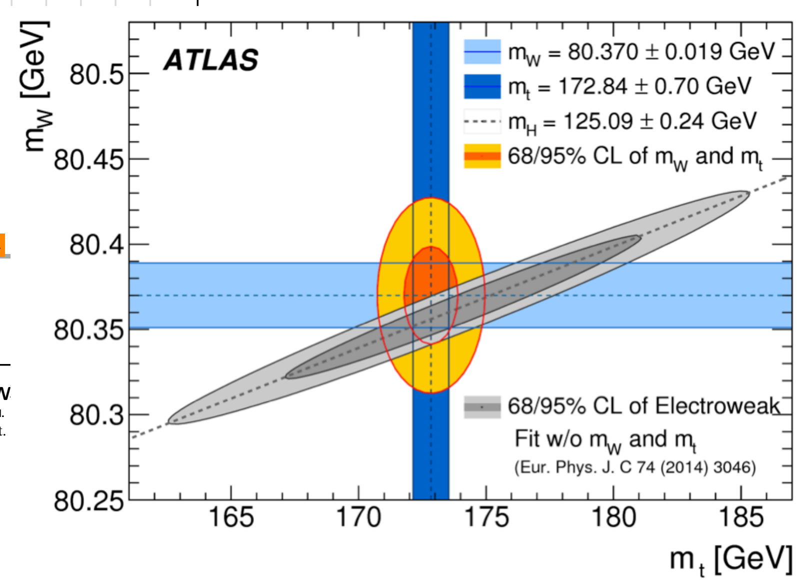
DISCRETE18

Introduction

The success of the Standard Model



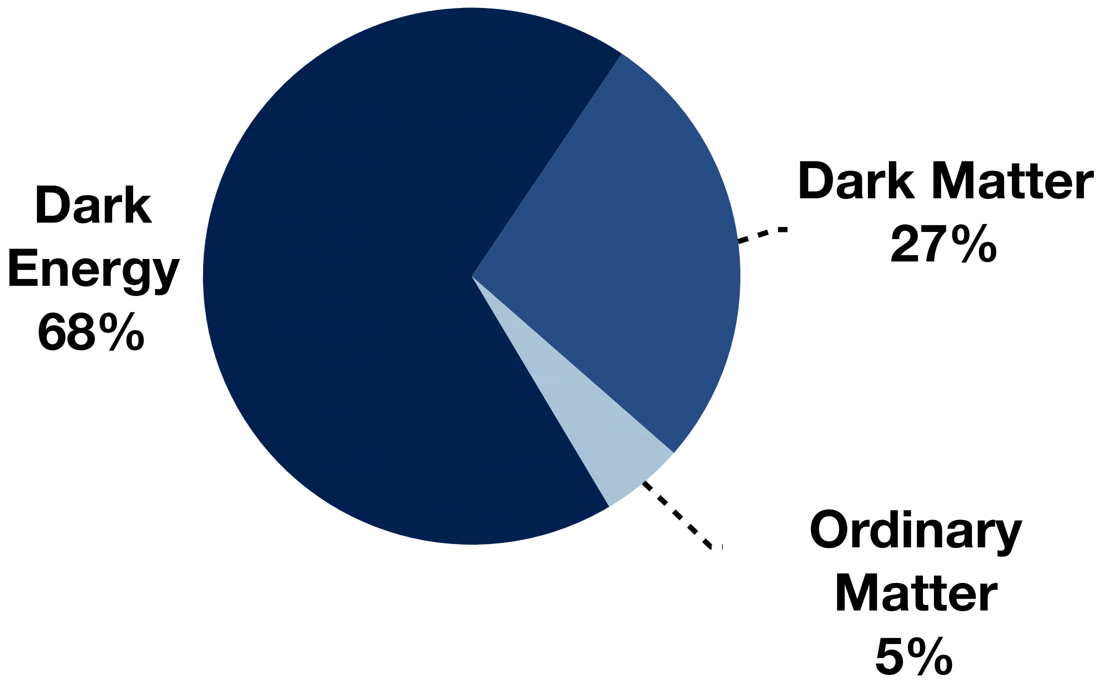




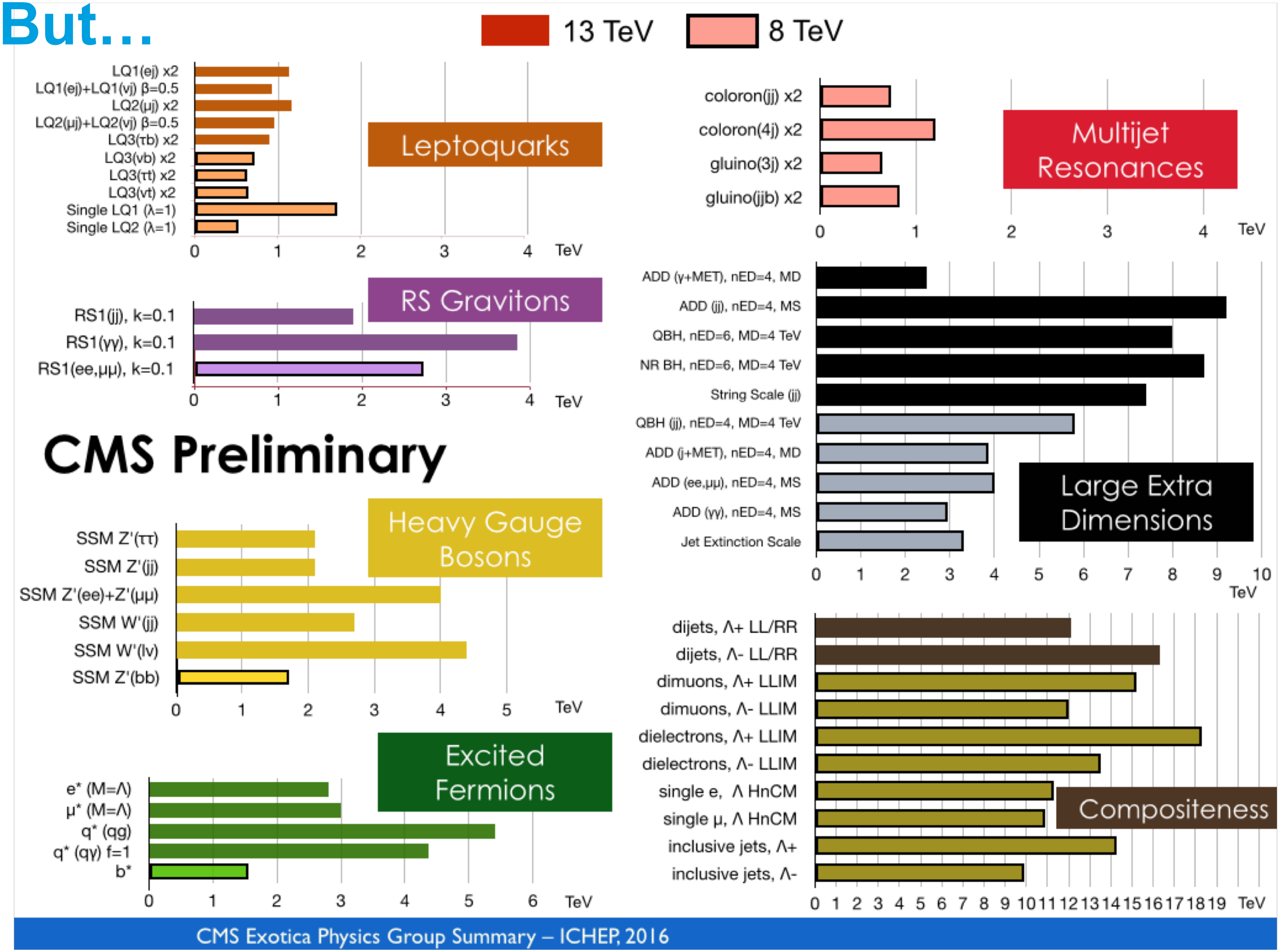
Standard Model shortcomings

Even with such a successful description of Nature, a few, but major, pieces are missing in the puzzle:

- Neutrino masses (and flavour oscillation) not predicted
- Matter-antimatter imbalance
- Unification of forces
- No gravity
- Missing dark matter/energy candidates
- Hierarchy problem
- …

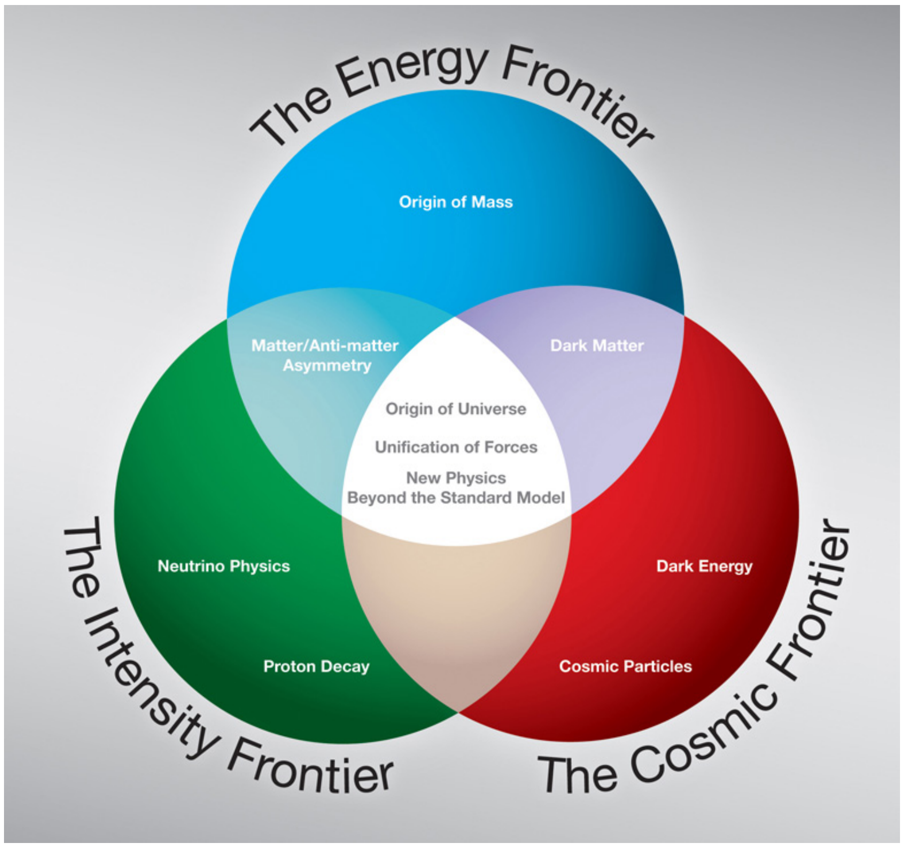


But…



13 TeV
8 TeV
LQ1(ej) x2
LQ1(ej)+LQ1(νj) β=0.5
LQ2(μj) x2
LQ2(μj)+LQ2(νj) β=0.5
LQ3(τb) x2
LQ3(νb) x2
LQ3(τt) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
Leptoquarks
TeV
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Multijet Resonances
RS Gravitons
RS1(jj), k=0.1
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
ADD (γ+MET), nED=4, MD
ADD (jj), nED=4, MS
QBH, nED=6, MD=4 TeV
NR BH, nED=6, MD=4 TeV
String Scale (jj)
QBH (jj), nED=4, MD=4 TeV
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
Jet Extinction Scale
Large Extra Dimensions
CMS Preliminary
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM Z'(bb)
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
Compositeness
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ) f=1
b*
CMS Exotica Physics Group Summary – ICHEP, 2016

Where to look?



LHC (and future colliders) offer a unique place where to look directly for new particles.

Precision measurements of SM

- Each deviation could be an hint of new physics!

Direct BSM searches

- A plethora of kinematic regions and possible new resonances from heavy particles

Other focused experiments give alternative and fundamental opportunities!

Particle physics at colliders

Why?

Broad exploration potential

- target well justified BSM scenarios but also have sensitivity to the unknown

Flexibility

- if (indirect) hints of NP arise somewhere, need to be able to re-direct efforts

Guaranteed deliverables

- if not a discovery, precision measurements!

Physics at Colliders fulfils all the above conditions, so it's important to guarantee a continuous progression in this direction with sufficient complementarity

PAST

Tevatron/HERA/LEP (fermiscale) → **LHC → HL-LHC** (Terascale) → **pp/(ep)/ee?** (multi-Terascale)

PRESENT

FUTURE

(Possible) future colliders

Options for the next 30+ years

proton - proton

High Energy - LHC √s = 27 TeV, beyond 2038

FCC - hh √s = 100 TeV, beyond 2045 (after FCC-ee), up to 30/ab

electron - positron

Linear

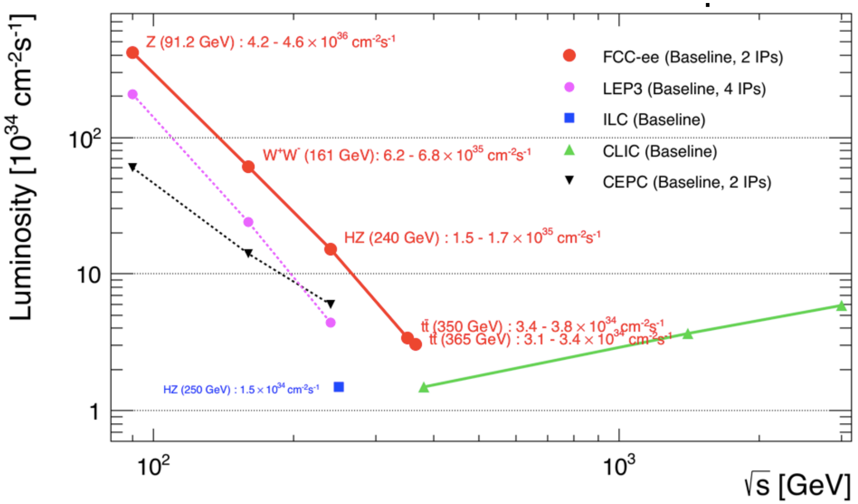
ILC √s ≈ 500 GeV with staging at 250 GeV

CLIC three stages √s ≈ 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

CepC >= two stages, √s ≈ 91 and 240 GeV, data-taking 2030-2040 (upgradable to pp, with ep and HI options)

FCC - ee beyond 2045, 5 different stages and luminosities



electron - proton

LHeC E_e = 60 GeV, p from LHC, up to 1/ab, running at the same time as HL-LHC

FCC-eh E_e = 60 GeV vs 50 TeV, up to 3/ab

The HL-LHC and the 2018 Yellow Report

$\sqrt{s}$ = 14 TeV, up to 3000 or 4000 fb^{-1} (300fb^{-1} for LHCb)

The only facility approved so far, on which most studies have been made

- ATLAS, CMS and LHCb detectors upgrade well on-going
- Data taking: 2025-2038
- 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

ESPP update due for approval by CERN council in May 2020

- Feedback gathered and discussed at the HL-/HE-LHC Workshops

Yellow report studies

Some commonalities

Three main approaches:

- Full simulation
- Analysis with parameterized detector performance (e.g. DELPHES with up-to-date phase-2 detector performance)
- Projections using Run-2 signal and background samples scaled at 14 TeV

Harmonised treatment of detector and theory uncertainties evolution with time

- Agreement between experimental collaborations and theorists involved in the Yellow Report
- General “rule of thumb”: detector and theory/modelling uncertainties will be halved, MC statistics are supposed to be infinite

Outline

I will discuss a personal (arbitrary/incomplete) selection of physics goals that we can achieve by the end of HL-LHC and complementarities with other facilities.

Start with indirect searches

- Precision measurements in the electro-weak sector
- Characterisation of the Higgs boson and its potential

Close with direct searches

- Supersymmetry
- New resonances
- Simplified dark matter models

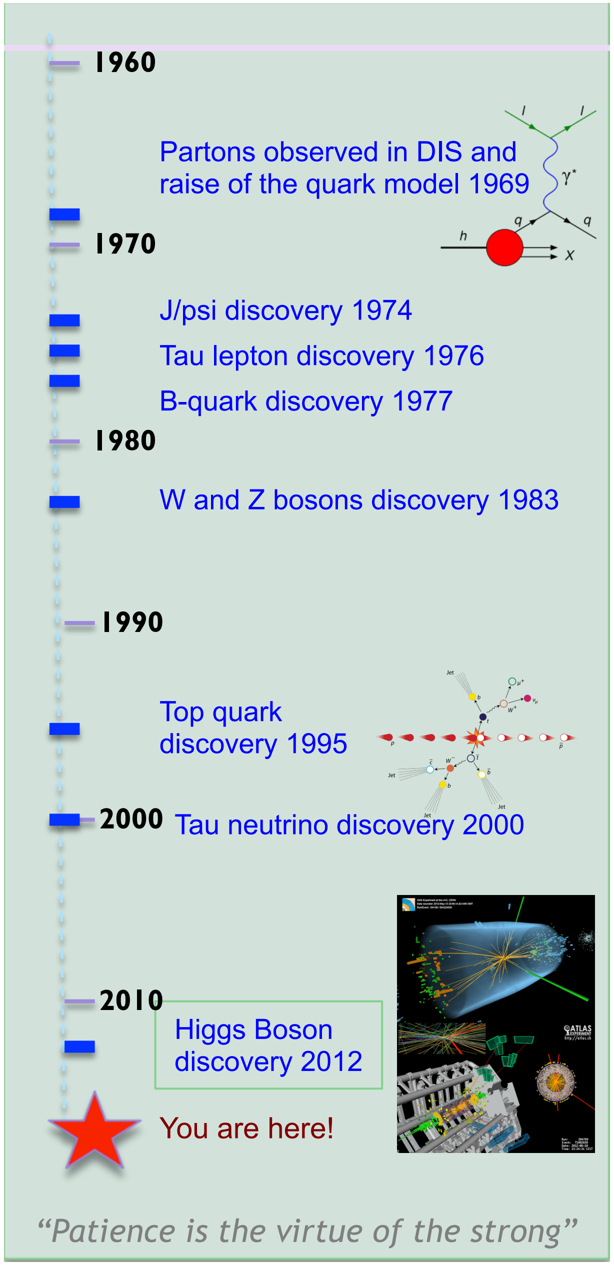


Image credit: M. D'Onofrio

Precision physics

Weak mixing angle

W boson mass

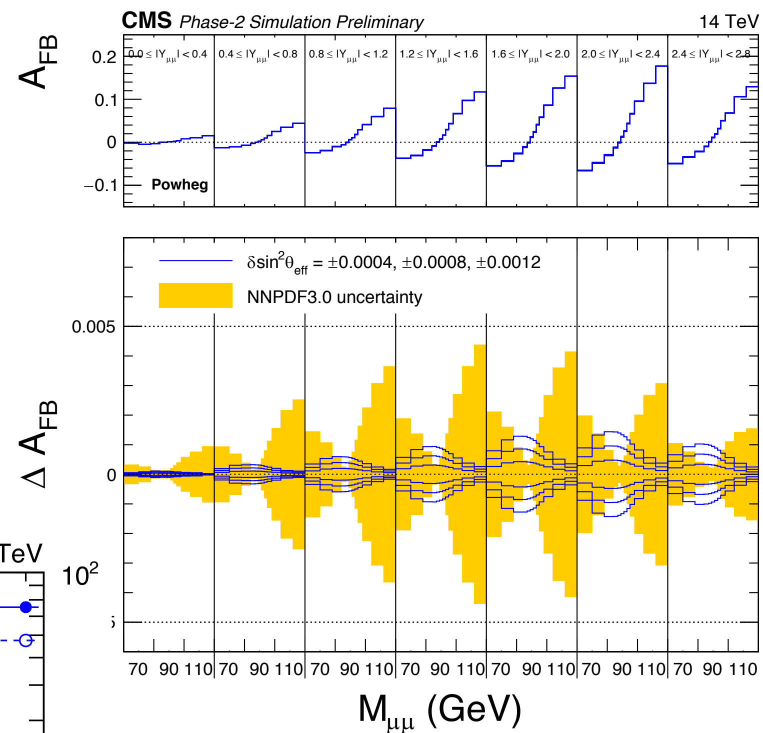
Vector boson scattering

Higgs boson properties

Measurement of the Weak Mixing Angle

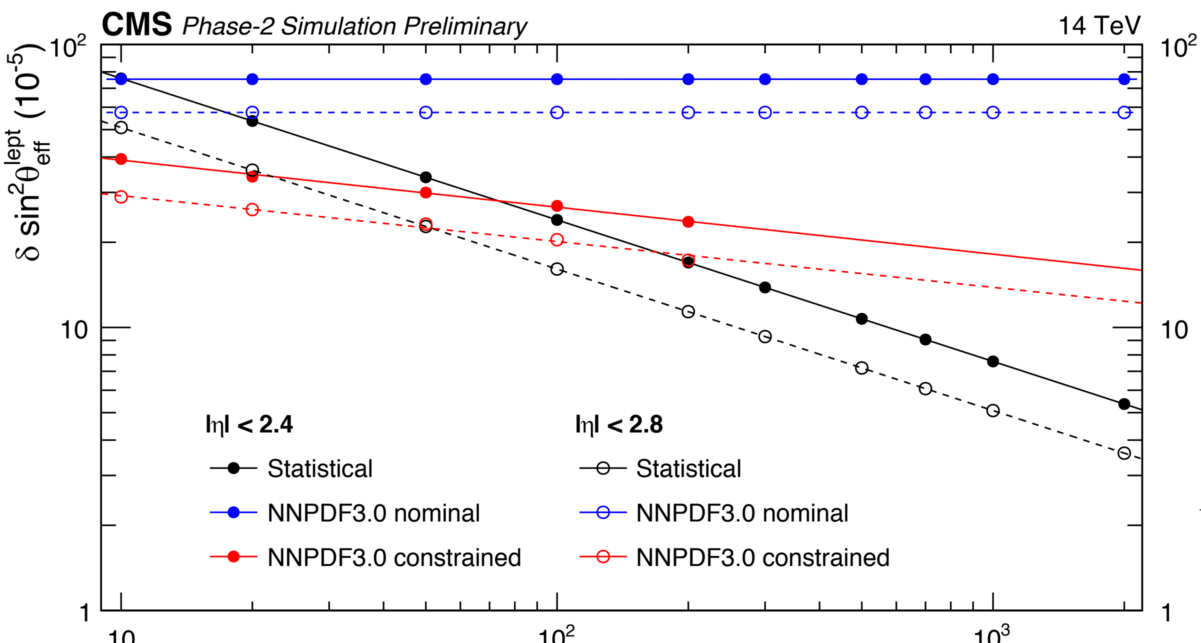
Measure the leptonic effective weak mixing angle ($\sin^2\theta^{lept}$) in dilepton events.

- Tension of about 3σ between the two most precise measurements (LEP and SLD)
- **Minimizing the χ^2** value between the simulated data and **template A_{FB} distributions** in 72 **dilepton mass** and **rapidity** bins
- The analysis is done at the generator level



$$\cos\theta^* = \frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{\sqrt{M^2(M^2 + P_T^2)}} \times \frac{P_z}{|P_z|}$$

$$A_{FB} = \frac{N(\cos\theta^* > 0) - N(\cos\theta^* < 0)}{N(\cos\theta^* > 0) + N(\cos\theta^* < 0)}$$

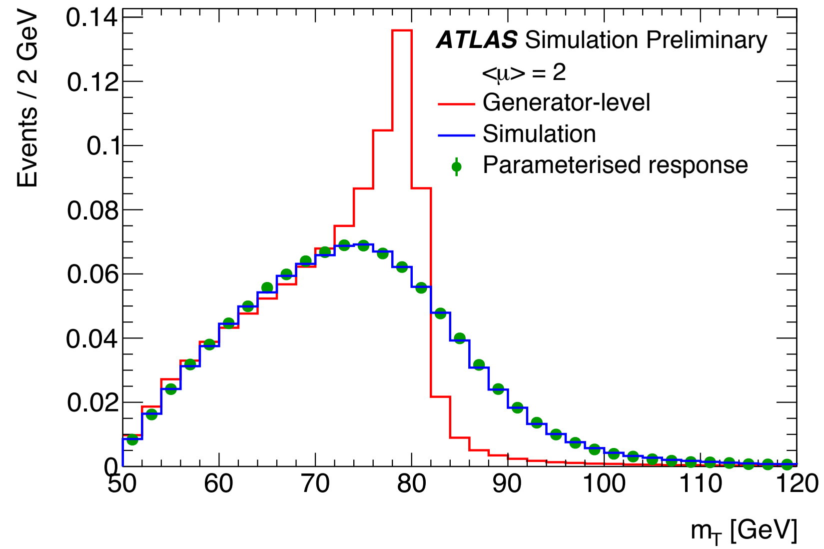


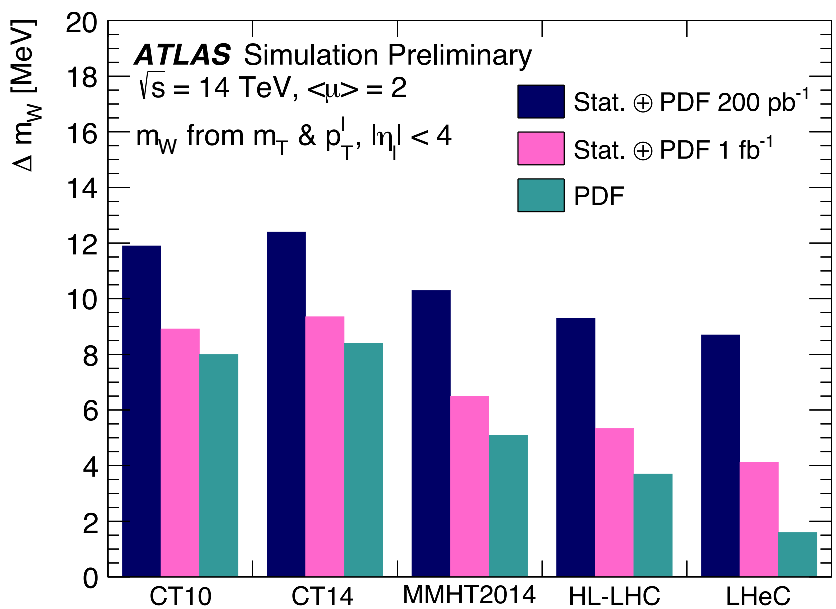
Measurement of the W boson mass

W boson mass measurement by ATLAS

- study potential of low pile-up data
- extended pseudo-rapidity range effect on decorrelation of PDF
- include PDF uncertainties from different sets

$\sqrt{s}$ [TeV]	Lepton acceptance	Uncertainty in m_W CT10
14	$\|\eta_\ell\| < 2.4$	16.0 (10.6 ⊕ 12.0)
14	$\|\eta_\ell\| < 4$	11.9 (8.8 ⊕ 8.0)
27	$\|\eta_\ell\| < 2.4$	18.3 (10.2 ⊕ 15.1)
27	$\|\eta_\ell\| < 4$	12.3 (7.5 ⊕ 9.8)
14+27	$\|\eta_\ell\| < 4$	10.1 (6.3 ⊕ 7.9)





Vector boson scattering

Electroweak production of a Z boson pair plus two jets

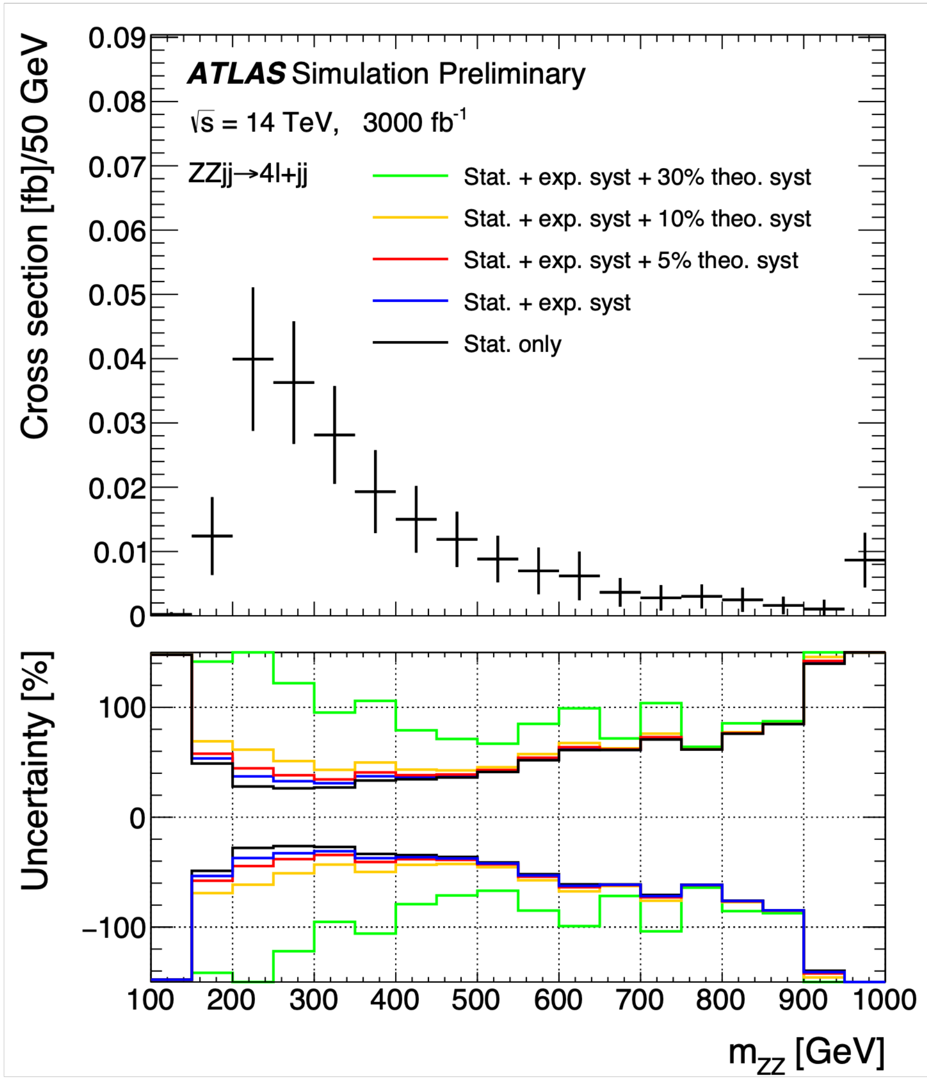
VBS is crucial for probing the mechanism of electroweak symmetry breaking in the Standard Model.

- At the HL-LHC, evidence of the EW-ZZjj processes becomes possible

Four lepton channel: two high-energy jets in the back and forward regions, with two vector bosons.

- Exploit the ZZ centrality

$$ZZ \text{ centrality} = \frac{|y_{ZZ} - (y_{j1} + y_{j2})/2|}{|y_{j1} - y_{j2}|}$$



Future colliders (FCC-ee)

	Observable	Measurement	Current precision	FCC-ee stat.	FCC-ee syst.	Dominant exp. error
Z pole	m_Z (keV)	Z Lineshape	91187500 ± 2100	5	< 100	Beam energy
Z pole	Γ_Z (MeV)	Z Lineshape	2495200 ± 2300	8	< 100	Beam energy
Z pole	R_l (×10³)	Z Peak ($\Gamma_{had}/\Gamma_{lep}$)	20767 ± 25	0.06	0.2 – 1	Detector acceptance
Z pole	R_b (×10⁶)	Z Peak (Γ_{bb}/Γ_{had})	216290 ± 660	0.3	< 60	$g \rightarrow bb$
Z pole	N_ν (×10³)	Z Peak (σ_{had})	2984 ± 8	0.005	1	Lumi measurement
Z pole	$\sin^2\theta_W^{eff}$ (×10⁶)	$A_{FB}^{\mu\mu}$ (peak)	231480 ± 160	3	2 – 5	Beam energy
Z pole	$1/\alpha_{QED}(m_Z)$ (×10³)	$A_{FB}^{\mu\mu}$ (off-peak)	128952 ± 14	4	< 1	Beam energy
Z pole	$\alpha_s(m_Z)$ (×10⁴)	R_l	1196 ± 30	0.1	0.4 – 1.6	Same as R_l
WW thresh.	m_W (MeV)	WW Threshold scan	80385 ± 15	0.6	0.3	Beam energy
WW thresh.	Γ_W (MeV)	WW Threshold scan	2085 ± 42	1.5	0.3	Beam energy
WW thresh.	N_ν (×10³)	$e^+e^- \rightarrow \gamma Z, Z \rightarrow \nu\nu, ll$	2920 ± 50	0.8	small	?
WW thresh.	$\alpha_s(m_W)$ (×10⁴)	$B_l = (\Gamma_{had}/\Gamma_{lep})_W$	1170 ± 420	2	small	CKM Matrix
$t\bar{t}$ thresh.	m_{top} (MeV)	Top Threshold scan	173340 ± 760 ± 500	17	< 40	QCD corr.
$t\bar{t}$ thresh.	Γ_{top} (MeV)	Top Threshold scan	?	45	< 40	QCD corr.
$t\bar{t}$ thresh.	λ_{top}	Top Threshold scan	μ = 1.28 ± 0.25	0.10	< 0.05	QCD corr.
$t\bar{t}$ thresh.	ttZ couplings	$\sqrt{s}$ = 365 GeV	± 30%	0.5 – 1.5%	< 2%	QCD corr

Table credit: A. Blondel

Characterising the Higgs boson

Complementarity and availability of results

Based as much as possible on the knowledge gathered from most recent analyses

- projections from the coupling combination
- dedicated truth-smearing studies for key analyses

Collaboration with LHC Higgs cross section Working Group

- 14 TeV and 27 TeV
- evaluated theory systematics

	ATLAS	CMS
Couplings	✓✓✓	✓✓✓
Differential xsec	✓✓	✓✓
Width	✓	
CPV	✓	✓✓
Rare decays	✓✓✓	✓✓
Di-Higgs	✓✓✓	✓✓✓
BSM	✓✓	✓✓

Legend: Past studies, 2017 TDRs, 2018 YR

Latest results: ATLAS CMS

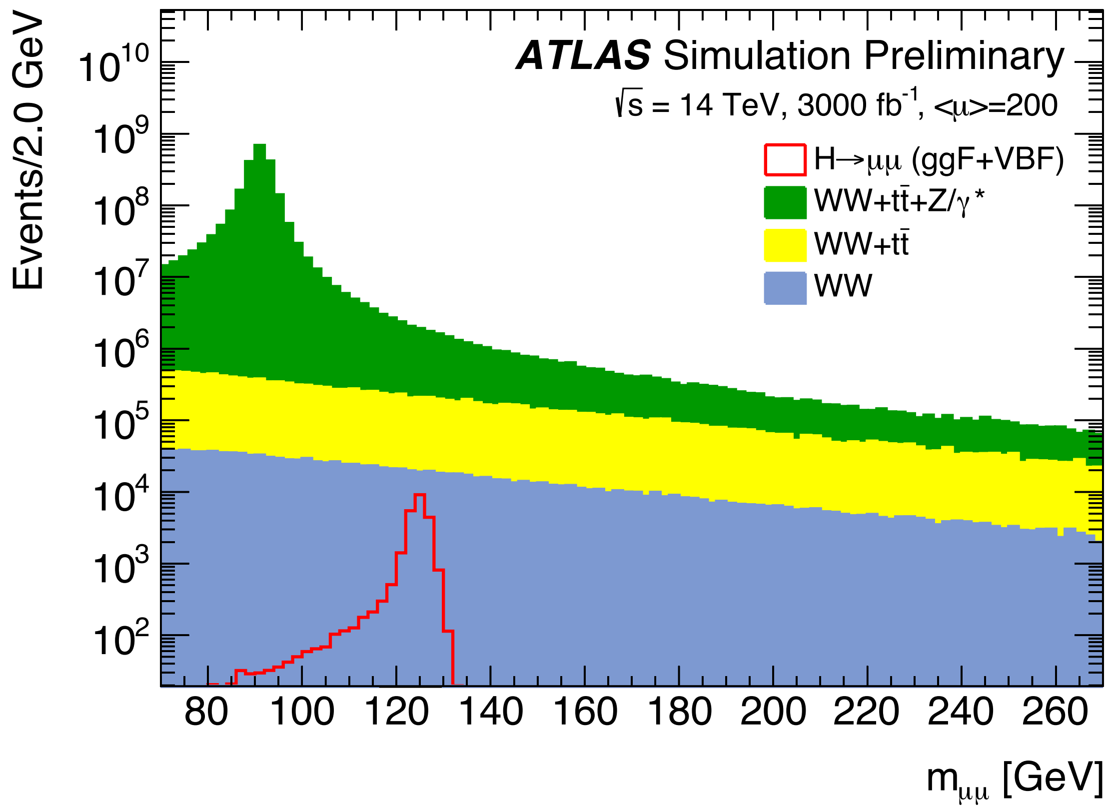
Higgs to pairs of muons

Couplings to second-generation fermions

- Opposite-charge muons with p_T > 15 GeV and |η| < 2.5
- Leading muon p_T > 25 GeV
- 110 < $m_{\mu\mu}$ < 160 GeV

Split the selected sample in subsets with different signal-to-background ratios

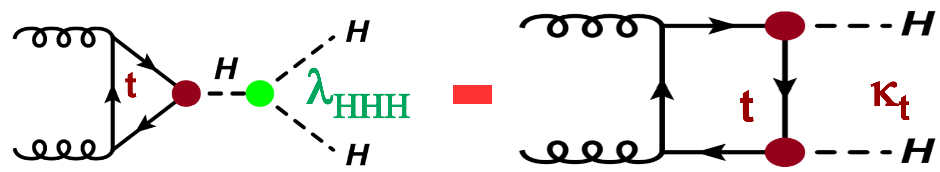
- a maximum likelihood fit to the di-muon invariant mass
- Systematic uncertainties are incorporated as nuisance parameters in the final fit



Scoping Scenario	$\langle\mu\rangle$	Overall significance	$\Delta\mu$ w/ syst. errors	$\Delta\mu$ w/o syst. errors
reference	200	9.5	±0.13	±0.12
middle	200	9.4	±0.14	±0.12
low	200	9.2	±0.14	±0.13

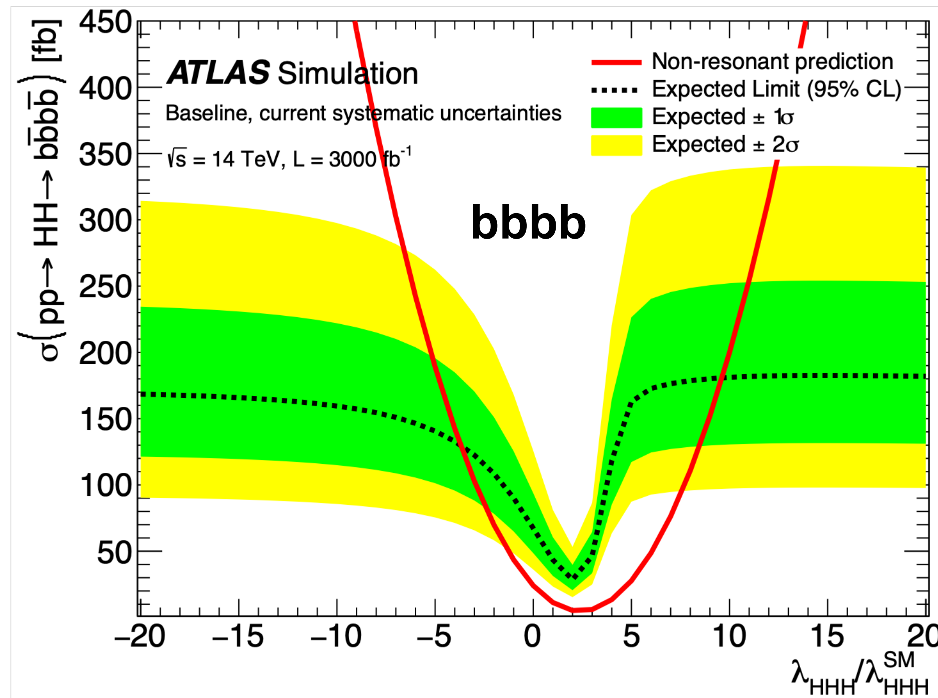
Double Higgs production

Ultra-rare processes

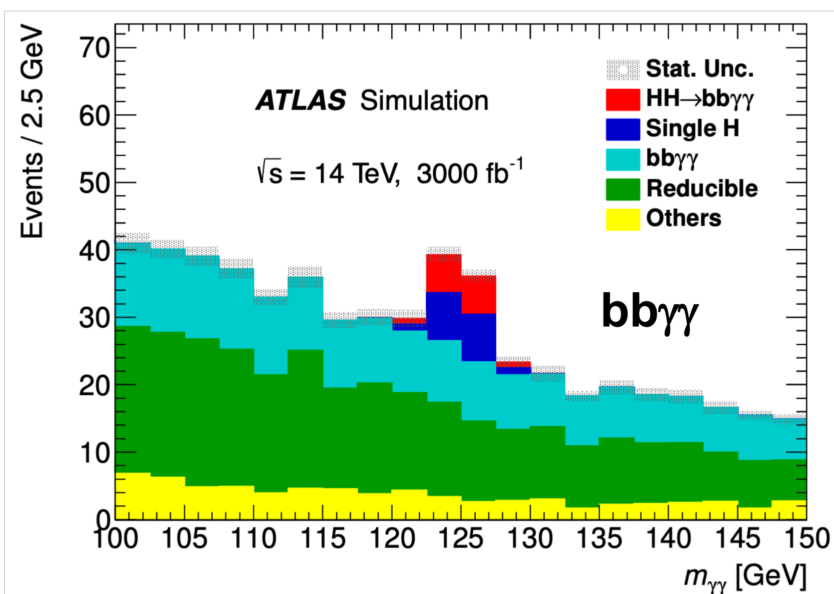


Plan to perform a combination to probe the expected reach for di-Higgs

- Measure λ_{HHH} (and k_t)
- Combination with CMS crucial
- Exploit three decay channels: bbbb, bbγγ and bbττ



$$0.2 < \lambda_{HHH}/\lambda_{HHH}^{SM} < 6.9$$



- Limited sensitivity (~1σ)
- Expect improvements and channel combination for YR

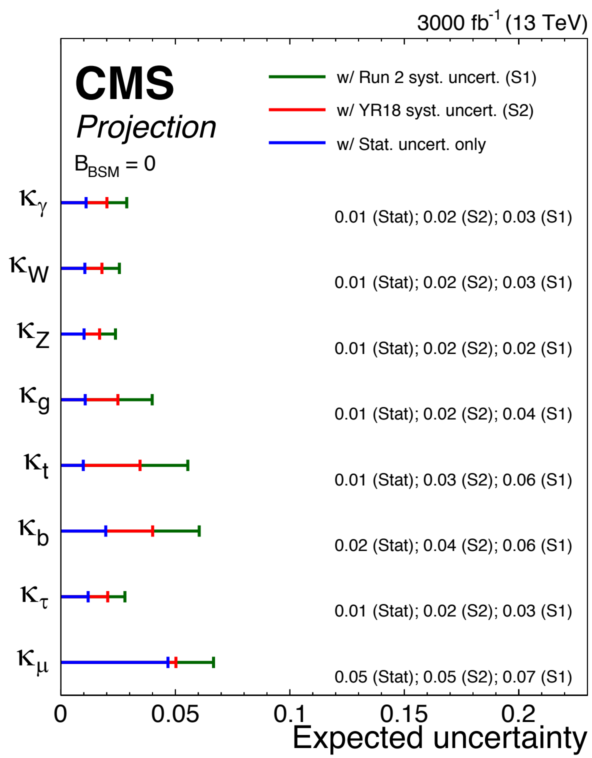
Higgs boson couplings

HL-LHC and beyond

CMS-PAS-FTR-18-011

CMS prospects for measuring Higgs boson **couplings**.

- Extrapolated from Run-2 results with 36 fb^{-1}
- Identical detector performances
- Two systematic uncertainty scenarios (Run-2 and halved)



g_{Hxx}	FCC-ee	FCC-hh	FCC-eh
ZZ	**0.15 %**		
WW	**0.20%**		
Γ_H	**1%**		
$\gamma\gamma$	1.5%	**<1%**	
$Z\gamma$	--	**1%**	
tt	13%	**1%**	
bb	**0.4%**		0.5%
$\tau\tau$	**0.5%**		
cc	**0.7%**		1.8%
$\mu\mu$	6.2%	**2%**	
uu,dd	H→ $\rho\gamma$?	H→ $\rho\gamma$?	
ss	H→ $\phi\gamma$?	H→ $\phi\gamma$?	
ee	**ee → H**		
HH	30%	**~3%**	20%
inv, exo	<0.45%	**10^{-3}**	5%

Table credit: A. Blondel

Beyond the Standard Model

Supersymmetry

New resonances

Searches for dark matter

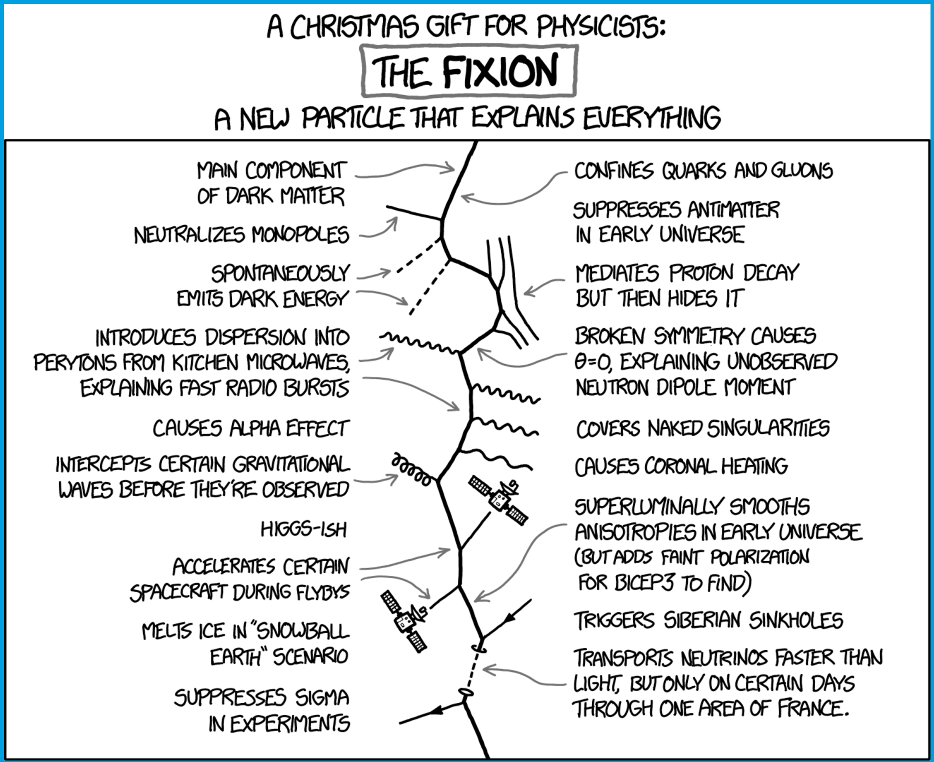


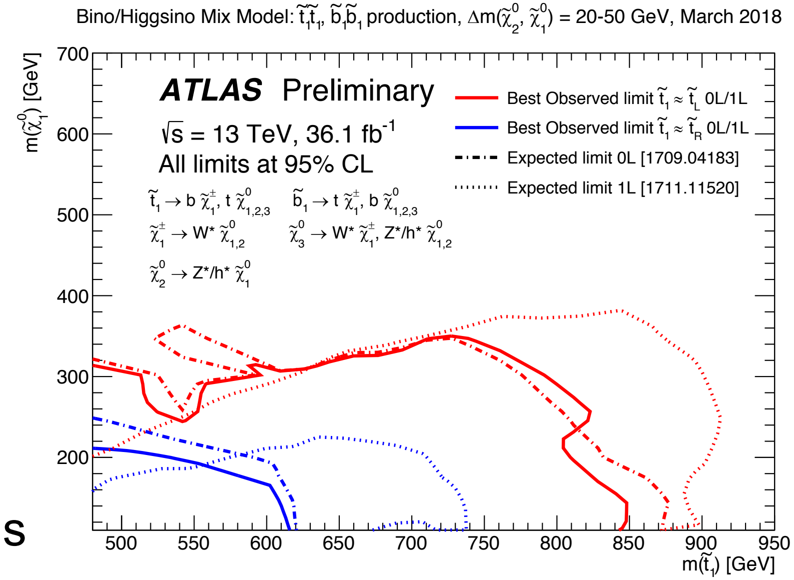
Image credit xkcd: https://xkcd.com/1621/

Supersymmetry

Theoretically sound, predictive framework

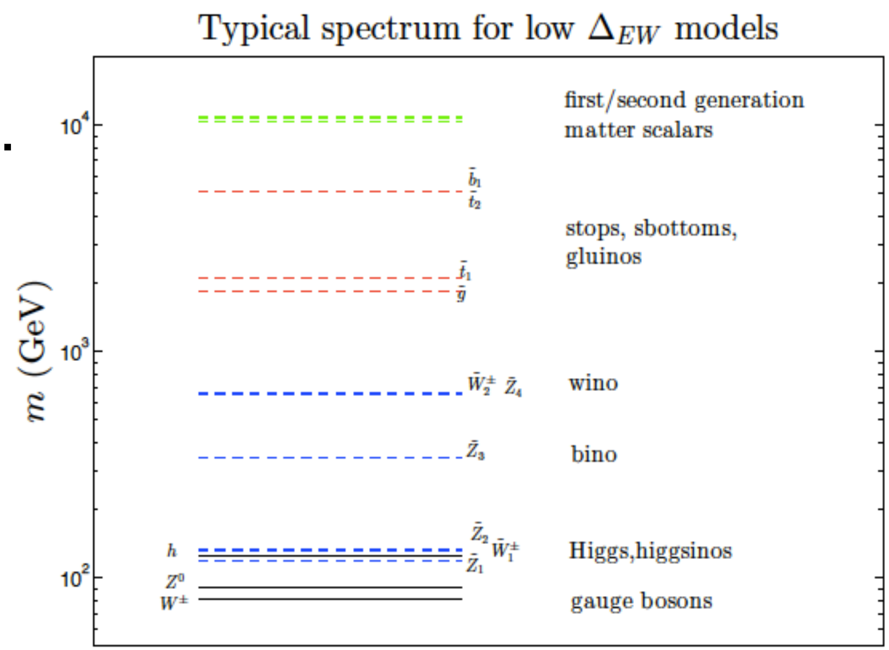
But where is SUSY?

- Barbieri-Giudice 3% naturalness
  - $m(\tilde{g}) \lesssim 1000$ GeV
  - $m(\tilde{t}_1) \lesssim 500$ GeV
- LHC limits severly constraining these models



Is SUSY unnatural? Is it dead? **Not really…**

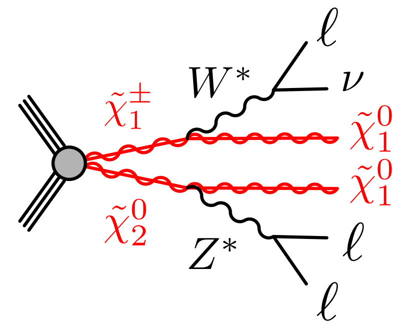
- Considering the electroweak fine-tuning (Δ_{EW}), SUSY is natural (3-10%) with:
  - $m(\tilde{g}) \lesssim$ 5-6 TeV
  - $m(\tilde{t}_1) \lesssim$ 2-3 TeV
  - $m(\tilde{q}) \lesssim$ 10-20 TeV
- Need **low μ ~ 100-300 GeV**

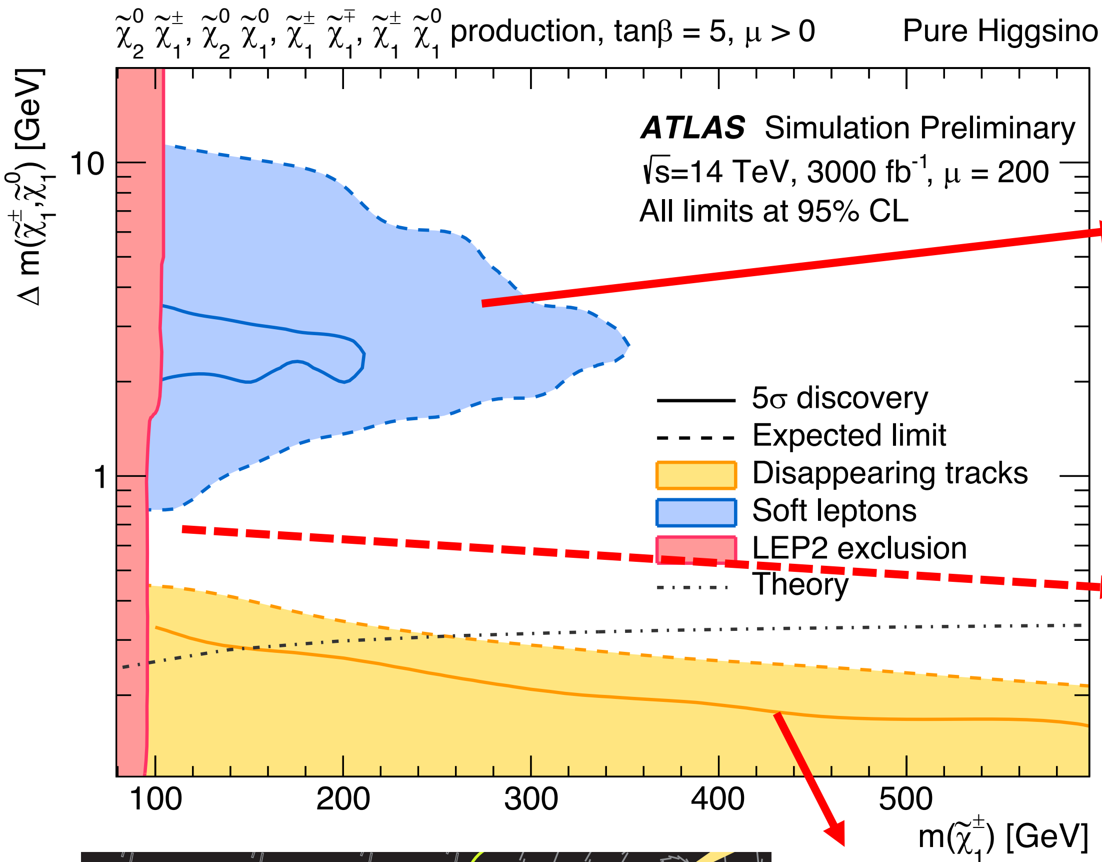


H. Baer, FNAL HL/HE-LHC workshop

Search for Higgsinos

One of the focuses of the HL-LHC programme



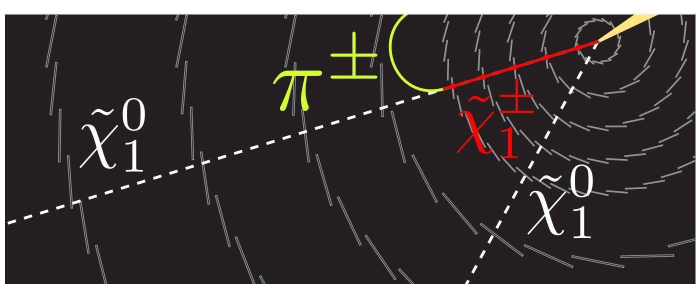


Exploit ISR jet + E_T^{miss} + soft leptons

- Challenging lepton identification

Gap that needs to be filled!

- Mono photon from FSR? VBF?

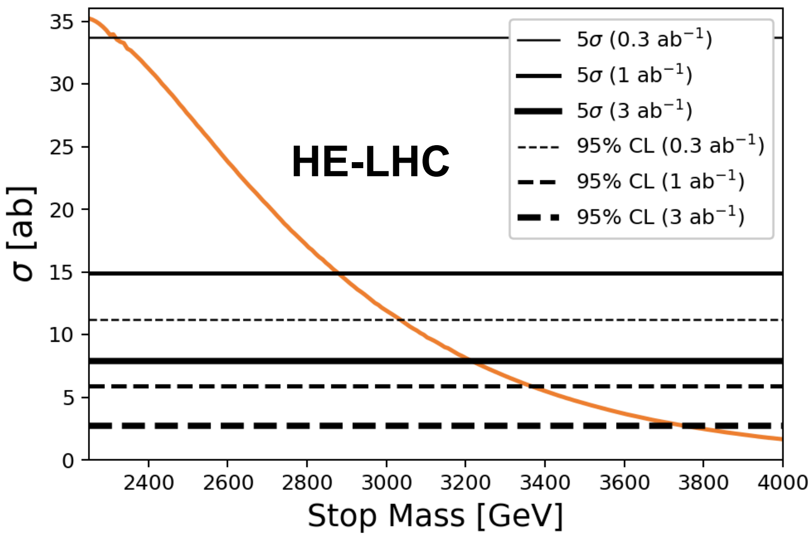


Disappearing tracks (long-lived charginos)

- New reconstruction options
- Challenging tracking environment!

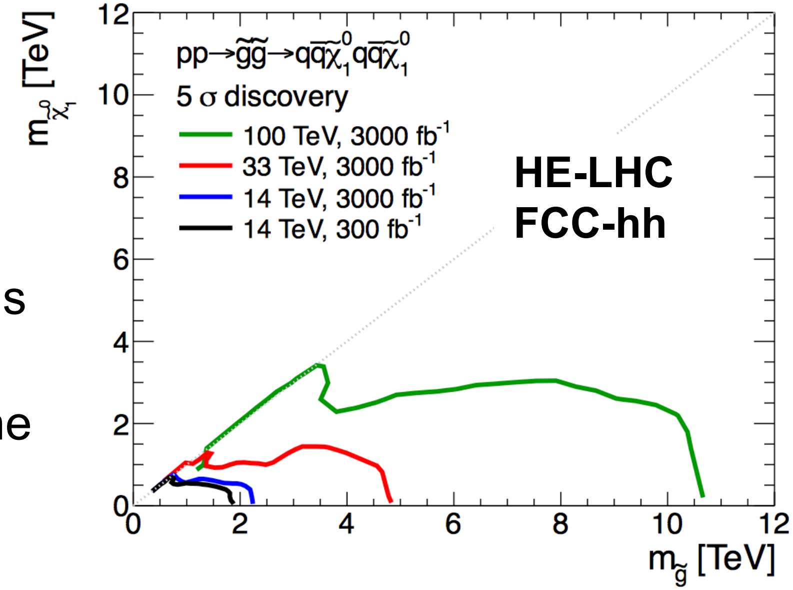
The hunt for the natural spectrum

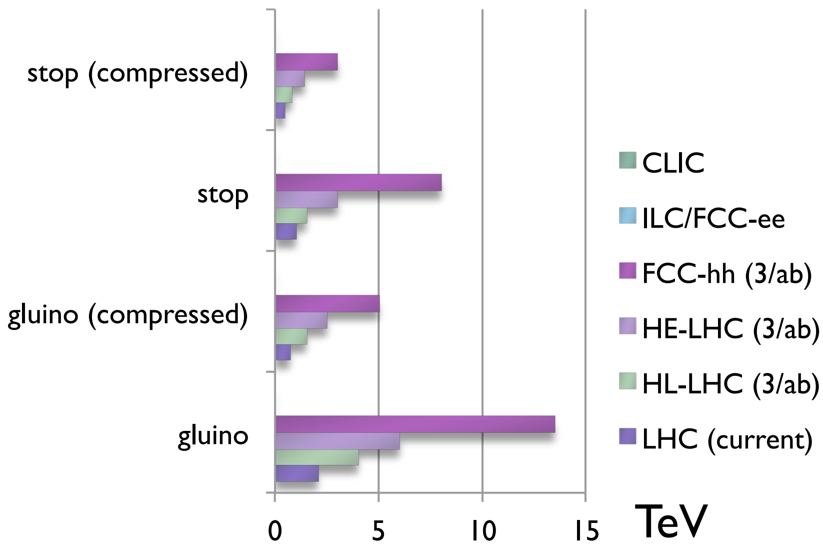
PRD96 (2017) 115008



Various projections available beyond the HL-LHC

JHEP04 (2014) 117





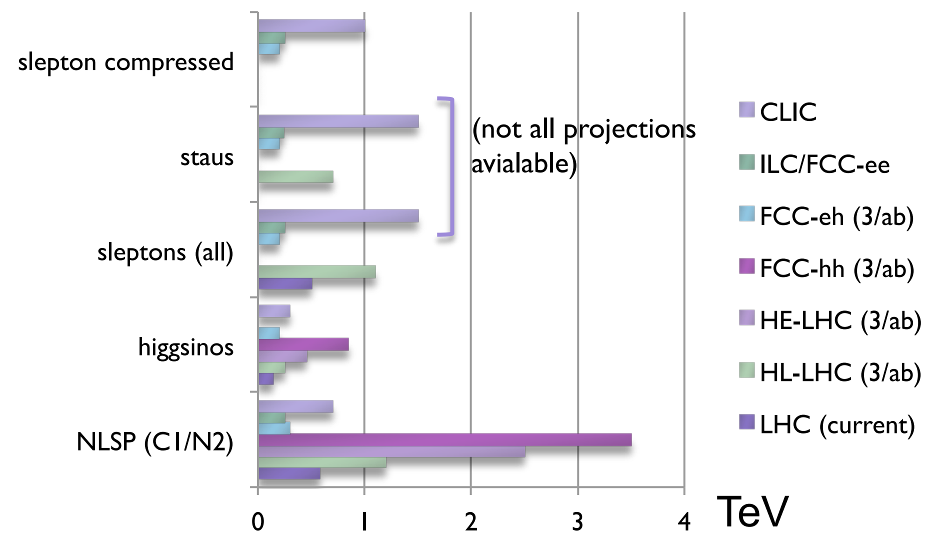
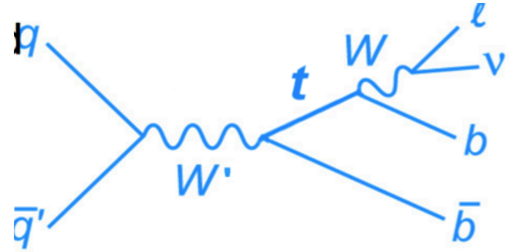


Image credit: M. D'Onofrio

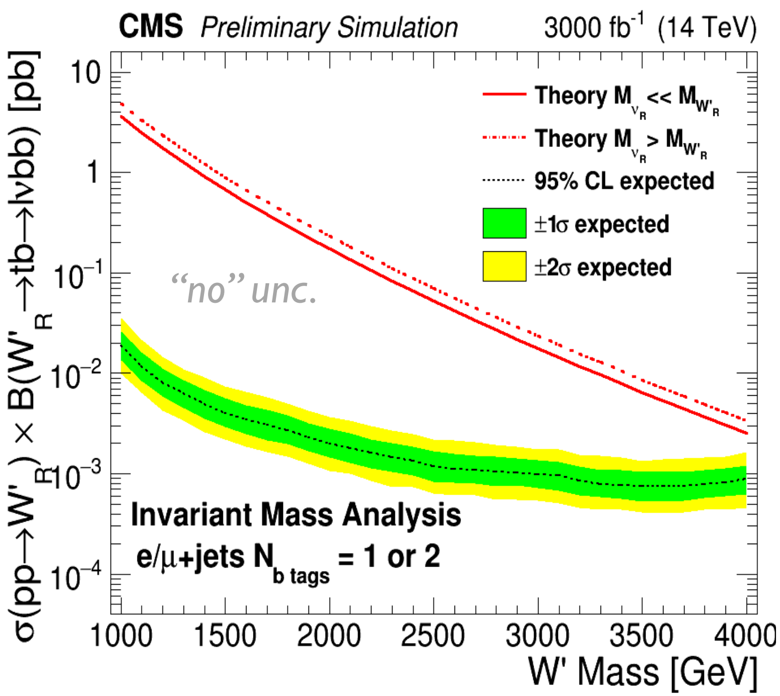
Heavy W prime

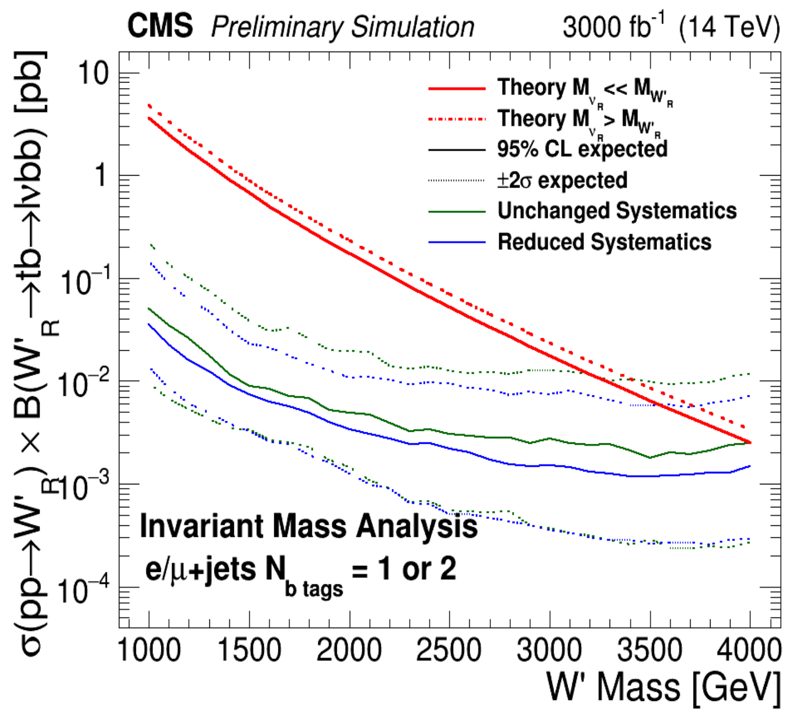
Search in tb channel



Projection assumes narrow width approximation from early Run-2 analyses.

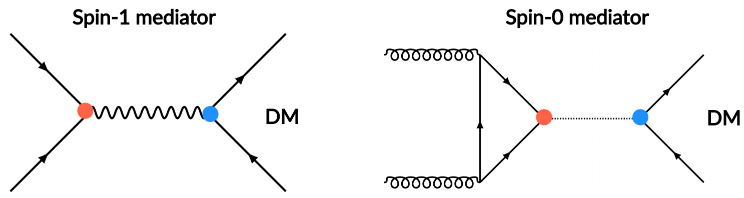
- Studied dependency on uncertainty evolution





Heavy resonances at future colliders: the higher the energy, the better…

Dark Matter searches



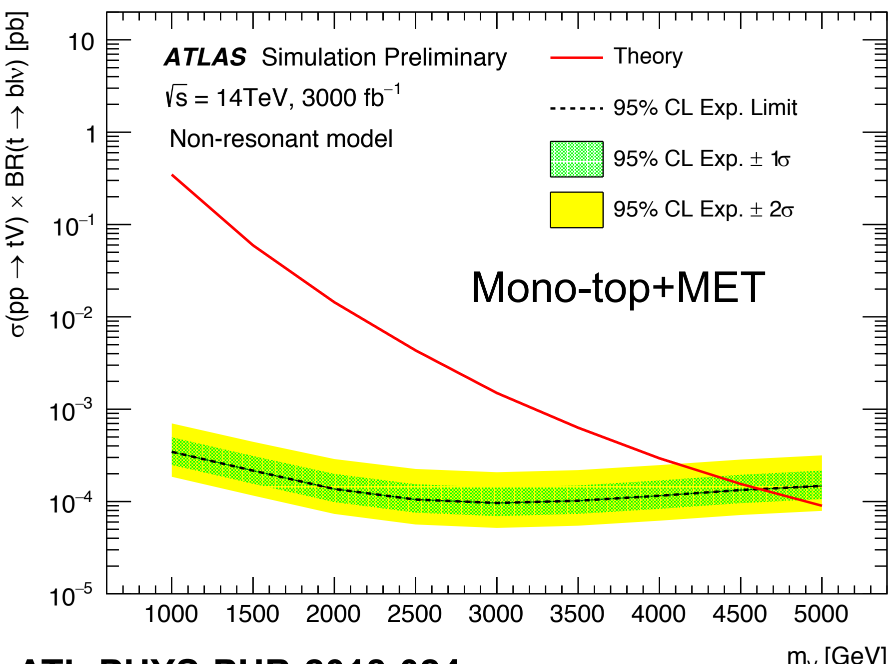
Simplified models with few free parameters:

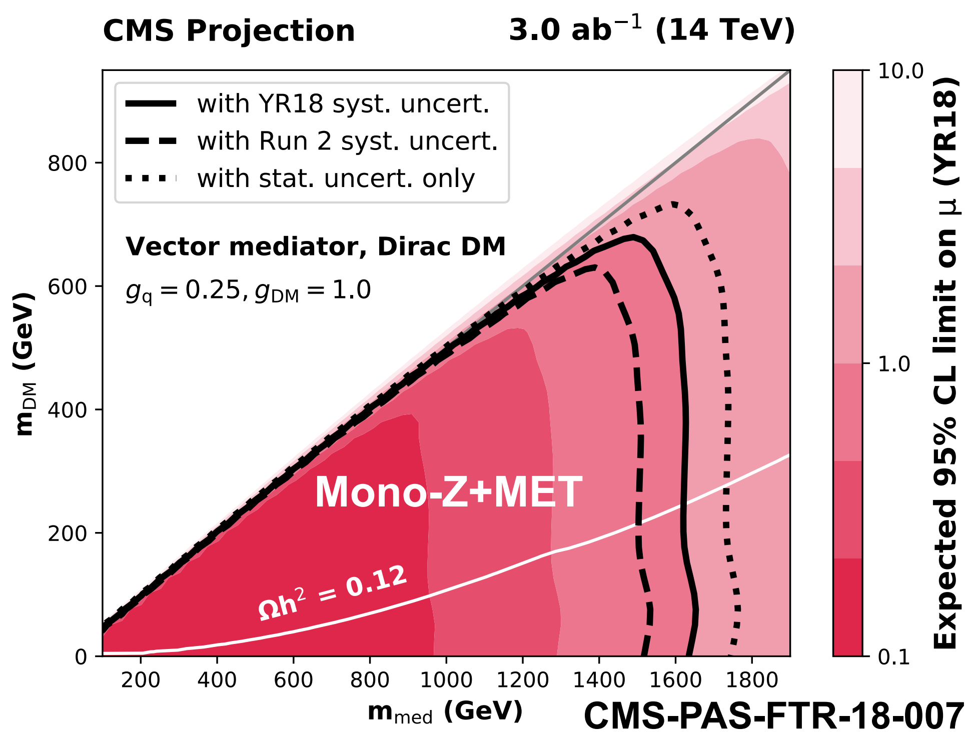
m_{med}, m_{DM}, med-quark coupling, med-DM coupling

Foreseen by full theories as SUSY but also searched with ‘simplified models’

Strategy: search for associated production with one of many SM tags:

- jet, photon, Z, single/double top, bottom, Higgs





ATL-PHYS-PUB-2018-024

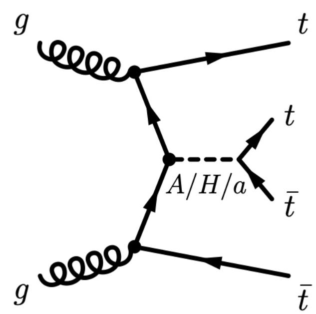
CMS-PAS-FTR-18-007

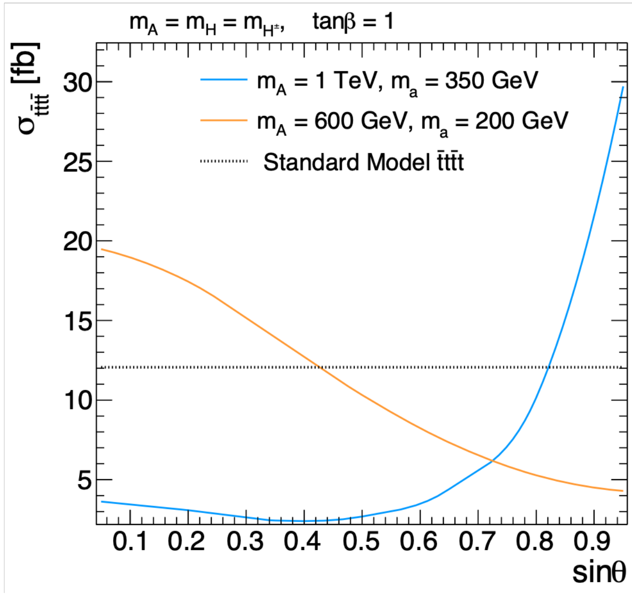
Four top quarks in 2HDM+a

Search in multi-lepton channel

2HDM+*a* models are considered

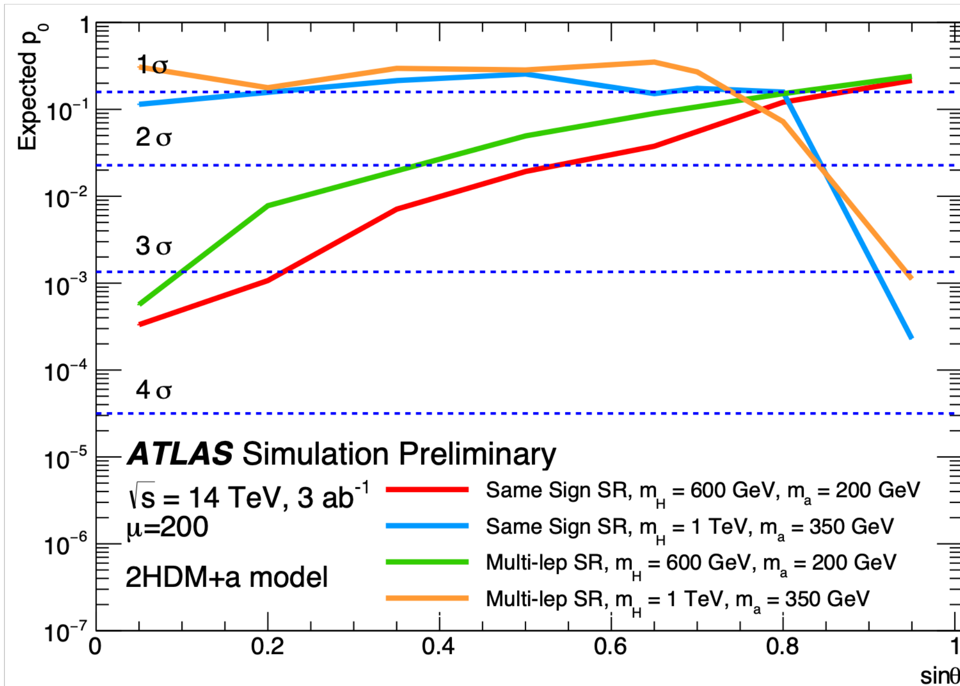
- type-II coupling structure
- the lightest CP-even state of the Higgs-sector, *h*, can be identified with the SM Higgs boson





Select at least two leptons with the same electric charge or at least three or more leptons

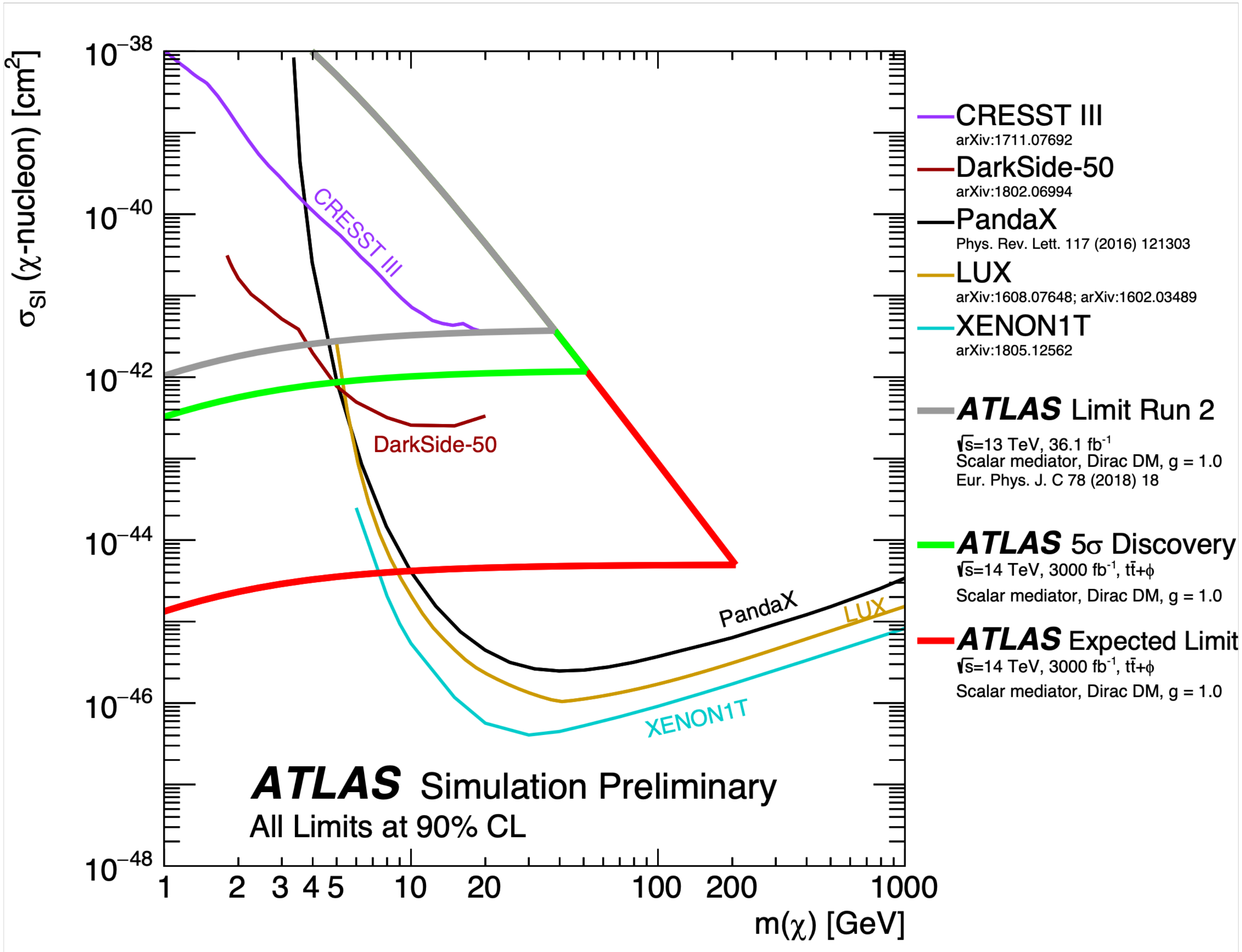
- Potential observations for a range of masses and mixings
- Adding the fully hadronic, semi-leptonic can further improve



Complementarity with Direct Detection

Recasting a di-lepton search for **DM+top quark pairs**

- Search for scalar/pseudoscalar mediator decaying to invisible
- Yukawa-like interactions

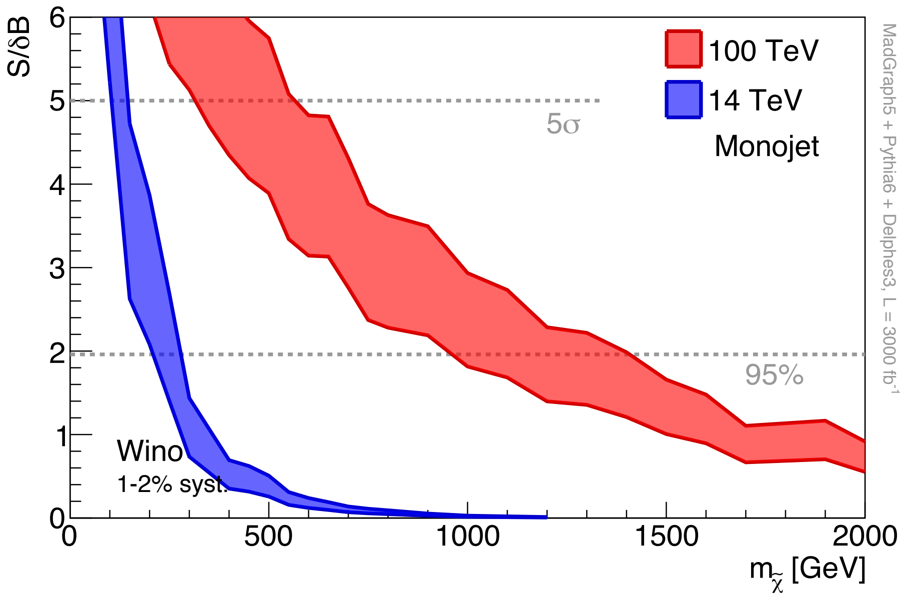


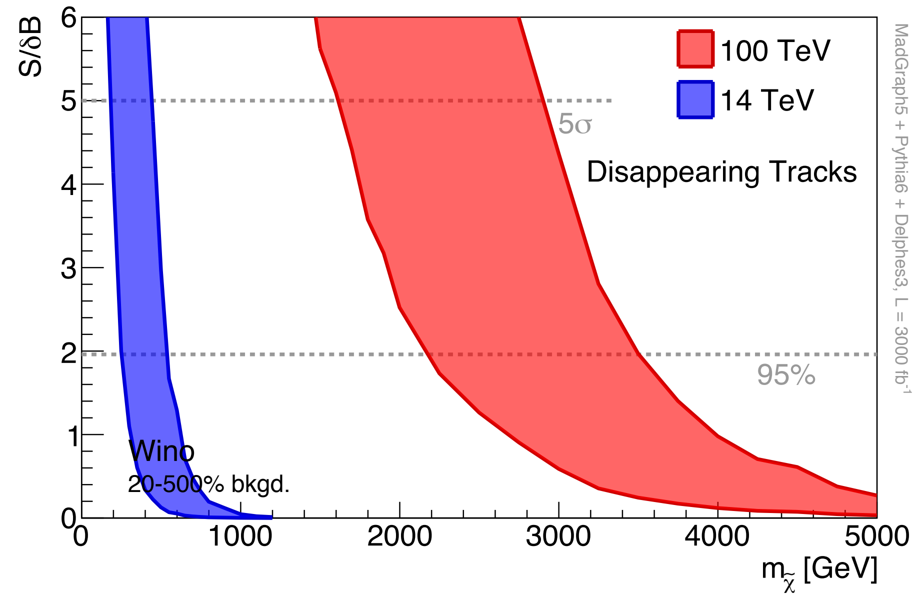
arXiv:1511.06495

Dark matter at the FCC-hh

Assume wino-like DM particles

- Extrapolation of mono-jet and disappearing track searches are expected to start covering the multi-TeV range
- Higgsino-like sensitivity just below the TeV





Summary

Several SM shortcomings require investigations that are expected to extend beyond the scope of the LHC.

I have presented some examples highlighting the reach of:

- Crucial SM precision measurements
- Direct searches for BSM phenomena

in the context of a variety of (possible) future collider facilities.

Other 50+ years of interesting physics lie ahead!

Thank you