Future Perspectives at HL-LHC
Prospects for Pheno26, Pheno31, and beyond

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on behalf of the ATLAS, CMS, and LHCb Collaborations

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From the LHC to the HL-LHC

Excellent performance of the LHC and experiments, over the last 10+ years, has illuminated a whole landscape of the Standard Model, and beyond

- Precision of SM measurements, including Higgs, impressive and growing
- Broad suite of searches for new physics have unveiled many corners of phase space where new phenomena *are not*

The HL-LHC will provide more than an order of magnitude more luminosity

- Illuminate measurements that are limited by stat uncertainty
- Detector upgrades + new analysis techniques will push down systematics
- Sensitivity to new physics in searches will broaden in all dimensions — higher mass, lower mass, weaker couplings, compressed regions, boosted final states, shorter lifetimes, longer lifetimes, wackier signatures

The potential for further discovery in the HL-LHC is broad

- In this talk, I will highlight a few selective projections
- Discuss the detector upgrades, and connect them to the challenges and opportunities of the HL-LHC

Setting the stage

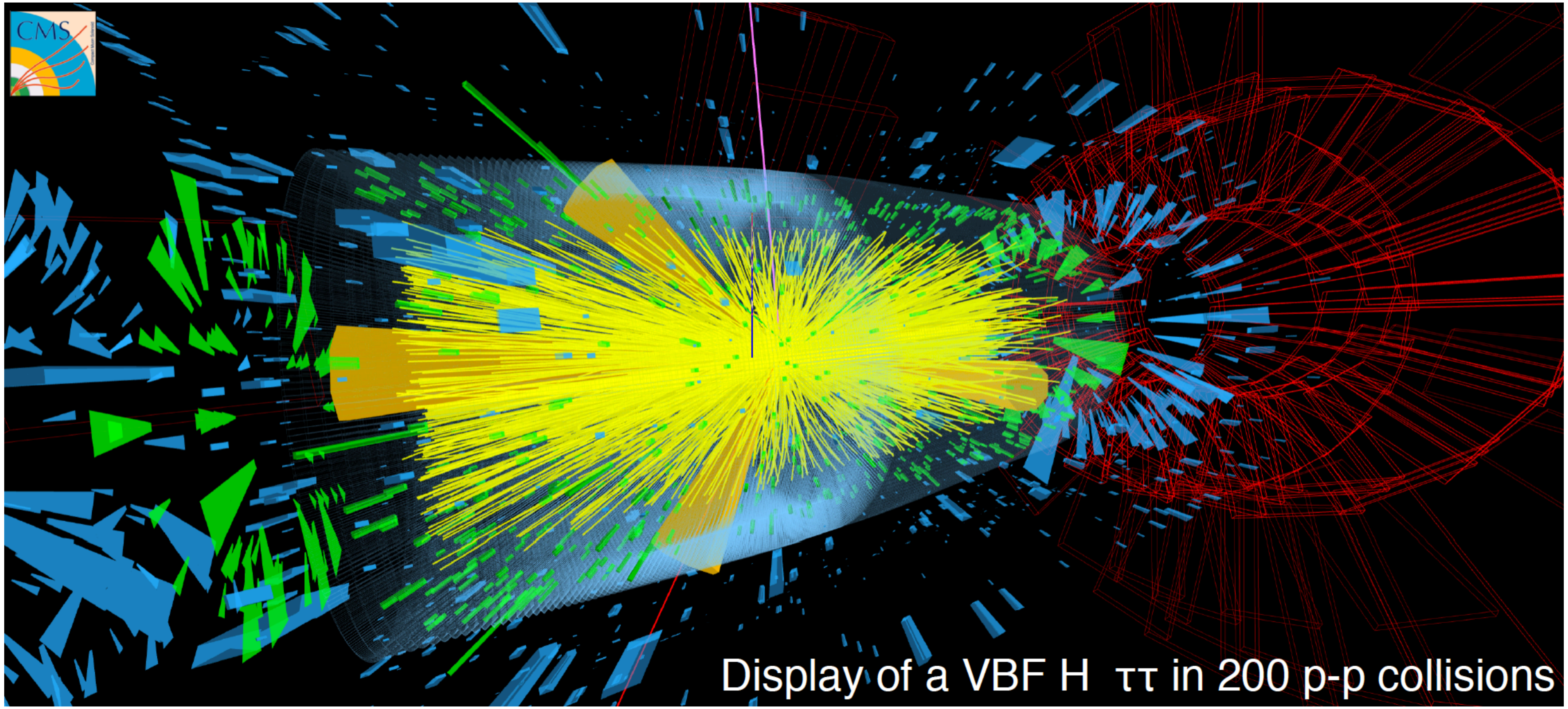
High Luminosity LHC (HL-LHC) outlook

- Center of mass energy of 14 TeV
- Instantaneous lumi of 5 - 7 10^{34} $cm^{-2}s^{-1}$
- Pileup of 140-200
- Total lumi delivered 3-4 ab^{-1}

Challenges and opportunities: high (instantaneous) luminosity

Challenges in all areas

- Detector
- Trigger
- Reconstruction
- Performance
- Analysis challenges

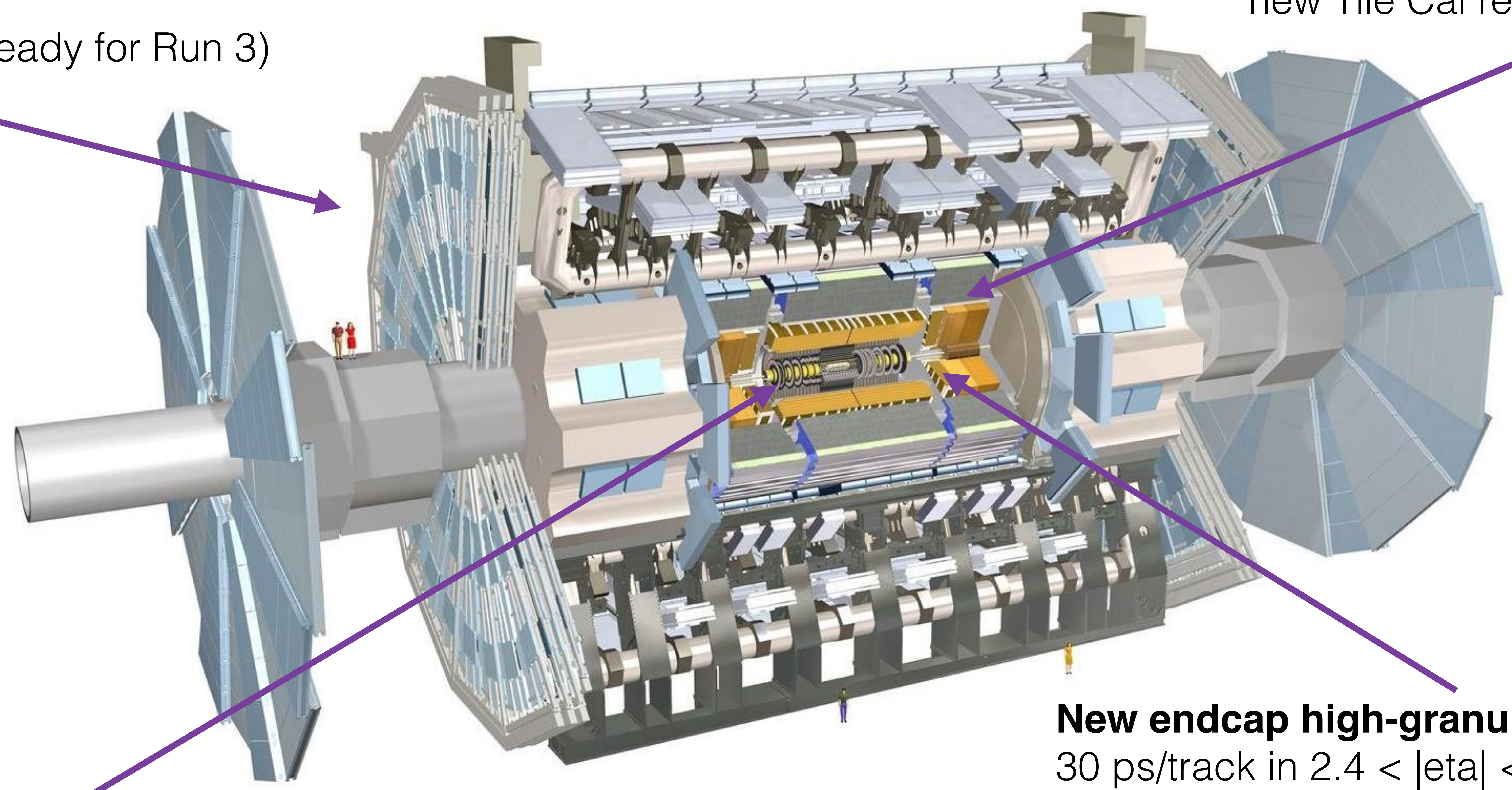


Extensive detector upgrades to handle increased data rate, occupancy, pileup, and integrated luminosity

Upgraded detectors for HL-LHC: ATLAS

Improved muon coverage and trigger
new RPCs in innermost layer
new MDT readout
new small wheels (already for Run 3)

Updates to calorimeter and trigger
new, higher granularity trigger
new Tile Cal readout



New inner tracker
all silicon tracker
5 layers of pixels
4 layers of strips
coverage to $|\eta| < 4$

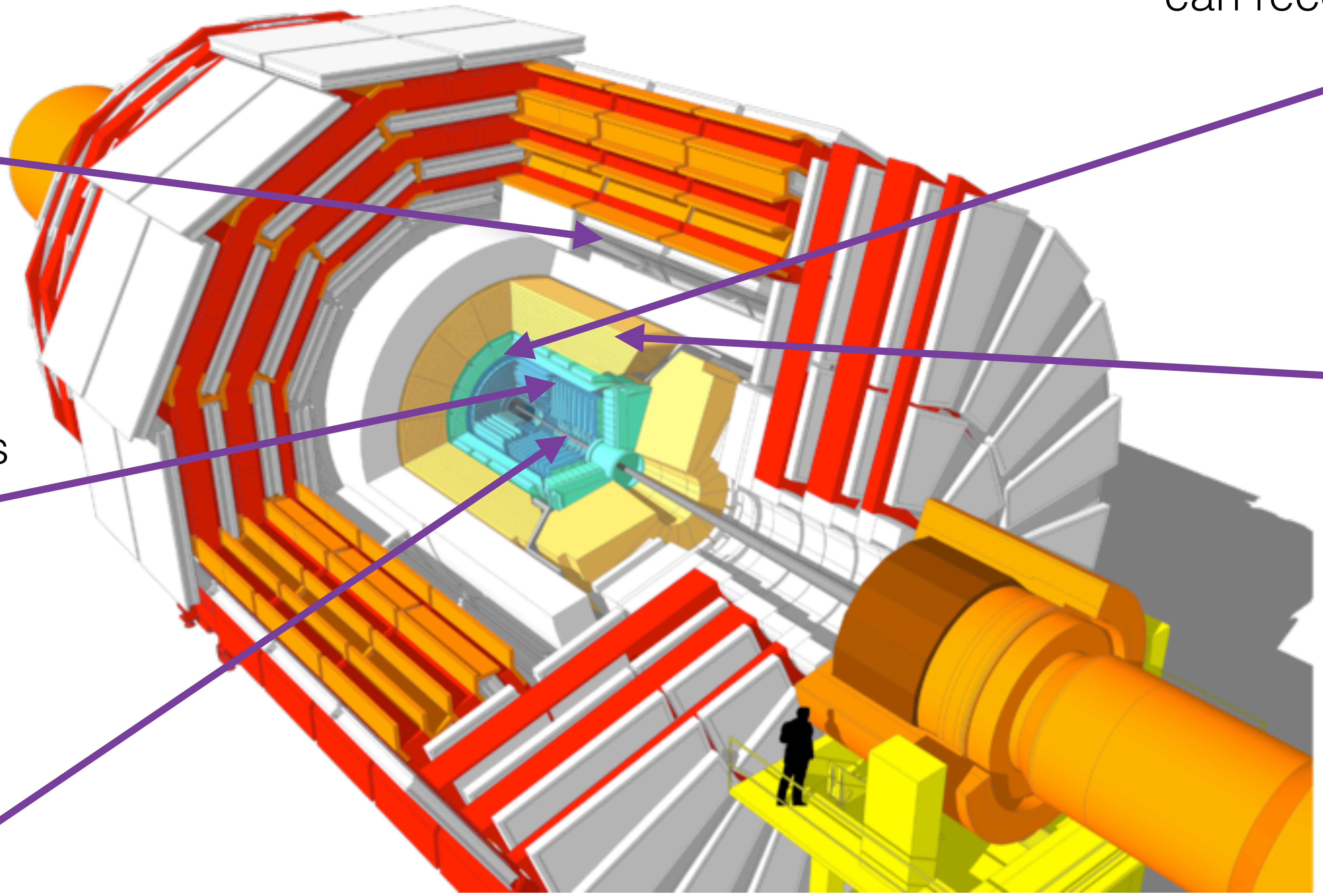
Upgrade to trigger and DAQ
L1 rate increased to 1 MHz
High Level trigger rate to 10 kHz

New endcap high-granularity timing detector
30 ps/track in 2.4 < |eta| < 4.0
resolution of time dimension of beam spot

Upgraded detectors for HL-LHC: CMS

Improved muon coverage and trigger
increased RPC coverage (1.5 < |η| < 2.4)
new electronics

New endcap calorimeters
high granularity
can reconstruct showers in 3D



Updates to calorimeter and trigger
higher granularity
electronics for trigger

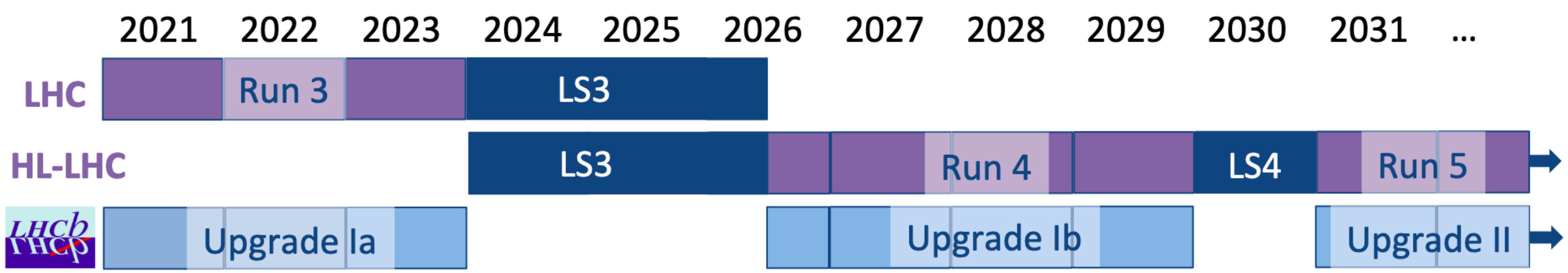
New precision timing detector
Timing resolution of 30-40 ps for MIPs
full coverage of |η| < 3.0

New inner tracker
all silicon tracker
4 layers of pixels
5 layers of strips
coverage to |η| < 4

Upgrade to trigger and DAQ
L1 rate increased to 750 kHz
High Level trigger rate to 7.5 kHz
Track information at L1

[LHCb TDRs]

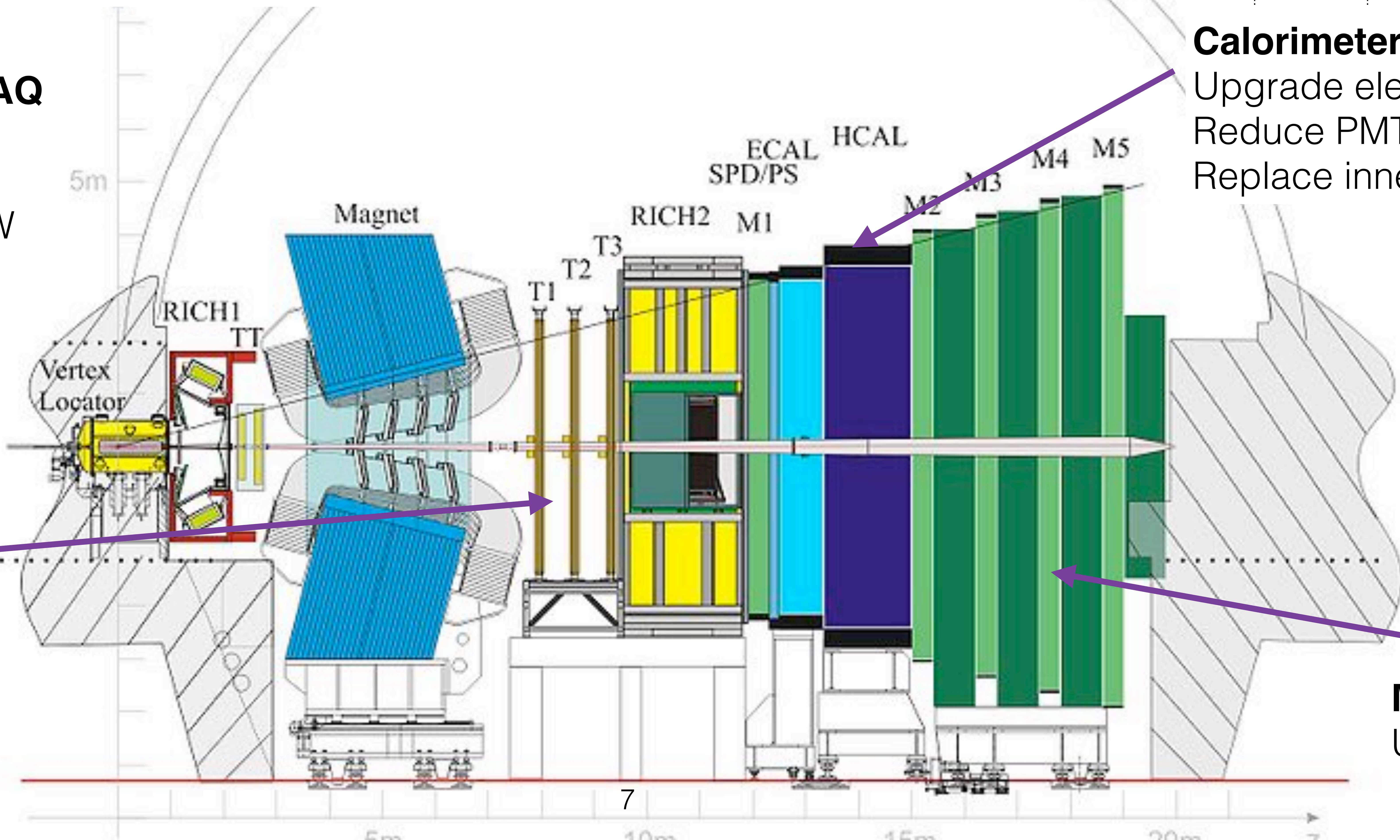
Upgraded detectors for Run 3 and HL-LHC: LHCb



Integrated lumi for LHCb

Run 1	Run 2	Run 3	Run 4	Run 5
3 fb^{-1}	9 fb^{-1}	25 fb^{-1}	50 fb^{-1}	300 fb^{-1}

Upgrade to trigger and DAQ
Triggerless readout —>
Readout at 40 MHz
Event selection by HLT SW



Calorimeters
Upgrade electronics
Reduce PMT gains
Replace innermost ECAL cells

New tracker
Finer granularity for
reduced occupancy

Muon system
Upgrade electronics

Forecasting

Vast community effort

- Physics briefing book for European Strategy for Particle Physics 2020
- HL-LHC CERN Yellow Report
- US Snowmass process, underway

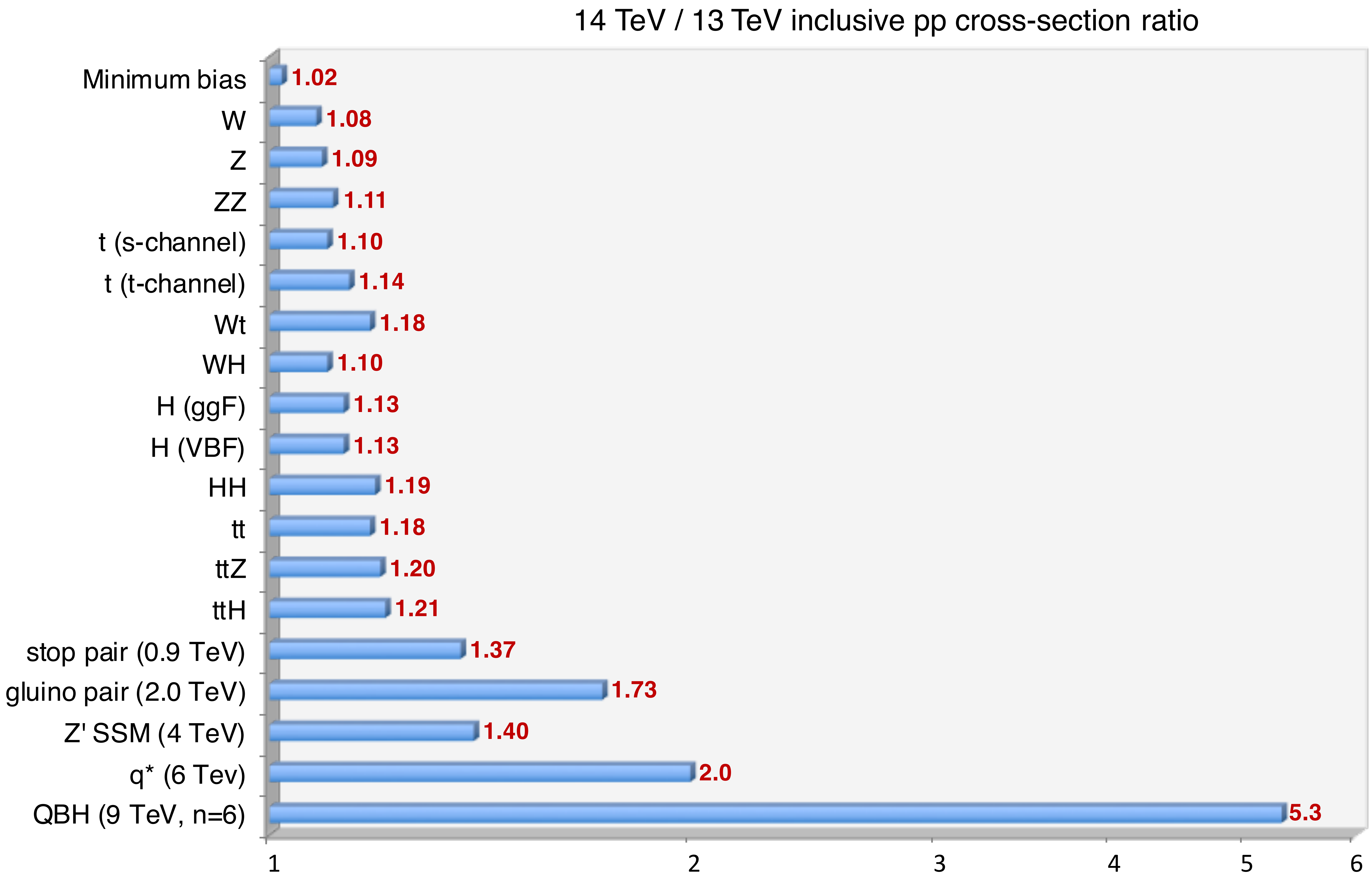
Predicting the future

- Cross-sections scaled from 13 —> 14 TeV
- Improvement in stat. uncertainty expected from more data
- Many analyses extrapolate from Run 2 results
- Impact of detector improvements
  - New or extended capabilities, acceptance, more layers
  - Based on simulated detector performance, when feasible and relevant
- Size of future systematic uncertainties
  - Two approaches used: current best values, or extrapolation based on agreed assumptions
- Impact of pileup, new analyses, new techniques, advances difficult to predict

Projecting systematic uncertainties

- Data statistics, improve by sqrt(L)
- Simulation statistics, set to 0
- Intrinsic detector limits ~constant, or studied in detail
- Theory uncertainties 50% of current values
- PDF uncertainties based on dedicated study

13 —> 14 TeV



ref: B. Petersen and A. David (CERN)

Measuring the SM…. (and beyond?)

Higgs Coupling Measurements

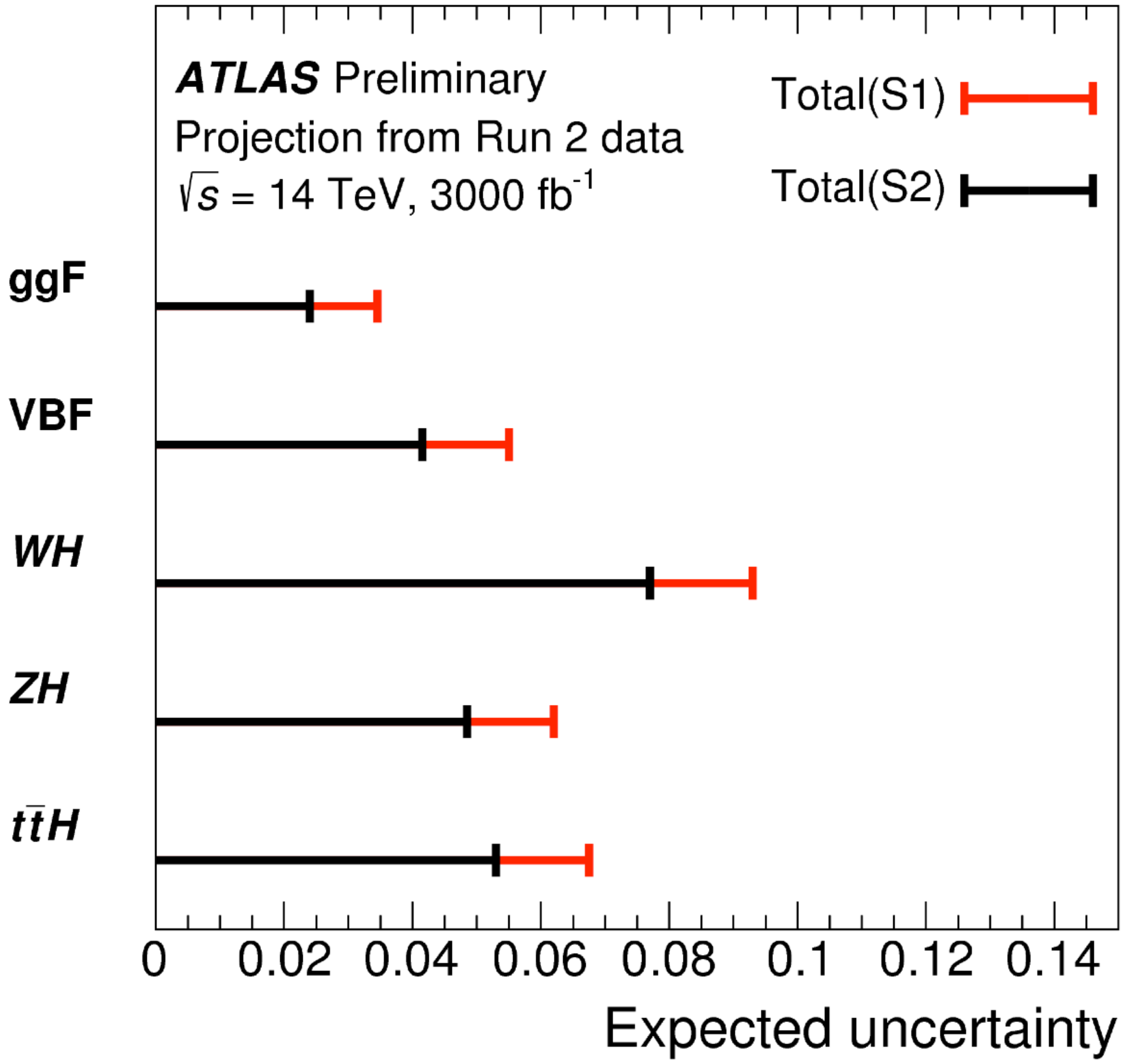
Measuring the Higgs couplings is a major goal of the HL-LHC, and moves into the precision regime

- Couplings (except rarest) can be constrained at the 2-7% level
- Even rare channels μμ and Zγ can be constrained, limited by statistics

For main channels, systematics dominate

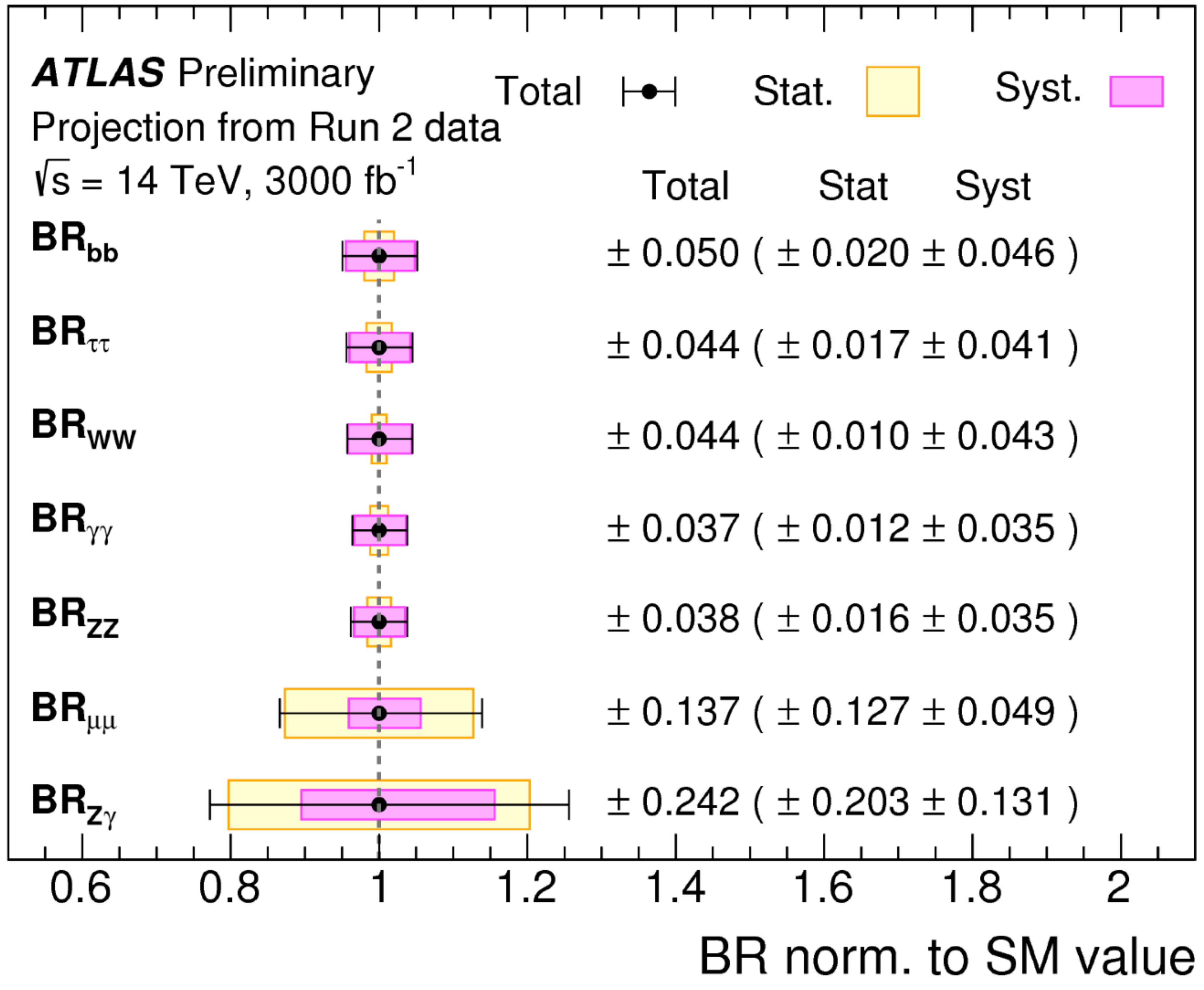
- For γγ, largest uncertainties are from pileup effects on photons, including isolation and ID
- For WW, largest uncertainties are from knowledge of WW background

By production mode



current syst.
improved syst.

By decay mode



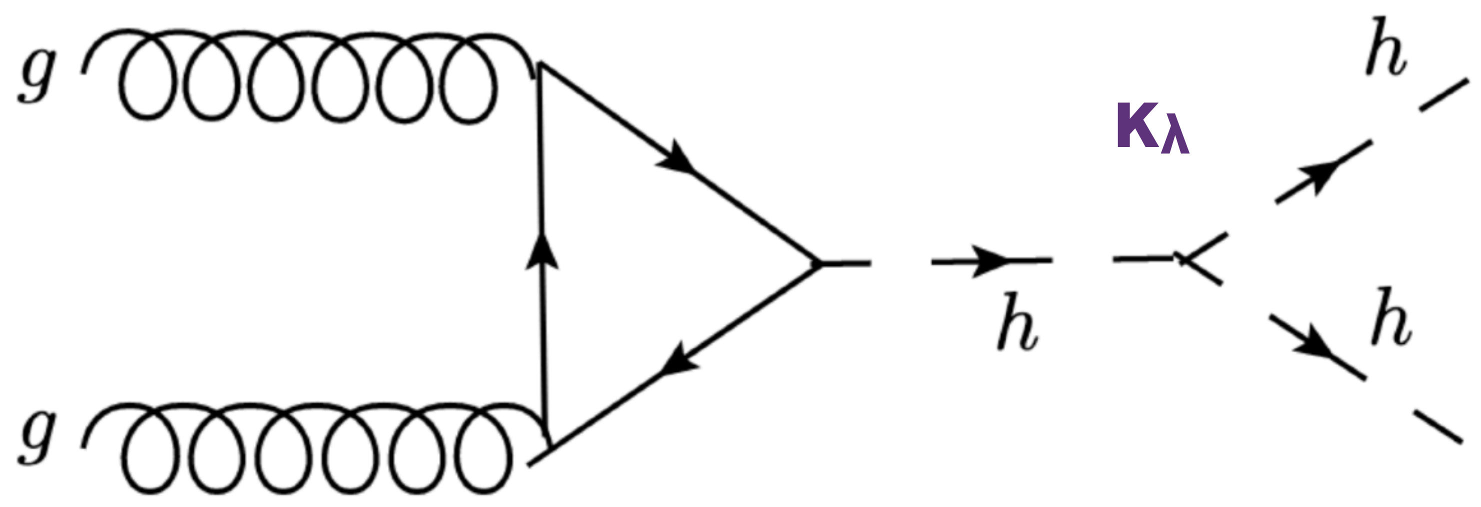
Higgs pair production

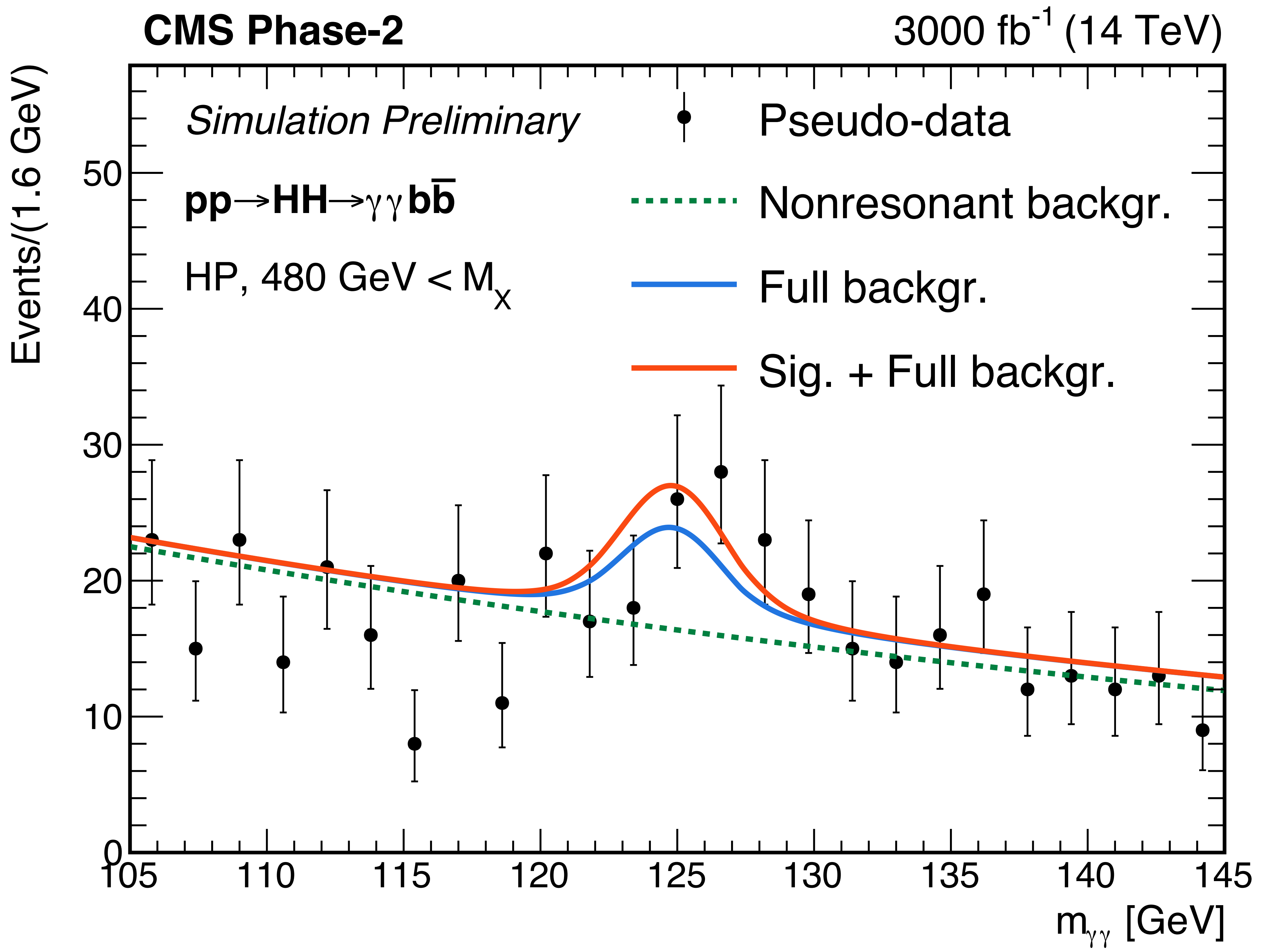
Observing di-Higgs production, and gaining access to the higgs self-coupling is a flagship measurement

- Direct access to the shape of the Higgs potential
- κ_λ sensitive to physics beyond the Standard Model

Both experiments except to achieve 3σ observation significance from a combination of channels

- Most sensitive channels are bbγγ (ML techniques) and bbττ (clean channel, fit background)
- Leading uncertainties are statistical, and from b-jet tagging
- Expect ~10% improvement in b-tagging efficiency from new trackers
- Expected 4σ significance from ATLAS/CMS combination (arXiv:1902.00134)





BR
33.6%
7.3%
2.7%
0.26%
0.0015%

Channel	Significance Stat. + syst.	Significance Stat. only	95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$ Stat. + syst.	95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$ Stat. only
bbbb	0.95	1.2	2.1	1.6
$bb\tau\tau$	1.4	1.6	1.4	1.3
$bbWW(\ell\nu\ell\nu)$	0.56	0.59	3.5	3.3
$bb\gamma\gamma$	1.8	1.8	1.1	1.1
$bbZZ(\ell\ell\ell\ell)$	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71

ATL-PHYS-PUB-2018-023

CMS-PAS-FTR-18-005

Electroweak physics

ATL-PHYS-PUB-2018-052

CMS-PAS-FTR-18-038

ATL-PHYS-PUB-2018-029

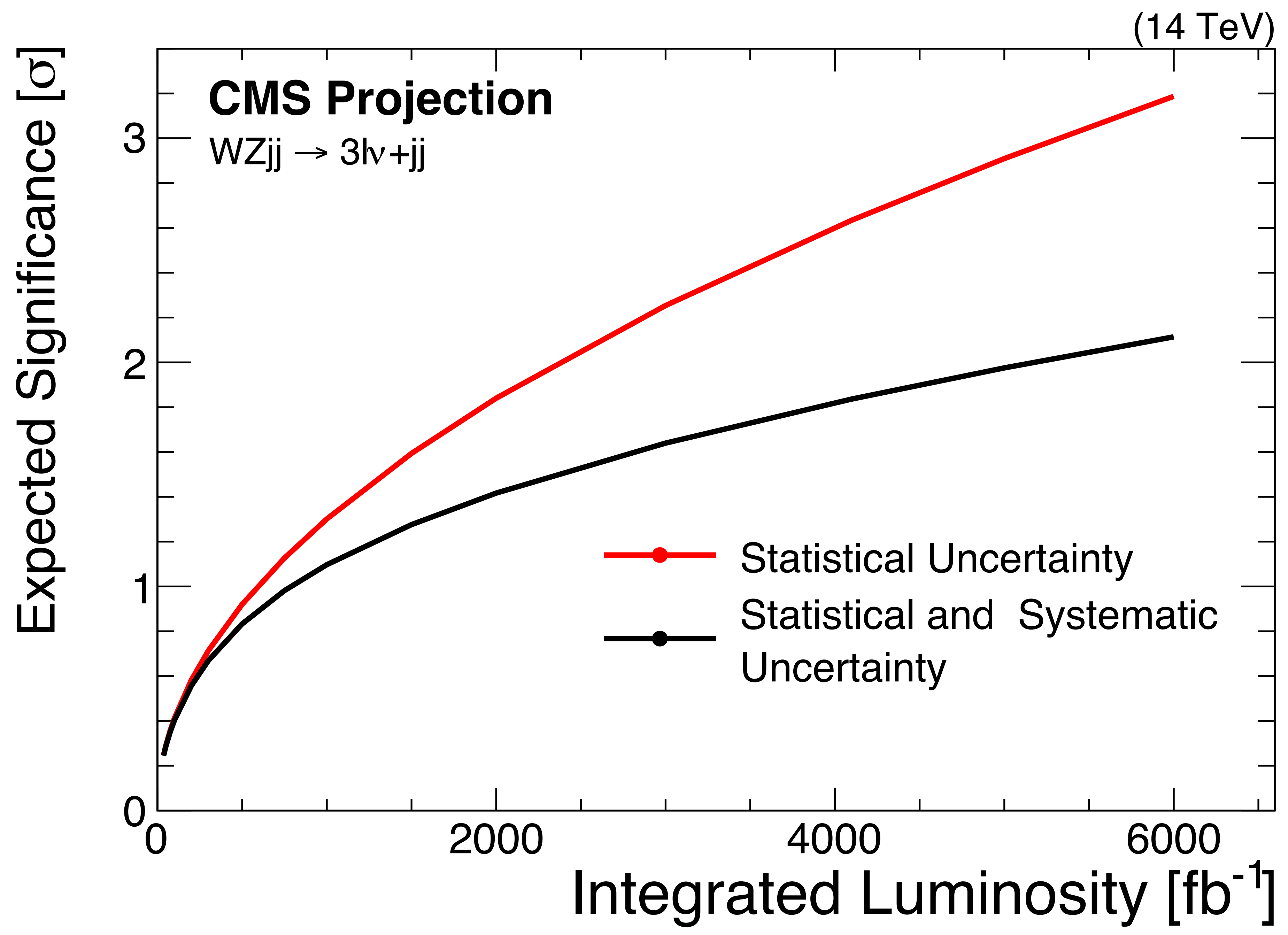
Sensitivity to longitudinal polarization in diboson scattering

- Another window to EW symmetry breaking, and precise SM cancellations open door for BSM contributions

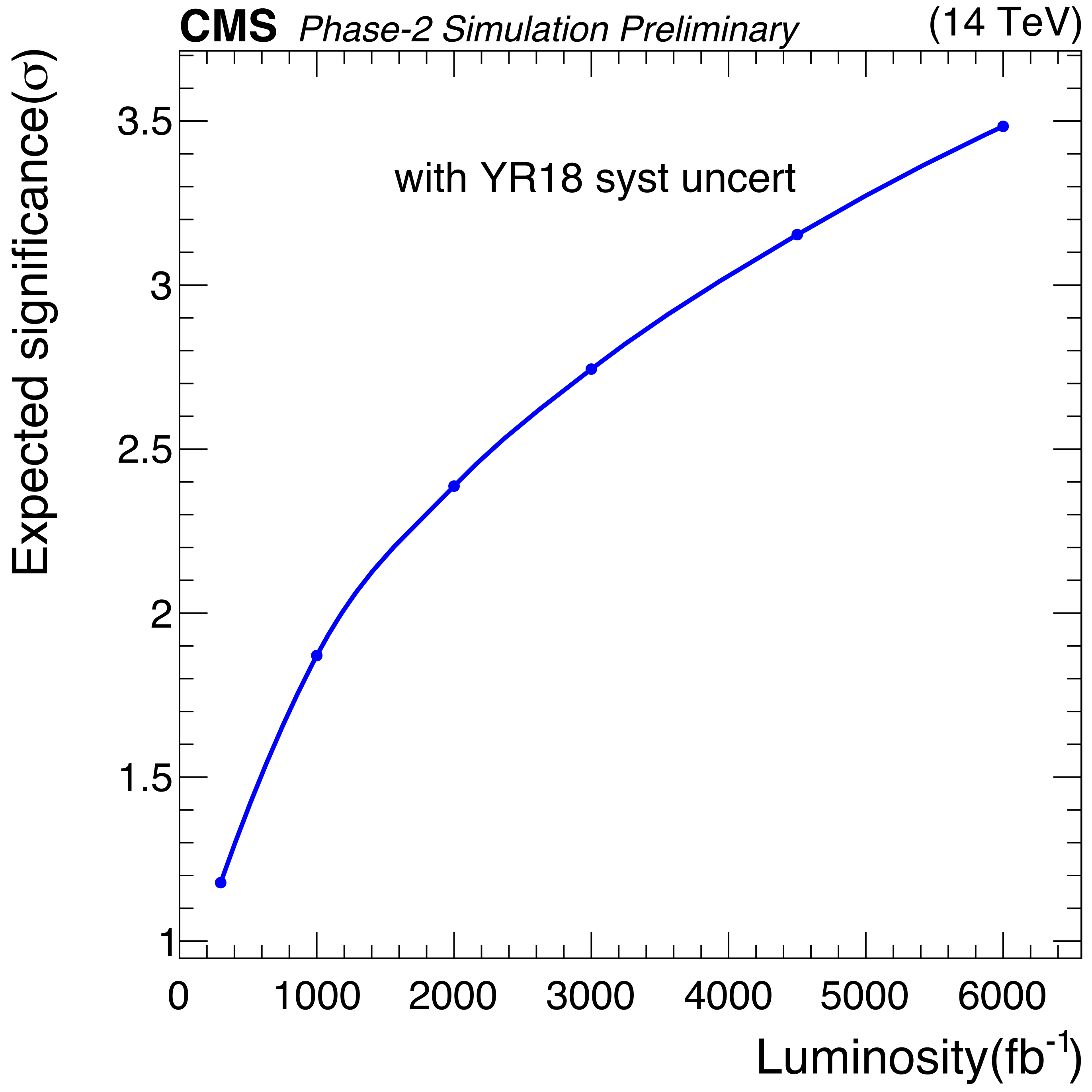
WW,WZ, and ZZ channels studied separately

- WW and WZ single channel sensitivity of 1-3σ to purely longitudinal scattering component, from shape of dijet azimuthal separation
- $W_L W_L$ uncertainty dominated by fake lepton and charge mis-ID contributions to backgrounds
- $W_L Z_L$ uncertainty dominated by theoretical QCD scale uncertainties and jet energy scale and resolution
- Increased tracker acceptance improves signal acceptance (both leptons and lower pT forward jets)

Sensitivity to $W_L Z_L$



Sensitivity to $W_L W_L$



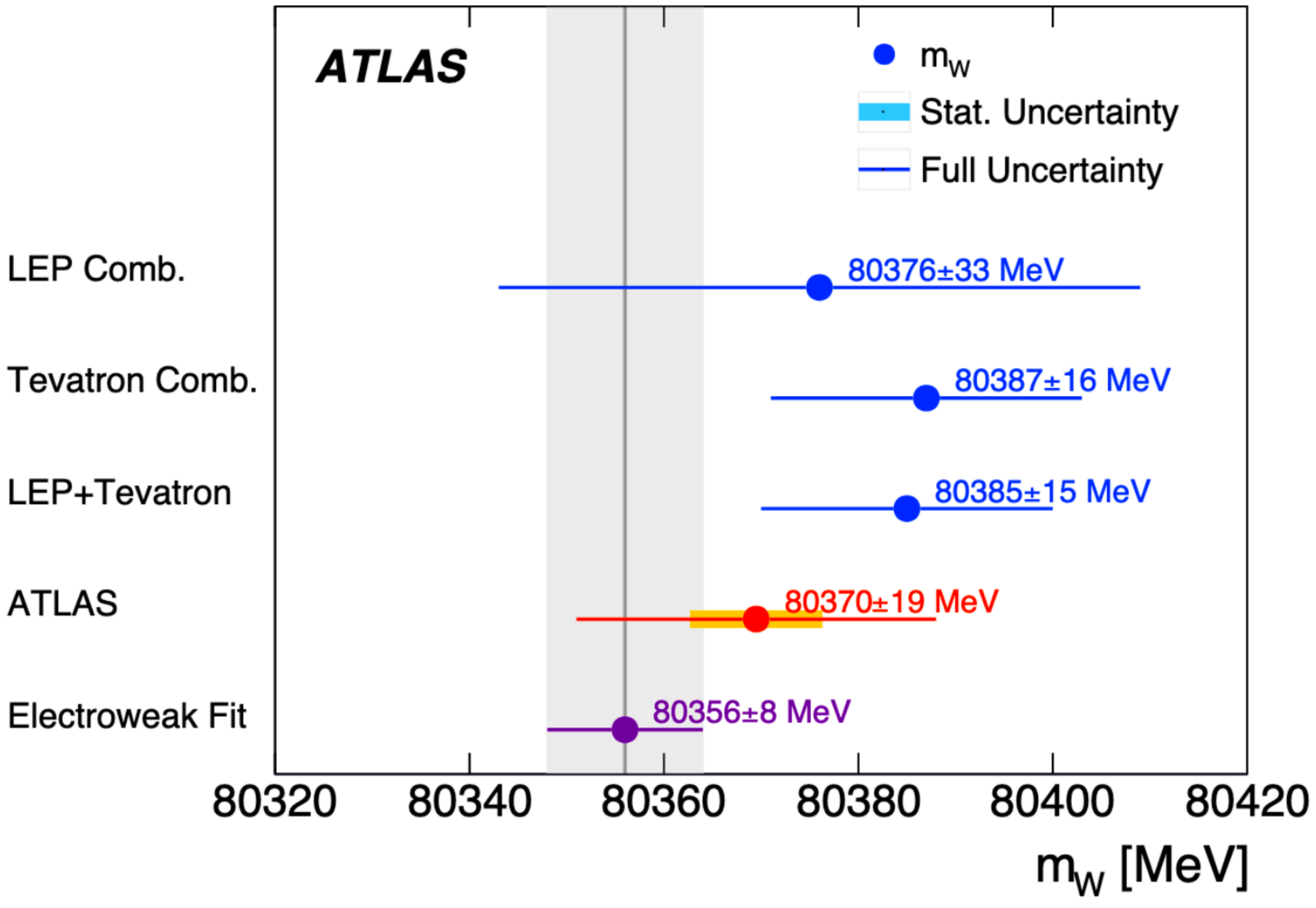
W mass: Precision at a Hadronic Collider

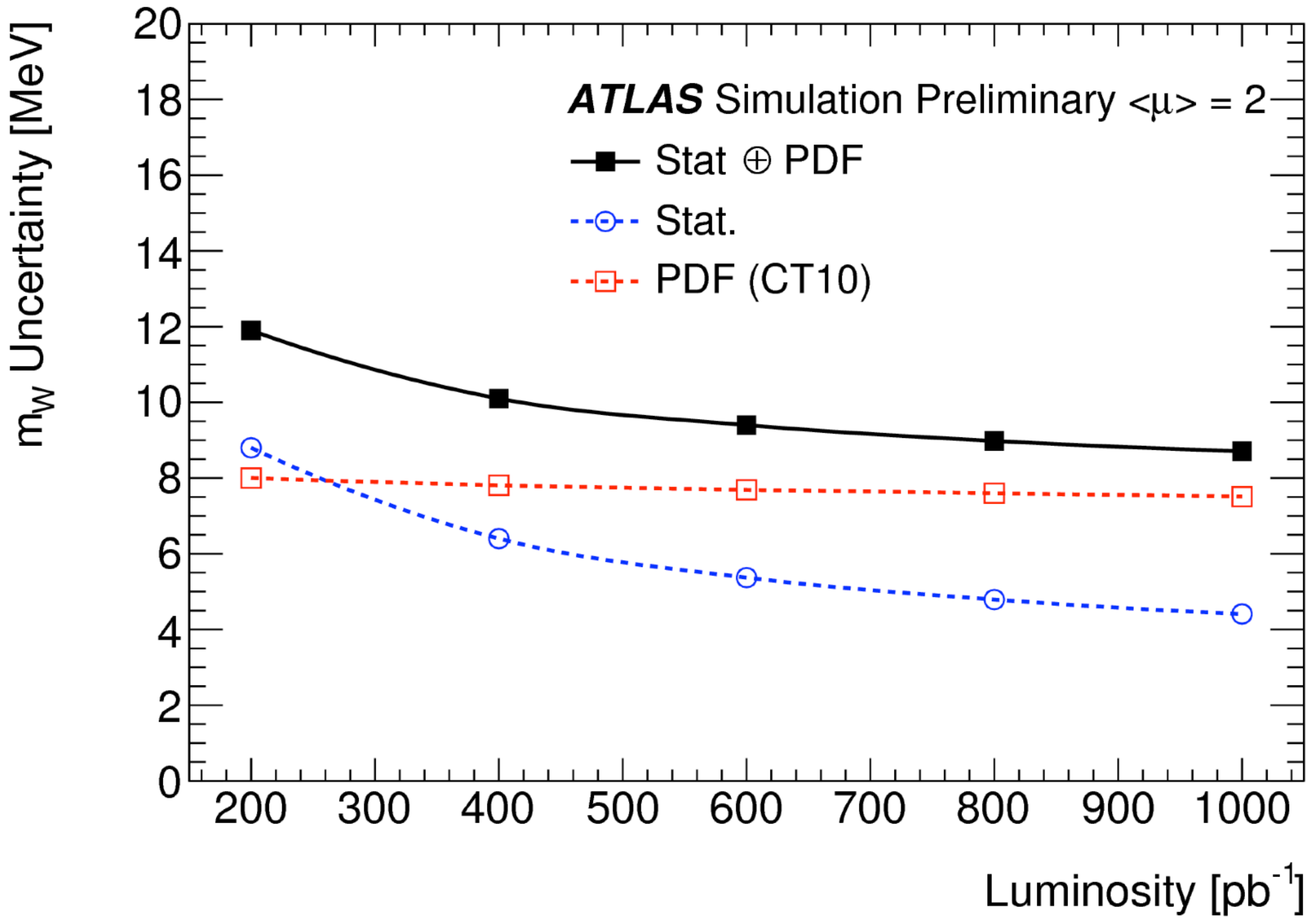
W mass essential ingredient to SM global fits

- Current precision limits constraints on new physics

Pushing precision to the limits

- Take data at low pile-up
- Dominant uncertainty beyond 260 pb^{-1} is due to PDF uncertainty
- Extended rapidity acceptance of tracker essential to reducing PDF uncertainties





W mass Uncertainty, total (stat ⊕ PDF) for 200 pb^{-1}, [MEV]

$\sqrt{s}$ [TeV]	Lepton acceptance	Uncertainty in m_W [MeV]		
		CT10	CT14	MMHT2014
14	$\lvert\eta_\ell\rvert < 2.4$	16.0 (10.6 ⊕ 12.0)	17.3 (11.4 ⊕ 13.0)	15.4 (10.7 ⊕ 11.1)
14	$\lvert\eta_\ell\rvert < 4$	11.9 (8.8 ⊕ 8.0)	12.4 (9.2 ⊕ 8.4)	10.3 (9.0 ⊕ 5.1)

Top physics

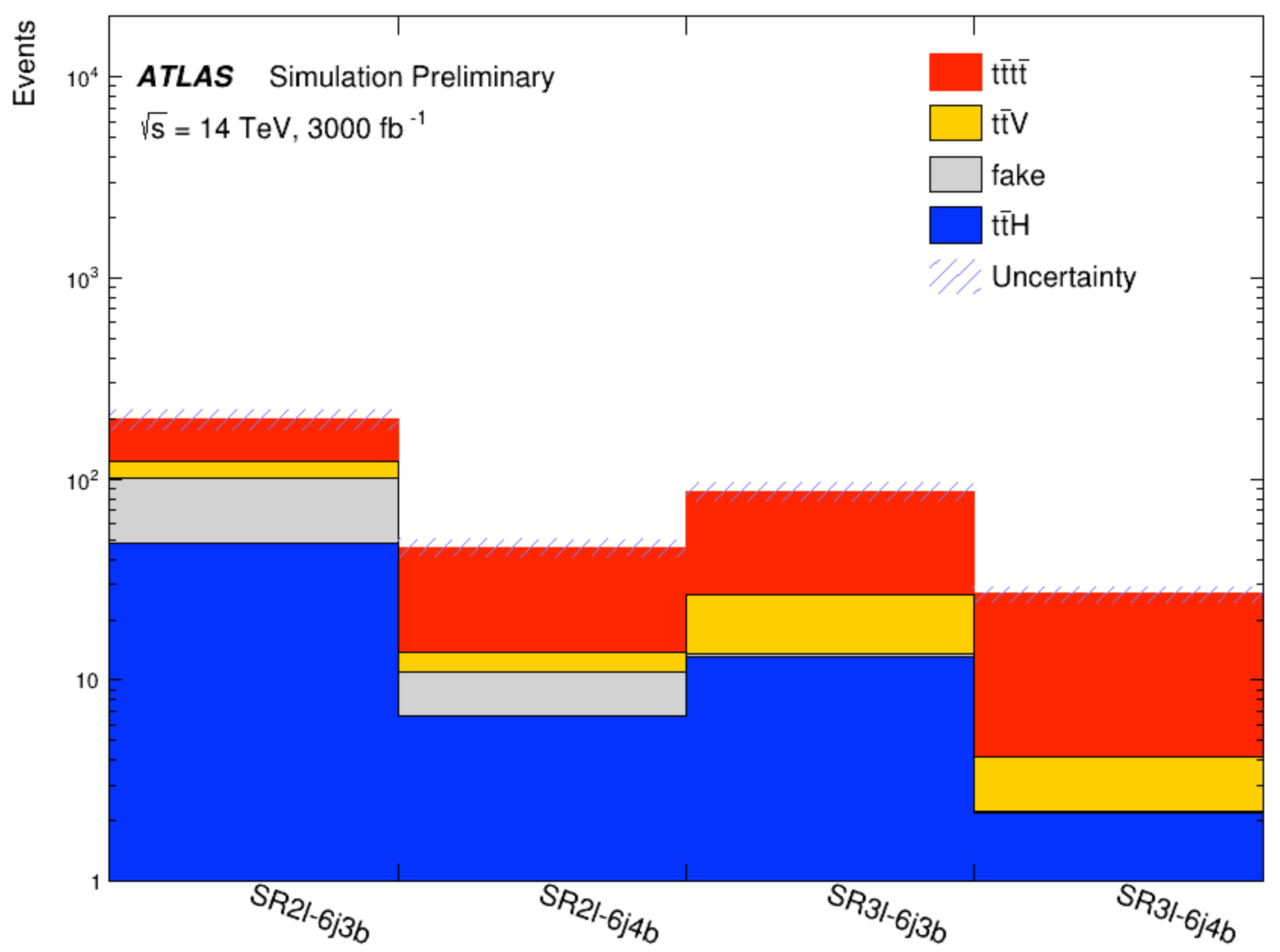
ATL-PHYS-PUB-2018-042
CMS-PAS-FTR-18-031
CMS-PAS-FTR-18-015
ATL-PHYS-PUB-2018-047

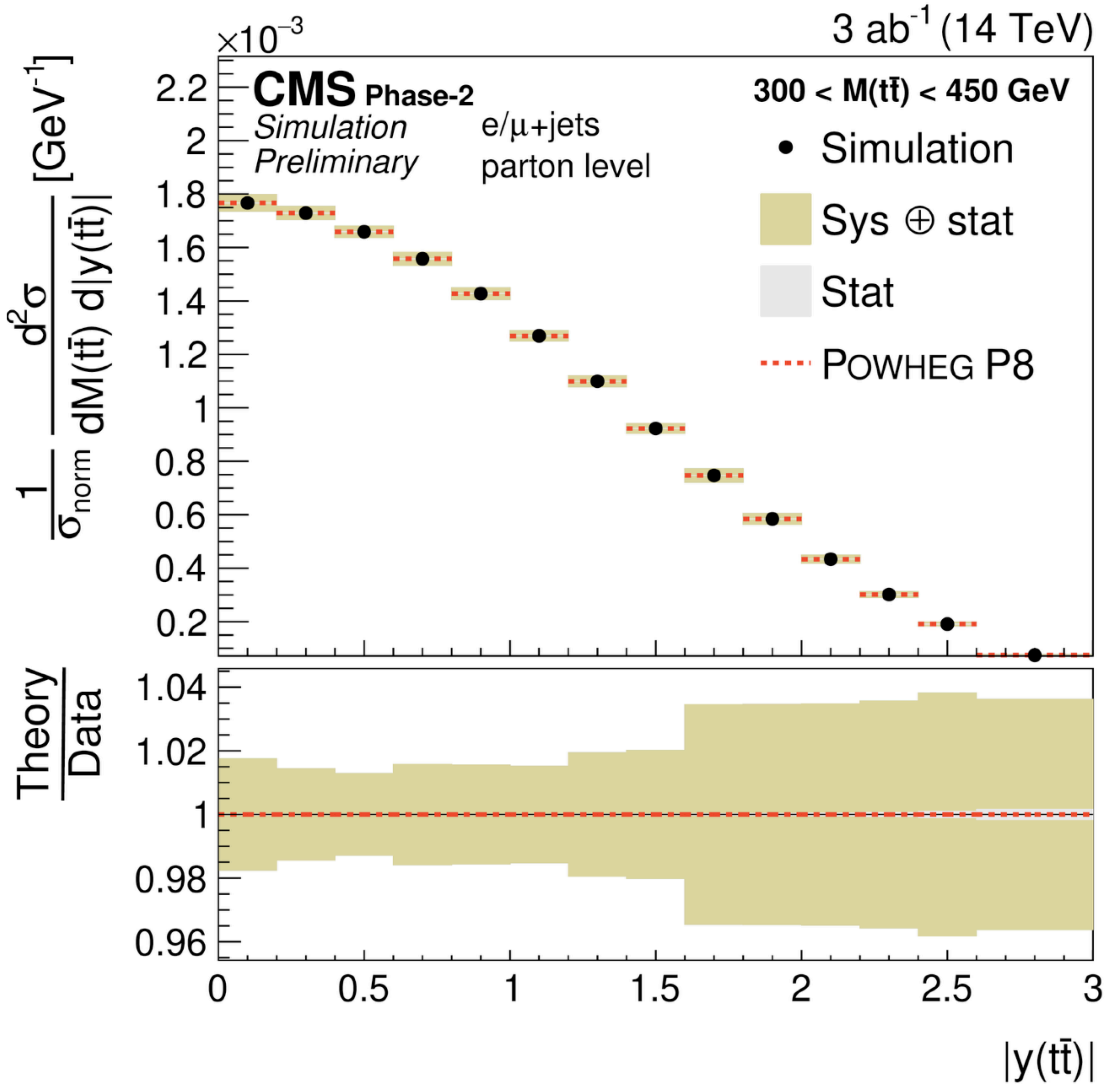
Precision measurement of top properties

- Measure top quark mass to ± 0.14 (stat) ± 0.48 (syst) GeV
- Measure differential distributions precisely using large stats and extended η, lower lepton p_T trigger thresholds
  - Example: double differential M_{tt}, y_{tt} cross-section, useful to constrain PDFs

Measurement of rare top processes

- Expect 10-30% uncertainty on 4-top cross-section
- ttγ fiducial cross-section measured to 3%, differential distributions with uncertainty below 5%



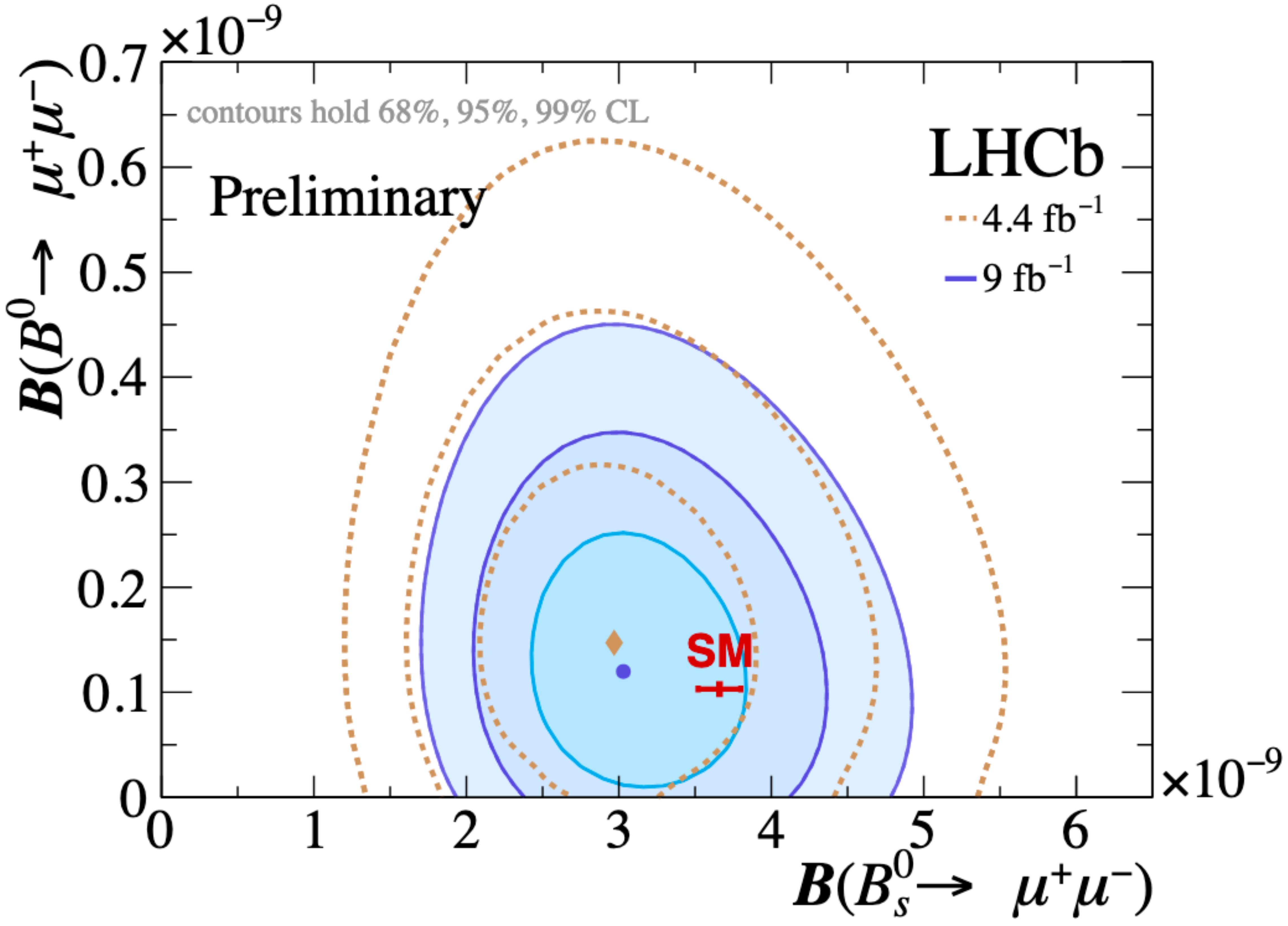


Very rare decays

Precision measurements of very, very rare decays

- Precision tests of SM and sensitive to high mass scales of new physics
- Ratio of BR of $B^0 \rightarrow \mu^+\mu^-$ / $B_s^0 \rightarrow \mu^+\mu^-$ currently 90%:
  - To ~ 30% with 23 fb^{-1}
  - To 10% with 300 fb^{-1}
- $B^0 \rightarrow \mu^+\mu^-$ will be limited by statistics
- $B_s^0 \rightarrow \mu^+\mu^-$ will be limited by systematic uncertainties, but increased statistics will reduce the syst. from ~ 6% to 4%
- Many corners of MSSM phase space will be probed by this sensitivity

Run 2 result



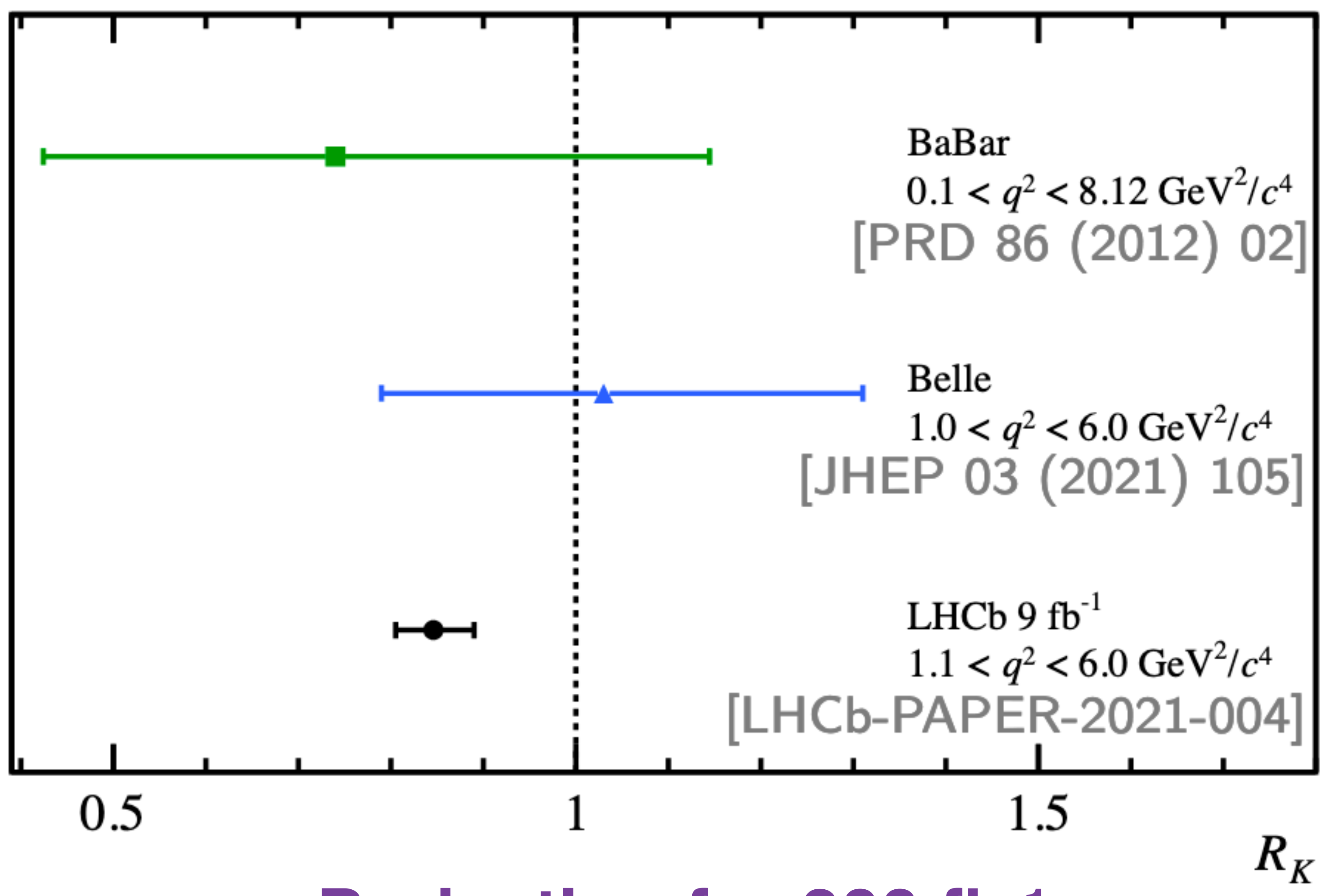
Lepton-flavor universality tests

Precision measurement of BR ratios

$$R_X = \int \frac{\mathrm{d}\Gamma(B \to X\mu^+\mu^-)}{\mathrm{d}q^2}\,\mathrm{d}q^2 \Big/ \int \frac{\mathrm{d}\Gamma(B \to Xe^+e^-)}{\mathrm{d}q^2}\,\mathrm{d}q^2$$

- Precision tests of SM, sensitive to contributions from BSM flavor-violating processes
- Current measurements of R_K, R_{K^*}, R_D suggestive and may be the best pointers to where new physics is hiding
- Ultimate precision of R_K and R_{K^*} will be better than 1%
    - Ability to distinguish at 5σ many scenarios of new physics
    - Final achievable precision depends on upgrade detector design choices

Run 2 result

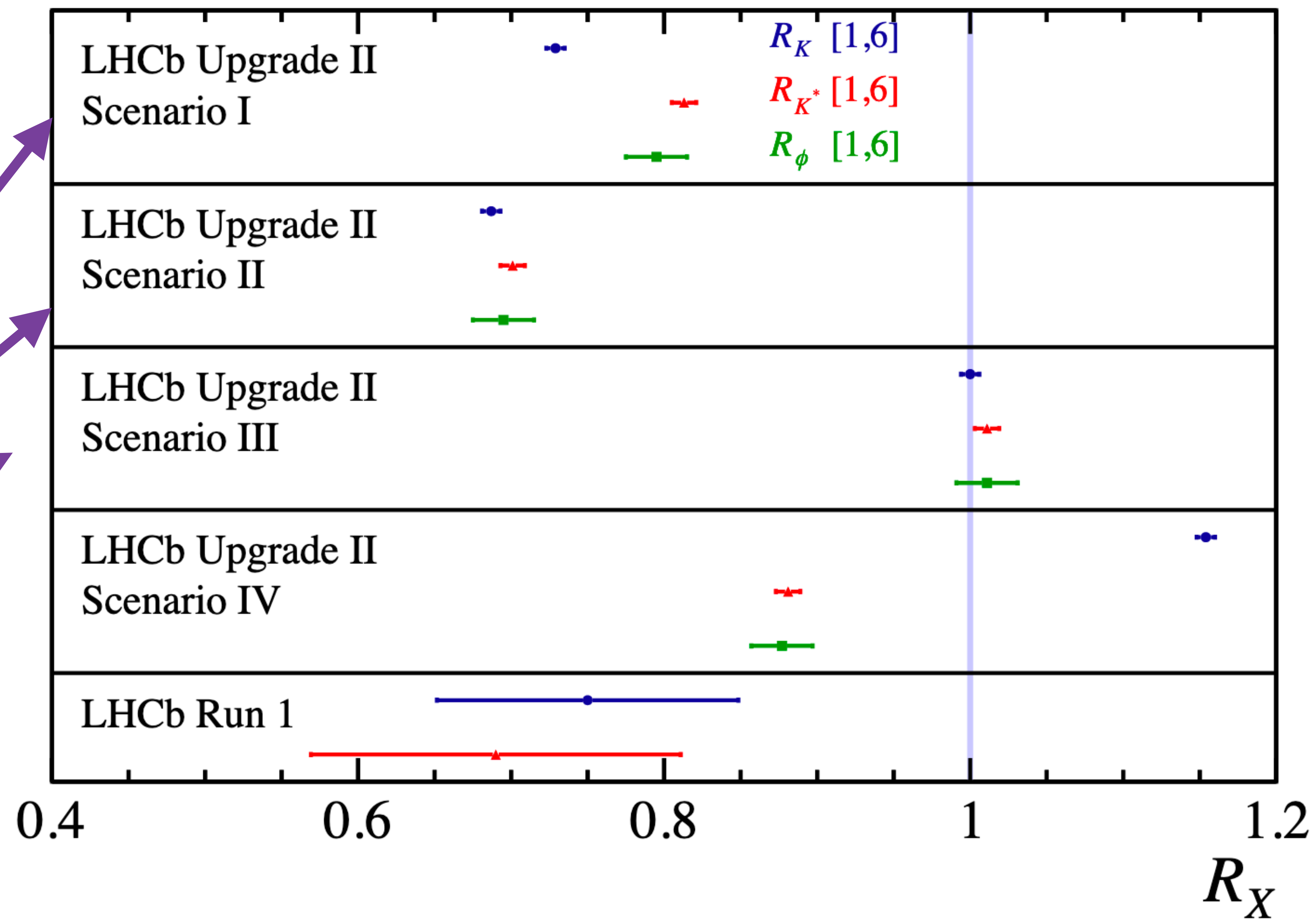


Expected Sensitivity for different datasets

R_X precision	Run 1 result	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
R_K	$0.745 \pm 0.090 \pm 0.036$ [274]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [275]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

< 1%

Projection for 300 fb^{-1}



different assumptions of new physics contributing

Beyond the Standard Model Searches… (and discovery?)

Dark photons at LHCb

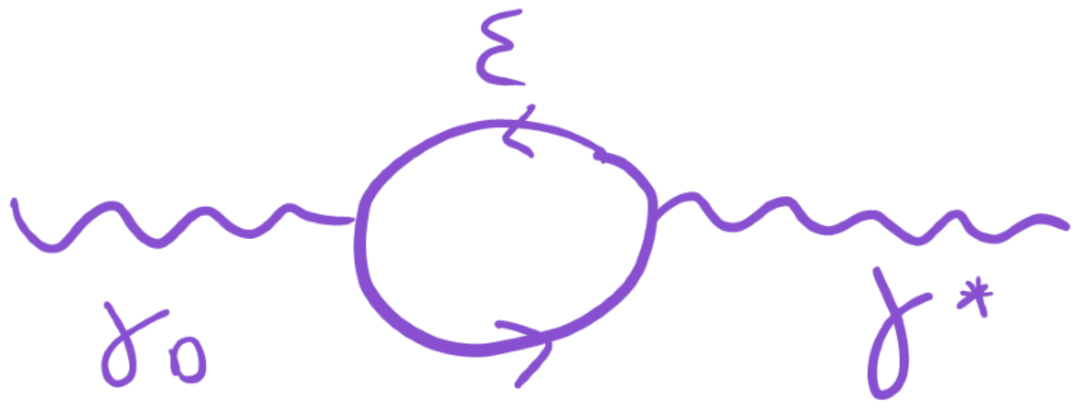
LHCb-PUB-2018-009

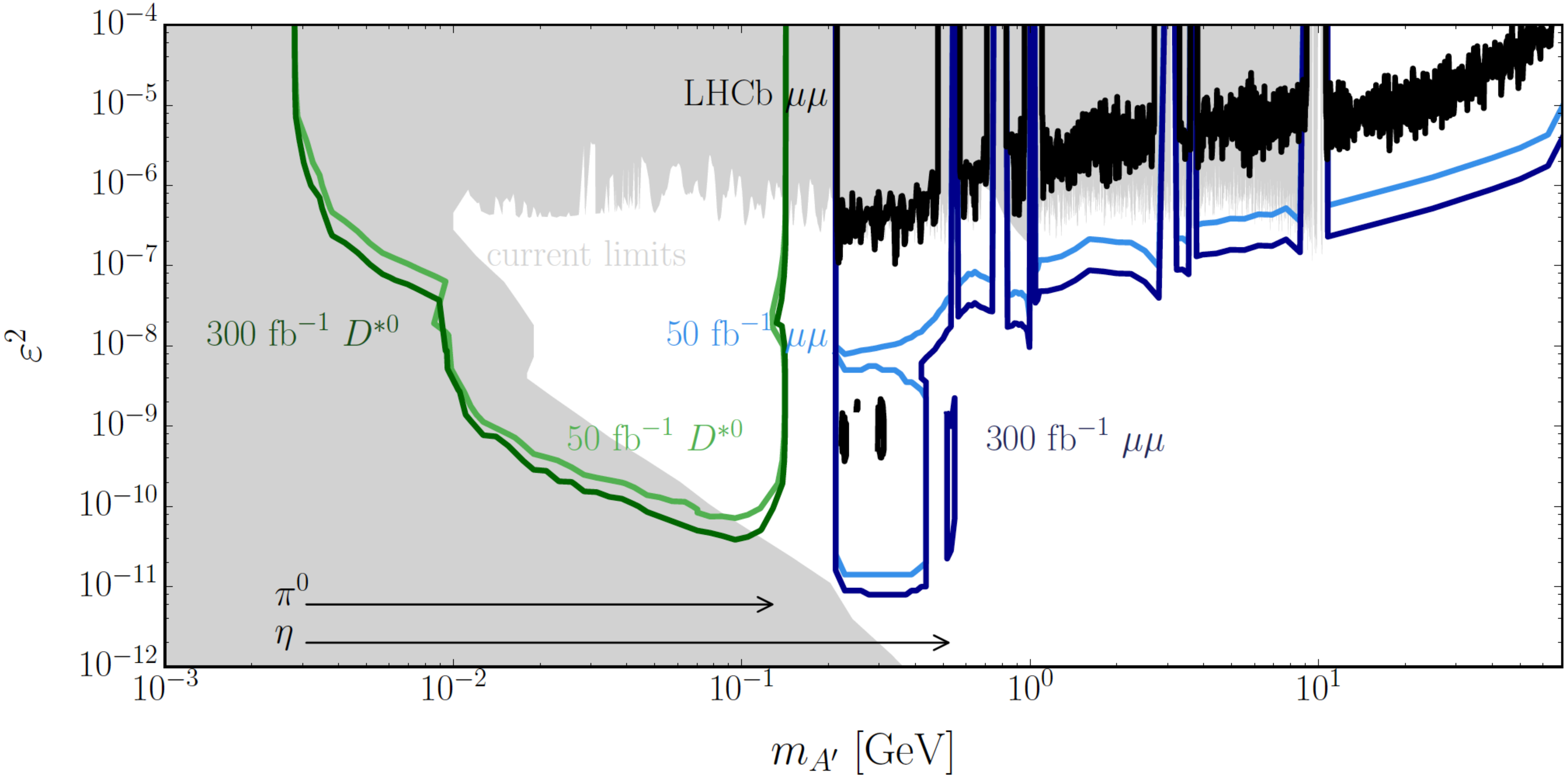
Pushing the frontier of light, weakly coupled particles

- Difficult and important phase space, benchmark for whole class of models including axions, ALPS, etc

A combination of prompt, long-lived, and meson analyses pursued to probe a large part of the mass and mixing plane for dark photons

- Triggerless readout essential to achieve necessary statistics at low muon p_T

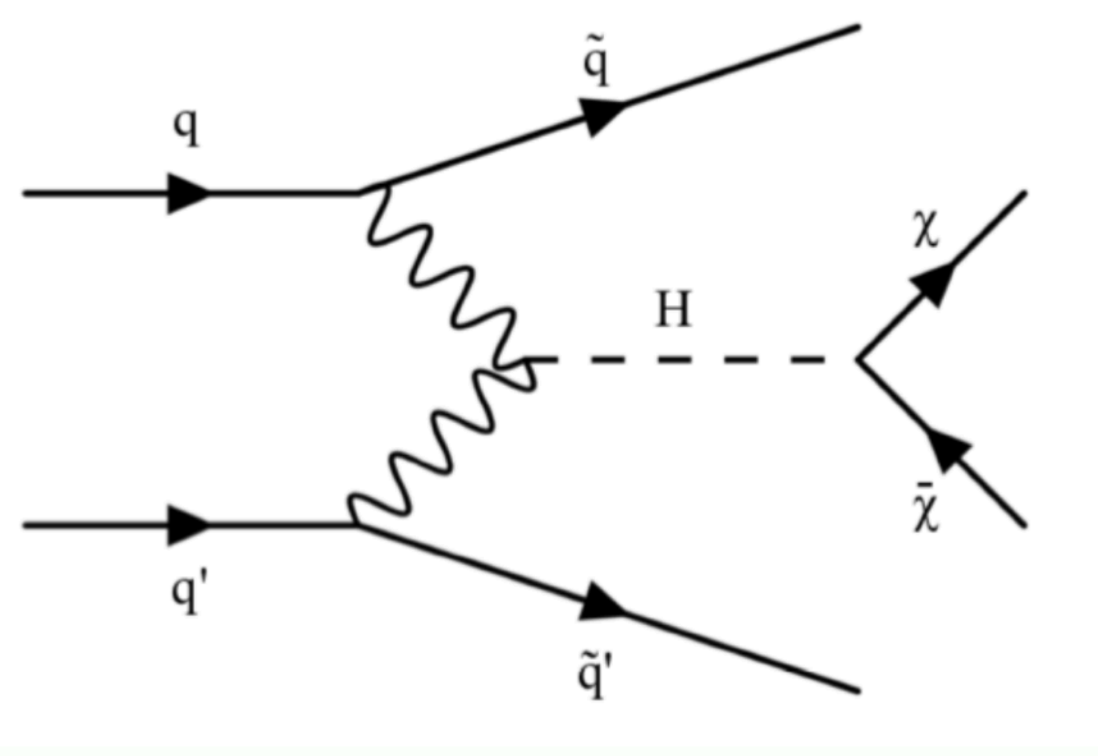




Higgs to Invisible

Higgs to invisible BR is powerful and independent probe for light dark matter

- current limit on BR (H—> inv.) 0.11, driven by vector boson fusion production



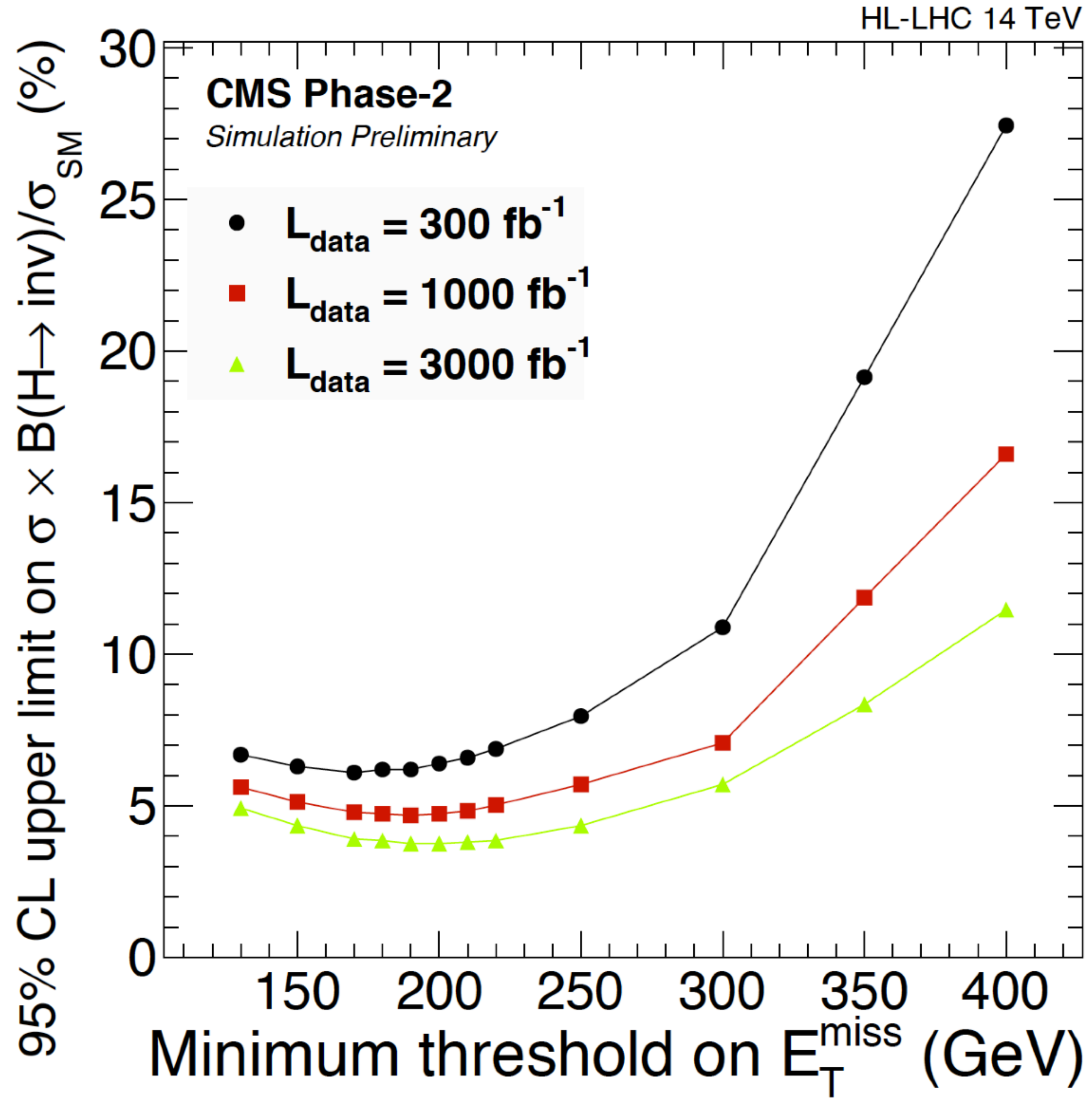
Maintaining signal efficiency and background rejection is key and challenging at high pileup

- main signal is 2 forward jets and MET, rejection of pileup jets is paramount
- main backgrounds behave differently at HL-LHC relative to LHC
- single channels from CMS/ATLAS expected to reach 4% on BR (H—> inv.)
- combination of experiments and channels expected to give limit to **2.5%**

Run 2 syst **goal / assumptions for HL-LHC syst**

Systematic	From Ref. [14]	This analysis
e-ID	1%(gsf)⊕1%(idiso)	1%
μ-ID	1%(reco)⊕1%(id)⊕0.5%(iso)	0.5%
e-veto	0.6%(gsf)⊕1.5%(idiso)	1%
μ-veto on QCD V+jets	5%(reco)⊕5%(id)⊕2%(iso)	2%
μ-veto on EWK V+2jets	10%(reco)⊕10%(id)⊕6%(iso)	6%
τ-veto	1–1.5% for QCD–EWK	0.5–0.75%
b-tag-veto	0.1% (sig) 2% (top)	0.05% (sig) 1% (top)
JES	14%(sig) 2%(W/W) 1%(Z/Z)	4.5%(sig) 0.5%(W/W) 0.2%(Z/Z)
Integrated luminosity	2.5%	1%
QCD multijet	1.5%	1.5%
Theory on W/Z ratio	12.5%	7%
ggH normalisation	24%	20%

different sources of systematic uncertainty considered in Ref. [14] and for the HL-LHC setup considered in this analysis.



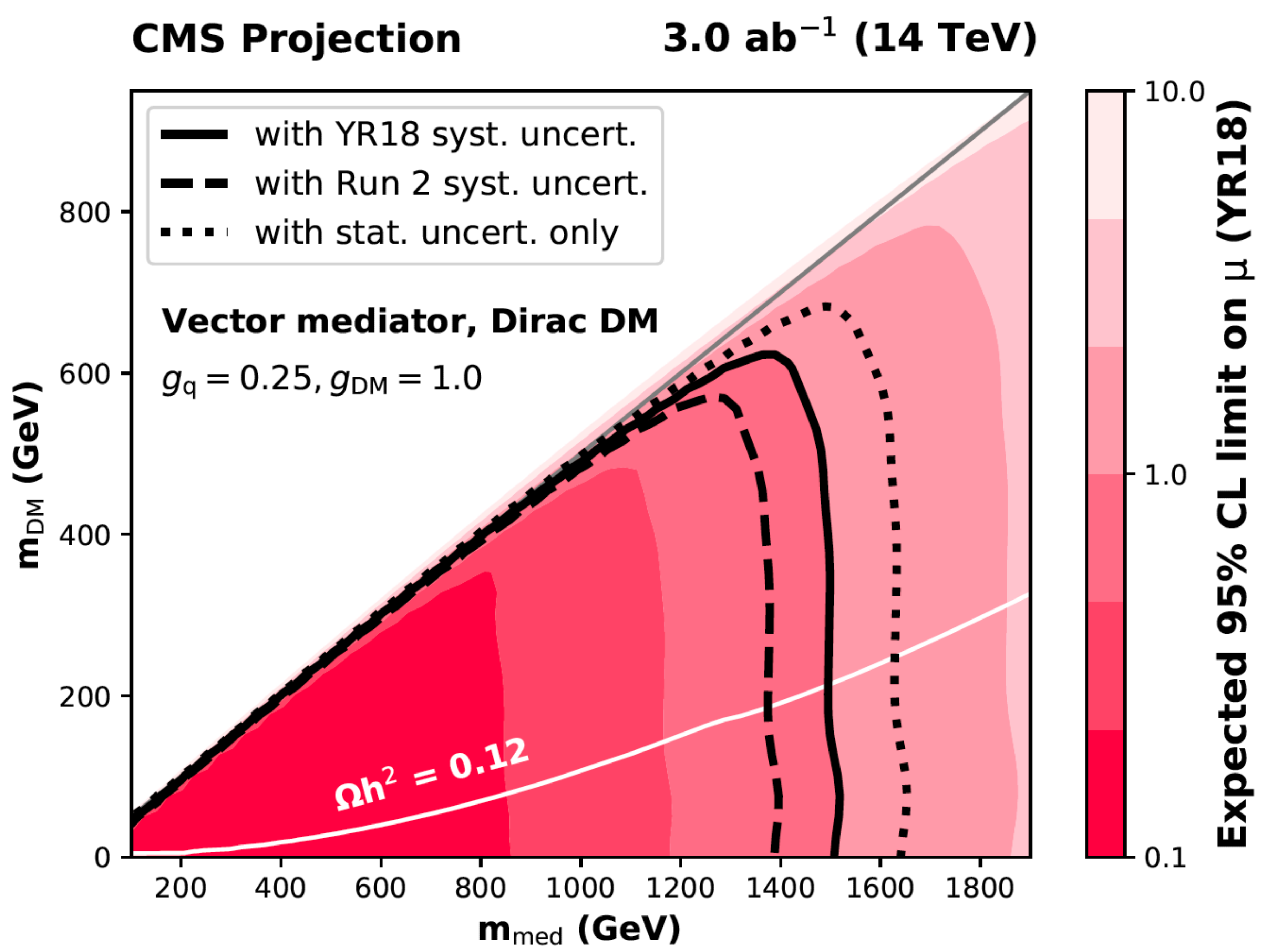
ATL-PHYS-PUB-2018-043

CMS-FTR-18-007

Dark Matter

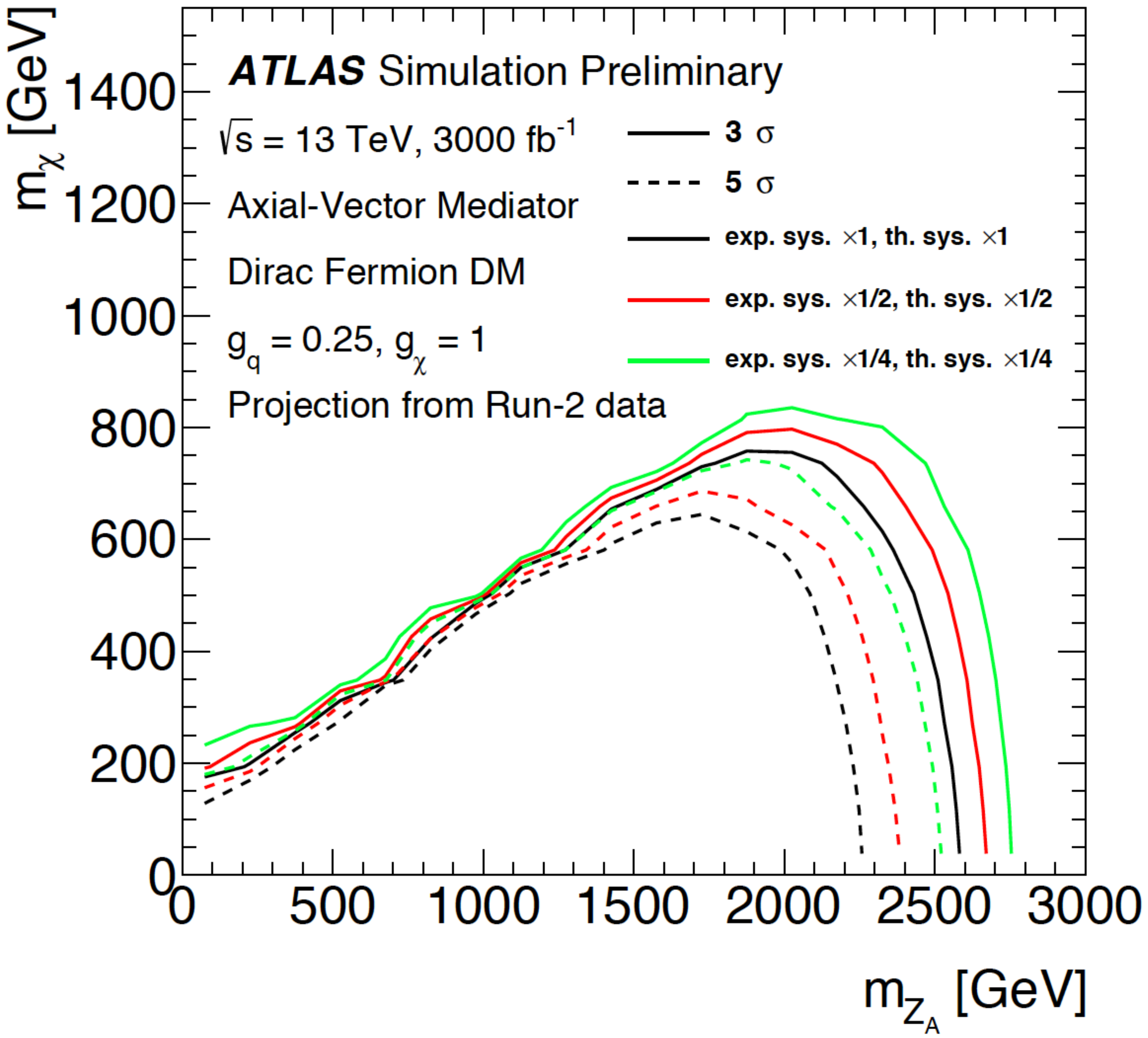
- Mono-X searches will continue to push sensitivity to DM produced in association with other objects
  - Pushing sensitivity to large DM mass as well pushing down in couplings
  - Synergy between different collider searches for DM, SUSY, H—> inv, simplified models X + DM
  - Mono-X will be competitive in some regions with direct neutralino searches, sensitivity from 200 (300) GeV for higgsino (wino) neutralinos
  - Very sensitive to systematic uncertainties, largely on background (W/Z+jets, diboson) estimates

Exclusion sensitivity in mono-Z



- extends the sensitivity of mediator masses by up to a factor of 2 relative to current LHC results

Discovery reach for mono-jet



ATL-PHYS-PUB-2018-044

CMS-FTR-18-009

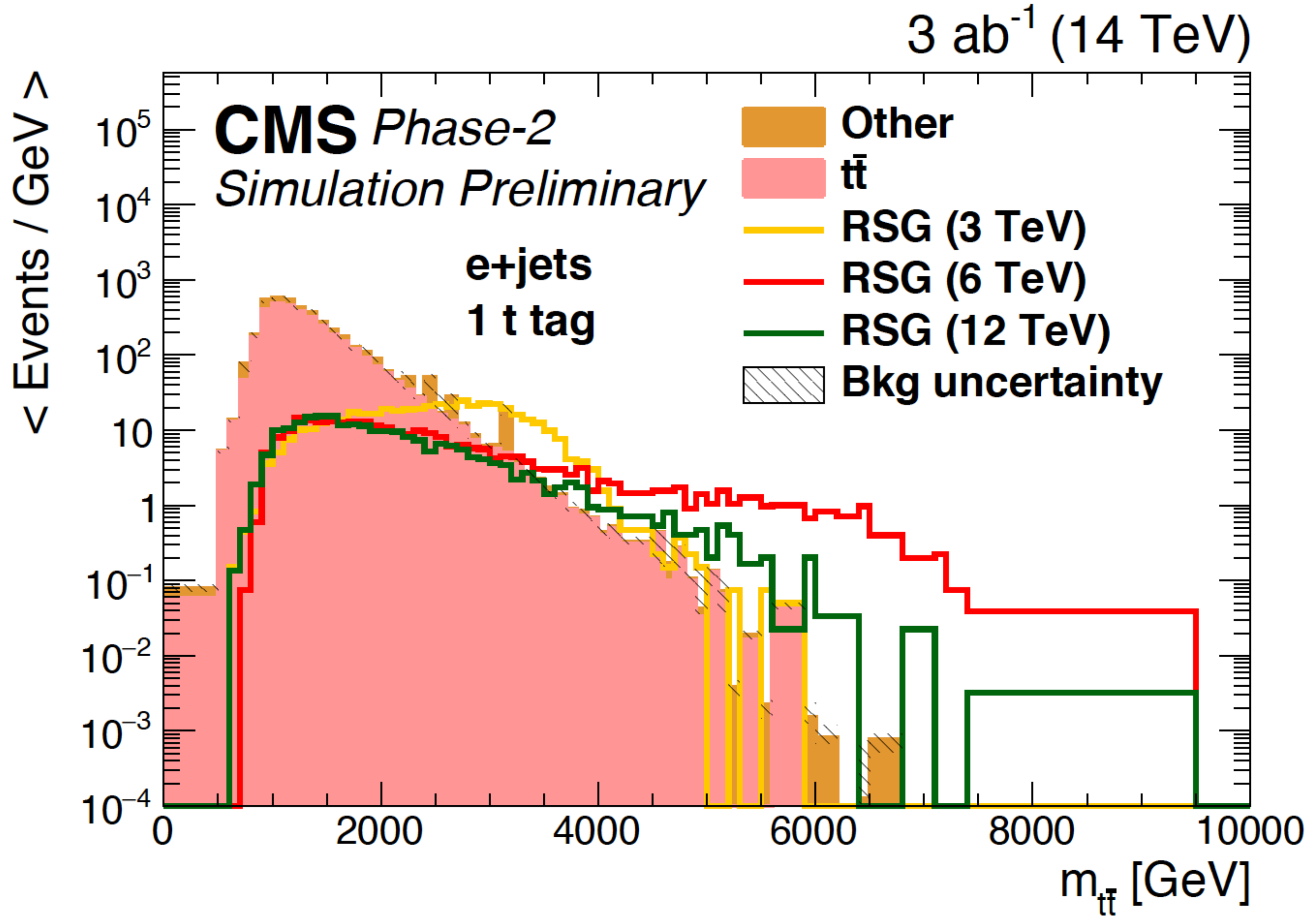
Pushing the energy frontier (high mass)

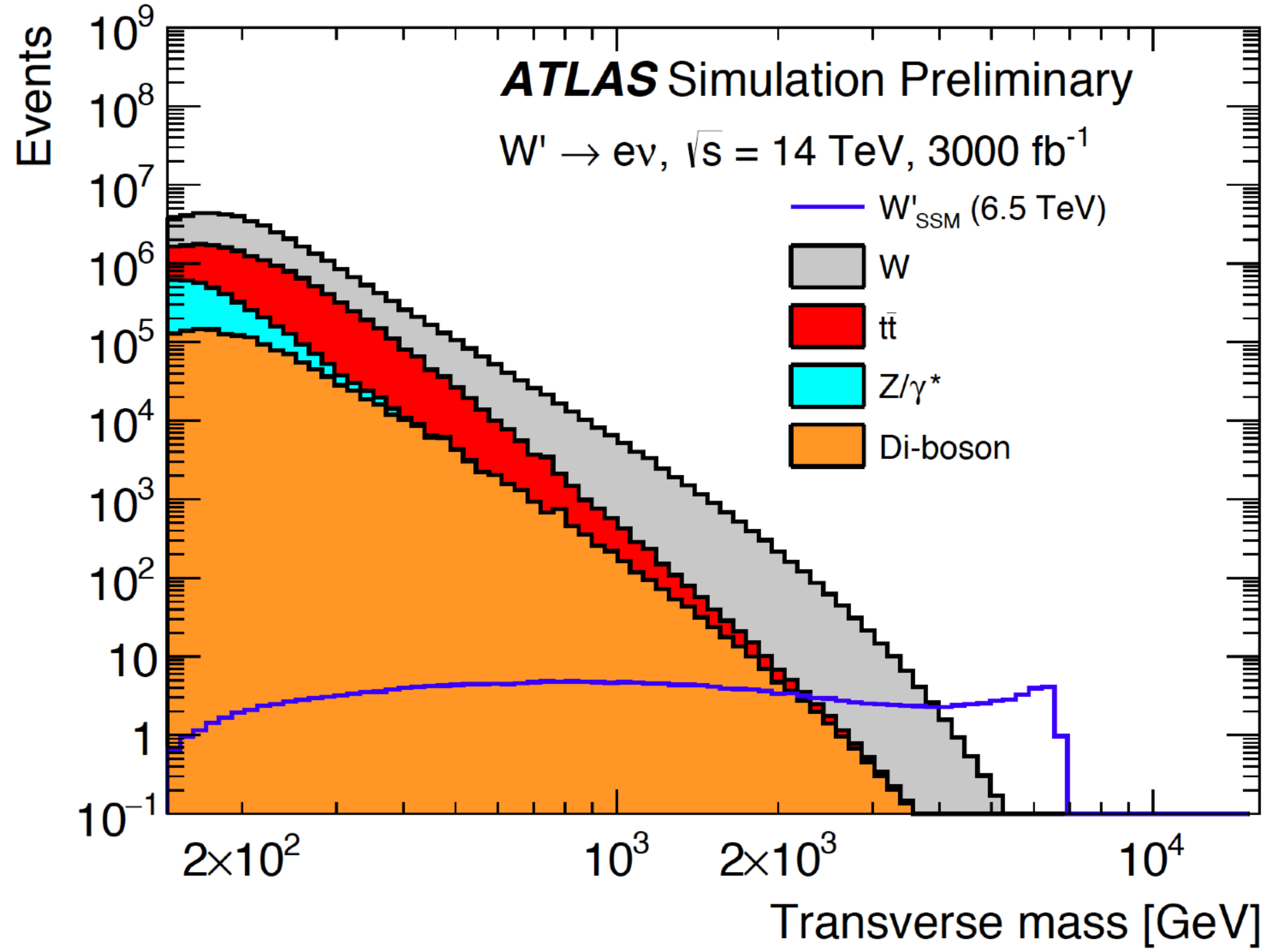
Continuation and expansion of the current resonance search program, across a vast variety of channels

- requires continued excellent performance of object reconstruction and energy / mass resolution
- high mass sensitivity is dominated by statistics

- W' discovery potential up to 7.7 TeV!
- RS Gluon discovery up to 5.7 TeV!

Decay	$\sqrt{s} = 13$ TeV Exclusion	$\sqrt{s} = 13$ TeV Discovery	$\sqrt{s} = 14$ TeV Exclusion	$\sqrt{s} = 14$ TeV Discovery
$Z'_{\mathrm{SSM}} \to ee$	6.0 TeV	5.9 TeV	6.4 TeV	6.3 TeV
$Z'_{\mathrm{SSM}} \to \mu\mu$	5.5 TeV	5.4 TeV	5.8 TeV	5.7 TeV
$Z'_{\mathrm{SSM}} \to \ell\ell$	6.1 TeV	6.1 TeV	6.5 TeV	6.4 TeV
$Z'_{\psi} \to ee$	5.3 TeV	5.3 TeV	5.7 TeV	5.6 TeV
$Z'_{\psi} \to \mu\mu$	4.9 TeV	4.6 TeV	5.2 TeV	5.0 TeV
$Z'_{\psi} \to \ell\ell$	5.4 TeV	5.4 TeV	5.8 TeV	5.7 TeV





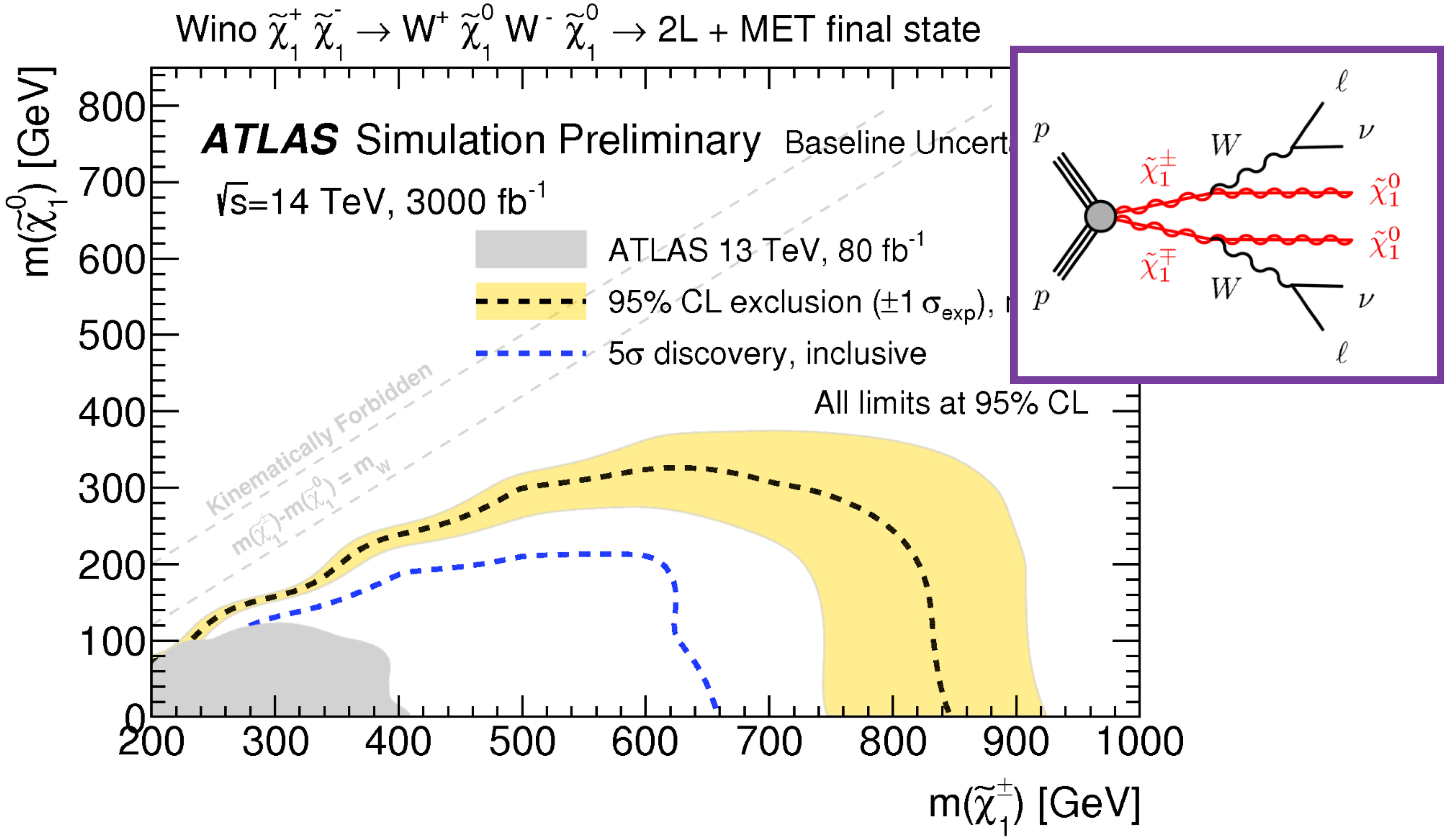
Supersymmetry

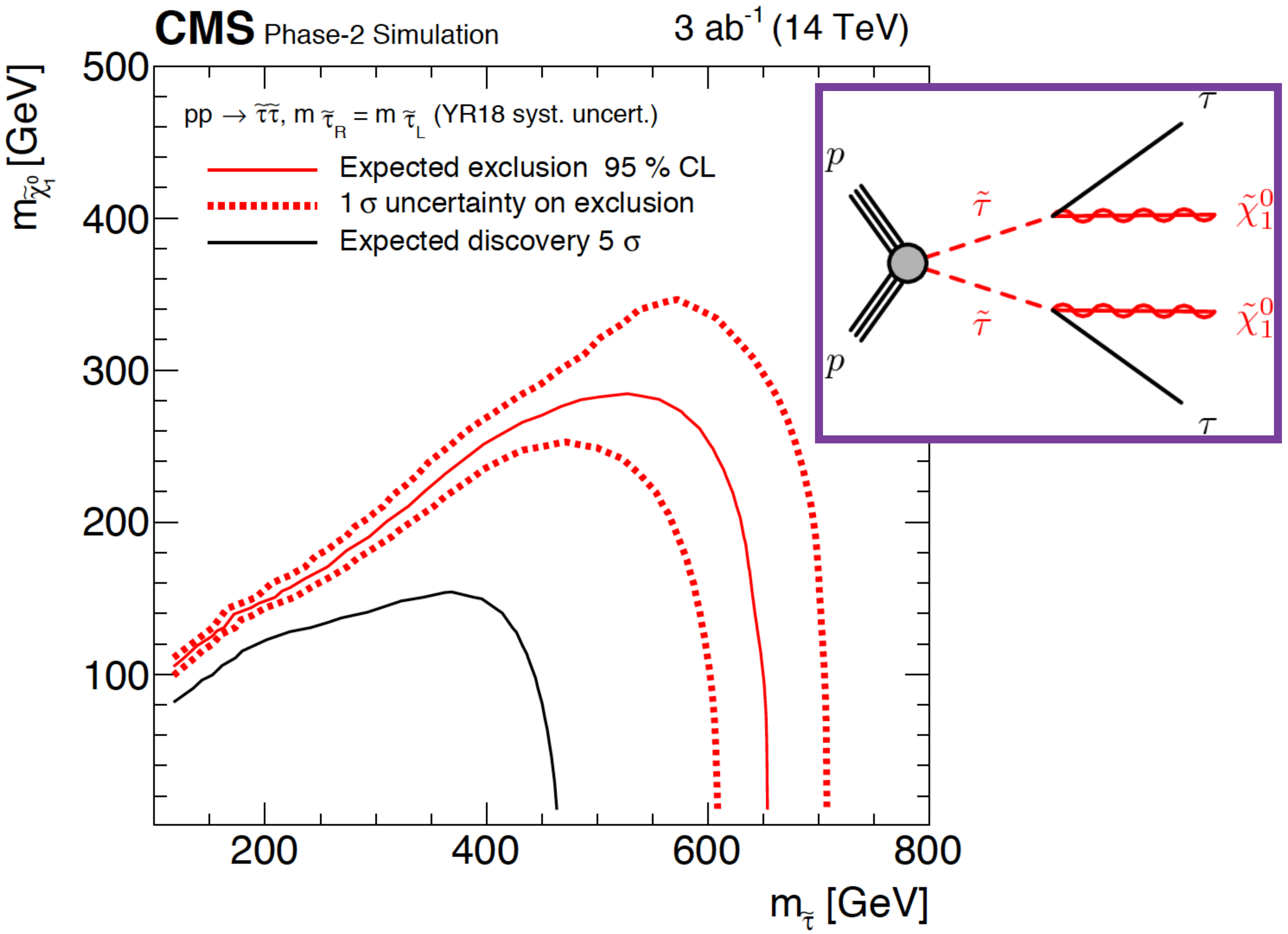
Covering electroweak production up to ~ 1 TeV and pushing into compressed regions a major goal of HL-LHC

- Sensitivity to sleptons and electroweakinos an order of magnitude beyond LEP and 500 GeV above current limits
- HL-LHC will probe most of the natural EW SUSY parameter space

Detector upgrades, performance work, and new analysis techniques essential

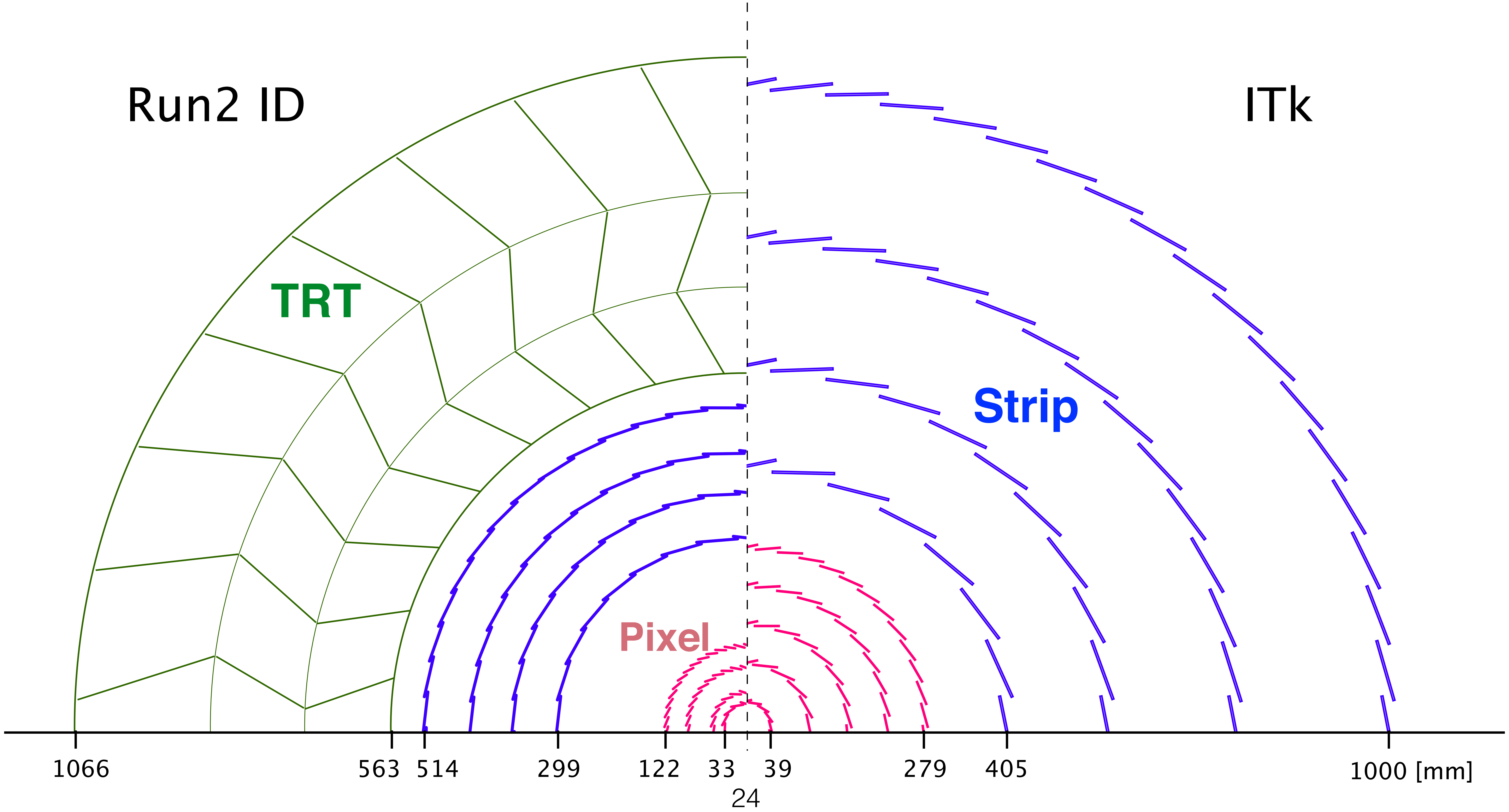
- Upgrades to trigger at L1 and HLT to maintain lepton trigger thresholds
- Detector upgrades to maintain and even improve object performance (b-jets, taus, leptons, MET, isolation…)
- New and advanced techniques including machine learning, soft object tagging, photon production, etc, necessary to cover compressed gaps





Challenges and opportunities: new detectors

Case study: new inner detector in ATLAS and its impact on sensitivity of long-lived particle searches



ATL-PUB-2018-033

Displaced vertex signatures

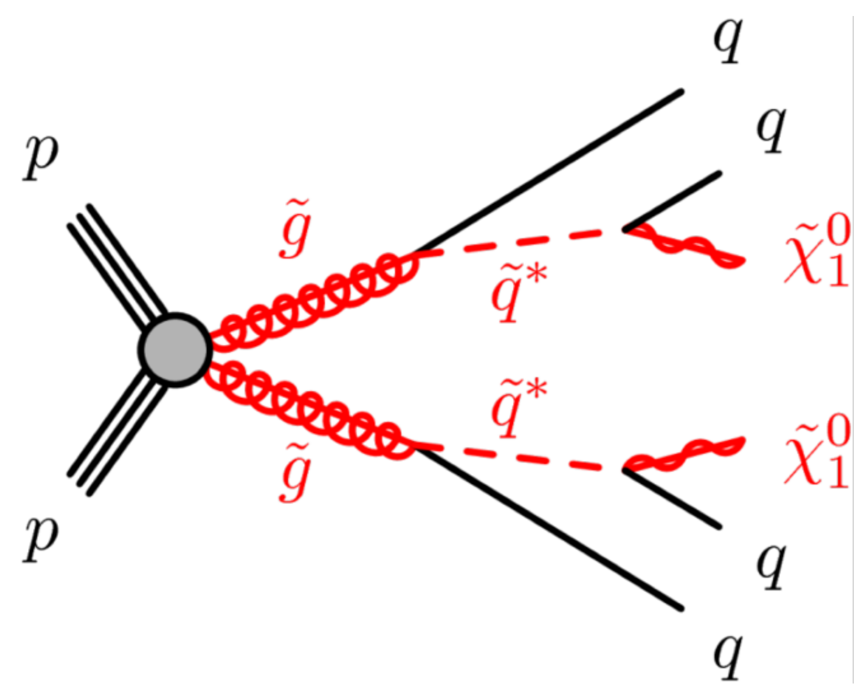
Displaced vertices in the inner detector are sensitive to long-lived particles with τ ~10 ps - 10 ns

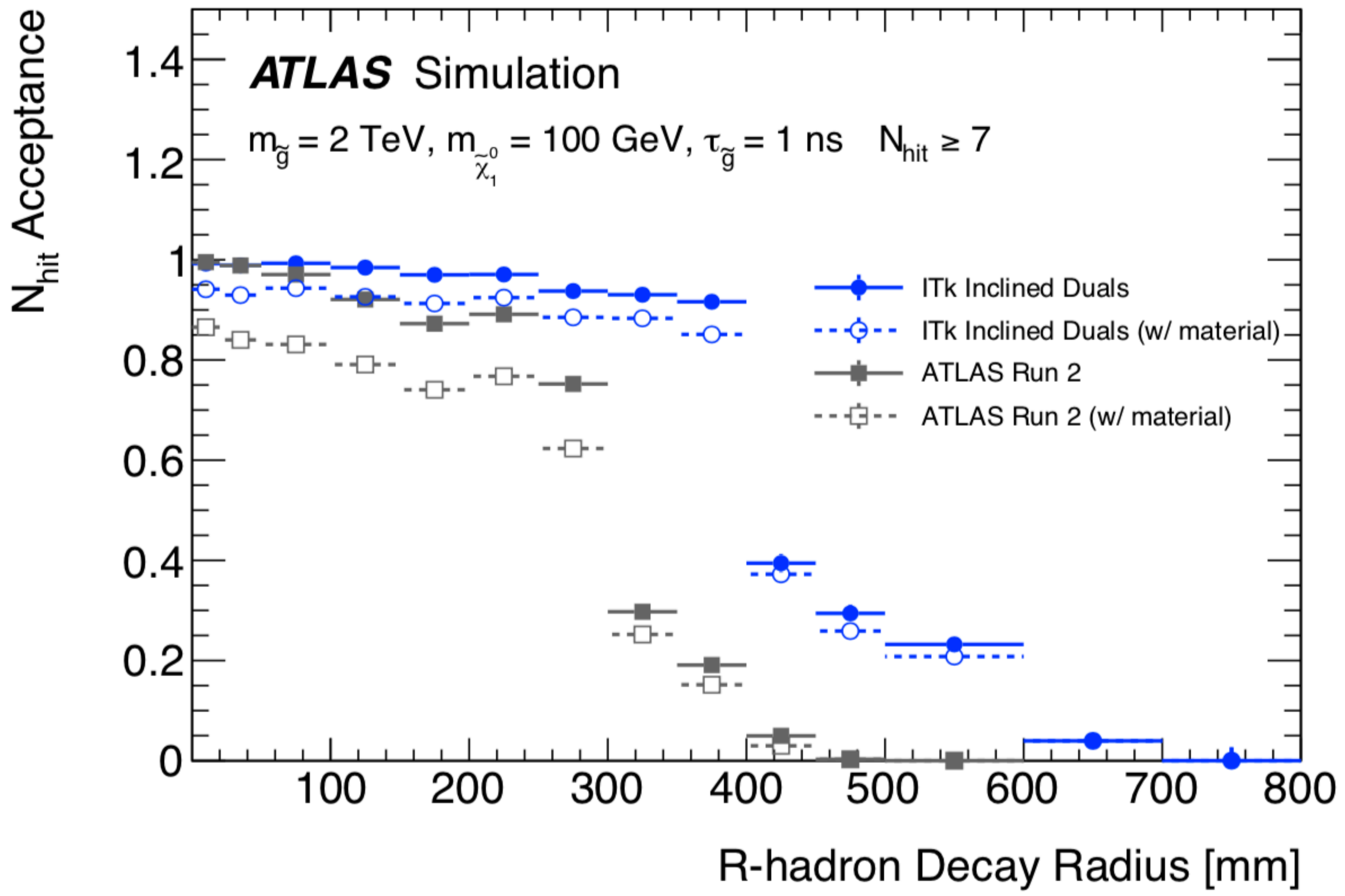
- Hadronic and leptonic final states targeted, DV + MET, jets, leptons, etc...

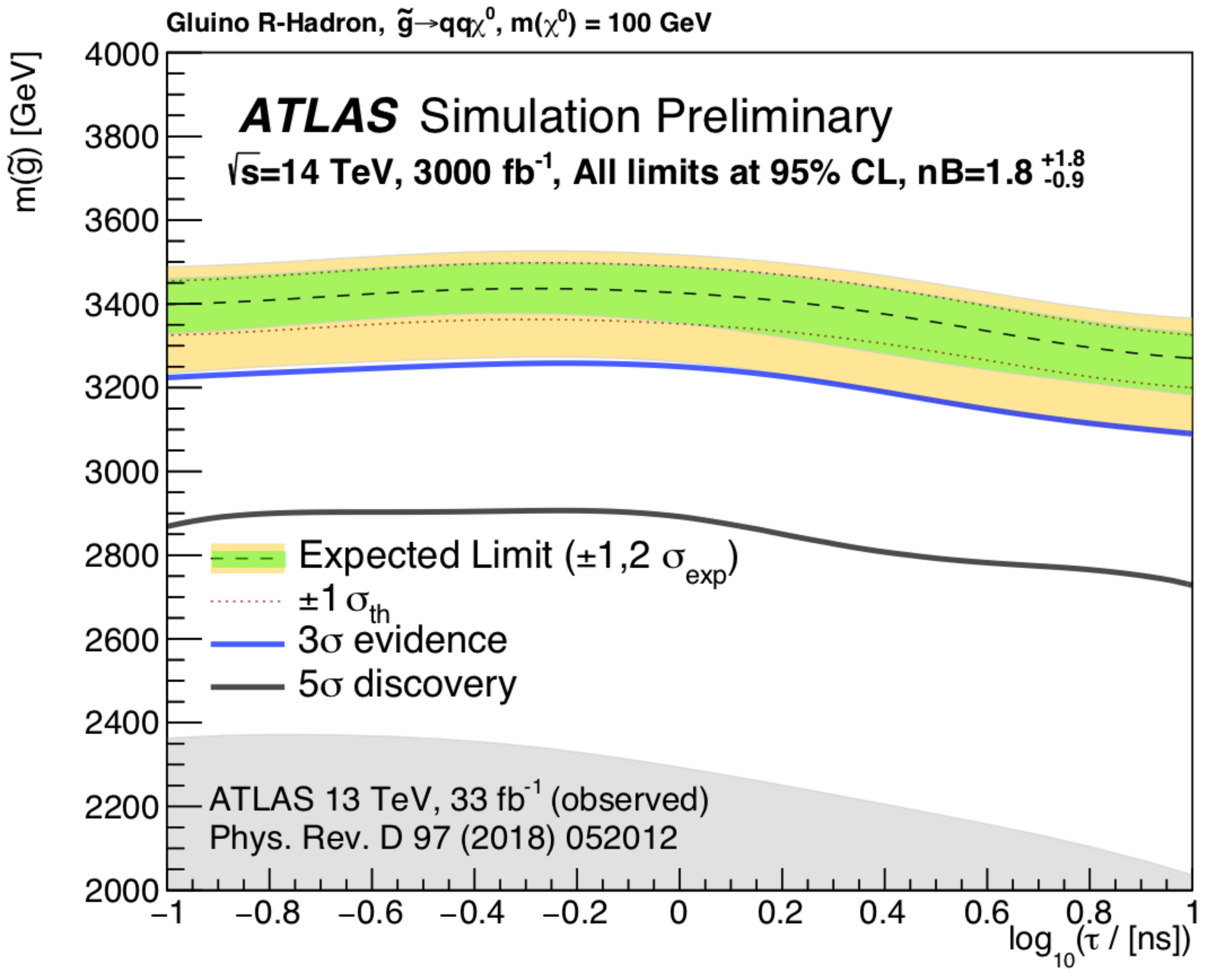
Sensitivity depends on detector geometry

- Need a minimum number of silicon hits after decay to well-reconstruct vertex and reject background
- Reconstruction efficiency gains relative to current detector from larger silicon volume

Translates to increased relative sensitivity at larger lifetimes relative to current analysis, purely from new detector geometry







Disappearing tracks

Class signature sensitive to wide class of natural DM models, including pure wino or higgsinos

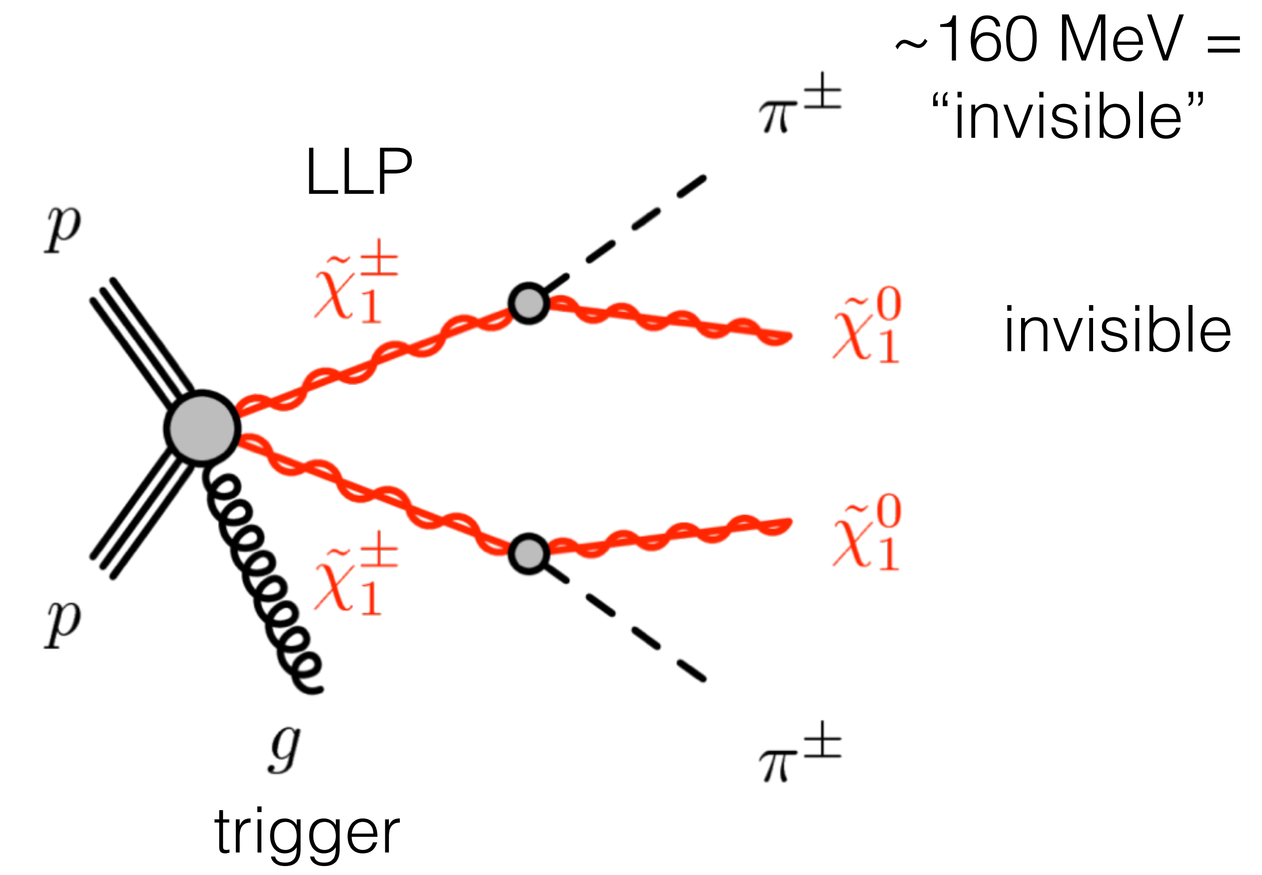
- Charged particle with lifetimes of a fraction of ns decaying to invisible + very soft SM —> short tracks

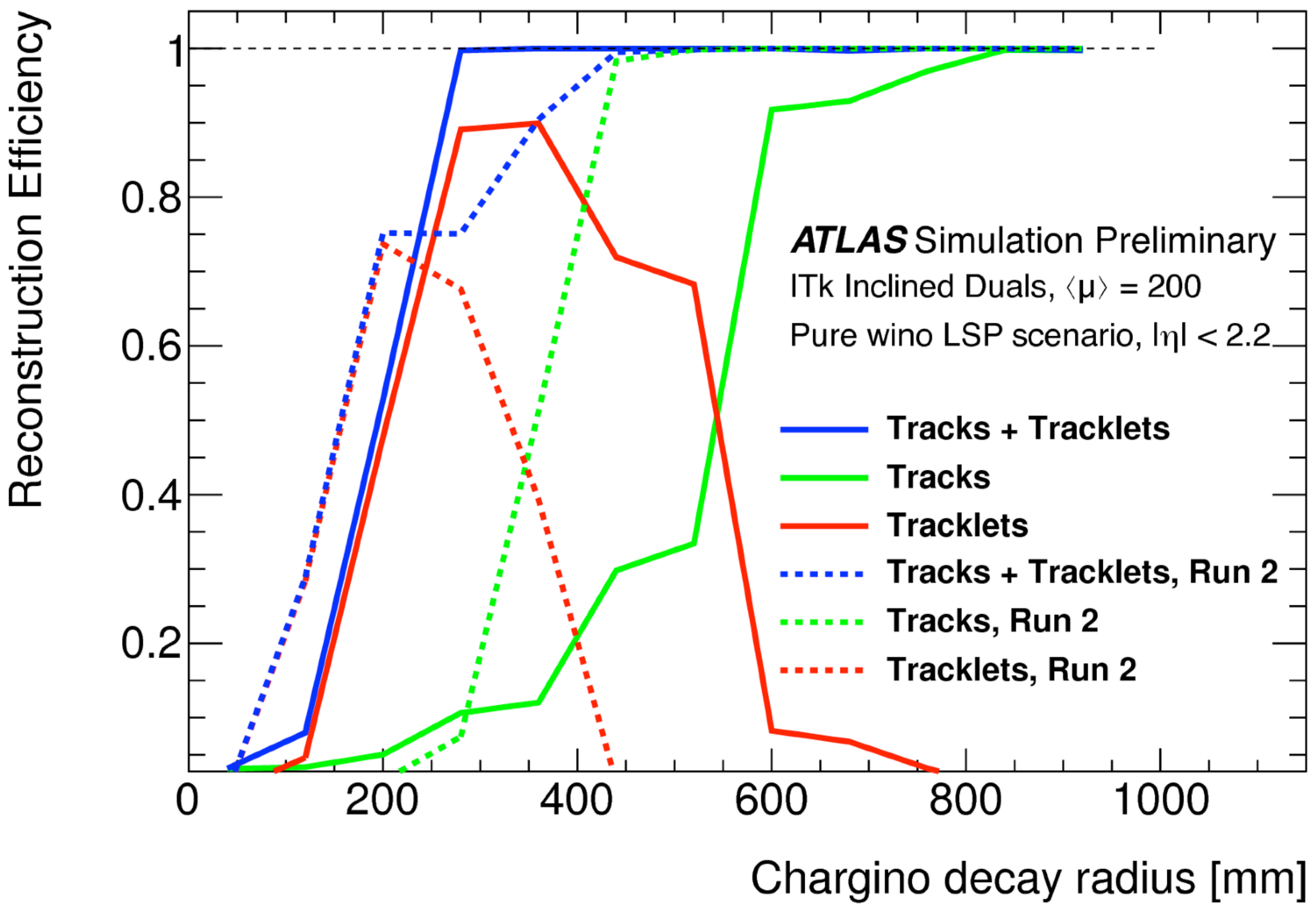
Sensitivity depends on detector geometry

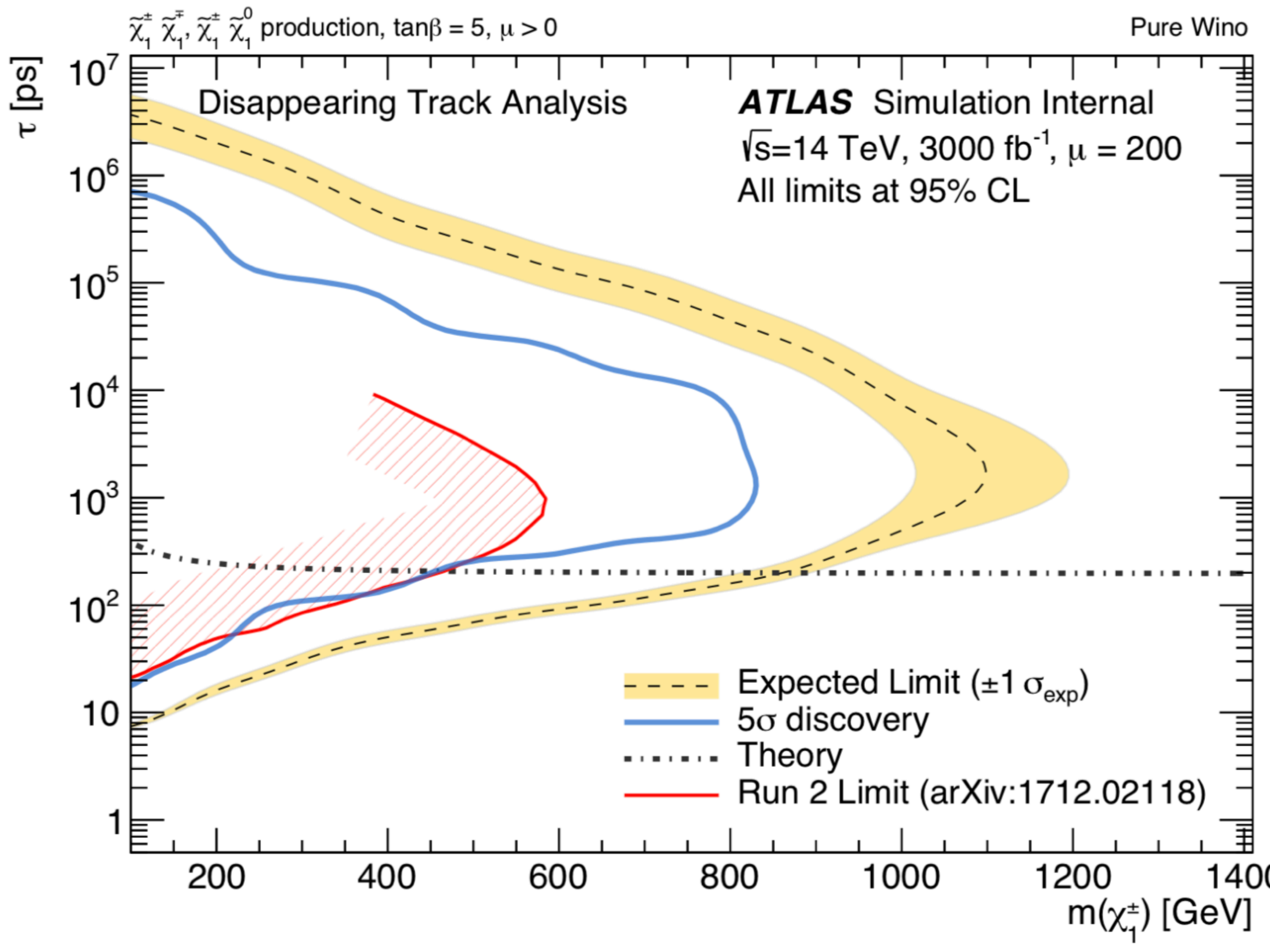
- Need a minimum number of silicon hits before decay to well-reconstruct short track
- Efficiency of short tracks very sensitive to position of first few layers of pixel detector

Sensitivity gains relative to Run 2 (3) more challenging at shorter lifetimes, solely from new detector geometry

- Innovative techniques under development to target full Δm phase space







Summary and outlook

Enormous work by community to study the potential physics reach of HL-LHC

Measurements of SM physics, including Higgs and flavor physics, into the (very) precision regime

Depending on the new physics, sensitivity (and the potential to discover!) new physics with masses from sub-GeV to many TeV

- Some channels have straightforward gains with higher energy, increased lumi, and upgraded detector
- Other channels will require more creative and sustained effort to improve over Run 3 sensitivity

The work is just beginning

- Detector upgrades are massive undertakings consuming a large part of the collaborations' current focus
- All projections rely on enormous work on many fronts — the accelerator upgrade, the detector upgrades, trigger, performance and reconstruction advancements, analysis improvements, theory improvements, PDF reduction, precise luminosity determination…