THE PHYSICS OF HIGH-LUMINOSITY LHC

PADOVA, NOV 23 2017

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WHAT AFTER LHC?

- Standard Model works beautifully at the LHC: no direct evidence of new physics
- Key questions remain unanswered
  - What gives rise to the matter-antimatter asymmetry in the universe?
  - What is dark matter made of? What is dark energy?
  - Why is gravity so weak? ➔ hierarchy problem
    - Small Higgs mass requires spectacular cancellations if SM is valid to Planck scale
    - Strong motivation for new physics at the TeV scale (➔ new particles, interactions, dimensions)
- The answers may still lie at the TeV scale…
- HL-LHC will deliver 3/ab (x50 today's data sample) @ 14 TeV
  - Study the Higgs boson in detail —> BSM physics could manifest itself in deviations from SM predictions
  - Measure rare SM processes —> BSM could have a large effect
  - Search for new particles/phenomena at the TeV scale
- HE-LHC might double the collision energy to 27 TeV
  - Higher mass reach for new physics – deeper exploration of TeV scale

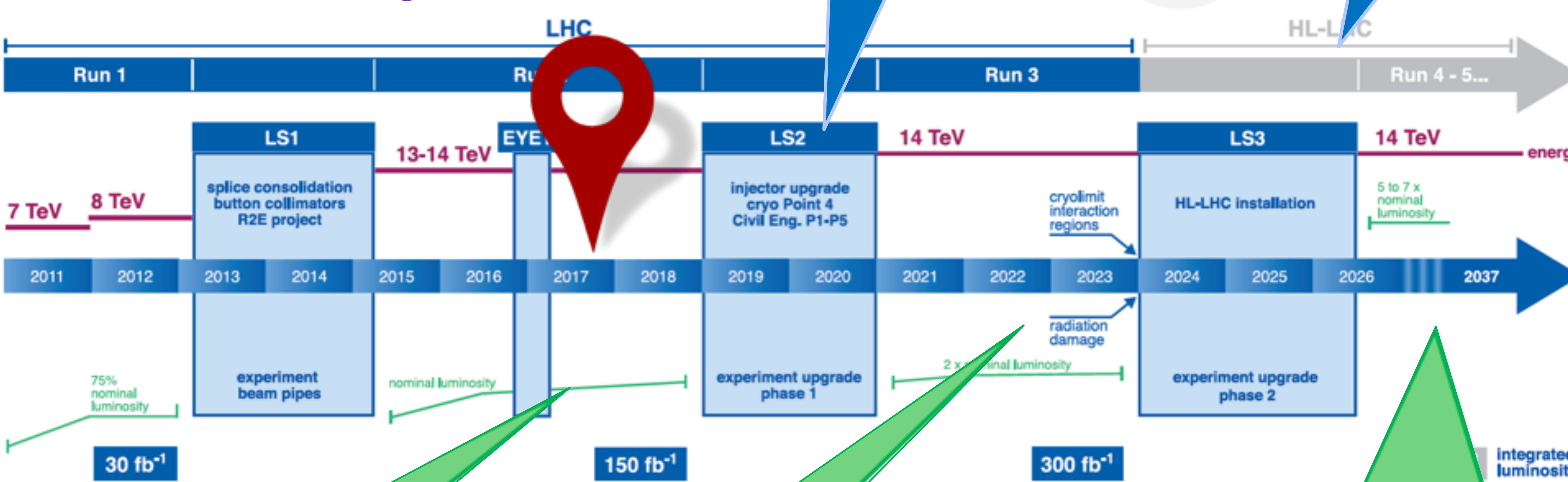
My view: take the opportunity to ask ourselves not hat we CAN do at HL-LHC but what do we NEED to study.

upgrade of injector chain to deliver brighter bunches

new interaction region layout and crab cavity

HL-LHC

LHC



Run 2:
Design $\mathcal{L} = 10^{34}/\text{cm}^2/\text{s}$

Run 3:
$\mathcal{L} = 2{\times}10^{34}/\text{cm}^2/\text{s}$
for 300/fb

HL-LHC: Peak $\mathcal{L} = 2 \times 10^{35}/\text{cm}^2/\text{s}$
level luminosity to
Nominal scenario: $\mathcal{L} = 5 \times 10^{34}/\text{cm}^2/\text{s}$
for 3000/fb; Pile-up $<\mu>$ = 140
Ultimate Scenario: $\mathcal{L} = 7.5 \times 10^{34}/\text{cm}^2/\text{s}$
for 4000/fb; Pile-up $<\mu>$ = 200
$\Rightarrow$25% increase in integrated lum.

HL-LHC PLAN

HE-LHC

- Center of mass energy: 27 TeV pp collision
  - [~ 14 TeV x 16 T/8.33T]
  - "This "Energy Doubler" option with high-field magnets constitutes an adiabatic approach to pp-collisions at higher energy."*[1]
  - Target luminosity ≥ 4 x HL-LHC
  - Integrated Luminosity: >10 ab^{-1} over 20 years
- Pile up of up to ~800 at 25 ns bunch spacing
  - (~400 at 12.5 ns or with luminosity leveling)
  - excellent prospects for lepton-hadron & heavy-ion collisions

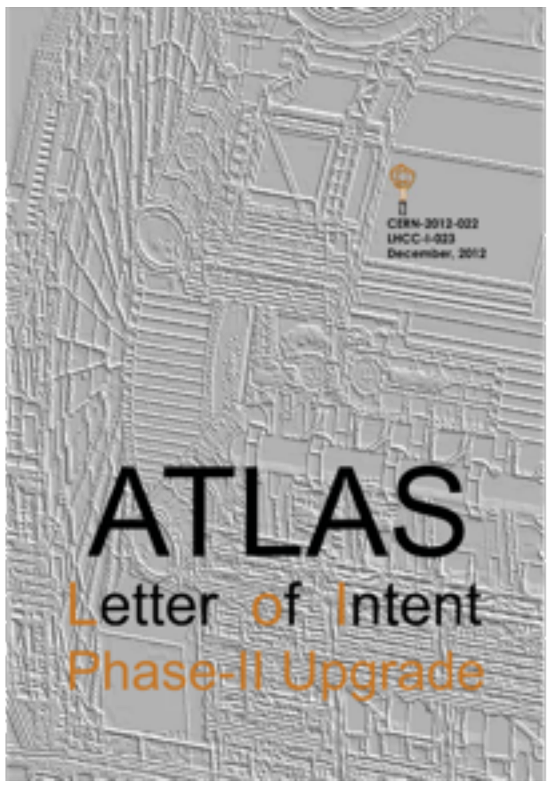
- HE-LHC main challenges
  - Technical schedule defined by the magnet program
- Earliest technically possible start of physics: 2040
  - This would require HL-LHC stop at LS5 (in 2034)

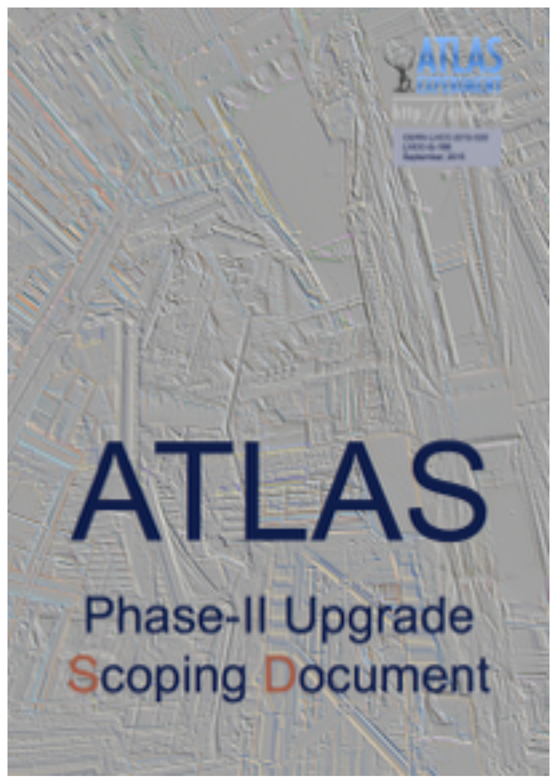
- [1] For details see presentations at the HL/HE-LHC kick-off workshop at CERN: https://indico.cern.ch/event/647676/.

ATLAS & CMS DETECTOR UPGRADES

ATLAS AND CMS DOCUMENTS

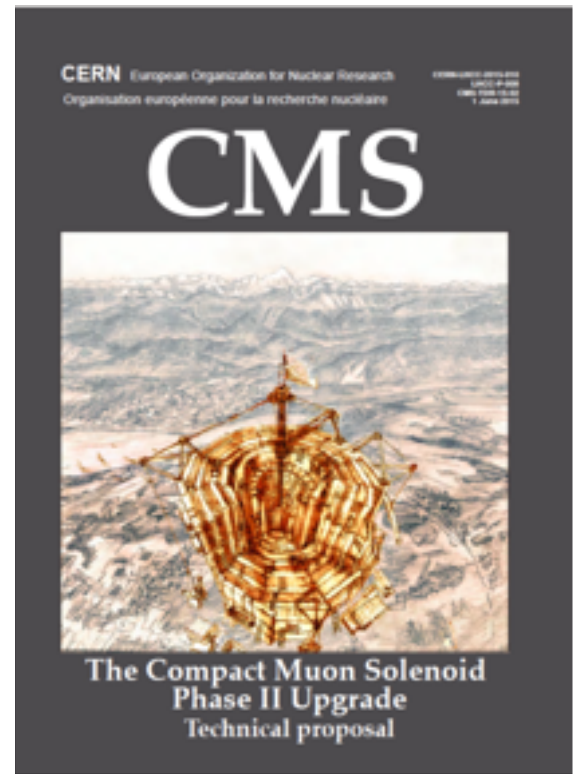
- ATLAS letter of intent and scope document

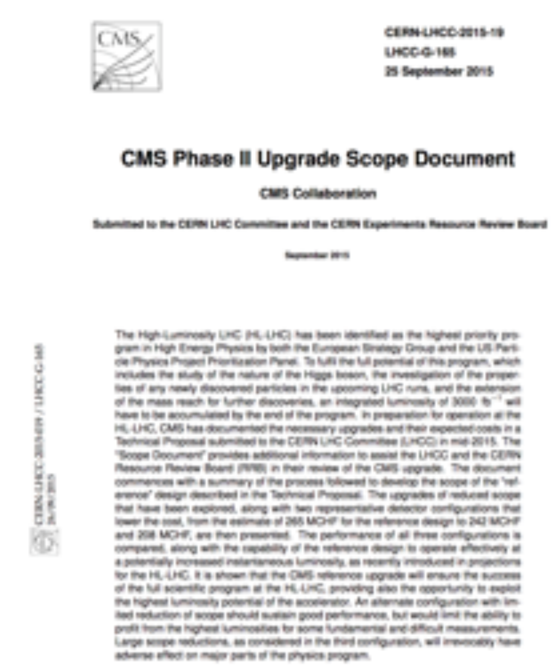




CERN-LHCC-2012-022
https://cds.cern.ch/record/1502664
CERN-LHCC-2015-020
https://cds.cern.ch/record/2055248

- CMS technical proposal and scope document





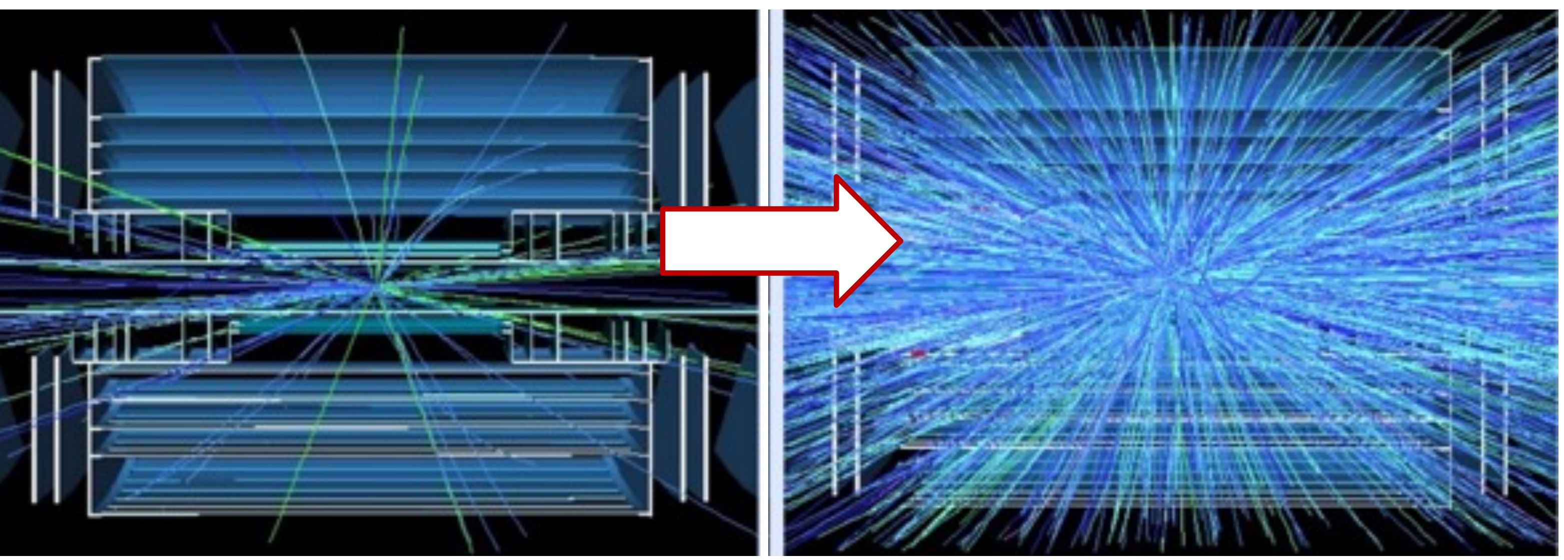
CERN-LHCC-2015-010
https://cds.cern.ch/record/2020886
CERN-LHCC-2015-019
https://cds.cern.ch/record/2055167

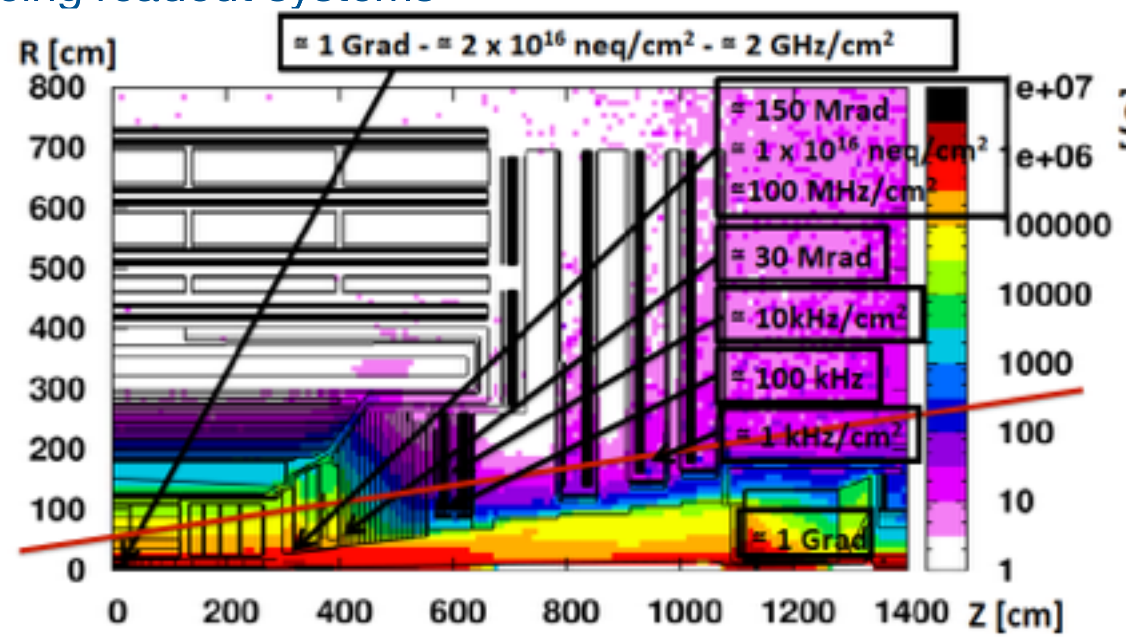
Technical Design Reports for sub detector systems are being prepared & under review now

SWARMS OF PARTICLES AND HIGH RADIATION

- High luminosity ➔ 200 soft pp interactions per crossing
  - Increased combinatorial complexity, rate of fake tracks, spurious energy in calorimeters, increased data volume to be read out in each event
- Detector elements and electronics are exposed to high radiation dose
  - Requires new tracker, endcap calorimeters, forward muons, replacing readout systems

25 pileup 200 pileup





Roughly reaching limits of current techniques in several systems

- Goal of ATLAS and CMS detector upgrades
  - make HL-LHC events look like LHC events (~25 additional interactions)
  - For precision measurements and observations of very rare processes, we need to at least maintain current performance for all physics objects. Requires excellence in every corner
  - associating particles with primary hard scatter collision with high efficiency
  - Increased spatial granularity to resolve signals from individual particles
  - Precise timing measurements to provide an additional dimension for discrimination

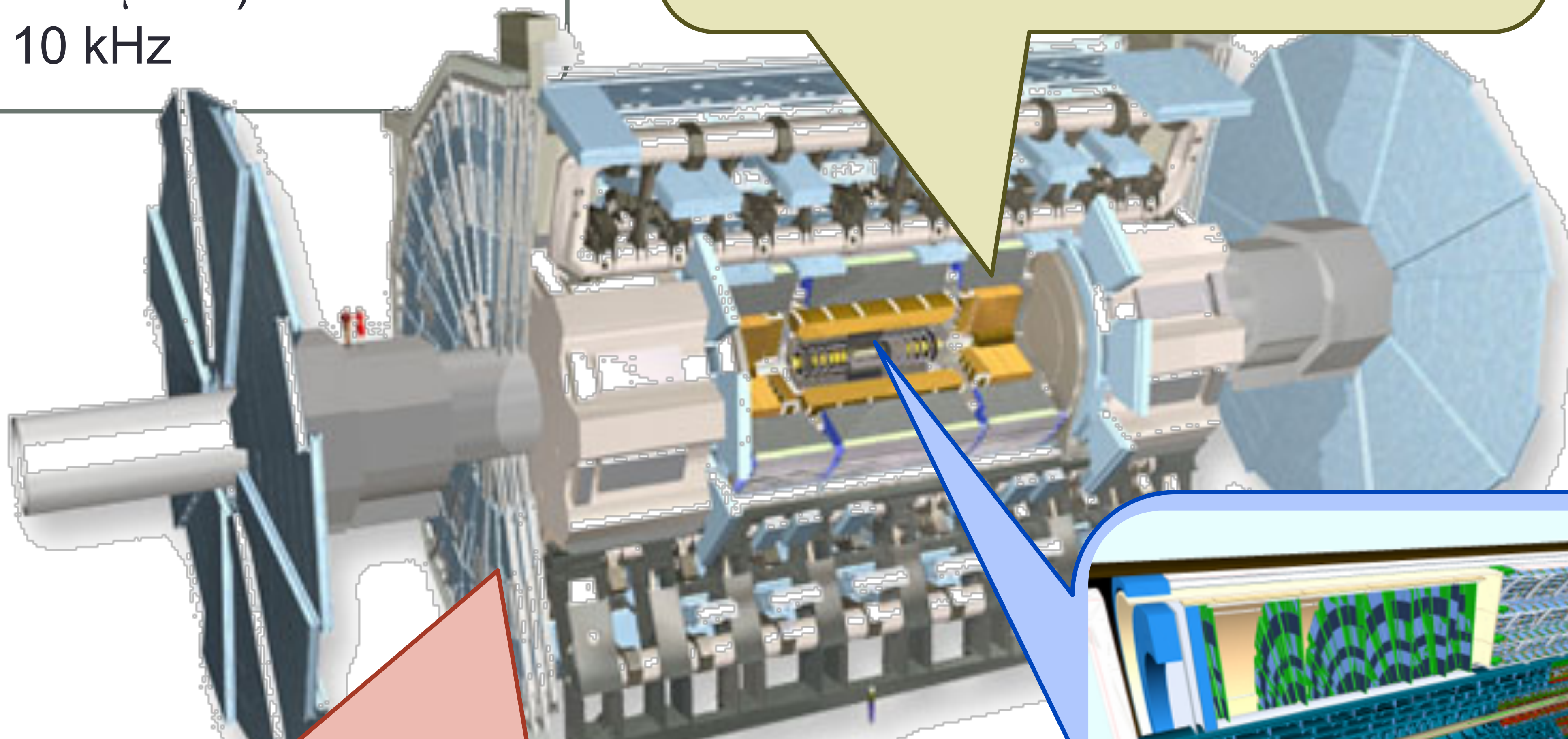
ATLAS PHASE 2 UPGRADE

Trigger and DAQ

- L0 (Calo+μ): 1 MHz
- L1 (Calo+μ+Itk): 400 kHz
- HLT: 10 kHz

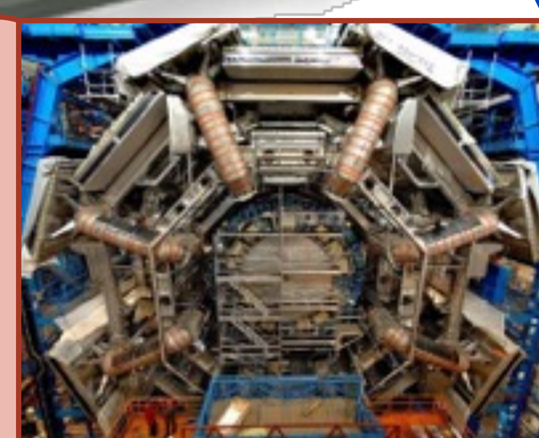
Calorimeters

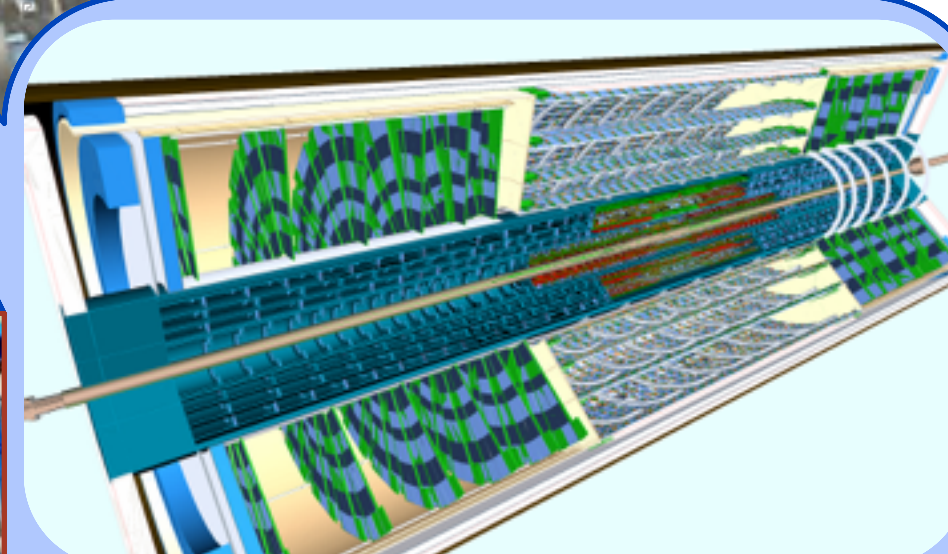
- New readout electronics compatible with L0 1 MHz rate
- High granularity timing detector (under discussion)



Muon systems

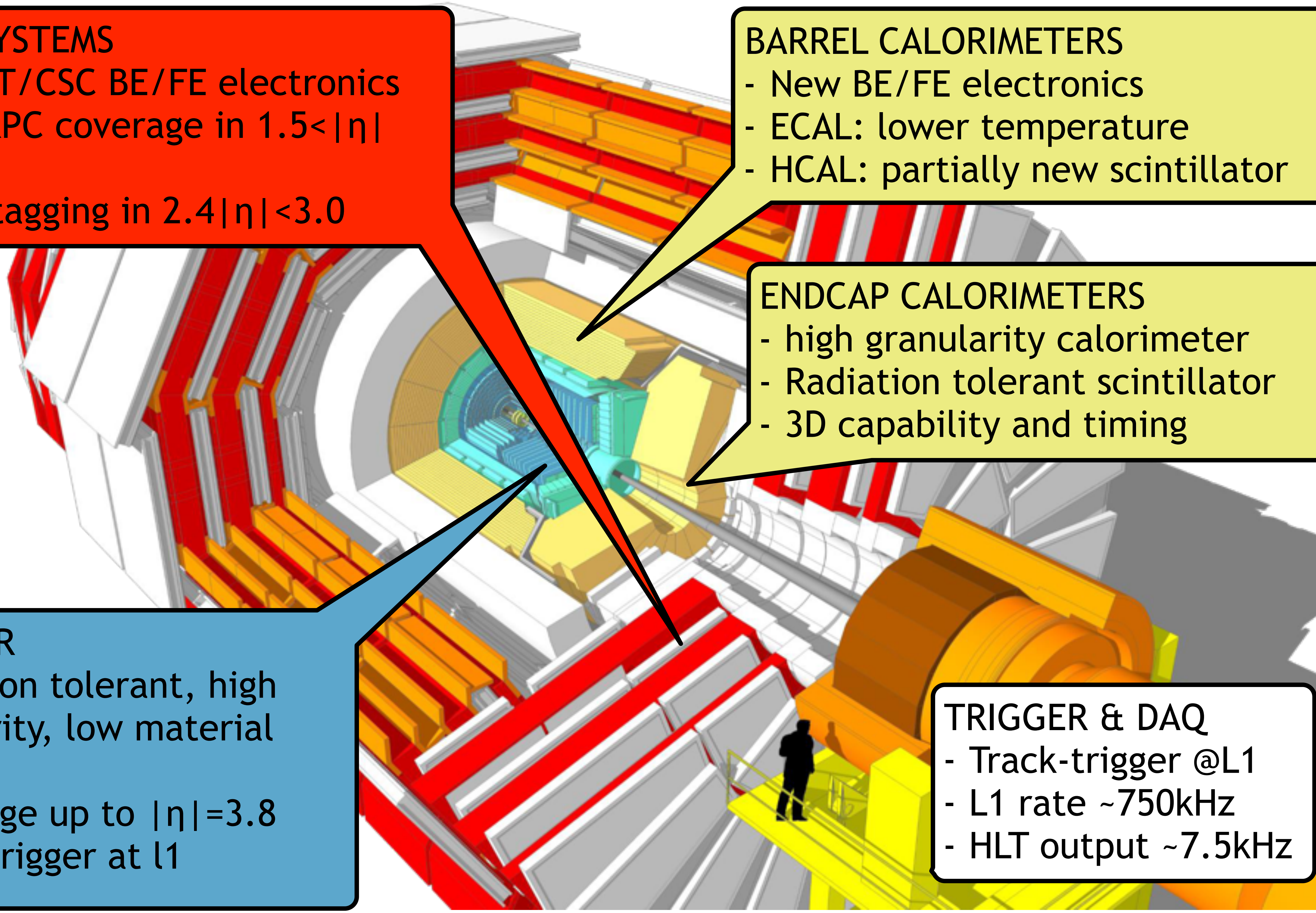
- New readout and trigger electronics
- Additional chambers for inner barrel layer improves acceptance
- Muon tagger for $2.7<|\eta|<4.0$





All-silicon tracking detector
5 pixel+4 strip layers to $|\eta|<4$

CMS PHASE 2 UPGRADE



MUON SYSTEMS
- New DT/CSC BE/FE electronics
- GEM/RPC coverage in $1.5<|\eta| <2.4$
- Muon-tagging in $2.4|\eta|<3.0$

BARREL CALORIMETERS
- New BE/FE electronics
- ECAL: lower temperature
- HCAL: partially new scintillator

ENDCAP CALORIMETERS
- high granularity calorimeter
- Radiation tolerant scintillator
- 3D capability and timing

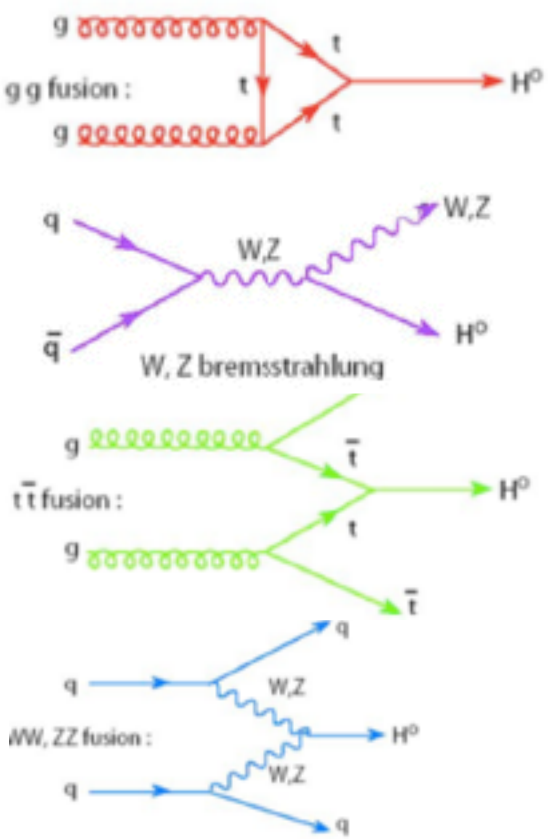
TRACKER
- radiation tolerant, high granularity, low material budget
- coverage up to $|\eta|=3.8$
- track trigger at l1

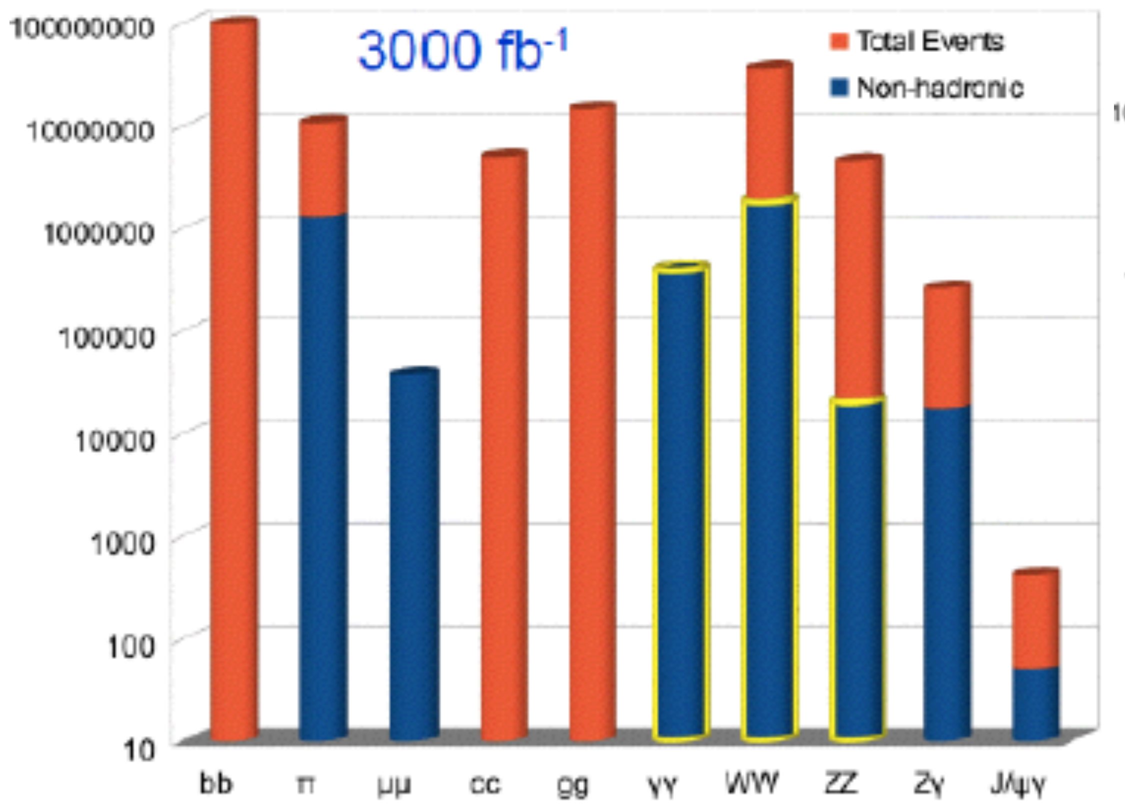
TRIGGER & DAQ
- Track-trigger @L1
- L1 rate ~750kHz
- HLT output ~7.5kHz

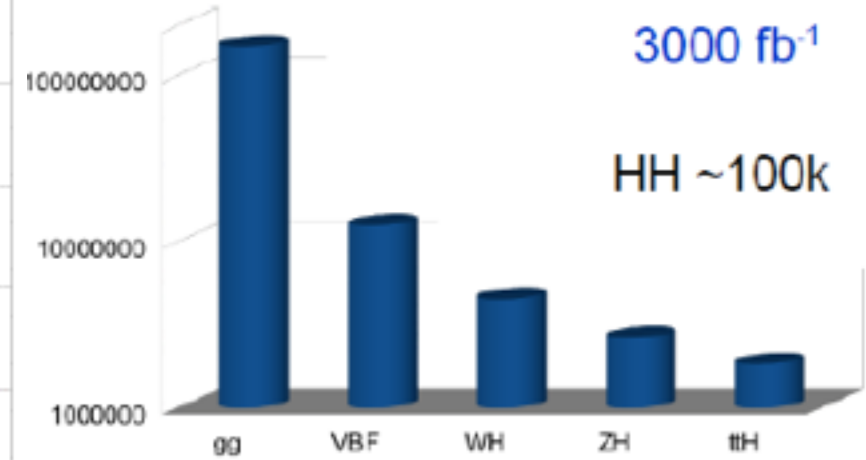
THE HIGGS SECTOR

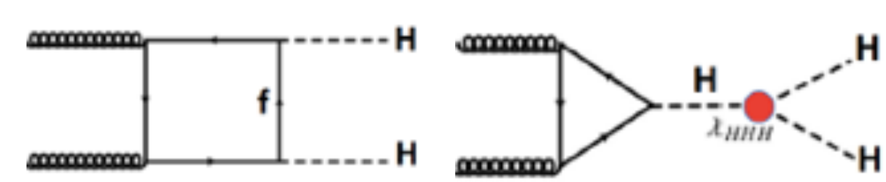
HL-LHC AS A HIGGS FACTORY

- At HL-LHC, we expect to produce ~170M Higgs Bosons, including ~120k of pair produced events
- Over 1Million for each of the main production mechanisms, spread over many decay





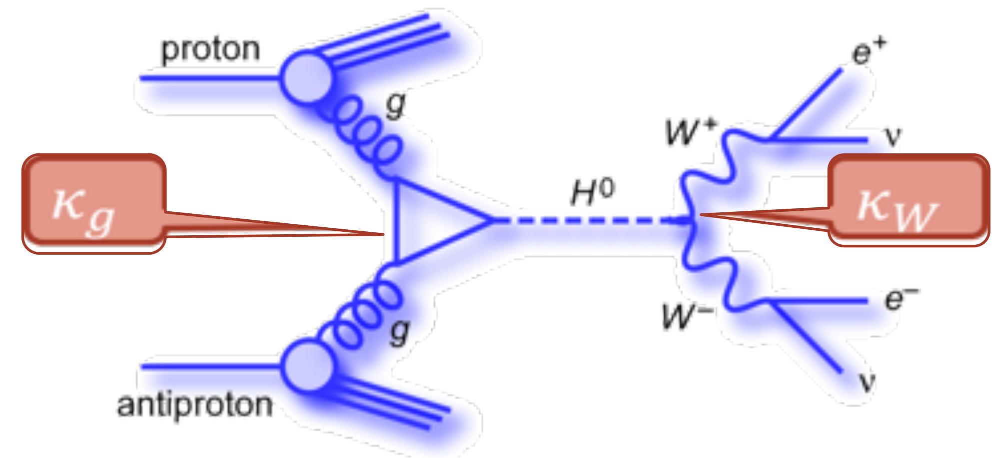


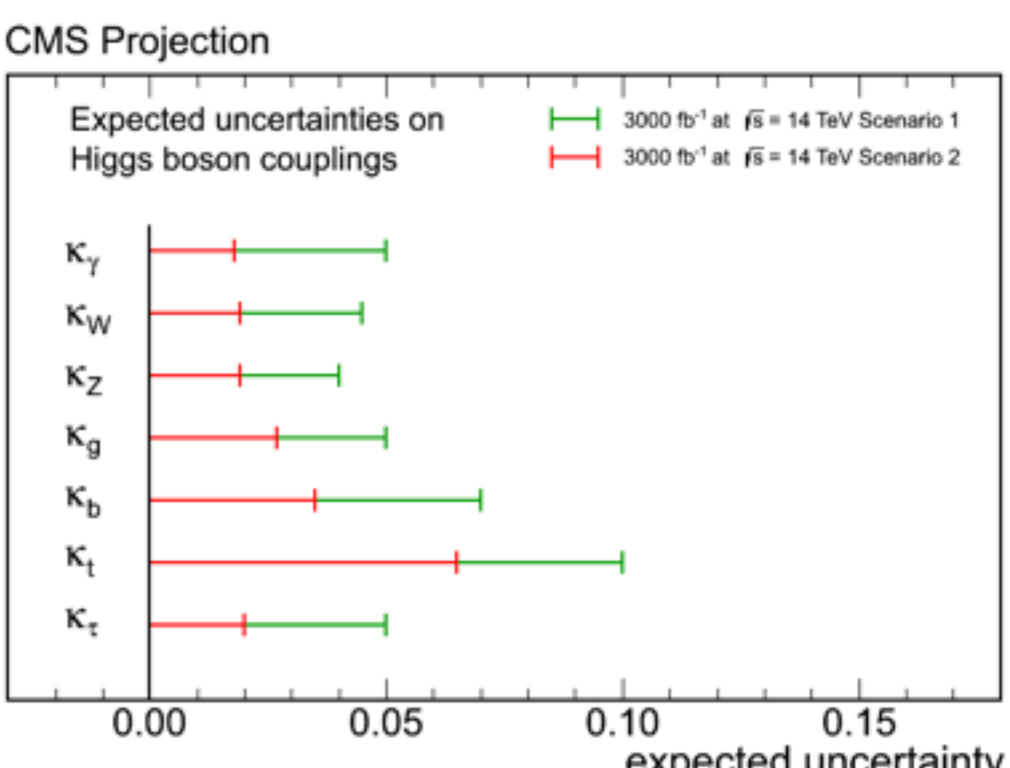


- Enables a broad program:
  - Precision O(few-10%) measurements of coupling across broad kinematics
  - Exploration of Higgs potential (hh production)
  - Sensitivity to rare decays involving new physics
  - extend BSM Higgs searches (extra scalars, BSM Higgs resonances, exotic decays…)

HIGGS COUPLINGS

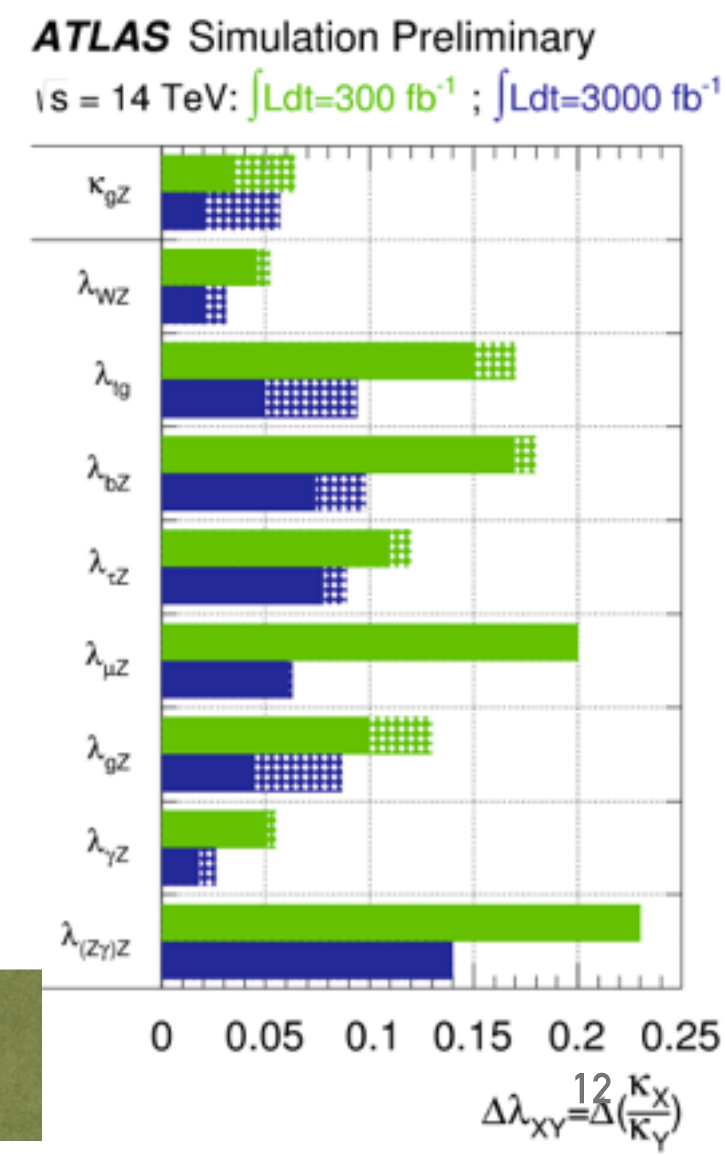
- Coupling measurements:
- Rate of a given process depends on several couplings
- Example gg→h→WW: $\sigma B \propto \frac{\kappa_g^2 \kappa_W^2}{\kappa_H^2}$
  - The κ's multiply the SM couplings. κ_g is a function of κ_t and κ_b.
  - κ_H multiplies the Higgs width and depends on all couplings
- Currently κ's are typically measured to ≈20%.
- Expected deviations from SM predictions by various models (Singlet mixing, 2HDM, Decoupling MSSM, Composite, Top Partner..) predicted to be between 1-10%.
- Comprehensive study of Higgs couplings at the HL-LHC





Projections at 3-10%-level with 3000 fb^{-1}.
HL-LHC will improve measurement precision by a factor 2-3!

Reduced theoretical uncertainties needed (improvement since 2014)



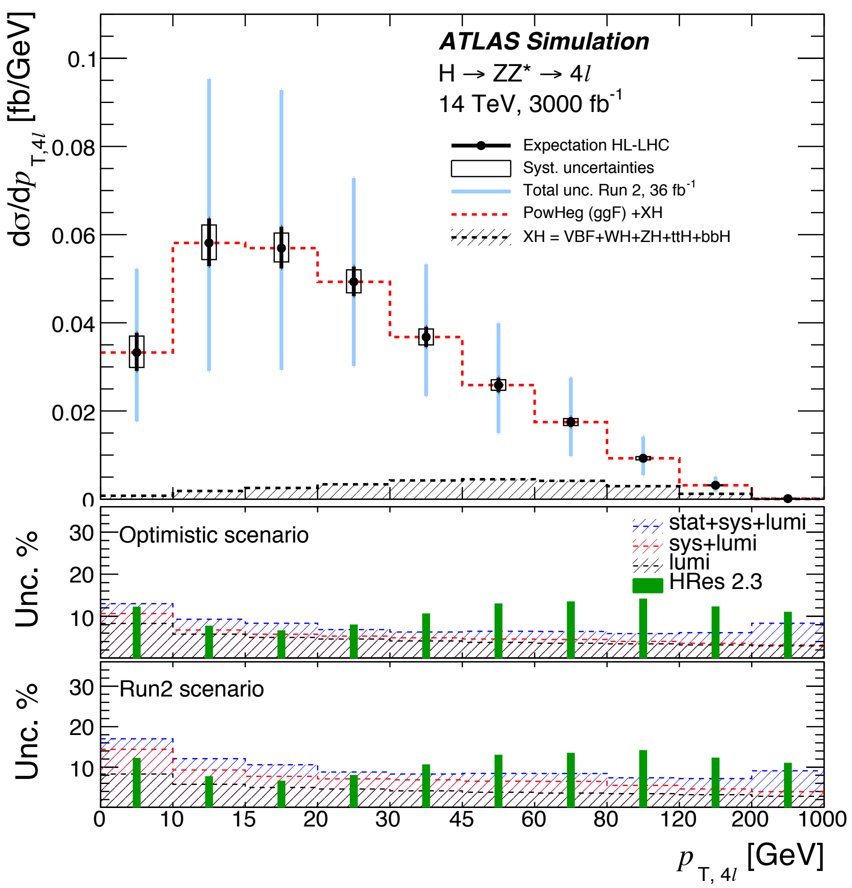
New extrapolations will be done in 2018 based on Run2 data

HIGGS PRODUCTION & COUPLINGS ($H \rightarrow ZZ$)

Differential Cross Section $p_T(h)$

- probes perturbative QCD calculations
- information on (new) particles contribution to the gluon fusion loop
- Sensitive to κ_b/κ_c (low p_T) κ_t/BSM (high p_T)

- @high p_T dominated by stat. unc ≈4-9%
- For 300 fb^{-1} stat. uncertainty: 10-29%!

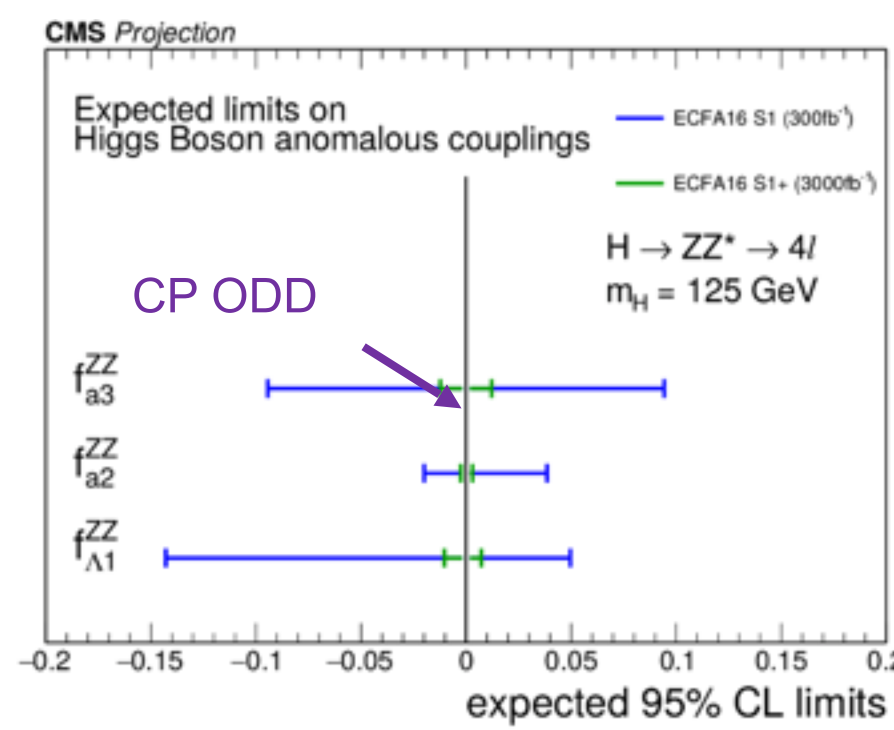


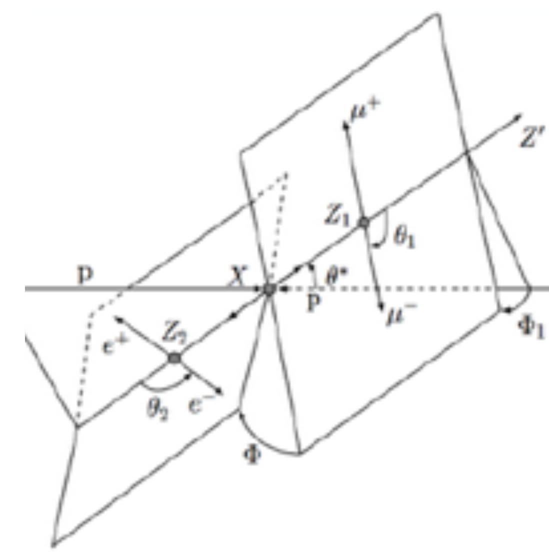
Anomalous couplings

$$A(H \to ZZ) = v^{-1}\left(\underbrace{a_1 m_Z^2 \epsilon_1^\star \epsilon_2^\star}_{\text{SM tree processes}} + \underbrace{a_2 f^{\star(1)}_{\mu\nu} f^{\star(2),\mu\nu}}_{\text{loop CP-even contributions}} + \underbrace{a_3 f^{\star(1)}_{\mu\nu} \tilde{f}^{\star(2),\mu\nu}}_{\text{CP-odd contributions (BSM)}}\right)$$

- H ZZ 4l : reconstruct the full angular decay structure

- Expect to constrain f < ~1% $f_{ai} = \frac{|a_i|^2\sigma_i}{\sum_j |a_j|^2\sigma_j}, \ \phi_{ai} = \tan^{-1}(a_i/a_1)$





- Statistically dominated: huge increase in sensitivity going from 300 to 3000 fb^{-1}.

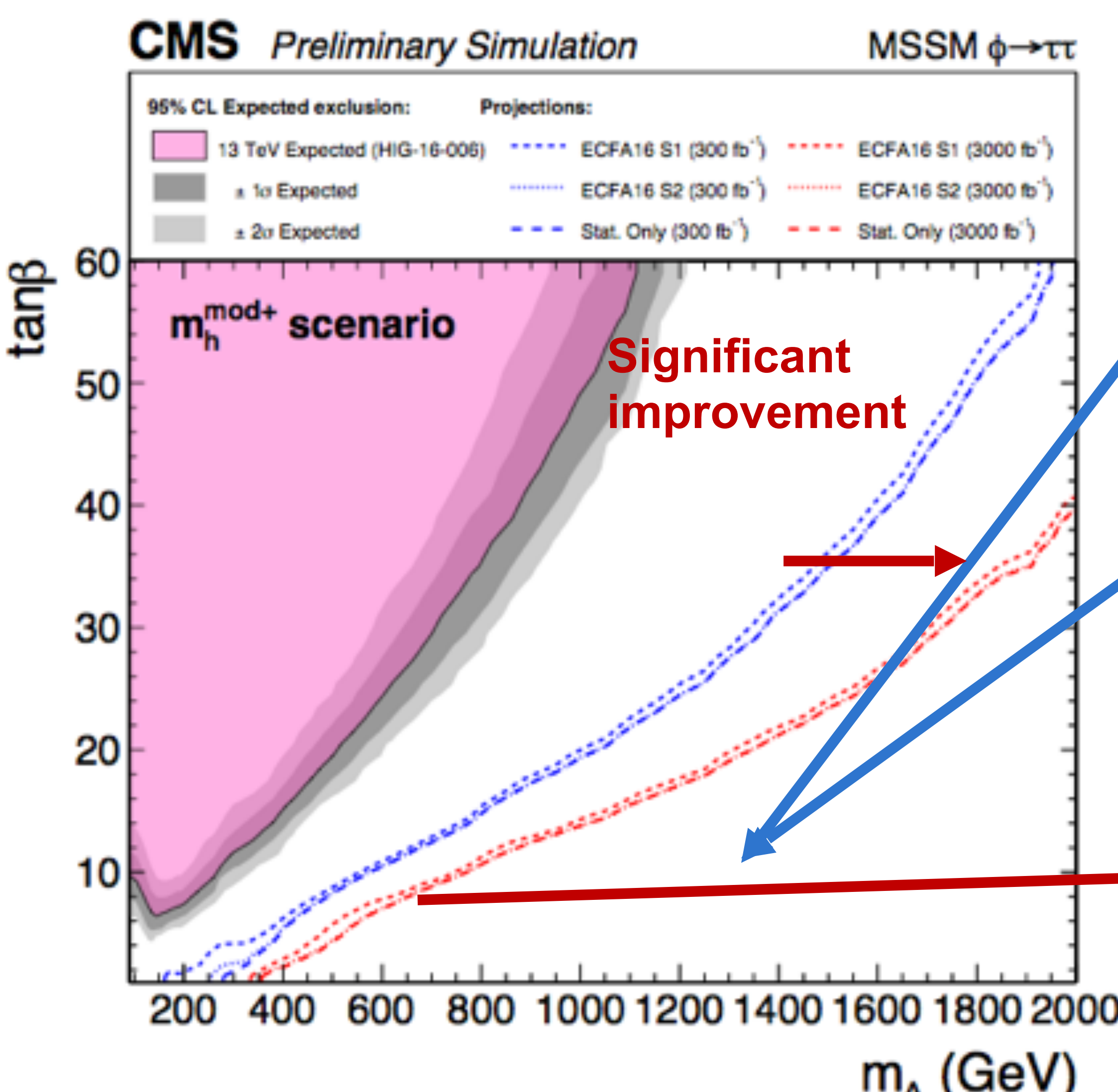
HIGGS BSM SEARCHES

➤MSSM Φ -> τ τ

- ➤ One of the most sensitive channels to constrain extended Higgs sectors
- ➤ MSSM parameter space can be constrained to a heavy Higgs boson with masses up to 2 TeV.

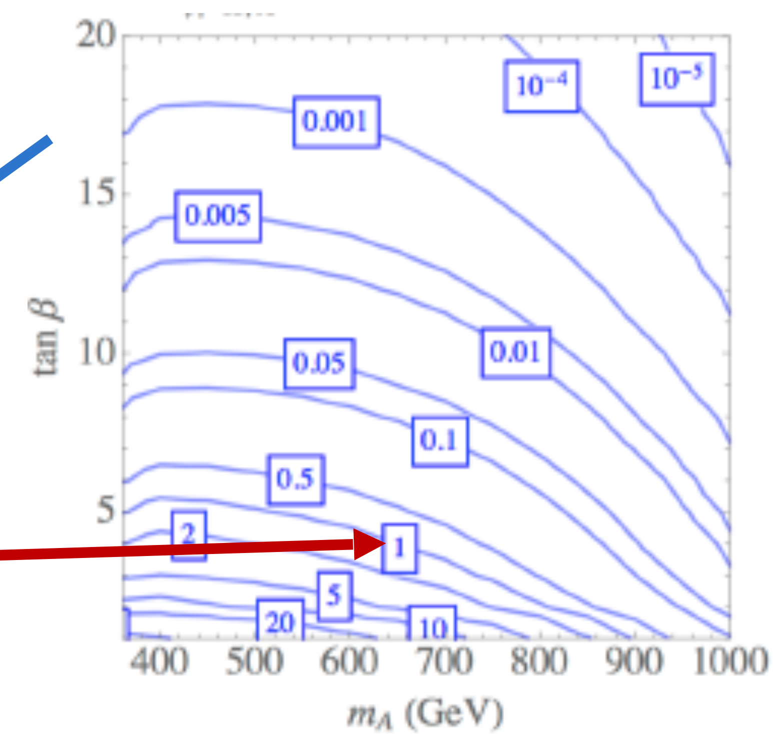
What about the low tanβ vs M_A region?

CMS-PAS-HIG-16-006



Consider tau-phobic signatures
A possible scenario is ttH production
Signatures: 4top or 2b+2top

$$\sigma(pp \to ttH, H \to tt)\ [fb]$$

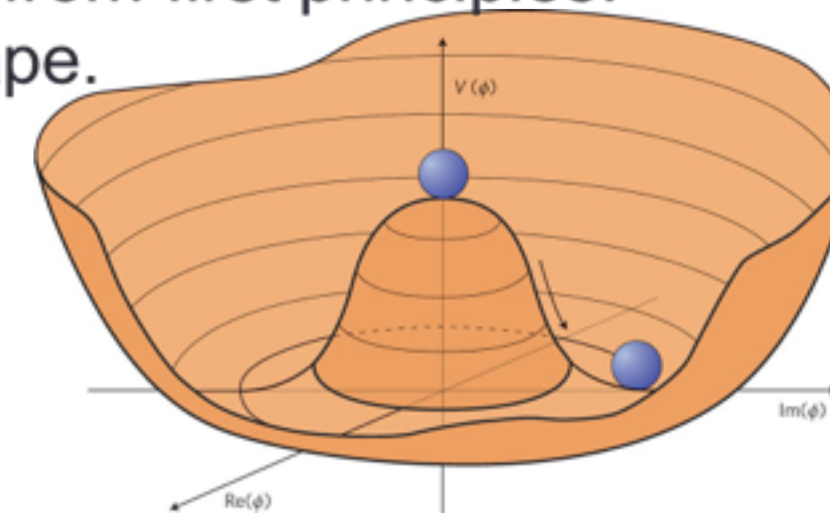


statistics limited!
~ 60 events now
Will benefit from
HL-LHC, HE-LHC

Gori et al, 1602.02782

HIGGS PAIR PRODUCTION AND SELF COUPLING

- Shape of the Higgs potential postulated but not taken from first principles.
- Indirectly constrained within SM assuming quartic shape.
- Higgs potential after spontaneous symmetry breaking

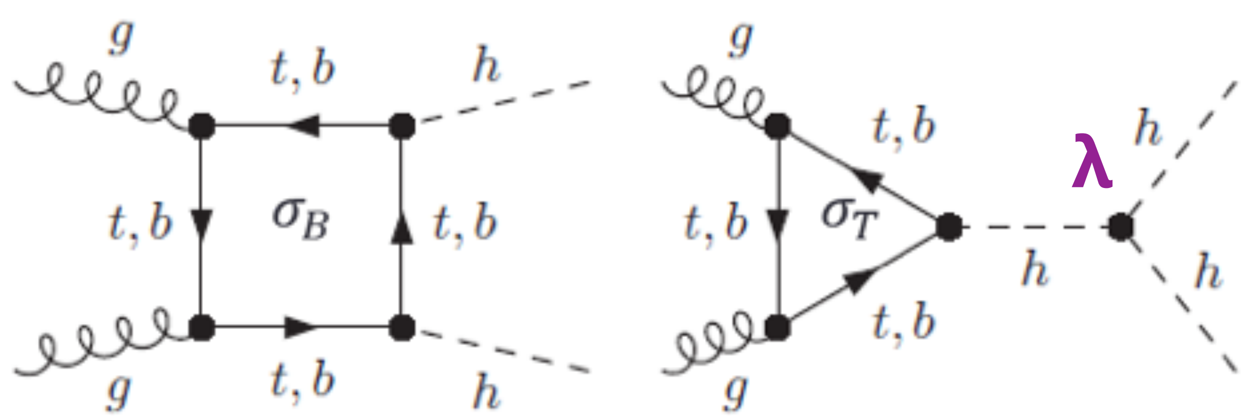


$$V = \frac{1}{2}m_h^2 h^2 + \lambda v h^3 + \frac{\lambda}{4}h^4$$

with $m_h^2 = 2\lambda v^2$ and $v^2 = \frac{1}{\sqrt{2}G_F}$

$\frac{\delta\lambda}{\lambda} = 2\frac{\delta m}{m} \approx 0.4\%.$ (indirect constraint)

- Thus in the SM, the Higgs potential is completely determined by m_h and G_F
- Direct constraint possible with Higgs pair production

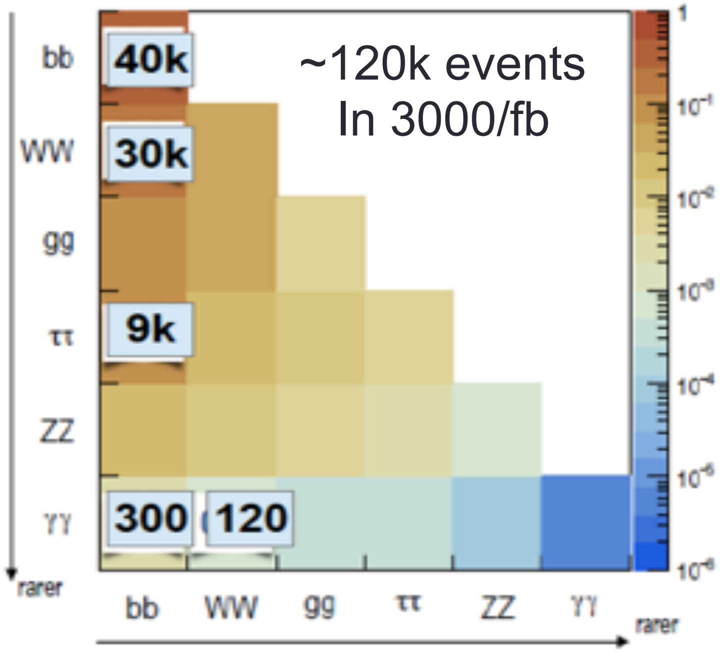


- Destructive interference → $\sigma_{hh} \approx \frac{\sigma_T+\sigma_B}{2.5}$ → σ_{hh} = 39.5 fb @14 TeV
- Models with extended Higgs sector modify σ by typically 20%
- Higgs resonances can also modify the Higgs pair production rate

HIGGS PAIR PRODUCTION AT HL-LHC

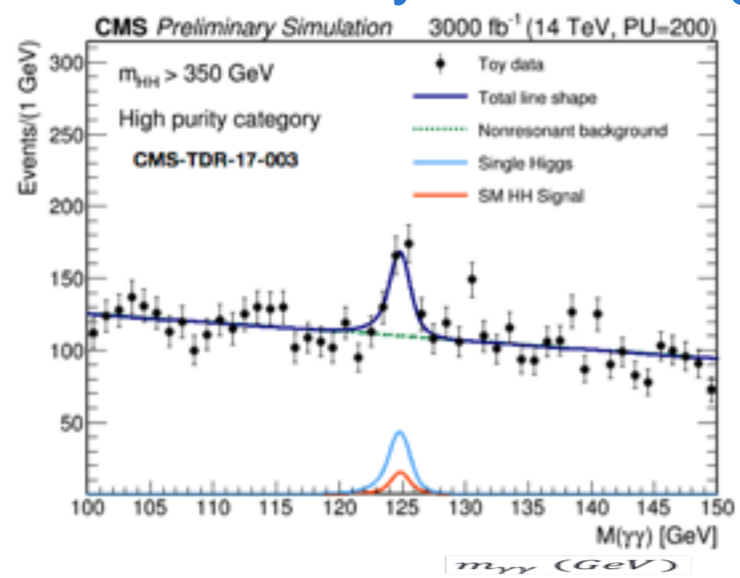
Promising final states

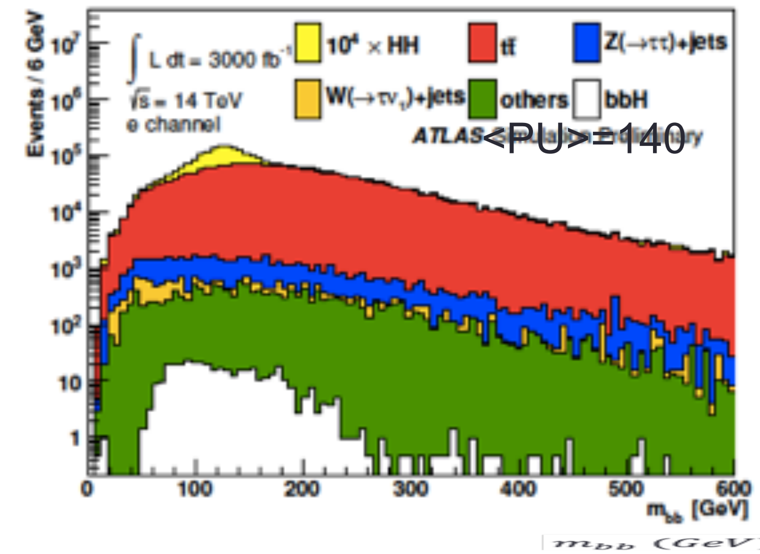
Expected number of events



HH → bbγγ HH → bbττ

Mostly studied signatures with 2b





HH physics is a benchmark channel for HL-LHC program

- Run II results are reaching 15 times SM, with loose constraint on κ_λ between -9 and 15.
- Exp. significance per experiment ≈1-2 σ (HL-LHC)
- The possibility of "evidence" of HH can be reached combining all channels in CMS and ATLAS.

- Improvement foreseen driven by :
  - Detector optimization, analysis algorithms
  - Theory : Impact of NLO correction on differential distributions ?

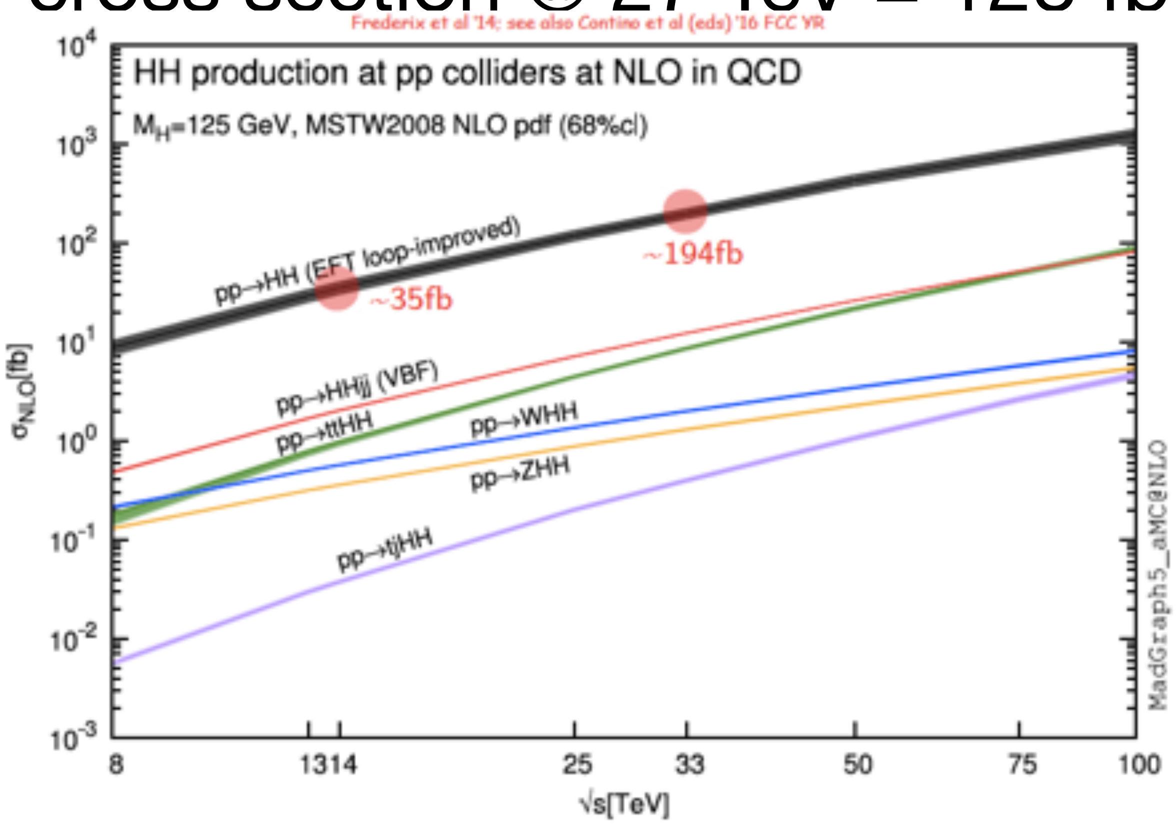
Expected significance

95% CL intervals

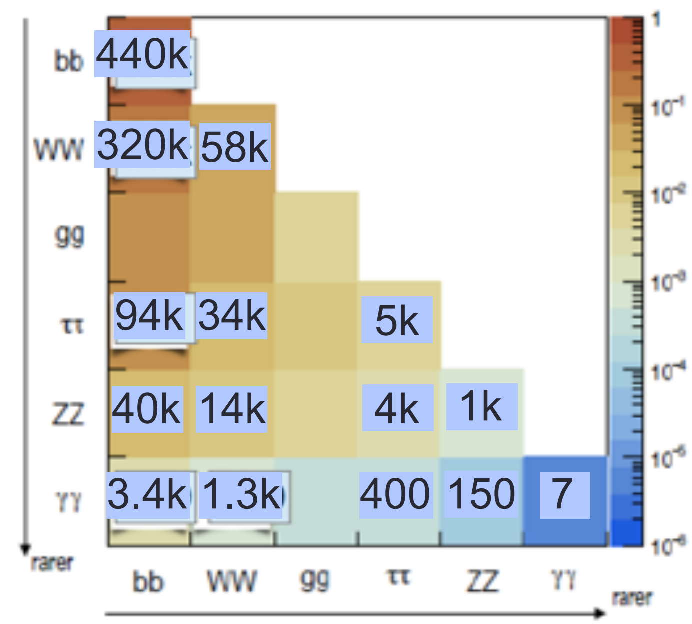
Final state	ATLAS	CMS
HH→bbγγ	1.05 σ $-0.8<k_\lambda<7.7$	1.43 σ
HH→bbττ	0.6 σ $-4.0<k_\lambda<12$	0.39 σ
HH→bbbb	$-3.5<k_\lambda<11$	0.39 σ
HH→bbVV		0.45 σ
ttHH, HH→bbbb	0.35 σ	

HIGGS PAIR PRODUCTION AT HE-LHC

➤HH cross section @ 27 TeV = 128 fb (±11%)



Expected number of events @ 27 TeV and 10/ab



➔ event yields increase by factor 10

➤Projections for λ from hh production: $\delta\kappa_\lambda$ ($\kappa_\lambda=\lambda/\lambda_{SM}$)

$\delta\kappa_\lambda$ bound / scenario	68%	95%
HL: h incl, hh incl	[0, 2.5] U [4.9, 7.4]	[−0.8, 8.5]
HL: h incl, hh diff	[-1.1, 1.3]	[−1.7, 6.5]
HE: h incl, hh incl	[-0.3, 0.3] U [5.0, 6.0]	[-0.5, 0.7] U [4.5, 6.7]
HL + HE	[-0.3, 0.3]	[-0.5, 0.6] U [4.8, 6.0]
FCC 100 TeV 30/ab h incl, hh diff	[−0.03, 0.03]	[−0.06, 0.06]

Factor of 3-10 improvement wrt HL-LHC

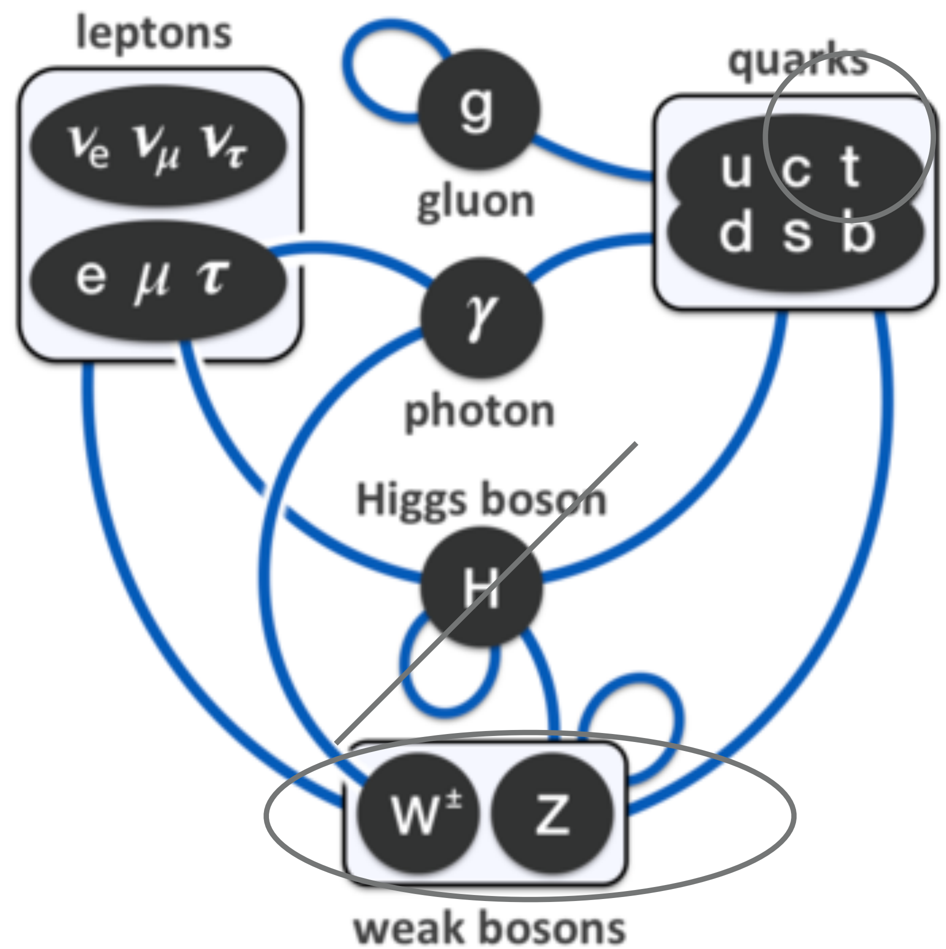
Work is just starting

S. Di Vita HE/HL-LHC workshop, Nov 2017

STANDARD MODEL PHYSICS (BACK IN THE SPOTLIGHT)

SM PHYSICS FOR THE HL-LHC

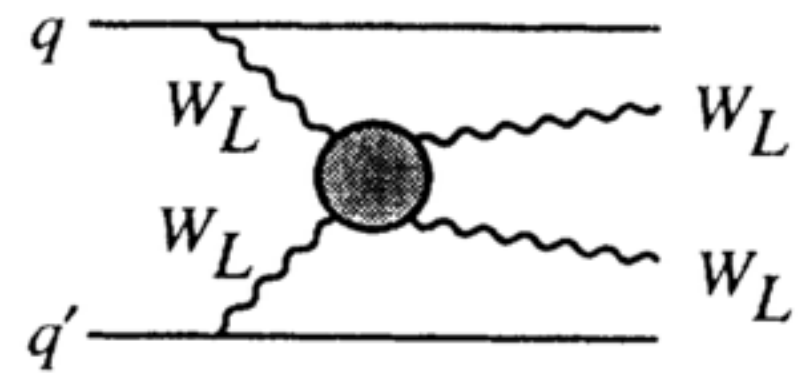
- Only moderate increase in energy
- But: incredibly high statistics
- Era of precision measurements
  - Need to improve our understanding of systematic uncertainties and their interplay
  - Improve techniques for uncertainty mitigation
  - High precision differential measurements
  - Era of 'dark' corners of phase space (BSM sensitivity at high Q2/Λ2 → tails!)

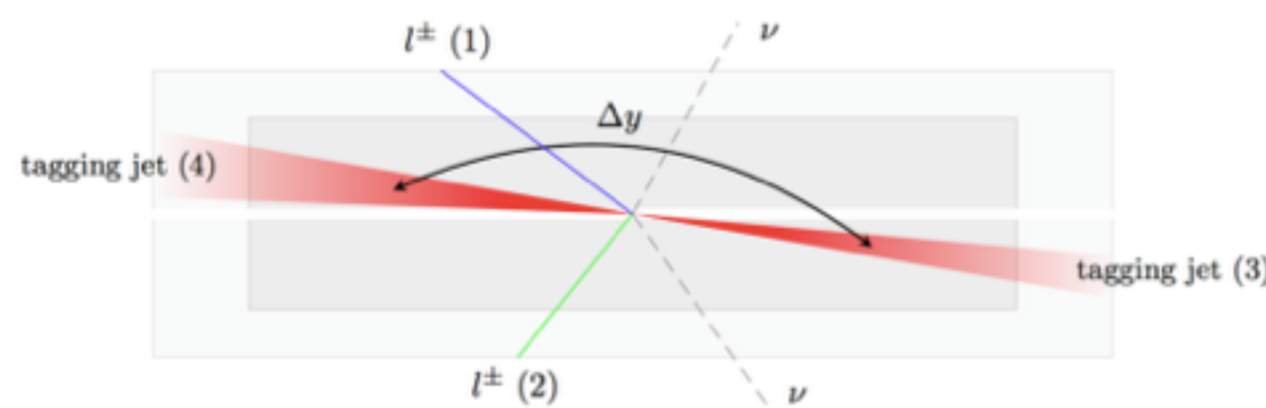


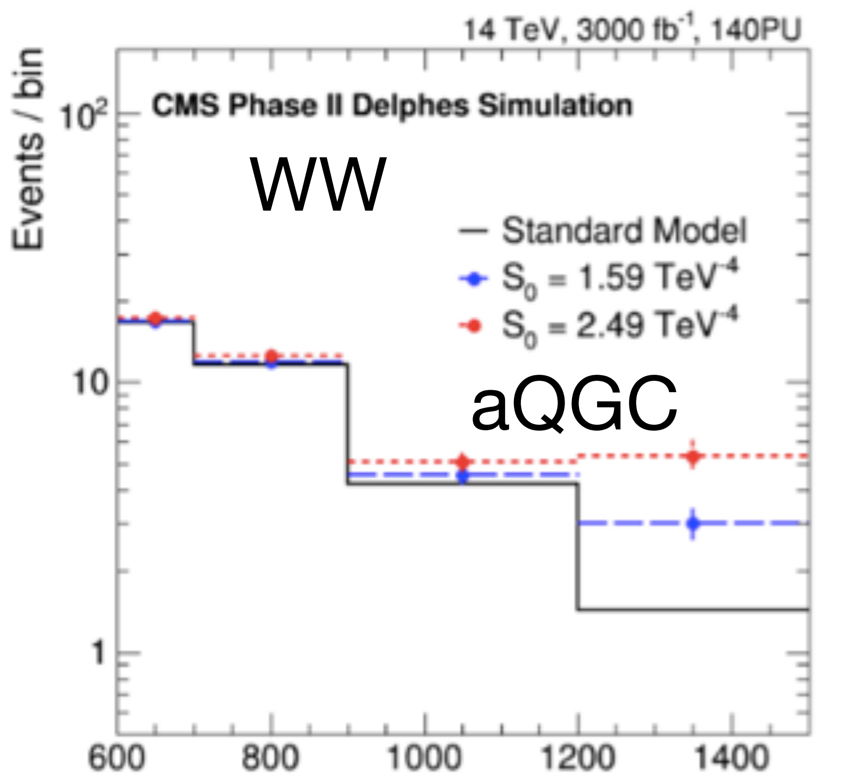
- Renewed recognition of importance of Standard model measurements

VECTOR BOSON SCATTERING

- Strong cancellation in SM of terms from TGC, QGC
  and Higgs boson exchange
  - Sensitive to no-Higgs scenario
  - Additional 8-dim EFT operators
  - Partial unitarisation
- Distinct signature in the detector
- Precision at high scales will provide strong sensitivity to new physics







CMS SMP-14-008

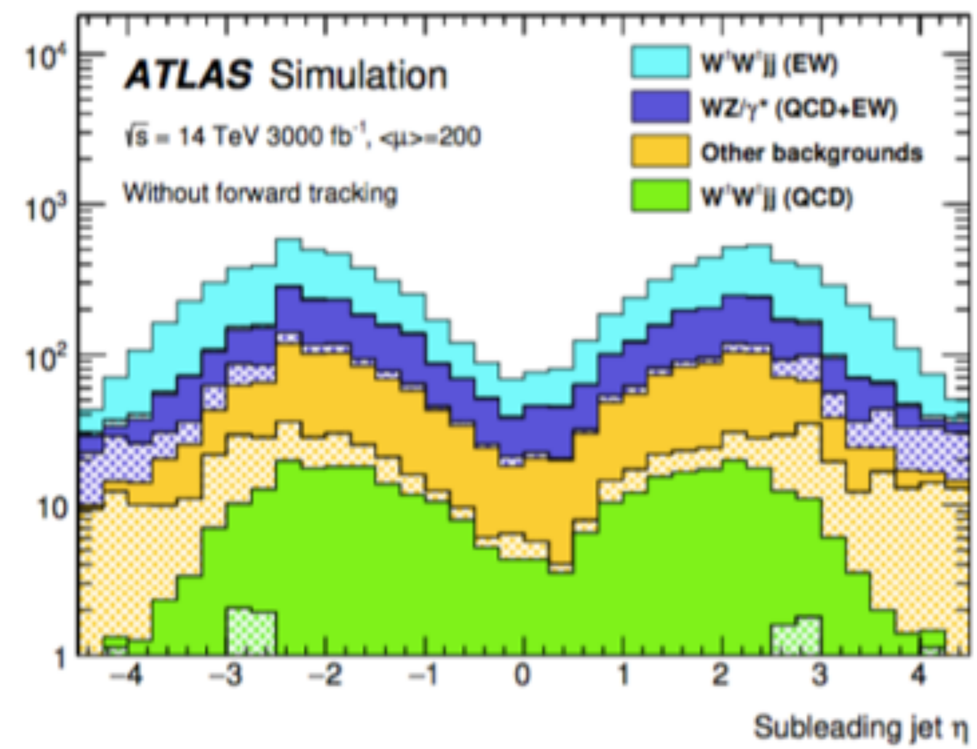
WWjj, WZjj: $\Delta\sigma/\sigma < 10\%$ (CMS)

$V_L V_L \rightarrow V_L V_L$ discovery significance up to 2.75σ (combining WWjj+WZjj)

	Phase I	Phase II	Phase I aged
noH 95% CL exclusion	0.14	0.14	0.20
LL scattering discovery significance	2.50	2.75	2.14

CMS SMP-14-008

VECTOR BOSON SCATTERING (2)



CMS & ATLAS: main gains from

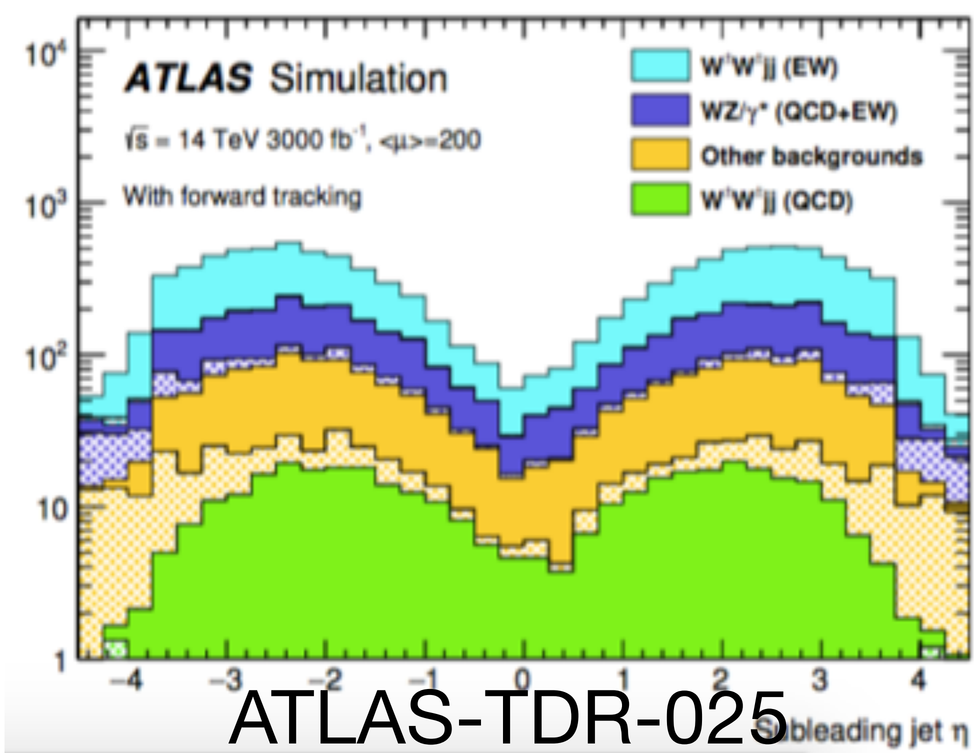
Extended tracking in forward region

PU rejection requires high granularity in forward region

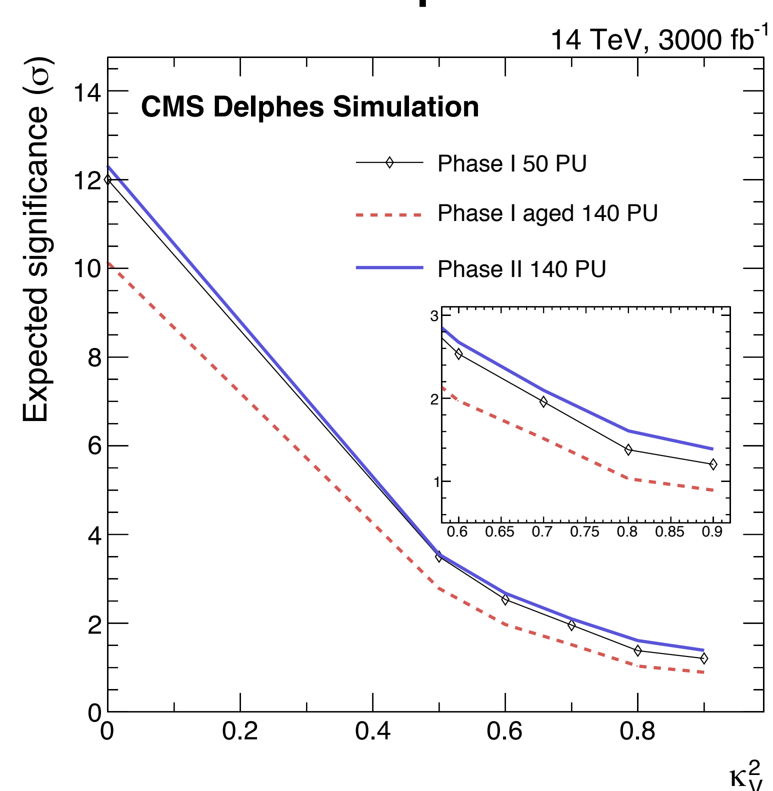
ATLAS-TDR-025 WWjj

	$\frac{\Delta\sigma}{\sigma}$
Without forward tracking	4.5%
With forward tracking	3.9%

➤ VBS enters precision regime



ATLAS-TDR-025



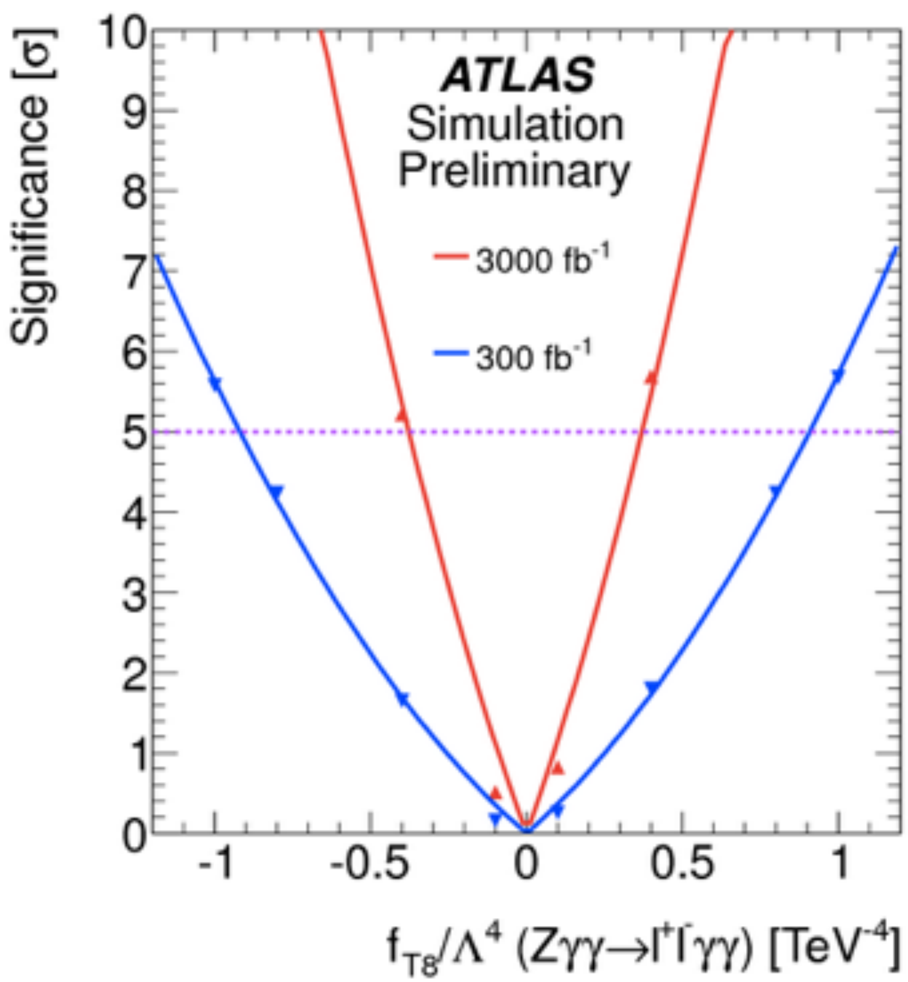
SMP-14-008

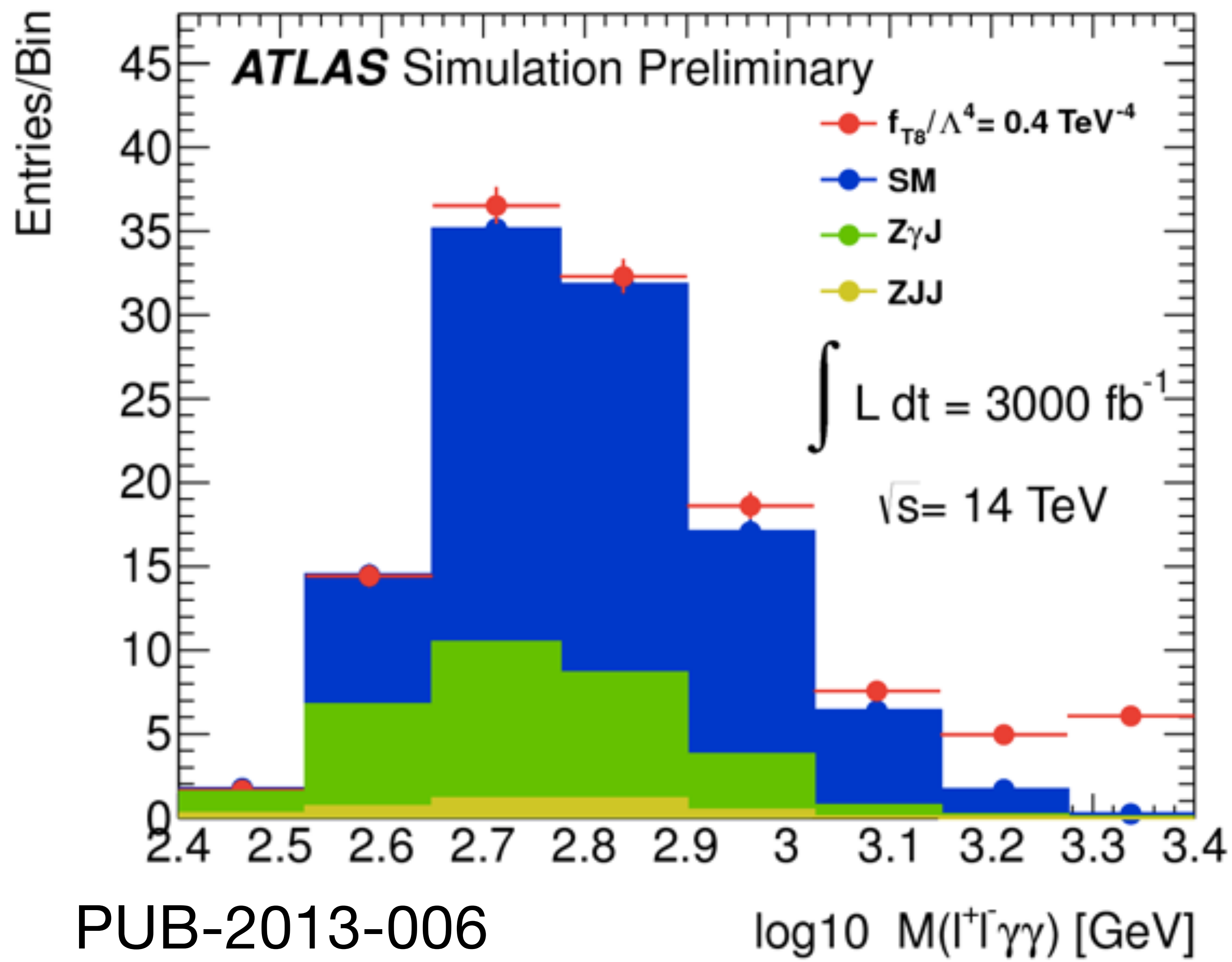
SM K_V=1

➤ Sensitivity to partial unitarisation

TRI-BOSON PRODUCTION

- Complementary to QGC
- Study production of Z bosons in association with 2 photons
- Contributions from BSM (EFT) in tails



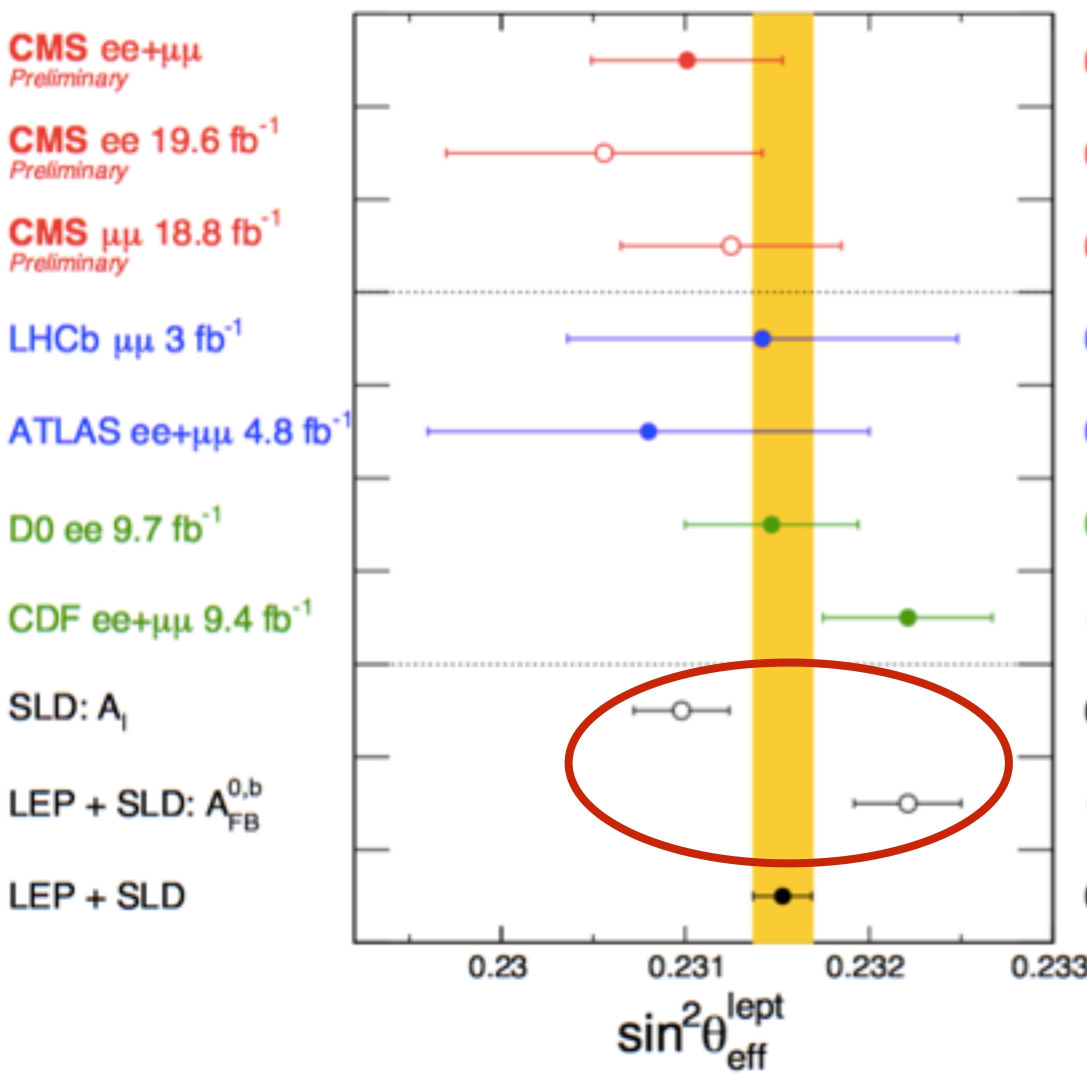


PUB-2013-006

High sensitivity gain from statistics

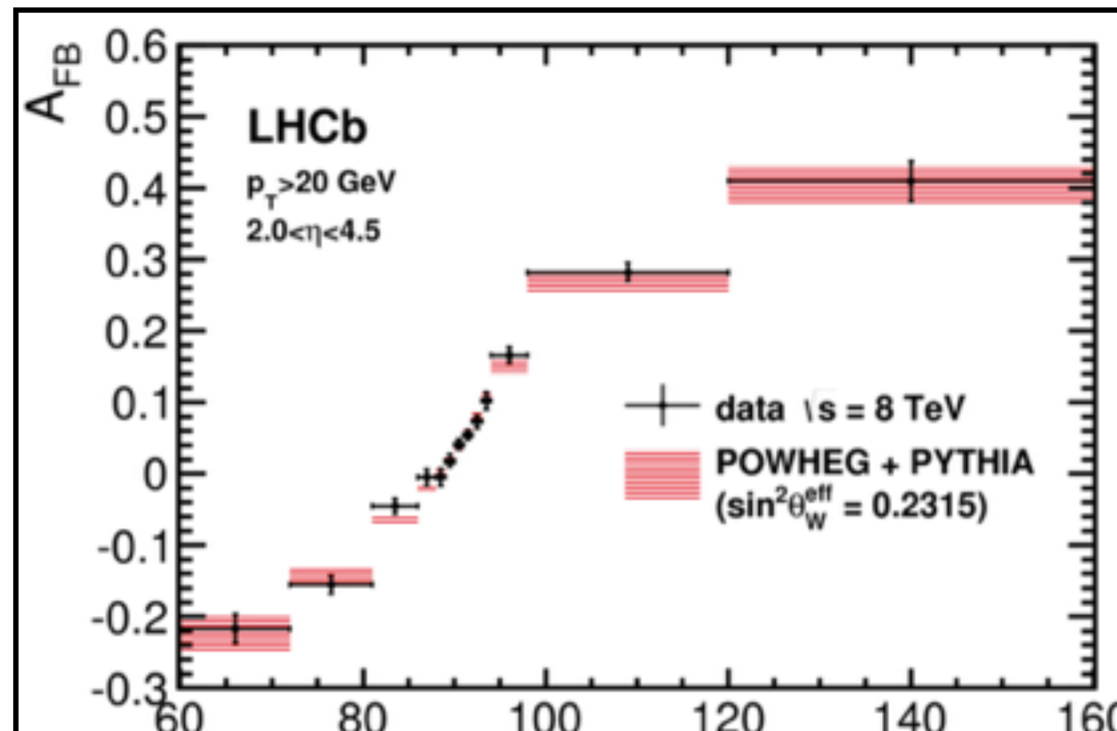
Requires excellent PU rejection (timing, high-granularity)

ELECTROWEAK MIXING SIN2 ΘW



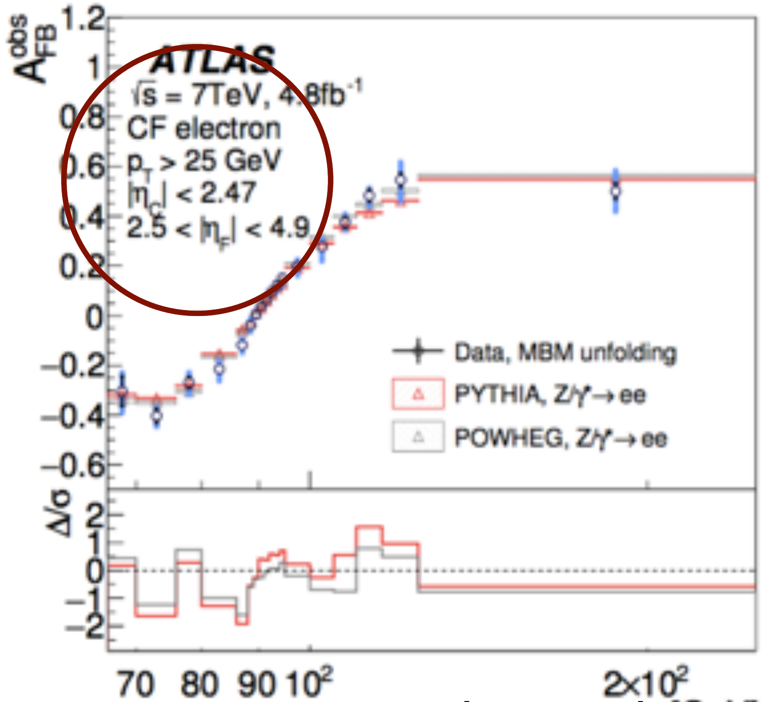
SMP-16-007

- Strong consistency test of the SM in global EWK fits
  - Δsin2θW = 16e-5 ⇔ ΔmW = 8 MeV
- LEP/SLD discrepancy mandates further investigation
- Current results from LHC still statistics + PDF limited

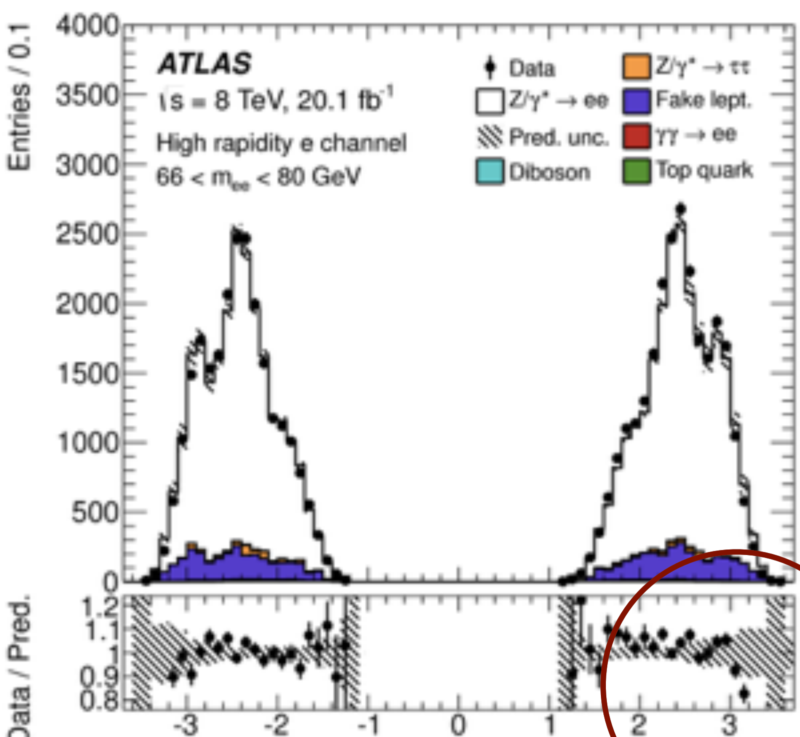


JHEP 1511(2015) 190

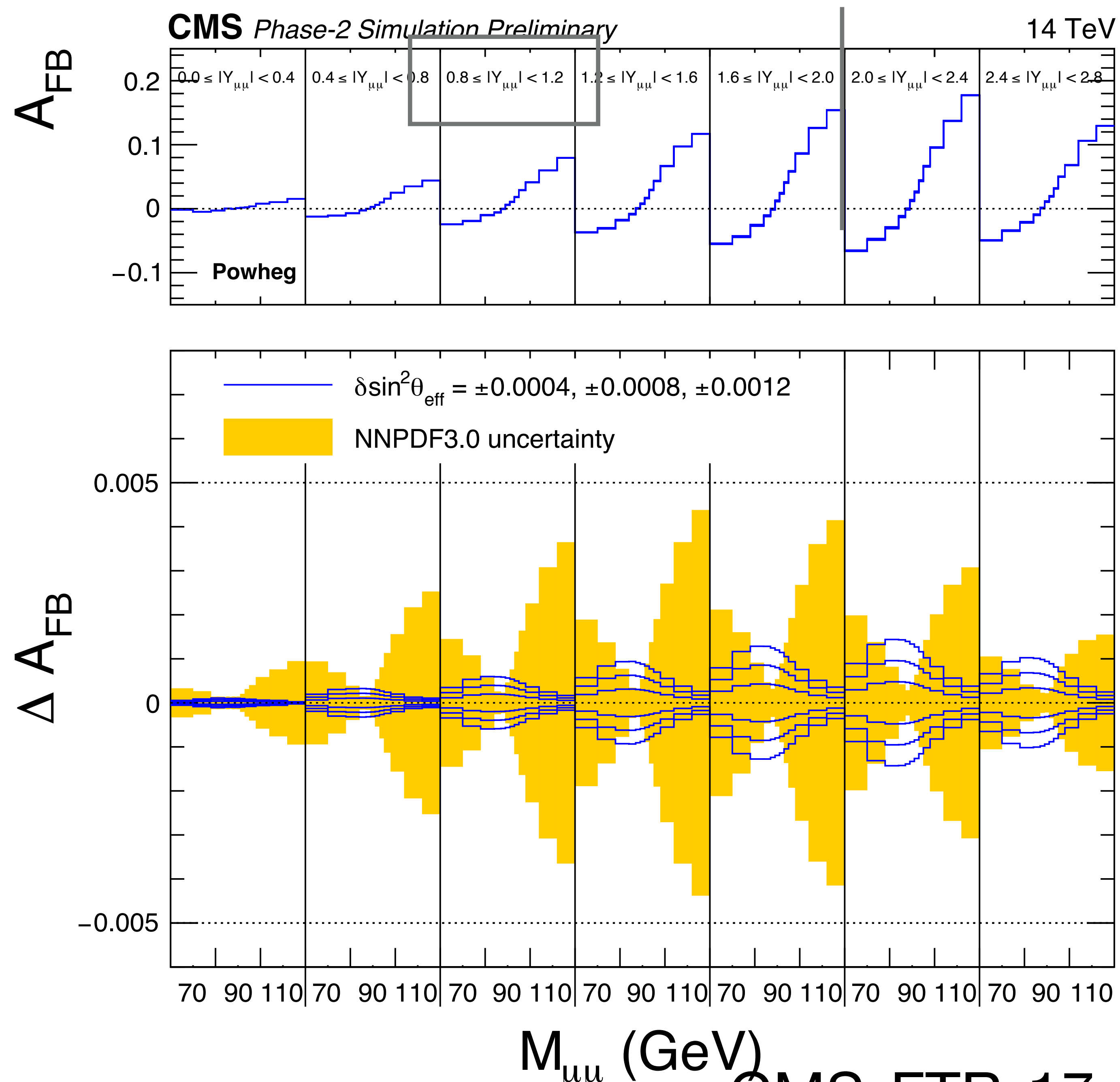
SIN2 ΘW @ CMS/ATLAS



JHEP09(2015)049



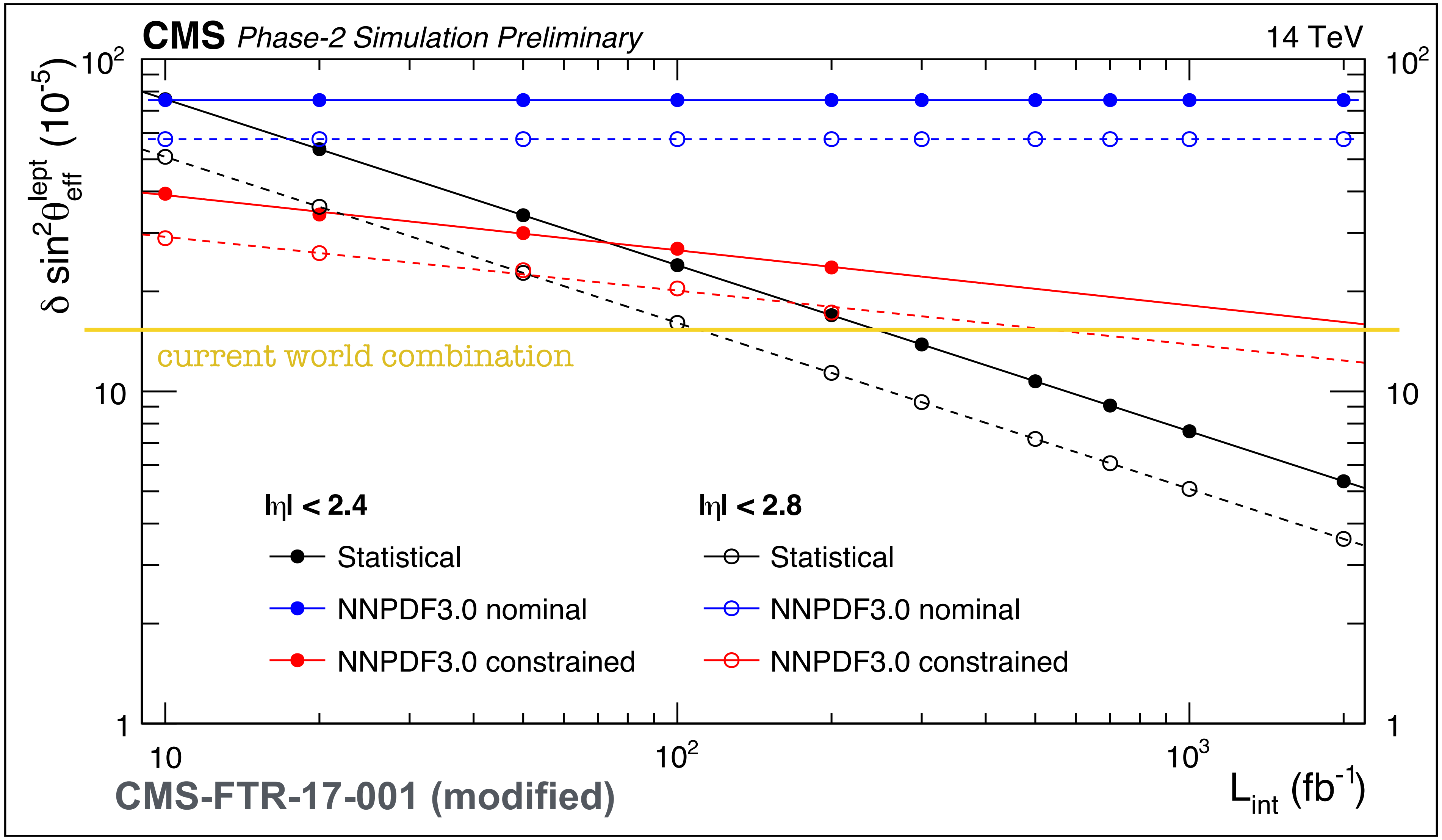
arXiv:1710.05167



CMS-FTR-17-001

- Reduce PDF uncertainty
  - go to high Y - even more possibilities with extended tracking

CMS Extrapolation



- Total uncertainty likely reduced by a factor of 3 @ HL-LHC
- Individual measurements reach current world-combination uncertainty ($16 * 10^{-5}$)
- Strong benefit from tracker/muon system coverage

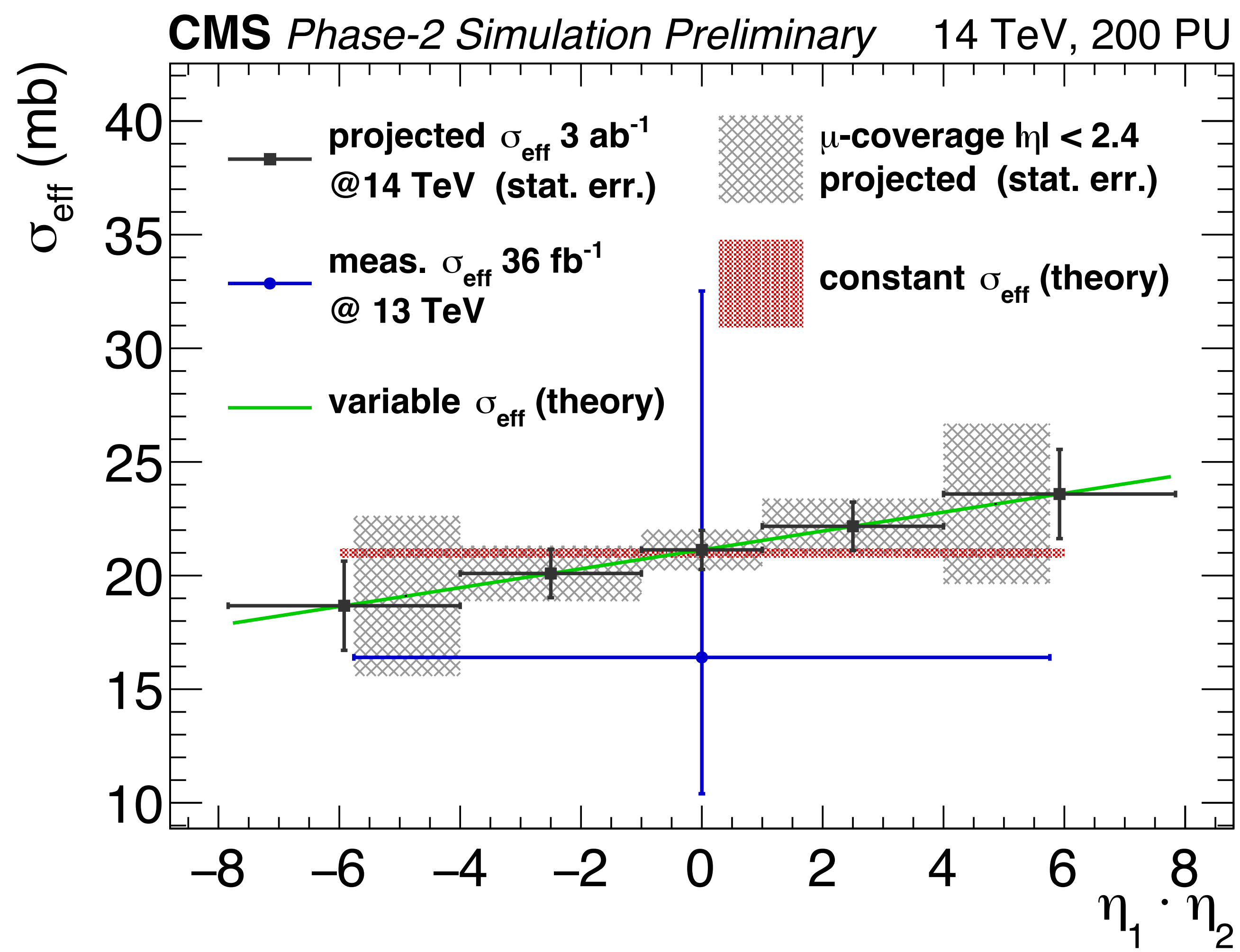
L_{int}	$\delta^{constrained}_{nnpdf3.0}$ $[10^{-5}]$	
(fb^{-1})	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.8$
10	39	29
100	27	20
500	20	16
1000	18	14
3000	15	12
19	27	
19 (from [1])	32	

DOUBLE-PARTON SCATTERING

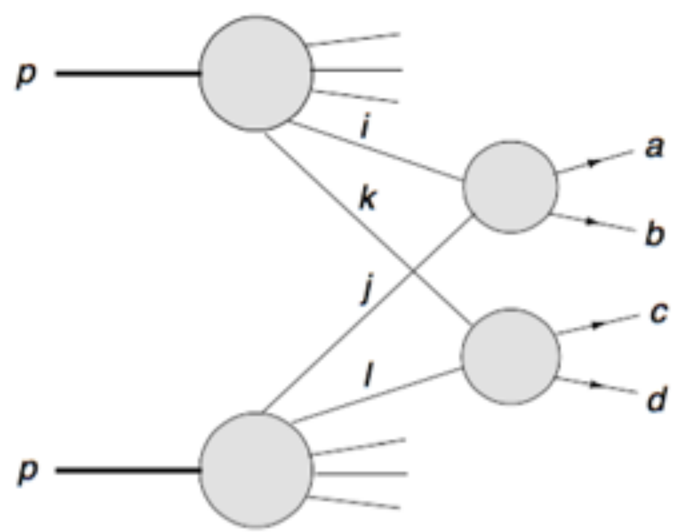
- Simultaneous scattering of multiple partons within the proton
- Do the cross-sections factorise?

$$\sigma = \frac{\sigma_1 \sigma_2}{\sigma_{eff}}$$

- Extrapolation from run 2 analysis
  - same-sign W
  - Adapt efficiencies/acceptance from full simulation
  - Most sensitive observable: η1 · η2



CMS-TDR-17-003



Slope uncertainty:
75% (50%) for |η|<2.4 (2.8)

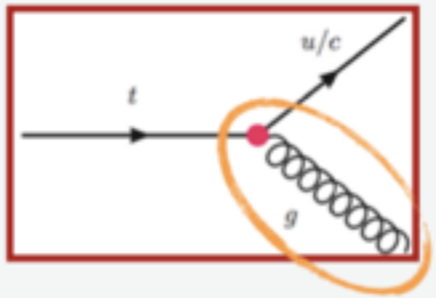
Possible to exclude factorisation hypothesis

Strong gain from statistics

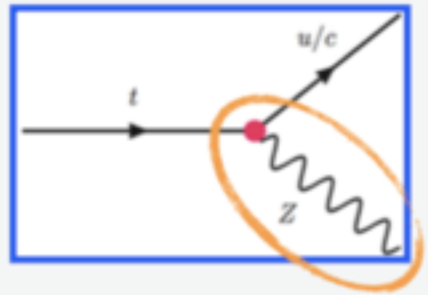
Large impact of extended coverage

TOP-QUARK FCNC

Top + gluon

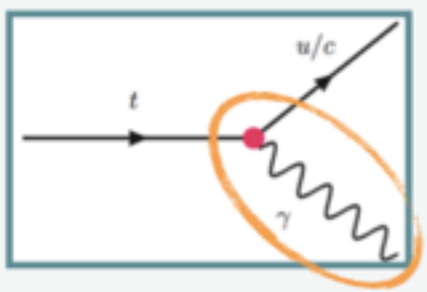


Top + Z

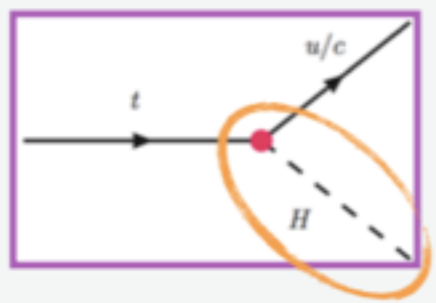


$$
\begin{aligned}
\mathcal{L} = \sum_{q=u,c}\Big[&\sqrt{2}\,g_s\frac{\kappa_{gqt}}{\Lambda}\bar{t}\,\sigma^{\mu\nu}T_a(f^L_{Gq}P_L+f^R_{Gq}P_R)\,q\,G^a_{\mu\nu}\\
&+\frac{g}{\sqrt{2}c_W}\frac{\kappa_{zqt}}{\Lambda}\bar{t}\sigma^{\mu\nu}(f^L_{Zq}P_L+f^R_{Zq}P_R)\,q\,Z_{\mu\nu}\\
&-e\frac{\kappa_{\gamma qt}}{\Lambda}\bar{t}\,\sigma^{\mu\nu}(f^L_{\gamma q}P_L+f^R_{\gamma q}P_R)\,q\,A_{\mu\nu}\\
&+\frac{g}{\sqrt{2}}\bar{t}\,\kappa_{Hqt}(f^L_{Hq}P_L+f^R_{Hq}P_R)\,q\,H\Big]+\text{h.c.}
\end{aligned}
$$

Top + gamma



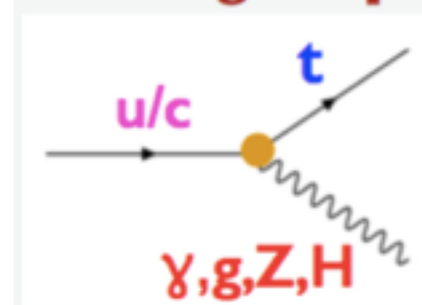
Top + Higgs



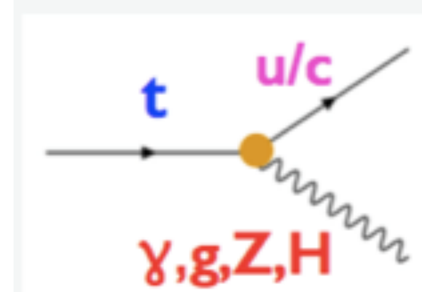
SM	2HDM	MSSM
BR(t→cg) ≃ 5×10^{-12}	10^{-8} - 10^{-4}	10^{-7} - 10^{-6}
BR(t→cZ) ≃ 1×10^{-14}	10^{-10} - 10^{-6}	10^{-7} - 10^{-6}
BR(t→cγ) ≃ 5×10^{-14}	10^{-9} - 10^{-7}	10^{-9} - 10^{-8}
BR(t→cH) ≃ 3×10^{-15}	10^{-5} - 10^{-3}	10^{-9} - 10^{-5}

- In SM
  - Forbidden at tree level
  - Only via loops, but highly suppressed
- Search
  - Single top (production)
  - Top-pair (decay)

in single top

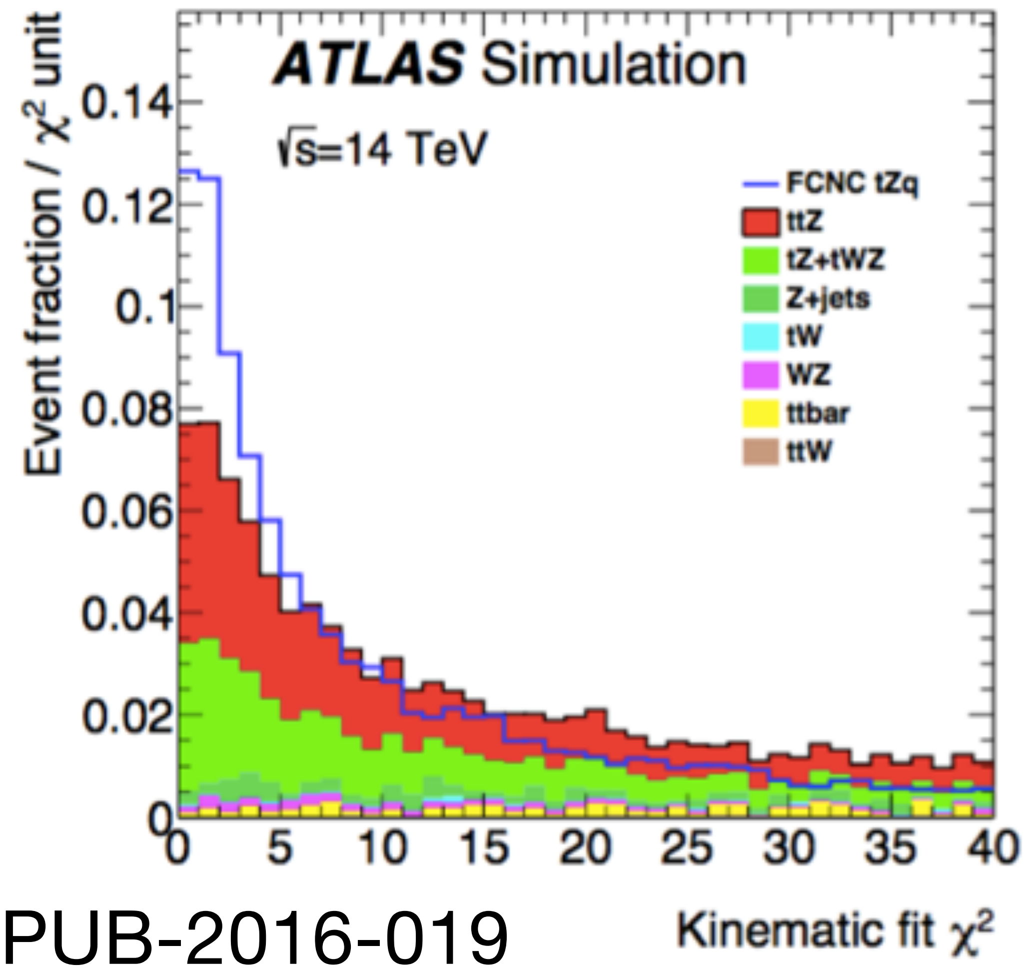


in ttbar

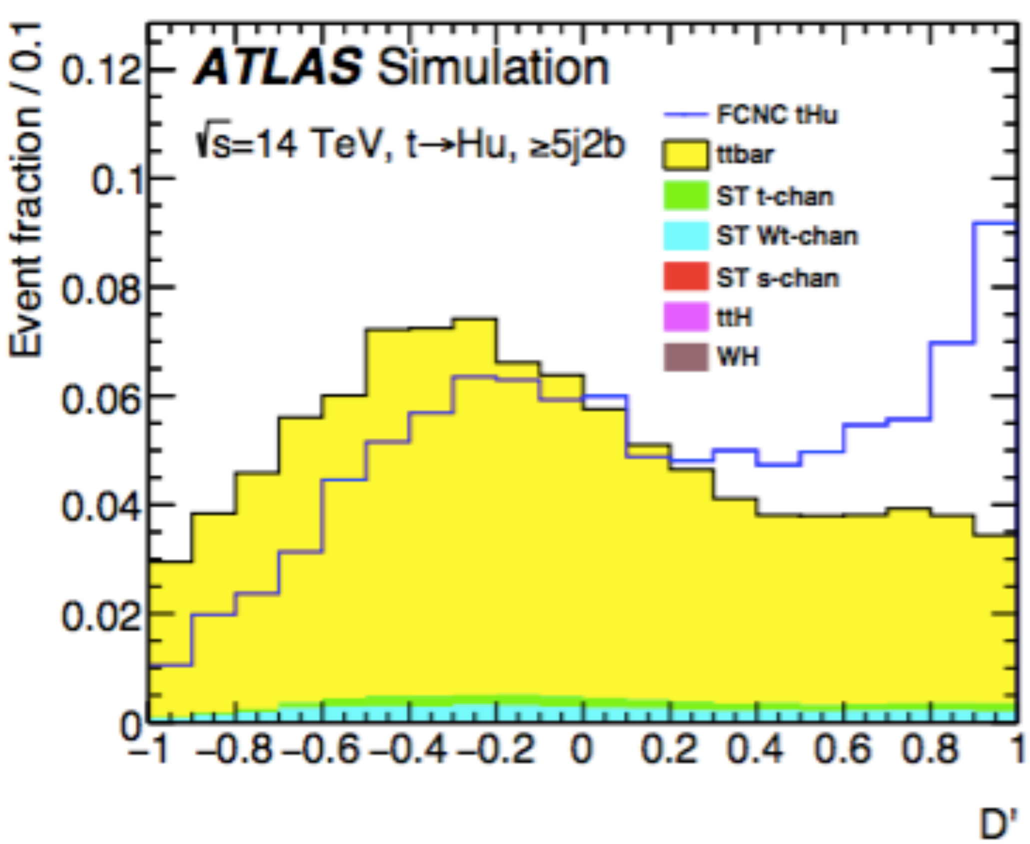


FCNC: TZQ, THQ

- ATLAS
  - tZq: Fit to χ2 of full kinematic fit of event. signal/background separation is highly dependent on overall detector performance at high PU
  - tHq: Fit to likelihood discriminant in jet,b-jet categories



PUB-2016-019



PUB-2016-019

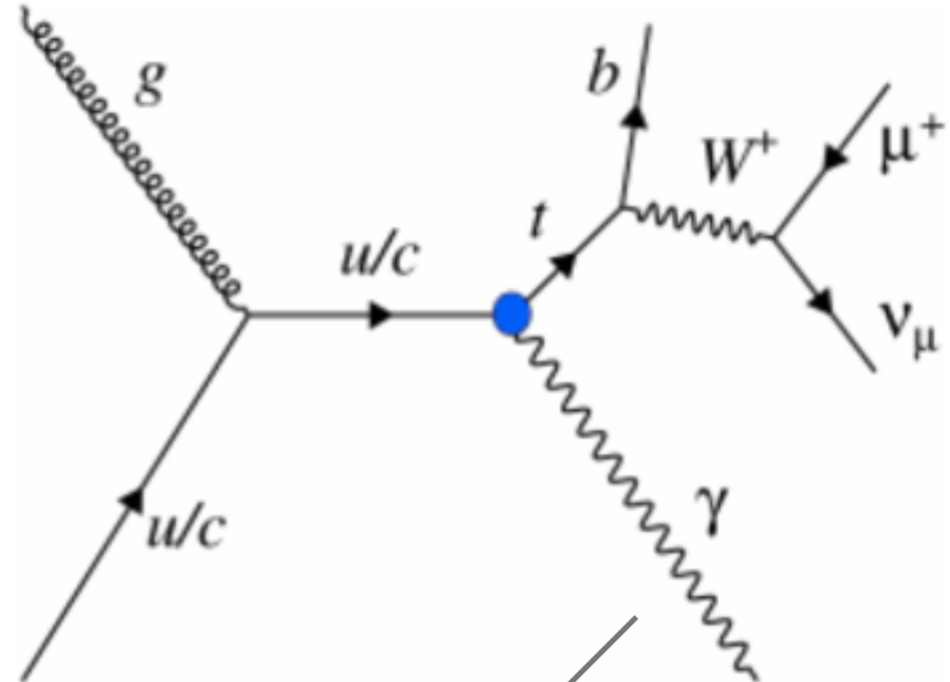
tZq: background normalisation becomes dominant uncertainty

tHq: strong constraints on uncertainties from simultaneous fit

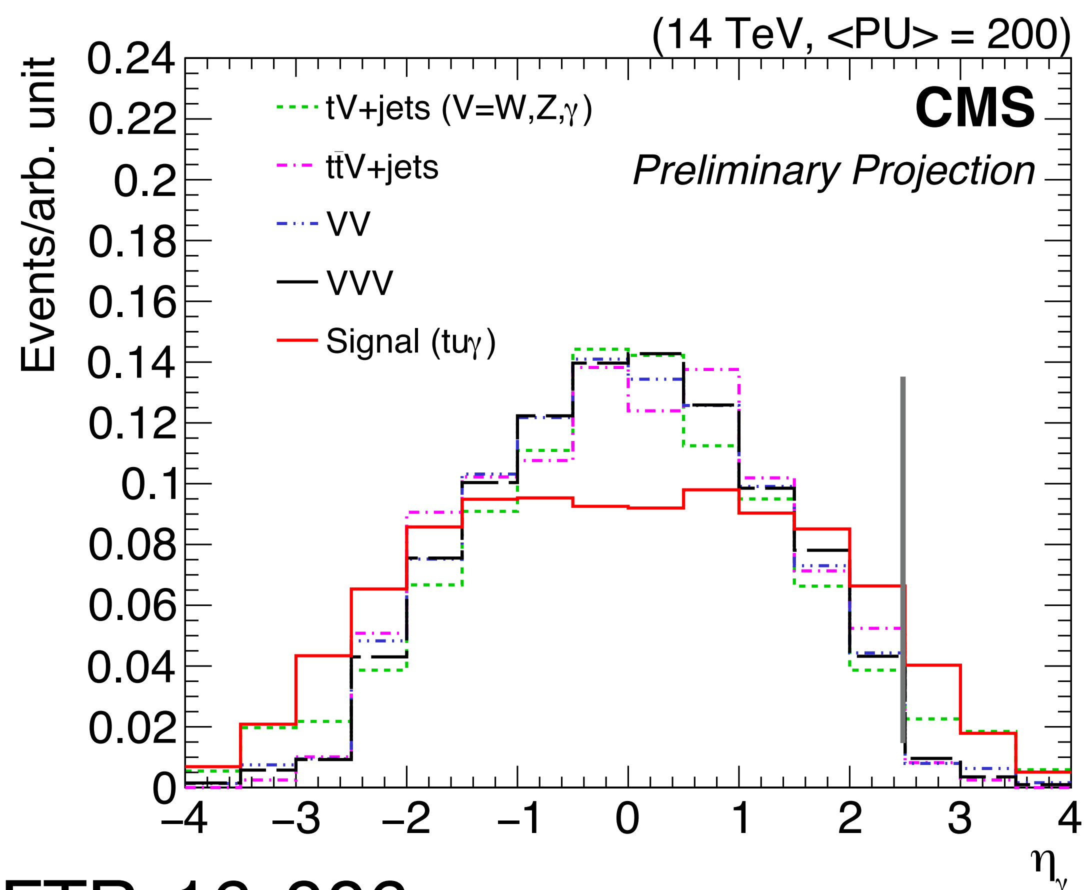
In general in-situ constraints have high potential for SM at HL-LHC, but needs good understanding of uncertainty sources

FCNC: TγQ

- CMS
  - Reconstruct top-quark system (overall detector performance)
  - Require high-energetic photon
  - here |ηγ|< 2.4 to extrapolate backgrounds from 8 TeV analysis
  - not yet optimised



high-energetic 'forward' photon



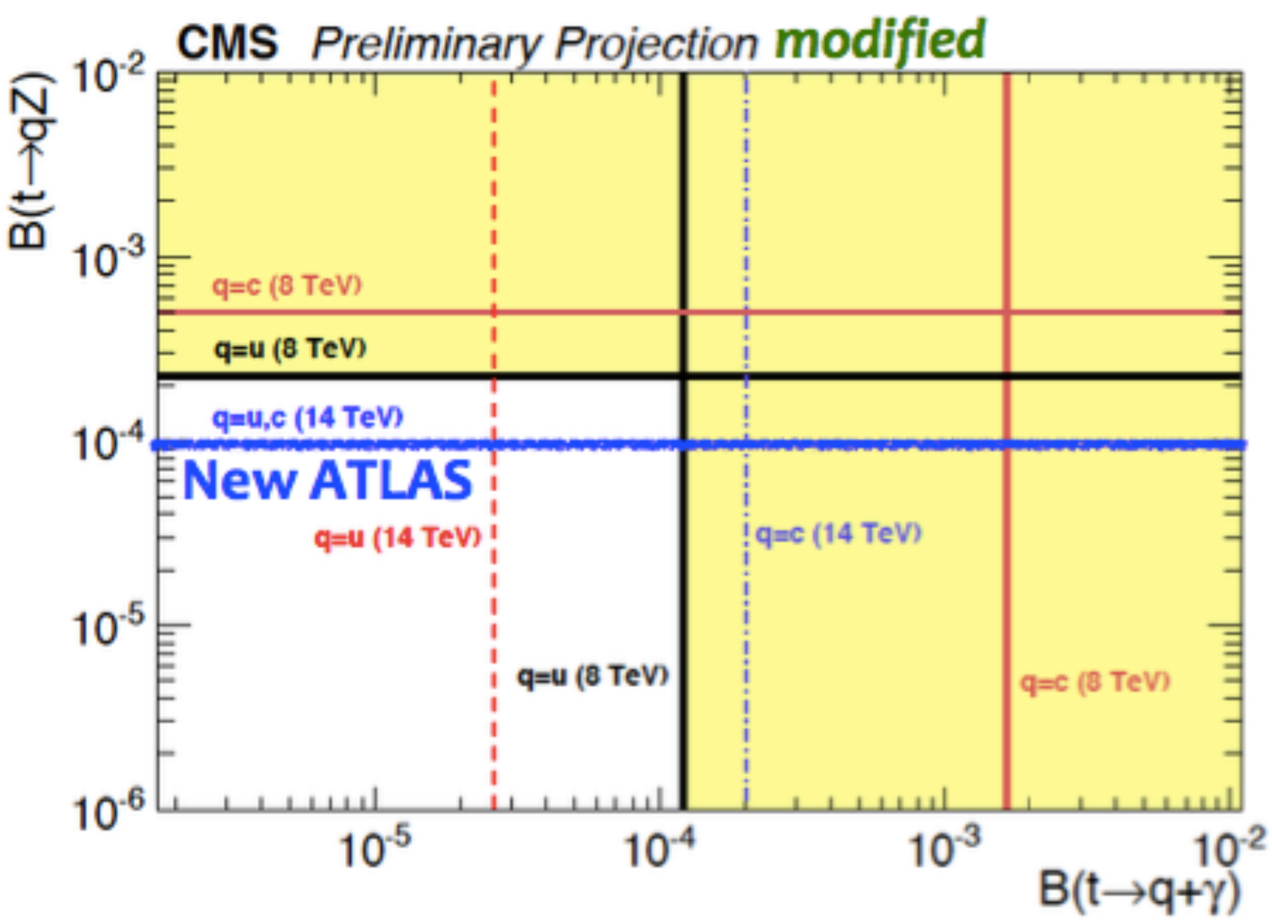
FTR-16-006

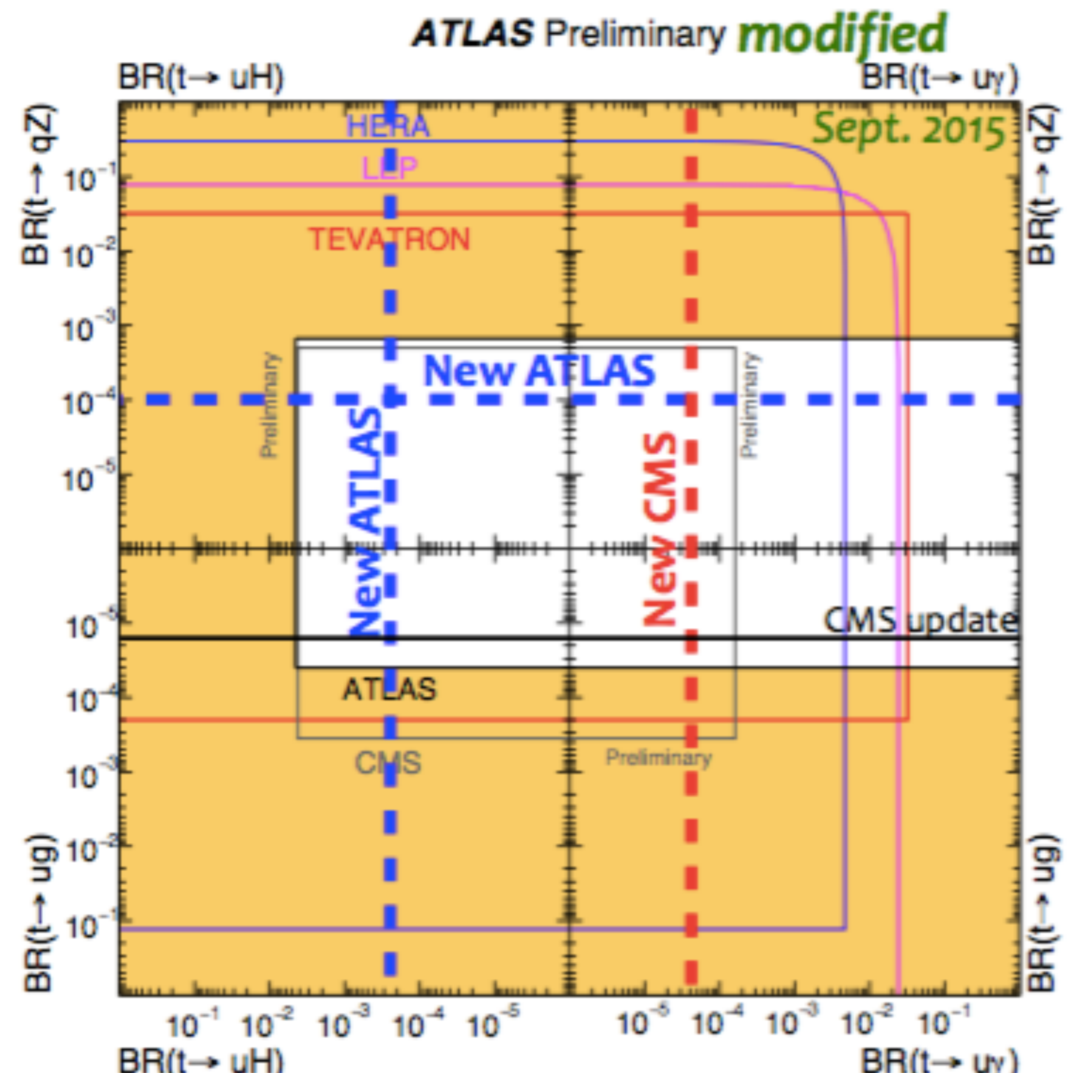
Strong gain from reconstruction of forward electromagnetic showers in high pileup

High granularity endcap calorimeter show-case

FCNC RESULTS

- Top-quark FCNC analyses show very strong potential
  - Closing the window

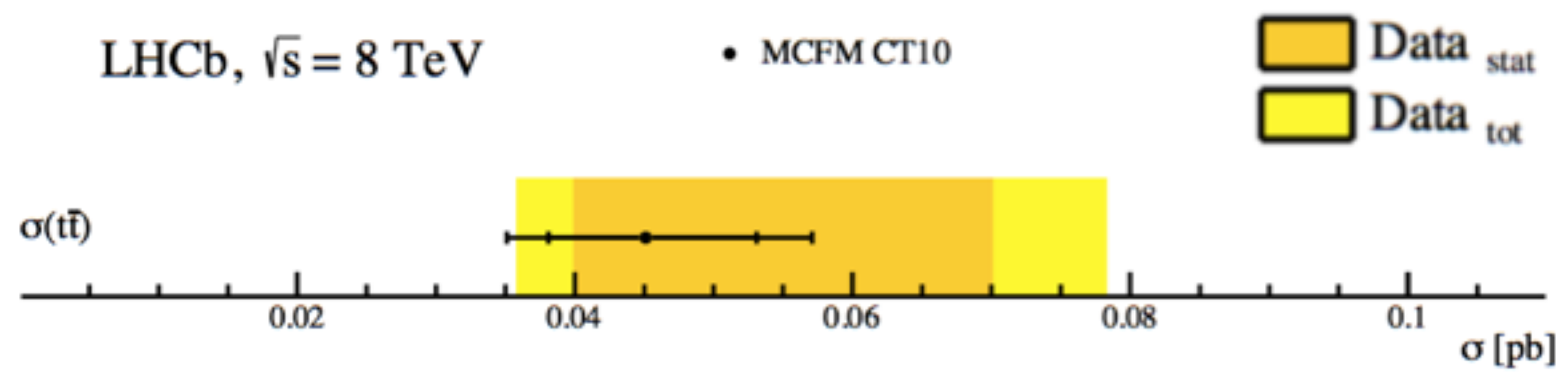




from M. Christi

FORWARD TOP-QUARK PRODUCTION

- ➢First measurements for LHCB at 8 TeV still statistics limited
- ➢Acceptance increases strongly (factor of 5) at 14 TeV
- ➢Fiducial cross section increases by a factor of 10
- ➢Assume constant object performance (leptons, b-tagging)



PLB 767 (2017) 110 (modified)

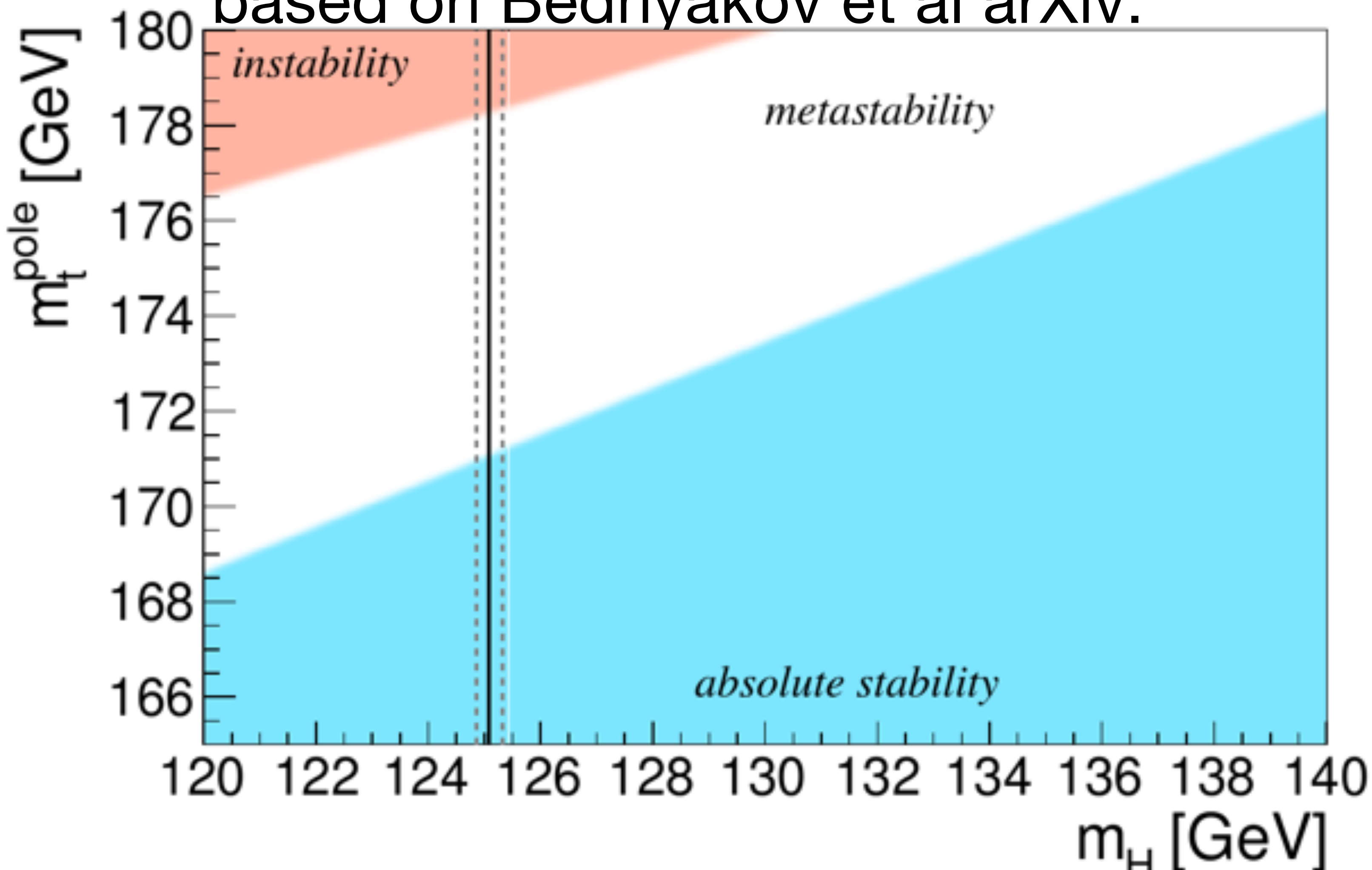
Channel	End of Run 2 (5/fb)	End of Run 4 (50/fb)	Future Upgrade 300/fb
lb	11,000	110,000	680,000
lbj	6,000	60,000	360,000
lbb	1,400	14,000	90,000
lbbj	800	8,000	50,000
ll	2,000	20,000	120,000
llb	800	8,000	50,000

- ➢Total increase in statistics by a factor of 20 (run 2) to 1200 (HL-LHC)
  - ➢ Non-zero asymmetry expected to be observable beyond 5σ significance
  - ➢ Differential measurements at very high y
  - ➢ Separate single-top and ttbar contributions

THE TOP-QUARK MASS

- ➤The top-quark mass - theory perspective
  - ➤ Parameter in the Lagrangian
  - ➤ Beyond LO: renormalisation
  - ➤ Definition becomes scheme dependent (pole, MSR MSbar…)
  - ➤ Essential for EWK precision fits, EWK vacuum stability
- ➤The top-quark mass - experimental perspective
  - ➤ Highly precise MC mass measurements
  - ➤ Pole mass measurements with increasing precision, work ongoing to relate both
  - ➤ Systematics limited measurements, require full detector

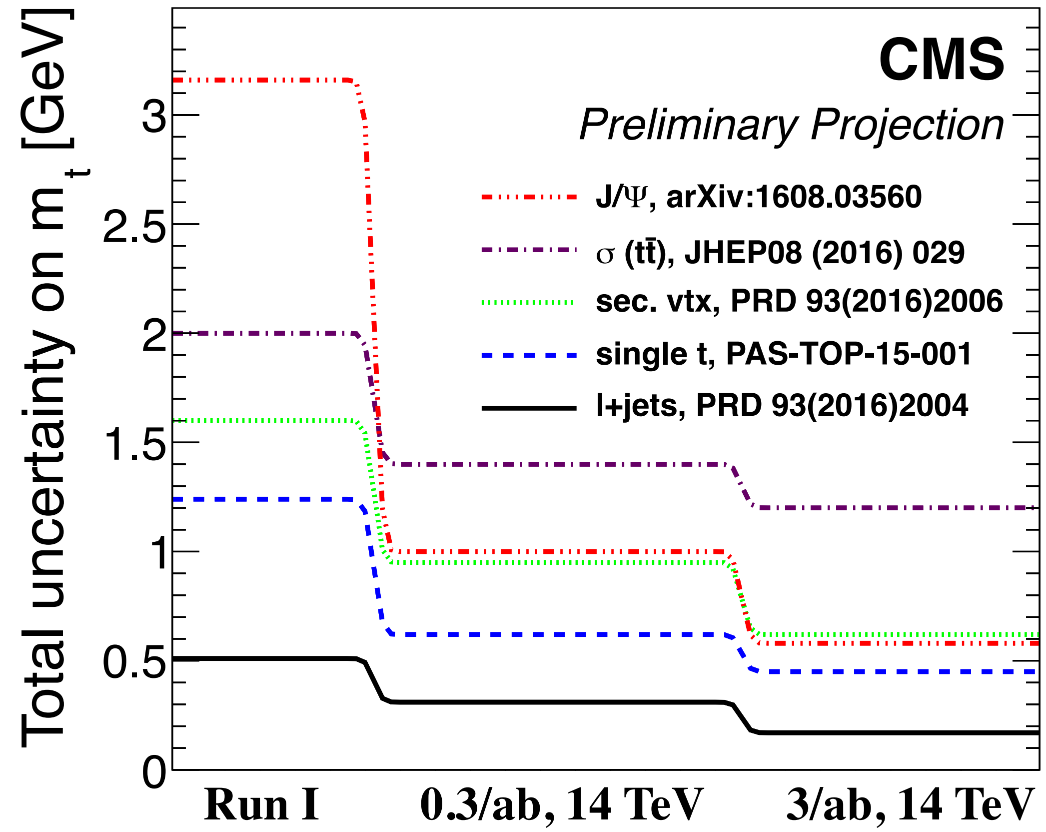
based on Bednyakov et al arXiv:



- ➤Worth to continue measuring the top-quark (MC) mass with HL-LHC?
  - ➤ High-precision ‘direct’ pole/running mass measurements
  - ➤ Possible to go (multi) differential measurements
    - ➤ Gain insight into tunes, different corners of phase space
  - ➤ Almost unlimited possibilities for data-driven constraints

TOP QUARK MASS EXTRAPOLATIONS

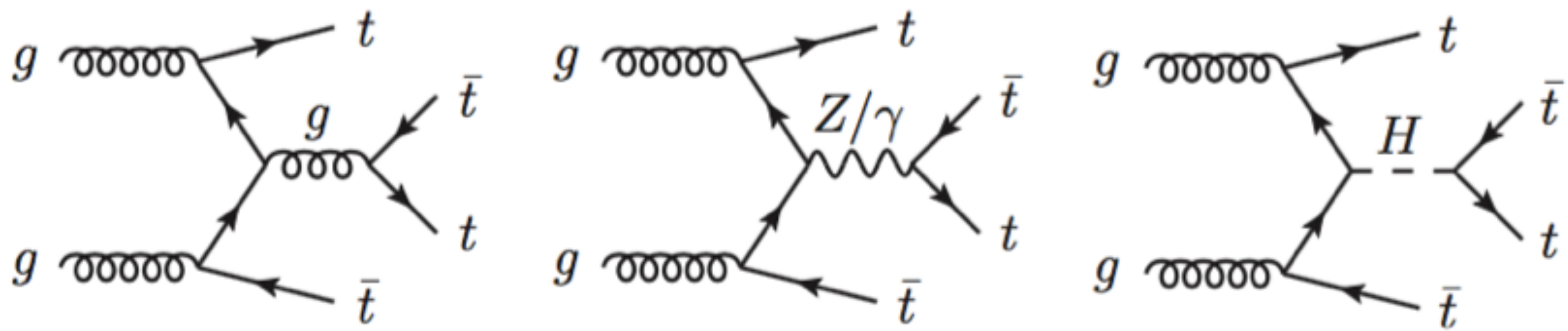
- Clear benefit from statistics for J/Psi
  - Independent of JES, uses mJ/Ψ,l
- Moderate improvement for pole mass from cross sections
  - Ultimately limited by luminosity uncertainty and theory uncertainty (no N3LO assumed)
- Single top:
  - EWK process, complementary to other tecl
  - Benefit from statistics and modelling improvements
- ‘standard’ l+jets
  - Benefit from differential studies constraining modelling



FTR-16-006

- **All MC mass analysis will go well below 1 GeV uncertainty.**
  - Differences in production/decay mechanism may become visible
- **Likely even more analyses techniques become available not covered here**
  - More in-situ constraints, differential (pole/MSbar) mass measurements…

HL/HE-LHC: 4-TOP PRODUCTION



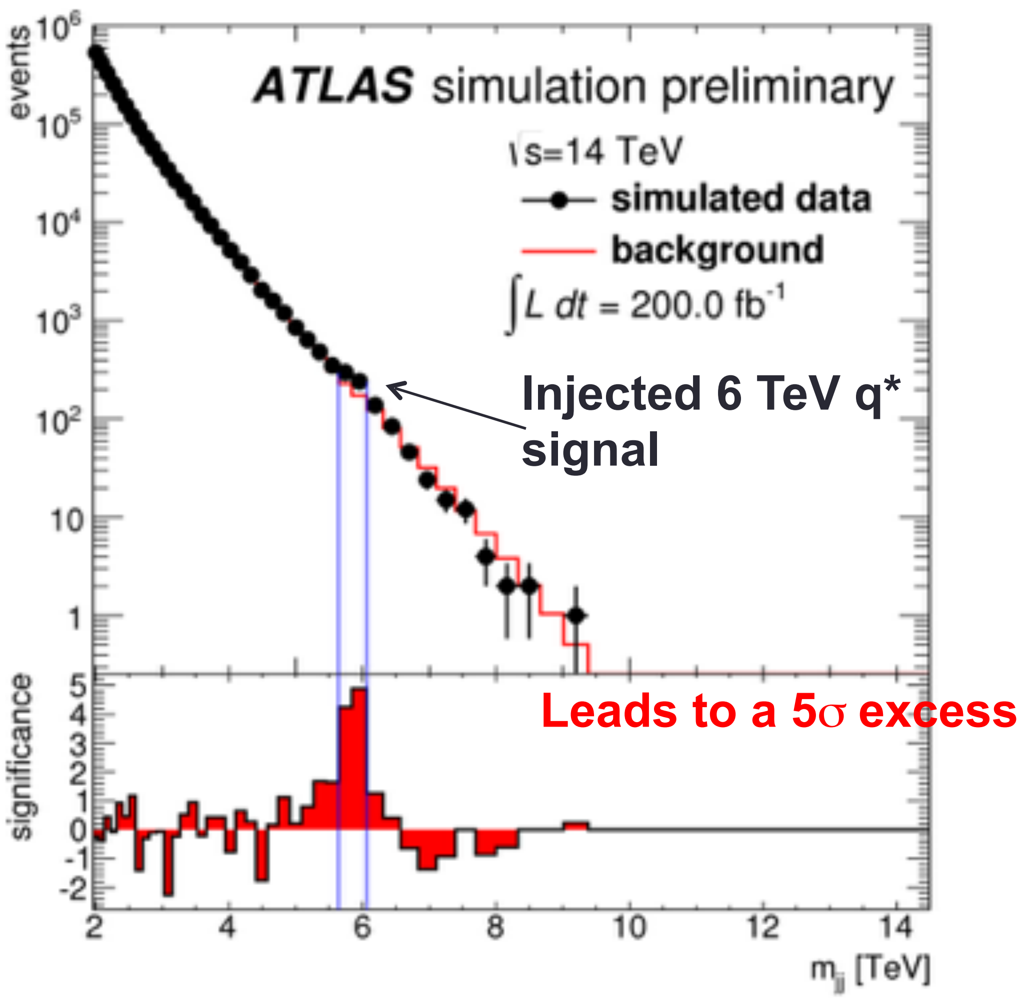
Q. Cao et al, PRD 95, 053004 (2017)

- Observation of 4-top production feasible with > 300 fb-1
- Gives access to top-yukawa coupling and Higgs width
- Challenges for detector performance (complex final state)
  - High jet multiplicity
  - Multiple b-tagging
  - Combinatorics
- 4*mt: strong increase in cross-section for 28 TeV (HE-LHC) to be expected

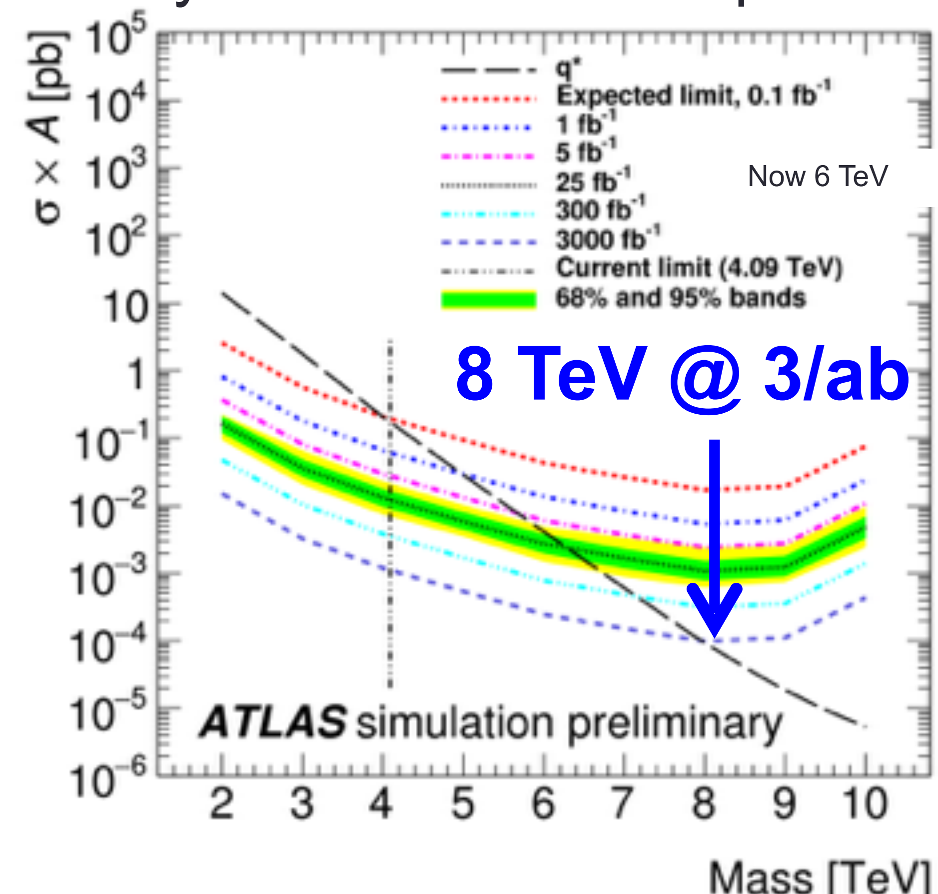
BEYOND THE STANDARD (MODEL) SEARCHES

STANDARD SEARCH: BUMP HUNTING

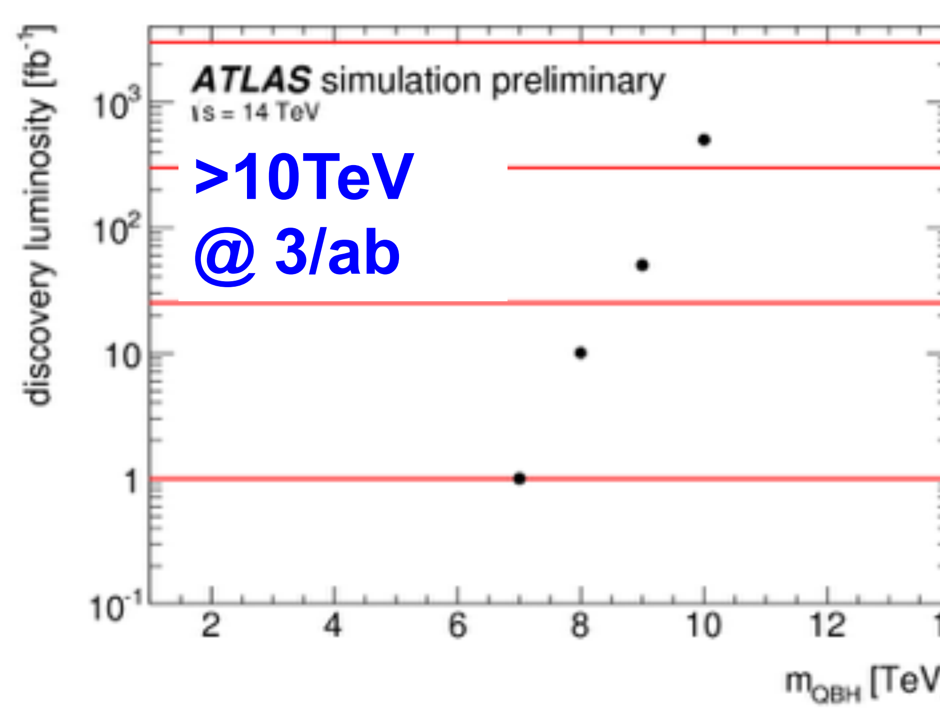
- Plethora of new physics models predicting resonances decaying to 2 jets: quantum black holes, excited quarks, Z'/W' bosons, W* bosons
- **Look for:**
  - **bumps in mjj**
  - deviations from flat distribution in $\chi=\exp|y_1-y_2|$
- Powerful search technique for new physics, model-independent as long as a sharp resonance.
- Greatly profit from increase in energy (HE-LHC)



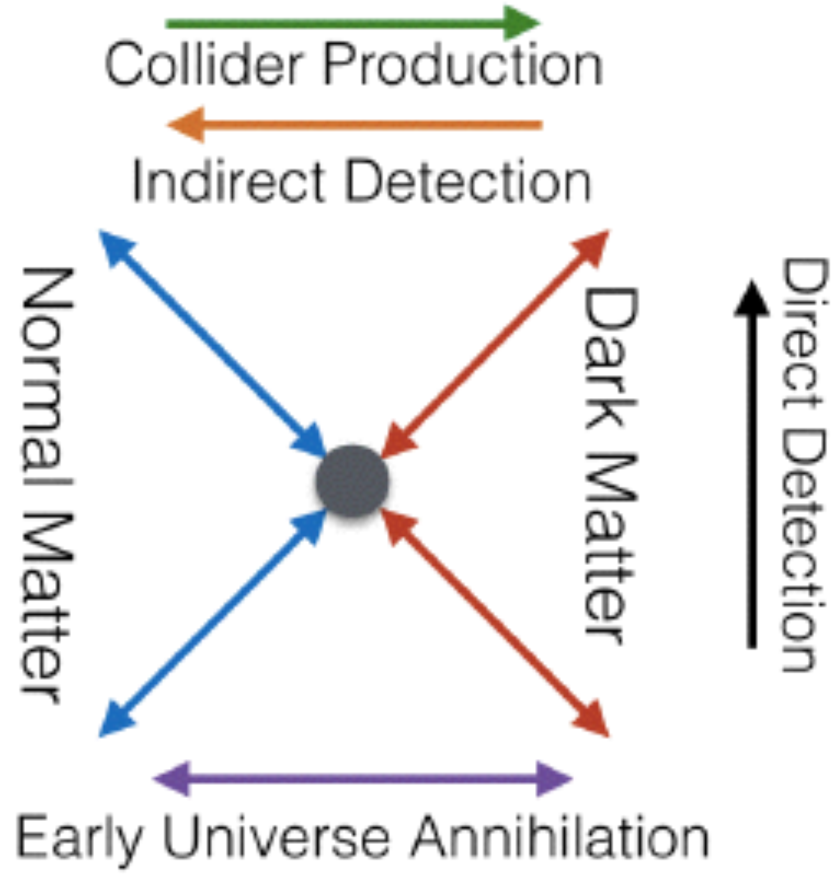
Discovery reach for excited quarks q*



Discovery reach quantum black holes



DARK MATTER

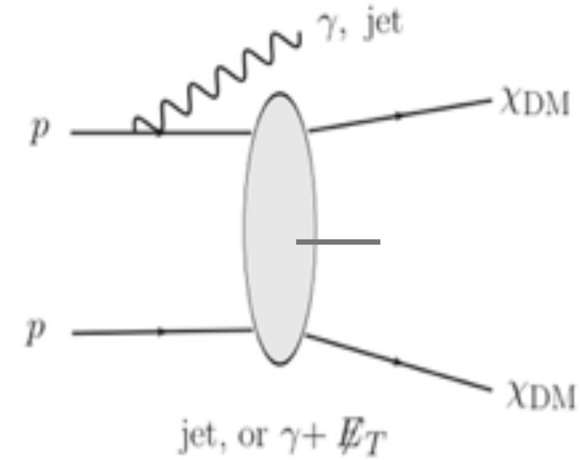


- Next discovery?
  - Guess: DM is a thermal relic of the early universe
  - Weak-scale interactions with the SM
  - LHC searches complement direct detection experiments.
  - Complication: translation between annihilaton and experimental cross section very model dependent.
- In recent years significant theoretical and experimental developments, e.g. EFT->simplified models.

DARK MATTER SEARCHES

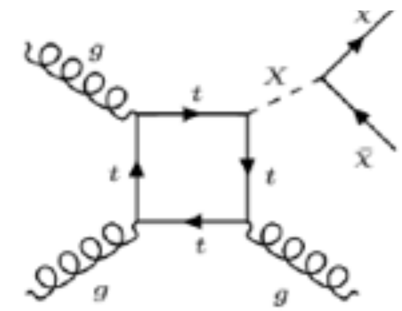
- Searches based on Simplified Models
  - Dirac WIMP mediators
    - scalar, pseudoscalar, vector/axial-vector
  - With distinct kinematic distributions
  - Aids in design of generic searches
    - Missing ET+ X (jets, g, Z, leptons, dileptons, ..)
- Search for Dark Matter in Missing ET+jets
  - Suppressed in direct detection.
  - LHC provides complementary sensitivity.
  - Benchmark among many DM collider searches.
- Interpretation in simplified models with 4 parameters (Mmed, mDM, gSM, gDM)
- Axial vector mediator :
  - Exclusion possible up to 3 TeV. (current reach ~2TeV)
- Pseudoscalar Mediator:
  - Spin-0 mediator, pseudoscalar gSM = 1, gDM = 1
  - Exclusion possible up to 900 GeV (current ~0.4 TeV)
  - Reach in mediator mass influenced by systematics.

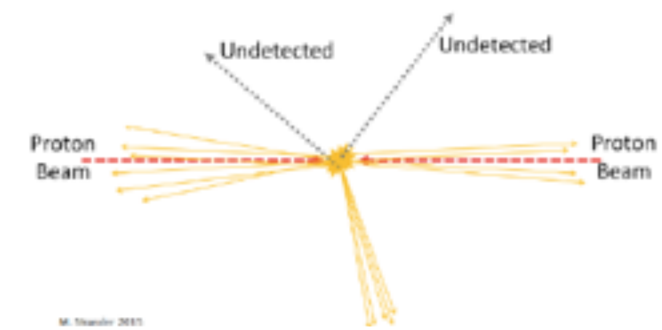
γ, jet, lepton, h

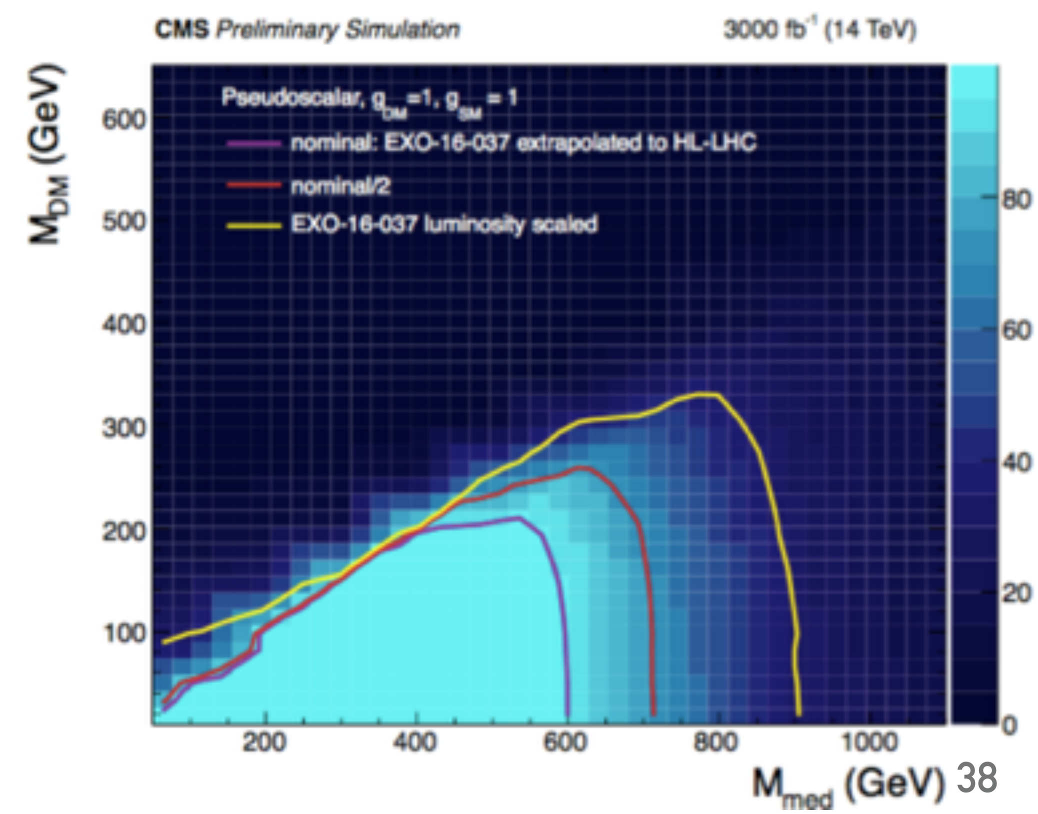


EFT or

simplified model







HE-LHC: WIMP SEARCH USING MISSING ET+JETS

➤Significant gains with the HE-LHC:

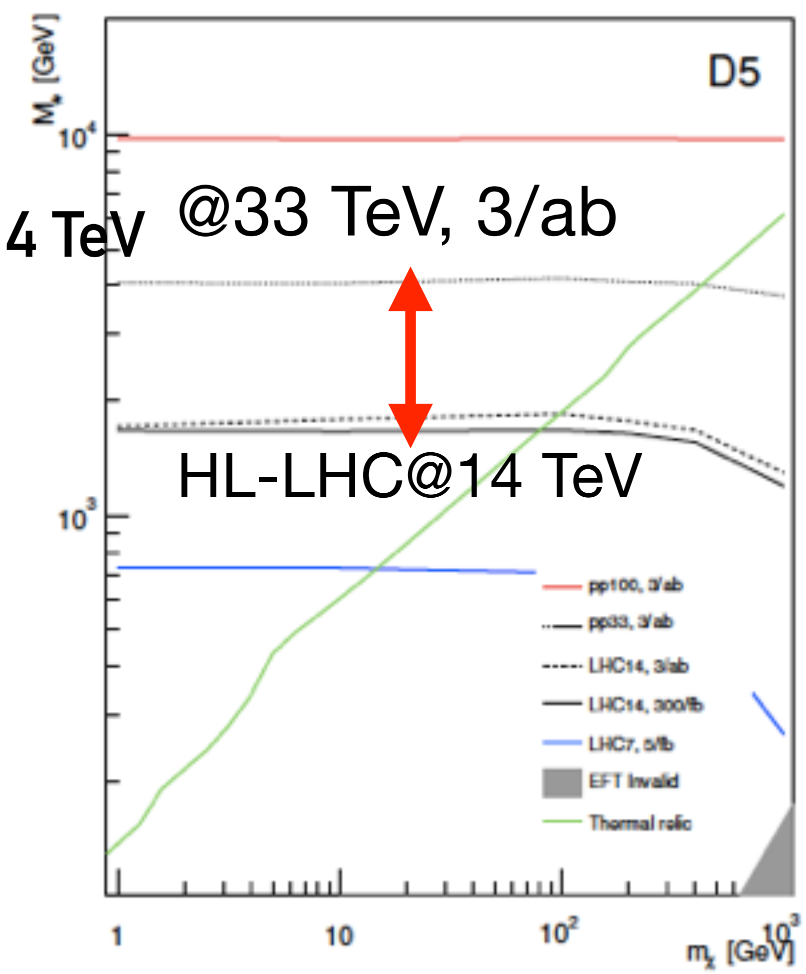
- ➤ several models tested – some where collider exclusion dominates, others where direct detection dominates.

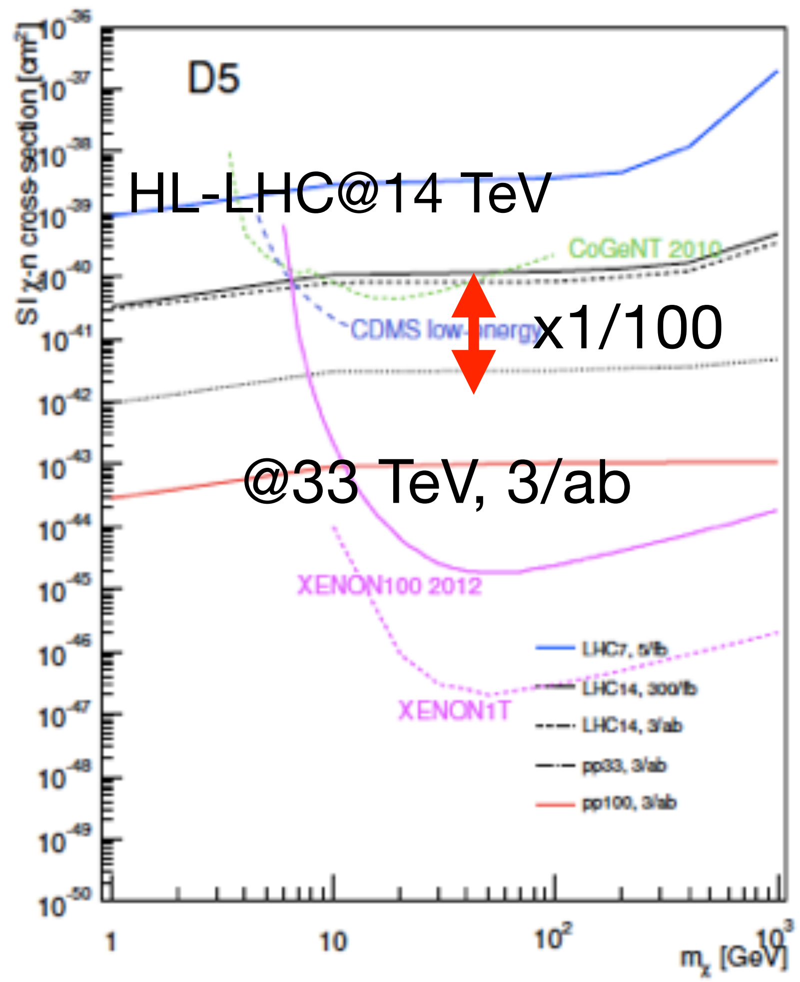
arXiv:1307.5327

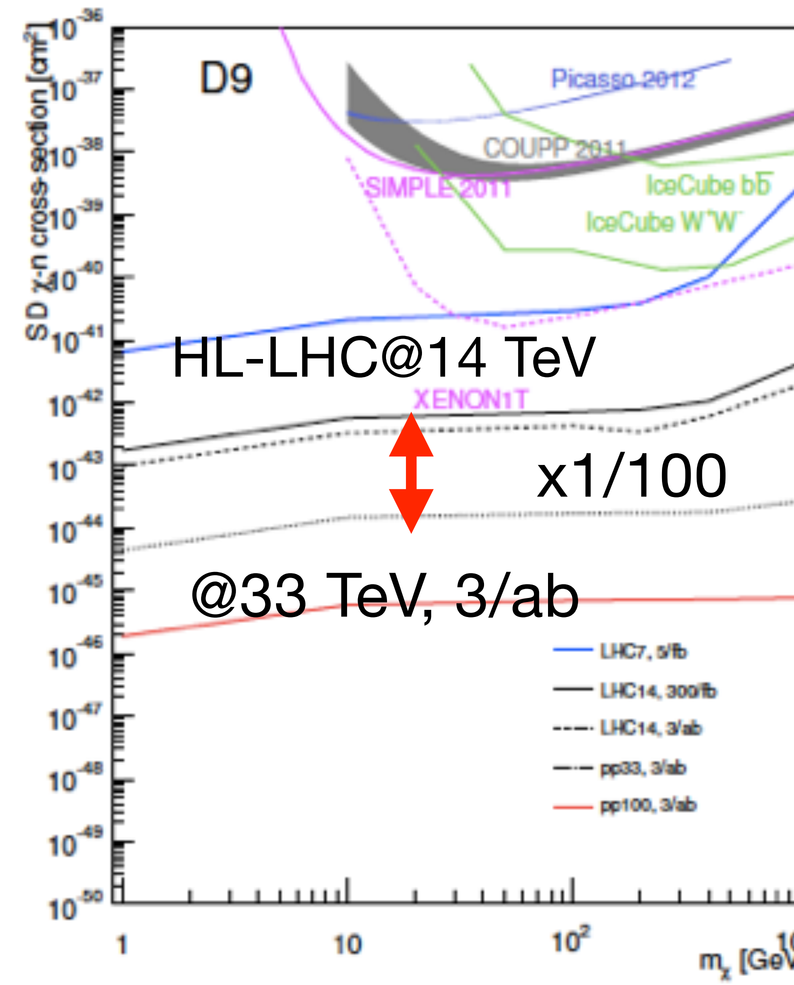
➤Sensitivity to WIMP pair production via effective operators and light mediators

Spin independent

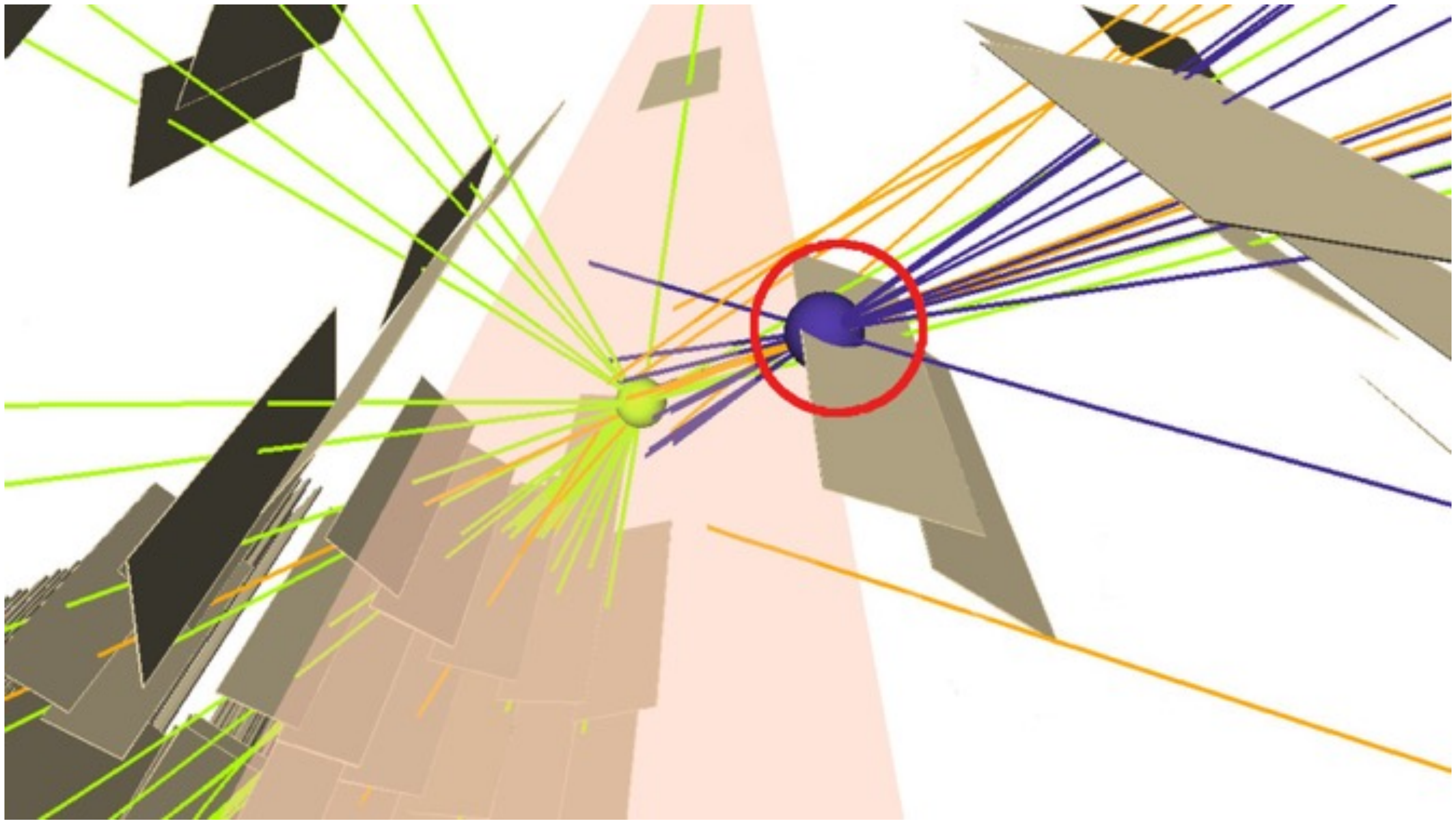
Spin dependent







LONG-LIVED PARTICLES (LLP) AND SPECIAL SIGNATURES



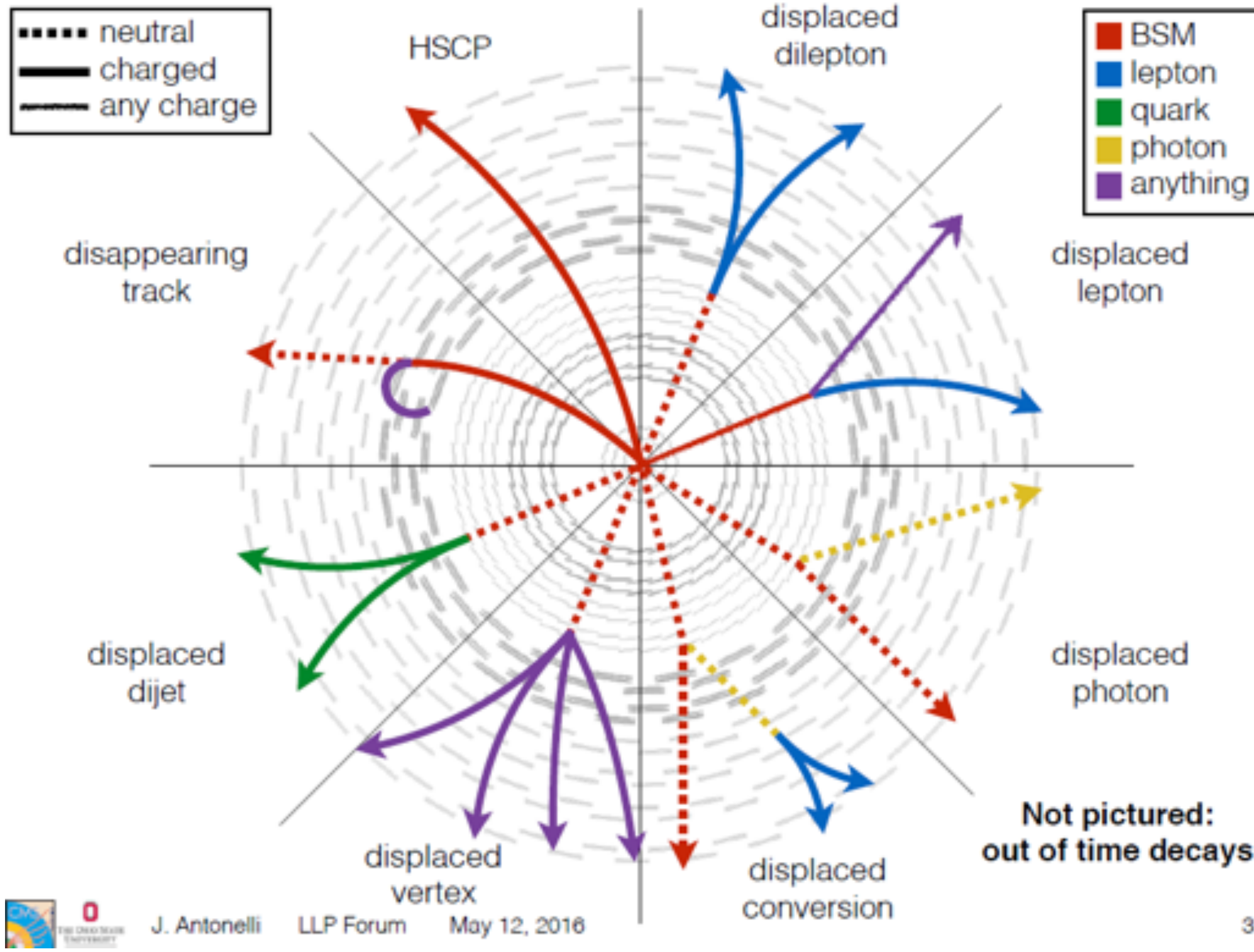
The secret lives of long-lived particles

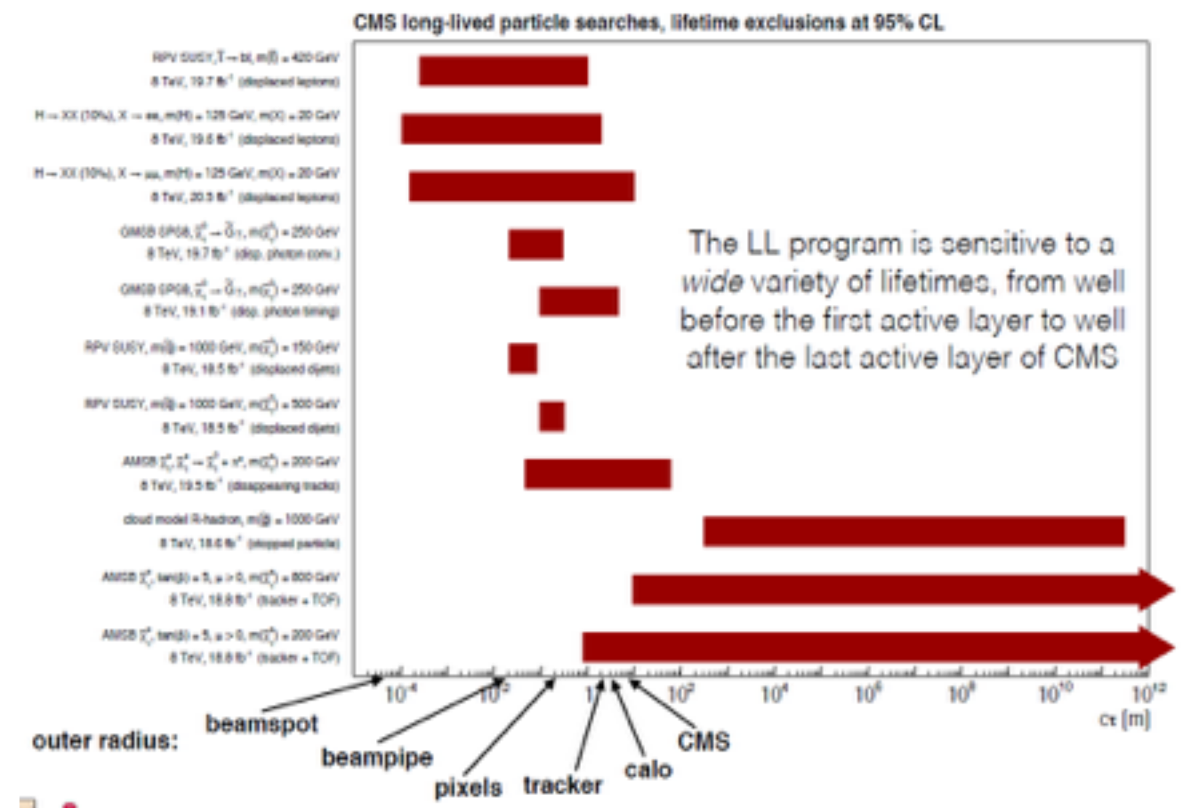
09/16/16 | By Sarah Charley

A theoretical species of particle might answer nearly every question about our cosmos—if scientists can find it.

LONG LIVED PARTICLES (LLP)

Target complementary lifetimes and ranges. Variety of dedicated techniques to cover whole range of lifetimes (cτ)





- ➢Particles decaying non-promptly are a new focus at the LHC, for present and future
- ➢Long-lived neutral particle (X) decays after some cτ to displaced leptons or jets.
- ➢Signature driven searches, with great discovery potential, Issues and opportunities with LLP signatures:
    - ➢ Need dedicated tools for non-standard objects, custom trigger/reconstruction/simulation
    - ➢ Potential gains from high luminosity, track-trigger, fast timing, better directionality.

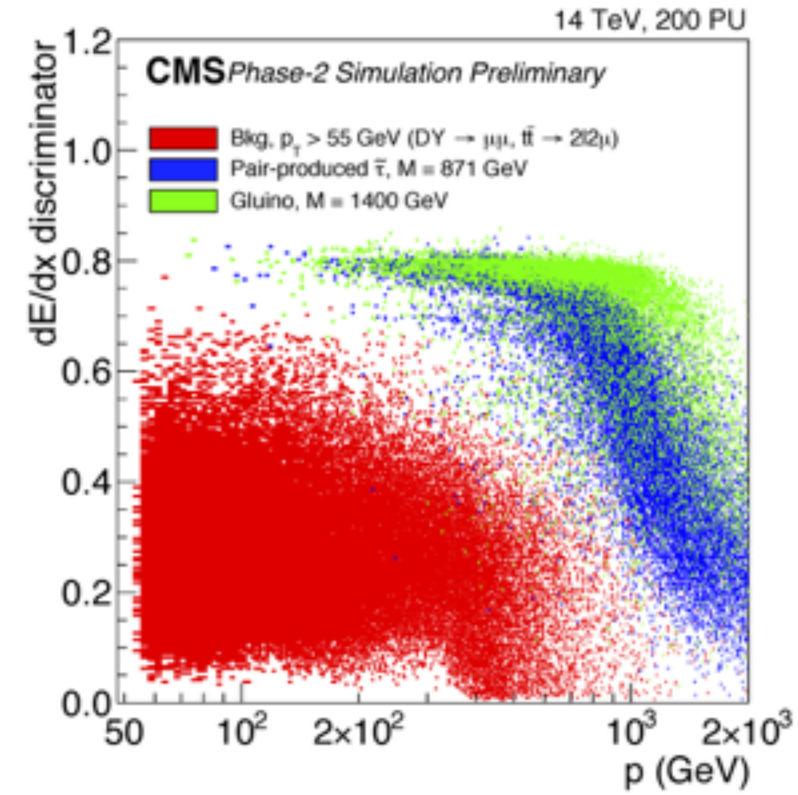
HEAVY STABLE CHARGED PARTICLES

➤HSCPs: New, heavy particles could propagate through the detector before decaying

➤Needs HL-LHC for sensitivity because of small xsec.

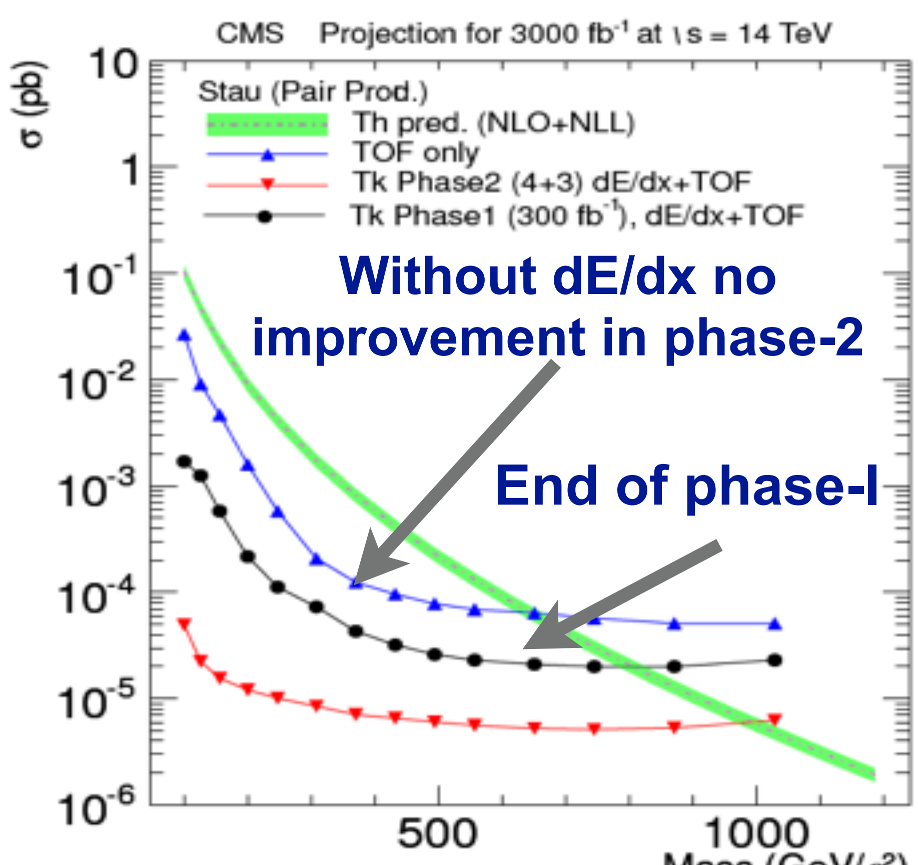
➤Detection technique

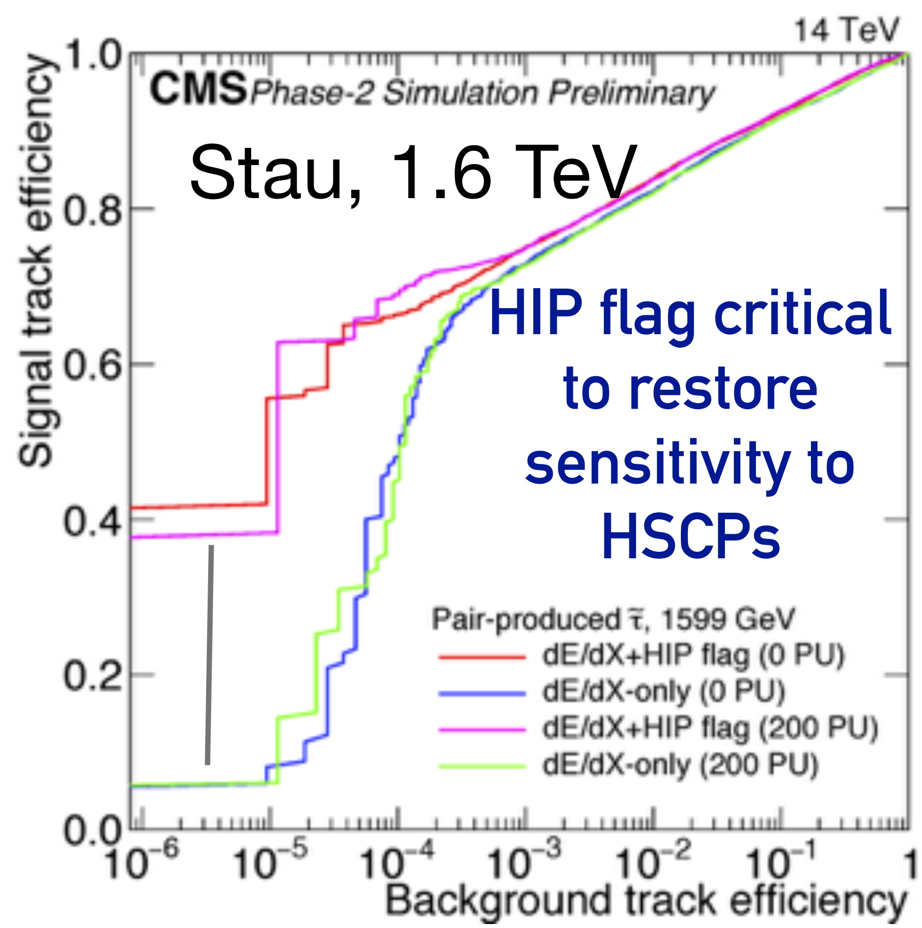
- ➤ Could look like heavy, highly-ionizing, slow-moving muons
- ➤ dE/dx discriminator shows large separation between signal and background
- ➤ Physics studied demonstrated the need to keep dE/dx capability in the tracker

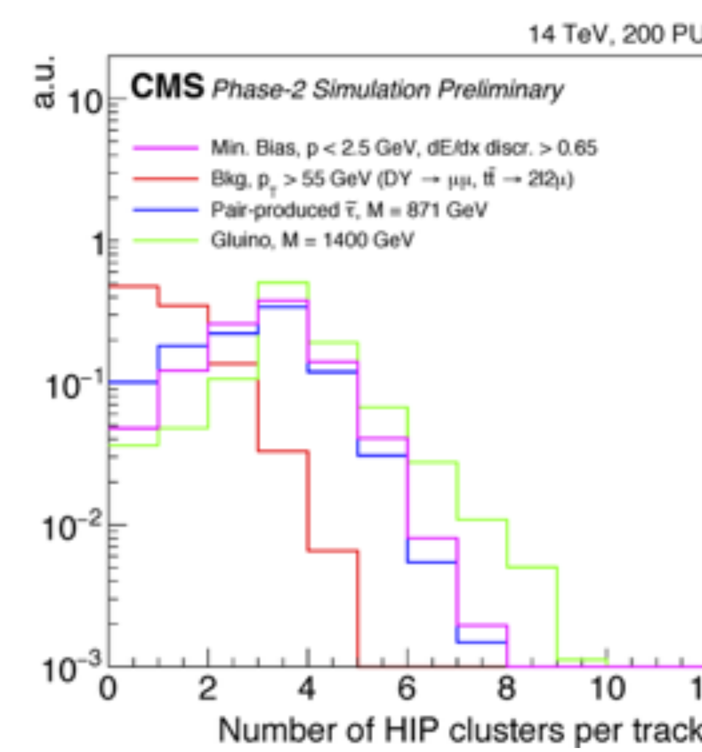


CMS TP and

CMS-PAS-EXO-14-007



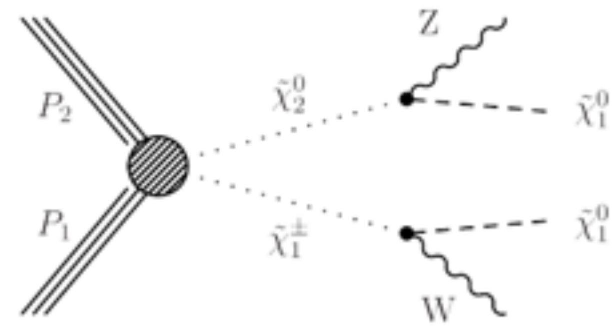


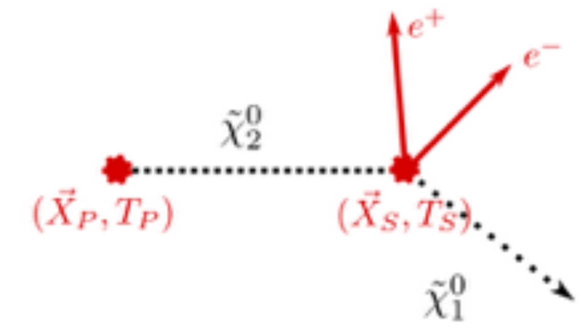


LONG-LIVED NEUTRALINOS

➤Long-lived neutralinos in GMSB with small mass difference

$$M(\tilde{\chi}^{\pm}) = M(\tilde{\chi}^0_2) = 400 \text{ GeV}, \quad M(\tilde{\chi}^0_1) = 390 \text{ GeV}$$





➤Use MIP timing detector for precision measurement time of flight

➤assign times to vertices and charged particles

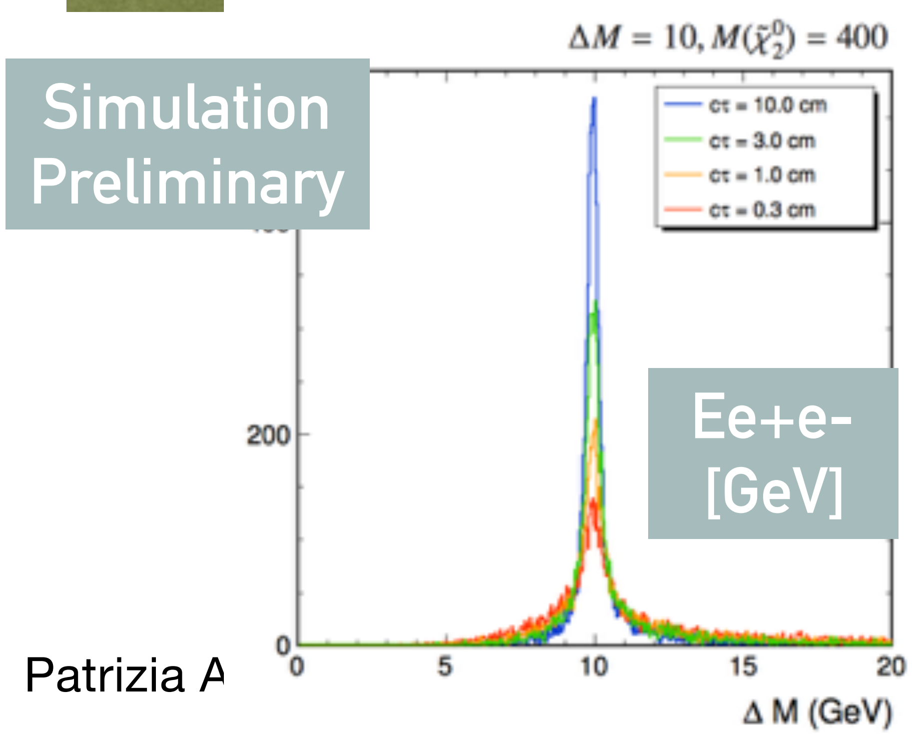
➤With the timing information, can reconstruct LLP time-of-flight and mass

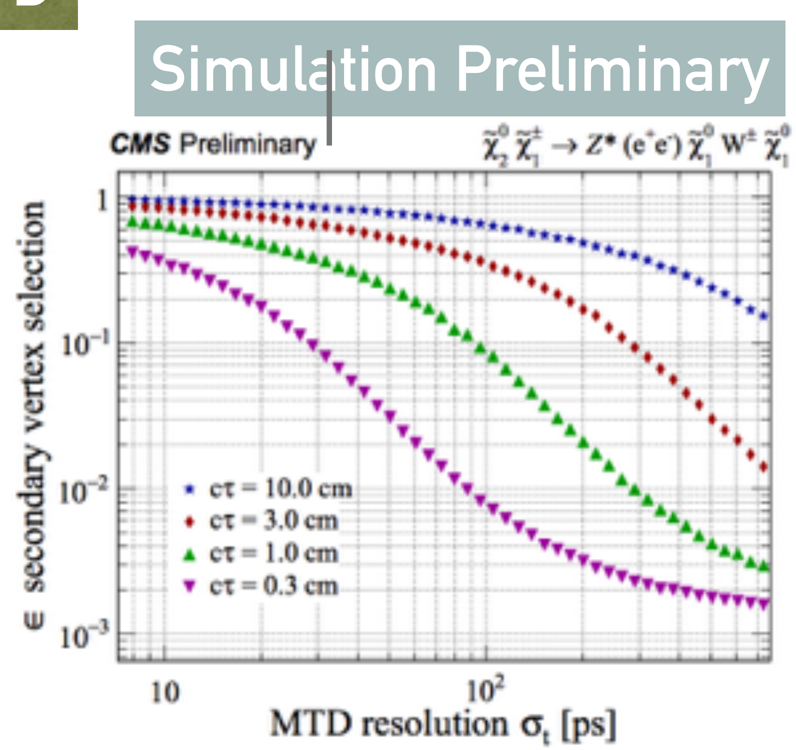
Reconstructed Ee+e-

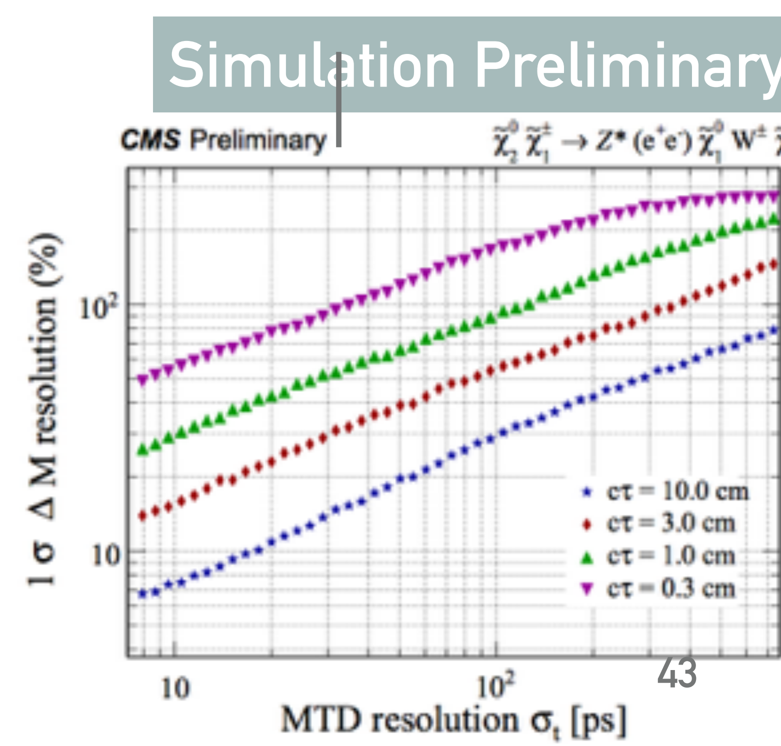
$$E = \Delta M = M(\tilde{\chi}^0_2) - M(\tilde{\chi}^0_1)$$

Assume 30 ps timing resolution of MTD

Select events with a displaced secondary vertex with 3σ significance in both space and time:







SUMMARY

- The HL-LHC program is a high-value flagship program of the HEP scientific community.

- HL-LHC will reach unprecedented running conditions, very challenging for the detectors but offering exciting physics perspectives
- Main challenge is mitigation of large number of pileup interactions
  - Trigger – more bandwidth, new capabilities
  - Increased detector granularity and acceptance in η
  - Timing measurements will add an additional dimension to pileup rejection
- Baselines for the upgraded detectors have been defined

- Compelling program of precision measurements in Higgs sector, testing further the SM and constraining BSM
- Continued exploration of the TeV scale via heavy new particle searches
- Various Physics prospects are under study with simulations that are continuously optimized.

- HE-LHC – needed for discoveries; increased sensitivity to larger masses
  - Work on compiling the physics prospects is beginning (in the context of European Strategy document)
- We look forward to an exciting physics program at LHC for the next 20+ years

REFERENCES

- CMS Collaboration, “Technical Proposal for the Phase-II Upgrade of the Compact Muon Solenoid”, Technical Report CERN-LHCC-2015-010, LHCC-P-008, 2015.
- CMS scope document LHCC-G-165, 2015.
- Documents on ATLAS and CMS Public Results pages
- For details see presentations at the HL/HE-LHC kick-off workshop at CERN: https://indico.cern.ch/event/647676/.
- Higgs Working Group Report of the Snowmass 2013 Community Planning Study, arXiv:1310.8361 [hep-ex]
- Slides of previous talks by colleagues
  - Some of which I have shamelessly borrowed/co from (many thanks).