New Physics at the Energy Frontier

Sadia Khalil
University of Kansas

On behalf of ATLAS and CMS Collaborations

DPF2017, Fermilab, USA
Jul 31, 2017

Photo by Marty Murphy

A brief History of Achievements

1960

Parton observation in DIS and quark model -1969

1970

J/ψ discovery -1974

τ discovery -1976

B-quark discovery -1977

1980

W and Z discovery - 1983

1990

Top quark discovery - 1995

2000 ν_τ discovery - 2000

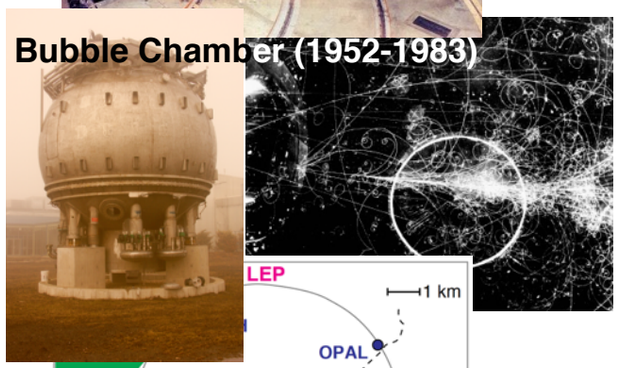
2010

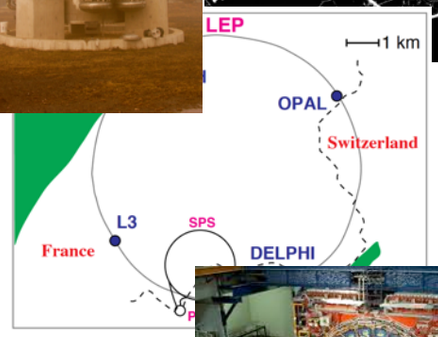
Higgs boson discovery - 2012

2017

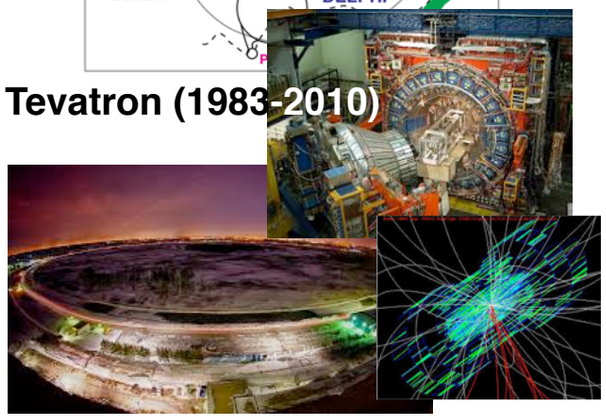
SLAC Spectrometer (1969)

Bubble Chamber (1952-1983)

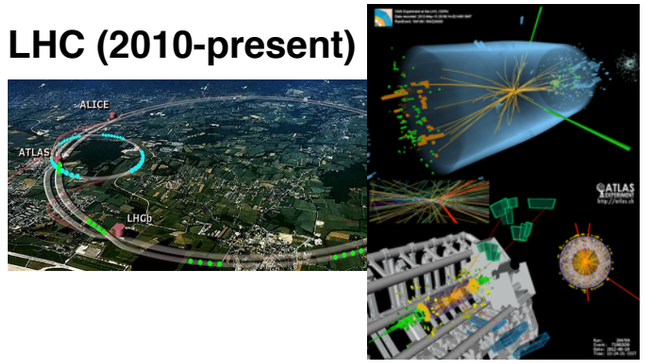




Tevatron (1983-2010)



LHC (2010-present)



A brief History of Achievements

1960

Parton observation in DIS and quark model -1969

1970

J/ψ discovery -1974

τ discovery -1976

B-quark discovery -1977

1980

W and Z discovery - 1983

1990

Top quark discovery - 1995

2000 ν_τ discovery - 2000

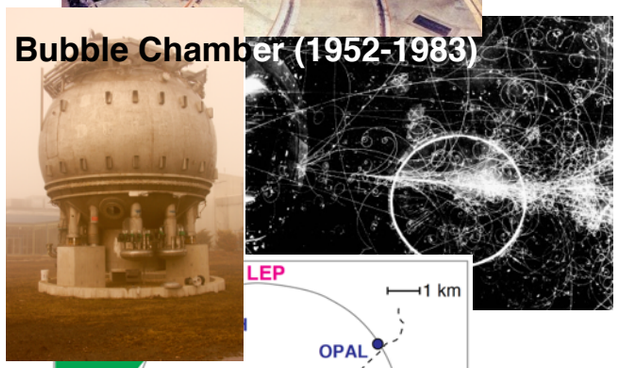
2010

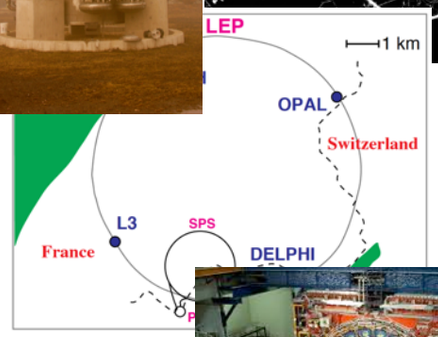
Higgs boson discovery - 2012

2017

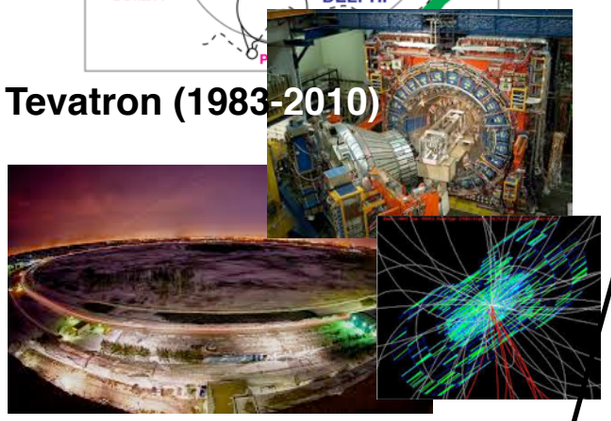
SLAC Spectrometer (1969)

Bubble Chamber (1952-1983)

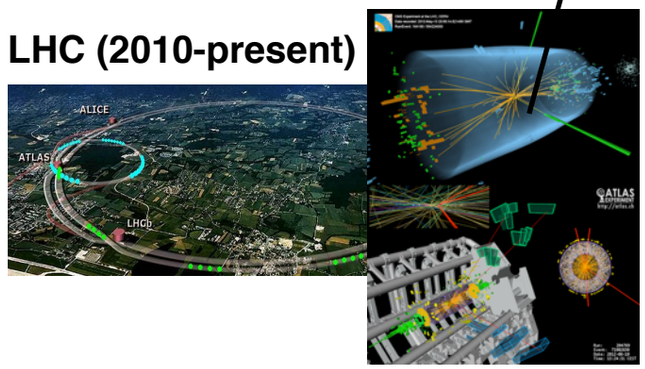




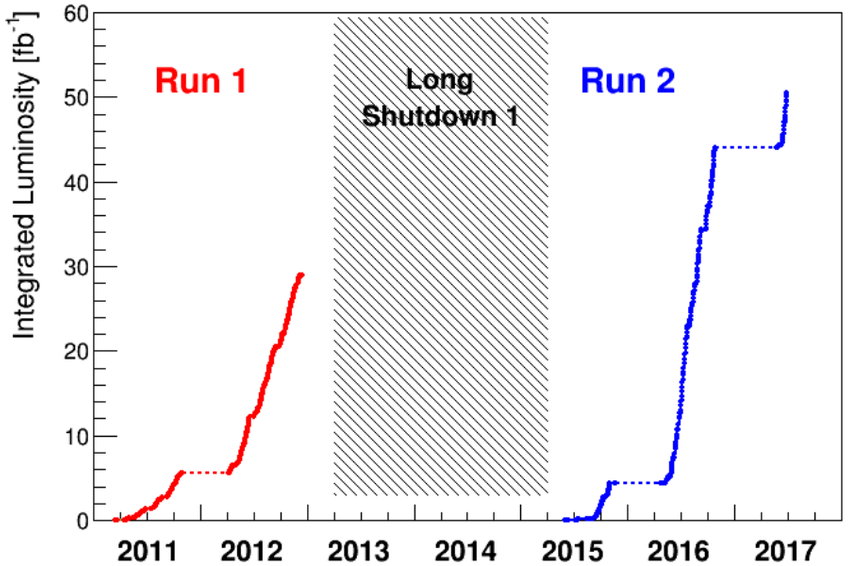
Tevatron (1983-2010)



LHC (2010-present)



- LHC and its injectors



- Higgs discovery and its properties
- Precision measurement of SM particles
- Measurements of rare B and D decays
- Precision measurement of CKM parameters
- Discovery of exotic Pentaquark, Tetraquark,

$$\Omega_c^0 \rightarrow \Xi_c^+ + K^-$$

(See Steven Blusk plenary talk on Wed, 2/8)

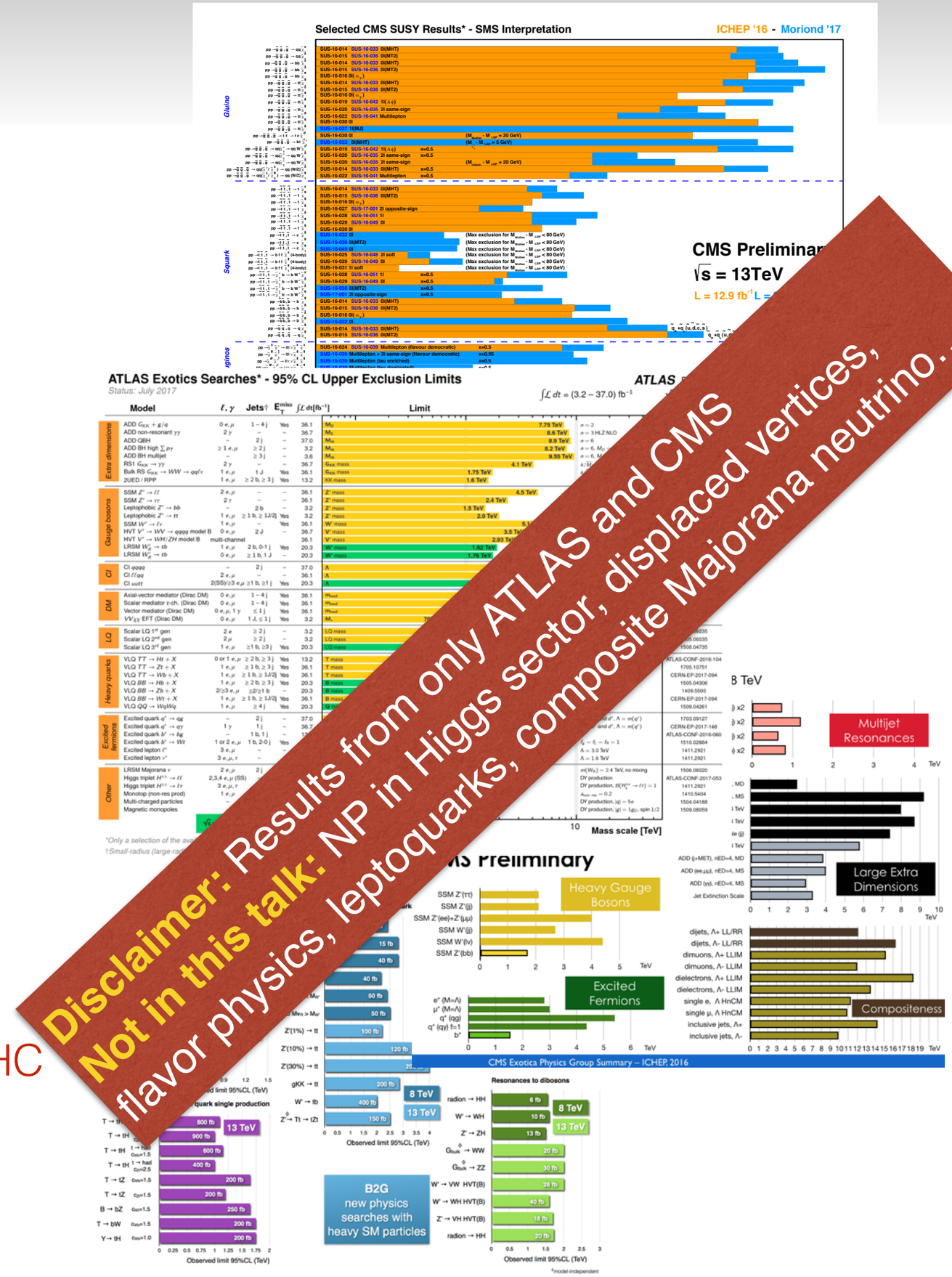
- Understanding of charm hadronization and nuclear effects in Pb-Pb/Pb-p collisions

- Are there any new symmetries beyond standard model that can also address mass hierarchy?
  - Supersymmetry
    - many variants and kind (MSSM, NMSSM, R-parity conserving, R-parity violating) of models
  - Global symmetry such as compositeness, extra dimension
    - Are there any additional new particles such as vector-like quarks, excited quarks, leptons, Higgs and gauge bosons?
- Dark matter
  - non-SUSY DM models, lepto-quarks, dark/hidden sectors
- Baryogenesis, leptogenesis
- Strong Charge Parity
- …

Today I am going to give highlights of some of these questions at the Energy Frontier

Outline

- What is required to discover new physics?
  - understanding SM backgrounds
  - tools and techniques
  - common procedures
- New Physics status
  - Supersymmetry
    - Strong and EWK processes
  - New heavy particles
    - VLQ, excited quarks, heavy bosons
  - Dark matter
- Prospectives of discovering NP at the HL-LHC



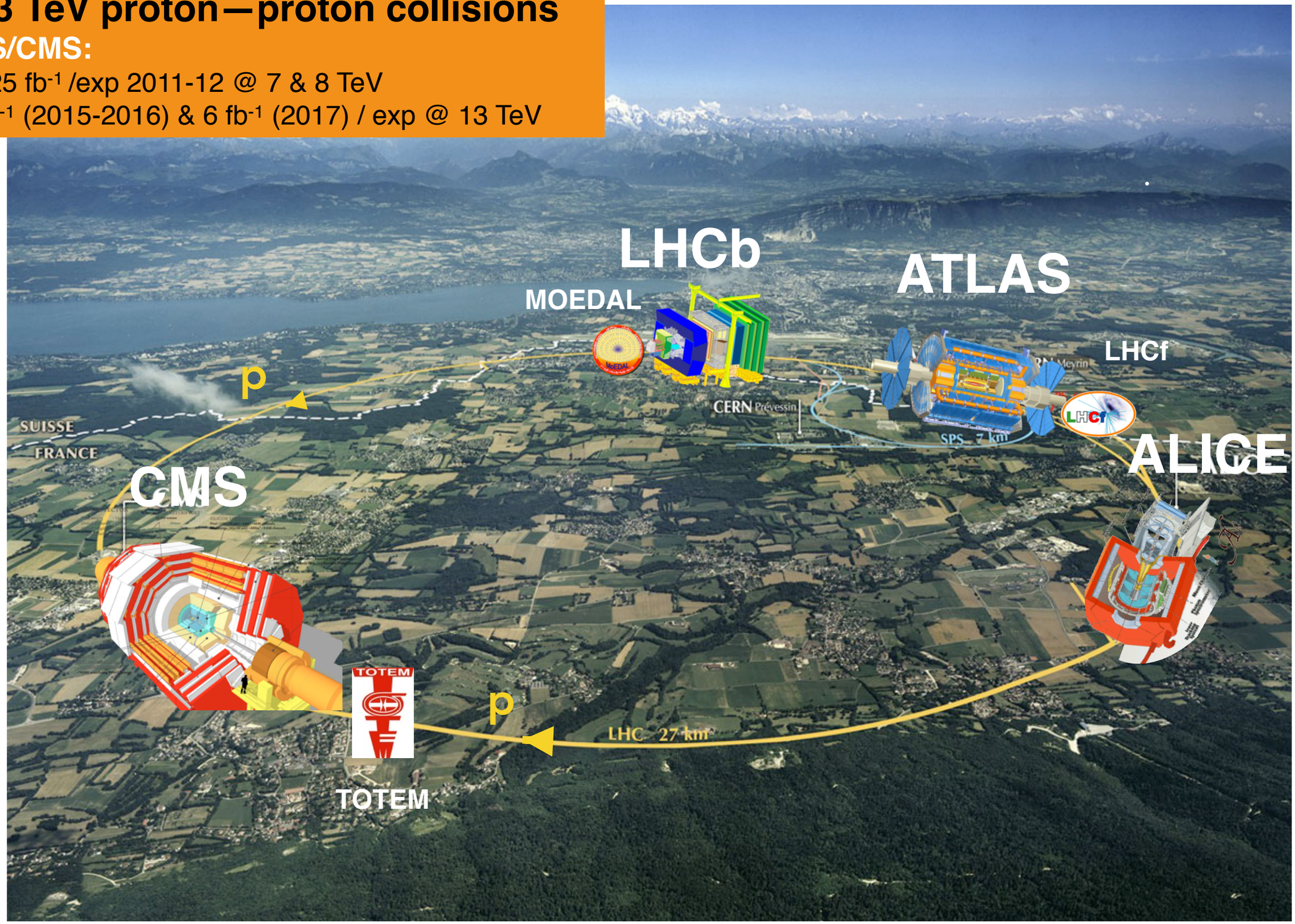
Disclaimer: Results from only ATLAS and CMS
Not in this talk: NP in Higgs sector, displaced vertices, flavor physics, leptoquarks, composite Majorana neutrino...

Large Hadron Collider

7/8/13 TeV proton—proton collisions

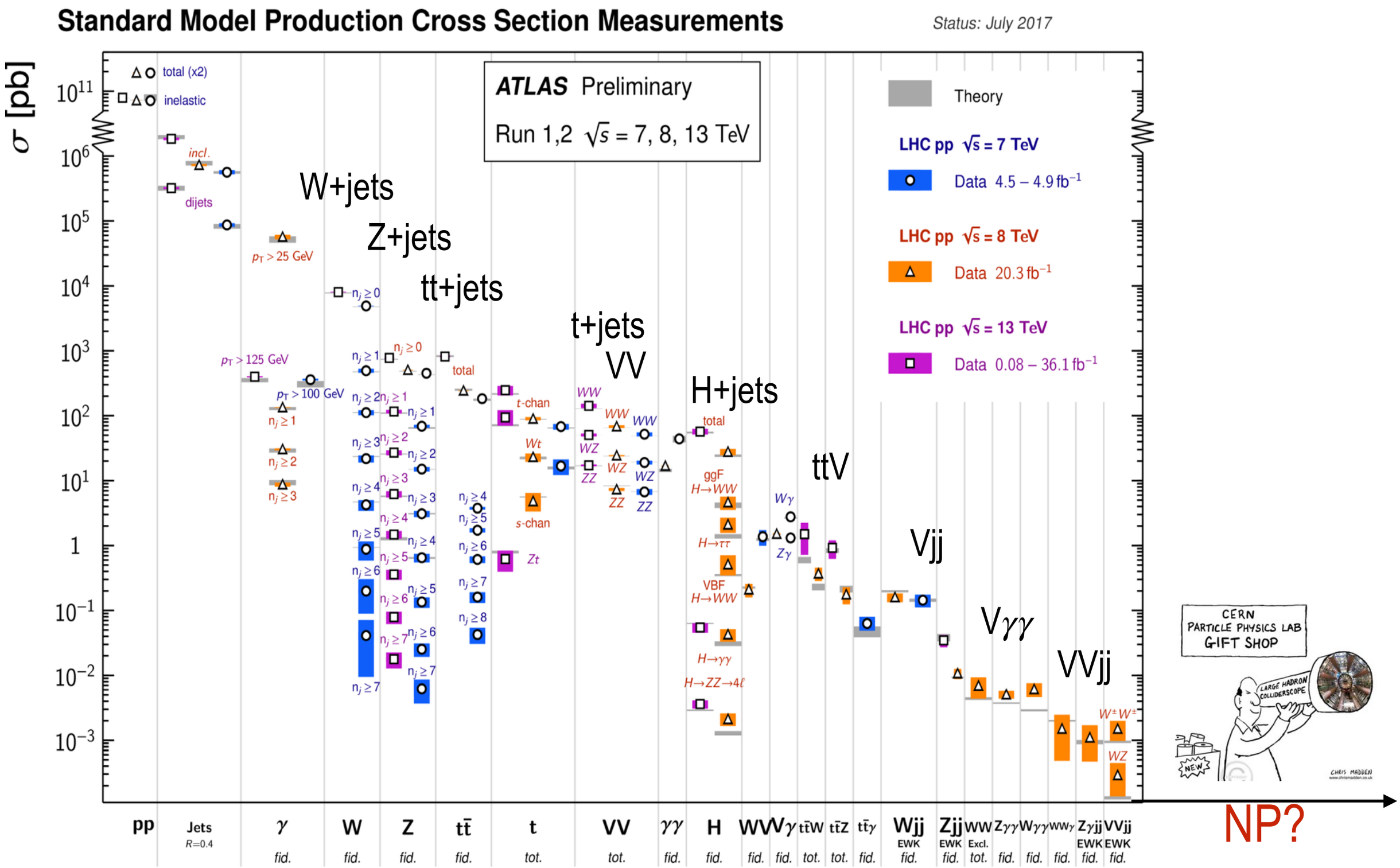
ATLAS/CMS:

- 5 & 25 fb^{-1} /exp 2011-12 @ 7 & 8 TeV
- 36 fb^{-1} (2015-2016) & 6 fb^{-1} (2017) / exp @ 13 TeV



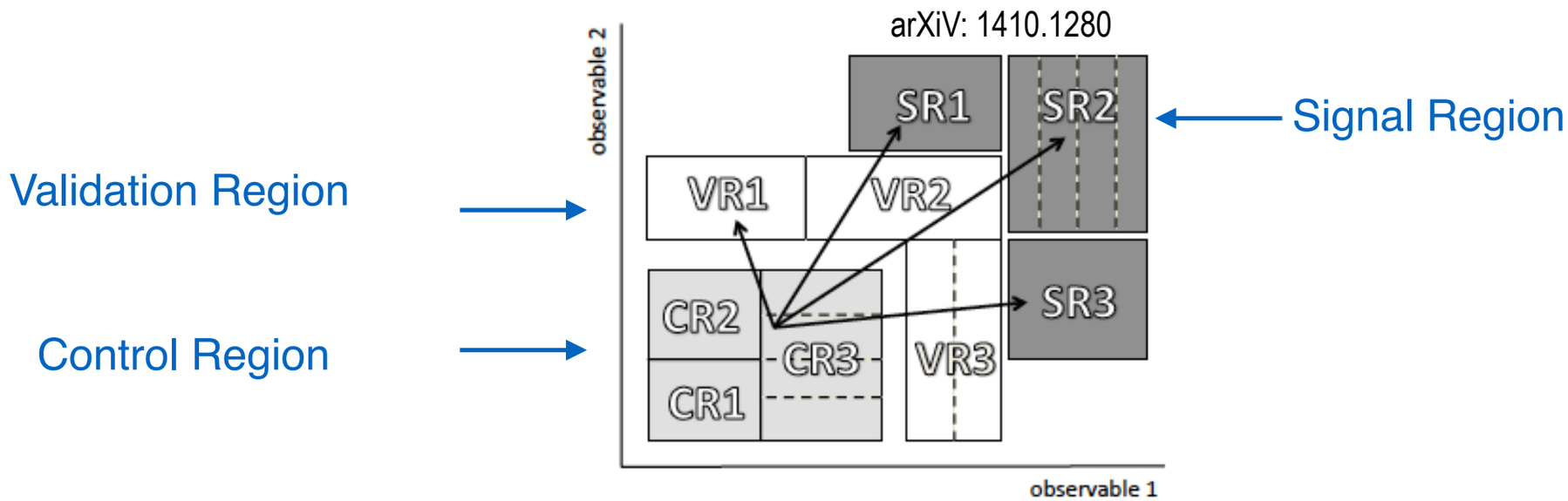
Standard Model Backgrounds

- Precise measurements of SM background is essential for accurate MC simulations



Background Estimation

- Main backgrounds are mostly estimated from data
  - Significant reduction in total systematic uncertainty due to detector response/simulations

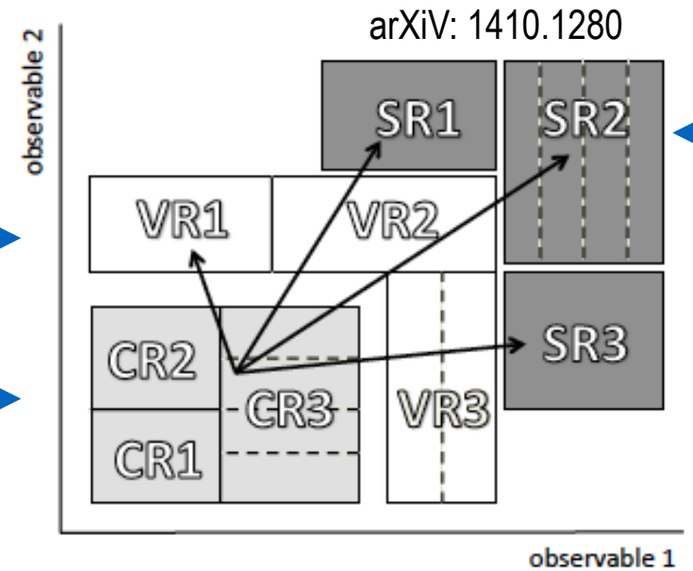


Background Estimation

- Main backgrounds are mostly estimated from data
  - Significant reduction in total systematic uncertainty due to detector response/simulations

Validation Region

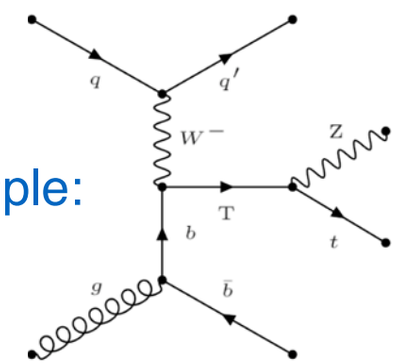
Control Region



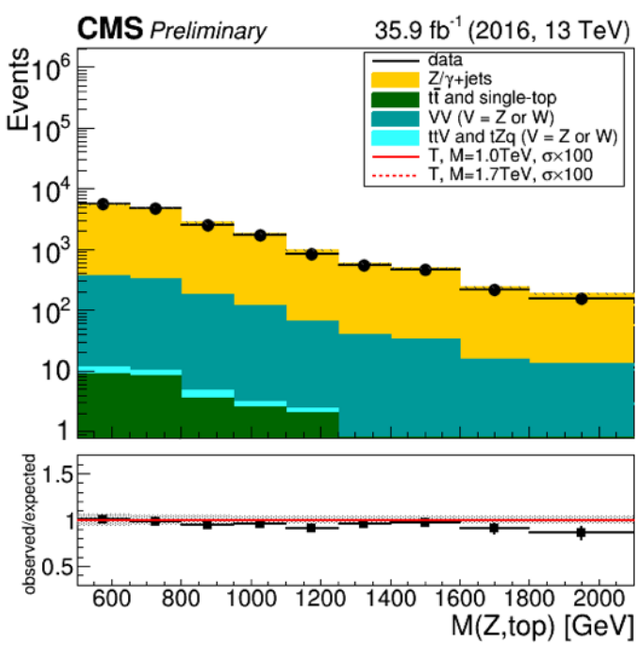
Signal Region

$$N_{bkg} = \frac{N^{CR}_{data}}{N^{CR}_{mc}} \times N^{SR}_{mc}$$

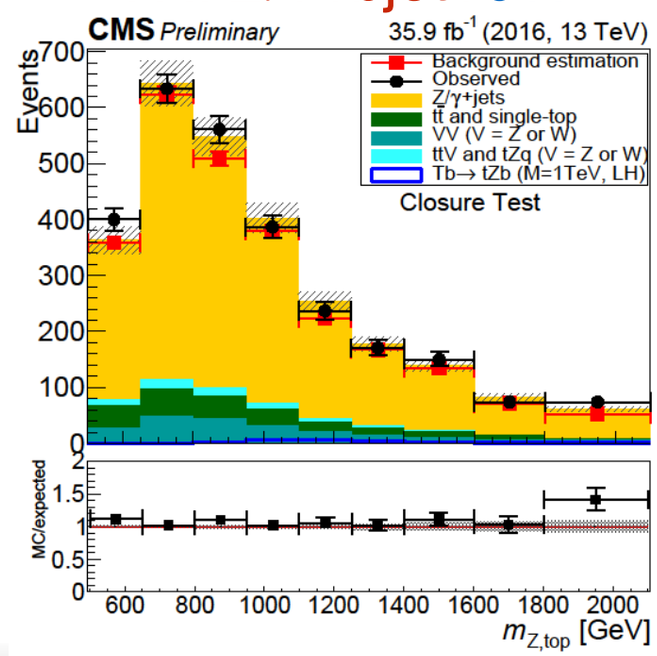
Example:



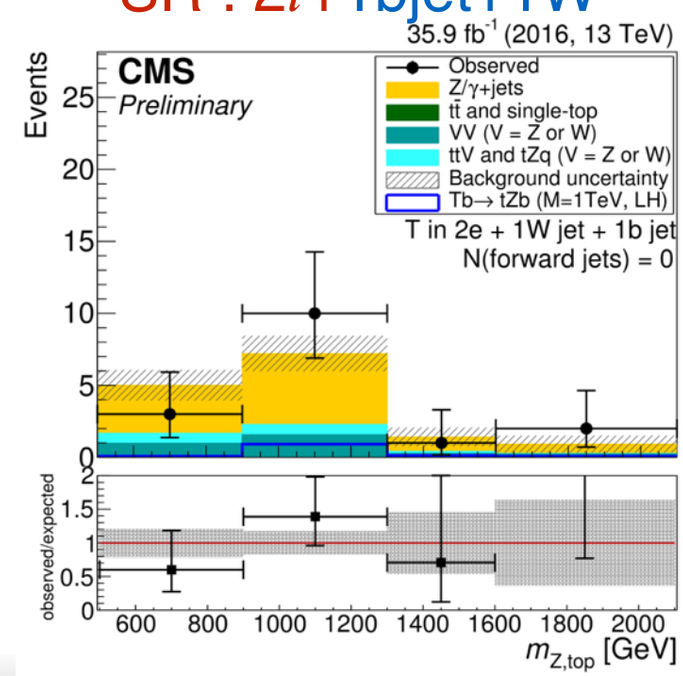
CR: 2*l*+0b+1W



VR: 2*l*+1bjet+0W



SR : 2*l*+1bjet+1W

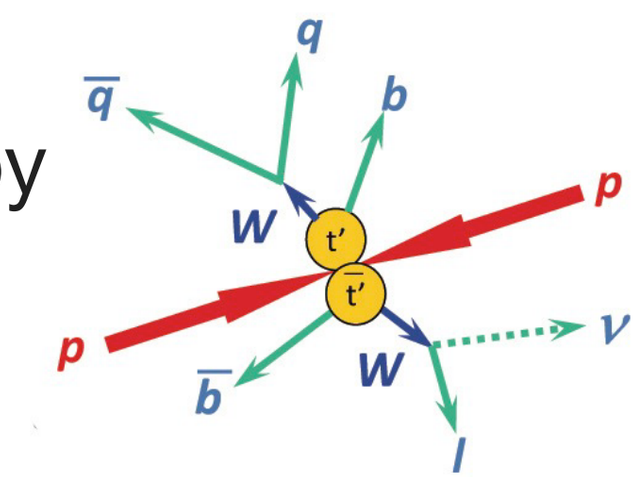


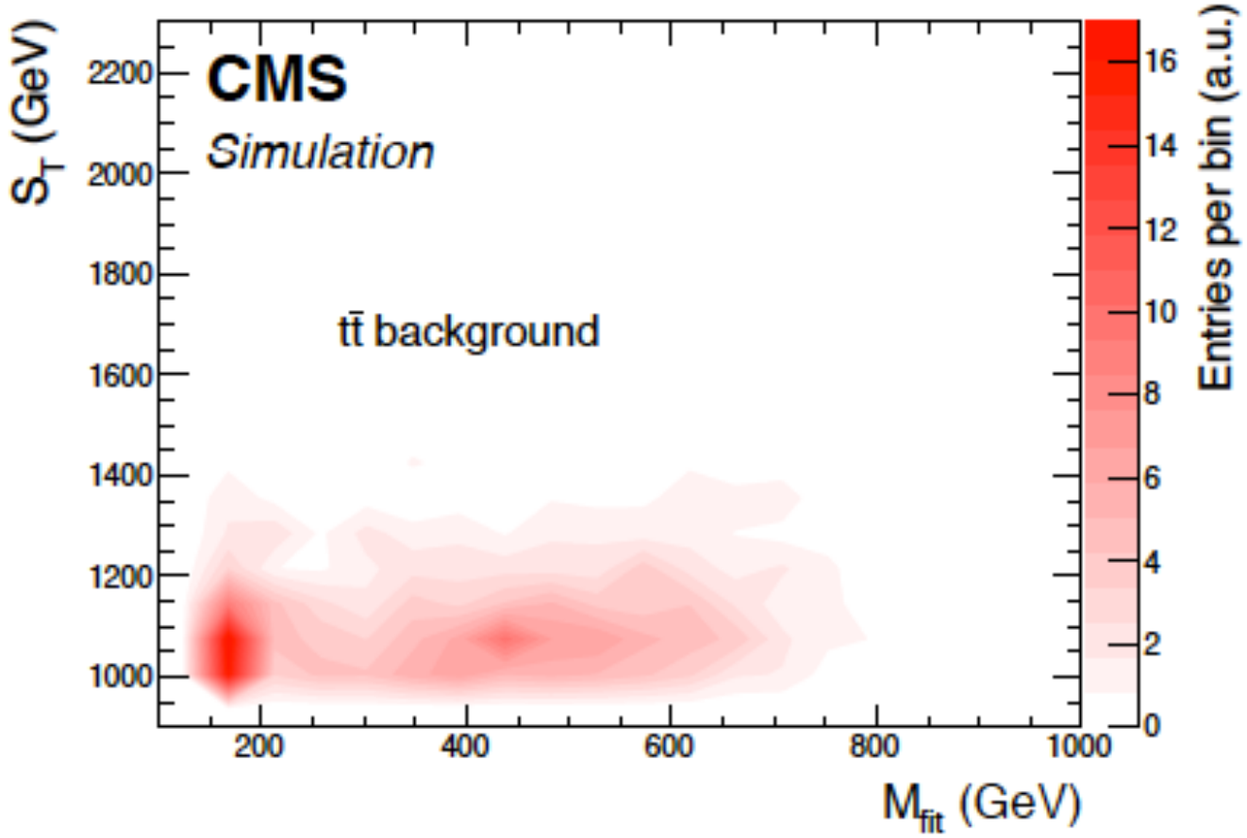
CMS-PAS-B2G-17-007

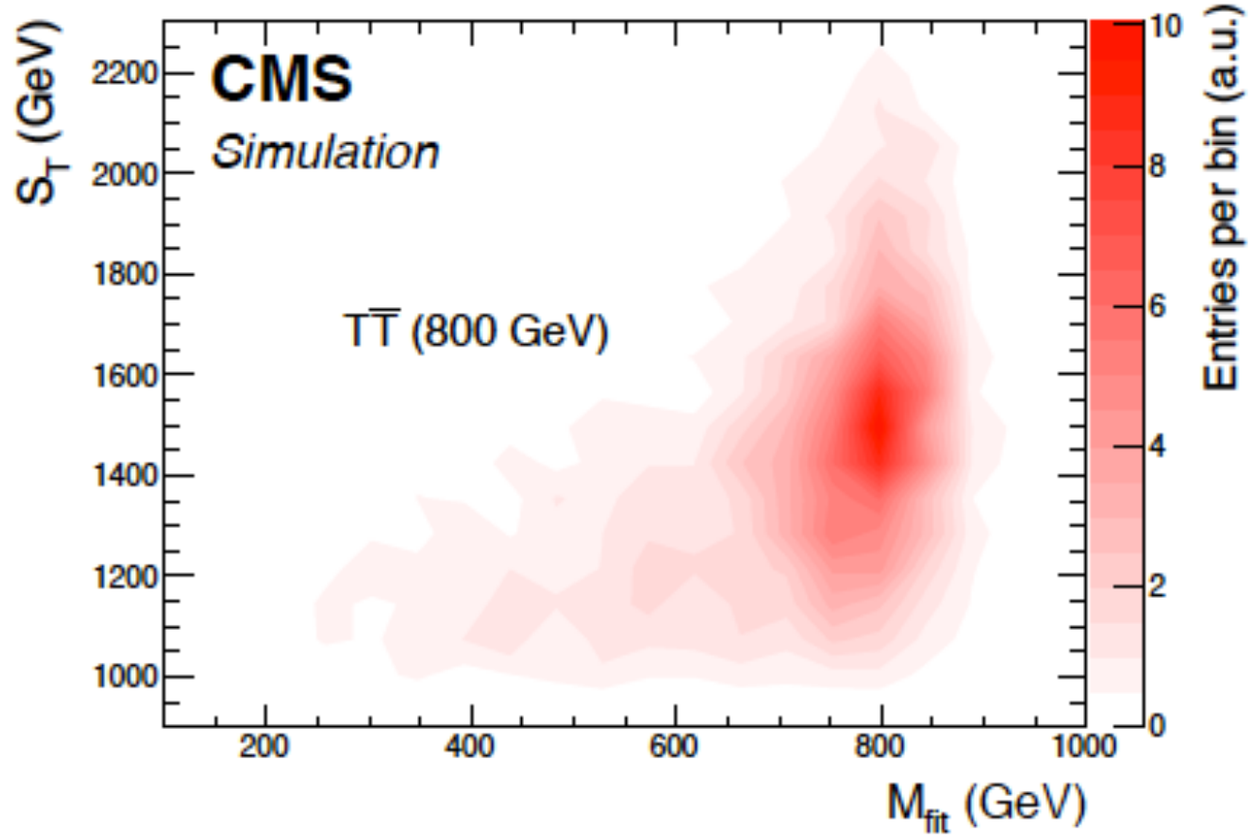
Search Procedures

- Look for excesses over known backgrounds
- *Example 1:* Search for vector-like quark $T_{2/3}$ by reconstructing its mass in high S_T tails

$$S_T = l(p_T) + \sum P_T^{jets} + E_T^{Miss}$$







Search Procedures

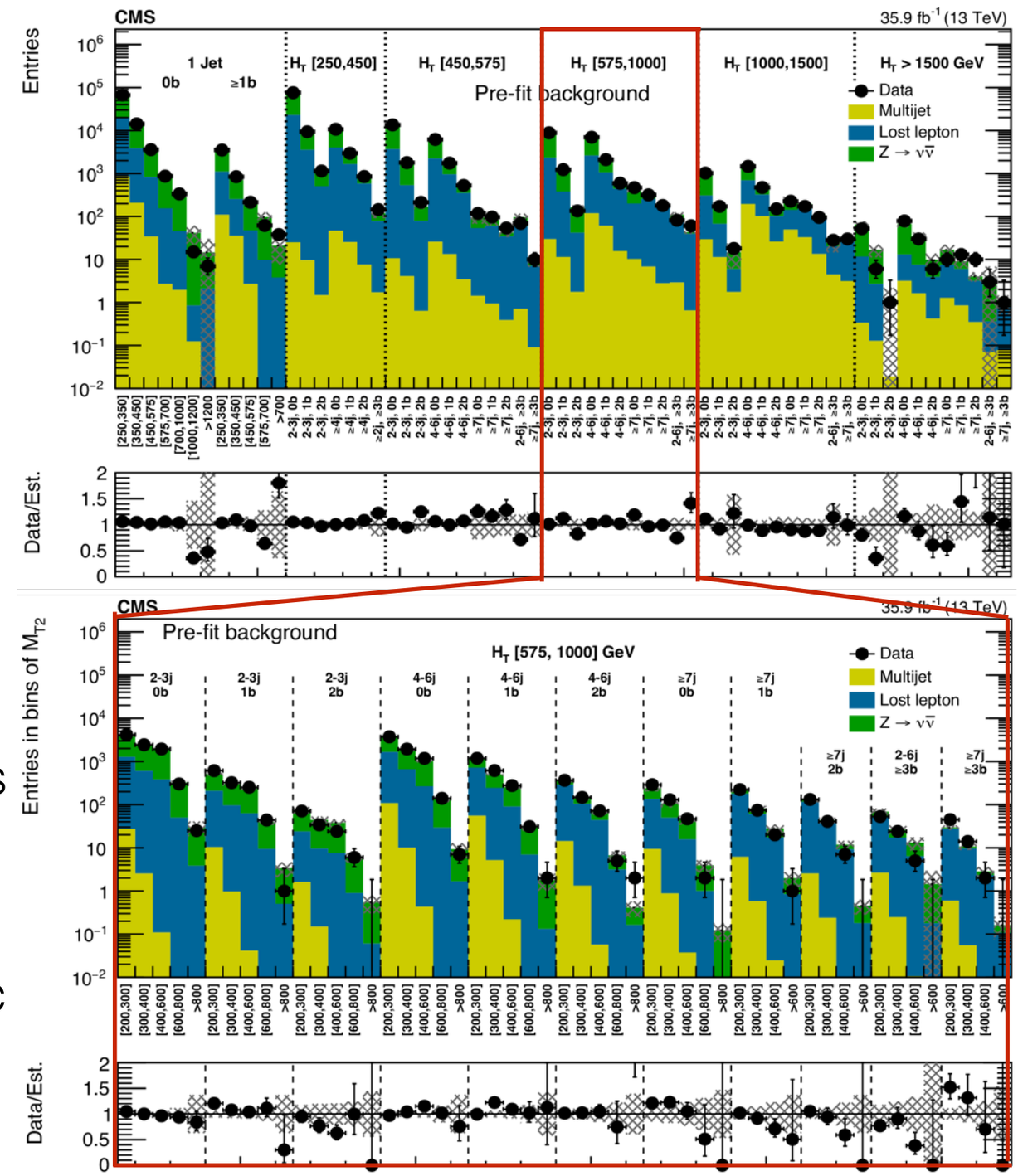
- Divide and conquer, and leave no stone unturned
  - Multi-dimensional bins considering various discriminating observables

- *Example 2:* Search for SUSY in all-hadronic final states
  - Consider SRs categorized with respect to N_{jets}, N_{bjets}, H_T
  - Each region with a certain H_T range is further split in terms of M_{T2}

$$M_{T2} = \min_{\vec{p}_T^{X(1)} + \vec{p}_T^{X(2)} = \vec{p}_T^{miss}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$

- Great complexity of the current searches
- Model-independent upper limits

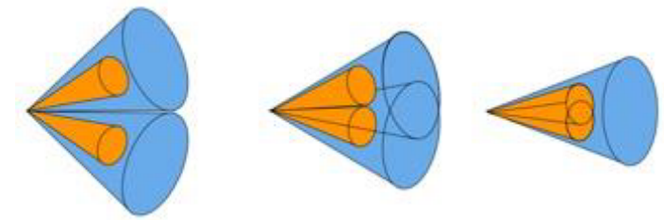
  ⇒ allows interpretations in other specific NP model(s)

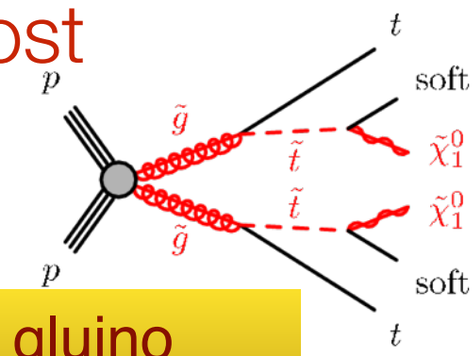


arxiv:1705.04650

Search Tools: Jet substructure

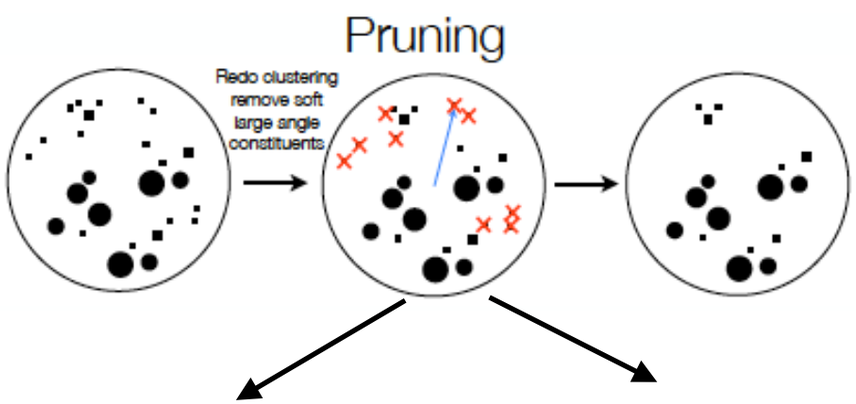
- Techniques focus on boosted final states where the whole heavy particle decay can be captured in a single jet
  - SUSY signature: moderate boost
  - Heavy vector-like quark and boson decays: large boost



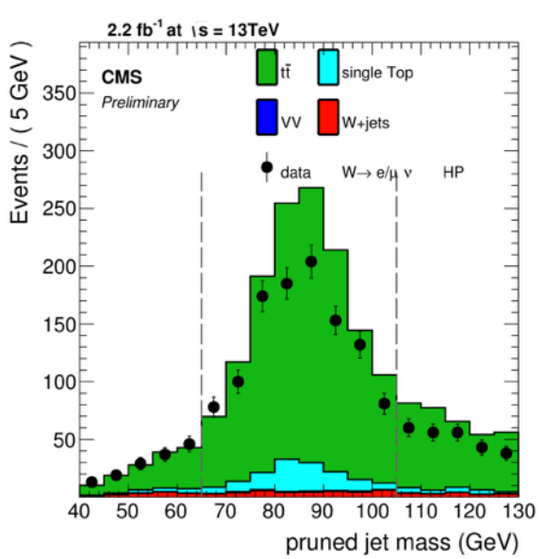


ATLAS-CONF-2017-020

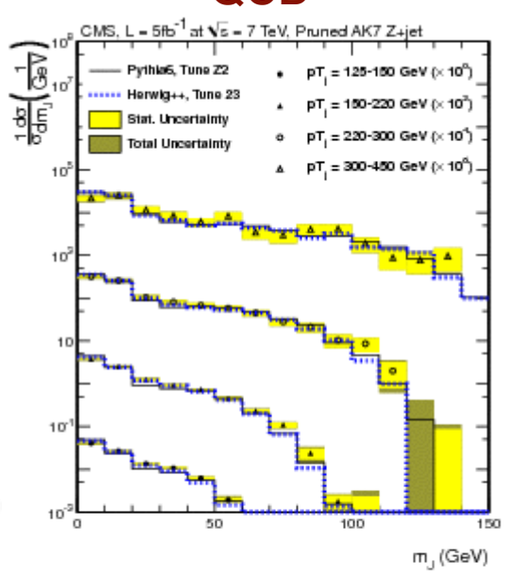
Jet grooming and Wjet identification



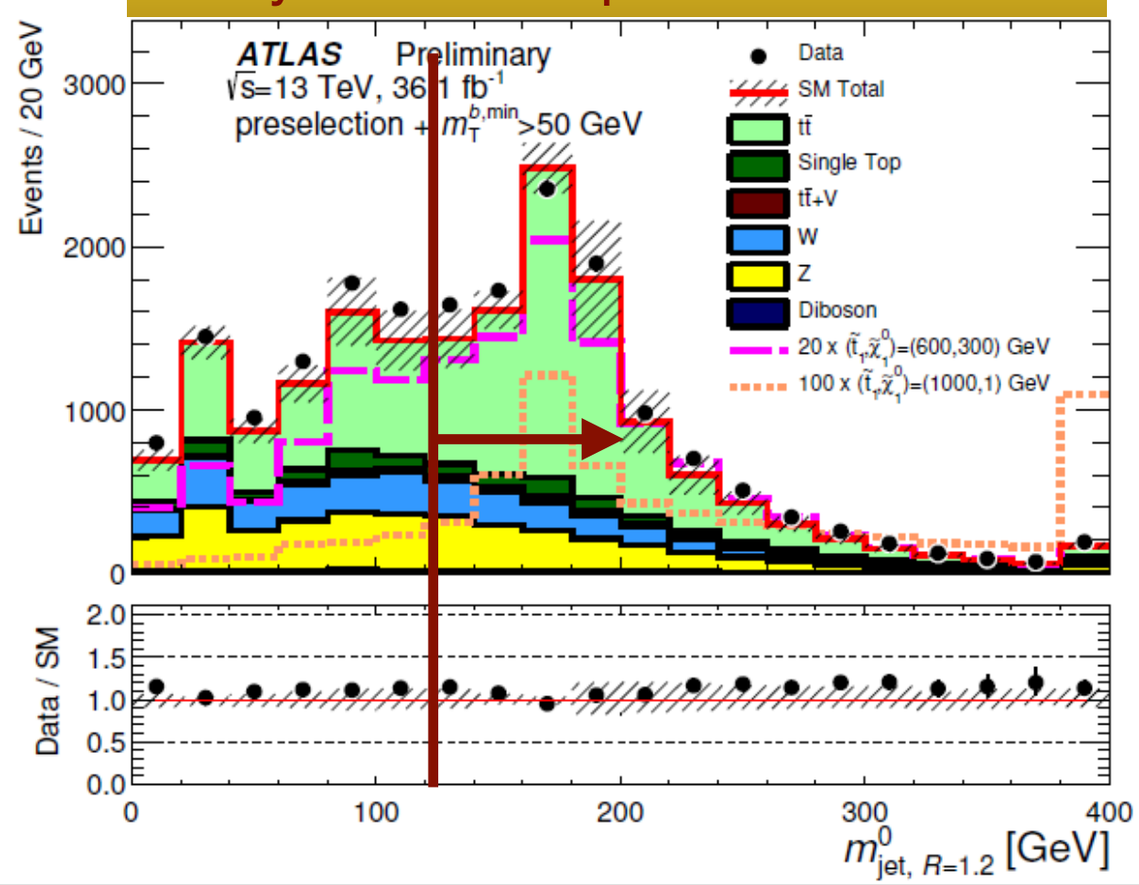
WJets



QCD



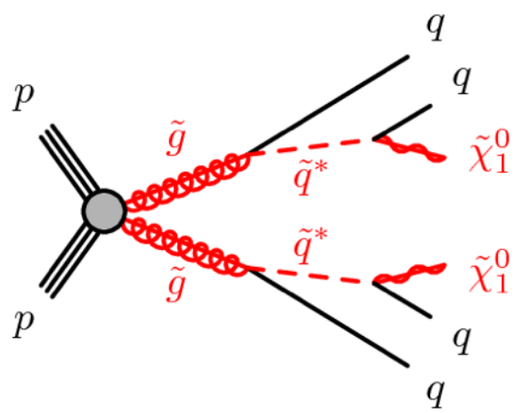
stops production through gluino decays with no leptons

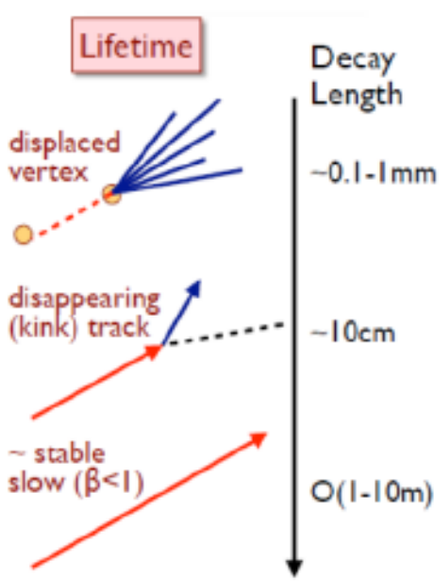


Search Tools: Re-tracking@ATLAS

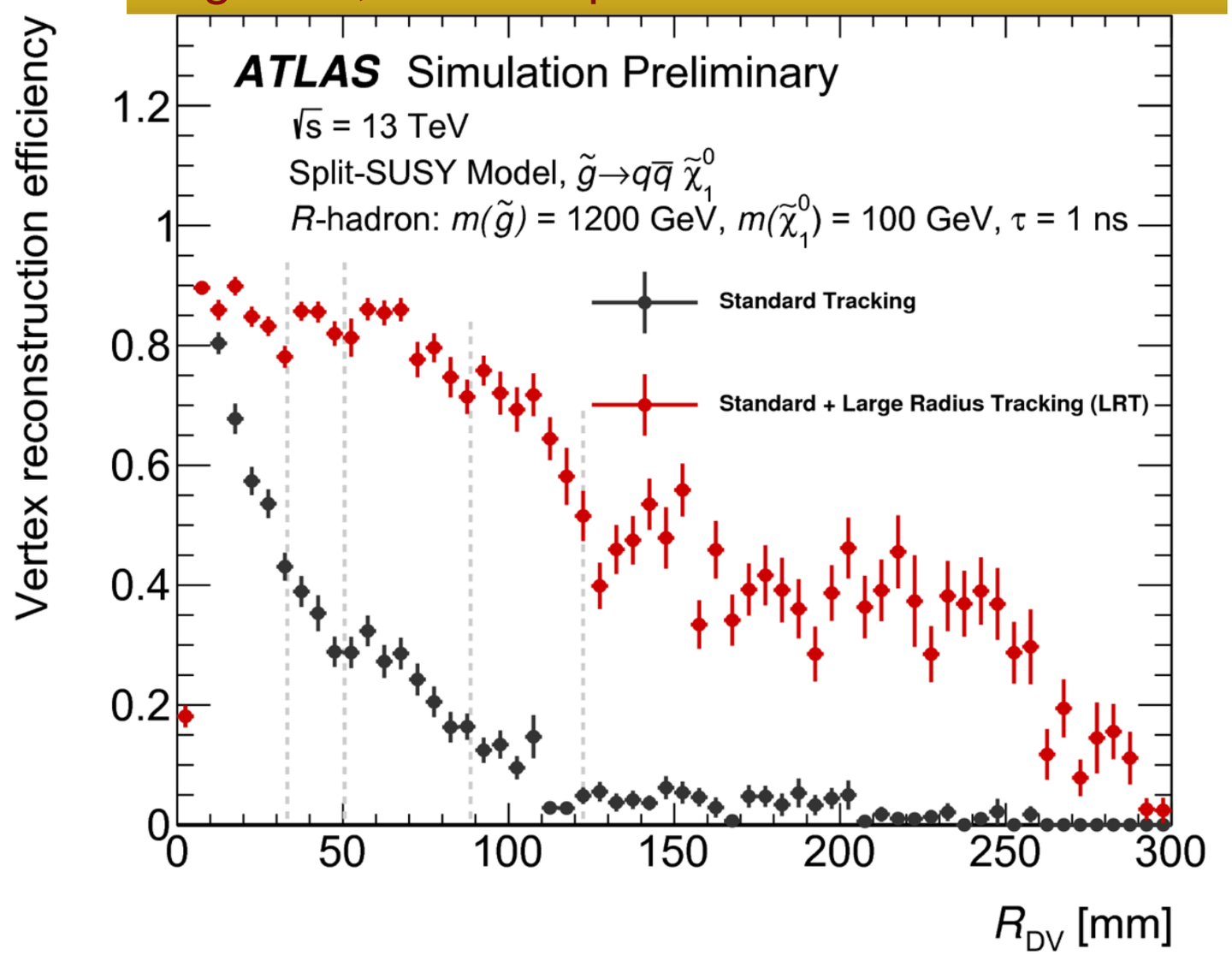
- "Unconventional" signatures such as long-lived particles (LLP)
  - Small medium decay lengths appears as displaced vertex (DV)
- Silicon-seeded Large-Radius Tracking (LRT) algorithm ATLAS-CONF-2017-026

Split-SUSY

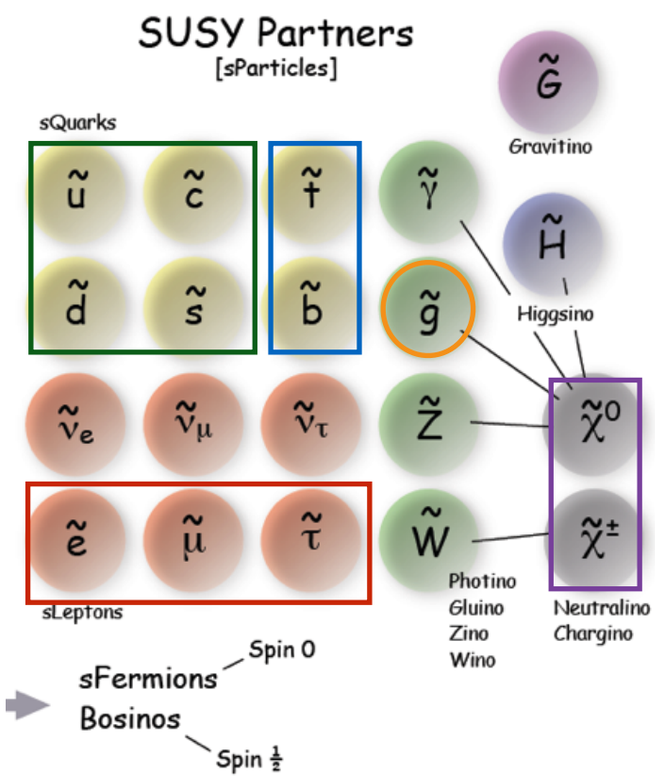




long-lived, massive particles with DV and E_T^{Miss}

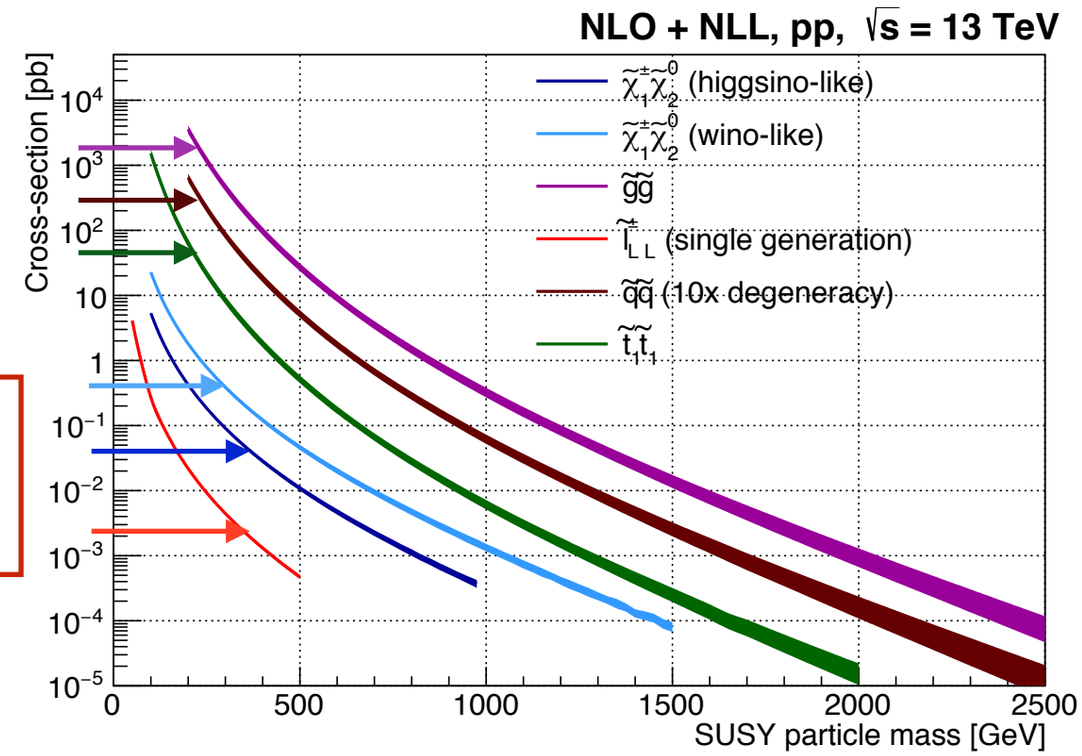


Supersymmetry



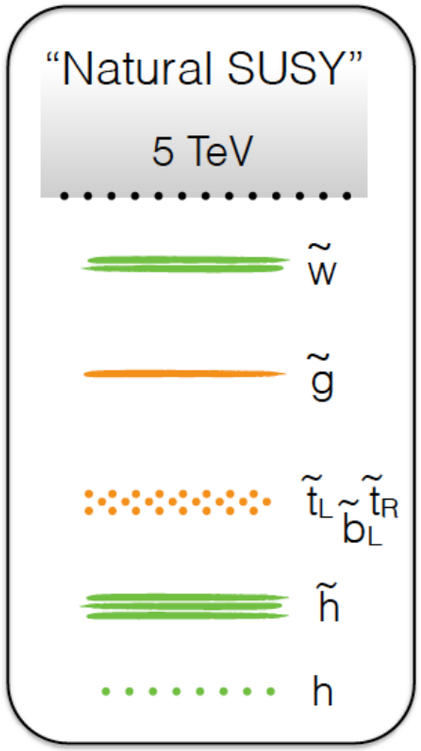
Strong production
(gluinos, squarks)

EWK production
(charginos, neutralinos, sleptons)



arxiv:1610.08059

The Higgs could be the lightest of the SUSY-higgses…



Nathaniel Craig, EPS2017

Partner mass hierarchy inversely proportional to the contribution to Higgs mass

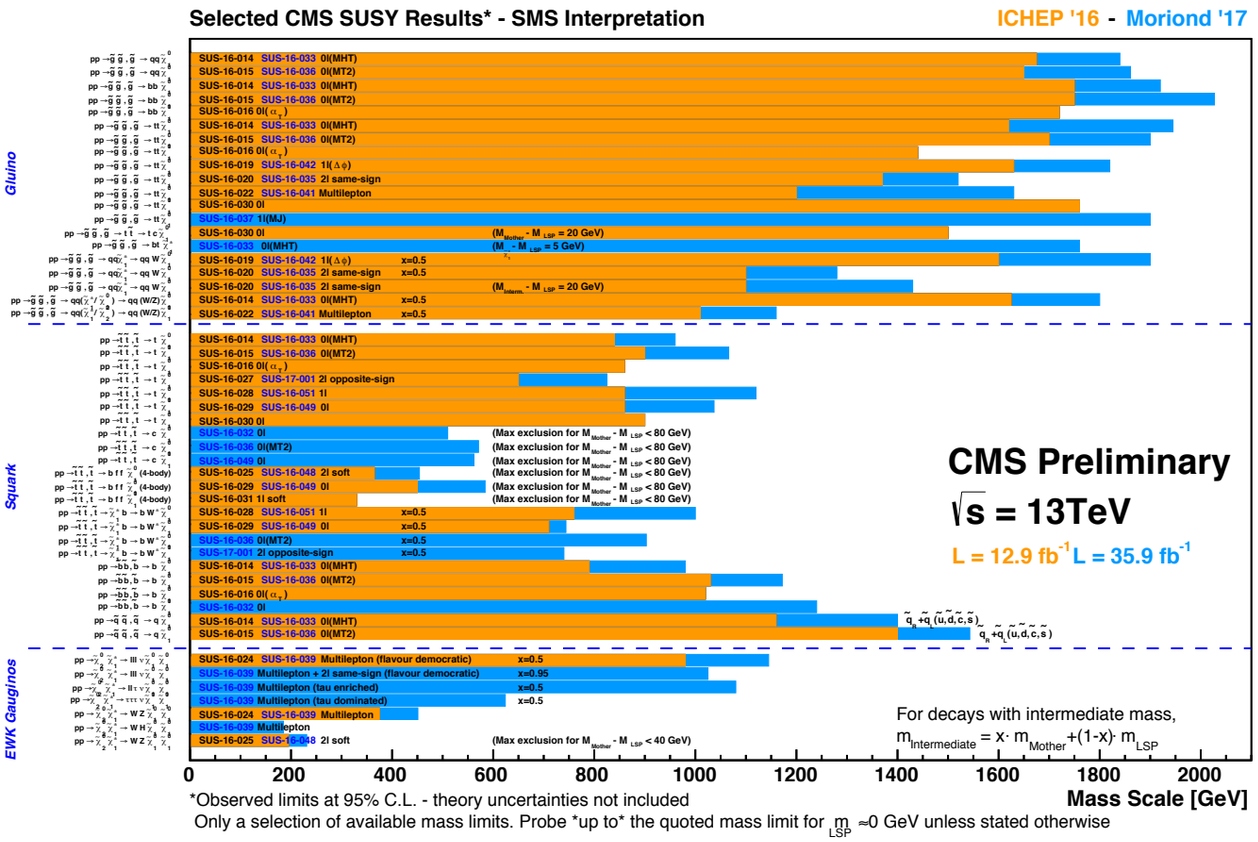
$$\delta m_H^2 = \mu^2 \quad \text{(Higgnino)}$$

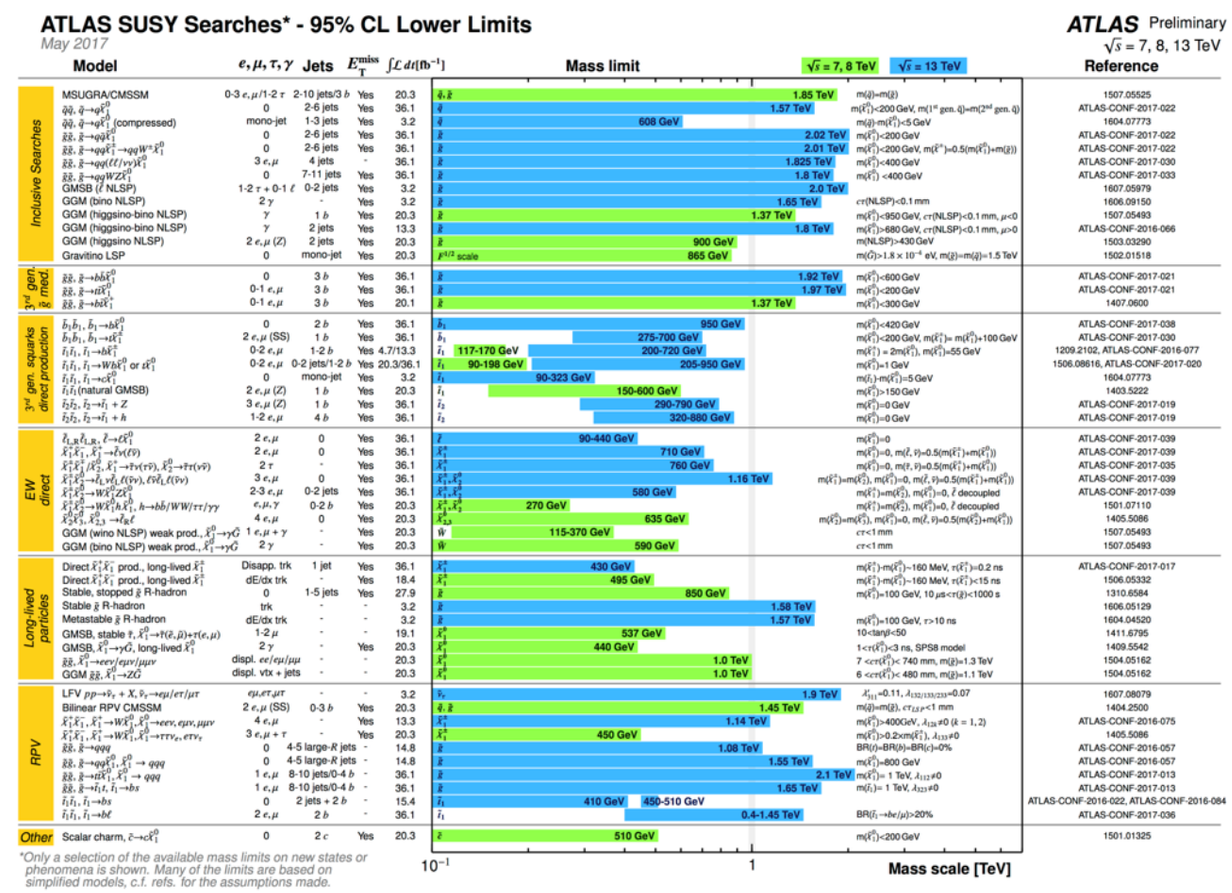
$$\delta m_H^2 \propto \frac{3y_t^2}{8\pi^2} m_{\text{stop}}^2 log(\Lambda/Q) \text{(stops)}$$

$$\text{if } \Delta \equiv 2\frac{\delta m_H^2}{m_h^2}; \quad \text{tuning} \sim \frac{1}{\Delta}$$

Supersymmetry

Large number of searches both at ATLAS and CMS!





Typical mass limits for direct production:

squarks > 1 TeV

gluino > 2 TeV

sleptons/chargino > 0.5-0.6 TeV

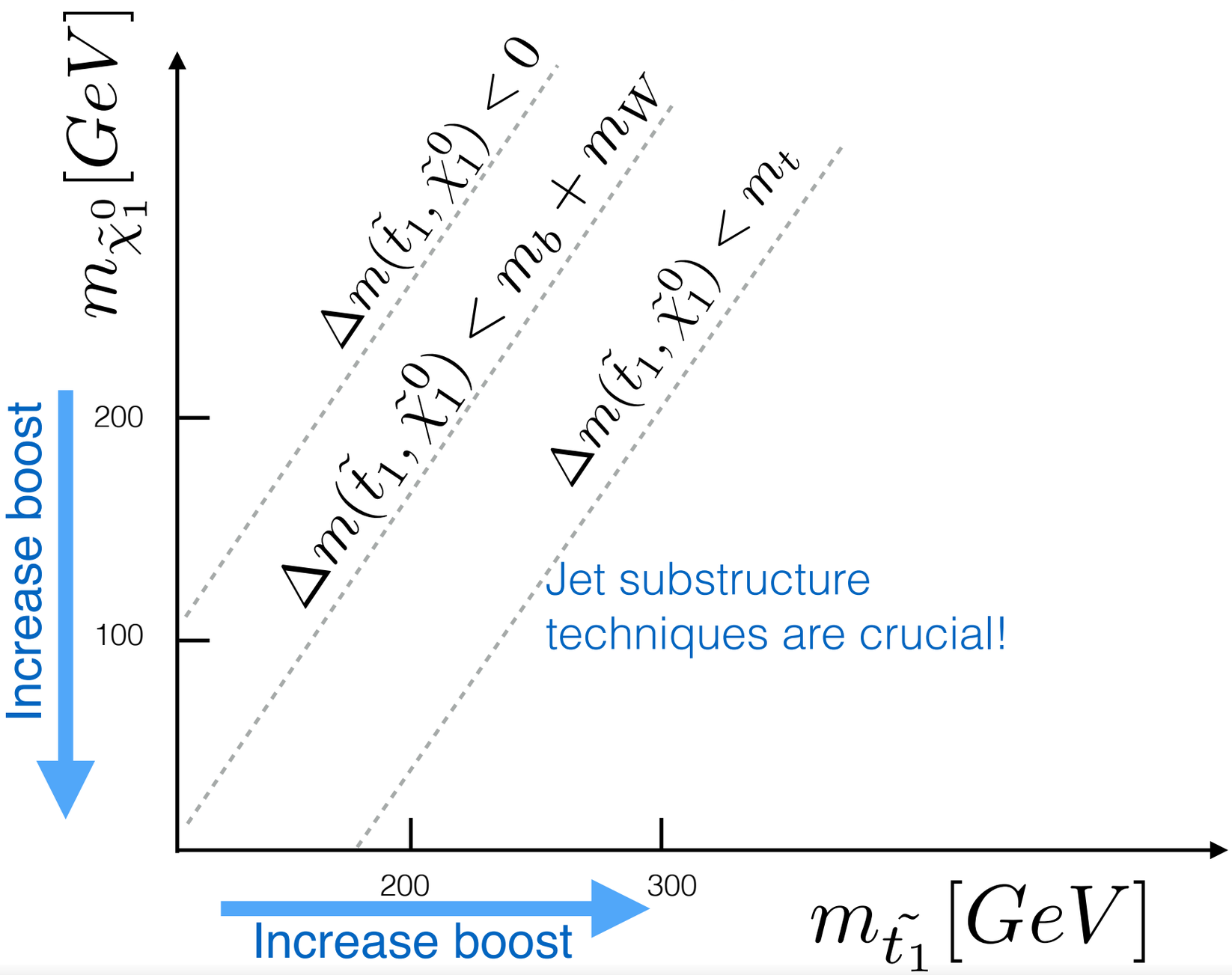
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

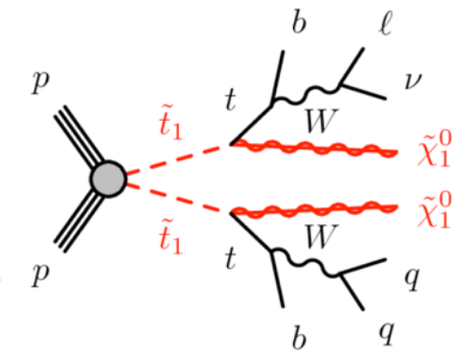
Compressed Regions

Challenging to access!

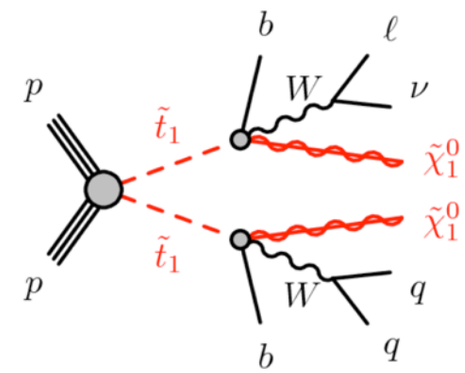
- Example: direct stop pair production in multiple final states
  - top + LSP → $0l, 1l, 2l$ + b-jets + E_T^{Miss}
  - charm + LSP



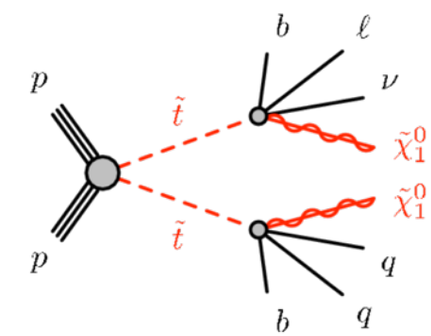
2 body decay
stop → t + LSP



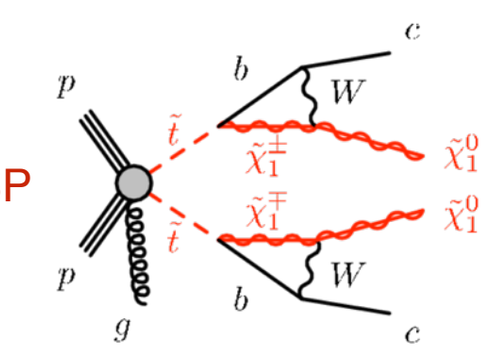
3 body decay



4 body decay



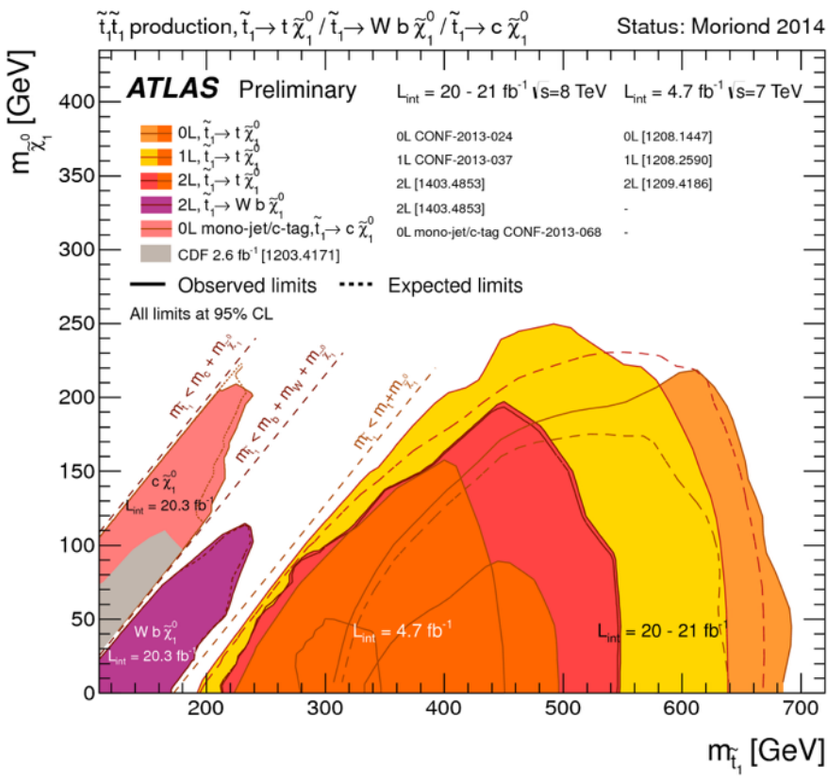
stop → c + LSP

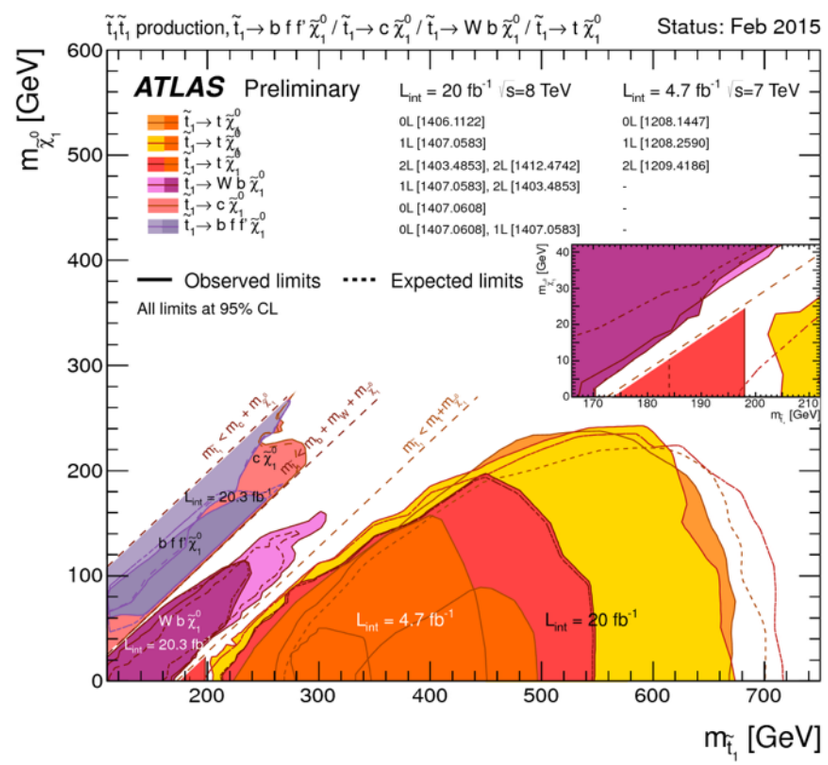


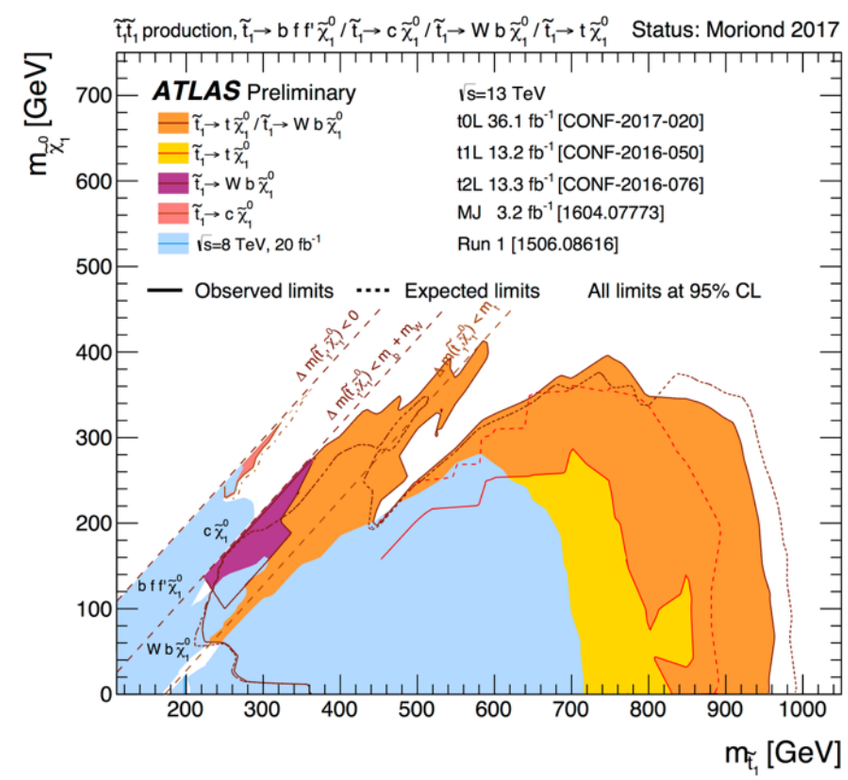
Third generation stops

Historical development!

Moriond 2014 → Feb 2015 → Moriond 2017

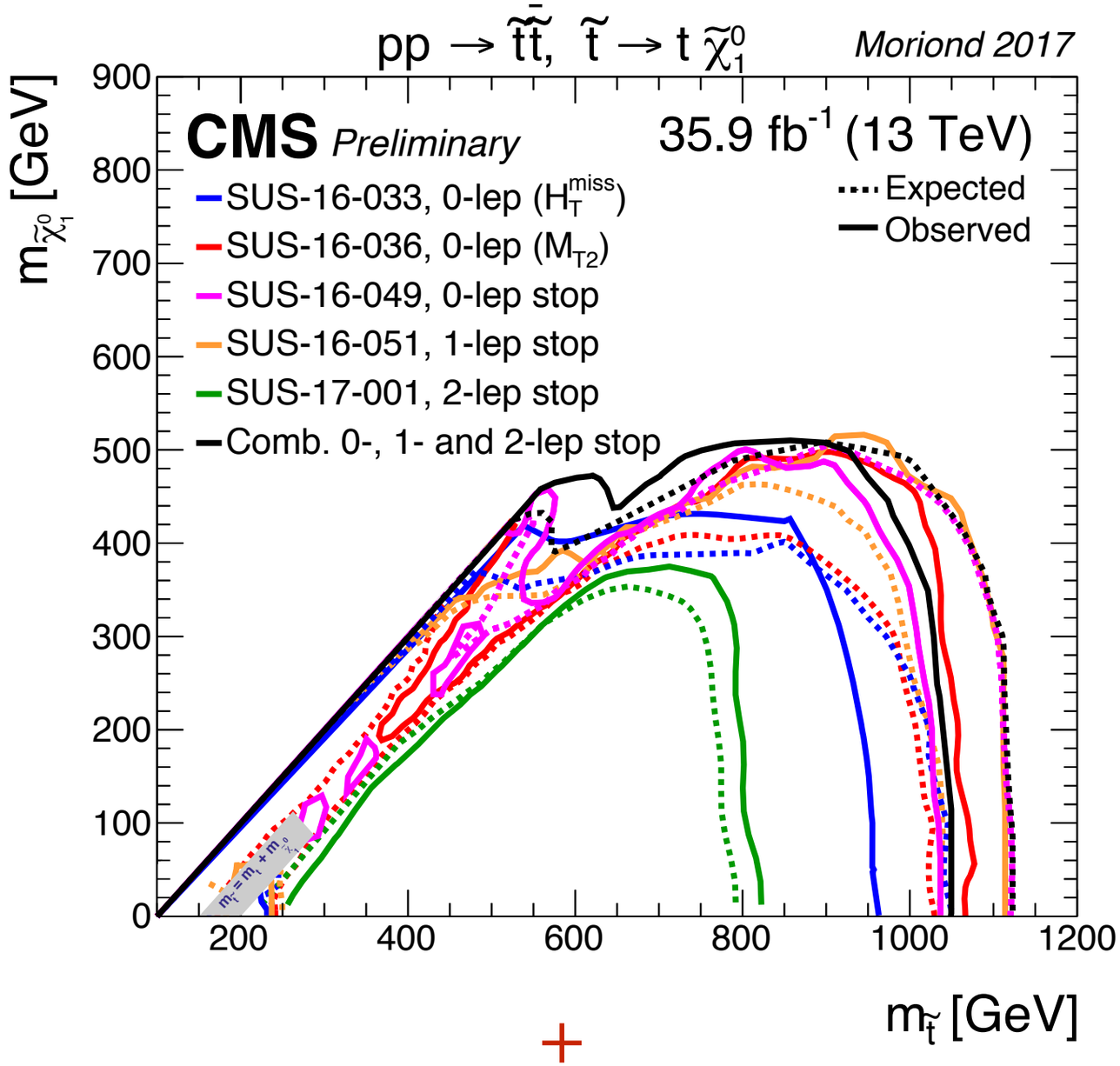


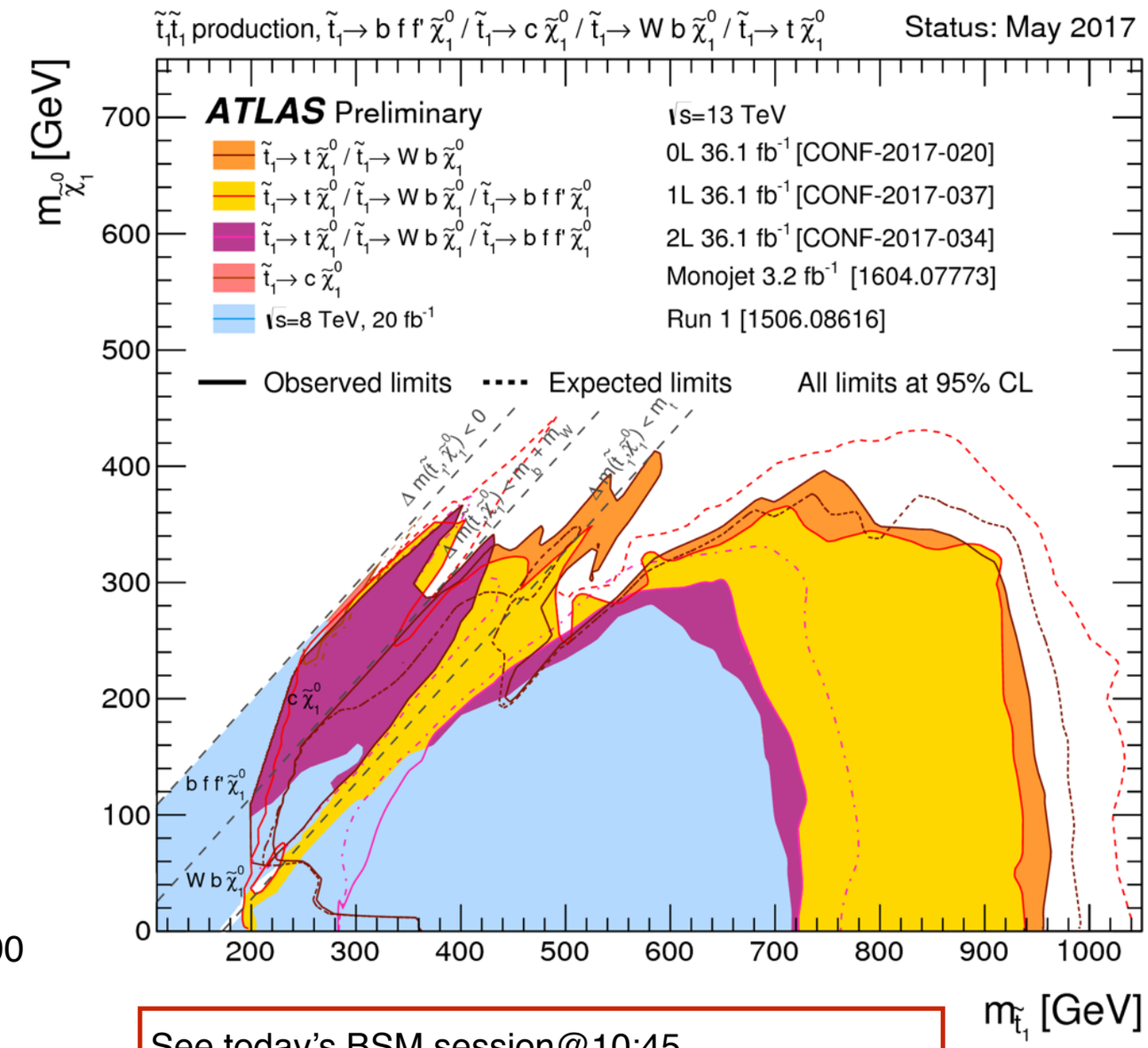




Similar developments happened at CMS at the same time

Third generation stops





+

CMS equivalent for 4 body decays: SUS-16-050 (0*l*+top), SUS-16-052 (1*l* compressed)

CMS equivalent for charm + E_T^{Miss} : EXO-16-048

See today's BSM session@10:45
Keisuke YOSHIHARA, Nathaniel PASTIKA
Wednesday's BSM session @10:45
Leigh SCHAEFER (RPV)

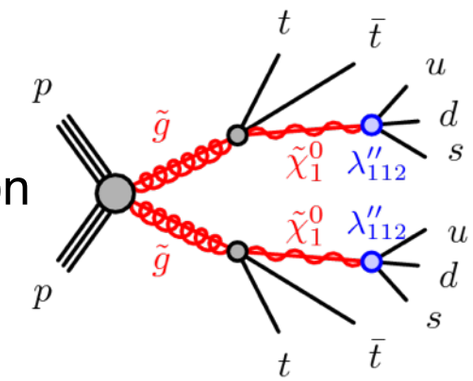
- For sbottom: Exclusion limits beyond 1 TeV in both experiments

CMS-PAS-SUS-16-032 ATLAS-CONF-2017-038

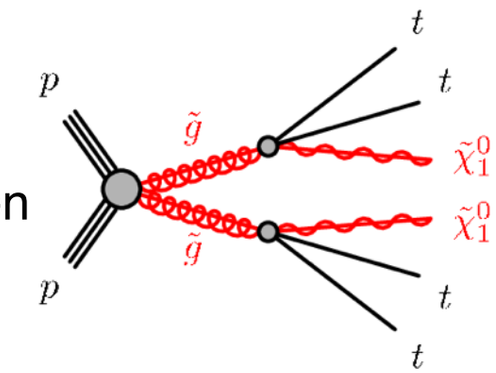
Gluinos

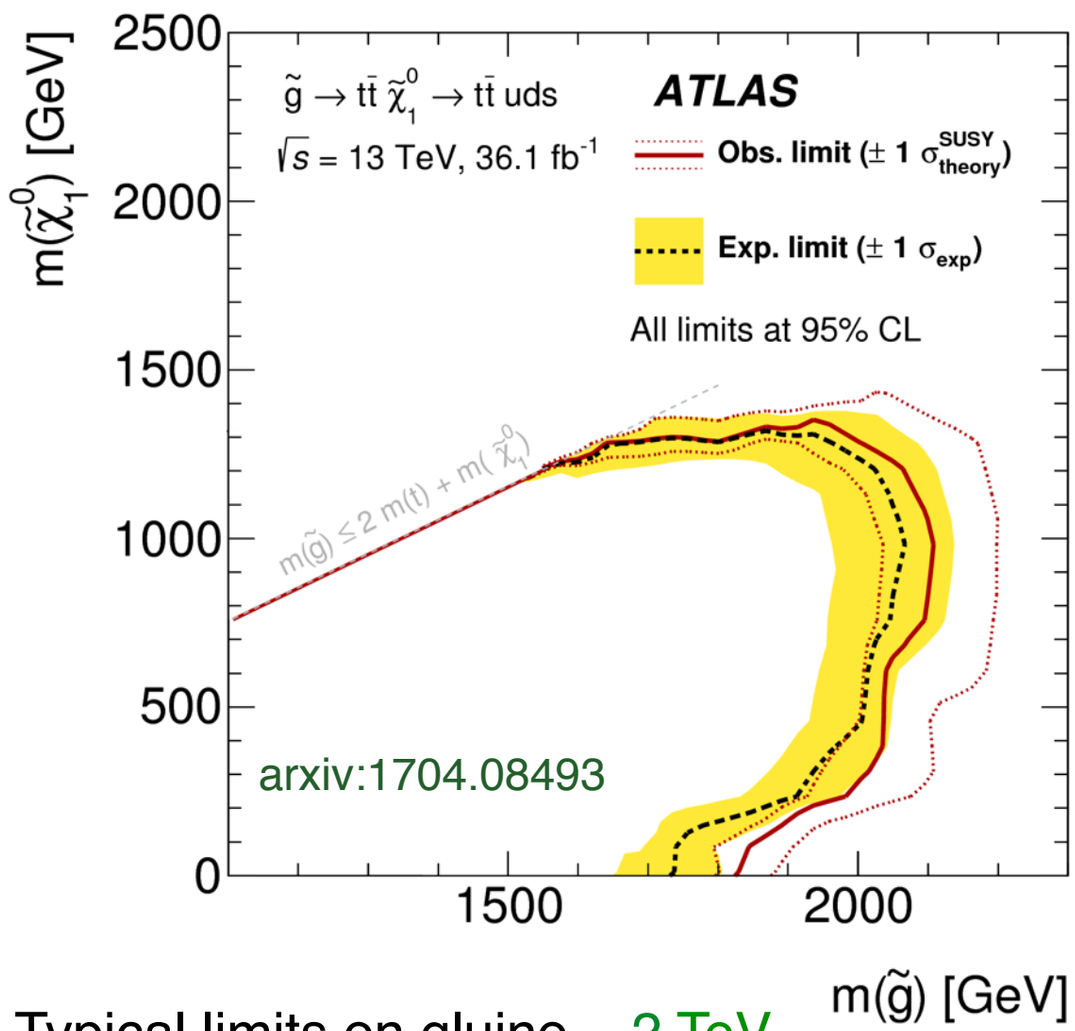
- A spectacular number of regions scrutinized in 0,1, or more lepton final states, in a a variety of hypotheses

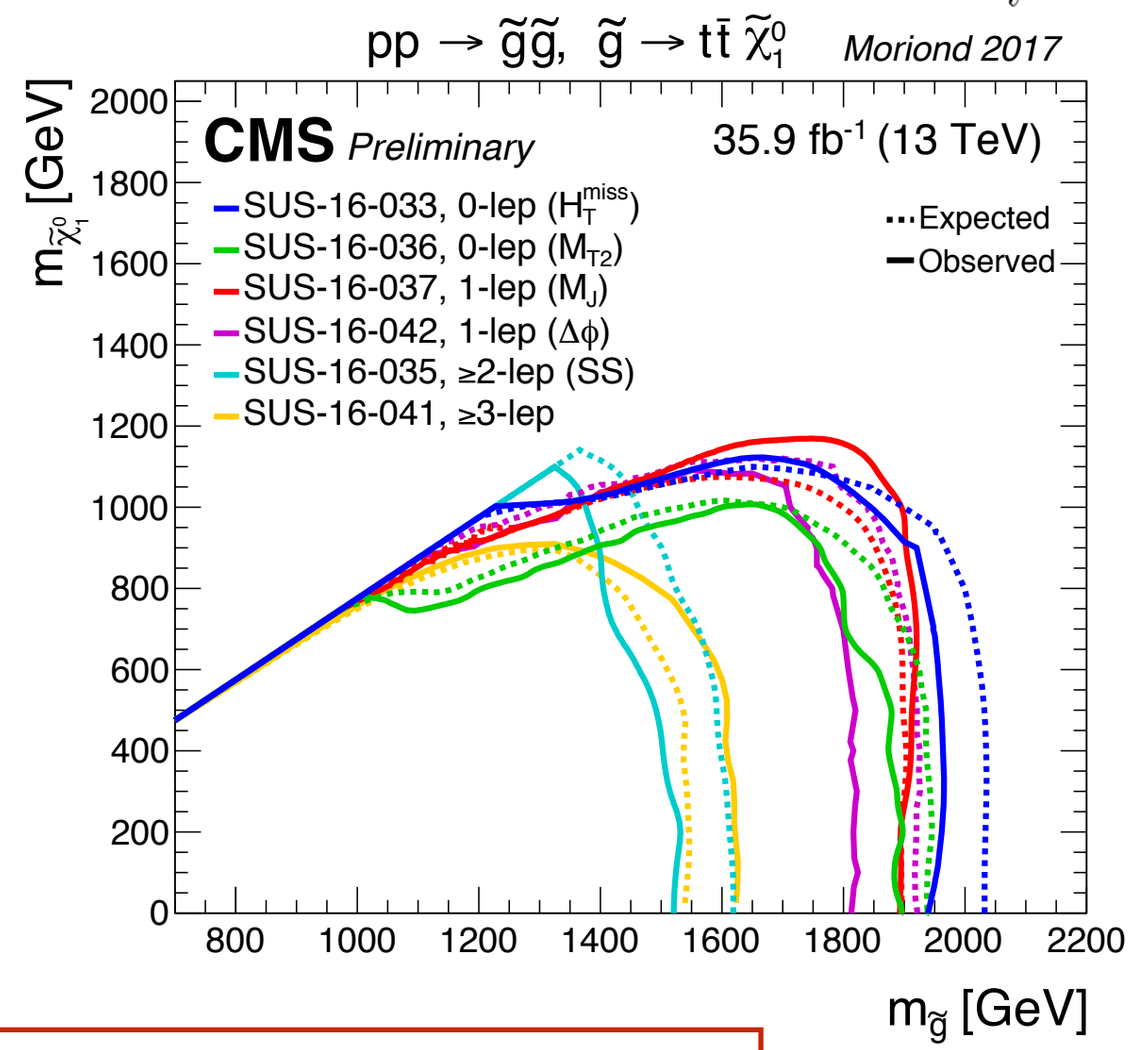
R-Parity violation



R-Parity conservation





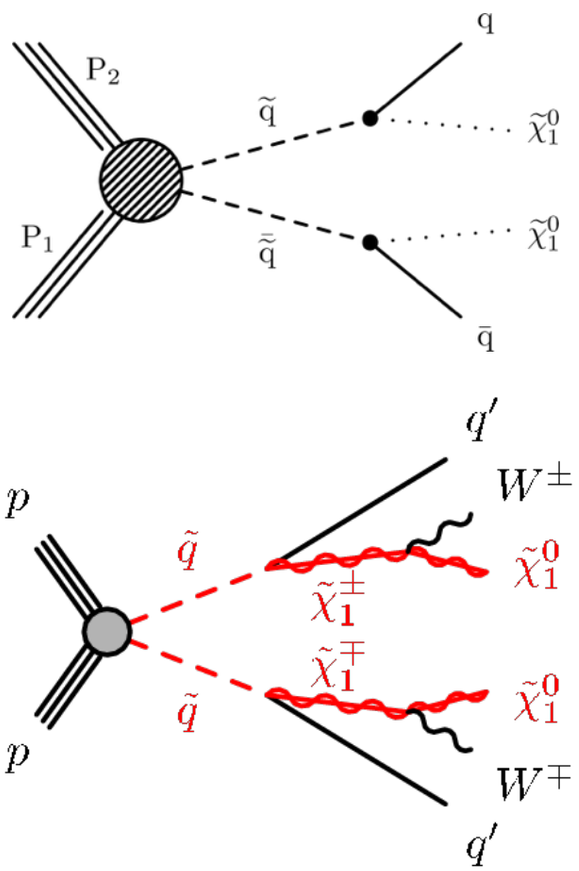


Typical limits on gluino ~ 2 TeV

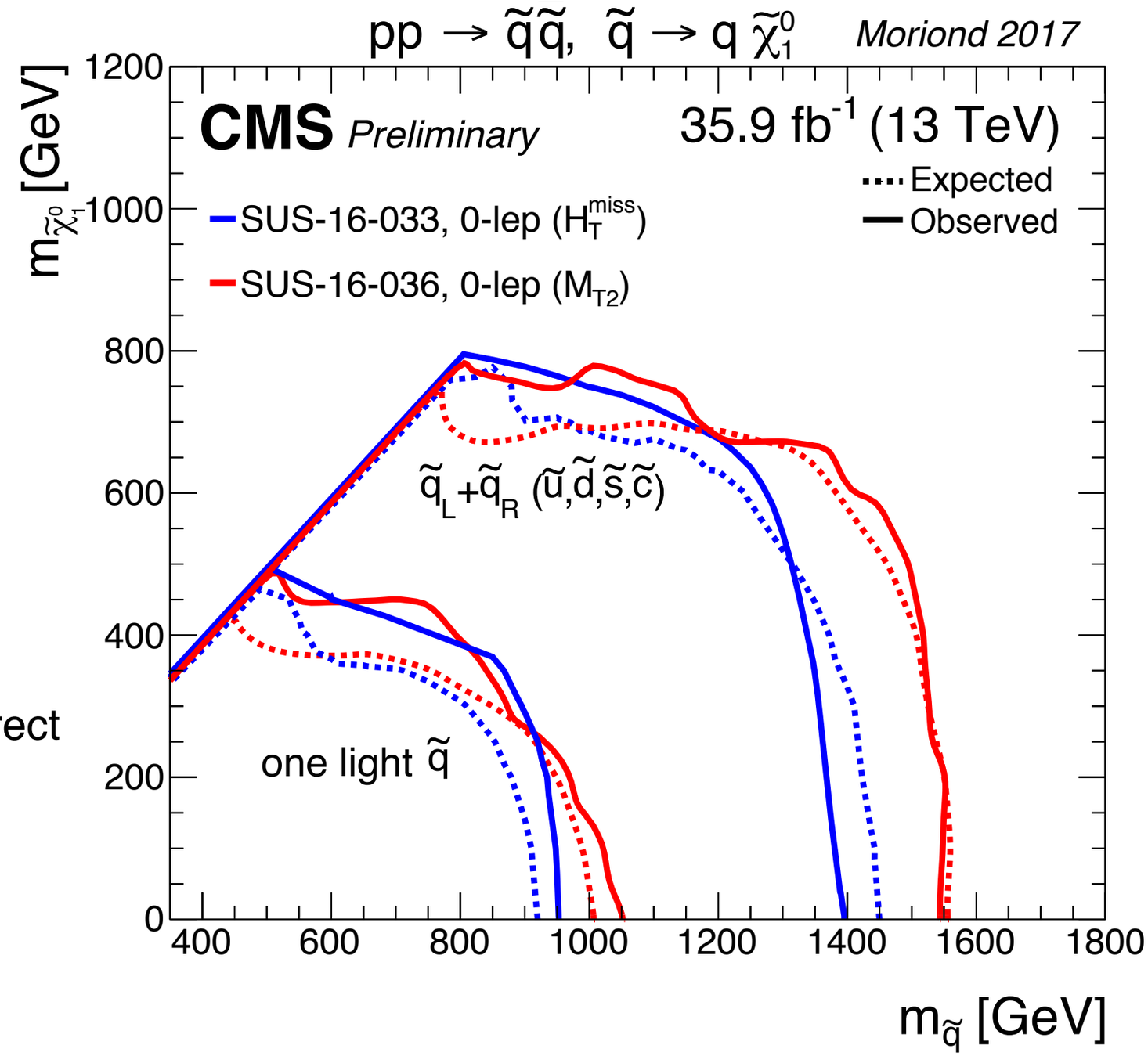
See today's BSM session@10:45
Kevin PEDRO, Giordon STARK, Frank JENSEN

Light squarks

- Searches are interpreted in terms of exclusion limits on the mass of squarks, considering sophisticated search regions



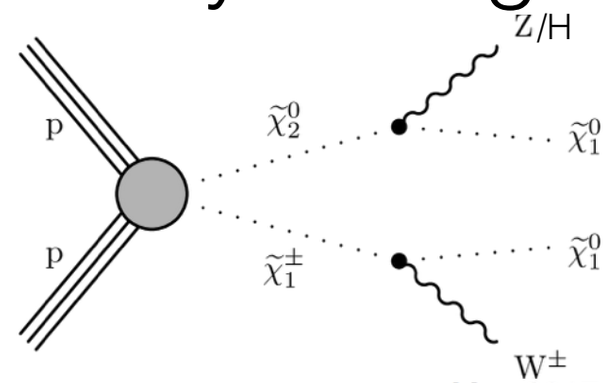
Limits on light squarks ~ 1 TeV for direct decays [one-type only]



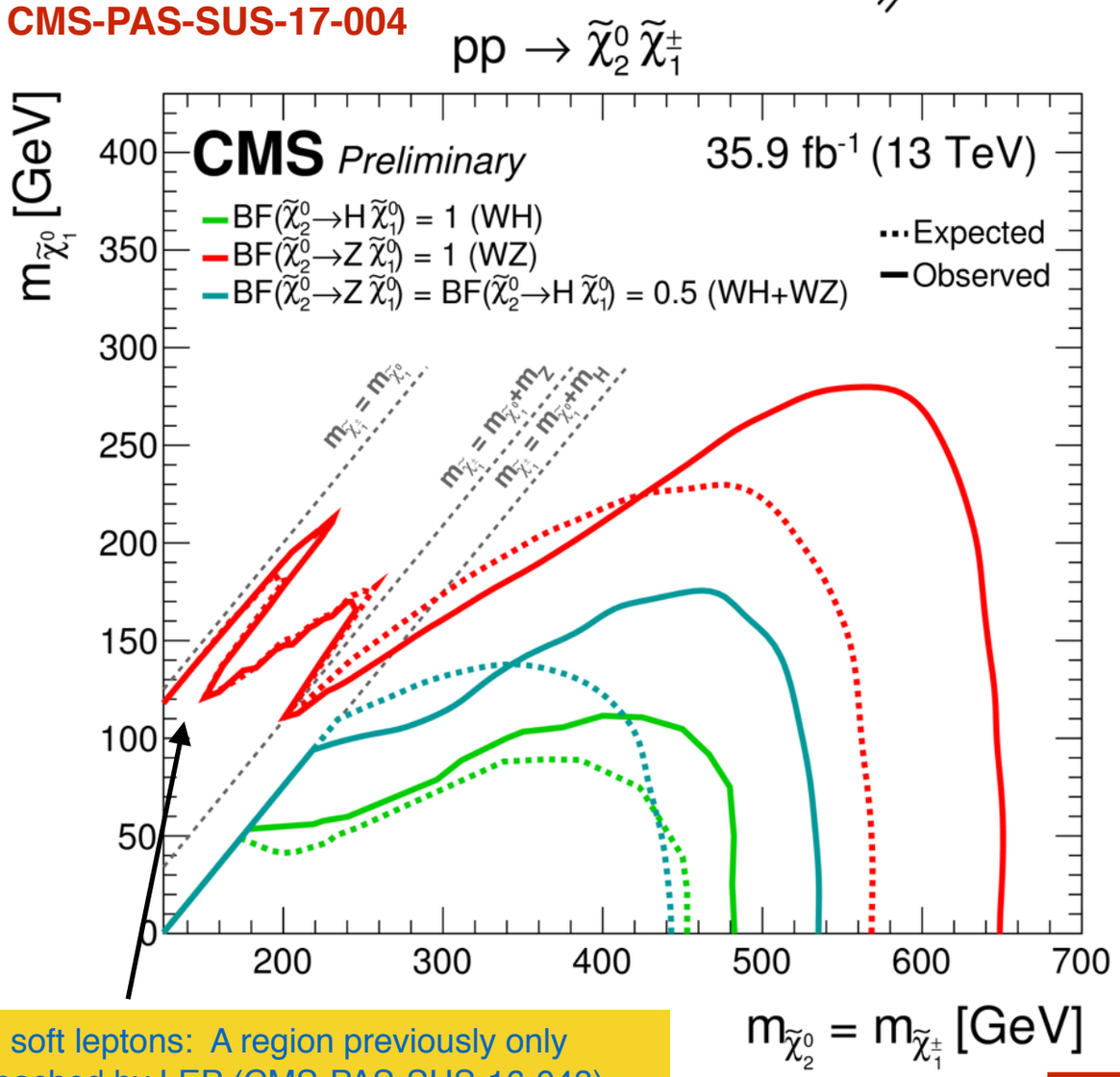
See today's BSM session@10:45 am
Kevin PEDRO, Frank JENSEN

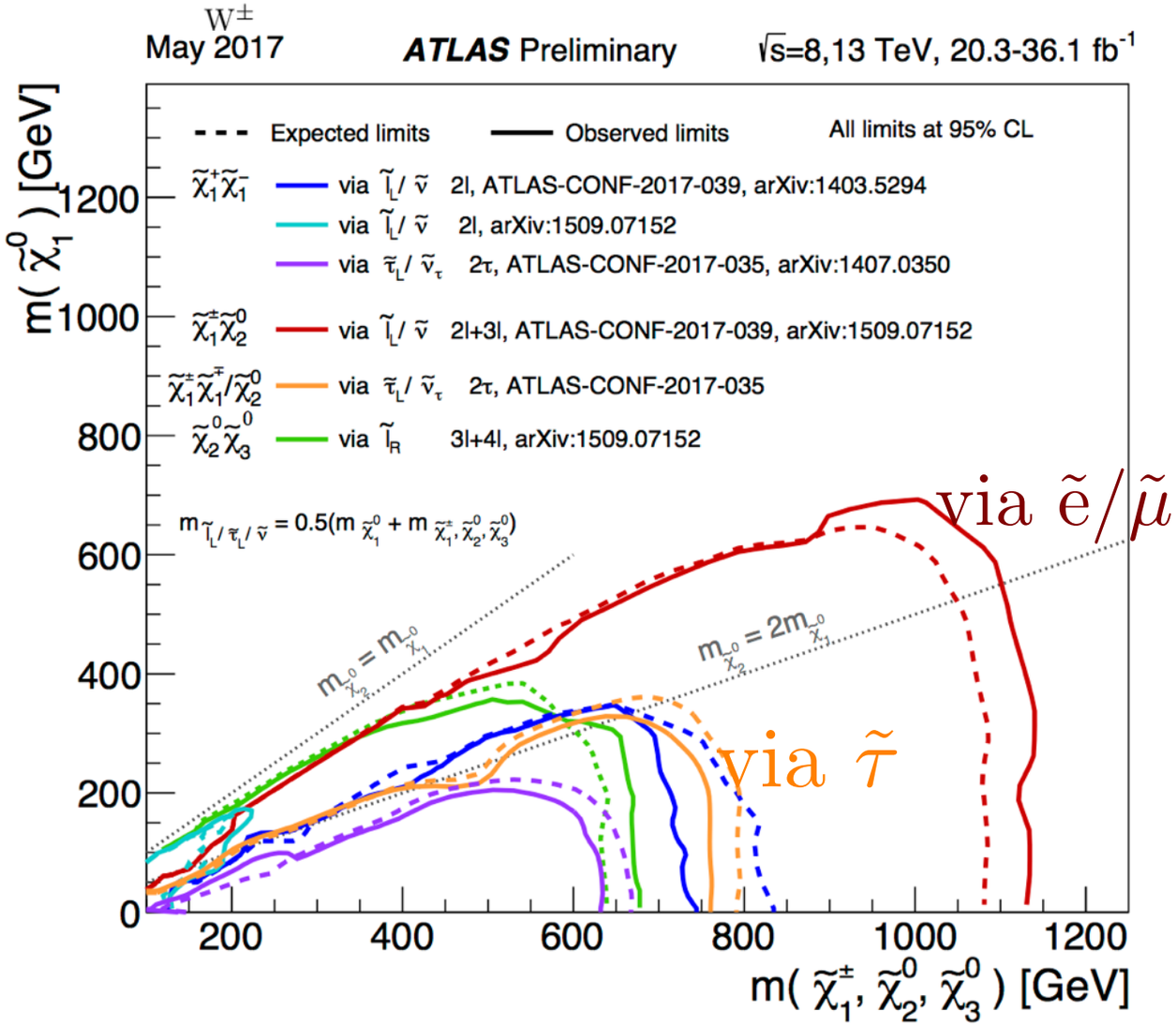
Electroweak SUSY: chargino

Powerful exclusions in decays using multi-leptons final states



CMS-PAS-SUS-17-004





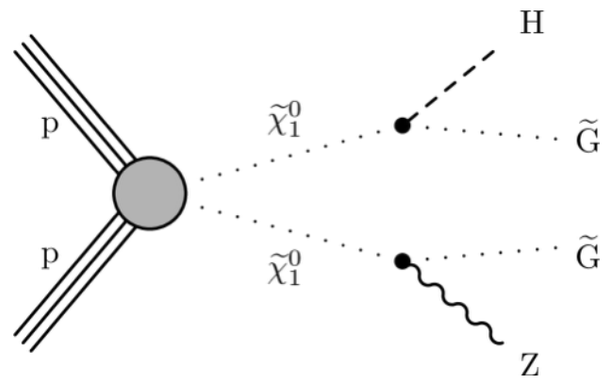
2 soft leptons: A region previously only reached by LEP (CMS-PAS-SUS-16-048)

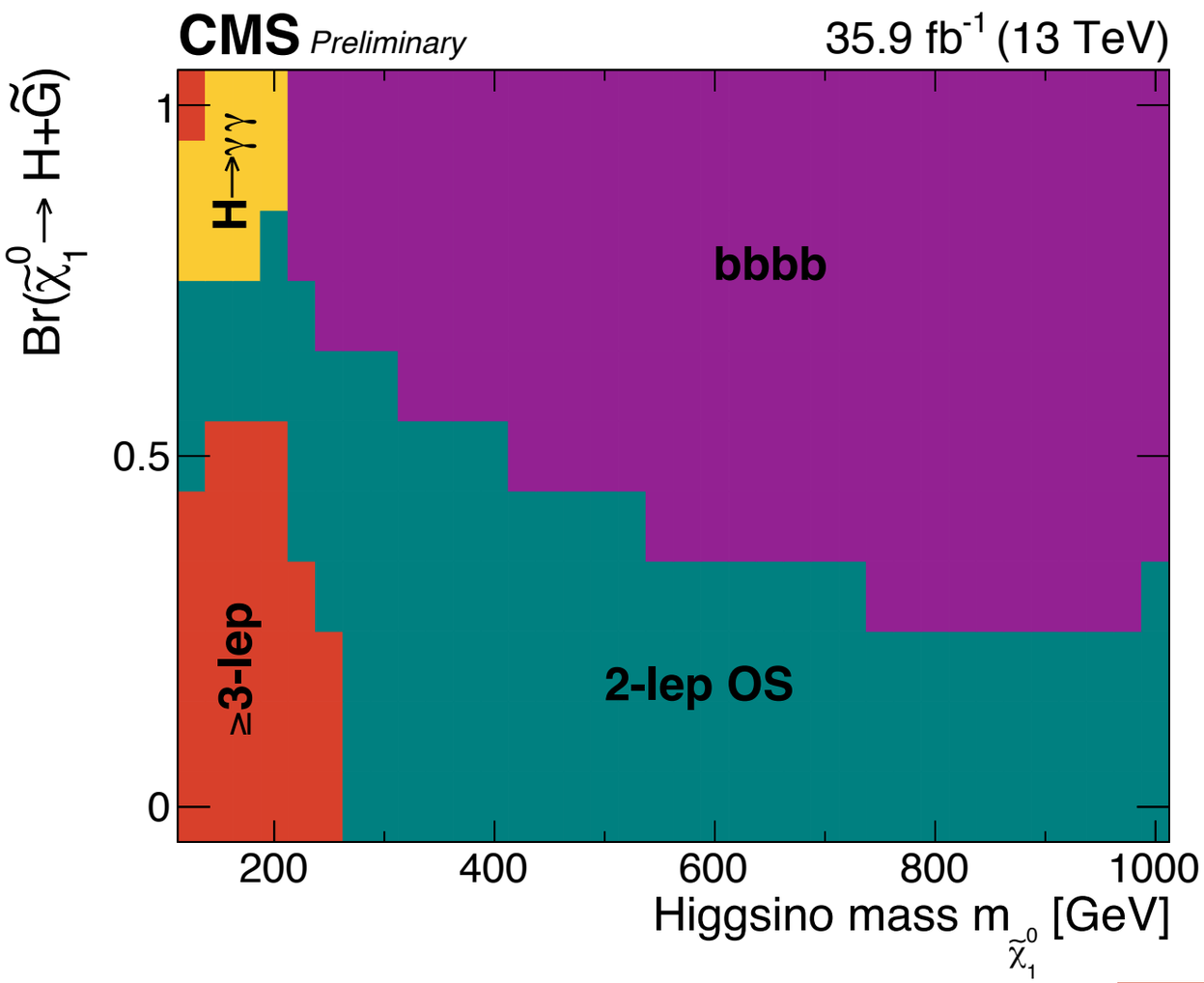
See today's BSM session@10:45 : Frank JENSEN
BSM session@13:30: Joseph REICHERT, Elodie RESSEGUIE

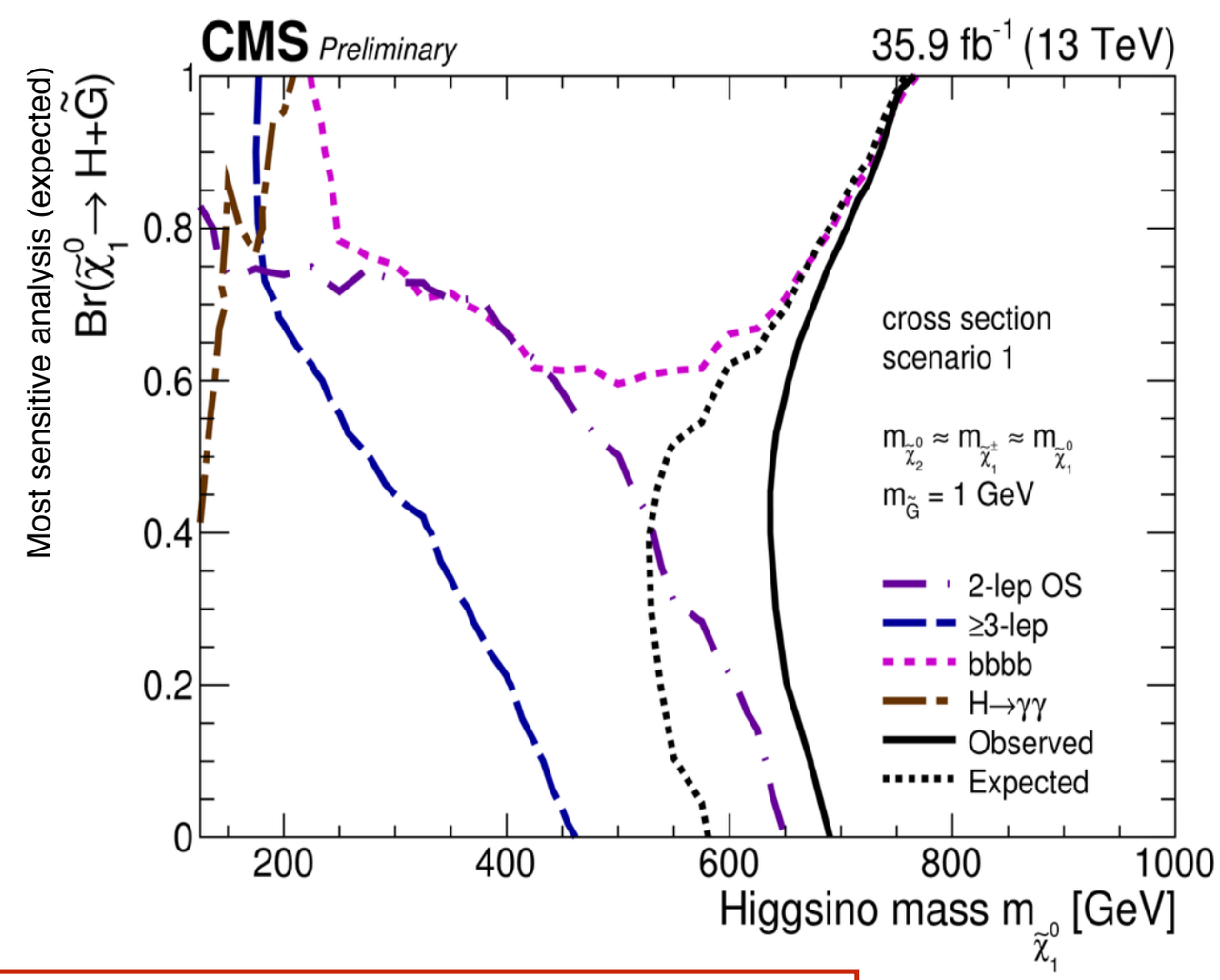
Electroweak SUSY: higgsino

Sensitivity to Gauge mediated SUSY breaking models

CMS-PAS-SUS-17-004



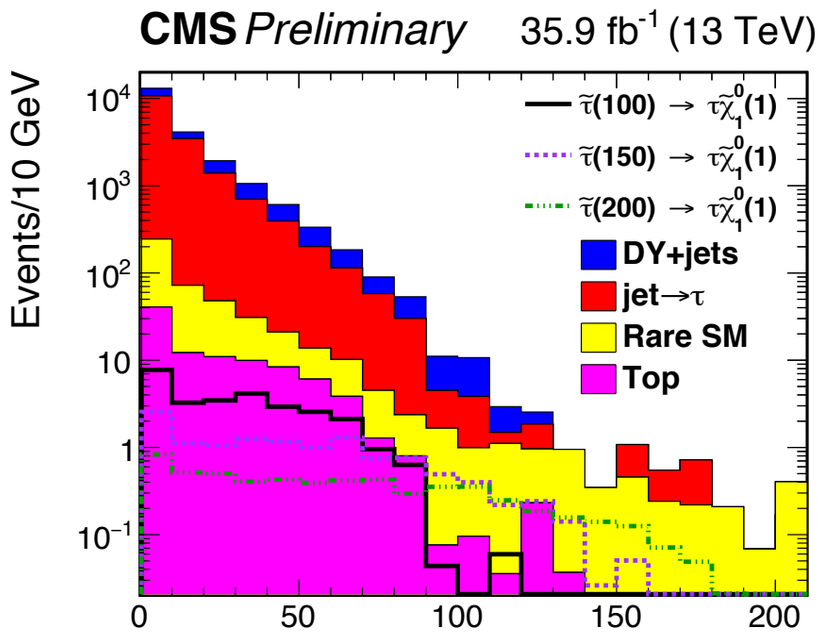




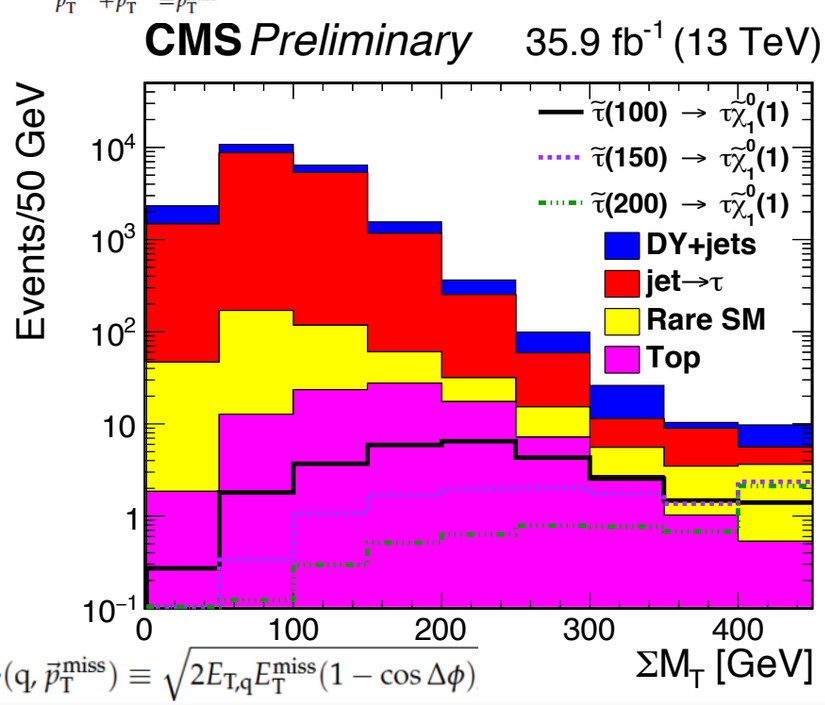
See today's BSM session@13:30 : Basil SCHNEIDER

Electroweak SUSY: sleptons

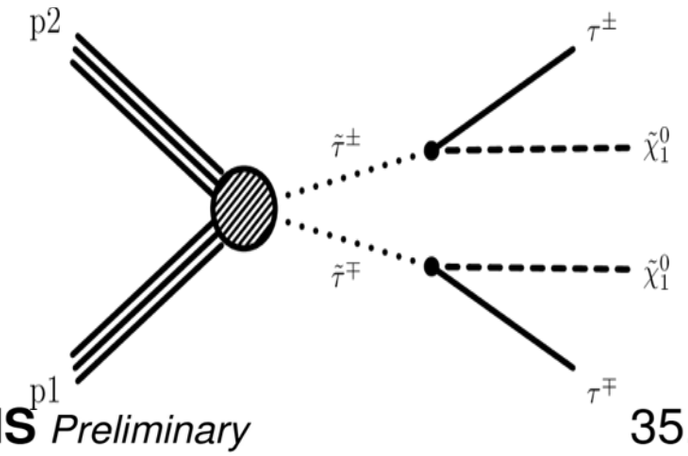
- Powerful exclusions in decays via sleptons
  - **Best sensitivity:** left-handed stau of around 125 GeV and a massless LSP, with expected exclusion of 1.5 times the expected SUSY cross-section.



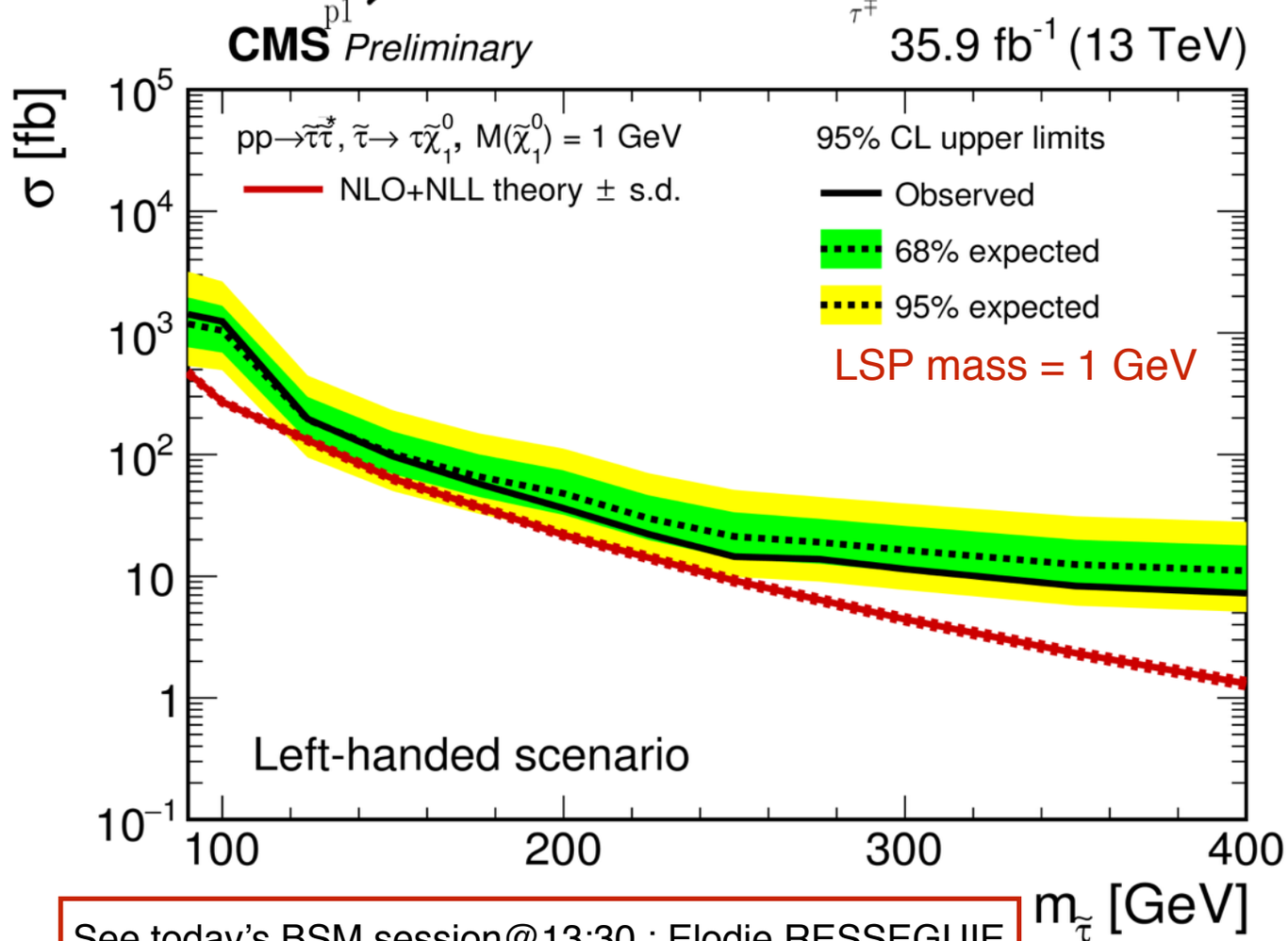
$$M_{T2} = \min_{\vec{p}_T^{\chi(1)}+\vec{p}_T^{\chi(2)}=\vec{p}_T^{miss}} \left[\max\left(M_T^{(1)}, M_T^{(2)}\right)\right]$$



$$M_T(q, \vec{p}_T^{miss}) \equiv \sqrt{2E_{T,q}E_T^{miss}(1-\cos\Delta\phi)}$$



CMS PAS SUS-17-003

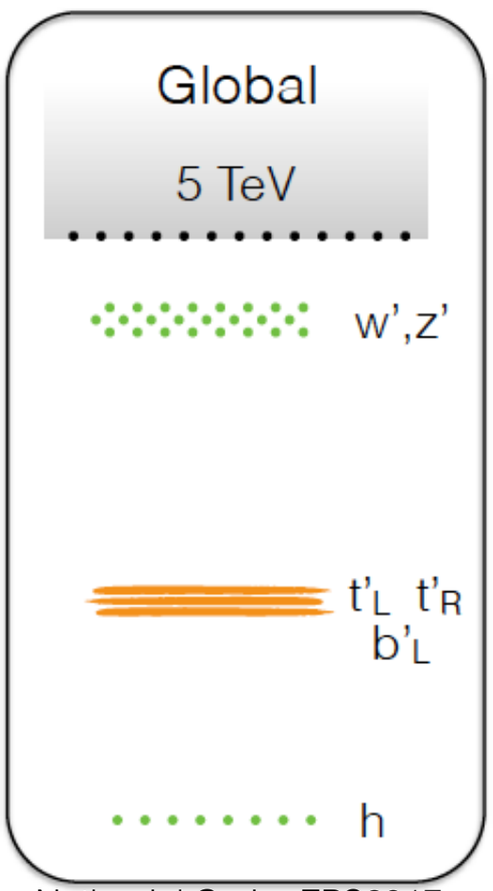


See today's BSM session@13:30 : Elodie RESSEGUIE

Global Symmetry

Complementary to SUSY, with light fermonic partners & Higgs tuning

$$\delta m_H^2 \propto \frac{3y_t^2}{8\pi^2} m_T^2 log(\Lambda/m_T)$$



Nathaniel Craig, EPS2017

Vector-like quarks:

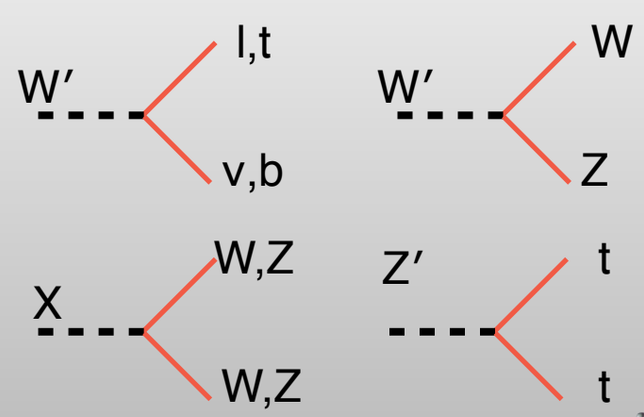
Non-chiral matter and with its own mass, $\mathcal{L}_{\mathrm{M}} = -\mathrm{M}\bar{\psi}\psi$

Transforms under the same representation of the SM $SU(3)_c \times SU(2)_W \times U(1)_Y$ gauge symmetry

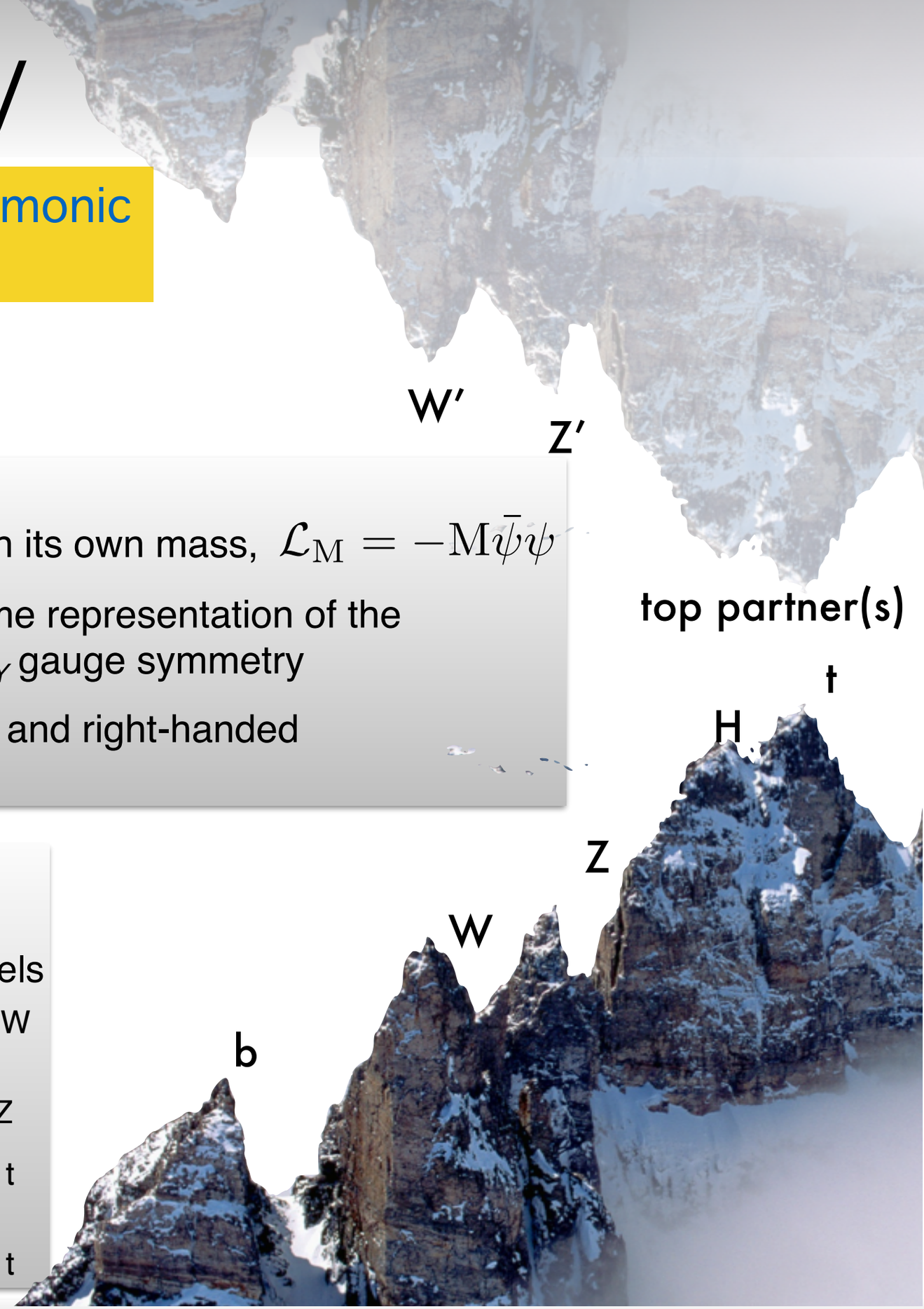
→ has both left-handed and right-handed charged currents

Partner bosons:

Z', W' and G' appear as **resonances** in BSM Models



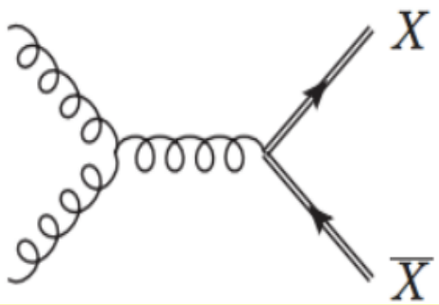
arxiv:1506.05110



Vector-like quarks

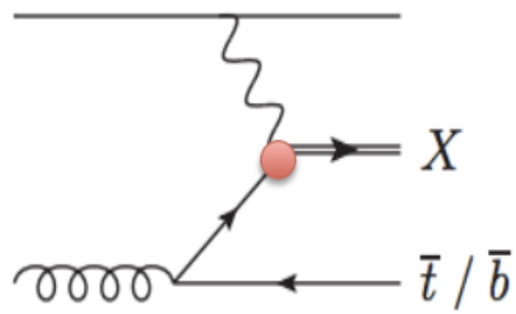
Produced either as in pair or as a single

Pair

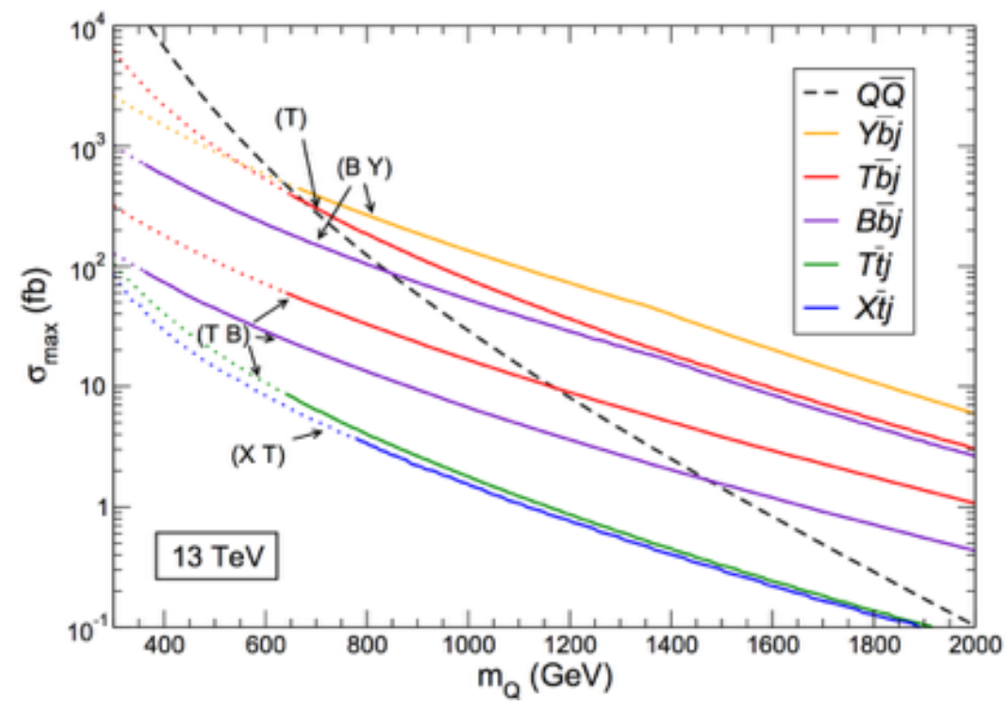


cross-section is independent of production mechanism

Single



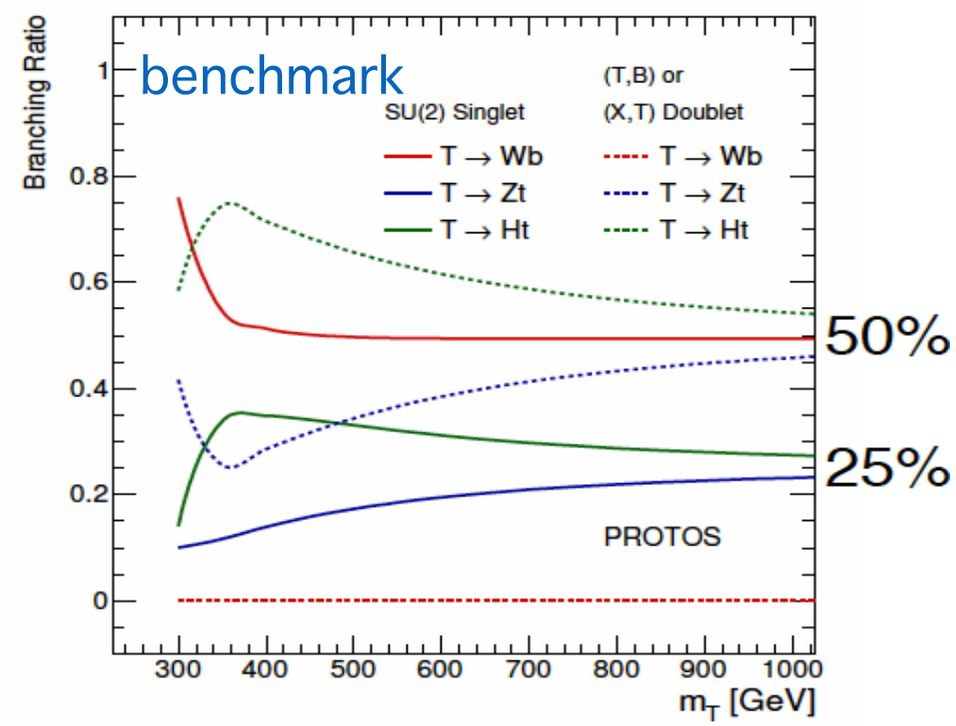
cross-section dependents of ewk couplings and production mode



Decays and allowed combinations

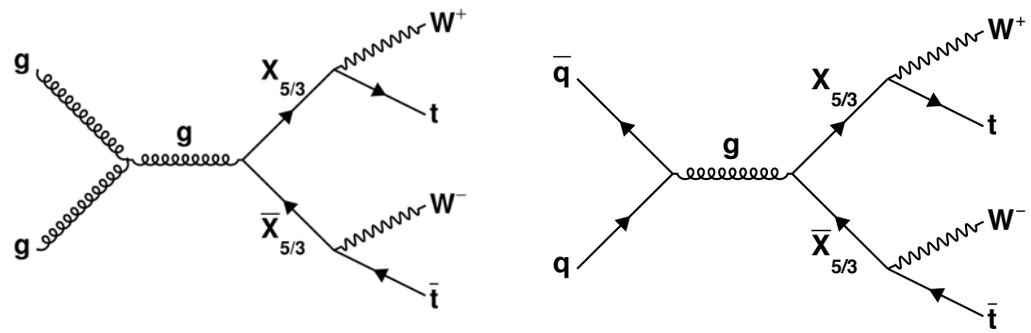
$Q^{Ele.Charge}$	Decays
$T^{2/3}$	bW^+, tH, tZ
$B^{-1/3}$	tW^-, bH, bZ
$X^{5/3}$	tW^+
$Y^{-4/3}$	bW^-

		I	Y
Singlet	T	1	2/3
	B	1	-1/3
Doublet	T, B	2	1/6
	T, X	2	7/6
	B,Y	2	-5/6
Triplet	T, B, X	3	2/3
	T, B, Y	3	-1/3

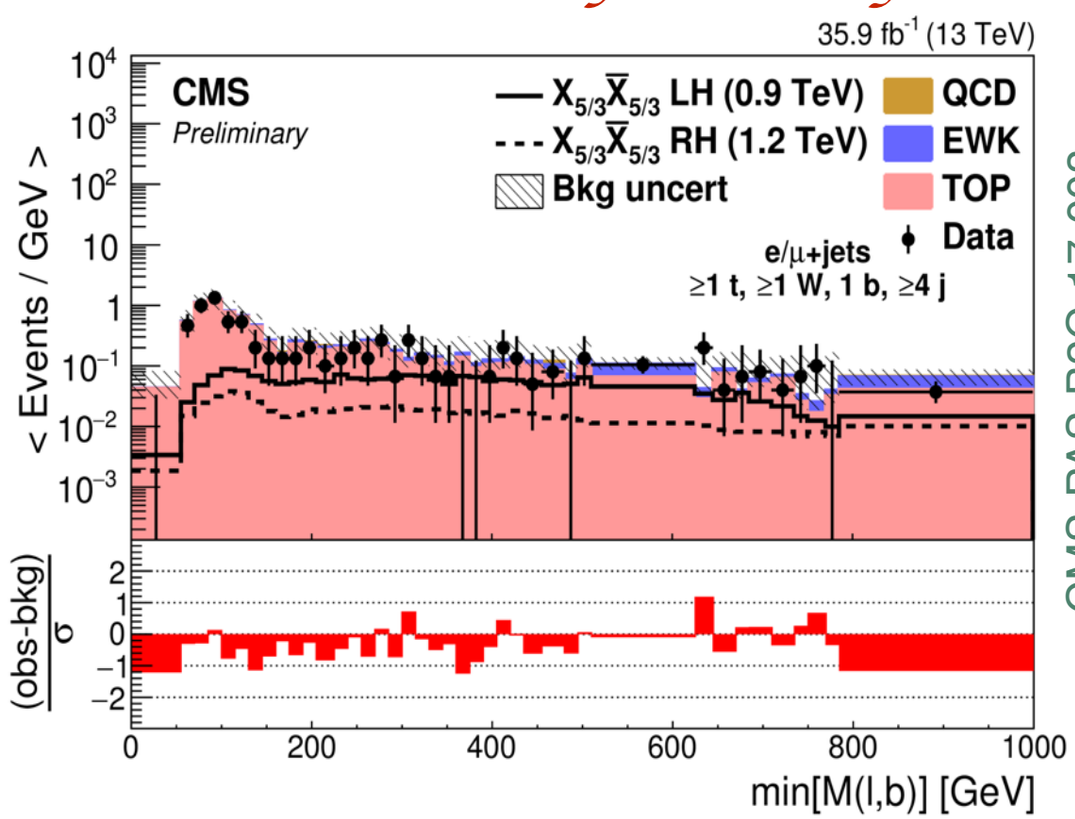


VLQ Searches

Pair Production in 1l+jets+ E_T^{Miss}



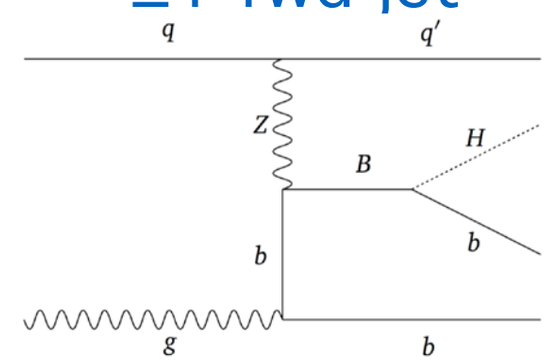
Extensive use of boosted jets!

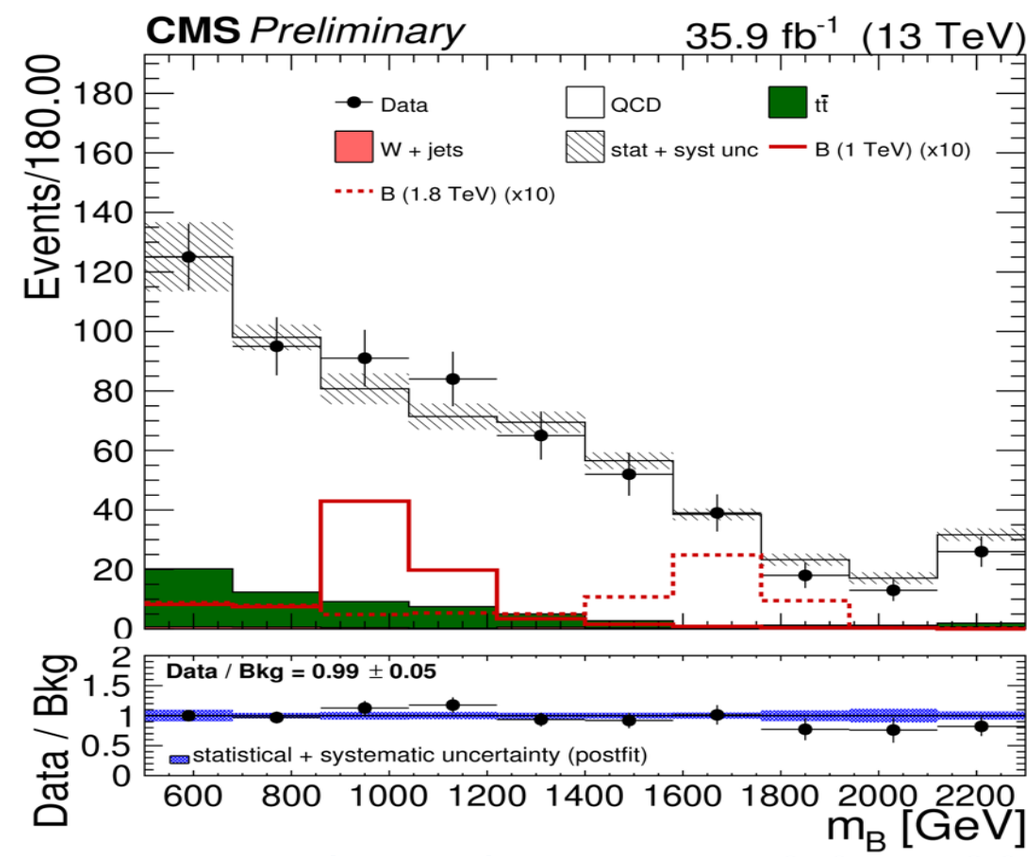


CMS-PAS-B2G-17-008

Mass exclusion limits up to 1.3 TeV

Single Production in all hadronic with ≥1 fwd jet





CMS-PAS-B2G-17-009

$\sigma \times$ BR exclusion limits up to 0.07-1.28 pb for B masses 700-1800 GeV

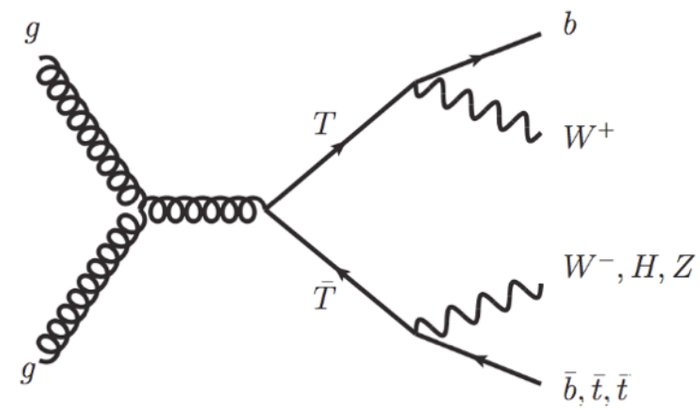
See Tuesday's (01/08) BSM sessions at 13:30
Anthony BARKER, Rachitha MENDIS, Rizki SYARIF, Tyler MITCHEL, Erich SCHMITZ

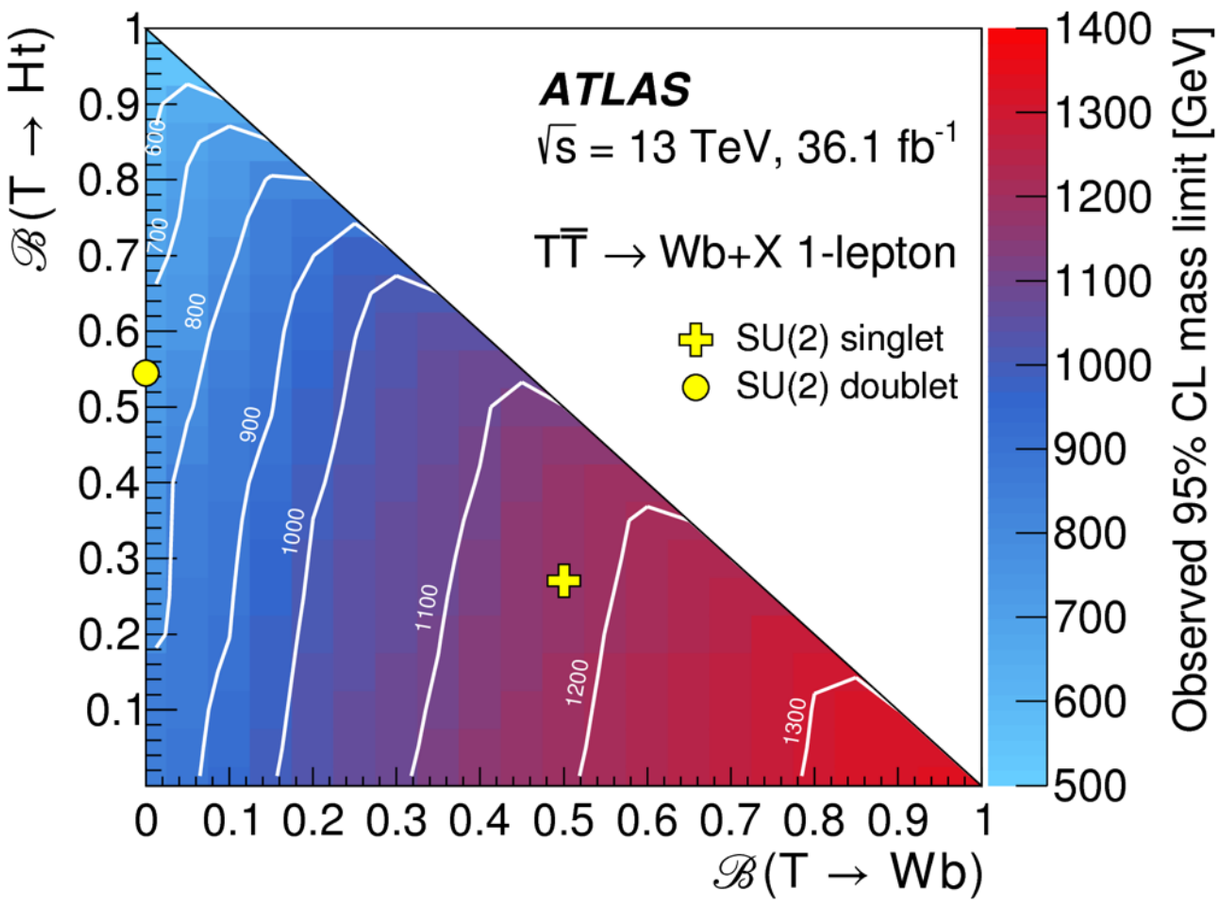
VLQ Searches

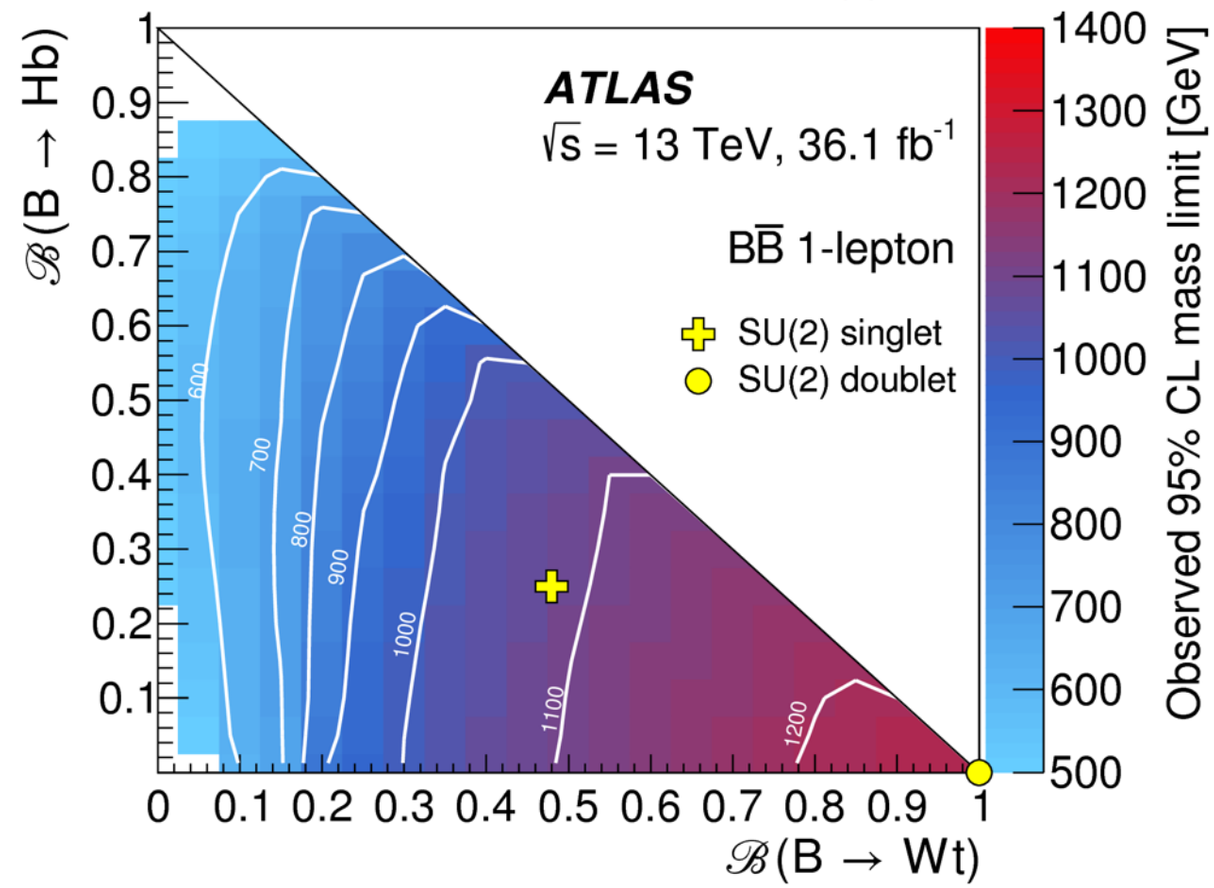
TT/BB in 1l+jets+ E_T^{Miss} using mass reconstruction

Extensive use of boosted jets!

arXiv:1707.03347







Typical mass limits for singlet T/B pair production >1 TeV

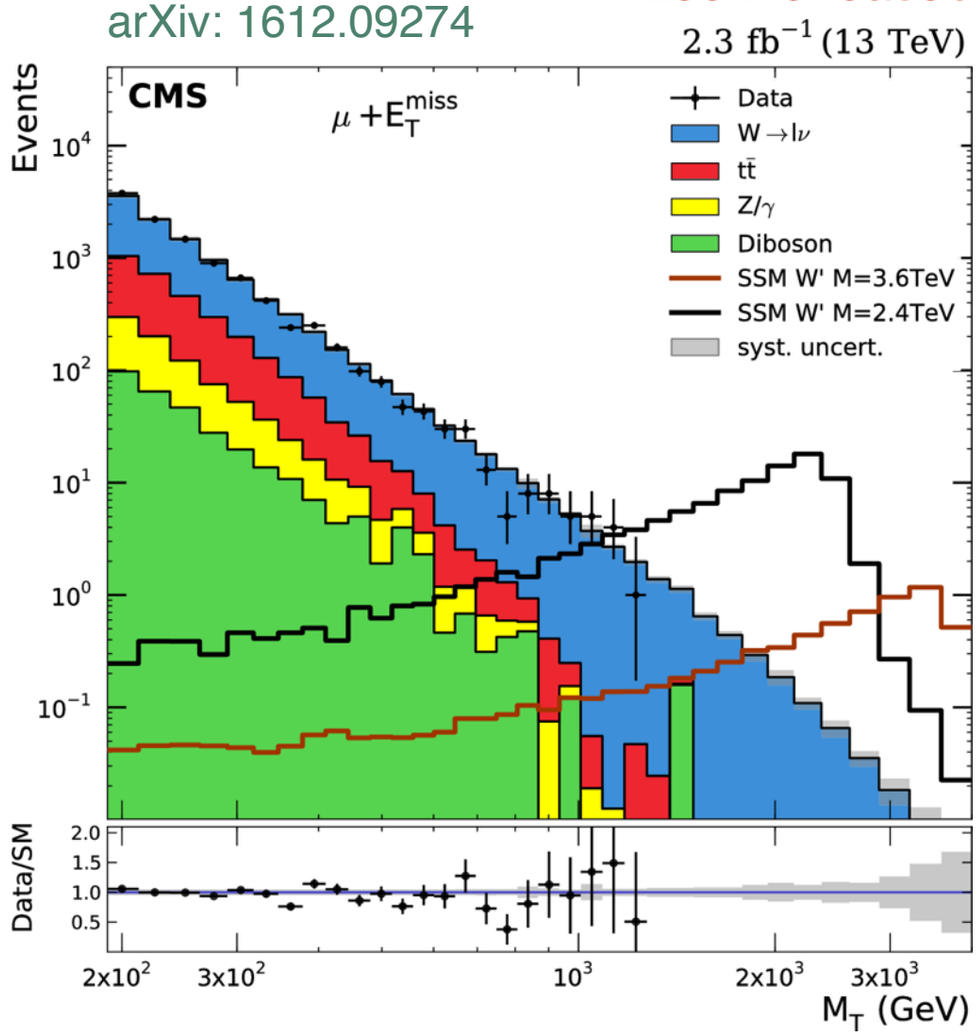
See Tuesday's (01/08) BSM session talk by Joseph HALEY

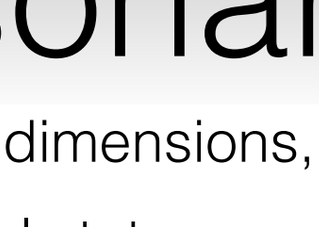
Resonances

- Sensitive to many BSM scenarios: extra dimensions, new gauge bosons, heavy higgs (A/H) …
- New particle can decay into multiple final states:
  - **dileptons, lepton+ E_T^{Miss}, dijets, γ+jets, dibosons (VV, V_γ, γγ), tt, tb ..**

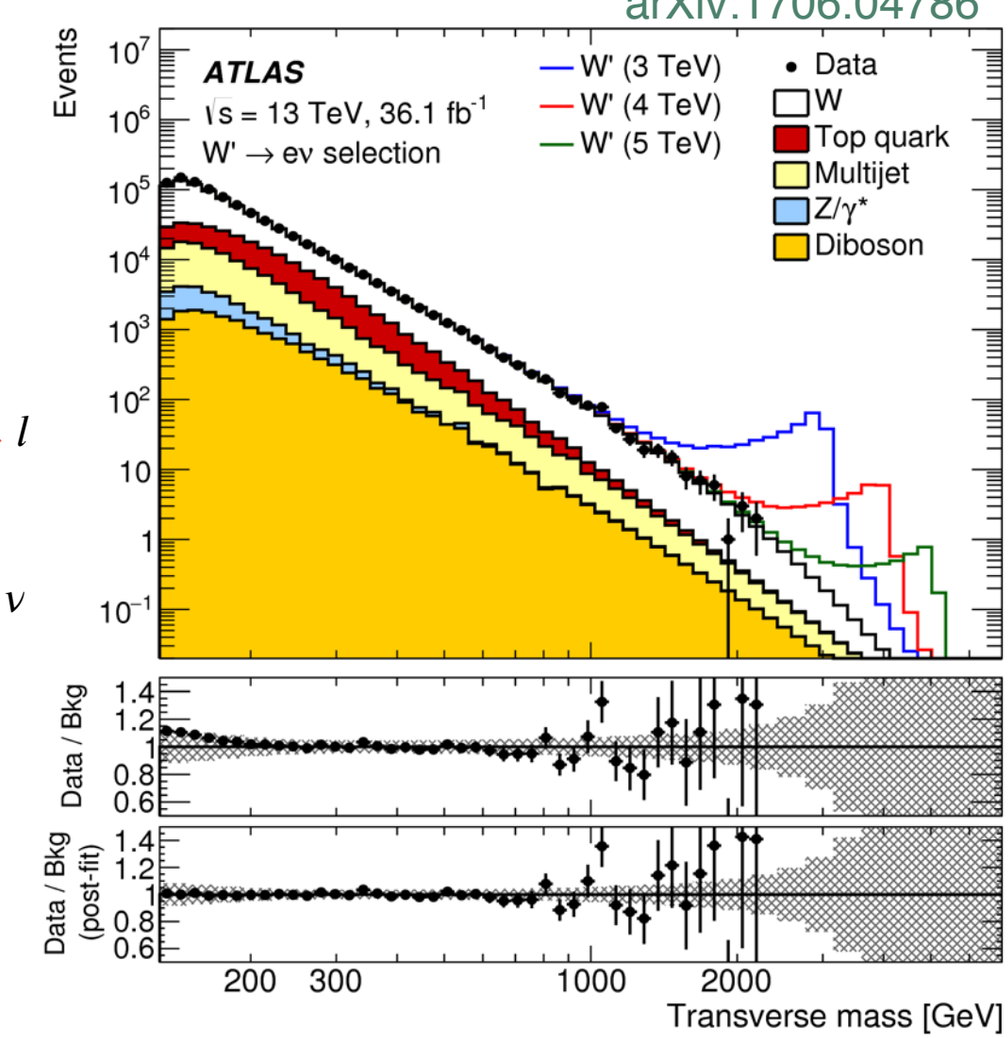
Look for Jacobian-Peak in W-transverse mass, M_T

arXiv: 1612.09274





arXiv:1706.04786



- No significant deviation in data up to 2 TeV
- Simple SM extensions getting tightly constrained up to 4-5 TeV

See Tuesday's (01/08) BSM session
Norbert NEUMEISTER (Z', W', dijet)

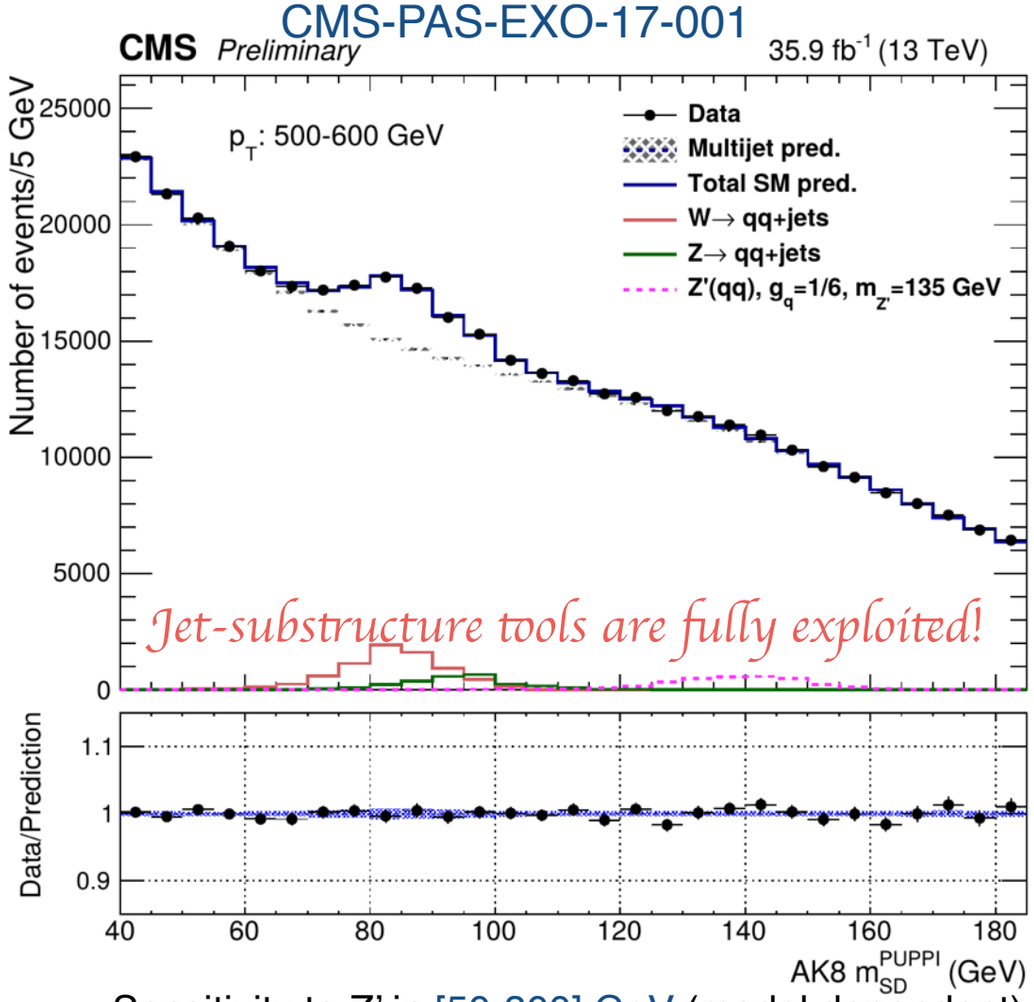
Resonances

- Sensitive to many BSM scenarios: extra dimensions, new gauge bosons, heavy higgs (A/H) …
- New particle can decay into multiple final states:
  - **dileptons, lepton+ E_T^{Miss}, dijets, γ+jets, dibosons (VV, Vγ, γγ), tt, tb ..**

Z' resonance in qqbar merged in 1 jet

Excited states of L/H flavor quarks in γ+jets

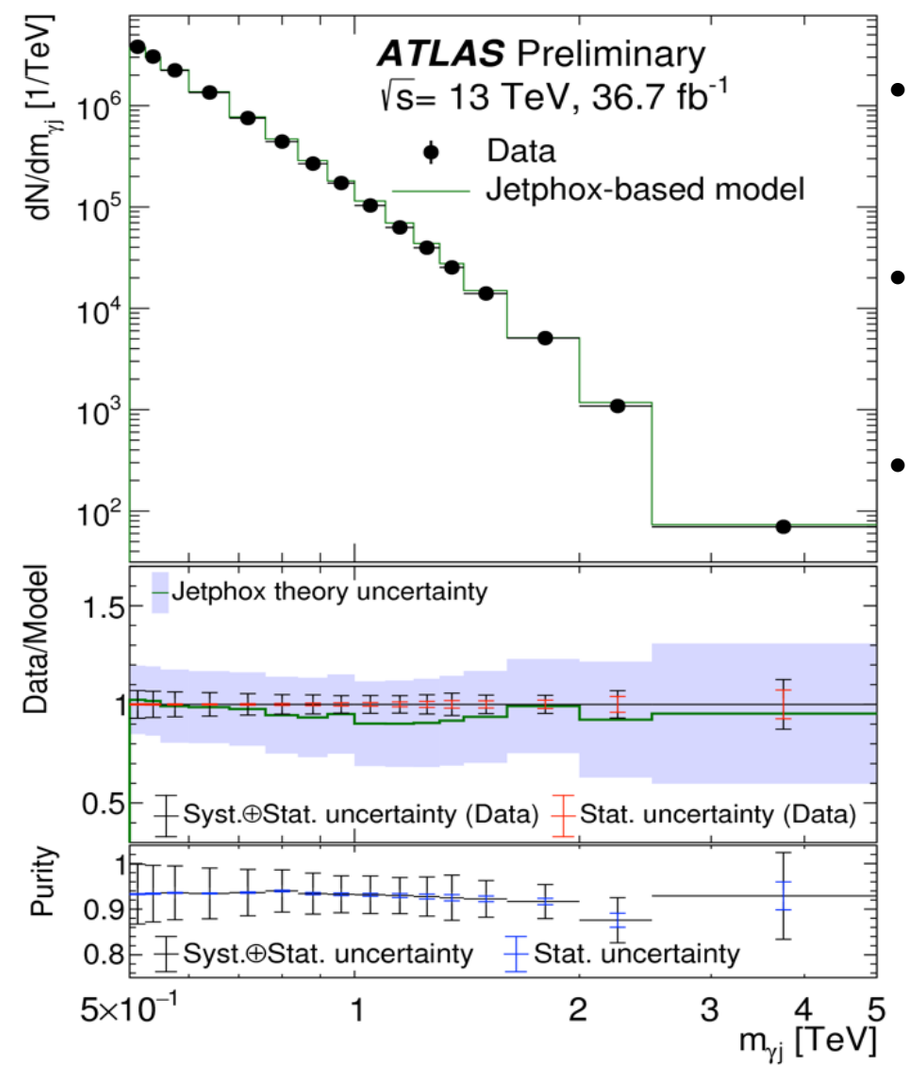
CMS-PAS-EXO-17-001



Sensitivity to Z' in [50-300] GeV (model dependent)

See Tuesday's (01/08) BSM session
Alejandro GOMEZ, Norbert NEUMEISTER, Laser KAPLAN, Cristina Ana MANTILLA SUAREZ

Presented at EPS2017



CMS results: CMS-PAS-EXO-17-002

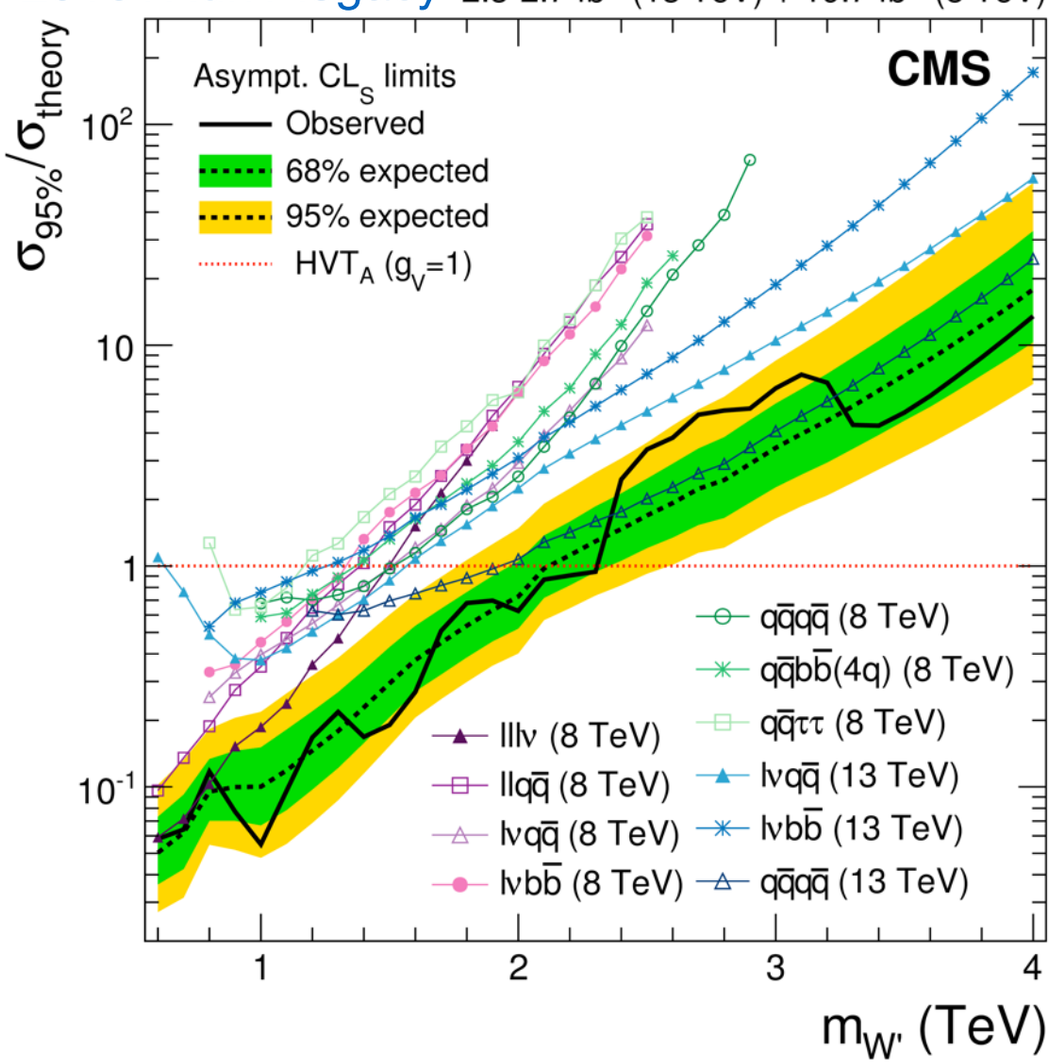
- Excited quarks: m < 5.3 TeV
- ADD-Quantum black holes: m < 7.1 TeV
- RS-Quantum black holes: m < 4.4 TeV

Resonances

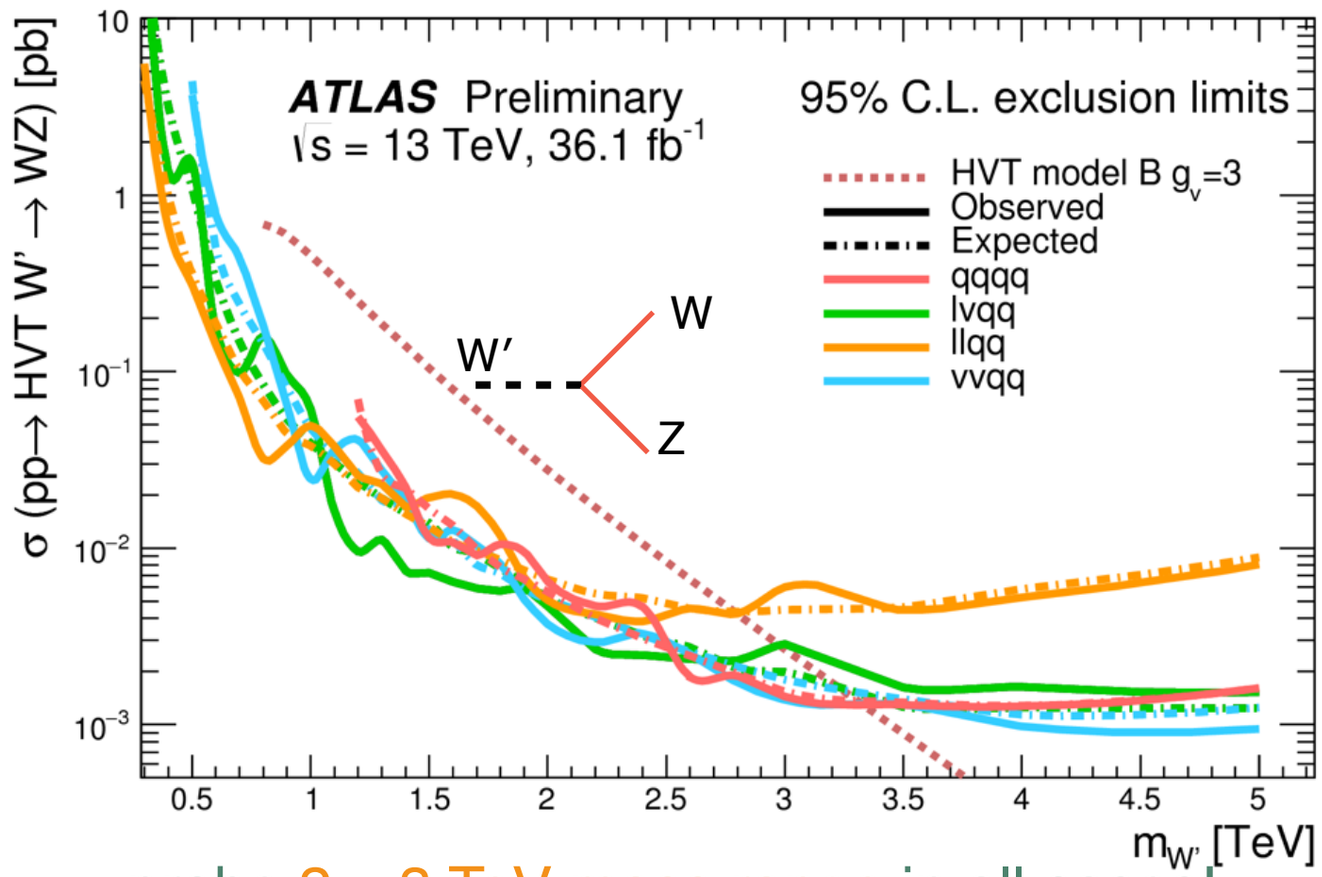
- Sensitive to many BSM scenarios: extra dimensions, new gauge bosons, heavy higgs (A/H) …
- New particle can decay into multiple final states:
  - **dileptons, lepton+ E_T^{Miss}, dijets, γ+jets, dibosons (VV, Vγ, γγ), tt, tb ..**

Sensitive to many model of NP, all final states explored: → llqq, llvv, vvqq, lvqq, qqqq, llll …

2016+Run1 legacy 2.3-2.7 fb^{-1} (13 TeV) + 19.7 fb^{-1} (8 TeV)



qqqq, 2l2ν, VH(bb), 2l2q, lνqq



probe 2 – 3 TeV mass range in all cases!

More results: CMS-PAS-B2G-17-005

See Tuesday's (01/08) BSM session
Manuel SILVA (γγ resonance)

Thursday's (03/08) BSM session@10:45
Caterina VERNIERI, Ines OCHOA,
Yanchu WANG, Wei TANG

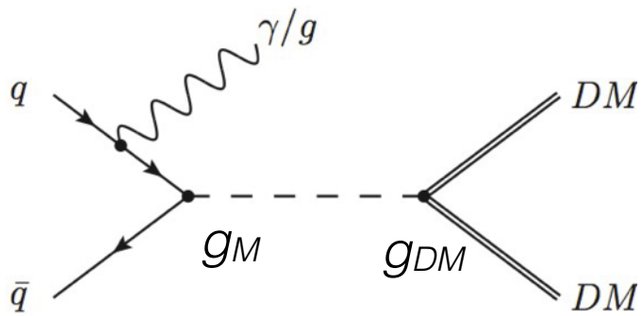
Dark Matter

The Indirect View

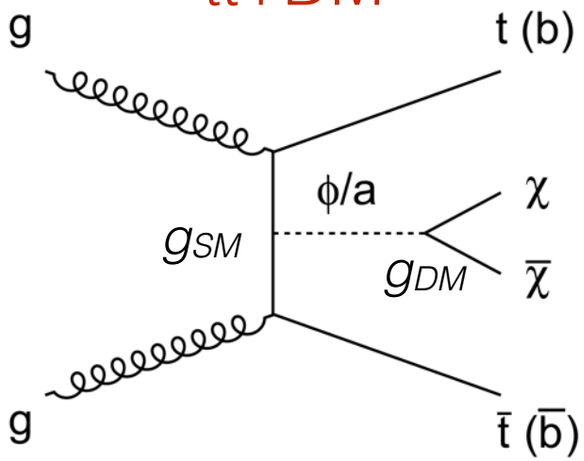
- Simplified models
  - 2 new particles: mediator and stable DM particle
  - Mediator: Vector, axial-vector, scalar or pseudoscalar
  - Rich phenomenology depends on mass of DM, mass of heavy mediator, and the value and type of the couplings
  - **Usually two free coupling constants: g_M and g_{DM}**

- Signatures at collider
  - An object recoiling against large E_T^{Miss}
    - Mono-jet
    - Mono-photon
    - Mono-lepton
    - Mono-W/Z/H
    - Mono-top quark
    - tt/bb pair + DM
  - Boosted boson in association with ISR jet

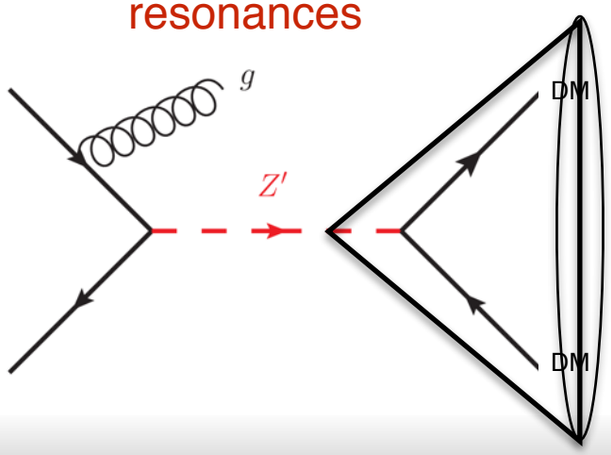
j/γ+DM



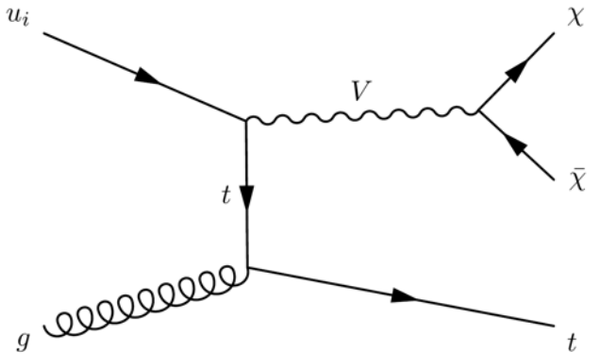
tt+DM



leptophobic vector resonances

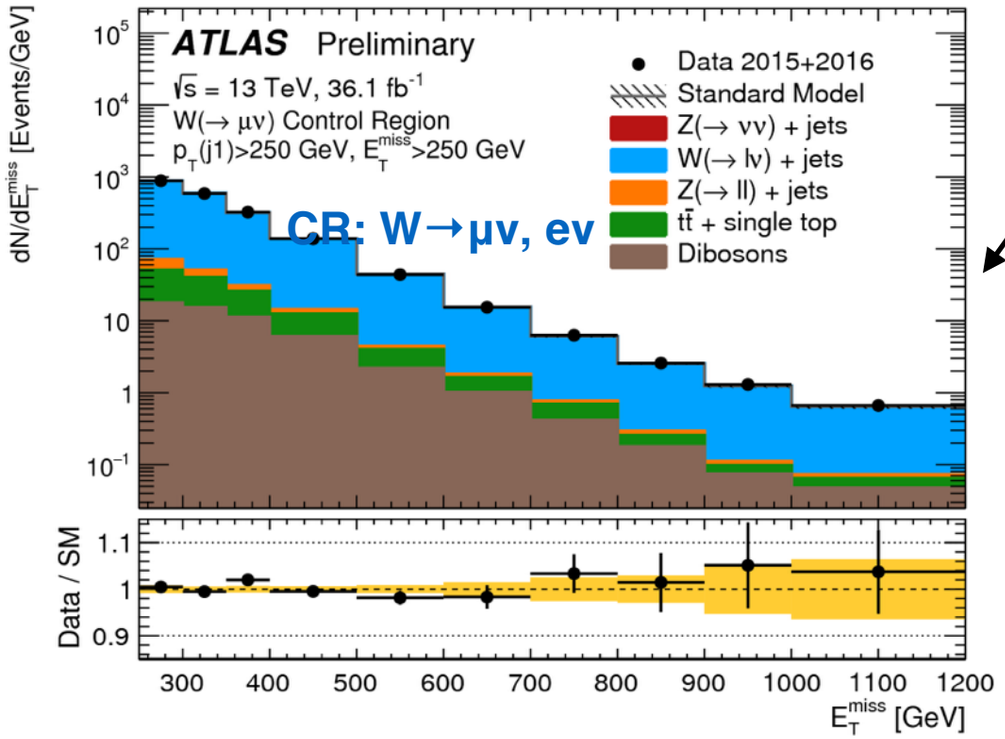


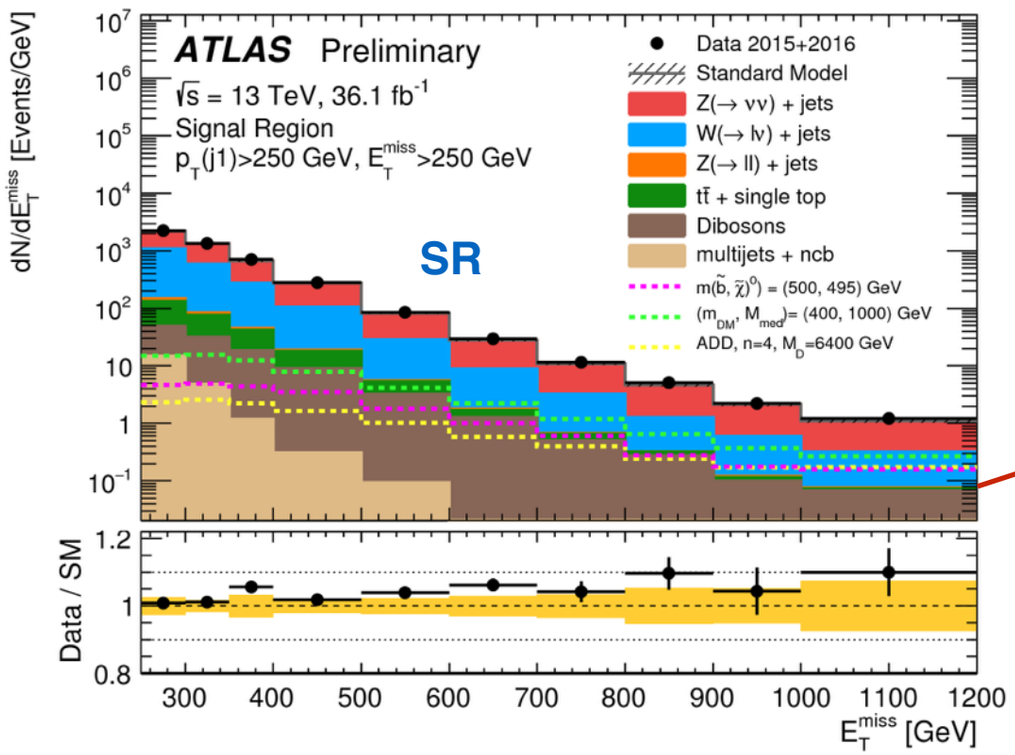
t+DM: FNCN



Dark Matter: Mono-jet

- Mono-jet: E_T^{Miss} based signal regions with E_T^{Miss} > 250 GeV



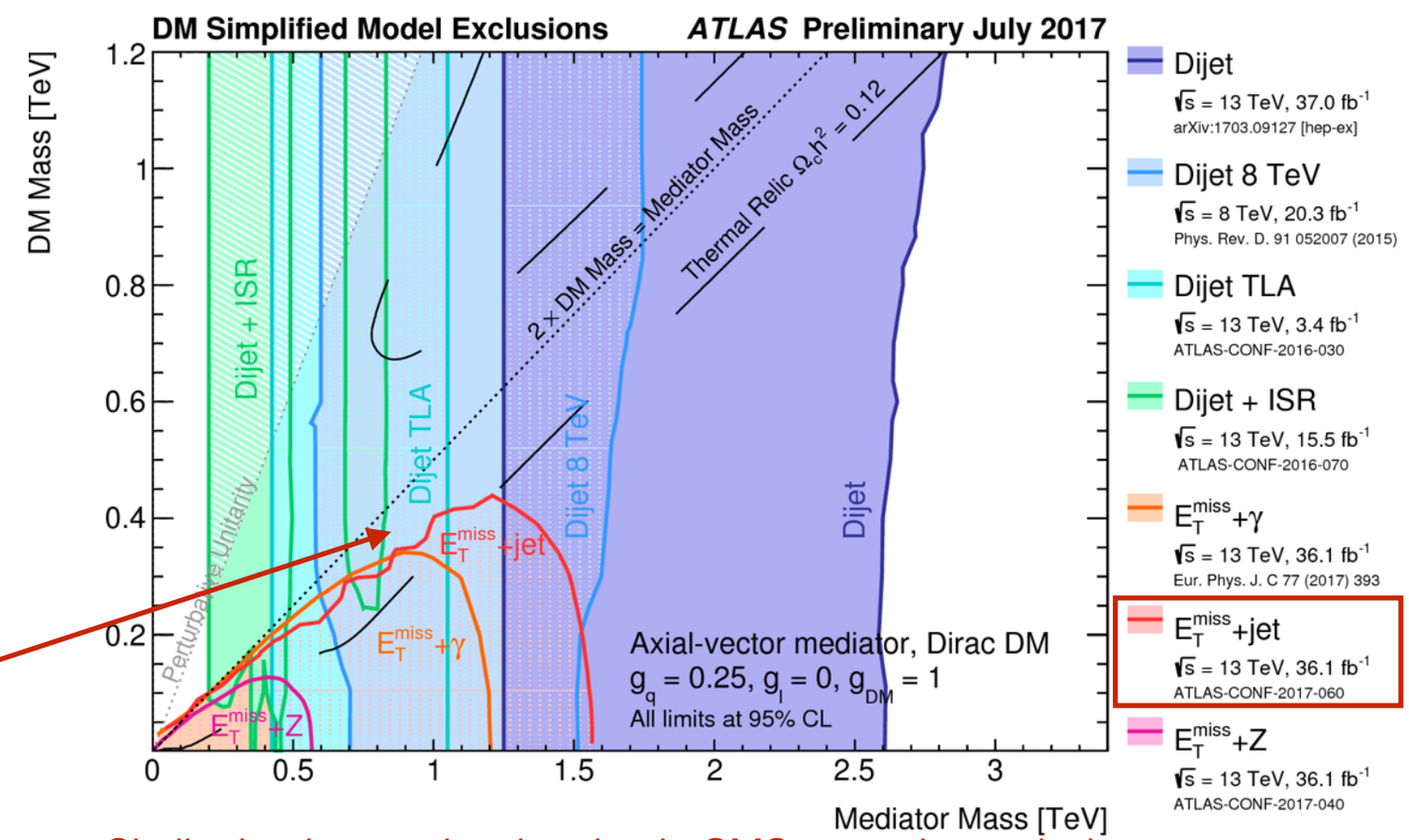


ATLAS-CONF-2017-060

- Constrain backgrounds by fitting simultaneously in W, Z/γ*, tt CRs ⇒ systematic uncertainties reduces up to 40%
- Variety of interpretations: DM models, SUSY stop in charm + E_T^{Miss}, extra dimensions

Model-dependent summary

ATLAS: arxiv:1704.03848



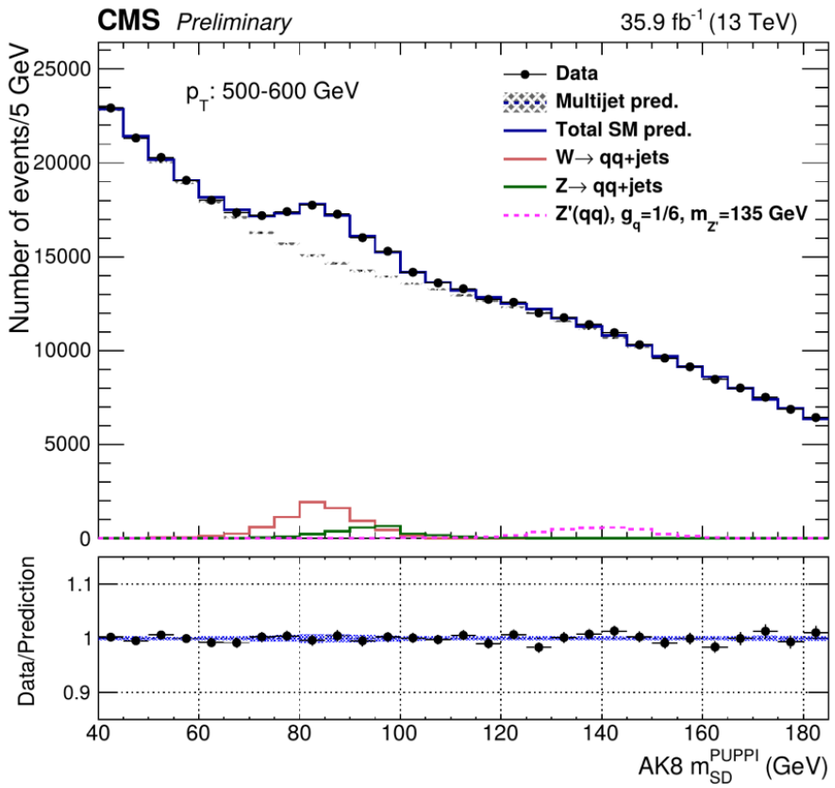
Similar background estimation in CMS mono-jet analysis (CMS-PAS-EXO-16-048)

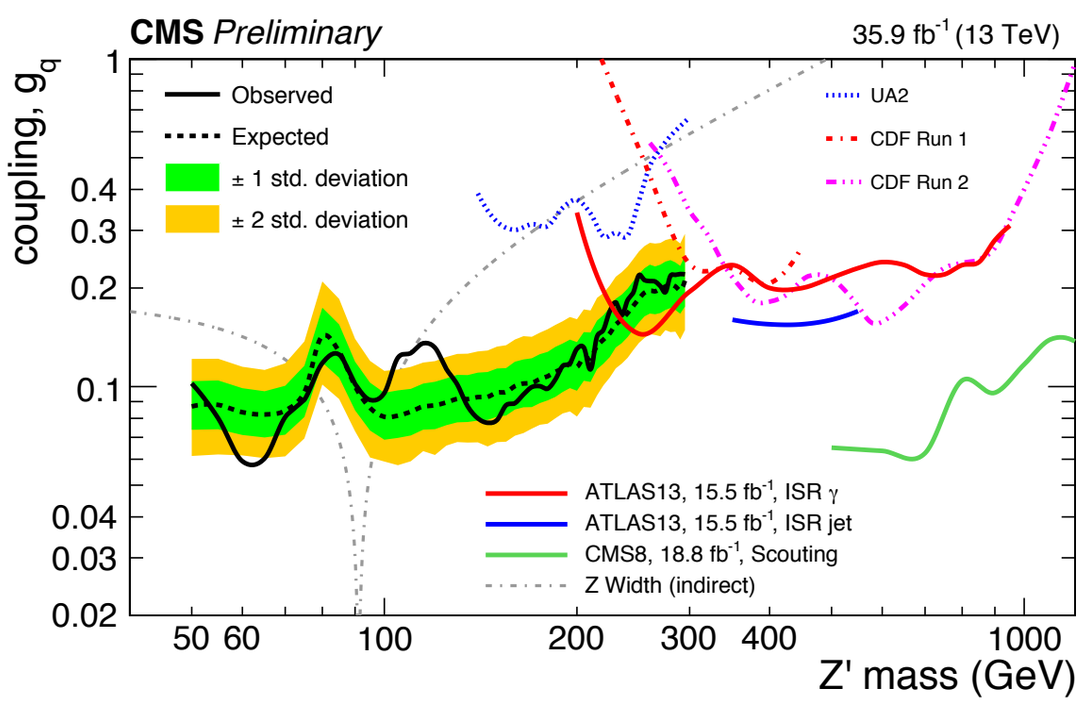
See Thursday's (03/08) BSM session CMS talk by Sonaina UNDLEEB

Dark Matter:di-jet

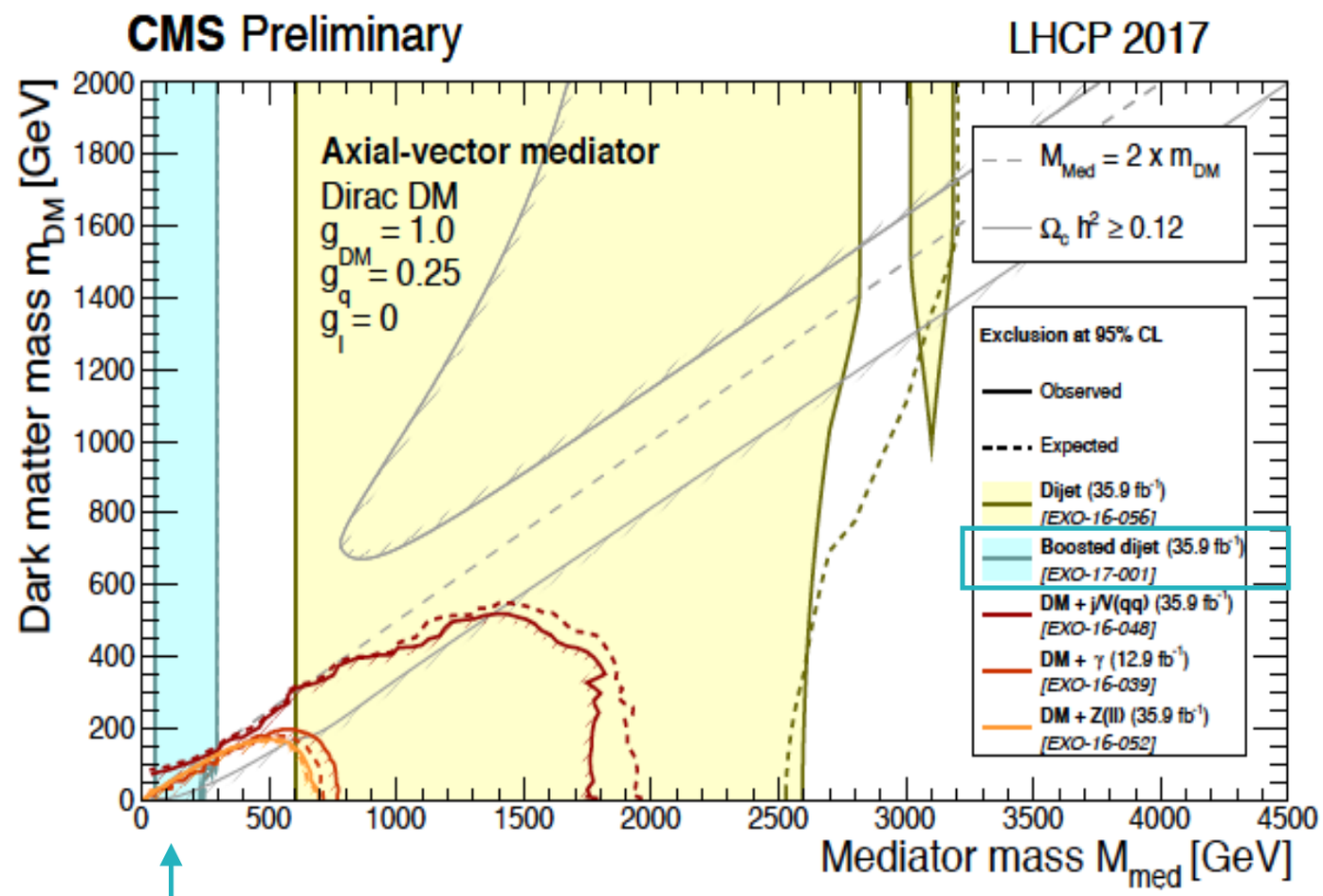
Di-jet resonance: one fat jet with p_T>500 GeV

CMS-PAS-EXO-17-001

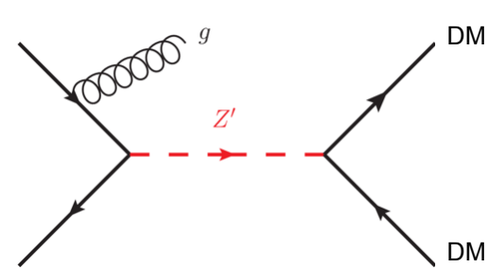




Model-dependent summary



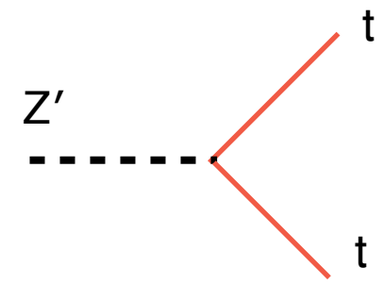
Most sensitive limits up to date for leptophobic Z' mediator interacting between quarks and dark matter particles through an axial-vector current



Similar results for vector mediator

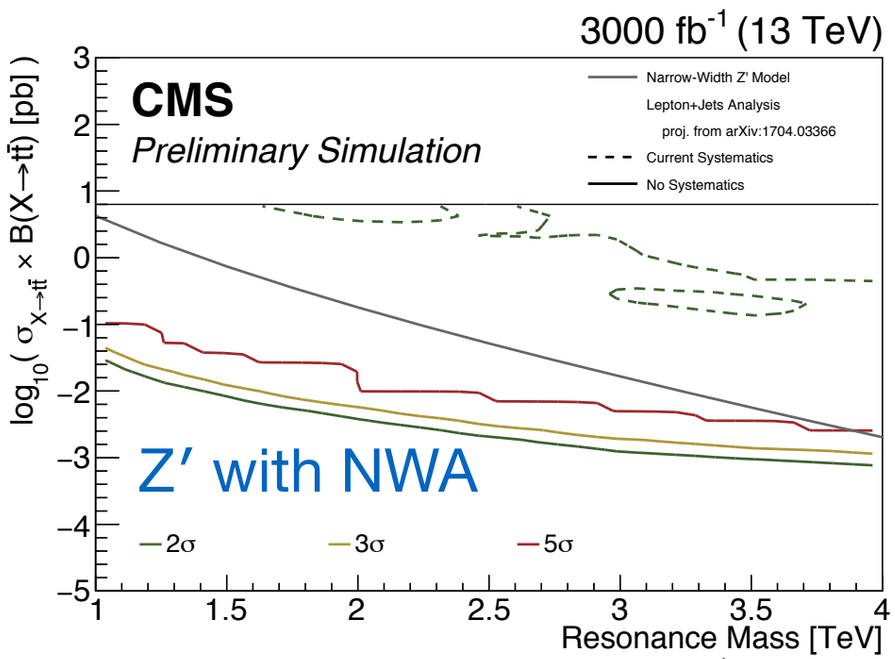
New Physics @ HL-LHC

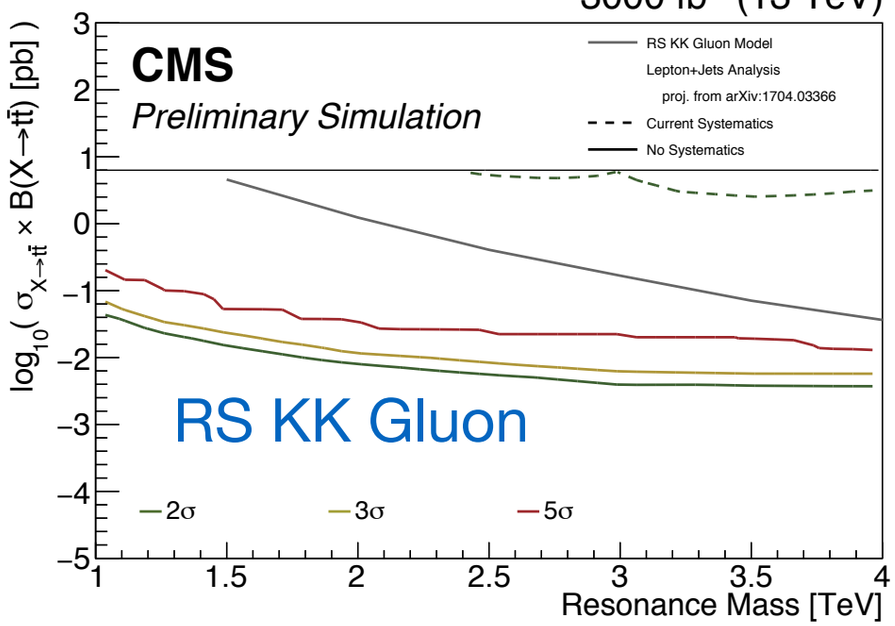
- With luminosity of 7×10^{34} Hz/cm^2 and a pileup of 200, both ATLAS and CMS foresee rebuilding the Tracker and Hadronic Calorimeter subsystems by 2025



Projections of Z′ in l+jets @ 13 TeV

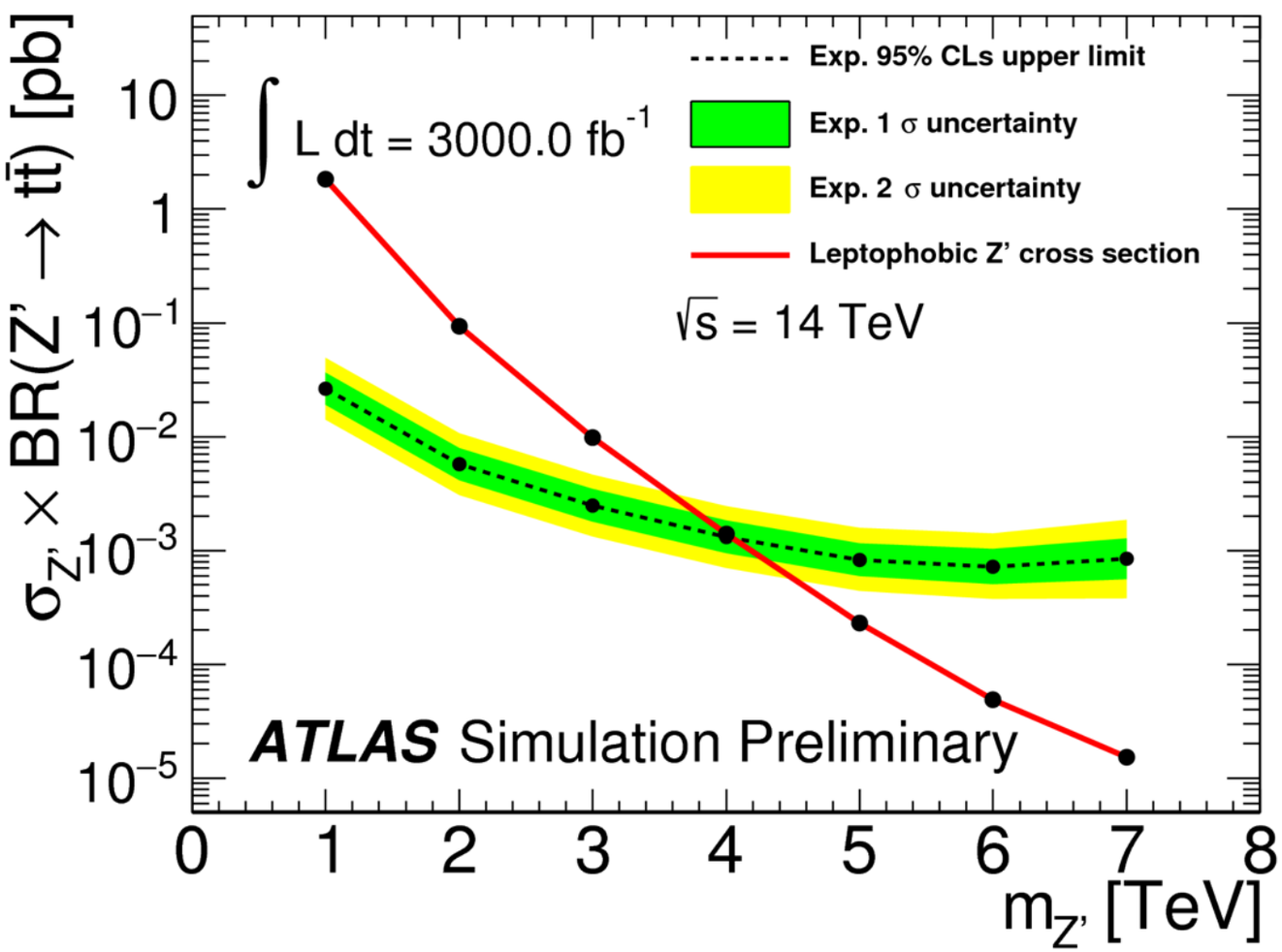
CMS-PAS-FTR-16-005





ATL-PHYS-PUB-2017-002

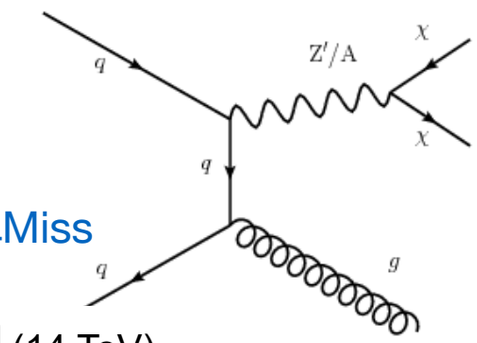
Topcolour Z' using full simulations



Exclusion limits up to 4 TeV @ 3/ab

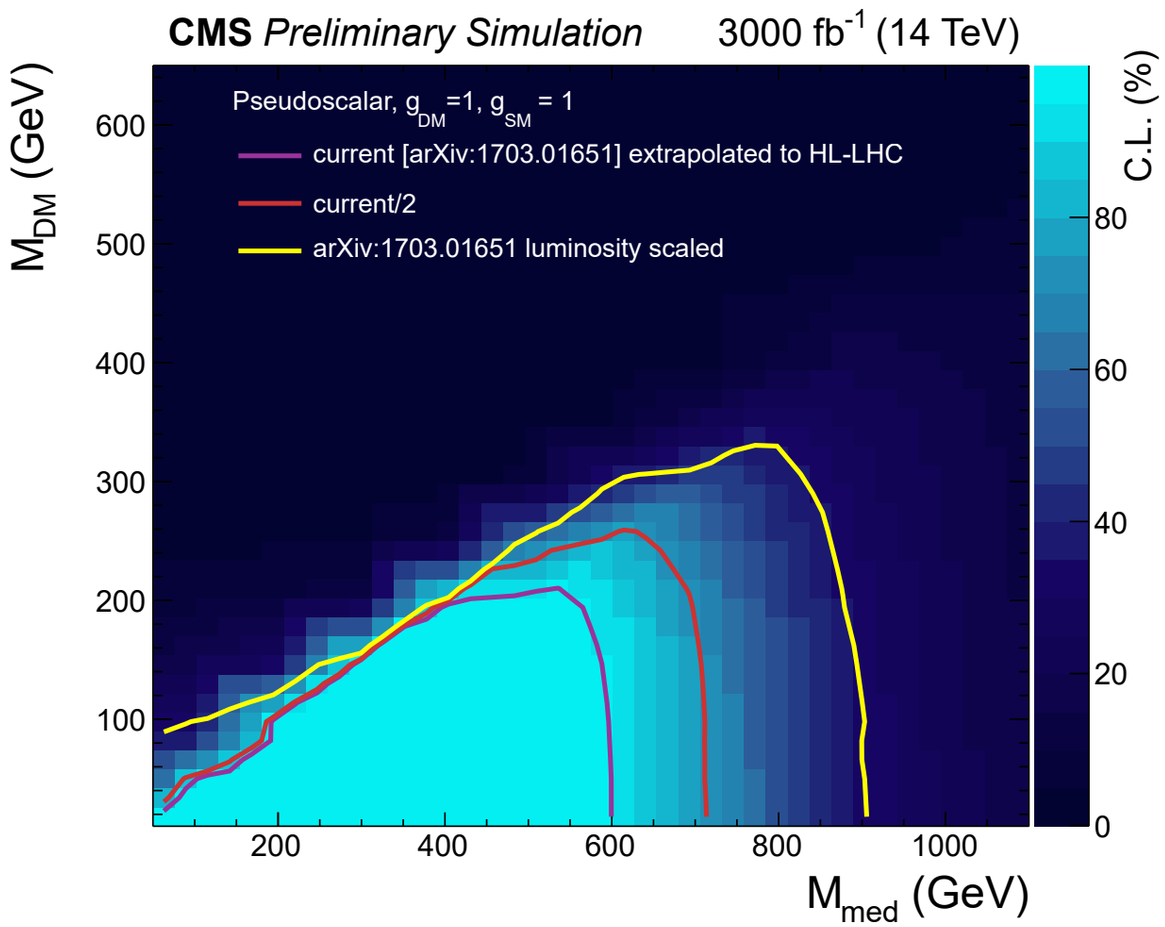
New Physics @ HL-LHC

- With luminosity of 7×10^{34} Hz/cm^2 and a pileup of 200, both ATLAS and CMS foresee rebuilding the Tracker and Hadronic Calorimeter subsystems by 2025

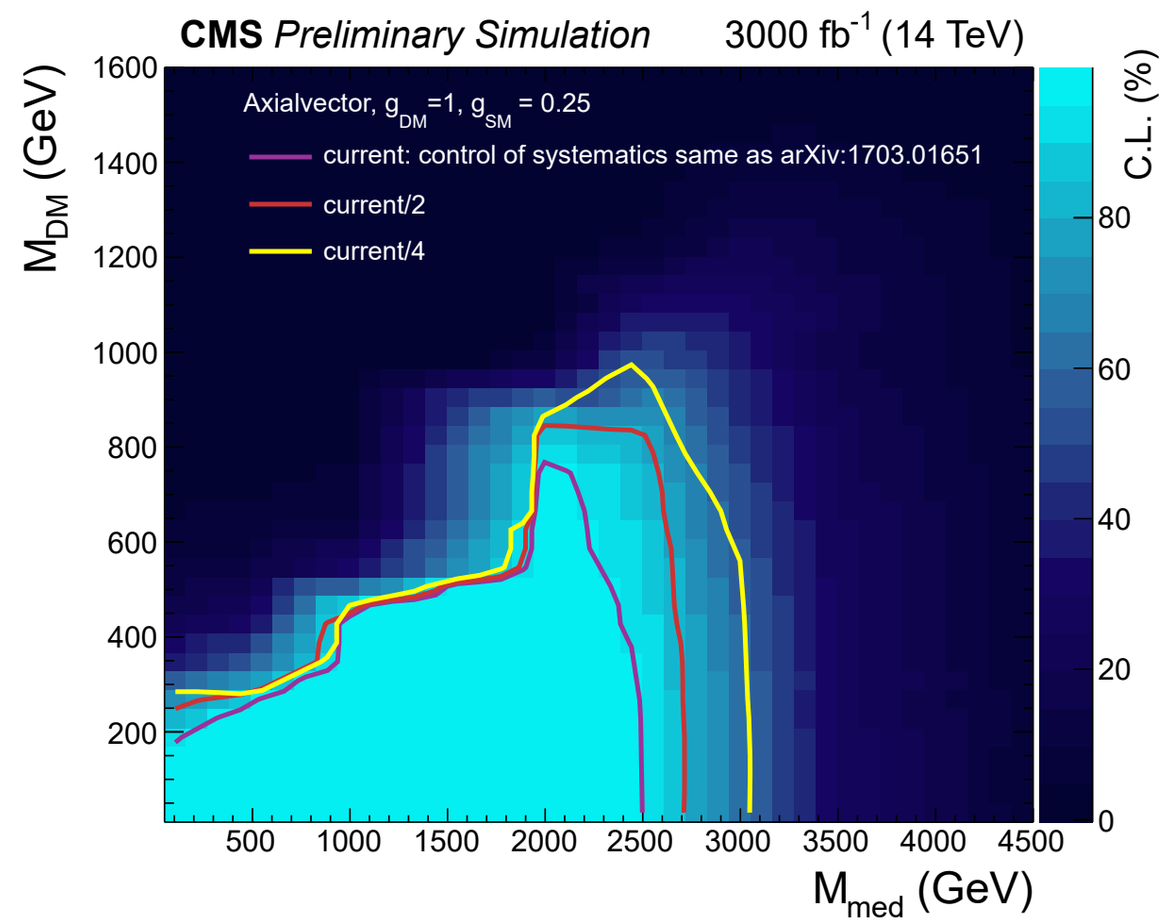


Mono-jet DM using Delphes Simulations

DM: Pseudo-scalar in jet+E_T^{Miss}



DM: Axial-vector in jet+E_T^{Miss}



CMS-PAS-FRT-16-005

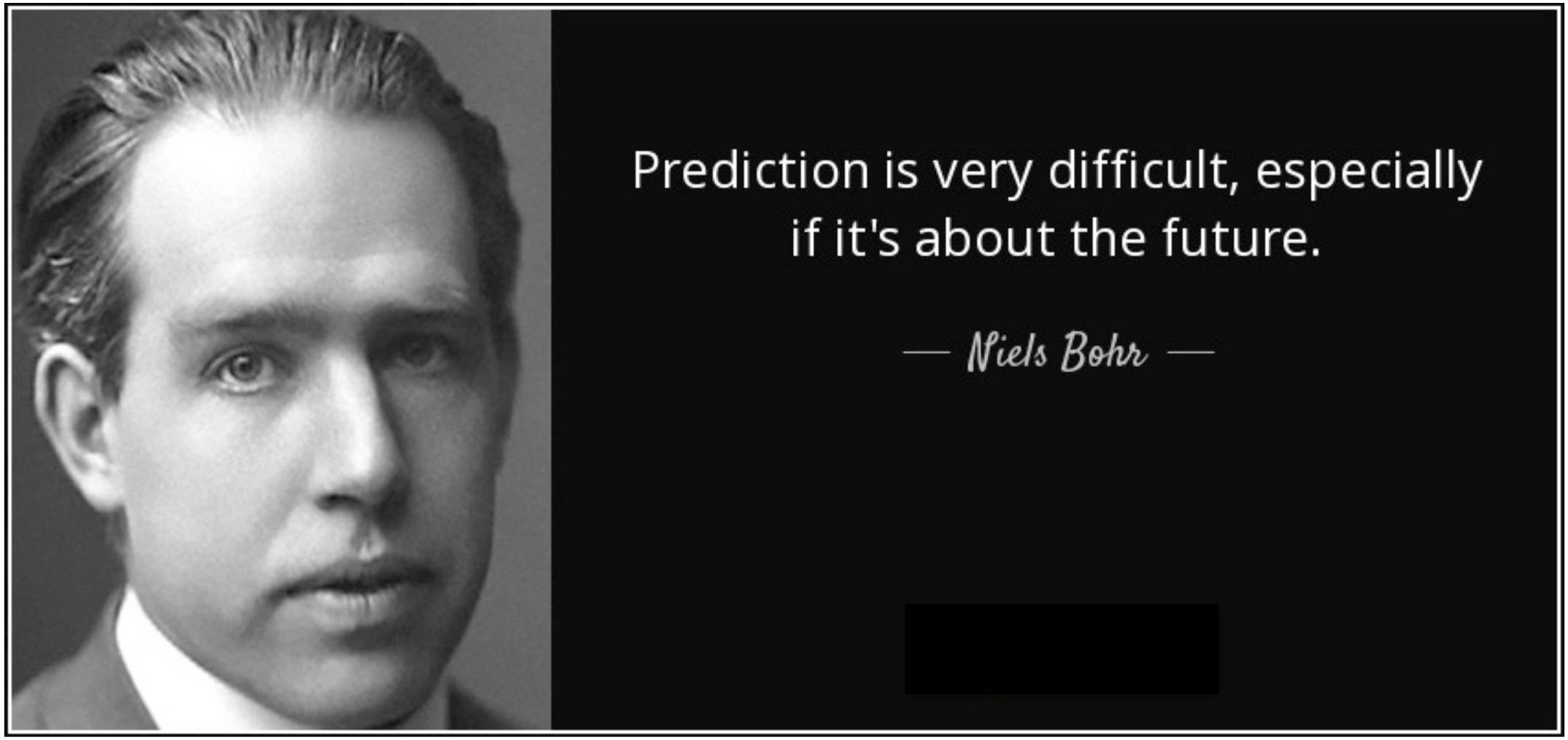
Maximum reach in mediator mass (M_{med}) ≈ **3 TeV @ 3/ab**

Reach in dark matter mass (M_{DM}) increases for high M_{med} with better knowledge of systematic uncertainties.

Summary

- LHC has an extensive program for new physics at the energy frontier
- We have developed sophisticated and ingenious techniques
- Discovery potential for generic QCD-charged states (stops, gluino) is shrinking but new opportunities lies at EWK scale
- Global symmetries provide a suite of new particles to address mass hierarchy
- Boosted jet substructure techniques have allowed to probe DM, stops, VLQ, Z'/W' in corner phase spaces that were not accessible at the LHC before
- This is less than 10% of the LHC data compared to the expectation of Run2
  - Many searches must yet be completed and/or will take long time
  - More data and ingenious theoretical guidance may lead to uncover the hidden nature of nature

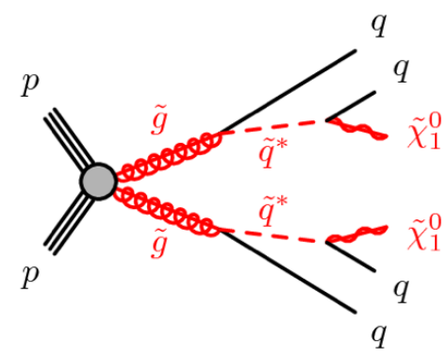
Thank you!


Prediction is very difficult, especially
if it's about the future.
— Niels Bohr —

Backup
Ctrl

Long Lived Particles

- What makes a particle long-lived?
  - small couplings: RPV decays, dark sector coupling
  - small mass-splittings: almost degenerate next-LSP heavy messenger: Z', split SUSY
  - hidden valley

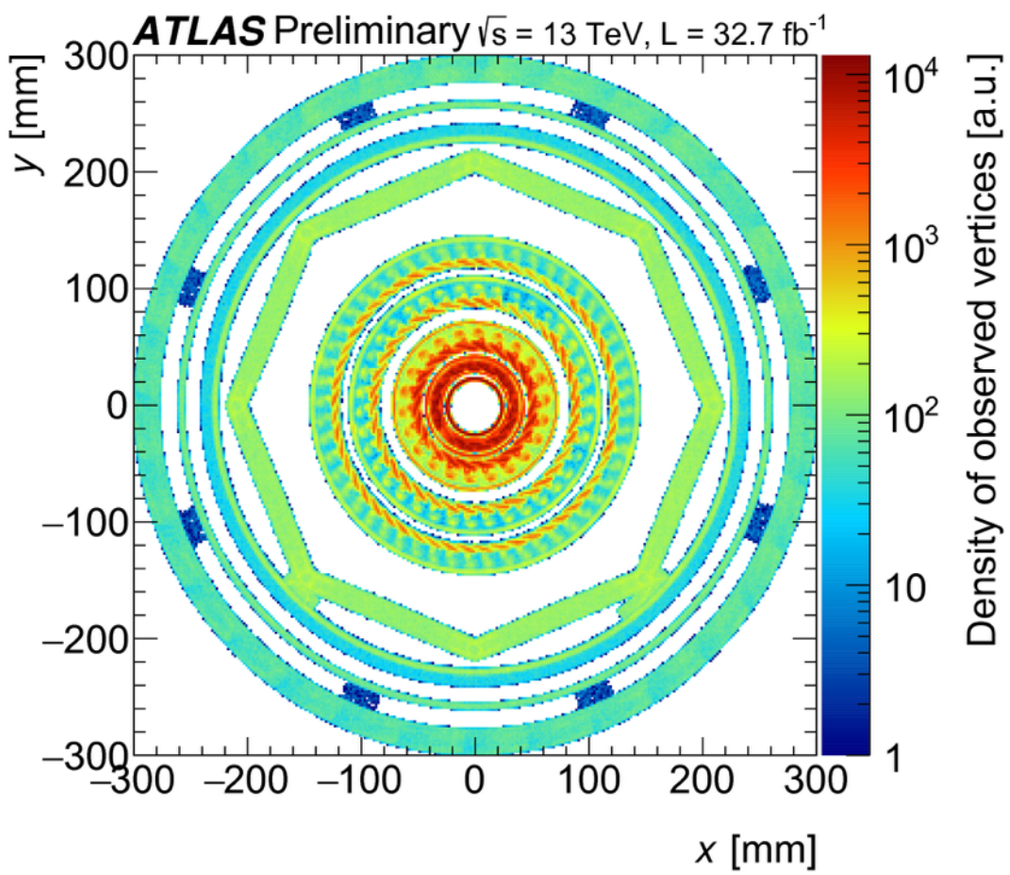


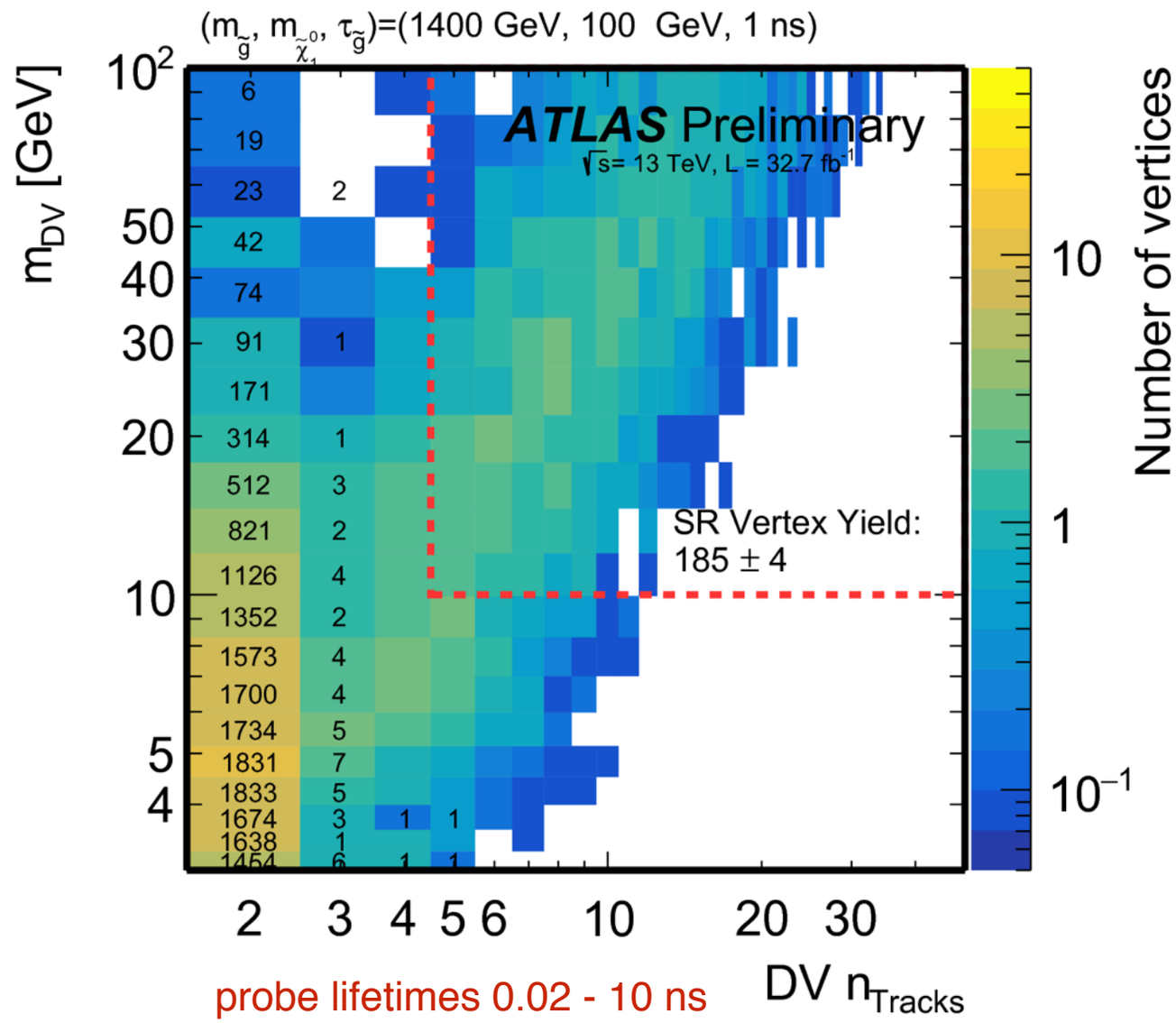
Signal: non-prompt gluino hadronize to meta-stable R-hadron that decays into SM q and LSP

Displaced VERTEX

- Dedicated re-tracking: Displaced Vertex from LLP
- Map based veto: Mask the detector material that is sensitive to tracks from K_S^0 and Λ^0

ATLAS-CONF-2017-026





probe lifetimes 0.02 - 10 ns

Other searches with displaced jets, leptons: EXO-16-003, EXO-16-022

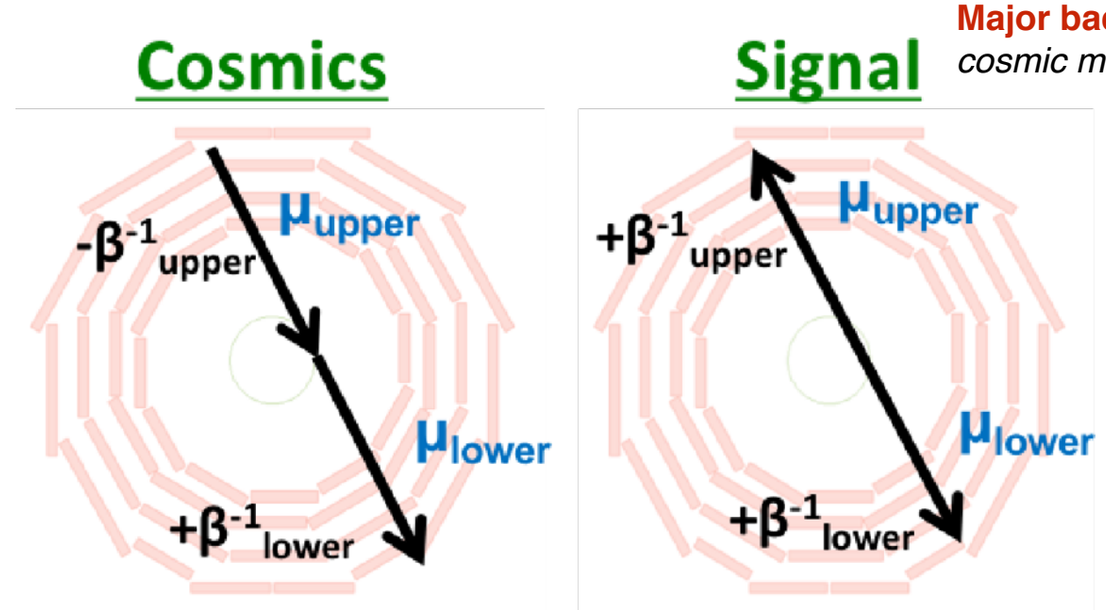
Long Lived Particles

- What makes a particle long-lived?
  - small couplings: RPV decays, dark sector coupling
  - small mass-splittings: almost degenerate next-LSP heavy messenger: Z', split SUSY
  - hidden valley

CMS-PAS-EXO-17-004

$\beta^{-1} = c/v \propto$ TOF of DT

Major background: *cosmic muons*



Stopped objects: muons

Signal: LLP - gluinos, multiple charged massive particles that have late decays to muons

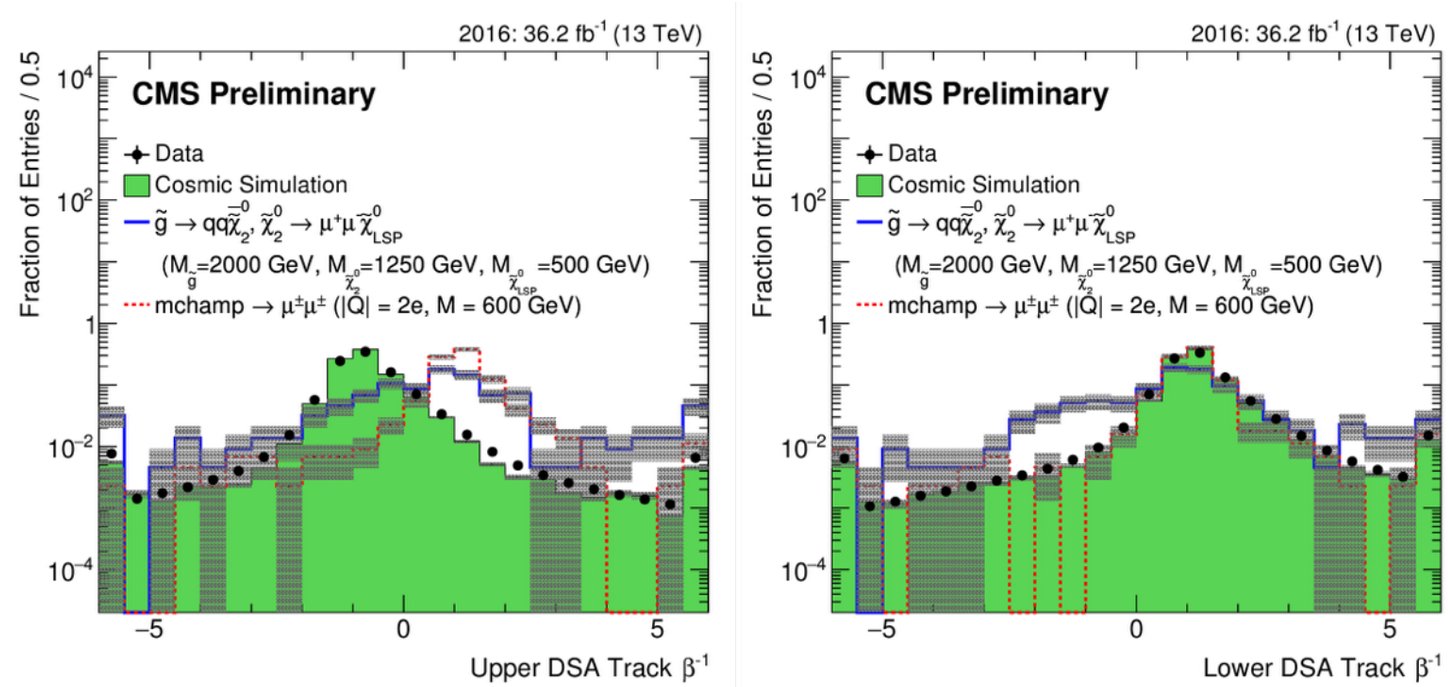
Custom trigger: record events out-of-time (50 ns) with pp collisions

Dedicated algorithm: **D**elayed **S**tand**A**lone muon tracks

tDT: time at the point of closest approach to the IP measured by Drift Tubes in muon system

t_{RPC}: RPC time for a track

See BSM session on Wed @ 13:30 am
Todd ADAMS



probe lifetimes 100 ns → 10 days

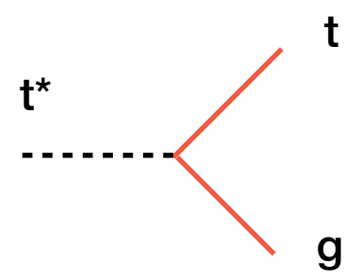
Other searches with displaced jets, leptons: EXO-16-003, EXO-16-022

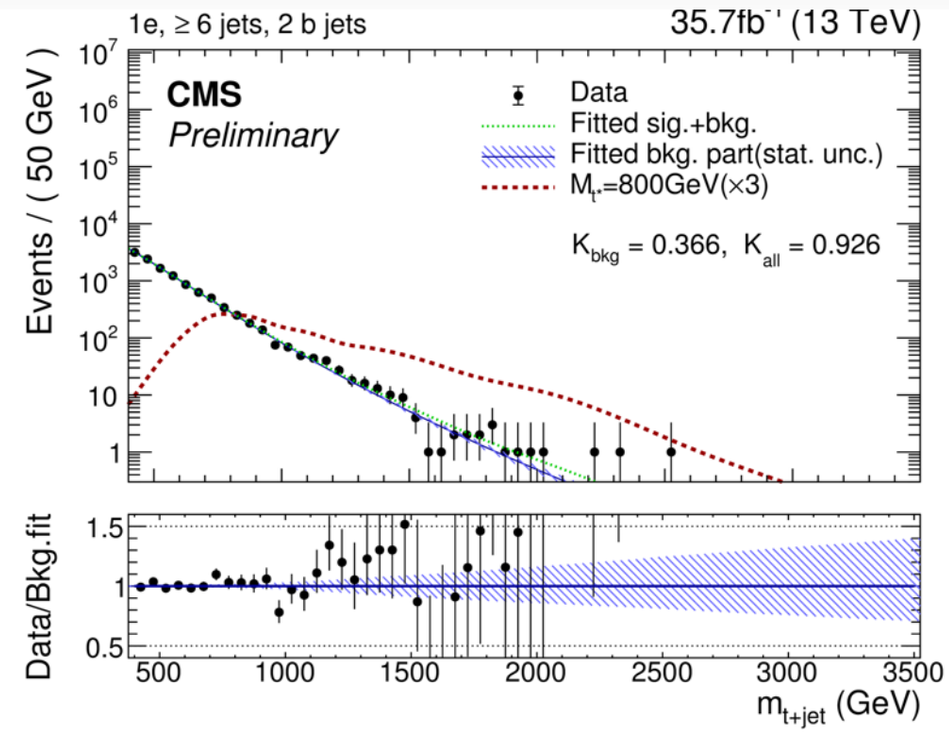
More on Resonances!

- *Jet-substructure tools are fully exploited!*

CMS-PAS-B2G-16-025

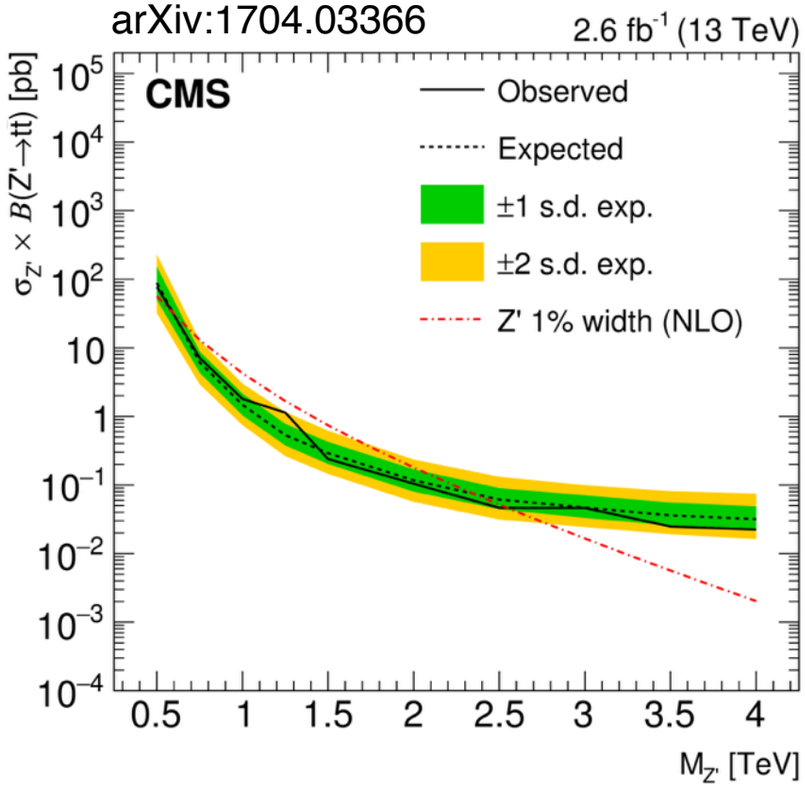
- Spin-3/2 t* fermion
  - Pair: t*t*→tgtg →qqbg lνbg
  - Exclusion limits up to 1.2 TeV

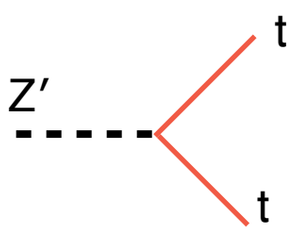




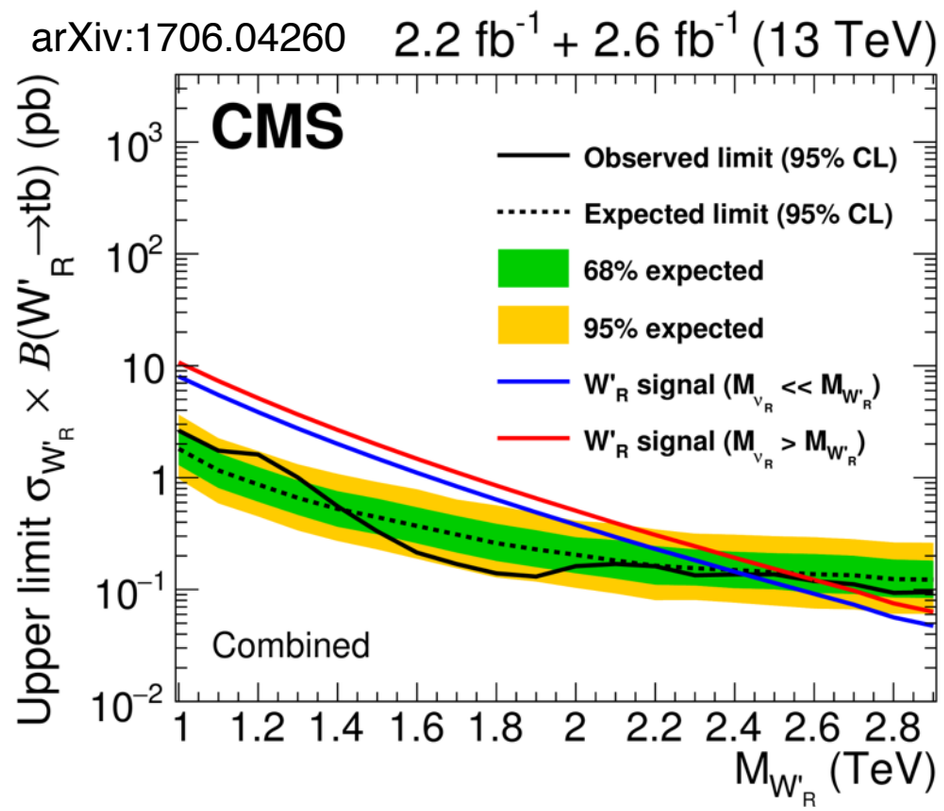
- New resonances in tt/tb production
  - combined *l+jets* and all-hadronic final states

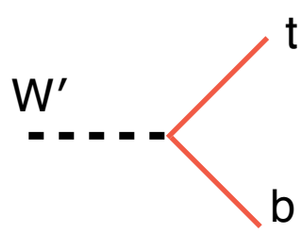
arXiv:1704.03366





arXiv:1706.04260

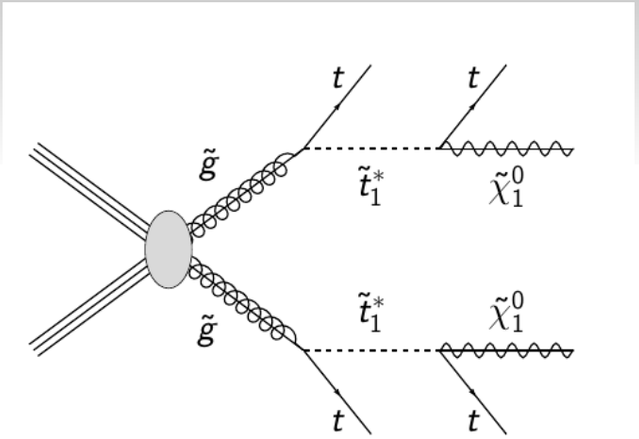




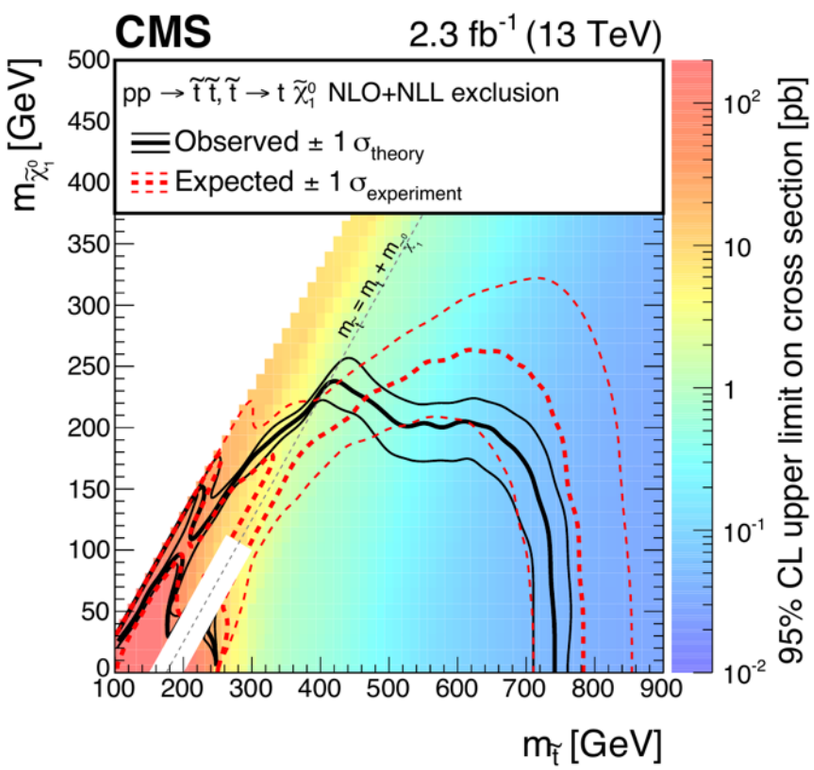
Similar results from ATLAS!

See Wednesday's (02/08) BSM session: talk by Douglas BERRY

stops with top-tagging

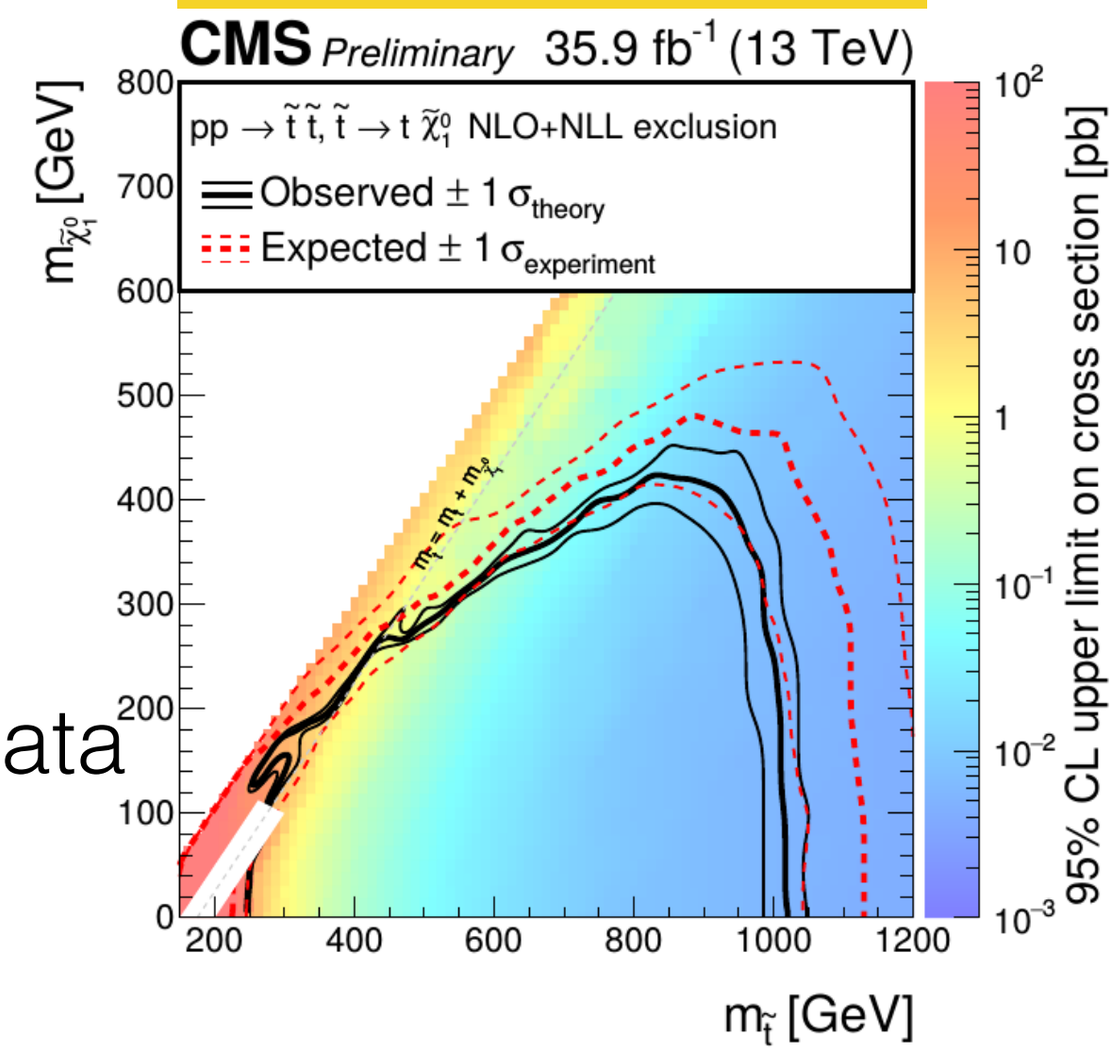


- Top reconstruction improvements
  - New pairing algorithm
  - Use of W- & t-tag algorithms



15 x more data

all-hadronic final states

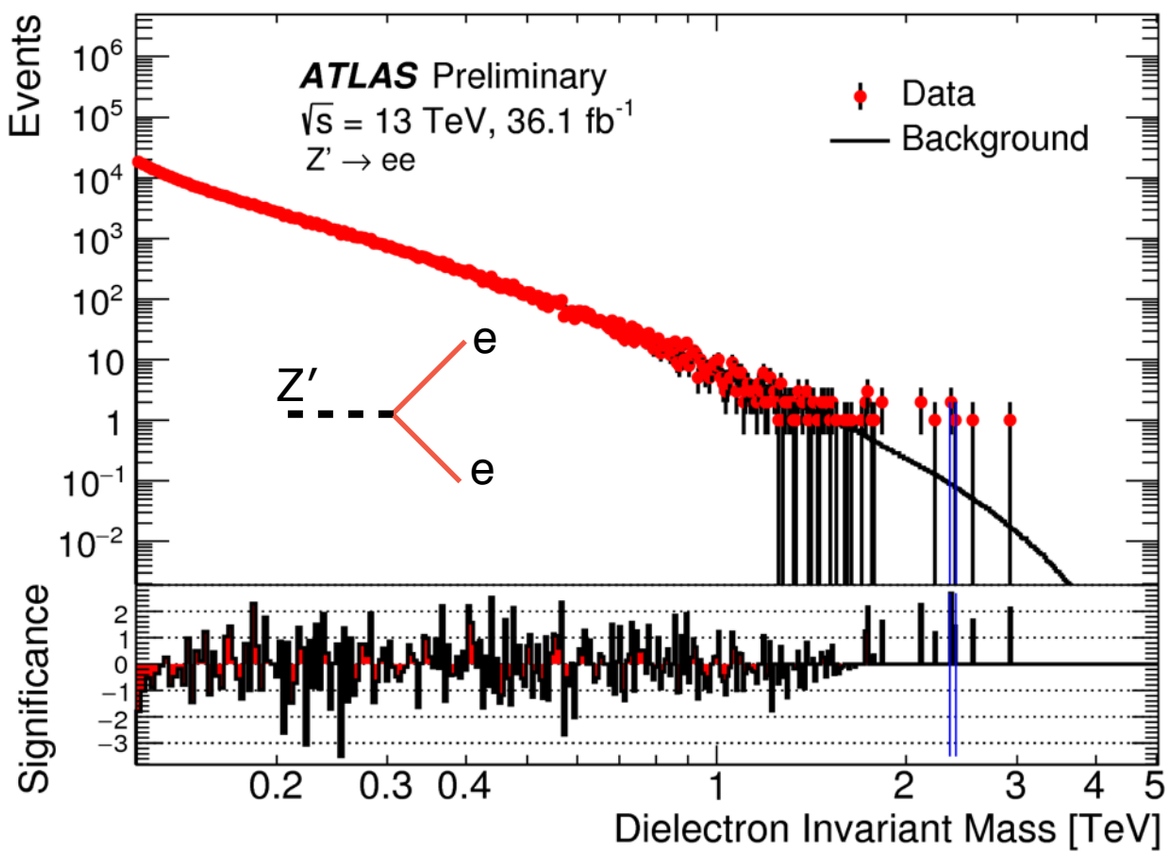


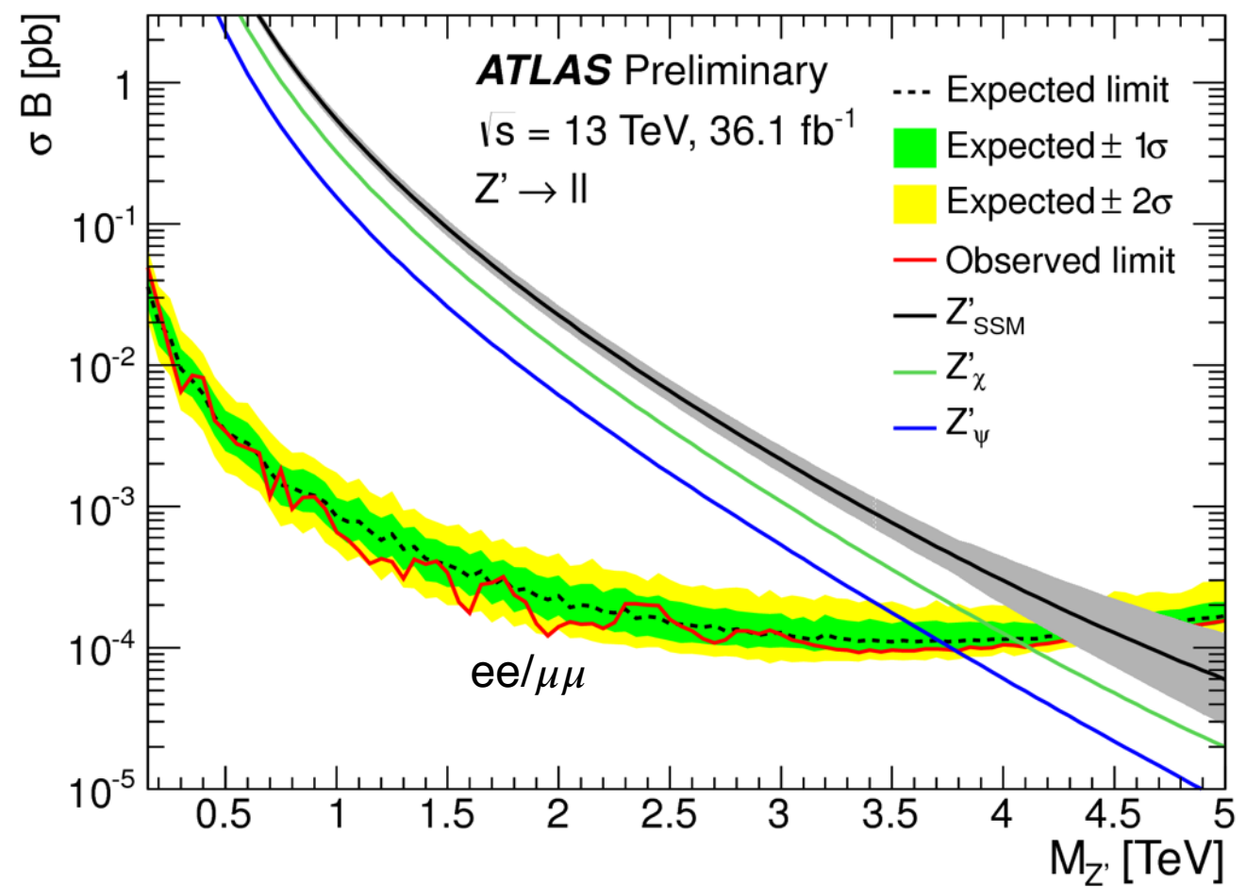
arXiv: 1701.01954

CMS-PAS-SUS-16-050

Resonances

- Sensitive to many BSM scenarios: extra dimensions, new gauge bosons, higgs …
- New particle can decay into multiple final states:
  - dileptons, lepton+ E_T^{Miss}, dijets, γ+jets, dibosons (VV, Vγ, γγ), tt, tb ..





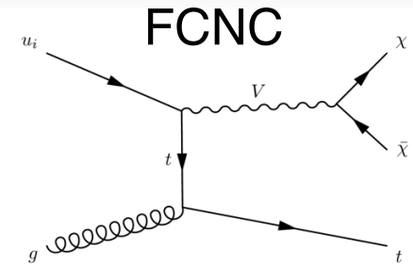
- No significant deviation in data up to 3 TeV (Z')
- Similar results from CMS:
- Simple SM extensions getting tightly constrained !

Dark Matter

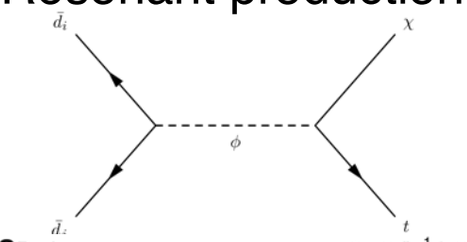
Mono-top:

- A boosted top-jet recoiling against E_T^{Miss}
- BDT based on substructure observables

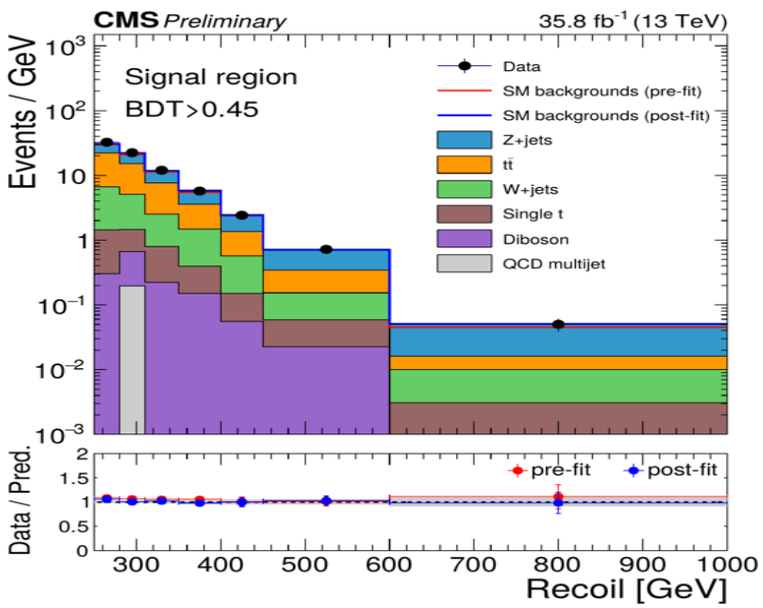
FCNC

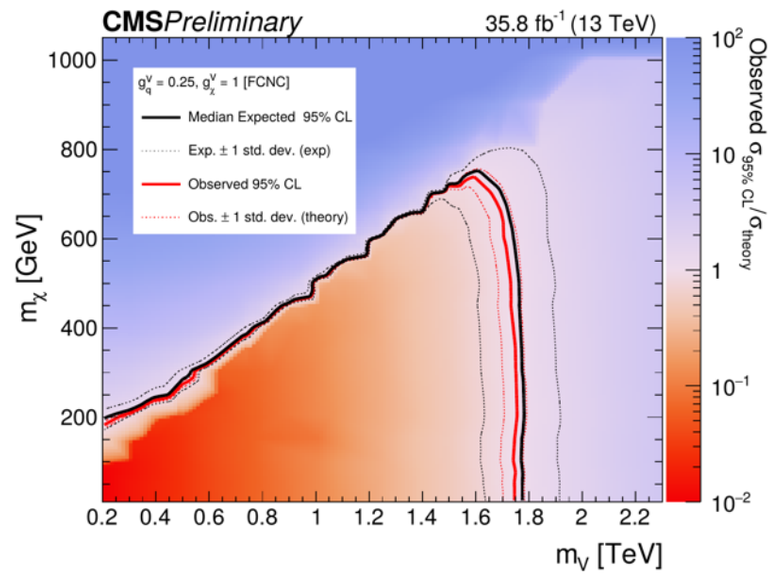


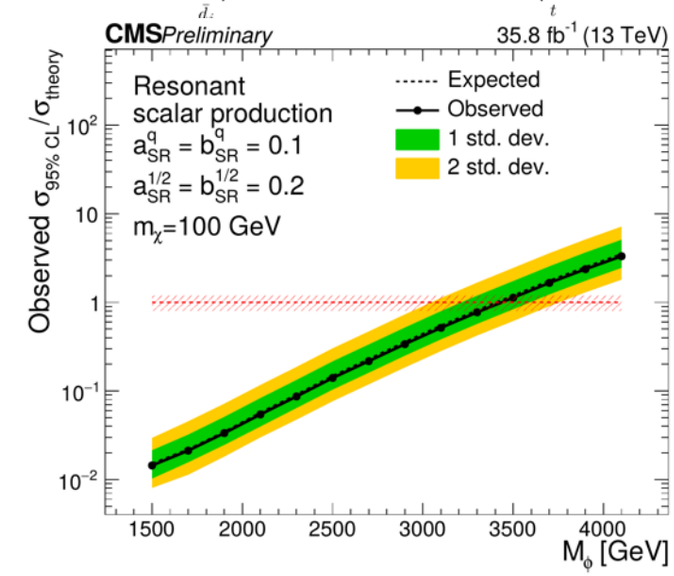
Resonant production



CMS-PAS-EXO-16-051





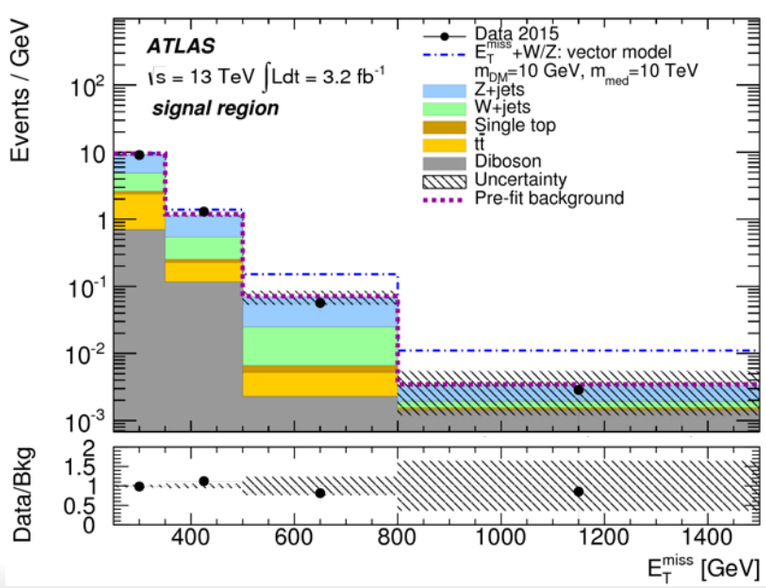


Other searches of DM + HF quarks: EXO-16-005, EXO-16-028, ATLAS-CONF-2016-086

Mono-W/Z/H:

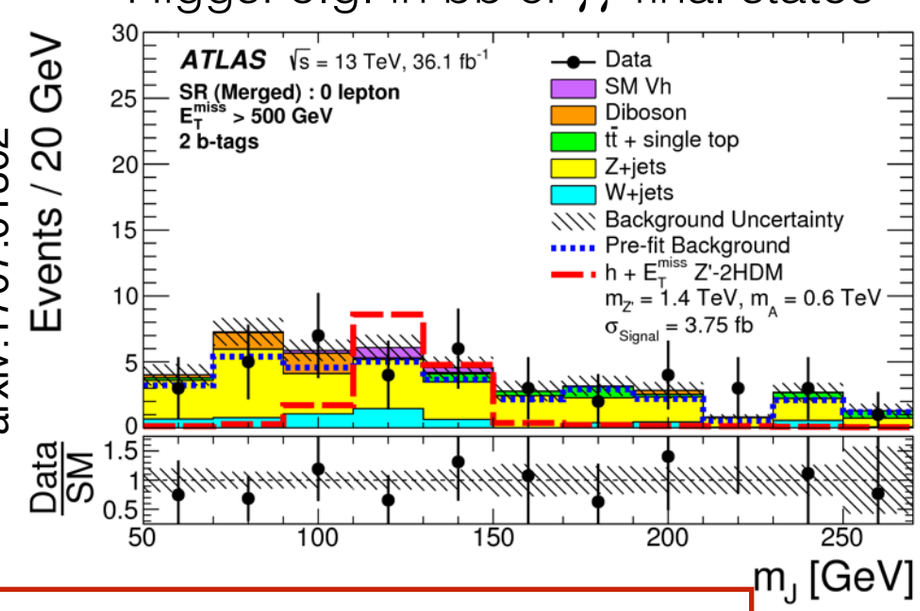
W/Z (leptonic or hadronic) recoiling against E_T^{Miss}

PLB 763(2016) 251



Higgs: e.g. in bb or $\gamma\gamma$ final states

arxiv: 1706.03948
arxiv:1707.01302



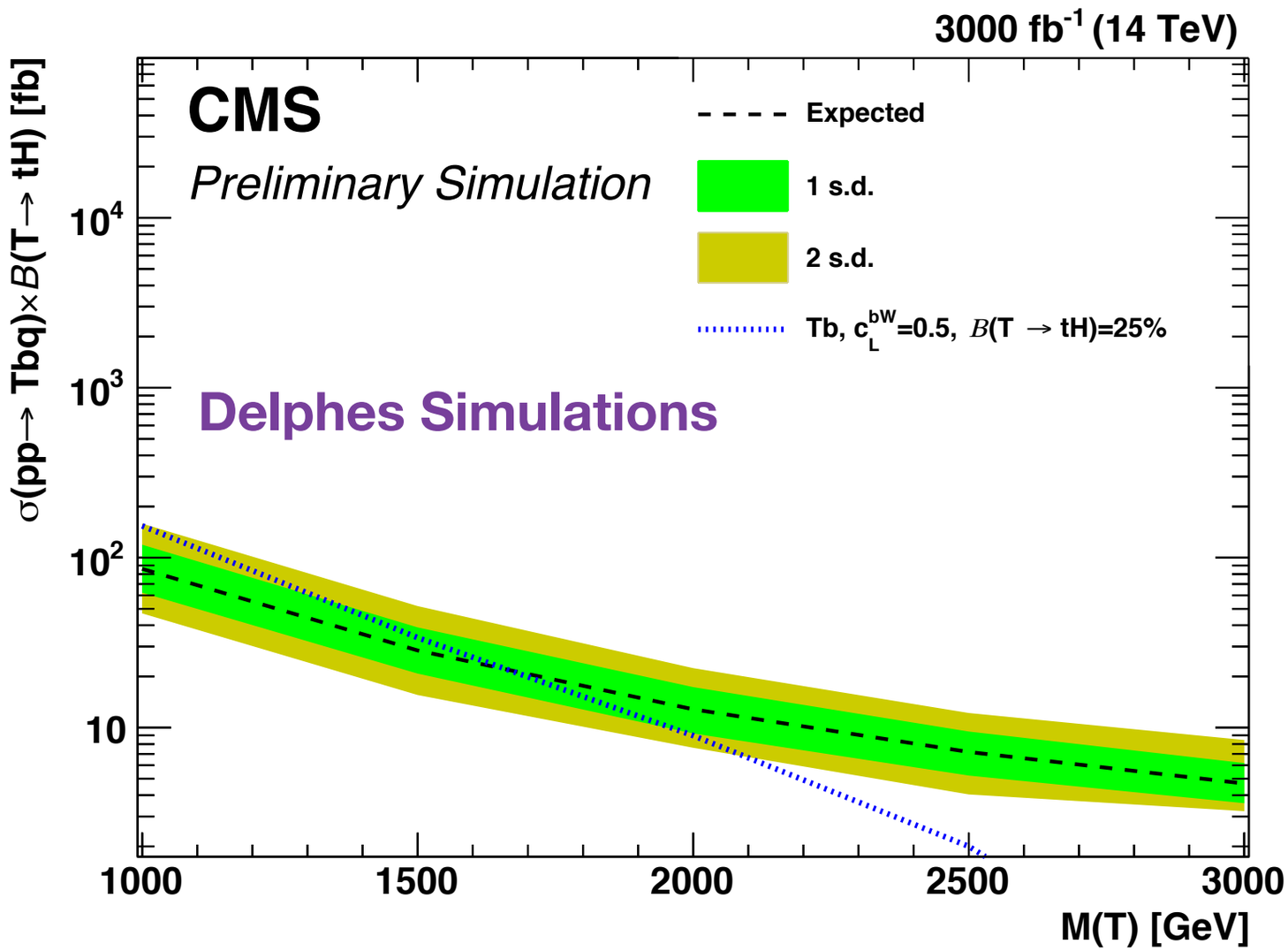
CMS equivalent: 1703.05236

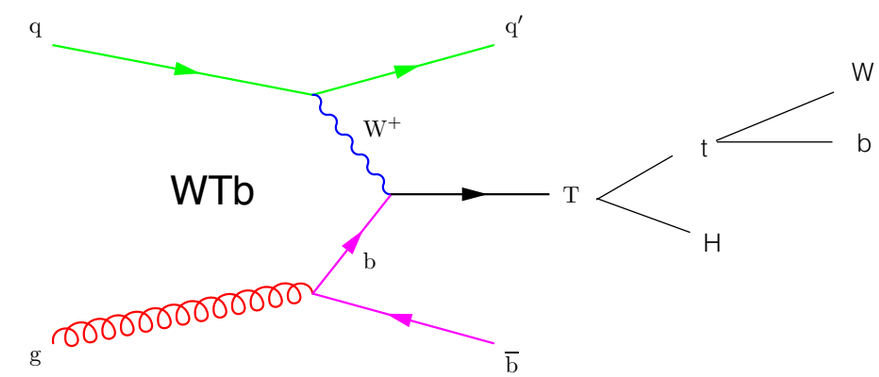
See Wednesday's (02/08) DM session:
Yicheng GUO (VV), Chen ZHOU($\gamma\gamma$), Efe YIGITBASI (bb)

New Physics @ HL-LHC

- With luminosity of 7×10^{34} Hz/cm^2 and a pileup of 200, both ATLAS and CMS foresee rebuilding the Tracker and Hadronic Calorimeter subsystems by 2025

Single VLQ, Tbq;T →tH in l+jets



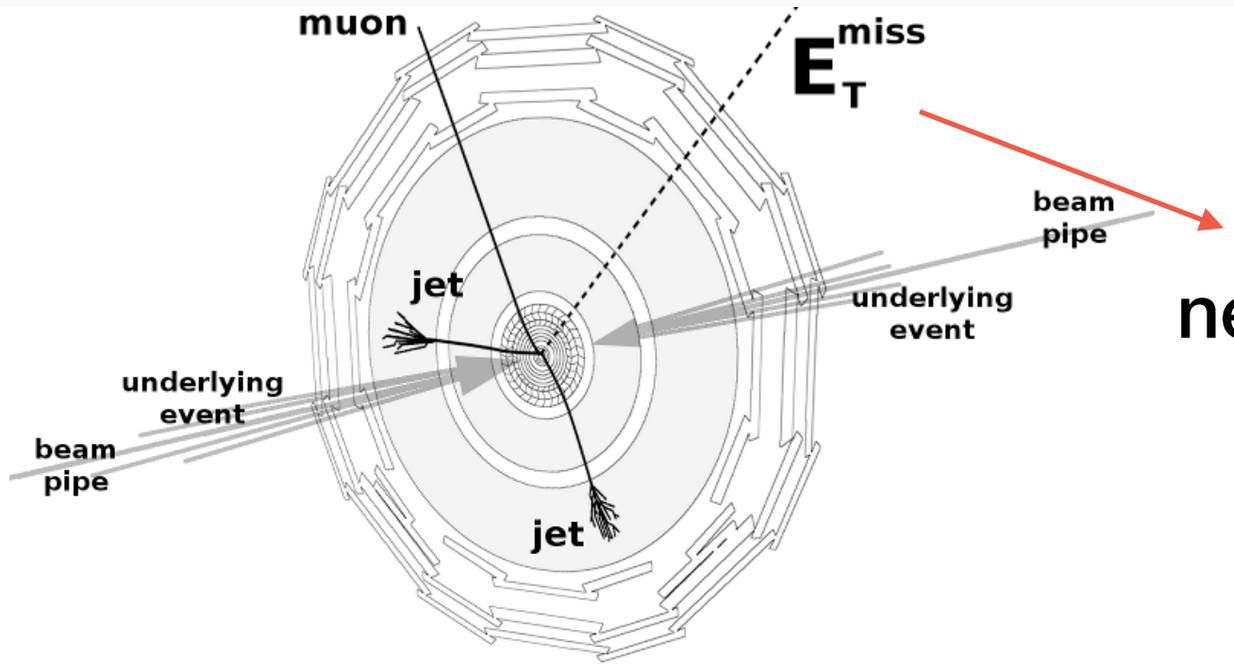


Sensitive to EWK couplings!

Expect improvement with new analysis techniques such as subjet b-tagging

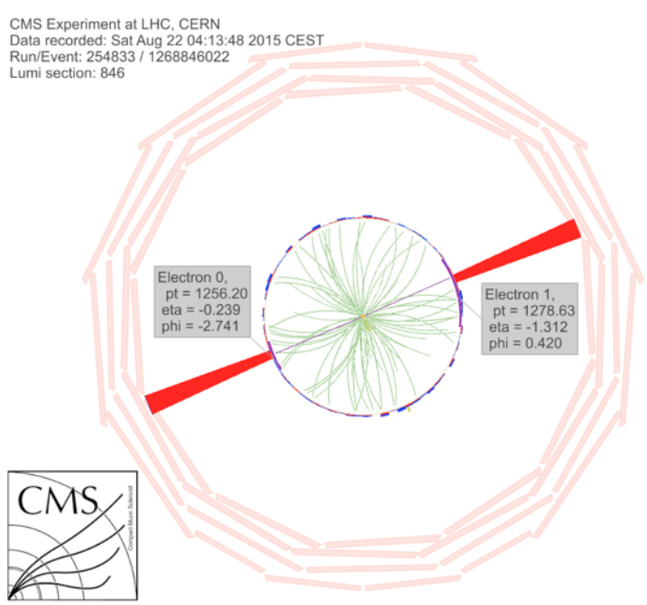
Systematic uncertainties plays an important role, with largest foreseen from top quark theory x-section, PDF, matrix-element Q^2 scale

Missing Transverse Energy

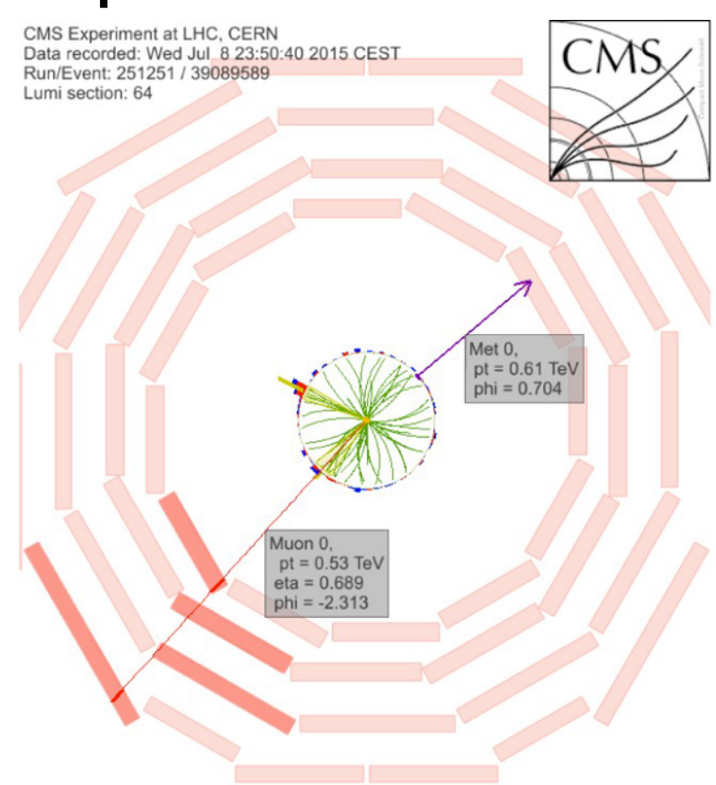


negative vector sum of energies of all final state particles

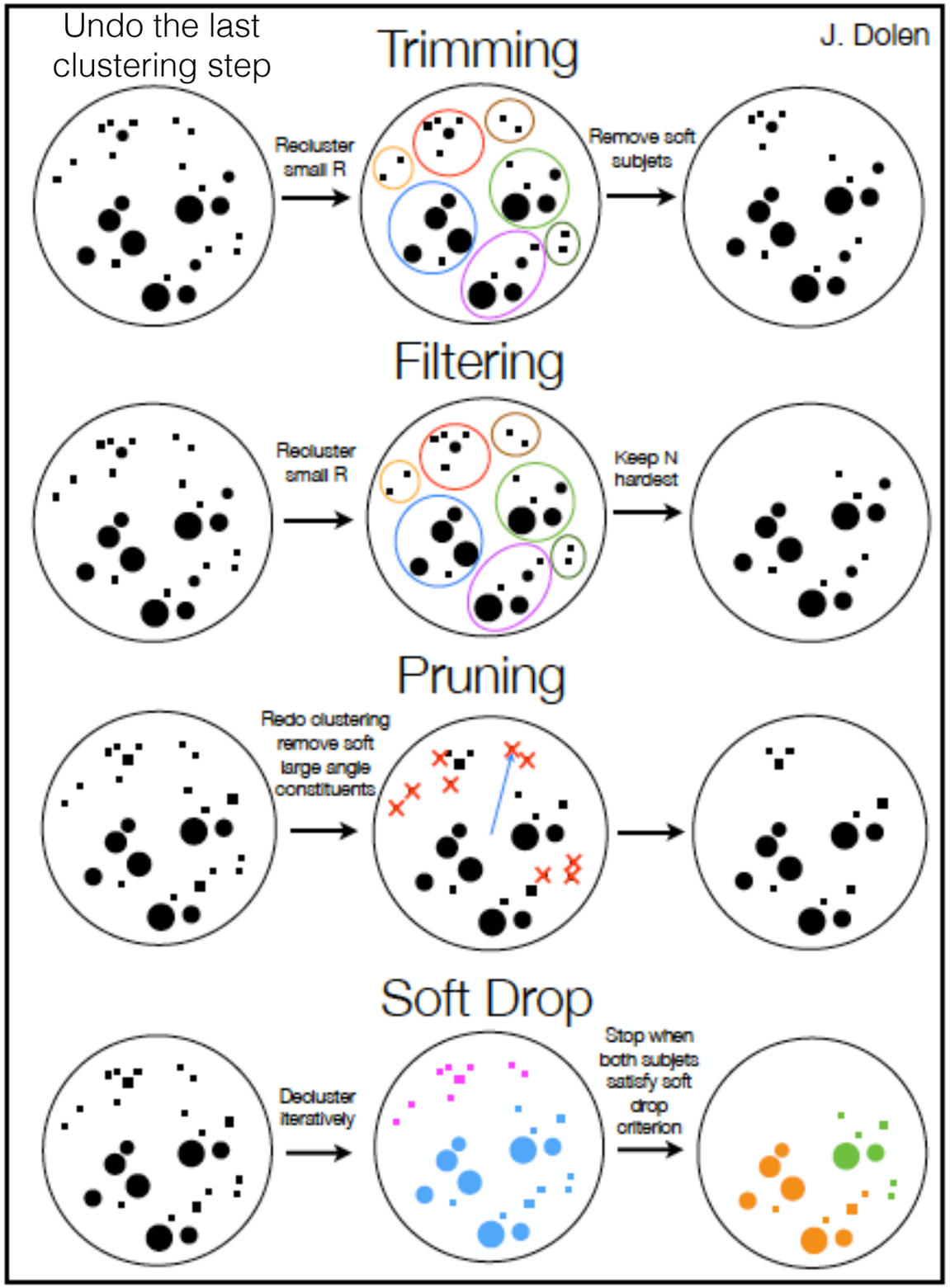
dilepton event



lepton+neutrino event



Jet Grooming



- **<u>Pruning - recluster.</u> Throw out subjets requiring that each recombination satisfy**

$$\frac{\min(p_{\mathrm{T}1}, p_{\mathrm{T}2})}{p_{\mathrm{T}p}} > 0.1$$

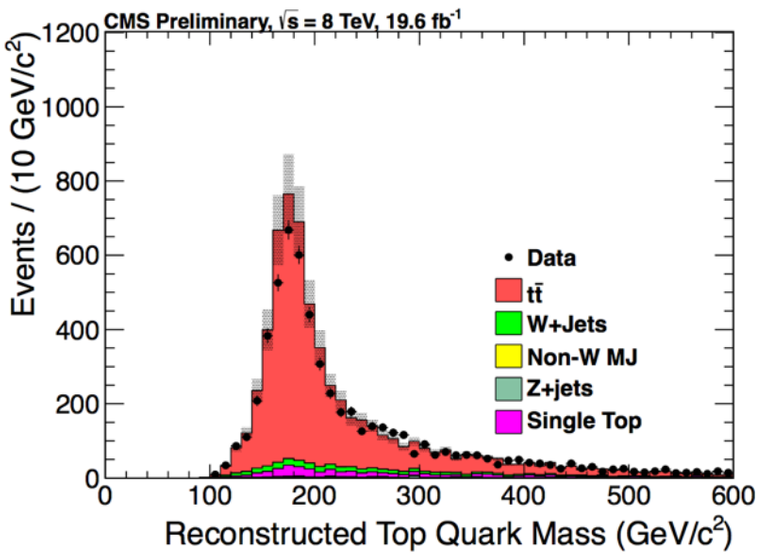
$$\Delta R_{12} < 0.5 \times \frac{m_{\mathrm{jet}}}{p_{\mathrm{T}}}$$

- **<u>Soft drop - decluster.</u> Throw out subjets which do not satisfy**

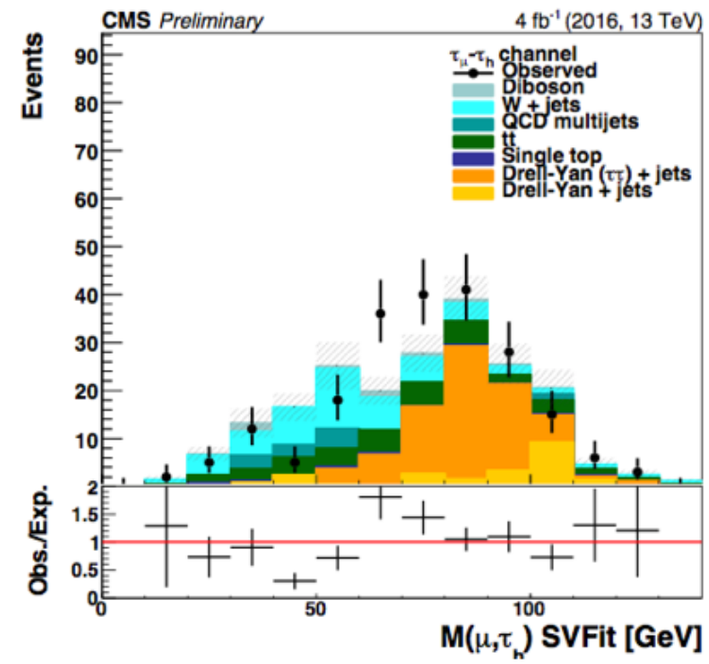
Soft Drop Condition: $$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

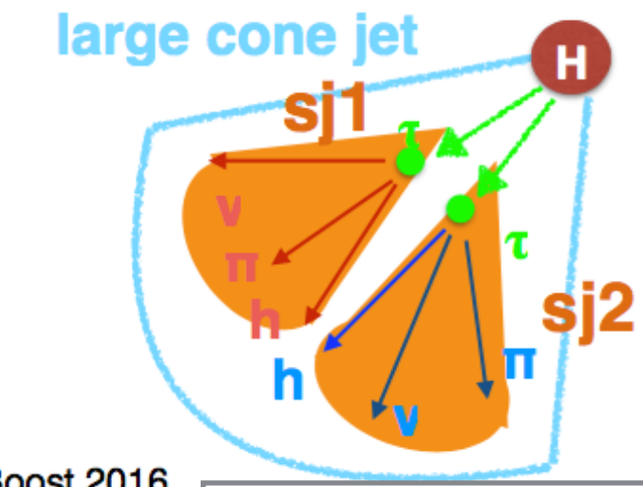
More taggers

top-tagging



Boosted tautau-tagging

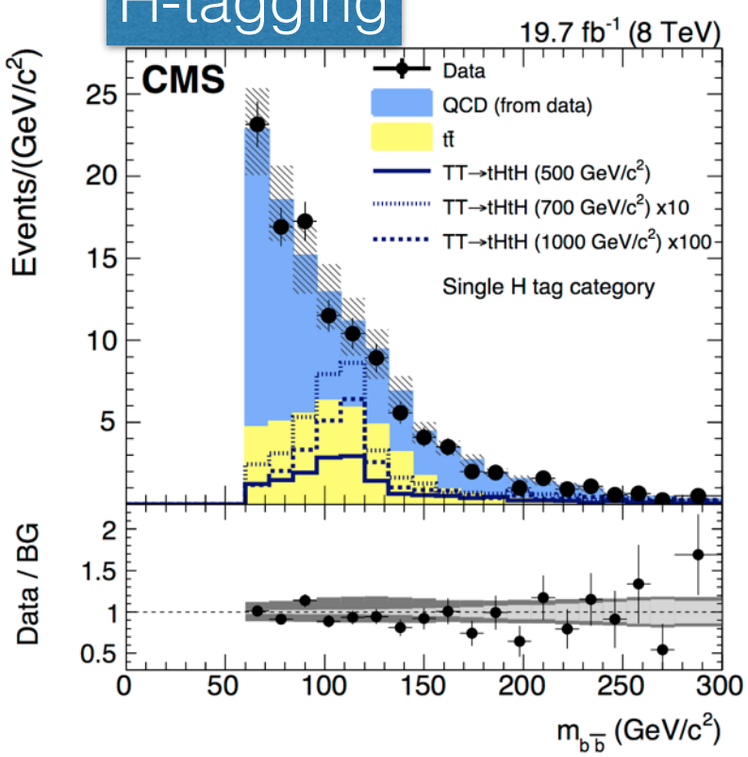




Boost 2016

CMS-DP-2016/038

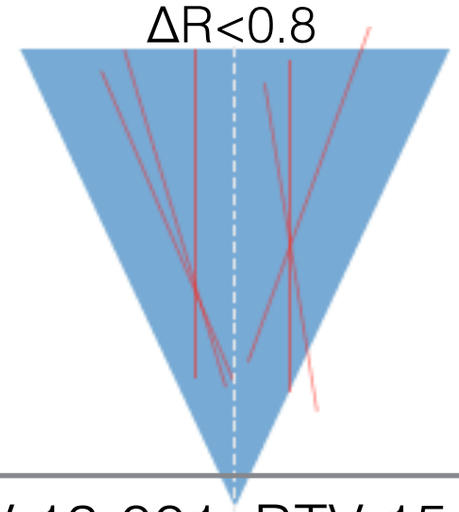
H-tagging

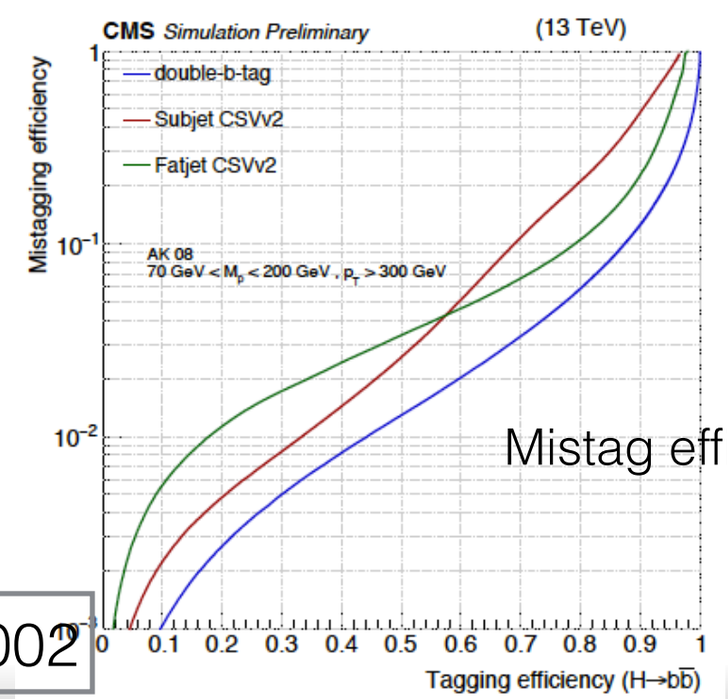


- Reconstruct the two B hadrons from the b and b̄ within the same fat jet

Double tagger

ΔR<0.8



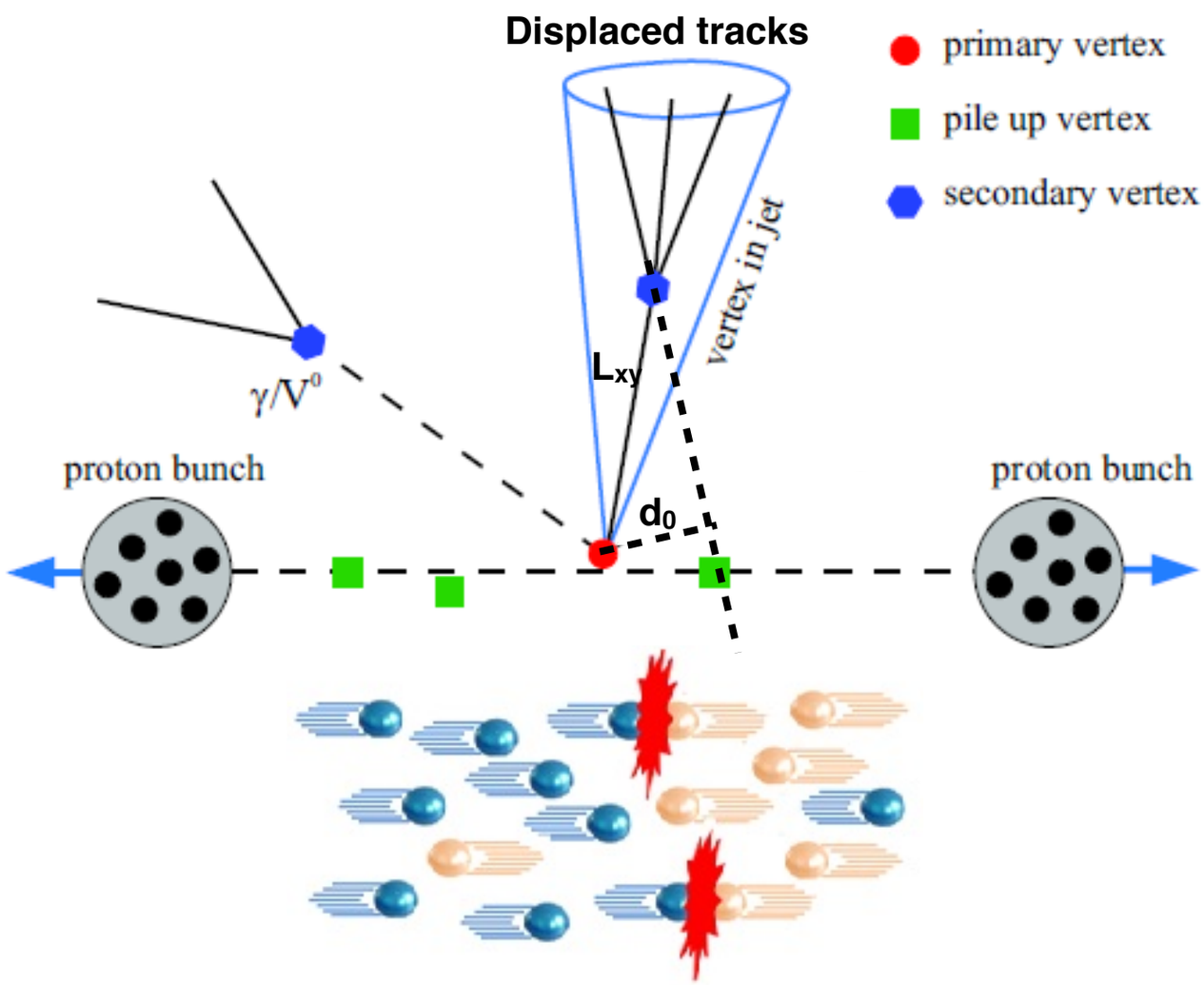


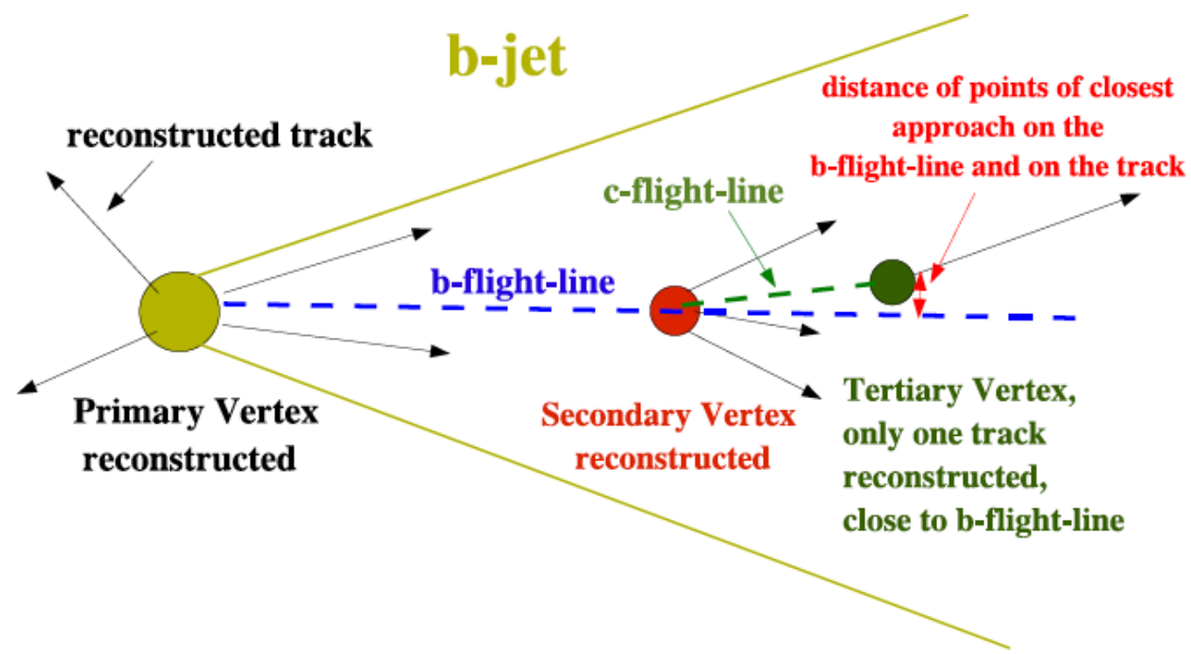
Mistag efficiency

BTV-13-001, BTV-15-002

b-jets

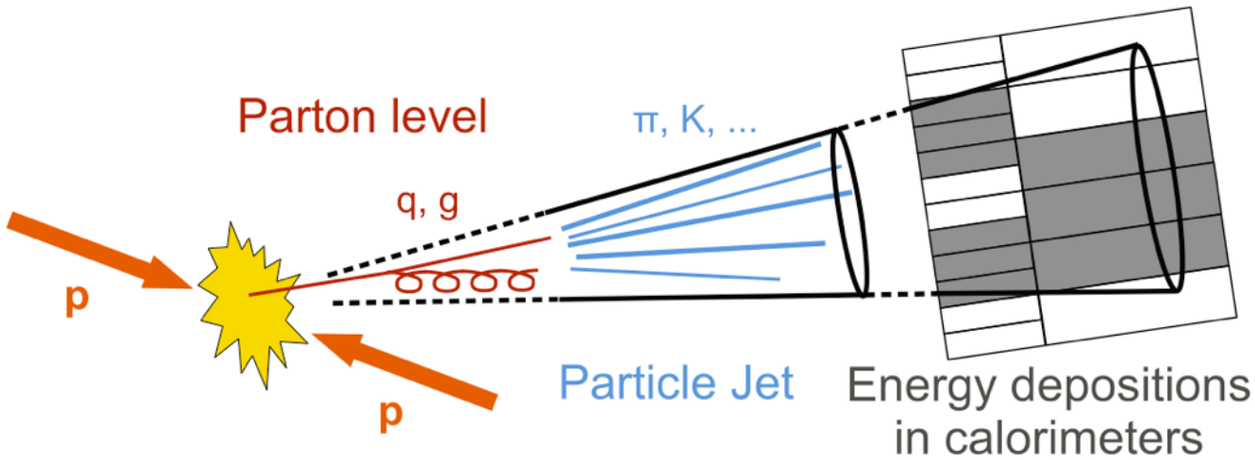
- Combined Secondary Vertex version 2 algorithm: secondary vertex and track-based lifetime informations
  - secondary vertex information is obtained with the Inclusive Vertex Finder algorithm
  - combines the variables with a neural network

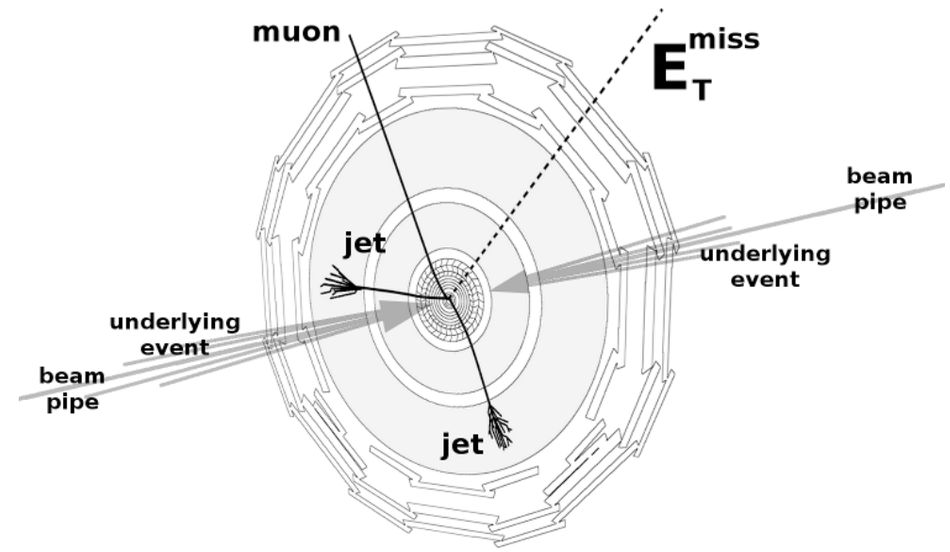




weakly decaying b, c (b-c chain) and the principle of the TertiaryVertexTrackFinder TVTF.

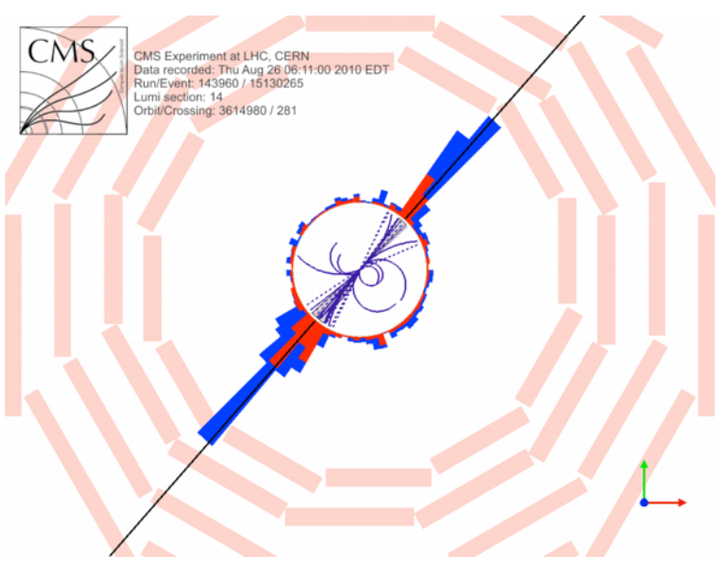
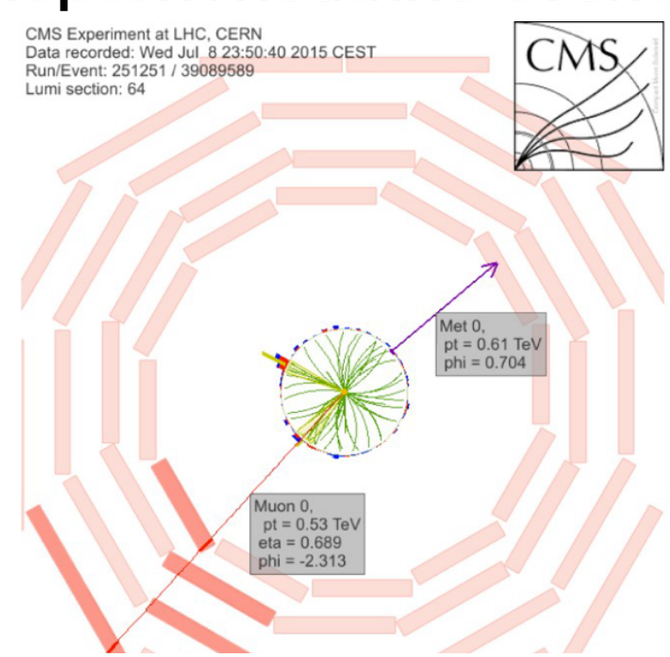
Jets/MET





- Need a "jet algorithm" to associate the charged/neutral hadrons in a spray to initial quarks and gluons
- Negative vector sum of energies of all final state particles

dijet event



lepton+neutrino event