ECFA Workshop Summary: Physics Projections for the High Luminosity LHC

Isabell-A. Melzer-Pellmann

HL-LHC – Highest Priority in European Strategy!

Introduction to ECFA Workshop by Manfred Krammer, ECFA Chair:
"Update of the **European Strategy for Particle Physics** adopted 30 May 2013 in special session of CERN Council at Brussels **fully supports the 3000 fb^{-1}** option:"

> c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. *Europe's top priority should be the exploitation of the full potential of the LHC, **including the high-luminosity upgrade of the machine and detectors** with a view to **collecting ten times more data than in the initial design**, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

"This is a big step, but it does not mean the approval of the HL- LHC project !!!

- Need to further elaborate physics capabilities
- Need experiments and machine to demonstrate feasibility, and establish timeline and cost estimates"

Kick-off done with the preparation for this ECFA workshop!

HL-LHC – Highest Priority in European Strategy!

Update of the European Strategy for Particle Physics adopted 30 May 2013 in special session of CERN Council at Brussels – statement c:

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Top priorities:

- **Higgs precision and rare decay measurements**

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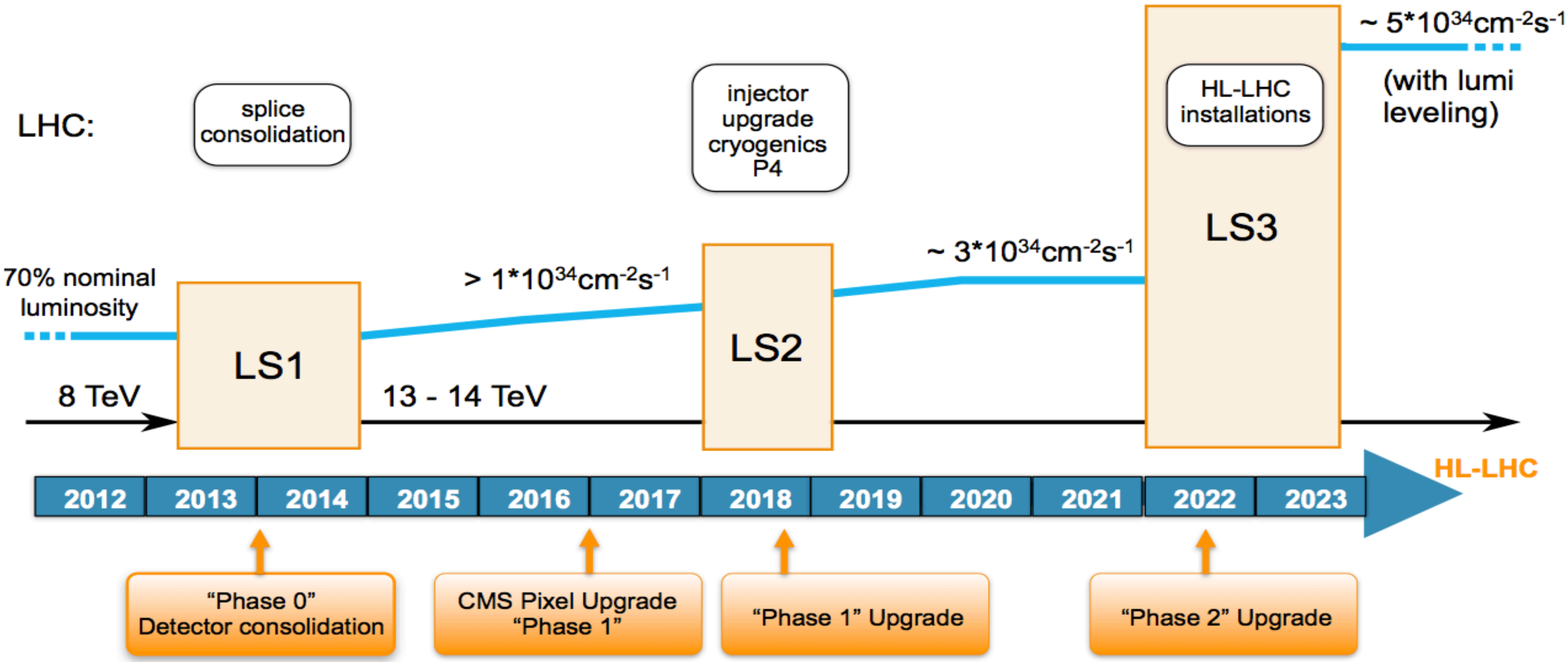
Top priorities:

- Higgs precision and rare decay measurements
- Search for new physics
- Flavor physics
- **Heavy ion physics**

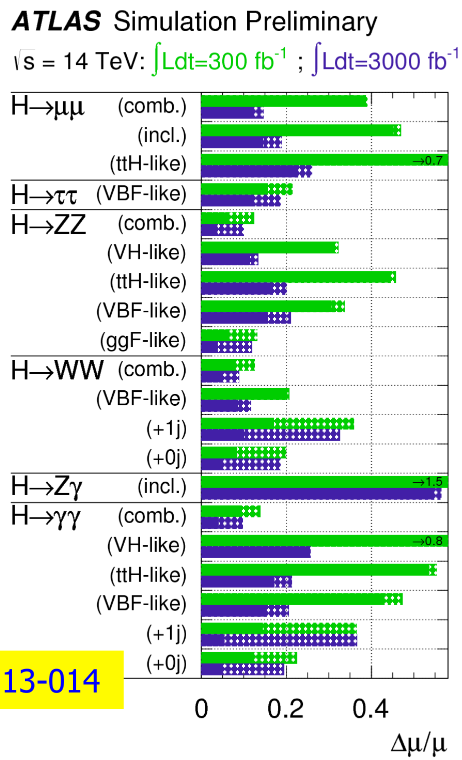
Luminosity: Best Guess for the next 10 years



Top Priority: Higgs measurements

c) The discovery of the Higgs boson is the start of a major programme of work to **measure this particle's properties** with the highest possible precision for testing the validity of the Standard Model…

See also talk of Bill Murray



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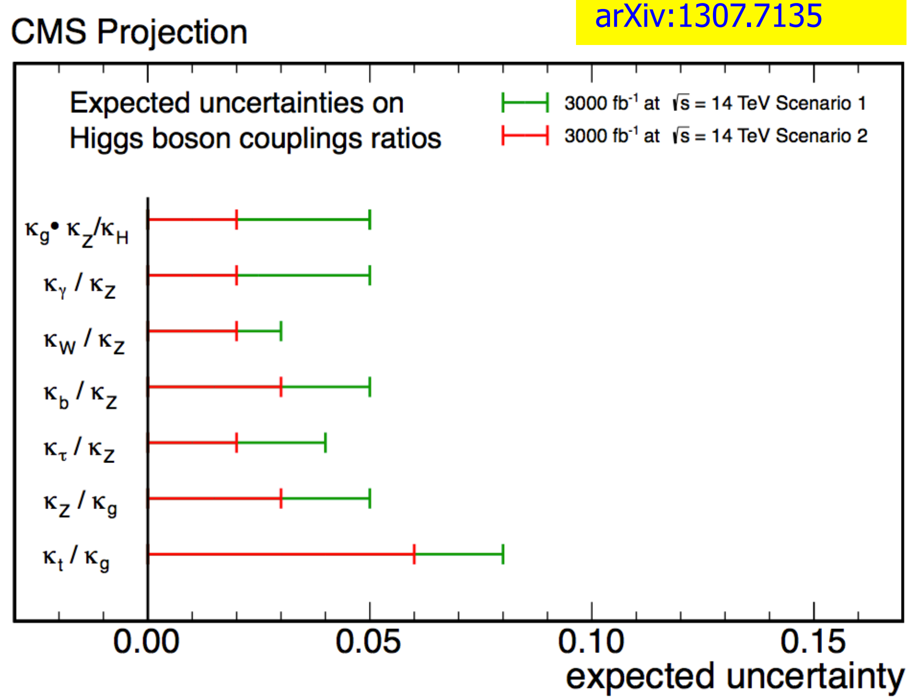
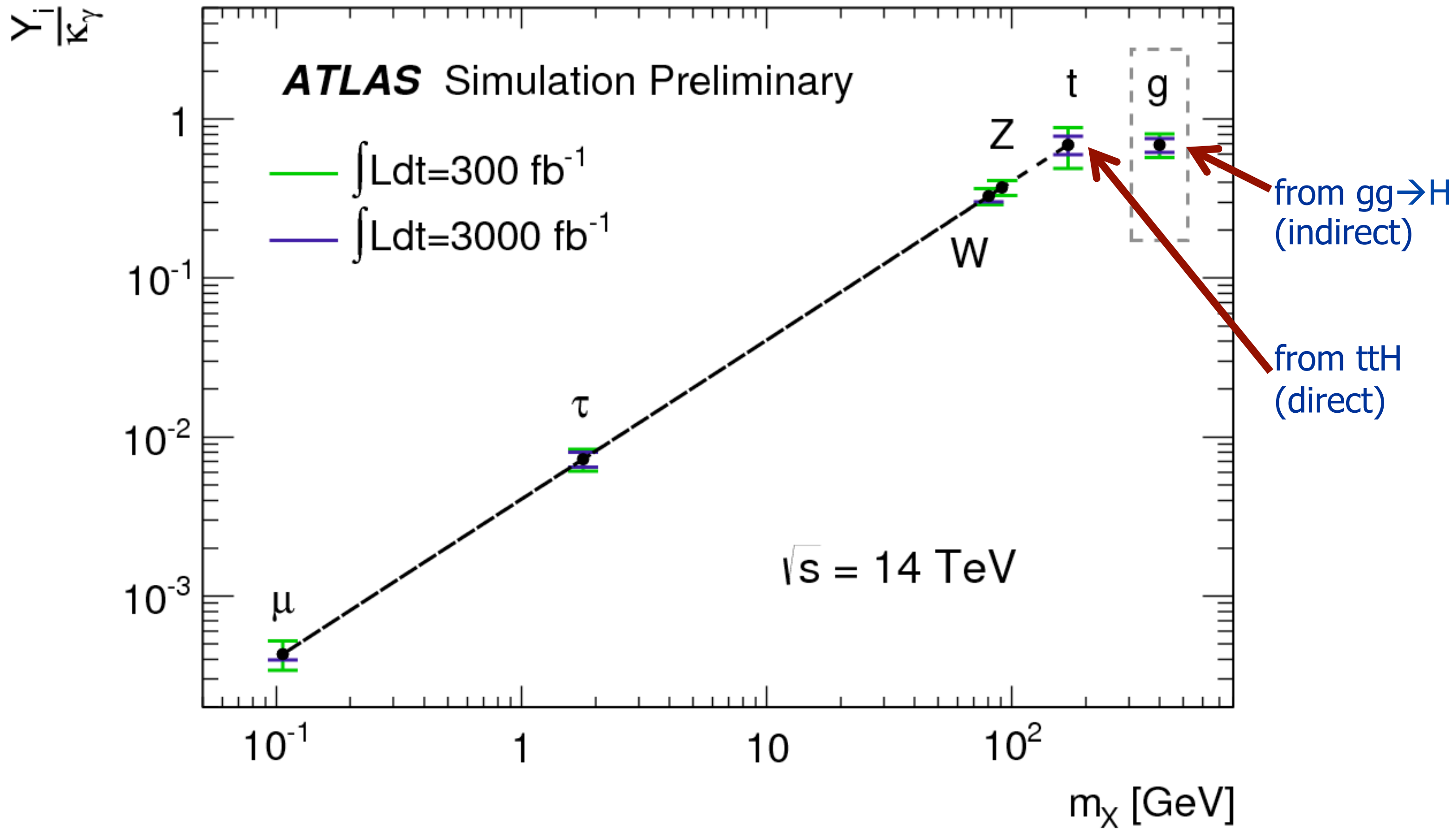
CMS Snowmass WP: arXiv:1307.7135



Uncertainty on **signal strength** and **coupling ratios** significantly improved

Higgs coupling measurements

Summarizing the mass-scaled coupling ratios vs particle mass



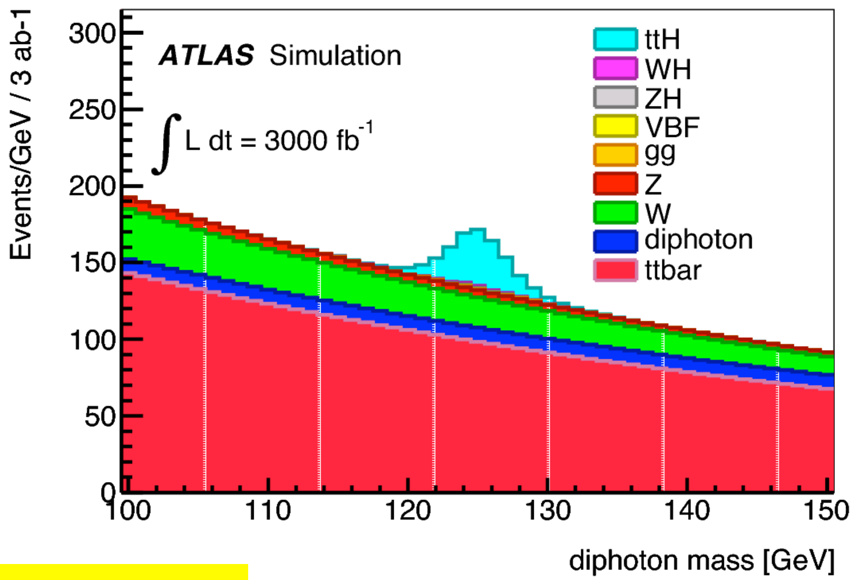
→ perhaps the "next generation blue band plot"?

For further comparison of ATLAS and CMS results see talk of Markus Klute in yesterdays Higgs meeting

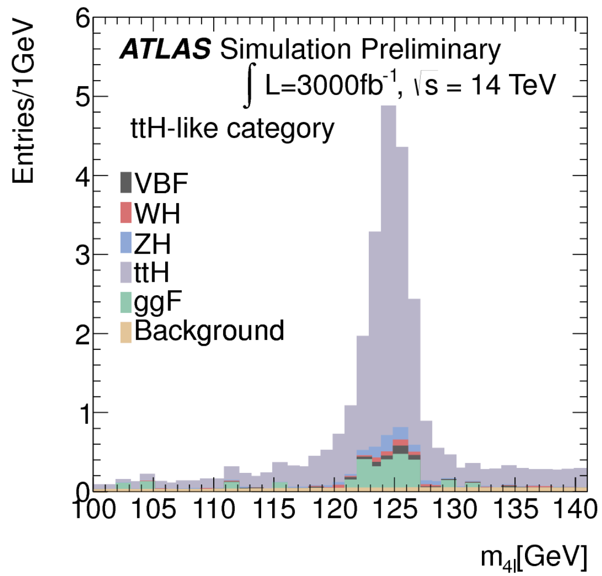
Higgs Rare Decays

3000 fb^{-1} offers new possibilities, e.g.:

- ttH
  - with H → γγ
    - Sensitive to top in both production and decay
    - Yields top Yukawa coupling
  - with H → ZZ
    - Very clean channel



ATLAS-Snowmass WP:
ATL-PHYS-PUB-2013-007



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→ **ttH measurements can be largely improved with HL-LHC**

Higgs Rare Decays

3000 fb^{-1} offers new possibilities, e.g.:

- ttH (with H→γγ and with H→ZZ)
- H→ μμ
  - Allows direct study of coupling to 2nd generation fermions
  - Tests lepton flavor-violation

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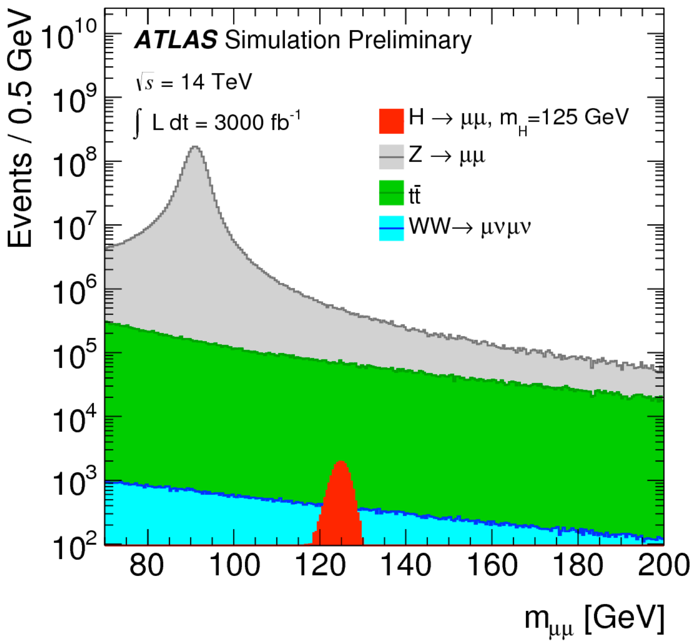
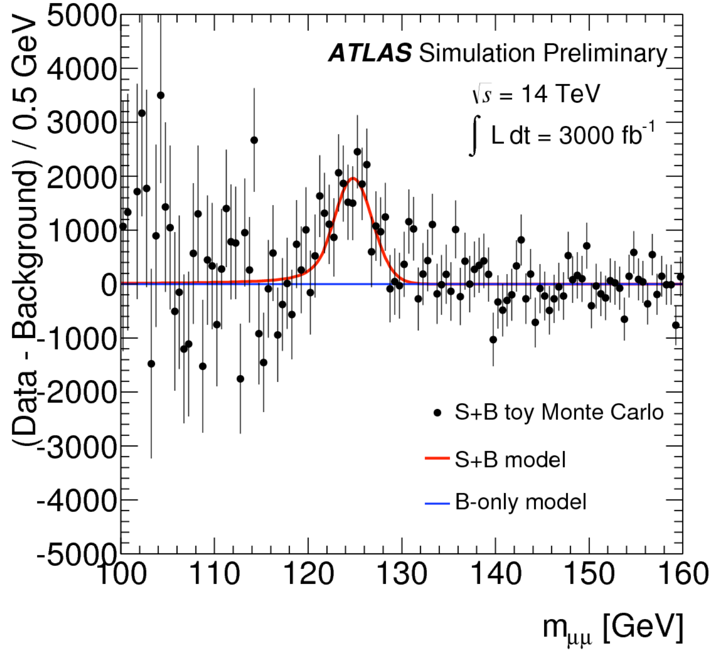


After BG subtraction

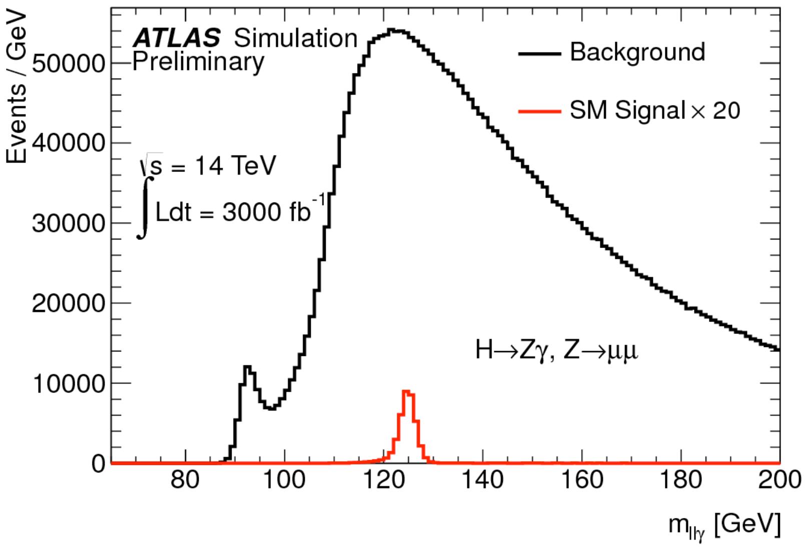


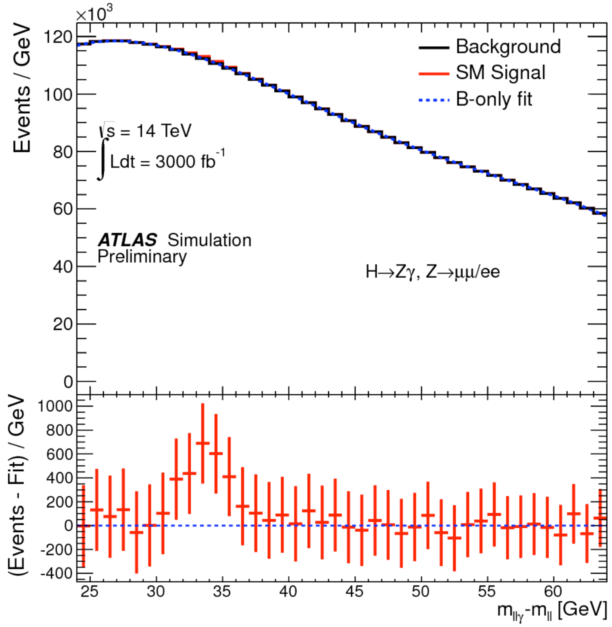
→ Only possible to observe in with HL-LHC

Higgs Rare Decays

3000 fb^{-1} offers new possibilities, e.g.:

- ttH (with H→γγ and with H→ZZ)
- H → μμ
- H → Zγ
  - Interesting because SM Higgs boson can only decay via charged particle loops to this final state





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→ **Only possible to measure with HL-LHC**

Higgs Rare Decays

3000 fb^{-1} offers new possibilities, e.g.:

- ttH (with H → γγ and with H → ZZ)
- H → μμ
- H → Zγ
- Top FCNC:
  - t → Hc: Forbidden at tree level, highly suppressed by GIM mechanism (BR ~ $O(10^{-15})$)

    ATL-PHYS-PUB-2013-012

    → Discovery would hint for BSM (contribution by new bosons, yielding effective couplings orders of magnitude larger than those of the SM)

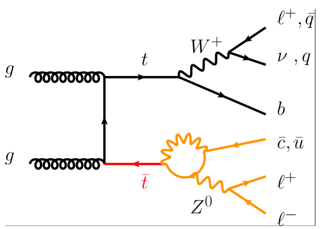
    → Expected limit on BR for T → Hc, with H → γγ at 3000fb^{-1}: 1.7×10^{-4} (95% CL)

    CMS-FTR-13-016

  - t → Zc: BR ~ 10x larger, but still out of reach

    → Discovery would hint for BSM (RPV SUSY, top-color-assisted technicolor models)

    → Expected limit on BR for t → Zc, with Z → ll at 3000fb^{-1}: 1.0×10^{-4} (95% CL)



2 Higgs Doublet Models

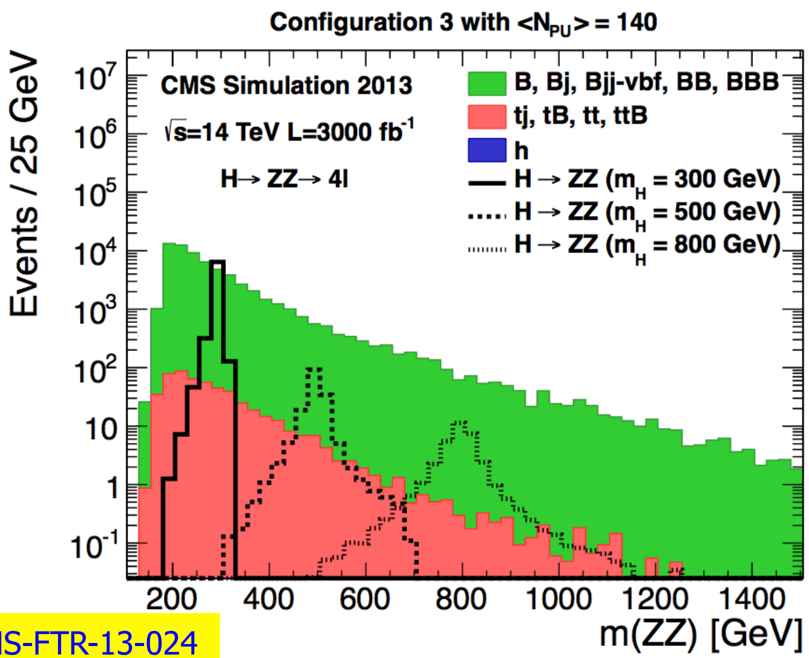
Extended Higgs sector predicted by several BSM theories (SUSY, Composite Higgs, …)

2HDM: Effective theory description for many extensions of the EWSB sector

→ compact relations between couplings of the observed Higgs boson and CS and BR of additional scalars

2HDMs contain five physical Higgs bosons:

- CP-even scalars **h** and **H**; CP-odd pseudo-scalar **A**; a charged pair **H±**



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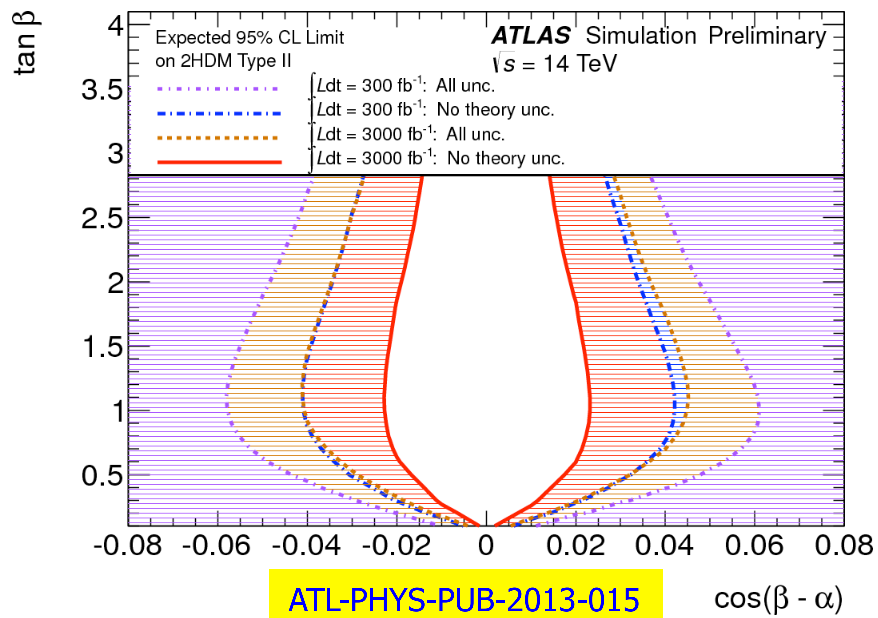

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High Priority: Search for new Physics

c) …and to **search for further new physics at the energy frontier**. …

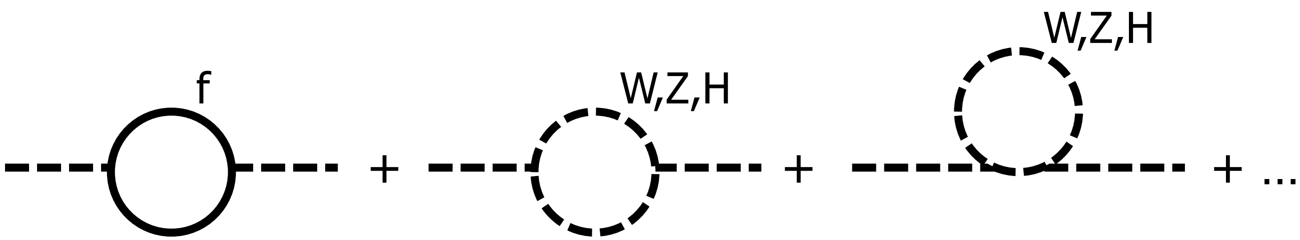
HL-LHC offers a unique variety of places to discover new physics with:

- Direct searches → Find or exclude natural stabilization of Higgs mass against quadratic divergences
- SM precision tests with sensitivity to couplings to new particles, e.g. in vector boson scattering
- Search for rare SM processes, that might be enhanced by new physics

See also IMP's talk

Big question: Naturalness

Higgs is found – but what about its mass corrections?



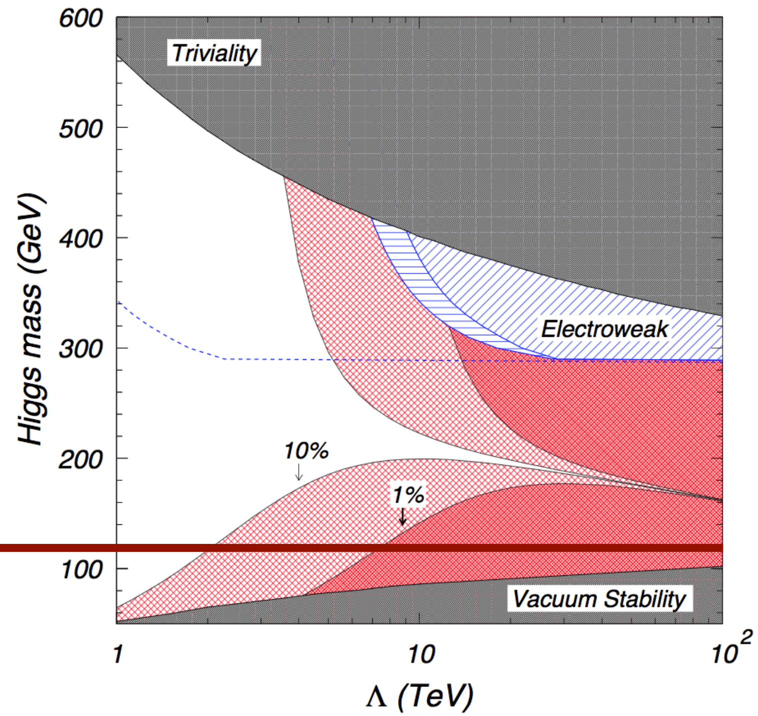
C. Kolda,
H.Murayama,
hep-ph/0003170

Corrections at loop level:

$\delta m_H^2 \sim \Lambda^2(4m_t^2 - 2m_W^2 - 2m_Z^2 - 2m_H^2)$

→ If no new physics at scale Λ, we need a cancellation with large fine tuning!

amount of fine tuning



How much finetuning is still natural?

Natural Supersymmetry

Natural 

R. Barbieri and G. F. Giudice, Nucl. Phys. B 306 (1988) 63; M. Papucci, J.T.Ruderman, A.Weiler, JHEP 09 (2012) 035

EWK SUSY sector

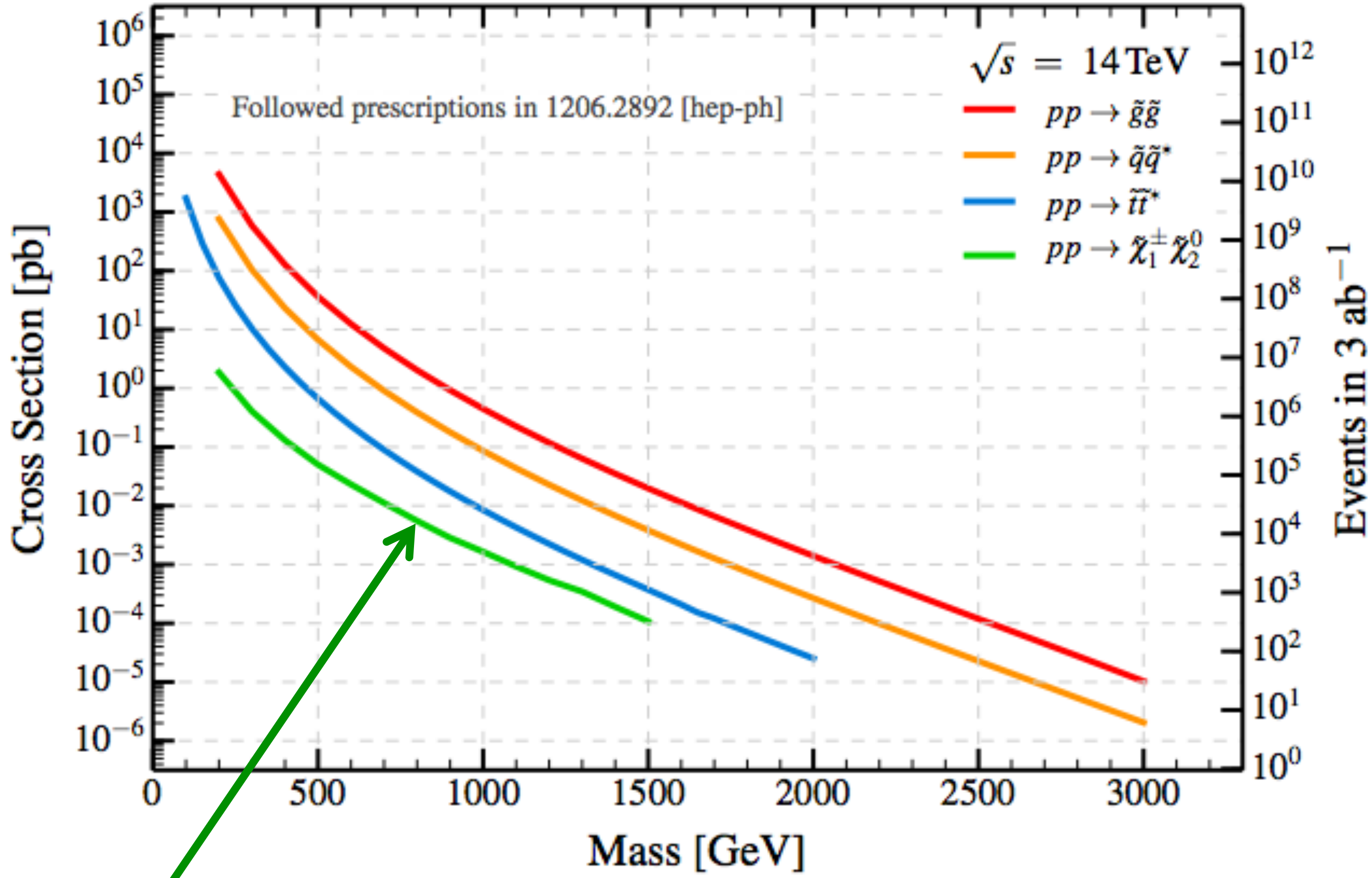
$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

Stop and gluino contribution

- → Especially superpartners with close ties to Higgs must not be too far above the weak scale – especially higgsinos (mass controlled by $\mu \sim m_h$)
- → If superpartners are too heavy, contributions on right must be fine tuned against each other to achieve electroweak symmetry breaking
- → Stop corrects m_{Hu}^2 at one loop: with $\mu \sim$ 150-200 GeV → m_{stop} = 1-1.5 TeV
- → Gluinos corrects M_{Hu}^2 at two loops: should be lighter than several TeV

- 1st and 2nd generation sfermions: O(10)TeV without problem for naturalness, yielding a decoupling solution to the SUSY flavor and CP problem

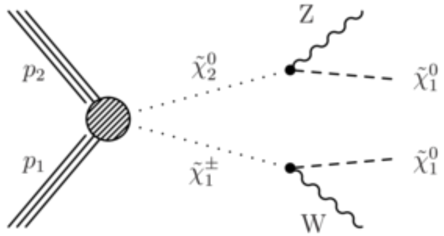
Supersymmetry – Cross sections @ 14 TeV

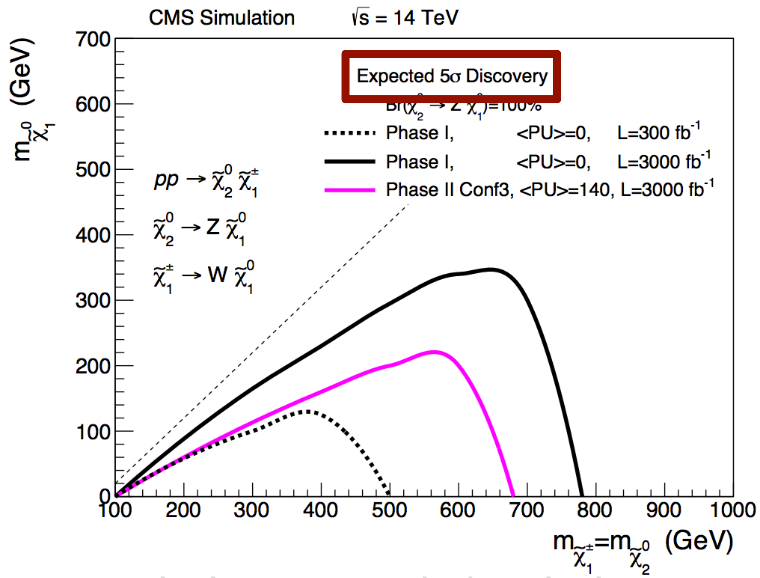


Neutralino/chargino cross sections (here assuming Wino states) are very small

→ need high luminosity!!!

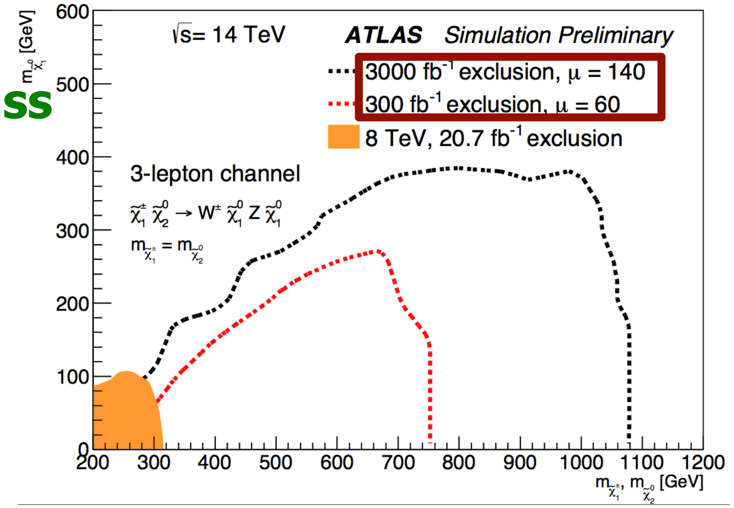
Search for direct $\chi^{\pm}\chi^{0}$ Production – Interpretation





Naturalness predicts light electroweak sparticles

- Investigation of final state with W and Z
- Exact branching ratio is strongly model dependent, here SMS with BR=100%
- Dedicated analysis: 3 leptons + MET

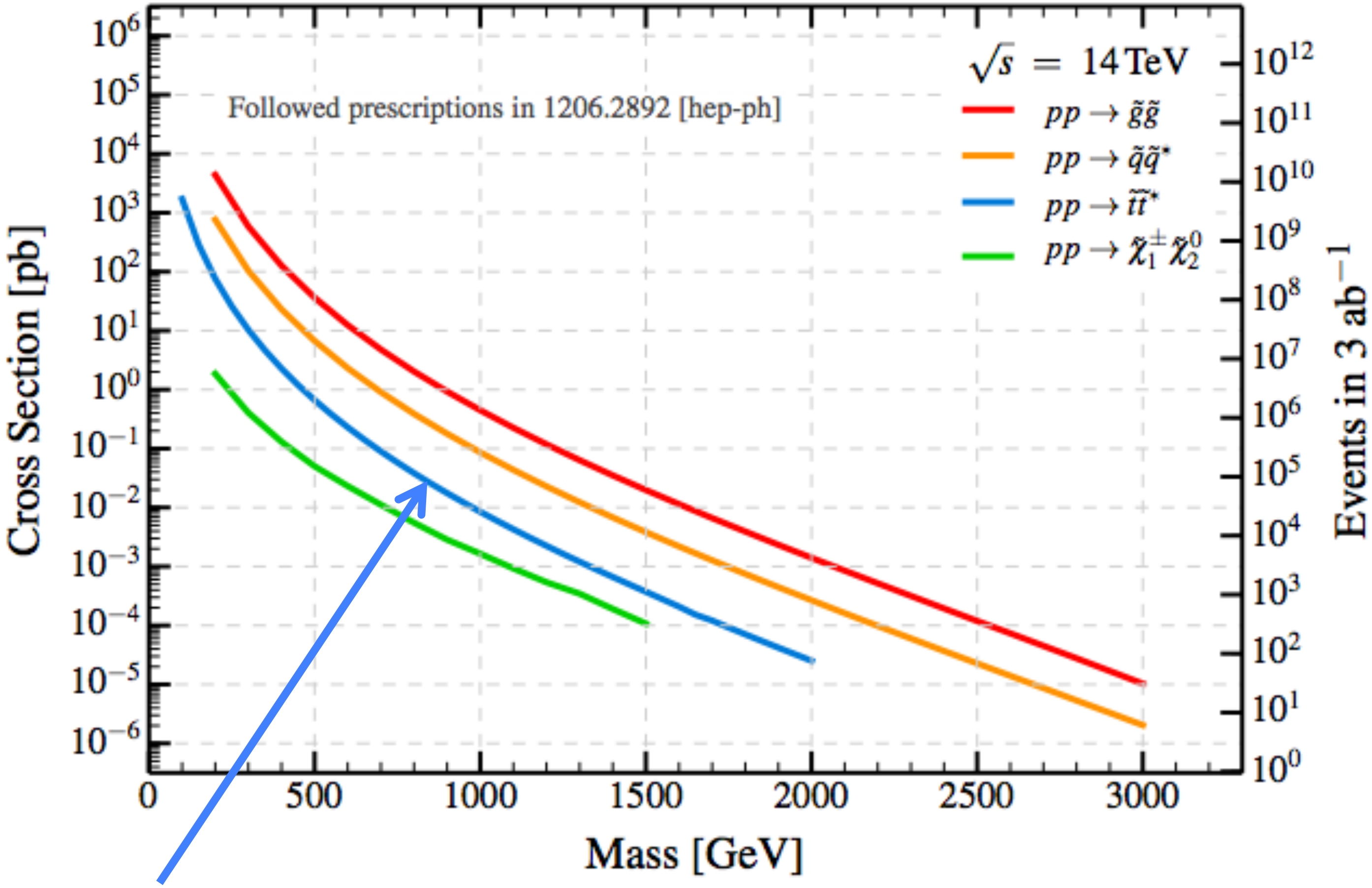


Gain of ~200 GeV in chargino/neutralino mass discovery reach when going from 300 fb^{-1} to 3000 fb^{-1}

→ **most interesting mass range could be covered!**

CMS-FTR-13-014
ATL-PHYS-PUB-2013-011

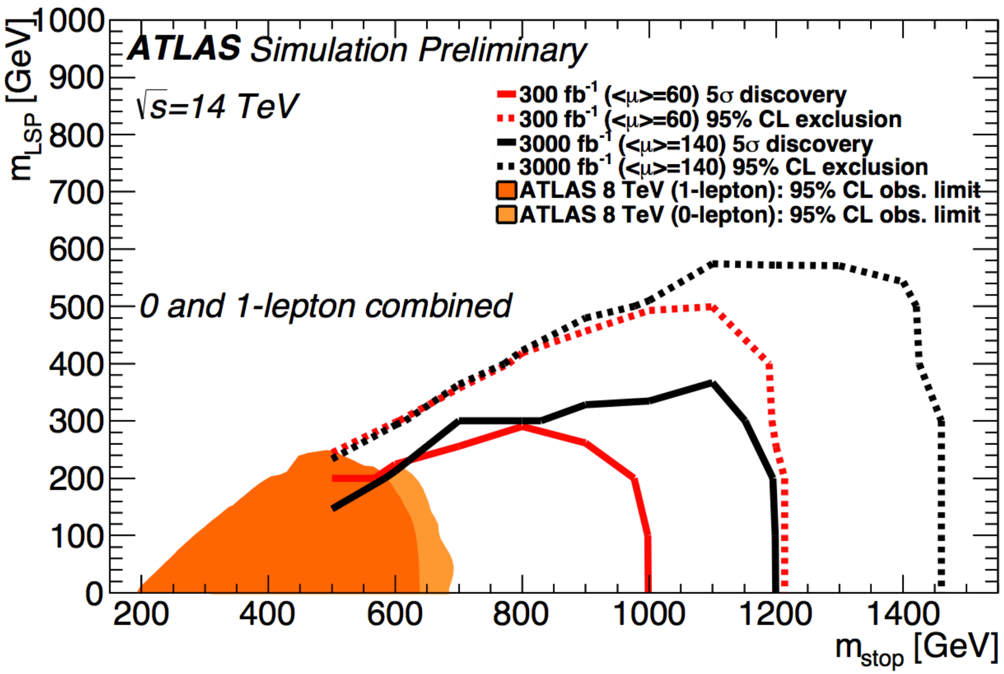
Supersymmetry – Cross sections @ 14 TeV

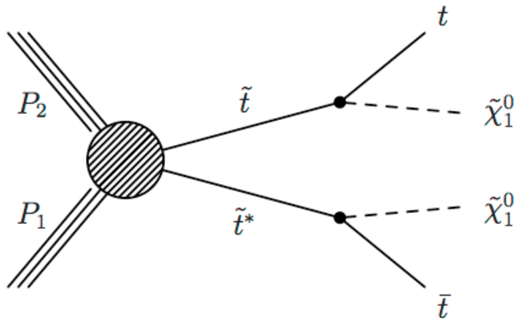


Also stop cross sections quite small → need high luminosity!!!

Search for Direct Stop Production – Motivation

Naturalness predicts a light third generation
→ investigate direct stop production

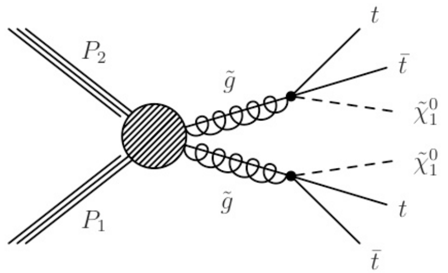




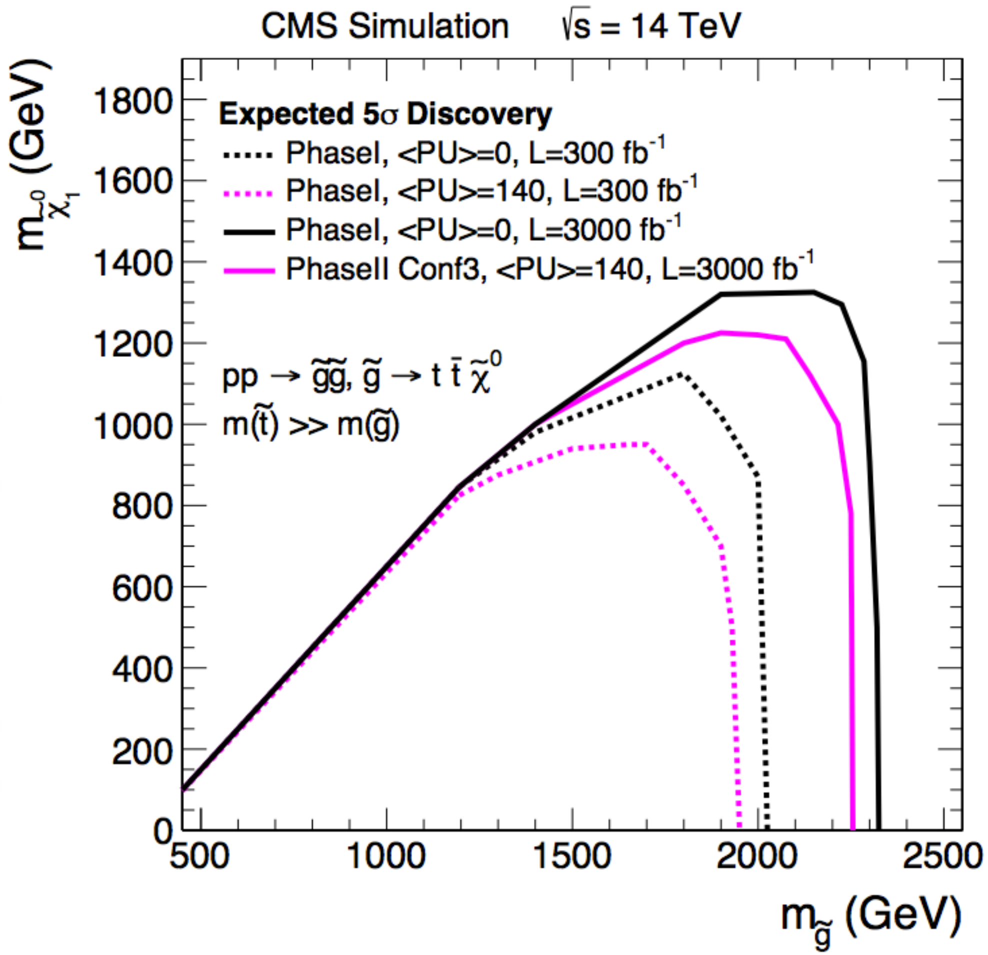
ATL-PHYS-PUB-2013-011

Limit on stop mass can be extended by 200 GeV
when going from 300 fb^{-1} to 3000 fb^{-1}
→ **most interesting mass range will be covered!**

Gluino (l+b) Search – Result



Sensitive to
gluino masses up to 2.2 TeV and
LSP masses up to 1.2 GeV



CMS-FTR-13-014

Gain of ~300 GeV in gluino mass
discovery reach when
going from 300 fb^{-1} to 3000 fb^{-1}

→ **about half of the interesting mass range will be covered!**

Vector Boson Scattering – Motivation

Vector boson scattering can happen through:

- Double triple gauge coupling (TGC)
- Quartic gauge coupling (QGC)
- s-channel & t-channel Higgs scattering

Cross section rises quickly with energy

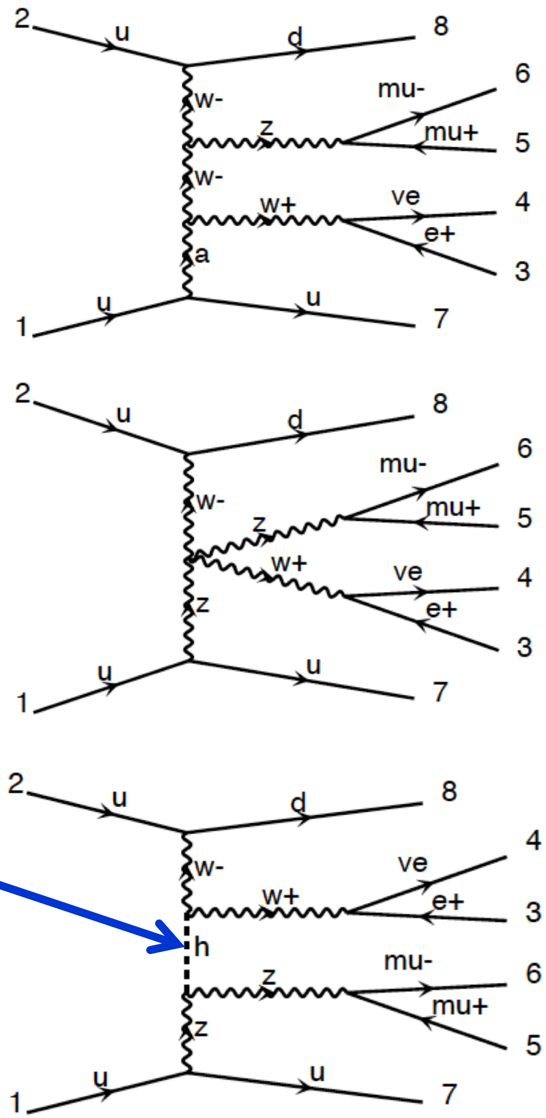
→ Individually these processes would violate unitarity

→ BUT: strong interference between these processes leads to finite cross section at all energies

Observation of the SM scattering process would be:

- First observation of processes involving the quartic coupling of two massive vector bosons
- First observation of scattering via a **Higgs**

Cross section sensitive to new physics (additional Higgs bosons, other scalar particles, additional gauge bosons)

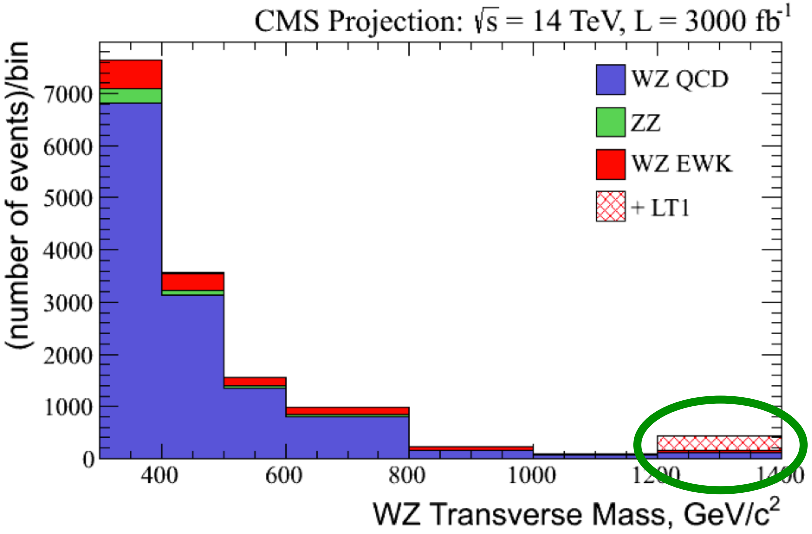


Vector Boson Scattering – Result for WZ Channel

WZ channel is sensitive to dimension-8 operator:

$$\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} \mathrm{Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times \mathrm{Tr}[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$$

Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
$\frac{f_{T1}}{\Lambda^4}$ at 300 fb^{-1}	0.8 TeV^{-4}	1.0 TeV^{-4}
$\frac{f_{T1}}{\Lambda^4}$ at 3000 fb^{-1}	0.45 TeV^{-4}	0.55 TeV^{-4}



SM discovery expected with 185 fb^{-1}
BSM contribution at TeV Scale possible at 300 fb^{-1}
3000 fb^{-1} probes much larger range of quartic coupling!

CMS-FTR-13-006

Vector Boson Scattering – Triboson Scattering

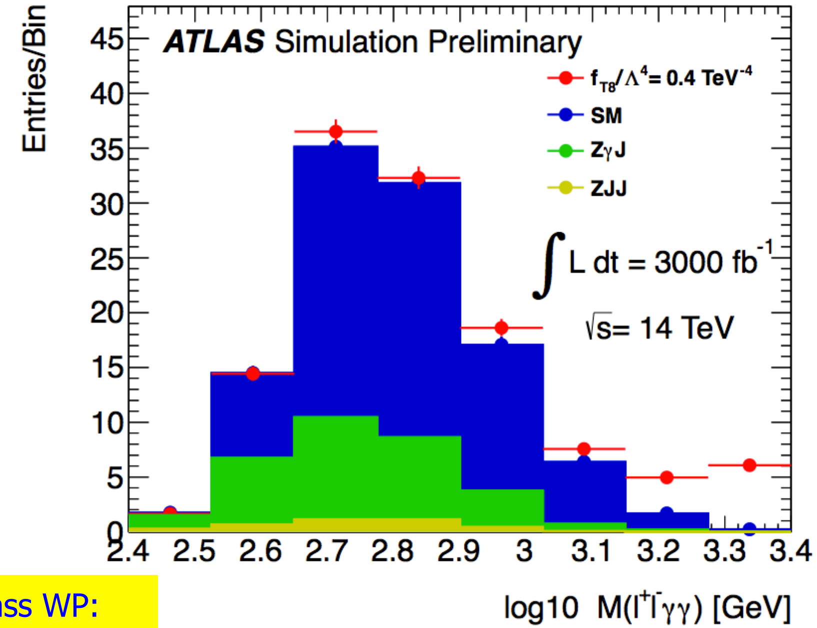
$Z\gamma\gamma$ mass spectrum at high mass:

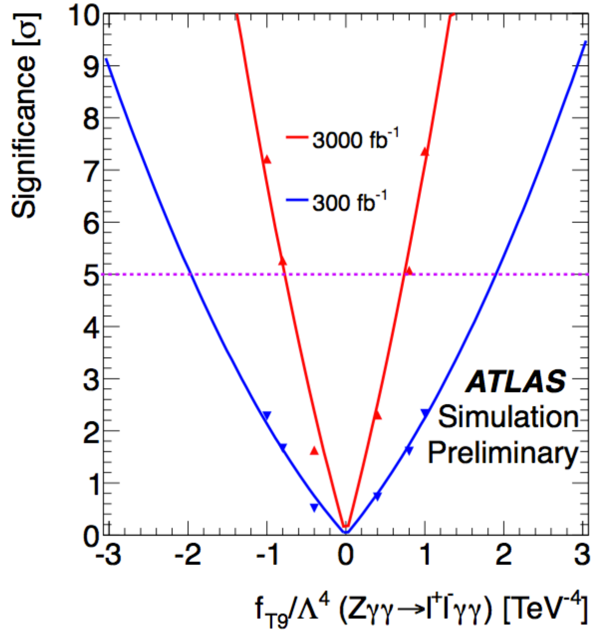
→ Lepton-photon channel allows full reconstruction of the final state and the $Z\gamma\gamma$ invariant mass

→ Sensitive to BSM operators:

$$\mathcal{L}_{T,8} = \frac{f_{T8}}{\Lambda^4} B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}$$

$$\mathcal{L}_{T,9} = \frac{f_{T9}}{\Lambda^4} B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}$$





ATLAS-Snowmass WP:
ATL-PHYS-PUB-2013-007

→Need high HL-LHC to test high invariant mass region

Conclusion

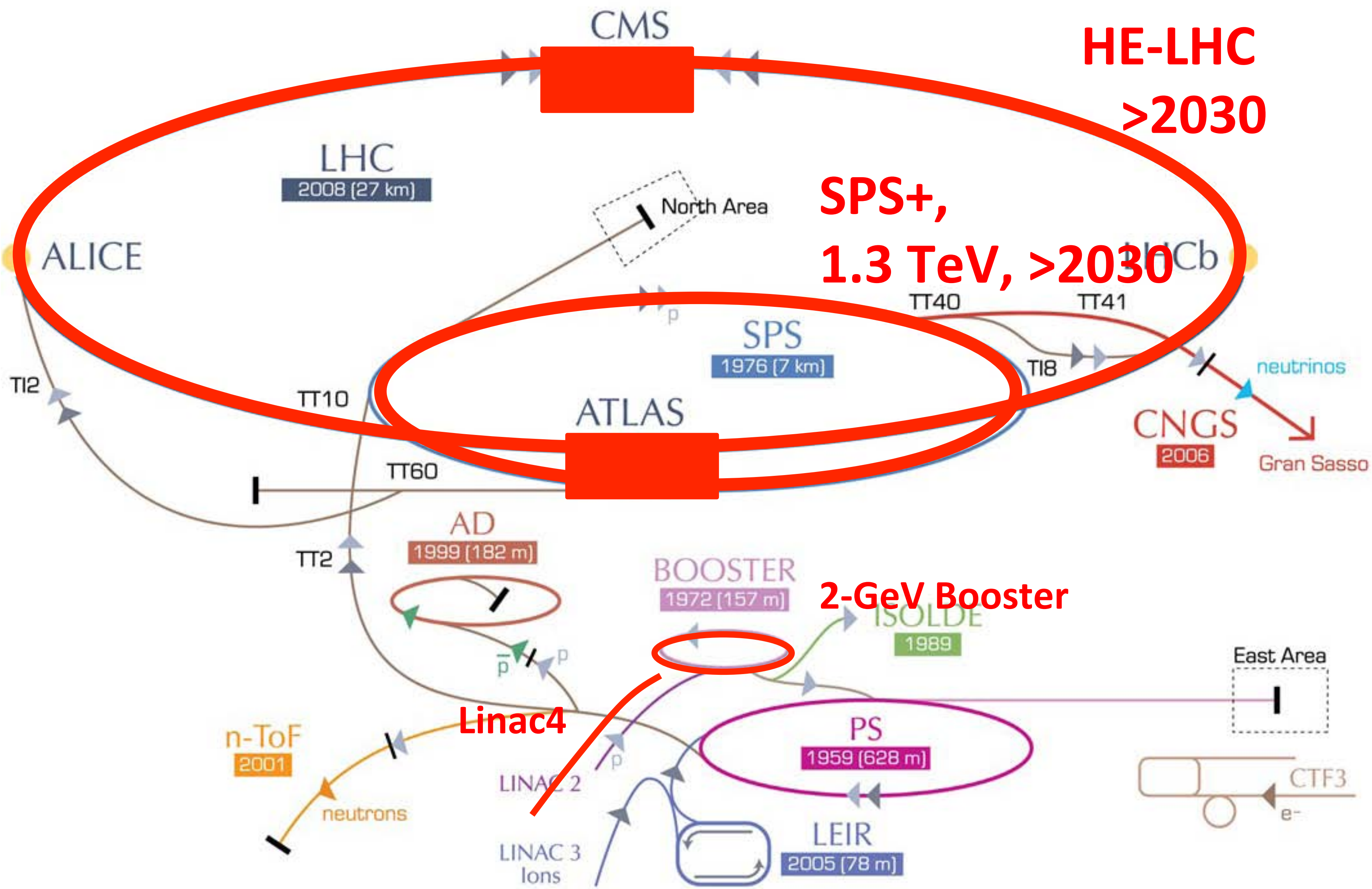
Large number of benefits from the HL-LHC

- Reduced statistical and systematic uncertainties in precision measurements and searches through further improvement of detector modeling and understanding of background processes
- Increased sensitivity to low cross section processes (e.g. electroweak processes, dark matter production) and rare decays
- Probe a significant part of the interesting range of phase space for new physics
- Possibility for 5σ discovery for cases where we might see some kind of excess with 300 fb^{-1}

The October ECFA workshop was just the beginning…

More workshop to keep the momentum will follow next year!

Outlook: High Energy - LHC



Very High Energy LHC

- **First studies on a new 80 – 100 km tunnel in the Geneva area**
  - **42 TeV with 8.3 T using present LHC dipoles**
  - **80 TeV with 16 T based on Nb_3Sn dipoles**
  - **100 TeV with 20 T based on HTS dipoles**

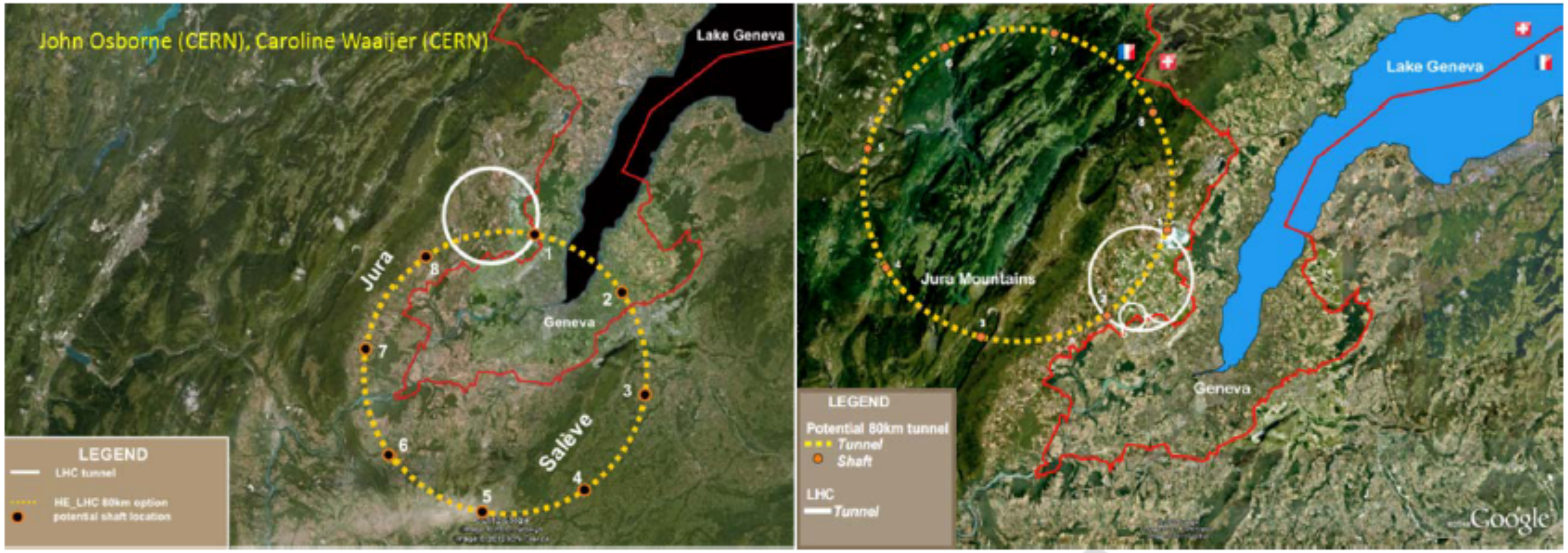
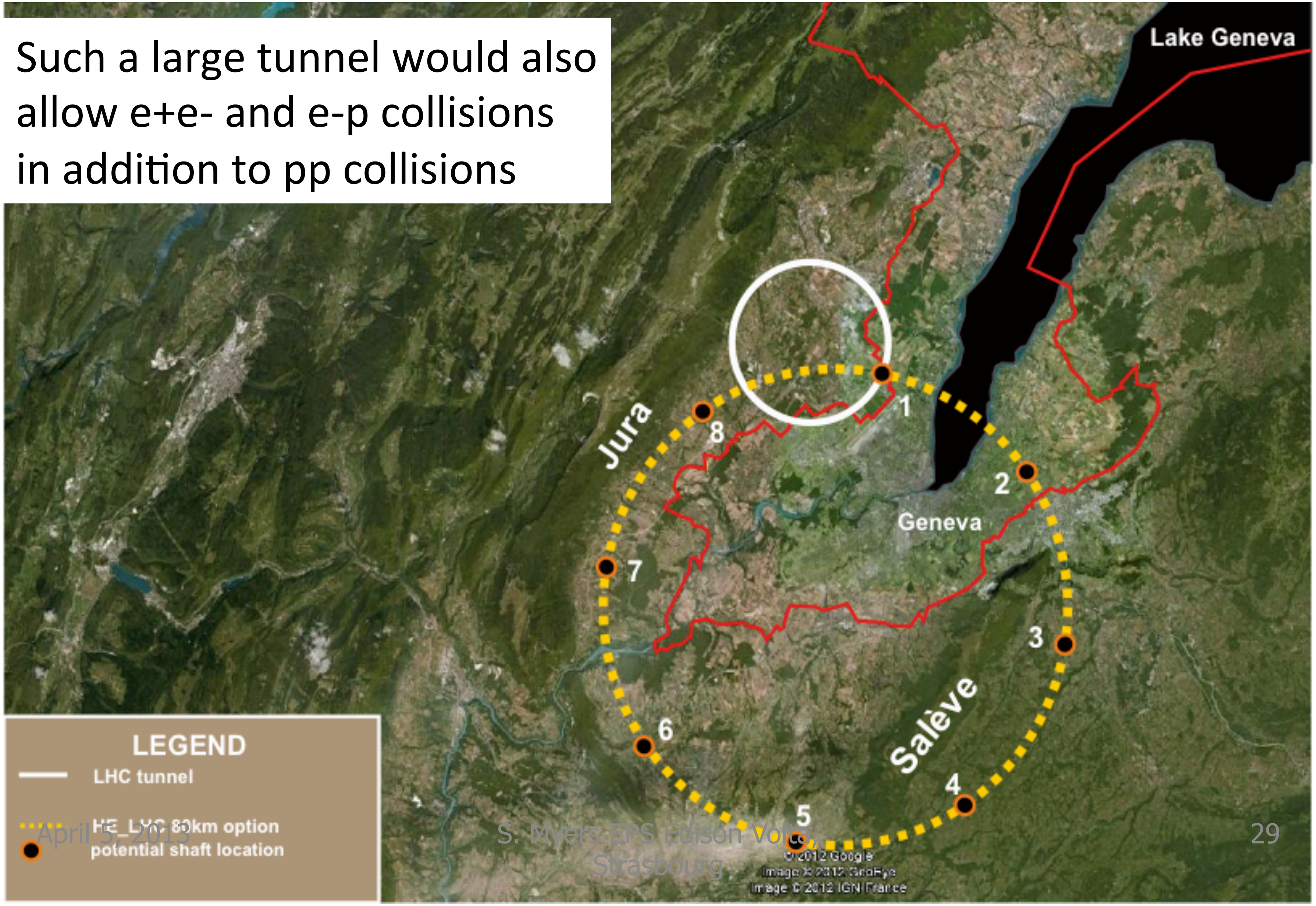


Figure 9. Two possible location, upon geological study, of the 80 km ring for a Super HE-LHC (option at left is strongly preferred)

Such a large tunnel would also allow e+e- and e-p collisions in addition to pp collisions



Thank you for listening…

… backup slides follow!

Many CMS Results public for ECFA

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP

TWiki > CMSPublic Web > PhysicsResults > PhysicsResultsFP (11-Oct-2013, ChristopherHill)

Edit Attach PDF

CMS Public Projected Physics Results

CMS Upgrade and Future Physics Documents

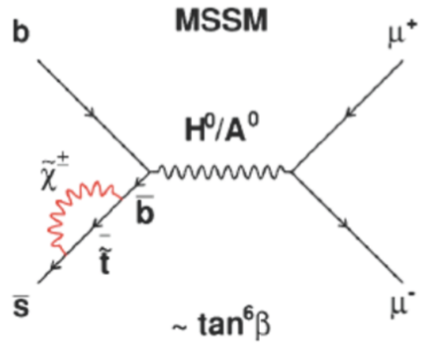
Study	CDS/ArXiv Entry	Projected Luminosity	TWikis with Additional Plots and Information
Projection of Higgs to ZZ to 4l Measurements for ECFA	CMS-PAS-FTR-13-003	Up to 3000/fb	
Projection of V V Scattering Measurements for ECFA	CMS-PAS-FTR-13-006	Up to 3000/fb	
Projections of SUSY Searches for ECFA	CMS-PAS-FTR-13-014	Up to 3000/fb	Plots
Projection of Top FCNC Searches for ECFA	CMS-PAS-FTR-13-016	Up to 3000/fb	Plots
Projection of Top Quark Mass Uncertainty for ECFA	CMS-PAS-FTR-13-017	Up to 3000/fb	Plots
Projection of B to mu mu measurements for ECFA	CMS-PAS-FTR-13-022	Up to 3000/fb	Plots
Projection of 2HDM Higgs Studies for ECFA	CMS-PAS-FTR-13-024	Up to 3000/fb	
Projection of Vector-like Top Quark (T') Searches for ECFA	CMS-PAS-FTR-13-026	Up to 3000/fb	
CMS Submission to Snowmass	CMS-NOTE-2013-002	Up to 3000/fb	SUSY
CMS Submission to European Strategy Group	CMS-NOTE-2012-006	Up to 3000/fb	Higgs
L1 Trigger Phase I Upgrade TDR	CERN-LHCC-2013-011	Up to 300/fb	Summary Plots
HCAL Phase I Upgrade TDR	CERN-LHCC-2012-015	Up to 300/fb	
Pixel Phase I Upgrade TDR	CERN-LHCC-2012-016	Up to 300/fb	
Phase I Upgrade Technical Proposal	CERN-LHCC-2011-006	Up to 300/fb	

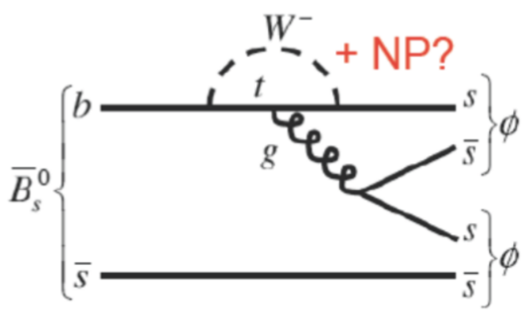
High Priority: Flavor Physics

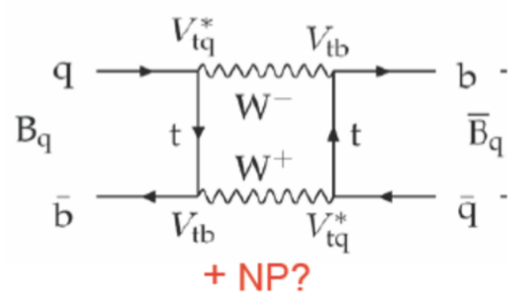
> c) … *This upgrade programme will also provide further exciting opportunities for the* ***study of flavour physics*** *…*

Discovery of new physics through indirect effects

- Precision measurements of CP asymmetries
- Measurement of rare decays







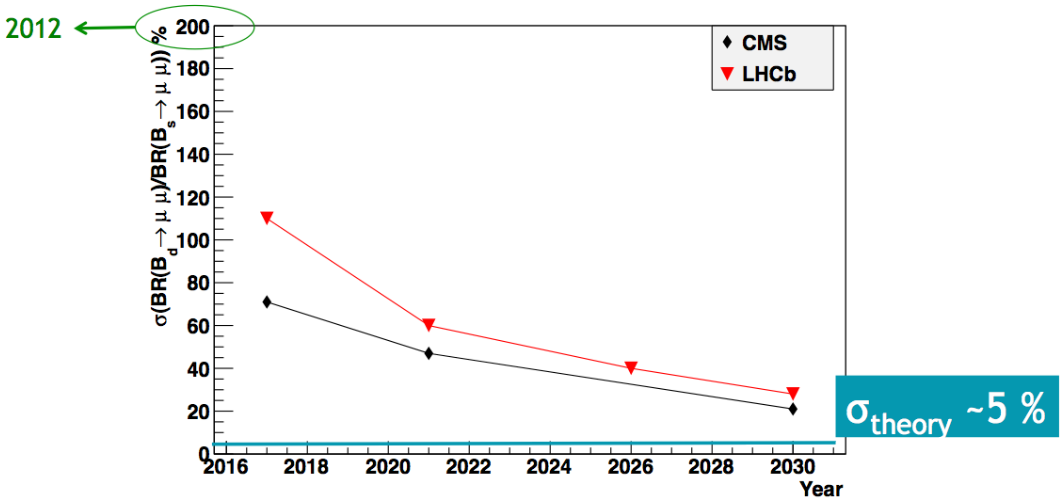
$B_s \rightarrow \mu\mu$ and $B_d \rightarrow \mu\mu$

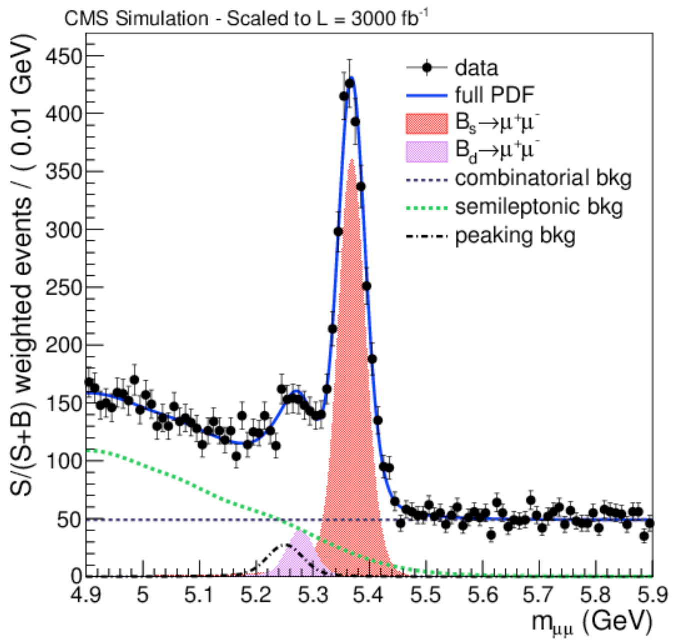
Measurement of B_s and B_d

- New physics effects can be different here
- B mass resolution is crucial for measurement of B_d:
  - CMS and LHCb can do it
  - ATLAS mass resolution has to be improved
- $B_d \rightarrow \mu^+\mu^-$ suffers from $B_d \rightarrow K\pi$ background

CMS-FTR-13-022

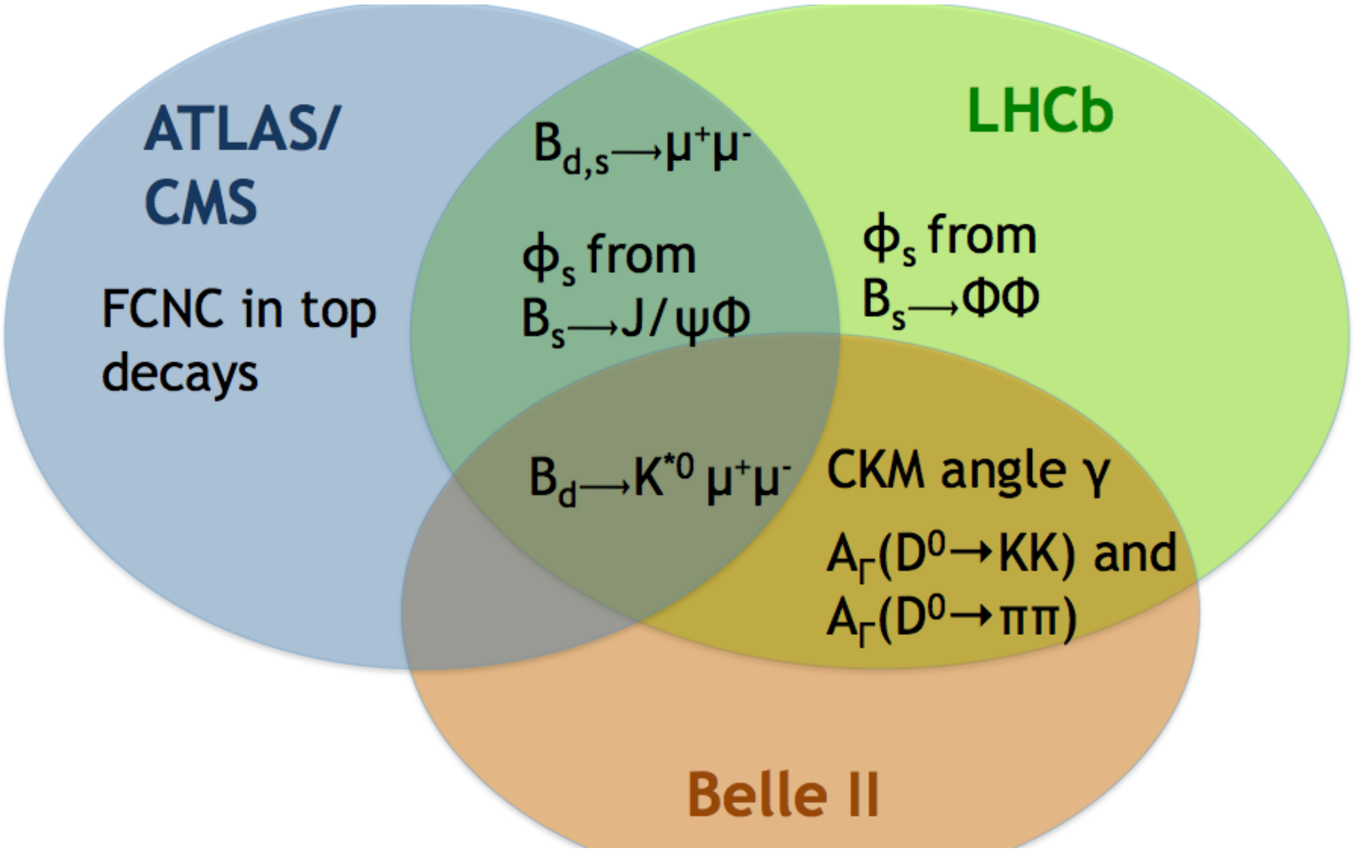
Expected precision on $BR(B_d \rightarrow \mu+\mu-)/BR(B_s \rightarrow \mu+\mu-)$





High Priority: Flavor Physics

Large variety of physics topics not covered here…



See also ECFA talk by Marie-Helene Schune

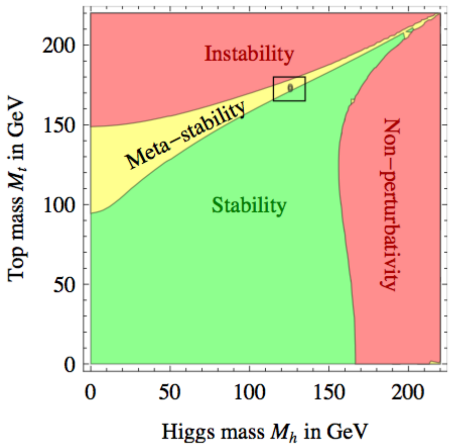
Top mass measurement

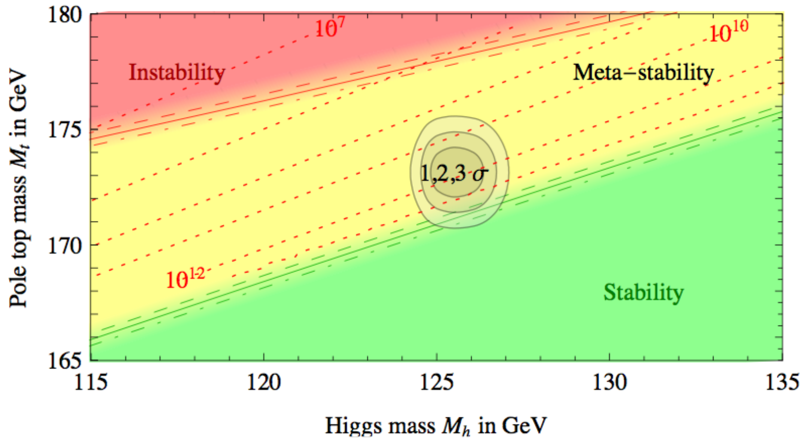
Current top mass precision:

- Tevatron combined: 0.87 GeV (0.50%)
- LHC combined: 0.95 GeV (0.55%)

Extrapolations of top mass precision:

- Sub-GeV range:
  - Theoretical interpretation important!
  - Alternative measurement methods based on observables that can be calculated in theoretically well-defined mass schemes might lead to better precision, but limited by Λ_{QCD} (approximately 200 MeV)



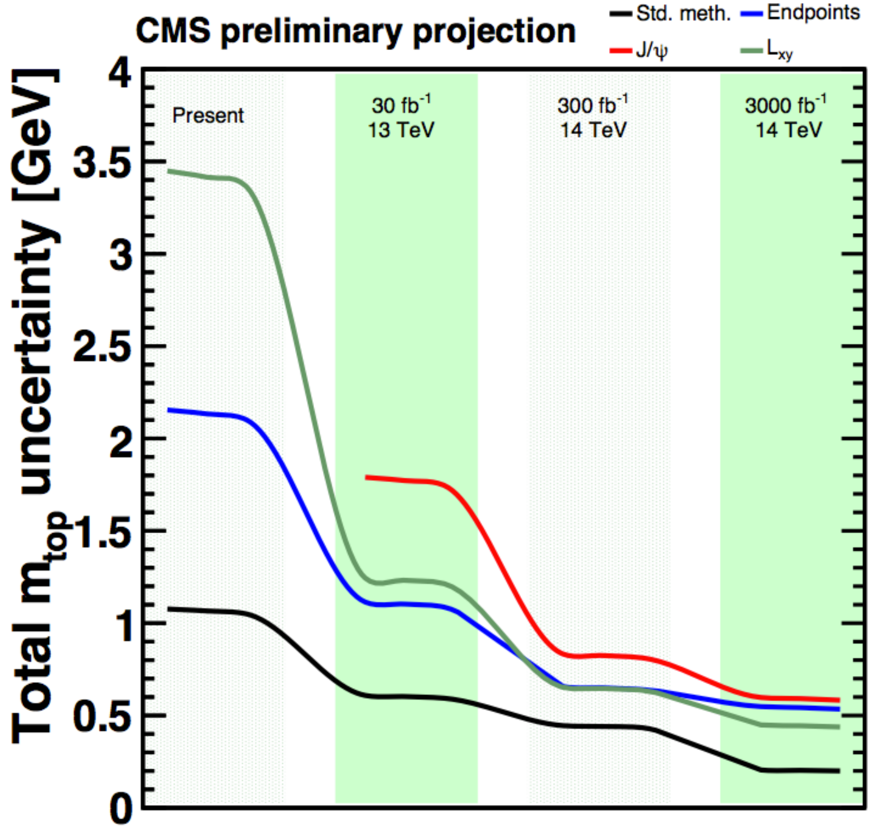


Degrassi et al. arXiv:1205.6497

Top Mass Measurement

Extrapolation requires developments on theory side:

- More precise quantitative estimate of the equality (or difference) between the theoretically well-defined **'pole mass'** and the effective **'MC top-quark mass'** used in MC
- Upper limit/measurement of the **effect of color reconnection in tt** events
- Use of proper **NLO ME+PS MC** generators that include tt production and decay to NLO, allowing a well-defined MC mass scheme and reduced scale uncertainties
- Improved MC validation with LHC data and UE tunes appropriate for tt events



CMS-FTR-13-017

High Priority: Heavy Ion Physics

c) *This upgrade programme will also provide further exciting opportunities for … **the quark-gluon plasma**.*

Experiments plan major upgrades during LS2 (2018/19)

HL-HI-LHC defined to be in Run 3 (after LS2) and 4

- Experiments request >10 nb^{-1} Pb-Pb (ALICE: 10 nb^{-1} at 0.5 T + 3 nb^{-1} at 0.2 T → electron acceptance down to p_T = 50 MeV with new inner tracker)
- p-Pb with high lumi, pp reference @5.5 TeV, possibly light ions (e.g. Ar-Ar)

Rich physics programme:

- Heavy flavor:
  - Precise characterization of the quark mass dependence of in-medium parton energy loss
  - Study of the transport and possible thermalization of heavy quarks in the medium
  - Study of heavy quark hadronization mechanisms in a partonic environment
- Quarkonia (dissociation and possible regeneration as probe of deconfinement and medium temperature)
- Jets
- Low-mass dileptons and thermal photons

See also talk of Andrea Dainese

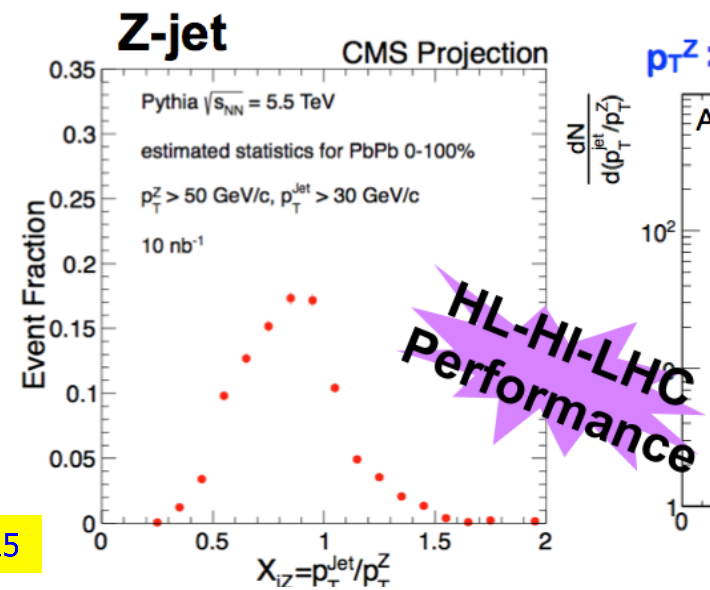
Heavy Ions: Jet Measurement

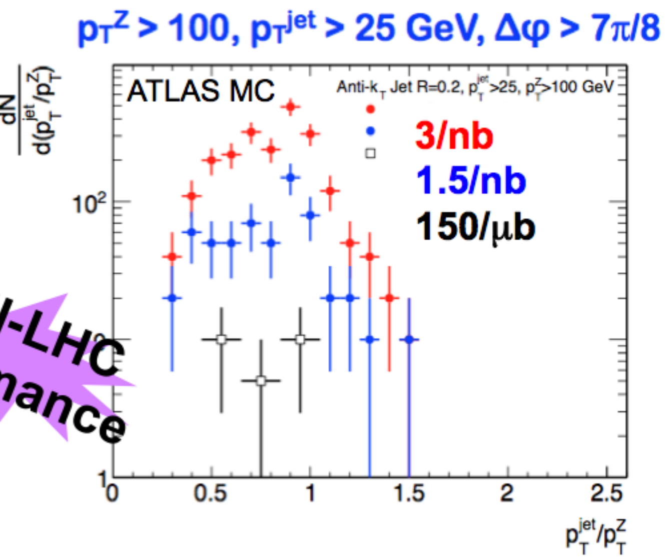
Detailed characterization of the in-medium parton energy loss mechanism

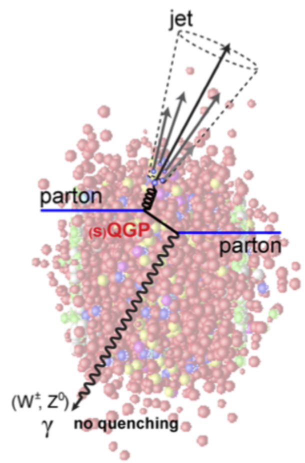
- Testing ground for the multi-particle aspects of QCD
- Probe of the Quark Gluon Plasma density

Relevant observables

- Jet structure and di-jet imbalance at TeV energies
- b-tagged jets
- Jet correlations with photons and Z bosons (unaffected by the presence of a QCD medium).







CMS-FTR-13-025

Heavy Ions: Low-mass dileptons and thermal photons

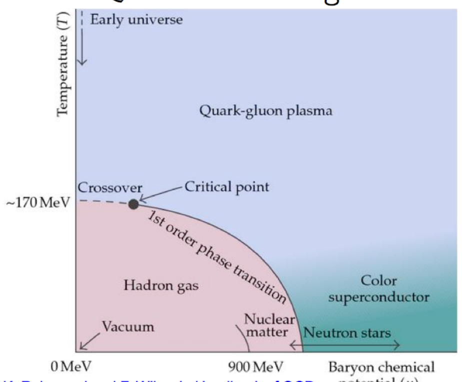
Sensitive to:

- Initial temperature and the equation of state of the medium
- Chiral nature of the phase transition

Measurement to be performed by ALICE due to need of:

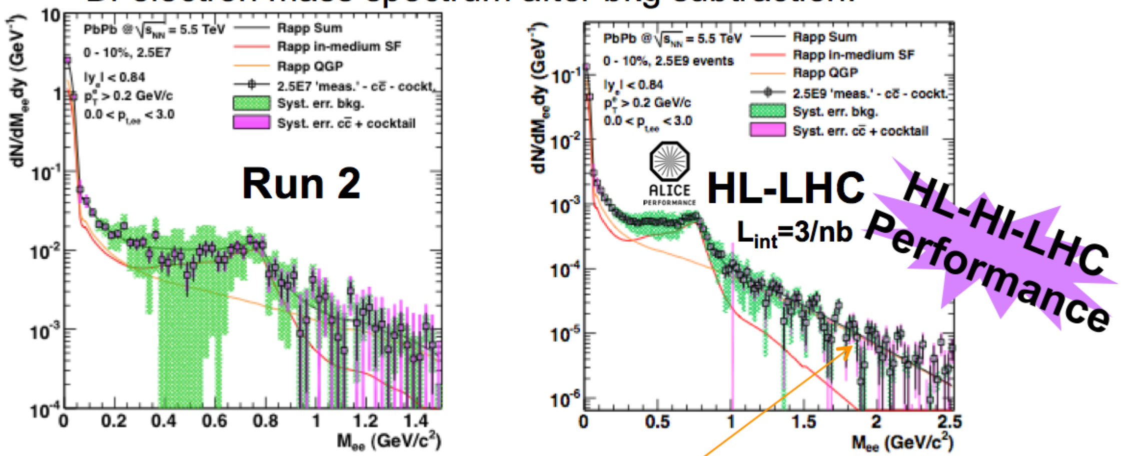
- Efficient electron and muon reconstruction capabilities down to almost zero p_T
- Read-out capabilities for recording very high statistics minimum-bias sample

QCD Phase Diagram



K. Rajagopal and F. Wilczek, Handbook of QCD

Di-electron mass spectrum after bkg subtraction:



Precision of ~10% on the inverse slope → T

ALICE CERN-LHCC-2012-012

Tools

ATLAS

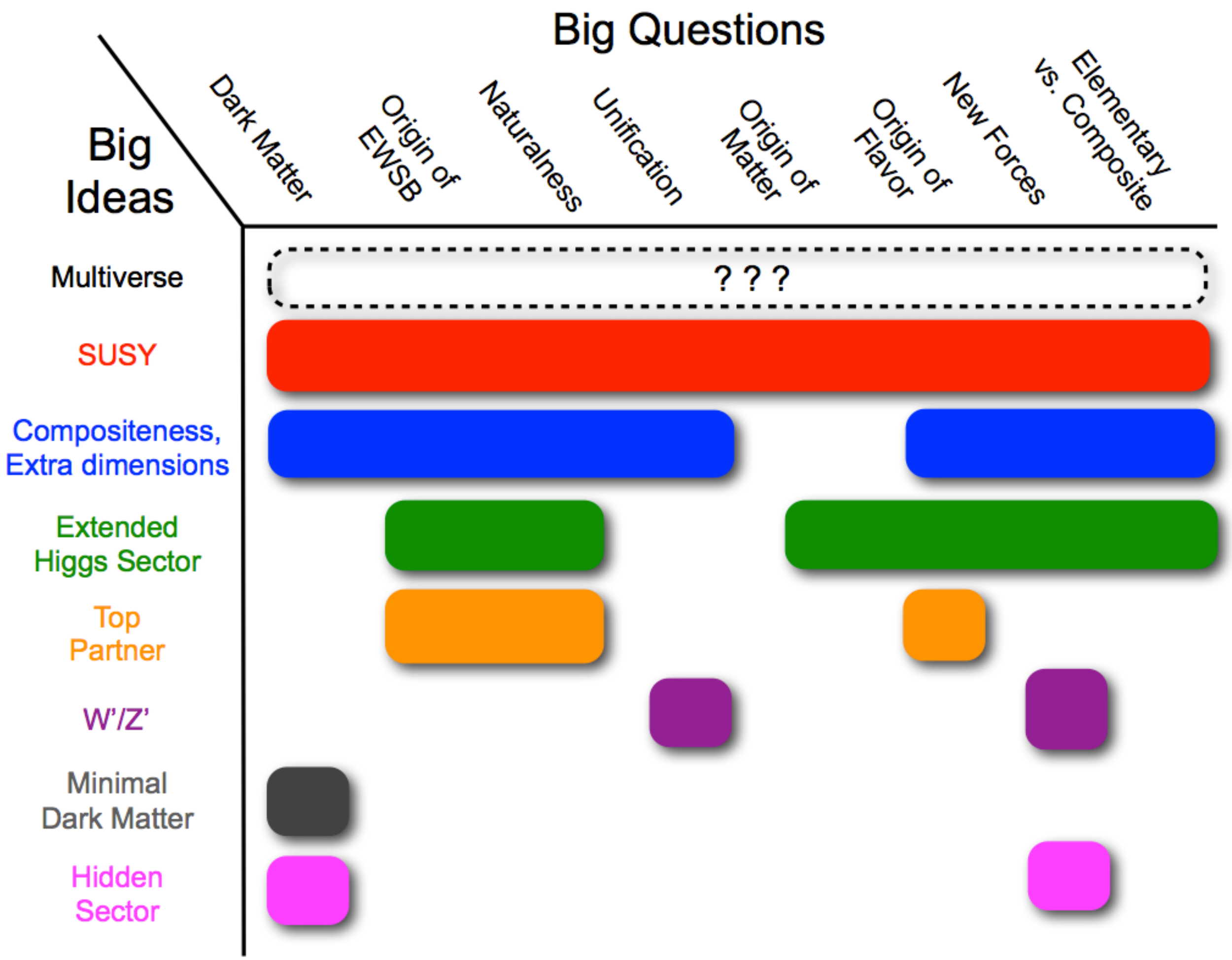
- Derived detector response function from full simulation
- <PU> ~ 50 assumed for 300/fb, including IBL and LAr trigger upgrade
- <PU> ~140 assumed for 3000/fb, including full tracker upgrade

CMS

- Scaling of Run I analyses or using Delphes
- Derived detector response function from full simulation of Phase I detector (caveat, reconstruction for Phase I not optimized)
- <PU> ~140 assumed for 3000/fb

Why do we want HL-LHC?

We are searching for answers for big questions in particle physics and cosmology!

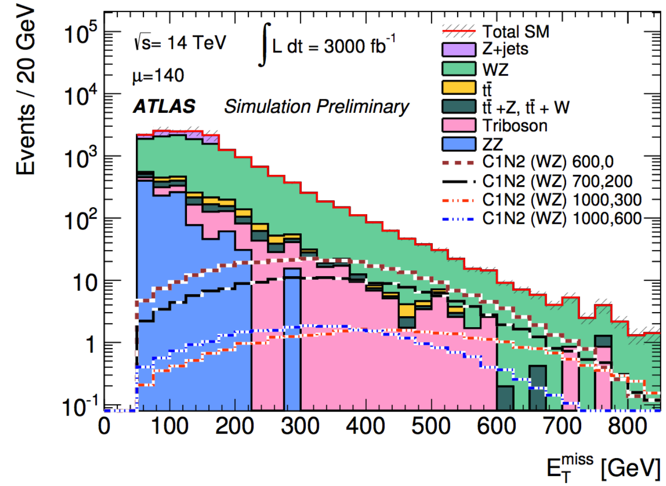


From Snowmass summary paper 2013

Search for direct $\chi^{\pm}\chi^{0}$ Production – Analysis Overview

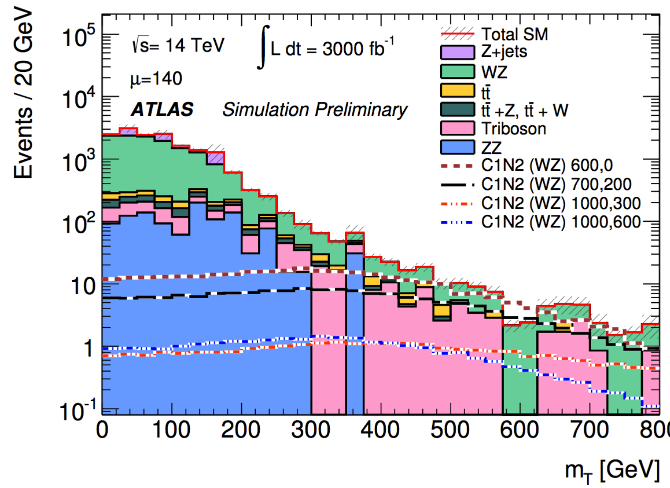
Event selection:

- b-jet veto
- 3 l (e, μ)
- 1 OSSF pair with inv. mass close to Z
- M_T calculated with 3rd lepton and MET
- Search regions defined by M_T and MET



Backgrounds:

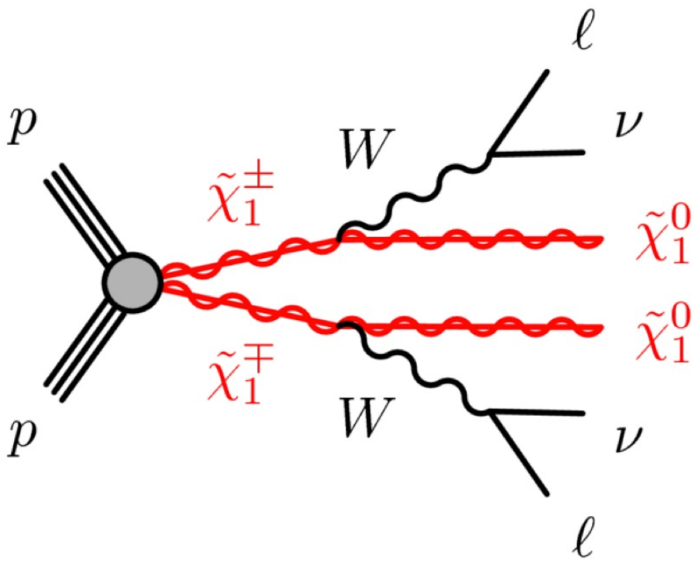
- WZ (3 leptons + MET from neutrino)
  → suppressed by MT cut
- ttbar (2 prompt l + 1 non-prompt l)
  → suppressed by b-jet veto
- Rare backgrounds
  → negligible due to low cross section
- Single boson background (no intrinsic MET)
  → suppressed by MET and MT cut



Search region binned in MET and MT

Search for direct $\chi^{\pm}\chi^{\pm}$ Production

EWKino predicted to be light even if colored sector is heavy



Final state:

- 2 leptons
- MET
- No hadronic activity

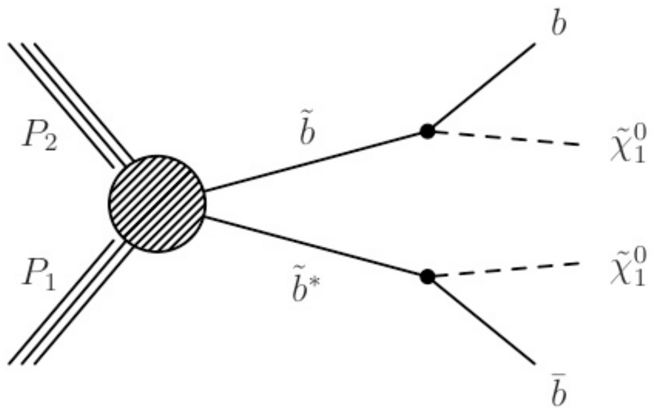
Extrapolation of existing 8 TeV analysis (ATLAS-CONF-2013-049):

- Background scaled
- Different pileup conditions not taken into account
- Event selection tightened

Result:

Gain of ~150 GeV in chargino mass up to 400 GeV
discovery reach when going from 300 fb^{-1} to 3000 fb^{-1}

Search for Direct Sbottom Production



Naturalness predicts a light third generation
→ investigate direct sbottom production

Extrapolation of existing 8 TeV analysis (arXiv:1308.2631)

- Background scaled (including PDF reweighting)
- Different pilup conditions not taken into account
- Event selection tightened

Result:

Gain of ~200 GeV in sbottom mass up to 1250 GeV
discovery reach when going from 300 fb^{-1} to 3000 fb^{-1}
→ **most interesting mass range will be covered!**

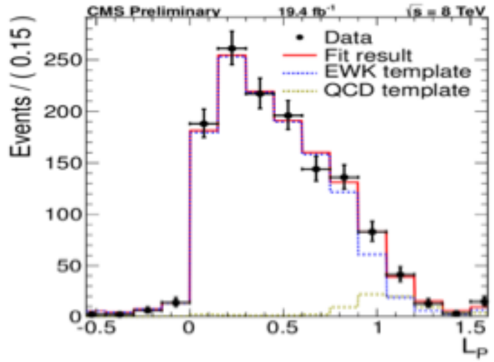
Gluino (l+b) – QCD background

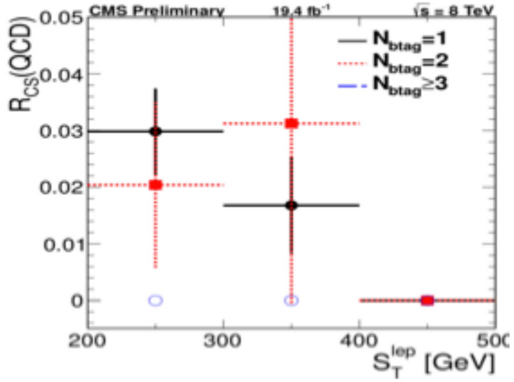
- **QCD background small compared to other bkgs**
  - negligible in the muon channel
- **Estimate QCD contribution using well tested method** [PRL (2011) 107:02180, CMS-SUS-11-015, CMS-SUS-12-010]
  - Invert electron id variables and estimate QCD shape from anti-selected data sample
  - Binned likelihood fit in Lp to estimate total QCD

    $$L_P = \frac{\vec{P}_T(l) \cdot \vec{P}_T(W)}{|\vec{P}_T(W)|^2}$$

    - EWK template from MC
  - Calculate R_{CS}[QCD] from anti-selected data
- **N_{QCD}<5% of total data, negl. for $\Delta\varphi$>1**
  - subtract contribution in control region
- **Prediction in electron channel:**

$$N_{SMest.}(\Delta\phi(W,l) > 1) = R_{CS}^{EWK} \cdot (N_{data}(\Delta\phi(W,l) < 1) - N_{QCD}(\Delta\phi(W,l) < 1))$$





Loukas Gouskos

RA4b (DP) Pre-Approval
Sep 6, 2013

4

Gluino (l+b) Search – Analysis Overview

Baseline selection:

- 1 lepton [e/mu] with p_T>20 GeV, $|\eta|$<2.4
- veto 2nd loose lepton
- $N_{jet} \geq 6$ with p_T> 40 GeV, $|\eta|$<2.4
- $N_{b\text{-}jet} \geq 2$
- H_T > 500 GeV
- S_T^{lep}>250 GeV
- $\Delta\Phi(W,l)$> 1

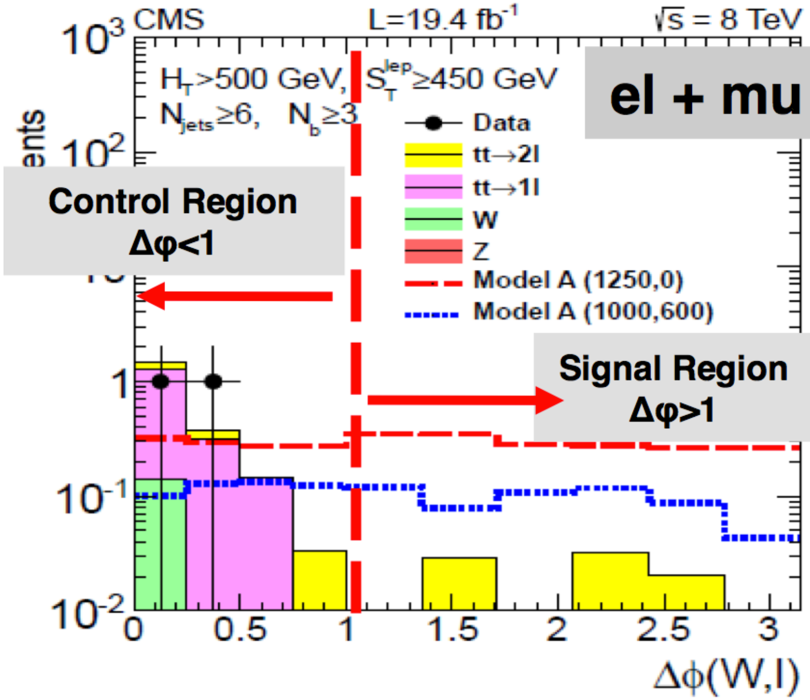
Search regions binned in:

- $N_{b\text{-}jet}$
- S_t^{lep}

based on 8 TeV analysis
CMS-PAS-SUS-13-007
with optimized signal regions

Gluino (l+b) Search – Method

Delta phi method:
The angle between W and lepton is larger for signal than for background



Jets + MHT Search – Search Regions

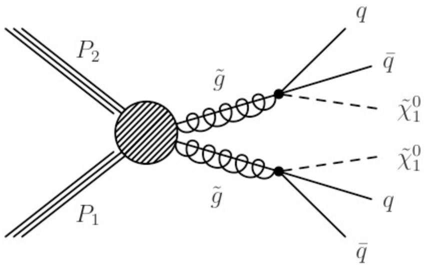
For simplicity, use inclusive bins in n_{jets}, HT and MHT

- most sensitive is $n_{jets} \geq 6$ for T1qqqq

The following search bins are used:

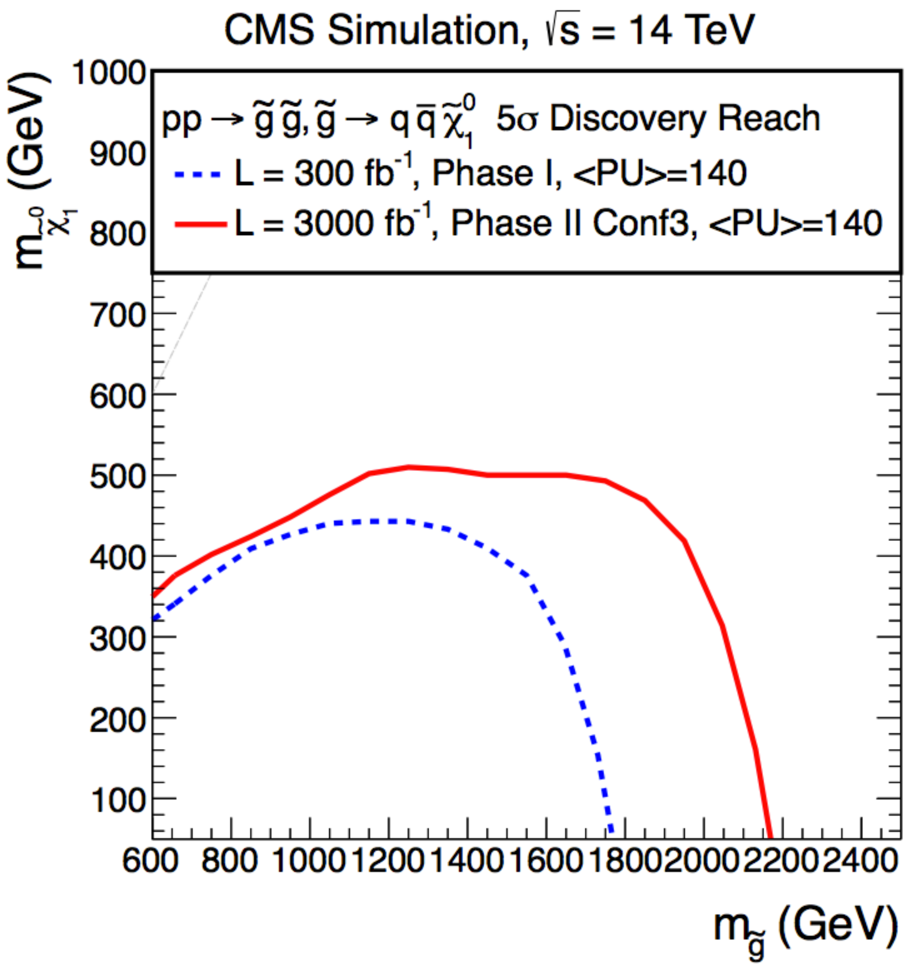
- 300fb^{-1}
  - R1: HT>=2100 GeV && MHT>=700 GeV (high gluino mass)
  - R2: HT>=1100 GeV && MHT>=600 GeV (high LSP mass)
  - R3: HT>=1600 GeV && MHT>=700 GeV (medium gluino and LSP masses)
  - R4: HT>=800 GeV && MHT>=400 GeV (low gluino mass and LSP masses)
- 3000fb^{-1}
  - R1: HT>2500 GeV && MHT>=1000 GeV (high gluino mass)
  - R2: HT>1600 GeV && MHT>=700 GeV (high LSP mass)
  - R3: HT>2000 GeV && MHT>=1000 GeV (medium gluino and LSP masses)
  - R4: HT>=800 GeV && MHT>=400 GeV (low gluino and low LSP masses)
  - R5: HT>=1100 GeV && MHT>=600 GeV (low gluino and high LSP masses)

SUSY: Jets + MHT Search – Result



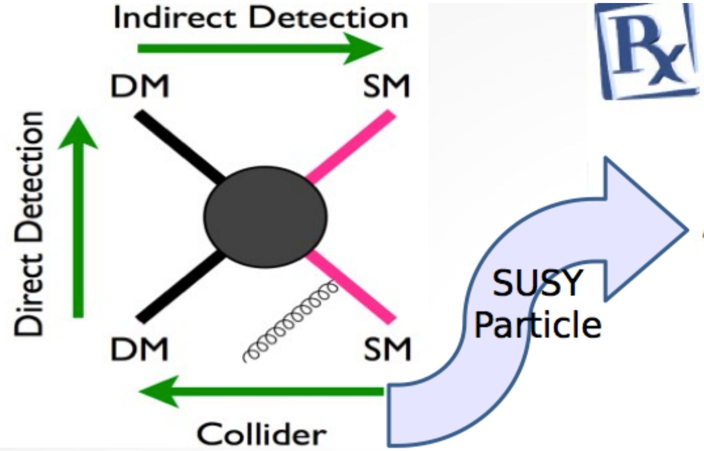
Sensitive to
gluino masses up to 2.2 TeV and
LSP masses up to 500 GeV

Gain of ~400 GeV in gluino mass
discovery reach when
going from 300 fb^{-1} to 3000 fb^{-1}



VBF Dark Matter Search – Motivation

Determination of the N1 composition is important to understand the early universe cosmology



℞ to Probe Ωh^2

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

$s_W = \sin(\theta_W) \quad c_W = \cos(\theta_W)$

$s_\beta = \sin(\beta) \quad c_\beta = \cos(\beta)$

$M_1 << M_2, \mu \Rightarrow \tilde{\chi}_1^0 \approx \tilde{B}$ Pure Bino

$M_2 << M_1, \mu \Rightarrow \tilde{\chi}_1^0 \approx \tilde{W}$ Pure Wino

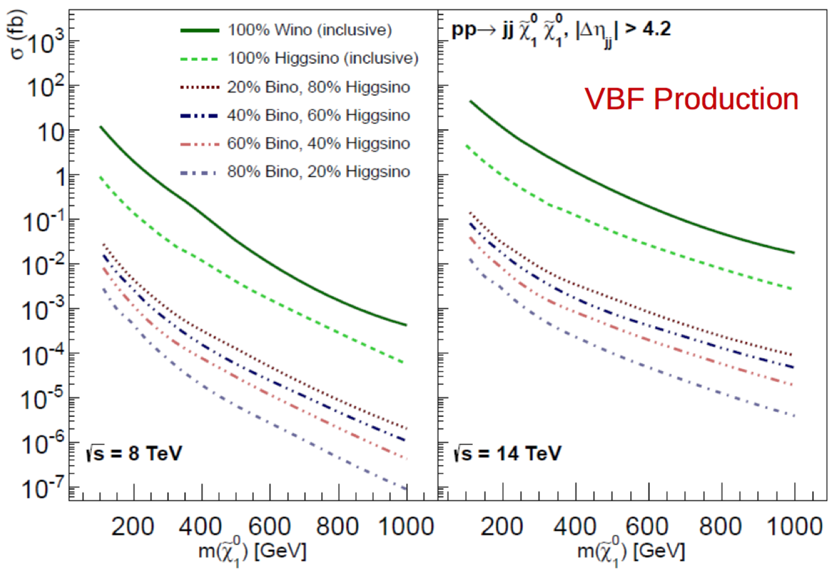
$\mu << M_1, M_2 \Rightarrow \tilde{\chi}_1^0 \approx \tilde{H}_h + \tilde{H}_d$

Pure Higgsino

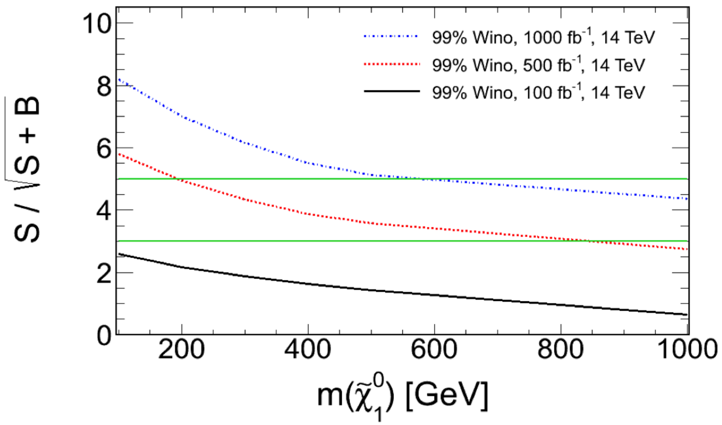
From A. Gurrola, Snowmass Seattle

VBF Dark Matter Search – Prediction from Pheno Paper

Largest cross section from 100% Wino



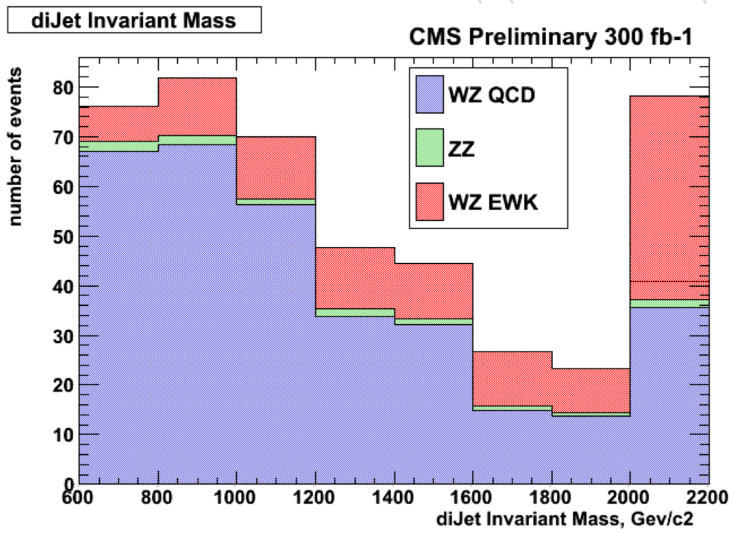
Pheno paper (1301.7779) predicts 5σ discovery (omitting influence of syst. unc.)



Vector Boson Scattering – Event Selection for WZ Channel

Event selection for WZ Channel

- Three identified leptons (e or μ) with $p_T > 20$ GeV and $|\eta| < 2.4$
- 2 leptons must be OSSF pair (from Z) with $|m_{ll} - m_Z| < 20$ GeV and $m_{ll} > 20$ GeV
- Reject events with additional leptons with $p_T > 10$ GeV
- $\Delta R(ll') > 0.04$
- $\Delta R(lj') > 0.4$
- MET > 30 GeV (300 fb^{-1} only)
- Two parton "jets" from quarks or gluons with
  - $p_T > 50$ GeV and $|\eta| < 4.7$
  - $\Delta\eta_{jj} > 4.0$
  - $m_{jj} > 600$ GeV

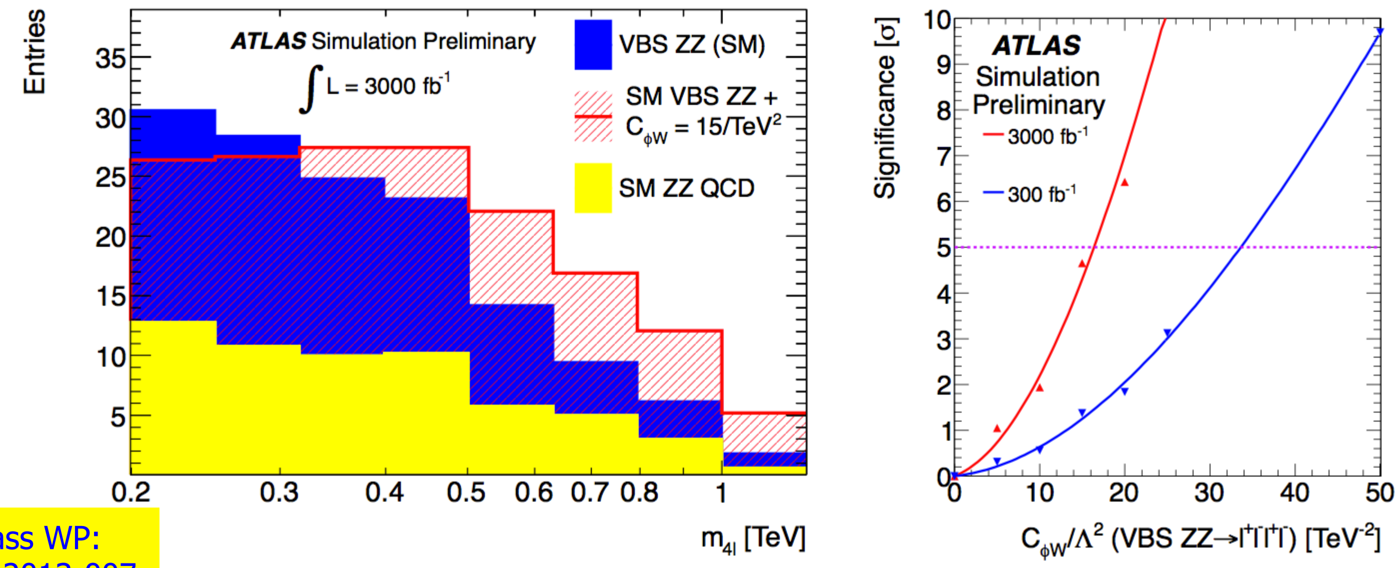


Vector Boson Scattering – Result for ZZ Channel

ZZ channel is sensitive to dimension-6 operator:

$$\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2} \mathrm{Tr}(W^{\mu\nu} W_{\mu\nu}) \phi^\dagger \phi$$

- Small cross section, but provides a clean, fully reconstructible ZZ resonance peak
- Forward jet-jet mass requirement of 1 TeV reduces the contribution from jets accompanying non-VBS di-boson production



ATLAS-Snowmass WP:
ATL-PHYS-PUB-2013-007

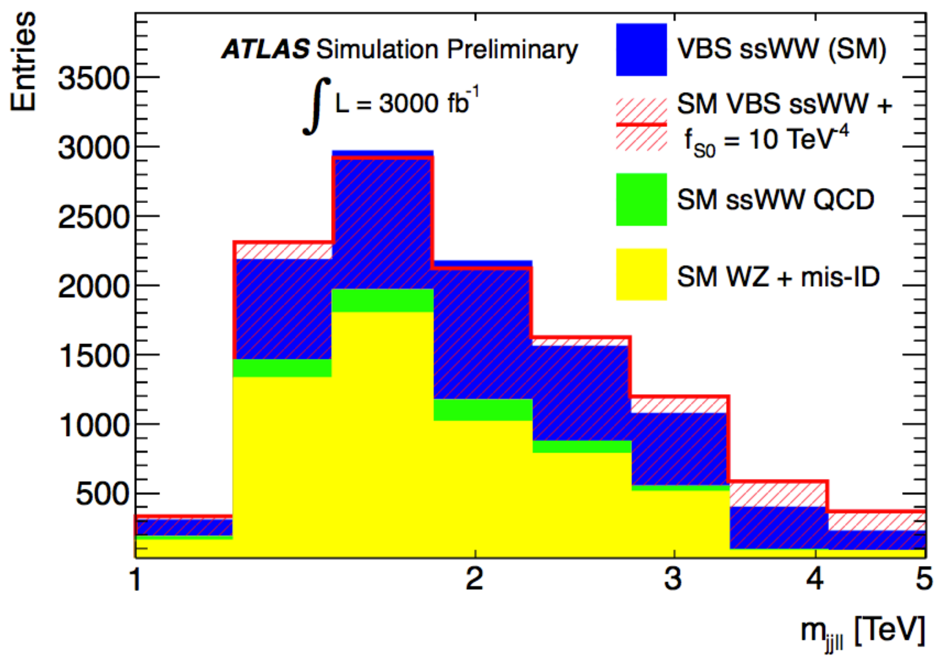
3000 fb^{-1} improves discovery range significantly

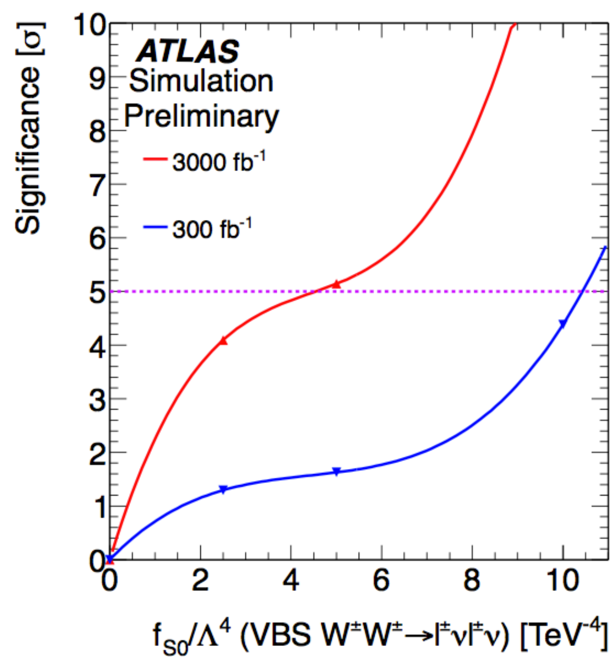
Vector Boson Scattering – Result for WW Channel

Result also obtained in WW (same-sign) channel, sensitive to dimension-8 operator:

$$\mathcal{L}_{S,0} = \frac{f_{S0}}{\Lambda^4}[(D_\mu\phi)^\dagger D_\nu\phi)] \times [(D^\mu\phi)^\dagger D^\nu\phi)]$$

- Two same-sign leptons + 2 forward jets with m_{jj} >1 TeV





$3000\ fb^{-1}$ improves discovery range significantly

Vector Boson Scattering – Summary

- HL-LHC enhances discovery range for new higher-dimension electroweak operators by more than a factor of two

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

Λ_{UV}: unitarity violation bound corresponding to the sensitivity with 3000 fb^{-1}

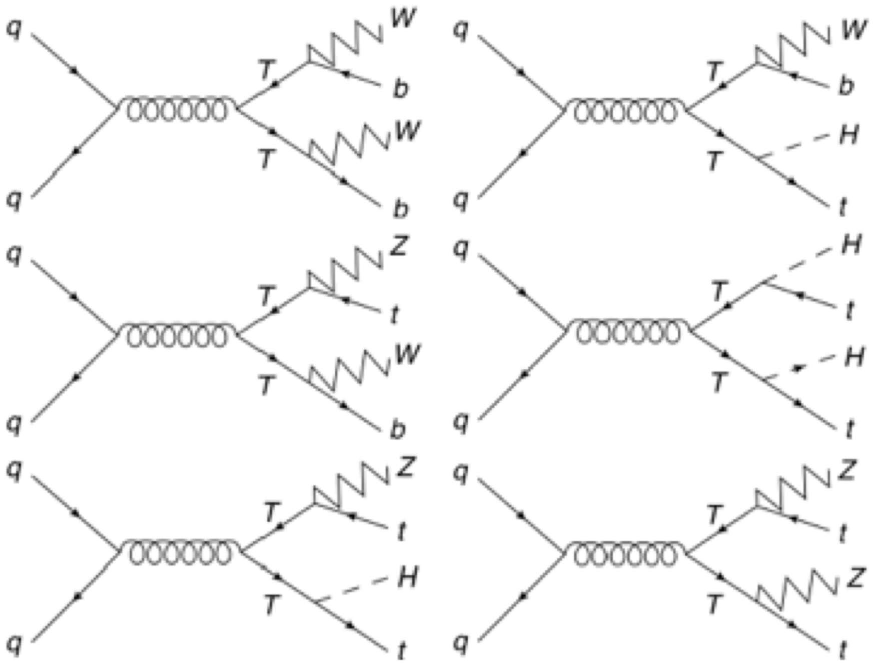
SM discovery expected with 185 fb^{-1}

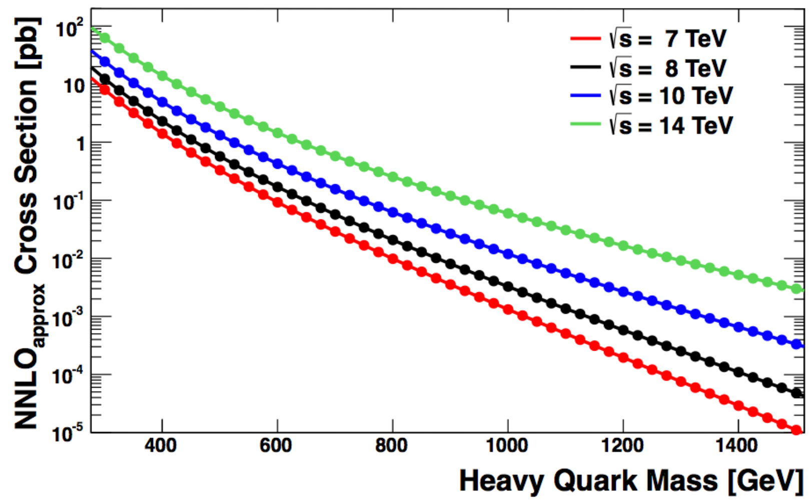
BSM contribution at TeV Scale might be observed at 300 fb^{-1}!

If BSM discovered in 300 fb^{-1} dataset, then the coefficients on the new operators could be measured to 5% precision with 3000 fb^{-1}

Vector-like Charge 2/3 Quark Search – Production Mechanism and CS

Decays to two vector bosons and two 3rd generation quarks

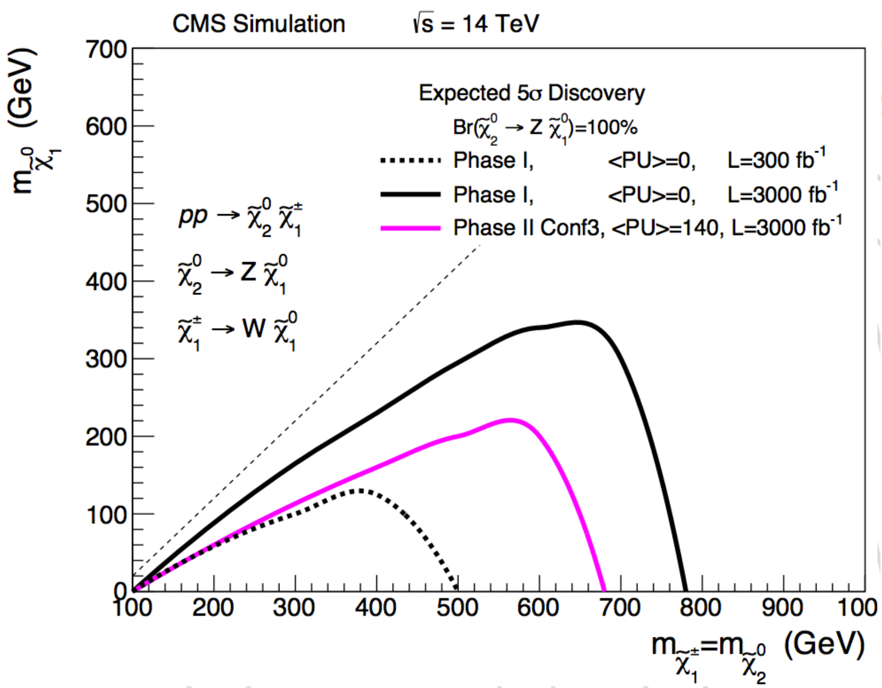


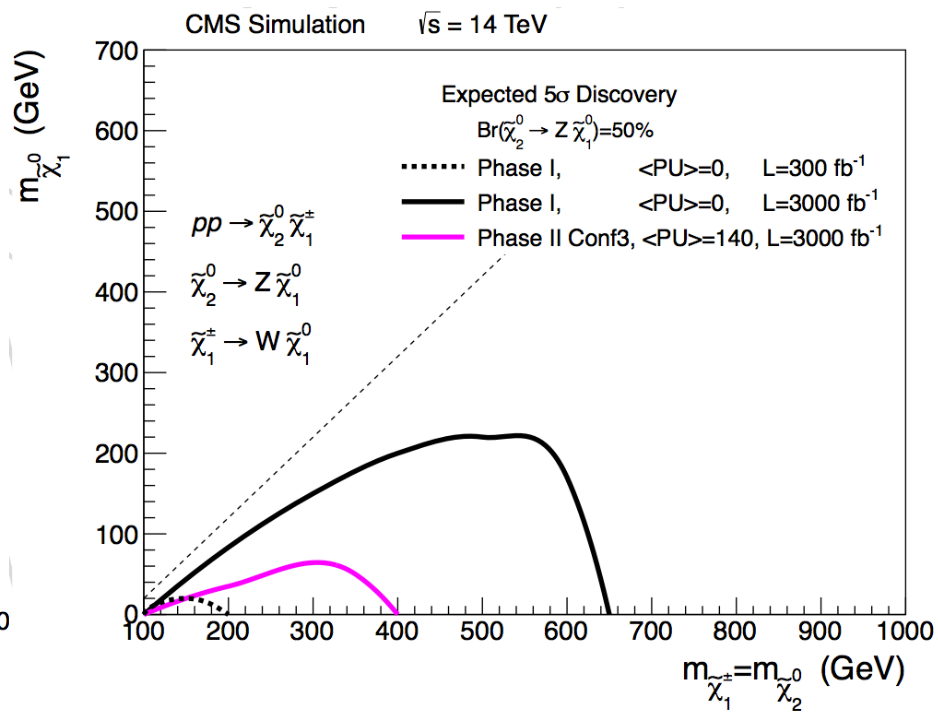


Cross section rises by order of magnitude from 8 → 14 TeV

Search for direct $\chi^{\pm}\chi^{0}$ Production – Interpretation

Comparison of 100% to 50% branching ratio to WZ+LSPs final state





Vector Boson Scattering – Theory

First Standard Model measurement, then BSM search!

Any EFT, also the SM, has higher-dimensional operators (Weinberg, 1979):

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{a_i}{\Lambda} \mathcal{O}_i^{(5)} + \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \frac{e_i}{\Lambda^4} \mathcal{O}_i^{(8)} \cdots \right]$$

Observation of **anomalous quartic gauge coupling** would indicate **new physics in the electroweak symmetry breaking sector!**

Vector-like Charge 2/3 Quark Search – Event Selection

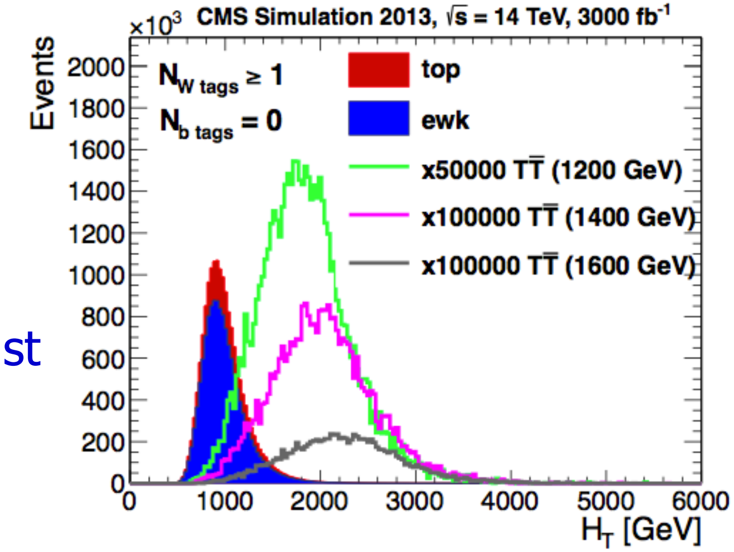
Single-lepton channel:

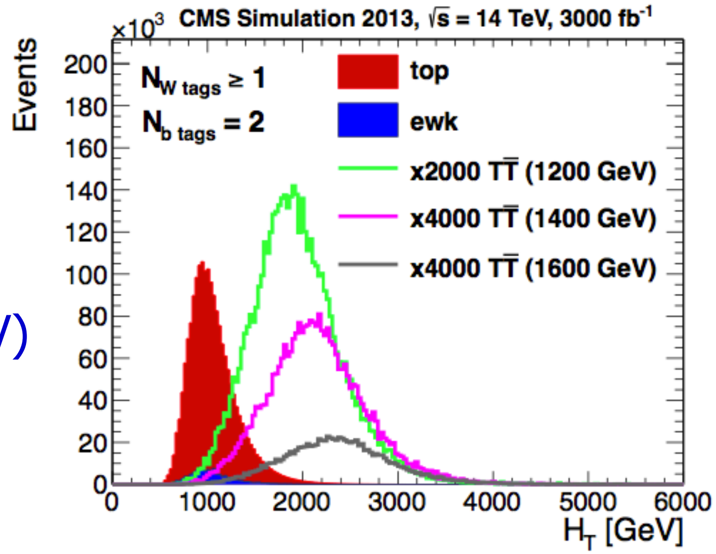
- 1 lepton (e or μ) with $p_T > 30$ GeV
- MET > 20 GeV
- $0 \leq n_{b\text{-jet}} \leq 3$
- p_T (leading b-jet) > 150 GeV
- $n_{jet} > 3$ with $p_T > 200, 90, 50$ GeV + at least 1 W-jet
- or $n_{jet} > 4$ with $p_T > 200, 90, 50,35$ GeV + no W-jet

Search in bins of $n_{b\text{-jet}}$, n_{jet}, $n_{W\text{-jet}}$

Multi-lepton channel:

- ≥ charged leptons (e/μ) with p_T >30 GeV
- define jet constituents:
- two: W-tagged jets (W-jet p_T>200 GeV)
- three - top-tagged jets (top-jet p_T>300 GeV)
- 4 Exclusive signal regions
  - 2 leptons: OS23, OS5+, SS
  - 3 leptons





Luminosities for Heavy Flavor Experiments

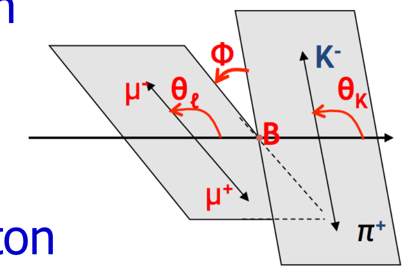
	LHC era		HL-LHC era		
	2010-2012	2015-2017	2019-2021	2024-2026	2028-2030+
ATLAS & CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	→	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}
Belle II	-	0.5 ab^{-1}	25 ab^{-1}	50 ab^{-1}	-

The LHCb upgrade design is qualified for an integrated luminosity of 50fb^{-1} but it is anticipated that LHCb will continue to be operational throughout the HL-LHC era

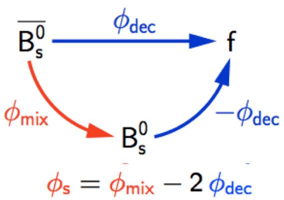
4

...and more excerpts from the rich Heavy Flavor programme

- Angular measurements in $B_d \longrightarrow K^{*0}\,\mu^+\mu^-$
  - Distributions of the angular variables precisely predicted in the SM
  - Deviations expected from NP
  - Probe the NP structure if any effect observed, e.g. in the low $M^2(ll)$ region the Φ distribution is sensitive to the photon polarization



- Φ_S from $B_s \rightarrow J/\psi\Phi$ and $B_s \rightarrow \Phi\Phi$
  - $B_s \rightarrow J/\psi\Phi$ (b → ccs)
    - NP can show up in mixing
  - $B_s \rightarrow \Phi\Phi$ (b → sss) – LHCb only
    - NP can show up in mixing or decay (penguin loops)



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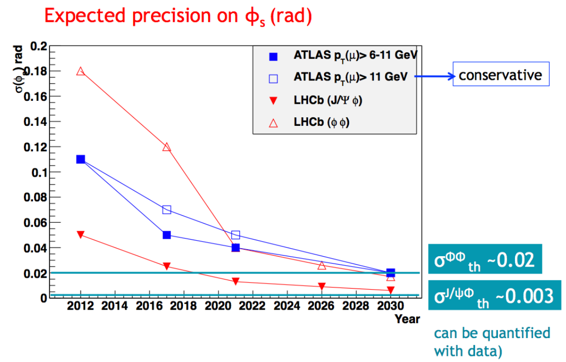

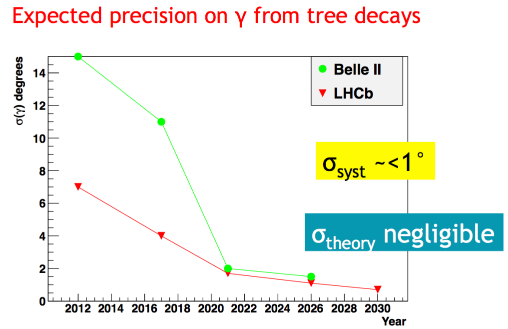

- Measurement of the CKM angle γ:

$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

  - Interferences between b→c and b→u transitions

Top mass measurement

Comparison of the precision of the different methods

Method	Precision @ 7/8 TeV / GeV		Precision @ 14 TeV / GeV	
	stat	**sys**	**stat**	**sys**
Full kin. rec.	0.43	0.98	0.01	0.20
Endpoint method	0.9	1.9	0.04	0.5
J/Ψ method			0.1	0.6
L_{xy} method	2.0	2.8	0.1	0.4
Extraction from CS	3.1		0.7 to 1.9	

The CKM Angle γ

$\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ Interferences between $b \to c$ and $b \to u$ transitions

Time independent measurements
($B \to DK^{(*)}$ large family)
Tree diagrams
SM reference point

Time dependent measurements
($B_s \to D_s K$)
tree (decay) + box (mixing) diagrams
sensitive to NP in mixing ($B_s \to J/\psi\Phi$)

charmless decays
box/loops diagrams
sensitive to NP