# Physics opportunities at the HL-LHC

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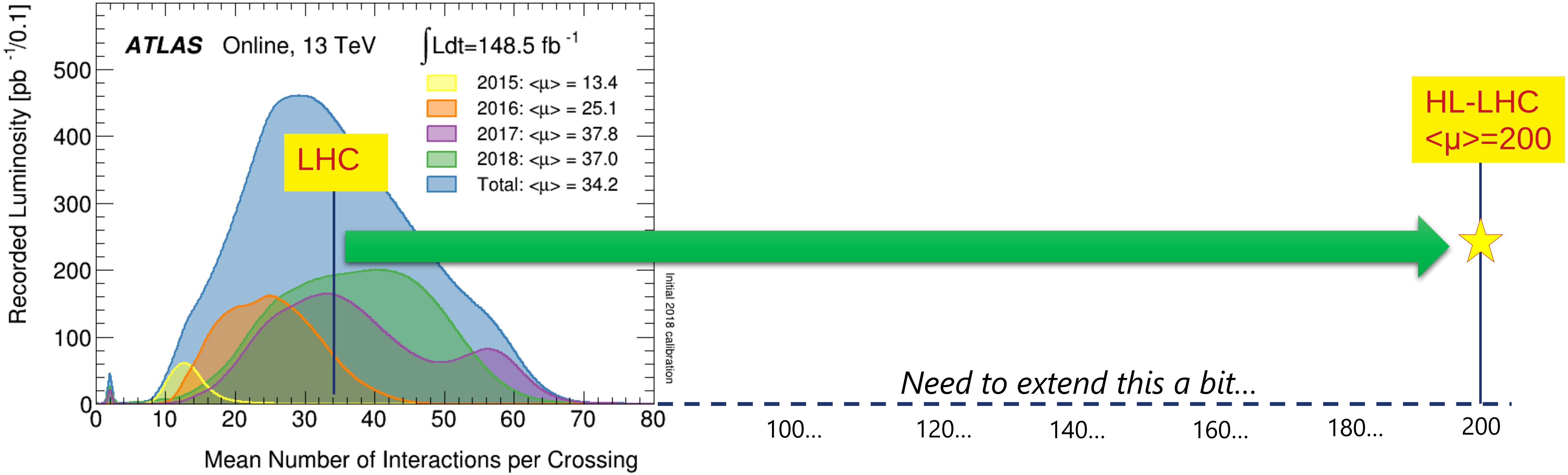
# The High-Luminosity LHC Upgrade


- The **High-Luminosity LHC (HL-LHC)** represents the ultimate evolution of LHC machine performance
- Operation at **up to $L=7.5\cdot10^{34}$ Hz/cm$^2$** (LHC run-2: $2\cdot10^{34}$) to collect up to **3000fb-1** of int. luminosity

# The High-Luminosity LHC Upgrade

- HL-LHC is **approved** and preparations have made significant progress
- Promise vast increase of statistical reach
- But high luminosity also implies **challenging experimental conditions**
  - ➢ Up to **200** p-p collisions per bunch crossing



# The High-Luminosity LHC Upgrade

Extensive **detector upgrades** enable experiments to operate under HL-LHC conditions

- Could fill a talk of its own (not today)
- Some reading for general purpose experiments below!

**All-new Tracking Detectors**

CERN-LHCC-2017-005 CERN-LHCC-2017-009
CERN-LHCC-2017-021

- Extended acceptance - $|\eta|<4$!

**Trigger & DAQ upgrades**

CERN-LHCC-2017-013 CERN-LHCC-2017-014
CERN-LHCC-2017-020

**Calorimeter upgrades**

CERN-LHCC-2017-011 CERN HCC-2017-018
CERN-LHCC-2017-019 CERN-LHCC-2017-023

**Muon system upgrades**

CERN-LHCC-2017-012 CERN-LHCC-2017-017

**New: Timing detectors**

CERN-LHCC-2018-023 CERN-LHCC-2017-027

- Use of timing information to improve pileup rejection

**Detector Performance studies**

ATL-PHYS-PUB-2019-005 CMS-NOTE-2018-006

# Physics opportunities at the HL-LHC

Development of **experiment upgrades at advanced stage** – approaching production readiness

- Simulataneously: Systematic **exploration of physics potential** at HL-LHC by experiments and theorists
  - Year-long **workshop** in 2017-18
  - ➢ Identify new opportunities, achievable reach, potential limitations
  - ➢ Provide input to European Strategy process

Generally profit from HL-LHC **in several ways:**

- Vastly increased size of dataset
  - Reduced **statistical** uncertainties
  - Reduced **experimental systematic** uncertainties – size of calibration dataset
  - Reduced **background** uncertainties – precise constraints through high-statistics control measurements
- Improved detectors – new capabilities (e.g. forward tracking, timing)

# General overview of HL-LHC physics programme

**Wide program** covering nearly all areas of hadron collider physics

**Main pillars** as identified for European Strategy input:

- Detailed exploration of **electroweak SM** and **top** sectors
  - Precision measurements (W/top masses, weak mixing angle, …)
  - Rare signatures such as VBS, 4-top, FCNC top decay…
- Precise characterisation of the **Higgs boson**
  - Coupling determination, total width, mass, CP, self coupling,…
  - Search for additional BSM Higgs bosons
- **QCD** measurements – side effect of constraining PDF uncertainties using LHC data
- **Flavour physics** programme
  - Constraints on CKM unitarity, rare b-decays, CPV in charm sector, LFV in tau, …
- Dedicated searches for **BSM physics**
  - Prompt and long-lived signatures, DM, heavy resonances, …
- **Forward physics** programme
- Extensive set of **high-density QCD** measurements – both in Heavy Ion and p-p collisions

**Today:**
Focus on **p-p programme** at the **ATLAS** and **CMS** experiments

- Only able to show a **small subset** of examples

➢ Wide range of further results, including prospects for an energy upgrade, available!

**Collections of studies**
arXiv:1902.04070 – SM Physics
arXiv:1902.00134 – Higgs Physics
arXiv:1812.07831 – BSM Physics

**Results *not* covered in this talk**
arXiv:1808.08865 – Physics case for LHCb Upgrade II
arXiv:1812.07638 – Flavour physics at HL/HE-LHC
arXiv:1812.06772 – High-density QCD at the HL-LHC

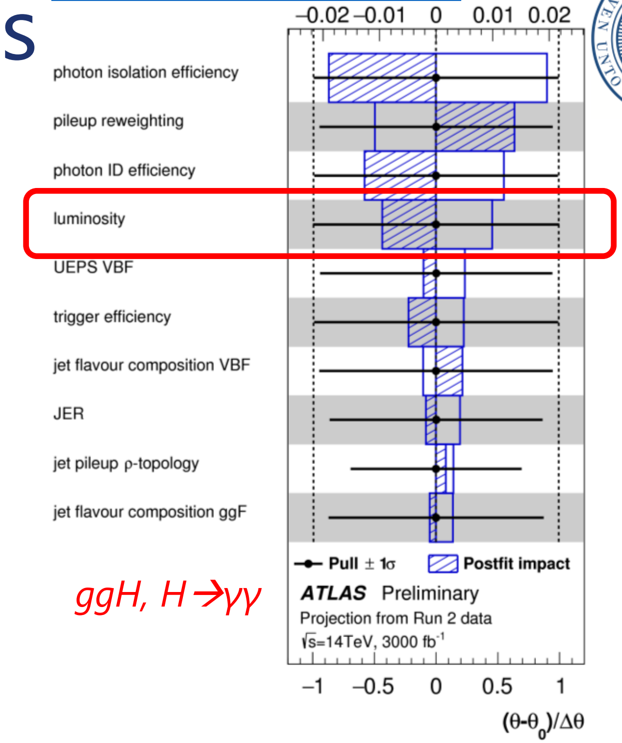
# Setting the stage for precision measurements

- With a dataset of 3ab$^{-1}$, **statistical** and **experimental** systematic uncertainties will be significantly reduced
  - ➢ Precision calibration with wealth of available statistics
- Role of **theory/PDF** and **luminosity** uncertainties will become more prominent

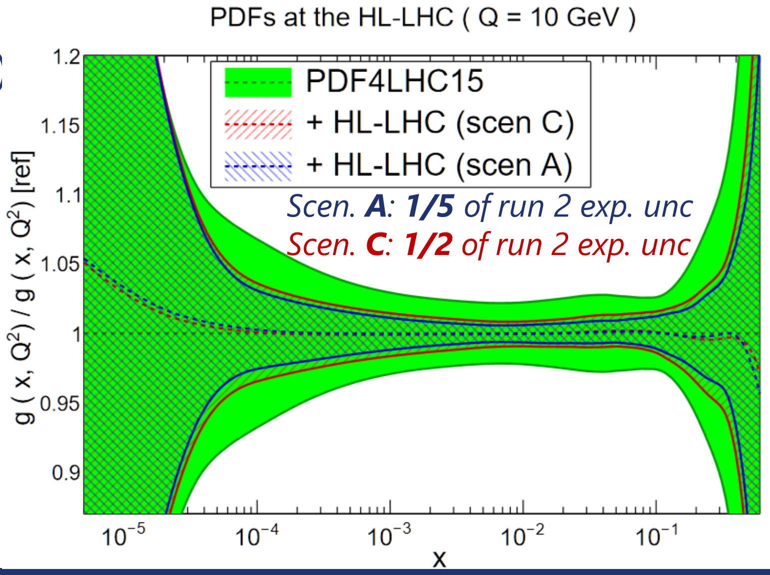
Vital to also **reduce** these uncertainties to fully exploit HL-LHC

- New generation of **precision PDF sets** including HL-LHC data
  - ➢ Exploit **improved experimental precision**
  - ➢ Profit from **enhanced forward acceptance** of upgraded experiments (|η|<4)
- Improved **luminosity calibration** – aiming for 1% precision
  - High-precision **luminosity detectors** in experiment upgrades
  - Refined **Van-der-Meer** scan analysis techniques
  - New calibration strategies (example: Z counting)
- Increasing availability of **higher order** theory calculations

ATL-PHYS-PUB-2018-054




*ggH, H→γγ*

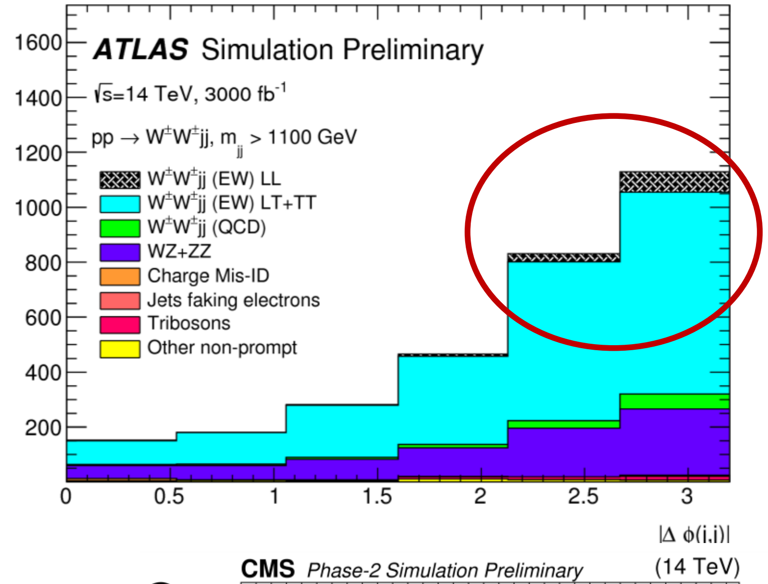


# Vector boson scattering

Status today: Talk by P. Azzurri

- **Vector boson scattering (VBS):** Rare process of great interest
- Three channels with massive gauge bosons: **WW**, **WZ**, **ZZ**
  - Signature: Gauge boson pair + 2 forward jets
  - ➢ Shared by **non-VBS** electroweak production and **QCD** production
  - ➢ Of particular interest: **Longitudinal** VV scattering amplitude
  - ➢ Preferred tool: **leptonic** final states

➢ **Low rates:** All processes still **statistically limited**




*ATLAS-CONF-2018-030*

*Phys. Rev. Lett. 120 (2018) 081801*

WW scattering: Expect measurement at **well below 10%** precision (currently: 20%)

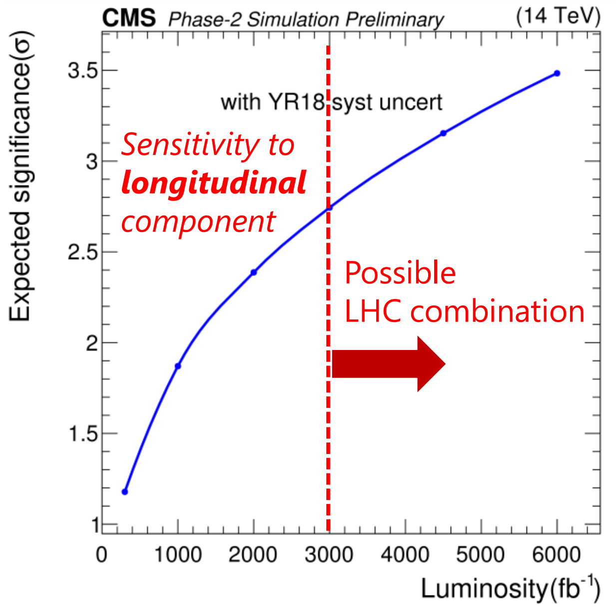
- **Forward tracking** capabilities of upgraded detectors help
  - suppress **pileup jets**
  - suppress WZ/ZZ/ttbar (additional leptons)
- Analysis will be **systematically** limited
  - ➢ importance of **precision calibration** to reduce experimental uncertainties
- Can extract **longitudinal component** from azimutal angle between jets

➢ Potential for **evidence** for longitudinal WW scattering when combining data from both experiments

*CMS-PAS-FTR-18-005*

*ATL-PHYS-PUB-2018-052*

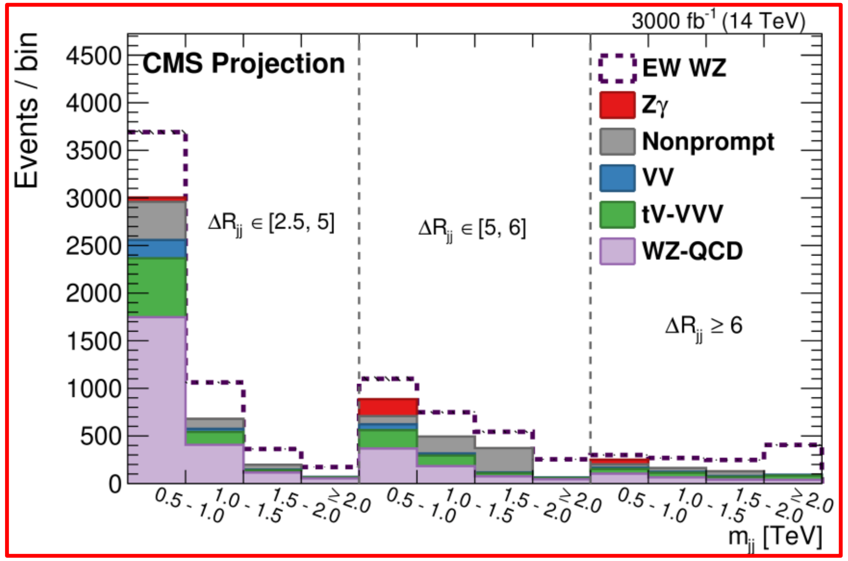
*ATL-PHYS-PUB-2018-022*

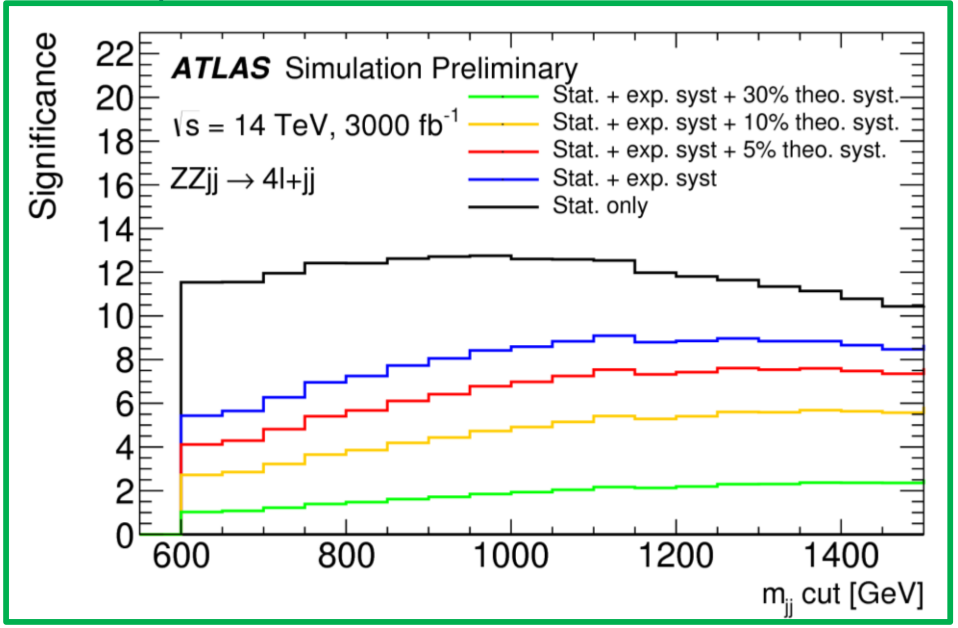


# Vector boson scattering

**WZ and ZZ scattering: Challenging discrimination against QCD production**

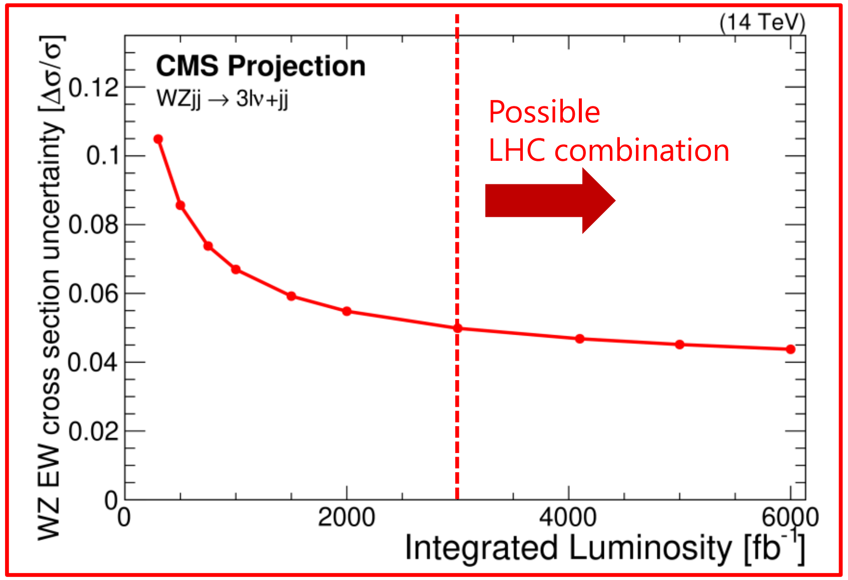
- Currently: arXiv:1708.02812 arXiv:1812.09740 arXiv:1901.04060
  - WZ observed at ATLAS, approaching evidence at CMS, measurement at ~30%
  - ZZ subject of CMS search, 2.7σ
- **HL-LHC:** Both in reach of observation and precise measurement at 6% / 10-40% level
- In particular for ZZ: **Theory** uncertainty on QCD ZZjj may be **limiting factor**
  - Important to exploit HL-LHC measurements to improve
- Longitudinal component: Constrained at ~60-75% level when combining experiments




CMS-PAS-FTR-18-014
CMS-PAS-FTR-18-038
ATL-PHYS-PUB-2018-023
ATL-PHYS-PUB-2018-029

| Process | $W^\pm W^\pm$ | $WZ$ | $WV$ | $ZZ$ |
|---|---|---|---|---|
| Final state | $\ell^\pm\ell^\pm jj$ | $3\ell jj$ | $\ell jjjj$ | $4\ell jj$ |
| Precision | 6% | 6% | 6.5% | 10–40% |
| Significance | $> 5\sigma$ | $> 5\sigma$ | $> 5\sigma$ | $> 5\sigma$ |

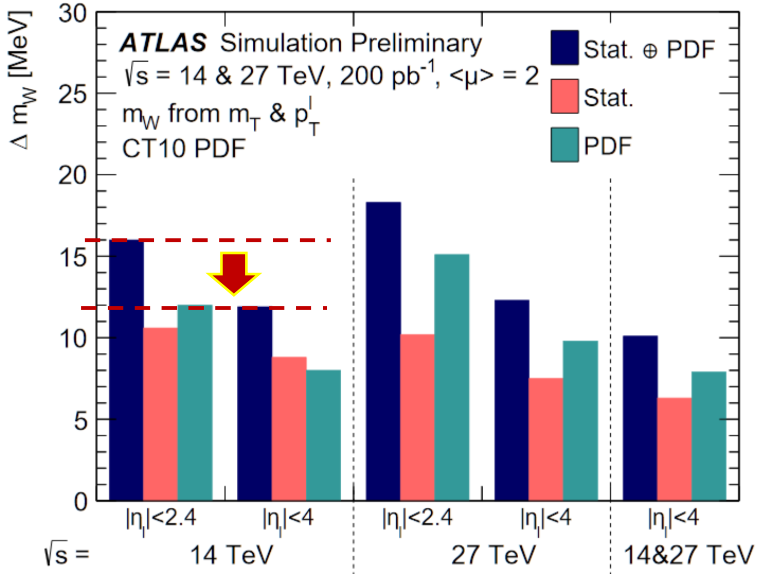


# Application of ultimate HL-LHC precision: **W boson mass**

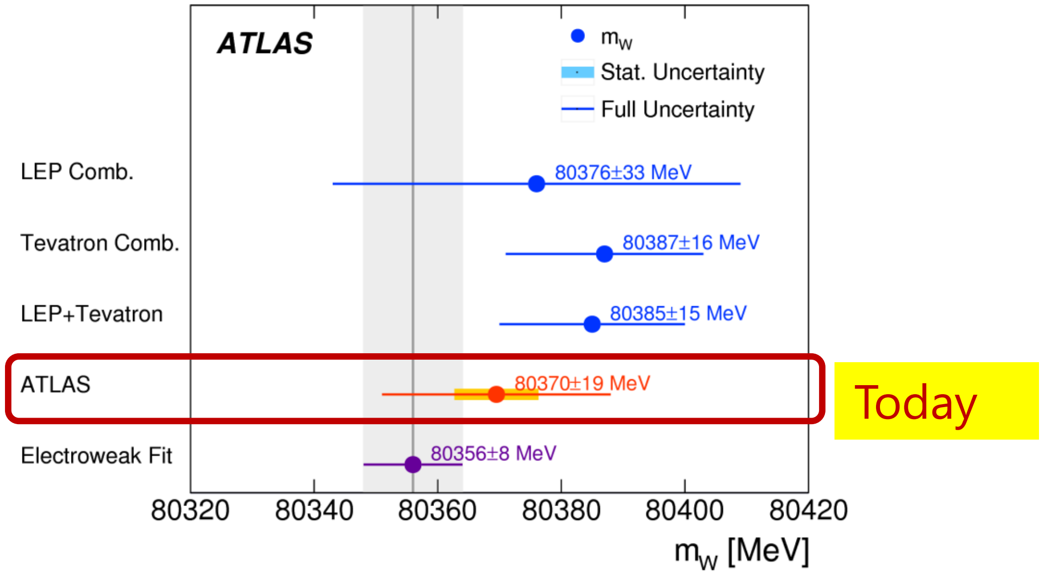
- One goal at the LHC: Improve **W boson mass** measurement
  - ➢ Require precise understanding of W boson recoil
  - ➢ Systematically limited already with existing dataset

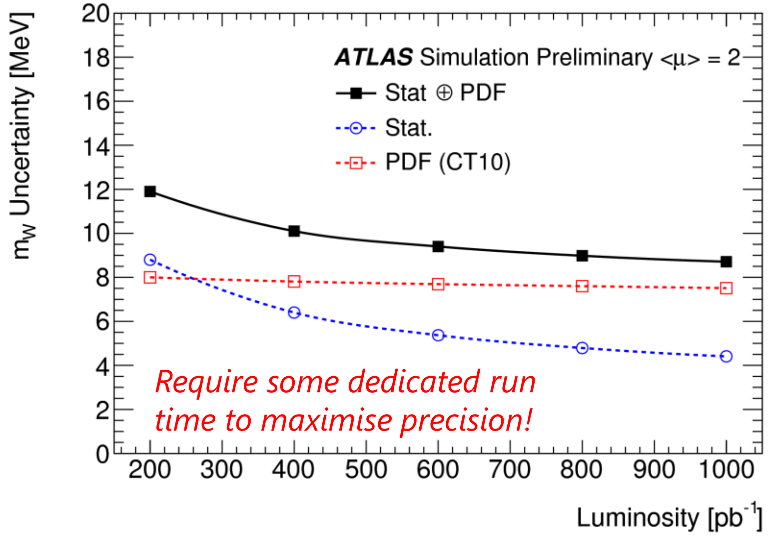
- Dedicated **low-pileup** run to obtain clean sample
- Significant precision improvement through **forward tracking** capabilities of HL-LHC detectors – also reduces PDF uncertainties
- Further gain through precision HL-LHC PDF sets
  - ➢ Ultimate projected HL-LHC precision: Below 10 MeV

*ATL-PHYS-PUB-2018-026*




*Eur. Phys. J. C 78 (2018) 110*



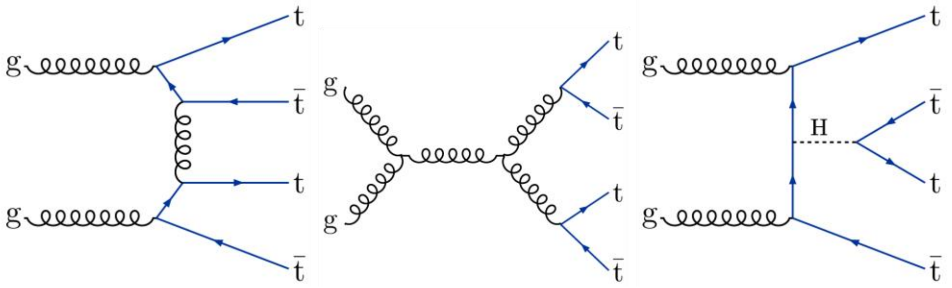



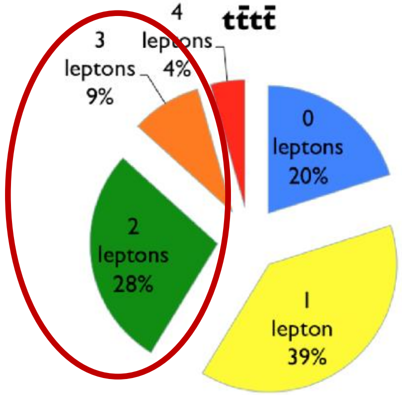
# 4-top production

Status today: Talk by D. Noonan

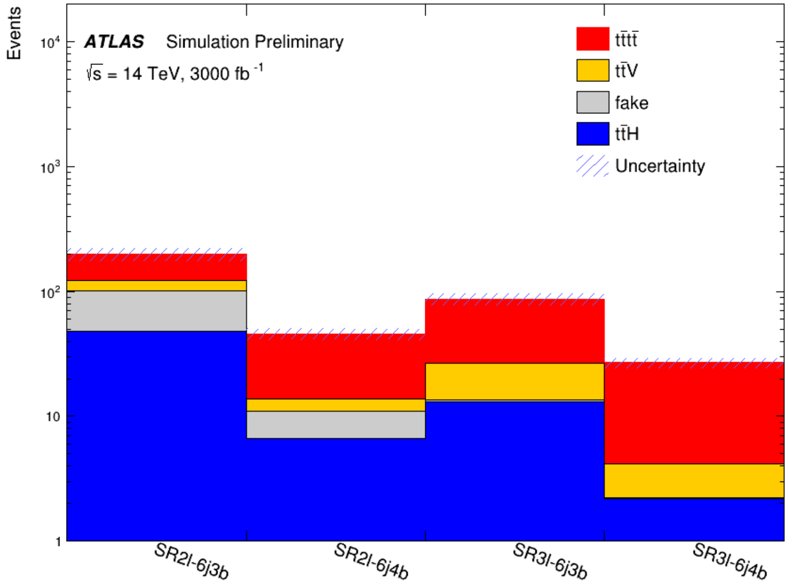
- Rare process - sensitive to enhancement by variety of BSM effects
- Currently sensitive only at ~1sigma level
- Background dominated by other rare processes – ttH, ttV
  - Additional contribution from fake leptons
- Expect measurement at 20% level with HL-LHC
  - Depends on **systematic uncertainties**, in particular bkg. normalisation

Eur. Phys. J. C 78 (2018) 140
arXiv:1811.02305




ATL-PHYS-PUB-2018-047



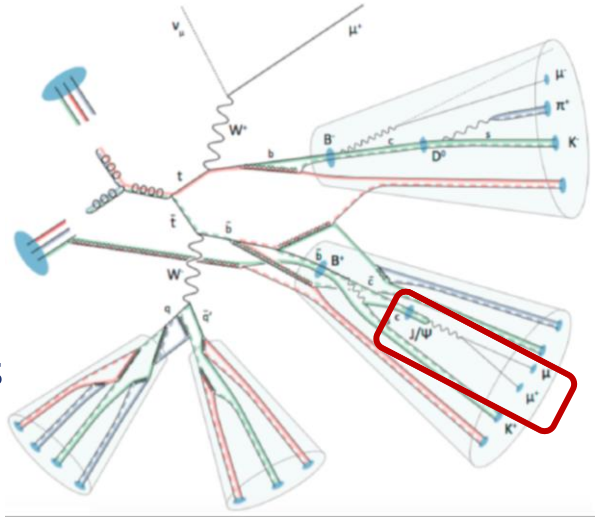

CMS-PAS-FTR-18-031

| Int. Luminosity | $\sqrt{s}$ | *Stat. only* (%) | *Run-2* (%) | *YR18* (%) | *YR18+* (%) |
|---|---|---|---|---|---|
| 300 $\text{fb}^{-1}$ | 14 TeV | $+30, -28$ | $+43, -39$ | $+36, -34$ | $+36, -33$ |
| 3 $\text{ab}^{-1}$ | 14 TeV | $\pm 9$ | $+28, -24$ | $+20, -19$ | $\pm 18$ |
| 3 $\text{ab}^{-1}$ | 27 TeV | $\pm 2$ | $+15, -12$ | $+9, -8$ | $+8, -7$ |
| 15 $\text{ab}^{-1}$ | 27 TeV | $\pm 1$ | | | |

# Constraining the top quark mass with HL-LHC

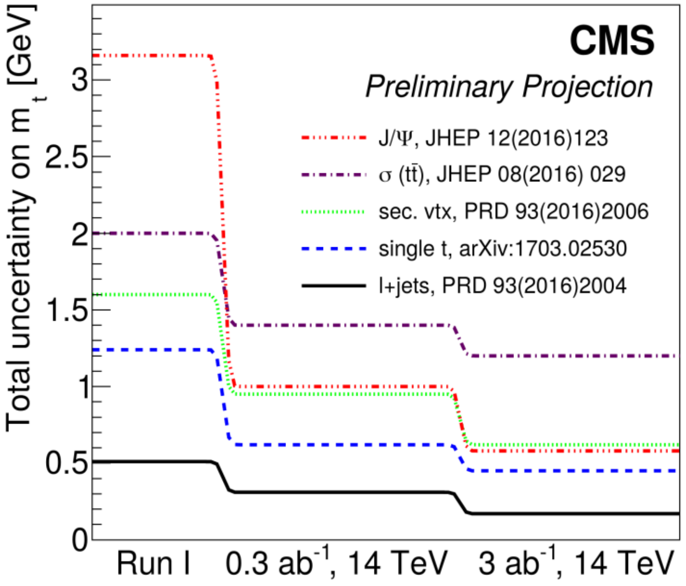
- **Top quark mass**: Another free SM parameter to be constrained at the LHC
- Current uncertainty: around **480 MeV**
  - Systematically limited
- **Systematics** can be **reduced** with **added statistics**
  - 3D fits to constrain uncertainties, exclusion of phase-space with high systematics
  - ➢ Expect improvement with HL-LHC

arXiv:1810.01772
arXiv:1509.04044

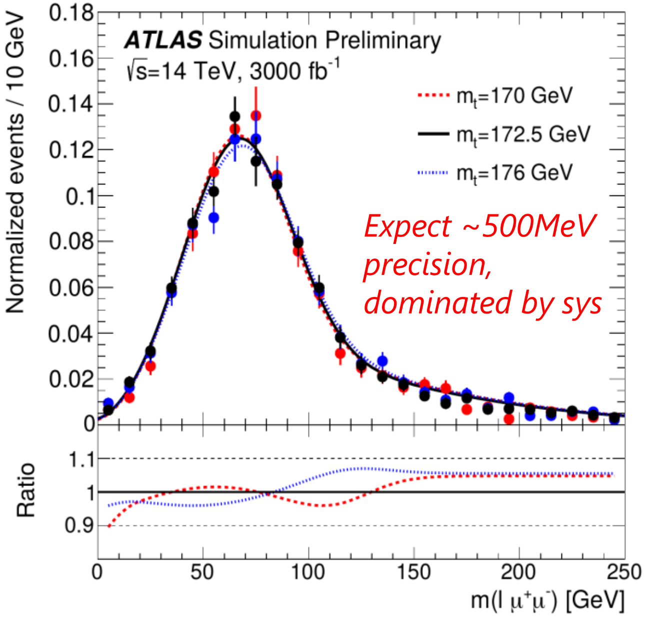



- **Complementary approaches** allow to further reduce uncertainties in combination with baseline measurement
- One such approach accessible at HL-LHC: Rare J/ψ→ μμ in b-decay (4e-4 BR!)
  - J/ψ + lepton from W decay: Sensitive to $m_t$ **and orthogonal** to jet based measurements

CMS-PAS-FTR-16-006




ATL-PHYS-PUB-2018-042




*Expect ~500MeV precision, dominated by sys*

# Higgs boson couplings and mass

Status today: Talk by A. De Maria

- As of today: Wide range of Higgs boson couplings explored
  - Latest addition: ttH production
  - Still open: H→μμ, H→Zγ
- Mass measured with ~200 MeV accuracy
- Many measurements still **statistically limited**

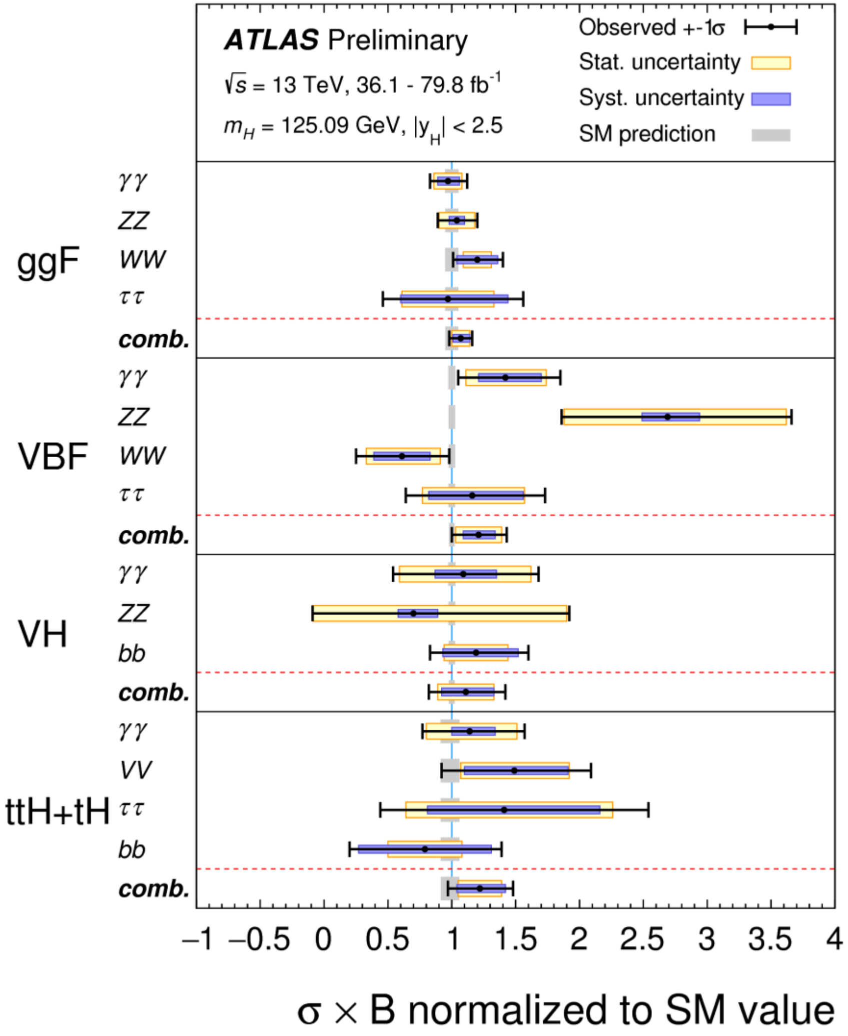
Phys. Rev. Lett. 120 (2018) 231801

Phys. Lett. B 784 (2018) 173

JHEP 11 (2017) 047

Phys. Lett. B 784 (2018) 345

ATLAS-CONF-2018-031



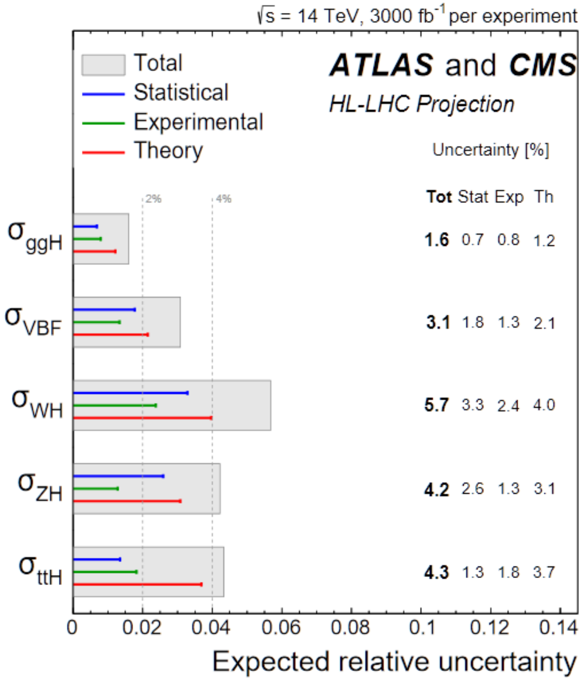

Precise characterisation of Higgs boson one main motivation for HL-LHC Upgrade!

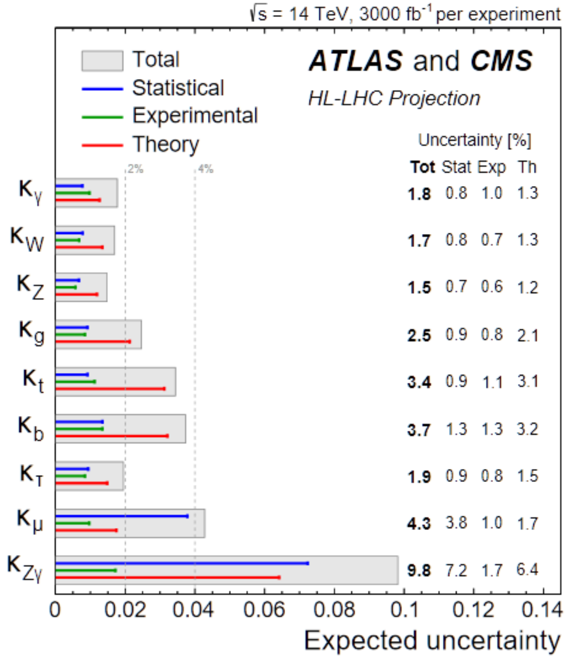
- Potential evaluated by projecting run-2 results to 3/ab

# Higgs boson couplings and mass

- All main production mechanisms measurable at <5% level
- Rare μμ decay mode expected to be observable
  - And precisely measured!
- Zγ decay in potential reach for evidence
- Interpretation in terms of modified couplings (κ framework):
  - Constrain at 5-10% level
- Mass measurement to profit dramatically from statistics in „golden“ 4l channel
  - Precision a factor 5-10 below run-2
  - Limited by detector resolution

ATL-PHYS-PUB-2018-054
CMS-PAS-FTR-18-011
arXiv:1902.00134

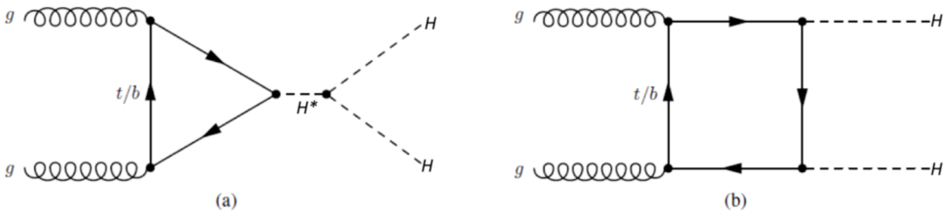



*Precision on $m_H$ with 3/ab*

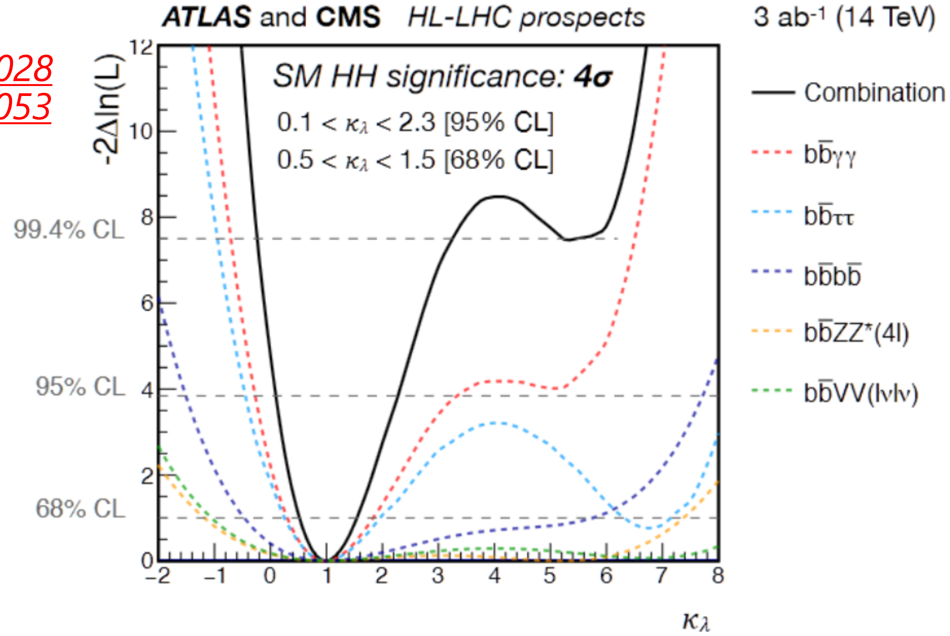
| | $\Delta_{tot}$ (MeV) | $\Delta_{stat}$ (MeV) | $\Delta_{syst}$ (MeV) |
|---|---|---|---|
| Current Detector | 52 | 39 | 35 |
| $\mu$ momentum resolution improvement by 30% or similar | 47 | 30 | 37 |
| $\mu$ momentum resolution/scale improvement of 30% / 50% | 38 | 30 | 24 |
| $\mu$ momentum resolution/scale improvement 30% / 80% | 33 | 30 | 14 |

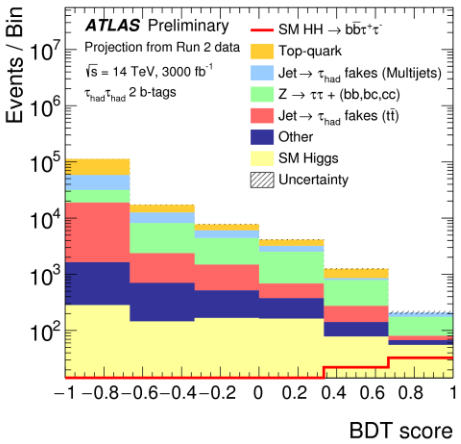
# Higgs boson – self coupling

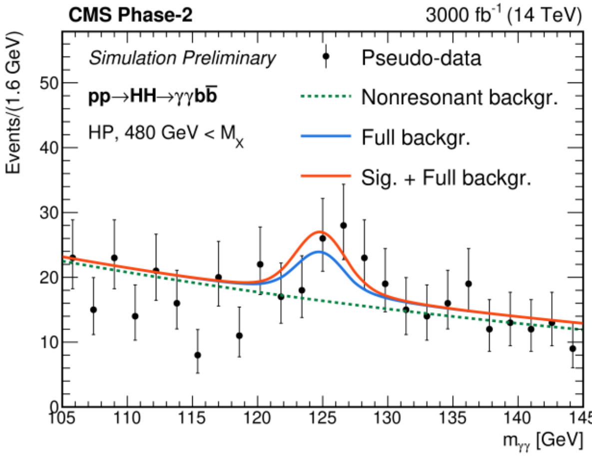



- HH self coupling theoretically very interesting, but **currently out of reach** (see talk by A. De Maria)
- With full HL-LHC dataset:
  - Combining all decay channels…
  - …and both experiments…
  - ➢ yields sensitivity at 4σ level!
- ➢ Able to exclude secondary minimum in $\kappa_\lambda$ at >99% CL
- Expect potential for further improvement with advanced analysis techniques and tuning of object reconstruction

*ATL-PHYS-PUB-2018-028*
*ATL-PHYS-PUB-2018-053*
*CMS-PAS-FTR-18-019*
*arXiv:1902.00134*



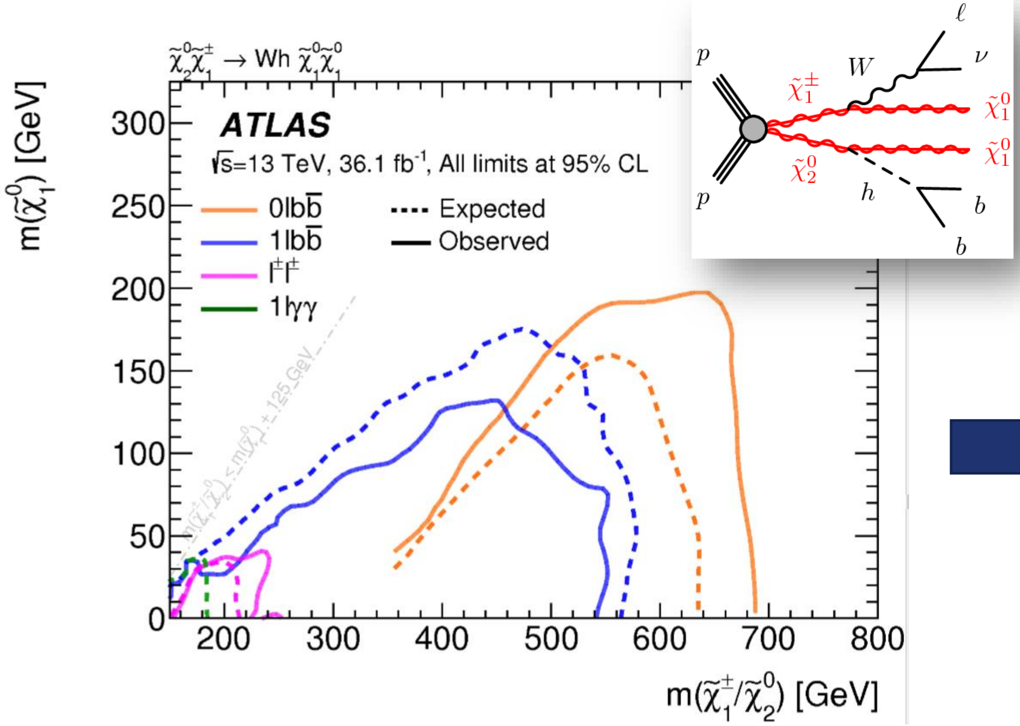




| | Statistical-only | | Statistical + Systematic | |
|---|---|---|---|---|
| | ATLAS | CMS | ATLAS | CMS |
| $HH \to b\bar{b}b\bar{b}$ | 1.4 | 1.2 | 0.61 | 0.95 |
| $HH \to b\bar{b}\tau\tau$ | 2.5 | 1.6 | 2.1 | 1.4 |
| $HH \to b\bar{b}\gamma\gamma$ | 2.1 | 1.8 | 2.0 | 1.8 |
| $HH \to b\bar{b}VV(ll\nu\nu)$ | - | 0.59 | - | 0.56 |
| $HH \to b\bar{b}ZZ(4l)$ | - | 0.37 | - | 0.37 |
| combined | 3.5 | 2.8 | 3.0 | 2.6 |
| | Combined 4.5 | | Combined 4.0 | |

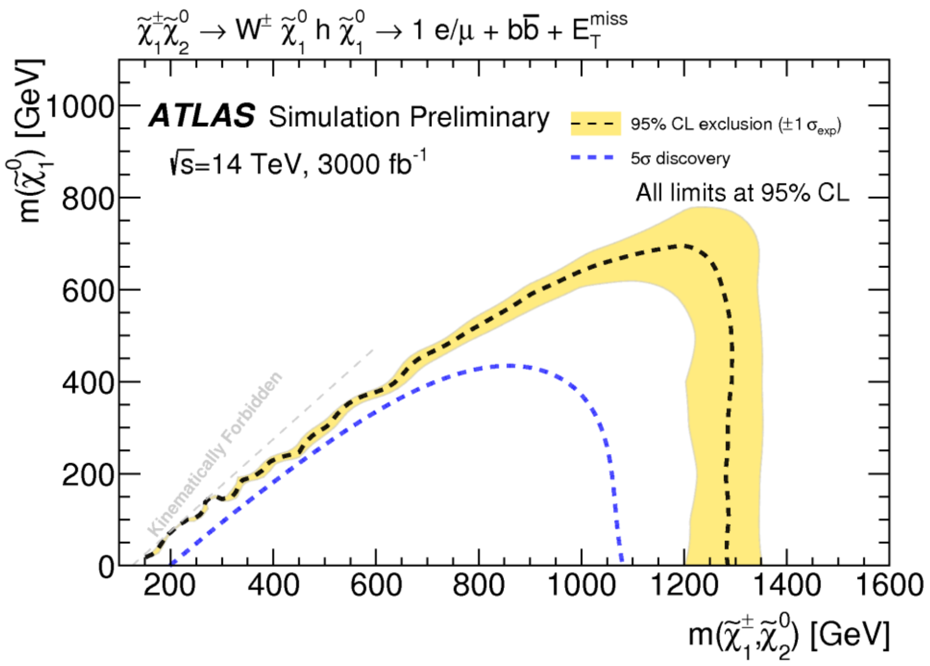
# Searches for supersymmetry (SUSY)

Status today: Talk by T.Lari

- SUSY searches: Also stand to profit from HL-LHC
  - Large dataset – can use stricter selection criteria, profit in particular for stat-limited searches
  - Typical examples: Electroweak sparticle production
- One example: C1N2 decay via WH – as discussed by Tommaso. Study a MVA-based selection
  - discovery potential with HL-LHC in the TeV range for the most optimistic, simplified scenario
  - ➢ Note: The usual disclaimers apply!



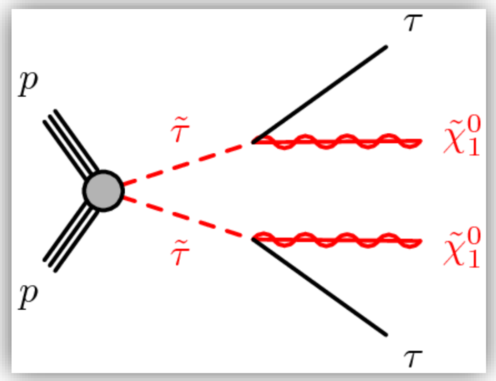

ATL-PHYS-PUB-2018-048



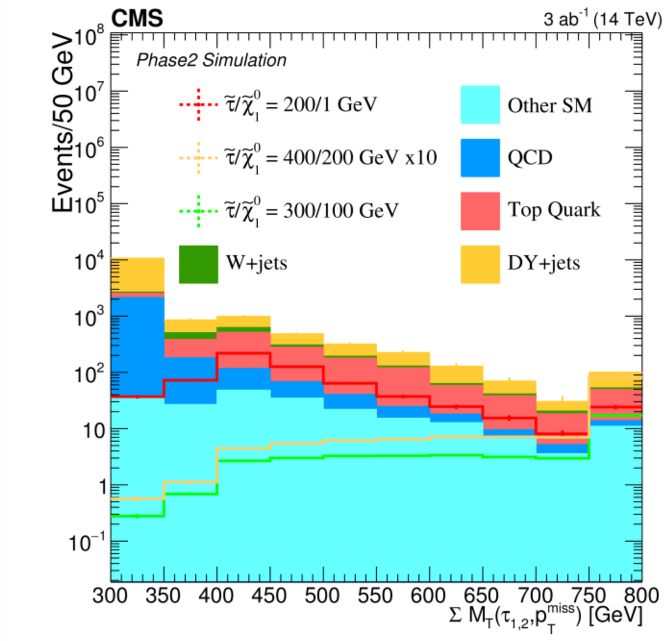
# Searches for supersymmetry (SUSY)

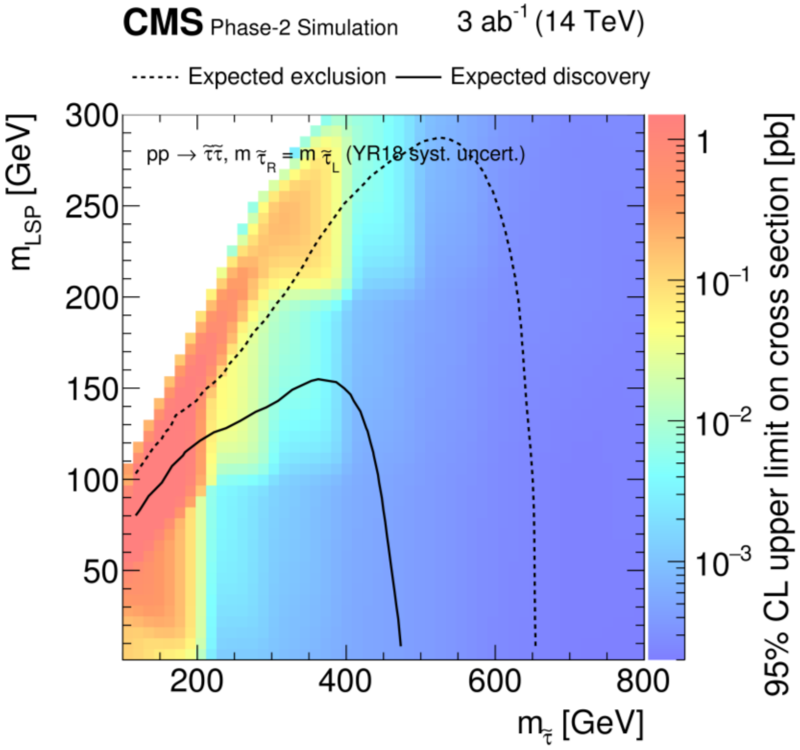
ATL-PHYS-PUB-2018-048
CMS-PAS-FTR-18-010

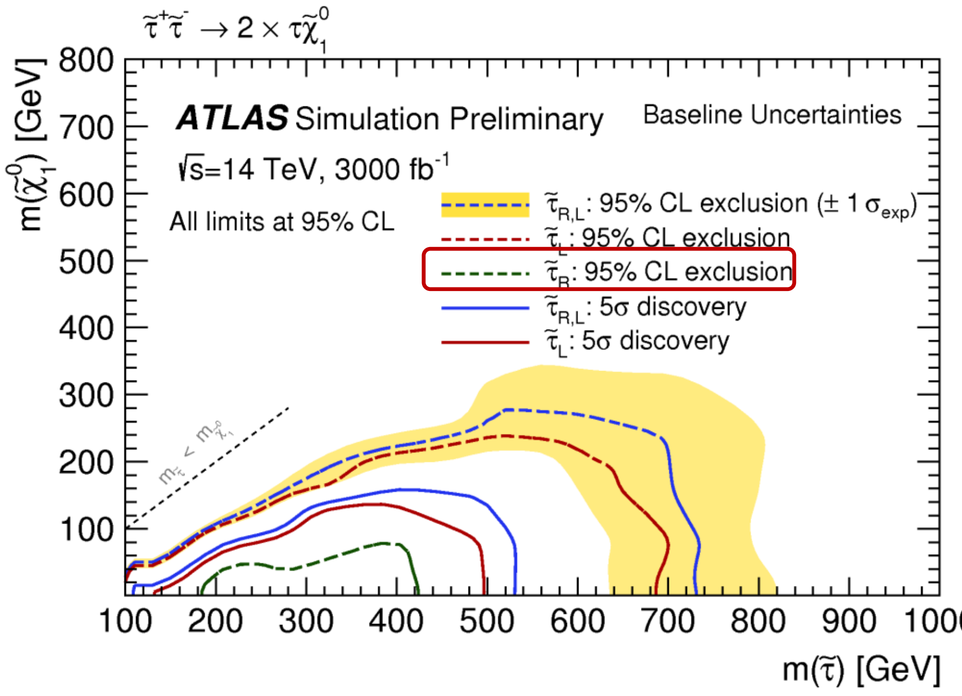
- One challenging scenario **without** sensitivity for LHC run-2: Direct **stau pair** production
  - ➢ Di-tau final state with missing transverse momentum




- With HL-LHC: Limited discovery potential as long as **some** $\tau_L$ admixture
  - ➢ For pure $\tau_R$, only limited exclusion potential even with 3/ab
  - ➢ Limited by production cross-section



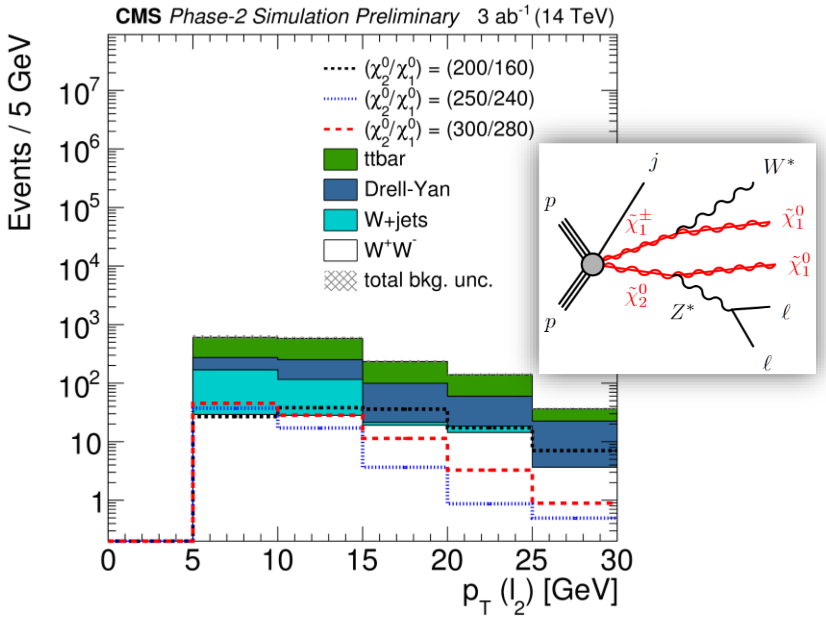



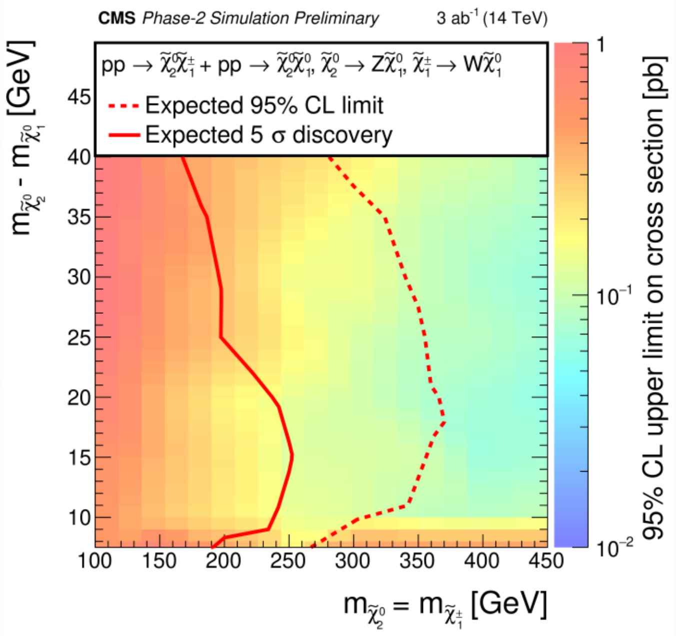
# Searches for supersymmetry (SUSY)

Another challenging topology: **Compressed signatures**

- Example: Higgsino-like LSP – lightest chargino and second neutralino nearly mass-degenerate with LSP
  - C1N2 production leads to final state with **very soft** objects
  - ➢ Rely on **ISR** jet activity to boost the system and become sensitive to soft lepton activity
  - ➢ Or (even lower mass splittings): Chargino becomes **long-lived** – reconstruct as a **disappearing track**
- Using **complementary approaches**, HL-LHC can provide discovery potential beyond LEP exclusions

CMS-PAS-FTR-18-001

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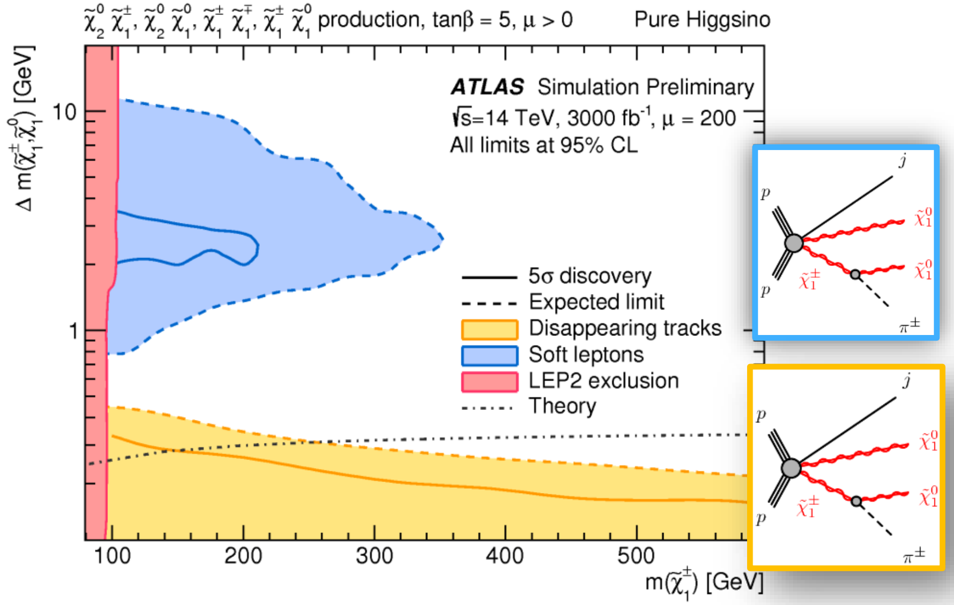
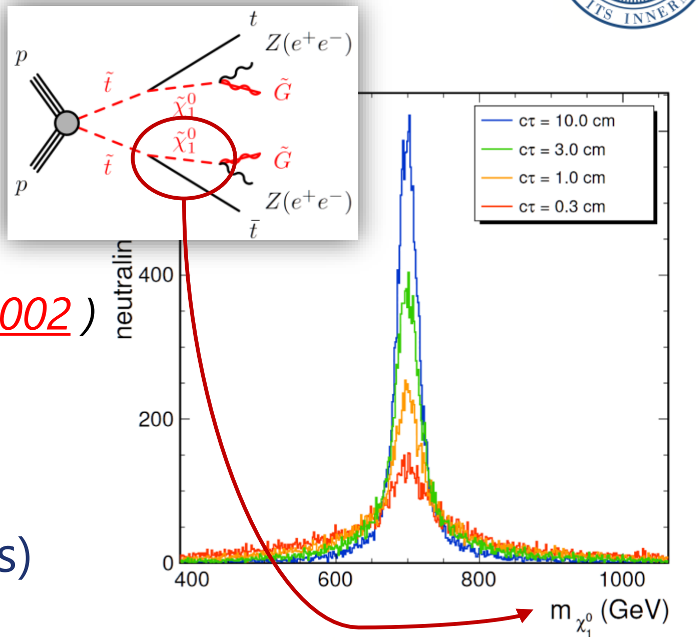
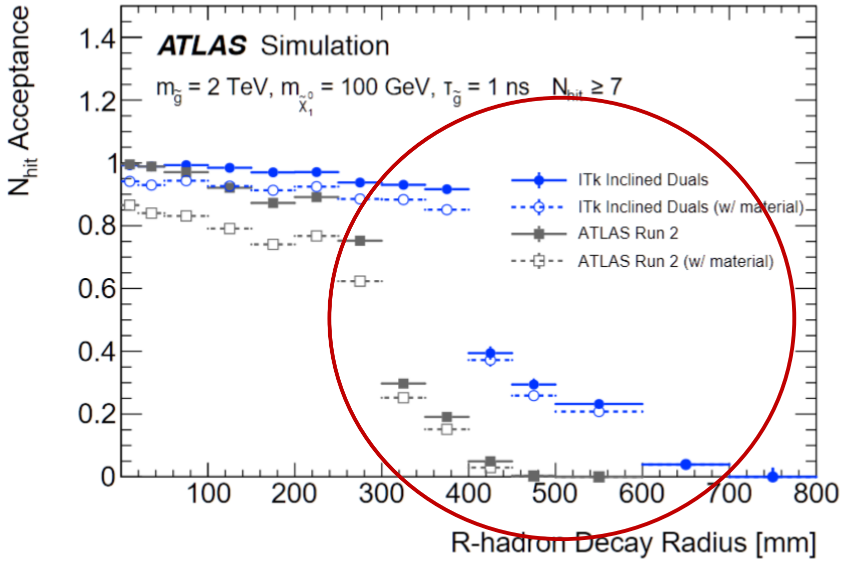


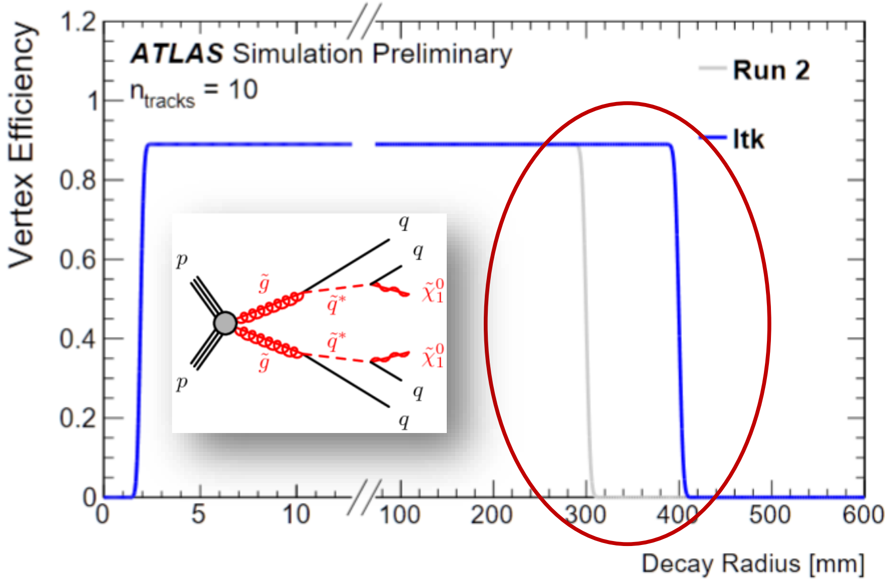
# Long-lived particles

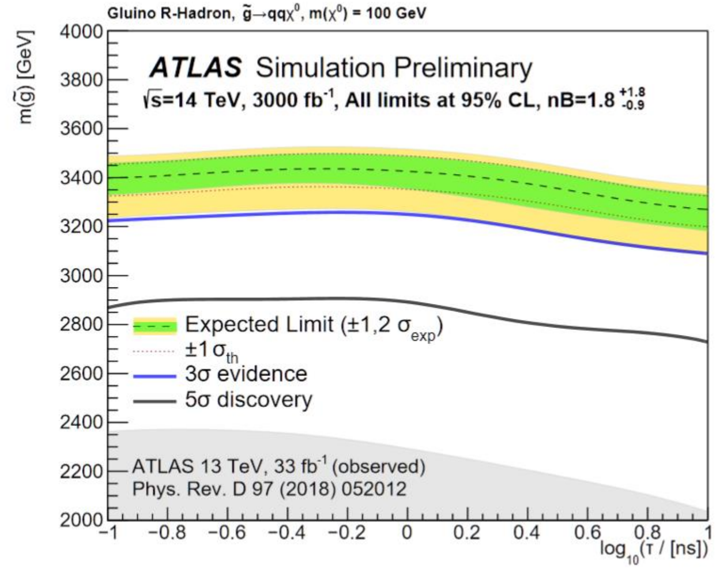
CERN-LHCC-2017-027
arXiv:1812.07831

- We learned on Friday: BSM physics could also appear in **long-lived particle** signatures
- ➢ Example: Search for **displaced vertices** from decaying BSM particles
- Acceptance gain due to improved tracking detectors
  - Also improved triggering capability for certain signatures (→ ATL-PHYS-PUB-2019-002 )
- Typically statistically limited, negligible background
  - profit strongly from increased dataset
- Example for new opportunities: Use of **timing detector** to measure mass of intermediate long-lived particle (with assumptions on invisible decay products)



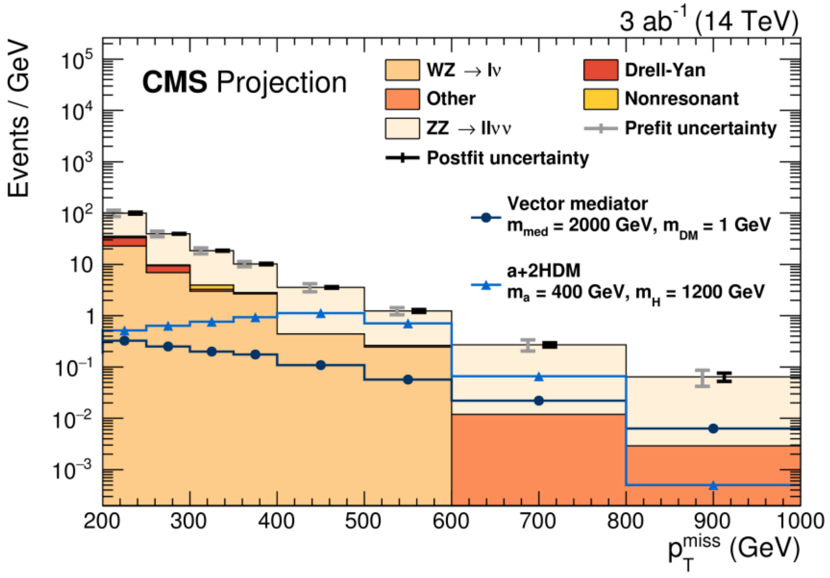



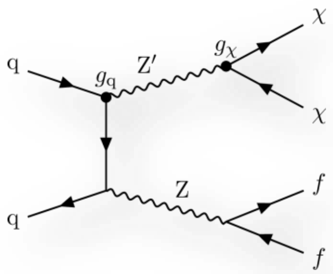



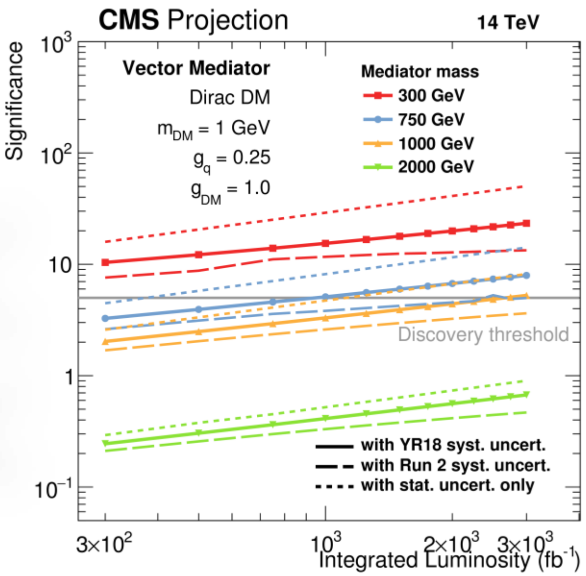
# Searching for dark matter at HL-LHC

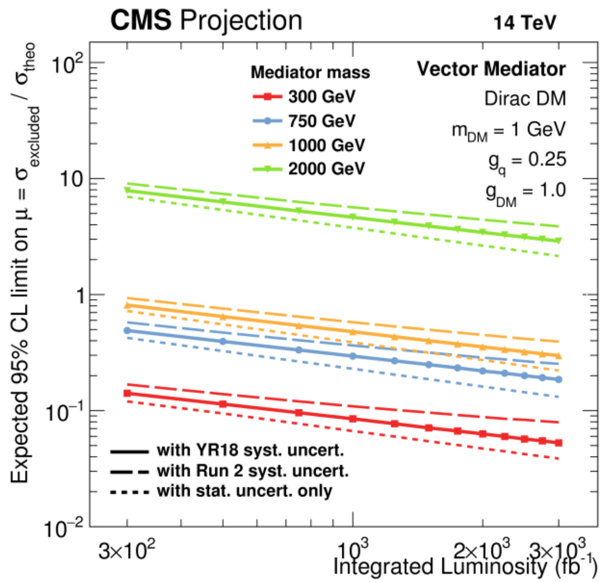
- Typical example: Search for production of **invisible** DM particles escaping the detector in association with visible particles from production / ISR – **„Mono-X“**
- More refined models – assumptions on nature of mediator for DM coupling
  - Motivation to look beyond initial monojet searches – Mono-H/Z, HF + Dark matter, …
- Example: Search for Z recoiling against missing transverse momentum
- Significant increase of discovery reach with HL-LHC – sensitive to heavier mediators / weaker couplings

*CMS-PAS-FTR-18-007*



# Summary

- HL-LHC will **significantly increase physics reach** of LHC experiments
- However: Challenging experimental conditions for experiments – unprecedented pileup!
  - Extensive detector upgrades will preserve performance
  - ➢ and even provide new capabilities!
- With HL-LHC, open several **rate-limited signatures** to measurement
  - Vector-boson scattering, di-Higgs production, four-top prodction, triple gauge bosons, …
- And **improve precision** on known signatures
  - Constrain Higgs boson couplings to SM particles to percent-level
  - Dramatically improve mass precision for H, also gain for W and top
- In addition to a measurement programme: Enhanced reach for **BSM** physics
  - Discovery reach well beyond current exclusions
  - Start closing existing sensitivity gaps
- However: Improvements **do not come „for free"!**
  - Rely on reduction of experimental and theoretical uncertainties to fully unlock potential of HL-LHC

# Backup

# Source of HL-LHC predictions

**Several approaches** in use:

- **Extrapolations**: Project existing run-2 analyses to HL-LHC using existing statistical framework
  - Scale individual contribution based on changes in $E_{CM}$, L, detector performance
    - Also includes rescaling of systematic uncertainties
  - Allows data-driven background predictions to be extrapolated
  - Assumes no change to analysis strategy
- **Fast-simulation:** Encode expected detector performance in DELPHES, use this to process Monte-Carlo events
  - Allows to reoptimize analysis strategies
  - Does not allow to easily transfer data-driven techniques
- **Parametric-simulation**: Analysis on generator-level Monte-Carlo, weigh and smear based on expected detector performance
  - Comparable to fast-simulation
- **Full-simulation** of Monte-Carlo events in the upgraded detectors

➢**Detector performance** assumptions: Obtained using **full simulation** of various physics processes in the upgraded detectors (where available) or best available estimates

# Treatment of uncertainties

**Common guidelines** adopted in assumptions on uncertainties in projections:

- **Statistical** uncertainty: Decreased by 1/sqrt(L)

- **Theory** uncertainties: Assumed to decrease by 50%
  - Includes assumptions on final HL-LHC PDF sets

- Neglect **MC statistical** uncertainties – expect sufficient simulated events for final analyses

- **Experimental** systematics due to **intrinsic detector effects**: preserved
  - Or revised based on detailed simulation of new detectors
- **Experimental** systematics due to **methodology / assumptions**: preserved
  - Assume improved techniques will cancel out with harsher environment

- **Luminosity** uncertainty: Assumed to be 1%
  - Requires improved luminosity calibration! See discussion in slides