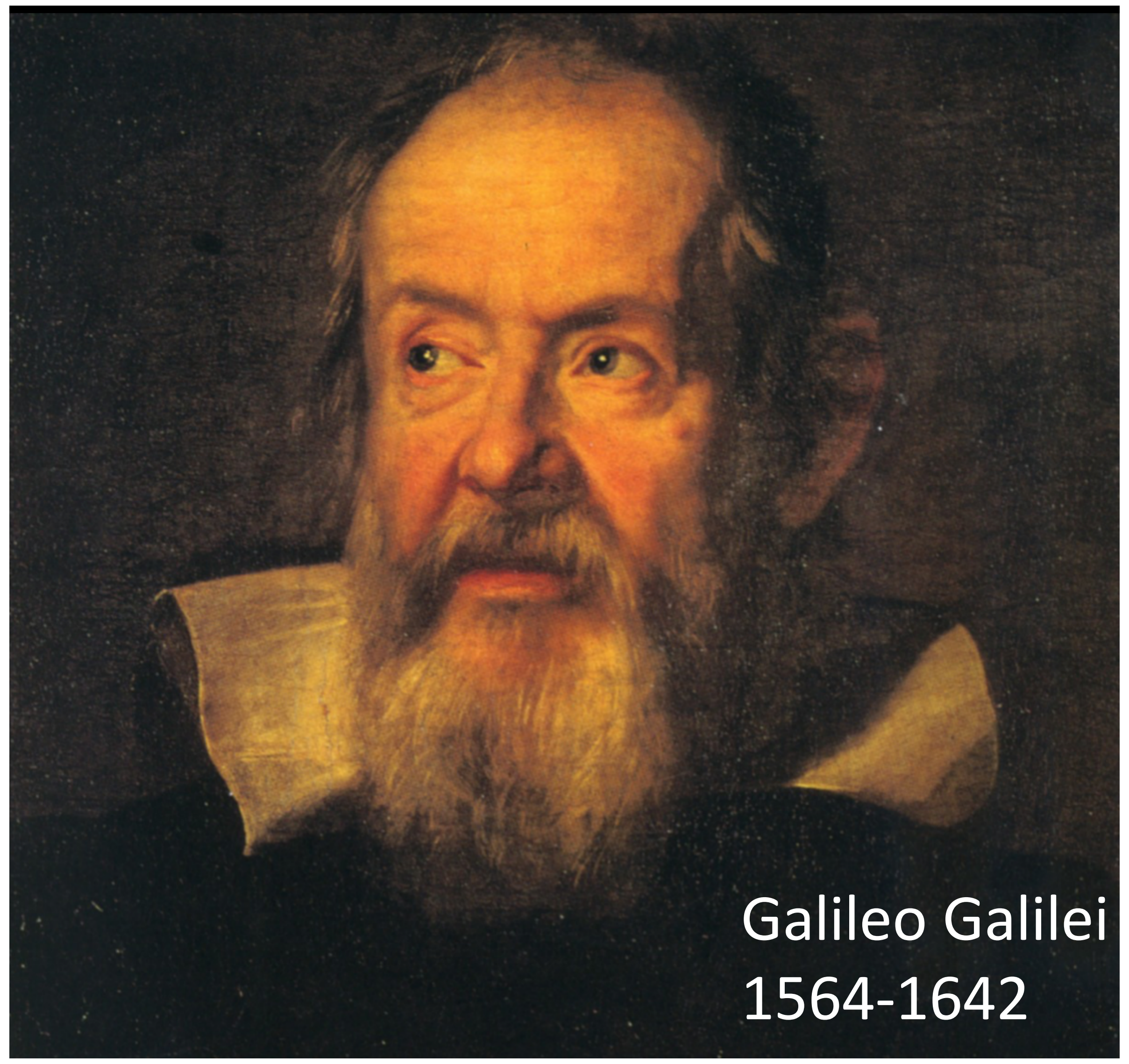
Measure what is measurable and make measurable what is not so

– Uncover new physics with bosons at the LHC and upgrades of the CMS detector to maximize the discovery potential

Mia Liu
FNAL
April.29.2019
Brookhaven National Lab



Eternal questions

- What is the world made of?
- What holds it together?
- What's the origin of the universe?

We aim at answering these questions in particle physics

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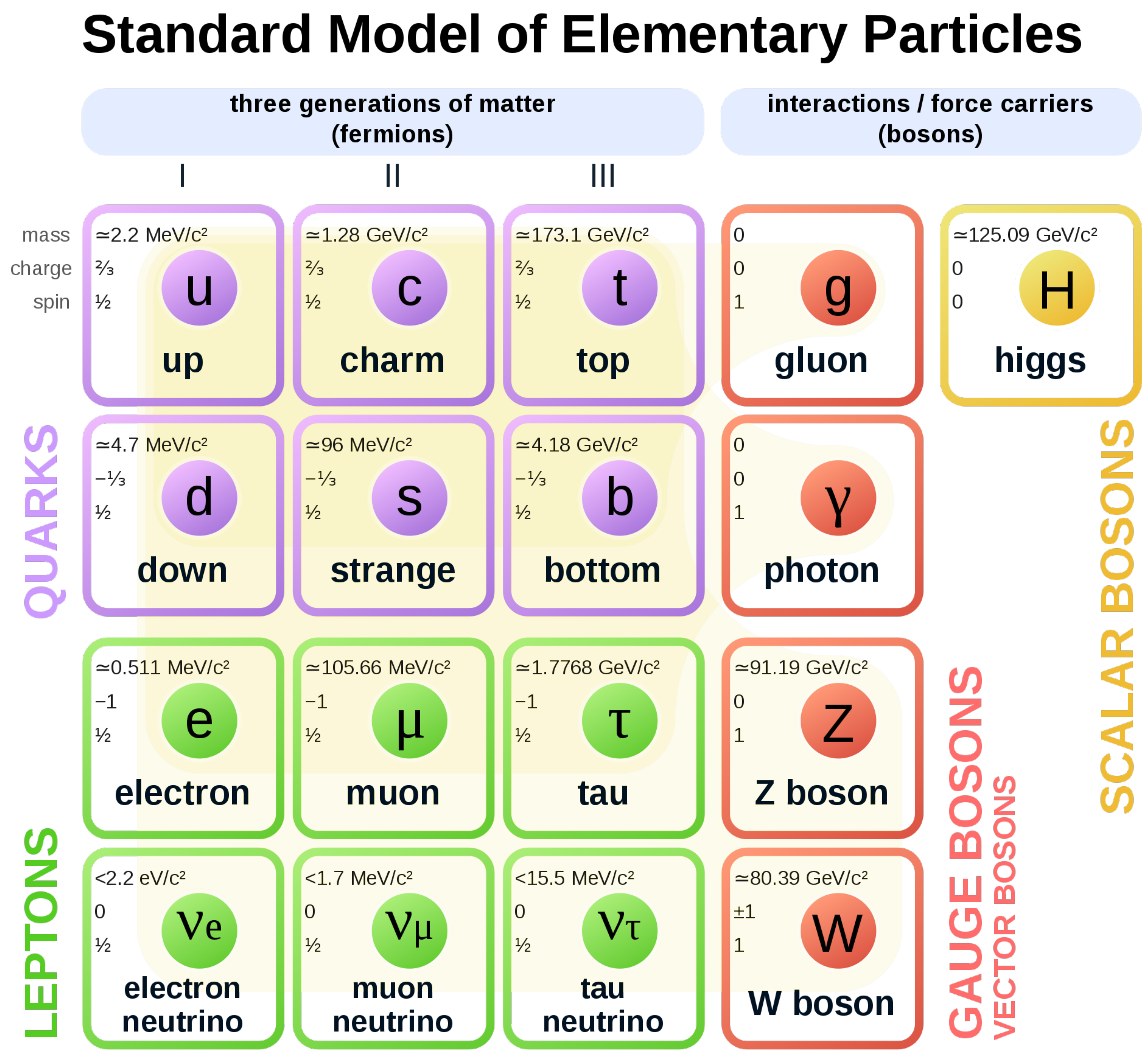
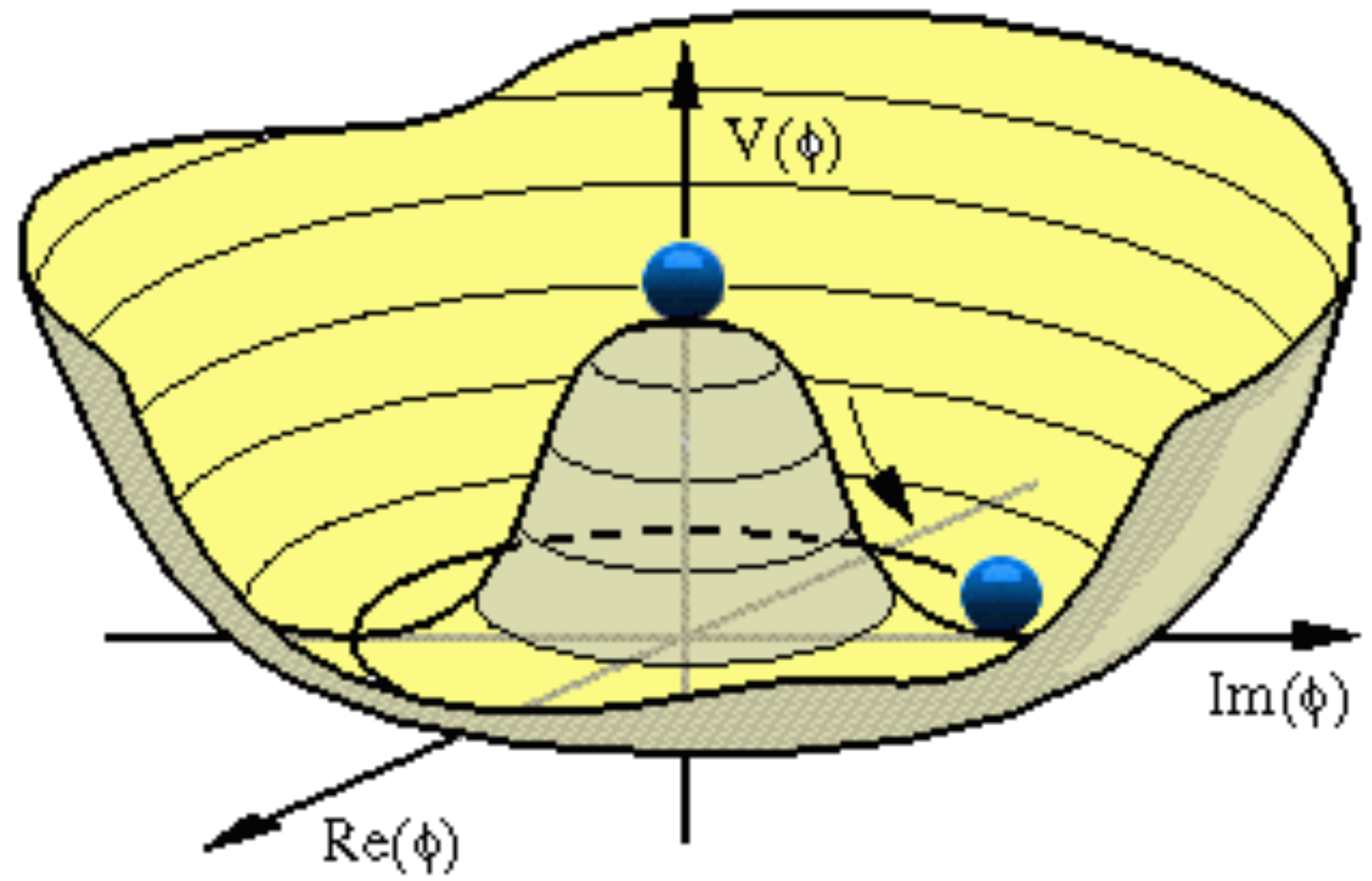
The Standard Model



- Our current answer
  - SM Symmetry structure: SU(2)xU(1)XSU(3)
  - Stringently tested with experimental data
    - Need massless particles to preserve the gauge structure
  - Higgs boson proposed



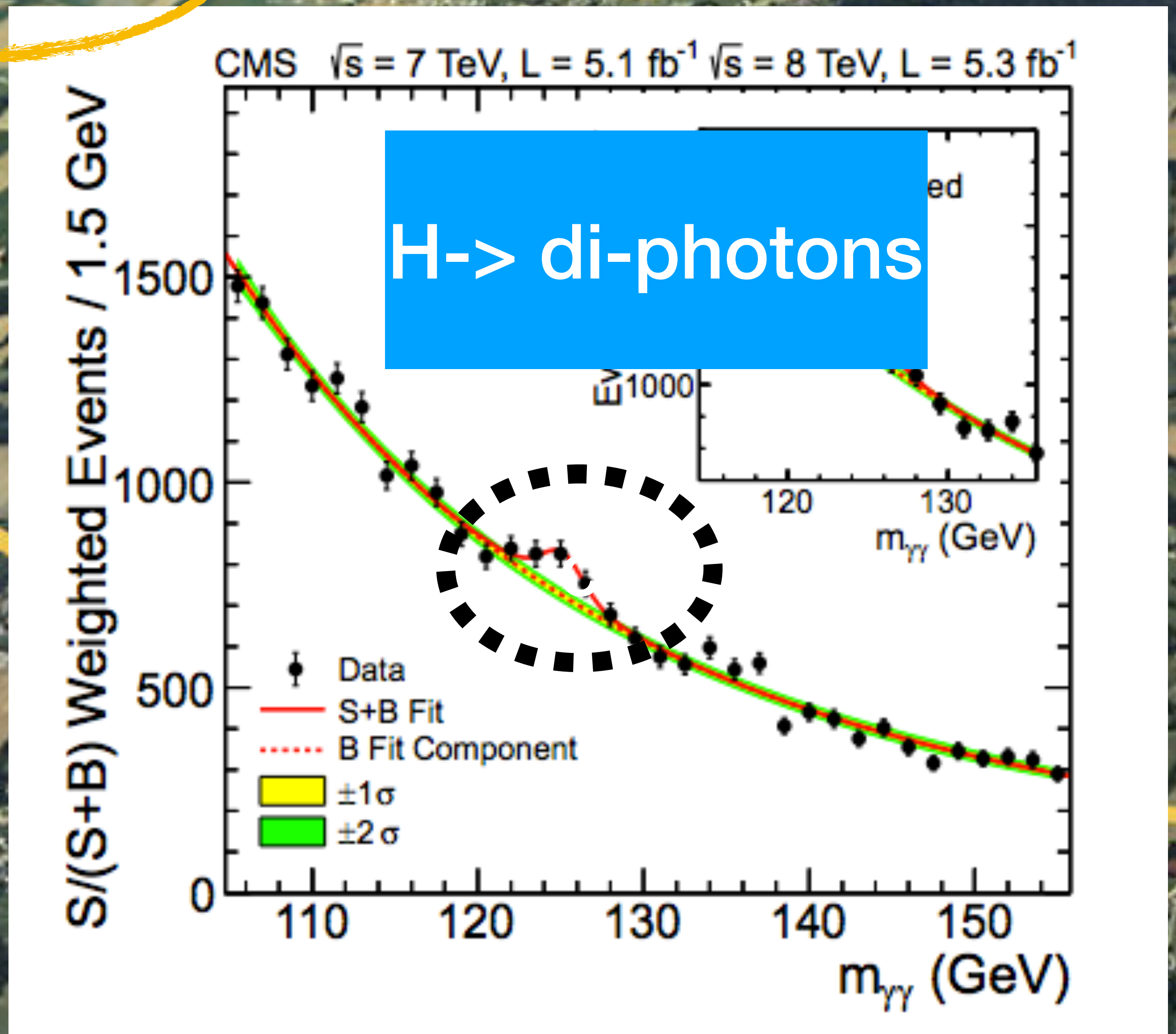
The Large Hadron Collider

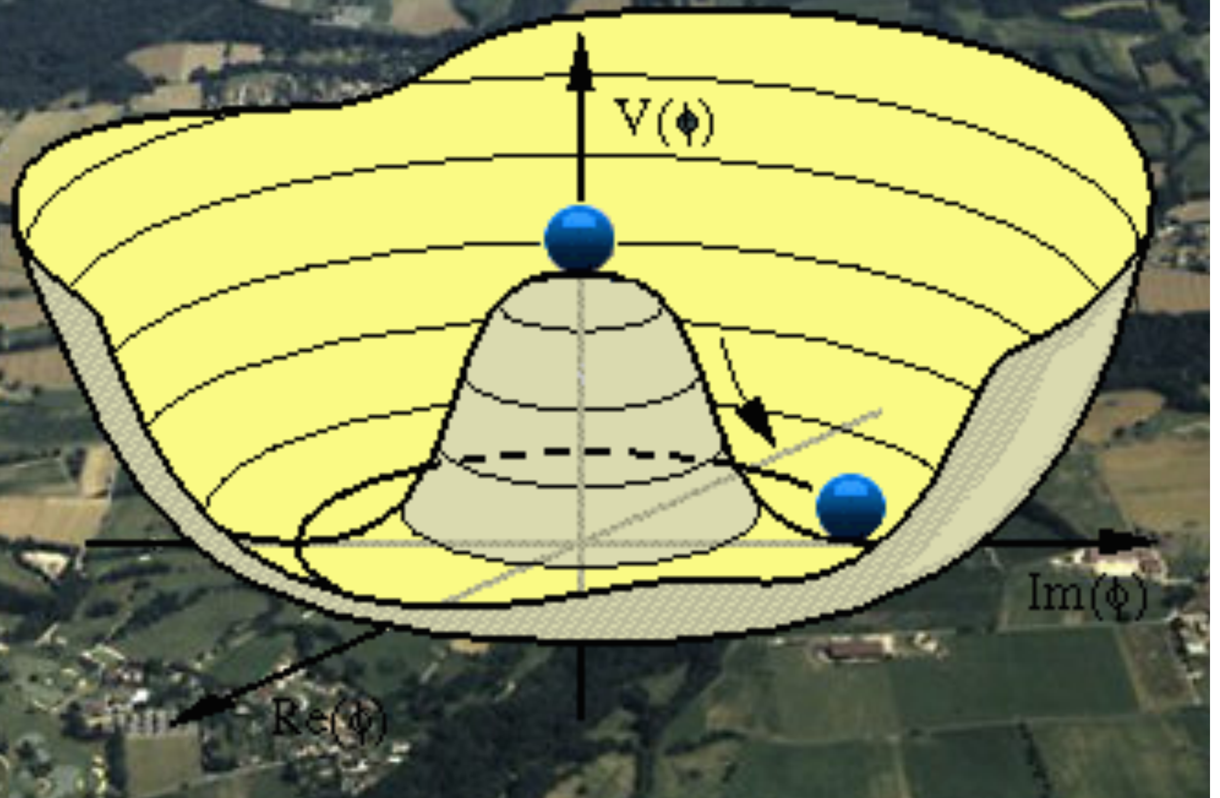
The Higgs boson completes the SM

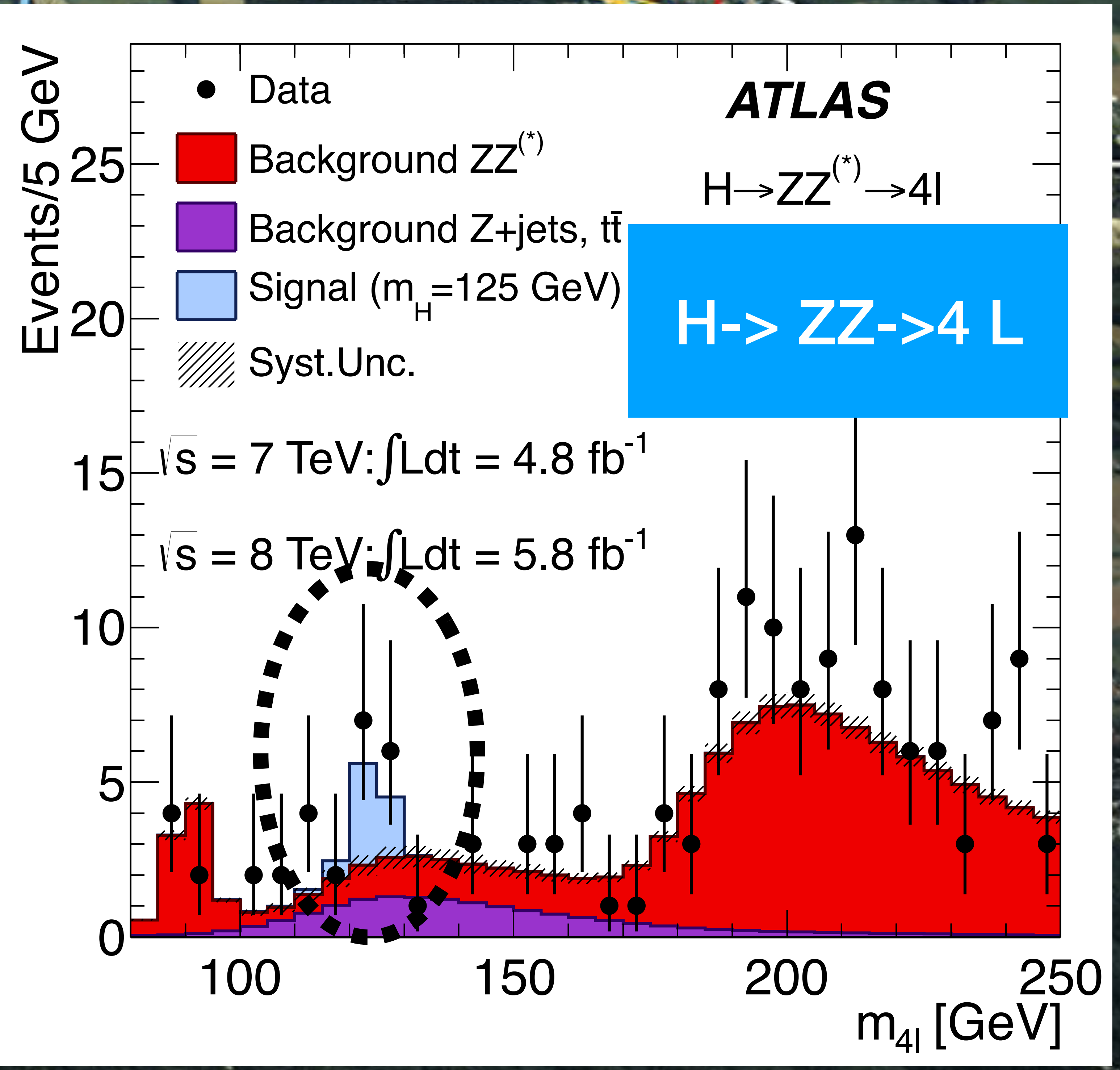

Physicists Find Elusive Particle Seen as Key to Universe

By DENNIS OVERBYE JULY 4, 2012

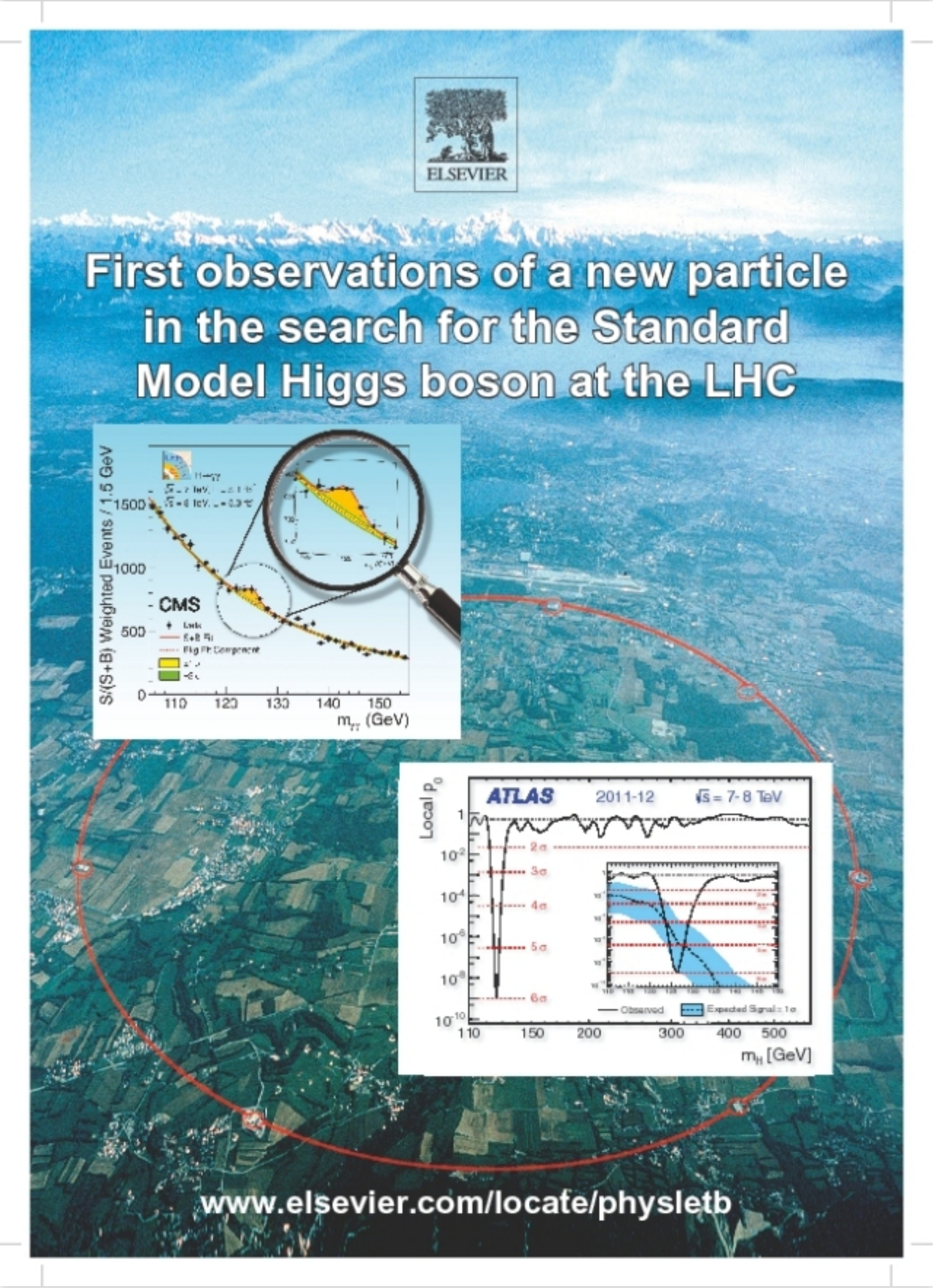
2012



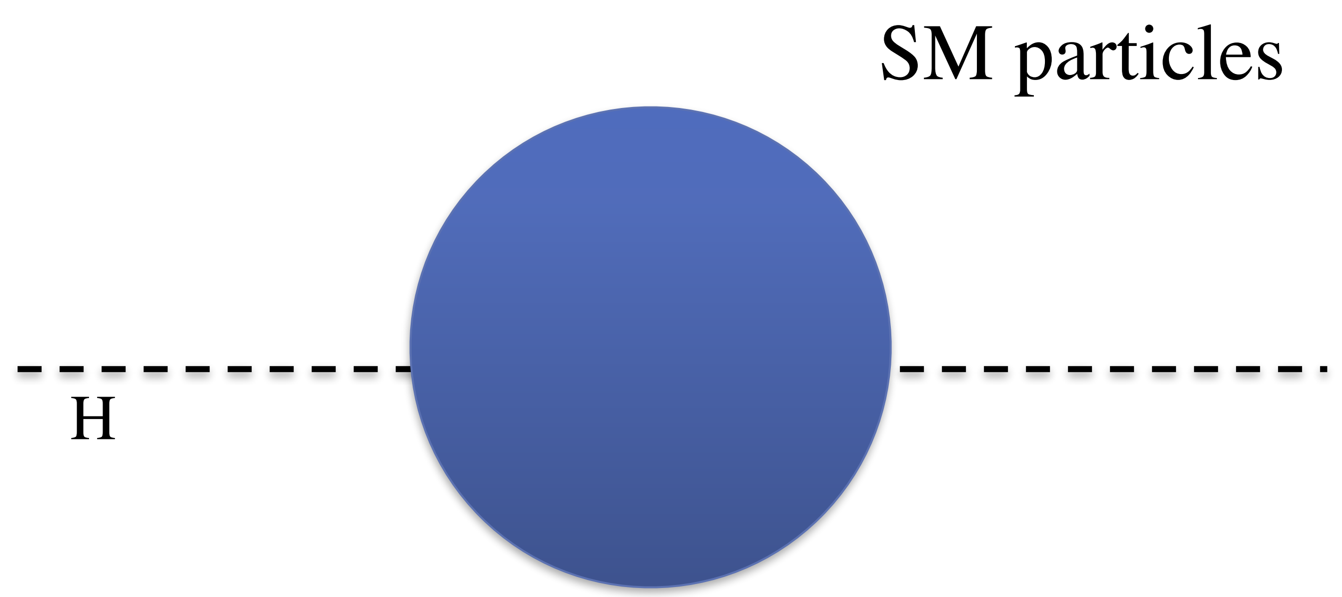




Is that all?


ELSEVIER
First observations of a new particle in the search for the Standard Model Higgs boson at the LHC
S/(S+B) Weighted Events / 1.5 GeV
CMS
$m_{\gamma\gamma}$ (GeV)
ATLAS
2011-12
$\sqrt{s}$ = 7-8 TeV
Local p_0
m_H [GeV]
www.elsevier.com/locate/physletb

Remaining Puzzles



$$m_{obs}^2 = m_{bare}^2 - \frac{\lambda_f^2}{8\pi^2}\Lambda^2$$

125 GeV

ε*10[19] GeV?

10^{19} GeV

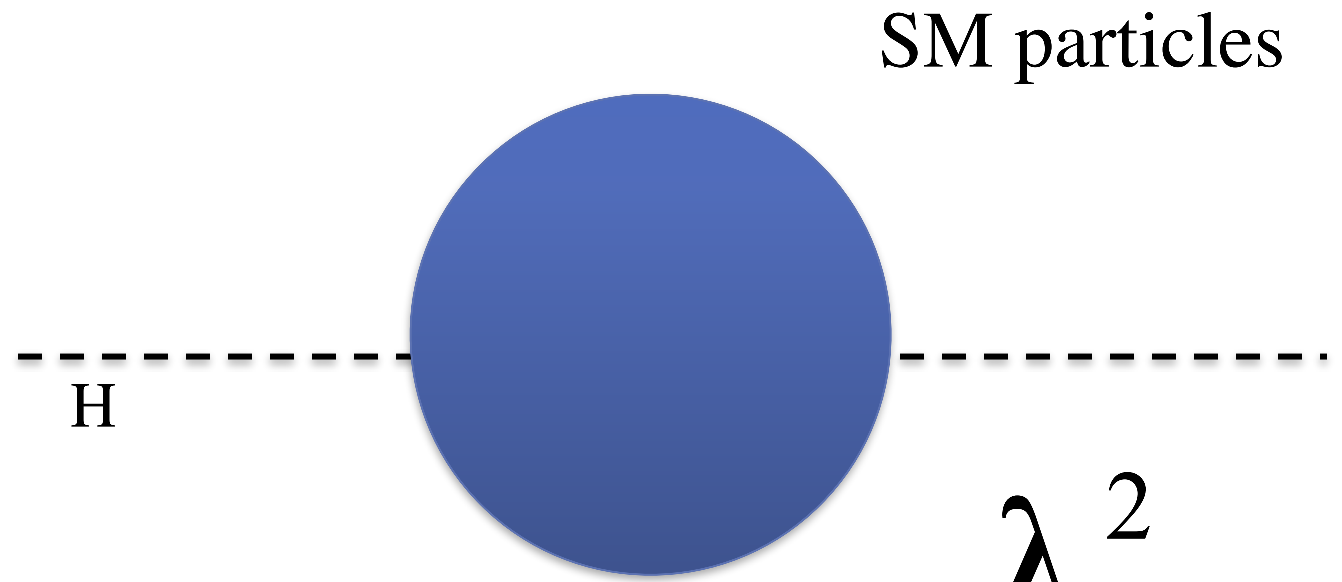
Planck scale

In the theory itself:

Fine tuned Higgs mass?

.....

Remaining Puzzles



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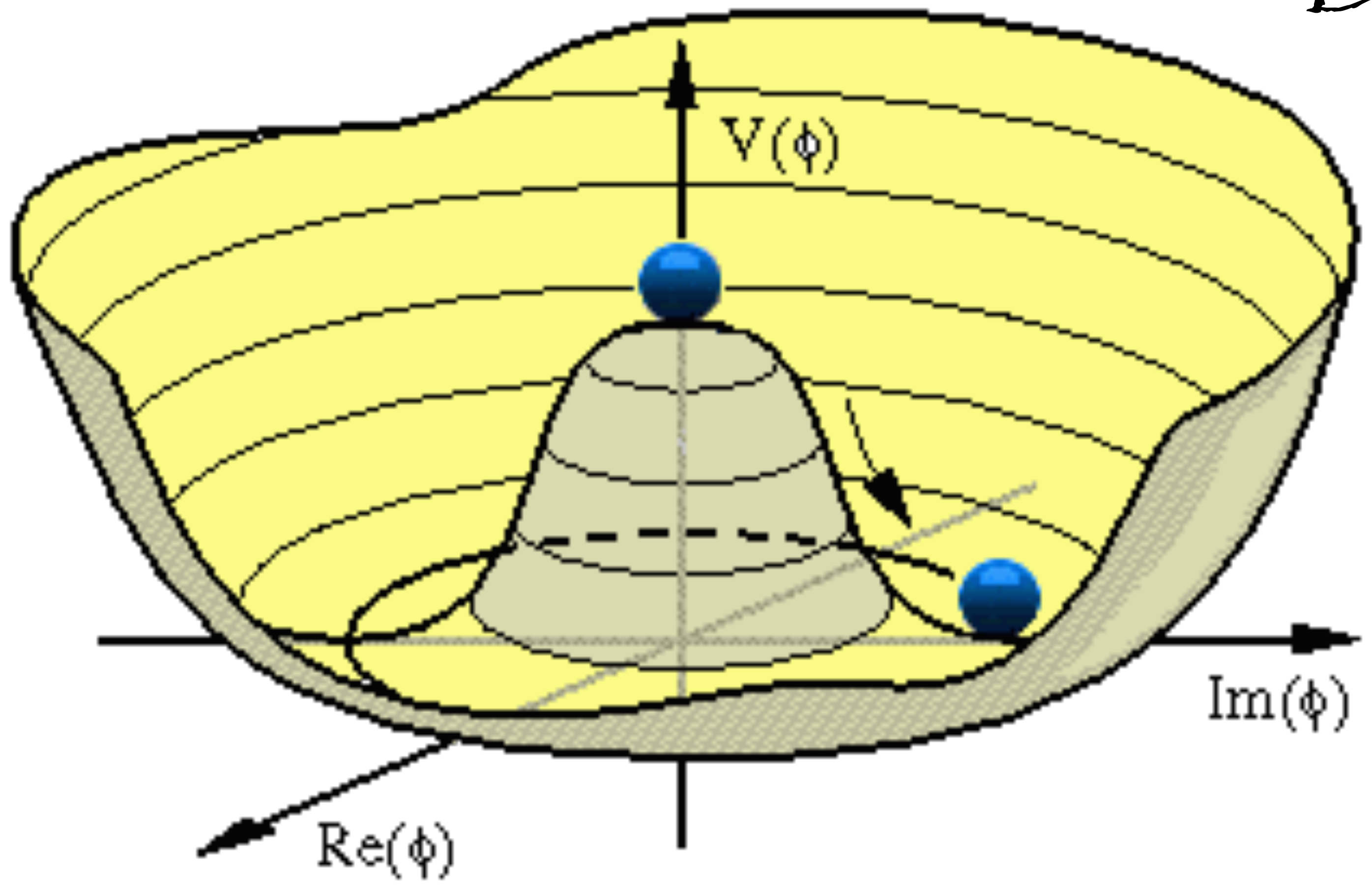
Dynamical origin of the Higgs potential



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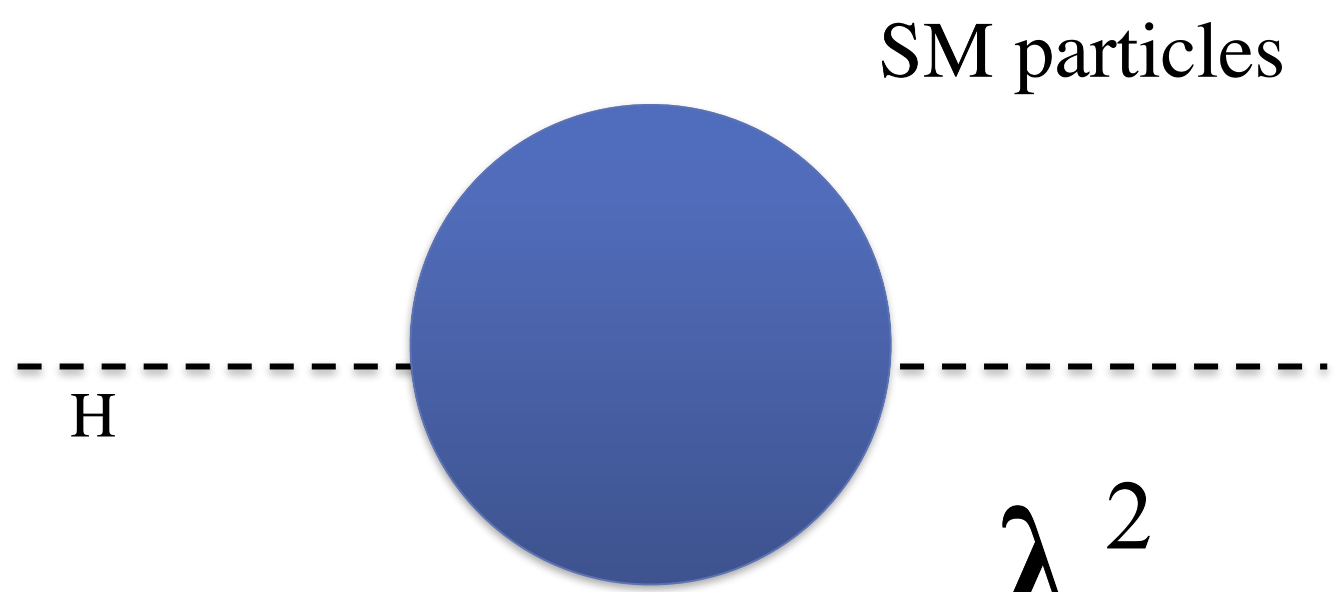
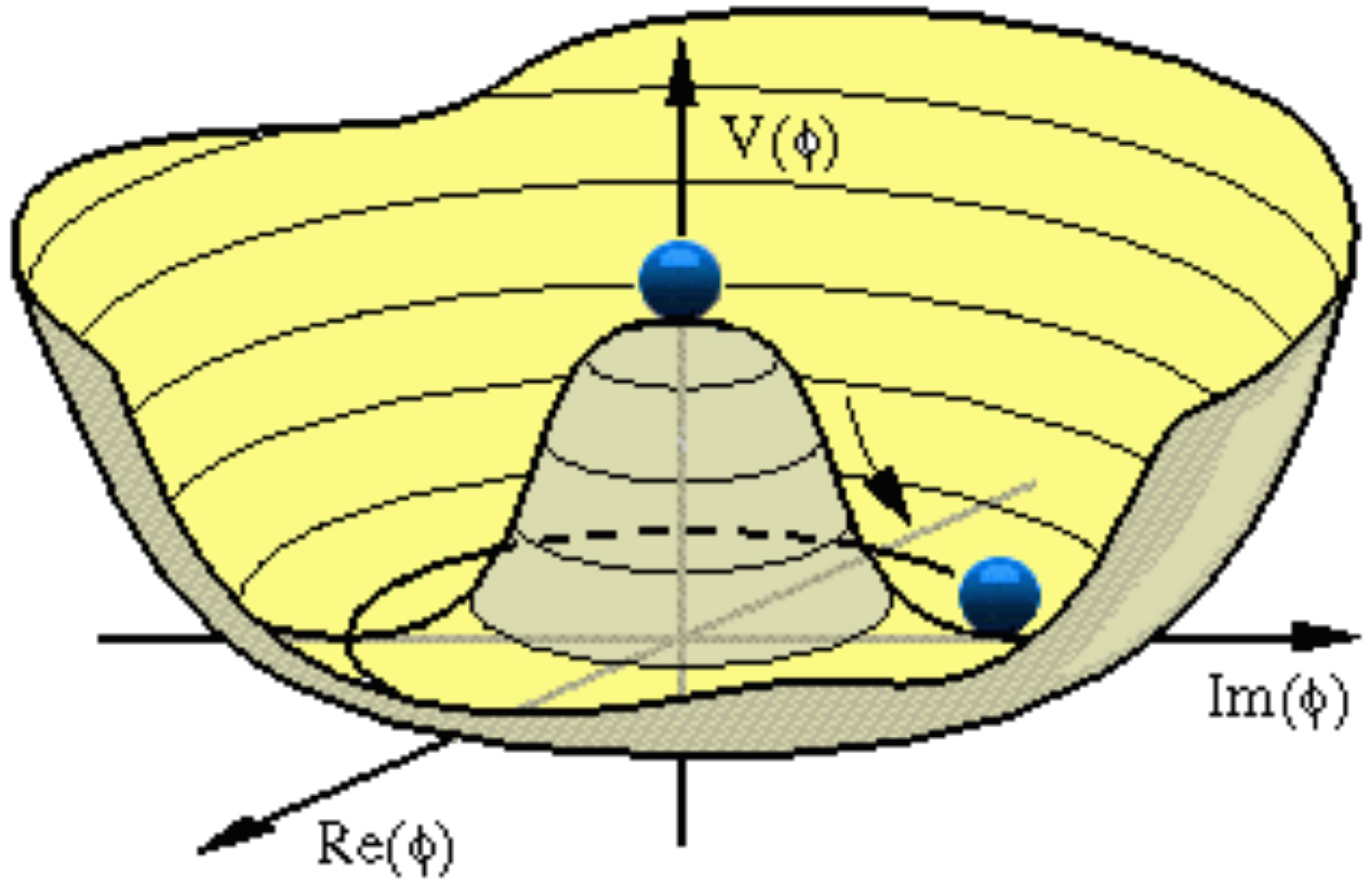
Remaining Puzzles



$$m^2_{obs} = m^2_{bare} - \frac{\lambda_f^2}{8\pi^2}\Lambda^2$$

125 GeV | **$\varepsilon*10^{19}$ GeV?** | 10^{19} GeV



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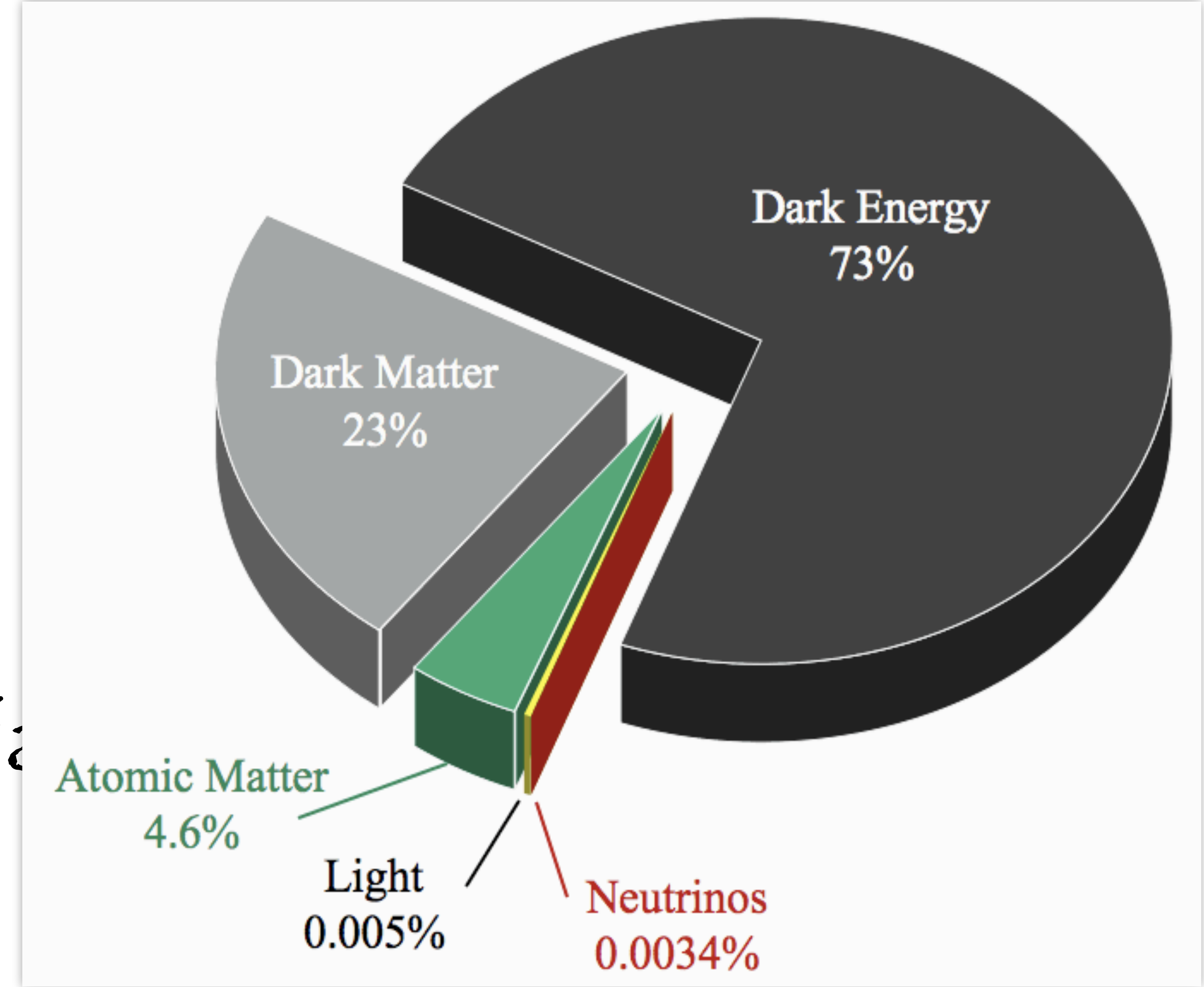

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Experimental anomalies:

What is dark matter/dark energy

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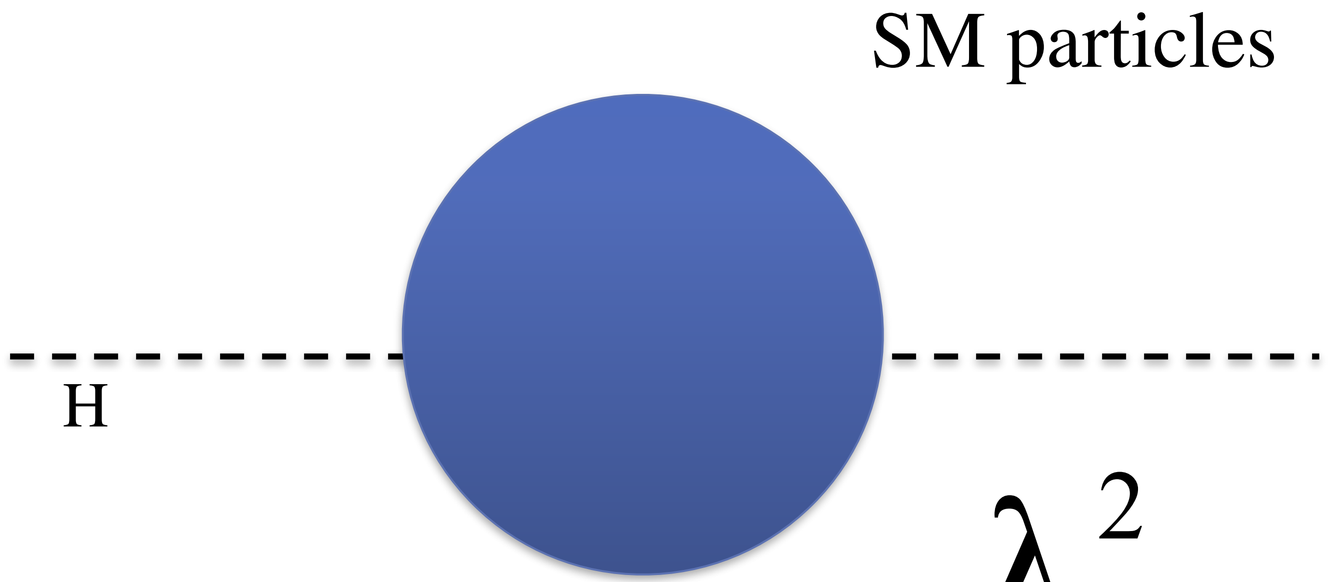
Remaining Puzzles



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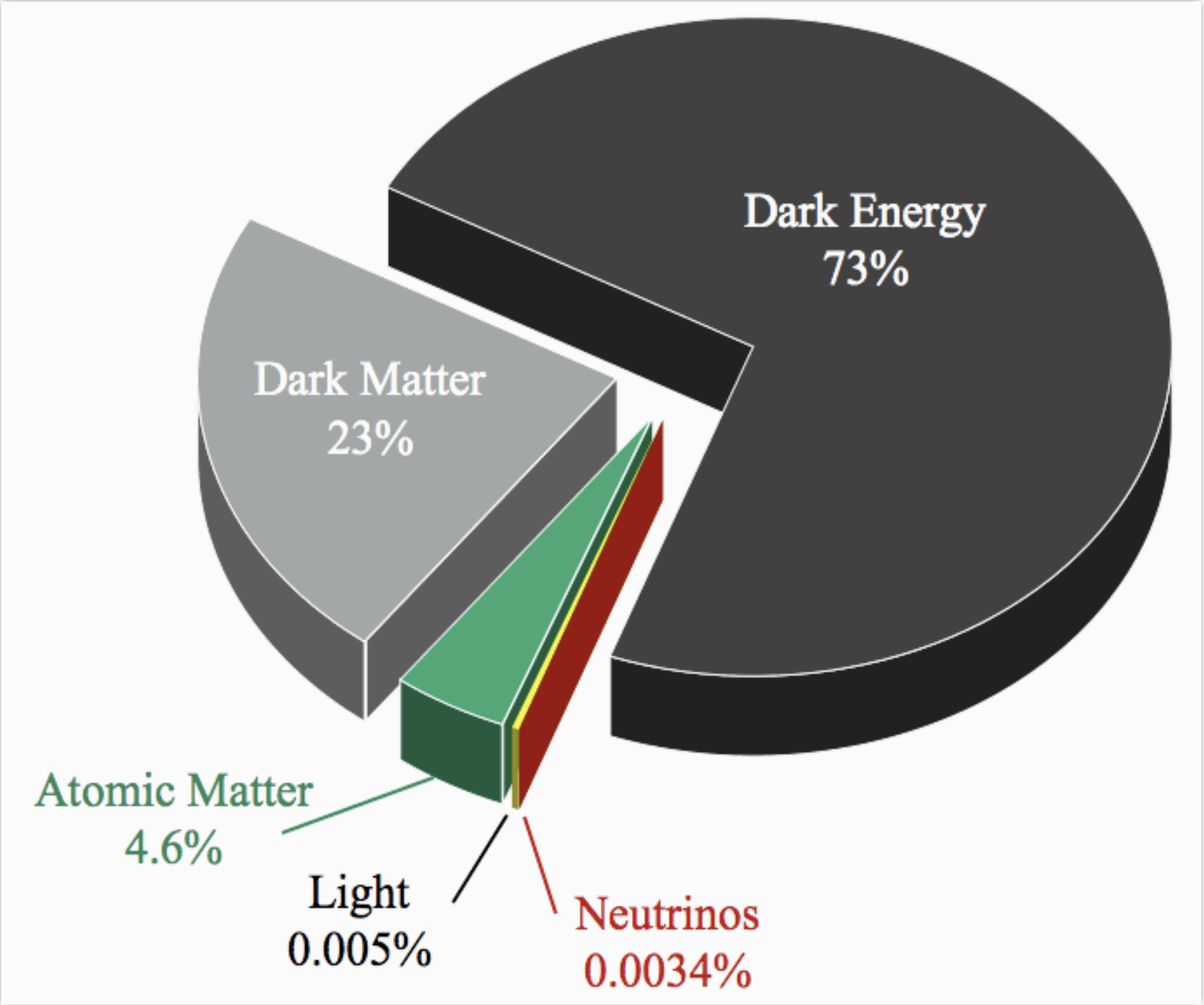
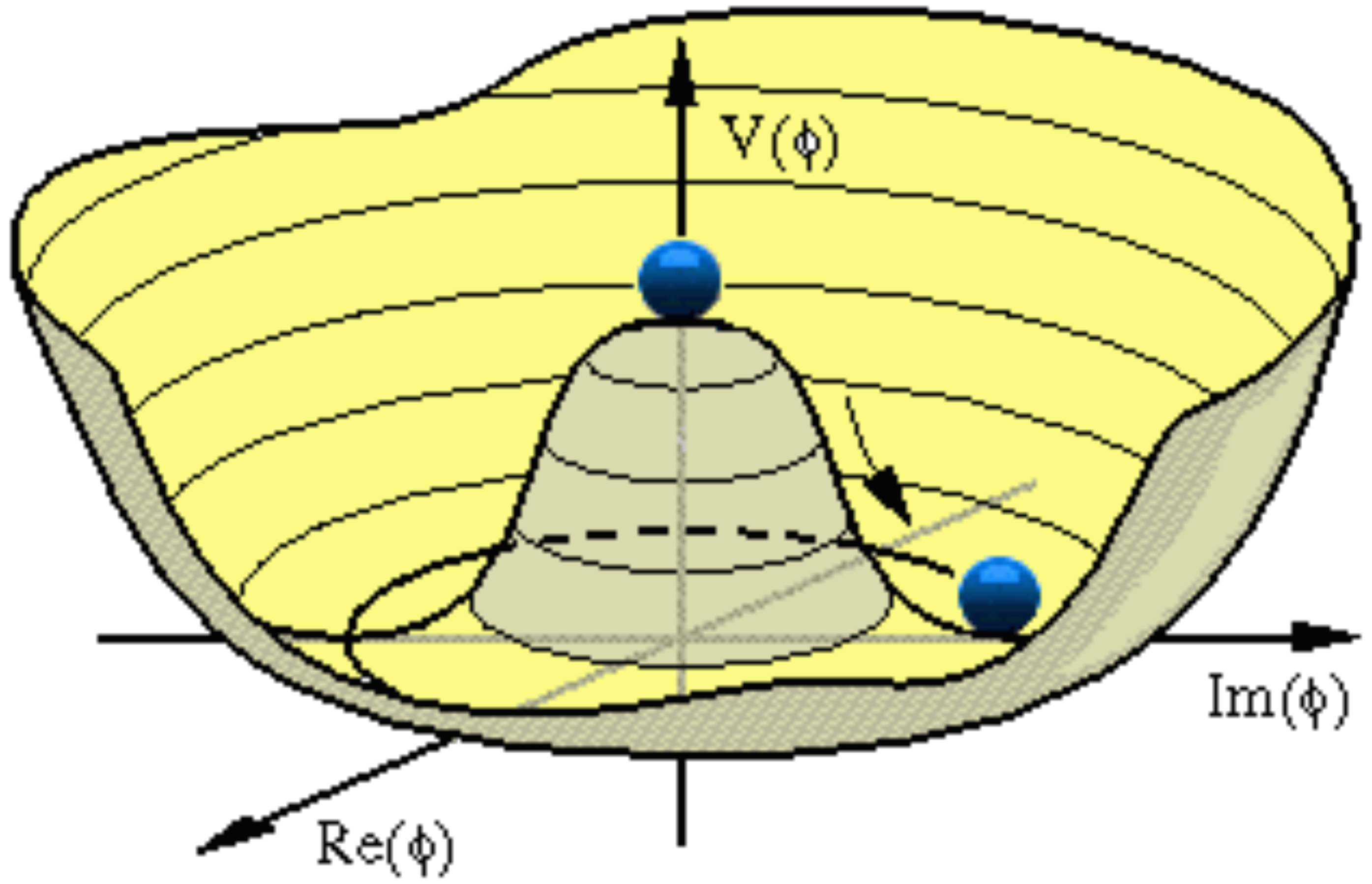
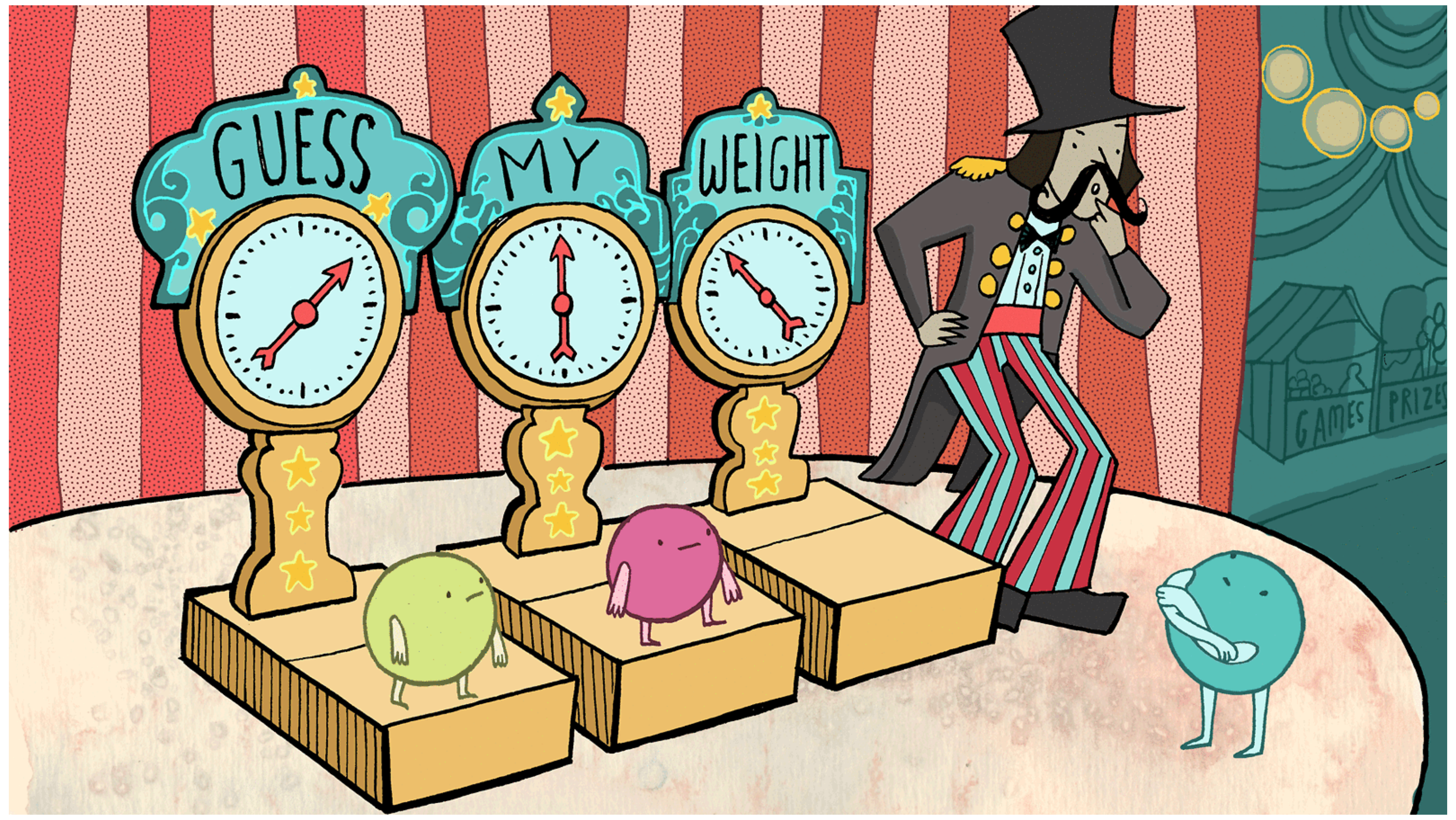




Experimental anomalies:

What is dark matter/dark energy

Neutrino masses/CP etc



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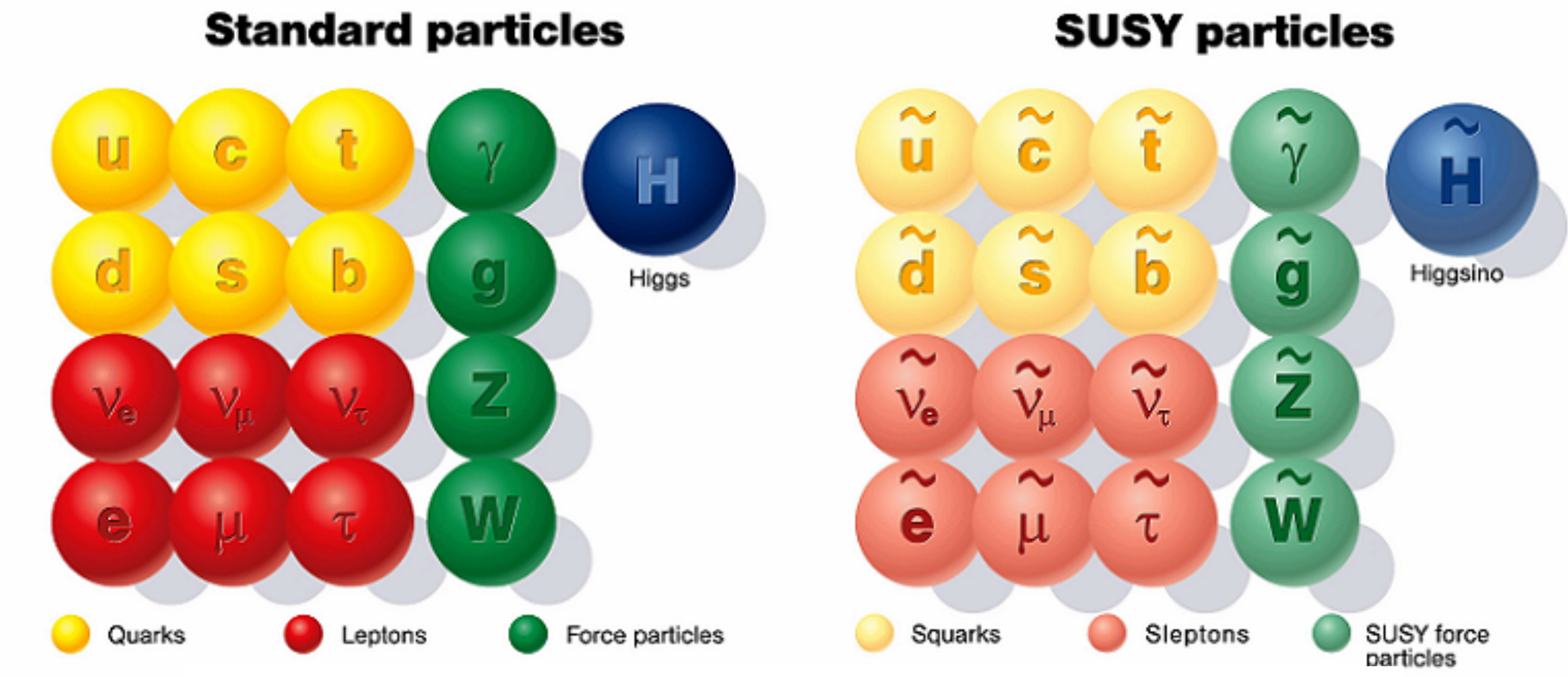
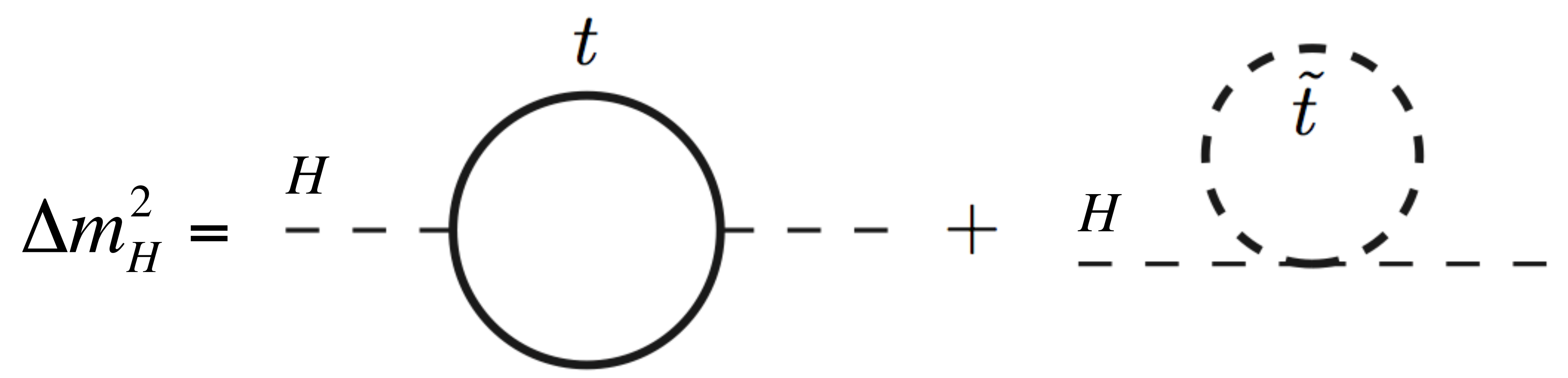
Solutions?
– Beyond the SM extensions

Supersymmetry

- Symmetry between bosons and fermions, appealing theory addition
    - Dark matter candidate, Unifies gauge couplings, stabilized Higgs mass

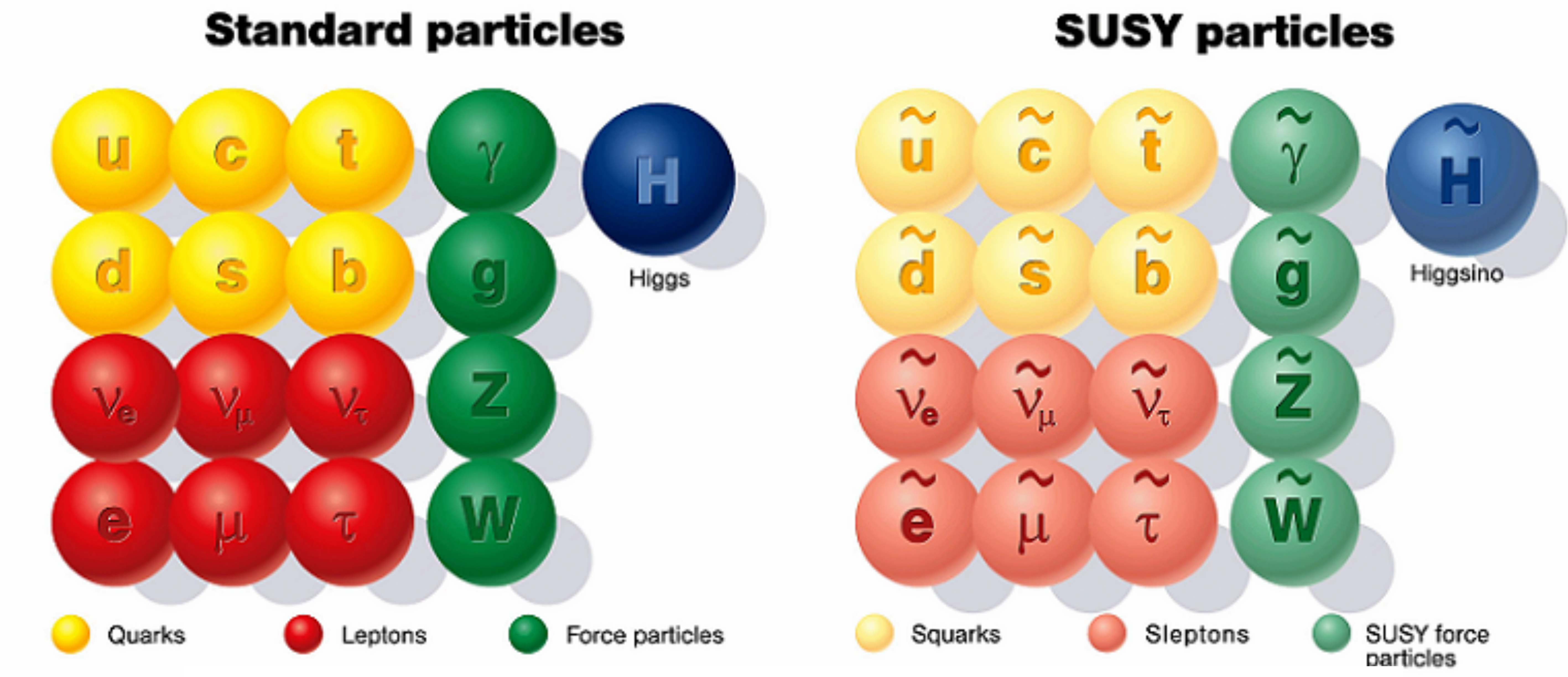


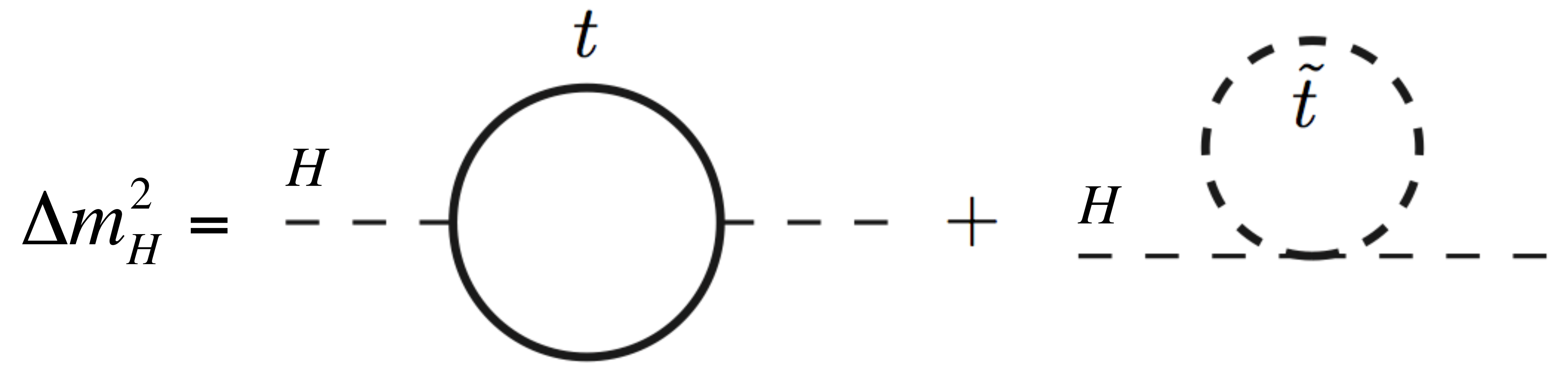


Stabilizes Higgs mass of 125 GeV: stop < 1 TeV

Supersymmetry

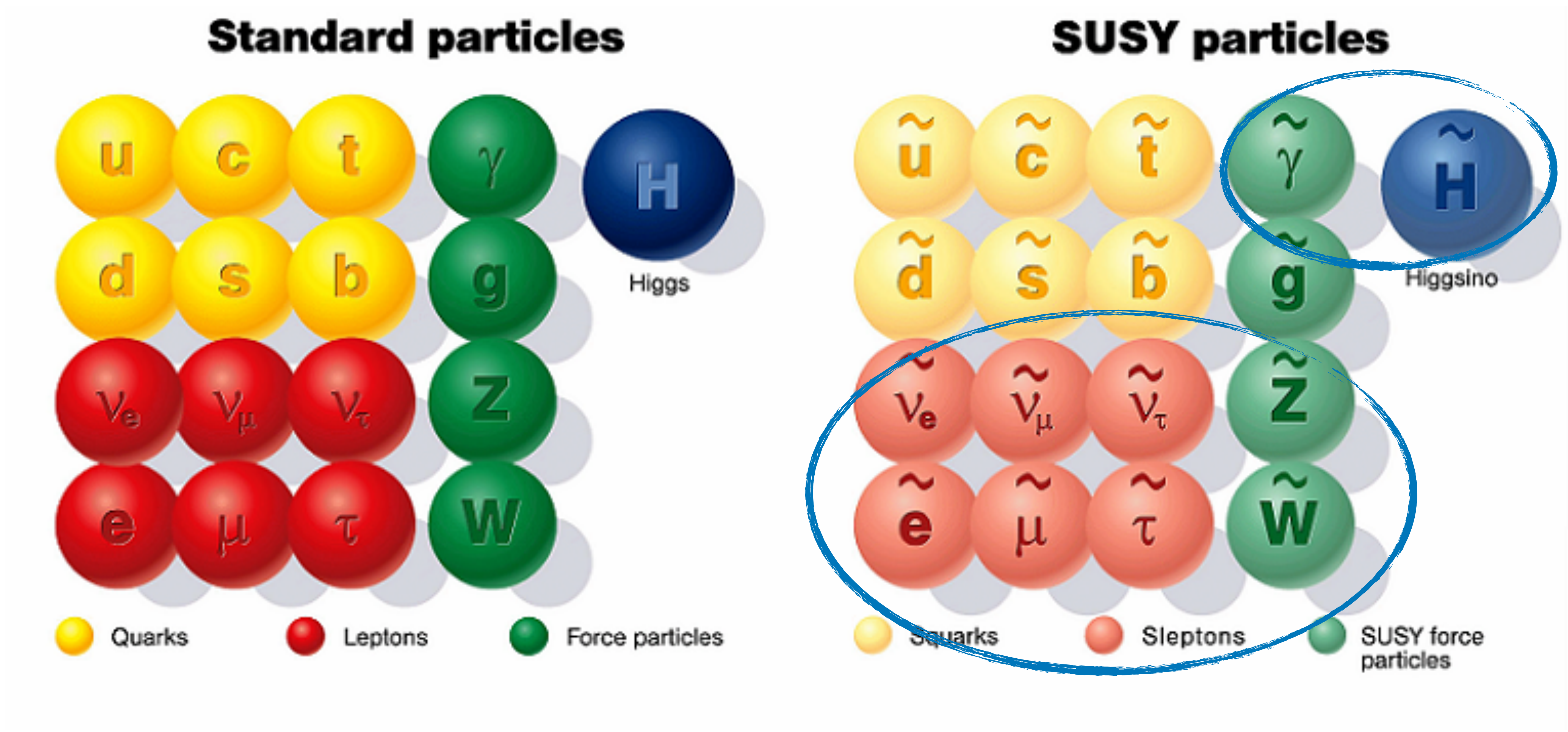
- Important to search for stop with LHC Run-2 data: 8 TeV -> 13 TeV energy increase
  - 1L channel: my first analysis on CMS
  - Quickly probed to 1 TeV with all analyses combined.





Stabilizes Higgs mass of 125 GeV: stop < 1 TeV

SUSY electroweak sector: less probed



SUSY partners of the electroweak sector of much lower rate:

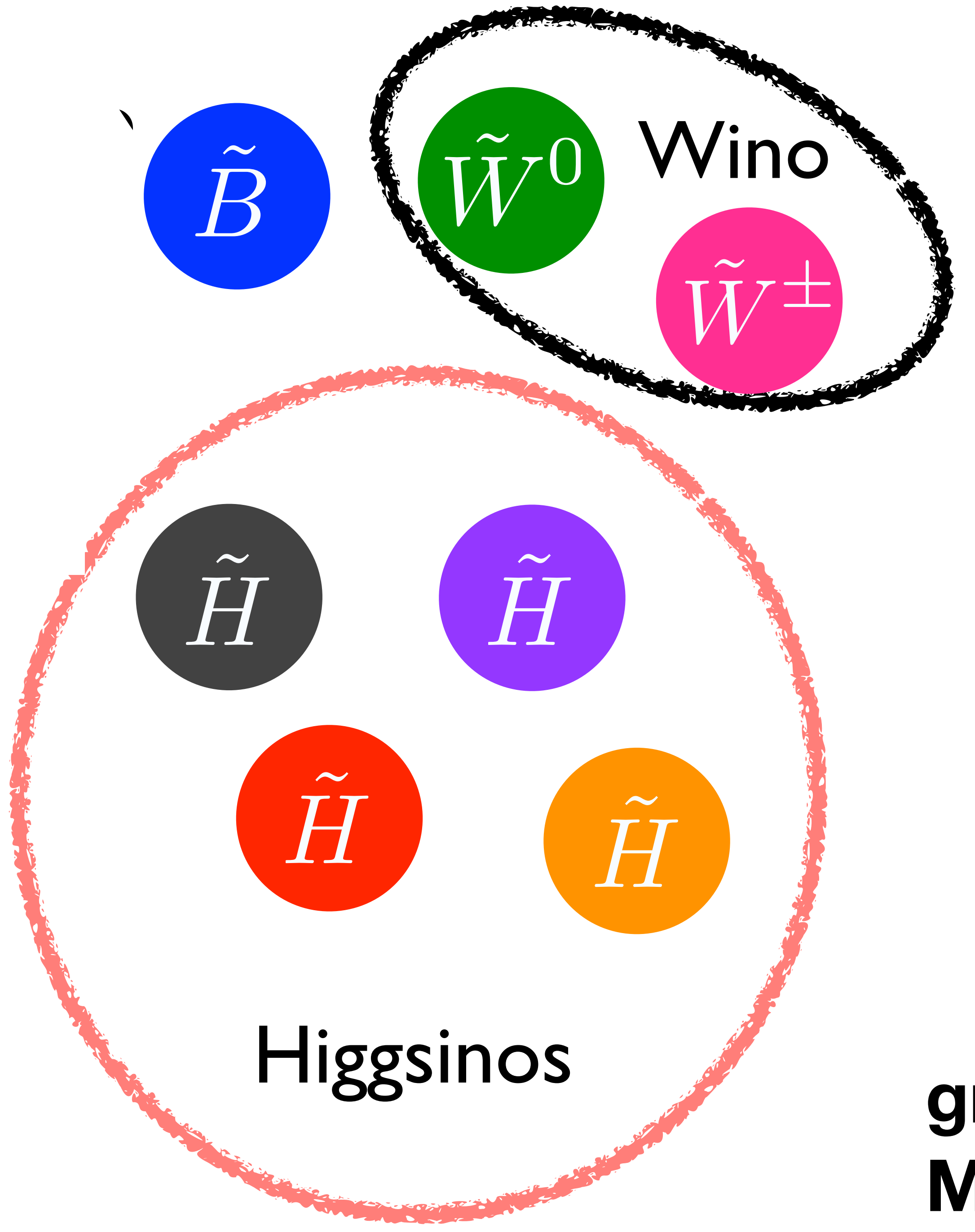
3 to 5 orders of magnitude lower

Review: Electroweak SUSY terminology

What are gauginos, Higgsinos and Sleptons ?

- SUSY partners of the SM electroweak sector
  - U(1)-> Bino, SU(2)->Winos
  - Higgs-> Higgsinos
  - Leptons-> sleptons

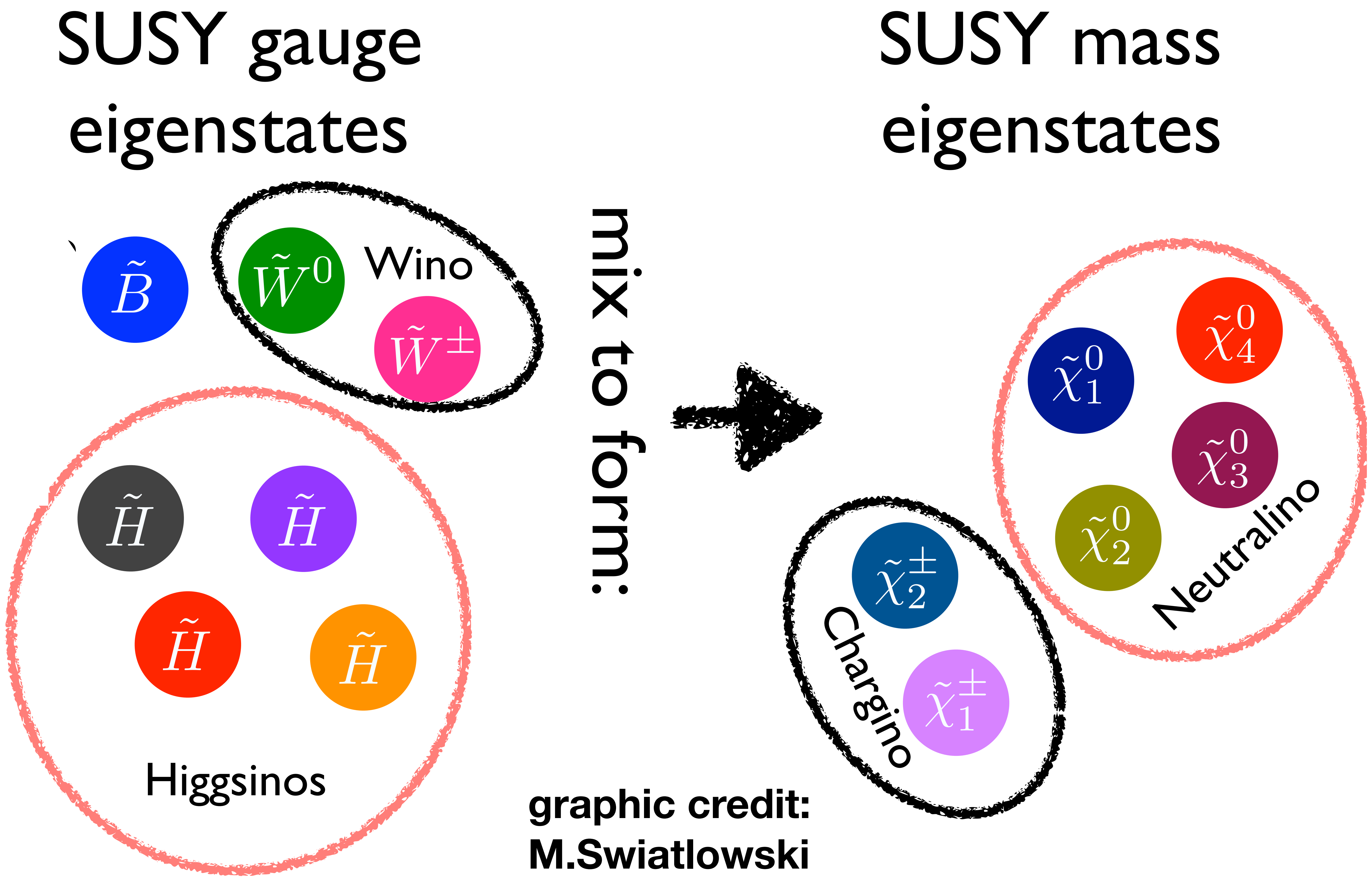
SUSY gauge eigenstates



graphic credit: M.Swiatlowski

Charginos and neutralinos

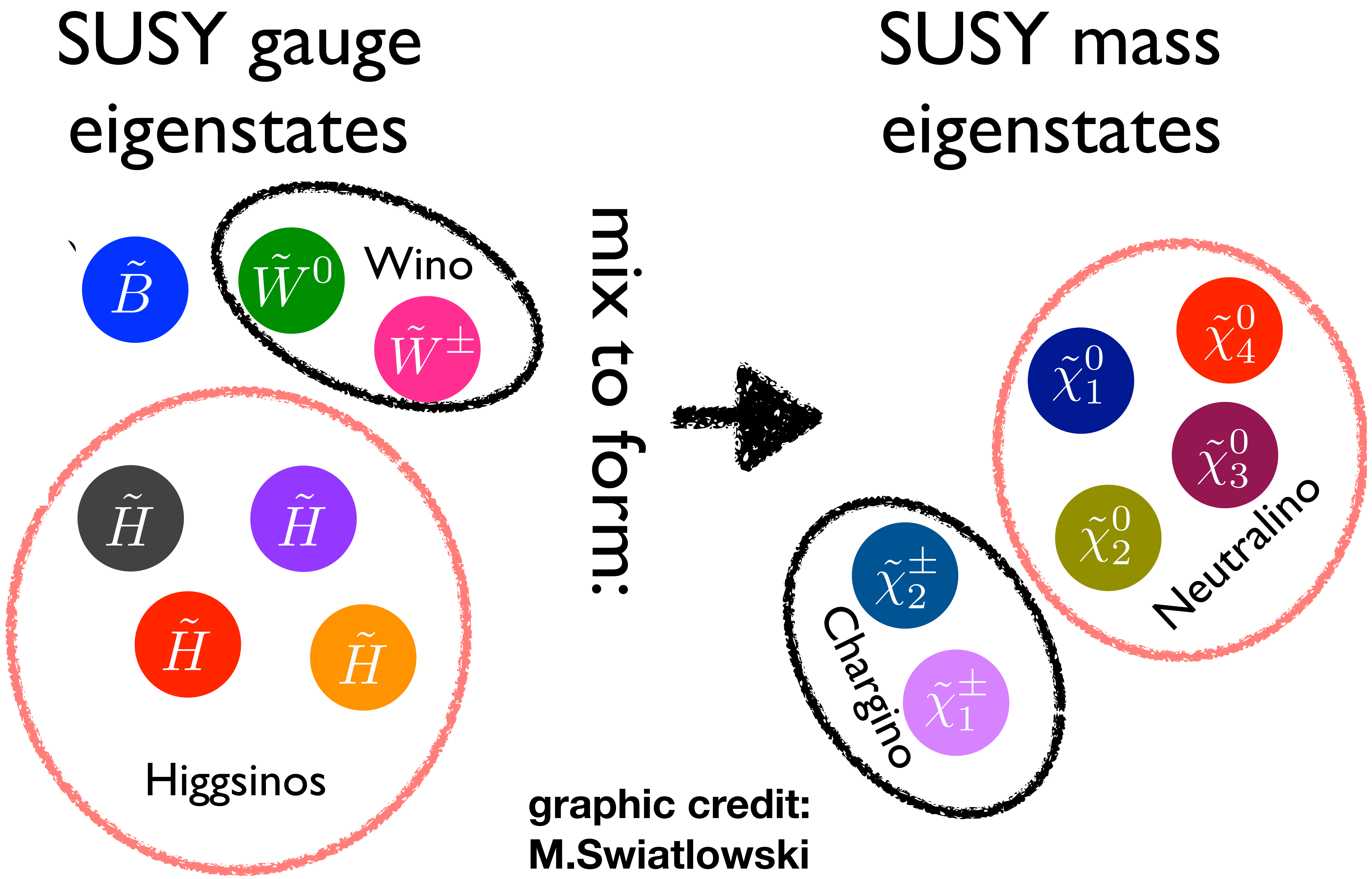
- SUSY partners of the SM electroweak sector
  - U(1)-> Bino, SU(2)->Winos
  - Higgs-> Higgsinos
  - Leptons-> sleptons



graphic credit: M.Swiatlowski

Gauginos and higgsinos can be light

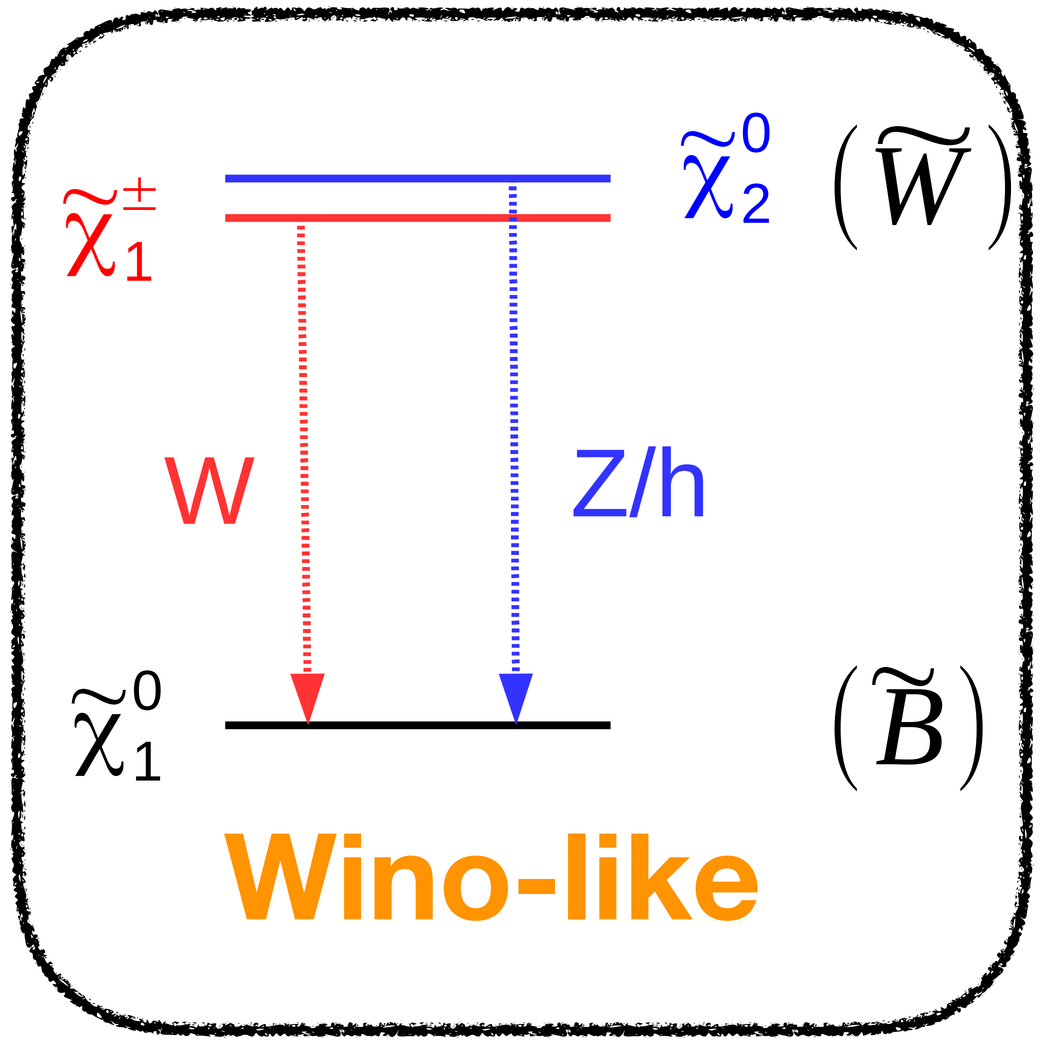
- Possible SUSY spectrum as of today:
  - Heavy squarks and gluinos
  - Gauginos and higgsinos are light
- Important to search for electroweak SUSY partners at the LHC!

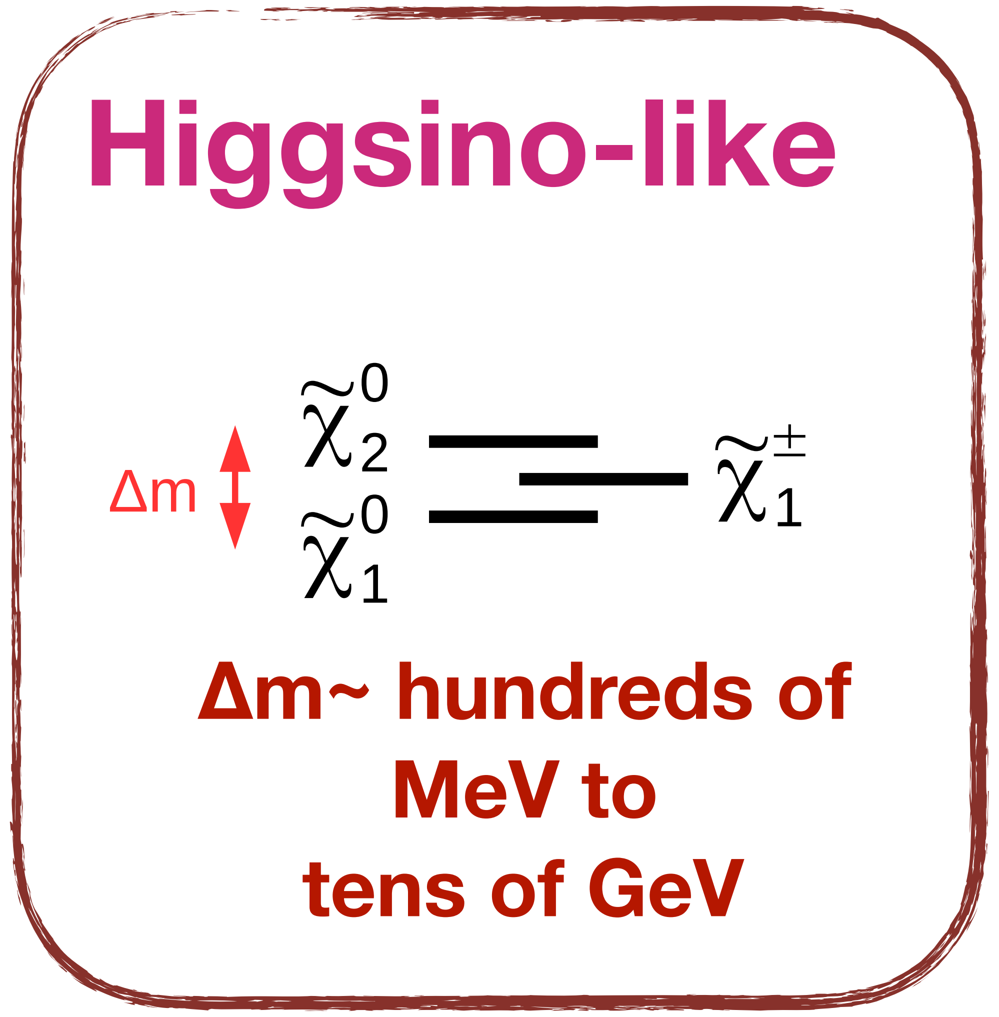


graphic credit: M.Swiatlowski

Typical mass spectrums of chargino-neutralinos

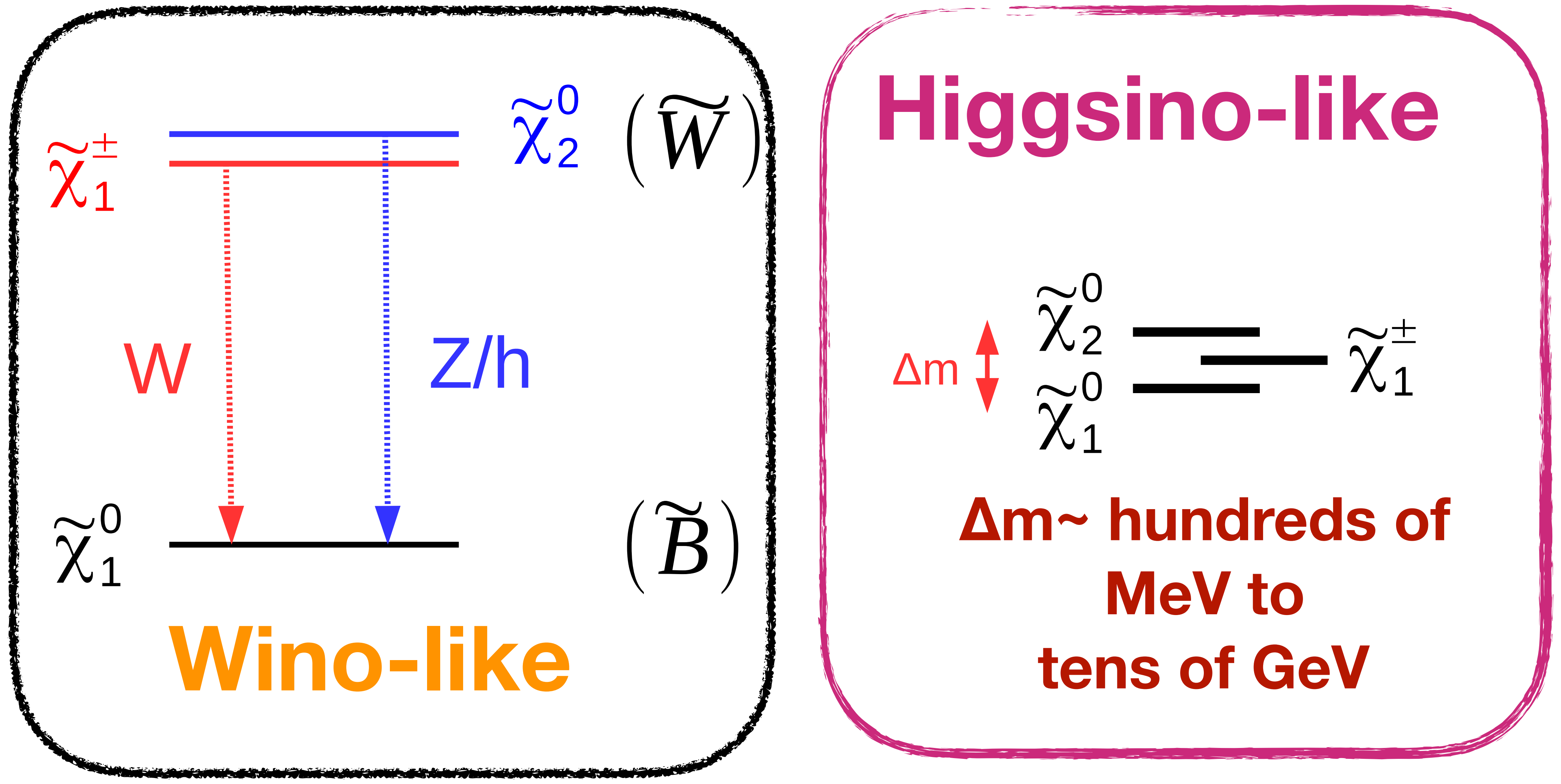
- Depending on the mass scales of Bino/Winos/Higgsinos:
  - lightest chargino/ neutralinos form different mass spectrums
- Two main mass spectrums explored at the LHC: Wino-like, Higgsino-like





Typical mass spectrums of chargino-neutralinos

- Wino-like spectrum has larger cross section—> Let's start looking here!



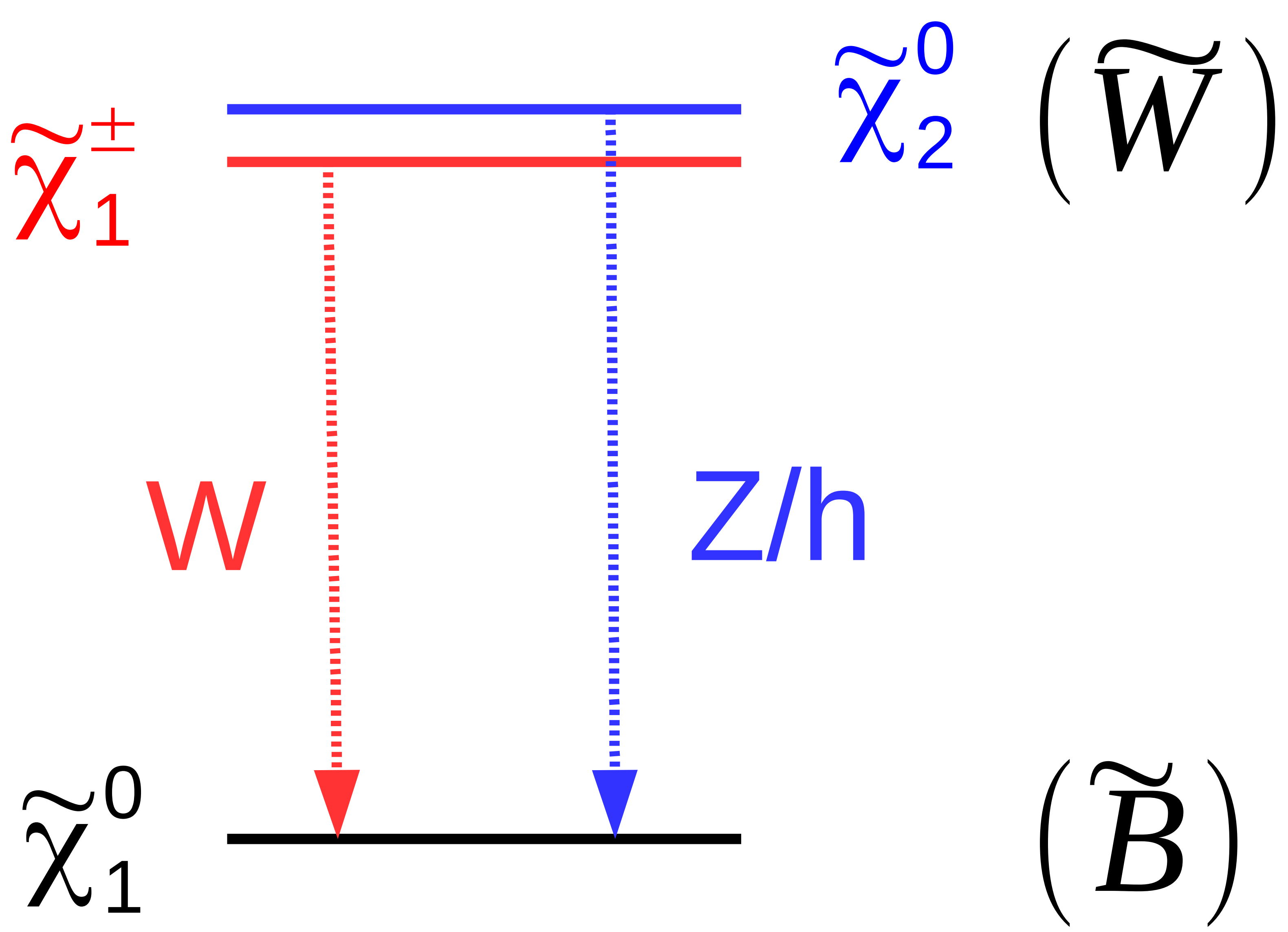
45 fb*

11 fb*

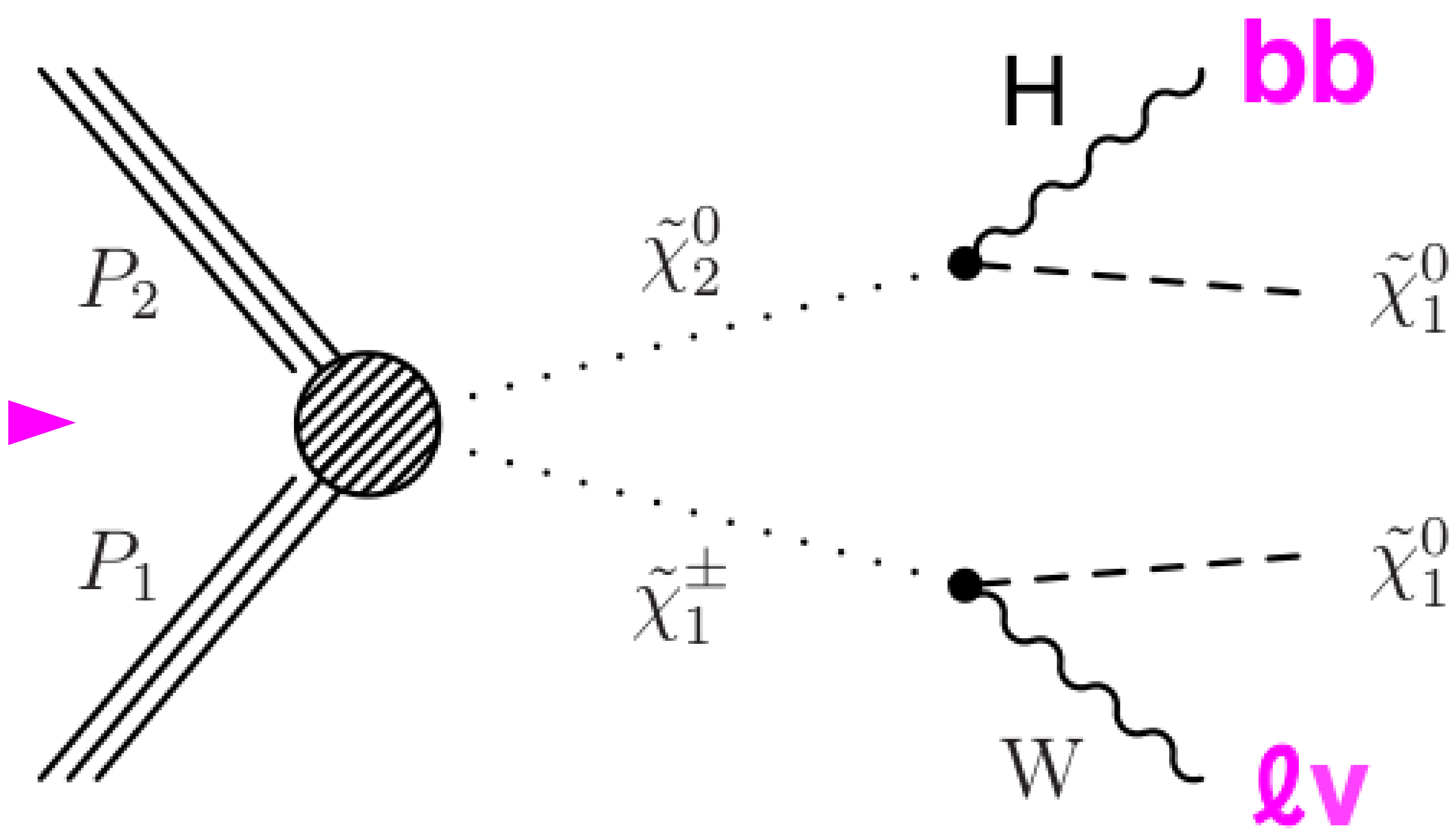
*Cross-sections for 500 GeV sparticles @ 13 TeV

($\tilde{\chi}_2^0 \tilde{\chi}_1^{\pm}$ only)

Why one lepton + bb +MET?

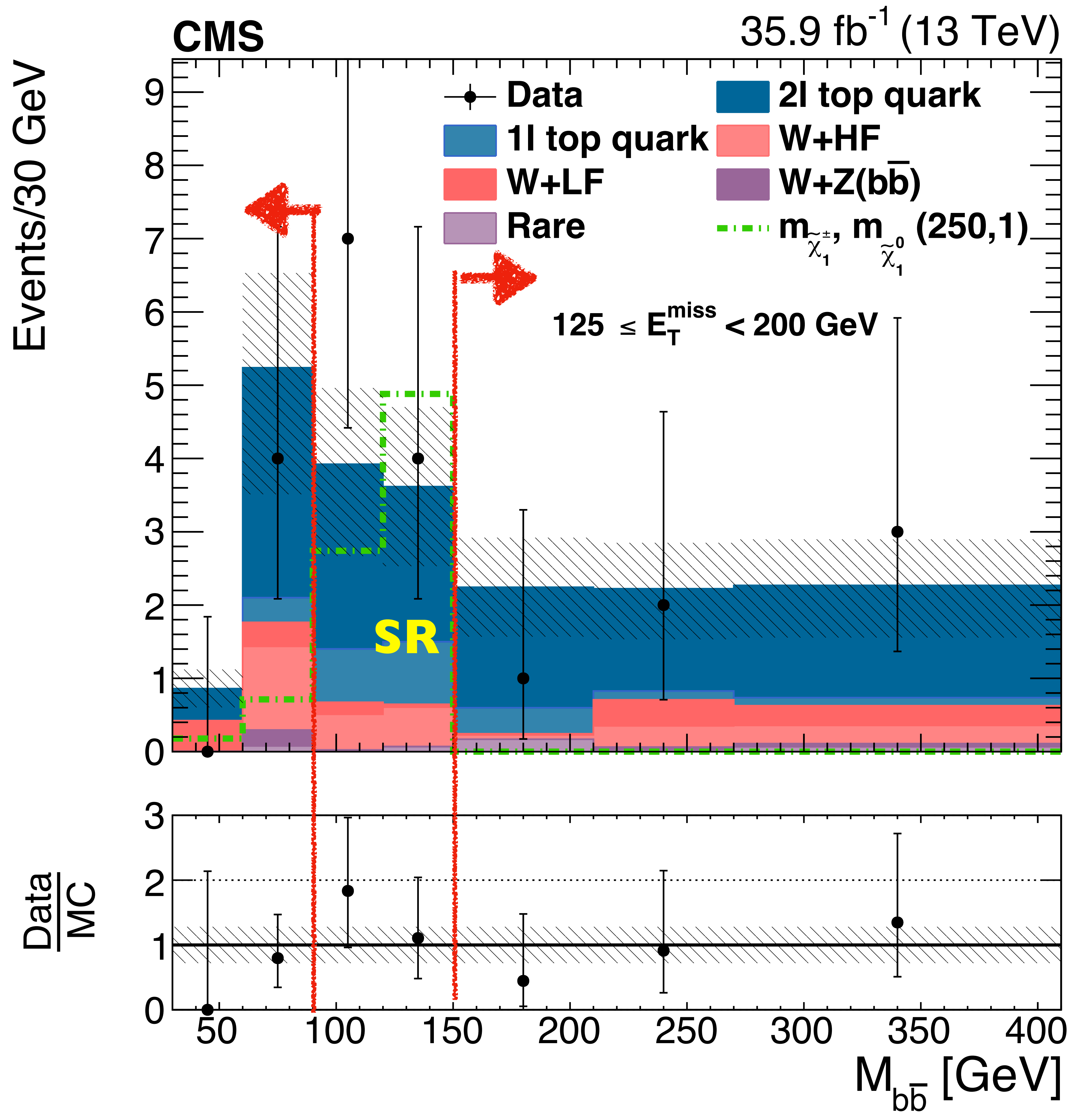


$\chi^{\pm}\chi^0 \rightarrow W(\ell v)H(bb)$+MET



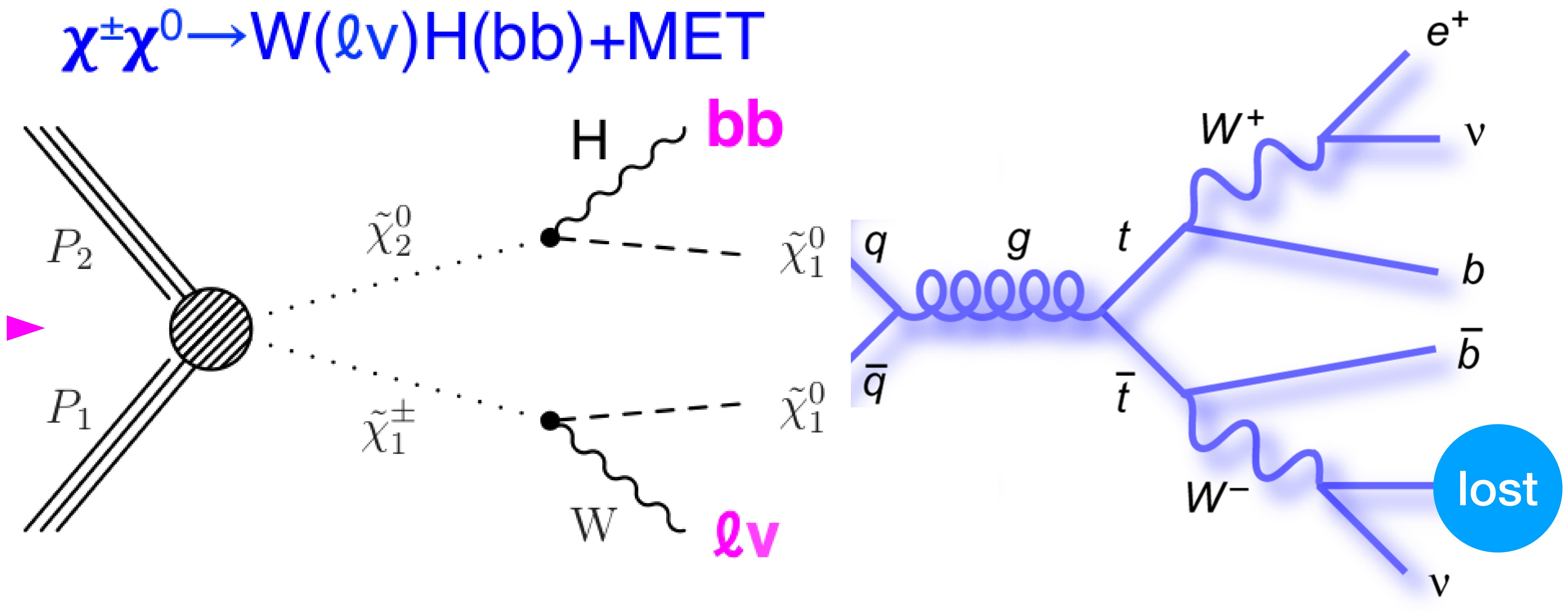
- WH topology: less constrained from 8 TeV searches compared to WZ
- In the WH topology: 1 lepton (e/μ)+bb: trigger on leptons and handle against backgrounds, large BF of H->bb (60%)

Search for Higgs peak in the kinematic tails



10.1007/JHEP11(2017)029

$\chi^\pm\chi^0 \to W(\ell\nu)H(bb)+MET$



- Mbb: Higgs peak in the kinematic tails of MET etc, where SM processes fall off quickly
- O(1) signal yields compared to backgrounds
- Higgs mass sideband: Directly control ttbar 2L

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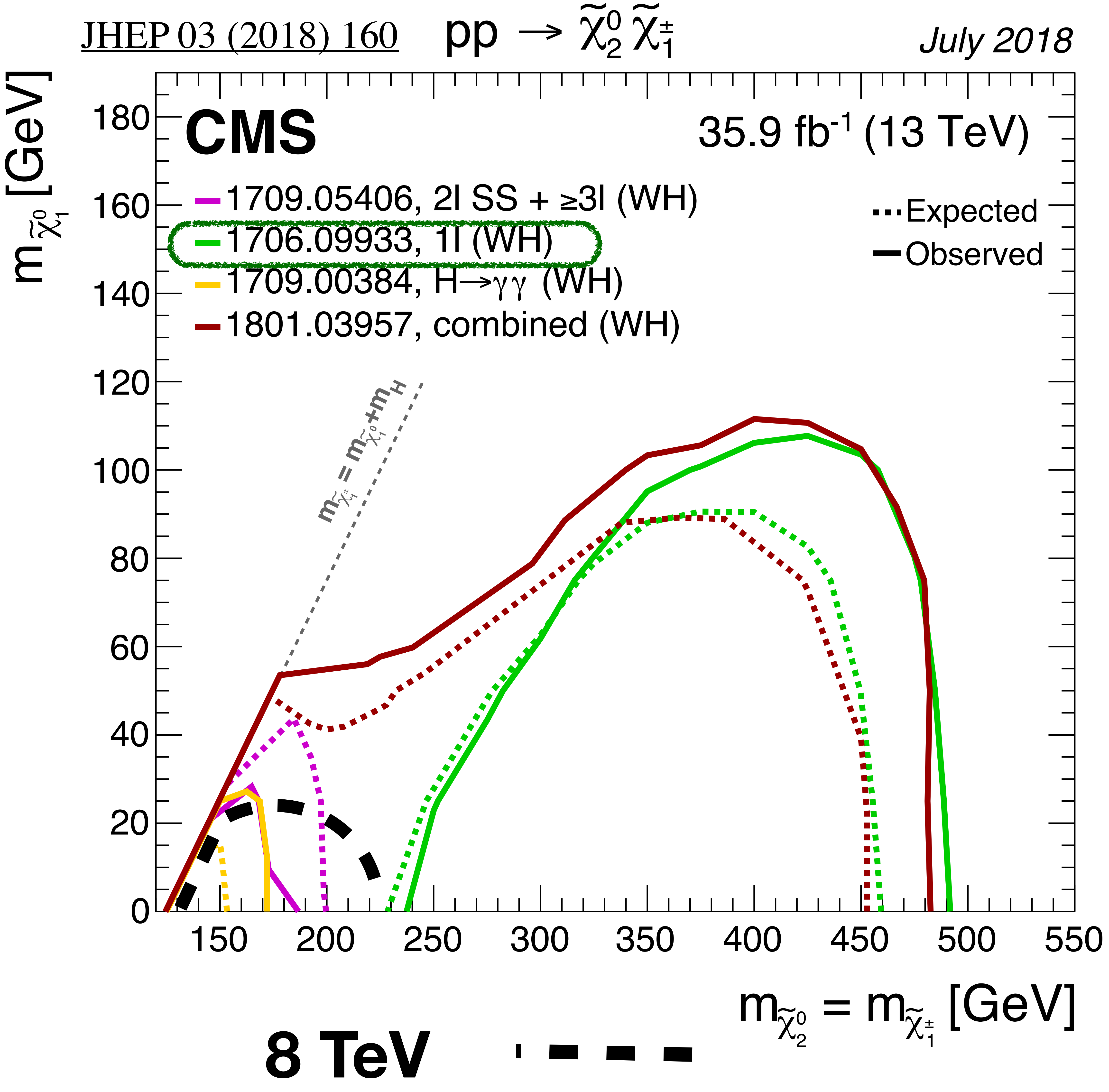
WH(lνbb) + MET: pushing Wino limits



- Probes chargino mass up to 500 GeV in the WH topology
- 300 GeV improvement wrt 8 TeV reach
- Dominates the sensitivity in the bulk.

No SUSY (or any other BSM physics which can enter our selections) found yet by ATLAS or CMS

Fermilab

Amazing predictions from the SM

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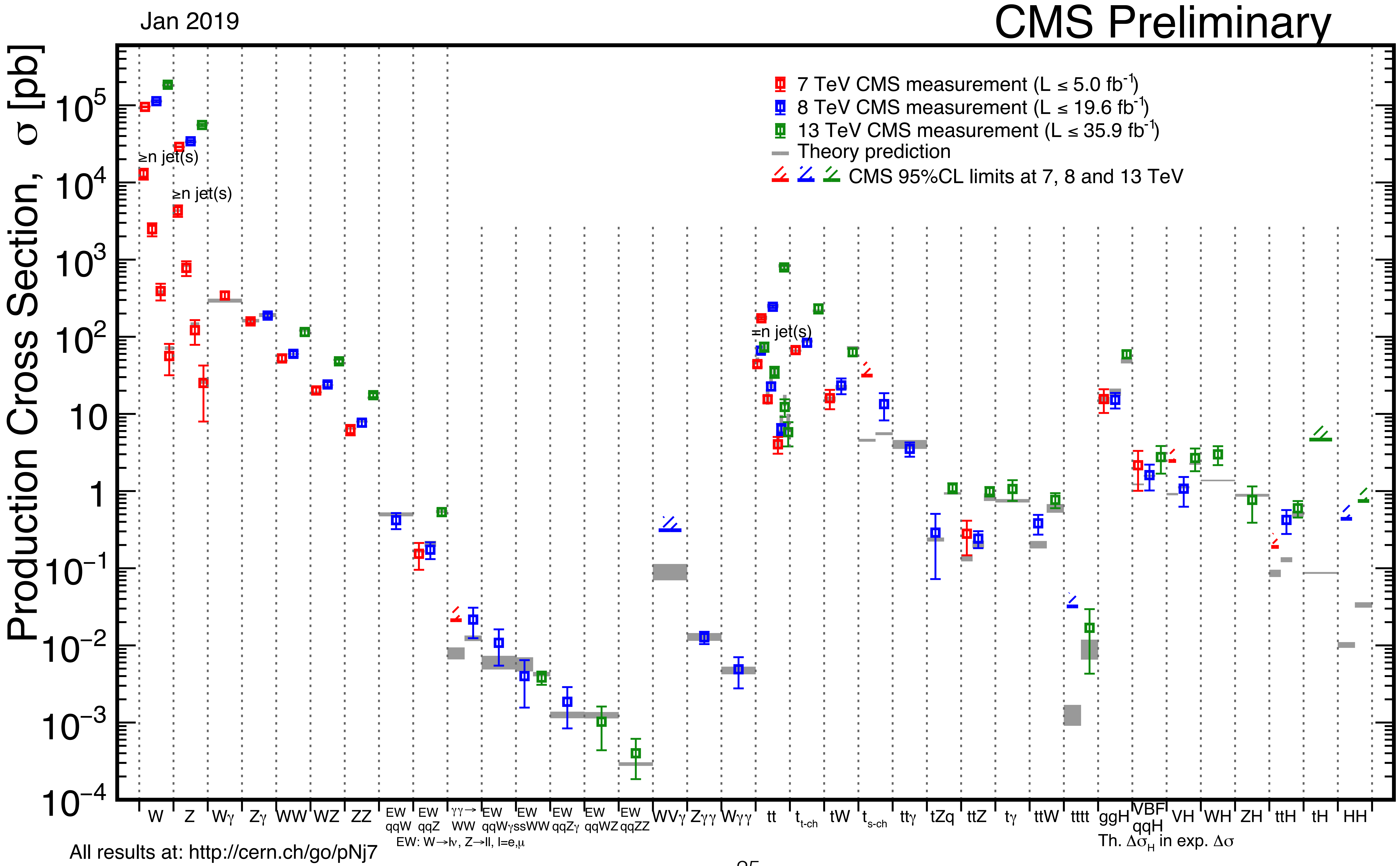
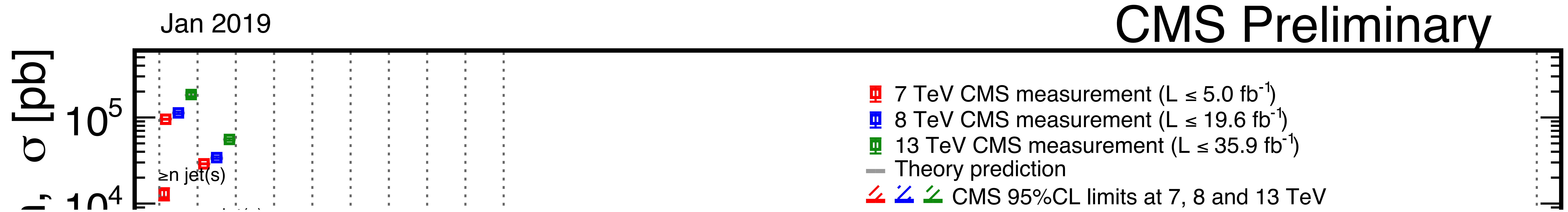


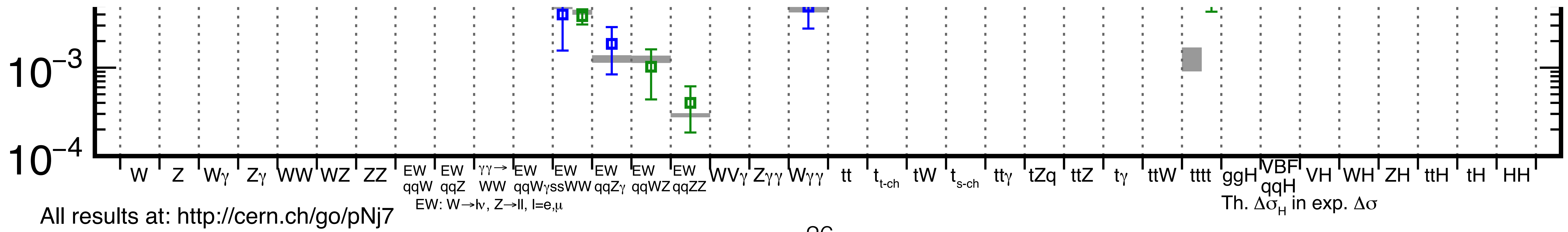
Amazing predictions from the SM



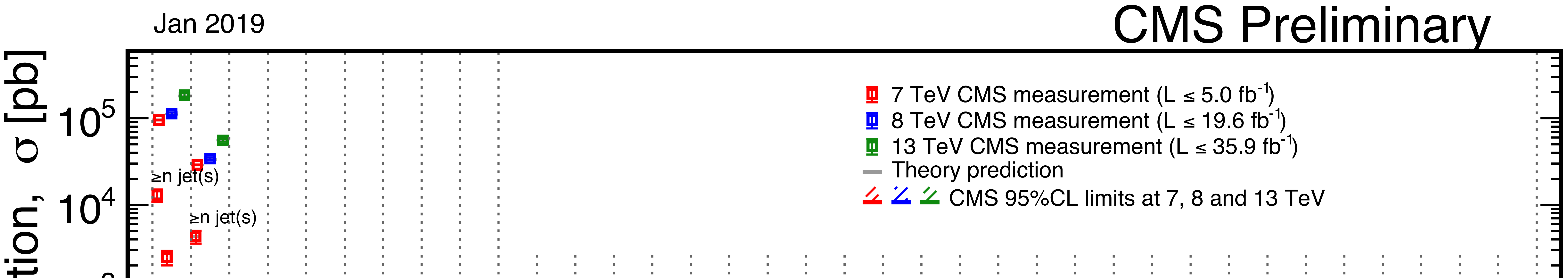
A historical reflection:

The development of the SM was driven by experimental anomalies: mesons/baryons…

–The SM then guided our searches of fundamental particles

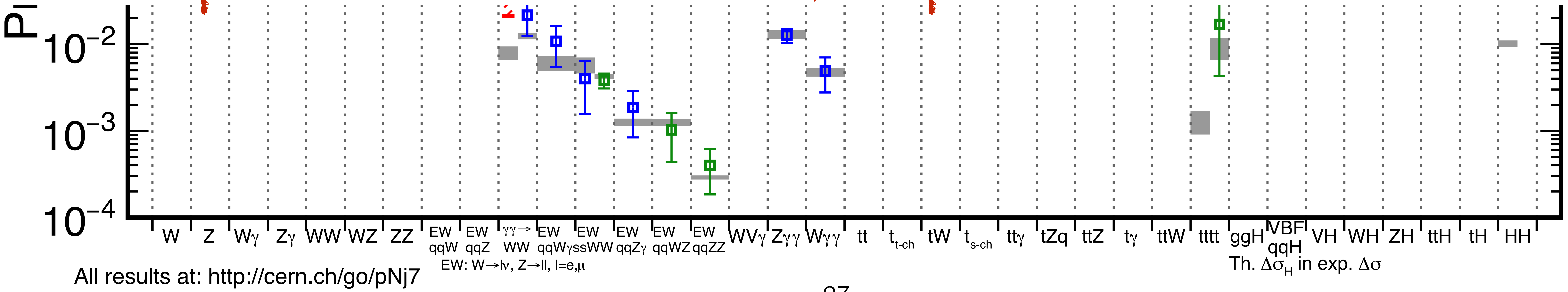


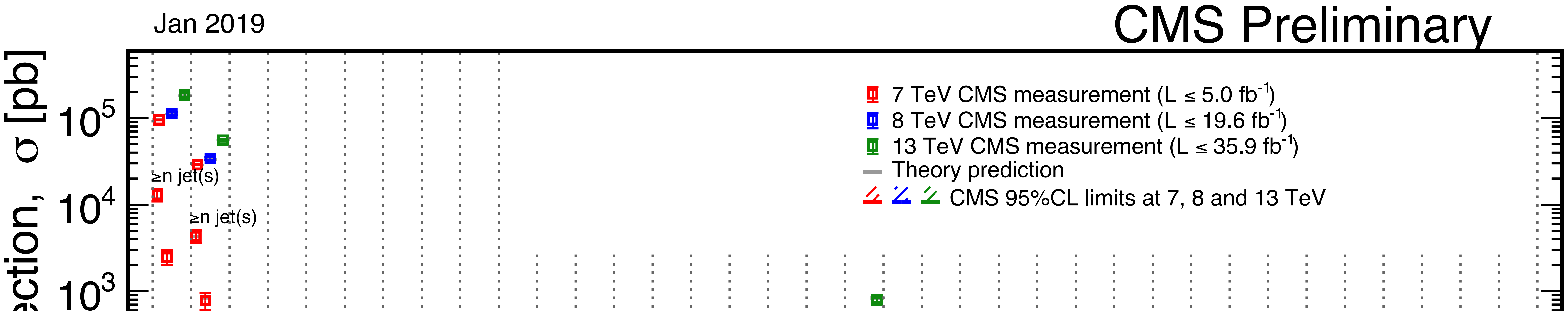
Amazing predictions from the SM



– BSM theory driven searches have large focus on kinematic tails (8 TeV->13 TeV) -> no anomalies

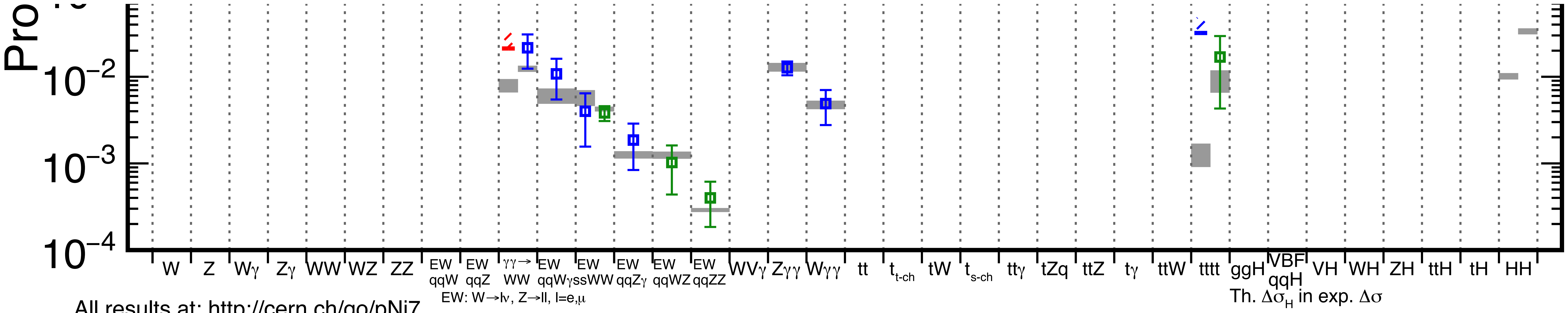
– Have to be accompanied by stringent tests of the SM predictions to look for possible anomalies





One way of doing this

- Test rare processes: rare top (four top)/rare Higgs (H->μμ)....
- Directly benefit from the large LHC Run-2 dataset: 150fb-1

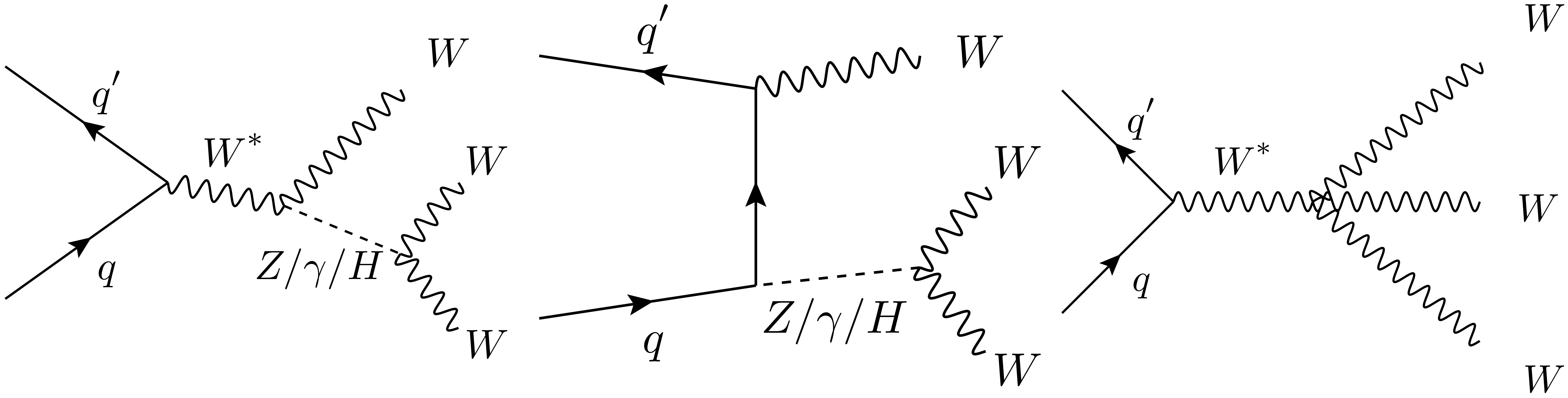


My interest:
Search for a very rare process in the electroweak sector:

WWW production at the LHC

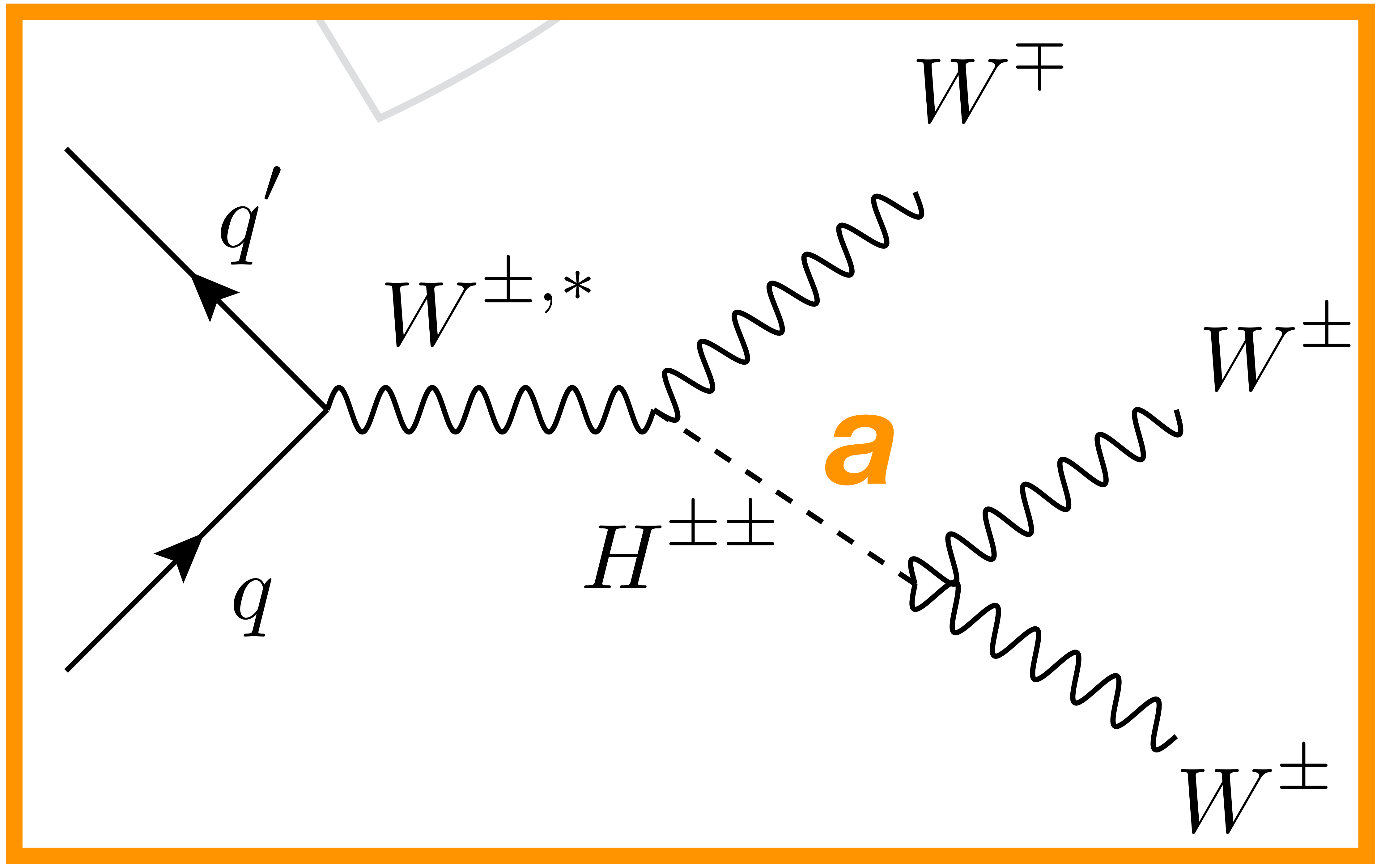
Physics motivation for measuring WWW

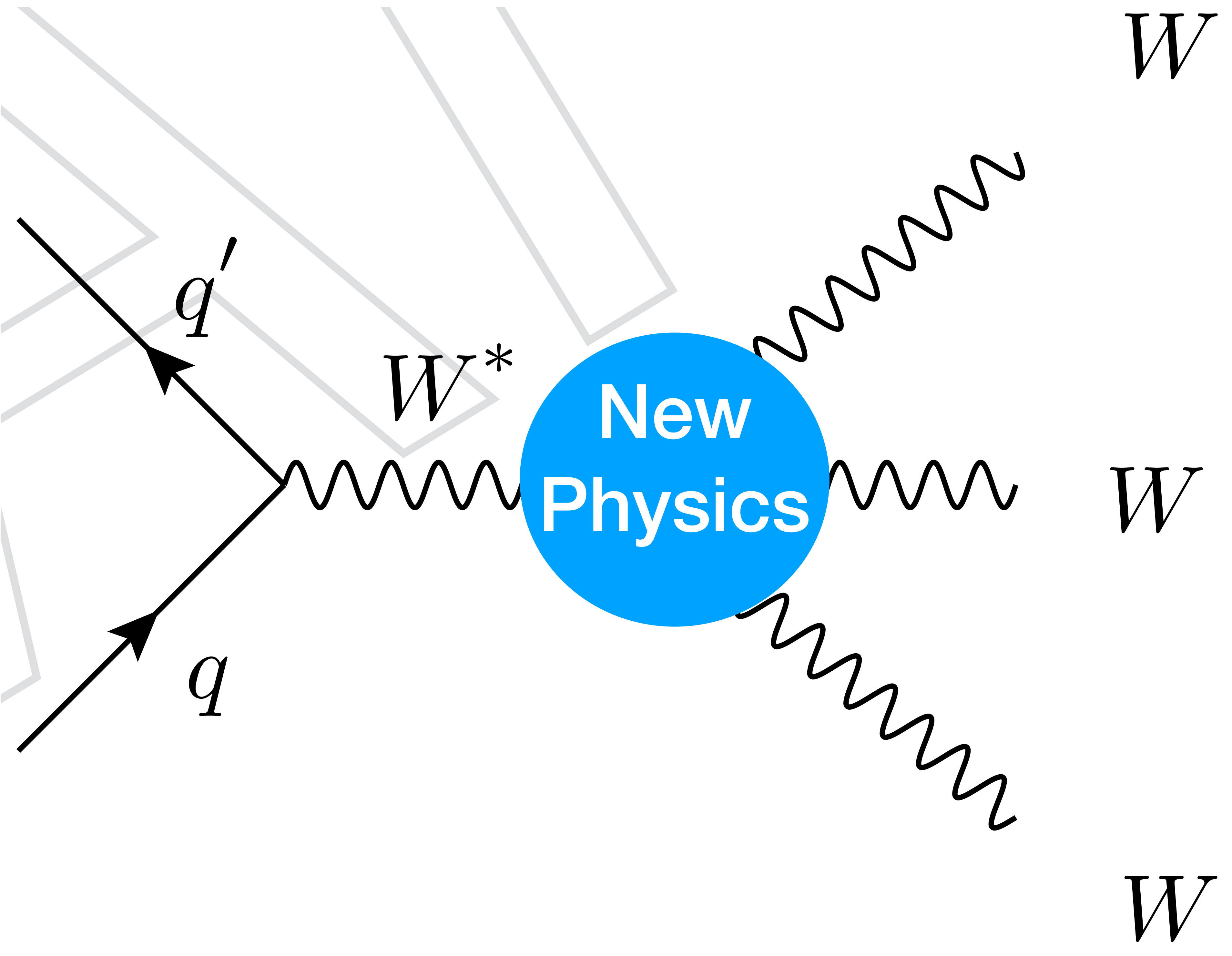
Higgs-mediated | triple gauge coupling | quartic gauge coupling



This process has low cross section
Requires Run 2 data @ 13 TeV to be studied

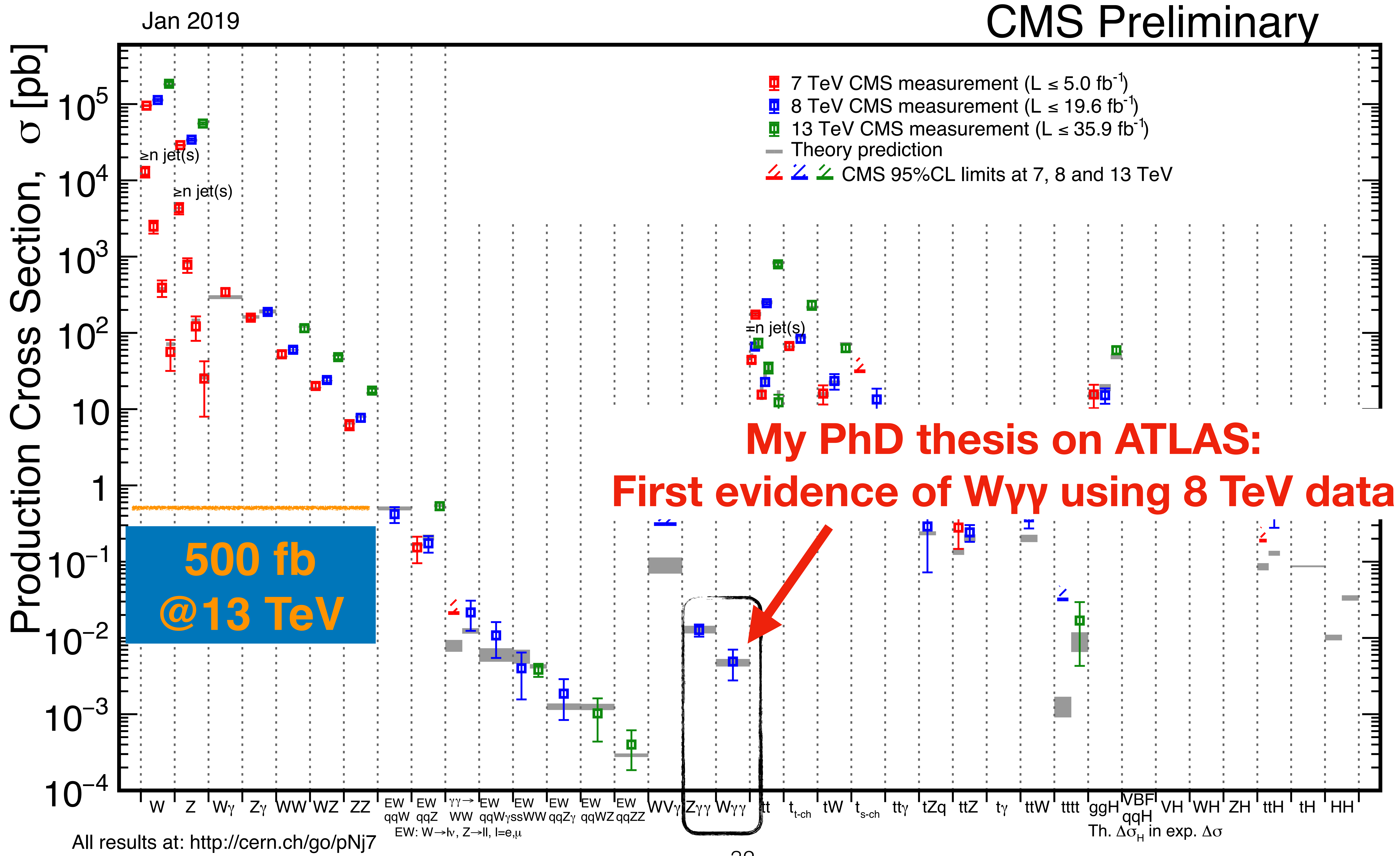
Sensitive to BSM contributions





Doubly charged Higgs/axion-like particles, anomalous couplings coming from new physics beyond our kinematic reach

WWW: Low cross section



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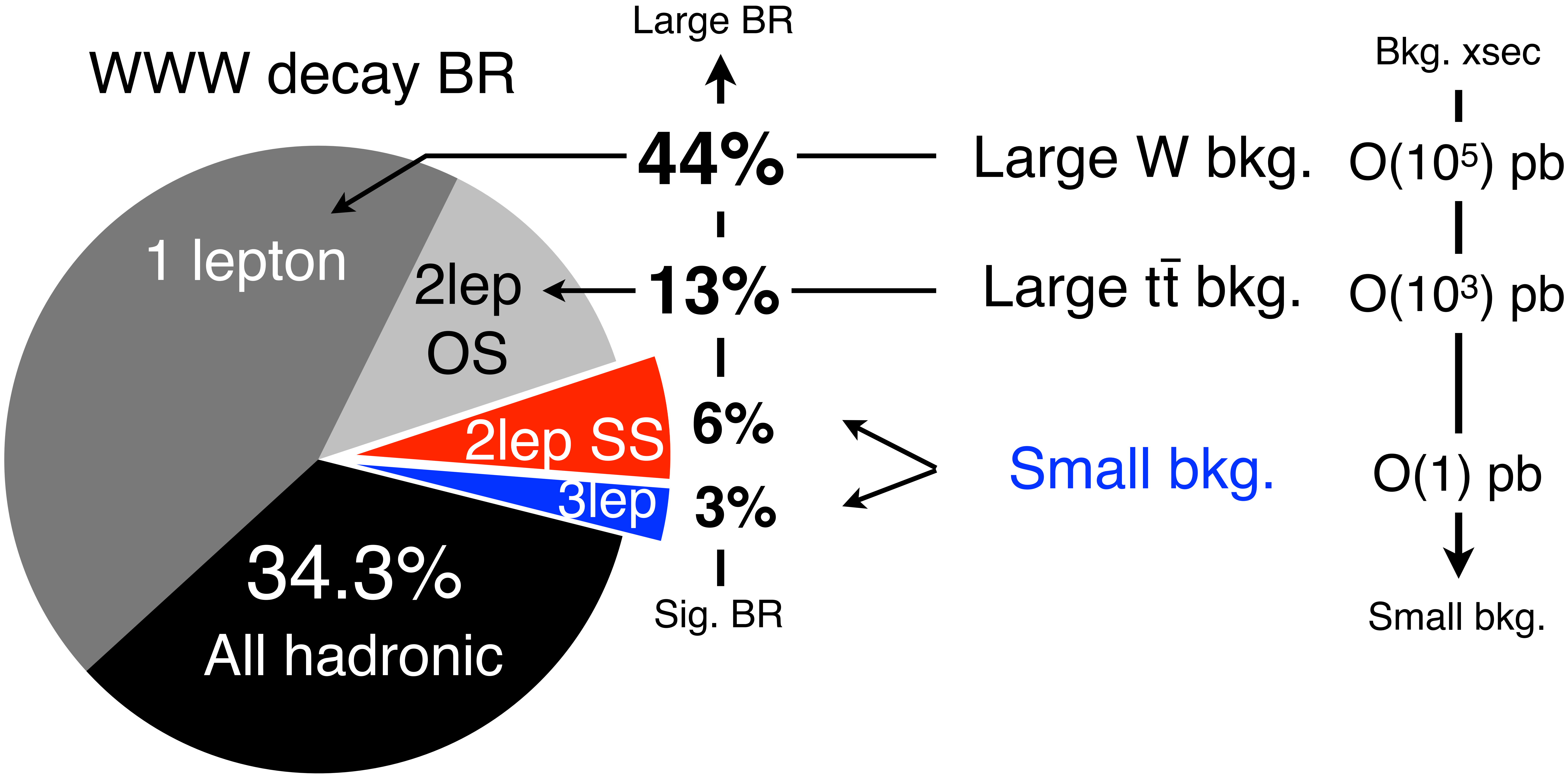
WWW: the "measurable" part is small…



Target same-sign 2 lepton and 3 lepton final state **:< 10 % of the total**

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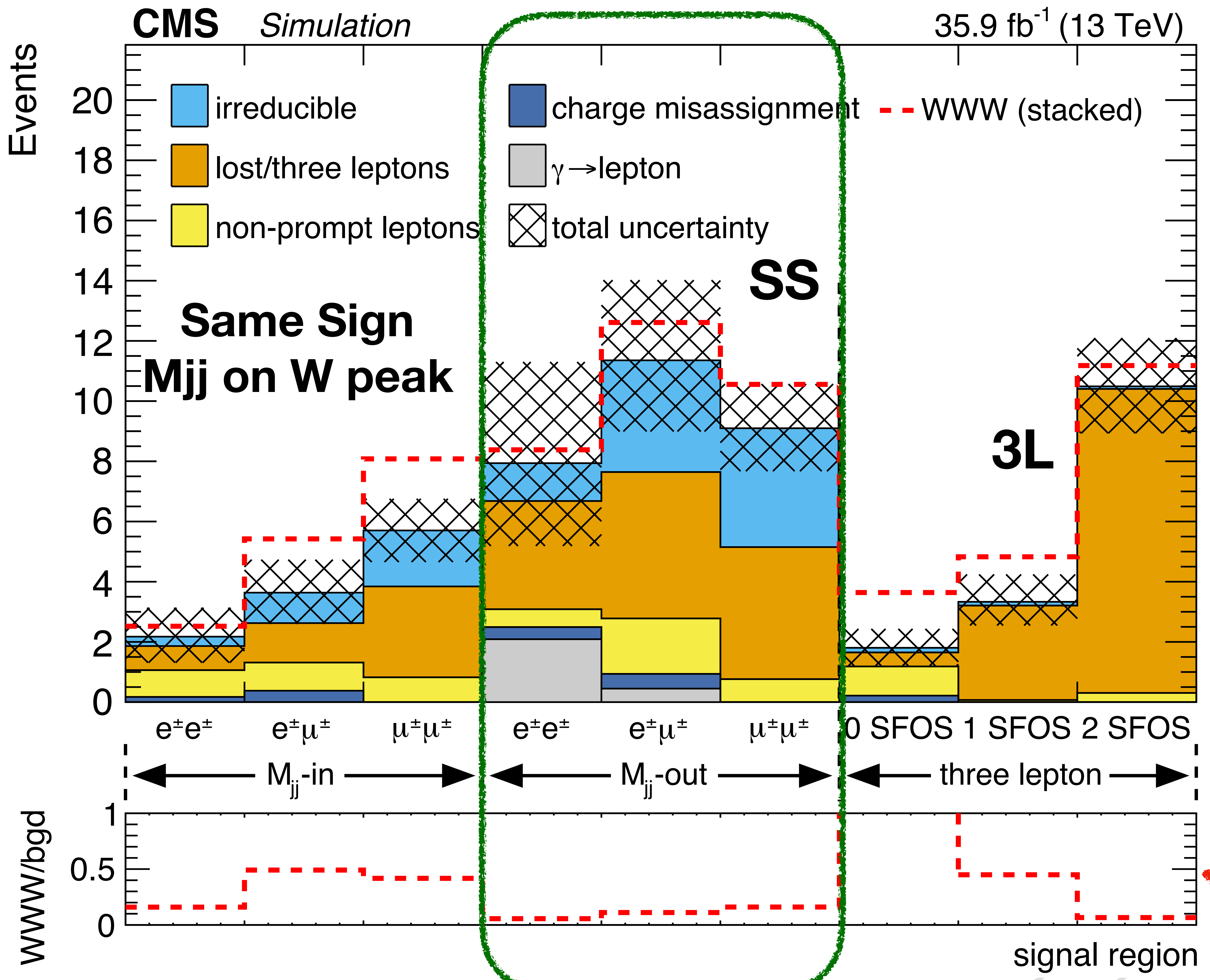
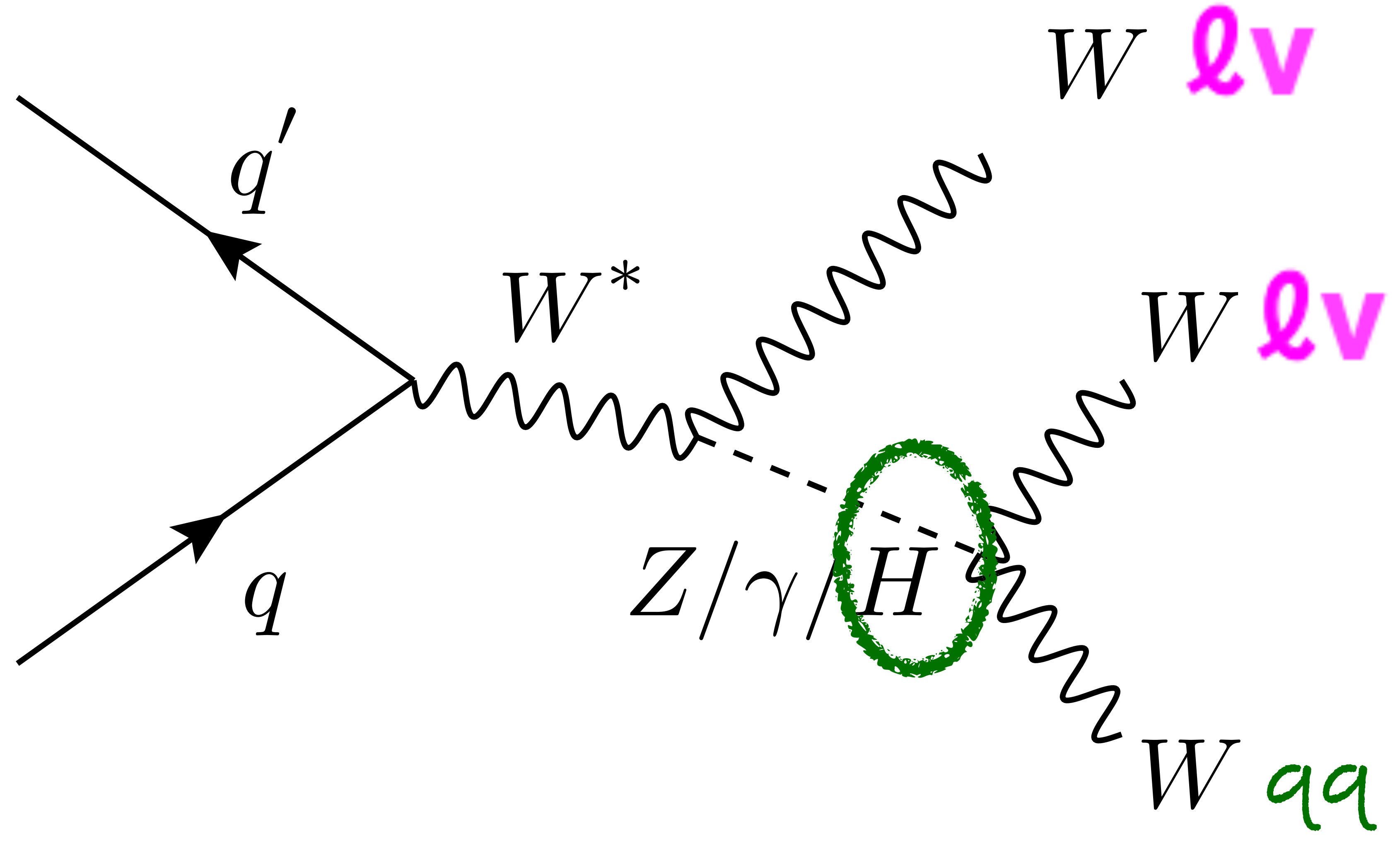
Maximize the sensitivity

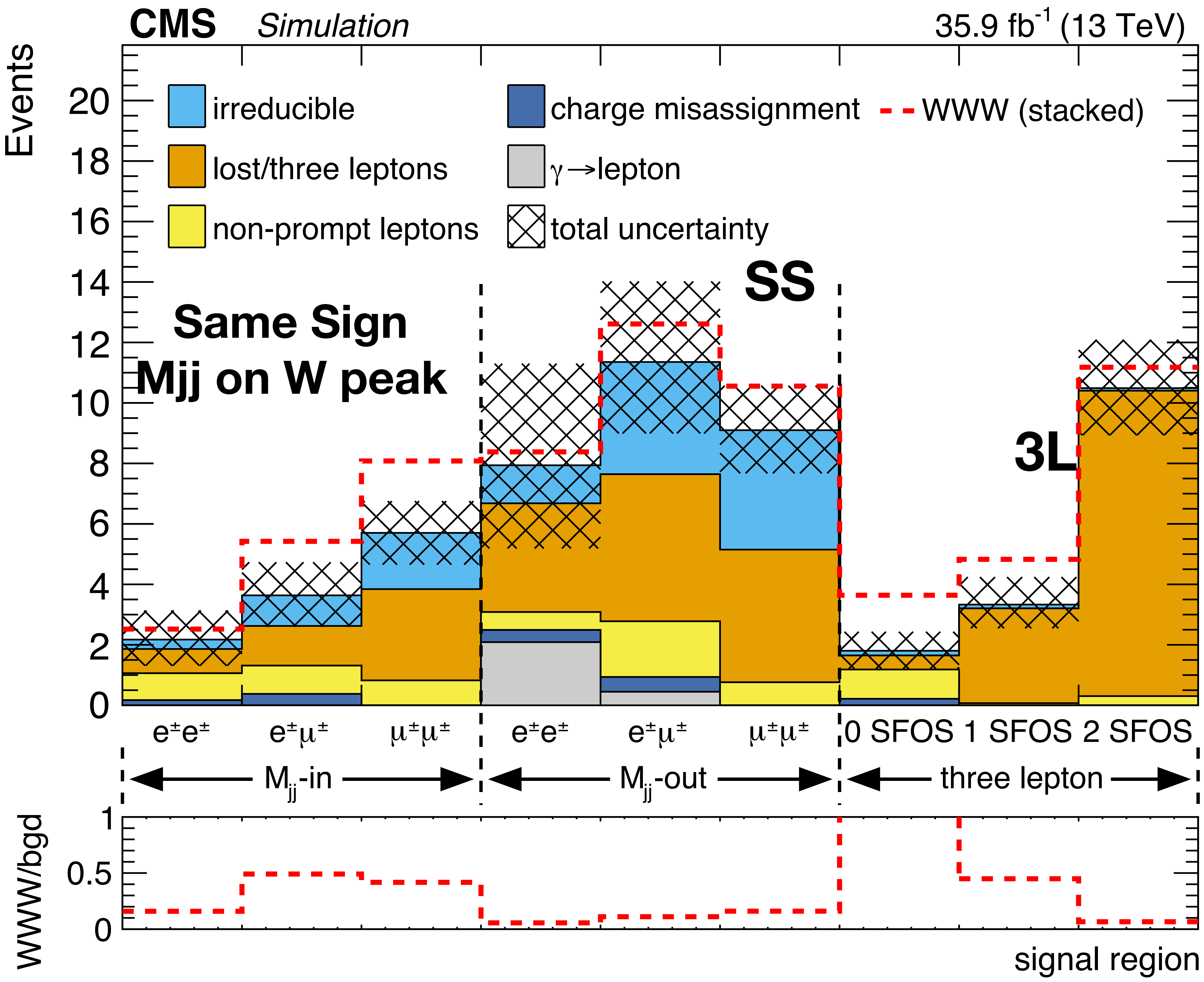




Recovers off-shell W's coming from Higgs decay

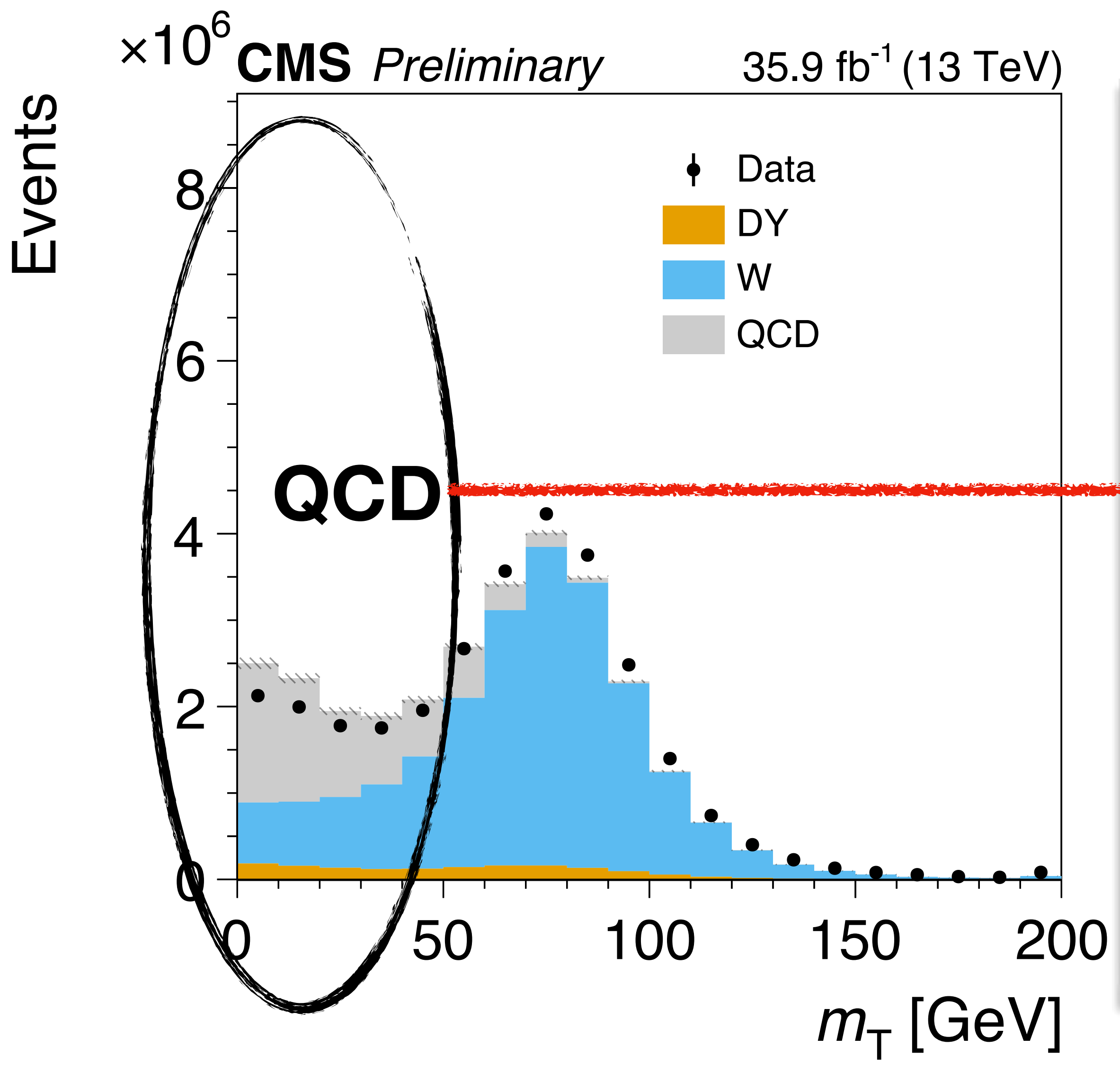
9 categories: varying sensitivity

Backgrounds overview in signal region

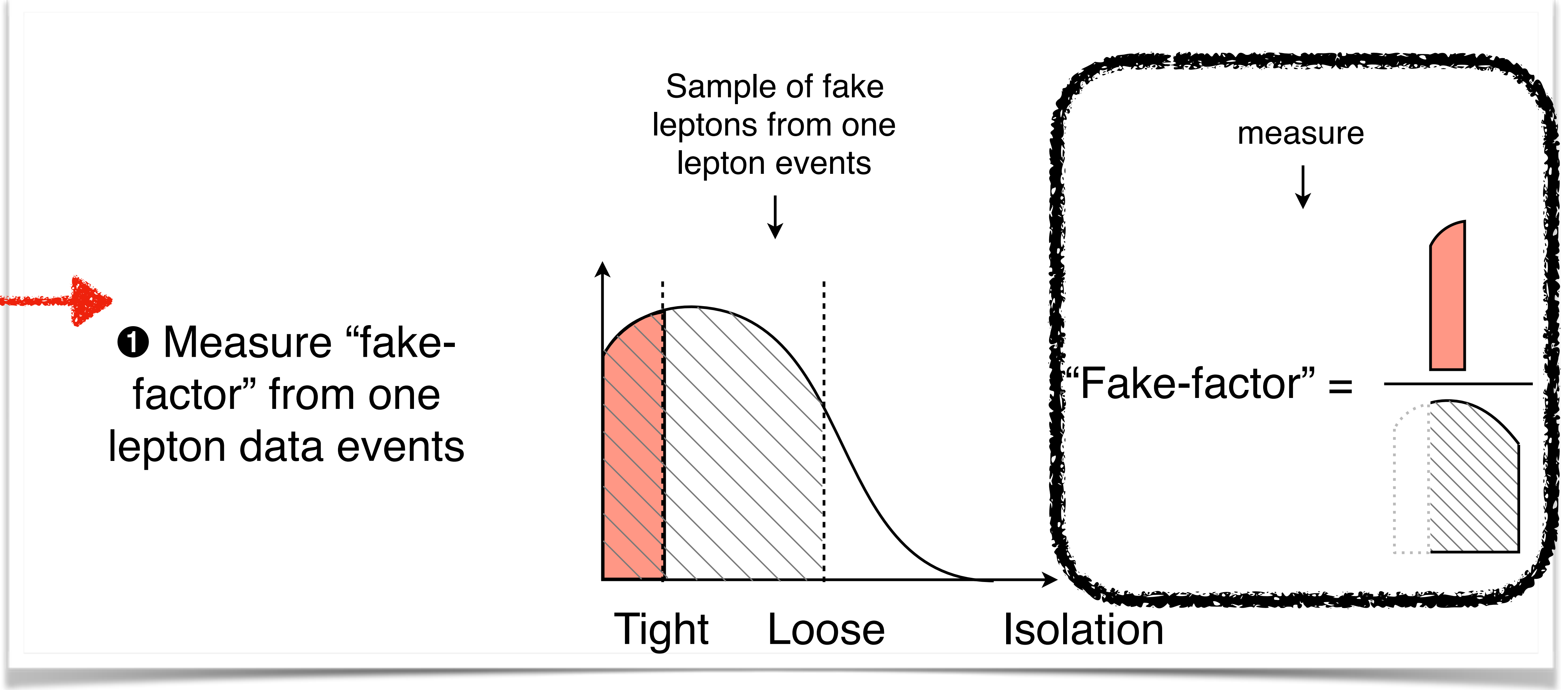


- Real same sign contributions (Same-sign WW (EWK,QCD), ttW, DPS) and Charge flip
- Lost lepton: WZ, ttV with 3 real leptons -> dominating.
- My focus: Non-prompt Lepton faked by hadronic jets (1L W+Jets, ttbar)
  - most challenging, poorly modeled in MC, needs full data-driven estimate

Estimate Non-prompt leptons

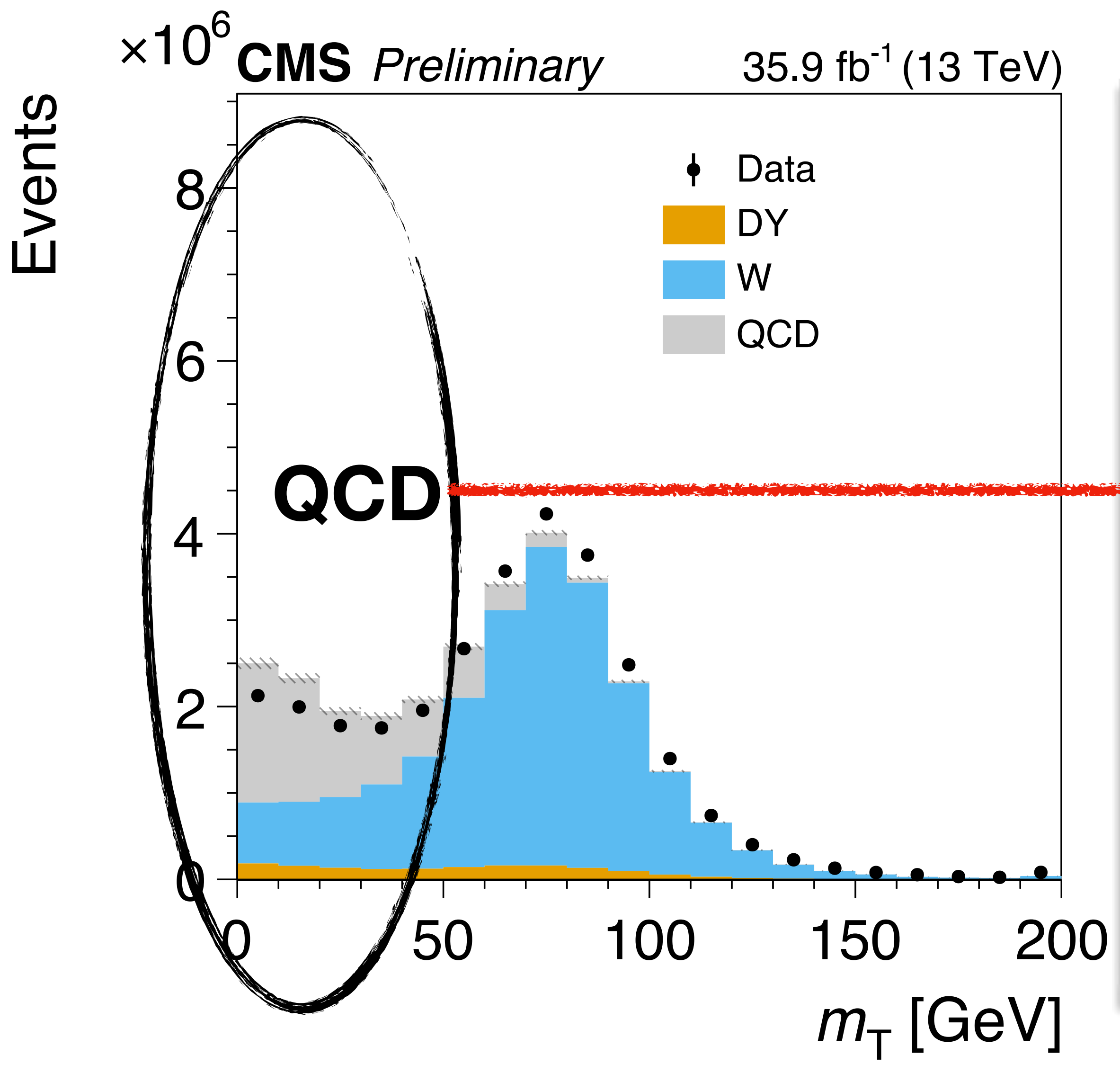


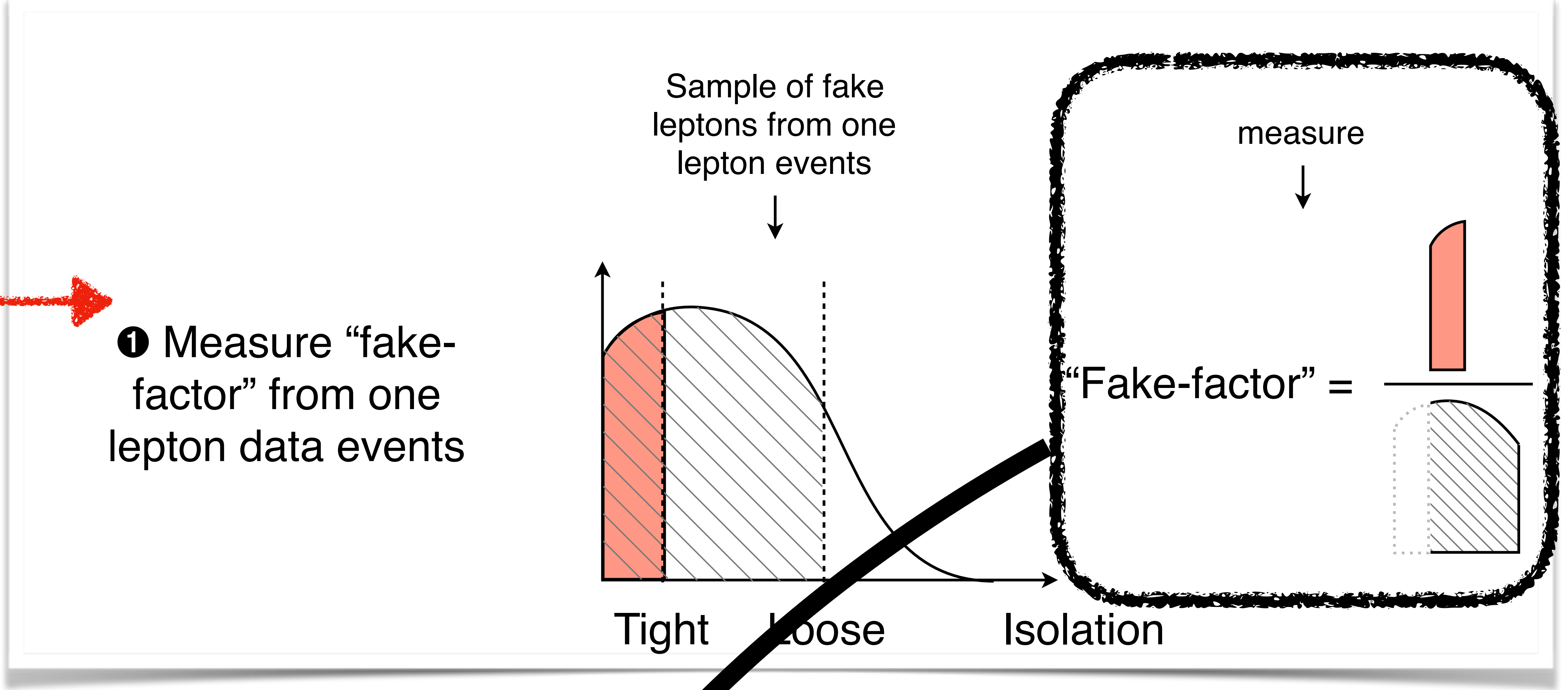
Single lepton events



- Data-driven estimate:
  - Step1: QCD enriched enriched region-> tight-to-loose

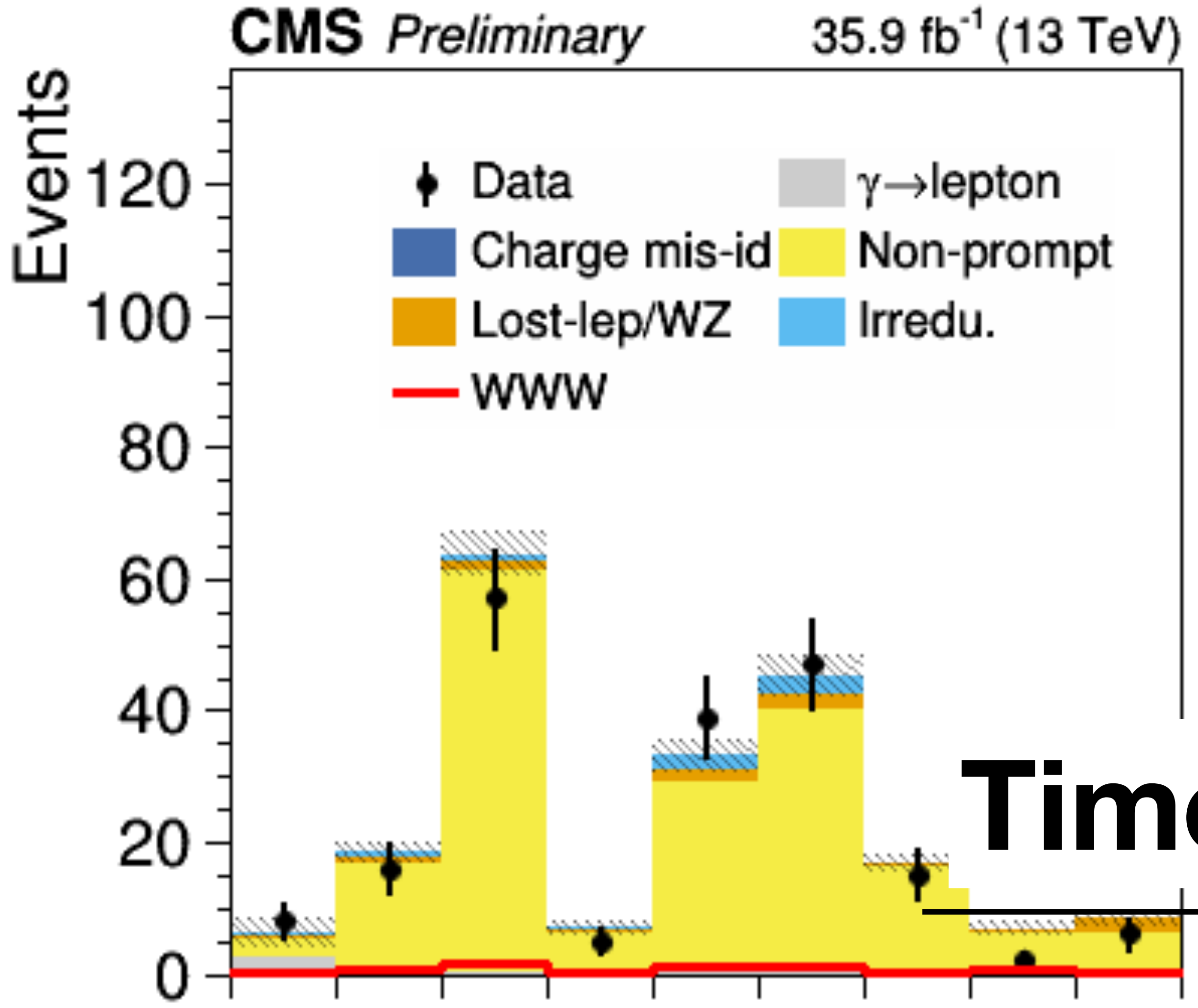
Estimate Non-prompt leptons



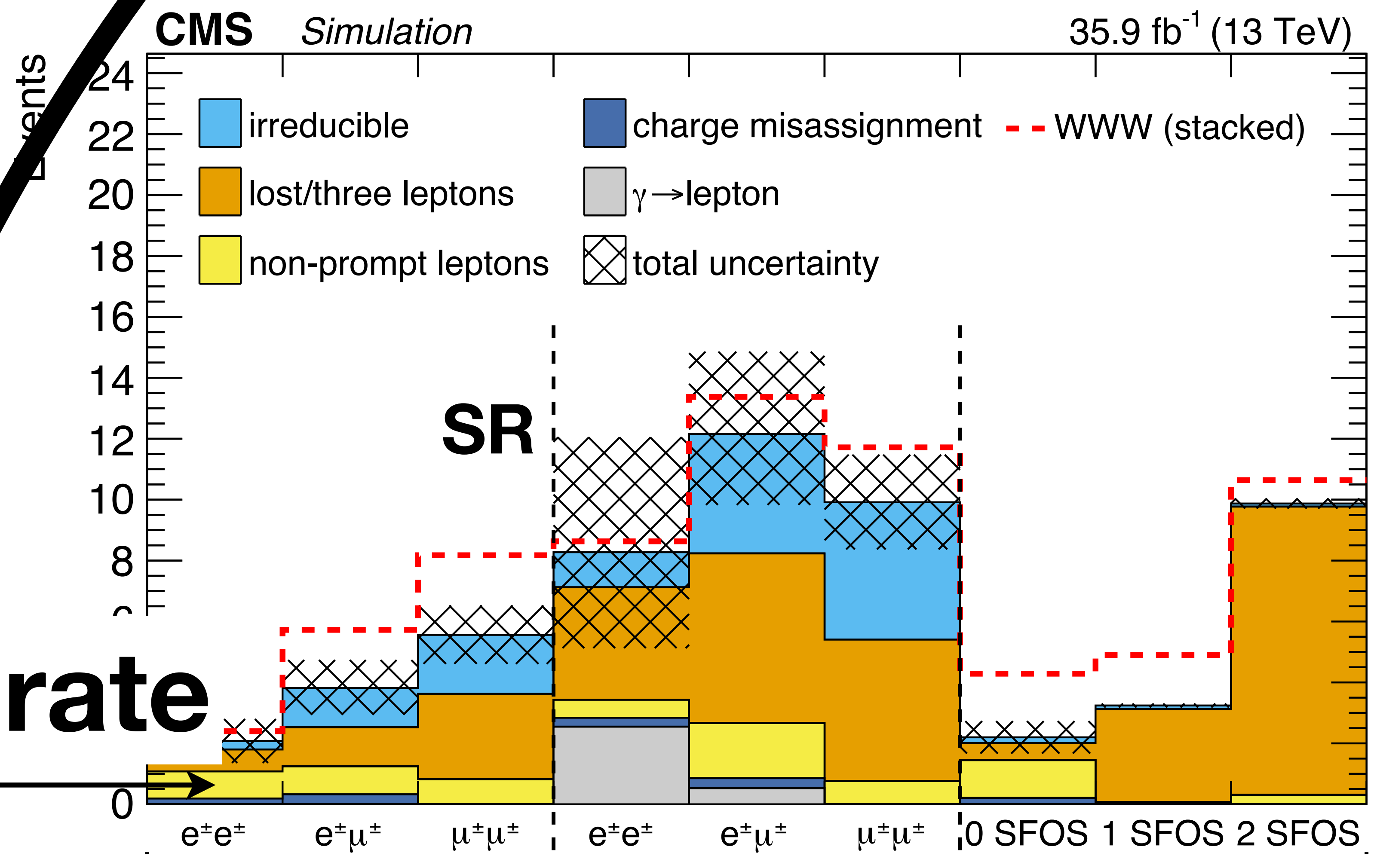


- Step 2: Tight-to-loose ratio applied to signal regions (2 lepton events)

→ fake estimates in signal region



Times fake rate



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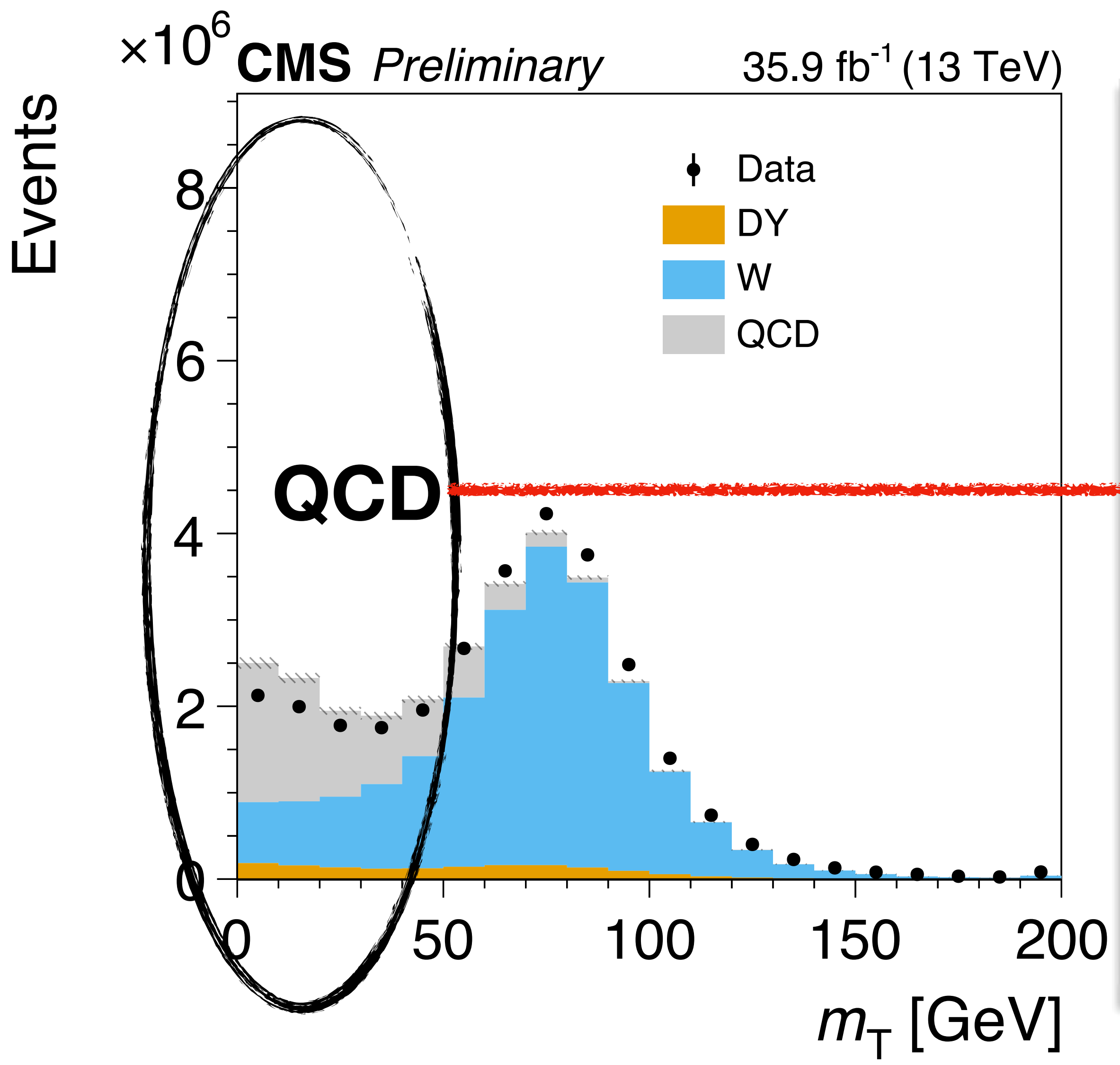
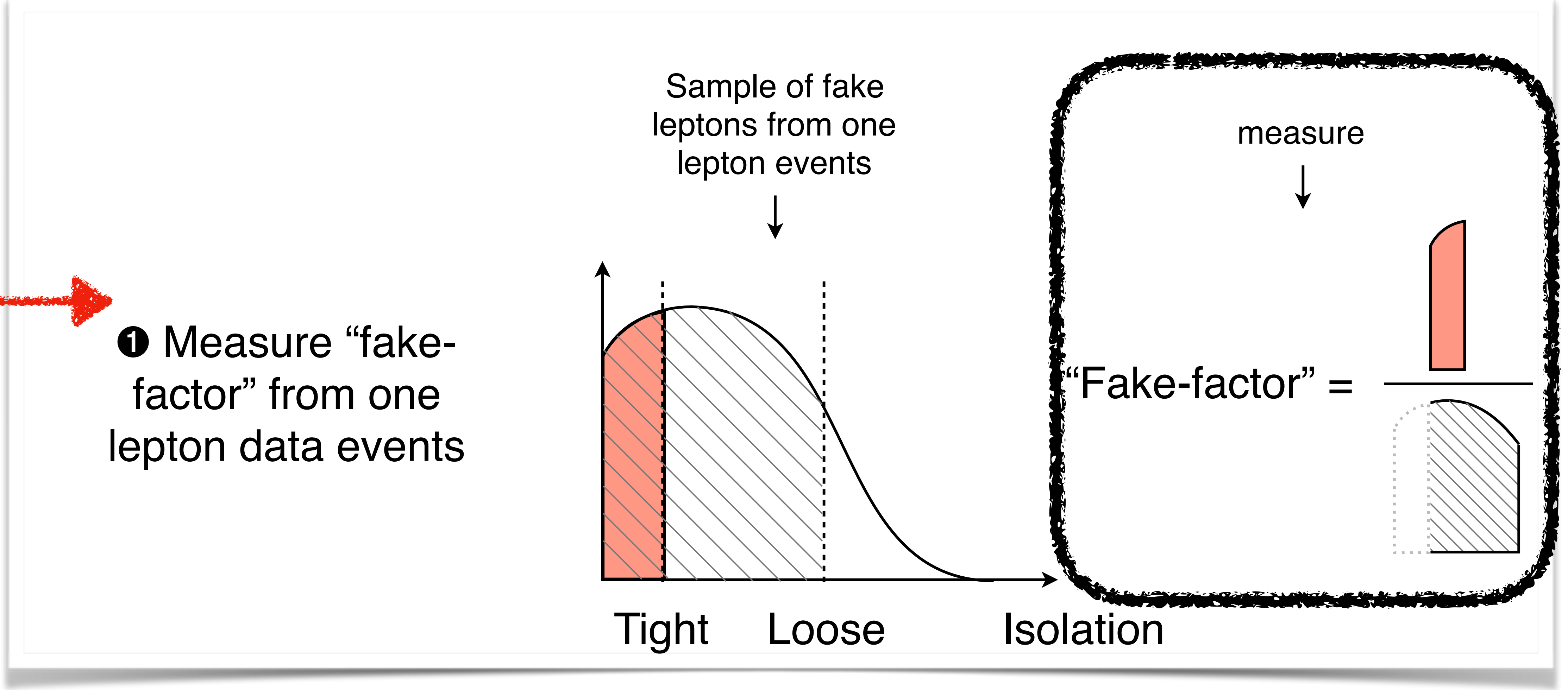
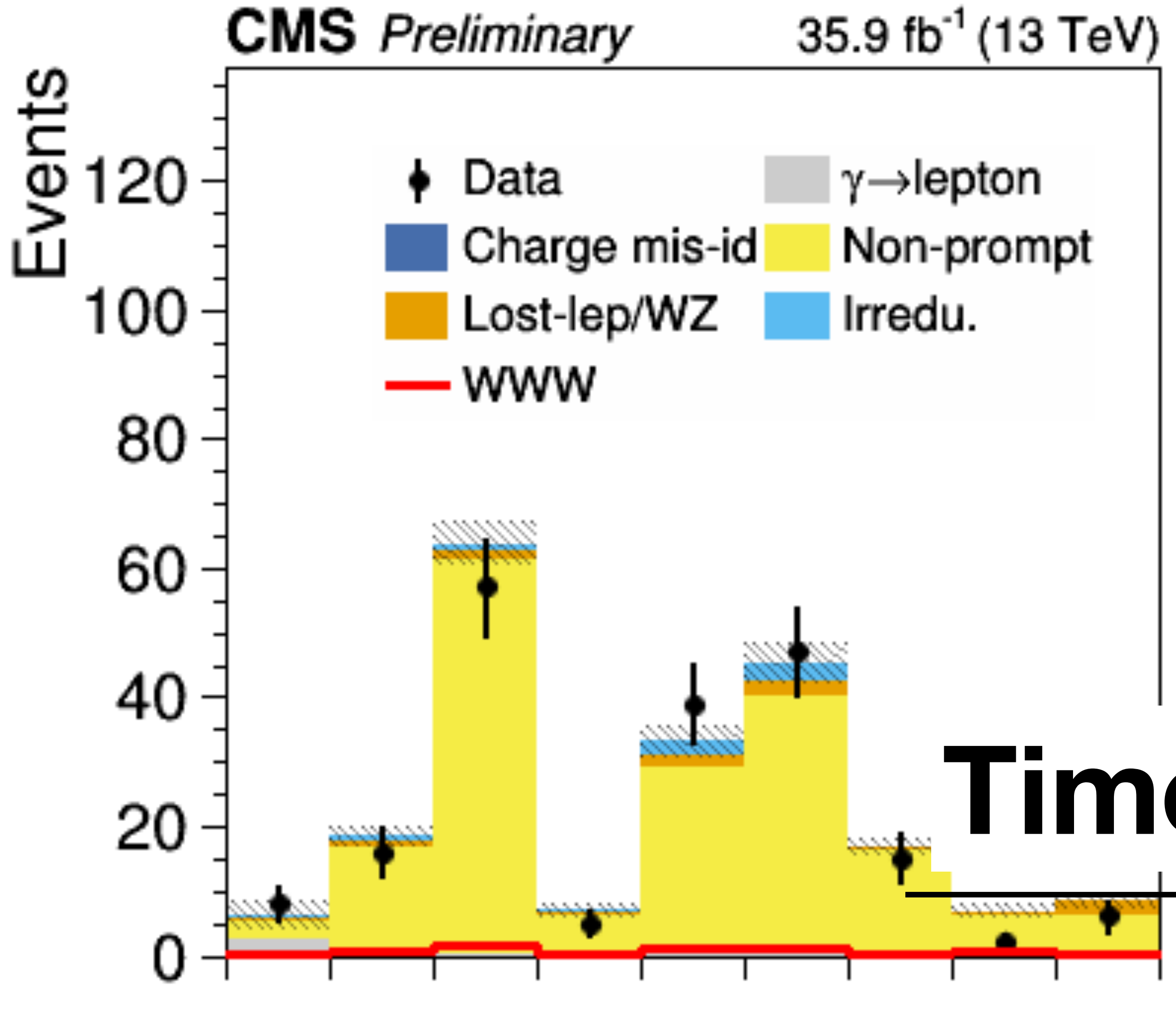
Estimate Non-prompt leptons

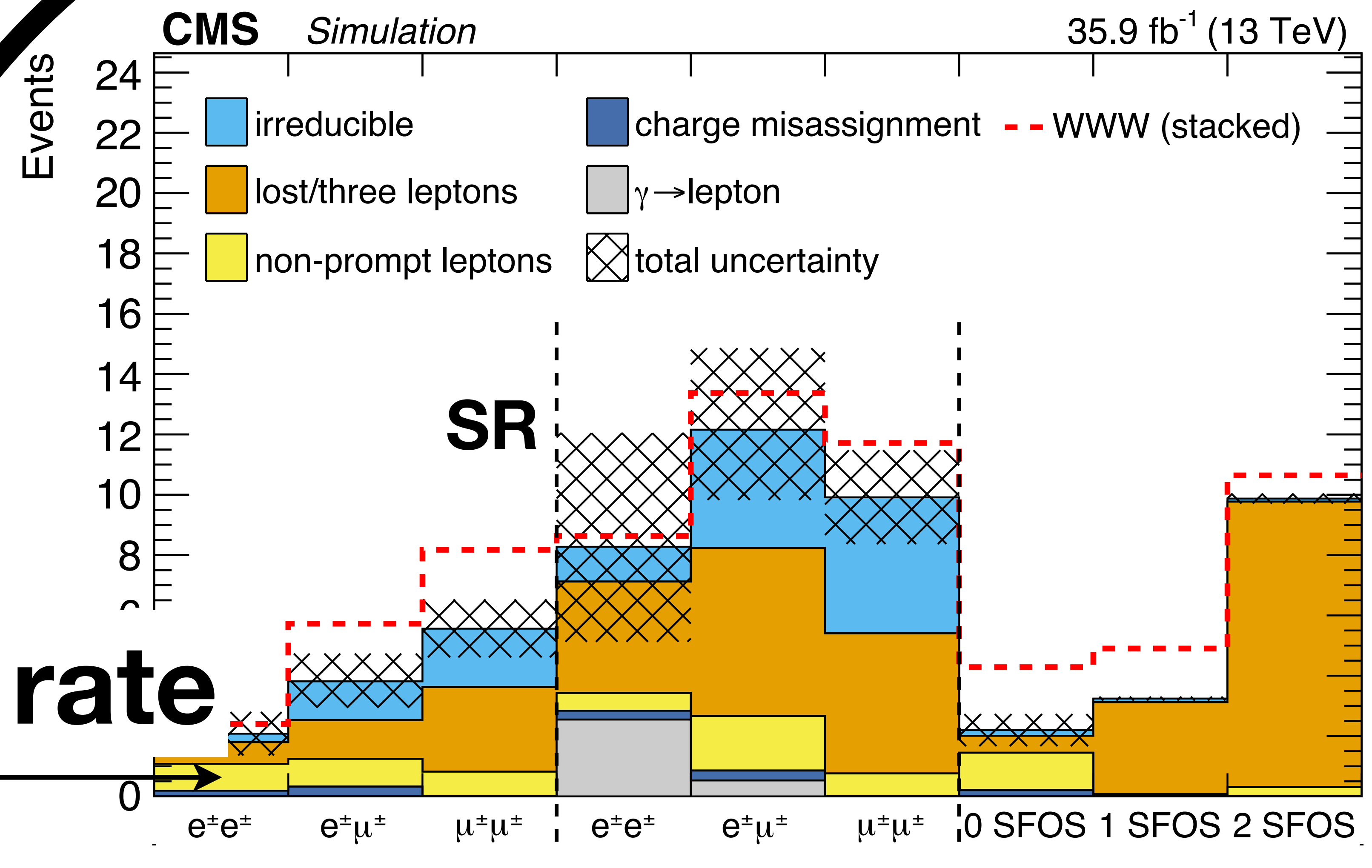






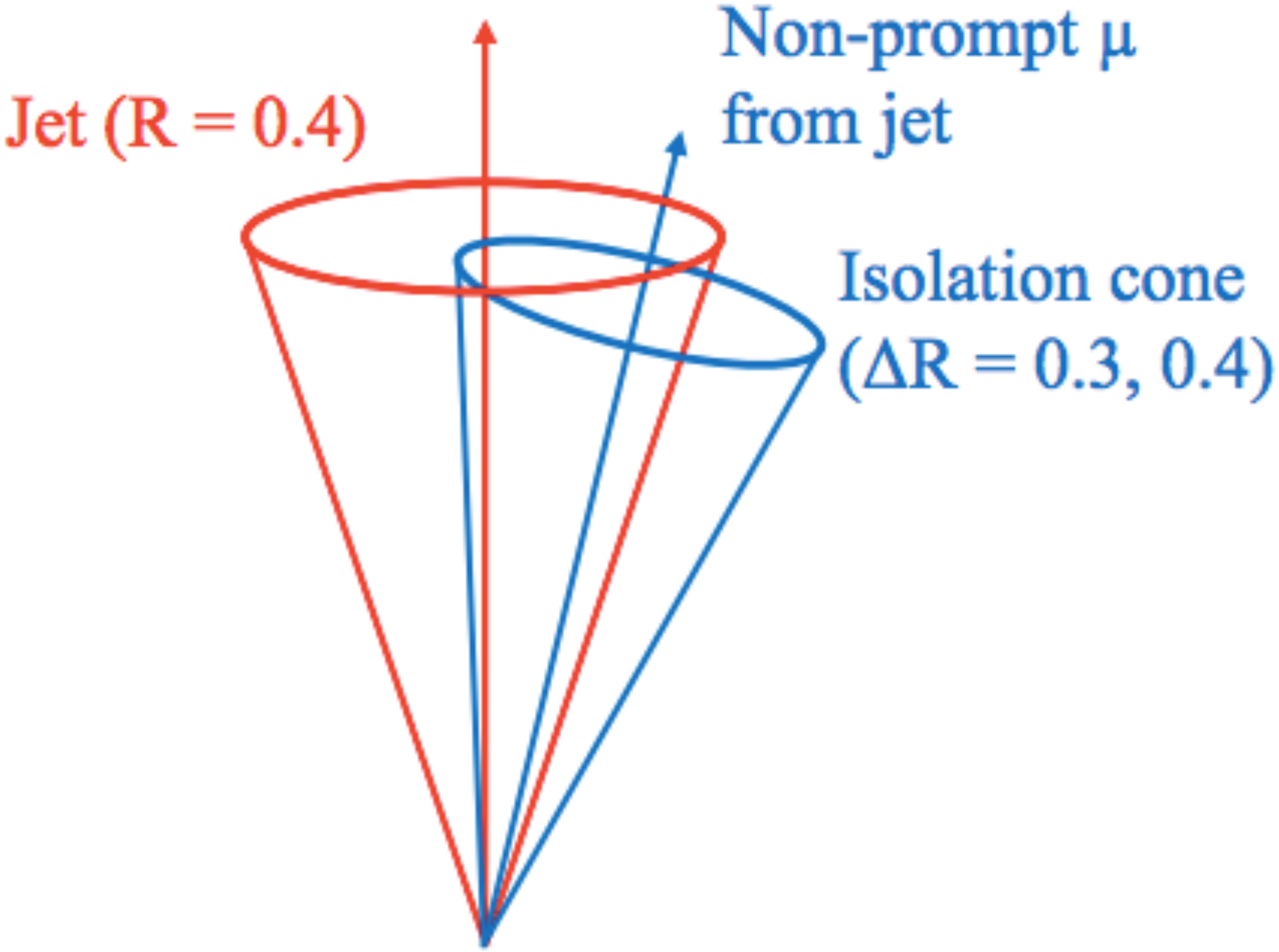
Tight+loose Signal bins

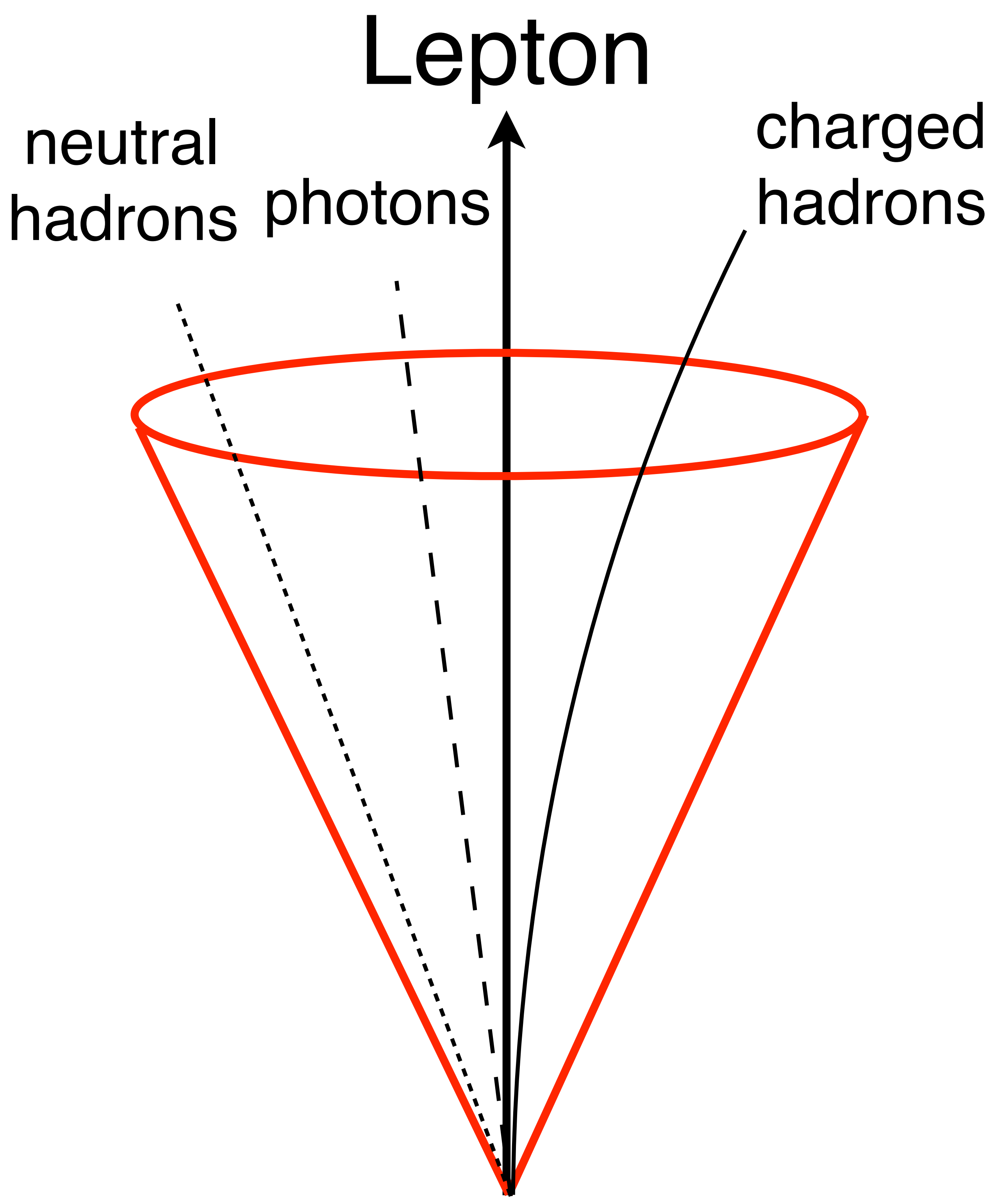
Times fake rate



- Large systematic uncertainties associated (50%-100%)
  - MC closure. Fake rate measurement statistics...
- Need to suppress it as much as possible

Reject Non-prompt leptons with isolation





$$Iso_{Rel} = \frac{\Sigma PF\ cand's\ P_T\ in\ the\ cone - PU}{Lepton\ P_T}$$

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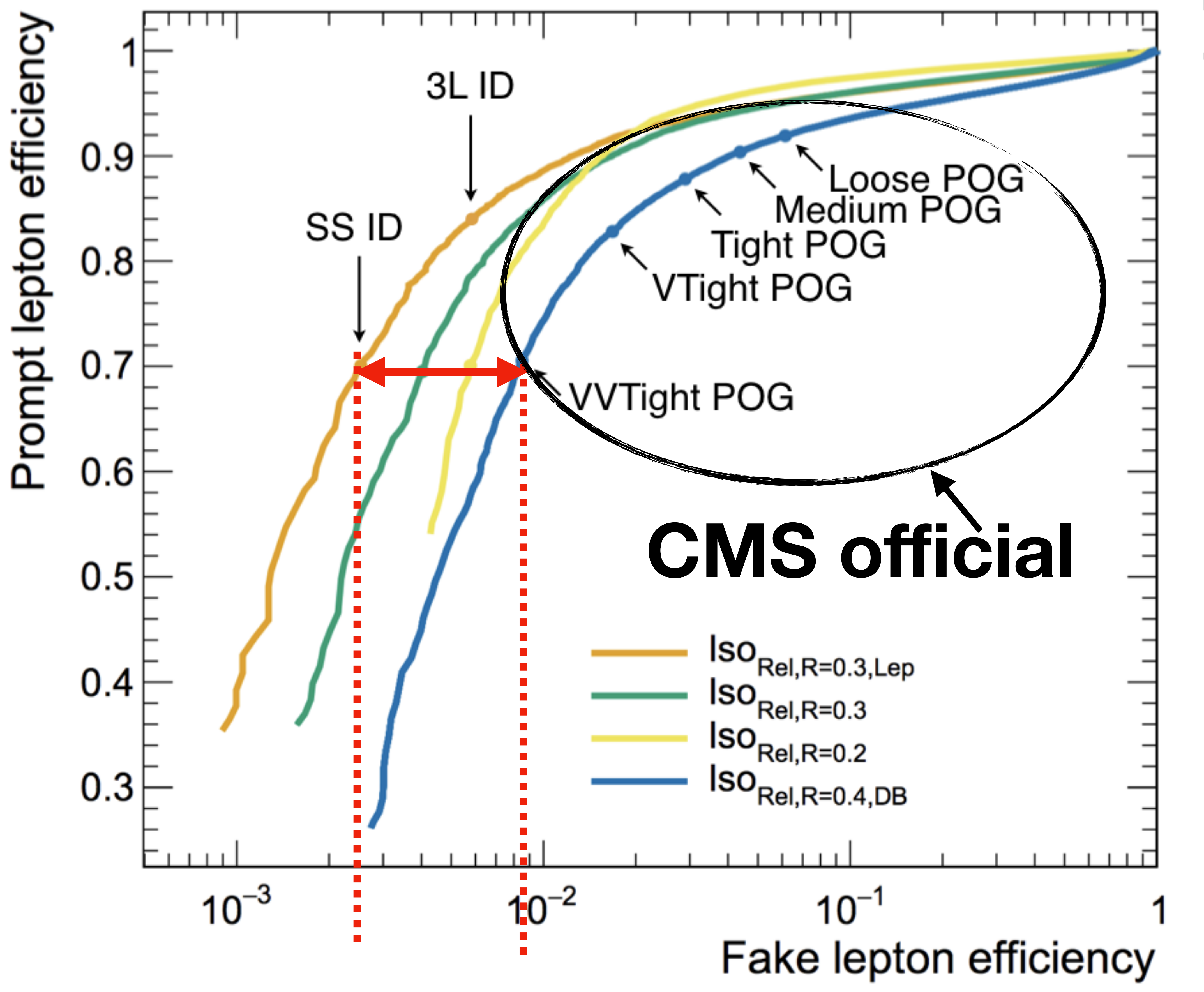
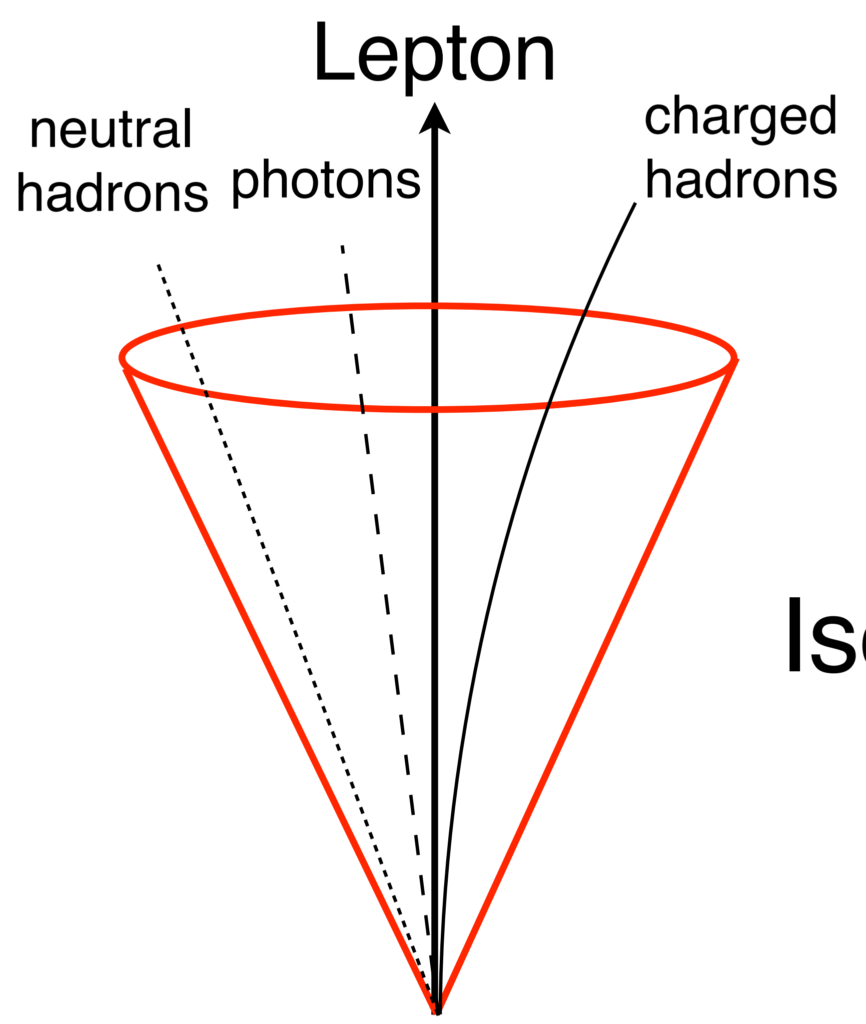
Improved isolation definition



3.5 X background rejection for muons



$$\mathrm{Iso_{Rel}} = \frac{\Sigma \text{PF cand's } P_T \text{ in the cone} - \text{PU}}{\text{Lepton } P_T}$$

- Smaller cone-size: 0.4->0.3
- Add lepton candidates to Isolation calculation improves rejection: heavy flavor decay (B→D→2 leptons + X), one of the leptons is selected as our good lepton.

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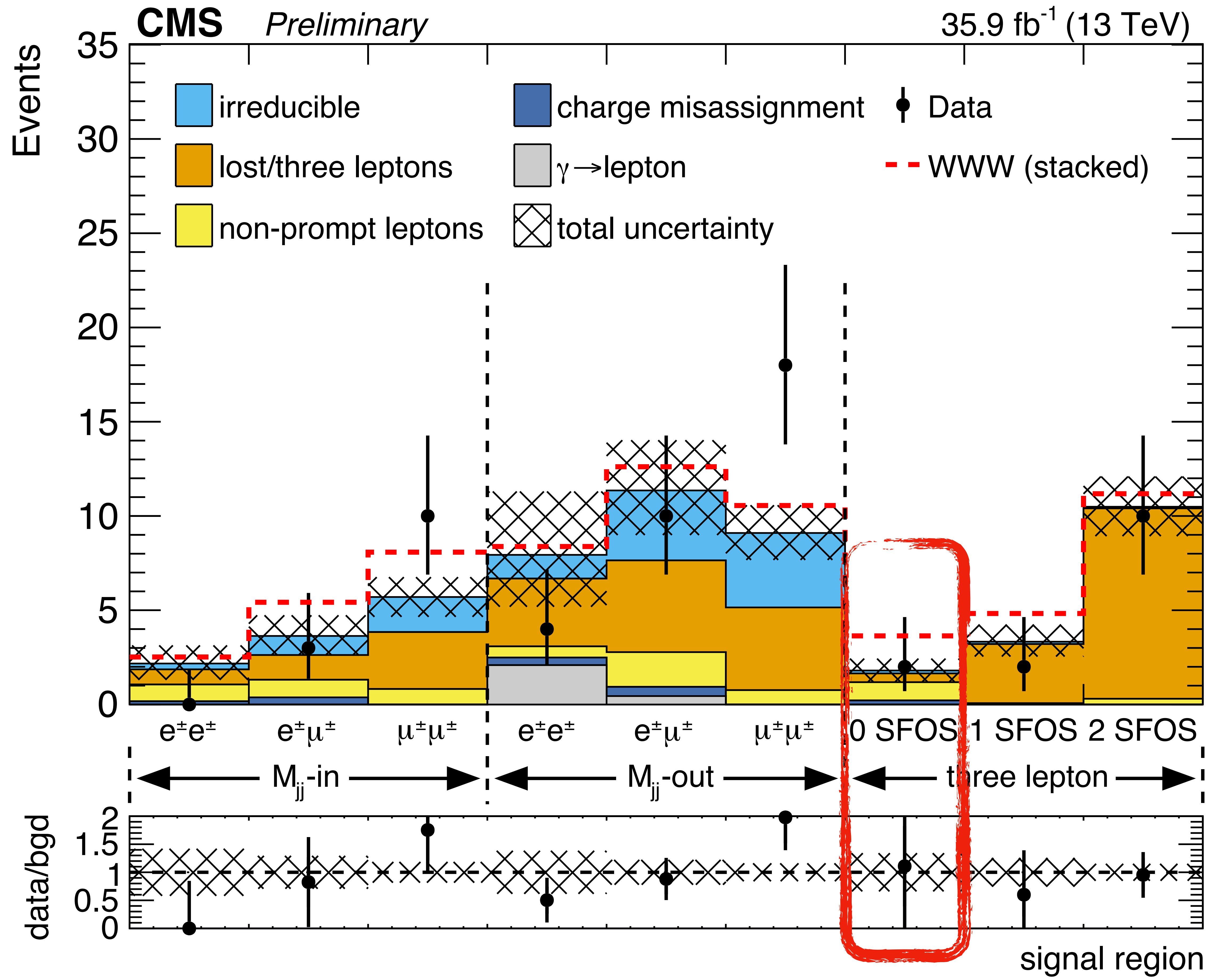
Results

- 2016 analysis presented at Moriond EWK.
  - Luminosity scaling gives ~3 σ for 150fb-1 Run-2 data.
  - Constraints placed on Axion-like particles and anomalous couplings.
- Actively improving the analyses:
  - Adding boosted signature.Neural network based lepton ID/Iso

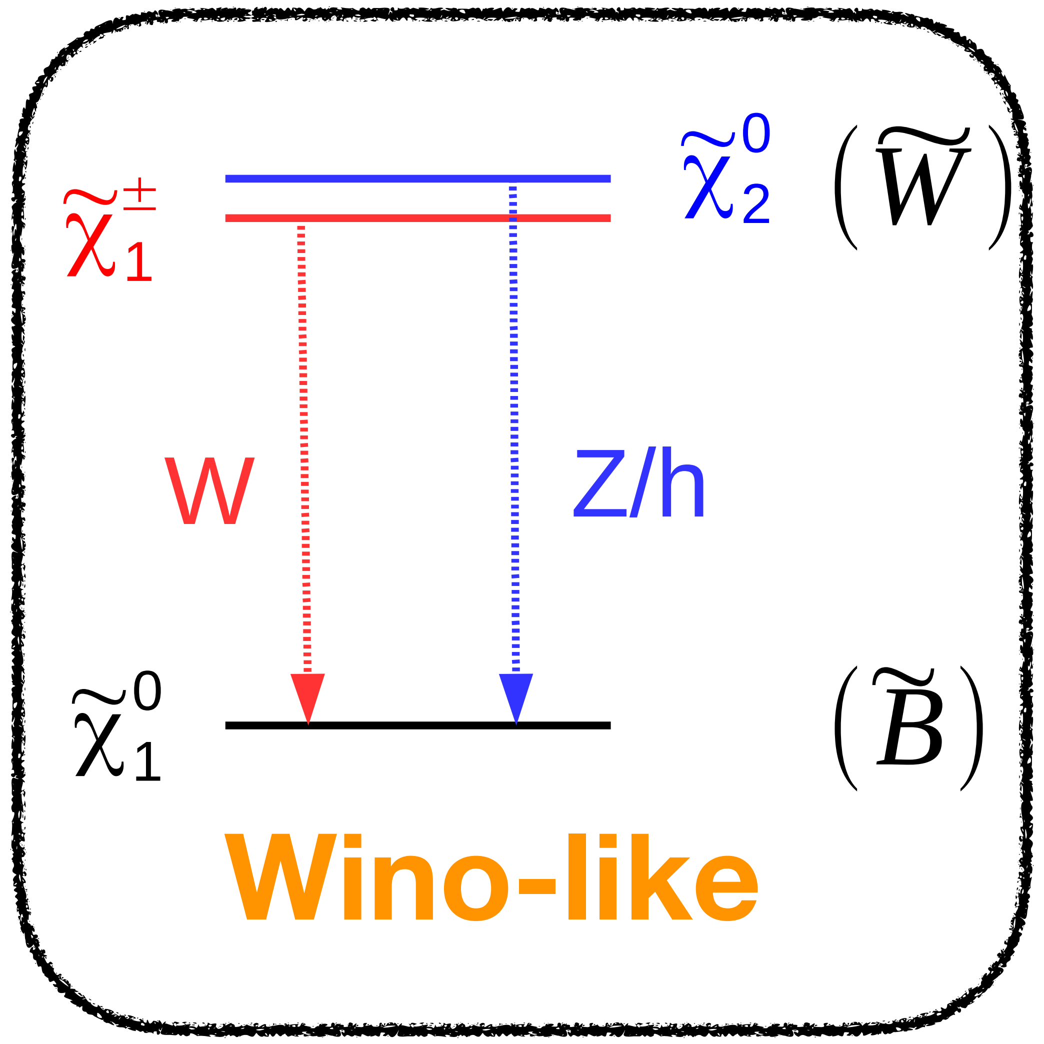
Expect the first evidence with full Run-2 dataset!

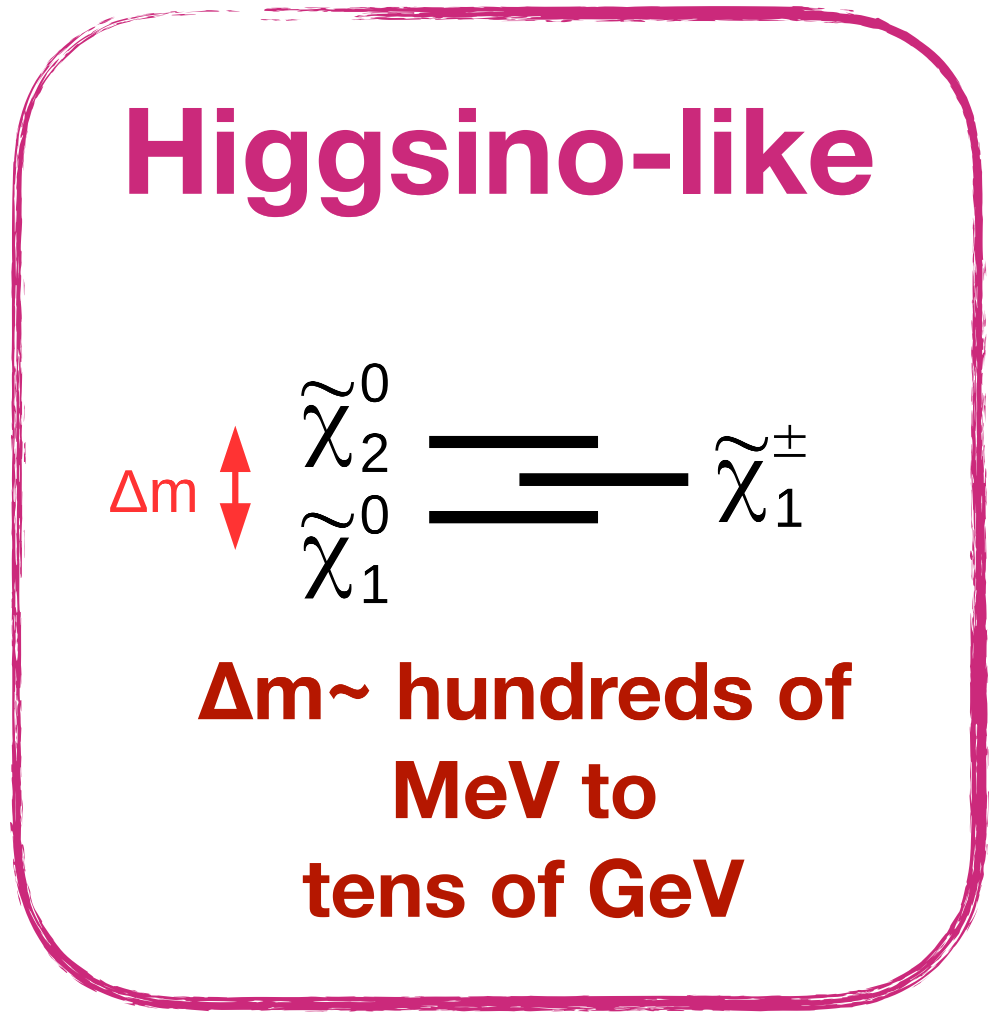


1.78 σ (expected)/0.6 σ observed with 2016 dataset

Some analyses need HL-LHC dataset

- 3000 fb-1 data expected at the HL-LHC
- e.g. Higgsinos: Low cross section, challenging signatures
  - Δm~ tens of GeV : Soft decay products
  - Δm~ hundreds of MeV : Long-lived signatures





45 fb*

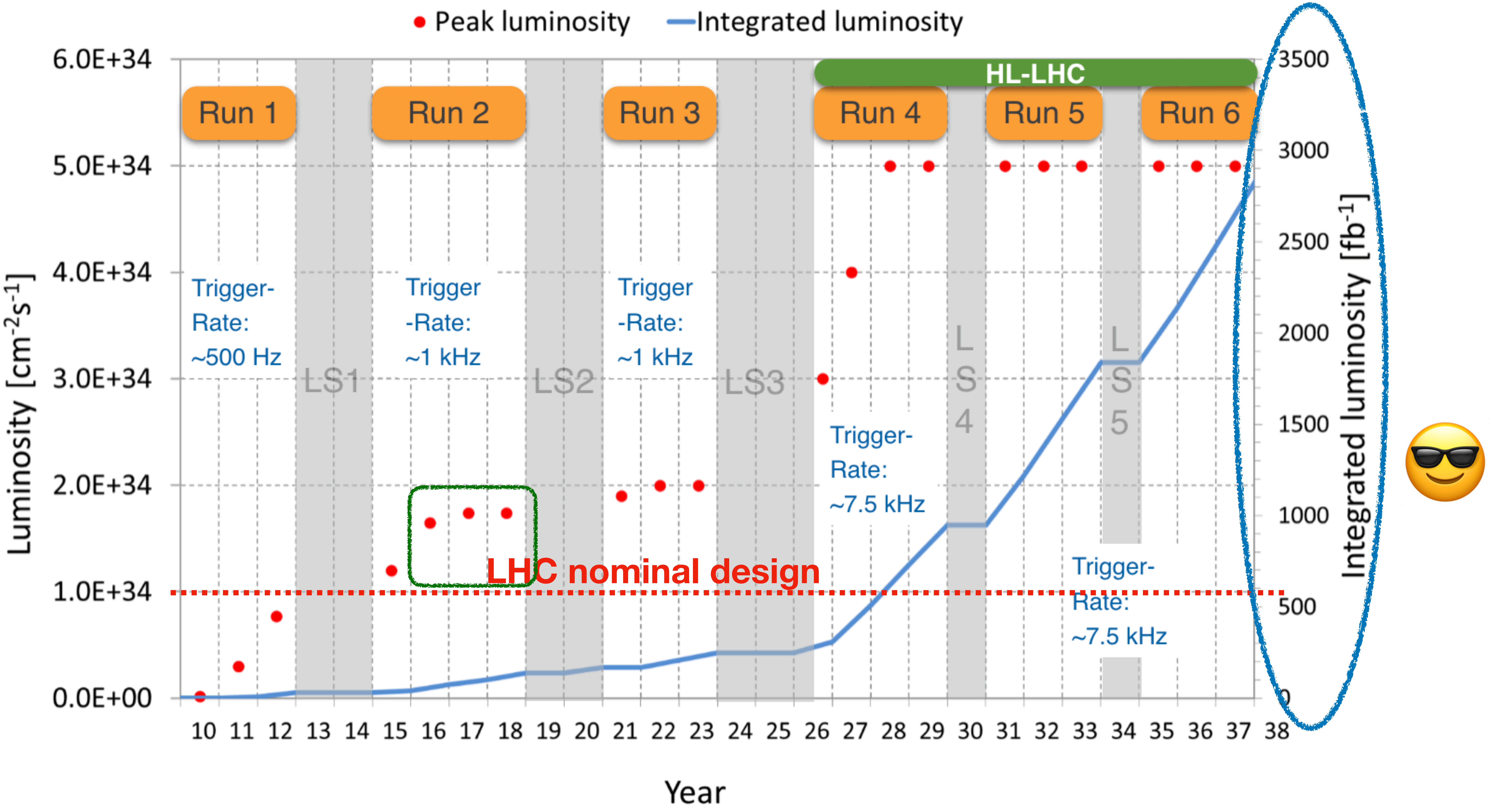
11 fb*

How do we enable physics at the HL-LHC?

Make measurable what is not so: Instrumentation

To set the scene, let's review the LHC/HL-LHC operation plans

GROWING DATASET AT THE LHC



COLLIDER ENVIRONMENT DRIVES DETECTOR UPGRADES

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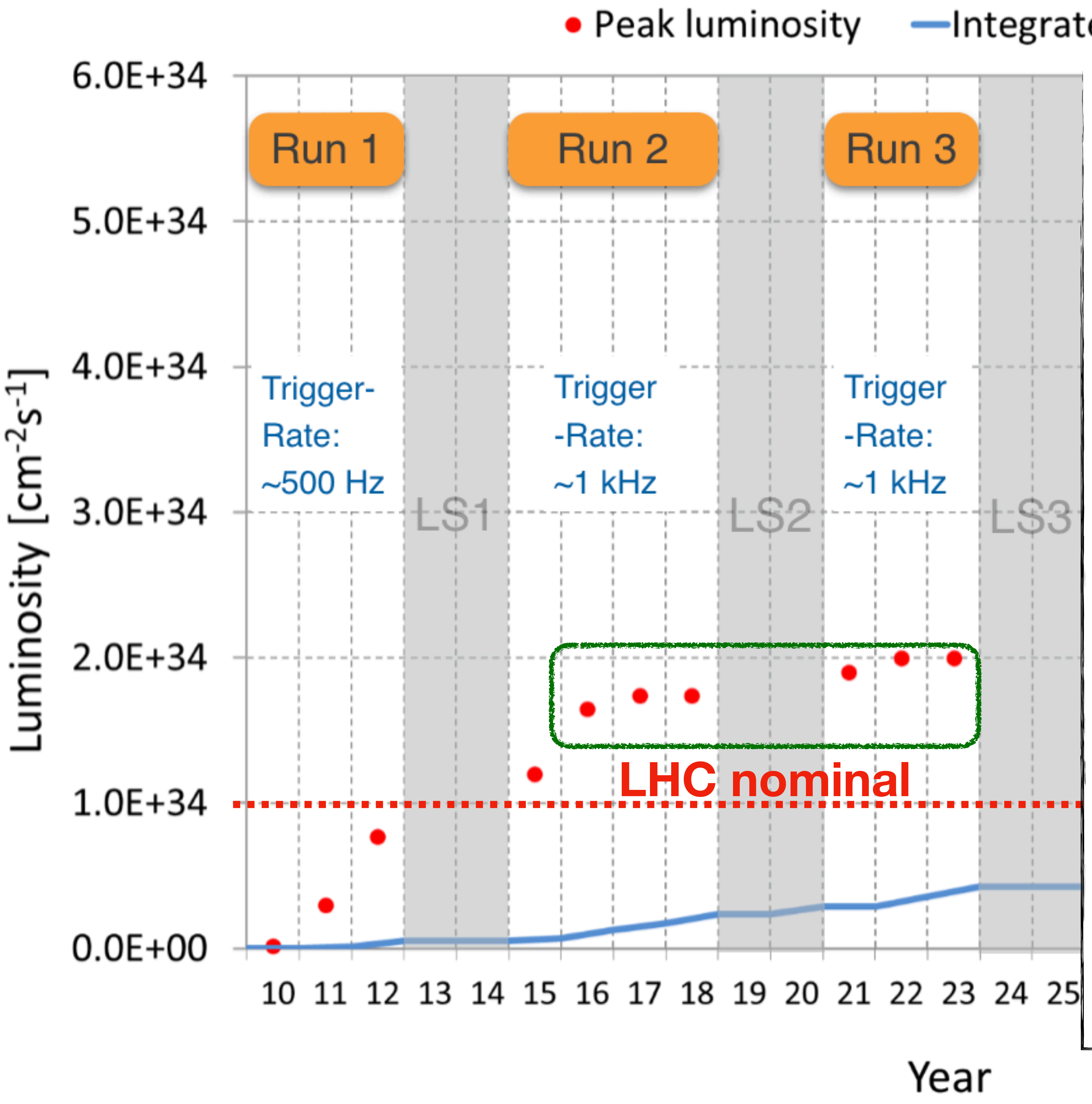
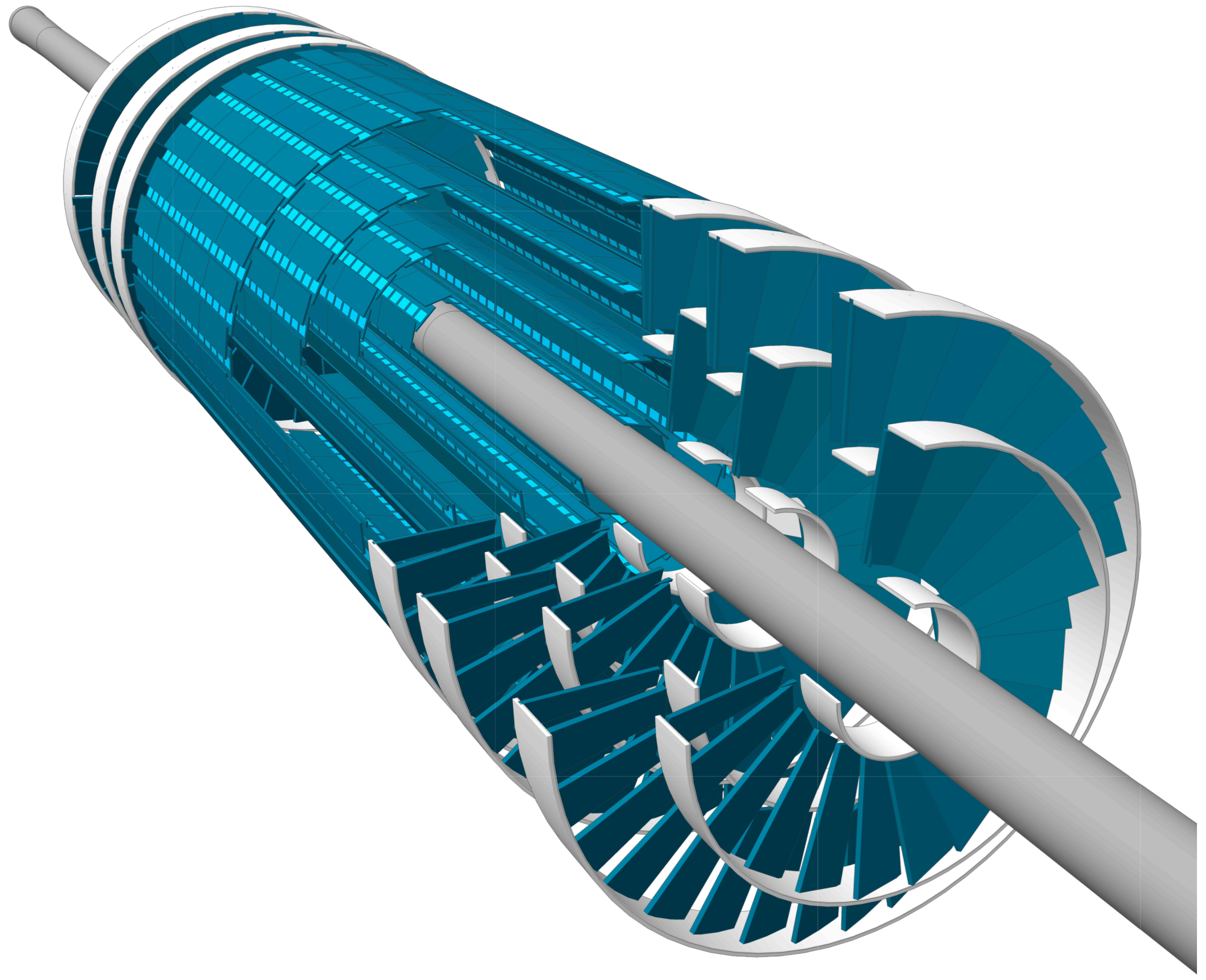


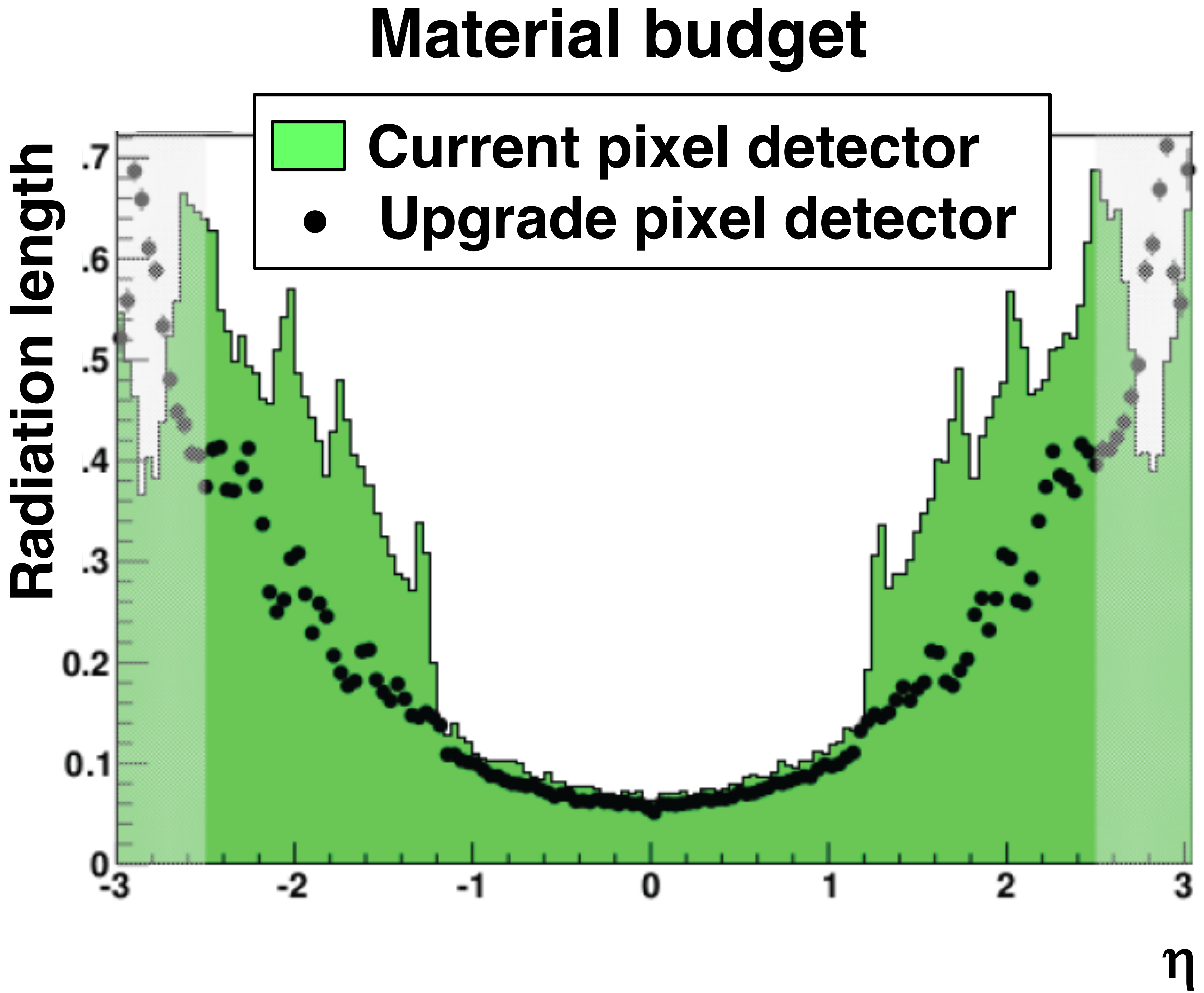
- **CMS Phase 0 detector designed for LHC nominal luminosity**
  5 % hit efficiency loss for Barrel Layer 1 @ 1.5*LHC nominal
  Tracking efficiency drops to 80% at PU=40

- **Phase 1 pixel detector with improved design installed in May 2017, will be taking data until the end of Run-3**

Phase 1 pixel detector design

- **Need to cope with more challenging LHC environment in Run 2 & Run 3 (300 fb^{-1}) until HL-LHC upgrade (2023).**
  - **Module designed to reduce dynamic inefficiency**
    - Digital readout chip (ROC). Faster readout.
  - **Geometry design: ensure tracking and vertex quality**
    - Added layers, channels doubled
  - **Services: reduce material budget**
    - CO2 cooling, DCDC powering, Service electronic out of tracker volume.





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Phase-1 pixel institutions

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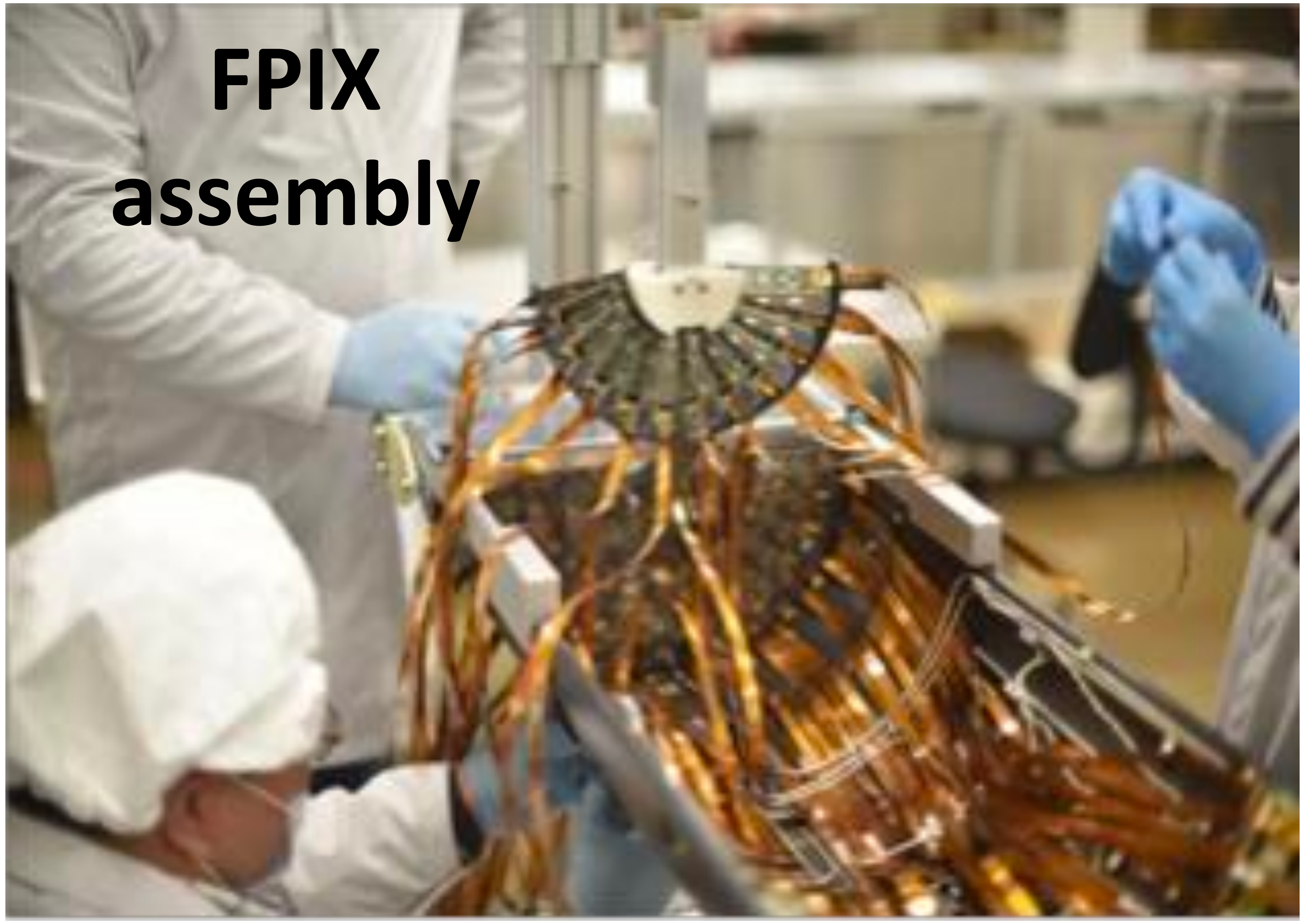

- **US CMS institutions were responsible for constructing the forward part of the pixel detector.**
  - Module production done at Purdue, Nebraska. Testing done at UIC, Kansas and Fermilab.
  - Assembly and system testing done at Fermilab (SiDet) and at CERN (main site and P5) post-transportation.

Half cylinders and service electronics

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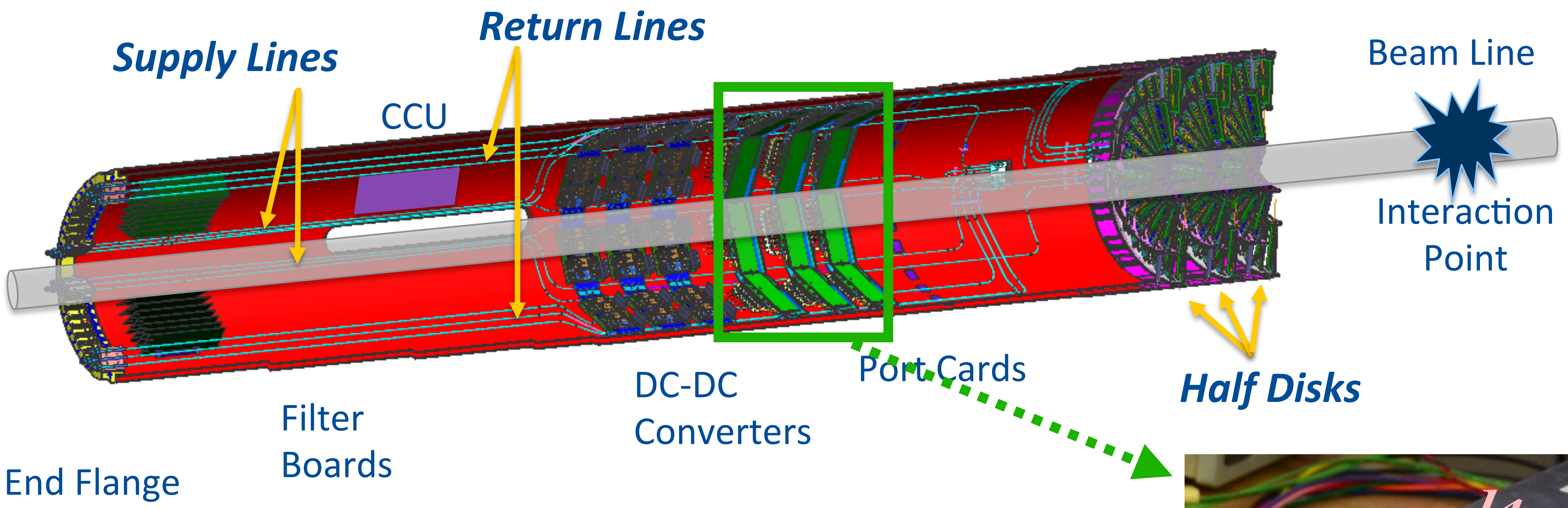
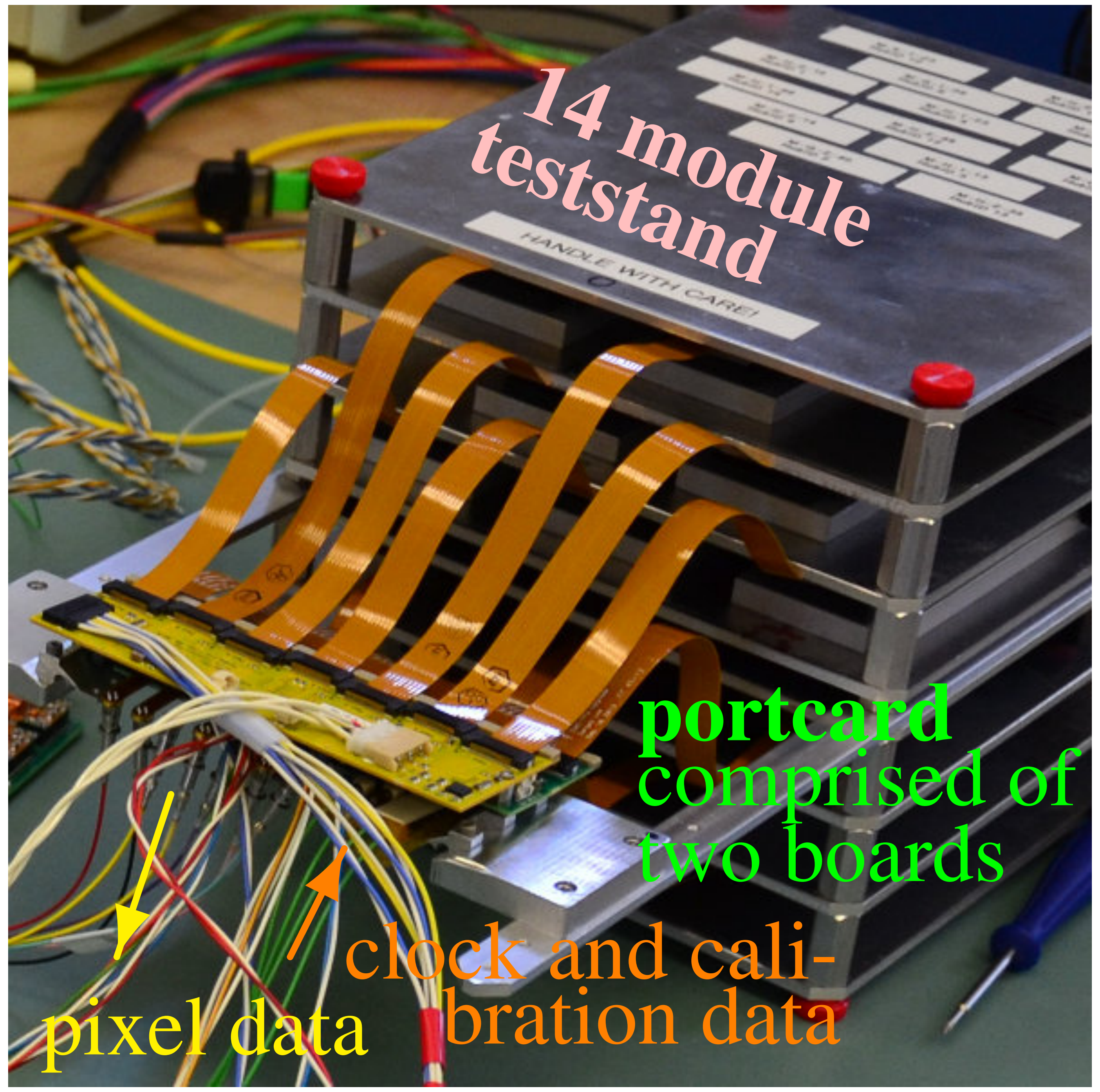
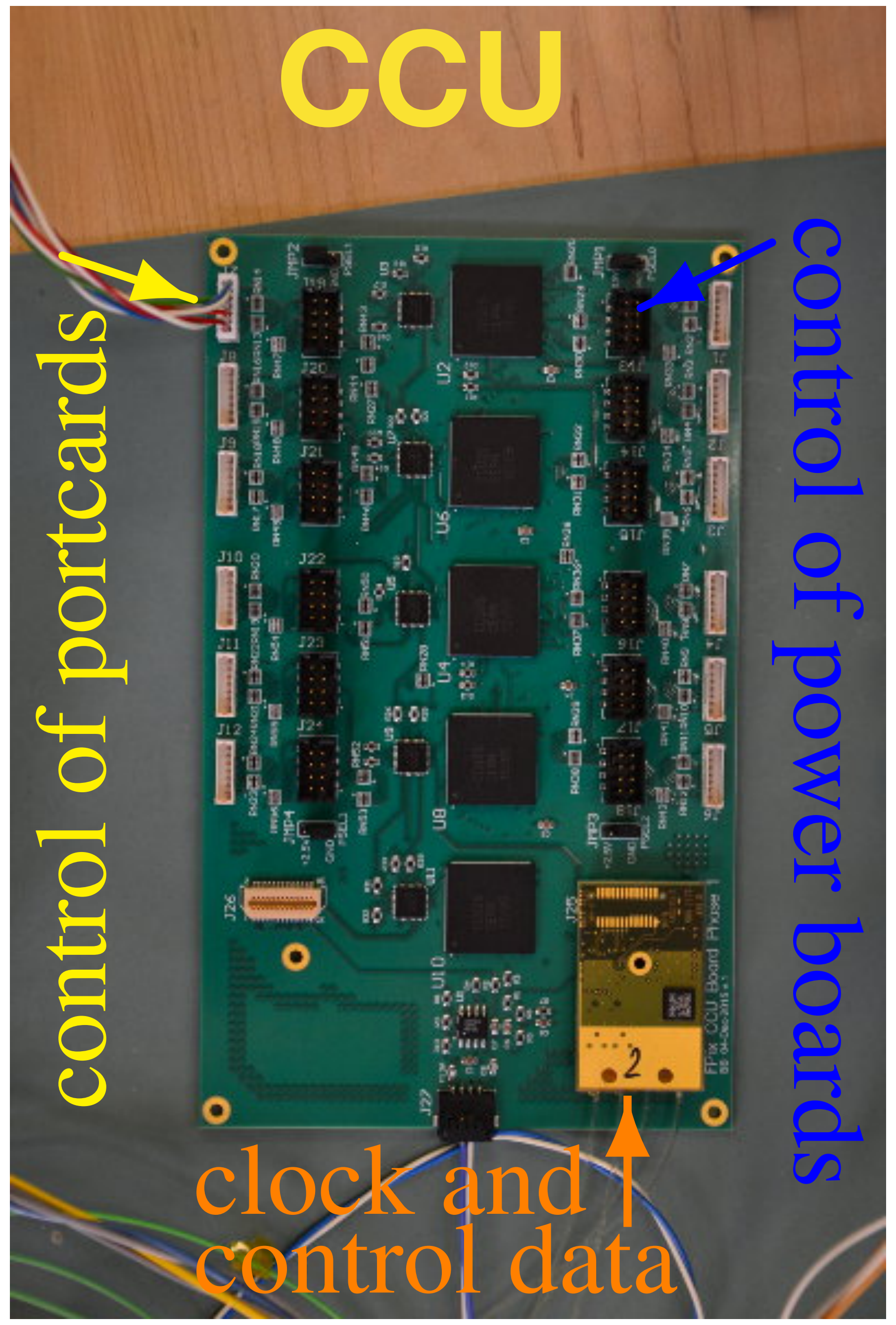


- **Portcard:**
  - Distributes power and bias voltages, clock, trigger and calibration signals to modules. Programs Modules (TBM and ROCs)
  - **Electric/optical Converters mounted**
    - Digital opto-hybrid (DOH): Optical—>Electrical
    - Pixel opto-hybrid (POH): Electrical—>Optical
- **CCU**:Communication & Control Unit
- **uTCA crate hosting front-end controller/drivers.**





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FPIX assembly at Fermilab

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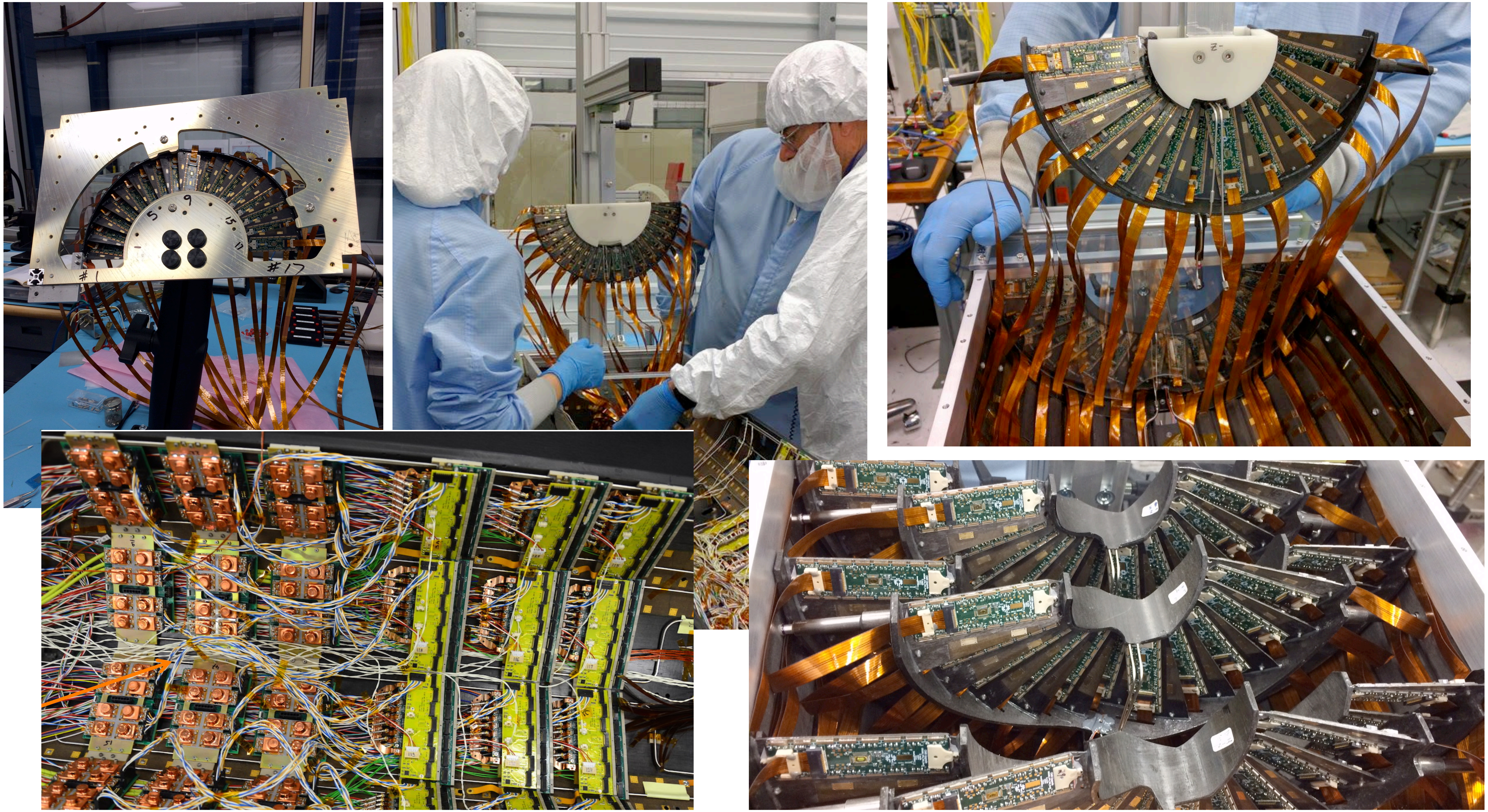

All four half-cylinders tested with full DAQ readout chain at Fermilab

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System testing and commissioning

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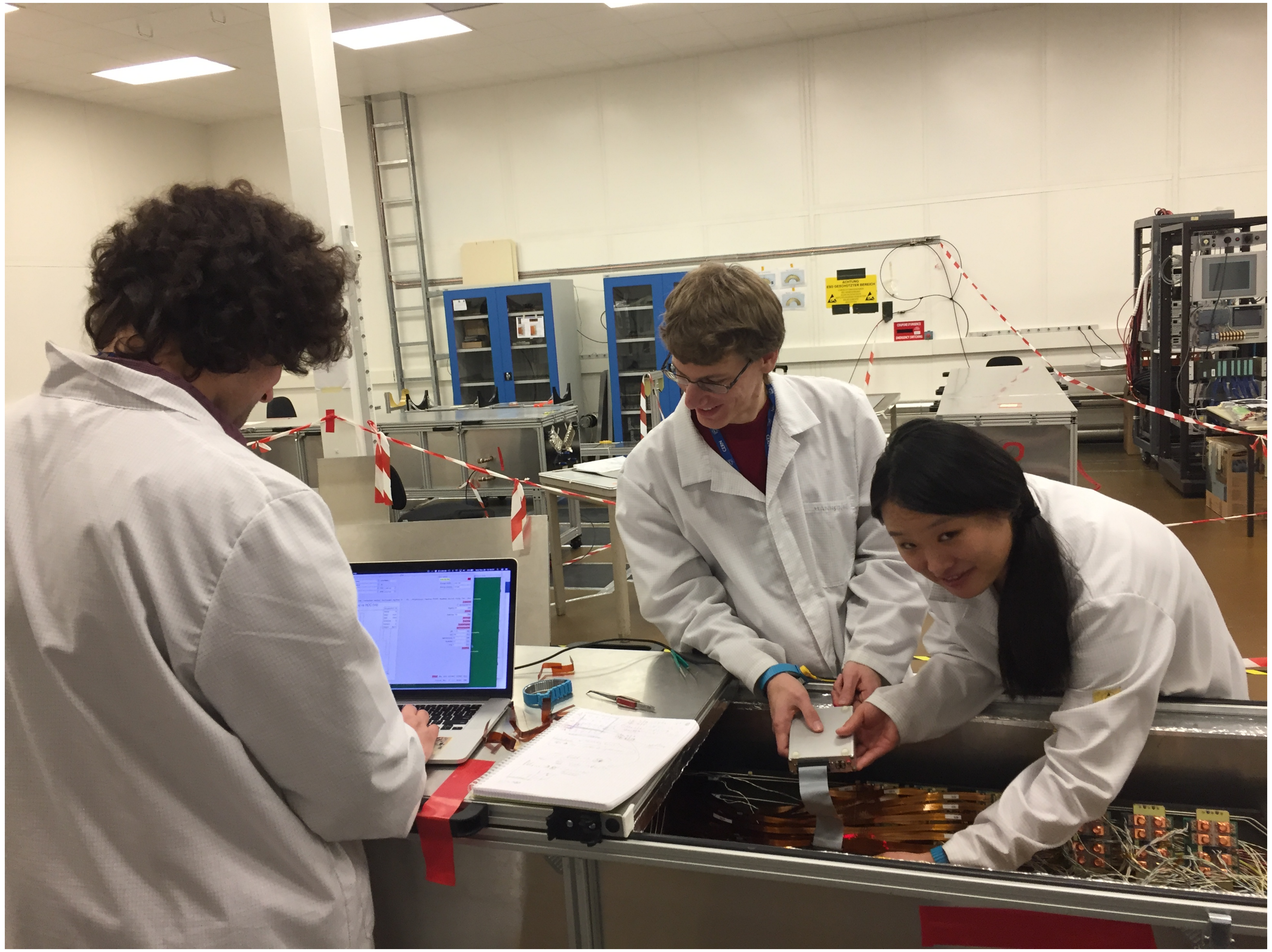
Tracker integration facility (TIF)@CERN



- **Half-disks taken off service half-cylinder in order to be transported to CERN**
  - Half-disks are hand carried
- **Disks are mounted on half-cylinder at Tracker Integration Facility (TIF) at Meyrin site.**
  - Detector checkout, identify and perform necessary repairs.
  - Develop calibration procedure and DAQ software/firmware development.
- **Transported after to cleanroom at P5 for final checkout pre-installation.**
- **More details in my phase 1 pixel seminar.**

SIGNIFICANT IMPACT ON PHYSICS

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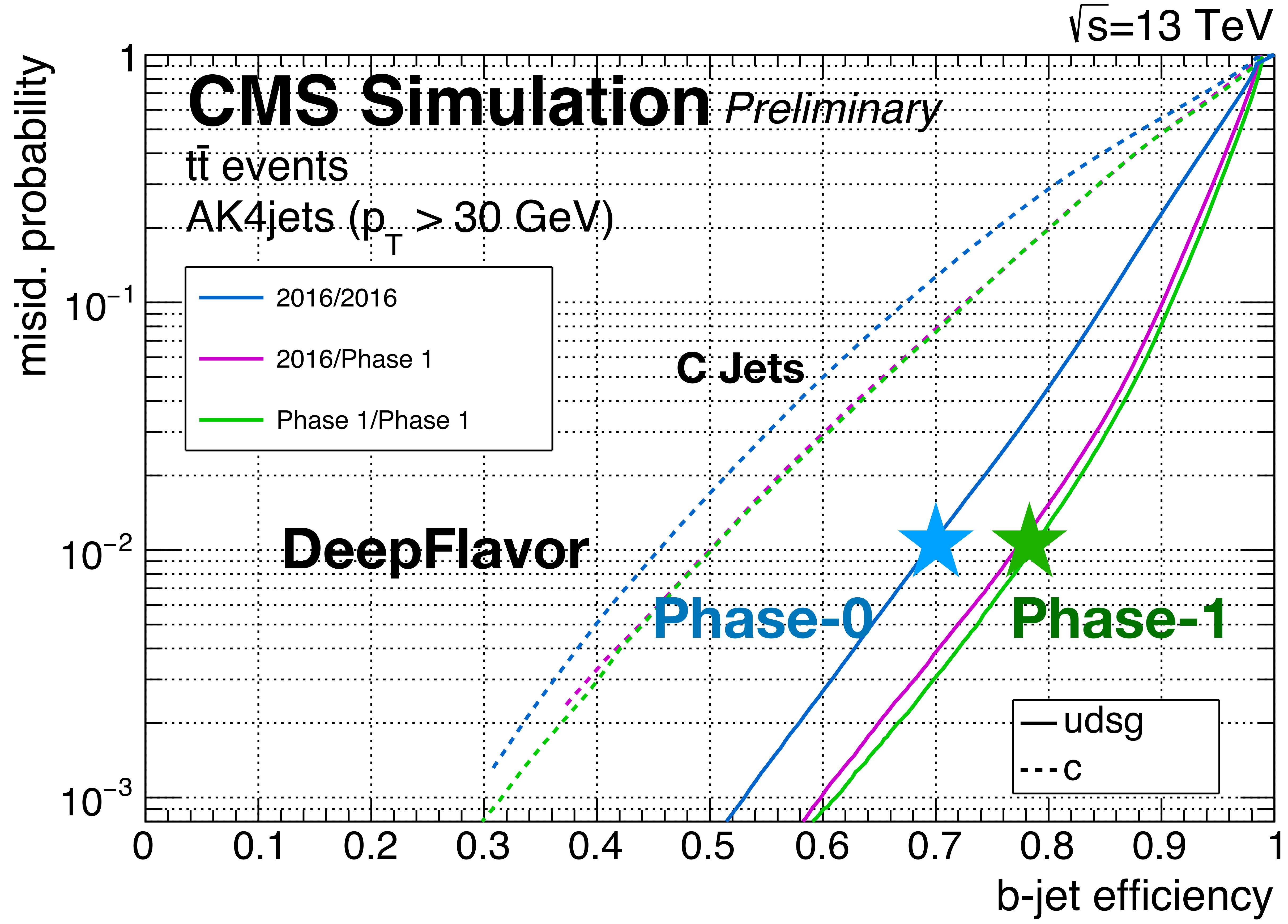
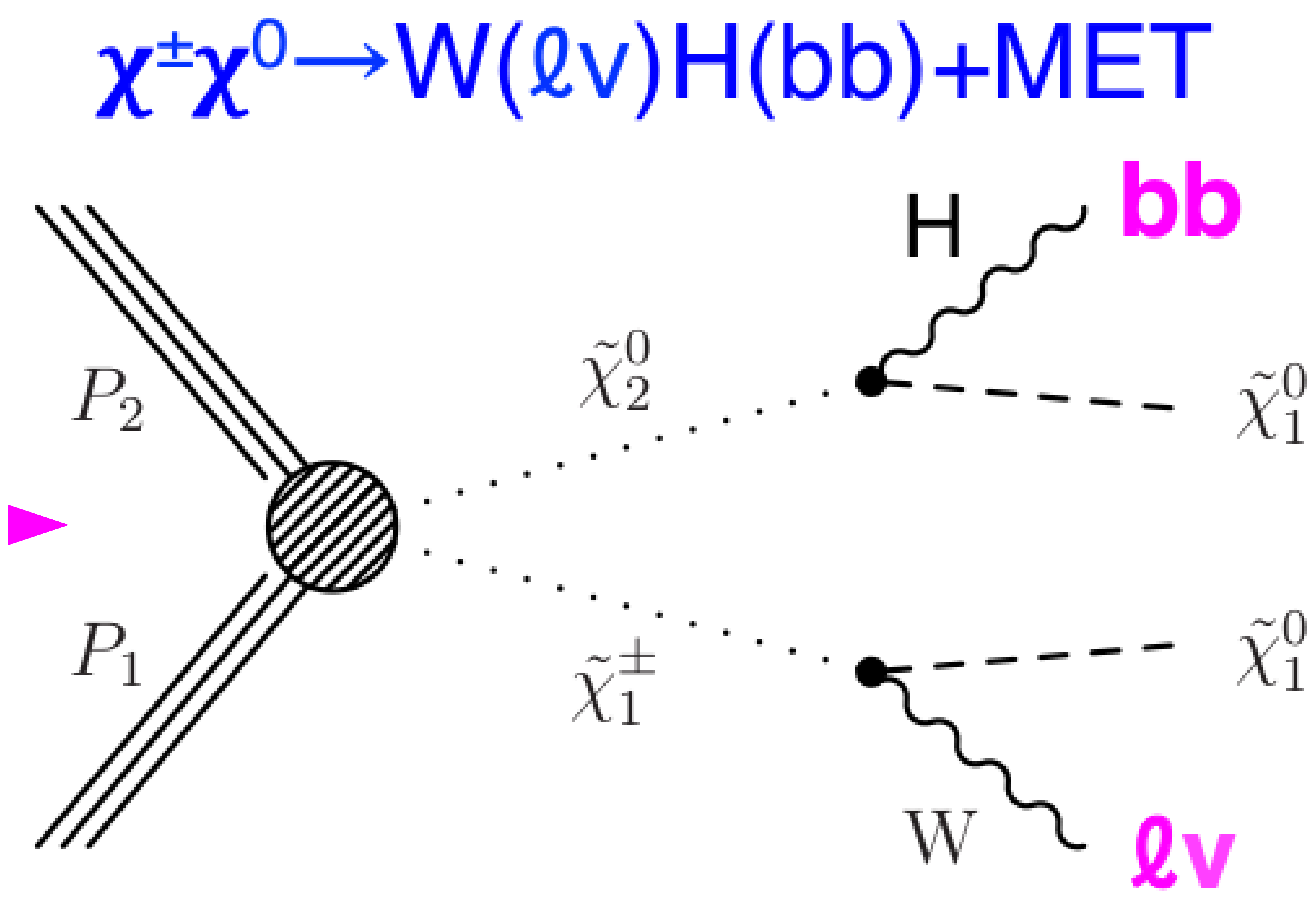
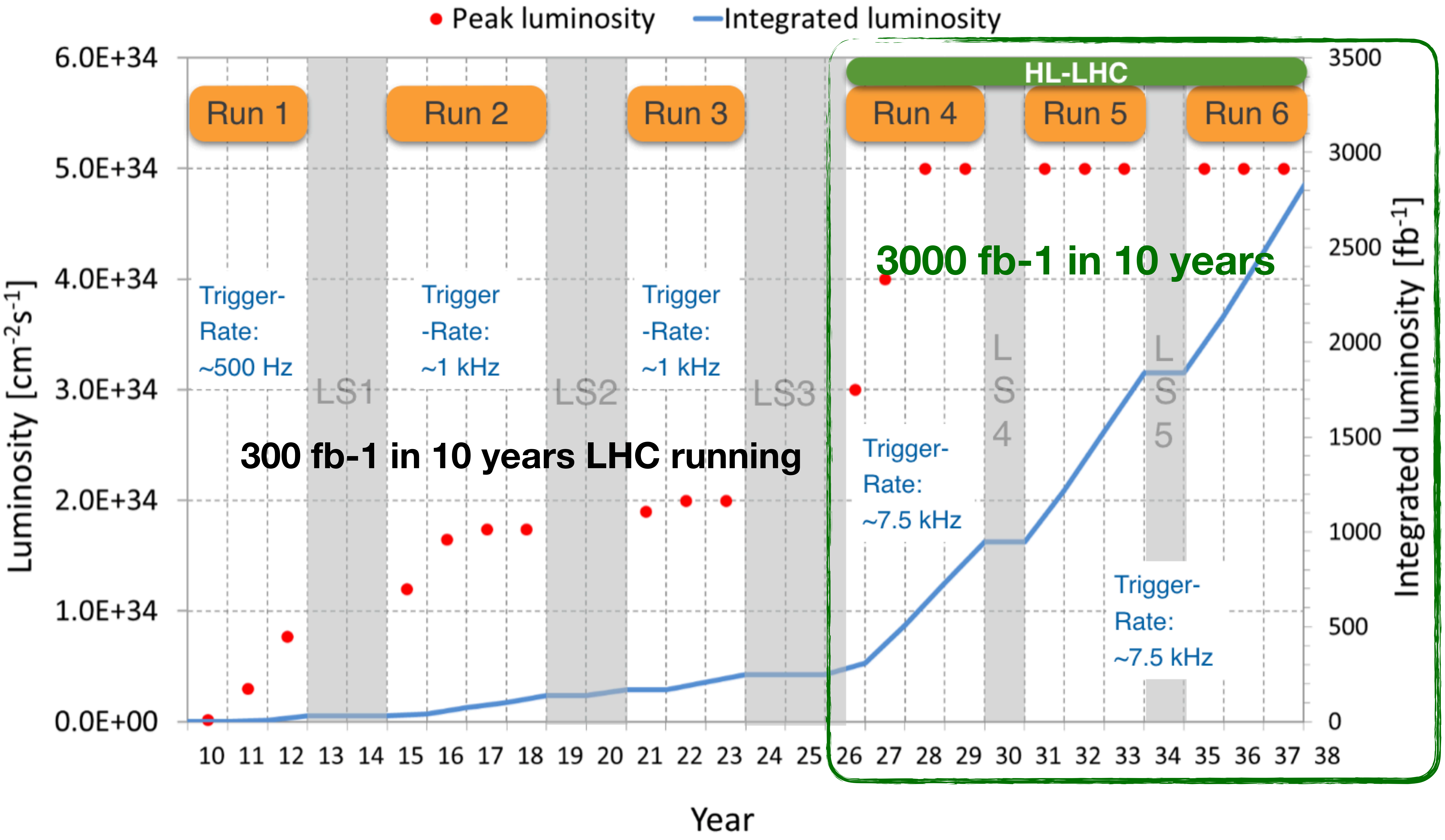


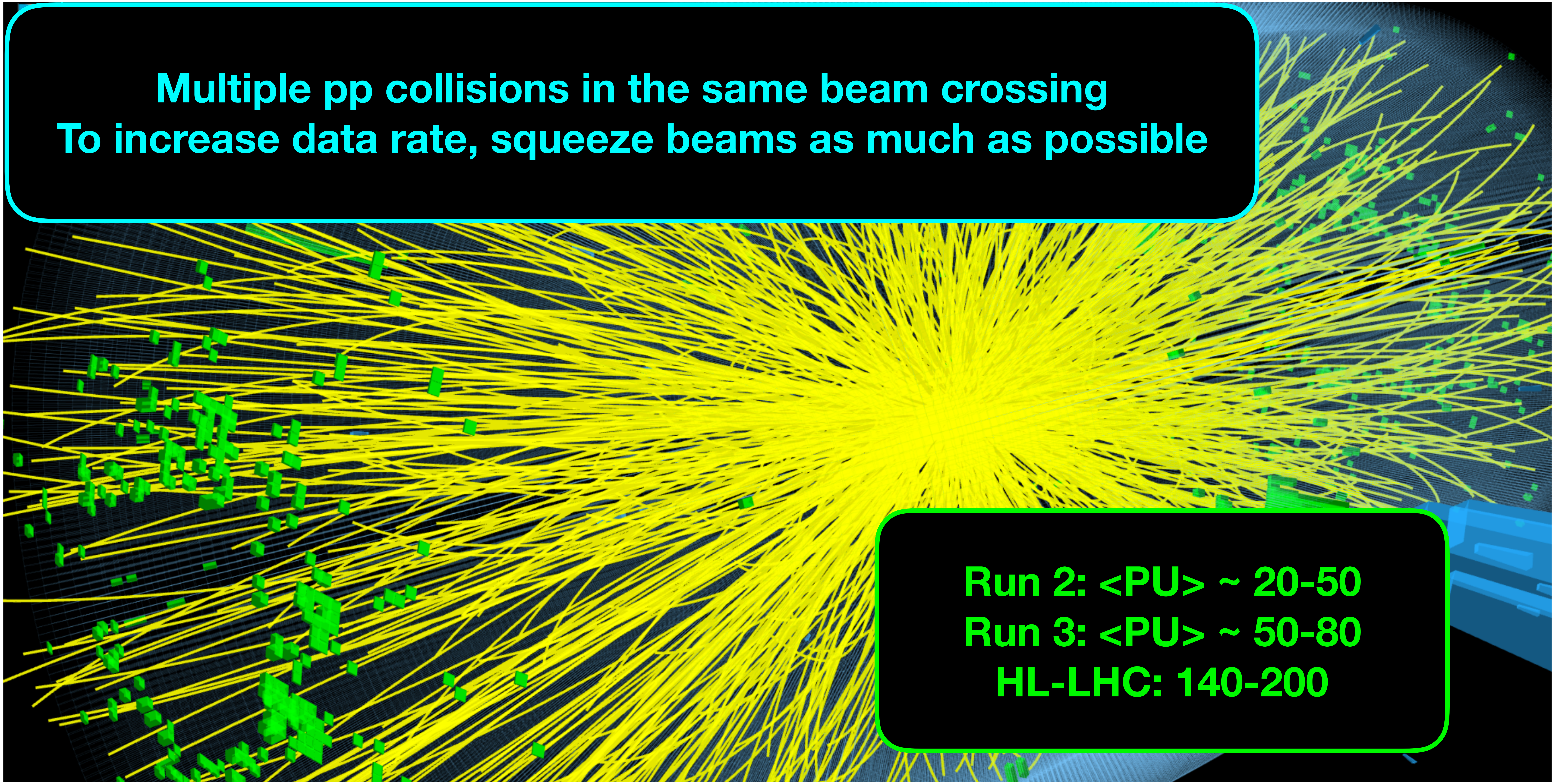


- **Improved vertex resolution/tracking efficiency**
- **★—>★: ~15% improvement in b-jet efficiency @ 1% mistag rate working point.**
- **WH+MET analysis: ~25 to 30 % improvement for H->bb efficiency**

PLANS FOR THE HL-LHC



HL-LHC AND THE PILEUP CHALLENGE



Multiple pp collisions in the same beam crossing
To increase data rate, squeeze beams as much as possible

Run 2: <PU> ~ 20-50
Run 3: <PU> ~ 50-80
HL-LHC: 140-200

AS A RESULT : DETECTORS GETTING MORE COMPLEX

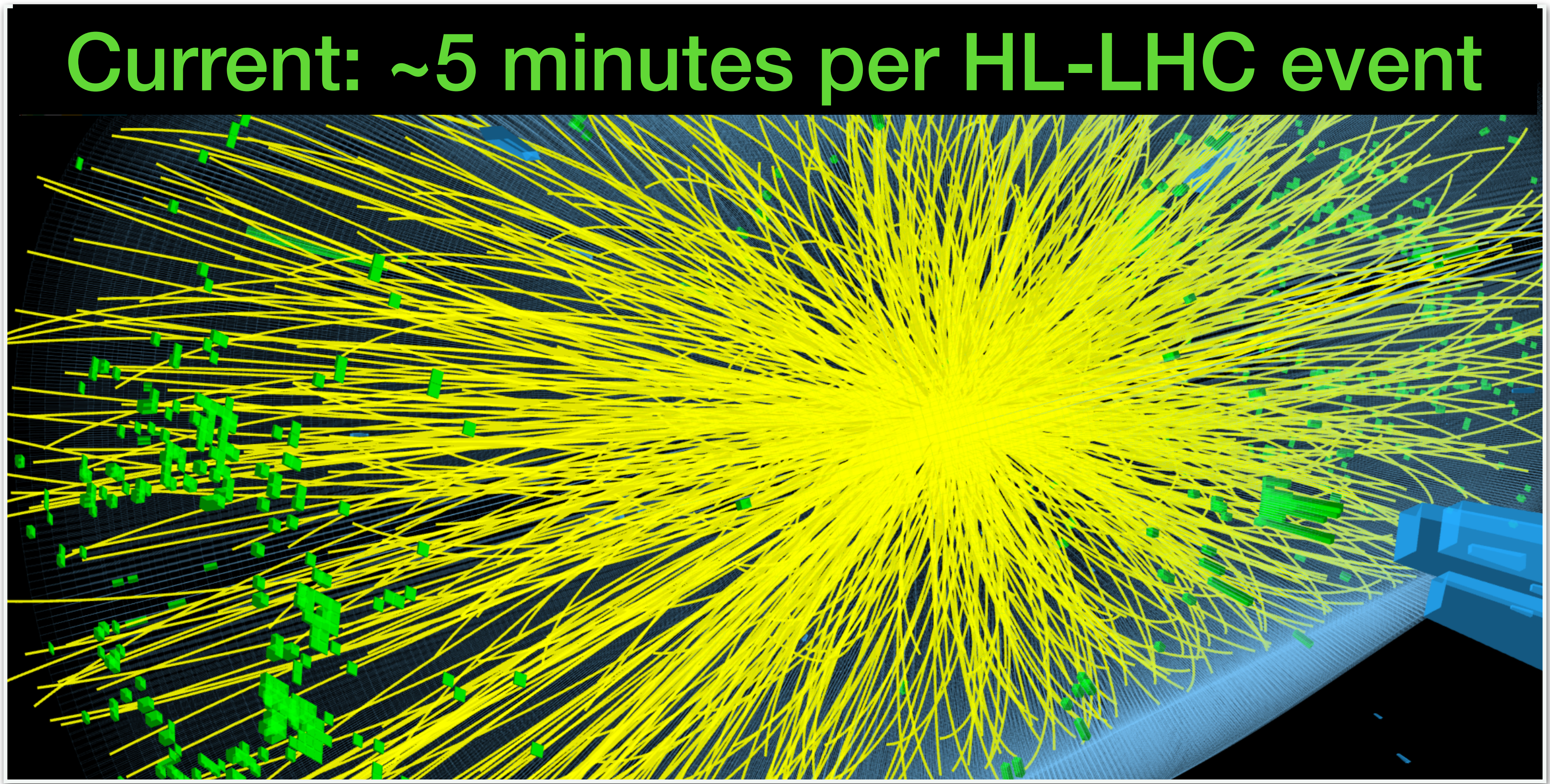
CMS pixel	#channels
Phase-0	66 M
Phase-1	123 M
Phase-2	2B

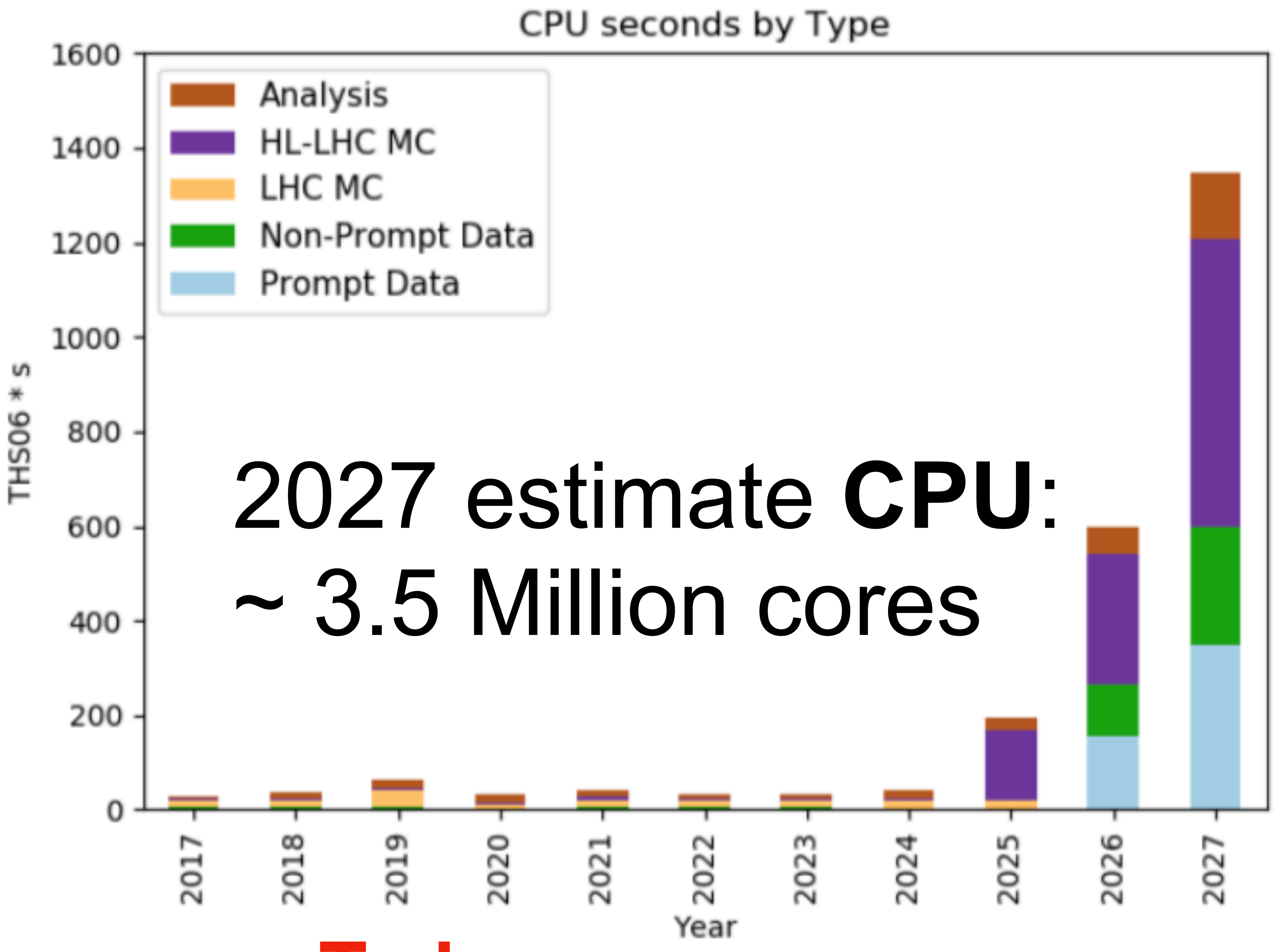
- ***Detector becoming more complex.***

TRIGGER AND COMPUTING CHALLENGES @HL-LHC

CMS pixel	#channels
Phase-0	66 M
Phase-1	123 M
Phase-2	2B

Event complexity





Today

- ***Detector becoming more complex: Increased data complexity with larger dataset***
    - ***Trigger and Computing challenges@ HL-LHC***

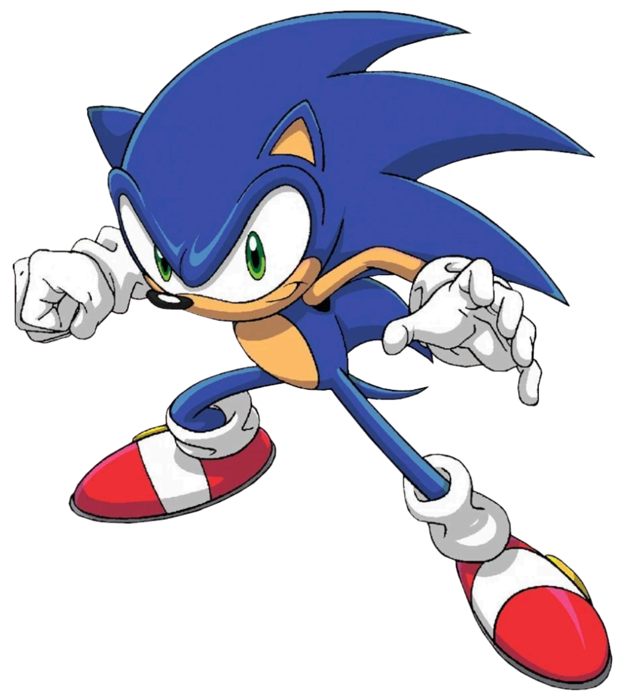
Actively pursuing trigger upgrades and Computing solutions:

- Trigger: tracking and particle flow objects at CMS Level-1
- Offline: Parallelized and Vectorized Tracking Using Kalman Filters

Novel approach: Fast inference of Neural Networks for trigger and computing applications

- Active exploration of Machine Learning applications in HEP.

PROOF OF CONCEPT: SONIC



Services for Optimized Network Inference on Co-processors

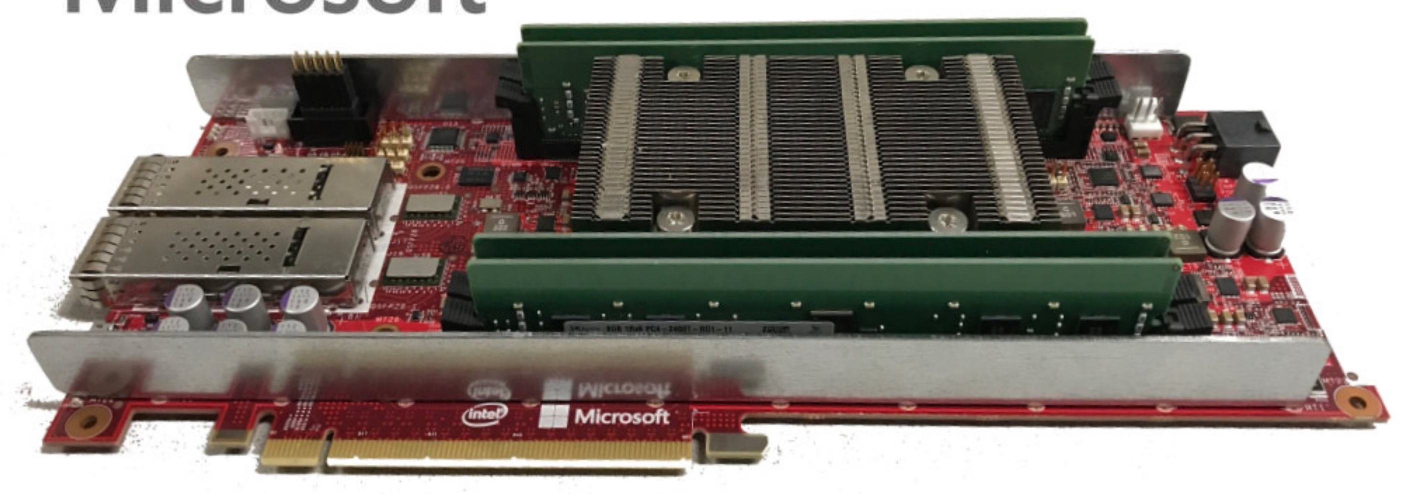
FPGA-accelerated machine learning inference as a service for particle physics computing

https://arxiv.org/pdf/1904.08986.pdf

Javier Duarte · Philip Harris · Scott Hauck · Burt Holzman · Shih-Chieh Hsu · Sergo Jindariani · Suffian Khan · Benjamin Kreis · Brian Lee · Mia Liu · Vladimir Lončar · Jennifer Ngadiuba · Kevin Pedro · Brandon Perez · Maurizio Pierini · Dylan Rankin · Nhan Tran · Matthew Trahms · Aristeidis Tsaris · Colin Versteeg · Ted W. Way · Dustin Werran · Zhenbin Wu

MS Brainwave: FPGA co-processors

Microsoft



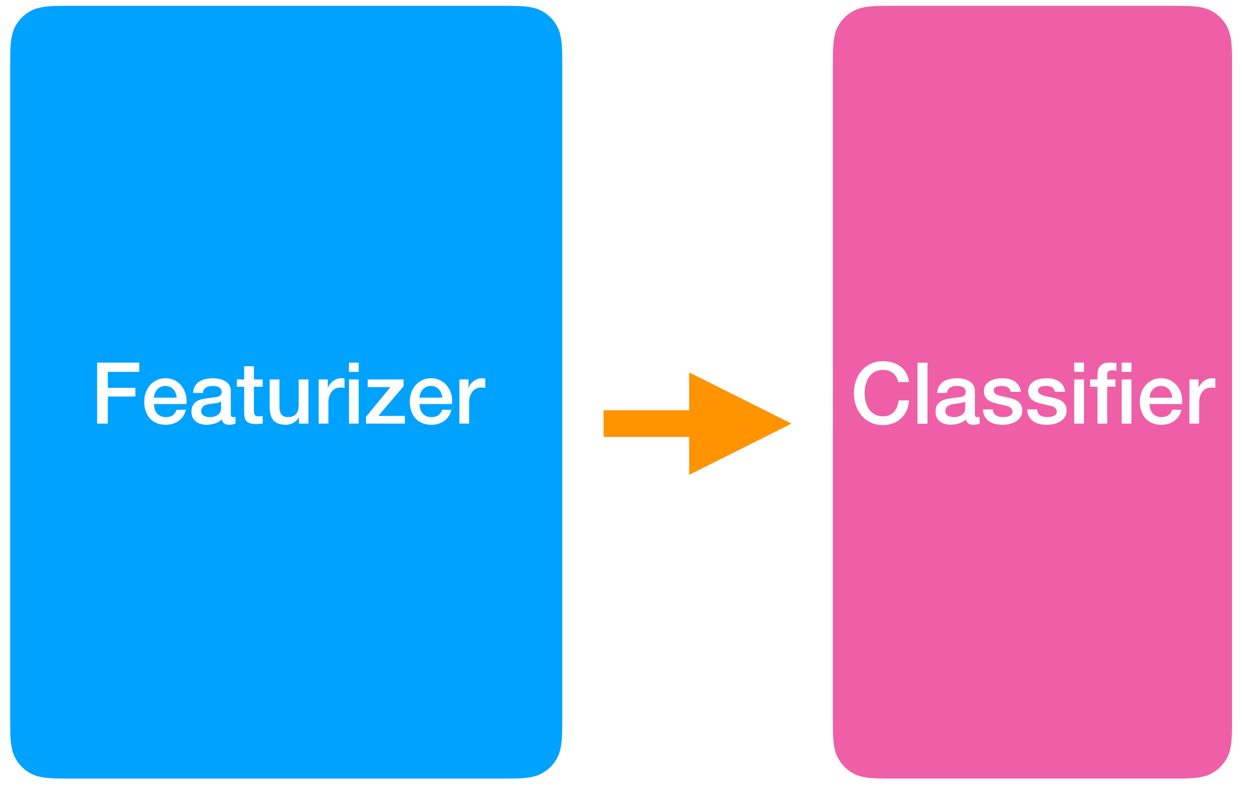
Question:

How do we help with physics event data processing model with industry developments?

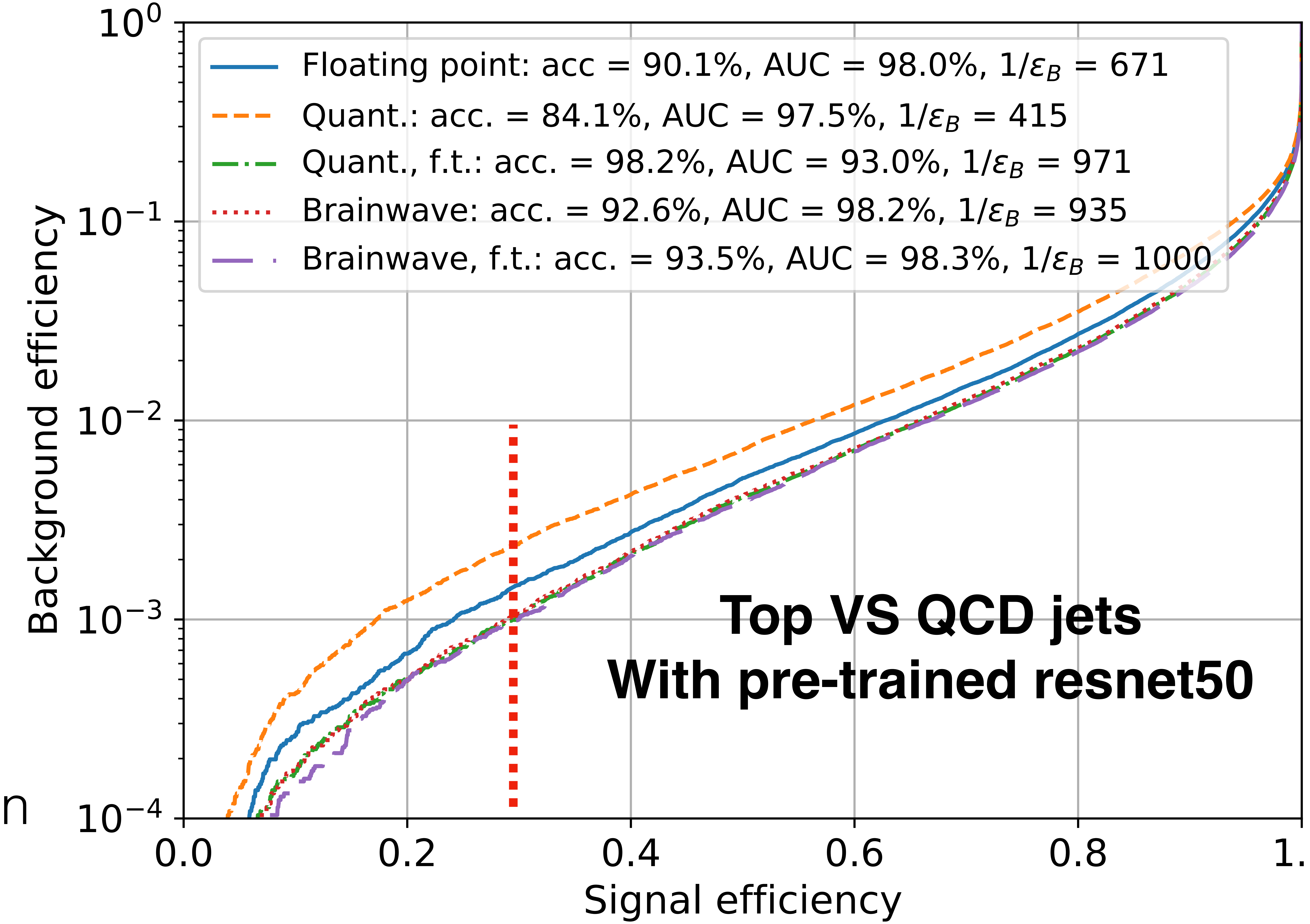
TOP TAGGING USING BRAINWAVE SERVICE

Re-train: Fine-tune

Re-train With 2 labels Top vs QCD



Quantized model:
Brainwave's implementation of ResNet50 on FPGA



APPLICATIONS NOT LIMITED TO LHC

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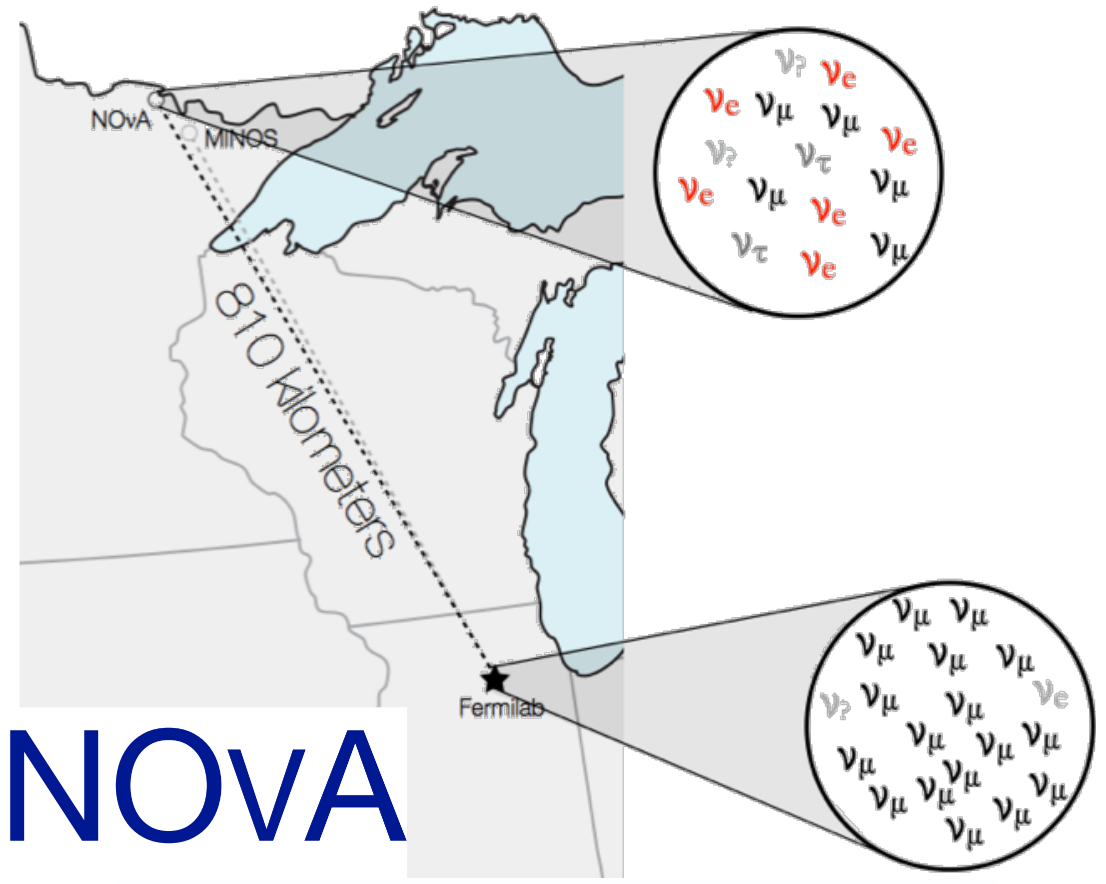
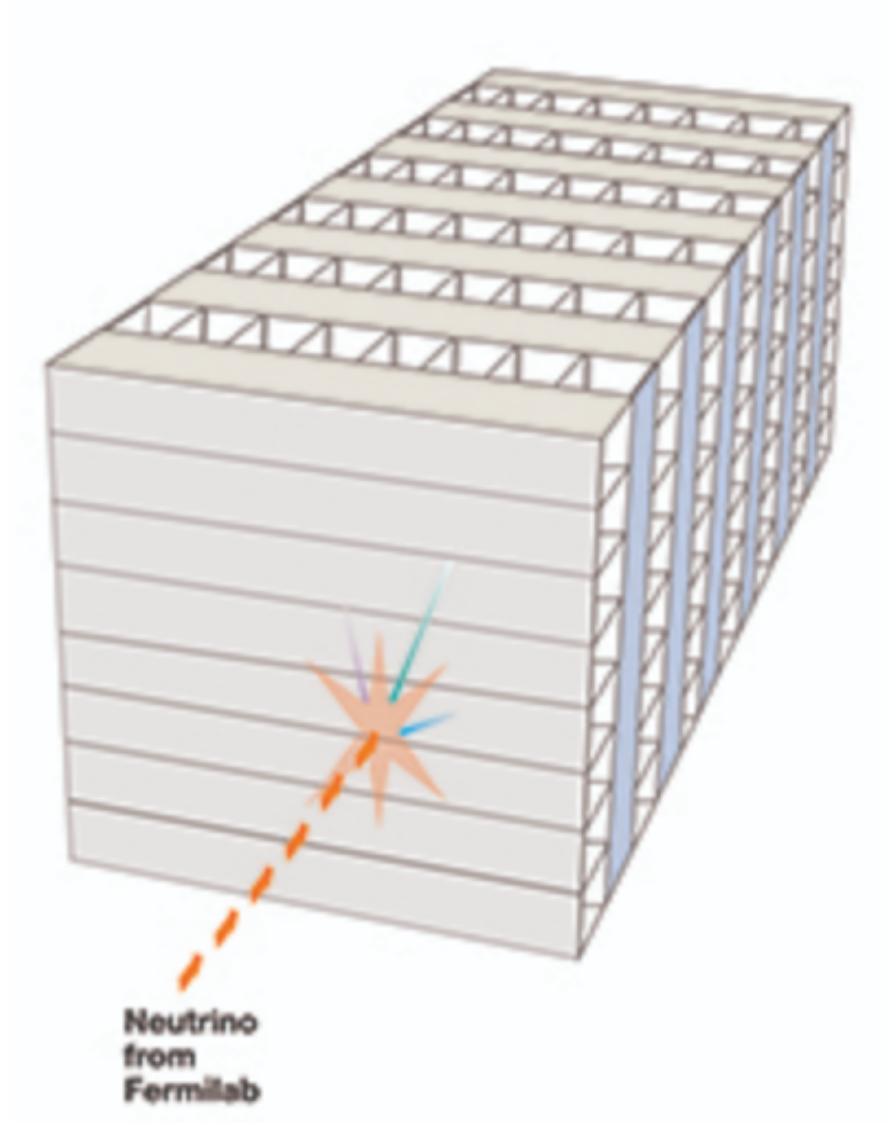
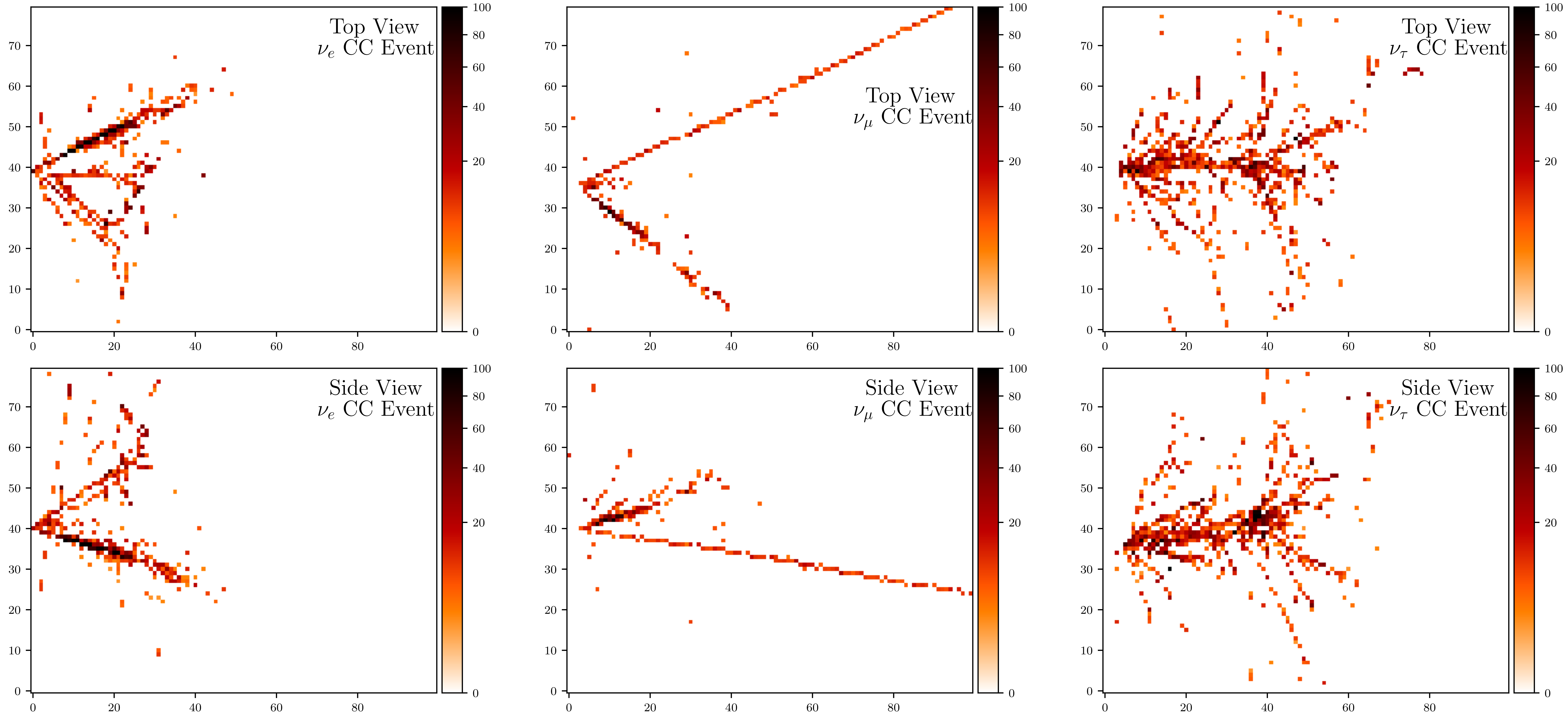






Electron neutrino Muon neutrino Tau neutrino

- Primary goal of NOvA: measurement of neutrino oscillations via νμ→νe: Classifying neutrinos with ResNet50 (transfer learning)

- Potential application for DUNE event processing.

Fermilab

Summary and outlooks

- Data enables physics
    - Electroweak SUSY with WH +MET and WWW analyses @ LHC Run2 @ 13 TeV
- Instrumentation enables data
  - Keep up with LHC data rate and volume:
    - CMS Phase 1 pixel upgrade (completed). Fast machine learning inference for trigger/computing challenges.
  - Impacts the HL-LHC physics program: Higgsino searches, Di-Higgs, polarization component of same-sign WW scattering….

We've collected only 5% of the LHC data.

Let's actively look for possible anomalies in LHC /HL-LHC datasets!

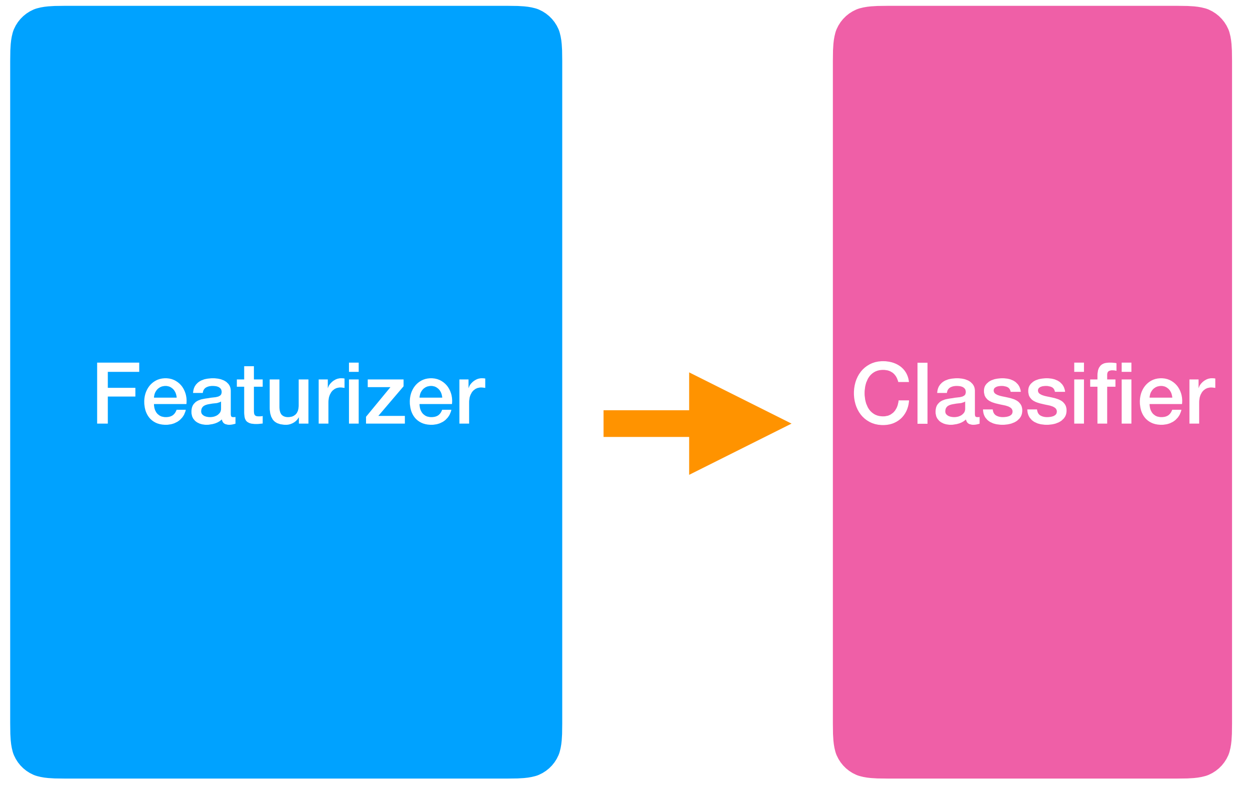
Thanks!

Applications not limited to HEP

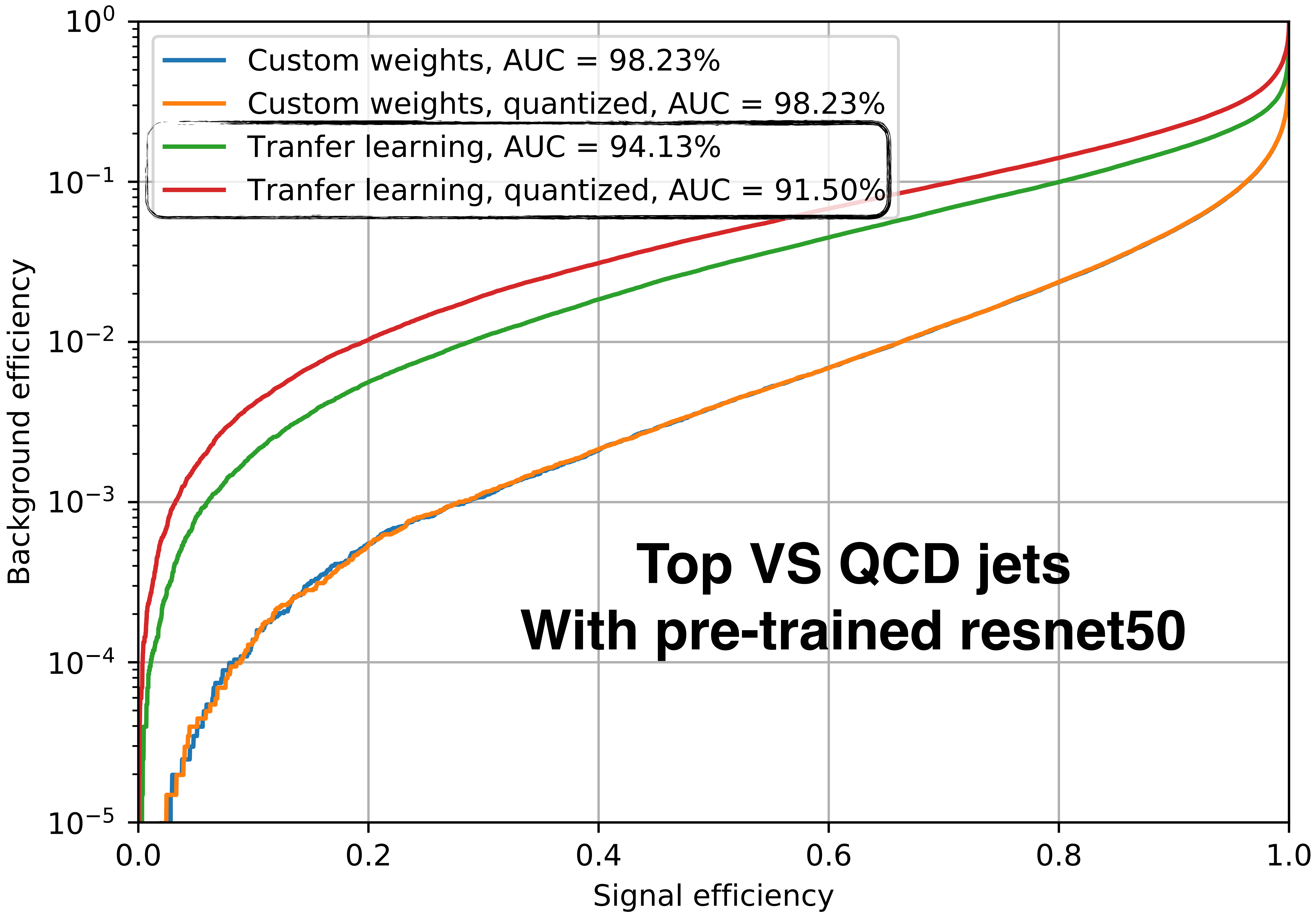
TRANSFER LEARNING: RESNET-50 FOR TOP TAGGING

Frozen

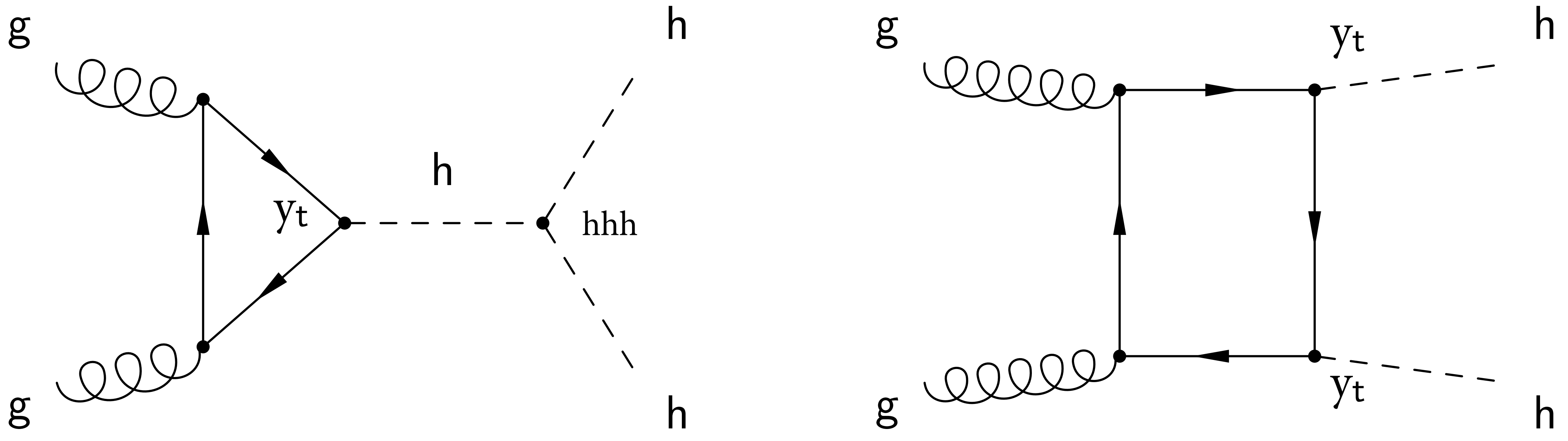
Re-train With 2 labels: Top vs QCD

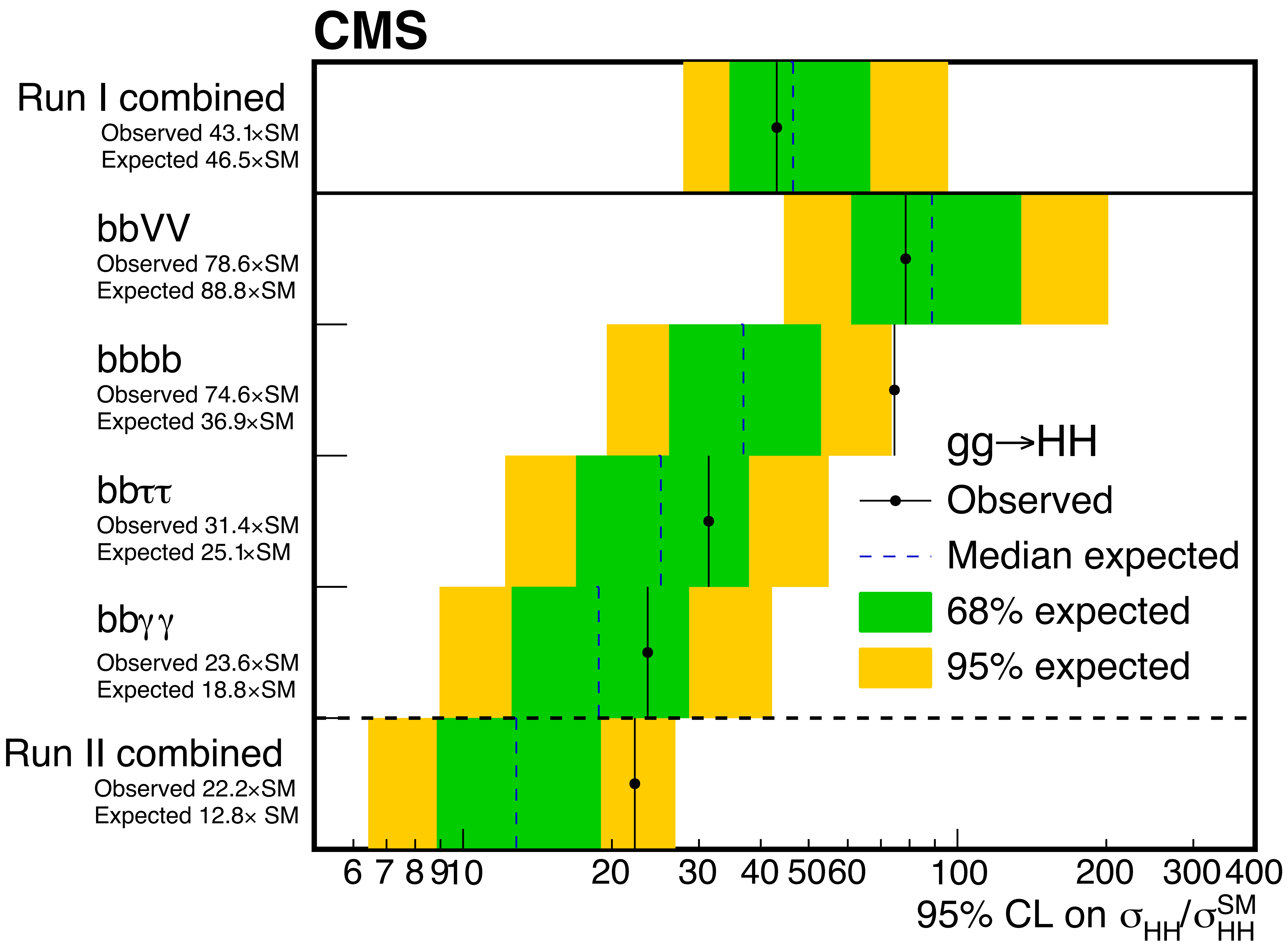


- **Quantized: MS's implementation of ResNet 50 on their FPGA co-processors**



Some processes need HL-LHC dataset (3000 fb-1) to be tested



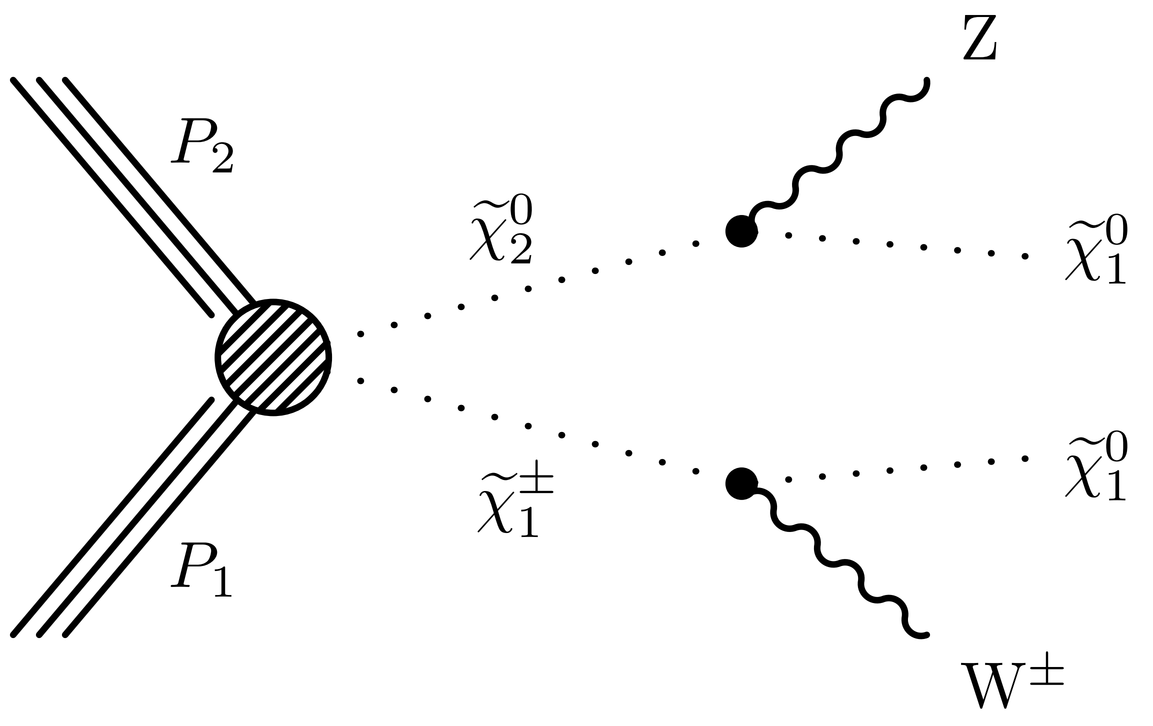


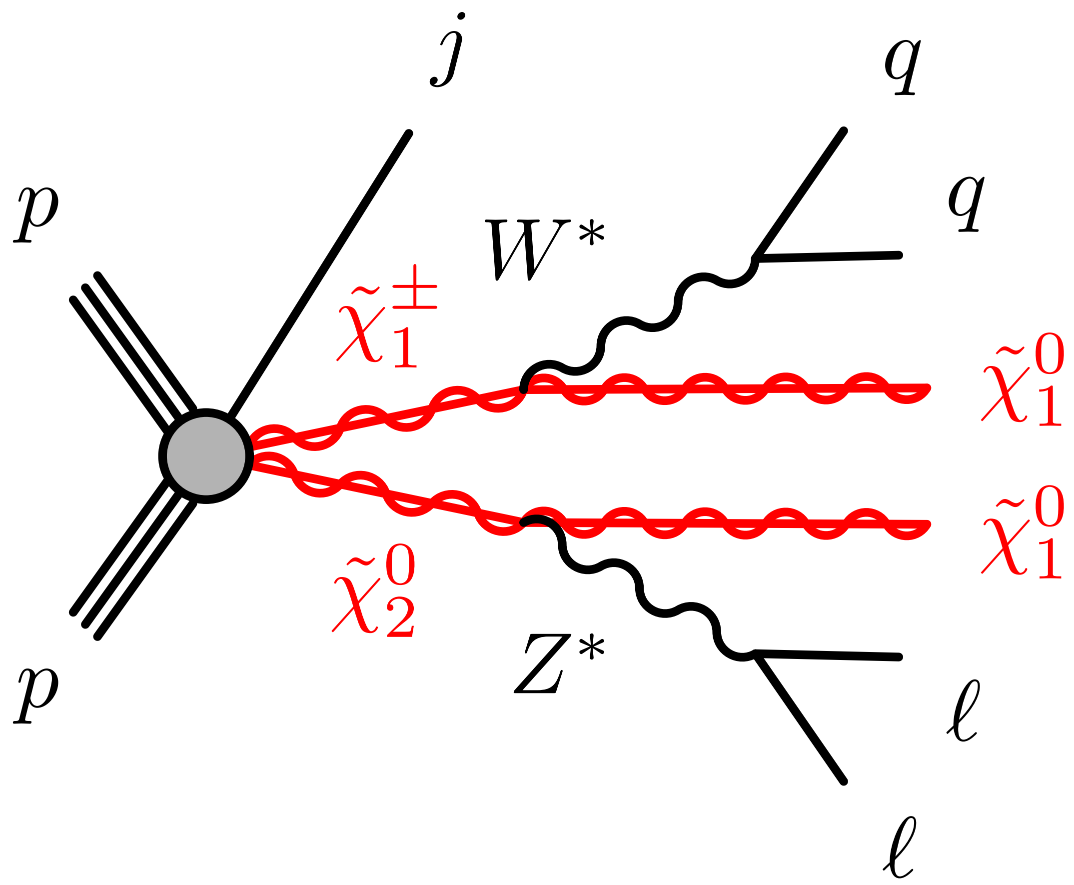
- 1500 lower than single Higgs production
- Di-higgs production to measure the Higgs self-coupling—> direct probe of the Higgs potential.

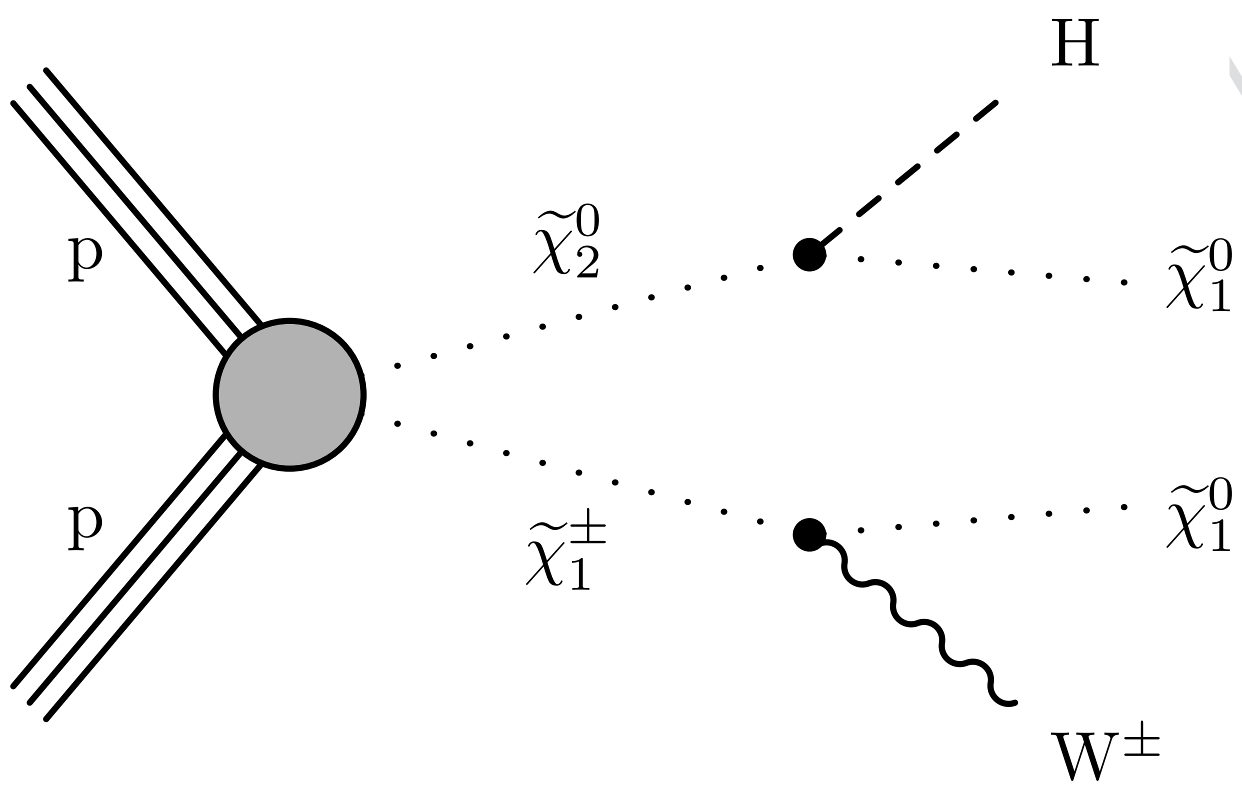
Channel	Significance Stat. + syst.	Significance Stat. only
bbbb	0.95	1.2
$bb\tau\tau$	1.4	1.6
$bbWW(\ell\nu\ell\nu)$	0.56	0.59
$bb\gamma\gamma$	1.8	1.8
$bbZZ(\ell\ell\ell\ell)$	0.37	0.37
Combination	2.6	2.8

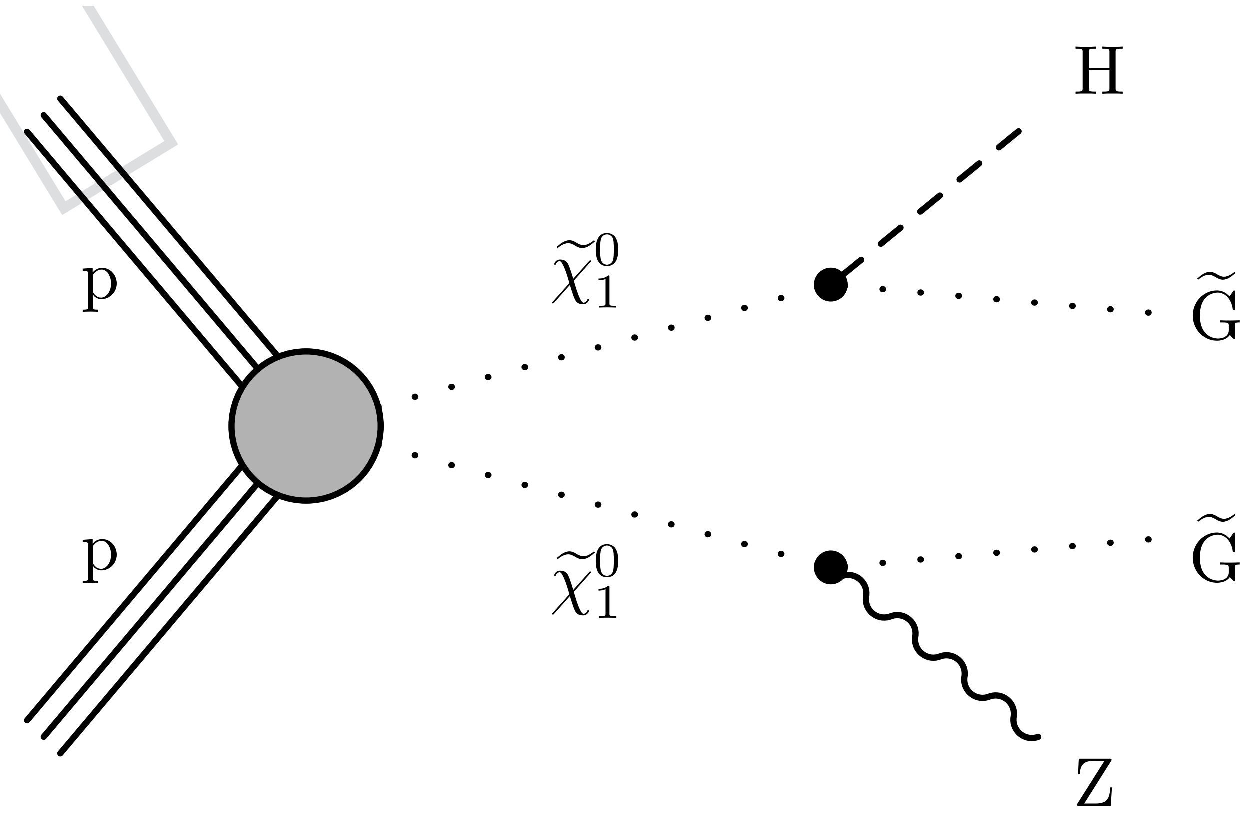
CMS PAS: FTR-18-019

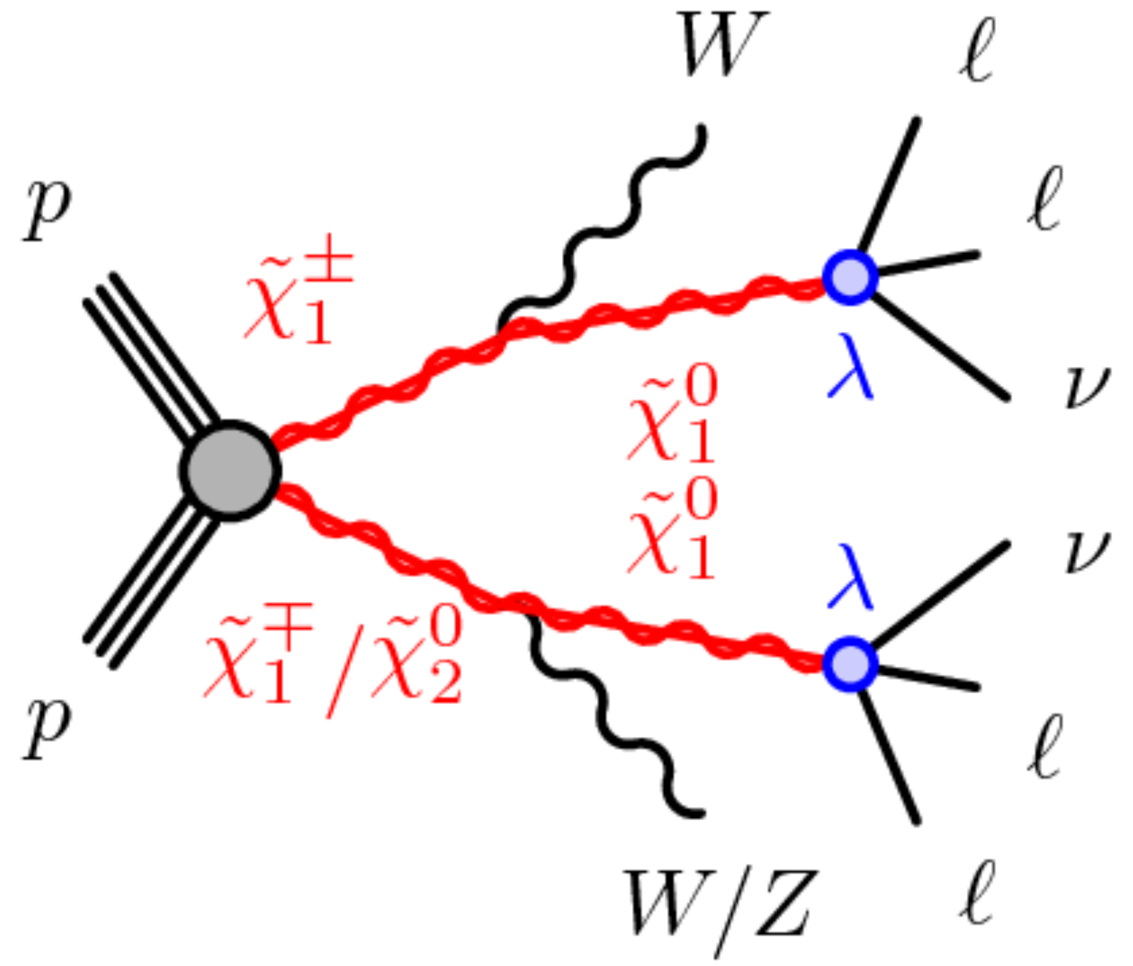
Examples of models explored at the LHC

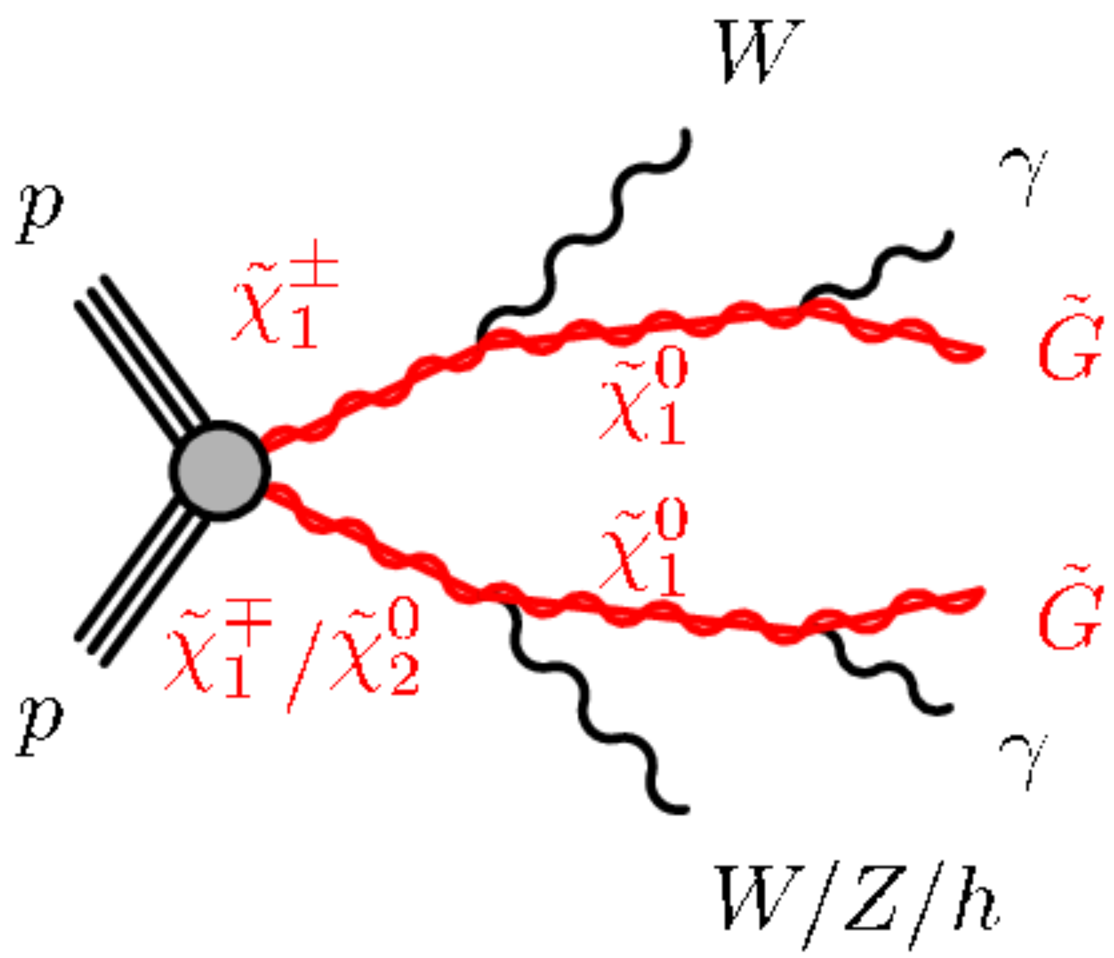


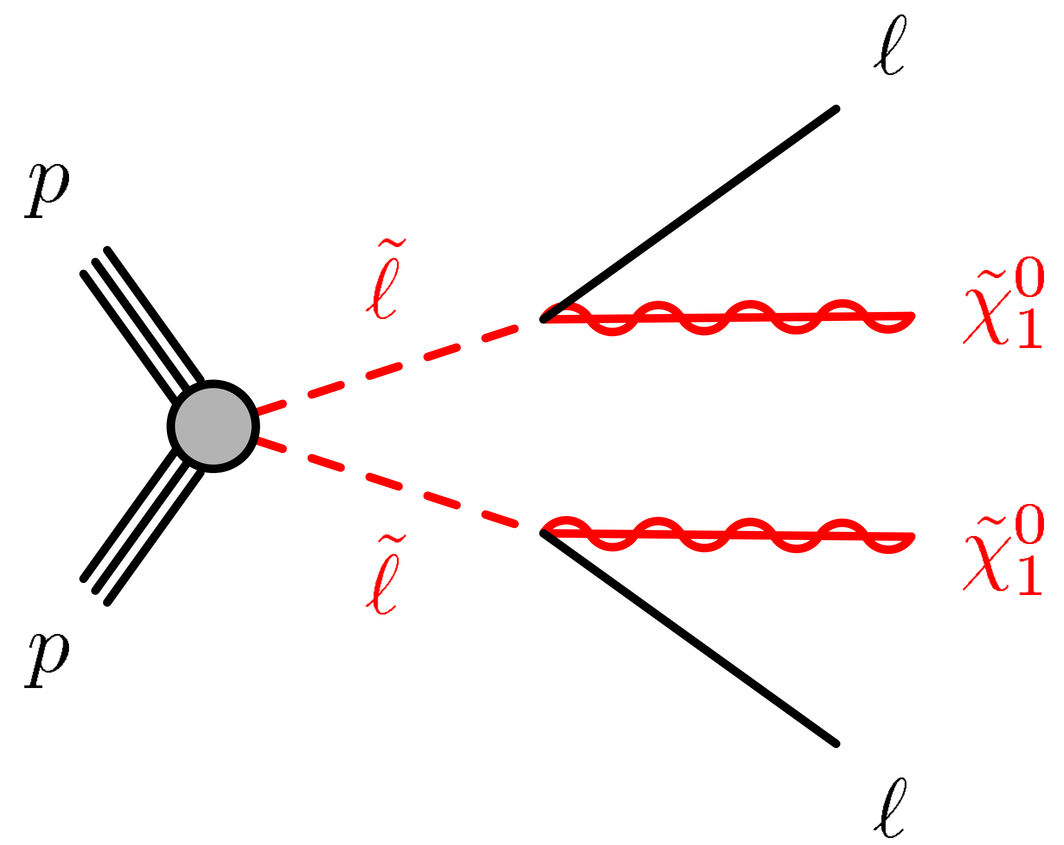




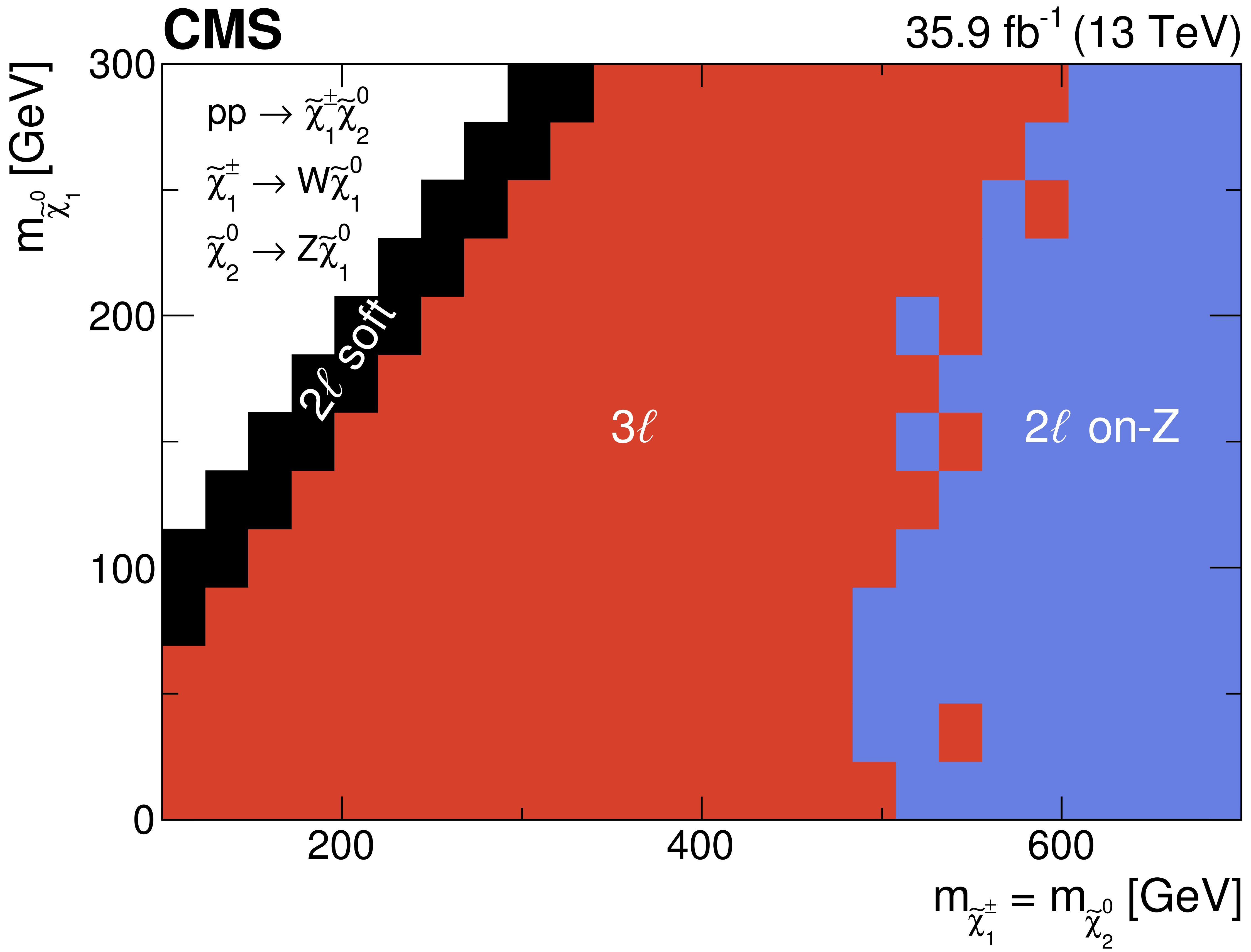


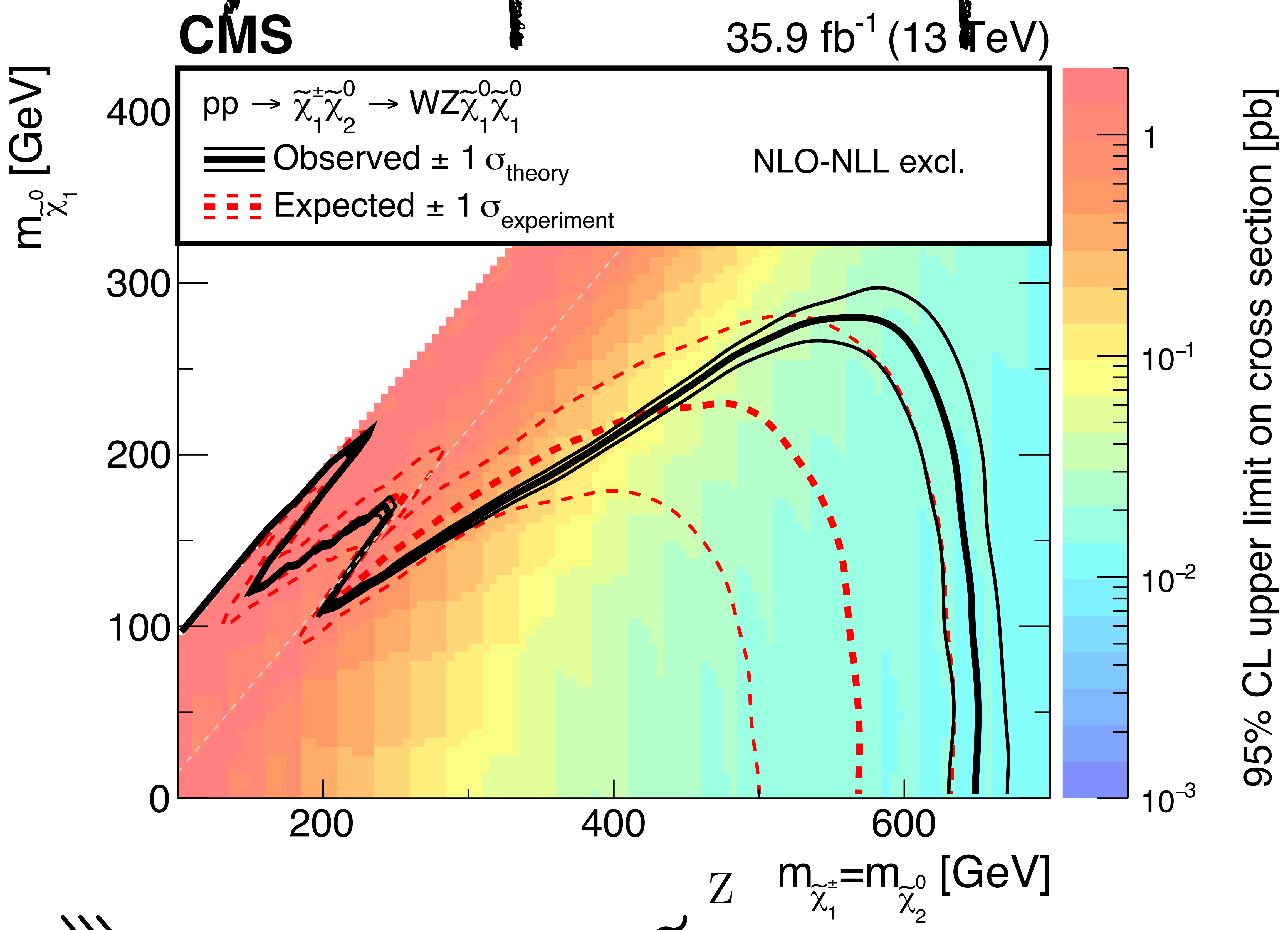




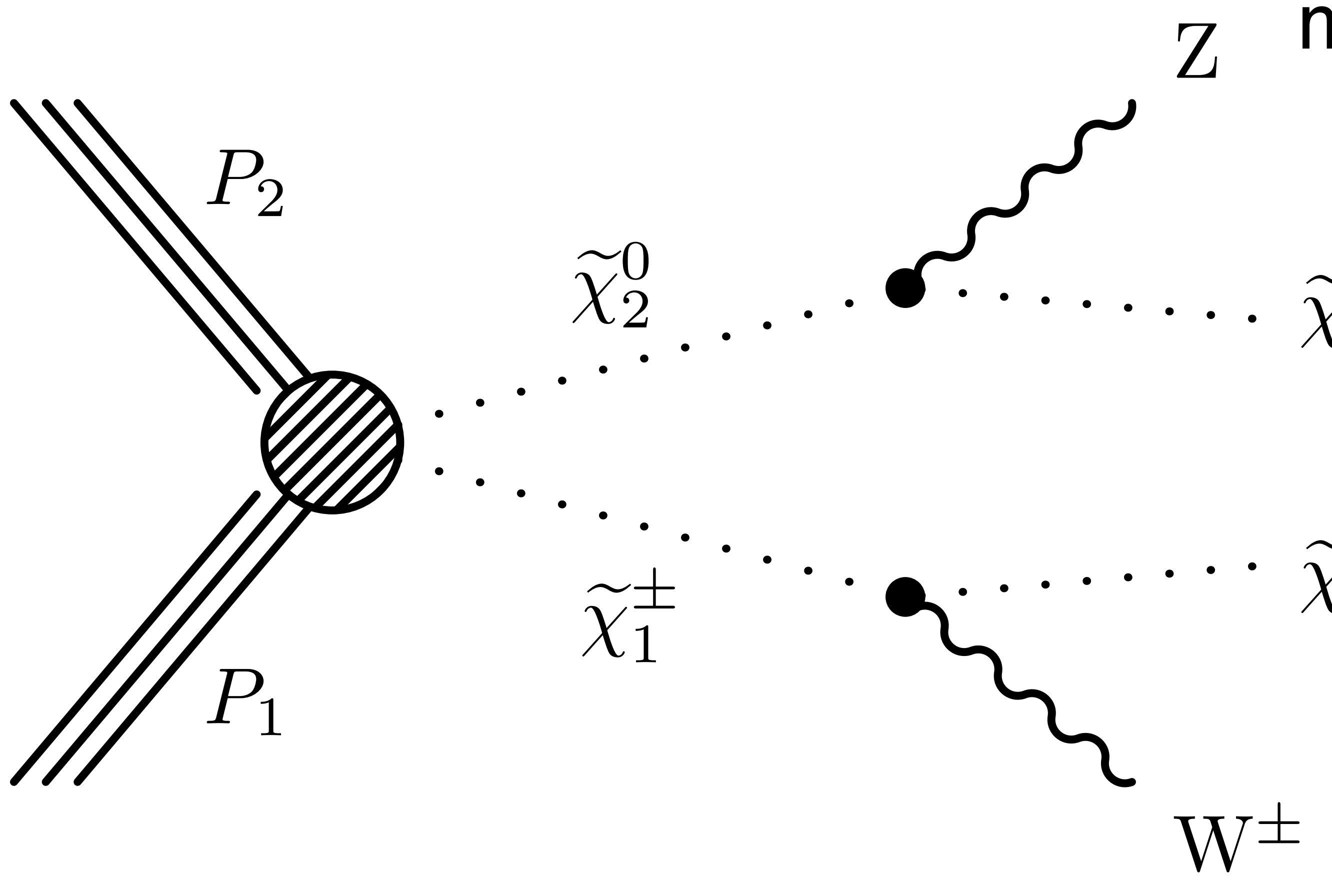


Combination to cover full phase space





- SUS-16-039: Multilepton: Same-sign 2L+ 3L
- SUS-16-034: OS 2L + MET + jets
- SUS-16-048: Soft-2lepton



Searches with soft leptons targeting compressed spectra

Variable	Common requirement	
Number of leptons	=2	
Lepton charge and flavor	e^+e^- or $\mu^+\mu^-$	
Leading lepton $p_T^{\ell_1}$	>5 (5) GeV for electron (muon)	
Subleading lepton $p_T^{\ell_2}$	>4.5 (4) GeV for electron (muon)	
$\Delta R_{\ell\ell}$	>0.05	
$m_{\ell\ell}$	$\in$[1, 60] GeV excluding [3.0, 3.2] GeV	
E_T^{miss}	>200 GeV	
Number of jets	≥1	
Leading jet p_T	>100 GeV	
$\Delta\phi(j_1, \mathbf{p}_T^{miss})$	>2.0	
min ($\Delta\phi$(any jet, $\mathbf{p}_T^{miss}$))	>0.4	
Number of b-tagged jets	= 0	
$m_{\tau\tau}$	<0 or >160 GeV	
	Electroweakino SRs	Slepton SRs
$\Delta R_{\ell\ell}$	<2	...
$m_T^{\ell_1}$	<70 GeV	...
E_T^{miss}/H_T^{lep}	$> \max\left(5, 15 - 2\frac{m_{\ell\ell}}{1\text{ GeV}}\right)$	$> \max\left(3, 15 - 2\left(\frac{m_{T2}^{100}}{1\text{ GeV}} - 100\right)\right)$
Binned in	$m_{\ell\ell}$	m_{T2}^{100}

Soft leptons

Reject photon conversions

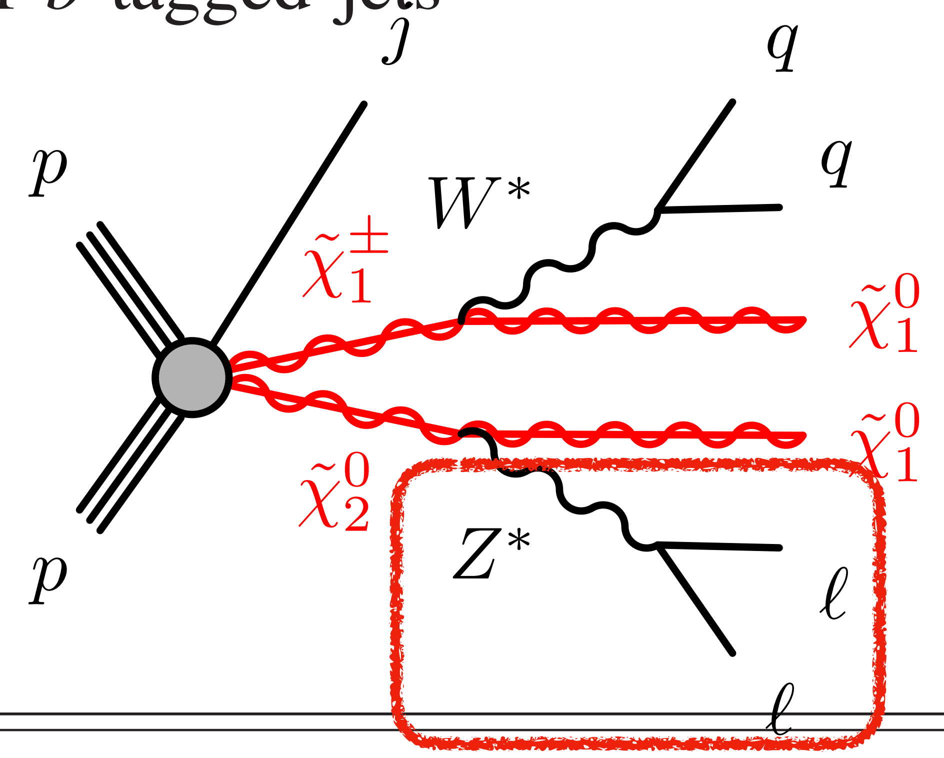
Reject Low mass resonants

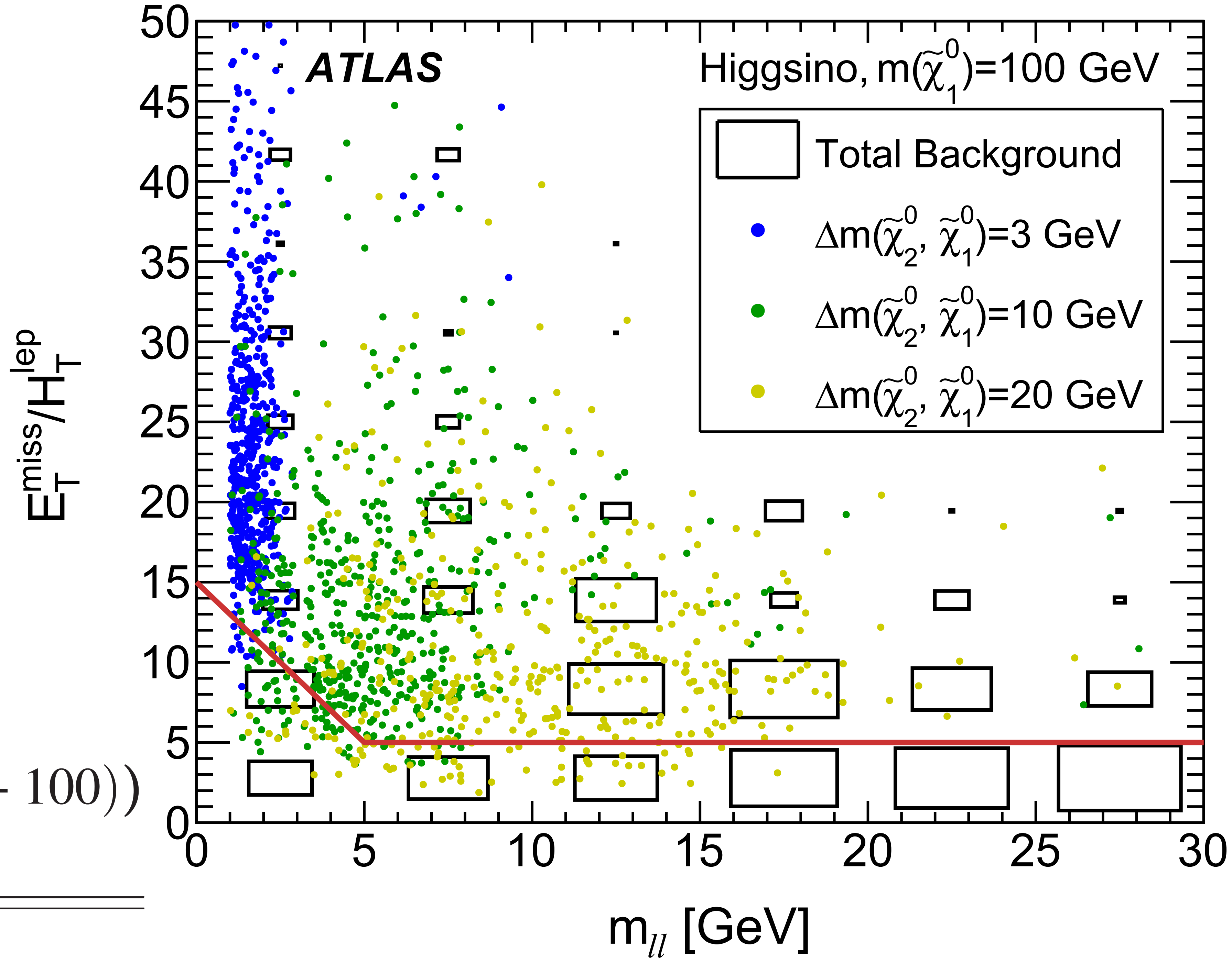
to be triggered

ISR boost to get MET

Reject top

Reject Z(ττ)

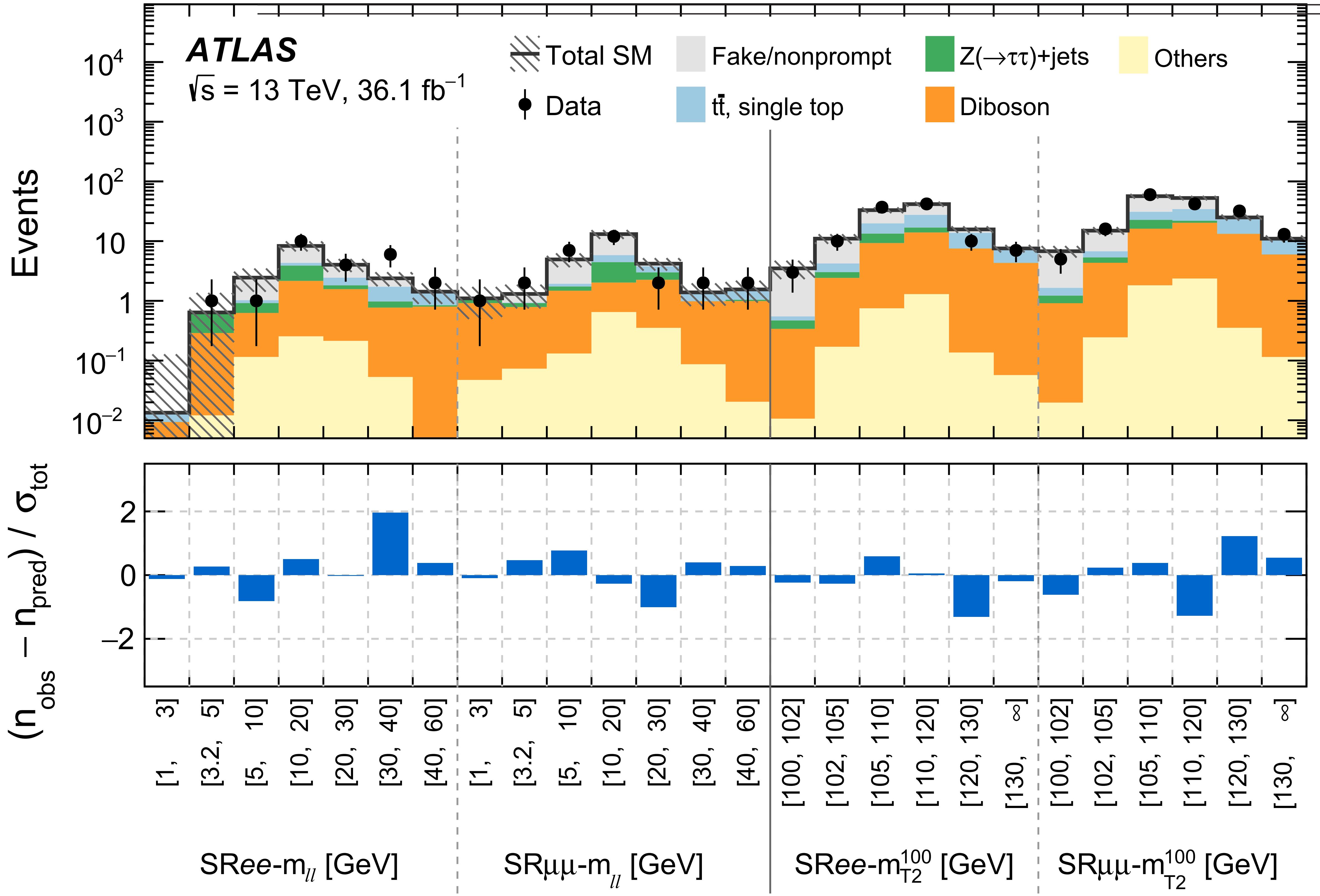




ATLAS: SUSY-2016-25

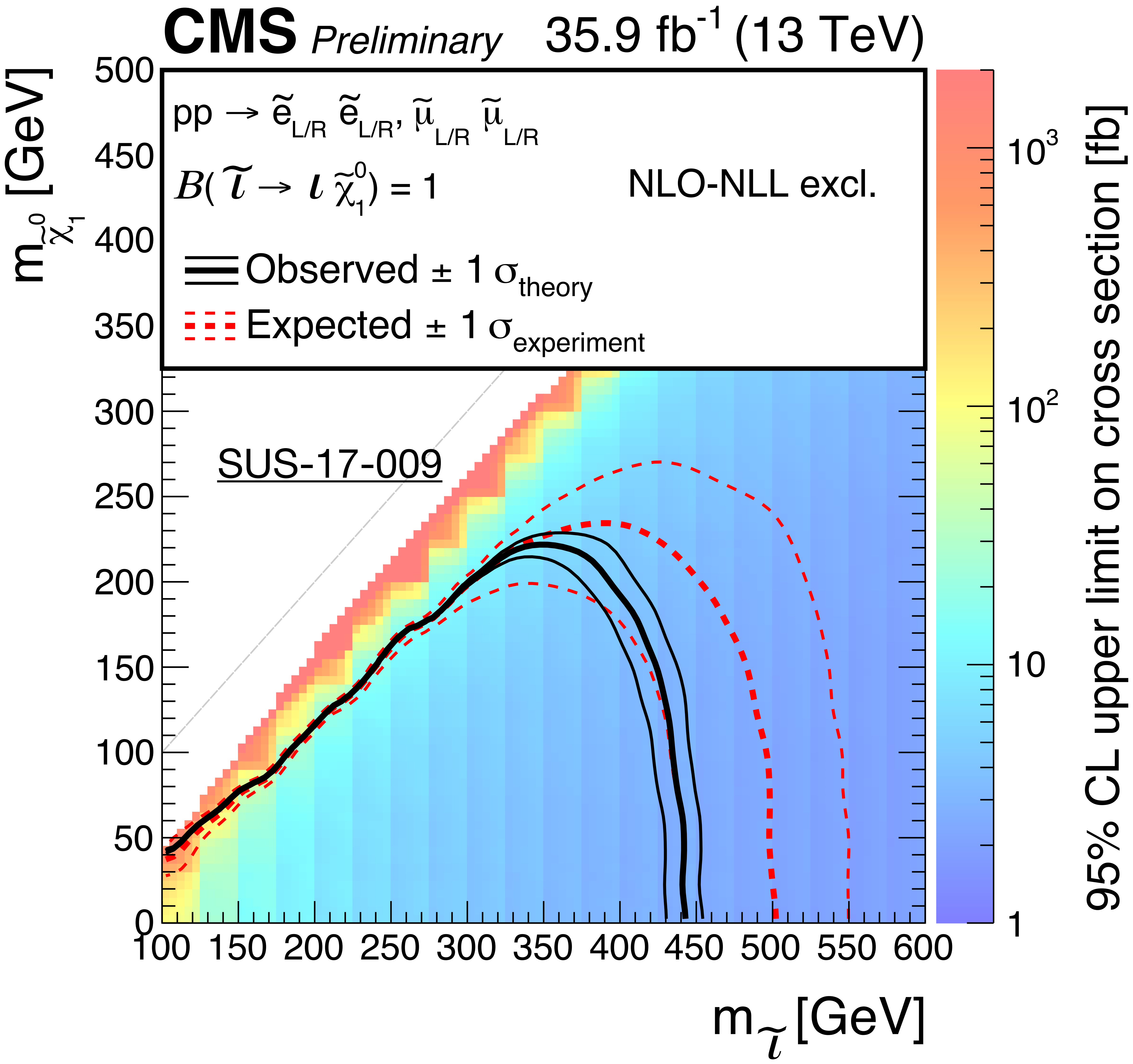
Searches with soft leptons targeting compressed spectra

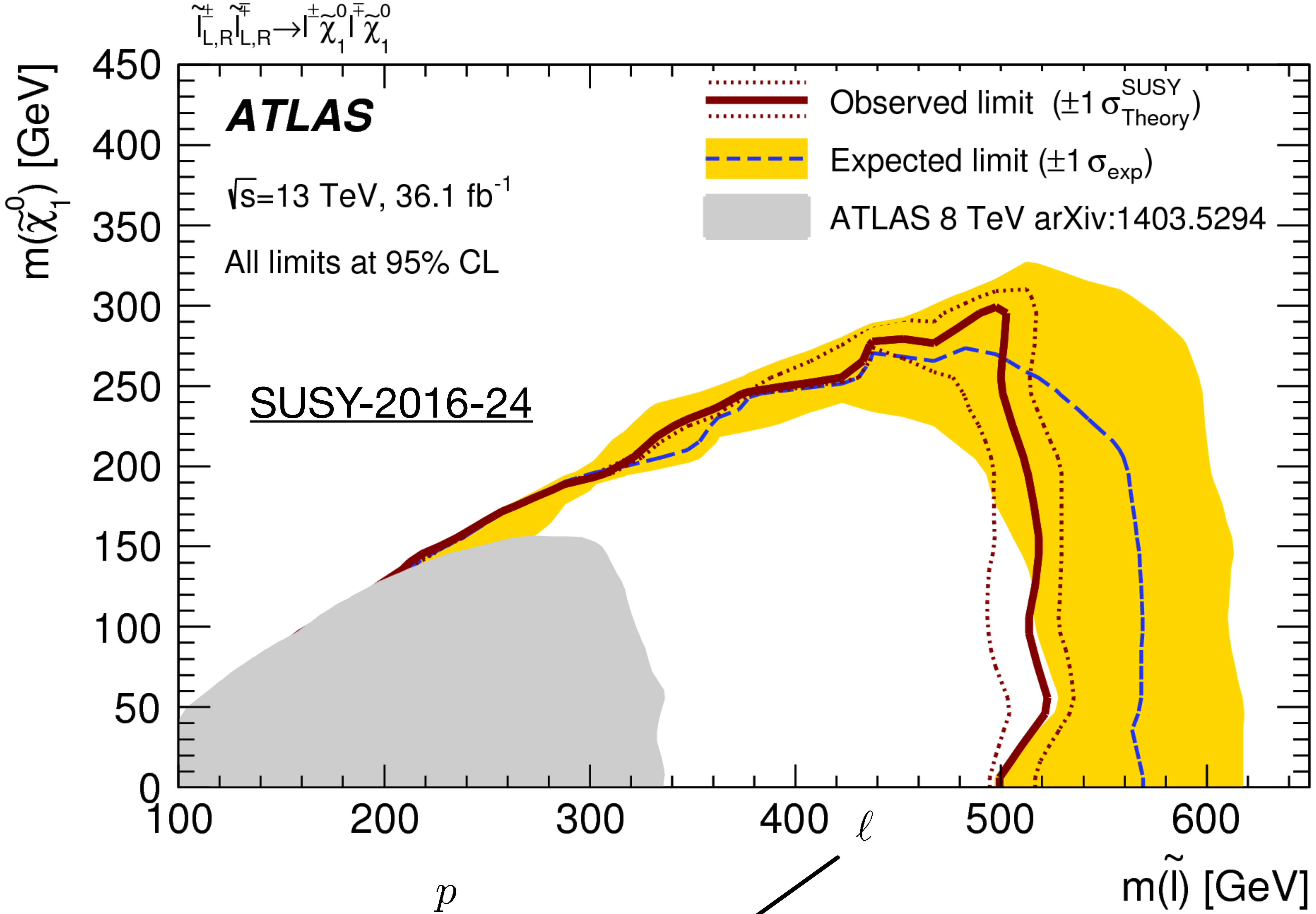
Region	Leptons	E_T^{miss}/H_T^{lep}	Additional requirements
CR-top	$e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$	>5	≥ 1 b-tagged jet(s)
CR-tau	$e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$	$\in [4, 8]$	$m_{\tau\tau} \in [60, 120]$ GeV
VR-VV	$e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$	<3	
VR-SS	$e^\pm e^\pm$, $\mu^\pm\mu^\pm$, $e^\pm\mu^\pm$, $\mu^\pm e^\pm$	>5	
VRDF-$m_{\ell\ell}$	$e^\pm\mu^\mp$, $\mu^\pm e^\mp$	$> \max\left(5, 15 - 2\frac{m_{\ell\ell}}{1\text{ GeV}}\right)$	$\Delta R_{\ell\ell} < 2$, $m_T^{\ell_1} < 70$ GeV
VRDF-m_{T2}^{100}	$e^\pm\mu^\mp$, $\mu^\pm e^\mp$	$> \max\left(3, 15 - 2\left(\frac{m_{T2}^{100}}{1\text{ GeV}} - 100\right)\right)$	

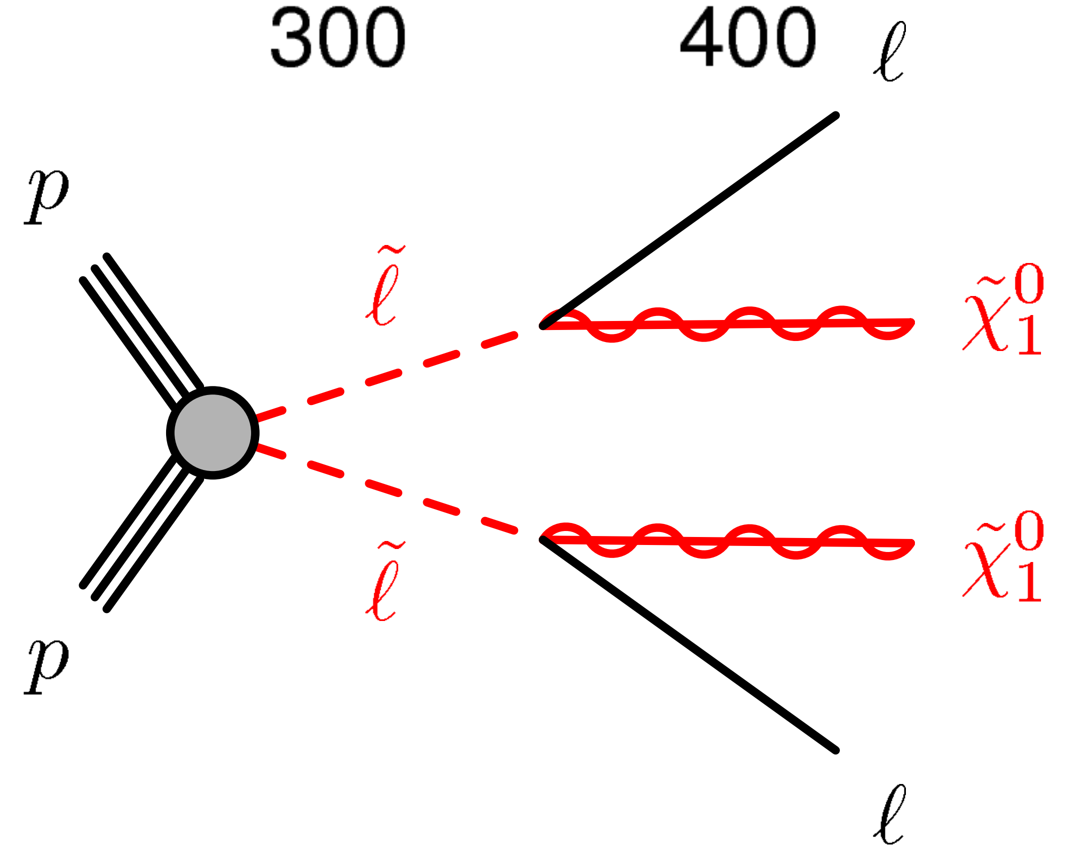


- Top background estimated from a b-tagged region.
- Tau background estimated on Z peak.
- Diboson backgrounds validated in data
- Fake lepton estimated with fake rate method, validated with a Same-sign dilepton region
- Mll and MT2 shape modeling validated using e/m events

Direct slepton production(ee/mm +MET)



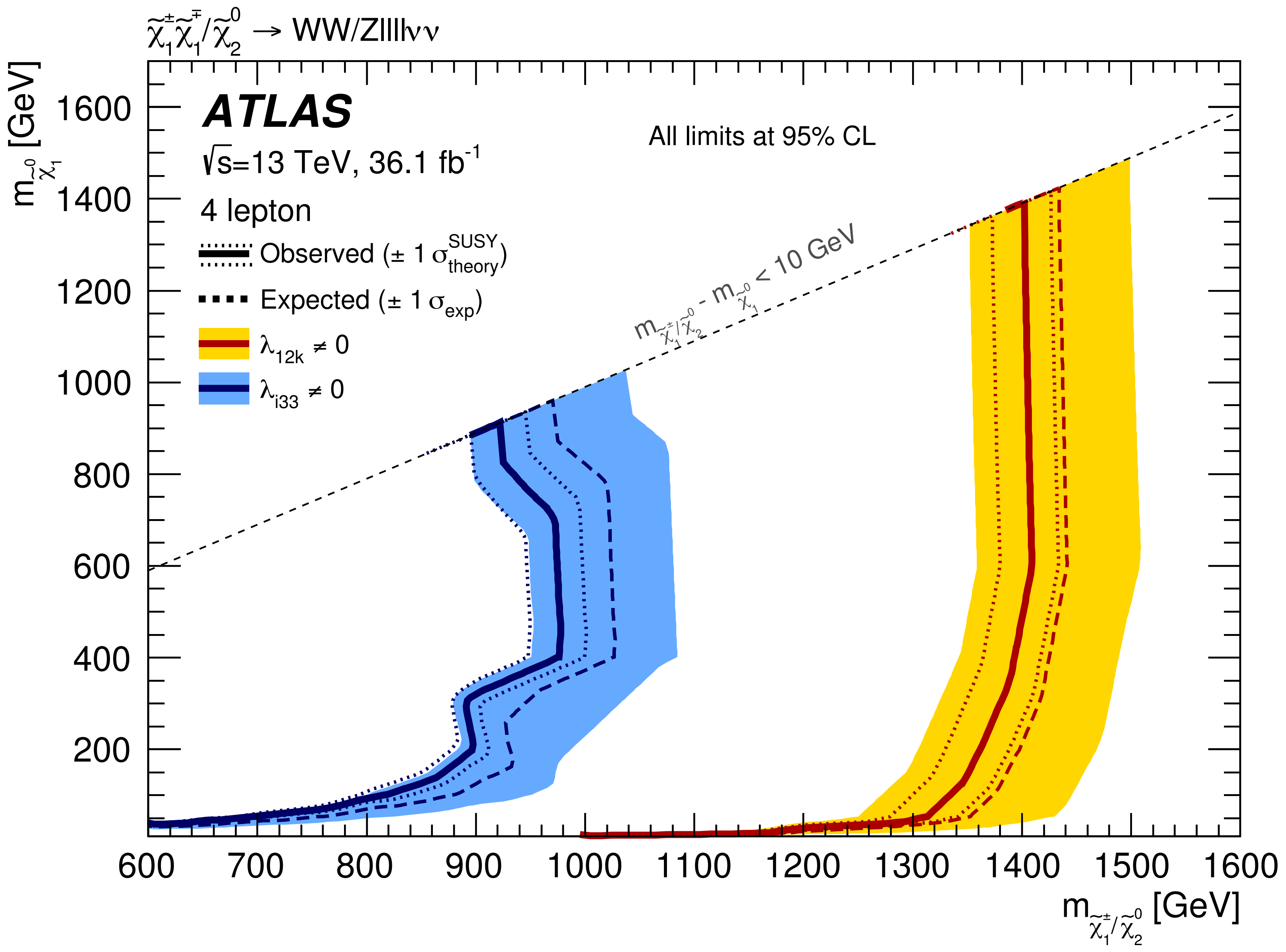




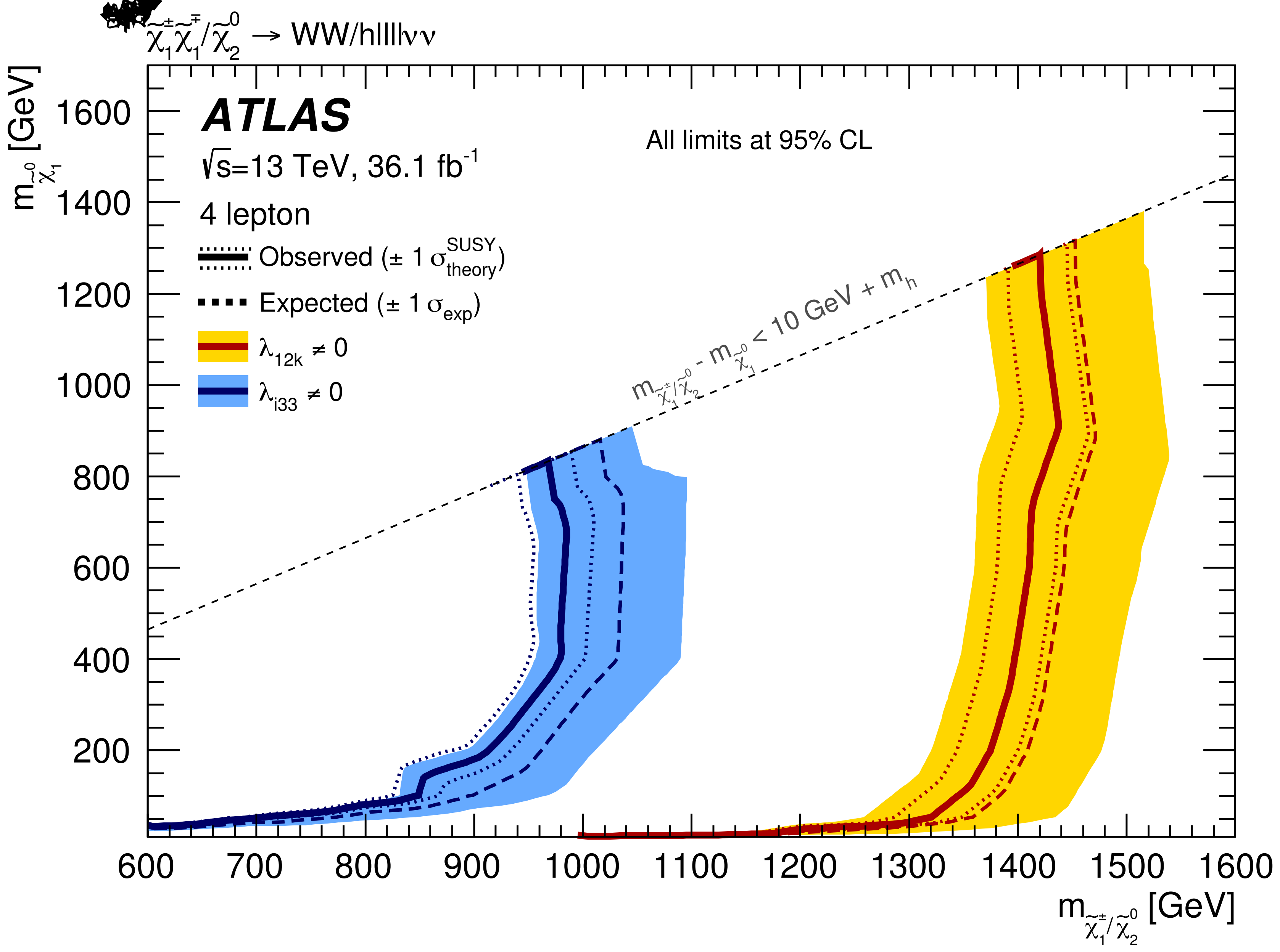
Fermilab M.LIU

R-Parity Violation models

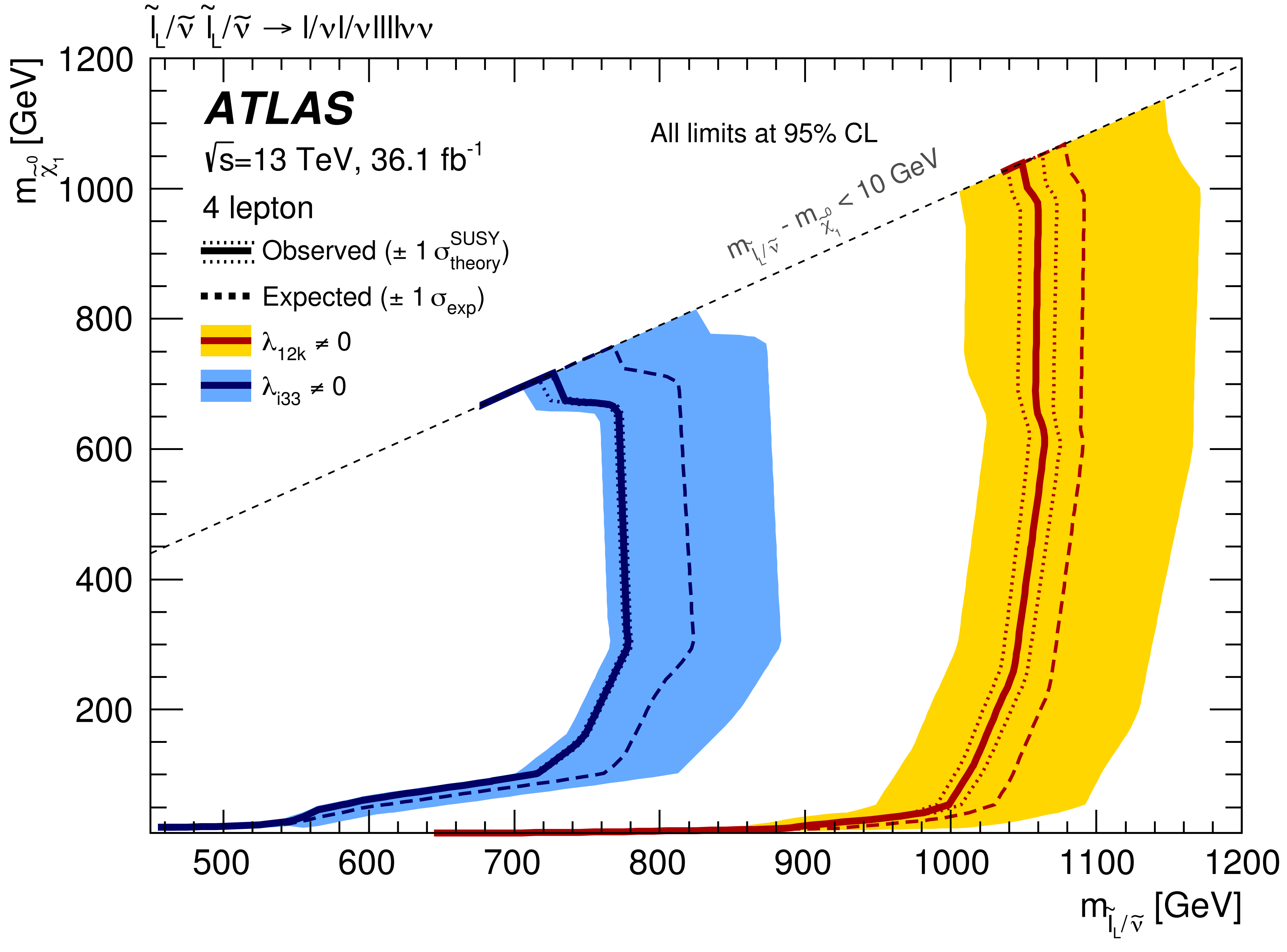
SUSY-2016-21



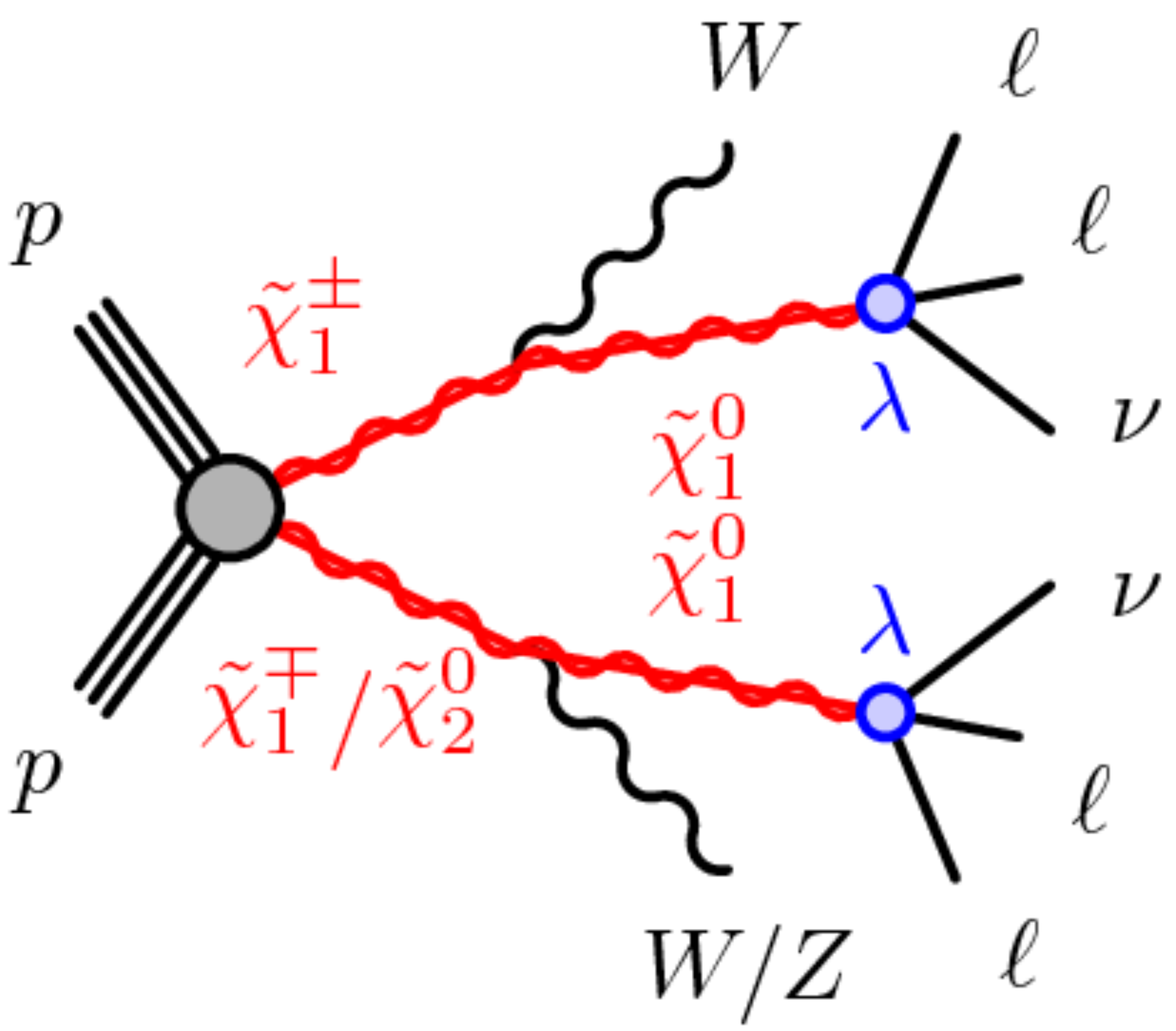
(a) RPV wino W/Z NLSP



(b) RPV wino W/h NLSP



(c) RPV $\tilde{\ell}_L/\tilde{\nu}$ NLSP

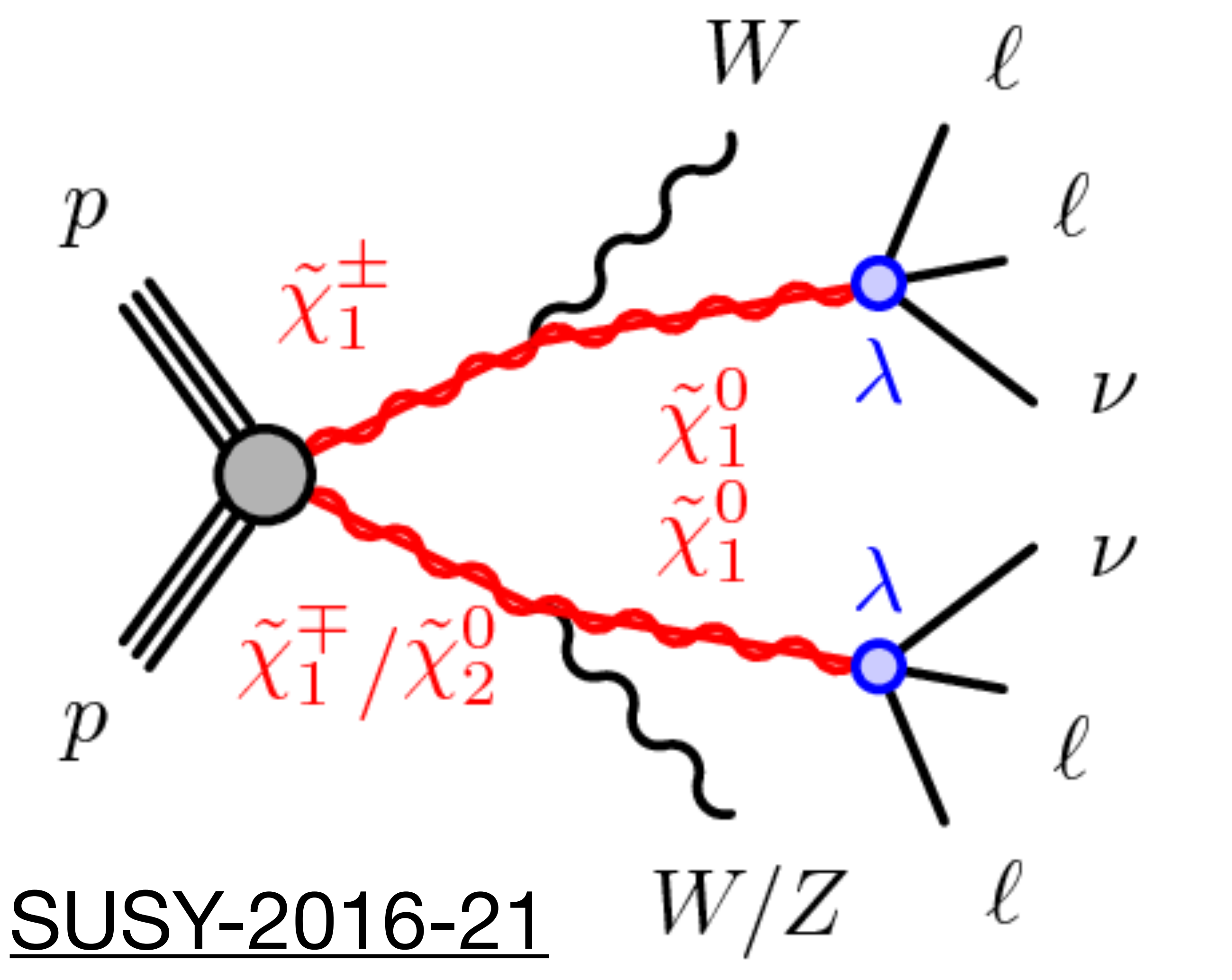


- In RPV models, lepton number violation, χ_1^0 decays to llν

- Wino-like $\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$ and $\tilde{l}_L/\tilde{\nu}$ masses up to 1.46 TeV, 1.06 TeV are excluded,

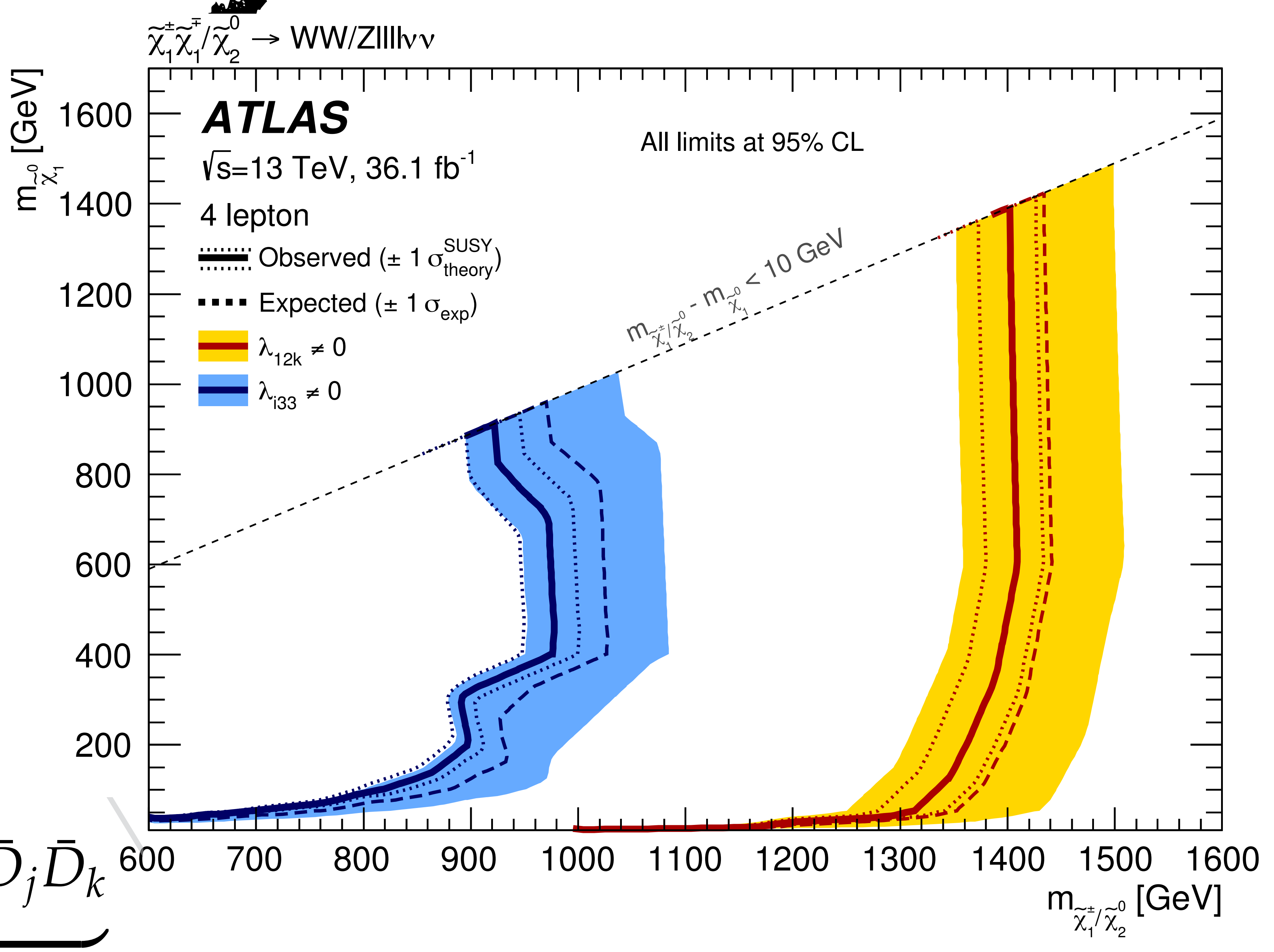
Fermilab M.LIU

R-Parity Violation models



SUSY-2016-21

$$\underbrace{\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k}_{LLE\text{ term}} + \underbrace{\lambda'_{ijk}L_iQ_j\bar{D}_k}_{LQD\text{ term}} - \underbrace{\kappa^iL_iH_u}_{LH\text{ term}} + \underbrace{\frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k}_{UDD\text{ term}}$$



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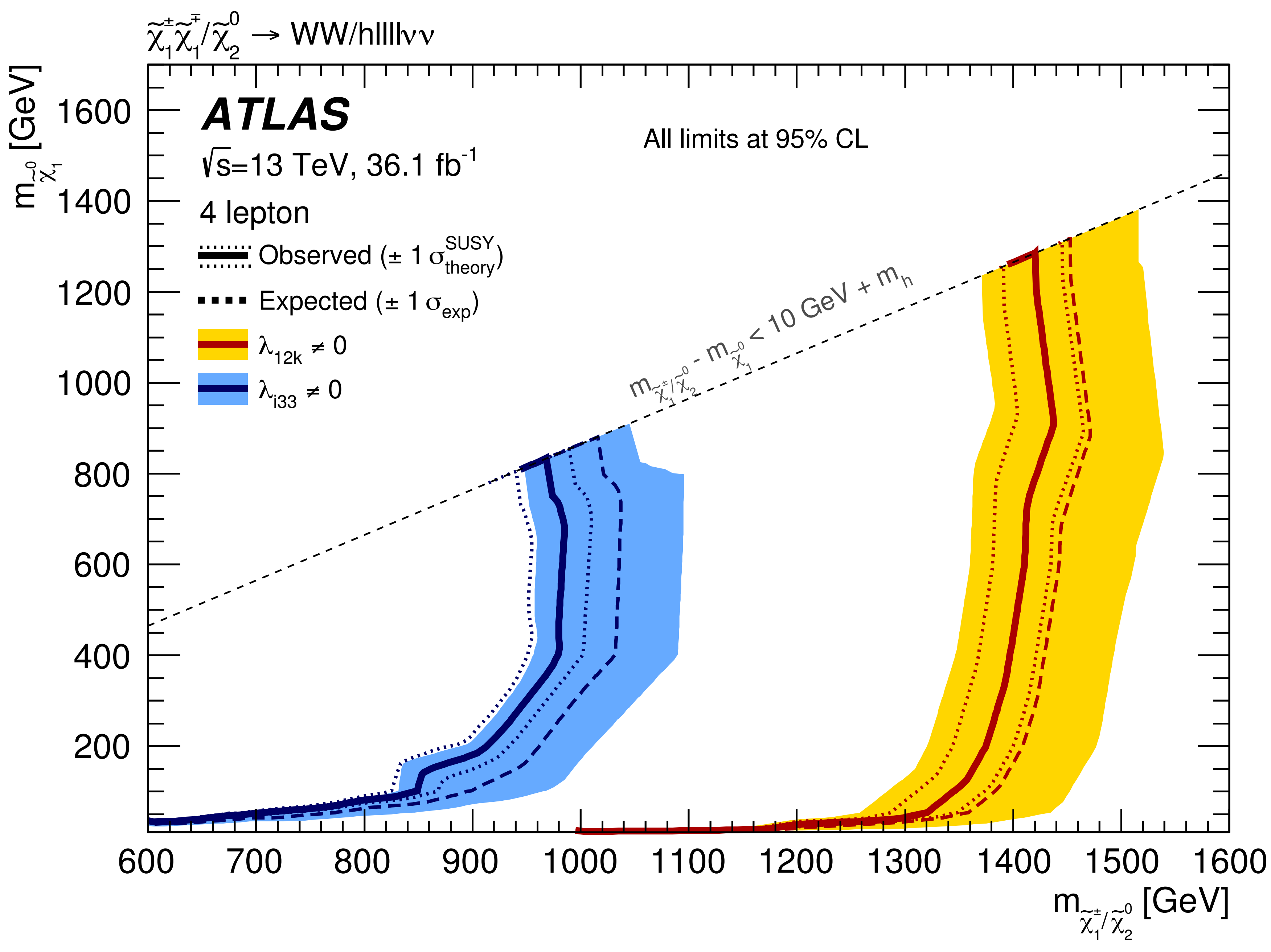
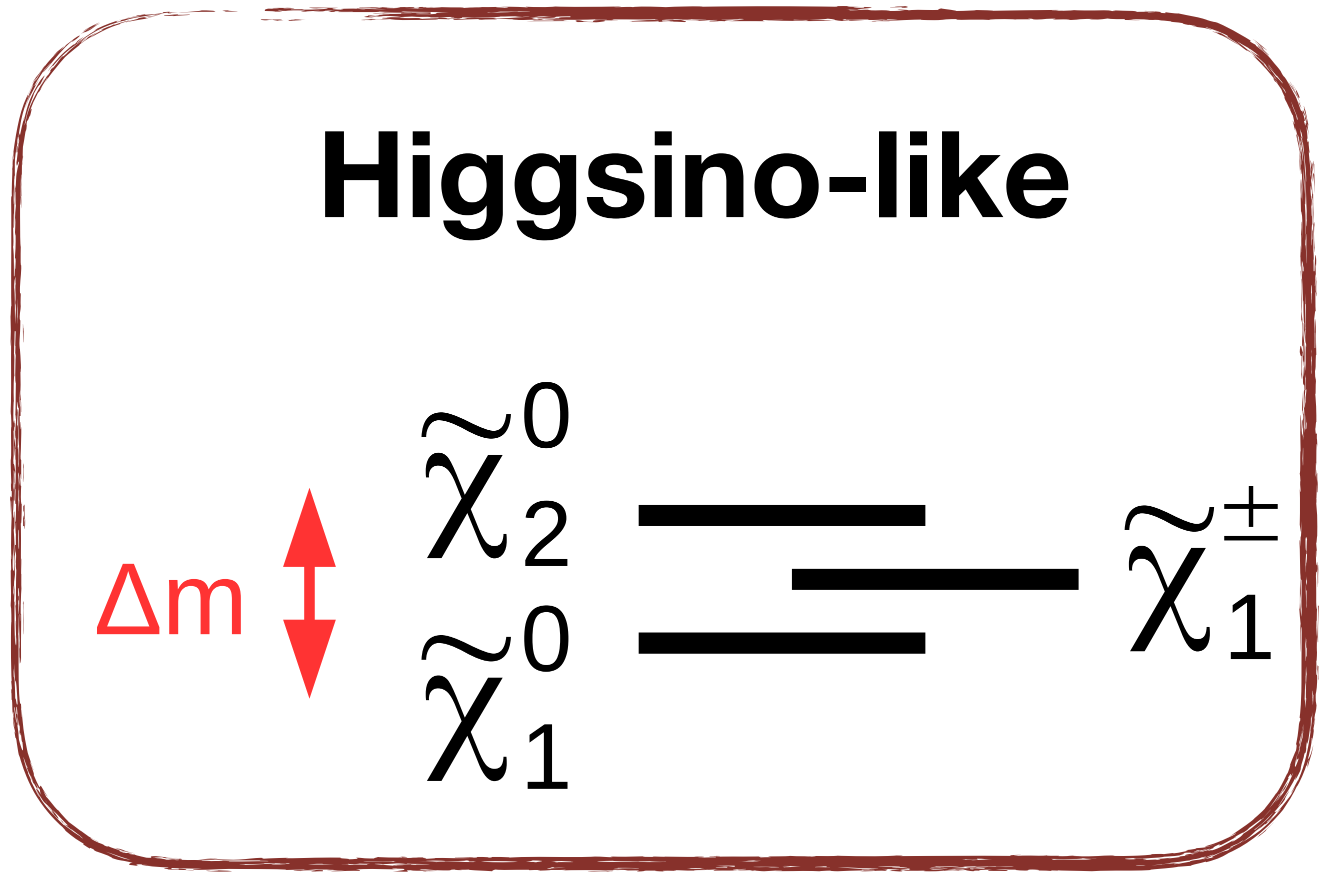


(b) RPV wino W/h NLSP

- In RPV models, lepton number violation, χ_1^0 decays to llν, low MET compared to RPC signatures
- Analysis selects 4 leptons: e/μ/τ, allowing up to 2 hadronically decaying τ.
- Events categorized with whether a dilepton pair is consistent with Z boson, MET and Meff
- Wino-like $\tilde{\chi}^{\pm}_1$ /$\tilde{\chi}^0_2$ and $\tilde{l}_L/\tilde{\nu}$ masses up to 1.46 TeV, 1.06 TeV are excluded,

Compressed Higgsino

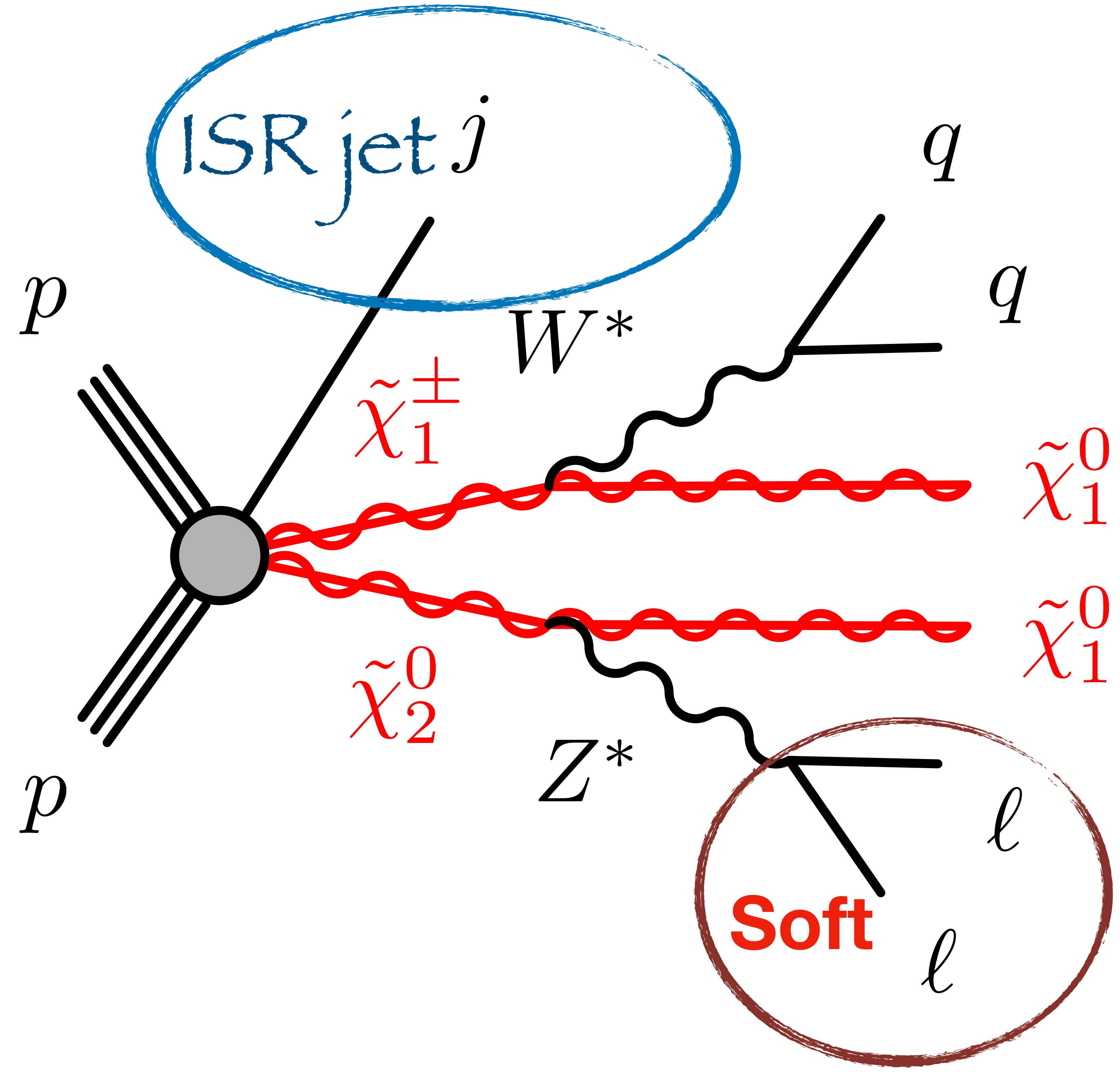
Δm~
hundreds of MeV
to
tens of GeV



- Higgsino-like spectrum:
  - Lower cross section
  - Challenging signatures:
    - Δm~ tens of GeV : Soft decay products
    - Δm~ hundreds of MeV : Long-lived signatures.

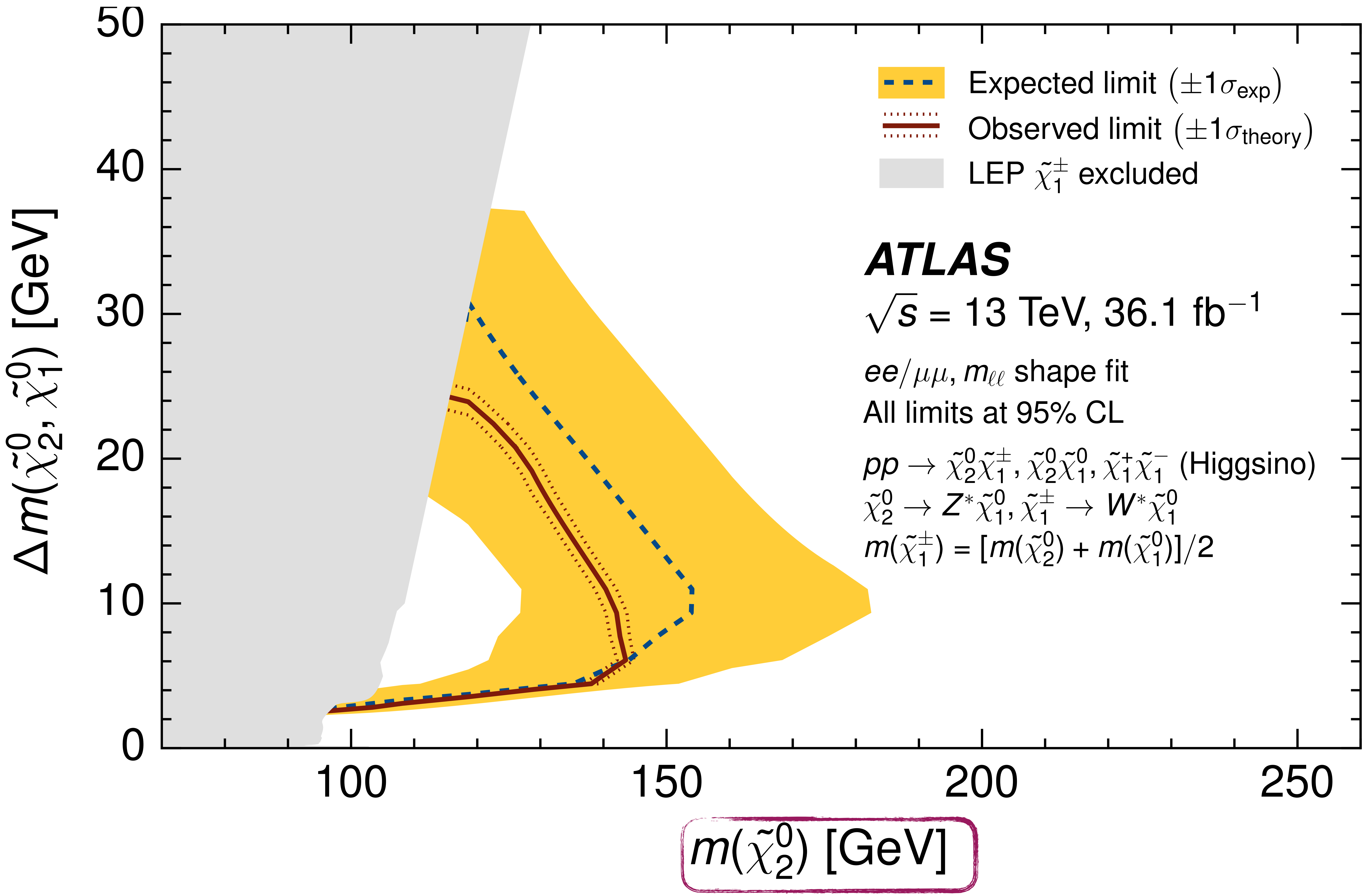
Search Highlights — compressed Higgsino with soft leptons

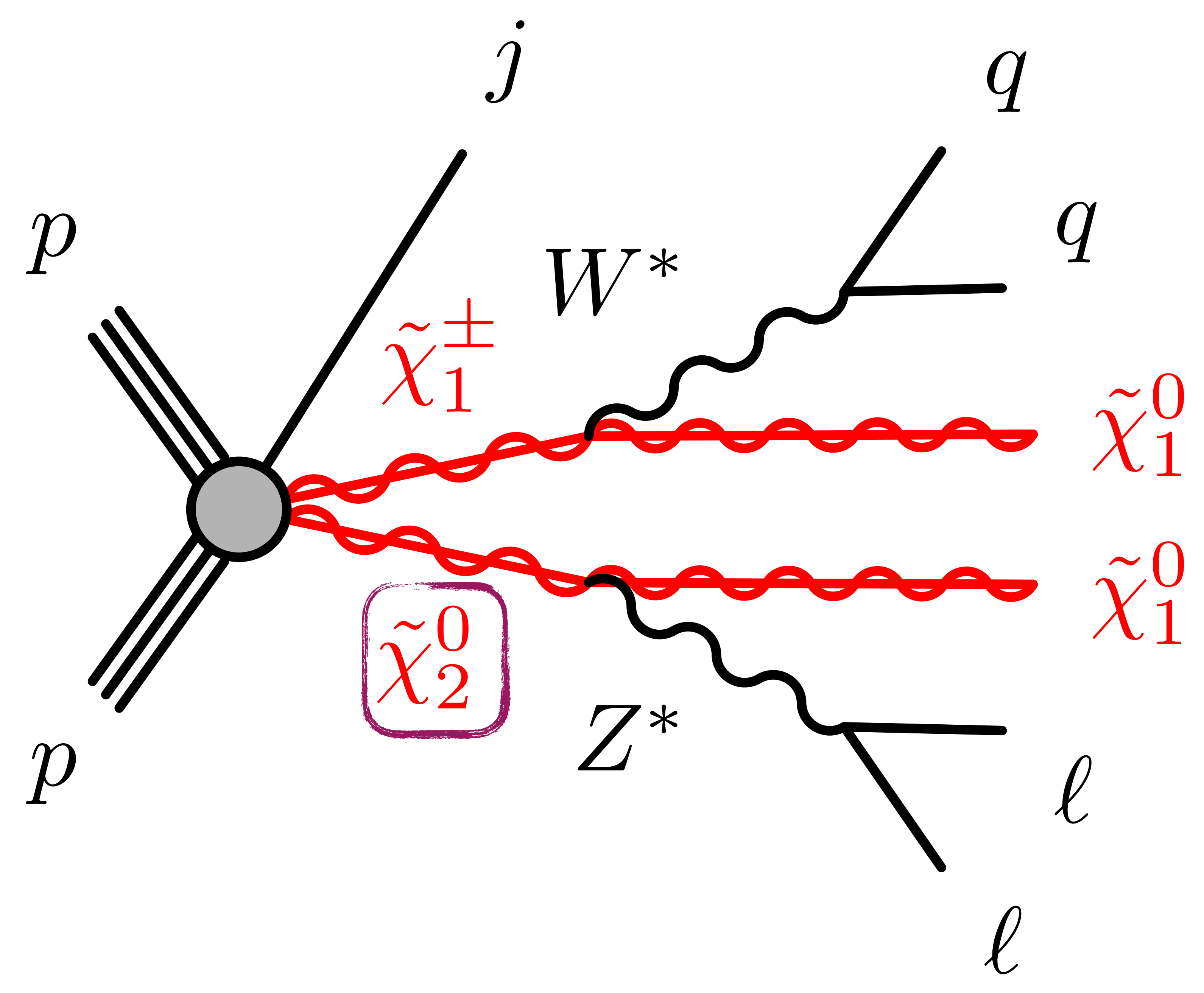
Higgsino-like



- Dedicated searches with similar search strategy : ATLAS: SUSY-2016-25 CMS: SUS-16-048,
- Soft leptons pt: 4-5 GeV, hard to trigger
- ISR jet to get the system boosted —> large missing transverse energy to be triggered:
  - MET > 200 GeV. (ATLAS pure MET trigger)
  - MET>125 GeV (CMS MET+ soft lepton trigger)

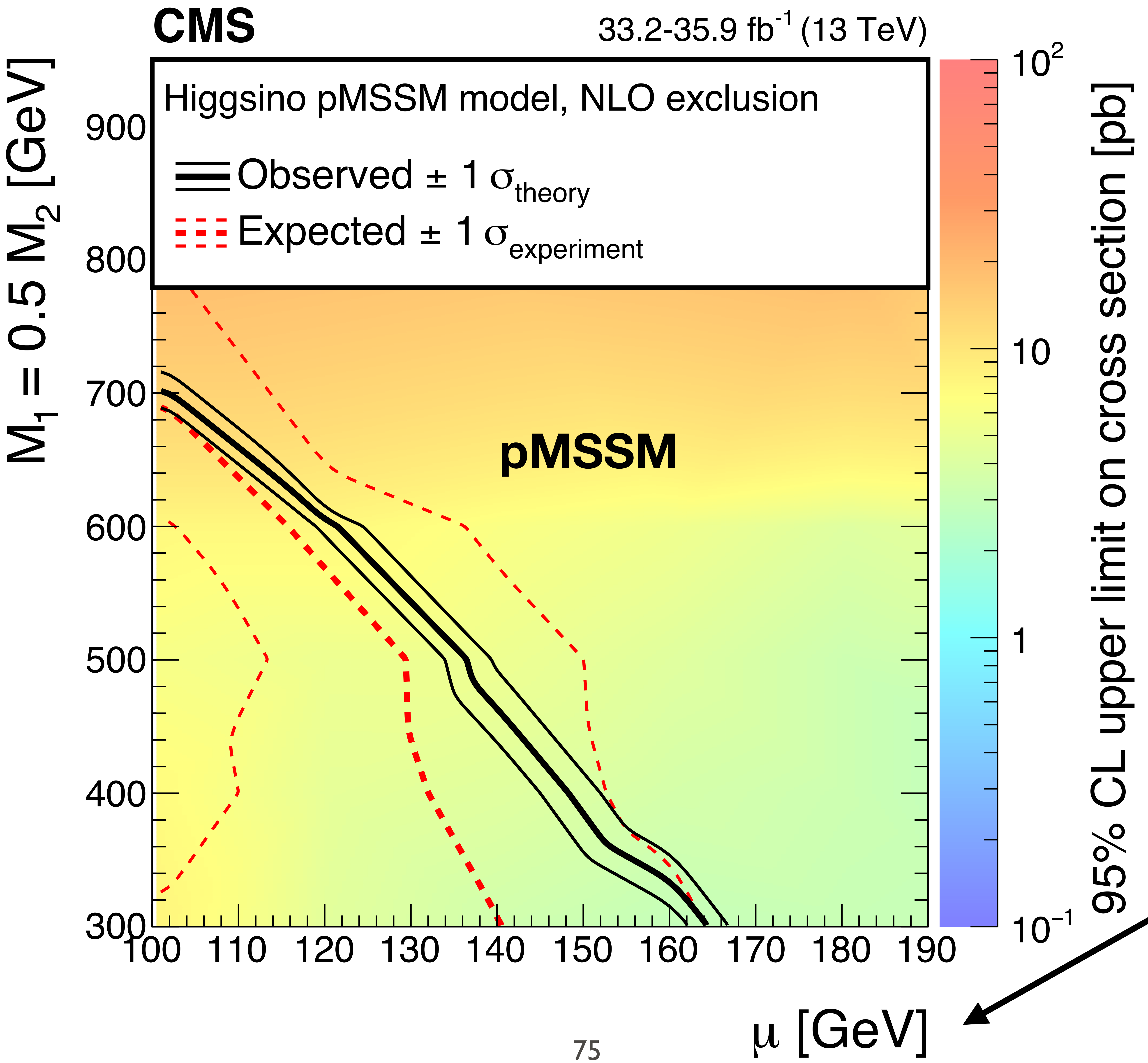
soft leptons – interpretations





Comparable exclusion by CMS
see backup

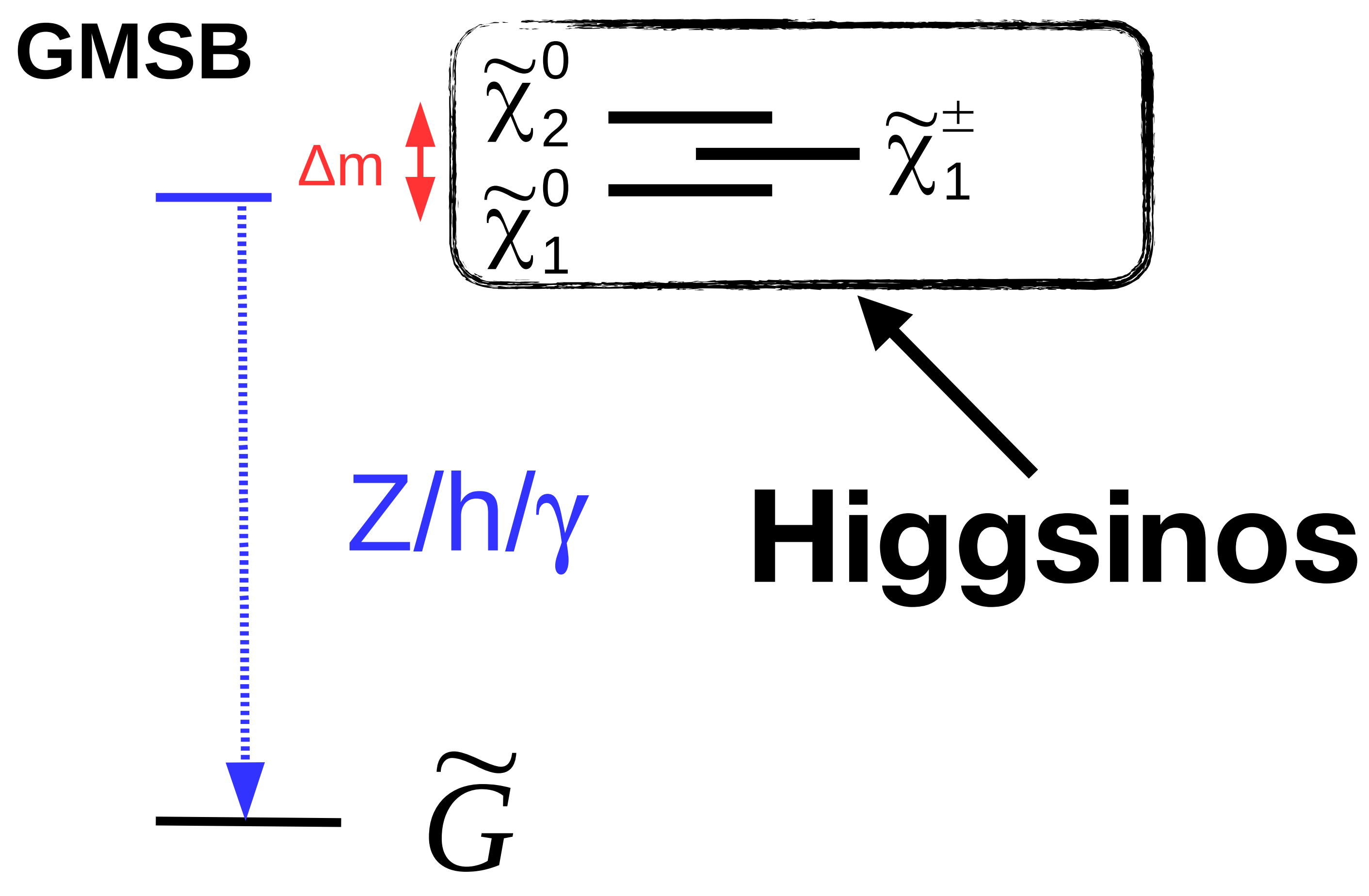
soft leptons – interpretations



Bino mass : 1/2 * Wino mass

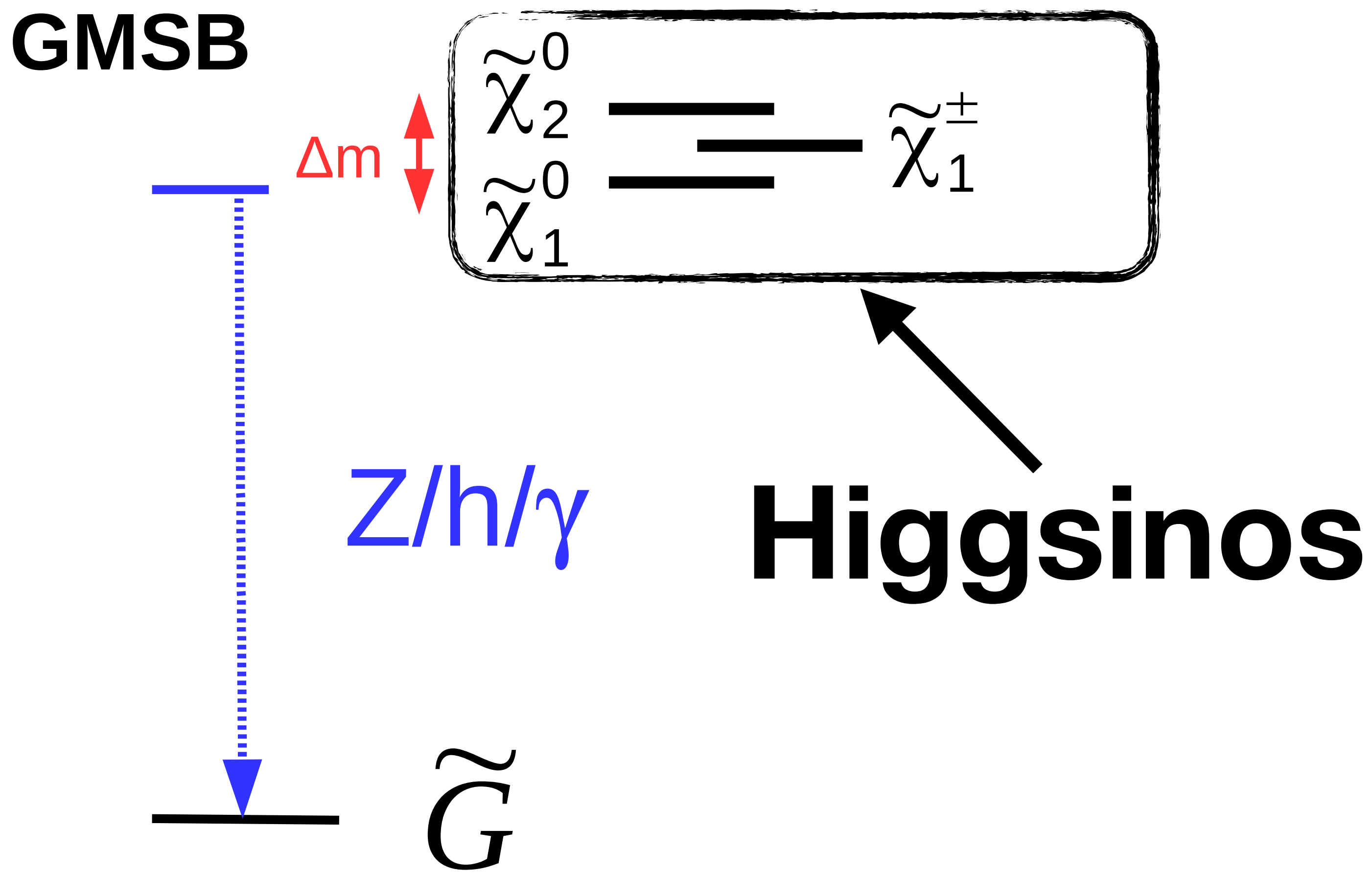
Higgsino mass

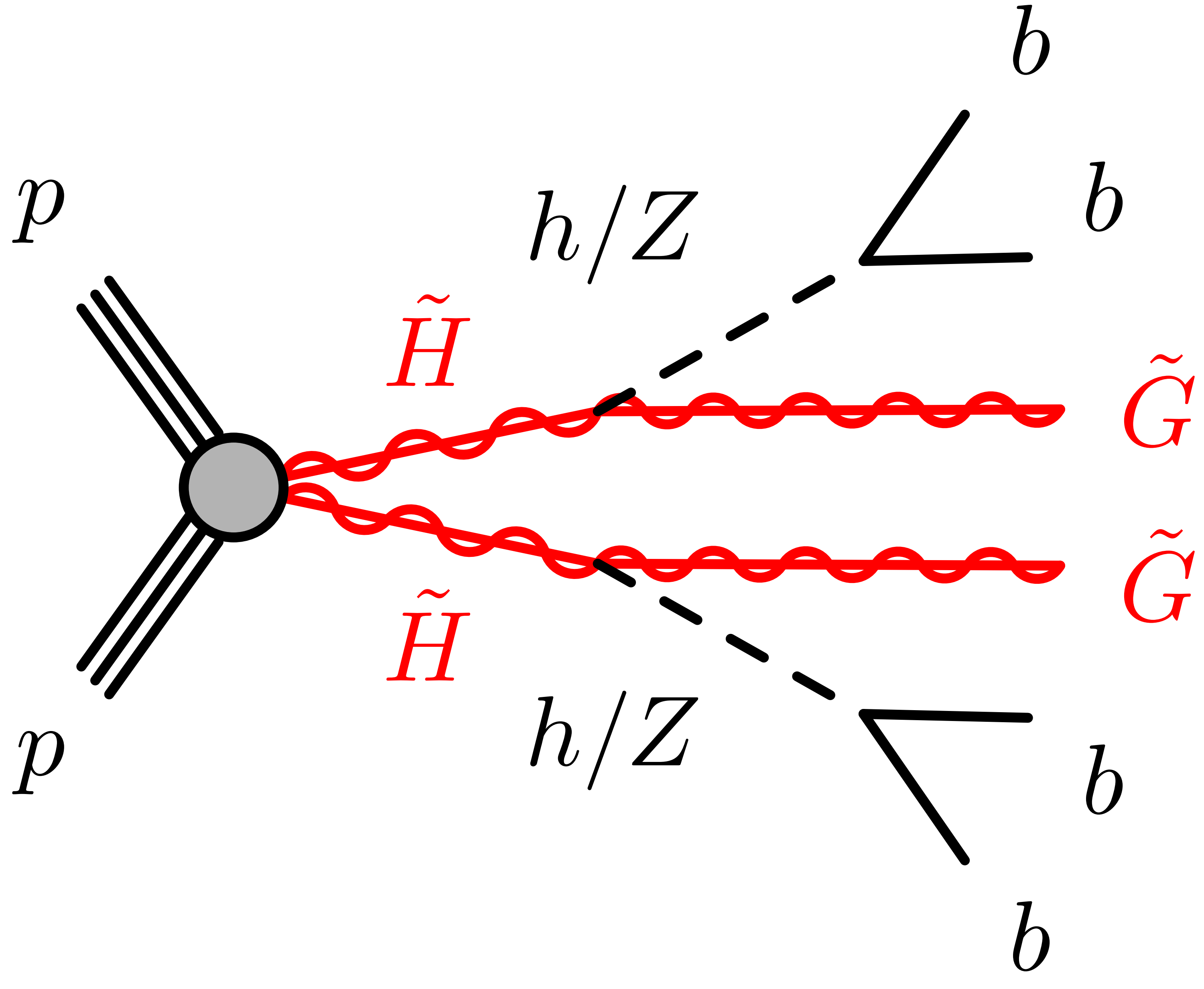
Search Highlights – GMSB Higgsino



- Special case : GMSB Higgsino:
  - Gravitino is the LSP
  - Enhanced production of $\tilde{\chi}_1^0\tilde{\chi}_1^0$+$X_{soft}$
    - Picks up all contributions from $\tilde{\chi}_2^0$ $\tilde{\chi}_1^{\pm}$ etc….
- Collectively referred to as higgsinos.

Search Highlights – GMSB Higgsino

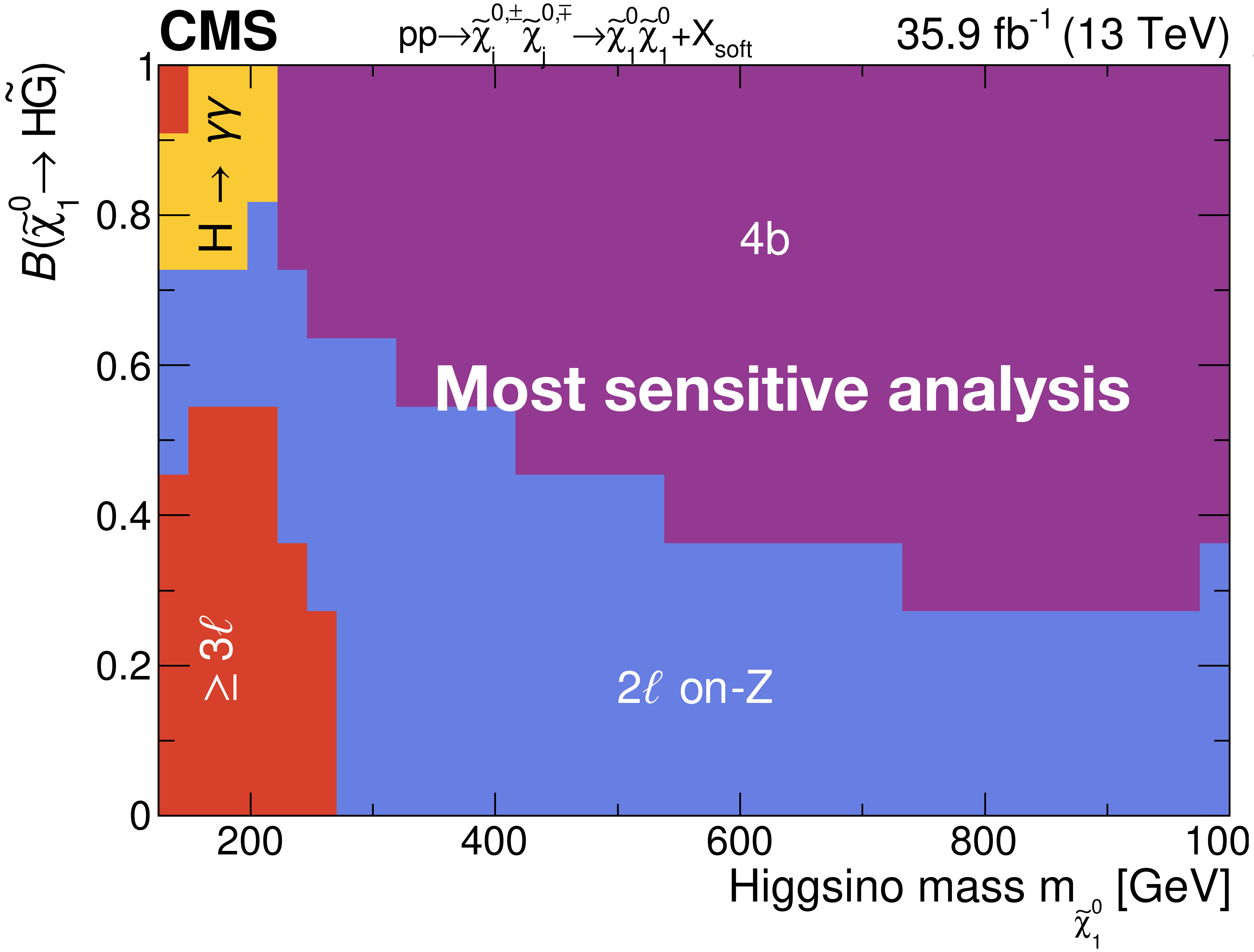


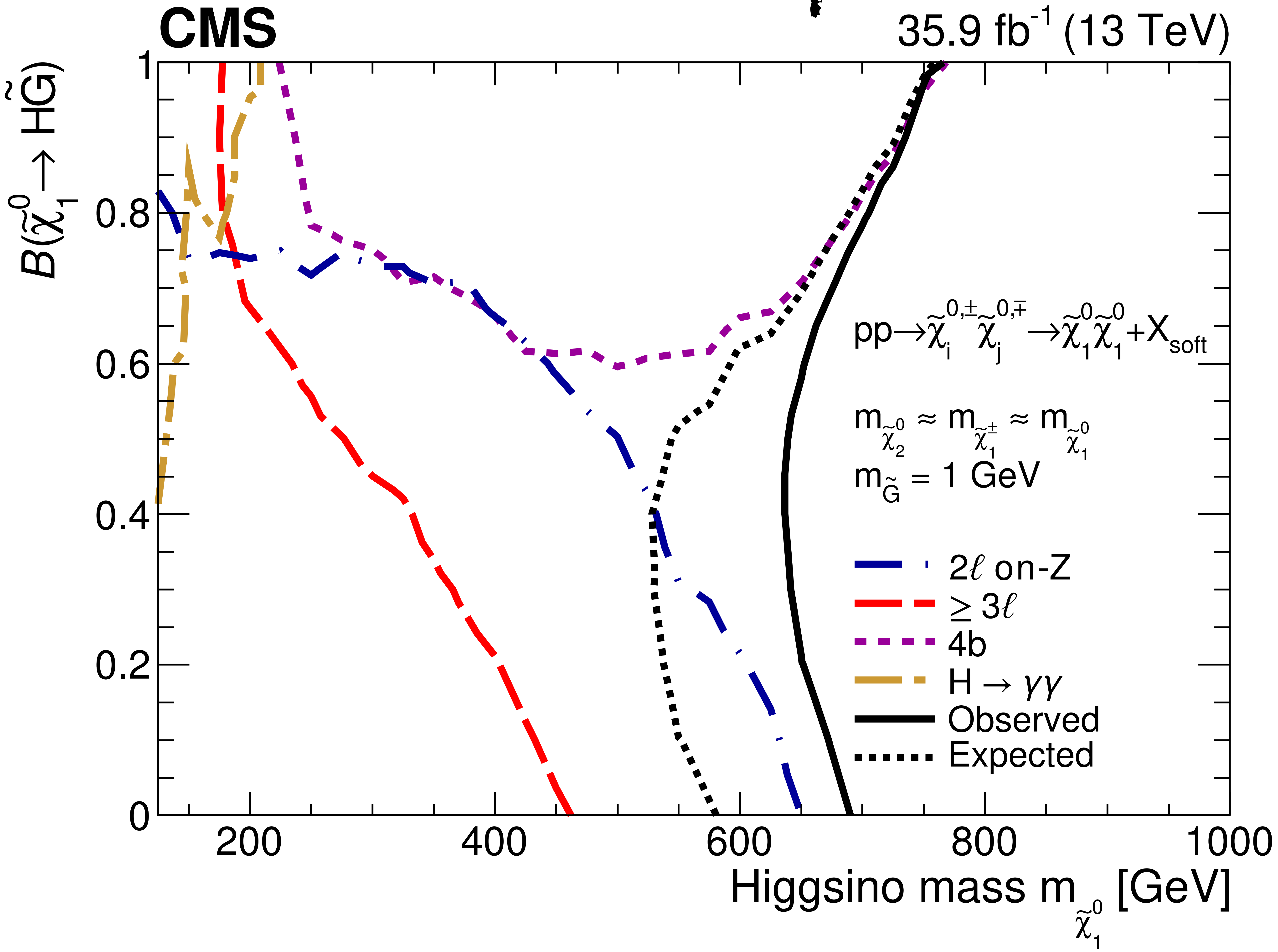


- Dedicated searches using events with >= 3 b jets
  - ATLAS-CONF-2017-081 CMS:SUS-16-044
  - Large branching fraction of H->bb

Fermilab M.LIU

Combination to cover full model space

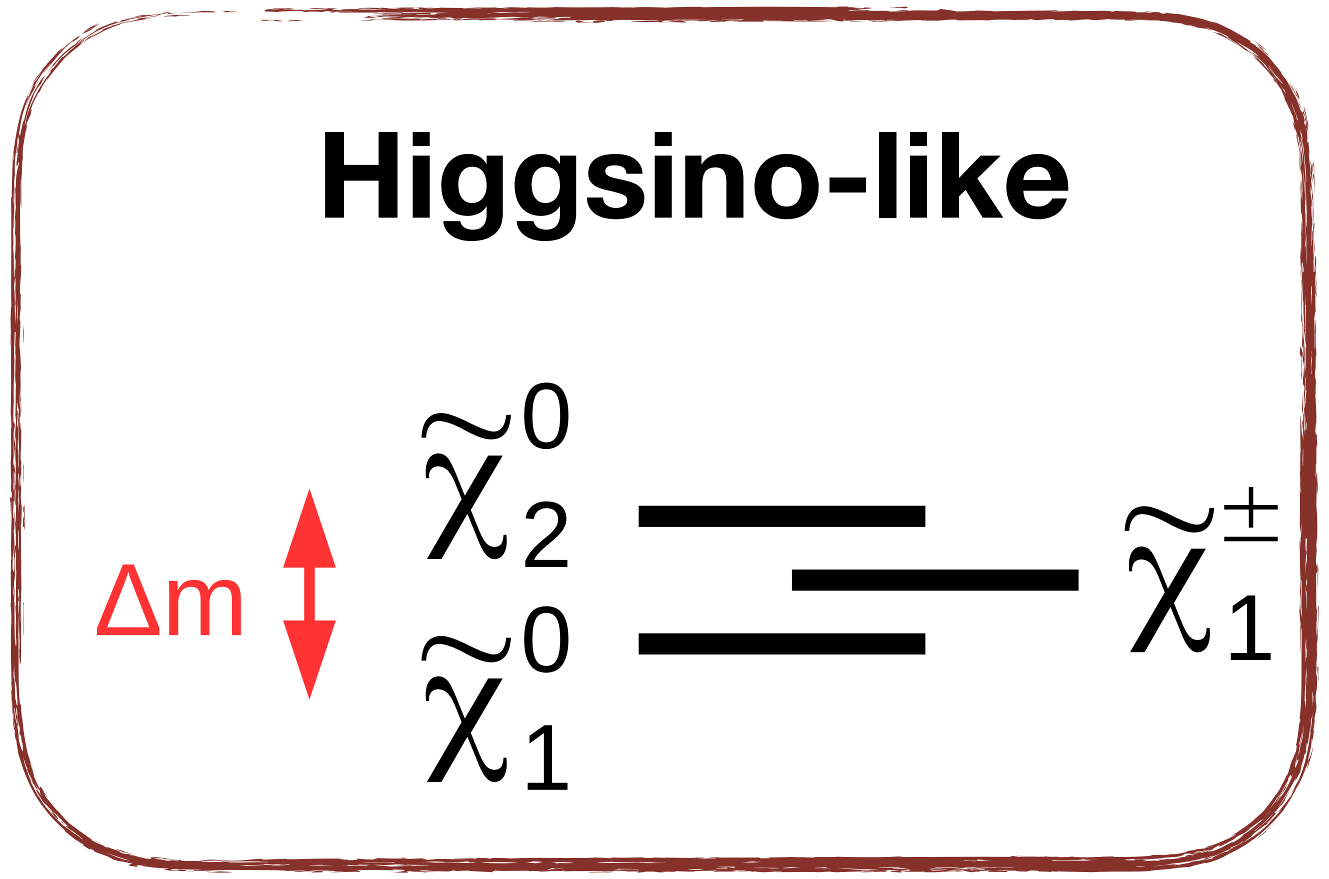




- Combined sensitivity : no strong dependence on the BR of Higgsino->H+Gravitino.

Compressed Higgsino

Δm~
hundreds of MeV
to
tens of GeV



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  - Lower cross section
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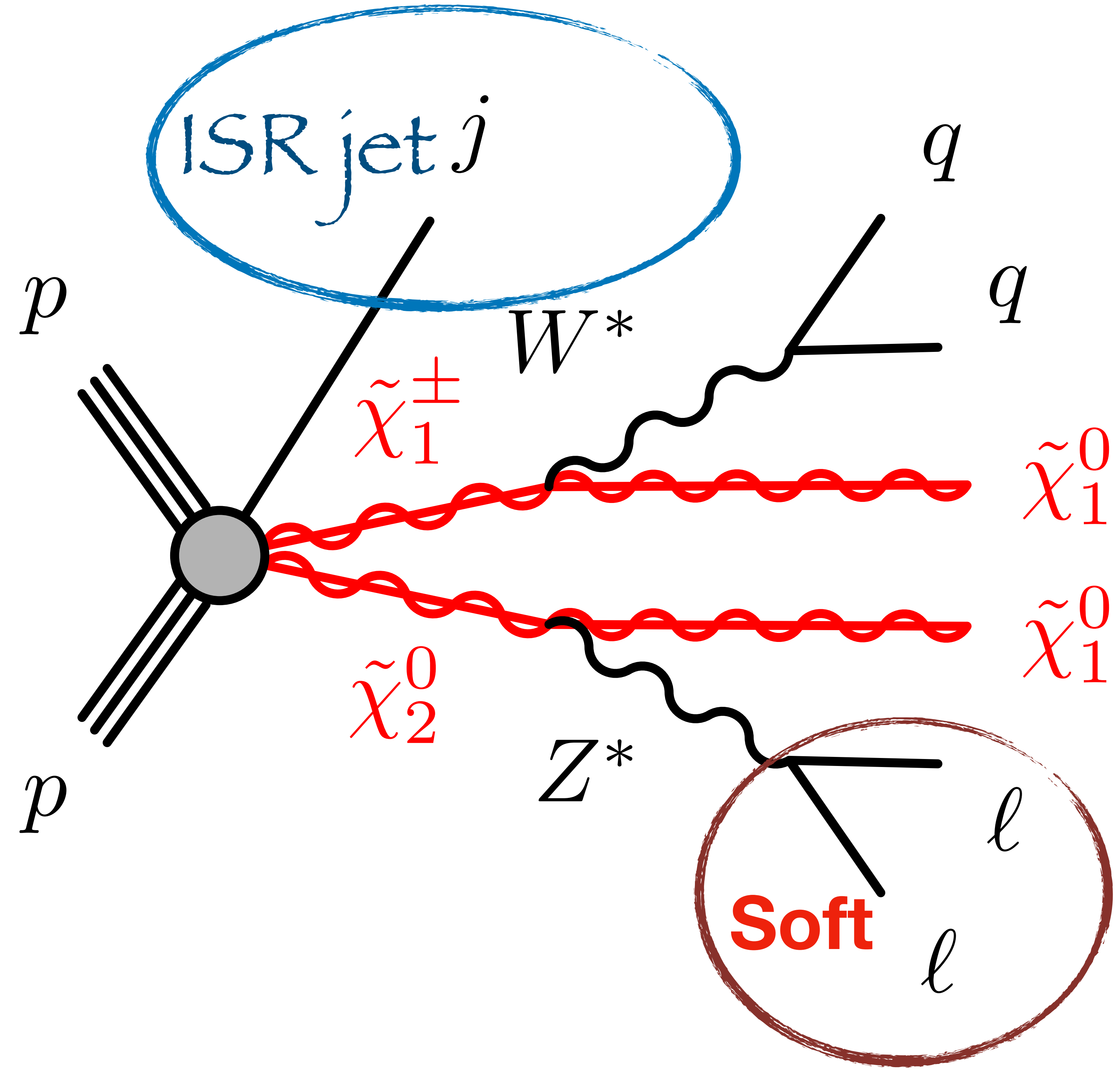
    - Δm~ hundreds of MeV : Long-lived signatures.

Search Highlights — compressed Higgsino with soft leptons

Higgsino-like



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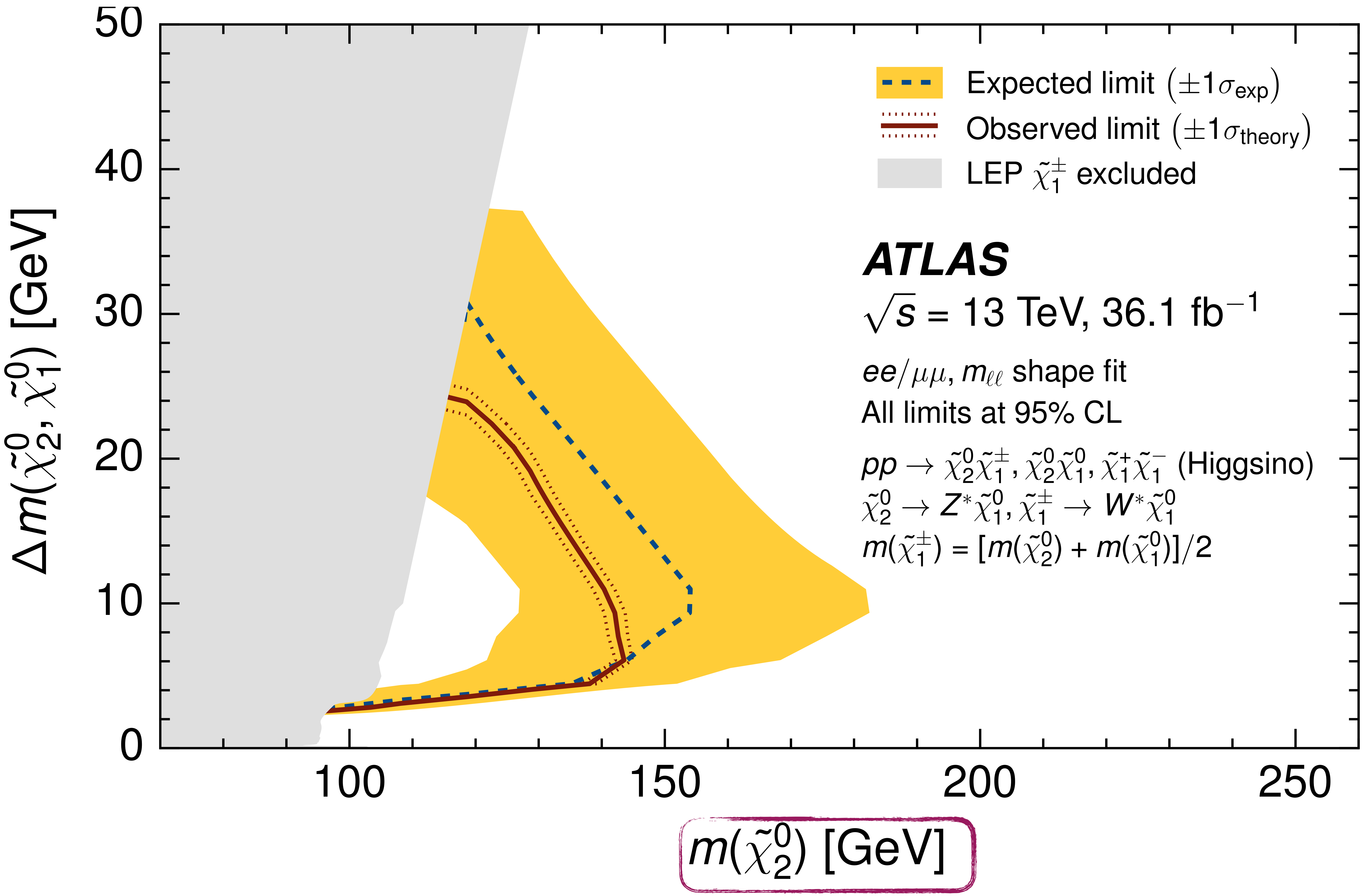
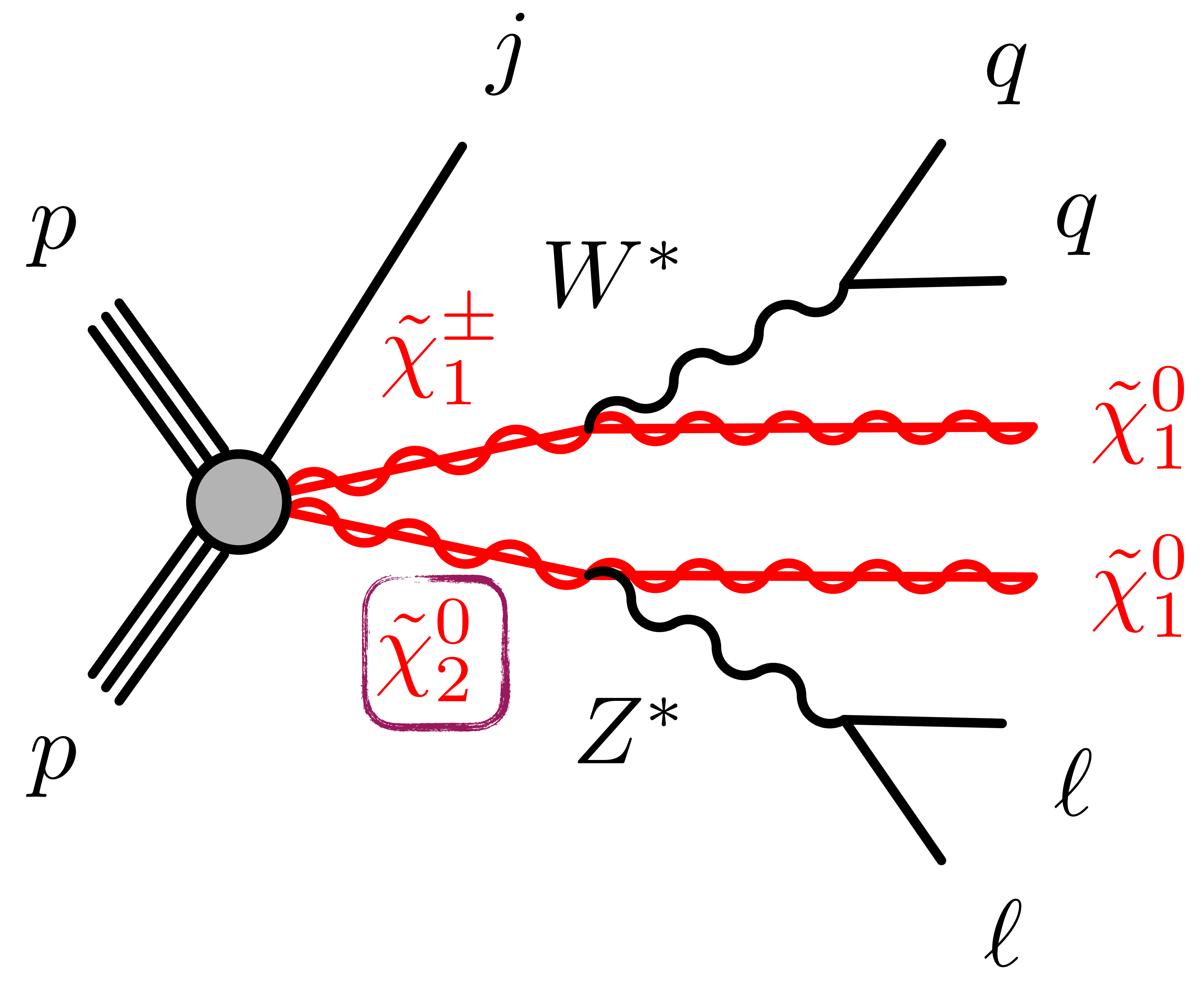
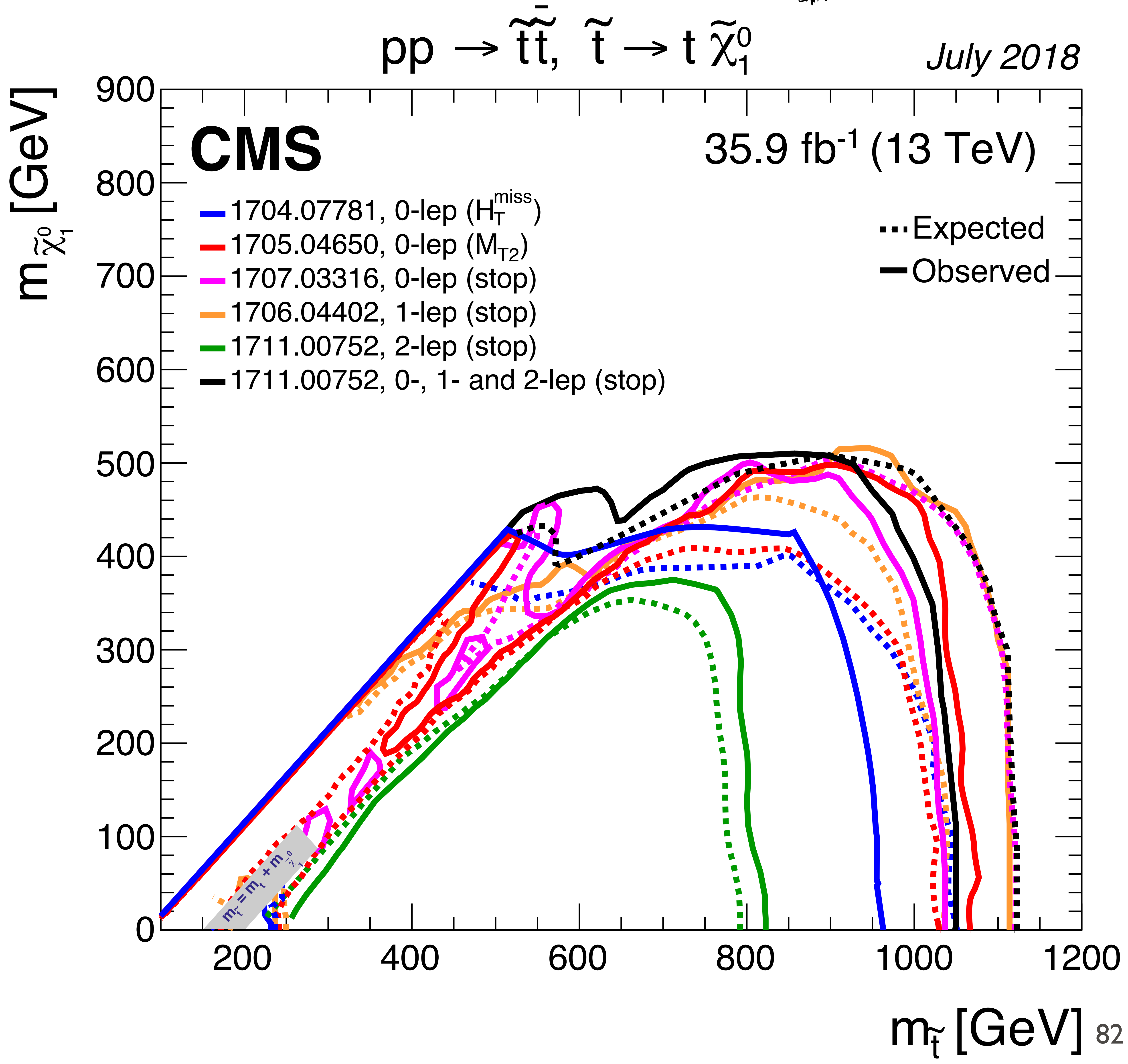
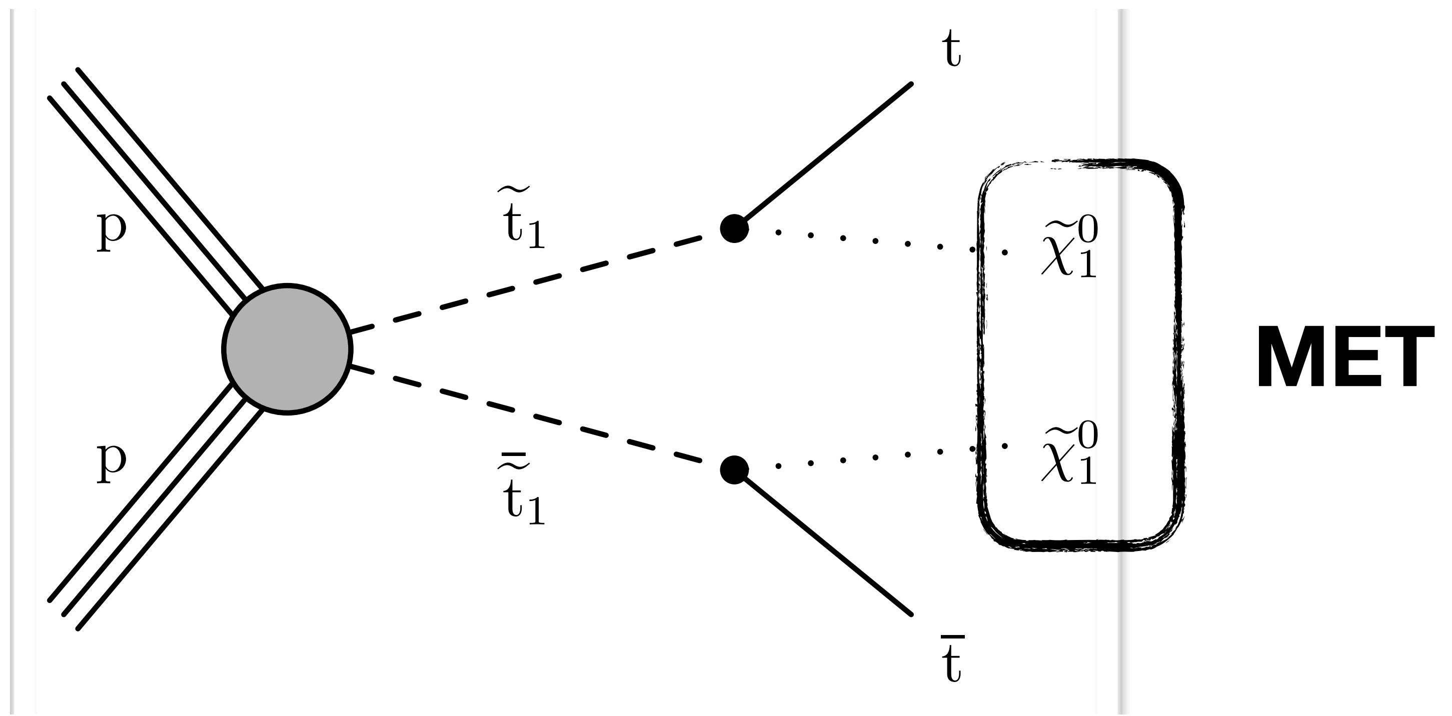




Comparable exclusion by CMS
see backup

We actively searched for stop





- Many other decay topologies explored
  - Cascaded decay via other SUSY particles, multibody decay

—>Mass reach varies drastically

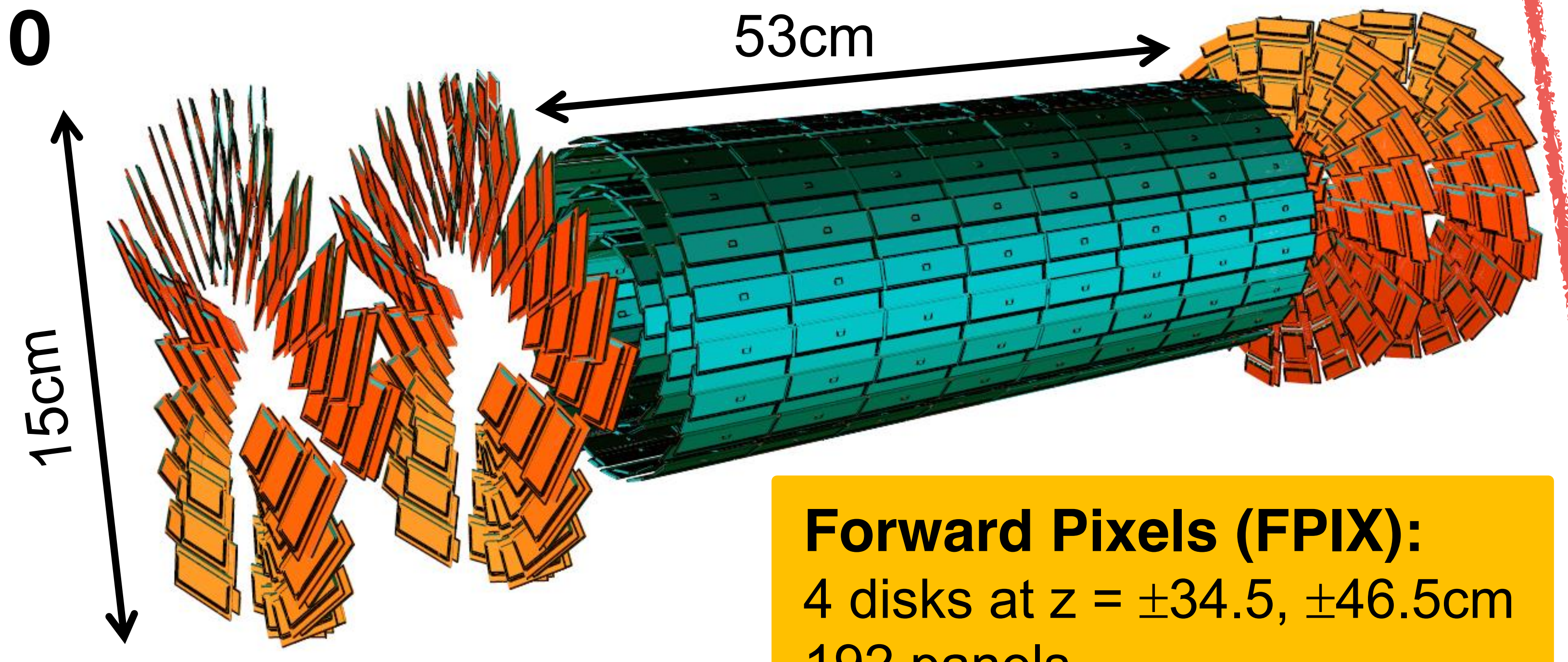
Impact on Phase 0 pixel detector

M.Liu

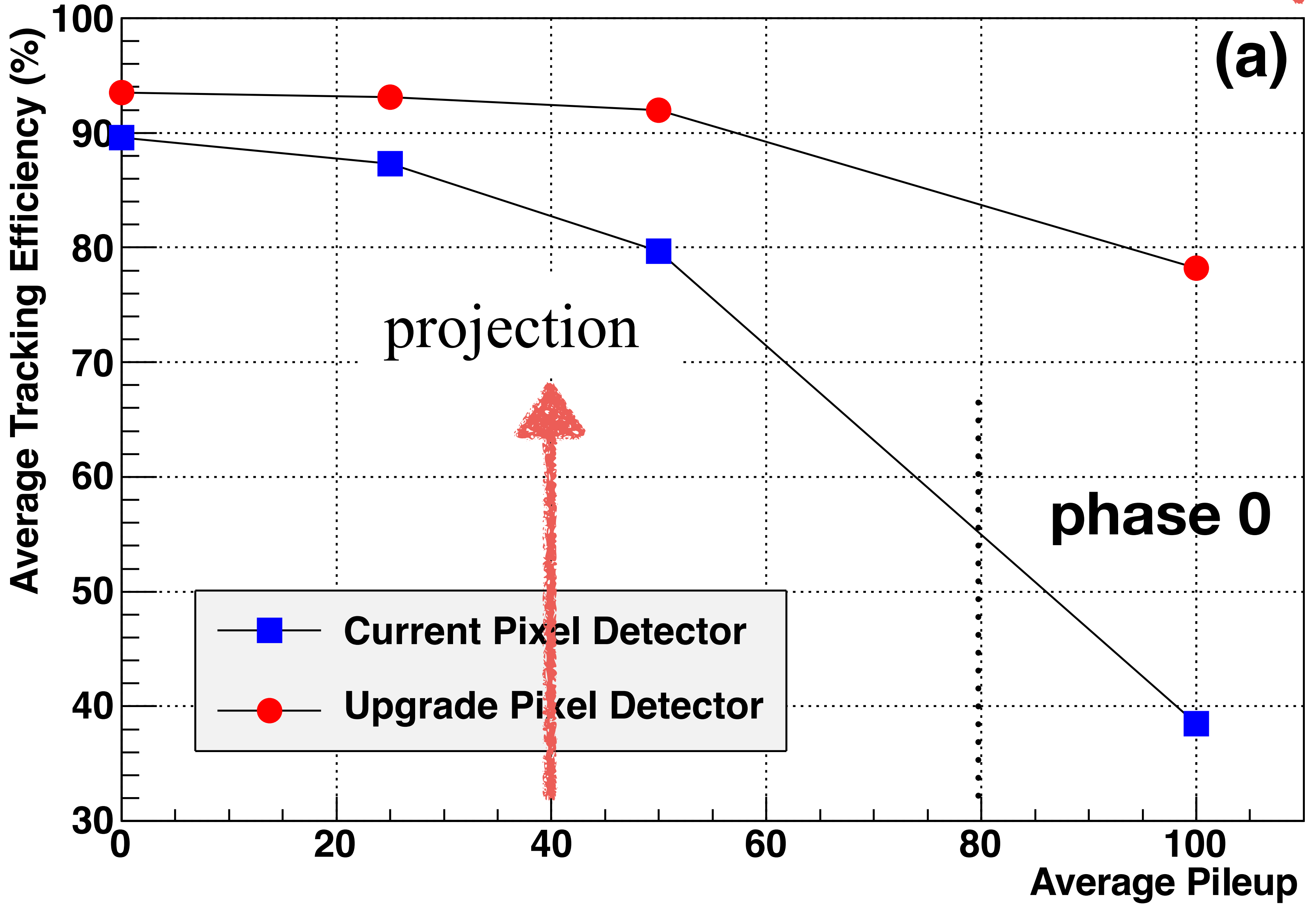
Barrel Pixels (BPIX):
3 barrel layers at 4.4, 7.3, 10.2cm
768 modules

designed for $10^{34}cm^{-2}s^{-1}$ and 25ns bunch spacing

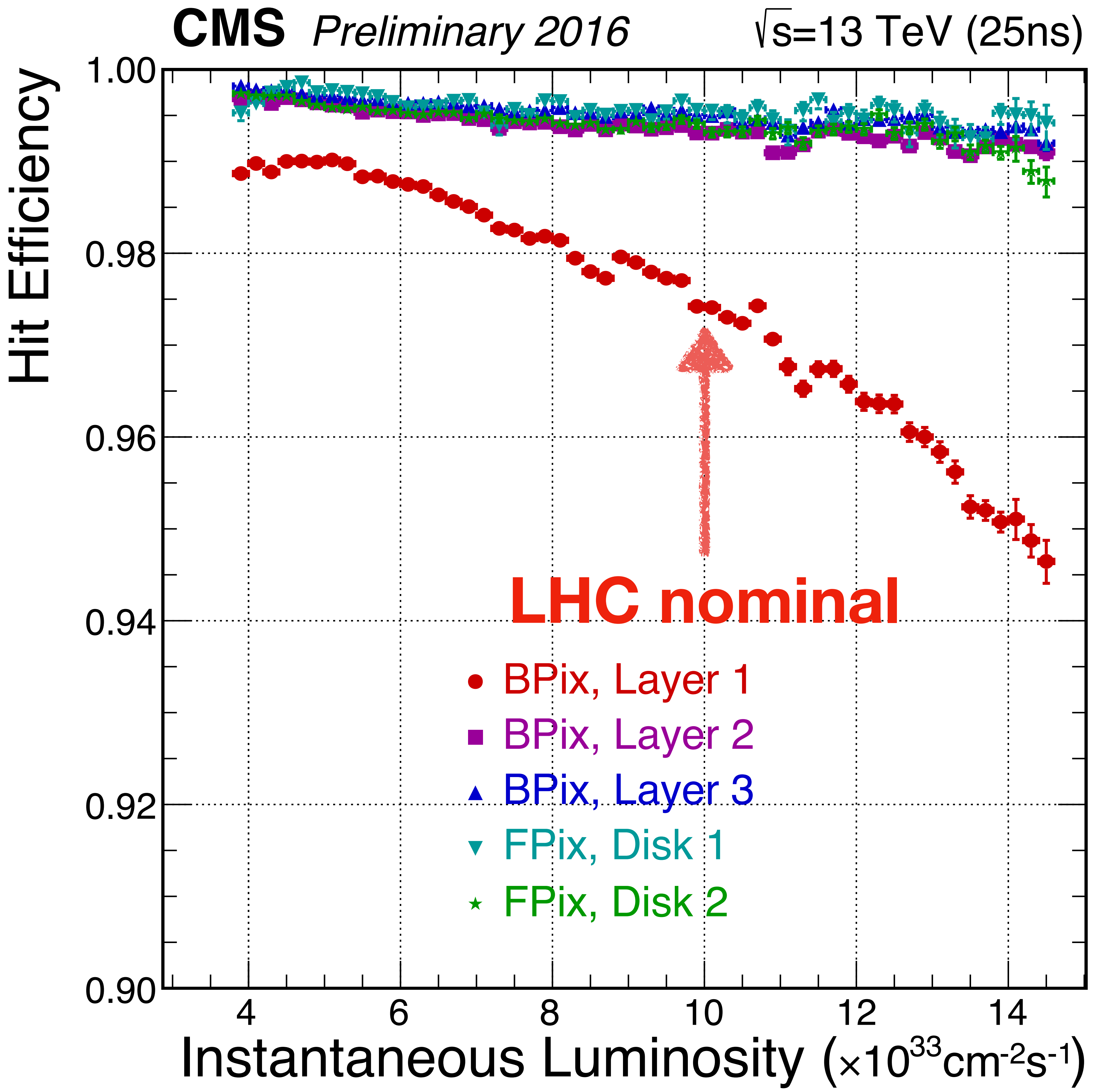
CMS Phase 0



Forward Pixels (FPIX):
4 disks at z = ±34.5, ±46.5cm
192 panels



End of 2016



- **Dynamic inefficiencies/ dead time caused by limited readout bandwidth.**

CMS Phase-0 Pixel Detector

M.Liu

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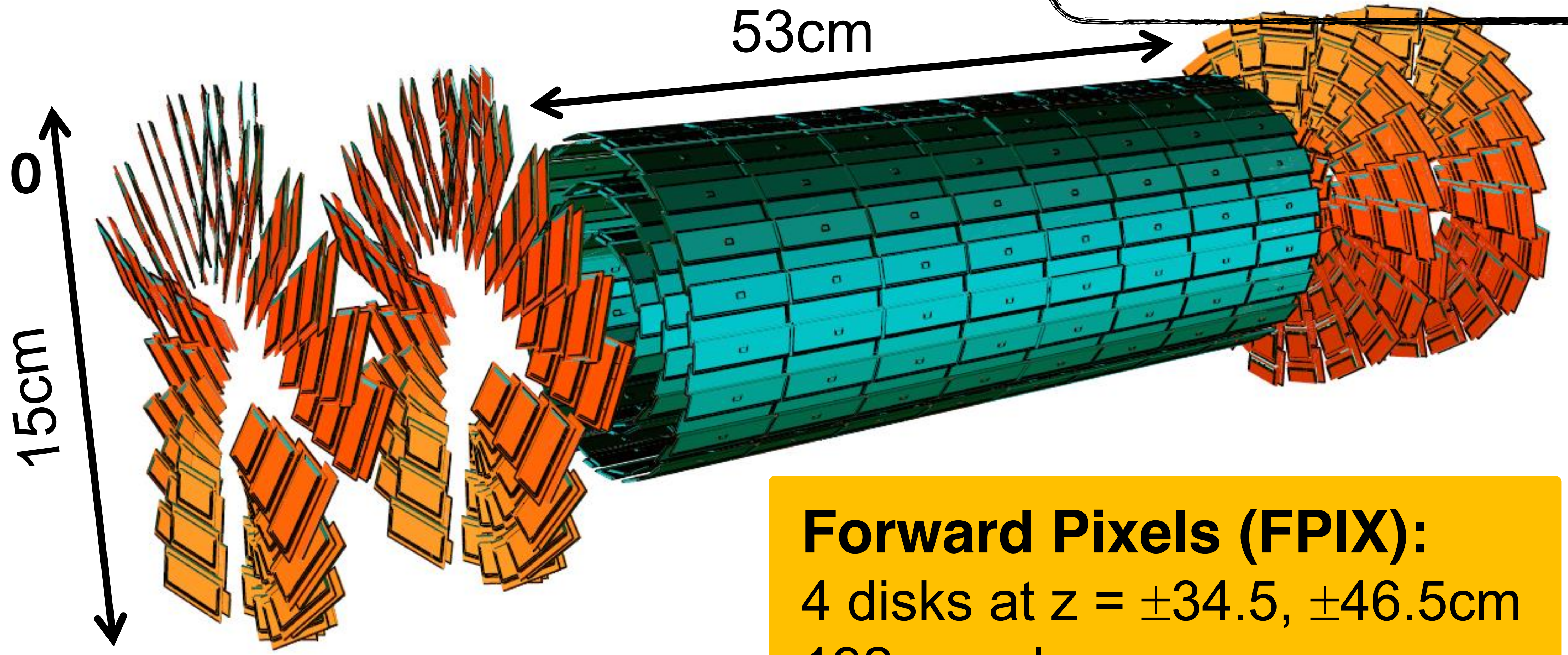
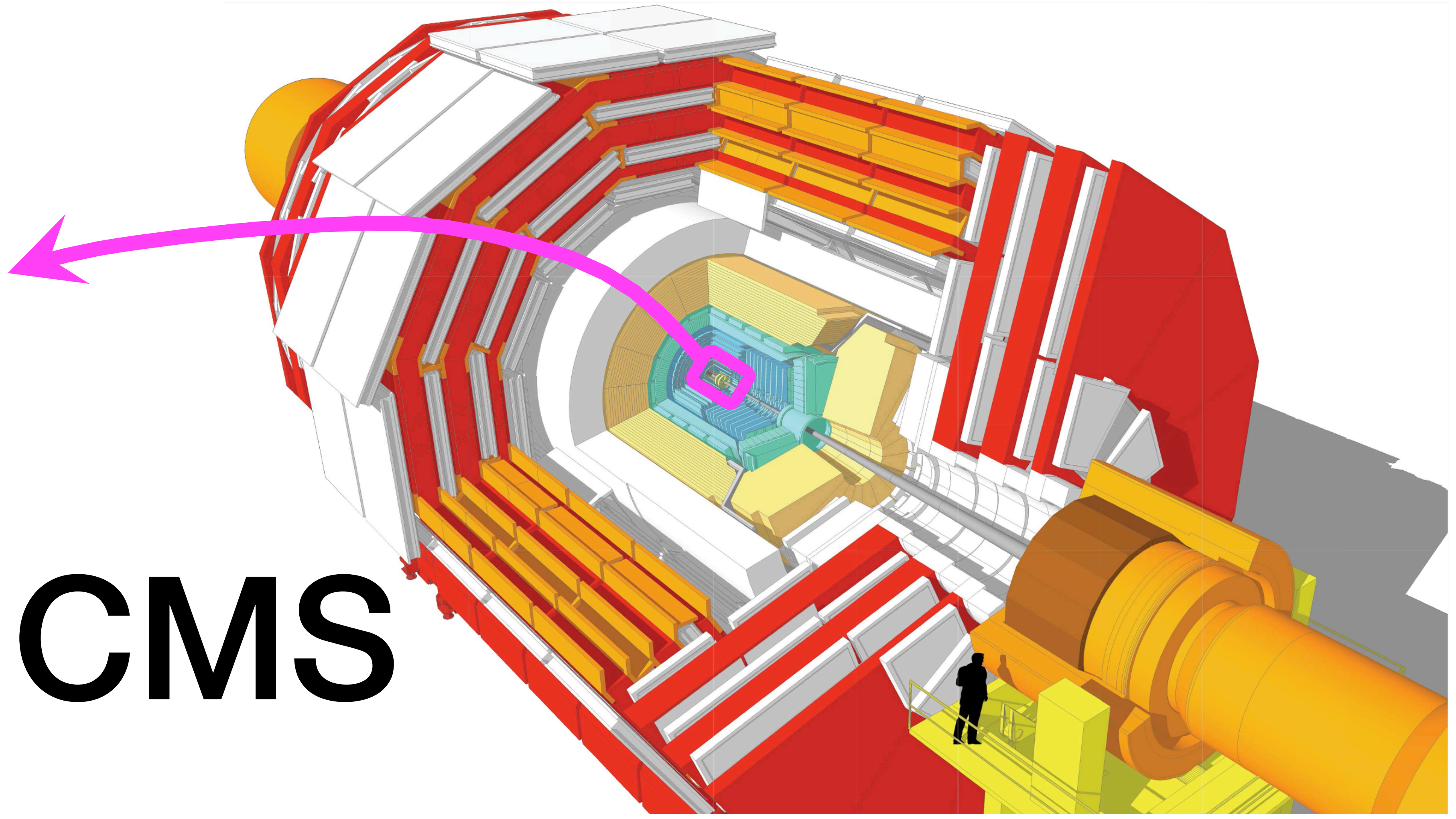
CMS Phase 0





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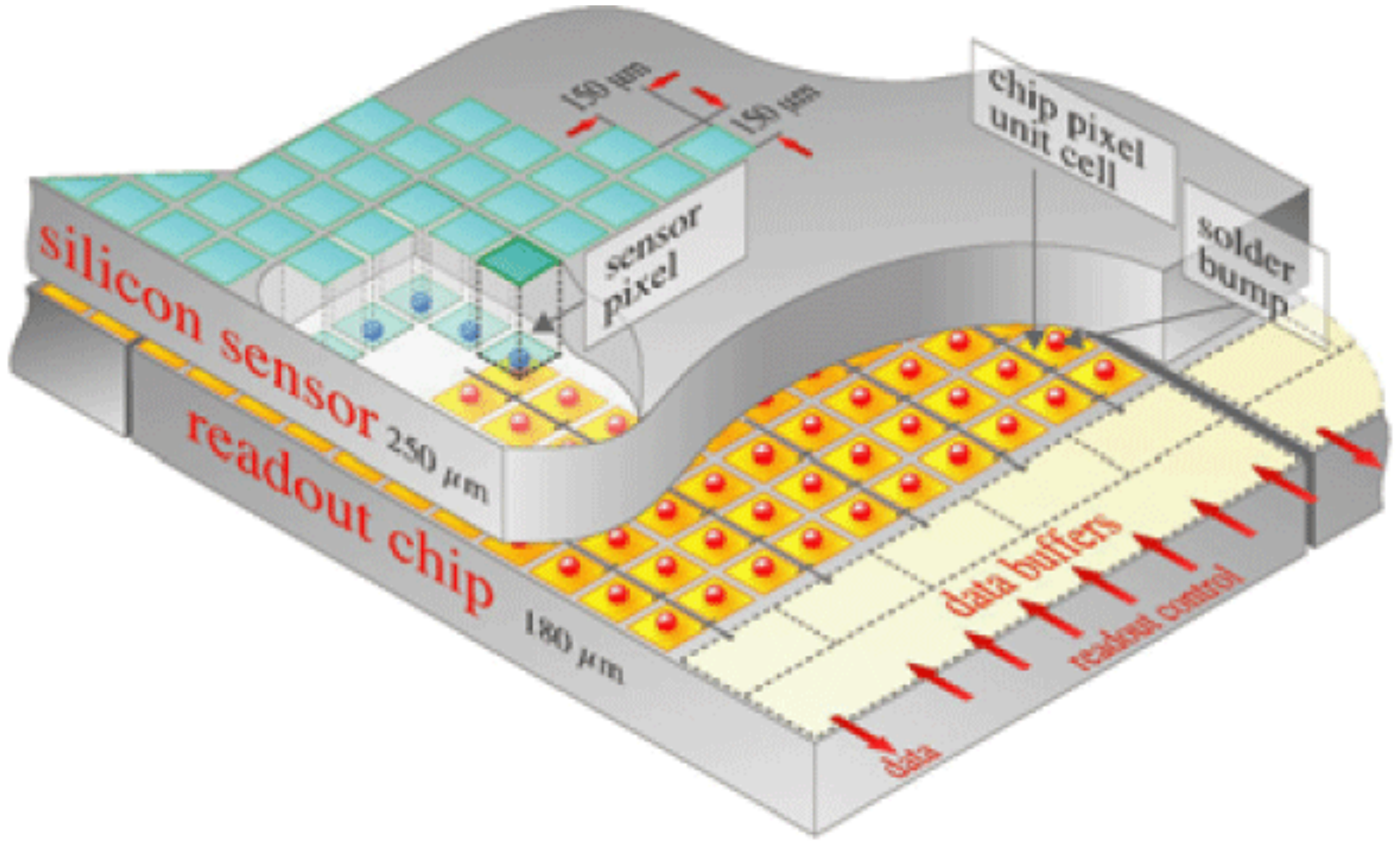
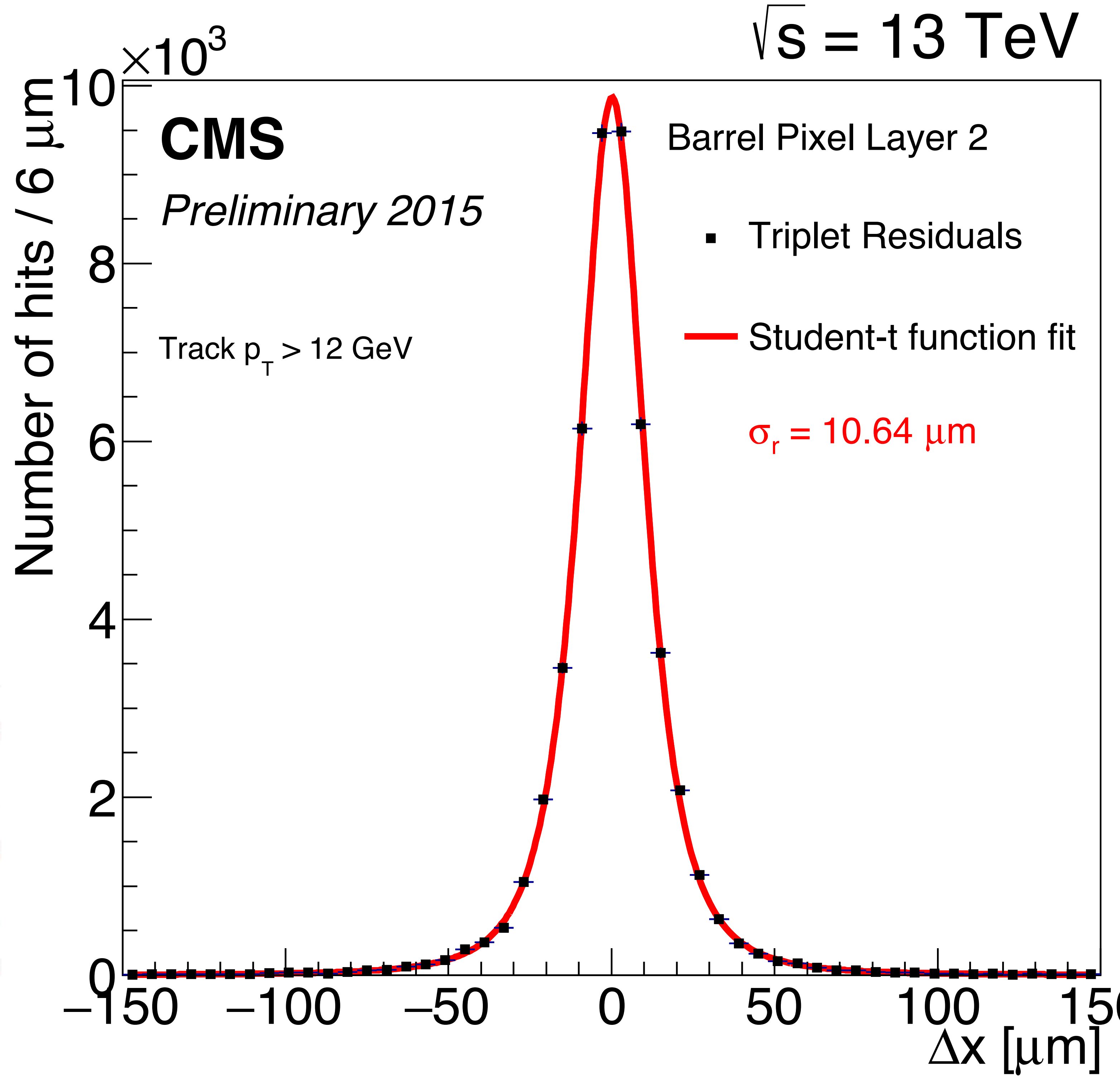
- **Most precise, 3-D measurement of hits on tracks.**
- **Crucial in tracking and vertex reconstruction**





CMS Phase-0 Pixel Detector

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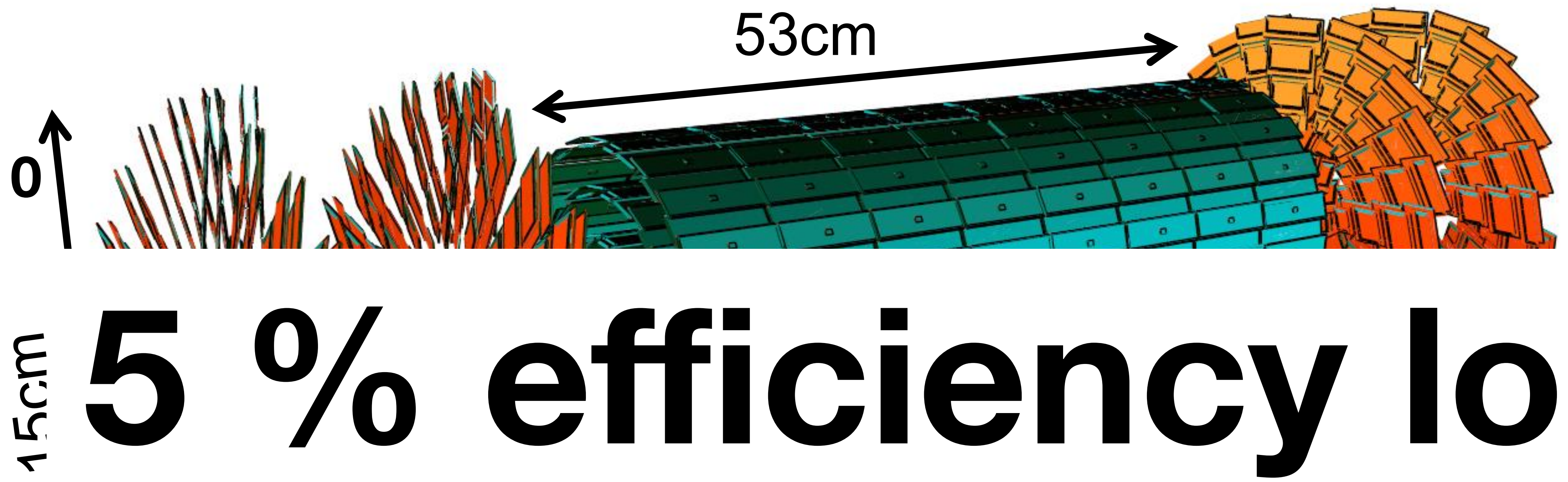
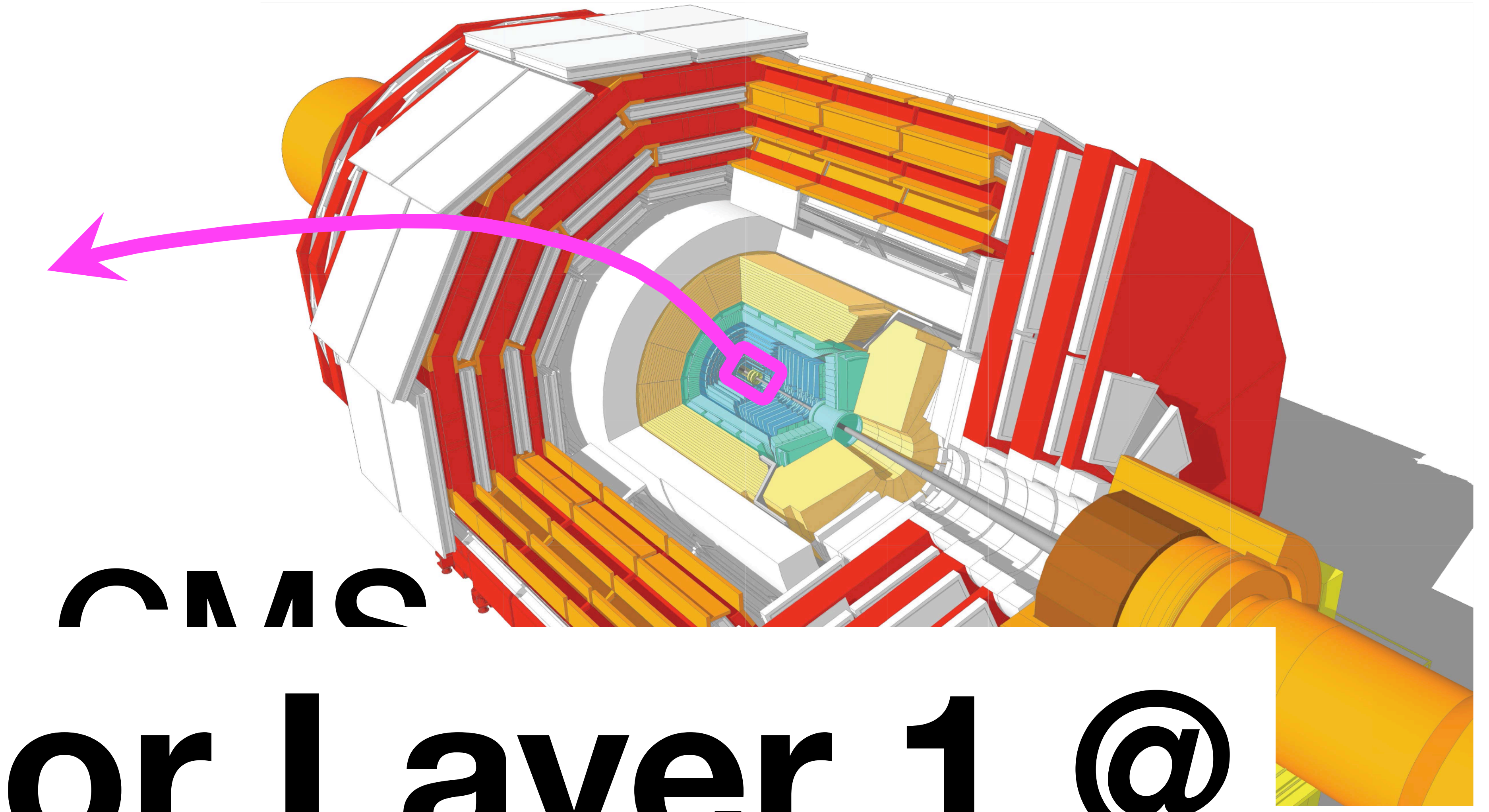
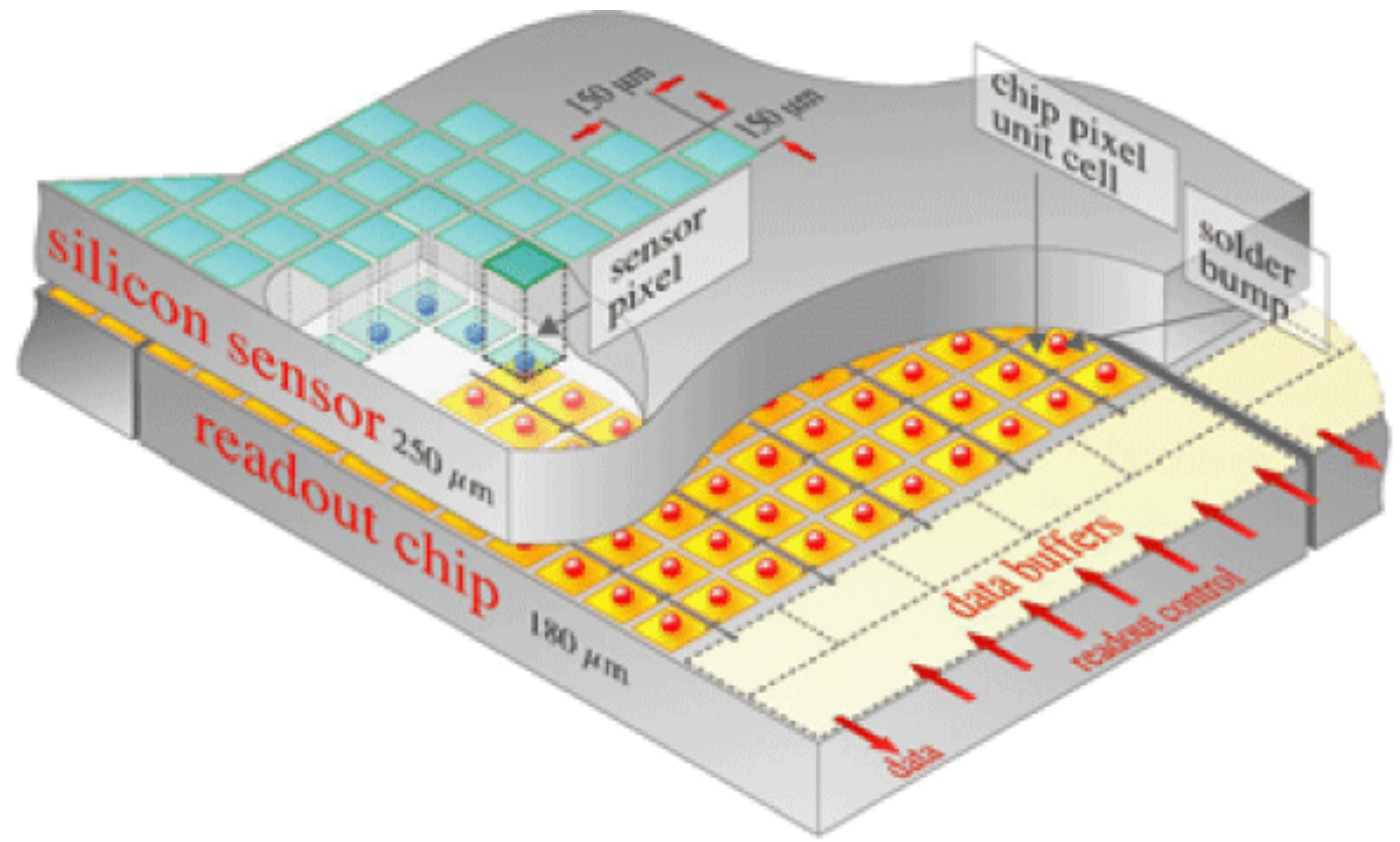
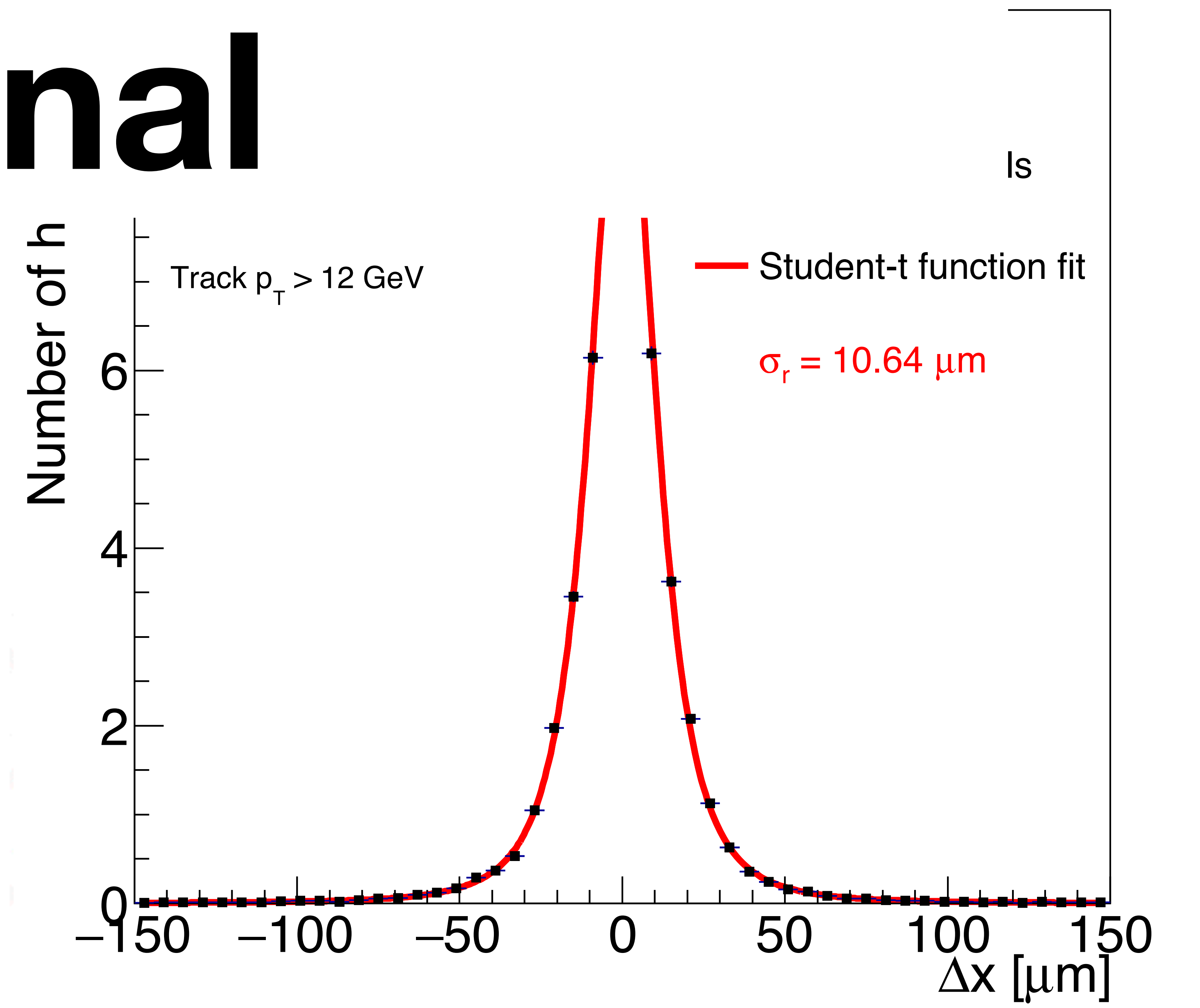




5 % efficiency loss for Layer 1 @ 1.5*LHC nominal

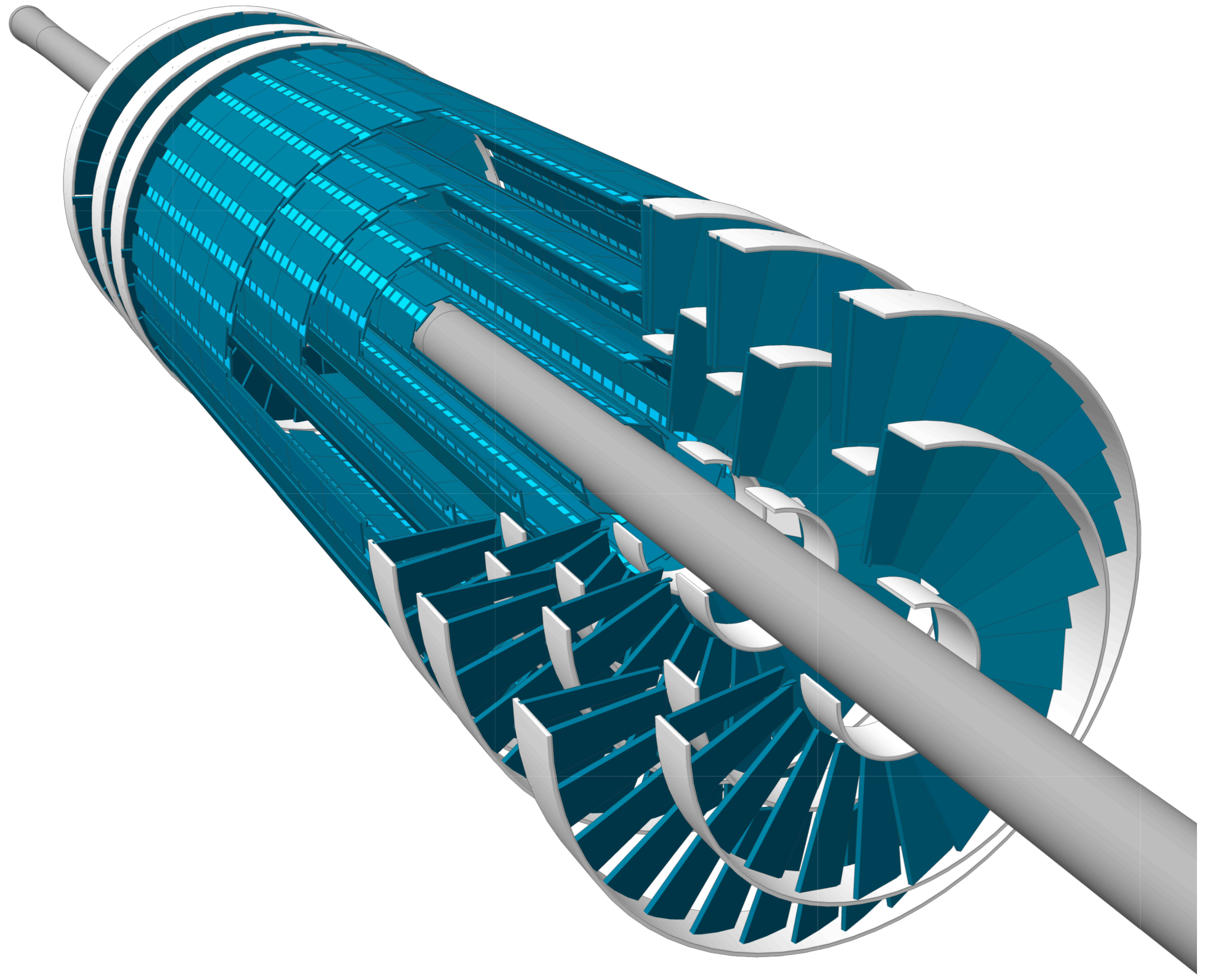
- **Most precise, 3-D measurement of hits on tracks.**
- **Crucial in tracking and vertex reconstruction**



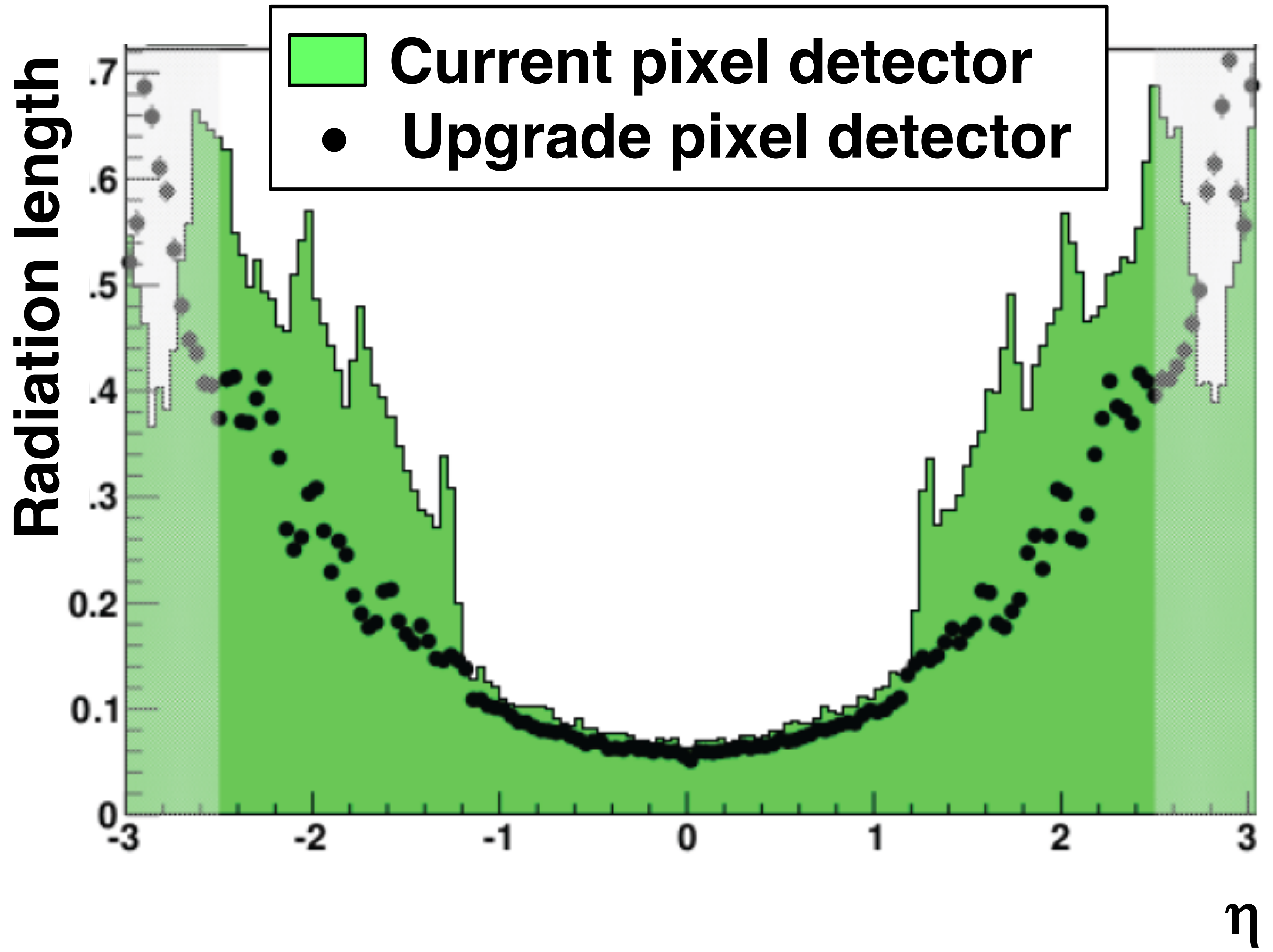


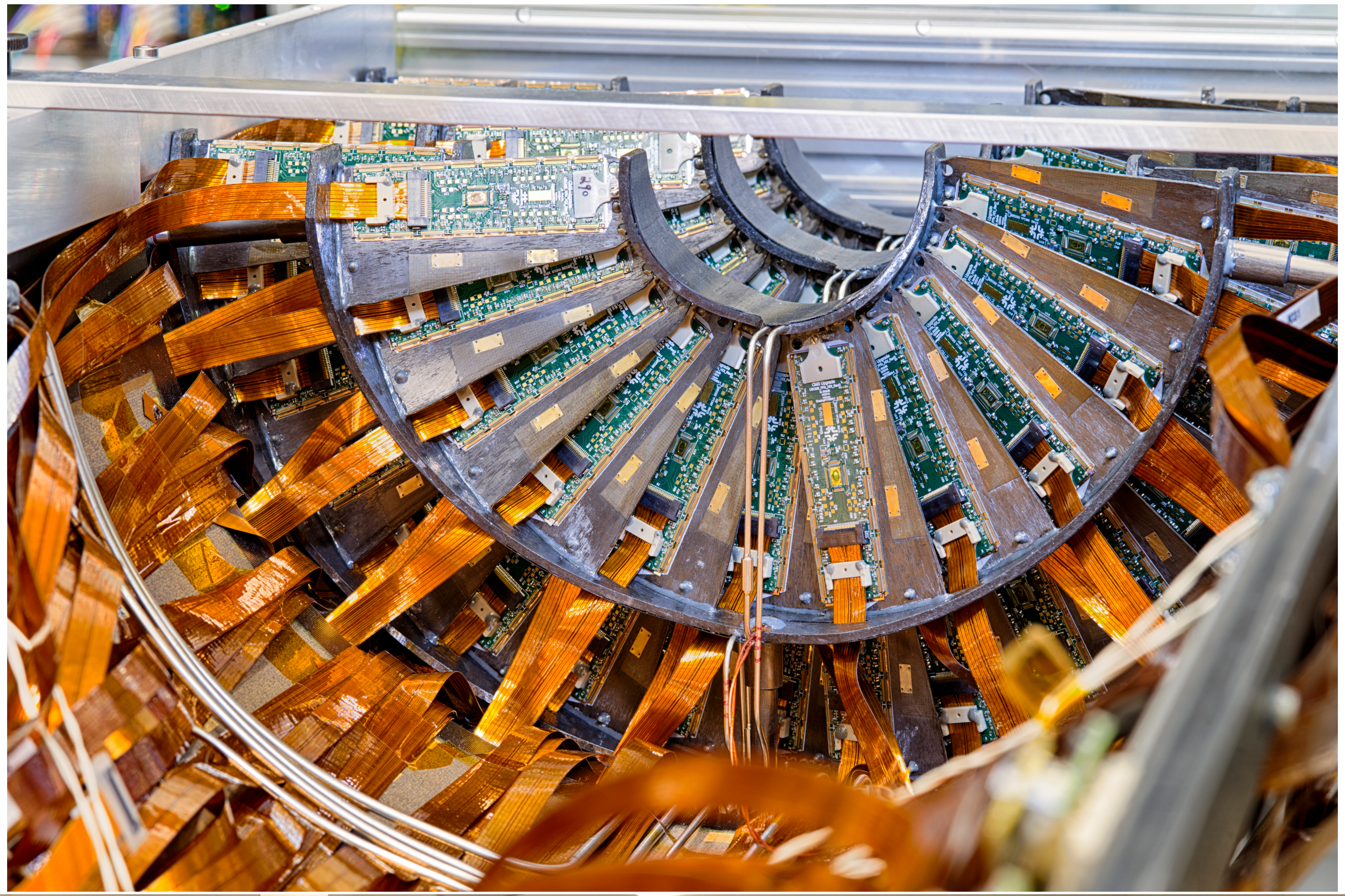
DESIGN OF PHASE 1 PIXEL DETECTOR

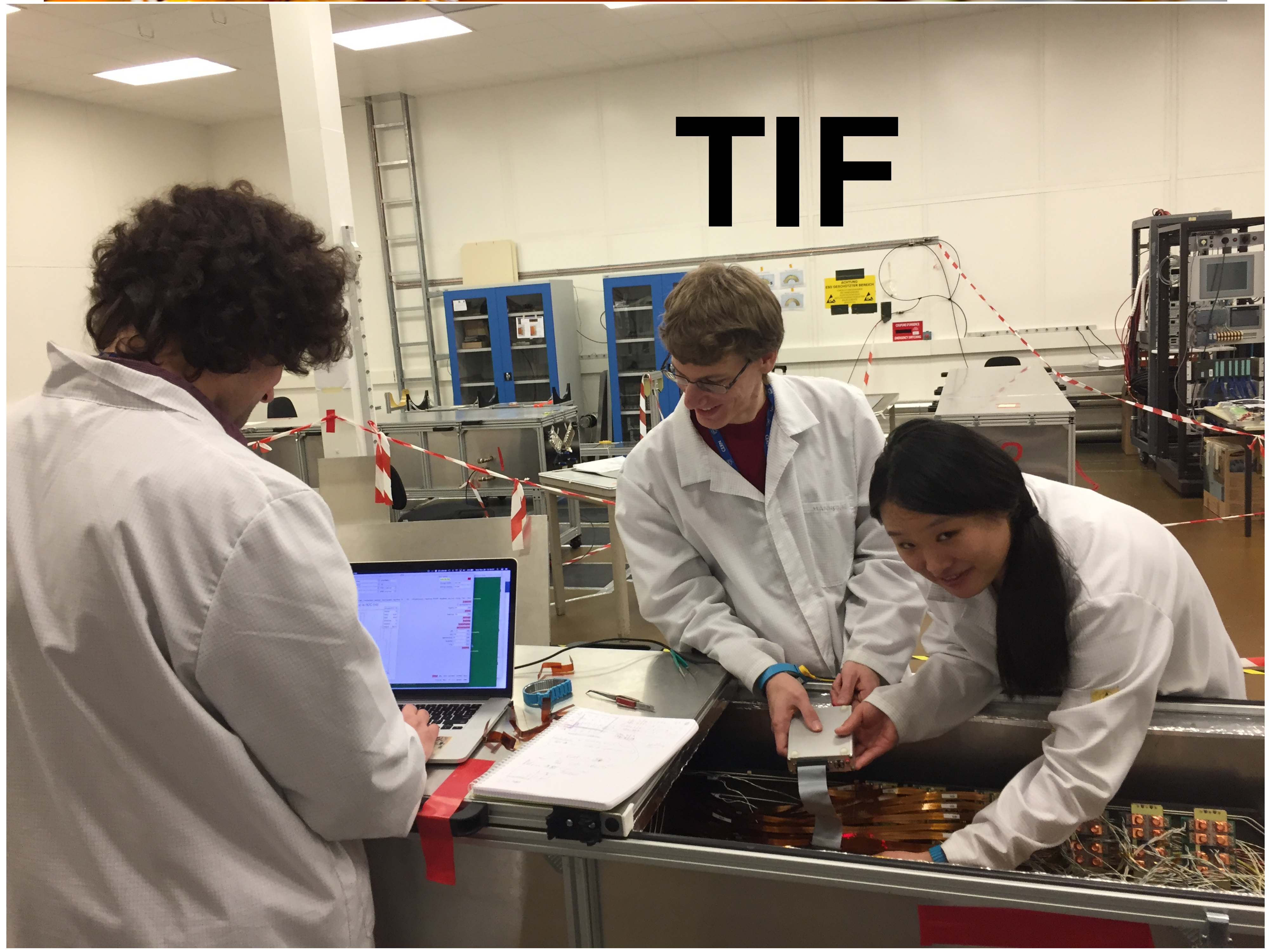
- **CMS planned an upgraded phase 1 pixel detector and requested an extended winter stop during 2016/2017 in Run 2 for installation.**
- **Designed to cope with more challenging LHC environment in Run 2 & Run 3 (300 fb^{-1}) until HL-LHC upgrade (2023).**
  - **Module designed to reduce dynamic inefficiency**
    - Digital readout chip (ROC). Faster readout.
  - **Geometry design: ensure tracking and vertex quality**
    - Added layers, **channels doubled**
  - **Services: reduce material budget**
    - CO_2 cooling, DCDC powering, Service electronics out of tracker volume.

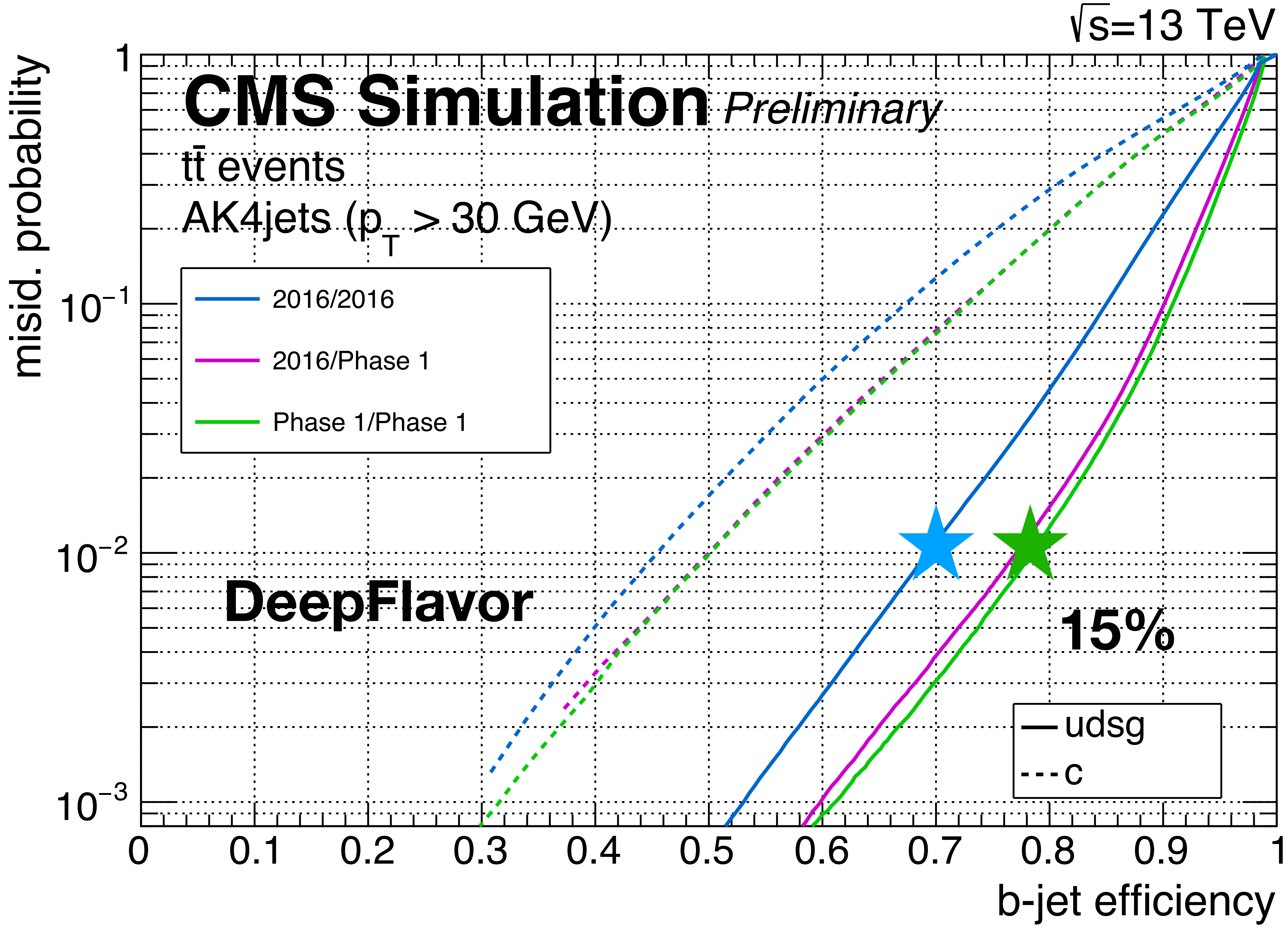


Material budget









- **Forward phase 1 pixel detector was constructed in Fermilab and transported to CERN for testing the end of September 2016.**
- **Installed in May 2017.**

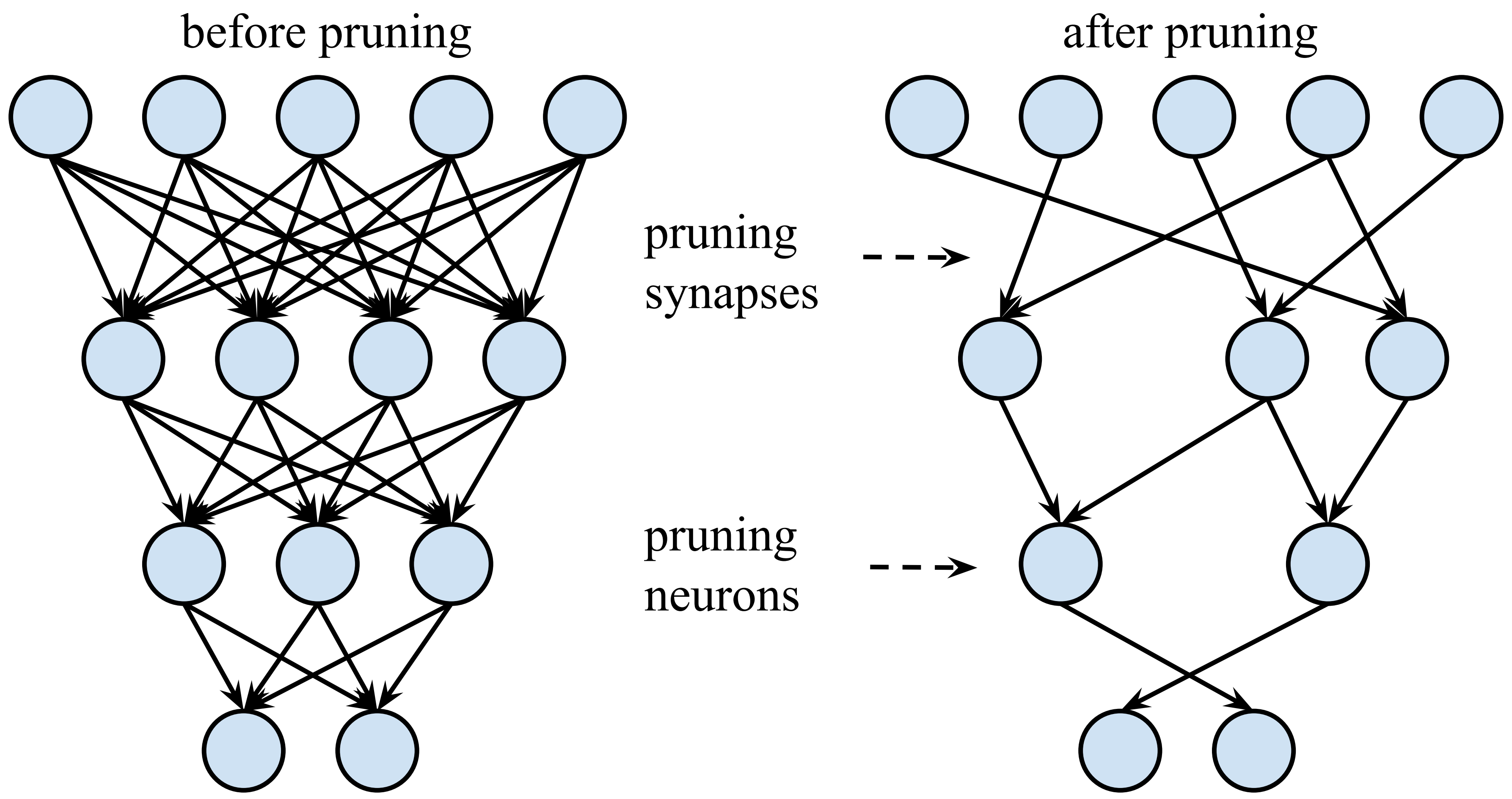
(ENERGY) EFFICIENT NEURAL NETWORKS

Emergent engineering field, efficient implementation of NN architecture

Parallelization: performing operations simultaneously (see next page)

Compression/Pruning:

maintain the same performance while removing low weight synapses and neurons (many schemes)



Quantization/Approximate math:

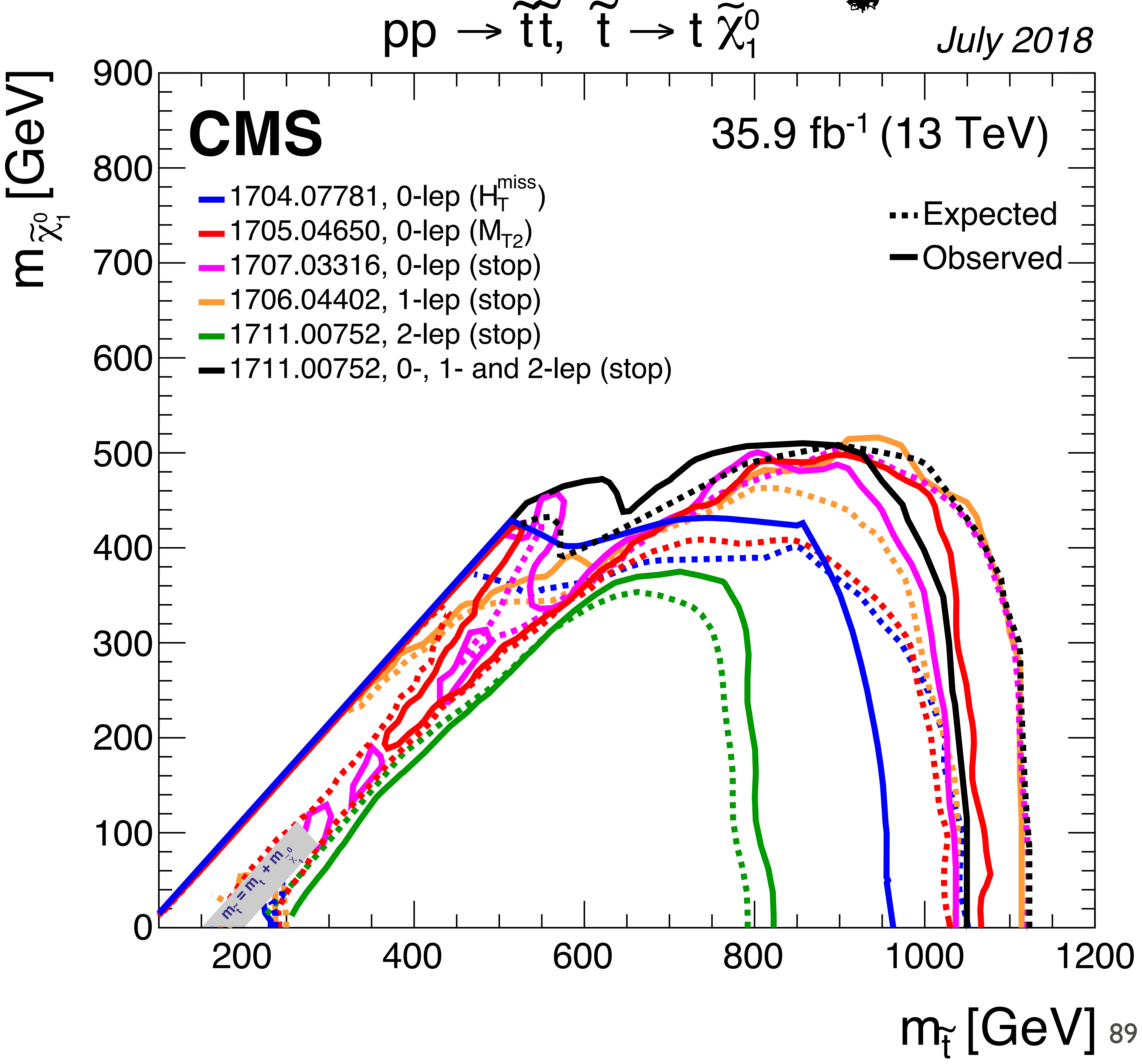
32-bit floating point math is overkill

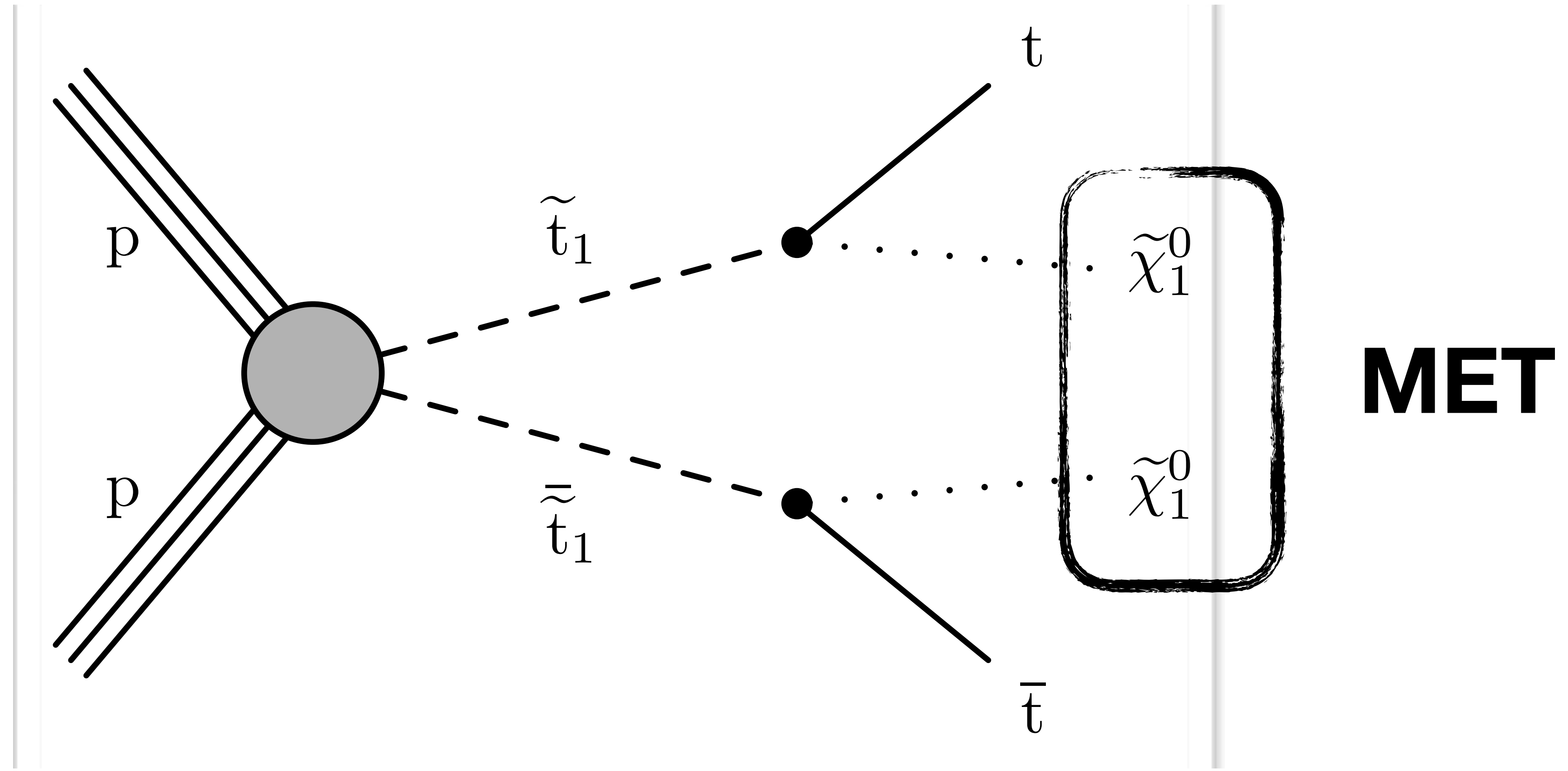
20-bit, 18-bit, …? fixed point, integers? binarized NNs?

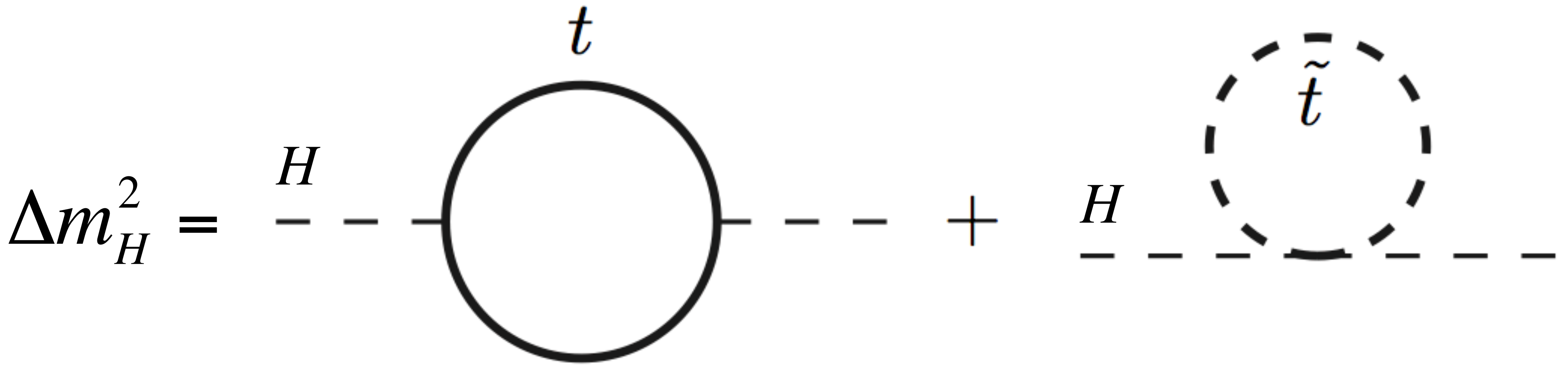
For further reading, start here: https://arxiv.org/pdf/1510.00149v5.pdf

M.LIU

We actively searched for stop

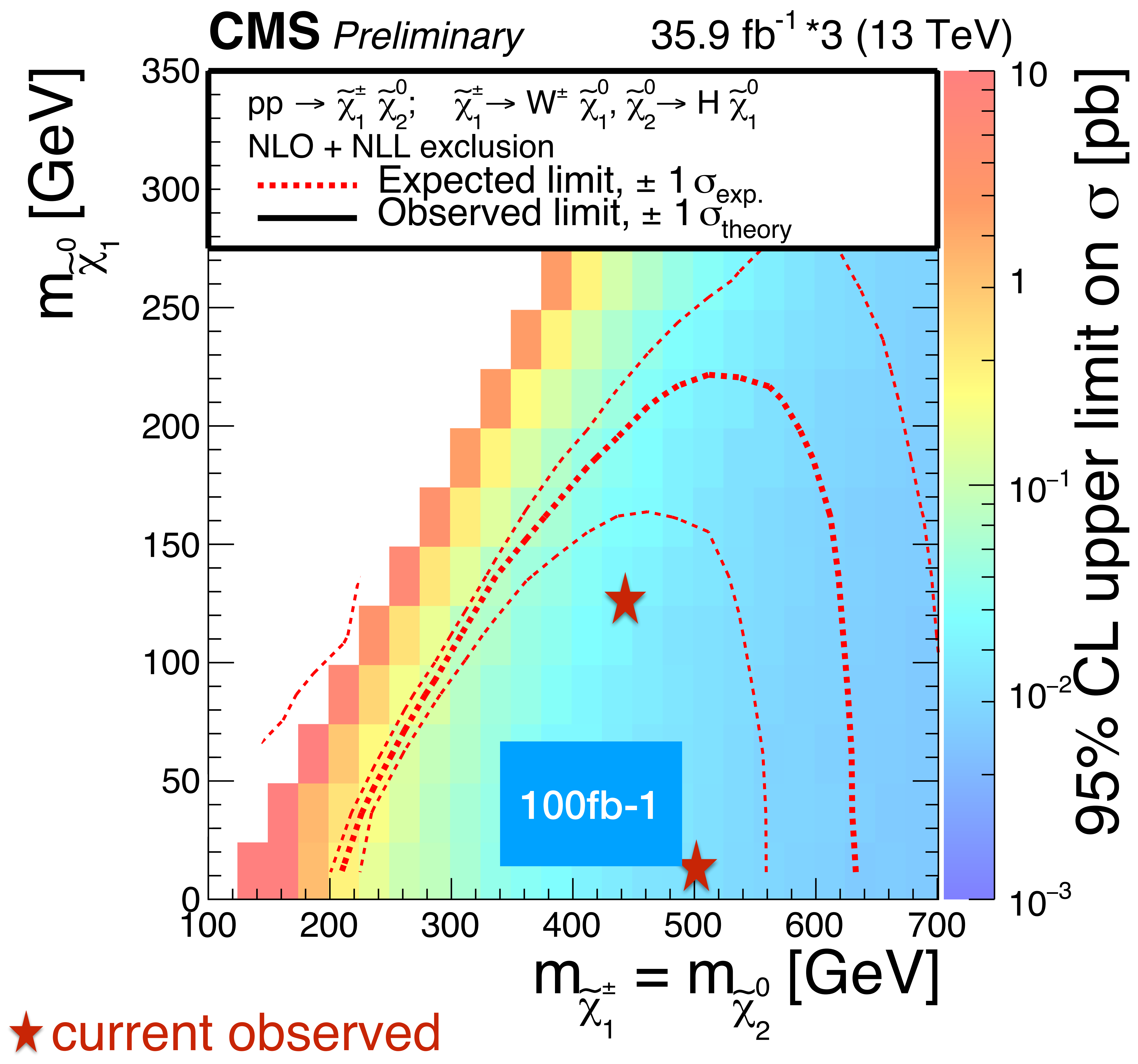






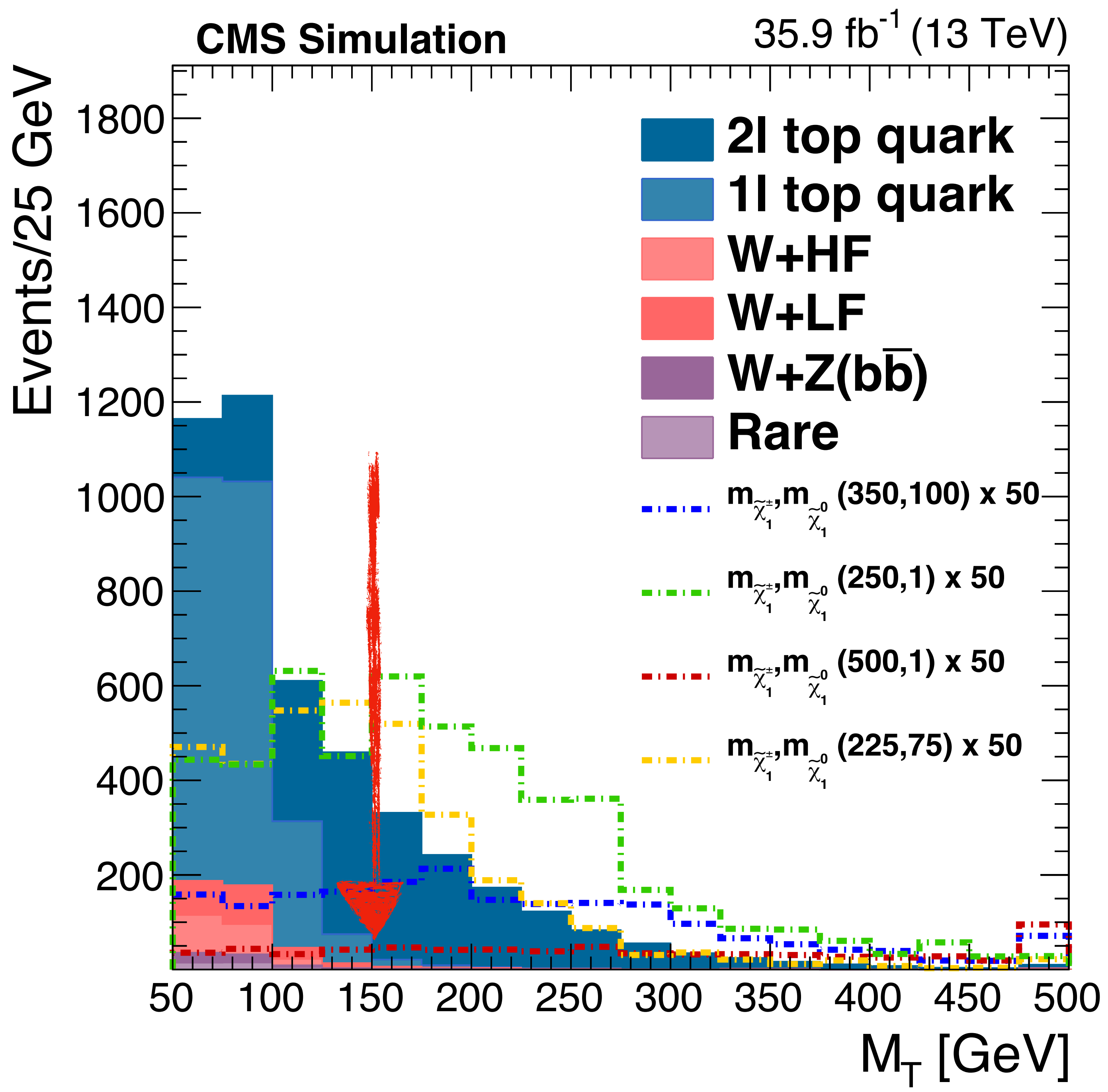
WH(lvbb) + MET: full Run 2 outlook

CMS: WH+MET paper



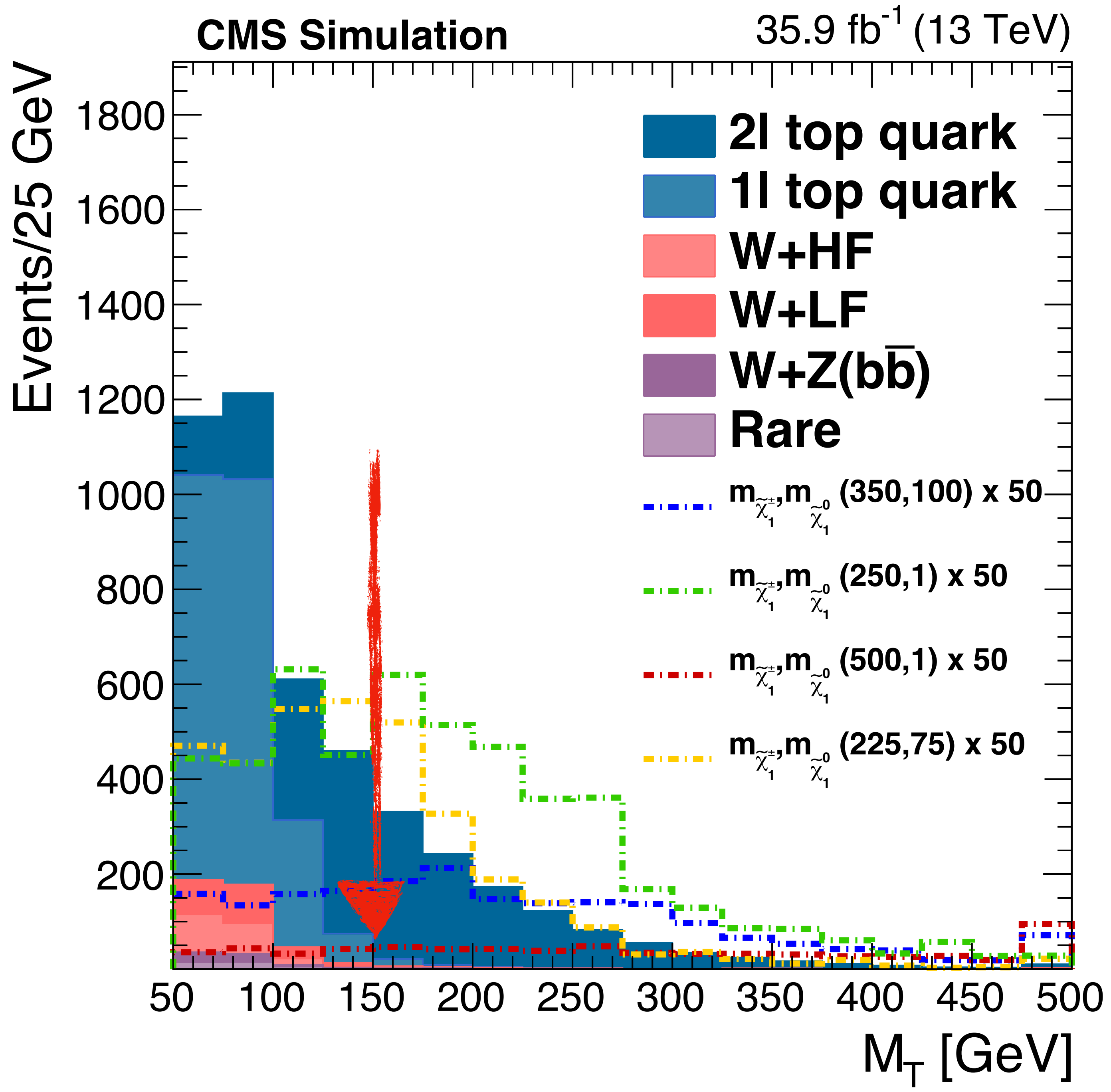
- Can benefit from full-Run 2 dataset
- Approaching regions with boosted objects.

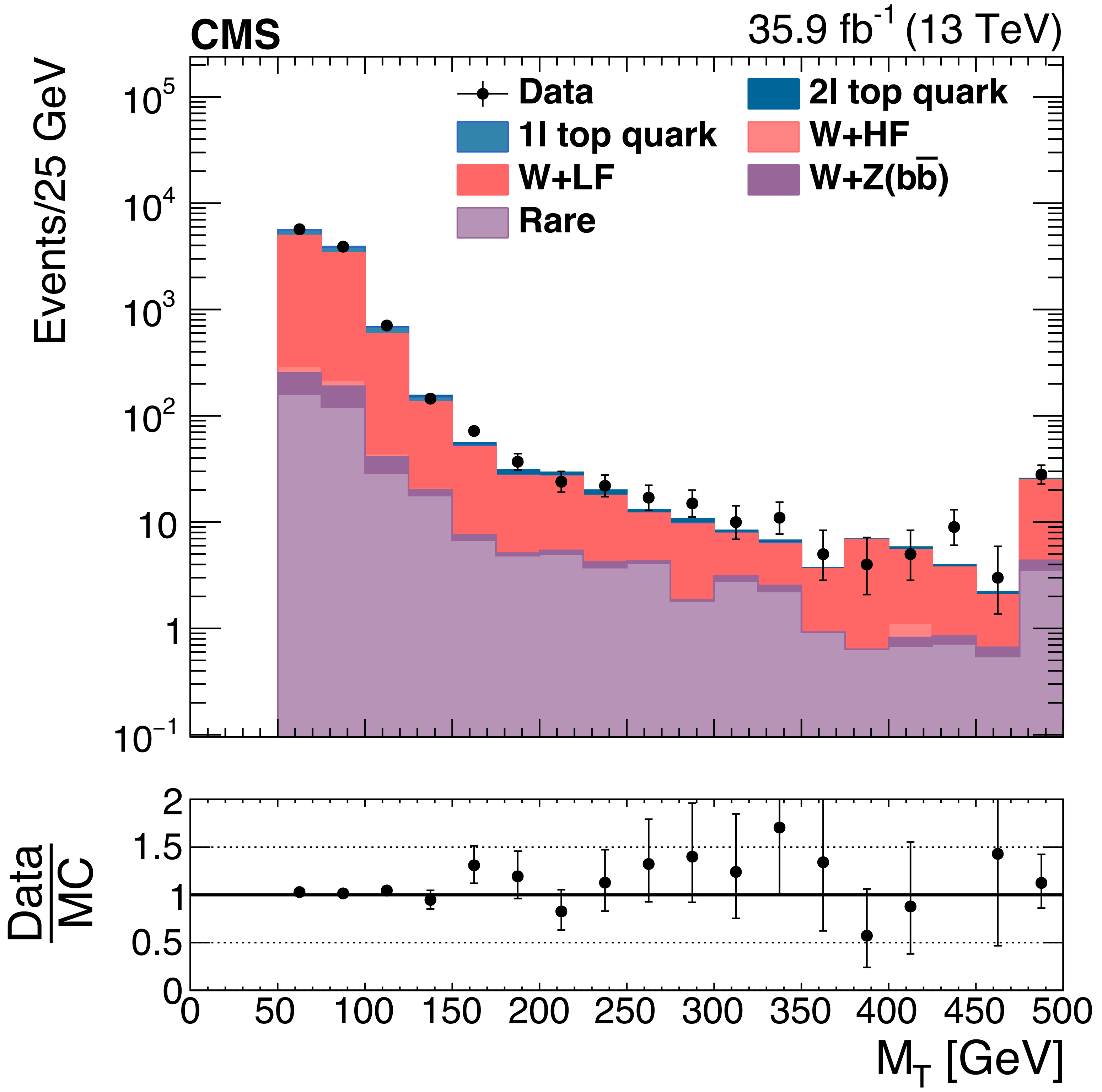
WH(lvbb) + MET: analysis strategy



- In addition to large missing transverse energy. Endpoint type of variables used to suppress backgrounds:
  - 1L TTBar has an endpoint in W transverse mass because of top quark mass constraint

WH(lνbb) + MET: analysis strategy





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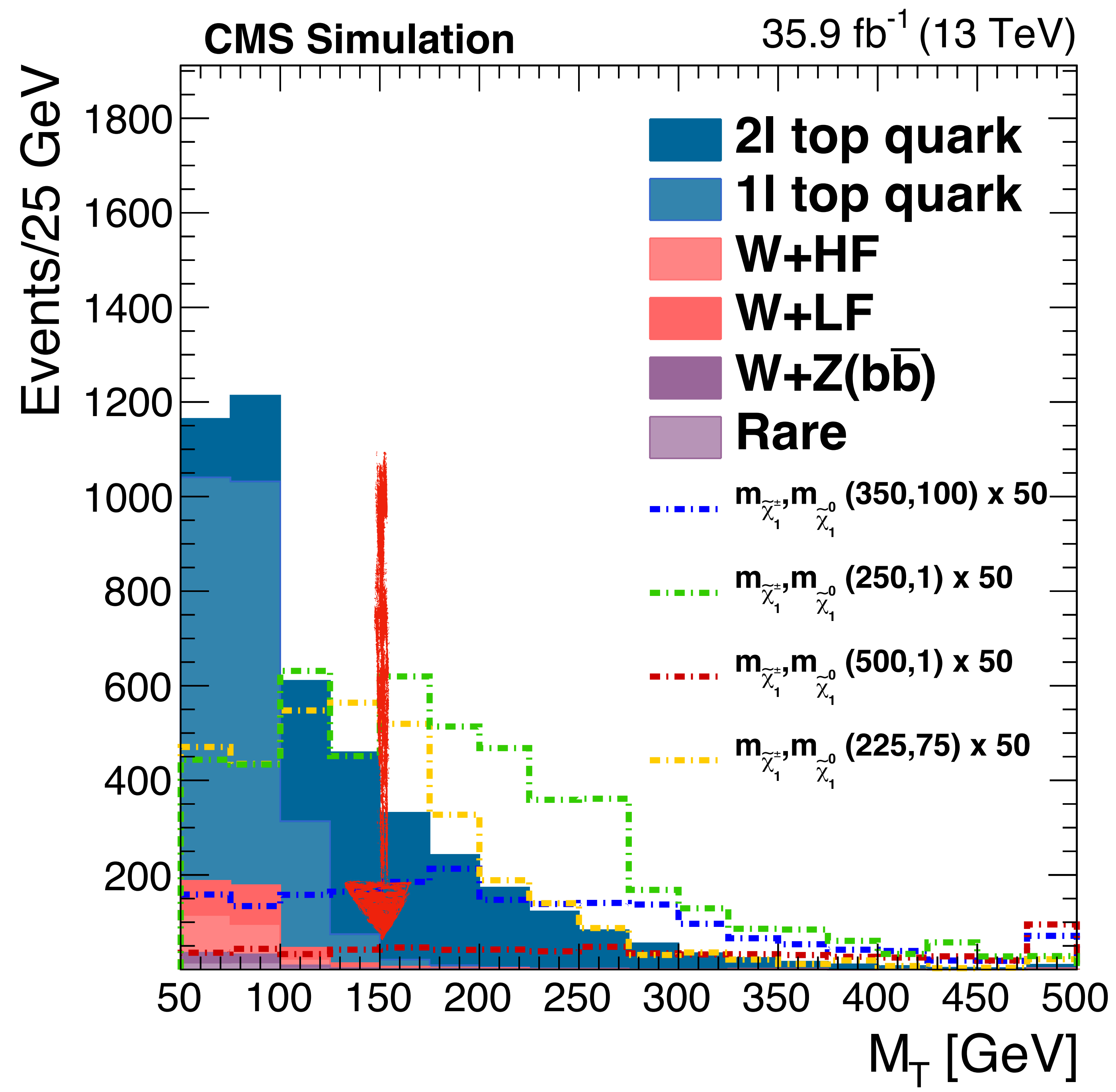

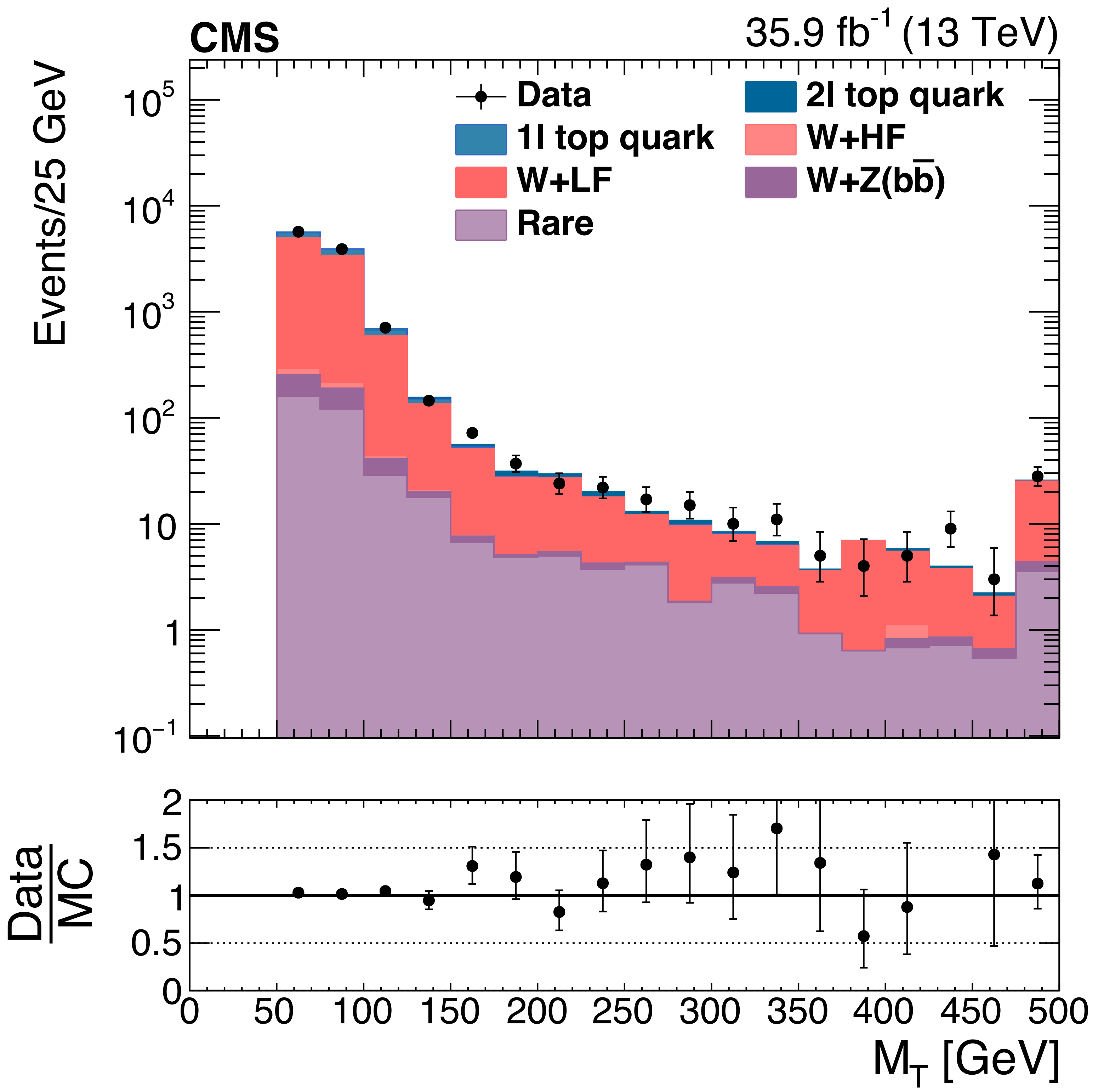

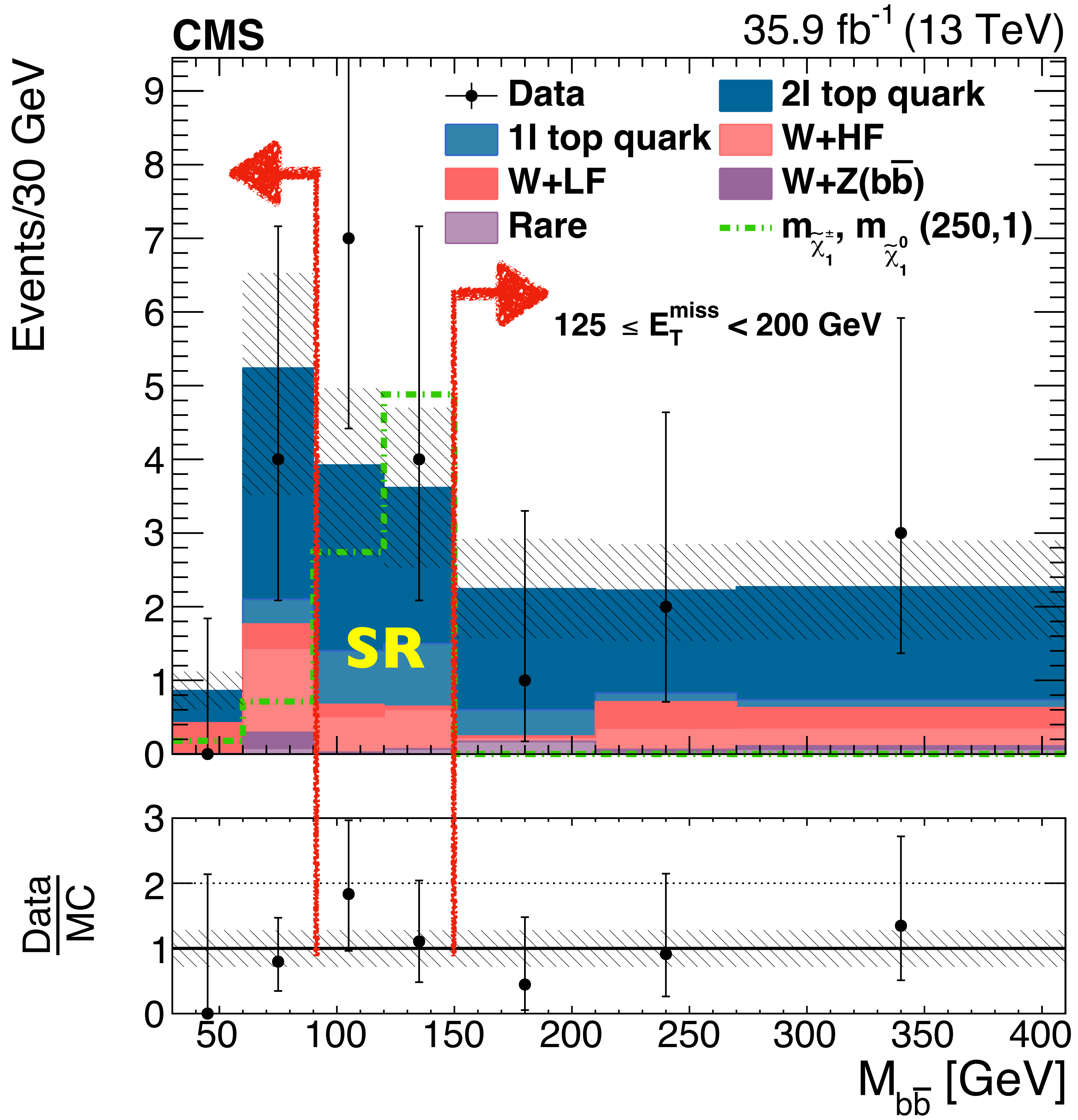

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  - 1L TTBar has an endpoint in W transverse mass because of top quark mass constraint
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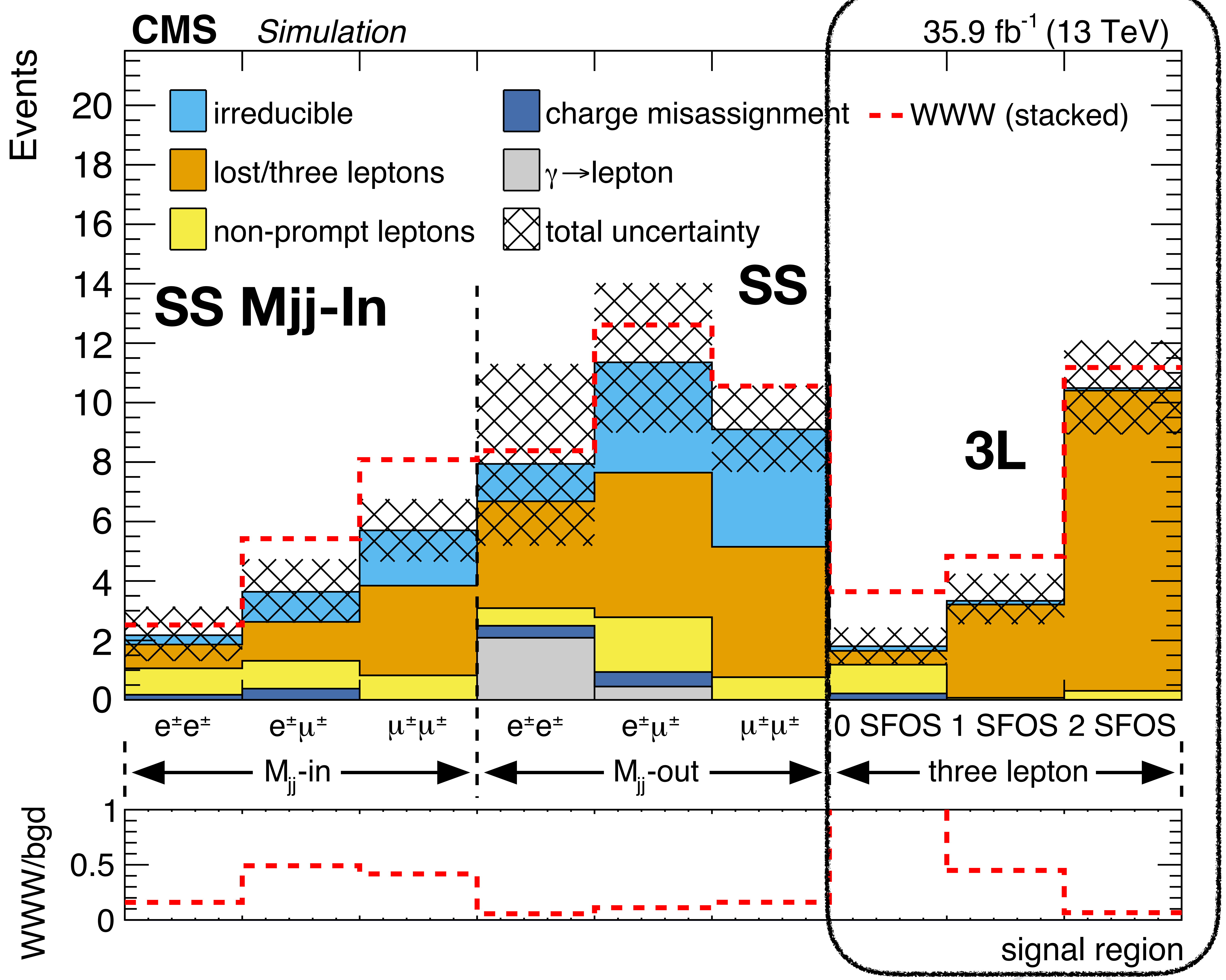
- Validated in 0 B-tagged region
- Two b's form Higgs mass peak, main background 2L TTbar directly controlled in the sideband.

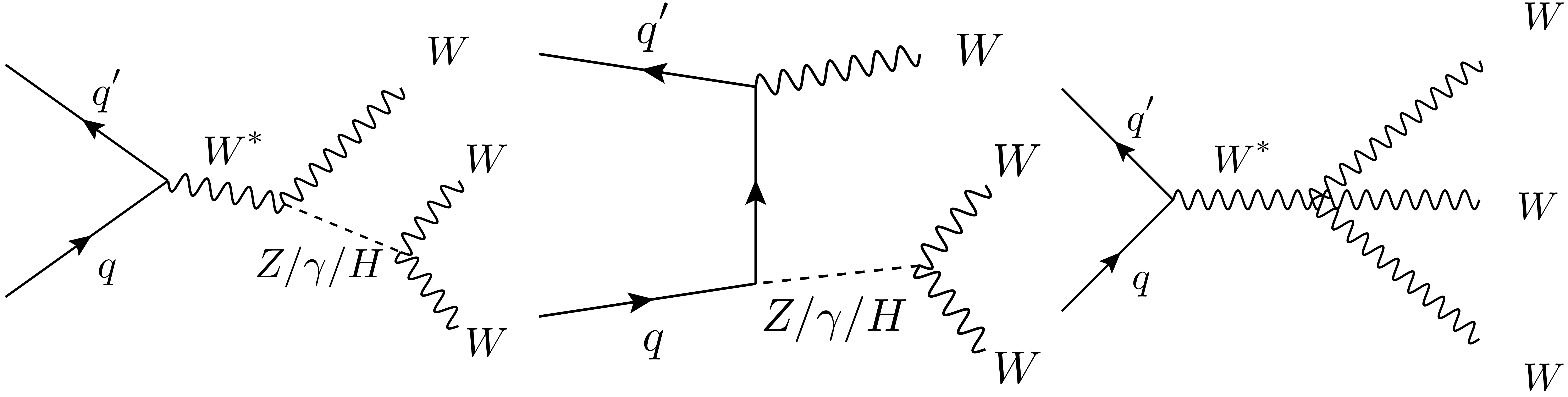
Backgrounds constrained with Data



- 3L events, < 2 jets
- Dominated by real 3L events in 1SFOS and 2SFOS
  - WZ, ttV with 3L in the final state
- Exploit kinematic difference in suppressing the background:
- eg: in 1 SFOS:
  - WZ: Mt formed by the 3rd lepton and the MET: W transverse mass
  - WWW: random, longer tail

Why electroweak physics

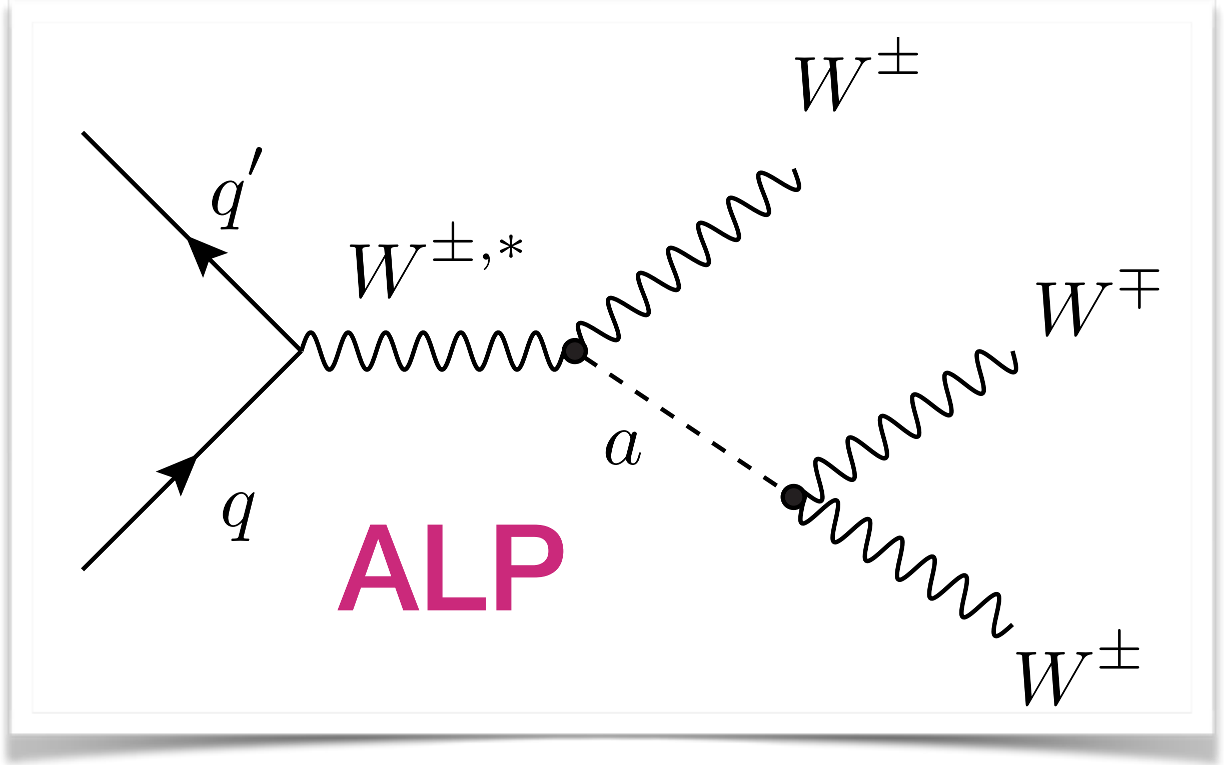
Higgs-mediated | triple gauge coupling | quartic gauge coupling



The process has a low cross section and has not been observed.

(ATLAS has an 8 TeV analysis with 1σ sensitivity. No 13 TeV result yet.)

Enhanced production from BSM contributions: e.g photophobic axion-like particle (ALP)



Fermilab

Storyline

- The success and shortcomings of the Standard Model
- Looking for new physics directly and indirectly with electroweak bosons and the Higgs boson:
  - Direct: Search for chargino-neutralino pair in the WH final state
  - Indirect: Search for WWW production
- Enhancing the CMS detector capabilities of discovering new physics
  - Phase 1 pixel upgrade (completed in 2017)
  - Fast Neural Network interference as a solution for triggering/computing challenges at the LHC/HL-LHC.

Storyline

- The success and shortcoming of the Standard Model

Measure what is measurable

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Fermilab

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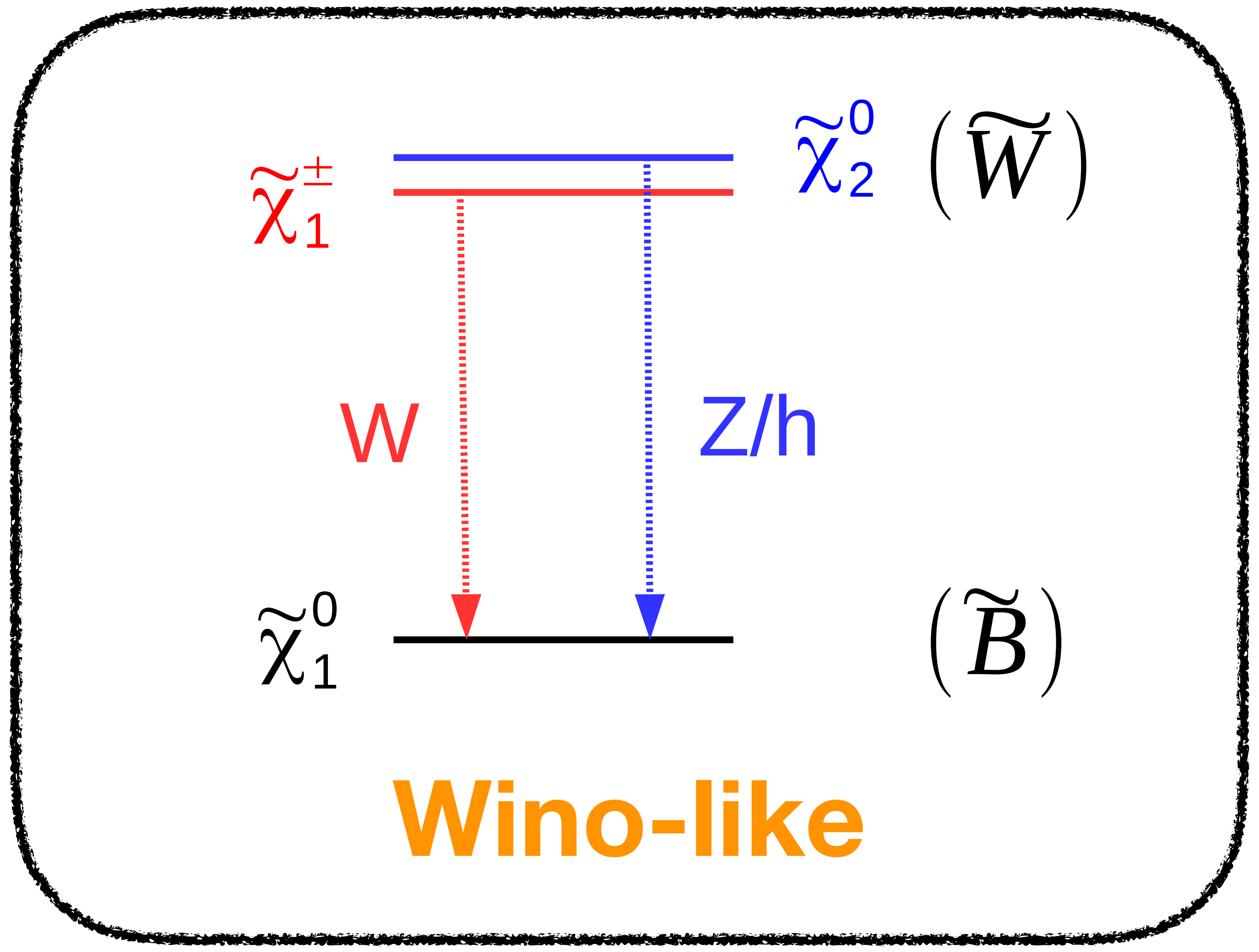
Make measurable what is not so

- Enhancing the CMS detector capabilities of discovering new physics
  - Phase 1 pixel upgrade (completed in 2017)
  - Fast Neural Network interference as a solution for triggering/computing challenges at the LHC/HL-LHC.

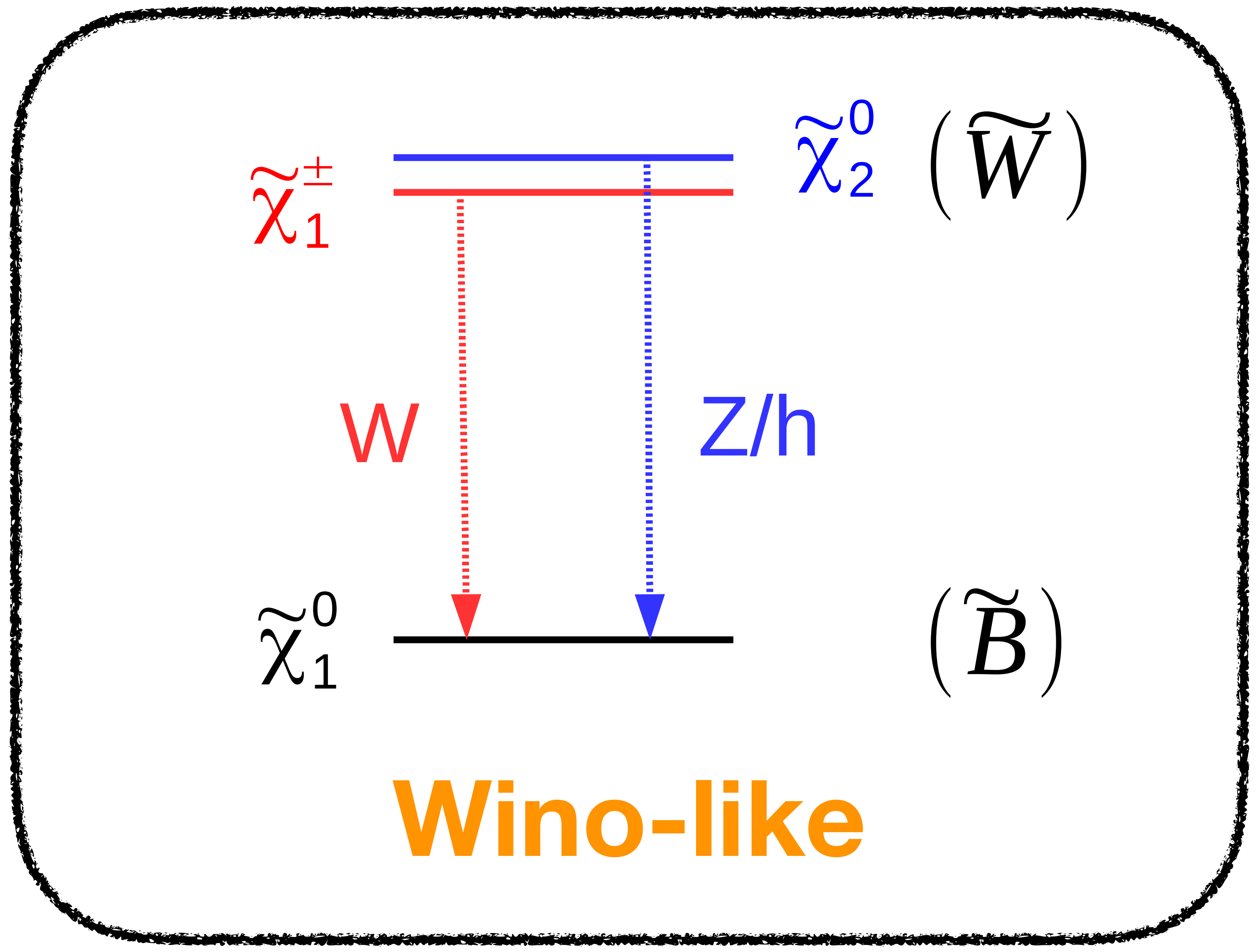
Overwhelming SM backgrounds



45 fb @ 500 GeV

$t\bar{t}$ **: 830 pb**

Overwhelming SM backgrounds



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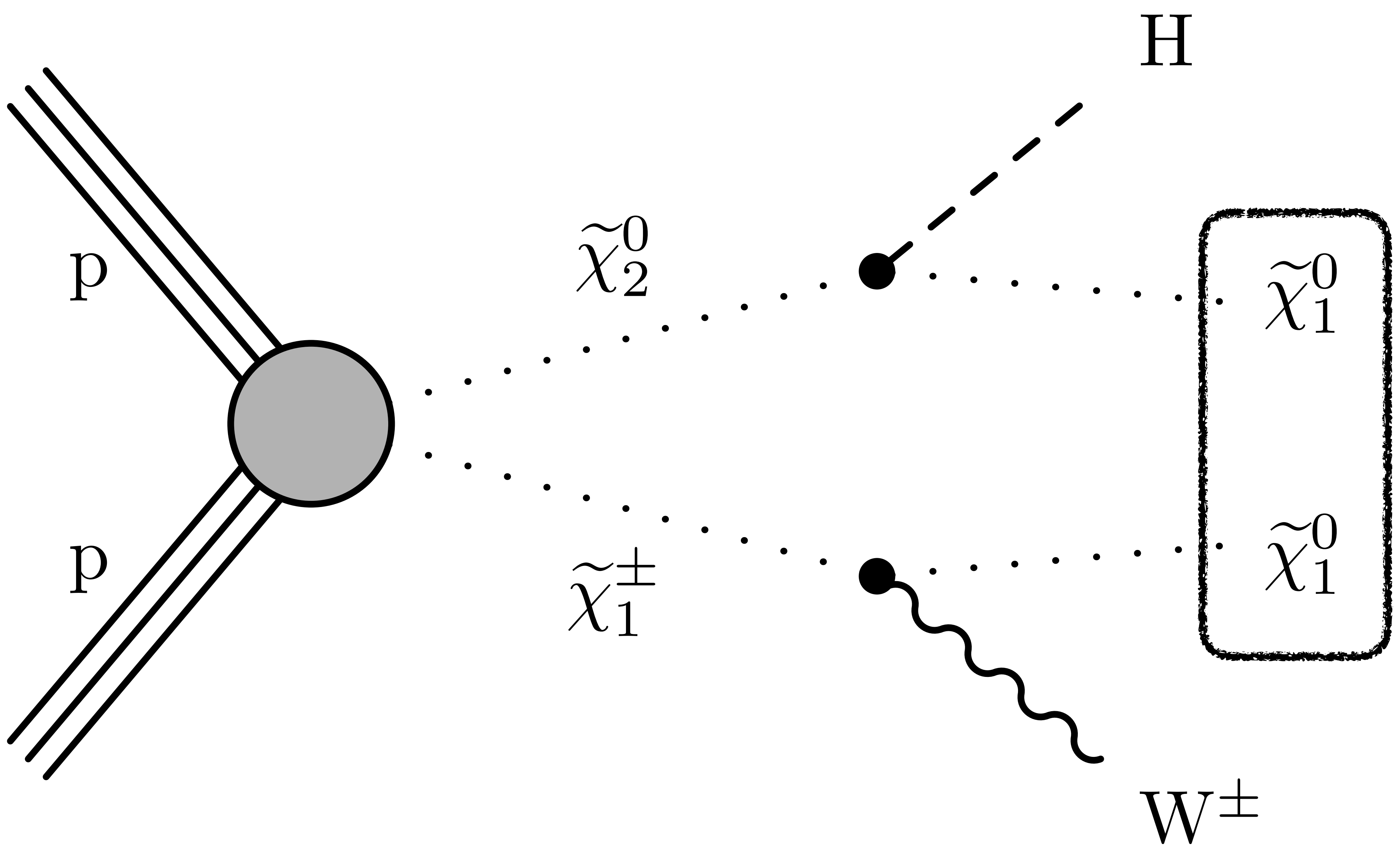
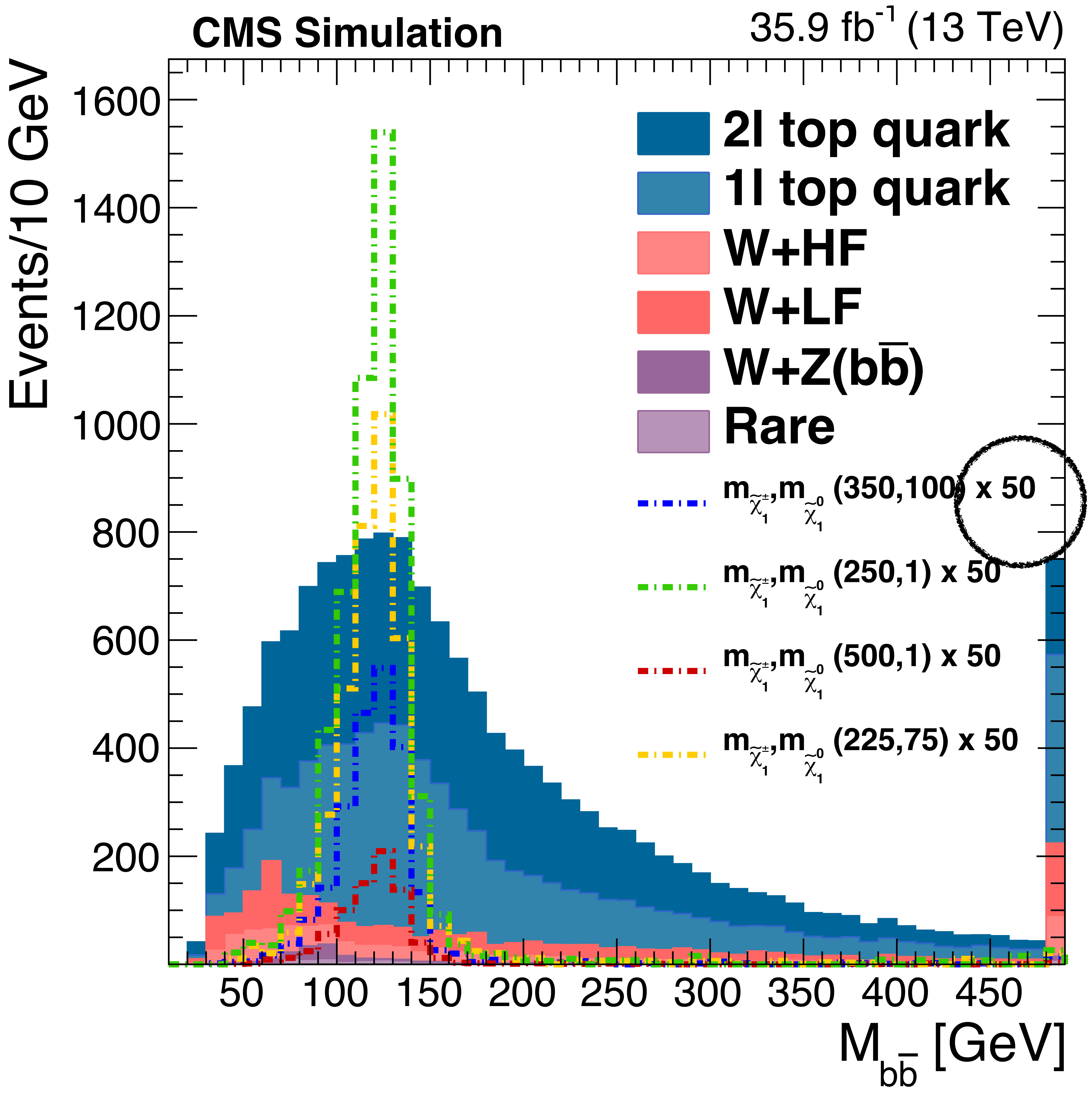


$t\bar{t}$ **: 830 pb**

Large MET

Overwhelming SM backgrounds



- 1 e/mu, two b jets,MET> 125 GeV
- Even after requiring large missing transverse energy!
- Need smart variables to exploit the topology differences between WH signal and backgrounds

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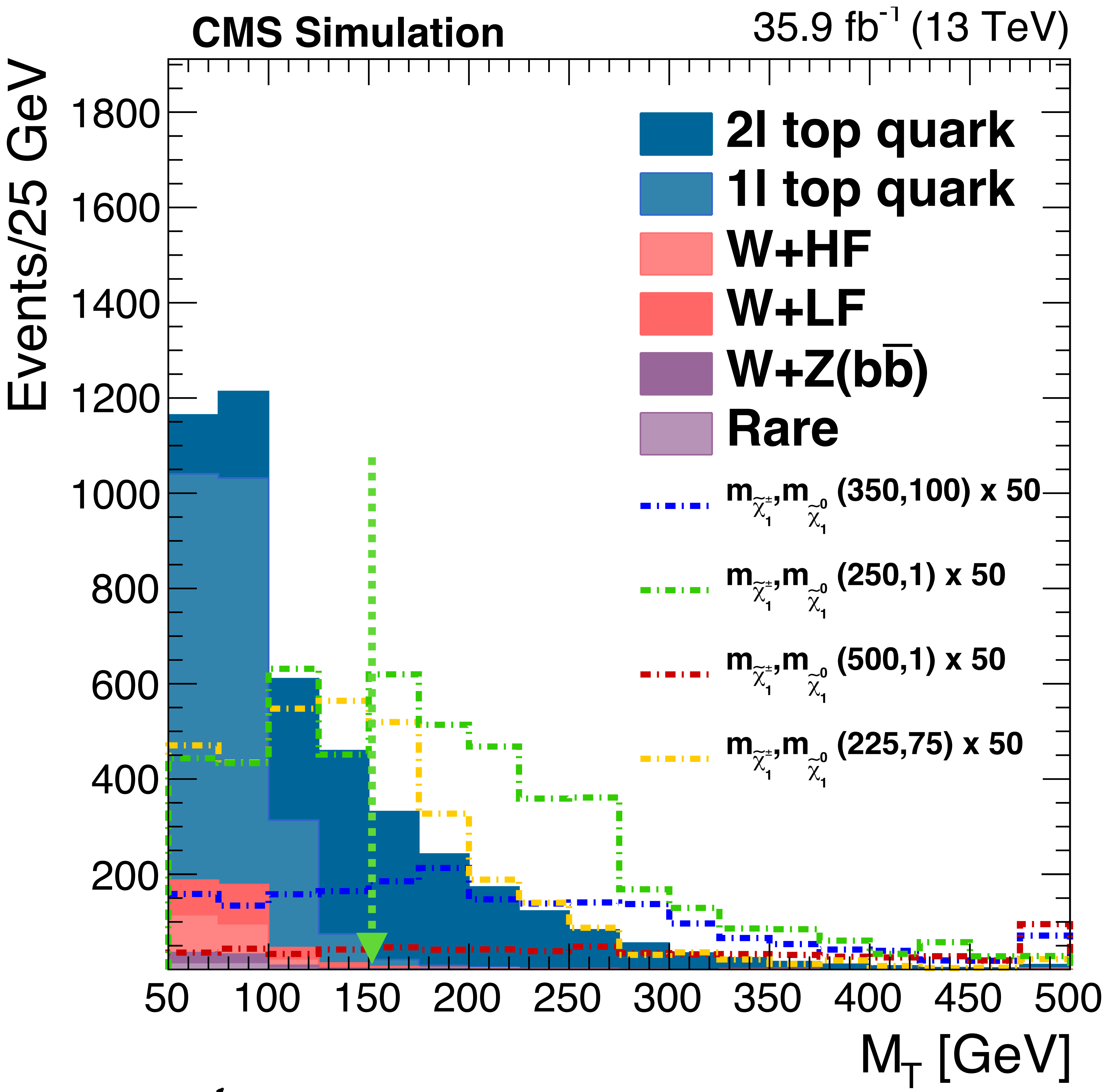
Background suppression: endpoint variables



- e.g 1L ttbar: W transverse mass constrained by top mass vs signal with extra MET from LSP

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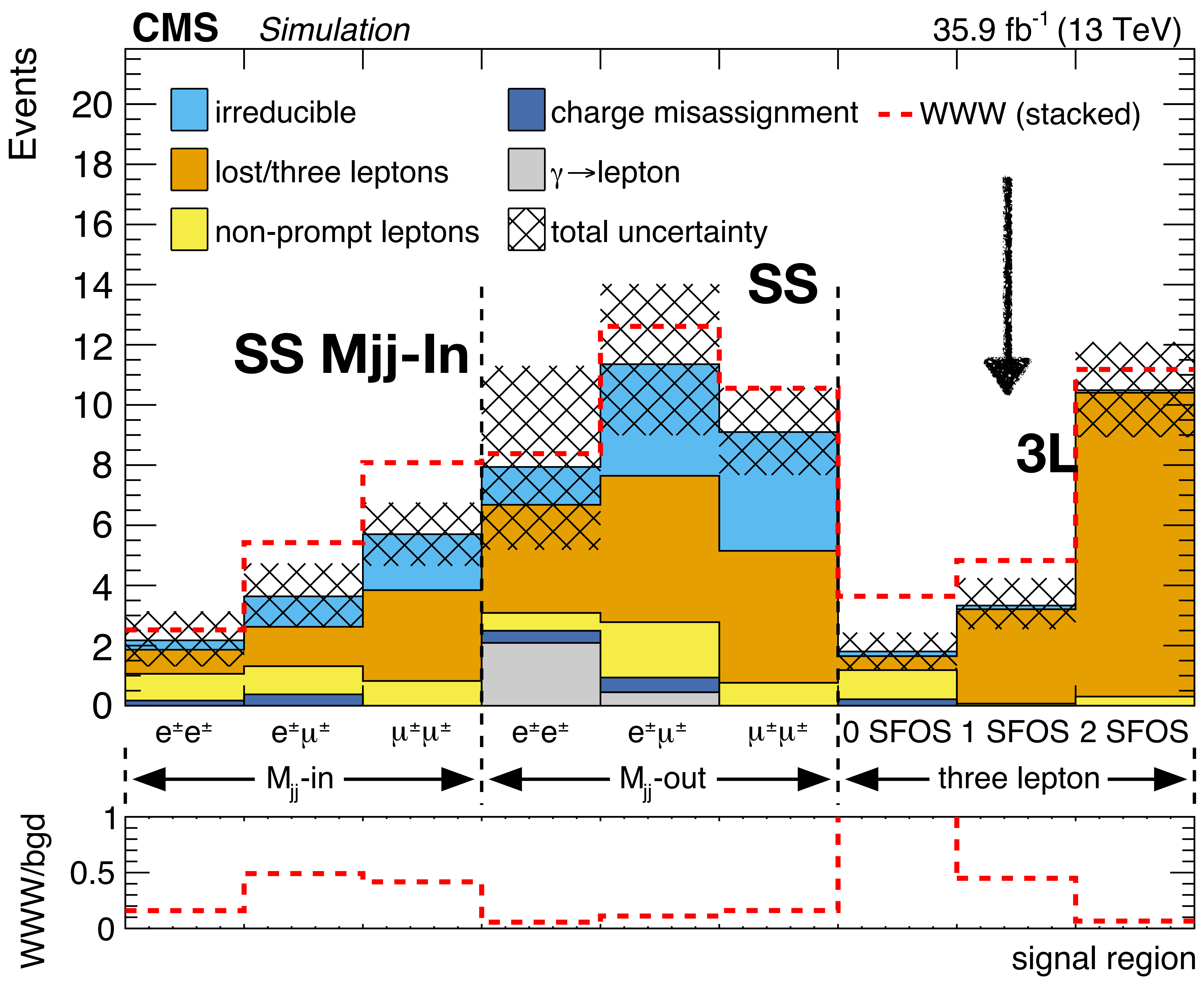
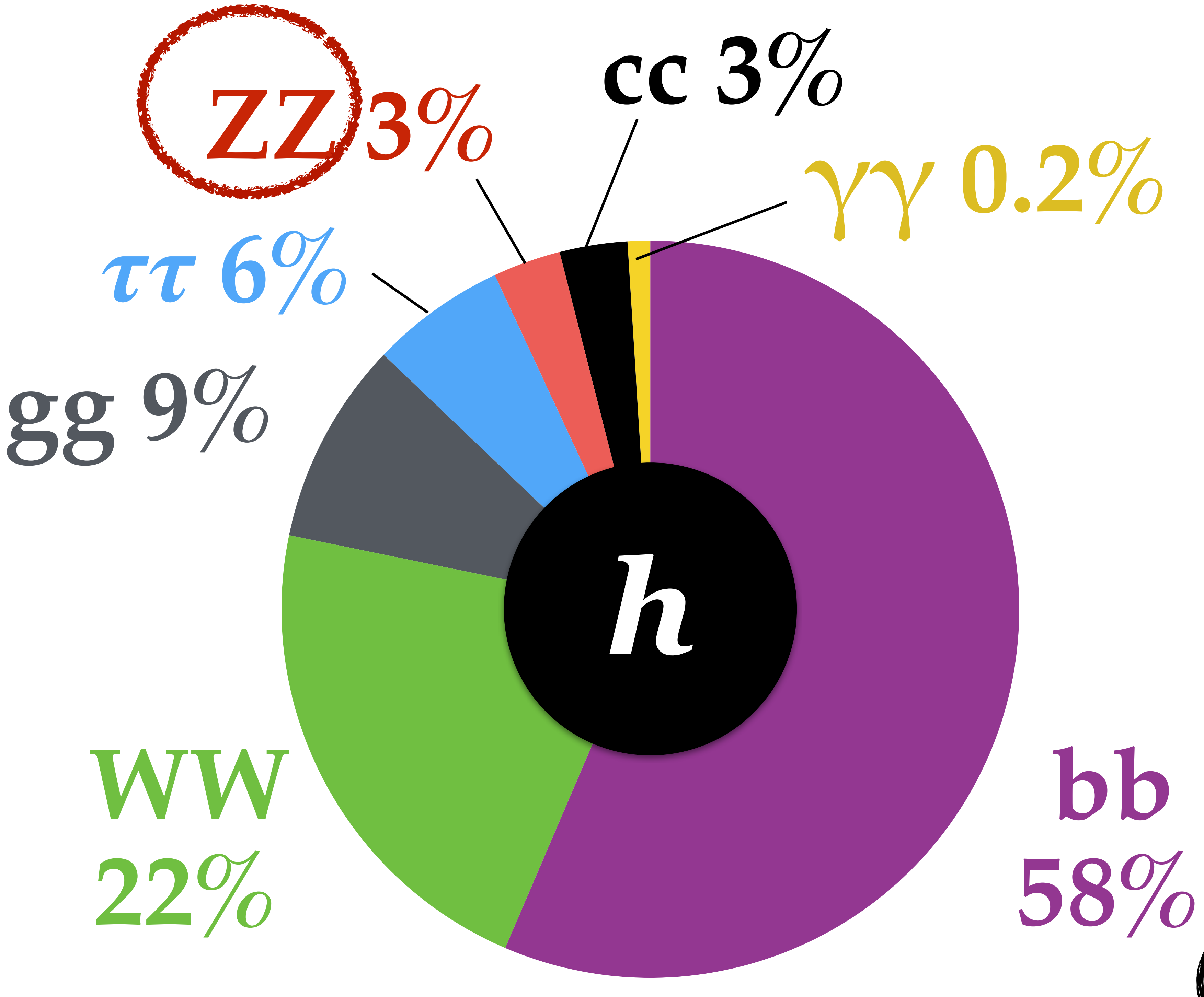
Maximize the sensitivity: Event categorization

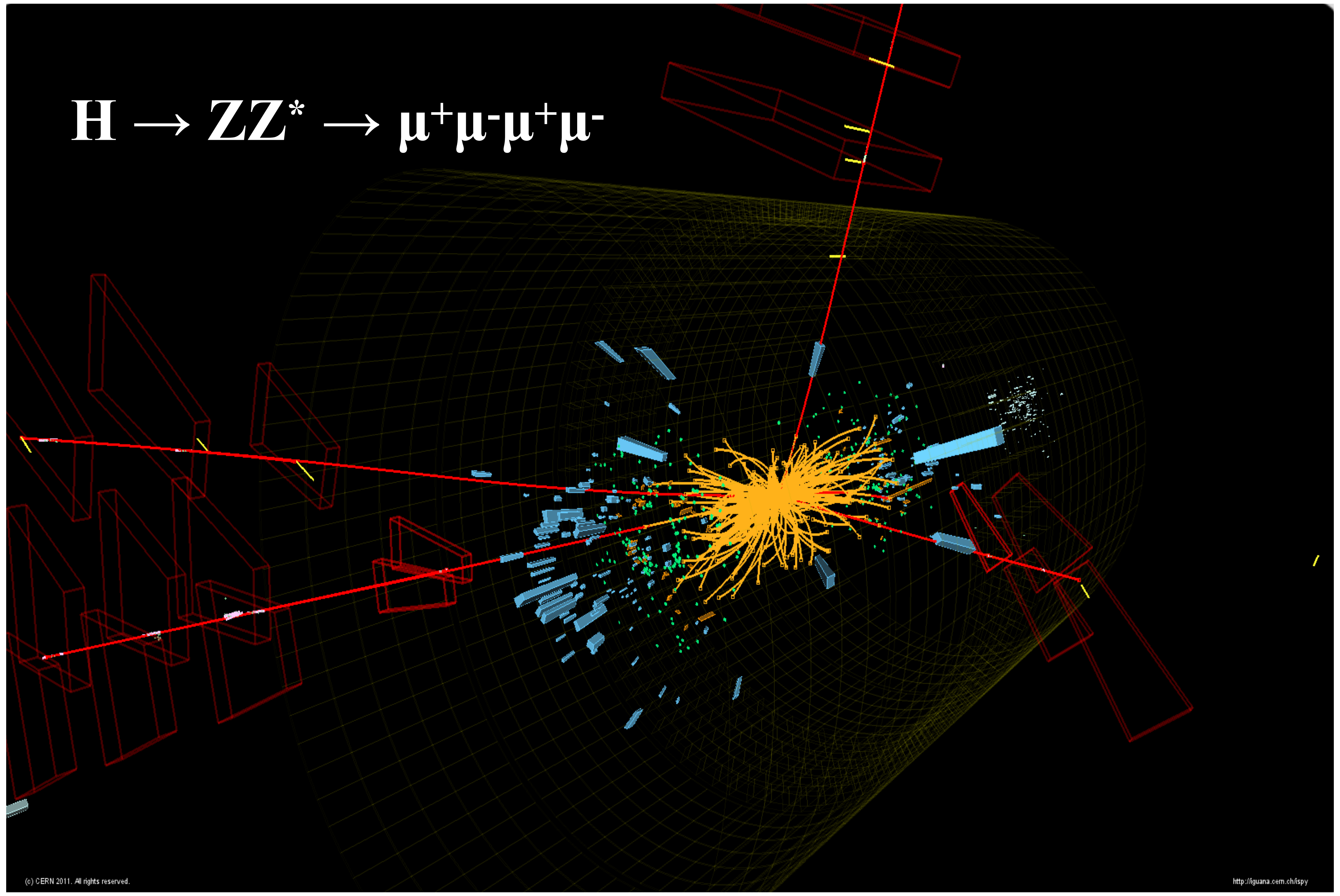


- Suppress background as much as possible:
    - e.g. 1 SFOS-> 3rd lepton from WZ background comes from W decay, therefore has a falling Mt spectrum-> 40% background rejection without signal loss

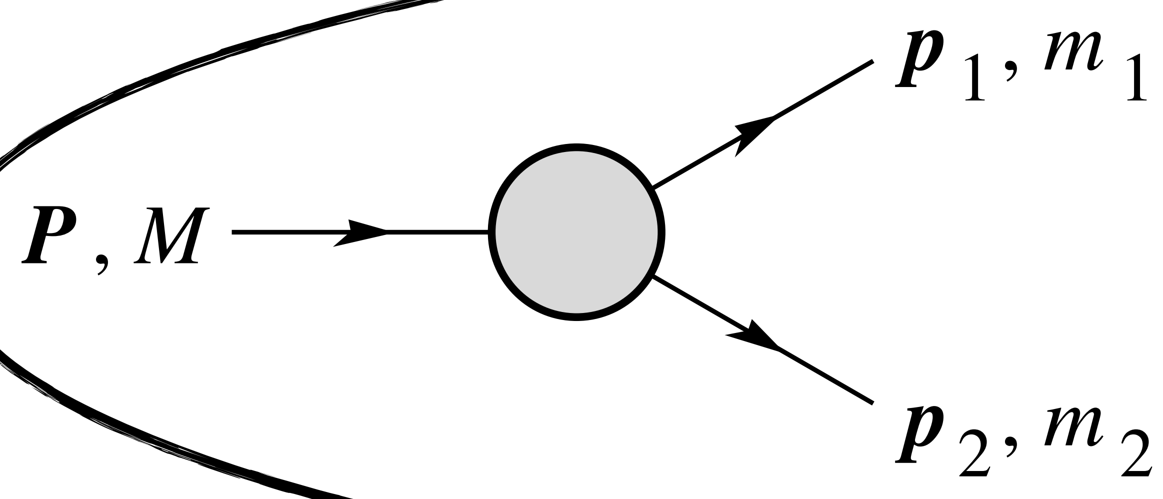
The Higgs boson detection in CMS

Higgs boson decays



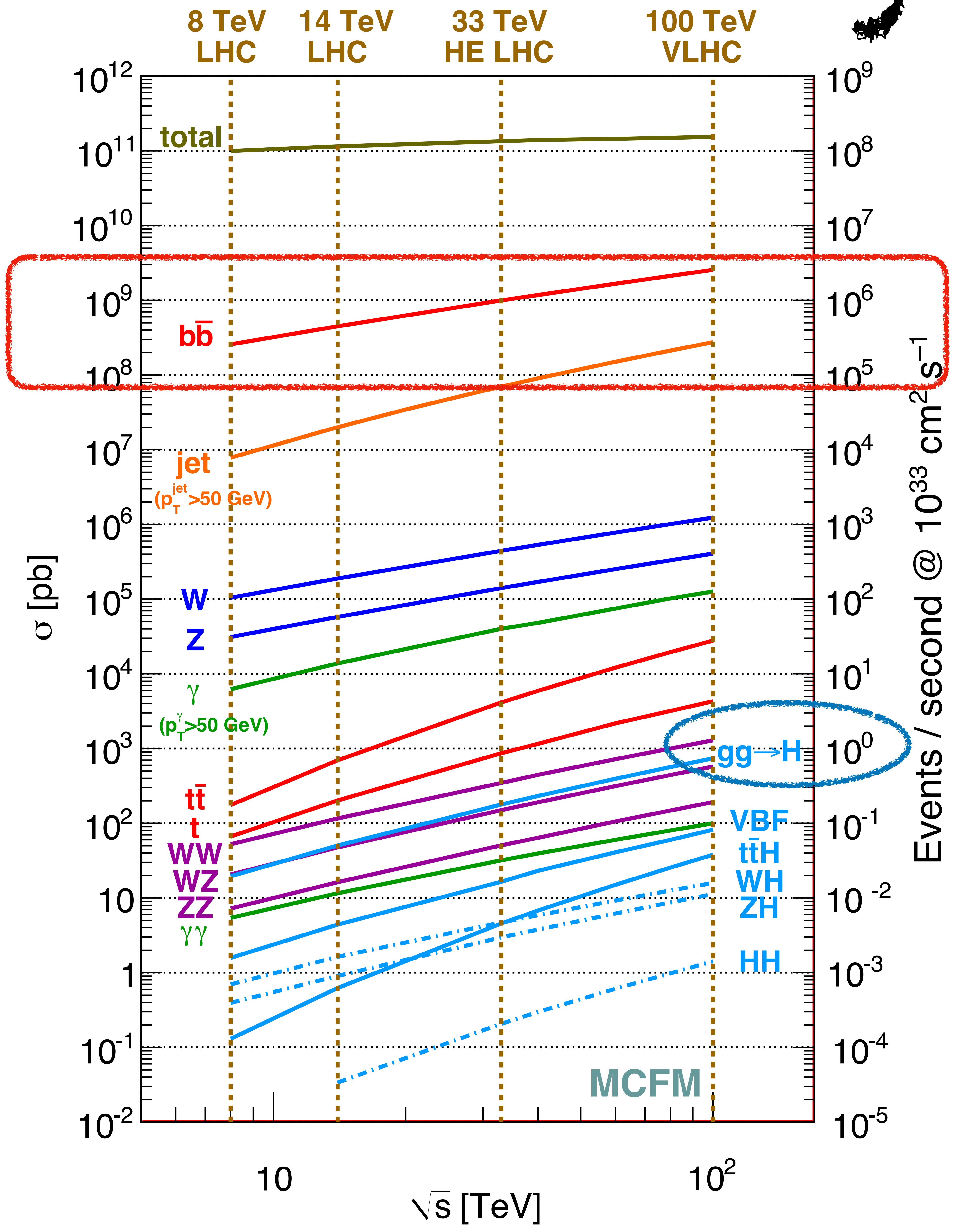


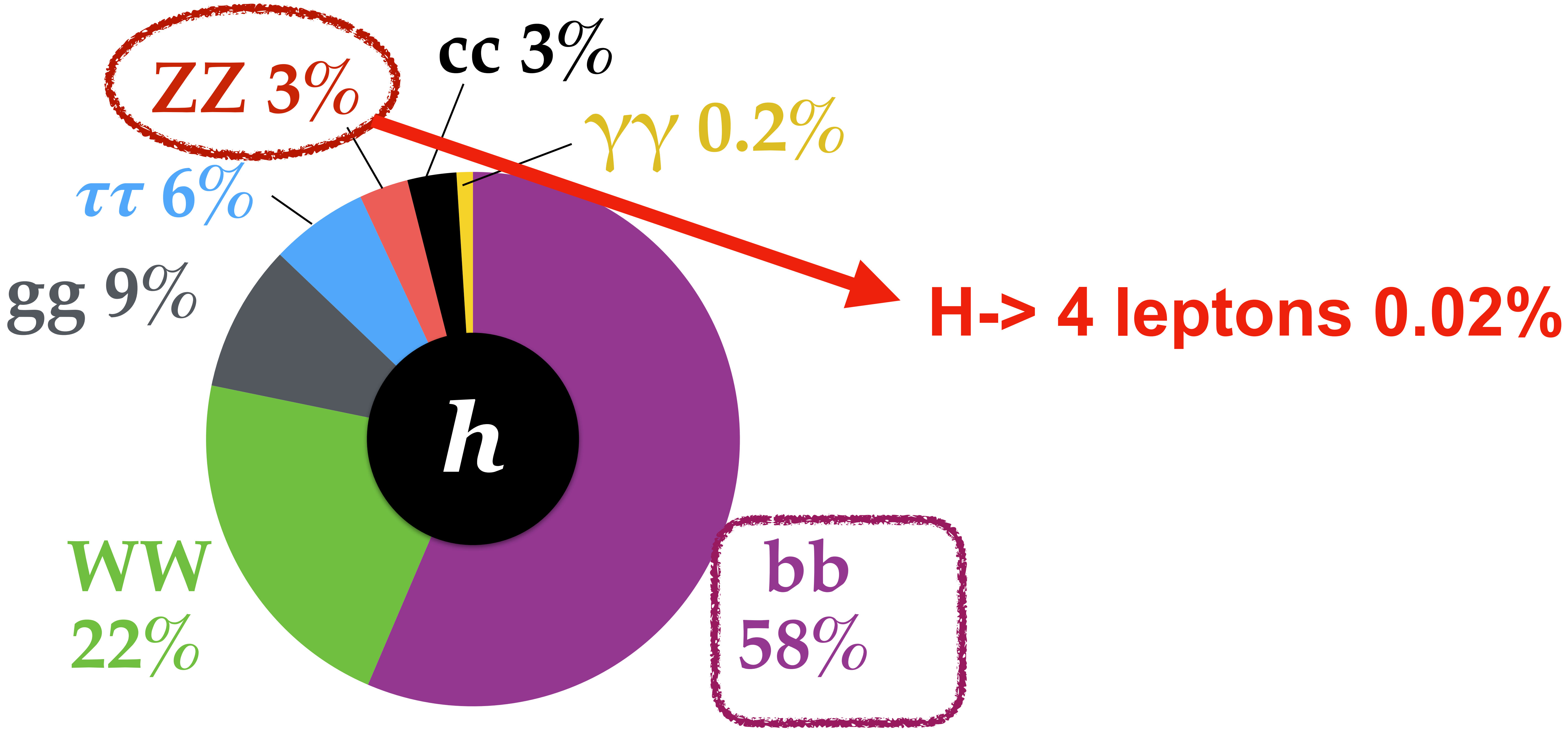
Construct invariant mass from decay products



$$E_{\mathrm{cm}} = \left[(E_1 + E_2)^2 - (\boldsymbol{p}_1 + \boldsymbol{p}_2)^2\right]^{1/2}$$

Why is it so hard





- key ingredients: Signal rate and background handling
- Observed the Higgs boson with decay modes of lower backgrounds (WW/ZZ/γγ).

Non-prompt Lepton

- Poorly modeled in the simulation
  - Chances of jet faking a lepton is very low (~10^{-5}).
    - Difficult to simulate the non-gaussian tail of detector's response to jets
  - Difficult to model different fake lepton sources
    - Mis-identified charged hadron, heavy flavor decay, photon conversions….
- Data-driven estimates crucial in making first measurement.
  - My main focus on the analysis

ATLAS vs CMS

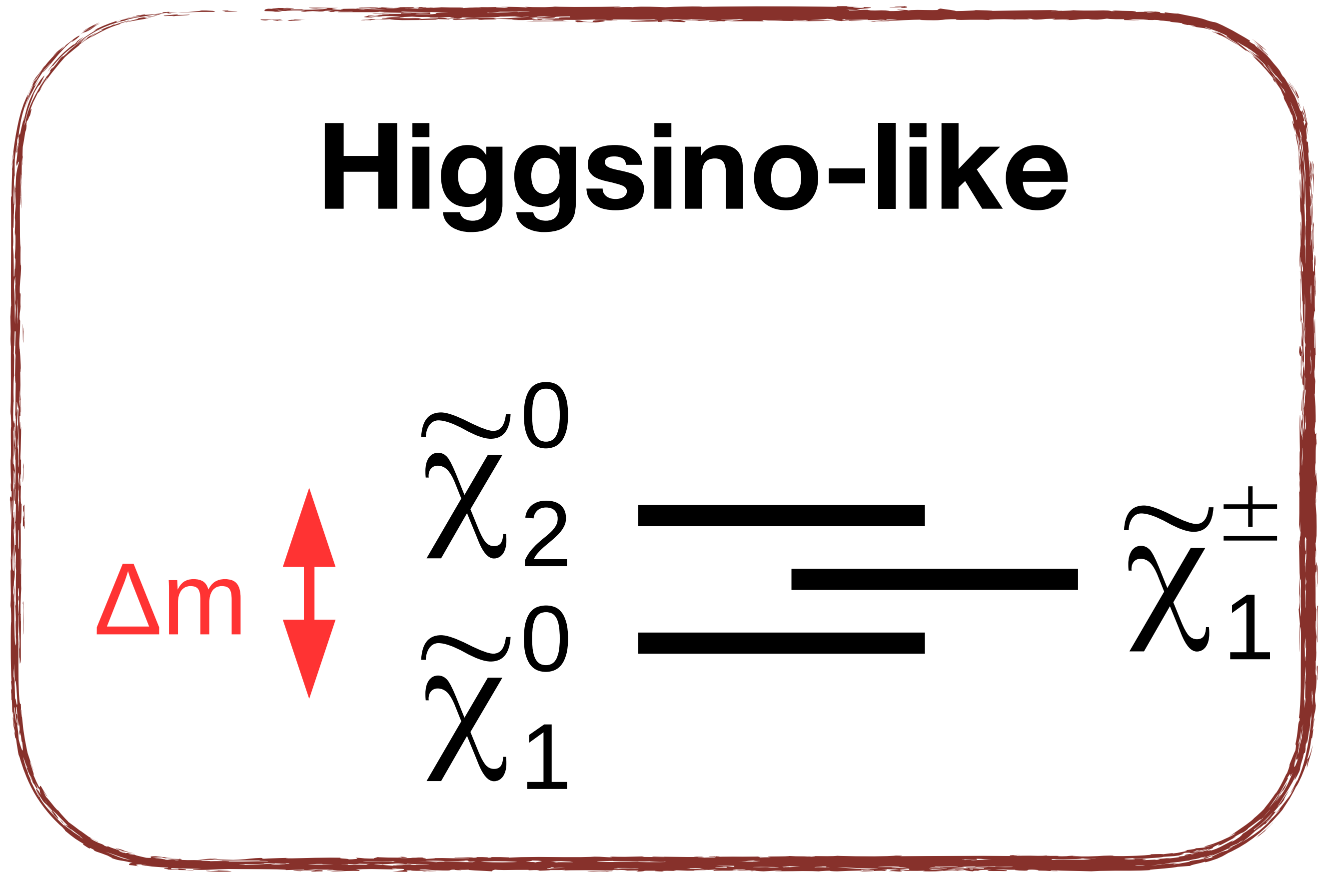
Table 2: A summary comparison of total inference time for Brainwave, CPU, and GPU performance

Type	Hardware	⟨Inference time⟩	Max throughput	Setup
CPU	Xeon 2.6 GHz, 1 core	1.75 seconds	0.6 img/s	`CMSSW`, `TF v1.06`
CPU	i7 3.6 GHz, 1 core	500 ms	2 img/s	python, `TF v1.10`
CPU	i7 3.6 GHz, 8 core	200 ms	5 img/s	python, `TF v1.10`
GPU (batch=1)	NVidia GTX 1080	100 ms	10 img/s	python, `TF v1.10`
GPU (batch=32)	NVidia GTX 1080	9 ms	111 img/s	python, `TF v1.10`
GPU (batch=1)	NVidia GTX 1080	7 ms	143 img/s	TF internal, `TF v1.10`
GPU (batch=32)	NVidia GTX 1080	1.5 ms	667 img/s	TF internal, `TF v1.10`
Brainwave	Altera Artix	10 ms	660 img/s	`CMSSW`, *on-prem*
Brainwave	Altera Artix	60 ms	660 img/s	`CMSSW`, *remote*

Example: Higgsino searches

- Higgsinos: Expected to be comparable to Higgs mass in 'Natrual SUSY': hundreds of GeV

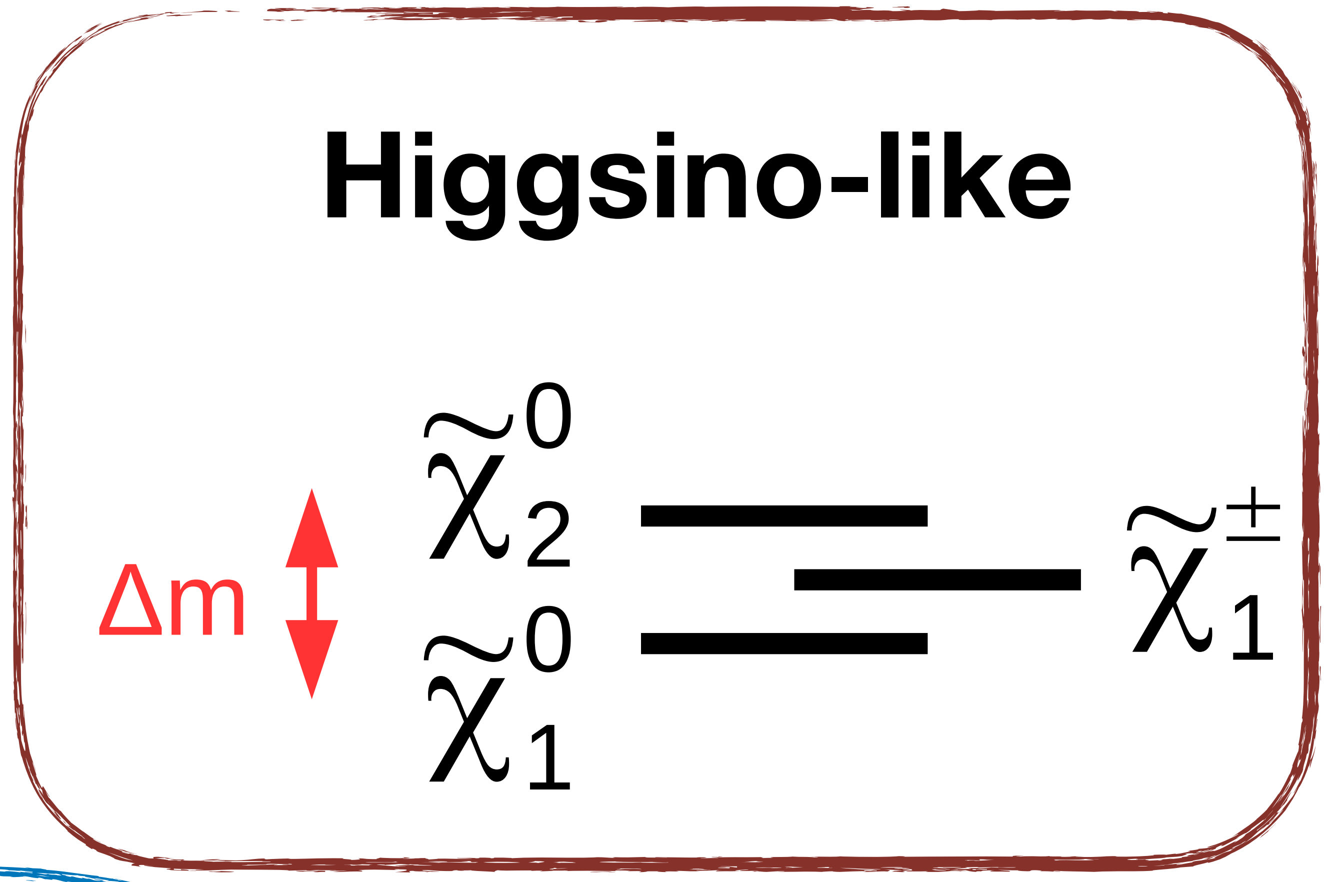
- More difficult to constrain than Wino :
  - Lower cross section.

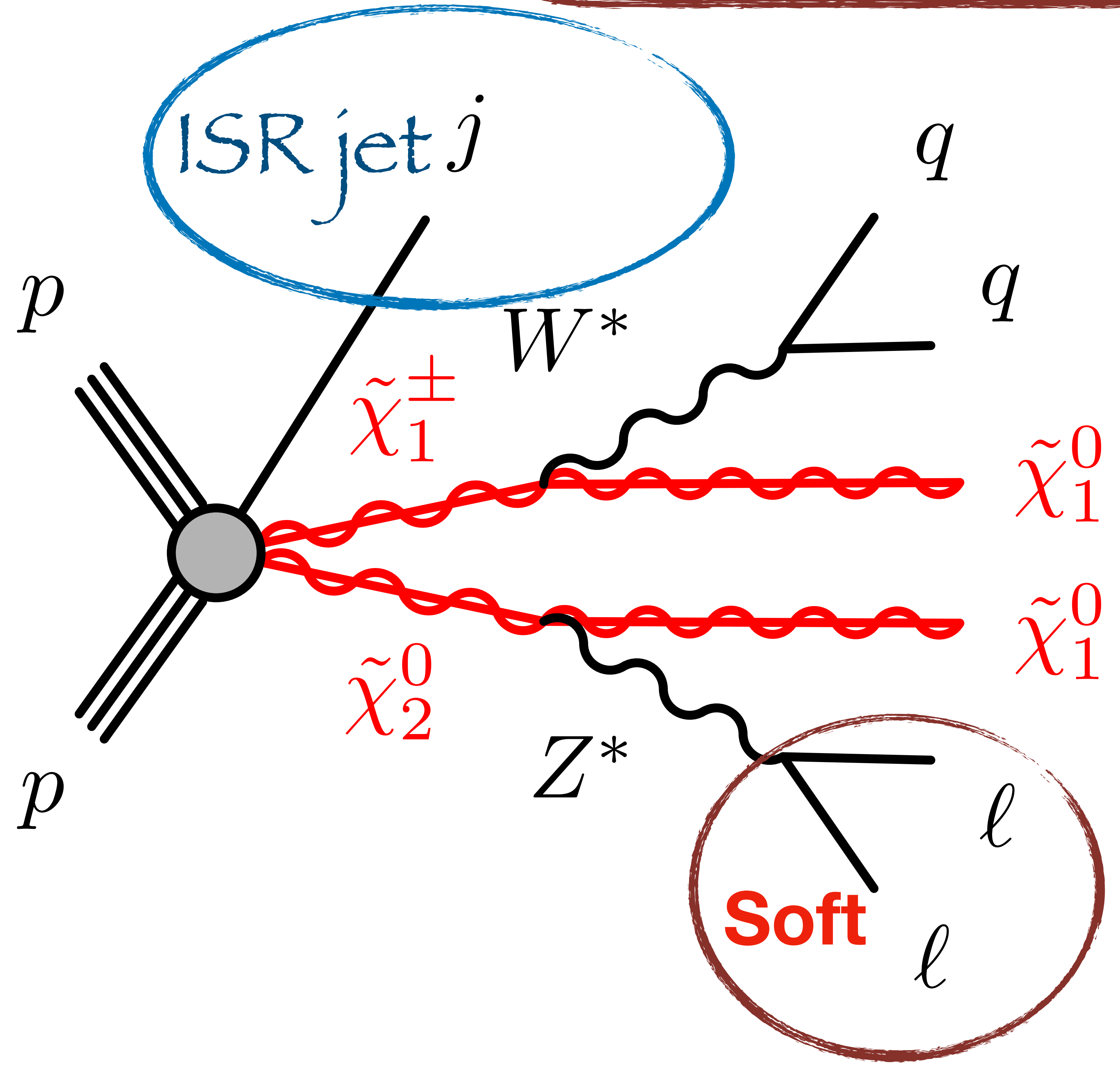


Challenging signatures in Higgsino searches

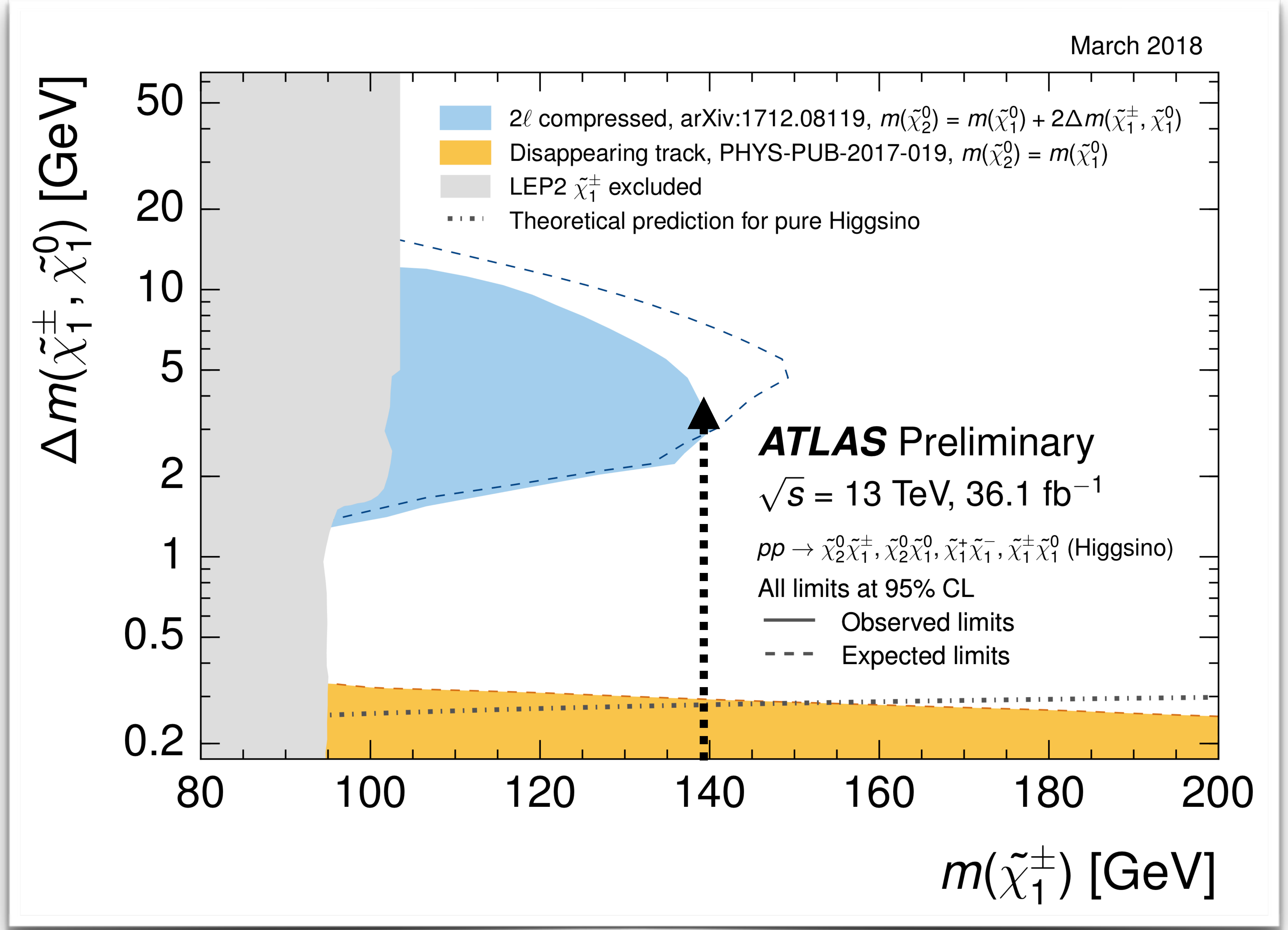
- More difficult to constrain than Wino :
  - Challenging signatures
    - Δm~ tens of GeV : Soft decay products
    - Δm~ hundreds of MeV : Long-lived signatures
  - Need special triggers/reconstruction

Δm~ hundreds of MeV to tens of GeV

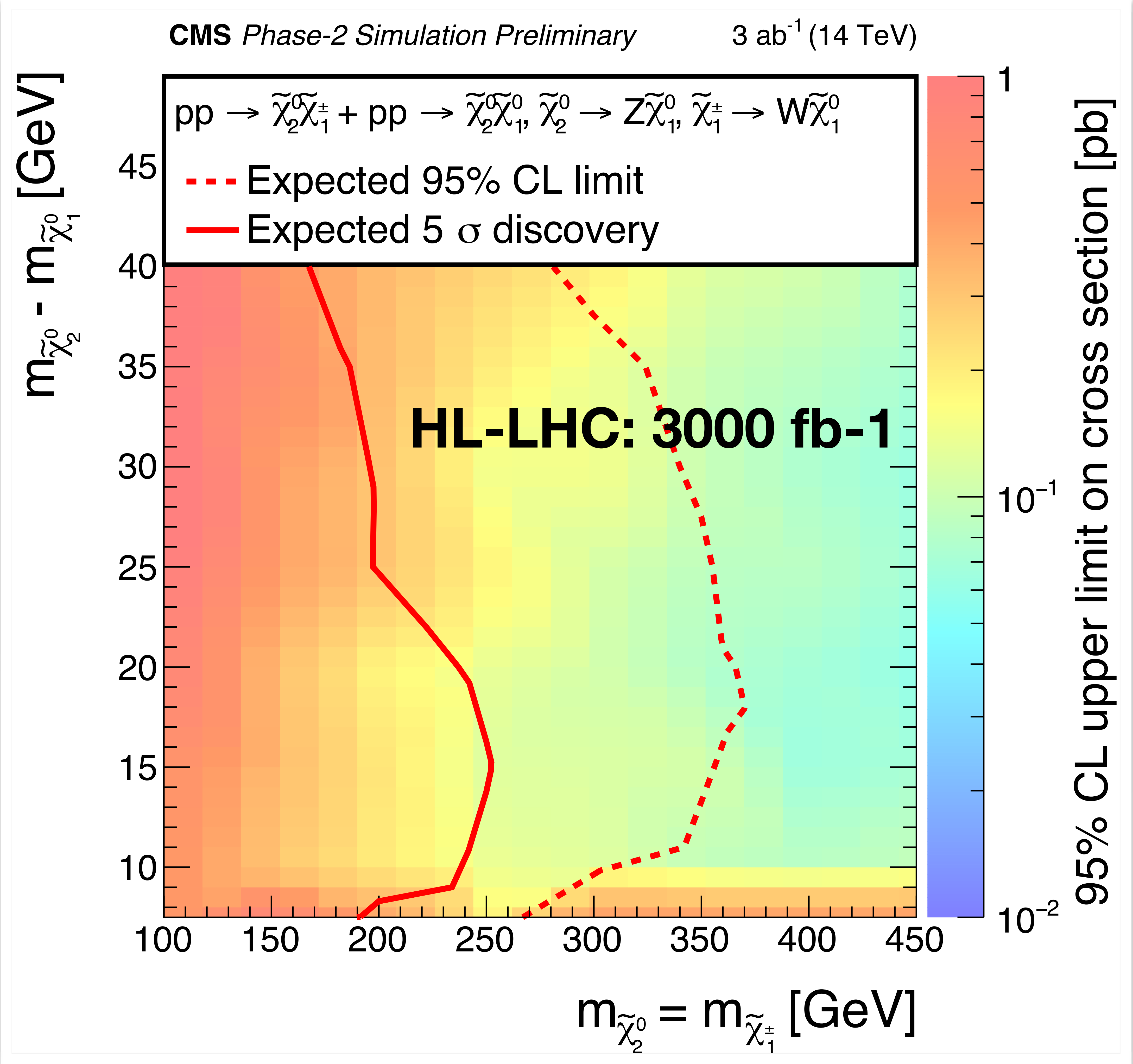




HL-LHC dataset will benefit Higgsino searches

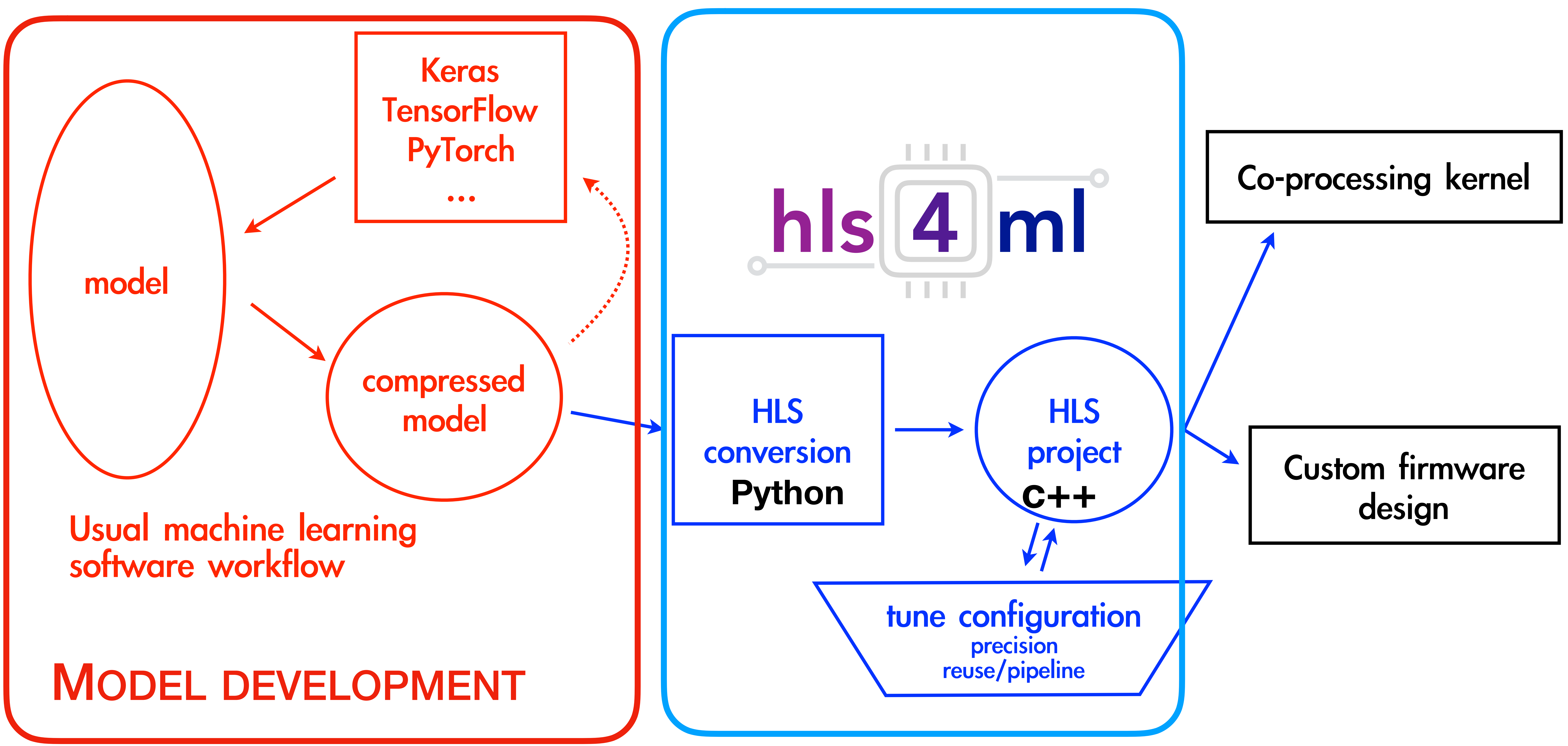


2016 data (36 fb-1)

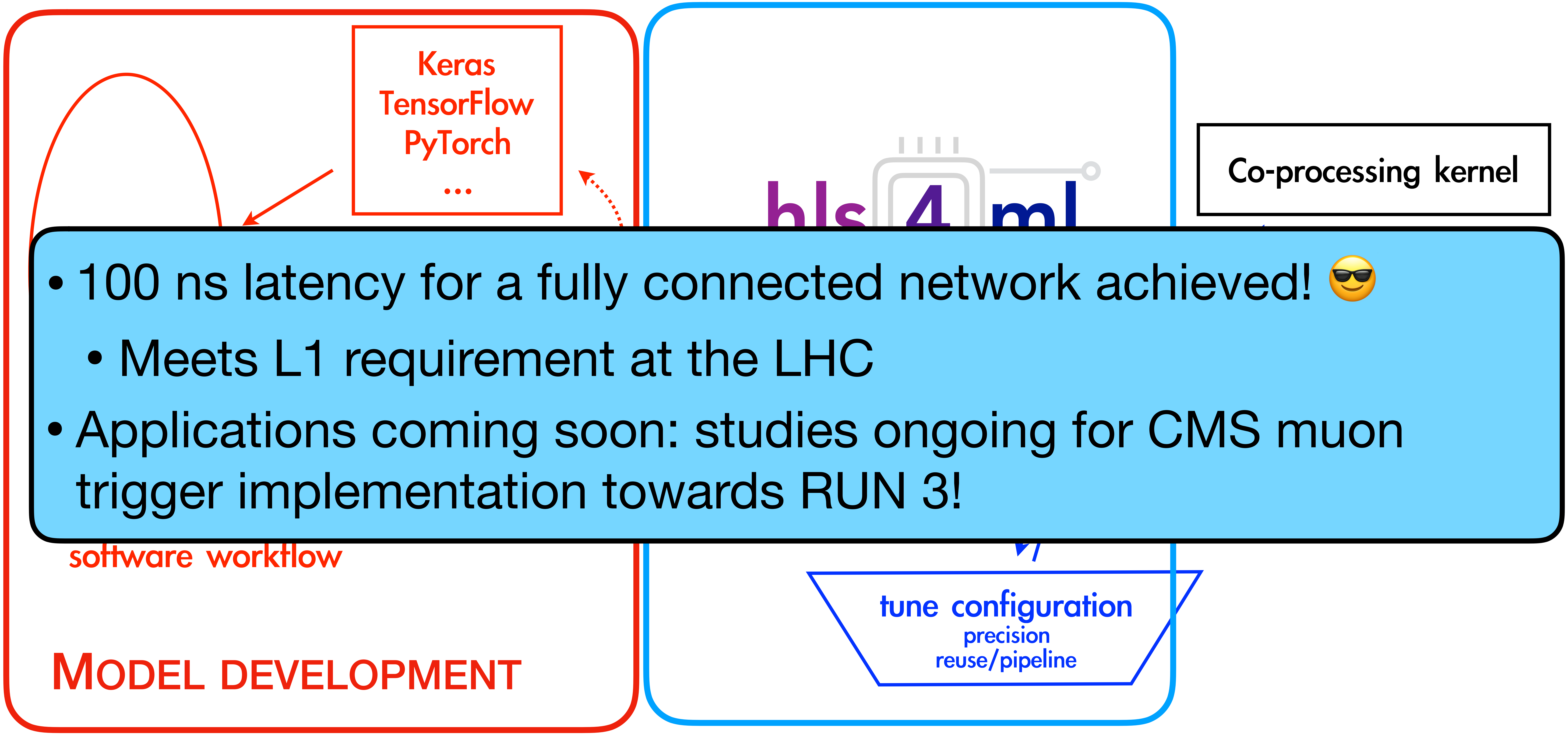


High-Level Synthesis for Machine Learning

HIGH-LEVEL SYNTHESIS FOR MACHINE LEARNING

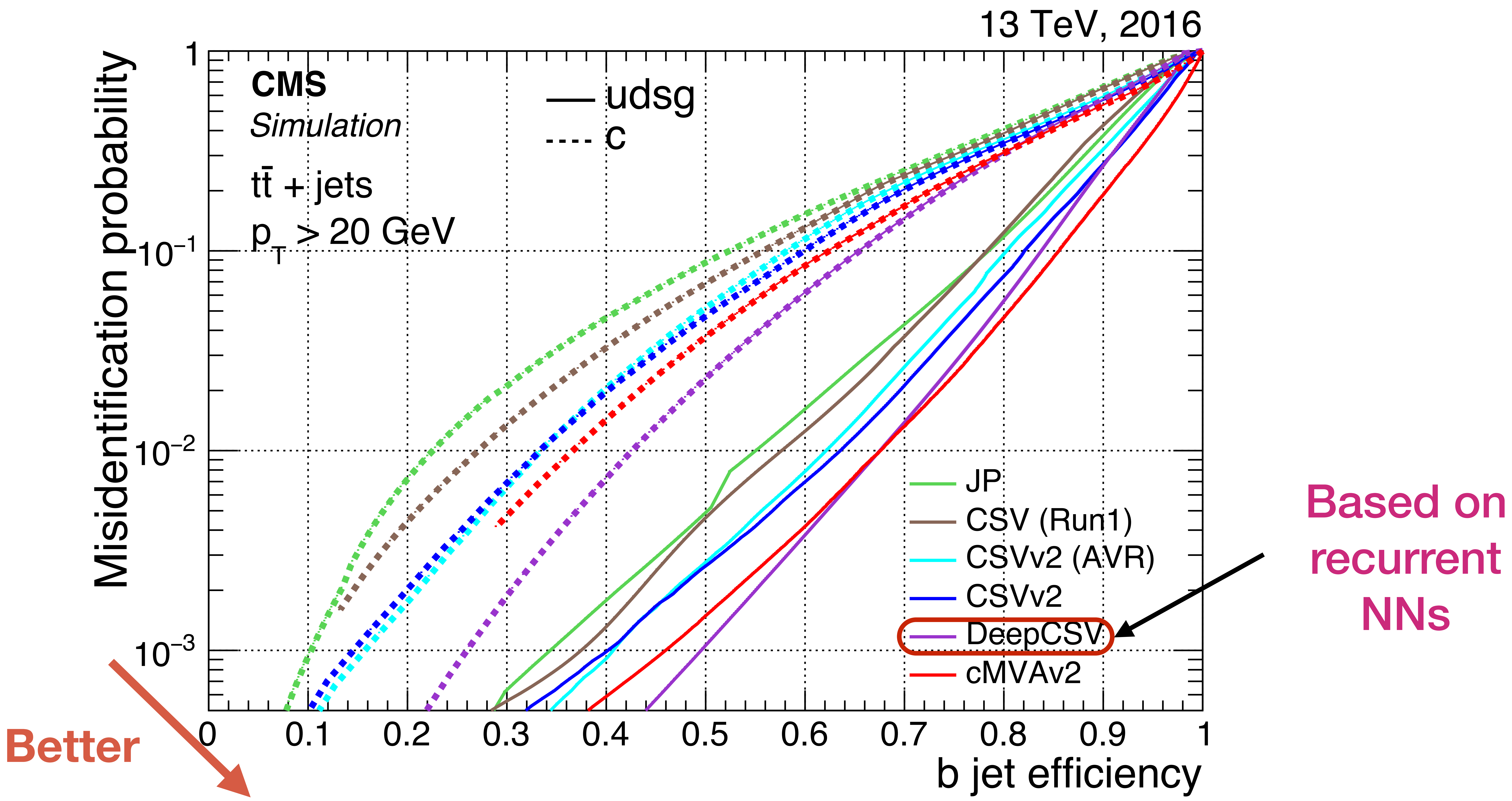


High-Level Synthesis for Machine learning

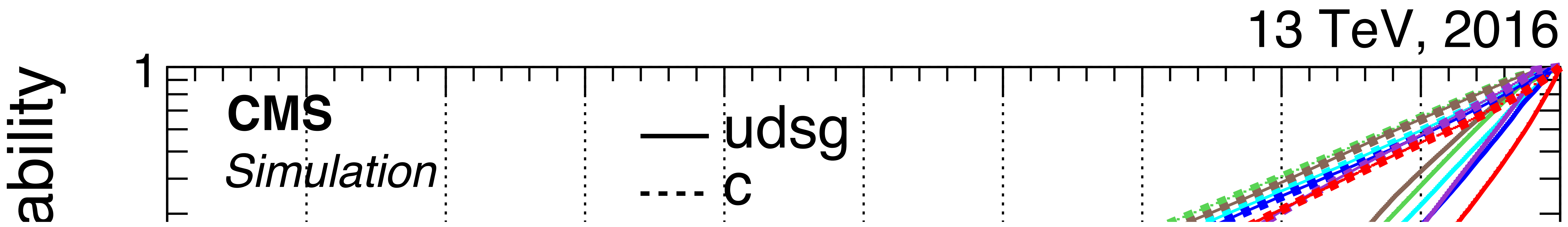


- 100 ns latency for a fully connected network achieved! 😎
  - Meets L1 requirement at the LHC
- Applications coming soon: studies ongoing for CMS muon trigger implementation towards RUN 3!

BOOM IN USING NEURAL NETWORKS BASED ALGORITHMS

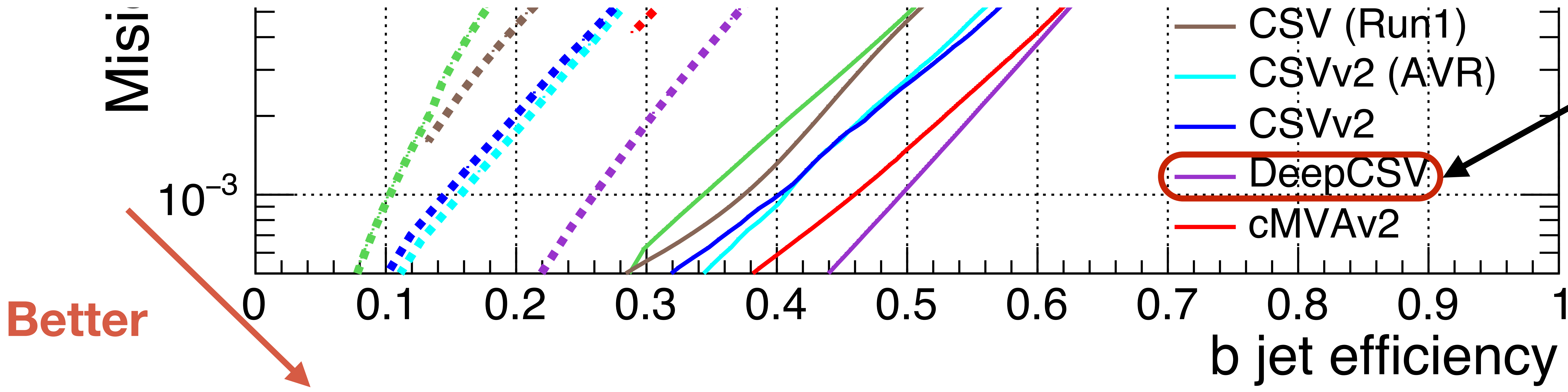


BOOM IN USING NEURAL NETWORKS BASED ALGORITHMS



Various applications actively explored in particle identification, regression, fast-simulation, anomaly detection…

Can we use neural networks in our triggers?

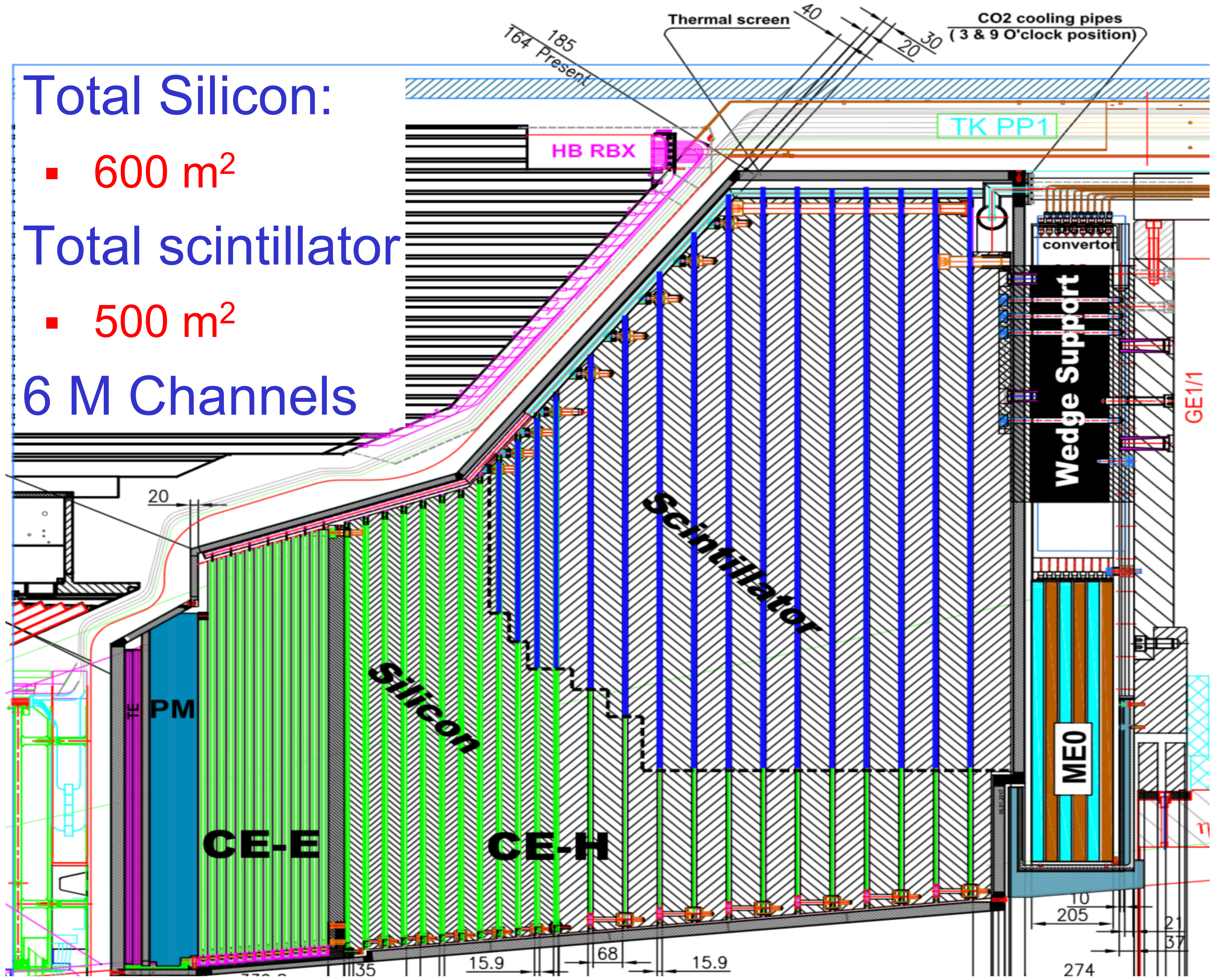


Based on recurrent NNs

AS A RESULT : DETECTORS GETTING MORE COMPLEX

In addition to designing & building the upgraded detectors….

Challenge:
How do we trigger and process the 10 times more data collected by such a complex machine?

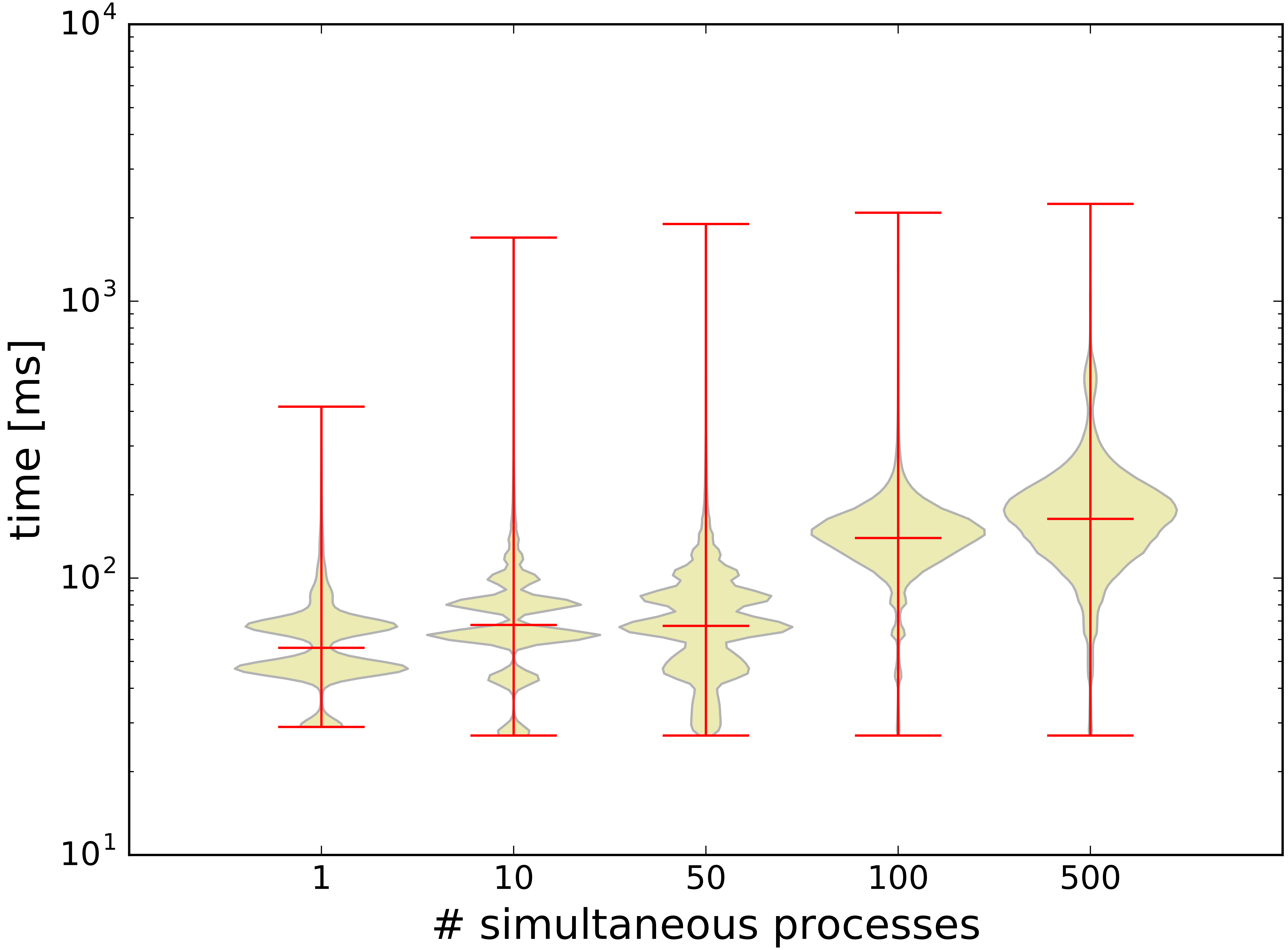


CMS **H**igh **G**ranularity **C**alorimeter

Number of channel increase:

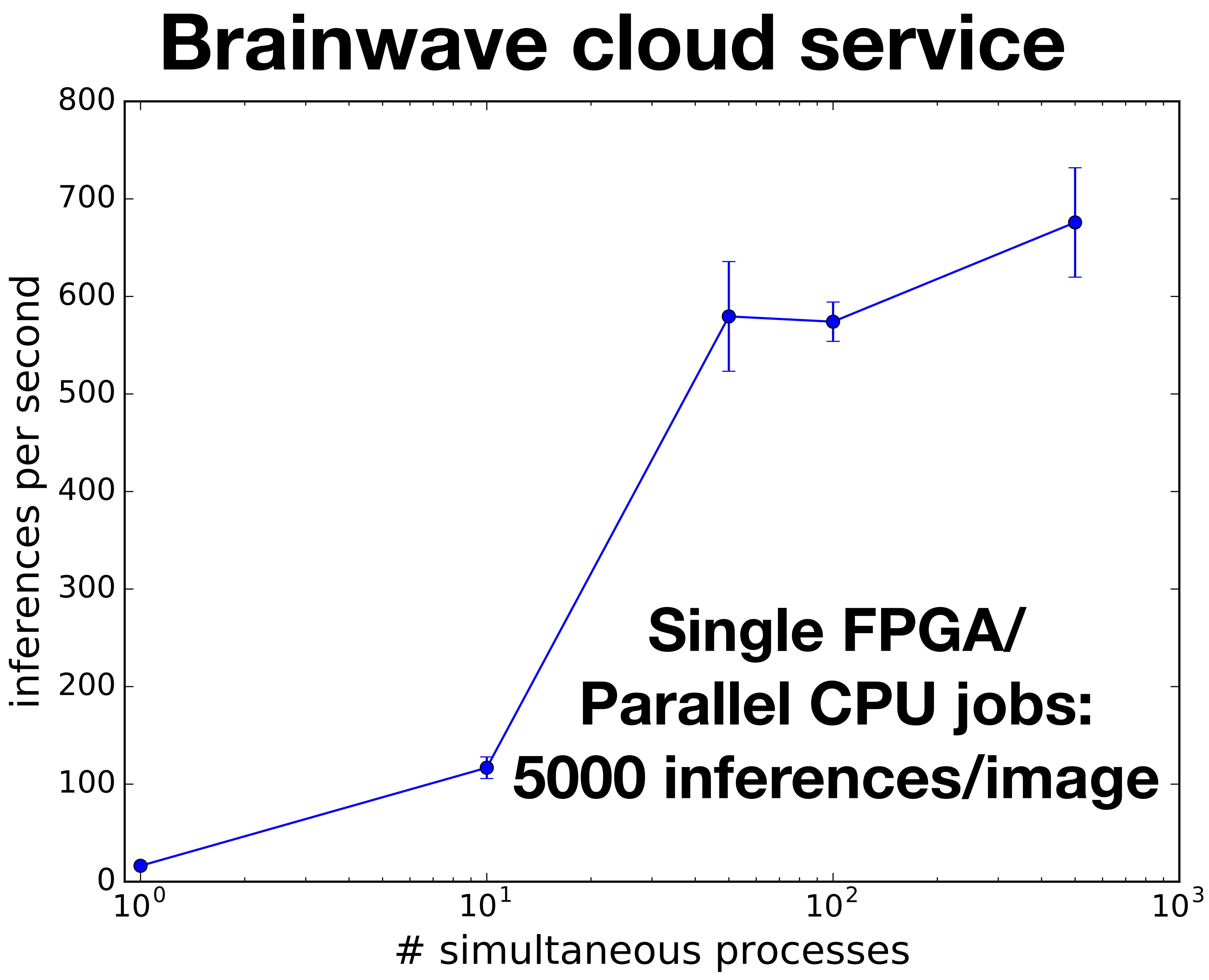
O(100k) —> 6 M

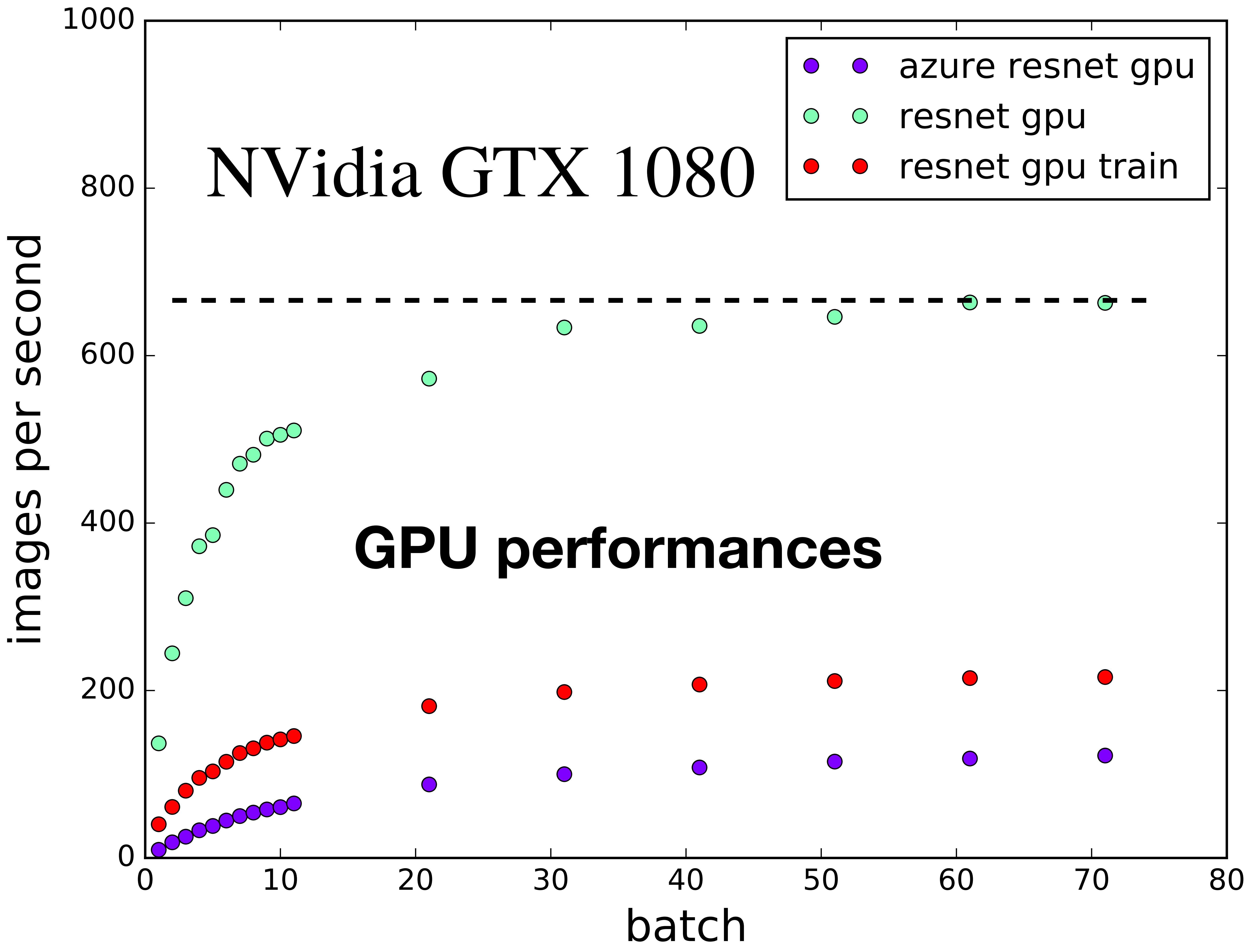
SONIC: STRESS TEST



- **Stress test: single service(one FPGA), multiple CPU requests**
- **Each request has 5000 inferences**

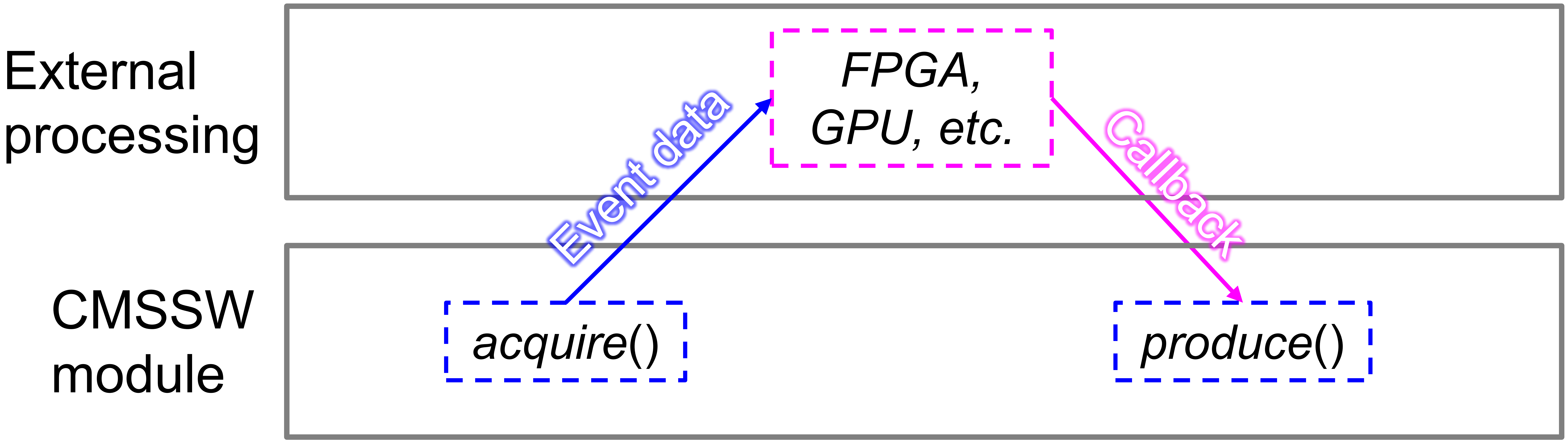
SONIC: DATA THROUGHOUT COMPARED TO GPUs





Comparable max data throughout: 600-700 images/sec

SONIC: IMPLEMENTATION IN CMSSW

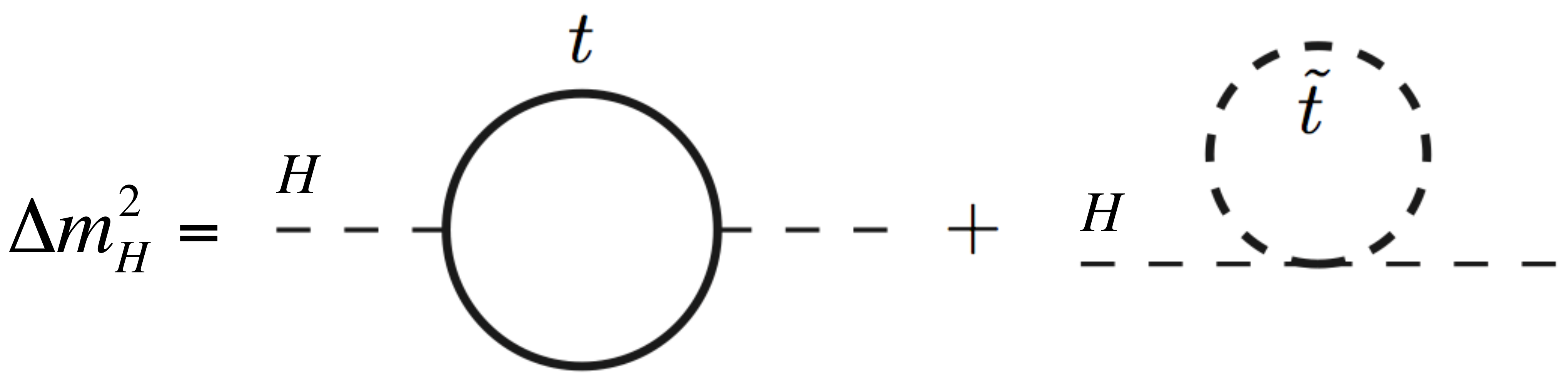


Deploy MS Brainwave as a service:

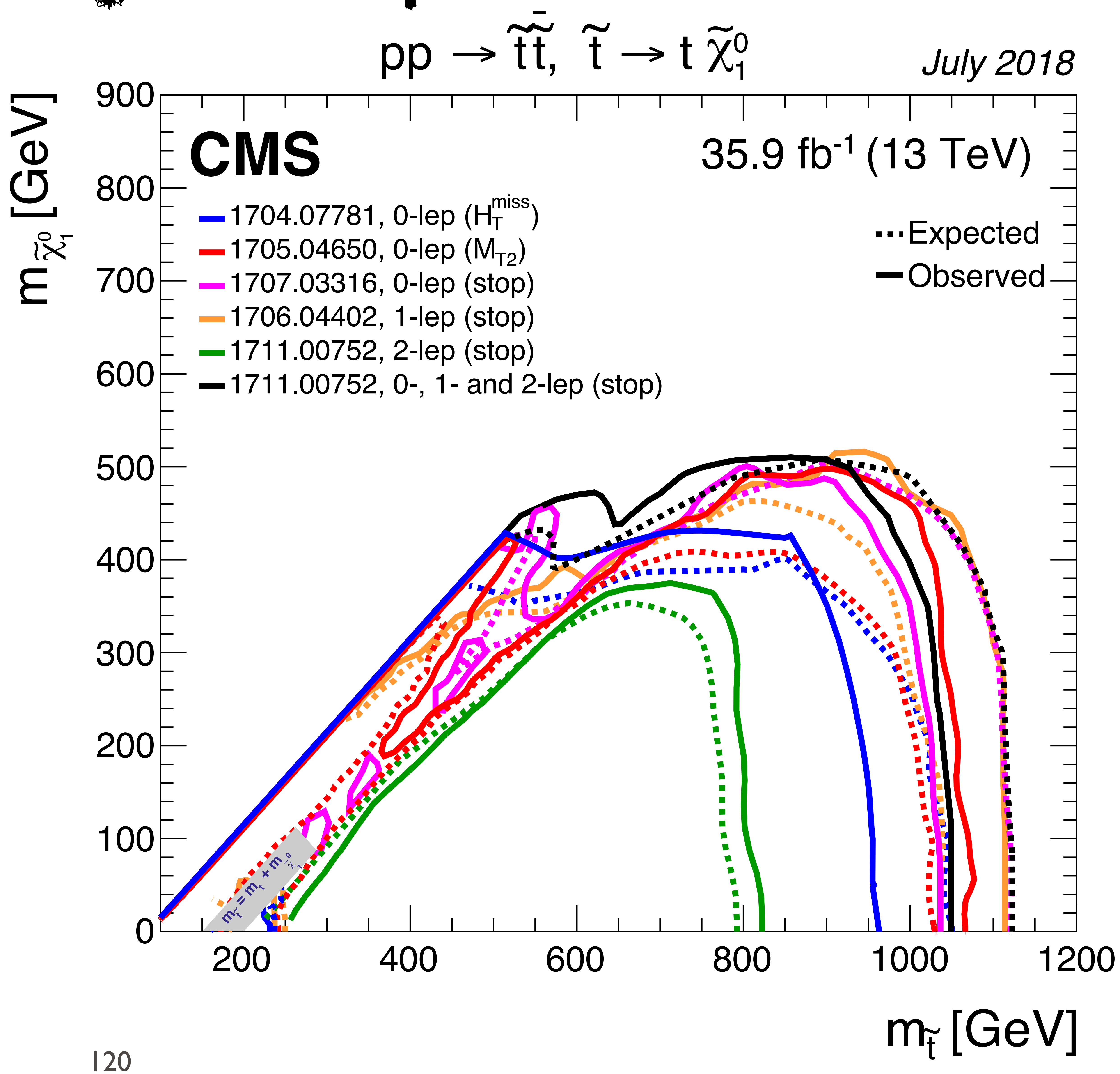
- Implemented with CMSSW ExternalWork module
- Fits CMS computing model in a non-disruptive way

Supersymmetry: stop search

- Quickly probed up to 1 TeV.
  - Still room in top-corridors
  - R-parity violated models



- 1L channel: my first analysis on CMS



Same sign selection

Table 1: Event selection criteria for the *SS category*, which contains events with two same-sign leptons and at least two hadronic jets

Variable	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Signal leptons	exactly 2 tight equally-charged leptons with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$		
Additional leptons	no additional rejection lepton		
Isolated tracks	no (additional) isolated tracks		
Jets	$\geq$ 2jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.5$		
b-tagged jets	no b-tagged jet		
Dijet mass (closest ΔR)	$65 < M_{\mathrm{jj}} < 95\,\mathrm{GeV}$ (M_{jj}-in) **OR** $\lvert M_{\mathrm{jj}} - 80\,\mathrm{GeV}\rvert \geq 15\,\mathrm{GeV}$ (M_{jj}-out)		
Dijet mass (leading jets)	$< 400\,\mathrm{GeV}$		
$\Delta\eta$ of two leading jets	< 1.5		
$p_{\mathrm{T}}^{\mathrm{miss}}$	$> 60\,\mathrm{GeV}$		$> 60\,\mathrm{GeV}$ if M_{jj}-out
$M_{\ell\ell}$	$> 40\,\mathrm{GeV}$	$> 30\,\mathrm{GeV}$	$> 40\,\mathrm{GeV}$
$M_{\ell\ell}$	$\lvert M_{\ell\ell} - M_{\mathrm{Z}}\rvert > 10\,\mathrm{GeV}$	—	
$M_{\mathrm{T}}^{\mathrm{max}}$	—	$> 90\,\mathrm{GeV}$	—

Three leptons

Table 2: Event selection criteria for the 3ℓ *category*, which contains events with exactly three leptons

Variable	0 SFOS	1 SFOS	2 SFOS
Signal leptons	exactly 3 tight charged leptons with $p_{\mathrm{T}} > 25/20/20\,\mathrm{GeV}$ and charge sum = ± 1e		
Additional leptons	no additional rejection lepton		
Jets	$\leq$ 1jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 5$		
b-tagged jets	no b-tagged jet		
$p_{\mathrm{T}}(\ell\ell\ell)$	—	$> 60\,\mathrm{GeV}$	
$\Delta\phi\left(\vec{p}_{\mathrm{T}}(\ell\ell\ell), \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right)$	> 2.5		
$p_{\mathrm{T}}^{\mathrm{miss}}$	$> 30\,\mathrm{GeV}$	$> 45\,\mathrm{GeV}$	$> 55\,\mathrm{GeV}$
$M_{\mathrm{T}}^{\mathrm{max}}$	$> 90\,\mathrm{GeV}$	—	
$M_{\mathrm{T}}^{\mathrm{3rd}}$	—	$> 90\,\mathrm{GeV}$	—
SF lepton mass	$> 20\,\mathrm{GeV}$	—	
Di-electron mass	$\lvert M_{\mathrm{ee}} - M_{\mathrm{Z}}\rvert > 15\,\mathrm{GeV}$	—	
M_{SFOS}	—	$\lvert M_{\mathrm{SFOS}} - M_{\mathrm{Z}}\rvert > 20\,\mathrm{GeV}$ and $M_{\mathrm{SFOS}} > 20\,\mathrm{GeV}$	
$M_{\ell\ell\ell}$	$\lvert M_{\ell\ell\ell} - M_{\mathrm{Z}}\rvert > 10\,\mathrm{GeV}$		

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Rare processes directly benefit from the large LHC Run-2 dataset