# Searching for Supersymmetry in 13 TeV proton proton collisions at LHC

## (using the CMS Experiment)


**Seema Sharma**

**Indian Institute of Science Education and Research (IISER), Pune**


**Tata Institute of Fundamental Research, Mumbai**

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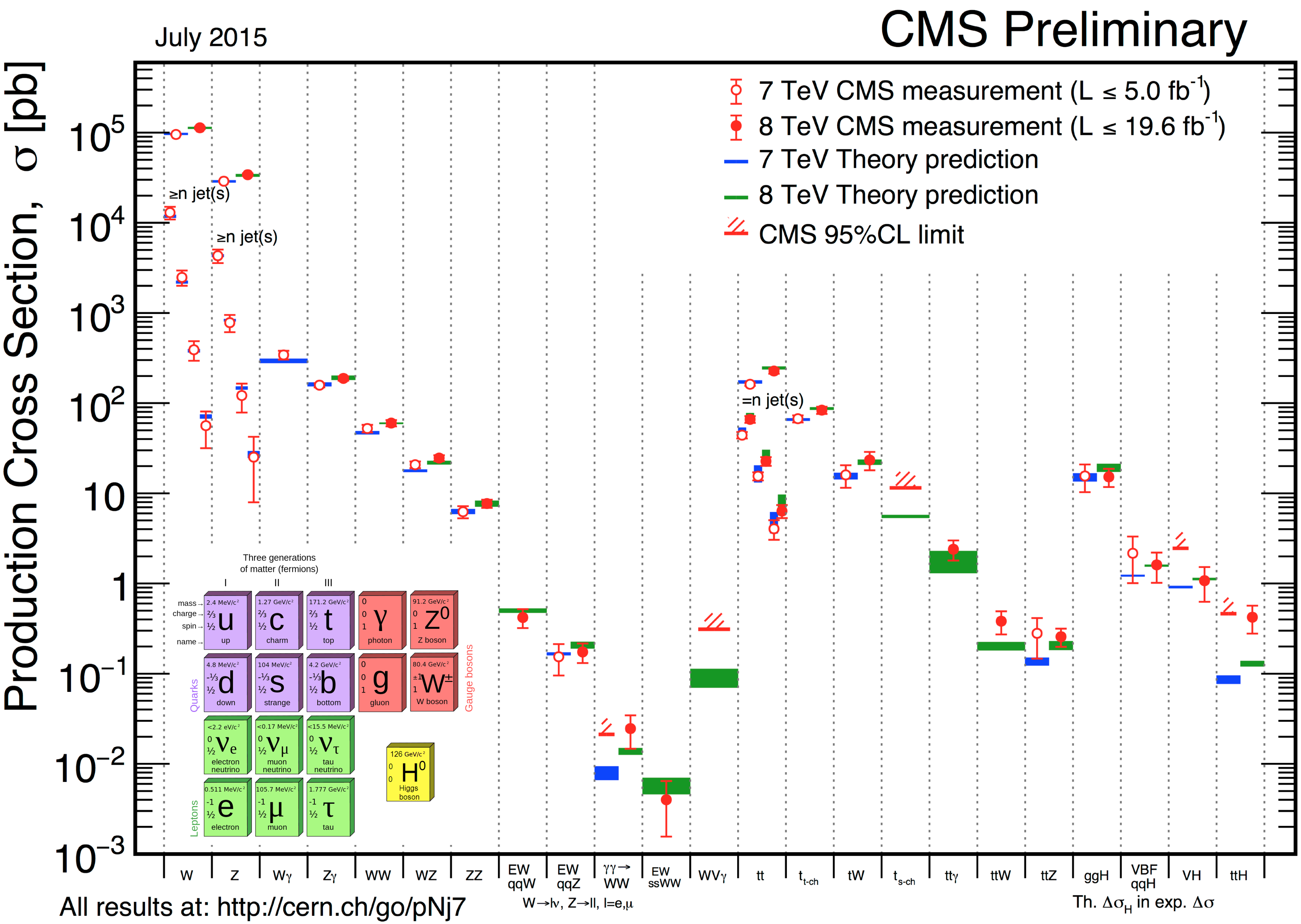
# Outline

- Introduction
- CMS in action - event reconstruction
- CMS SUSY search program
  - Jets+MET search
  - Other searches
- (Brief) Summary of present status

# Standard Model of Elementary Particles

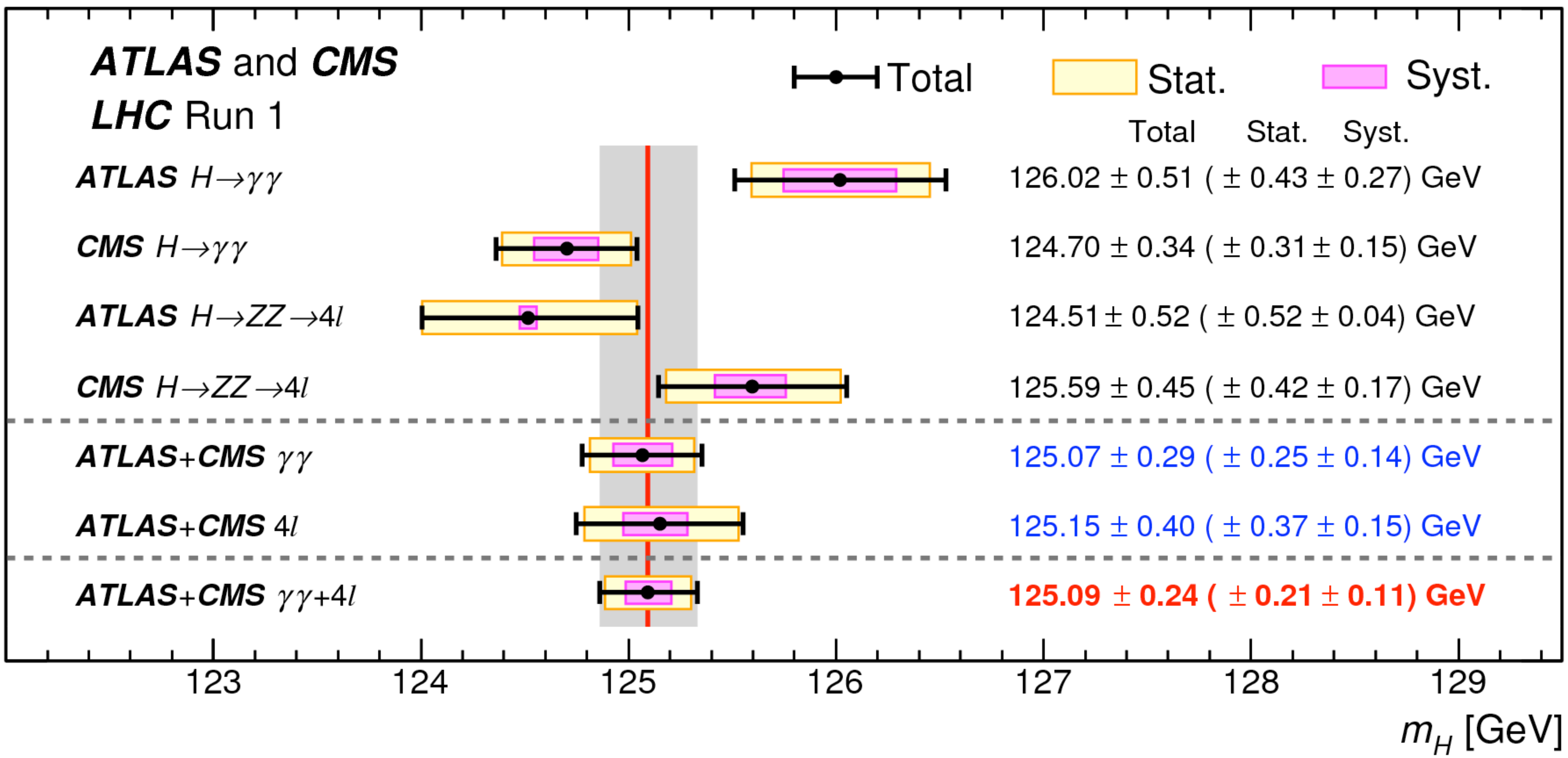
## A remarkably successful theory !!




The Standard Model has been tested at various collider and non-collider experiments with high precision !!

# A Successful LHC Run-I

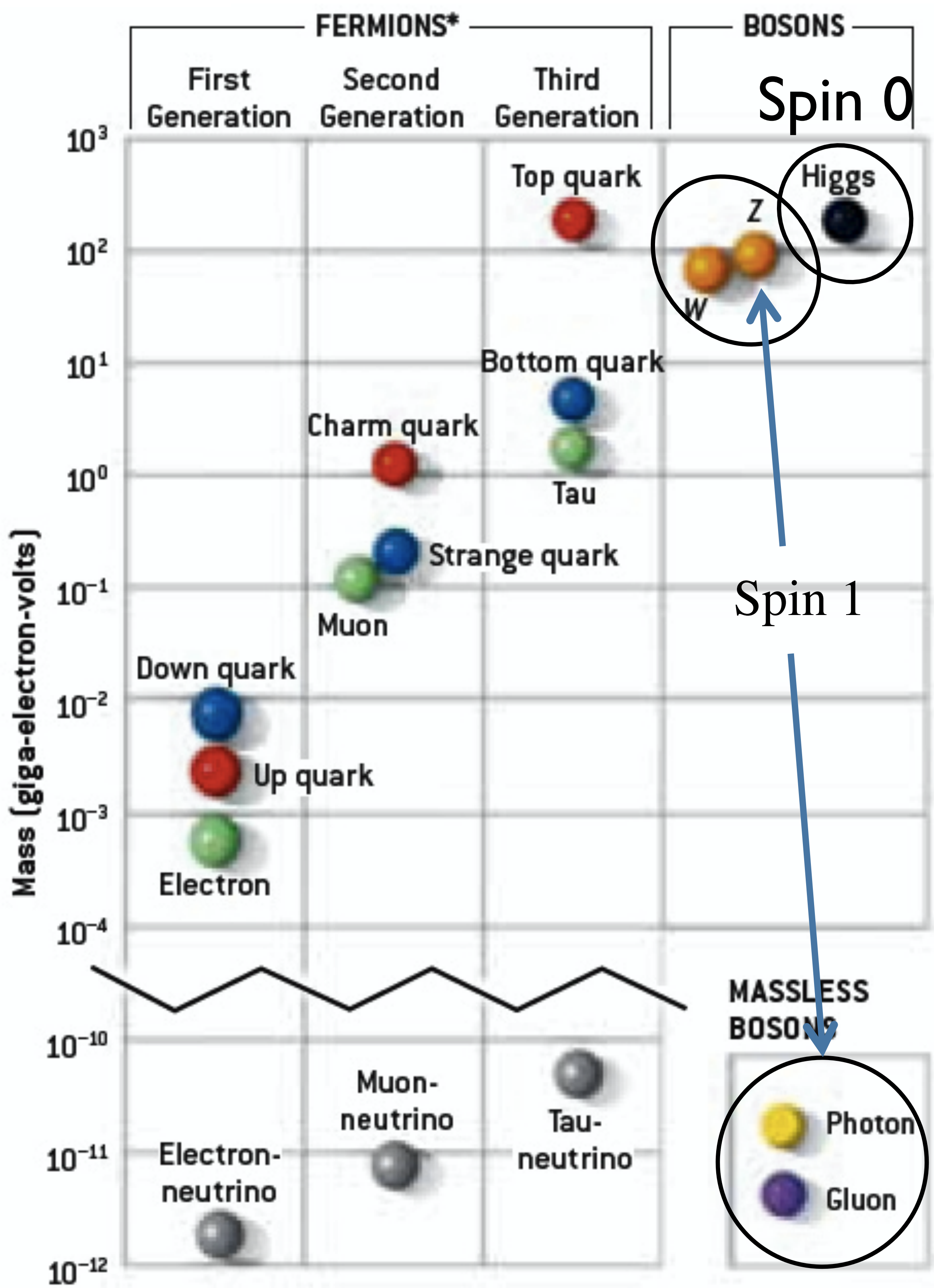
A scalar particle of mass ~125 GeV established using 7 TeV and 8 TeV data




Rate of different decay modes & various production mechanism cross-sections, and various couplings are consistent with SM expectations, although with large uncertainties in some cases.

More details: http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html

# Why Beyond Standard Model ?




A few fundamental questions of particle physics not addressed by the Standard Model :

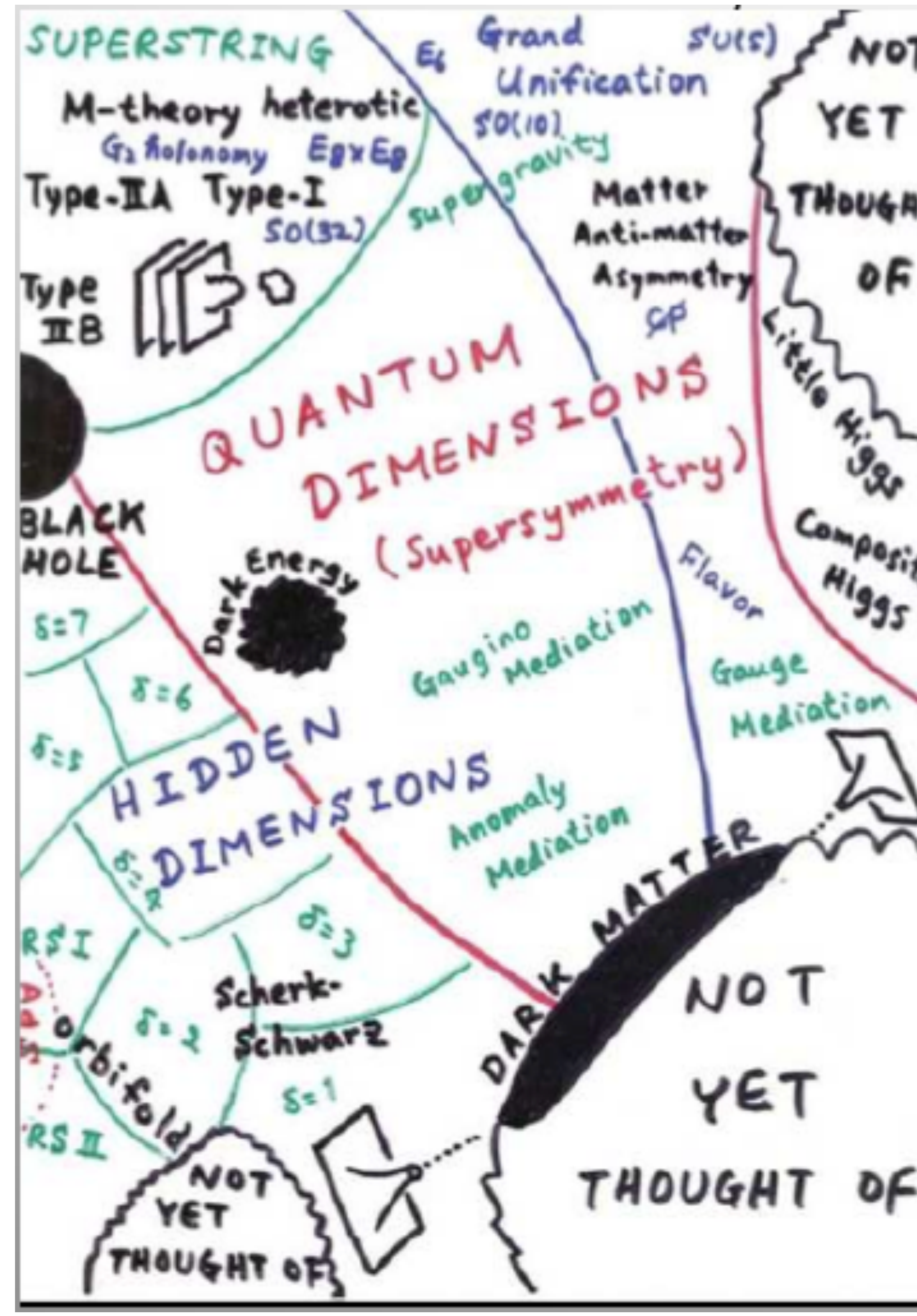
- How to stabilize the radiative corrections to Higgs mass in the theory?
- Why EWK and Plank scales are so separated ?
  - Any insight into gravity ?
- What is the nature and identity of dark matter ?
  - A new fundamental particle ?
- Why different particles have different masses
- Is there a new symmetry ?
  - Grand unification of all the forces
- What is the origin of matter-antimatter asymmetry in nature ?
  - Is CP violation the answer ?
  - How do neutrino masses and mixing fits in the big picture ?

**The Standard Model is an incomplete theory !**

# Physics Beyond Standard Model

**A lot of models which predicts new physics at the TeV scale accessible at LHC :**

- Supersymmetry (SUSY)
- Extra dimensions
- Grand Unified Theories (SU(5), O(10), E6 ..)
- LeptoQuarks
- TechniColor
- Compositeness
- Strong dynamics (composite Higgs)
- ...

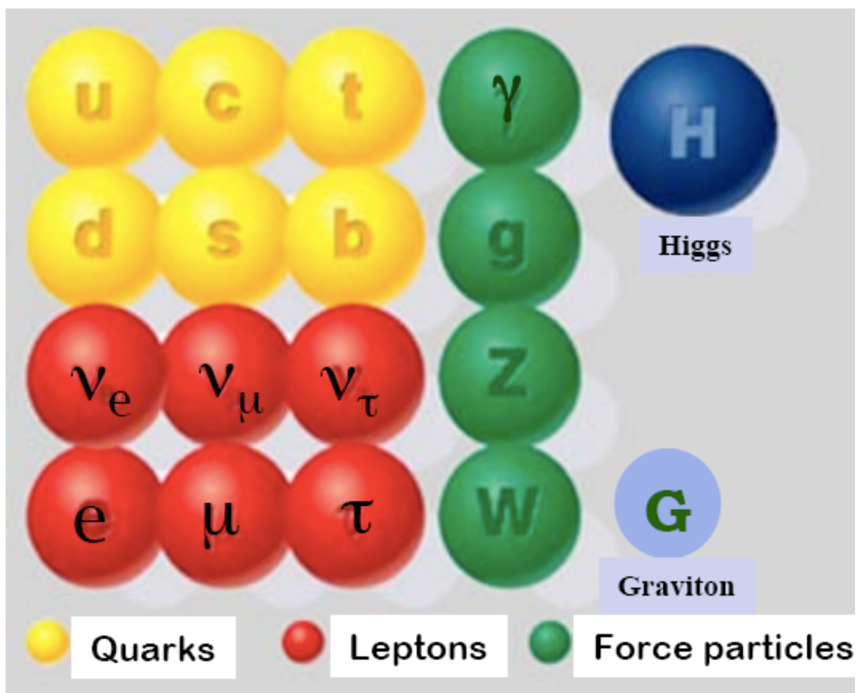



Most of these theories predicts new particles with mass scales of $\mathcal{O}$(TeV).

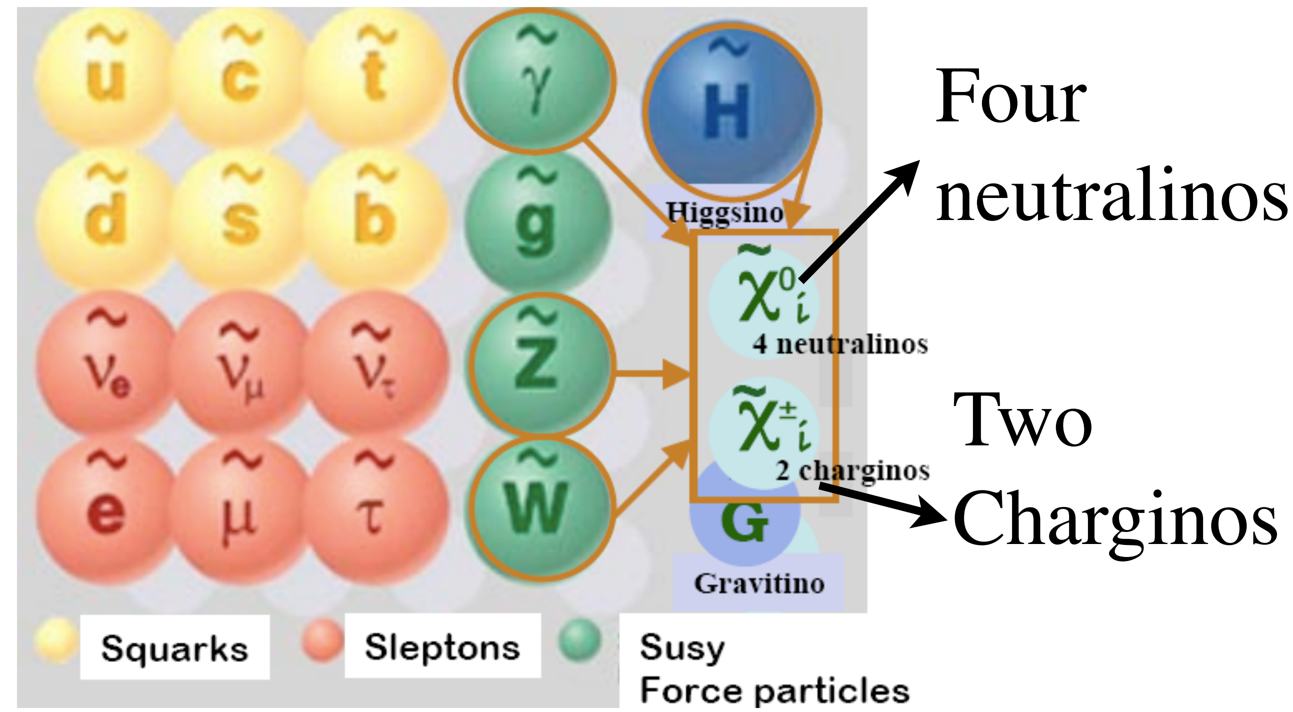
# Supersymmetry

Supersymmetry : A super-partner of every SM particle differing by spin-half

Standard Model Particles




Supersymmetry Particles




SUSY is a broken symmetry : Expect new particles in ~TeV range !

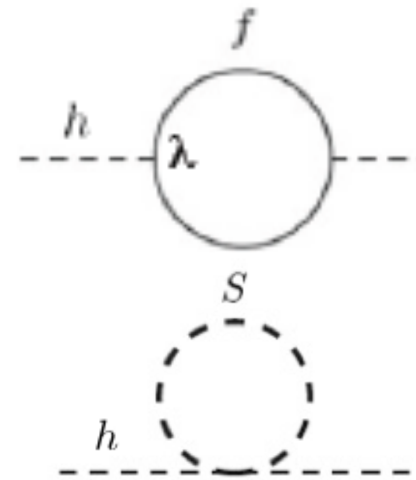
**"Natural SUSY" requires :**

- light stops, sbottoms (<1 TeV)
- not so heavy gluinos (1.5-2 TeV)
- light $\tilde{\chi}_1^0$ $\tilde{\chi}_1^\pm$ (few hundred GeV)

In **R-Parity conserving** models, lightest supersymmetry particle (**LSP**) is stable. Popularly lightest neutralino $\tilde{\chi}_1^0$ is an LSP.

# Why is Supersymmetry Attractive ?

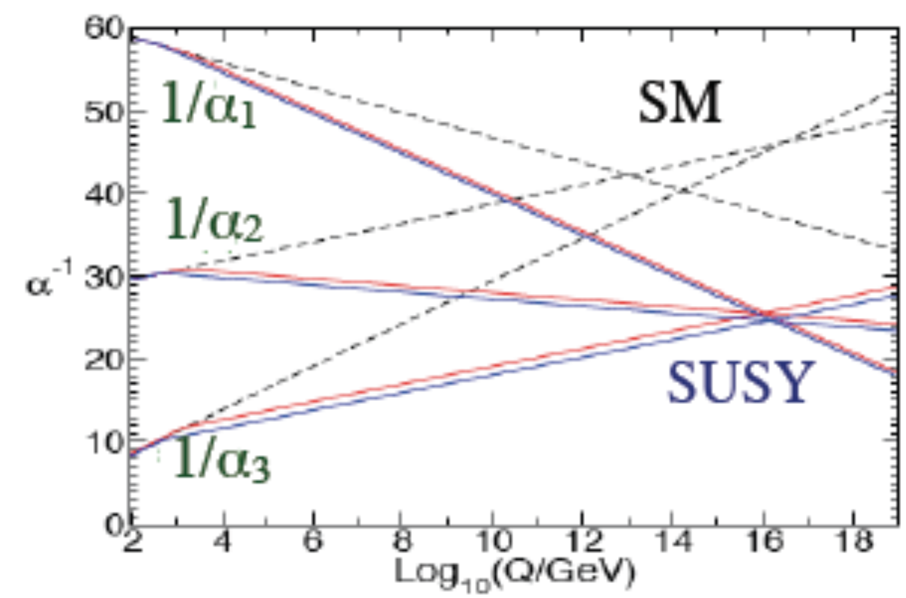
- Radiative corrections to Higgs boson mass :
  - Fermion and boson loops contribute to Higgs mass loop with opposite signs, hence avoid quadratic divergences



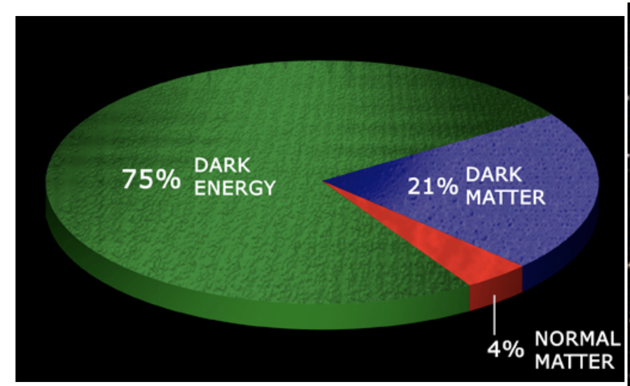

$$= -\frac{N_c \lambda^2}{16\pi^2}\left[2\Lambda^2_{cutoff} + \ldots +\right]$$

$$= +\frac{N_c \lambda^2}{16\pi^2}\left[2\Lambda^2_{cutoff} + \ldots +\right]$$

- Unification of couplings of three interactions
  - SM predicts “running” of coupling constants as a function of energy but without making these cross at the same energy




- Dark matter candidate
  - If the LSP is neutral and weakly interacting, it is a potential dark matter candidate




- A SUSY extension is a small perturbation consistent with the electroweak precision data

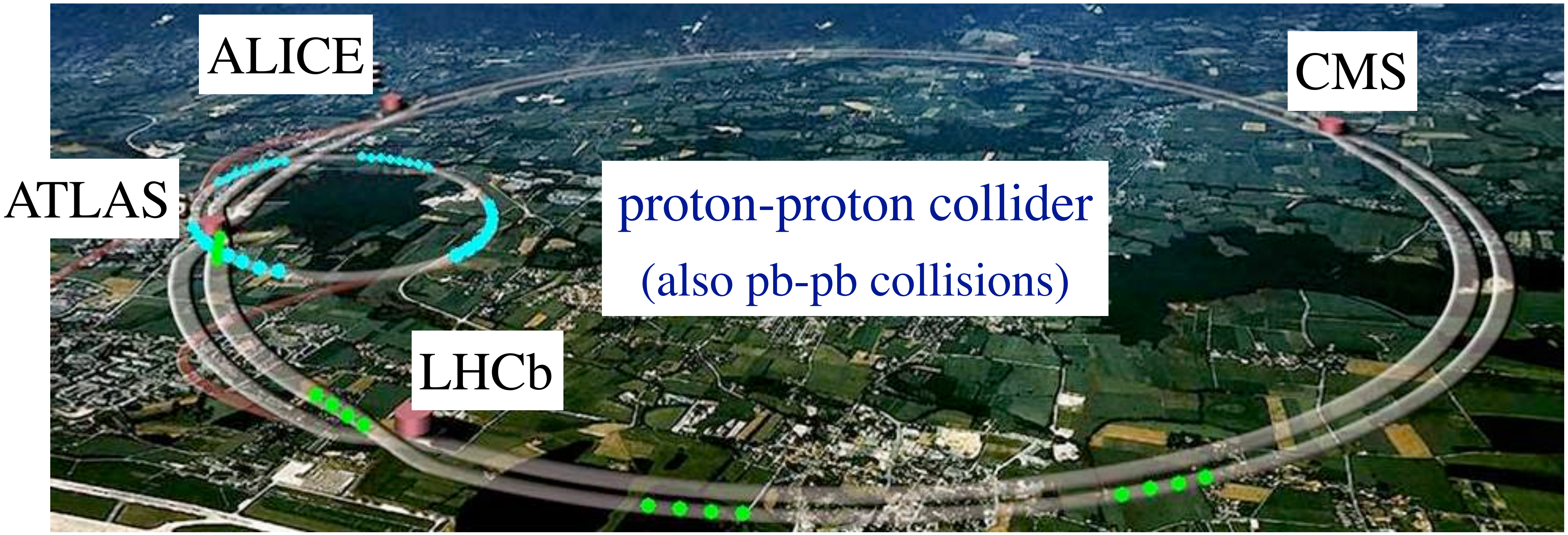
**Accelerate Particles**

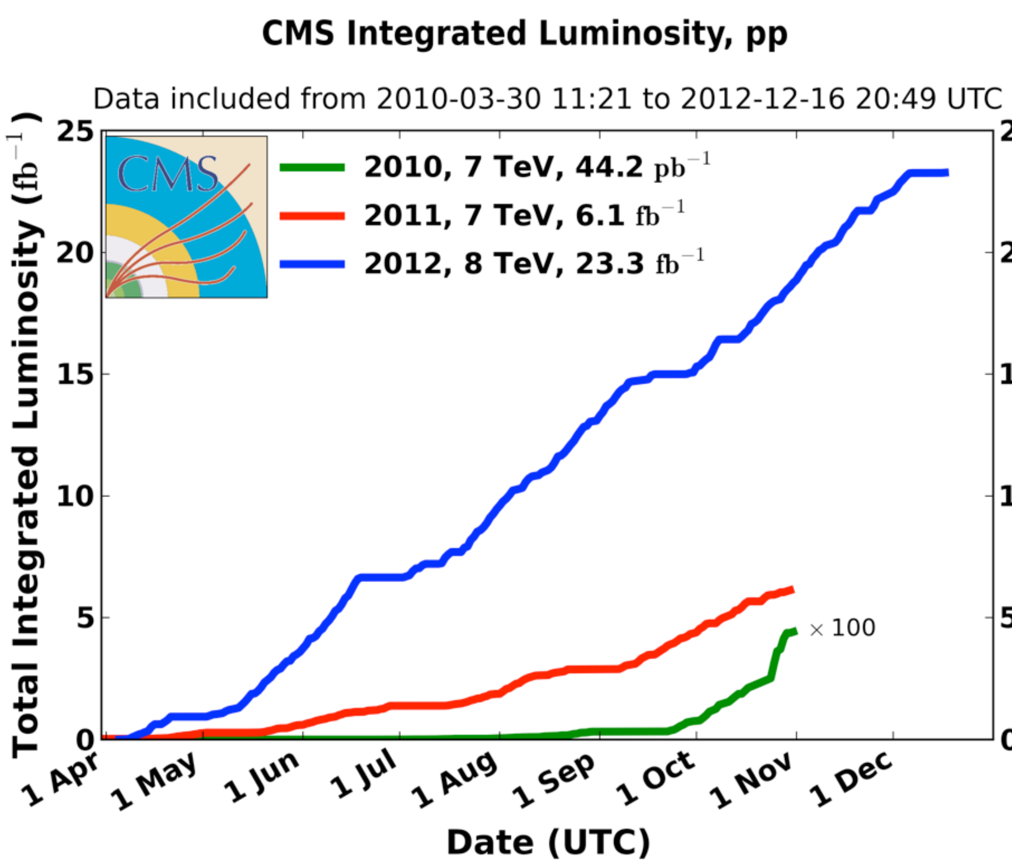
$$E = mc^2$$

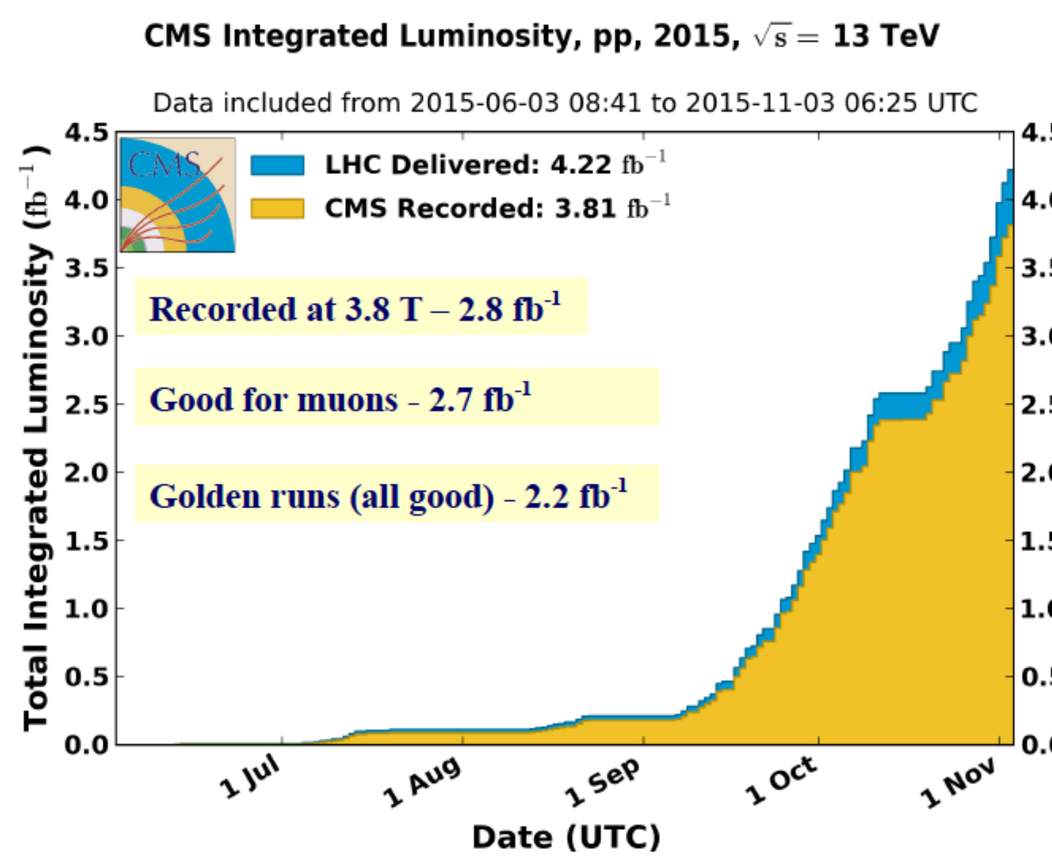
With sufficient centre-of-mass energy available, new massive particles can be produced

# Large Hadron Collider

Stellar performance during Run I and excellent start up of Run II !

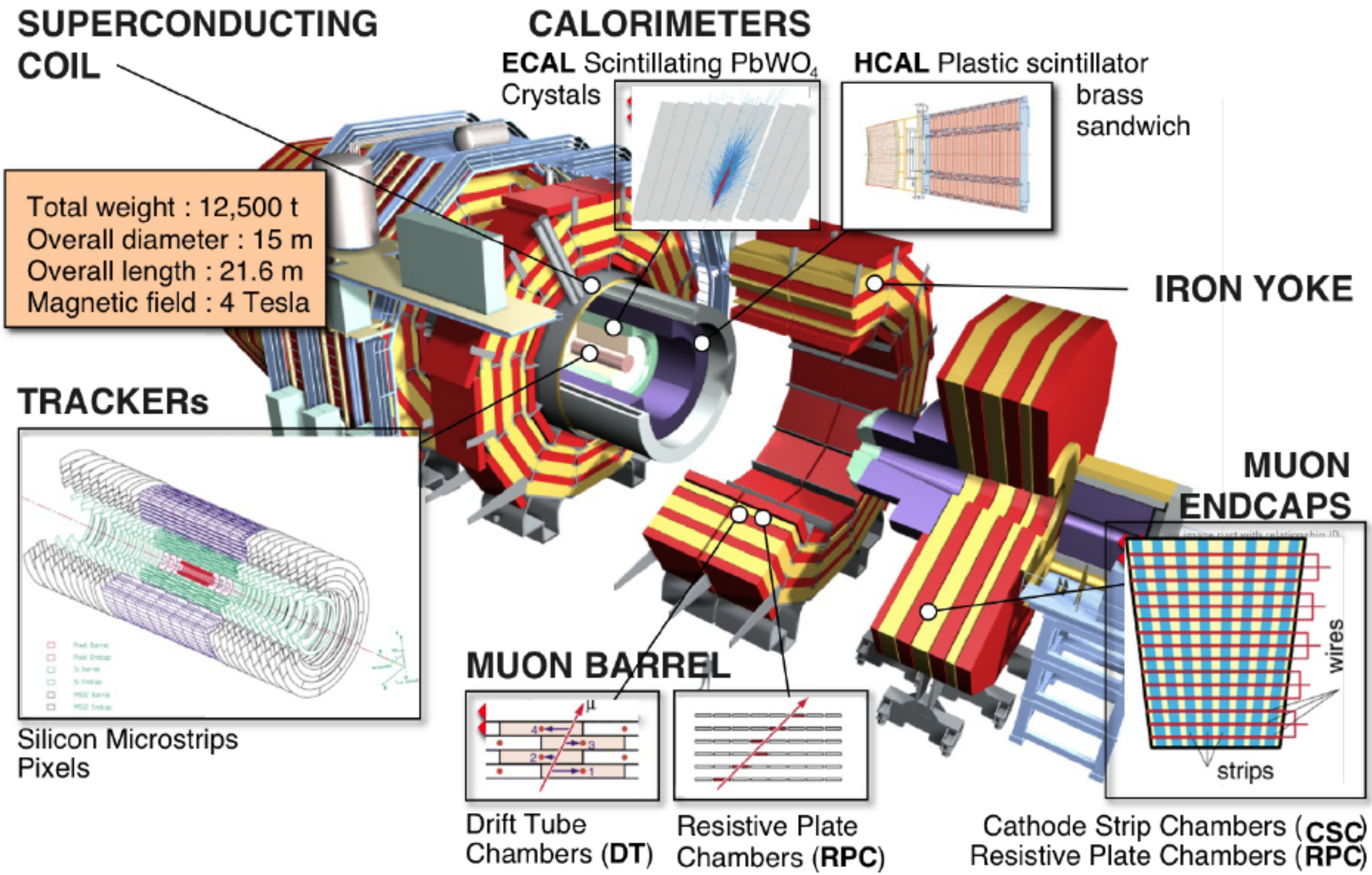


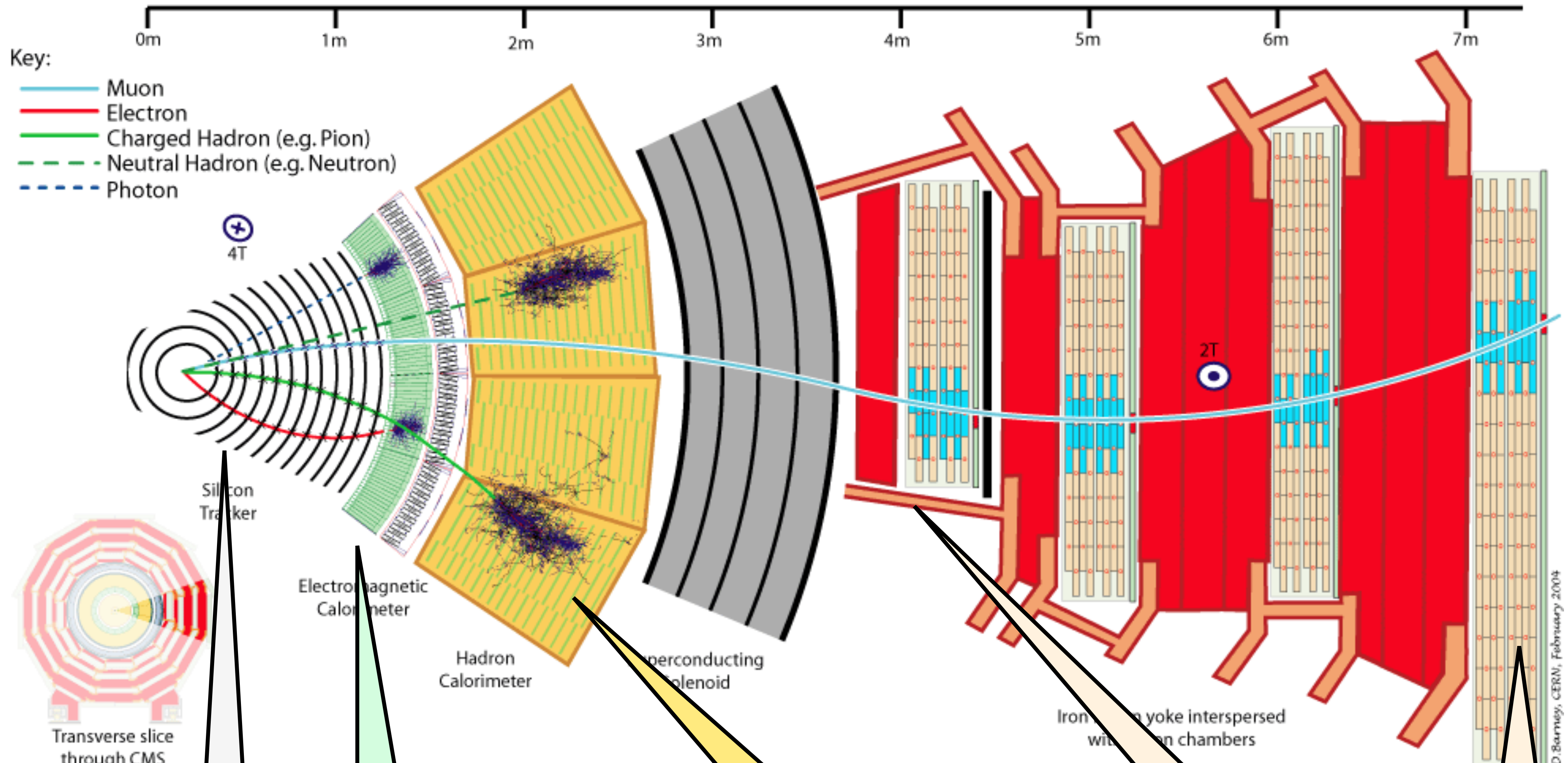



# How do We Study Collision Events ?
# (CMS Detector)

# Compact Muon Solenoid (CMS)



# Event Reconstruction using CMS




**Silicon Tracker**
Position, momentum of charged particles : **e±, π±, μ±**

**Electromagnetic Calorimeter**
Position & ID, energy of **e±, γ, π⁰**

**Hadron Calorimeter**
Energy of hadrons : **p, n, π±, K ..**

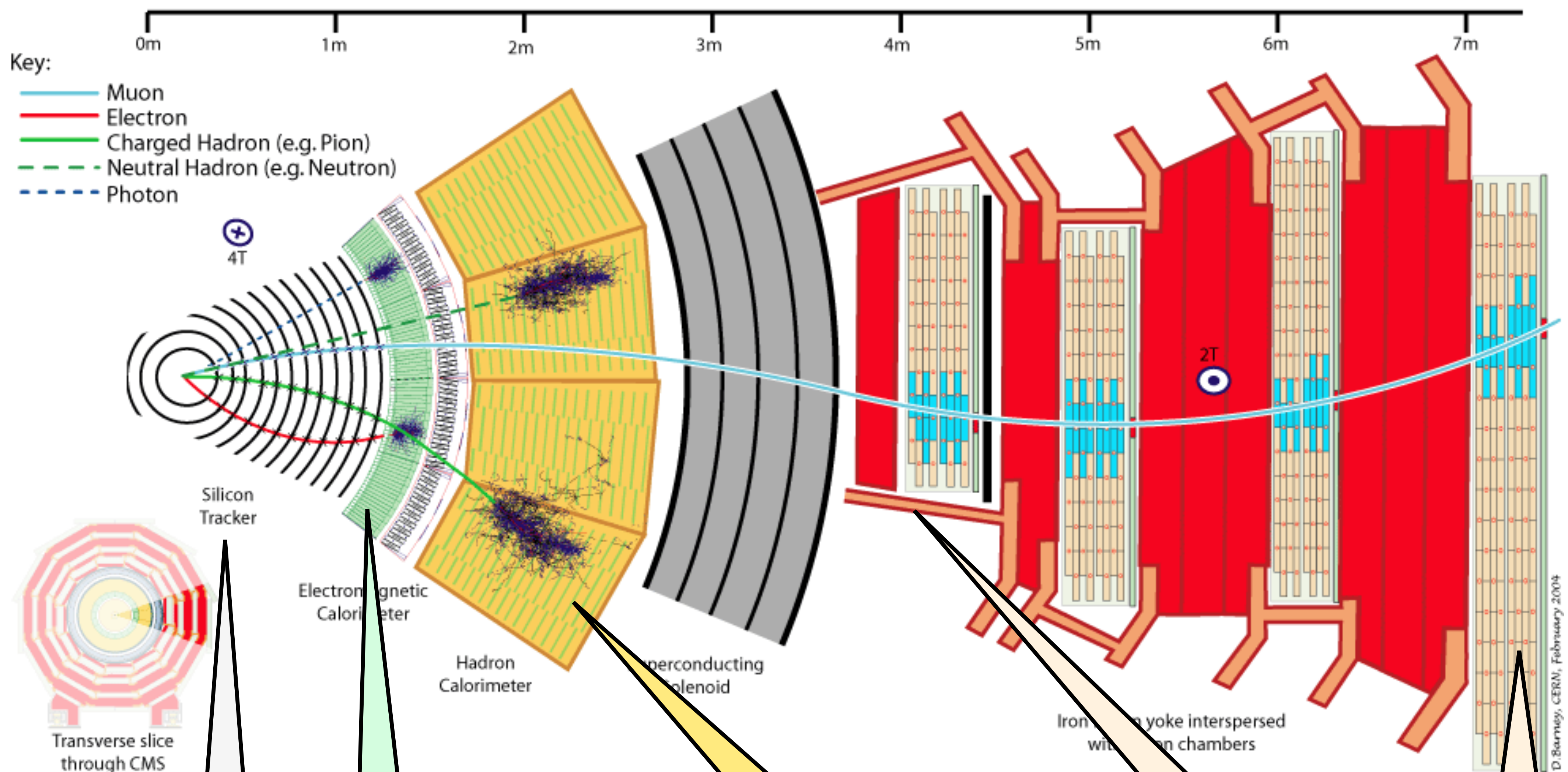
**Muon Chambers**
Position & momentum of **μ±**

$$\frac{\sigma}{p_T} \sim 1.5 \times 10^{-4} p_T(GeV)$$

$$\frac{\delta E_{e/\gamma}}{E_{e/\gamma}} \sim 1\%$$

$$\frac{\delta E_\mu}{E_\mu} \sim \mathcal{O}(1\%) \text{ for } p_{\mathrm{T}}^{\mu} \lesssim 100 \text{ GeV}$$

# Event Reconstruction using CMS




Silicon Tracker
Position, momentum of charged particles : **$e^{\pm}$, $\pi^{\pm}$, $\mu^{\pm}$**

Electromagnetic Calorimeter
Position & ID, energy of **$e^{\pm}$, $\gamma$, $\pi^0$**

Hadron Calorimeter
Energy of hadrons : **p, n, $\pi^{\pm}$, K ..**

Muon Chambers
Position & momentum of **$\mu^{\pm}$**

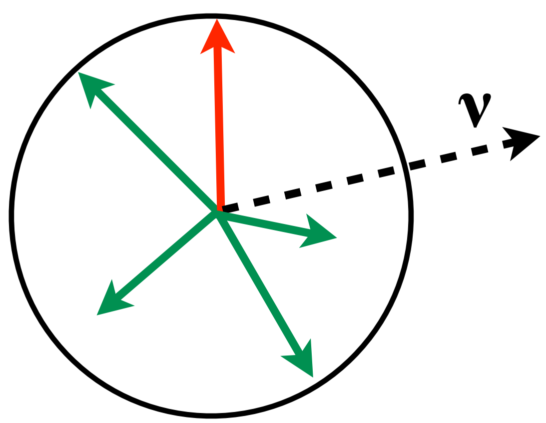
Weakly interacting neutral particles do not leave any trace in the detector, e.g. $\nu$ in SM and $\tilde{\chi}_1^0$ in SUSY.

# Missing Transverse Momentum (MET)

## (Measuring the Weakly Interacting Neutral Particles)

**MET** : vector sum of momentum of all particles transverse to the beam direction

$$\vec{P}_T^{P_1} + \vec{P}_T^{P_2} = 0 = \sum_i \vec{P}_T^i(measured)$$



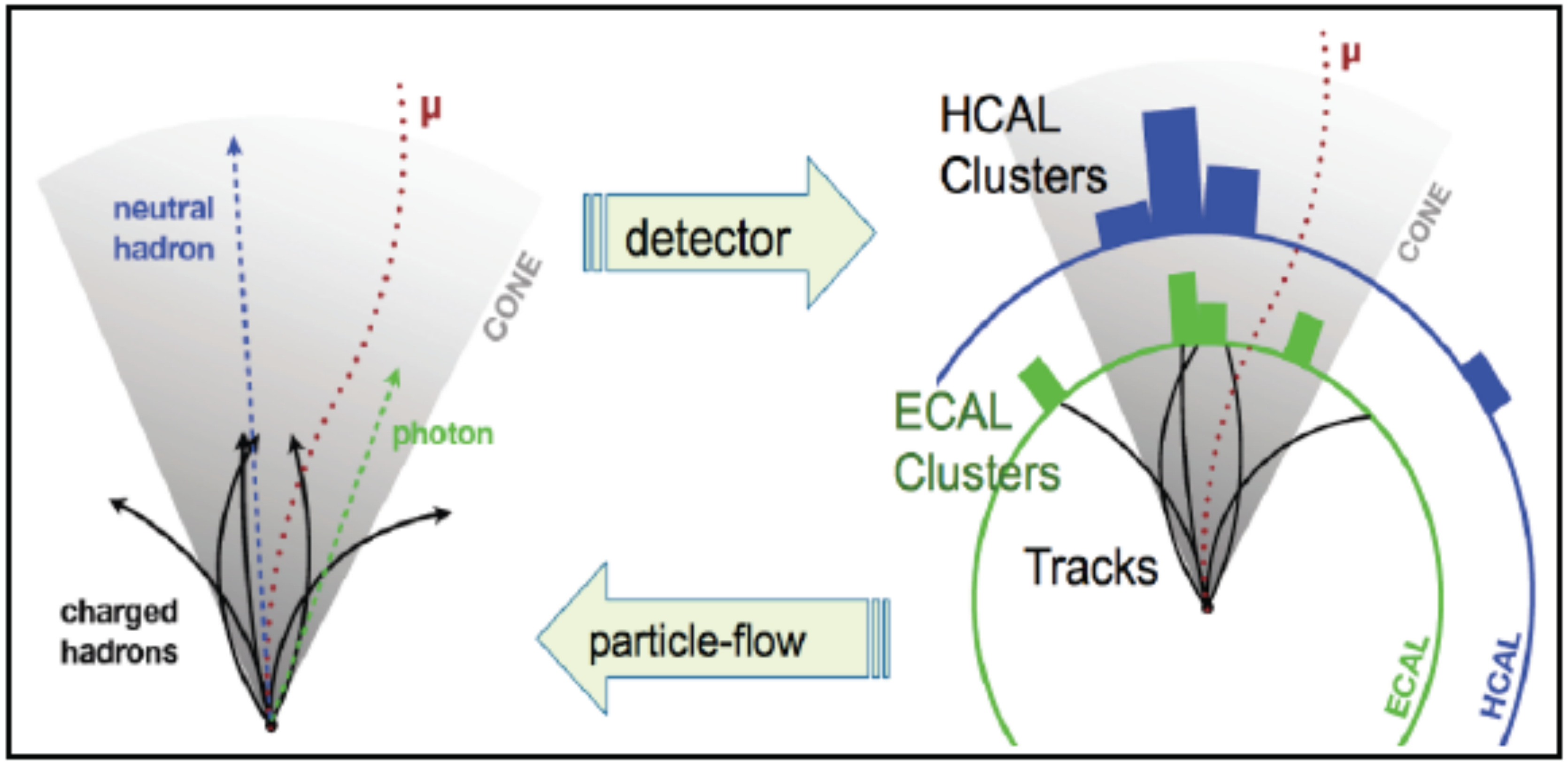

$$\vec{P}_T^{miss} = -\sum_i \vec{P}_T^i(measured) \neq 0 \Rightarrow$$

Some particles are not detected (e.g. ν, neutralino)

**In addition, any mis-measurement may result in an imbalance in $p_T$**

For e.g. non-functional detector channels, electronic noise, non-collision backgrounds ...

# Measurement of Jets

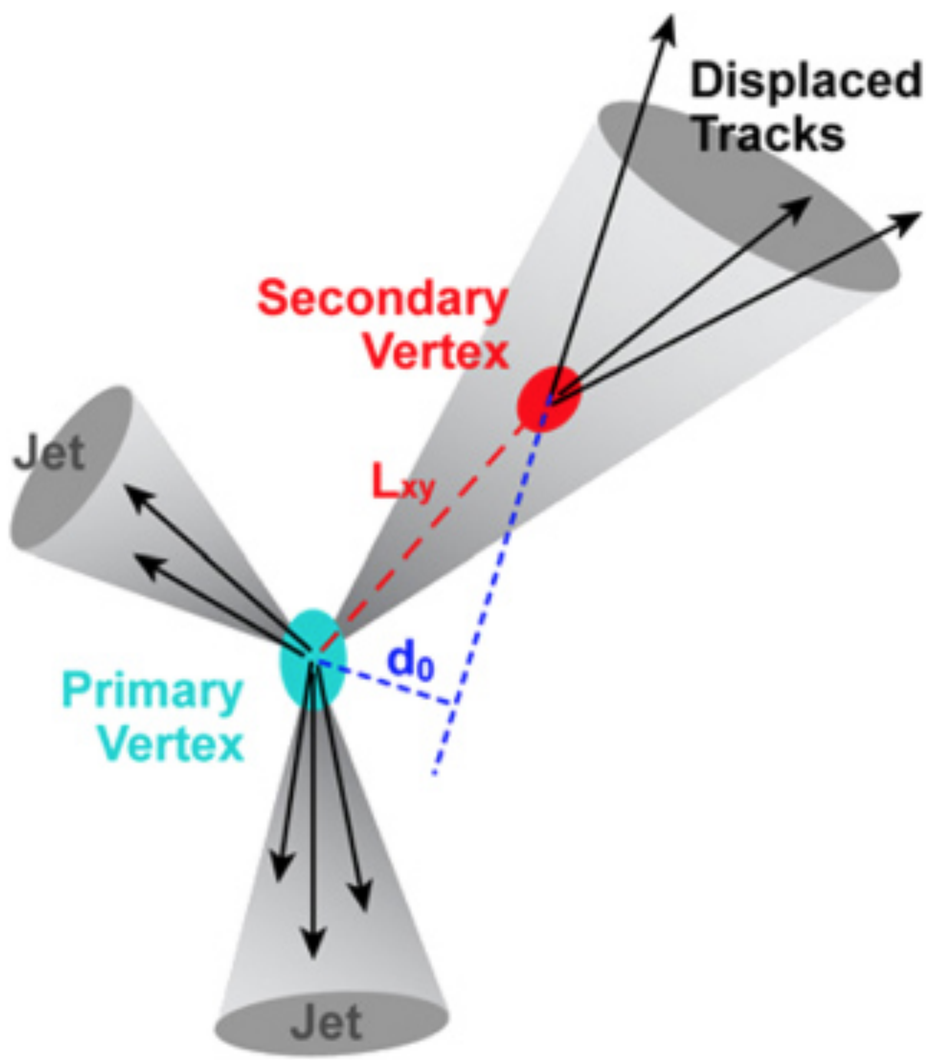


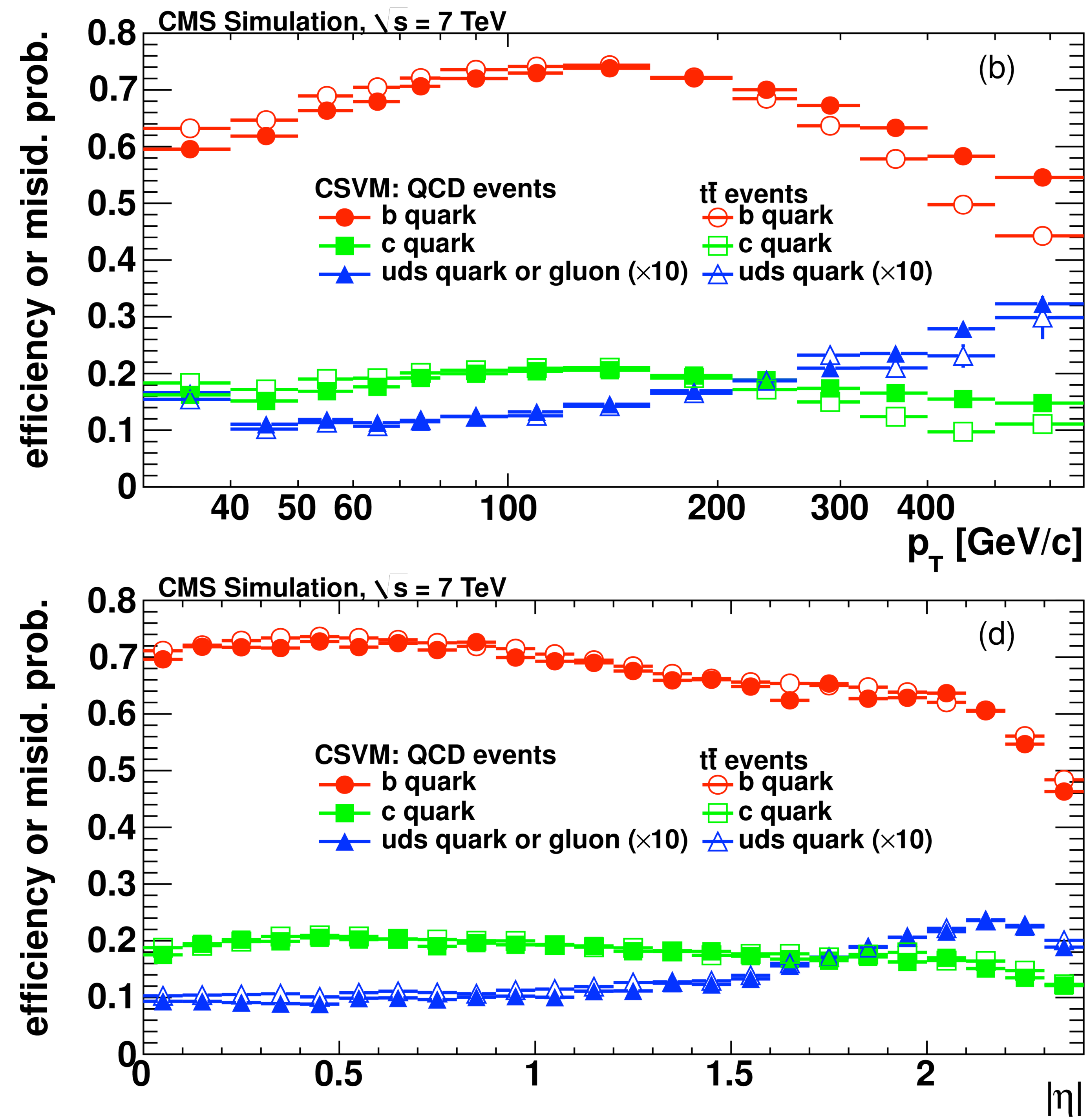

**Jets** : manifestation of quarks and gluons

- a collimated spray of "colorless" hadrons : $\pi^{\pm}$, $\pi^{0}$, $K^{\pm}$, $K^{0}$, p, n ...
- experimental probe to study properties of original quark or gluon
- Both the CMS and ATLAS use anti-kT clustering with distance parameter of 0.4 (know as AK4 jets)

# Identification of b-quarks

CMS-BTV-12-001

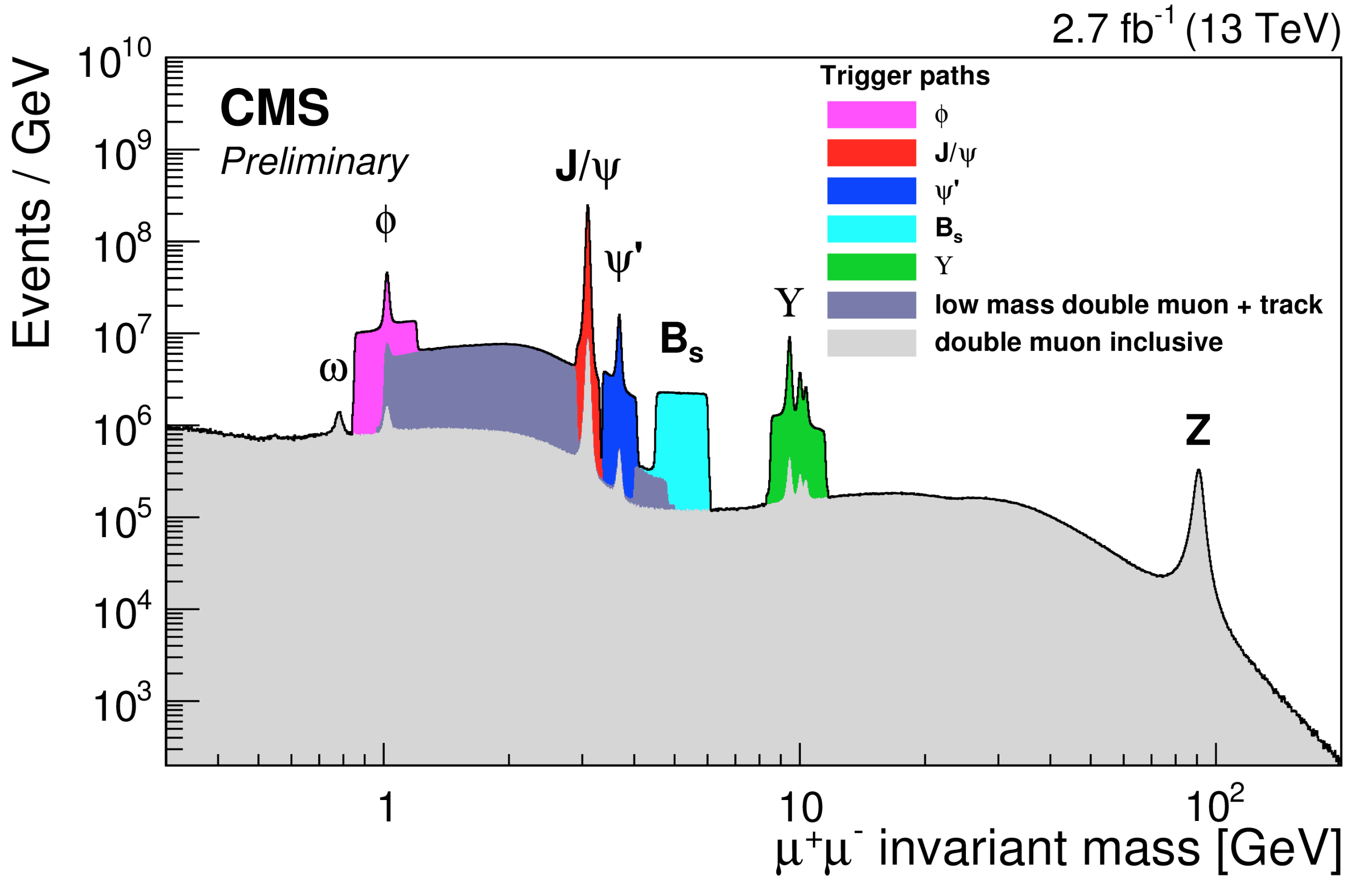


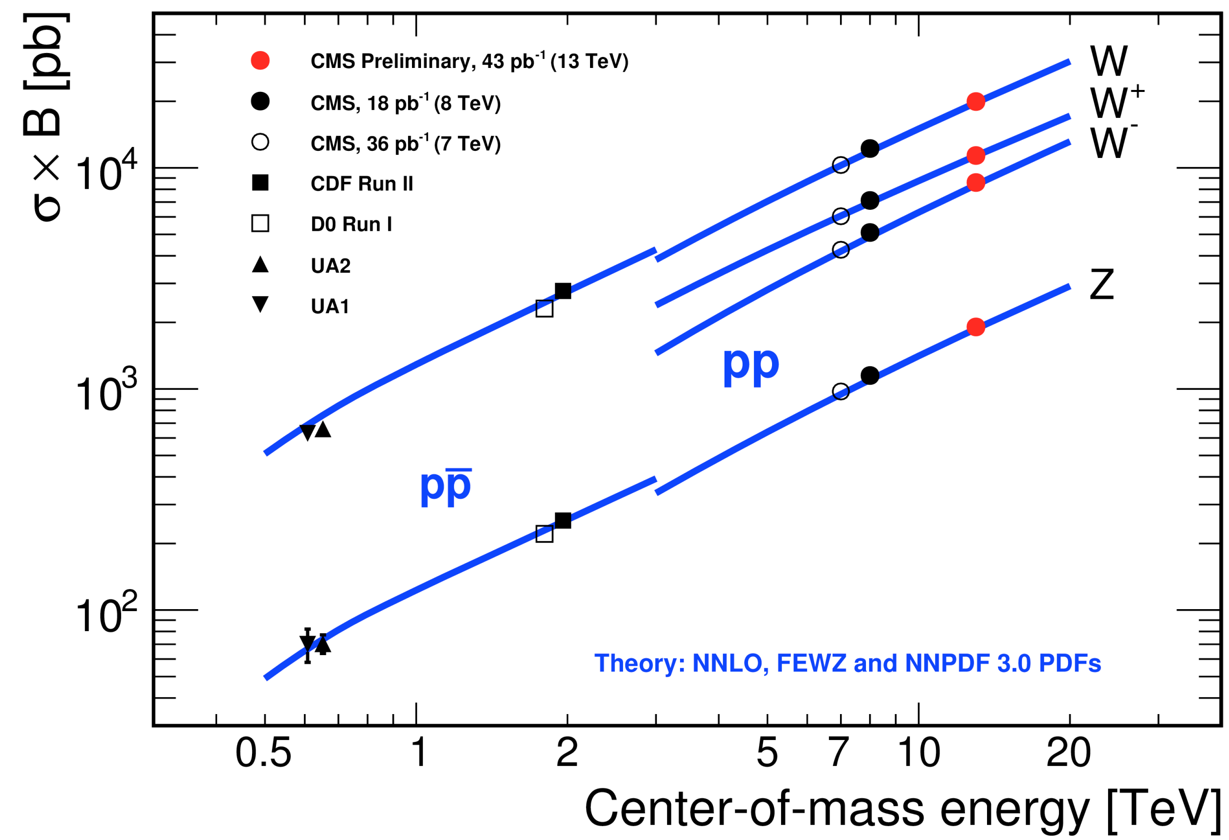




Using the properties of B-hadrons : displaced secondary vertices

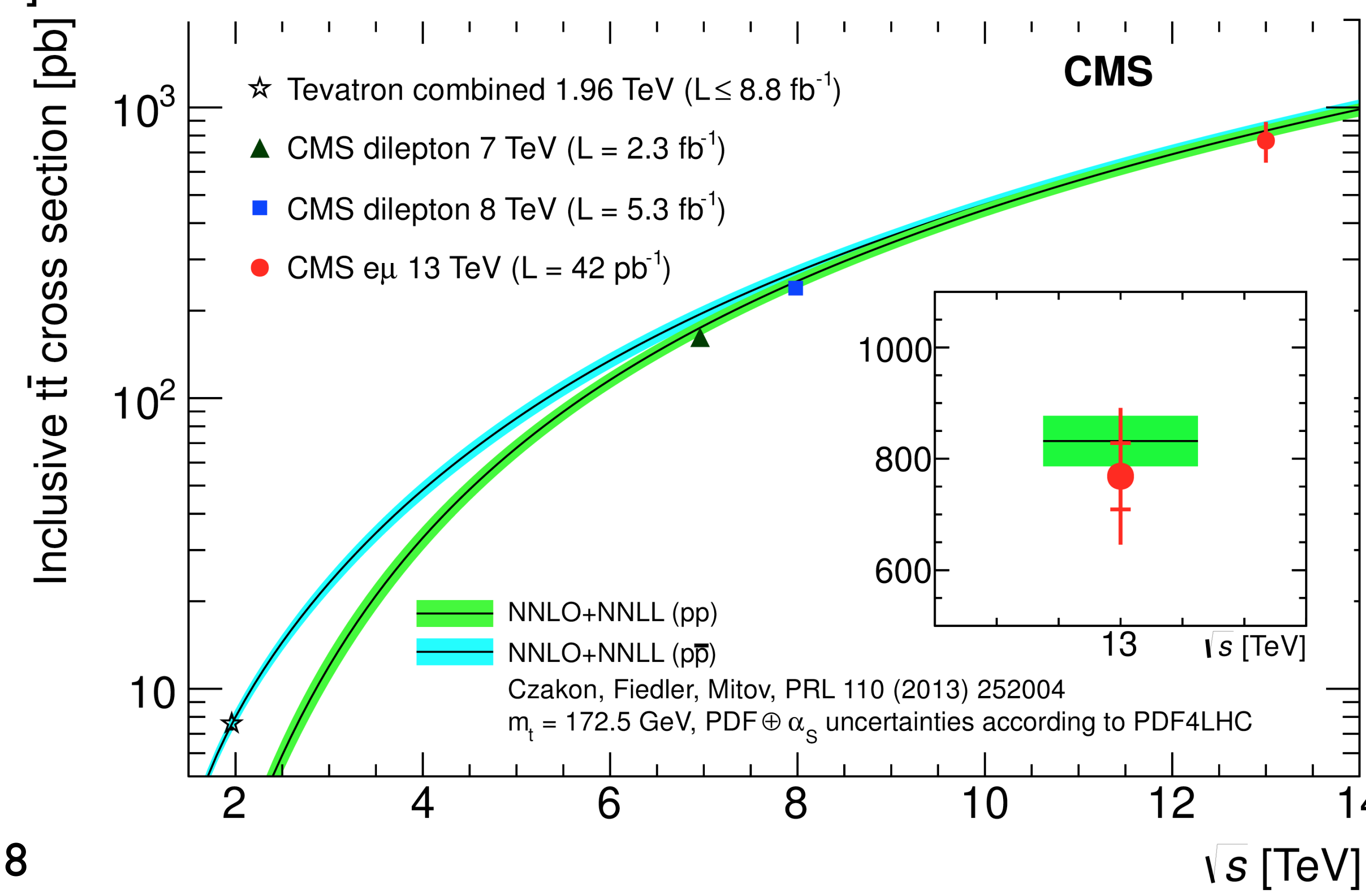
# The Continuing Paradigm @ 13 TeV

## Standard Model Measurements



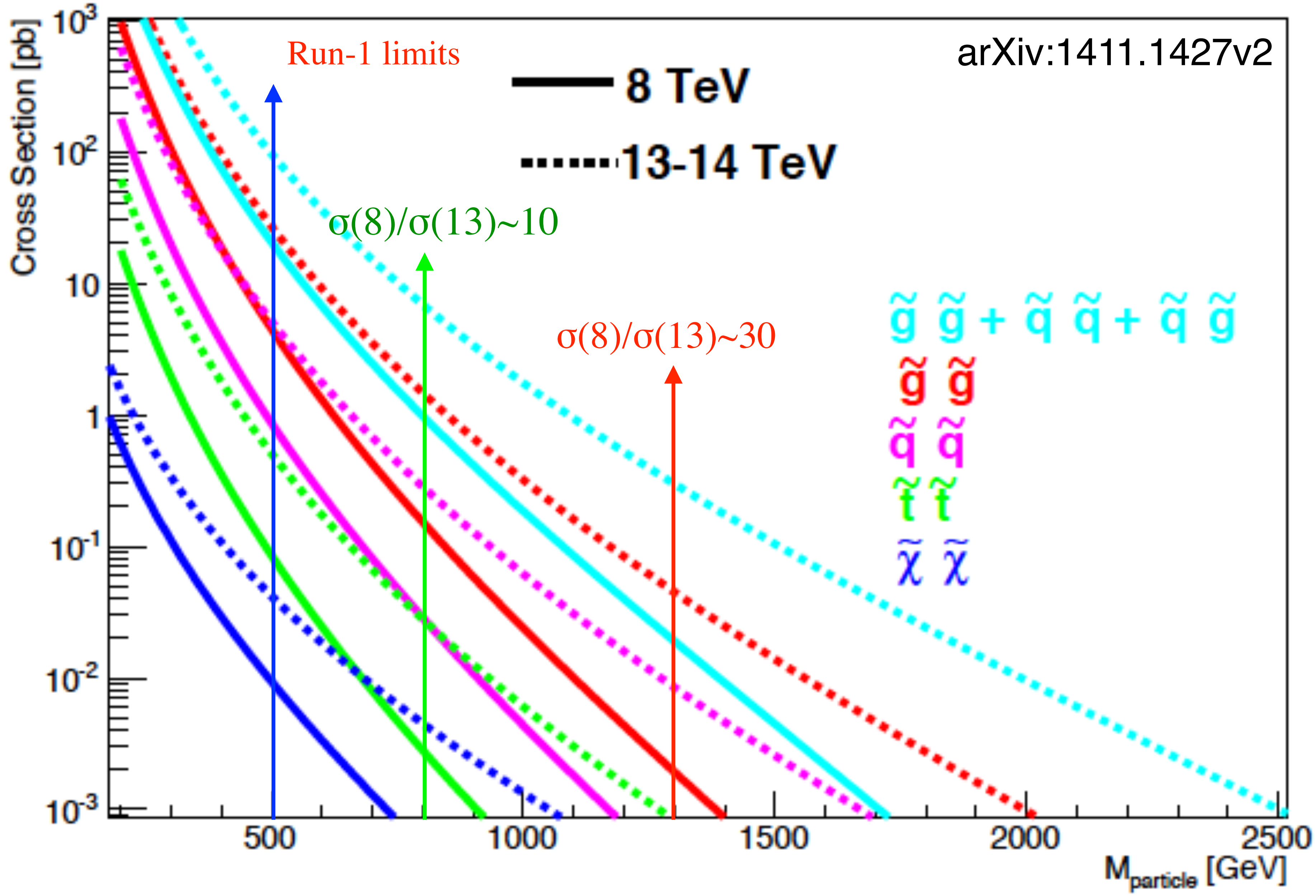

Key point for any new discovery is to understand the backgrounds due to SM processes and understanding performance of the detector components.



# SUSY Searches with CMS Experiment

# Going from 8 TeV → 13 TeV

Massive particles can be produced at higher energy thresholds as the LHC operational energy is increasing.




- Expect to enter new sensitivity regime for gluino searches with 1 $fb^{-1}$ data @13 TeV
- Stops and squark searches by 3-5 $fb^{-1}$ and elecroweak production by 8-10 $fb^{-1}$

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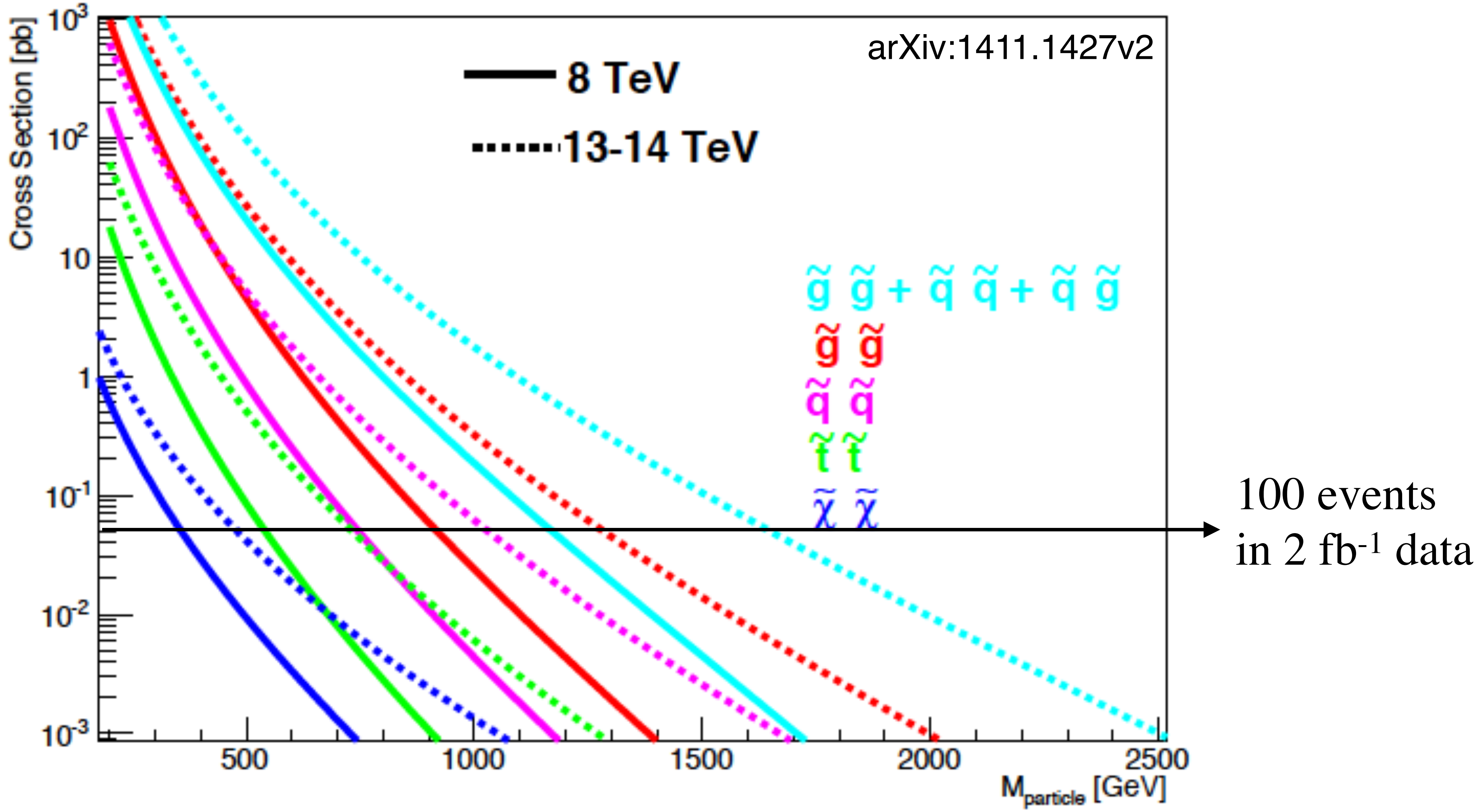


- Expect to enter new sensitivity regime for gluino searches with 1 $fb^{-1}$ data @13 TeV
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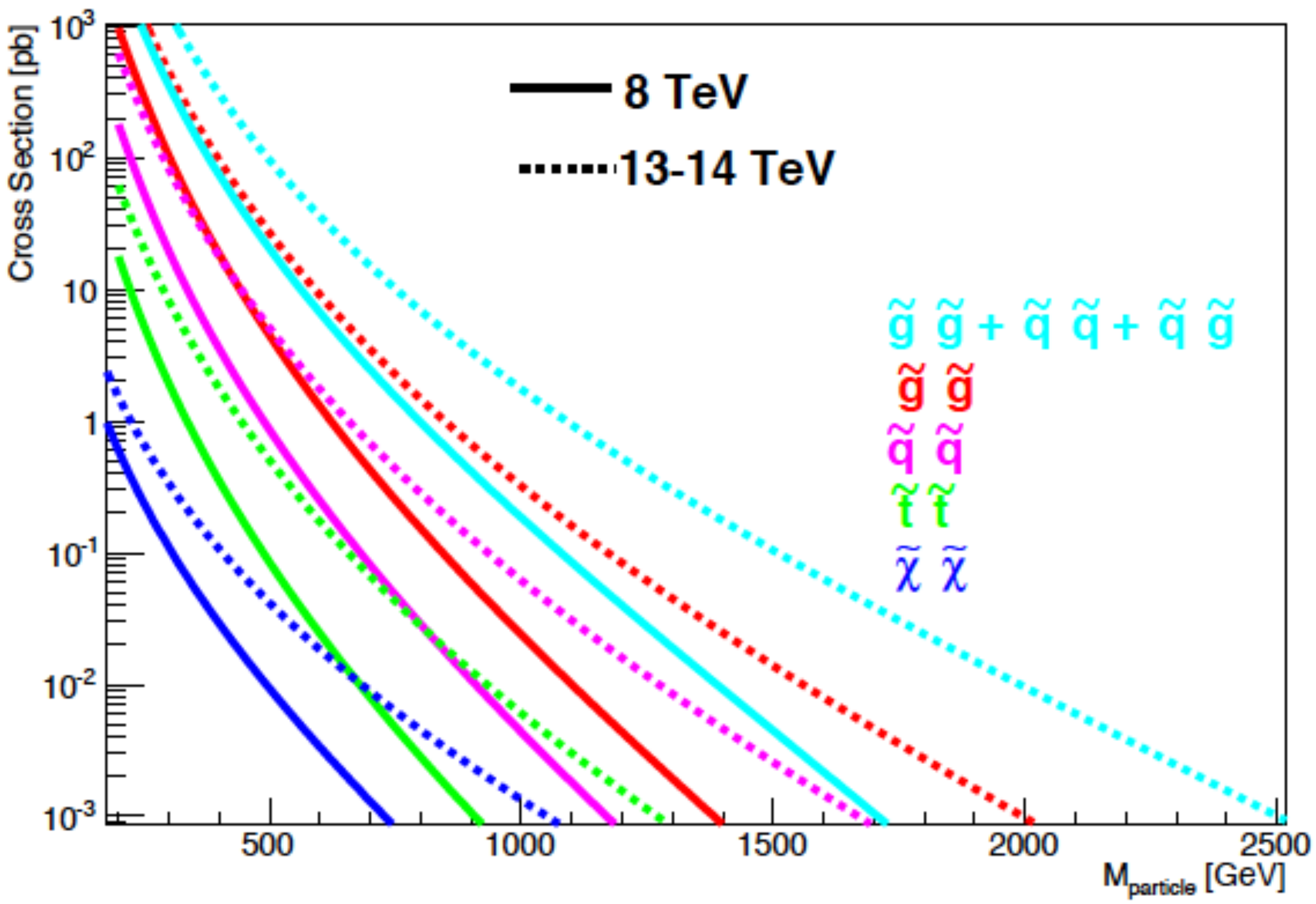
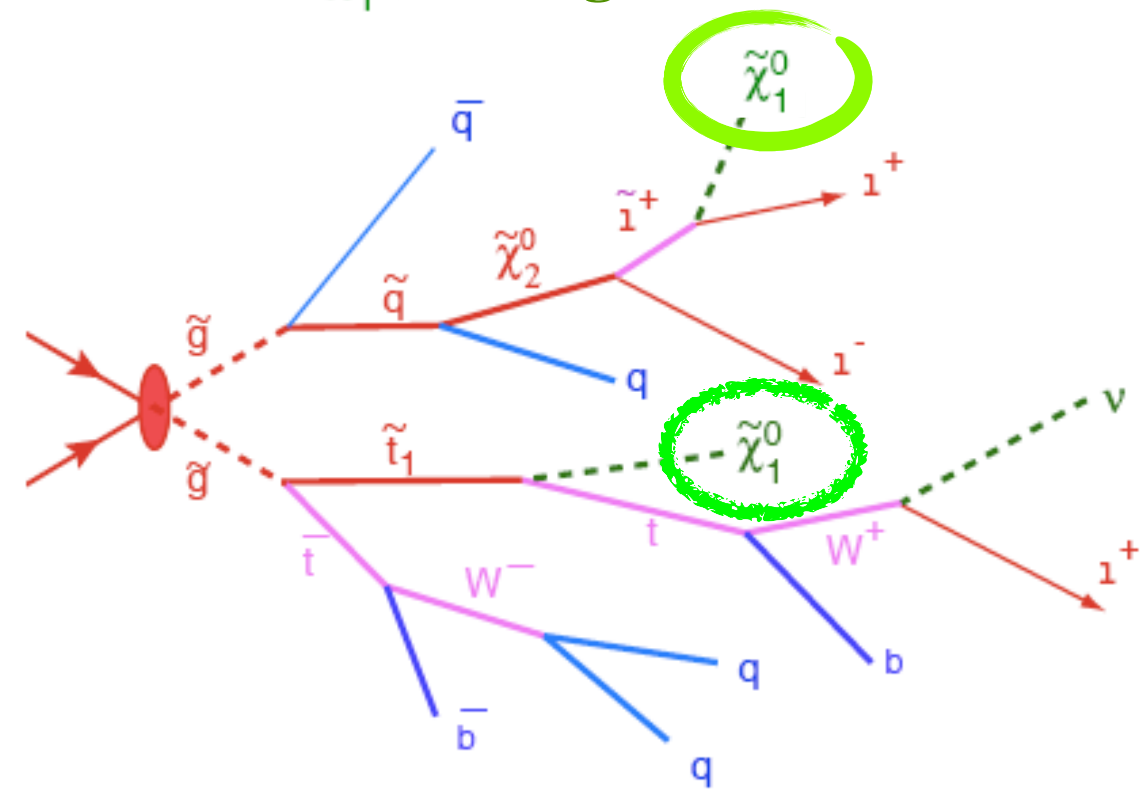
# SUSY Production @ LHC




An example decay chain of a SUSY event

**Two LSPs ($\tilde{\chi}_1^0$ ) : Large MET**




- **Strong production**
- squarks and gluino pairs, large cross-section at hadron colliders
- typically Jets & MET based searches categorized in numbers of leptons (and photons)

- **Third generation squarks**
- Small cross-section as compared to light squark pair productions
- Final state may include ttbar pairs, multiple b-jets

- **Weak production**
- direct neutralino/chargino production
- searches based on multi-leptons and MET signatures

# Generic Searches vs Targeted Searches

Two LSPs ( $\tilde{\chi}_1^0$ ) : Large MET

Mostly involves Jets

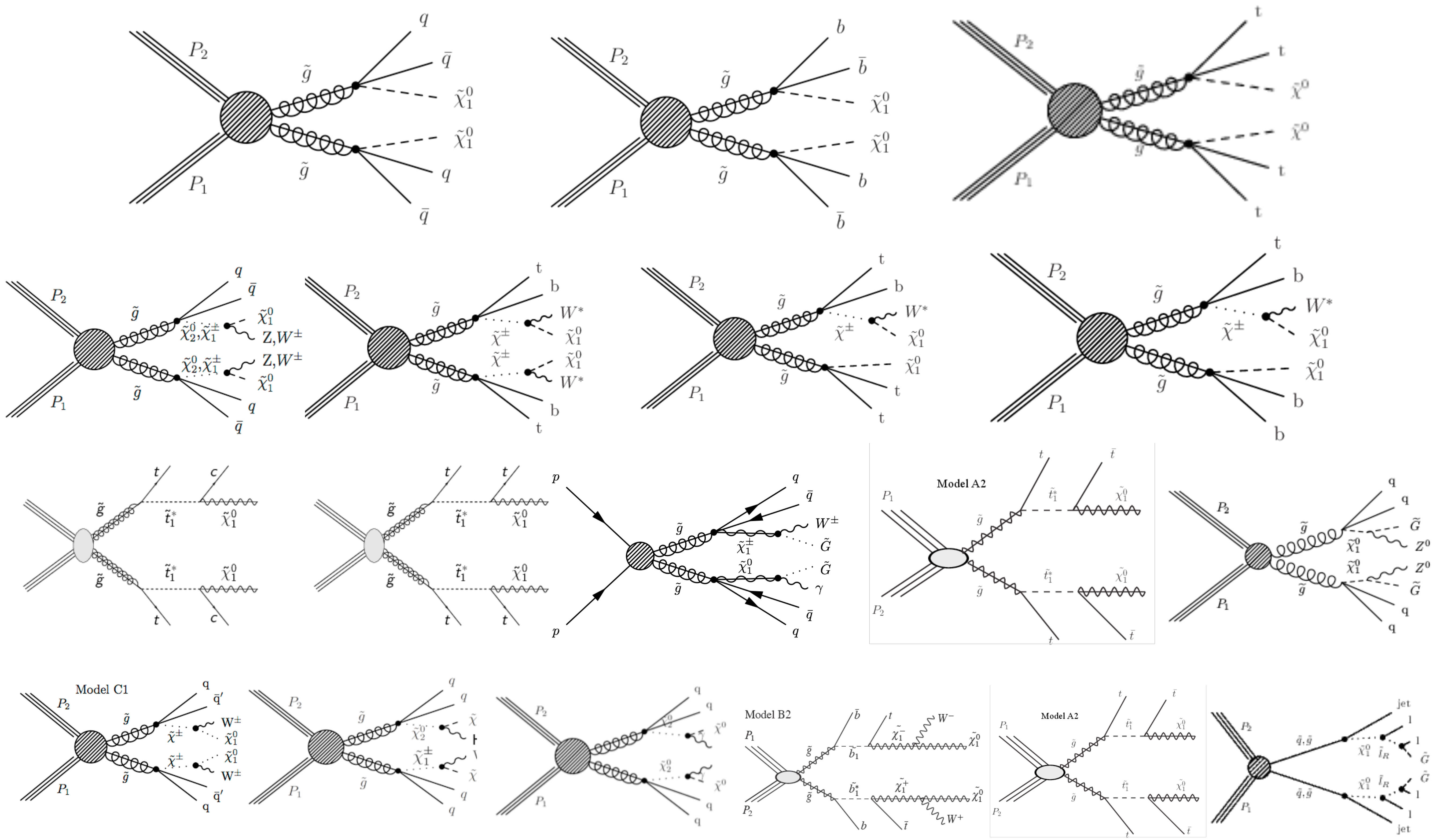
Categorize further in number of leptons and photons.

| 0-leptons | 1-lepton | OSDL | SSDL | ≥3 leptons | 2-photons | γ+lepton |
|---|---|---|---|---|---|---|
| Jets + MET | Single lepton + Jets + MET | Opposite-sign di-lepton + jets + MET | Same-sign di-lepton + jets + MET | Multi-lepton | Di-photon + jet + MET | Photon + lepton + MET |

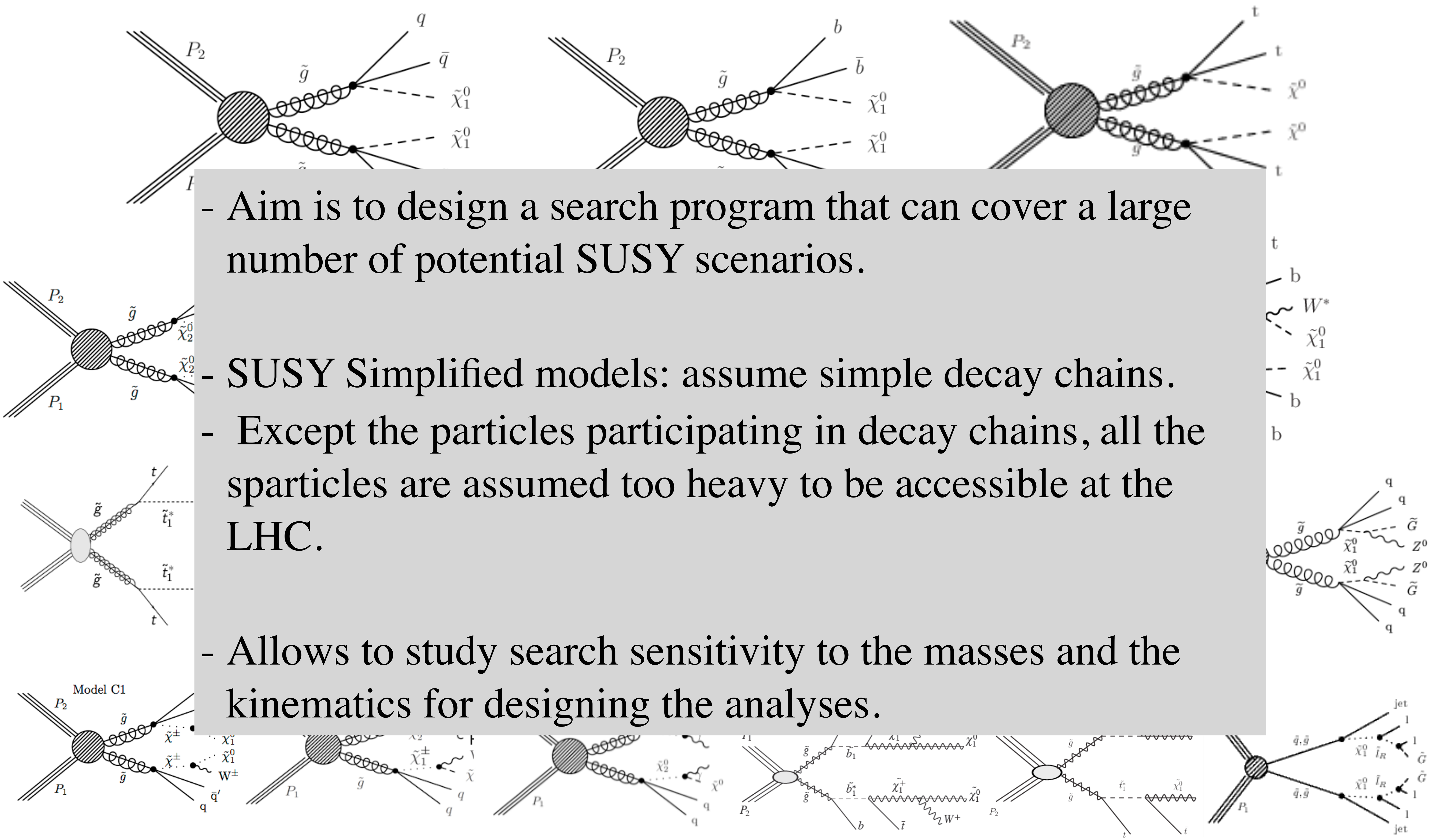
The targeted searches go in parallel and gain more significance with increasing data

- Searches for direct production of top and bottom squarks
  - Exploit the well establishes properties of top quarks
  - Aggressive on b/τ-tagging and specific kinematics
- Electroweakino and slepton production

# Gluino final states - a few examples



# SUSY Possibilities



- Aim is to design a search program that can cover a large number of potential SUSY scenarios.

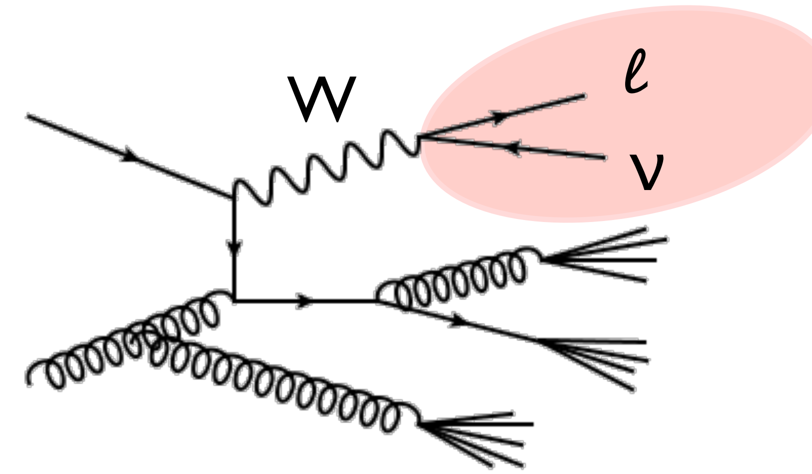
- SUSY Simplified models: assume simple decay chains.
- Except the particles participating in decay chains, all the sparticles are assumed too heavy to be accessible at the LHC.

- Allows to study search sensitivity to the masses and the kinematics for designing the analyses.

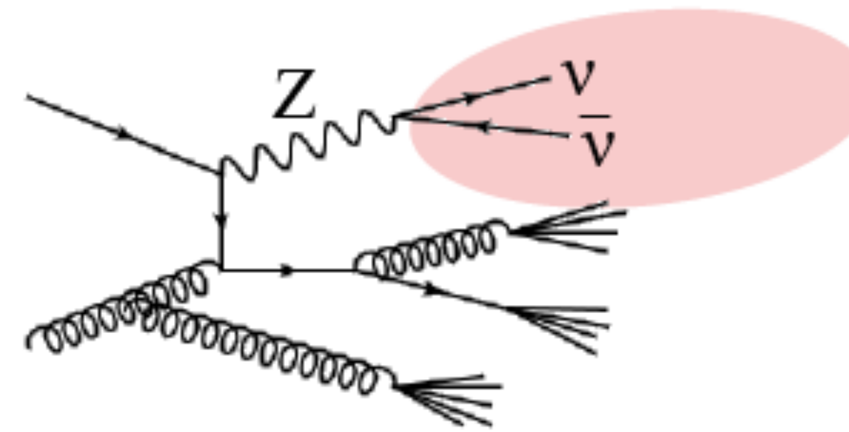
# All Hadronic Searches at CMS

## General Strategy: details may differ in varios analysis

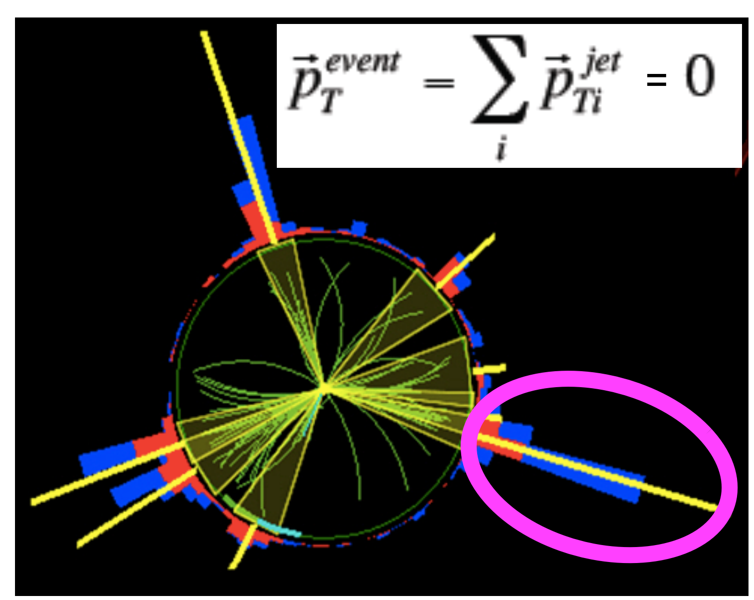
- Veto lepton to reject W/top + Jets with $W \to \ell\,\nu$
- Contributes as background if
  - $t \to W\,(e/\mu\,\nu)$ + Jets and e/μ is not identified
  - $t \to W\,(\tau\,\nu)$+ Jets  and τ decays hadronically reconstructed as a Jet

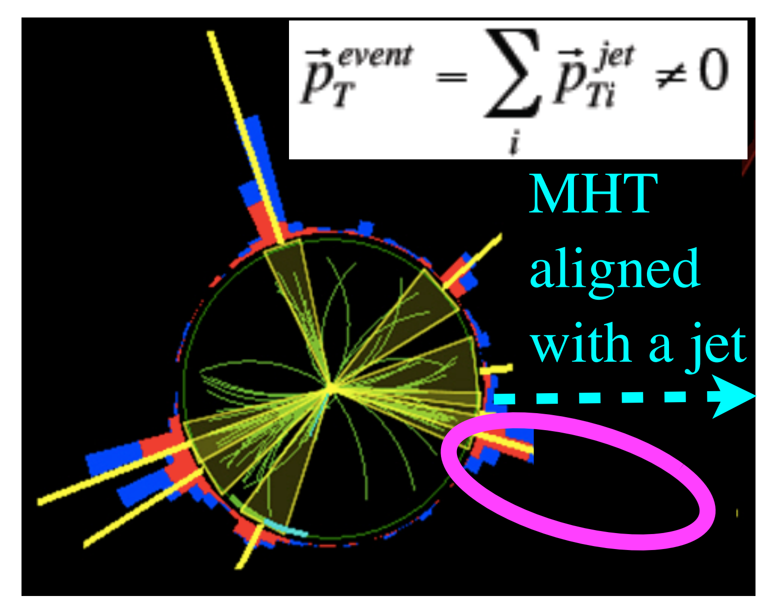



- Large hadronic as well as missing transverse momentum
  - Z (νν) + Jets - an irreducible background




- Large MET effectively reject QCD multijets (jet mismeasurement, instrumental effects etc.)
  - $\Delta\Phi(\mathrm{MHT}, \mathrm{Jets}^{\{1,2,3,4\}}) > (0.5, 0.5, 0.3, 0.3\ )$



# Analysis Designed Around Search Variables

IISER PUNE

**CMS-PAS-SUS-15-002**

Missing Transverse Hadronic Energy

(using jets with $p_T > 30$ GeV, $|\eta|<5.0$)

$$\not H_T = \left| -\sum_{i}^{jets} \vec{p}_{T,i} \right|$$

**CMS-PAS-SUS-15-005**

$$\alpha_T = \frac{E_T^{j_2}}{M_T}$$

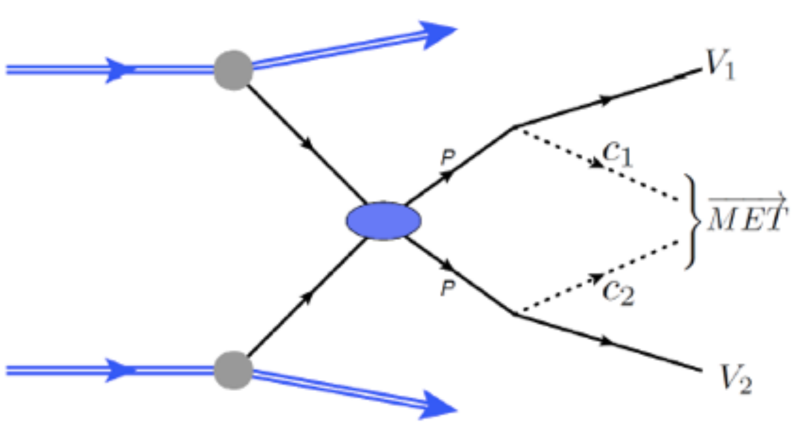
- $\alpha_T = 0.5$ for balanced diet systems
- $\alpha_T < 0.5$ for mismeasured jets (kills QCD)

For an multi-jet system, jets are merged to make an equivalent dijet system such that difference in $E_T$ of two systems ($\Delta H_T$) is minimum.

$$\alpha_T = \frac{1}{2} \cdot \frac{H_T - \Delta H_T}{\sqrt{H_T^2 - \not H_T^2}}$$

**CMS-PAS-SUS-15-003**

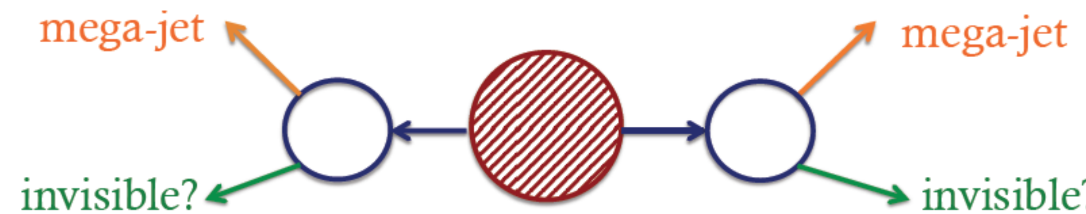
$$M_{T2} = \min_{p_T^{c1}+p_T^{c2}=\not p_T}\left[\max\left(m_T^{(1)}, m_T^{(2)}\right)\right]$$




- $M_{T2} \sim$ MET for symmetric topologies : SUSY
- $M_{T2} \sim 0$ for nearly balanced systems
- $M_{T2} <$ MET for imbalanced and asymmetric systems

**CMS-PAS-SUS-15-004**

RaZOR




Mass scale

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

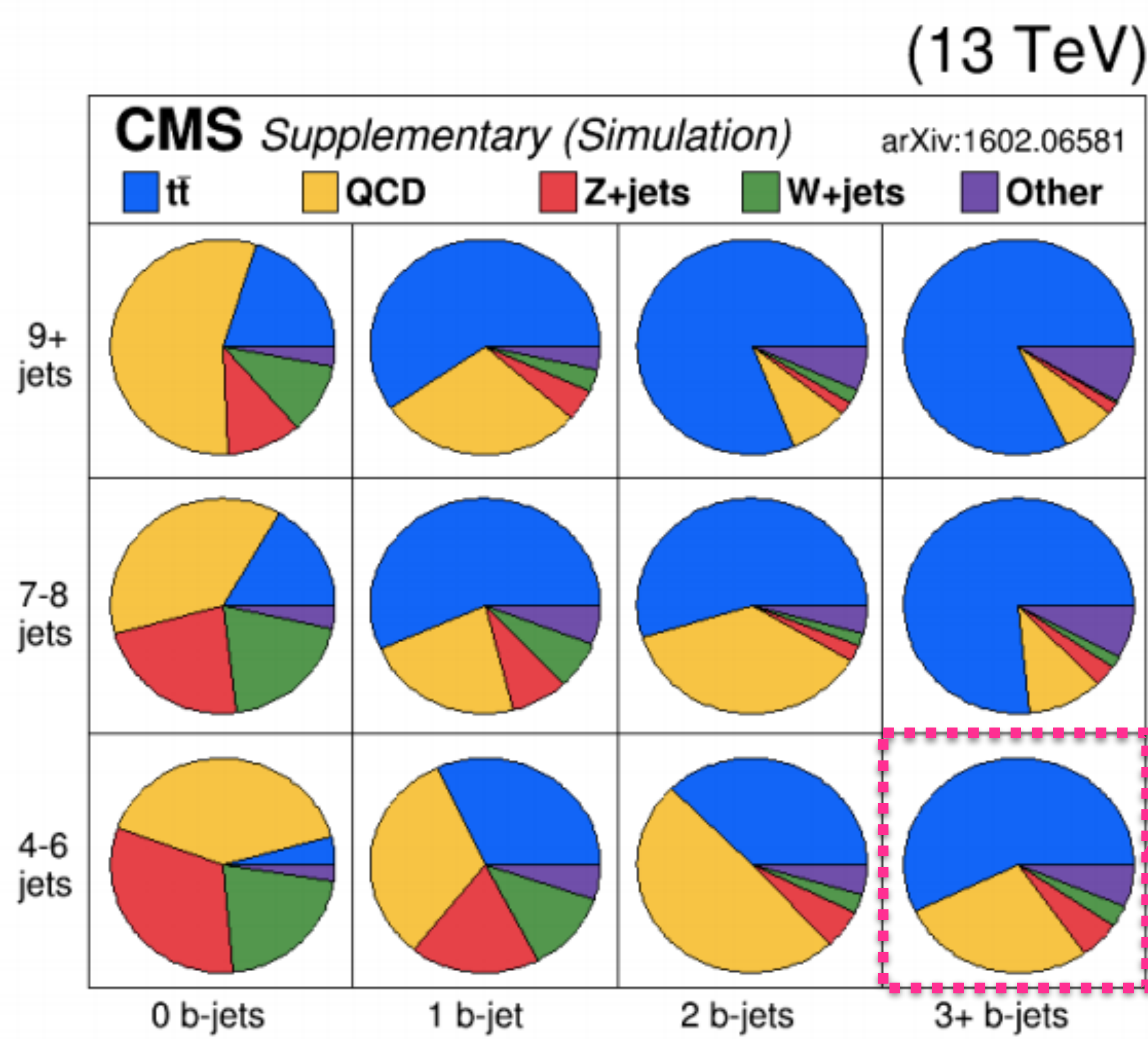
$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j1} + p_T^{j2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$

Scale-less even imbalance

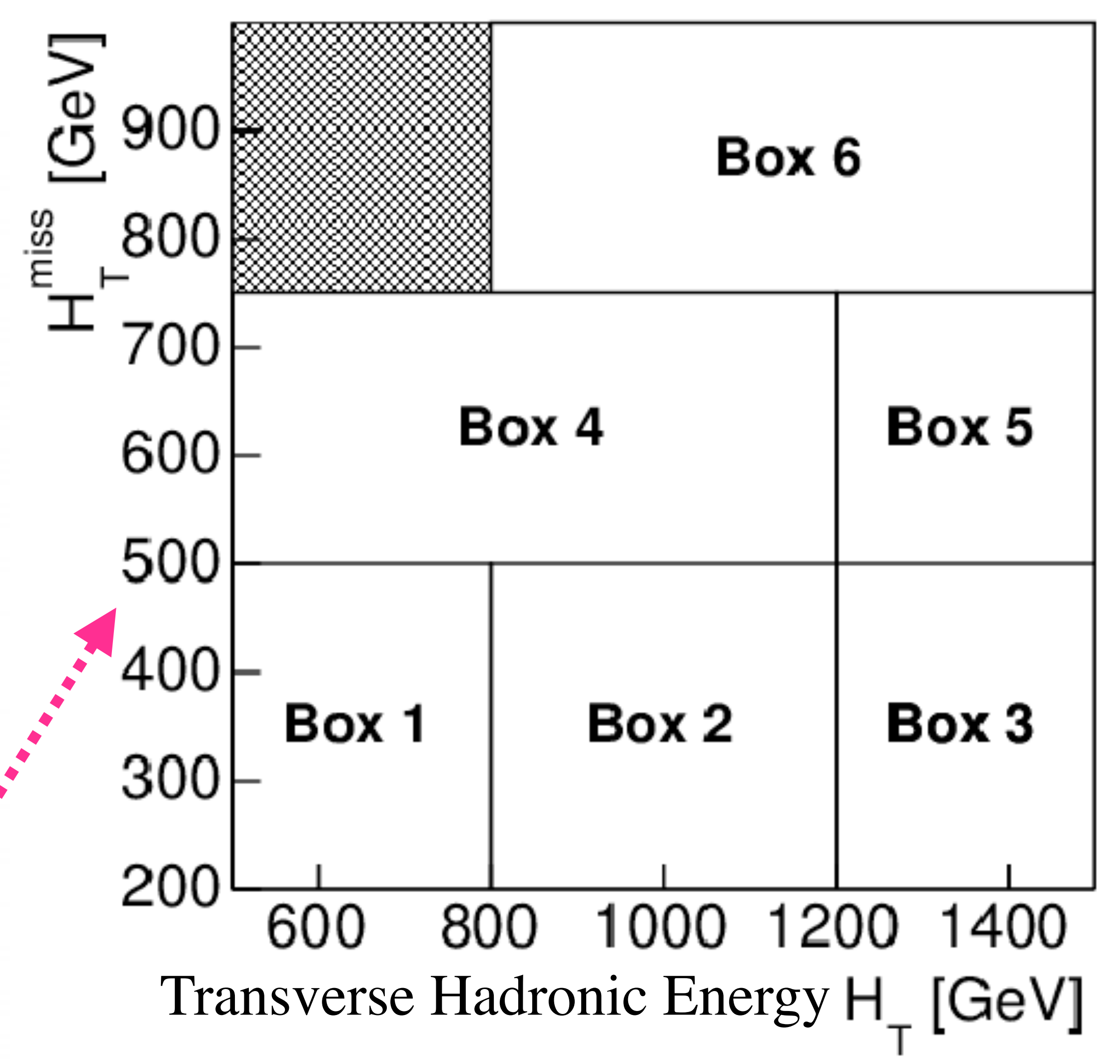
$$R \equiv \frac{M_T^R}{M_R}$$

# All Hadronic Searches at CMS
## (HT & MHT Analysis)

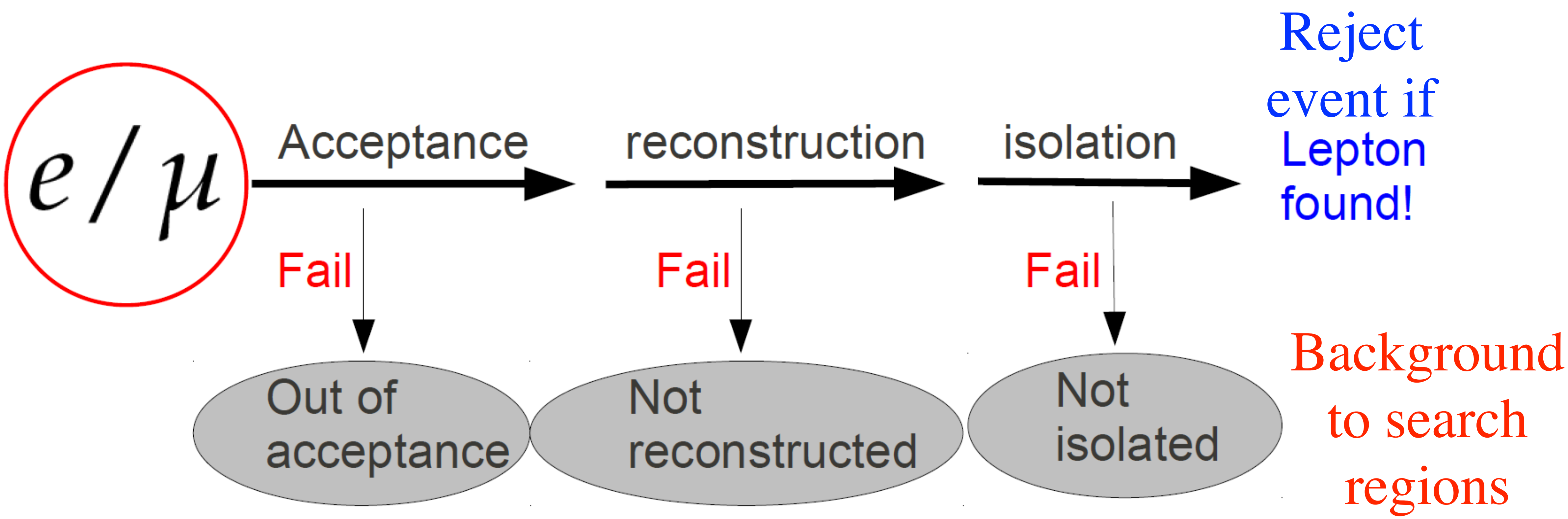
- The final state can have a large range of number of jets or b-jets depending upon the decay chains of mother particles



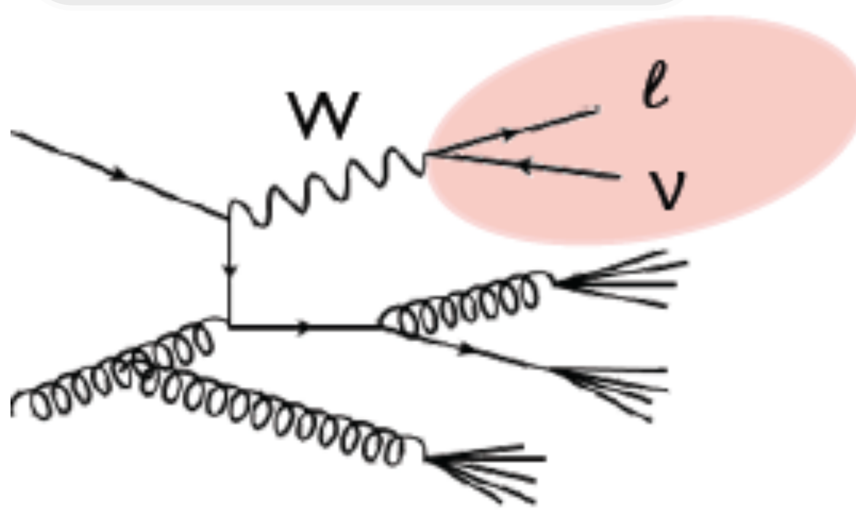

Each jet multiplicity region, there are six search regions in HT and MHT



# Background Estimation: Lost Lepton



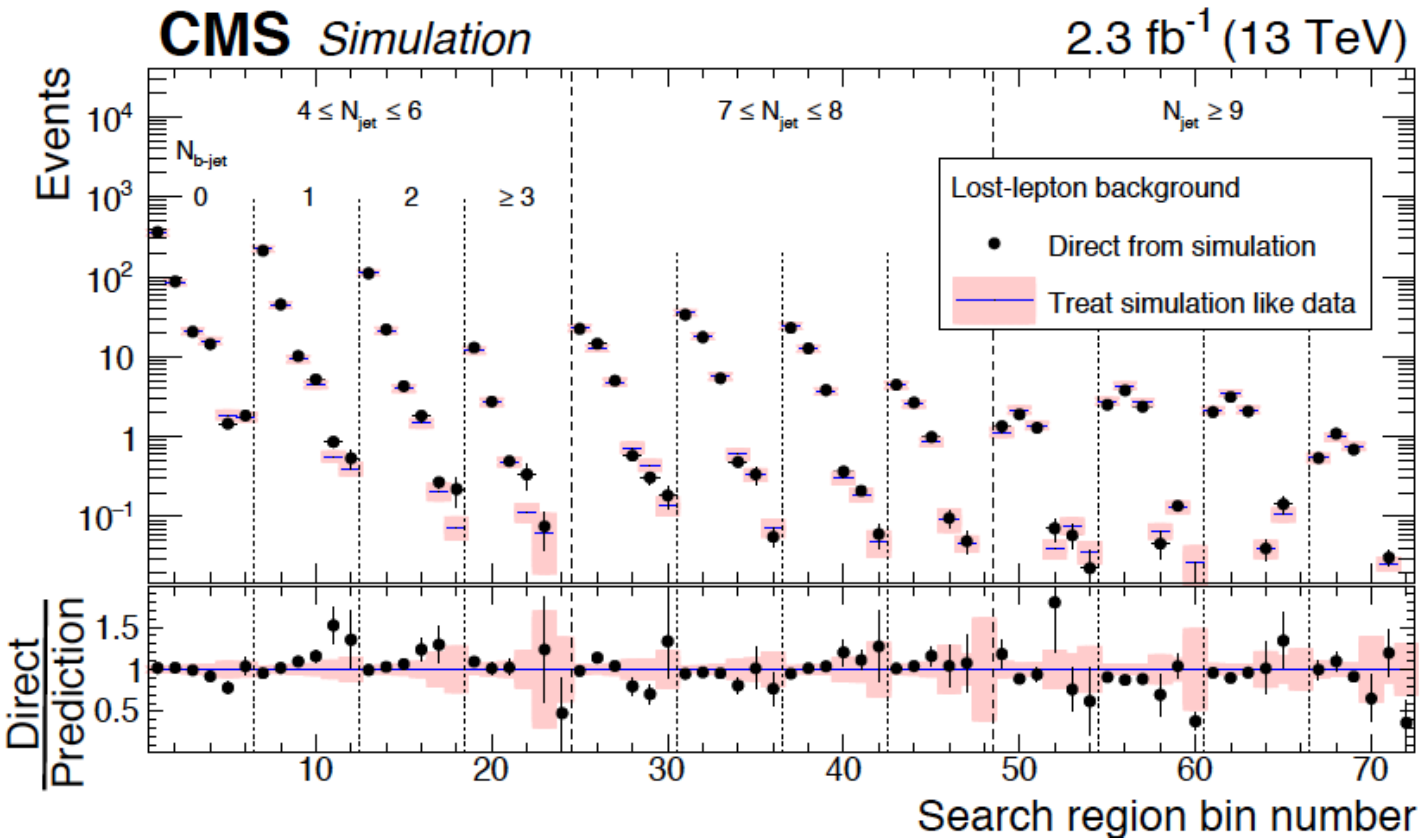

**Single μ/e control sample from data**




- Reweight each event in control region with μ/e (in)efficiencies (measure in data or MC, parametrized in lepton pT, hadronic activity etc.).
- Account for isolation efficiency, reconstruction efficiency and kinematic & detector acceptance.
- The method predicts the full kinematics of the events using data itself.

# Performance of Lost Lepton Method

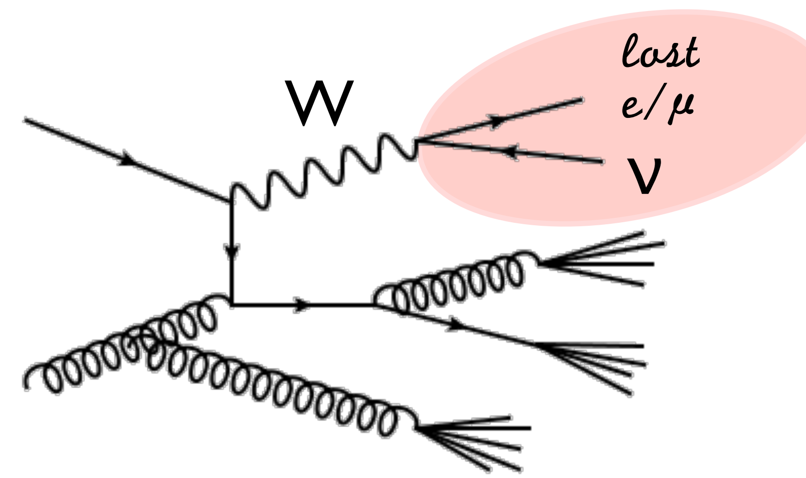
How do we know that this method works ?

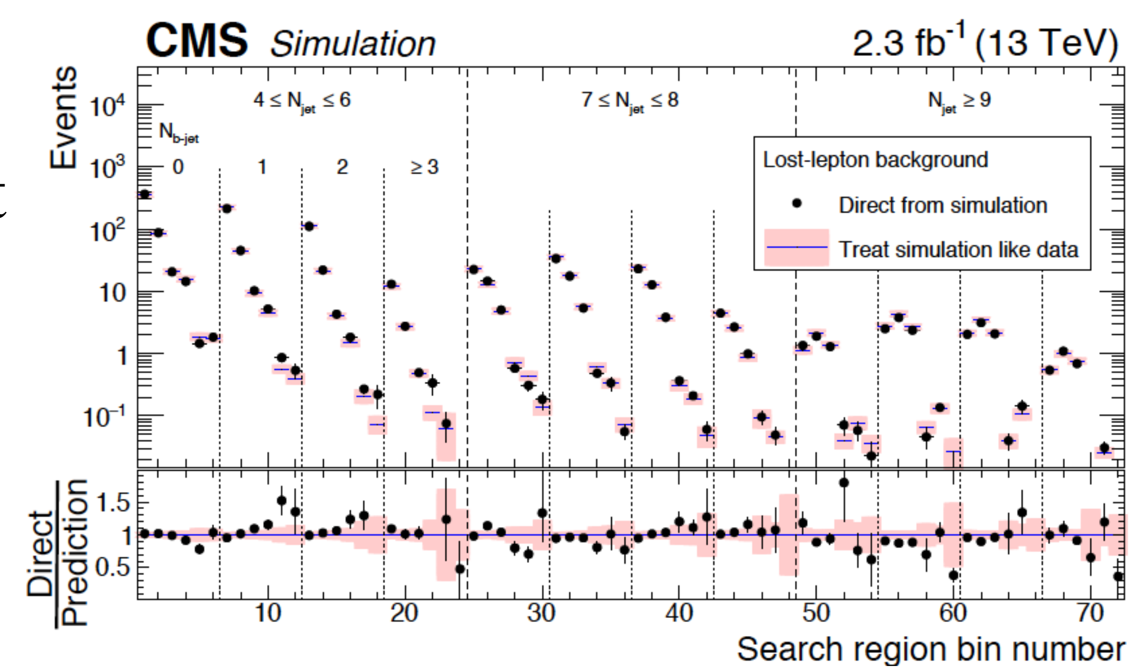


# Uncertainties in Lost Lepton Method

## How well do we understand estimated background ?

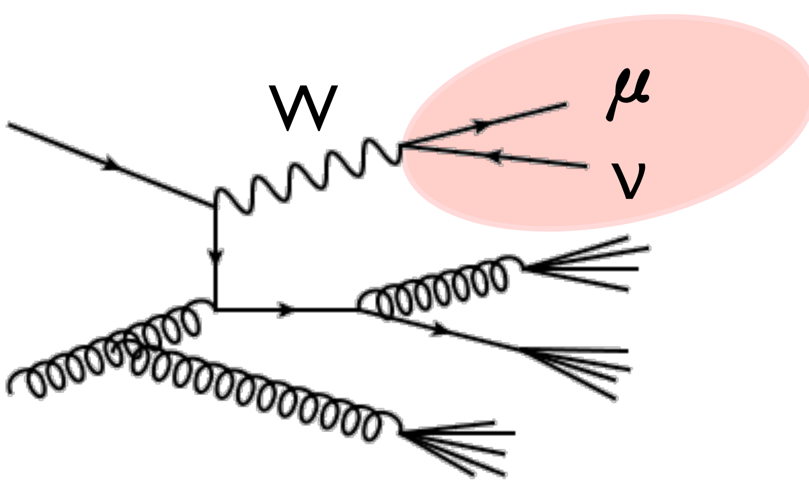
- Limited by statistics of single lepton events in data especially in the search regions defined by high jet multiplicity, large MHT etc. (3-100%)
  - These are generally most sensitive regions too !
- Precision of closure test (2-30%) :
  - The control region (isolated) and search regions (non-isolated) leptons are basically in different environments.
  - Efficiencies are parametrized in terms of lepton kinematic properties, and may not exactly reflect search region environment.
- Efficiencies are taken from simulations and any differences wrt those measured in data contribute to the uncertainties (1-5%).
- Kinematic acceptance is taken from simulation (<1 %).



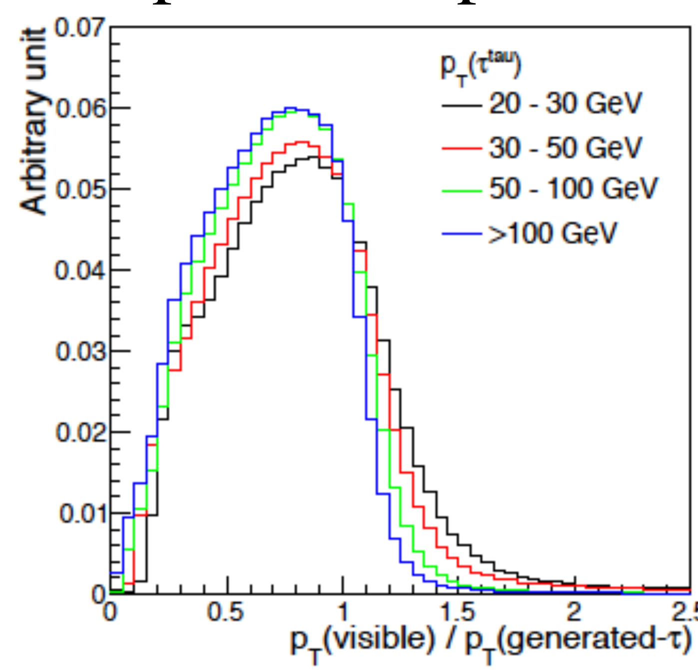



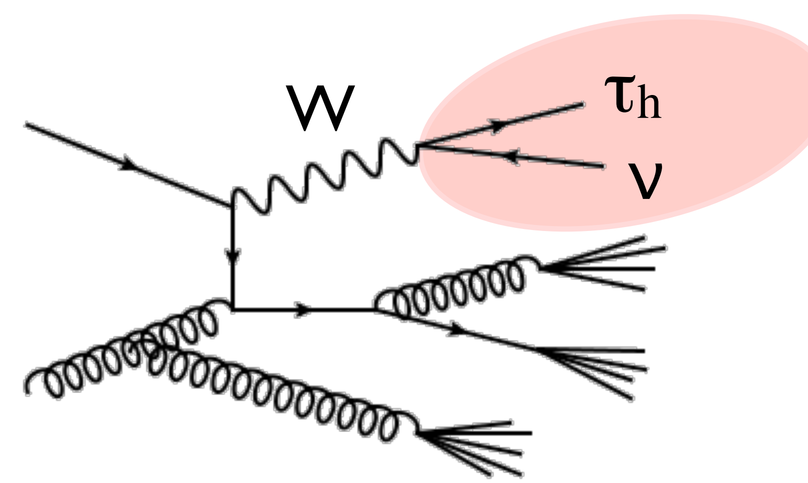
# Hadronic Tau ($\tau_h$) Background

- No dedicated $\tau$ veto - hadronically decaying taus are reconstructed as usual AK4 jets.
  - A large fraction of single prong $\tau_h$ are rejected by an isolated track veto
  - Need to measure the contribution of remaining single and multi prong hadronic taus.




Smear the muon pT with $\tau_h$ response template

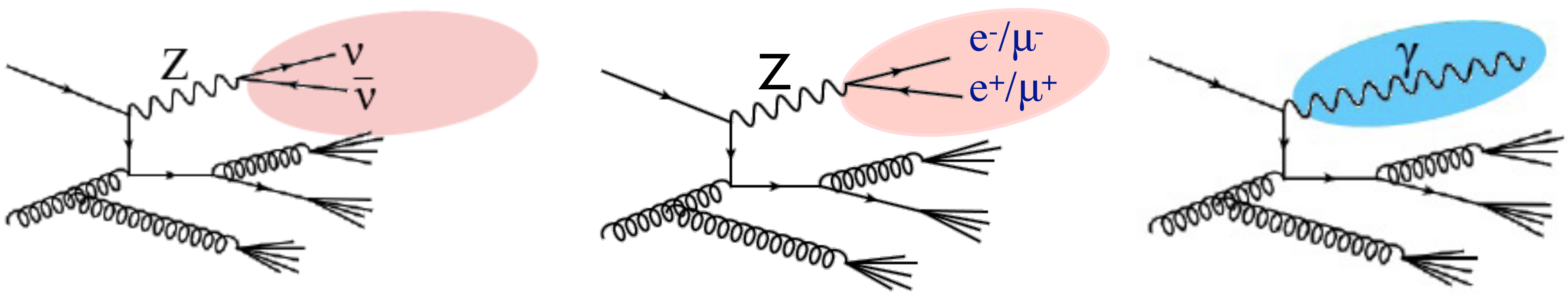



- Recalculate NJets, HT, MHT using this modified muon and count the number of events in the various search regions - $\tau_h$ background.
- Various corrections and branching fractions are appropriately applied.

# Background Estimation: ZInvisible

- A straightforward method is to use Z ($\rightarrow e^+e^-$ or $\mu^+\mu^-$) +Jets events as the topology of events is identical if one ignores leptons in the event
  - suffers from lack of statistics in tighter search regions, use hybrid method including $\gamma$ + Jets too.




Start with a $\gamma$+jets control sample with large hadronic activity and pT($\gamma$)>100 GeV.

$$\boxed{N^{\gamma+\mathrm{Jets}}} \times \boxed{\text{Correct for } \gamma \text{ identification, QCD contamination}} \times \boxed{\frac{\sigma(Z+\mathrm{Jets})}{\sigma(\gamma+\mathrm{Jets})}} = \boxed{N^{Z(\nu\nu)+\mathrm{Jets}}}$$

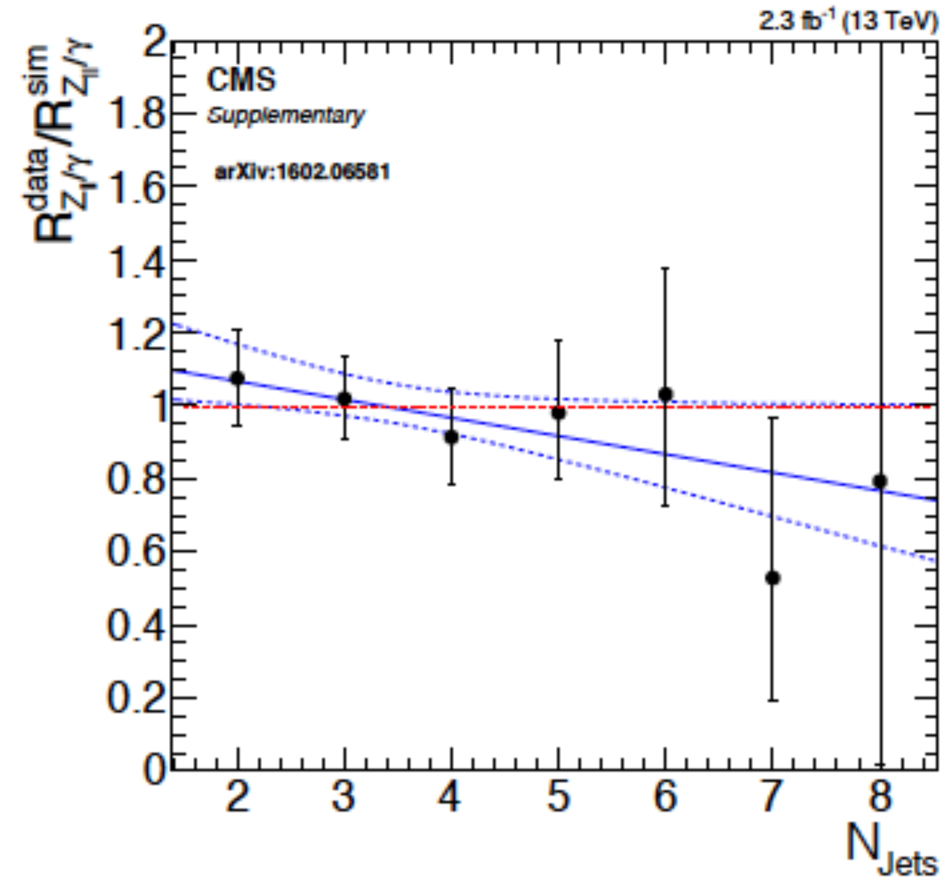
Main difficulty is to validate this Z to photon ratio which is taken from theory, especially in the phase space containing large jet or b-jet multiplicity, MHT tails

# Background Estimation: ZInvisible

(Understanding Z/γ ratio)

For N-bjets = 0

- Use $Z\mu\mu$+jets/γ+jets from data to correct MC and any trends as a function of jet multiplicity
  - Use γ+jets data events to estimate number of $Z(\nu\nu)$+Jets including shapes of jet multiplicity, HT, MHT etc.

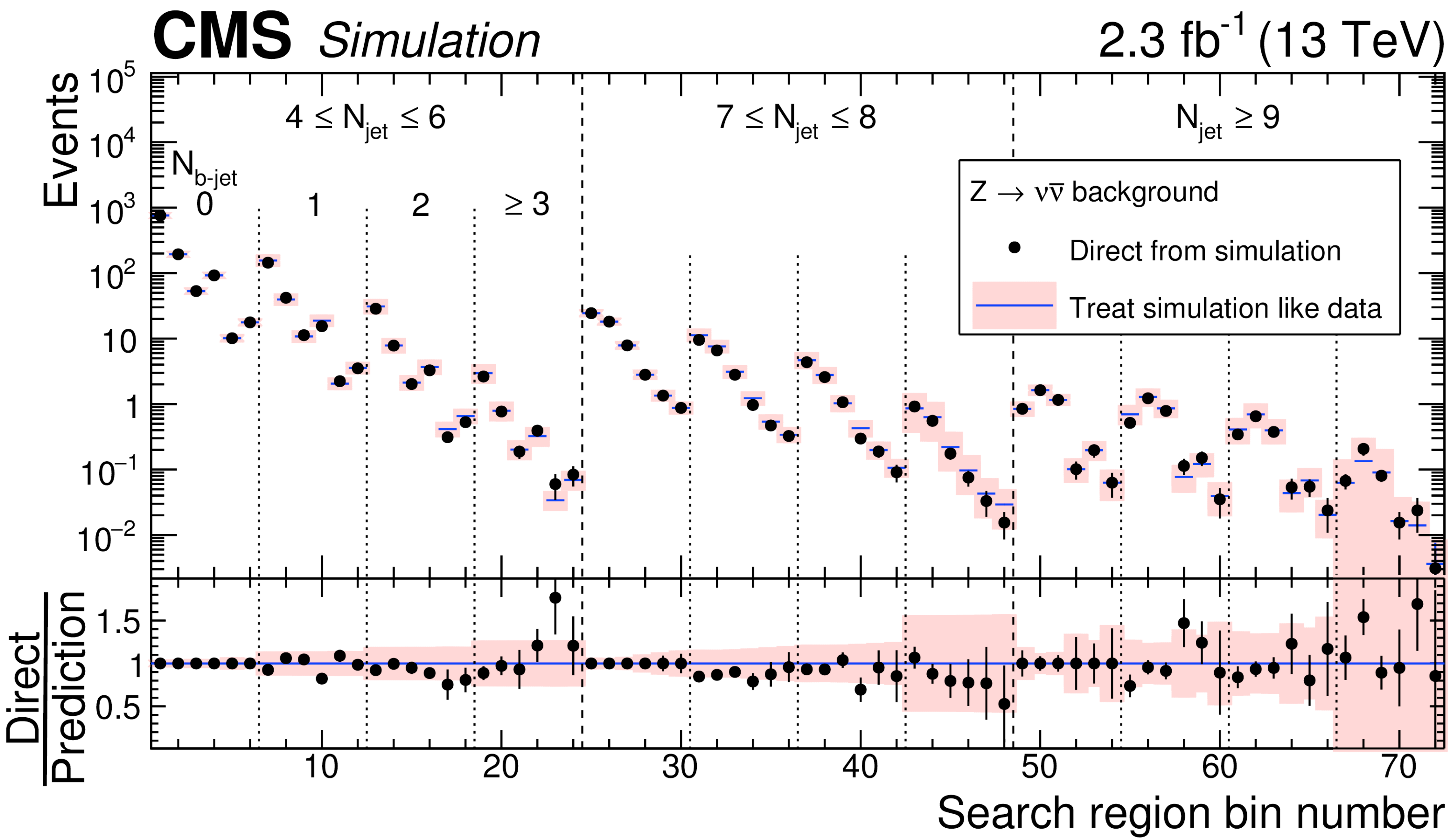



For N-bjets > 0

- Use $Z\mu\mu$+jets events to derive transfer factors from 0-bjets -> N-bjets
  - Use these transfer factors on γ+jets 0-b data events to estimate number of $Z(\nu\nu)$+Jets including shapes of jet multiplicity, HT, MHT etc.
  - For high jet multiplicity regions, use light quark -> heavy flavor mistagging probabilities.

# Background Estimation: ZInvisible

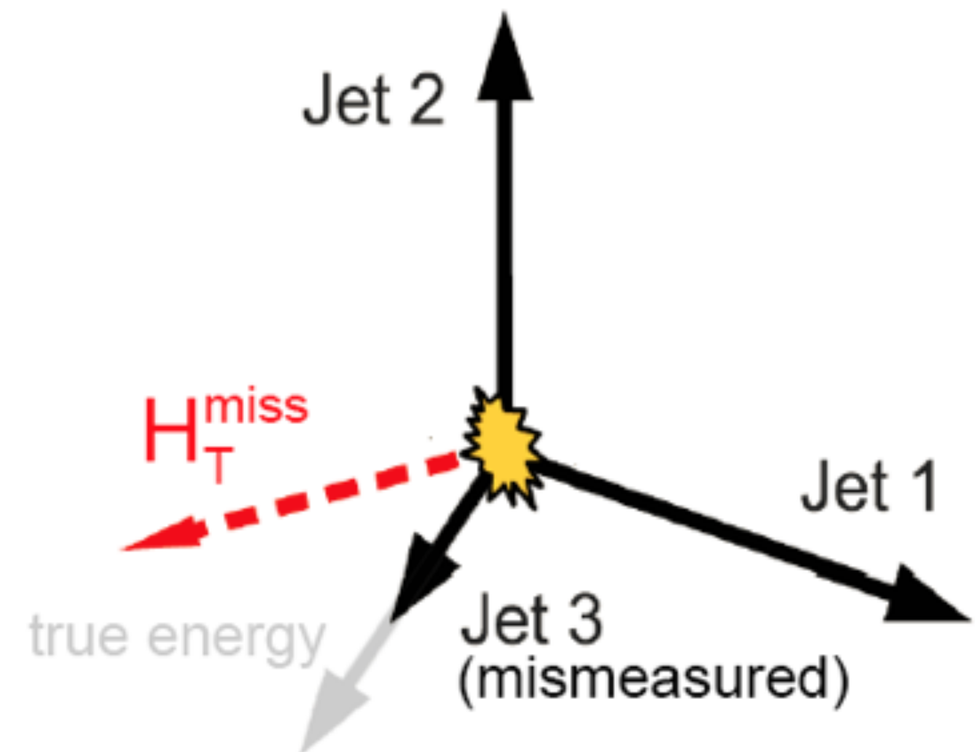
## How well the method performs ?




Major systematic uncertainties: photon purity, Z/γ ratio from data, b-jet extrapolation, Z(μμ)+jets kinematics.

# Background Estimation: QCD Multijets

- Large MET effectively reject QCD multijets (jet mismeasurement, instrumental effects etc.)
  - $\Delta\Phi(\mathrm{MHT}, \mathrm{Jets}^{\{1,2,3,4\}}) > (0.5, 0.5, 0.3, 0.3)$



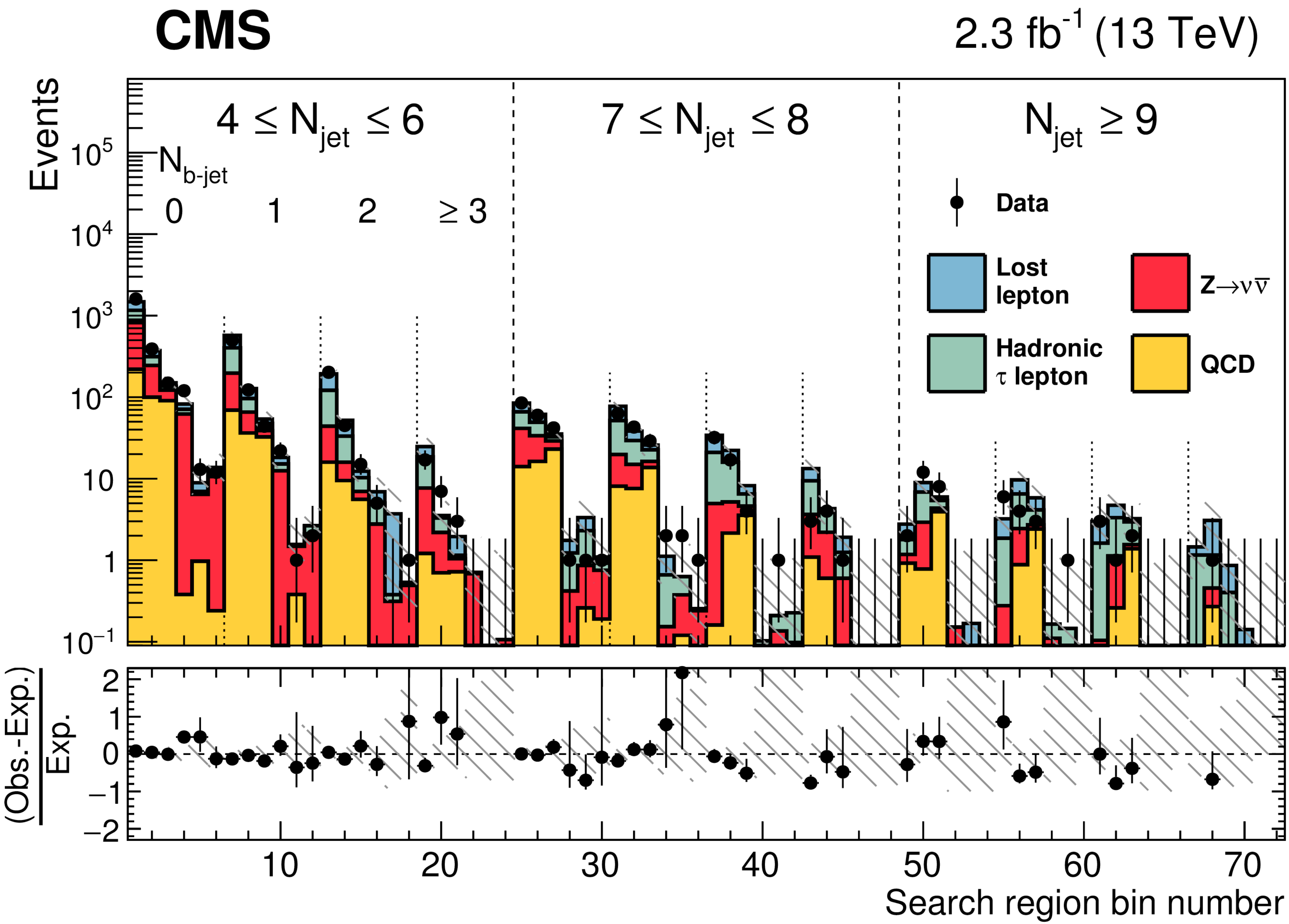

QCD background is estimates using a data driven method using the control sample defined by inverting the $\Delta\Phi$ selection.

# Results

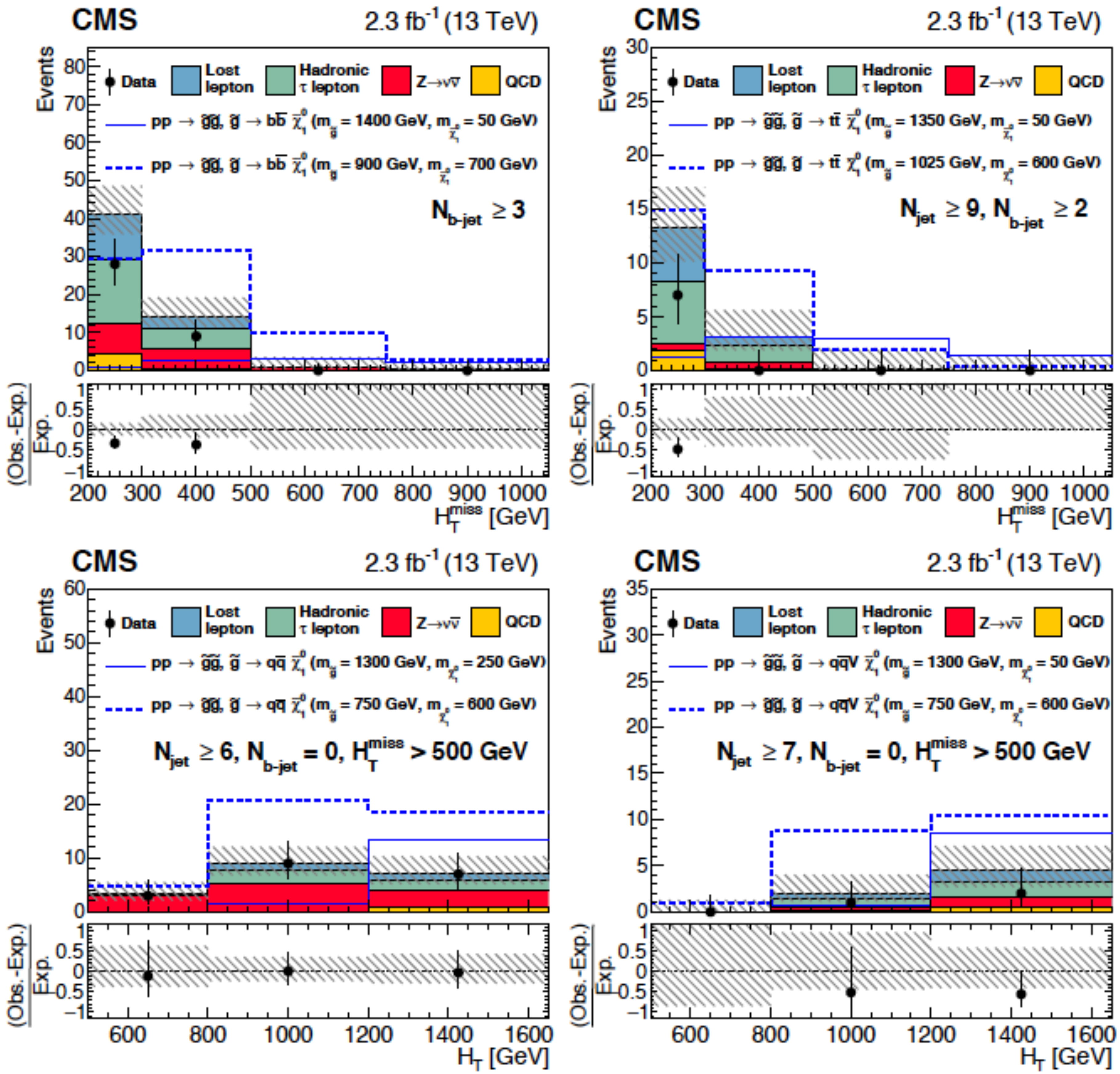
7≤Njet≤8.

| Bin | $H_T^{miss}$ [GeV] | $H_T$ [GeV] | $N_{b\text{-jet}}$ | Lost-e/$\mu$ | $\tau \to$ had | $Z \to \nu\bar{\nu}$ | QCD | Total Pred. | Obs. |
|---|---|---|---|---|---|---|---|---|---|
| 25 | 200-500 | 500-800 | 0 | $18.78^{+3.08+2.31}_{-3.05-2.20}$ | $24.50^{+2.68+2.02}_{-2.64-2.00}$ | $27.40^{+2.78+6.72}_{-2.78-5.14}$ | $14.05^{+1.72+8.19}_{-1.54-8.19}$ | $84.72^{+6.62+11.00}_{-6.52-10.12}$ | 85 |
| 26 | 200-500 | 800-1200 | 0 | $12.53^{+1.83+2.19}_{-1.79-2.17}$ | $15.60^{+2.26+1.27}_{-2.22-1.25}$ | $17.29^{+2.25+4.19}_{-2.25-3.17}$ | $16.29^{+1.20+7.12}_{-1.12-7.12}$ | $61.72^{+4.83+8.63}_{-4.73-8.19}$ | 60 |
| 27 | 200-500 | 1200+ | 0 | $2.88^{+1.15+0.32}_{-1.07-0.31}$ | $3.50^{+1.29+0.31}_{-1.20-0.30}$ | $6.03^{+1.29+2.34}_{-1.29-1.66}$ | $23.01^{+1.56+8.75}_{-1.46-8.75}$ | $35.42^{+3.17+9.07}_{-2.99-8.92}$ | 42 |
| 28 | 500-750 | 500-800 | 0 | $0.53^{+0.45+0.14}_{-0.26-0.13}$ | $0.81^{+0.66+0.19}_{-0.47-0.19}$ | $0.36^{+0.36+0.12}_{-0.36-0.00}$ | $0.06^{+0.10+0.09}_{-0.04-0.02}$ | $1.75^{+1.17+0.28}_{-0.82-0.23}$ | 1 |
| 29 | 500-750 | 1200+ | 0 | $1.03^{+0.88+0.33}_{-0.80-0.24}$ | $1.44^{+0.93+0.29}_{-0.80-0.29}$ | $0.60^{+0.43+0.26}_{-0.43-0.18}$ | $0.26^{+0.17+0.30}_{-0.11-0.15}$ | $3.34^{+1.87+0.54}_{-1.66-0.44}$ | 1 |
| 30 | 750+ | 800+ | 0 | $0.17^{+0.38+0.09}_{-0.17-0.00}$ | $0.17^{+0.49+0.11}_{-0.17-0.00}$ | $0.56^{+0.40+0.34}_{-0.40-0.16}$ | $0.19^{+0.16+0.23}_{-0.09-0.10}$ | $1.09^{+0.97+0.41}_{-0.53-0.19}$ | 1 |
| 31 | 200-500 | 500-800 | 1 | $25.79^{+2.93+3.13}_{-2.90-3.04}$ | $31.75^{+2.96+2.34}_{-2.93-2.30}$ | $11.68^{+2.24+3.63}_{-2.24-3.82}$ | $8.08^{+1.36+5.05}_{-1.18-5.05}$ | $77.30^{+6.45+7.29}_{-6.35-7.39}$ | 63 |
| 32 | 200-500 | 800-1200 | 1 | $9.01^{+1.63+1.28}_{-1.58-1.10}$ | $14.38^{+2.02+1.35}_{-1.97-1.34}$ | $7.37^{+1.54+2.27}_{-1.54-2.39}$ | $7.57^{+0.85+3.69}_{-0.76-3.69}$ | $38.34^{+4.06+4.67}_{-3.94-4.73}$ | 43 |
| 33 | 200-500 | 1200+ | 1 | $3.25^{+1.12+0.36}_{-1.01-0.34}$ | $6.33^{+1.49+0.67}_{-1.42-0.66}$ | $2.57^{+0.69+1.11}_{-0.69-0.99}$ | $13.70^{+1.22+5.93}_{-1.13-5.93}$ | $25.85^{+2.96+6.08}_{-2.77-6.06}$ | 29 |
| 34 | 500-750 | 500-800 | 1 | $0.46^{+0.49+0.11}_{-0.27-0.11}$ | $0.51^{+0.55+0.11}_{-0.29-0.11}$ | $0.15^{+0.16+0.06}_{-0.15-0.00}$ | $0.00^{+0.12+0.05}_{-0.00-0.00}$ | $1.12^{+1.06+0.17}_{-0.58-0.16}$ | 2 |
| 35 | 500-750 | 1200+ | 1 | $0.00^{+0.40+0.00}_{-0.00-0.00}$ | $0.25^{+0.49+0.05}_{-0.18-0.05}$ | $0.26^{+0.19+0.12}_{-0.19-0.07}$ | $0.12^{+0.14+0.16}_{-0.07-0.05}$ | $0.63^{+0.92+0.21}_{-0.27-0.10}$ | 2 |
| 36 | 750+ | 800+ | 1 | $0.00^{+0.45+0.00}_{-0.00-0.00}$ | $0.02^{+0.46+0.01}_{-0.01-0.00}$ | $0.24^{+0.17+0.15}_{-0.17-0.07}$ | $0.00^{+0.08+0.03}_{-0.00-0.00}$ | $0.25^{+0.93+0.16}_{-0.17-0.07}$ | 1 |
| 37 | 200-500 | 500-800 | 2 | $13.15^{+2.16+1.54}_{-2.11-1.51}$ | $16.03^{+1.87+1.20}_{-1.81-1.18}$ | $4.79^{+1.46+2.36}_{-1.46-2.43}$ | $0.16^{+0.32+0.57}_{-0.00-0.16}$ | $34.13^{+4.29+3.09}_{-4.18-3.10}$ | 32 |
| 38 | 200-500 | 800-1200 | 2 | $6.33^{+1.29+0.74}_{-1.22-0.71}$ | $10.73^{+1.82+0.89}_{-1.76-0.88}$ | $3.03^{+0.95+1.48}_{-0.95-1.53}$ | $2.15^{+0.48+1.12}_{-0.40-1.12}$ | $22.24^{+3.29+2.18}_{-3.15-2.21}$ | 17 |
| 39 | 200-500 | 1200+ | 2 | $1.73^{+0.79+0.20}_{-0.62-0.19}$ | $1.89^{+0.88+0.18}_{-0.75-0.18}$ | $1.06^{+0.38+0.61}_{-0.38-0.58}$ | $3.55^{+0.64+1.64}_{-0.55-1.64}$ | $8.22^{+1.82+1.77}_{-1.52-1.76}$ | 4 |
| 40 | 500-750 | 500-800 | 2 | $0.00^{+0.39+0.00}_{-0.00-0.00}$ | $0.04^{+0.46+0.01}_{-0.02-0.01}$ | $0.06^{+0.07+0.03}_{-0.06-0.00}$ | $0.00^{+0.12+0.05}_{-0.00-0.00}$ | $0.10^{+0.86+0.06}_{-0.06-0.01}$ | 0 |
| 41 | 500-750 | 1200+ | 2 | $0.00^{+0.43+0.00}_{-0.00-0.00}$ | $0.07^{+0.47+0.04}_{-0.07-0.00}$ | $0.11^{+0.08+0.06}_{-0.08-0.02}$ | $0.03^{+0.11+0.05}_{-0.02-0.01}$ | $0.21^{+0.90+0.08}_{-0.11-0.03}$ | 1 |
| 42 | 750+ | 800+ | 2 | $0.00^{+0.34+0.00}_{-0.00-0.00}$ | $0.13^{+0.48+0.06}_{-0.13-0.00}$ | $0.10^{+0.07+0.07}_{-0.07-0.02}$ | $0.00^{+0.08+0.03}_{-0.00-0.00}$ | $0.23^{+0.82+0.08}_{-0.15-0.02}$ | 0 |
| 43 | 200-500 | 500-800 | 3+ | $3.93^{+1.25+0.46}_{-1.16-0.45}$ | $5.78^{+1.31+0.68}_{-1.23-0.67}$ | $2.54^{+1.50+1.76}_{-1.50-1.04}$ | $1.09^{+0.62+0.86}_{-0.41-0.68}$ | $13.34^{+3.03+2.12}_{-2.85-1.48}$ | 3 |
| 44 | 200-500 | 800-1200 | 3+ | $0.44^{+0.49+0.05}_{-0.25-0.05}$ | $1.66^{+0.76+0.26}_{-0.60-0.26}$ | $1.60^{+0.96+1.11}_{-0.96-0.65}$ | $0.60^{+0.30+0.39}_{-0.21-0.39}$ | $4.30^{+1.60+1.20}_{-1.30-0.80}$ | 4 |
| 45 | 200-500 | 1200+ | 3+ | $0.66^{+0.72+0.12}_{-0.52-0.12}$ | $0.65^{+0.61+0.10}_{-0.40-0.10}$ | $0.56^{+0.35+0.42}_{-0.35-0.21}$ | $0.04^{+0.19+0.12}_{-0.00-0.04}$ | $1.91^{+1.39+0.47}_{-0.99-0.27}$ | 1 |
| 46 | 500-750 | 500-800 | 3+ | $0.00^{+0.52+0.00}_{-0.00-0.00}$ | $0.00^{+0.46+0.00}_{-0.00-0.00}$ | $0.03^{+0.04+0.02}_{-0.03-0.00}$ | $0.04^{+0.09+0.07}_{-0.03-0.01}$ | $0.07^{+0.98+0.07}_{-0.05-0.01}$ | 0 |
| 47 | 500-750 | 1200+ | 3+ | $0.00^{+0.47+0.00}_{-0.00-0.00}$ | $0.00^{+0.46+0.00}_{-0.00-0.00}$ | $0.06^{+0.05+0.04}_{-0.05-0.00}$ | $0.00^{+0.09+0.03}_{-0.00-0.00}$ | $0.06^{+0.94+0.05}_{-0.05-0.00}$ | 0 |
| 48 | 750+ | 800+ | 3+ | $0.00^{+0.61+0.00}_{-0.00-0.00}$ | $0.01^{+0.46+0.01}_{-0.01-0.00}$ | $0.05^{+0.05+0.05}_{-0.05-0.00}$ | $0.00^{+0.08+0.03}_{-0.00-0.00}$ | $0.06^{+1.07+0.06}_{-0.05-0.00}$ | 0 |

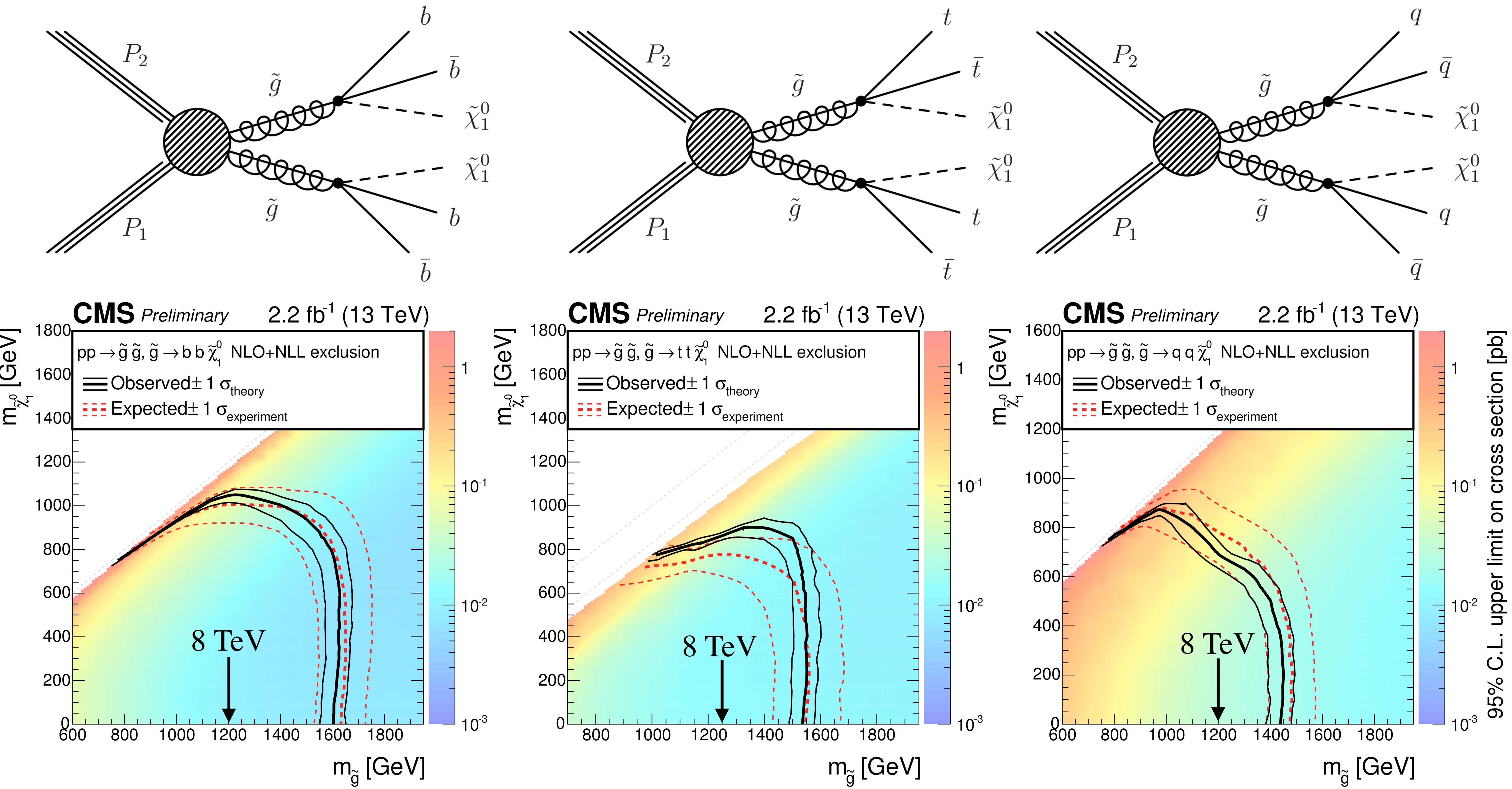
# Results


CMS
2.3 fb-1 (13 TeV)
Events
4 ≤ Njet ≤ 6
7 ≤ Njet ≤ 8
Njet ≥ 9
Nb-jet
0
1
2
≥ 3
Data
Lost lepton
Z→νν̄
Hadronic τ lepton
QCD
(Obs.-Exp.)/Exp.
Search region bin number

# If there was SUSY Signal ….



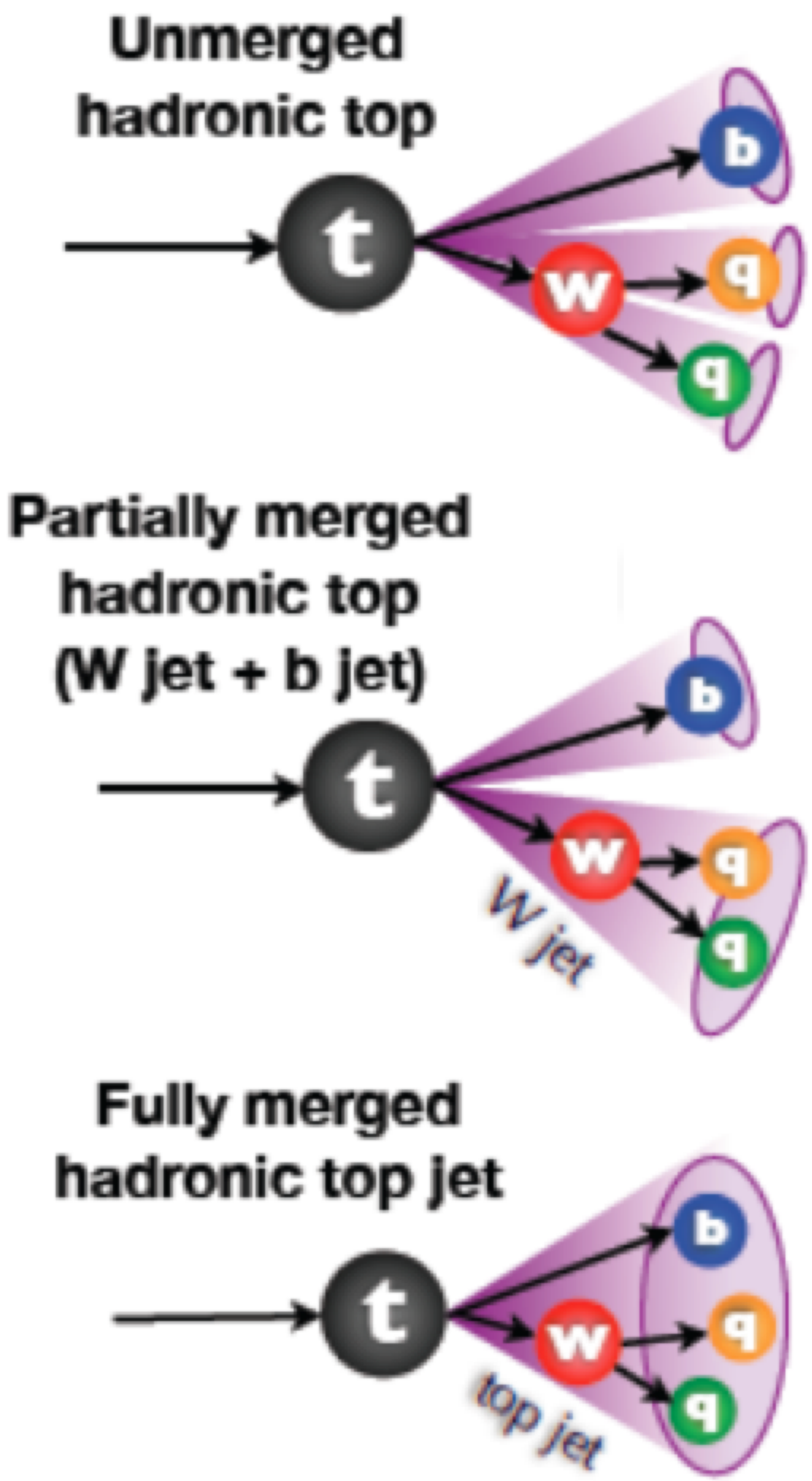
# Interpretation : Gluino Pair Production

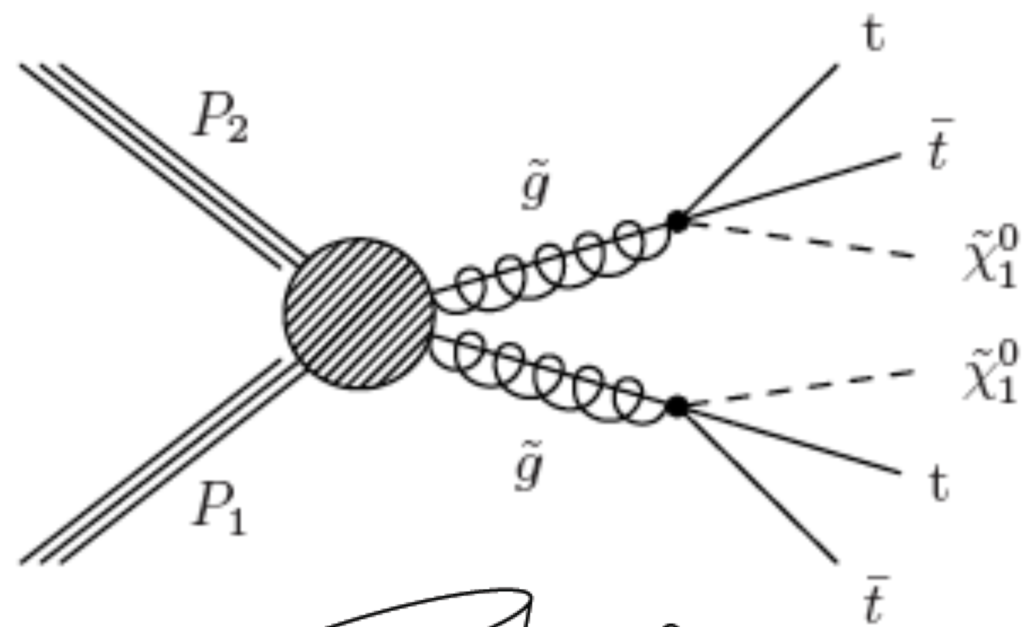


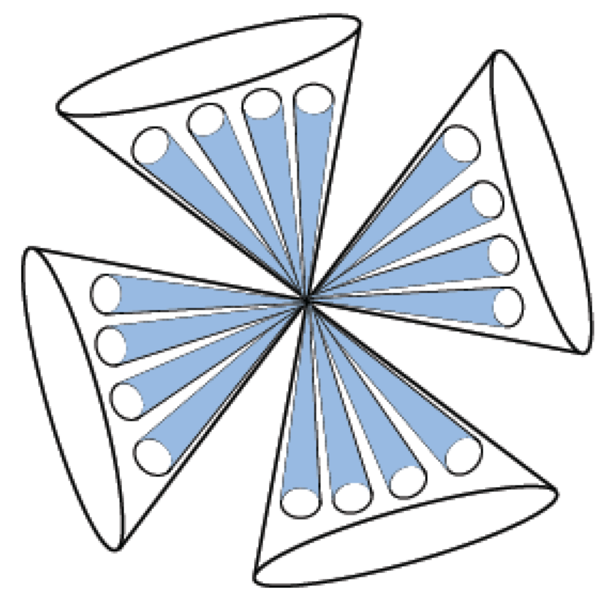

Systematic uncertainties applied on signal: luminosity, lepton track veto, trigger efficiency, ISR modeling, PDF uncertainty.

# Inclusive searches with one lepton final states

# Jets are increasingly becoming powerful tools !
## (Accidental substructure)



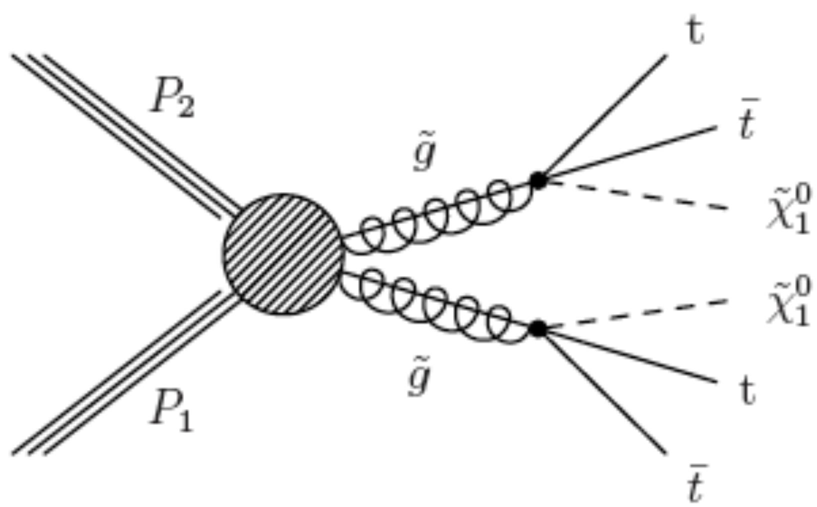



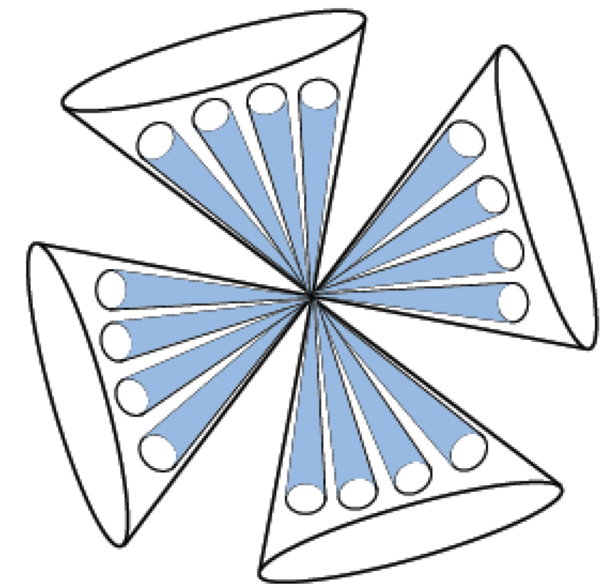



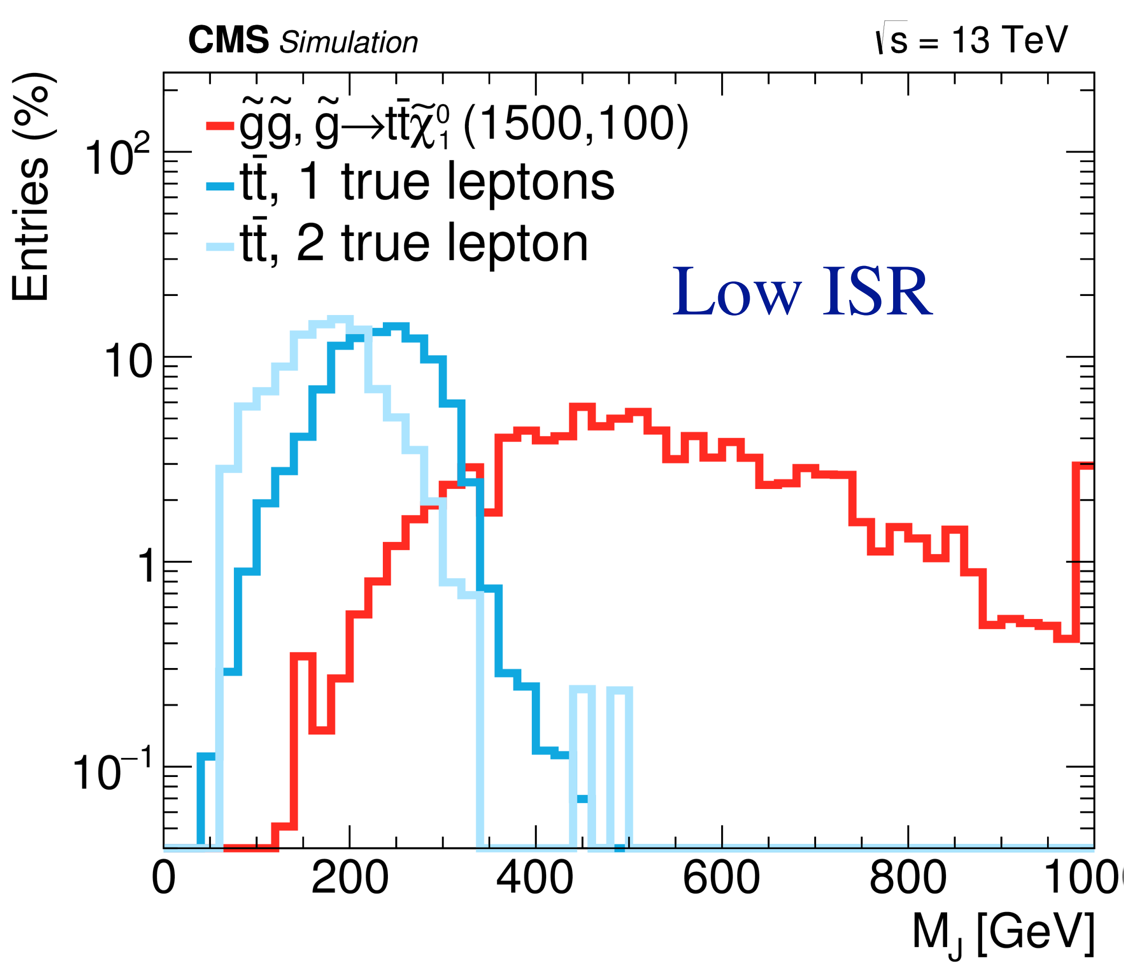
- A lot of development in identifying and reconstructing boosted heavy particles
    - Jet substructure techniques to identify fully hadronic topologies.

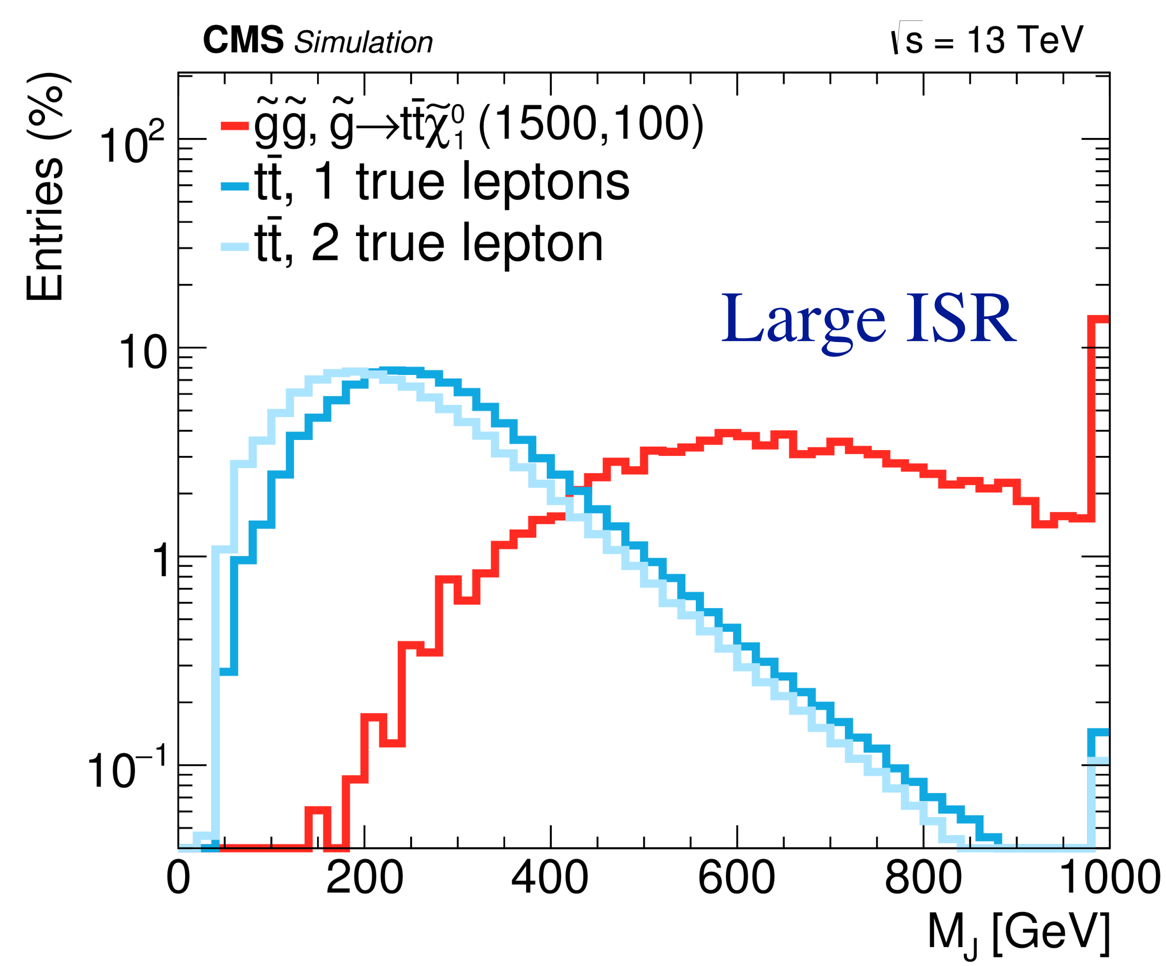
# Jets are increasingly becoming powerful tools !

## (Accidental substructure)



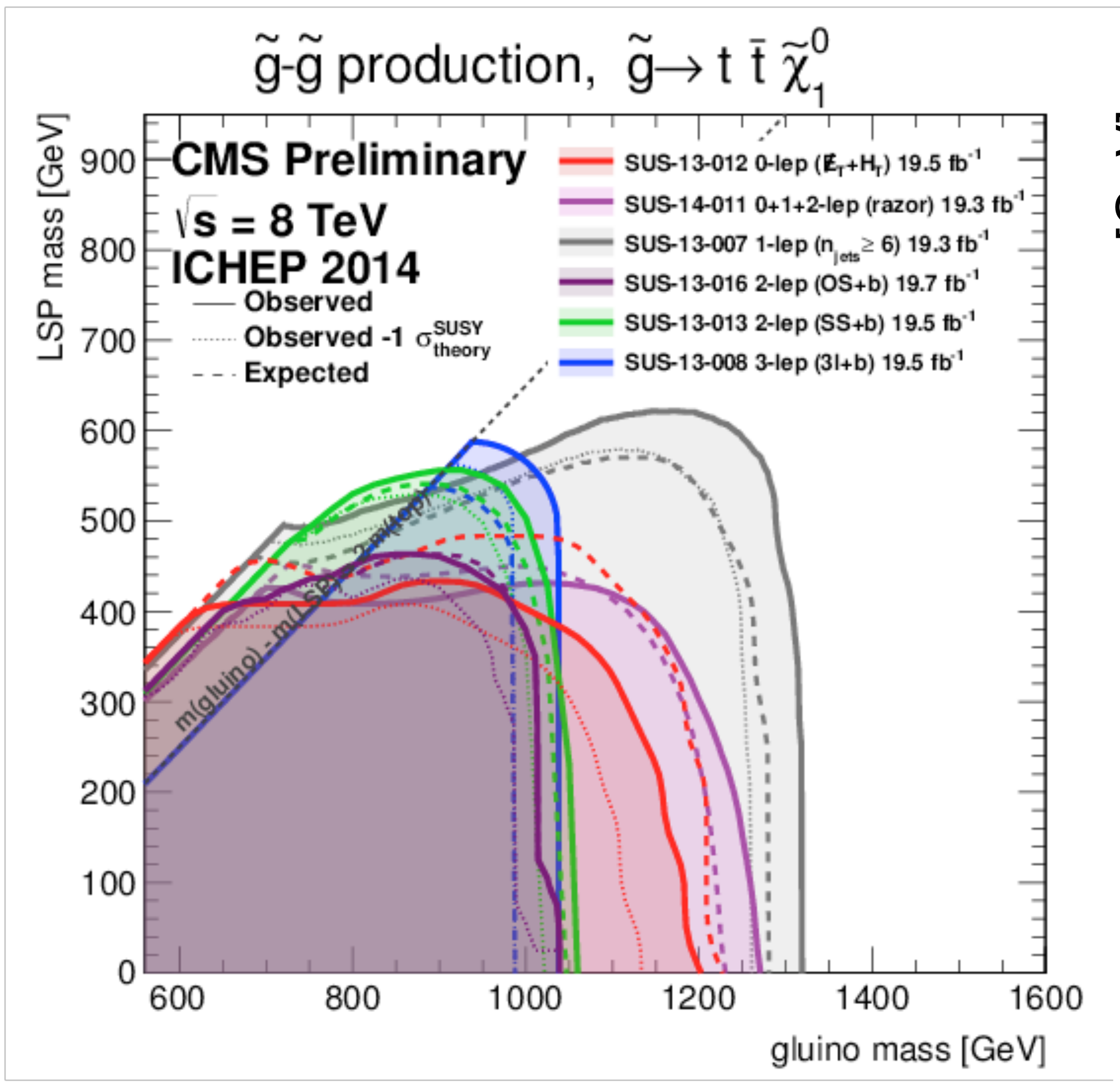





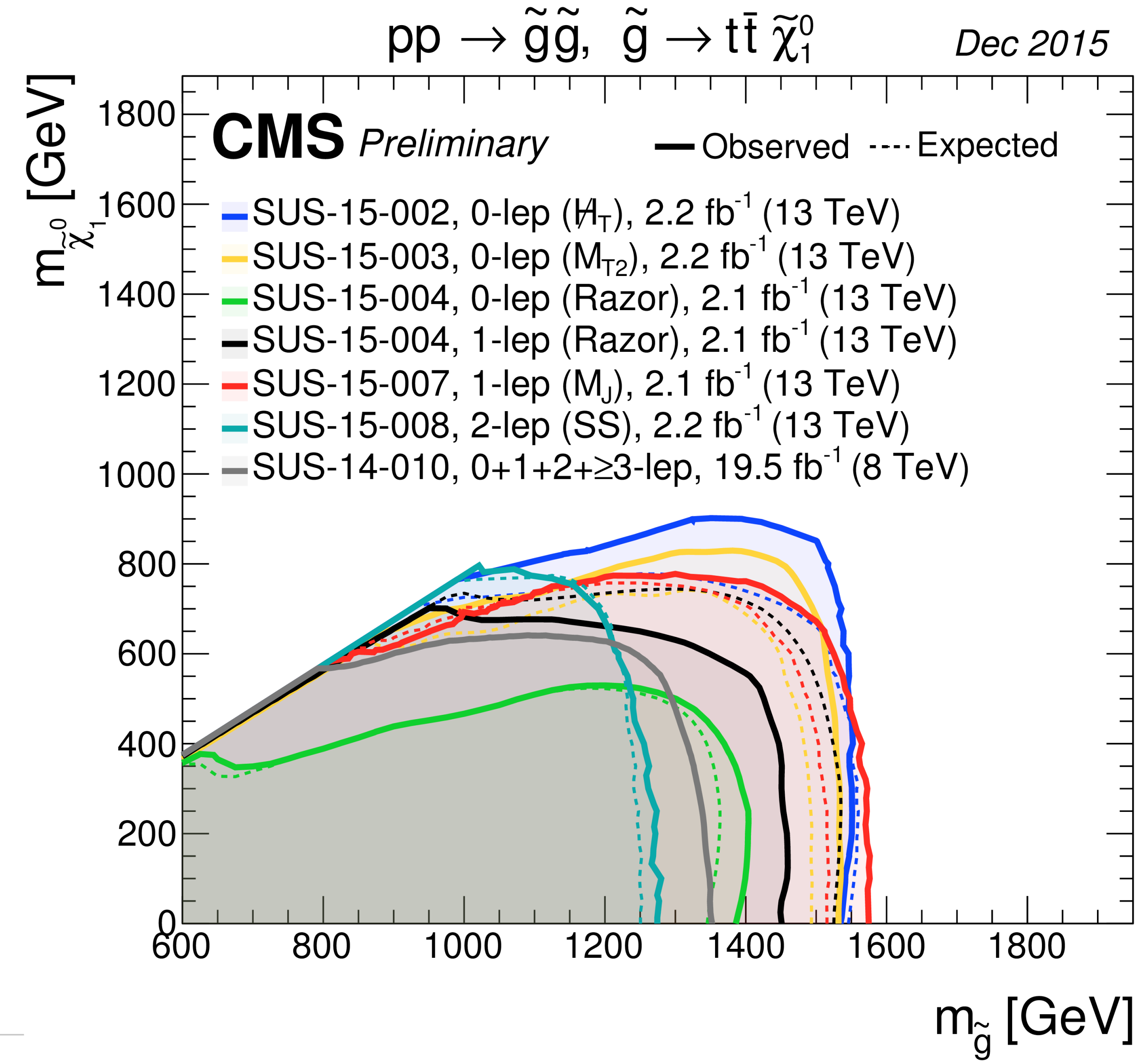



# Current Status

## 8 TeV

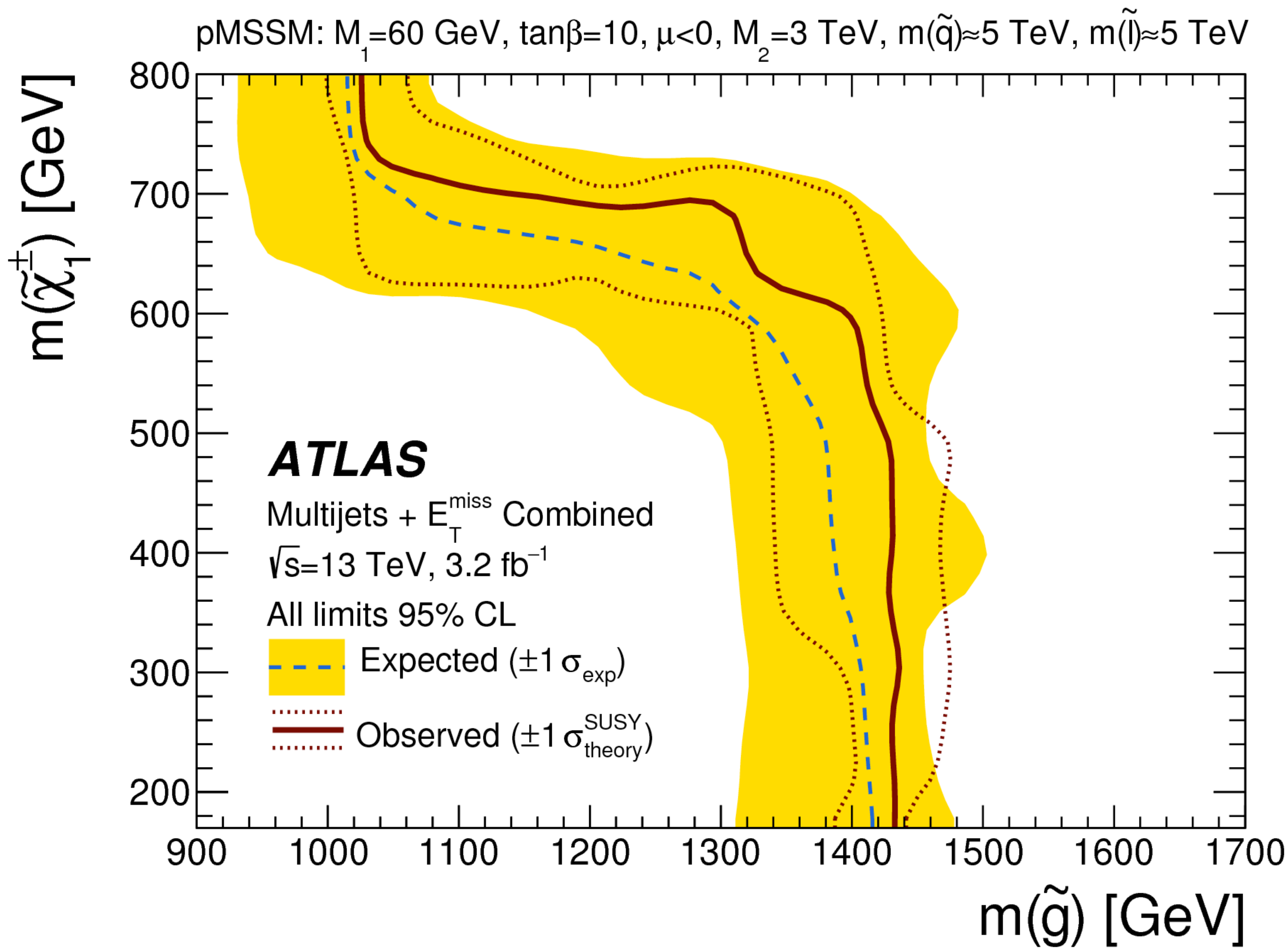



## 13 TeV



# Current Status (pMSSM)

arXiv:1602.06194



# More SUSY Results using 13 TeV data

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/LHC-Jamboree-2015.html

Search for Supersymmetry

- Supersymmetry in Multijet + Missing $E_{\mathrm{T}}$
- Supersymmetry in All-Hadronic Using $M_{\mathrm{T2}}$
- Supersymmetry in All-Hadronic Using $\alpha_{\mathrm{T}}$
- Supersymmetry in All-Hadronic Using Razor Variables
- Supersymmetry in One-Lepton Events Using Large Radius Jets
- Supersymmetry in Same-Sign Dilepton Events
- Supersymmetry in Opposite-Sign Dilepton Events

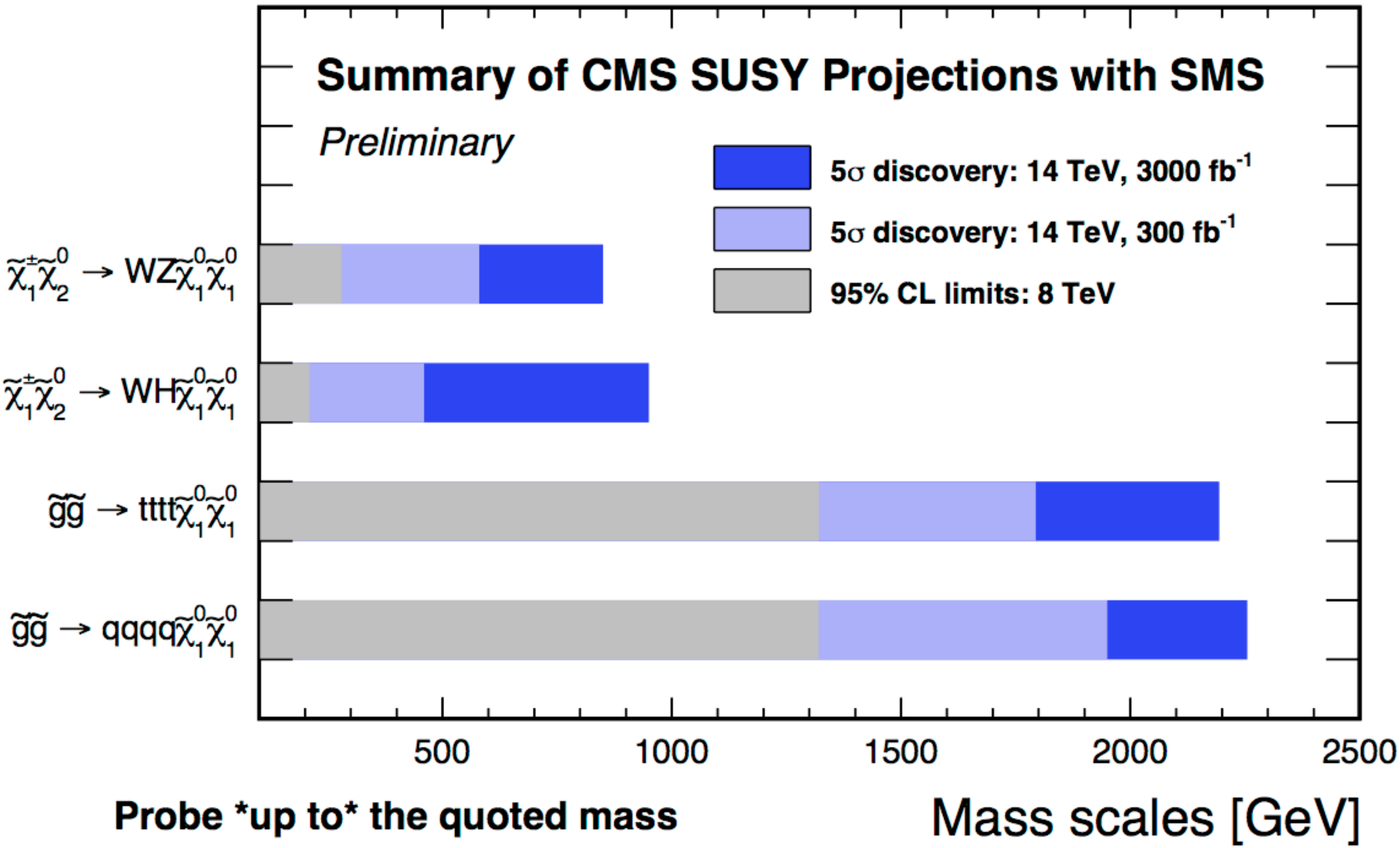
A few more which are yet to be linked on public pages.

# Summary

- A variety of analyses to search for supersymmetric partners in 2.3 $fb^{-1}$ of 13 TeV data
  - The gluinos of mass up to 1.6 TeV excluded for low LSP masses
  - The gluino exclusion limits are extended by 150-200 GeV as compared to 8 TeV results.
- Expecting up to 10 $fb^{-1}$ by the summer this year

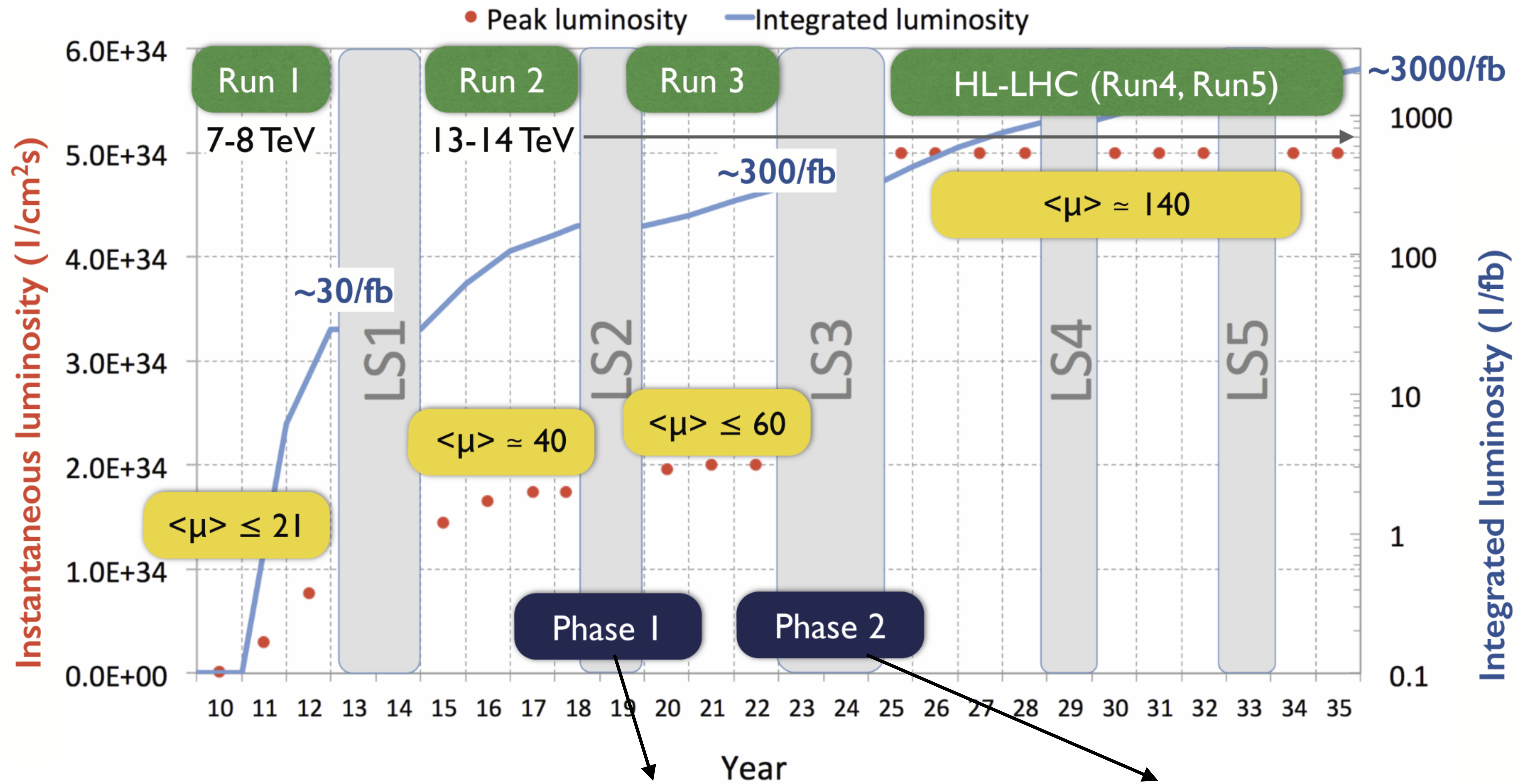
A lot of excitement ahead, stay tuned !

# Near Future




**Probe *up to* the quoted mass**

# Further Future




- **Physics reach:**

Higgs discovery!

Observe $B_s \to \mu\mu$!

Natural SUSY
Gluino discovery up to ~2 TeV
Stop discovery up to ~1 TeV
Higgsino discovery up to ~500 GeV

Higgs coupling to W,Z ~5%

Higgs potential: observe gg→HH

EWSB: observe WW scattering

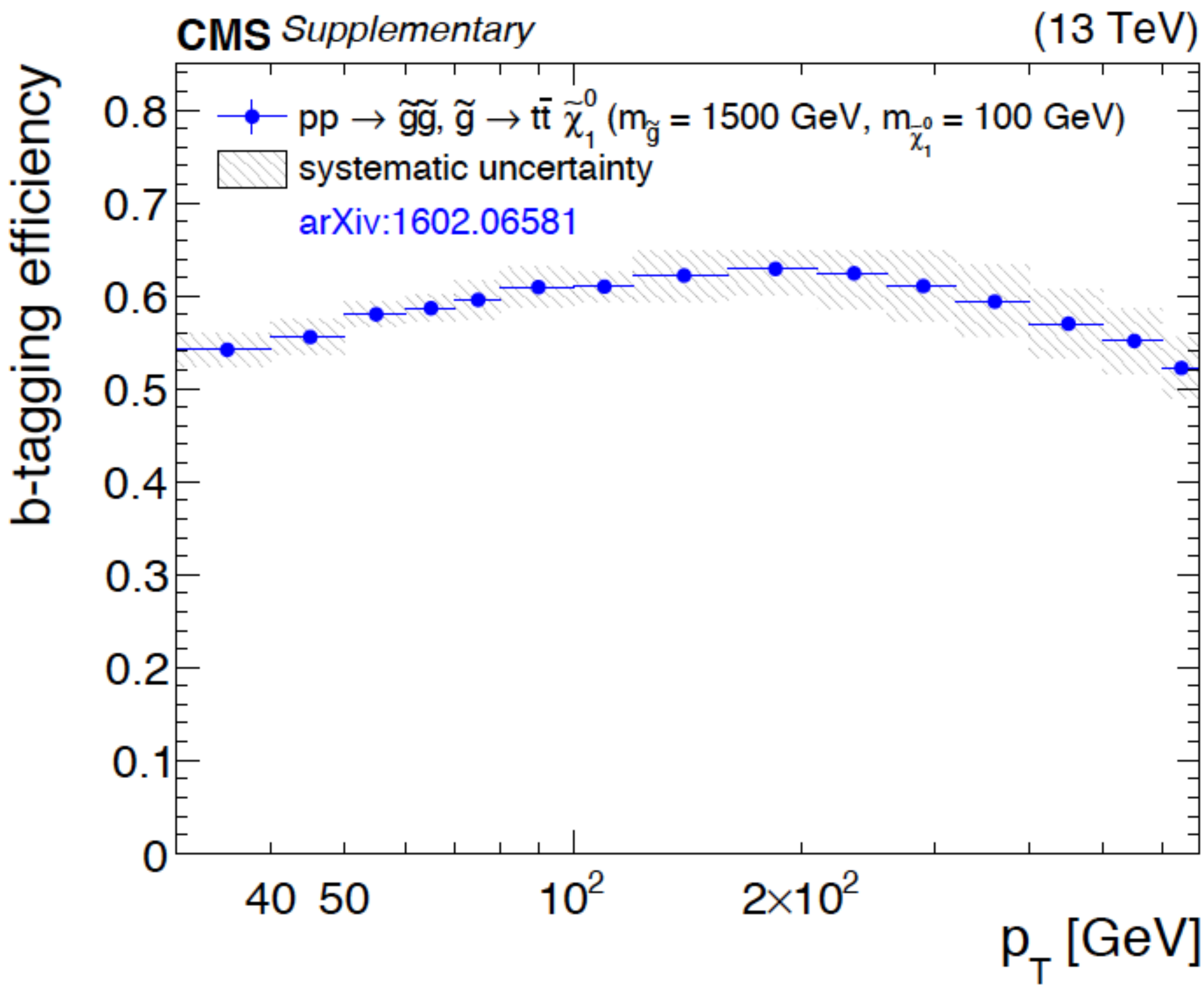
Higgs coupling to t,b,τ ~5%

Z'→ll discovery reach ~6 TeV

CMS Snowmass white paper 1307.7135

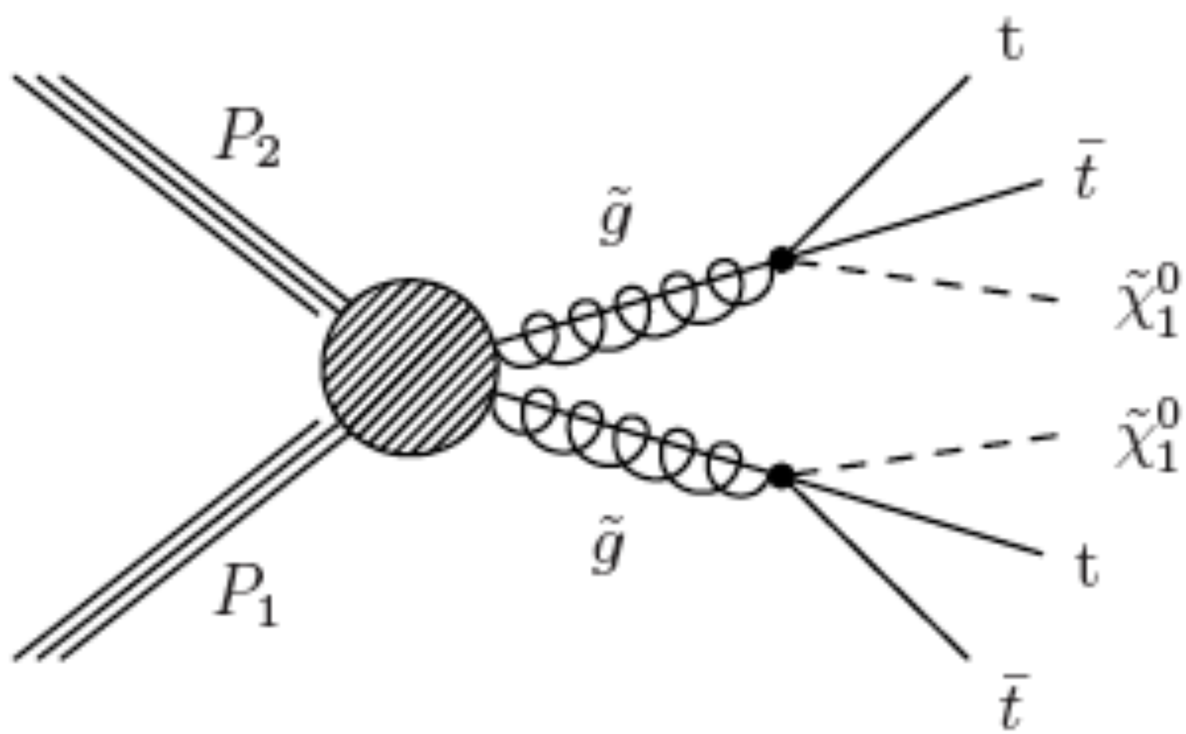
# Backup

# b-tagging efficiency

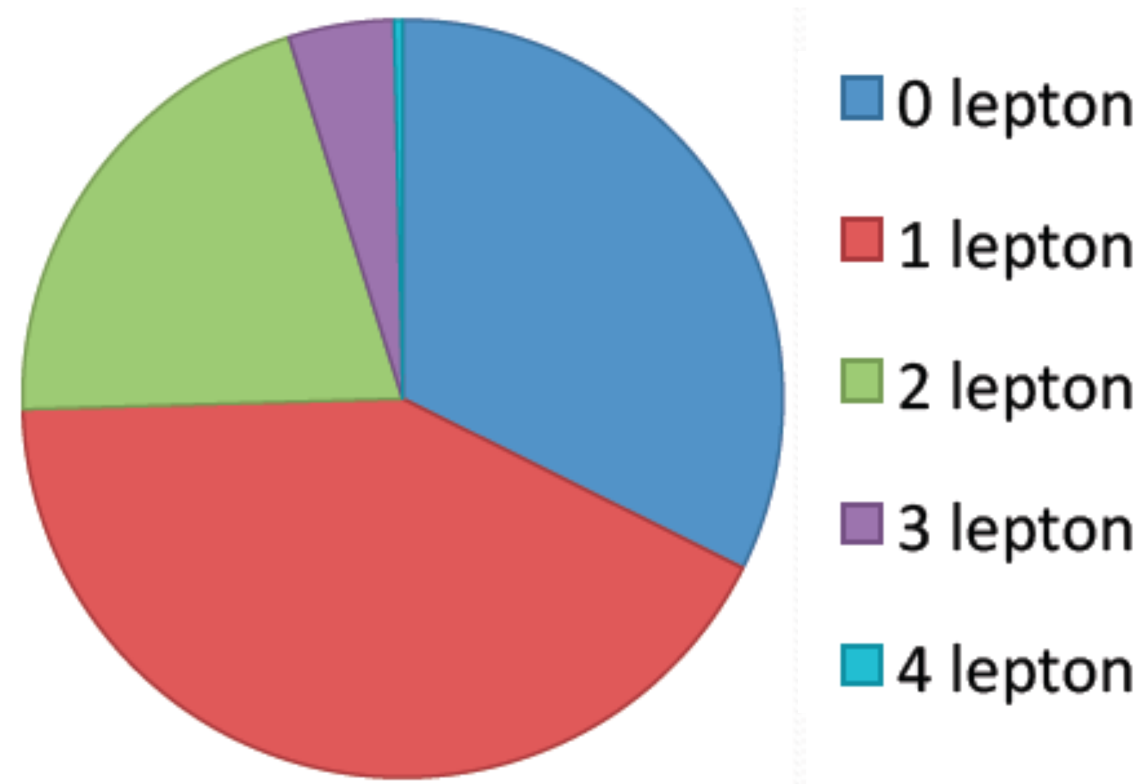


# Gluino Mediated Stop Production

Two LSPs ($\tilde{\chi}_1^0$ ) : Large MET




Signature : 4 Ws and 4 b-jets

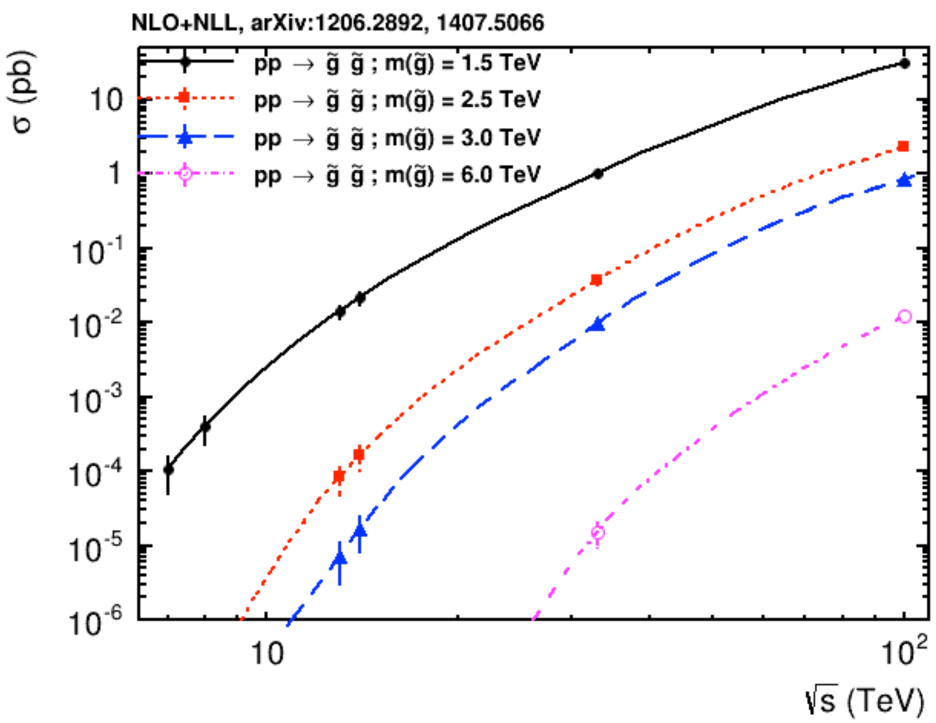


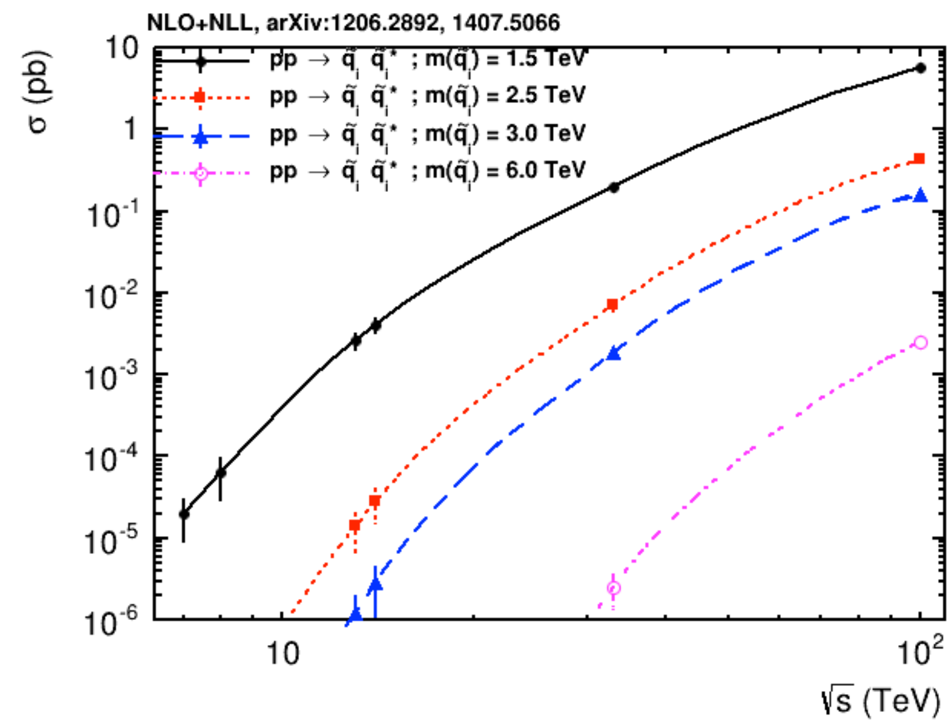

Branching fraction for 4Ws

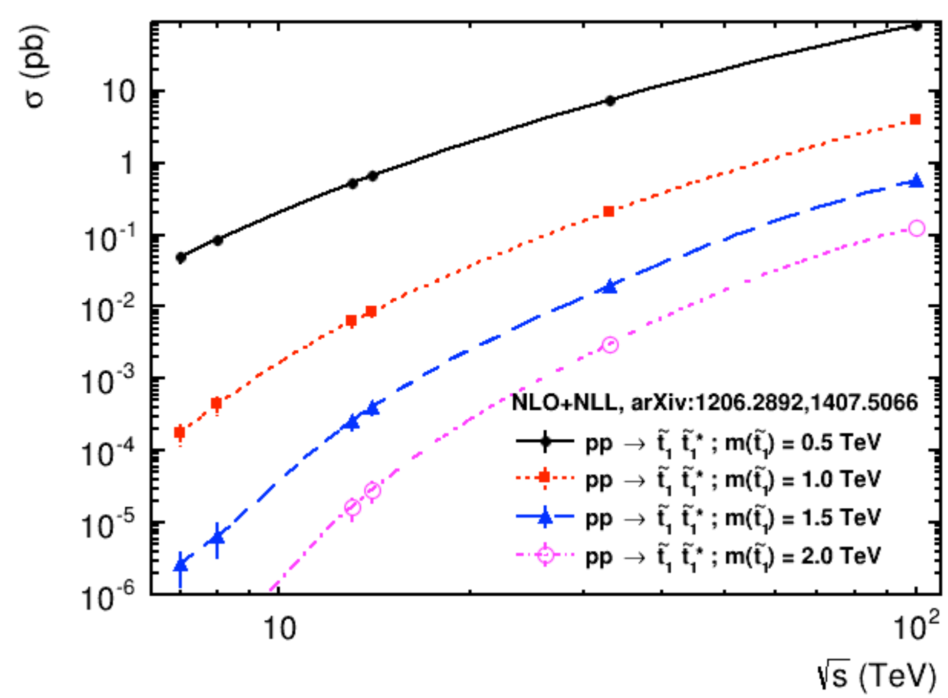
Searches performed in the final state categorized into :

Further categorized into 0, 1, SS/OS 2-leptons, multileptons

# New Physics Cross sections @ LHC

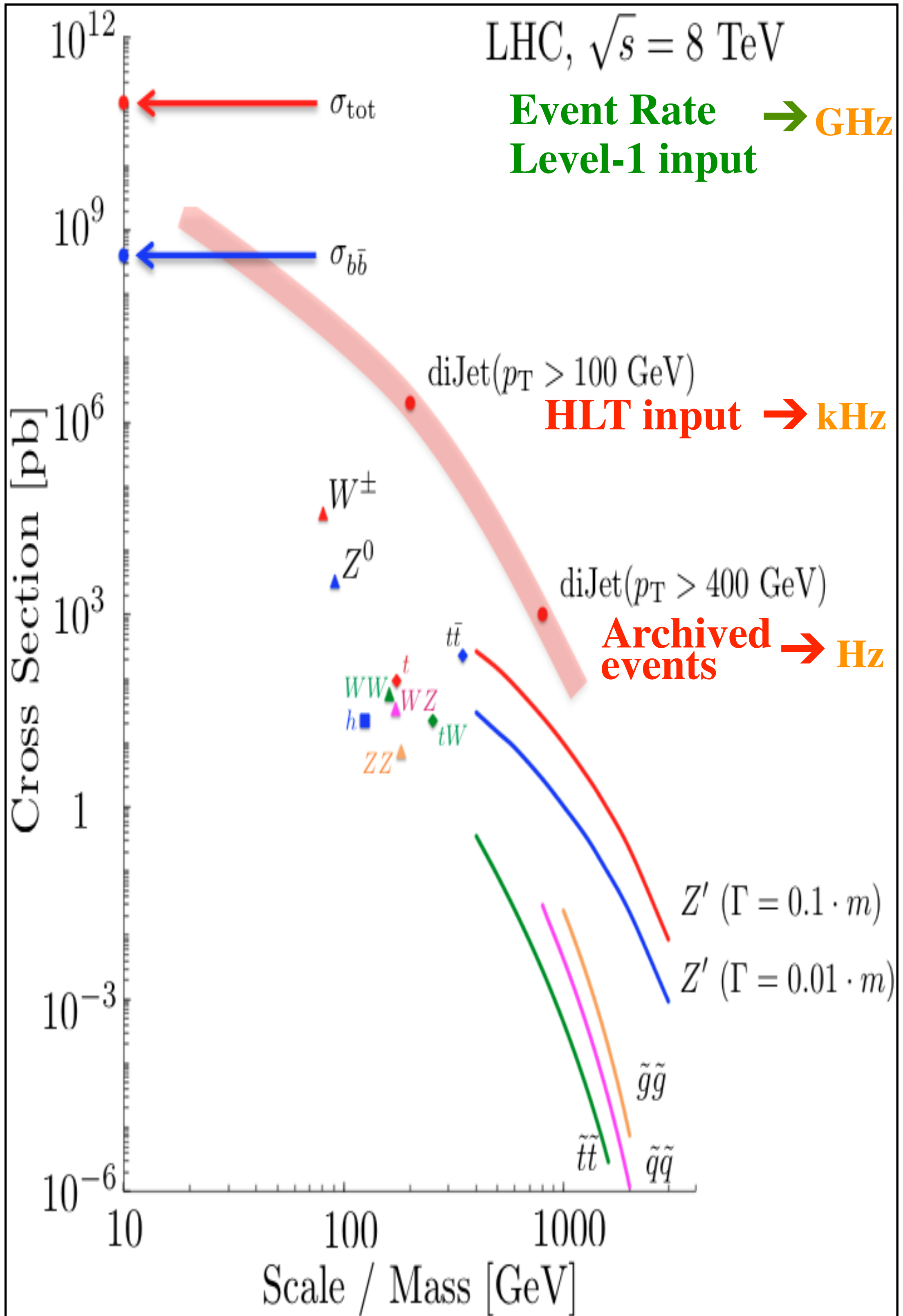


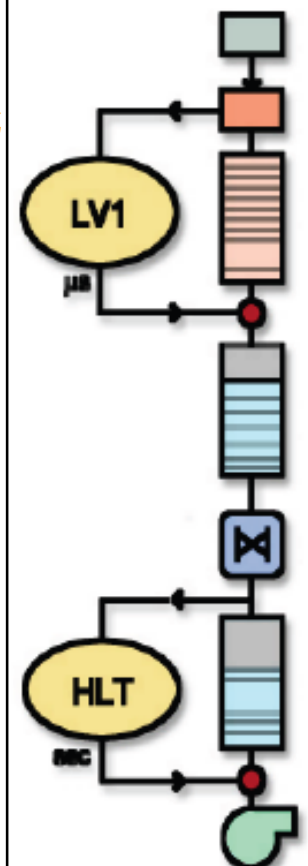




https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections#SUSY_Cross_Sections_using_8_TeV

# Acquiring Data of Interest



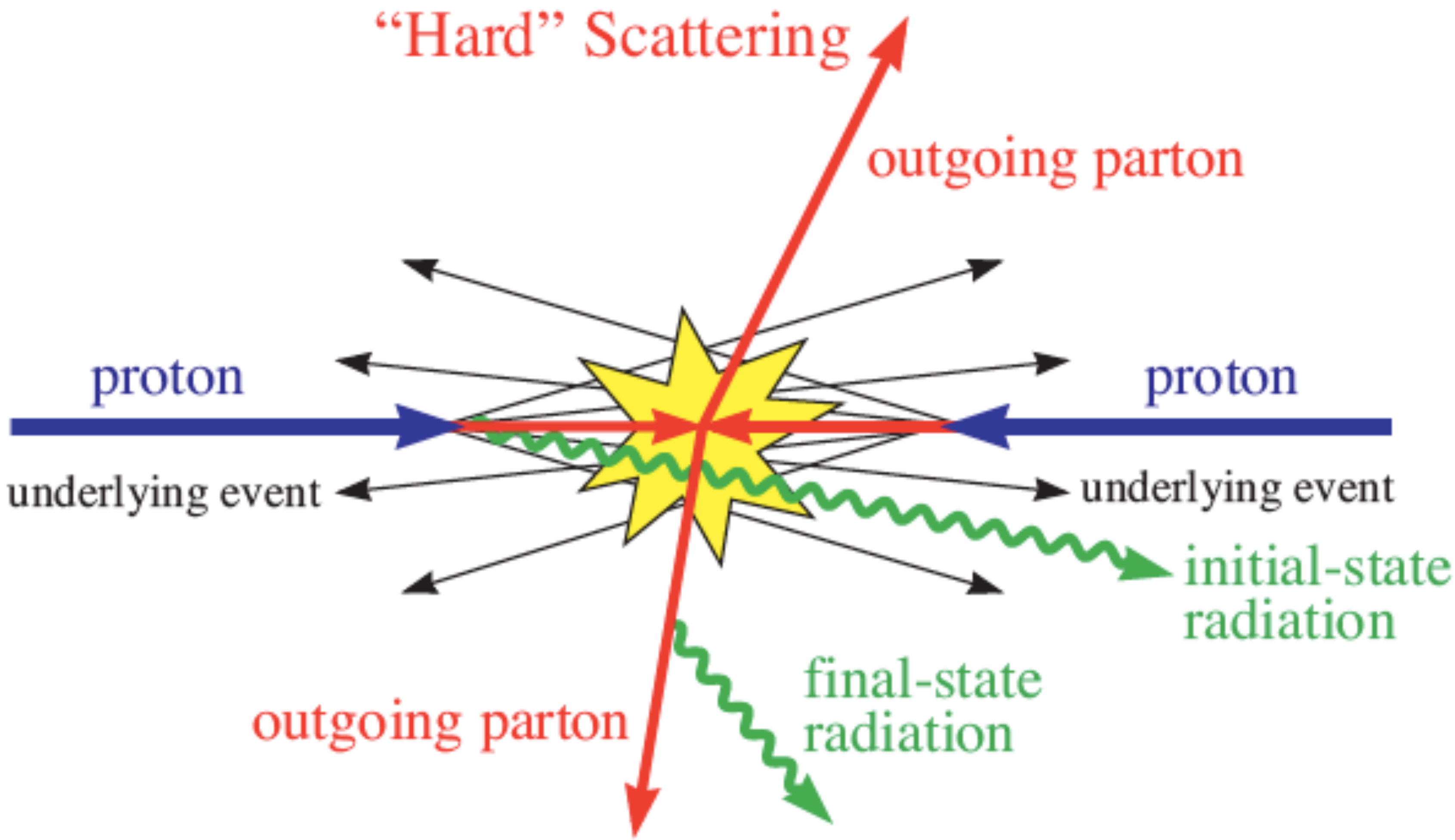

- Rate of pp events : 40 MHz
- Data acquisition capability : ~300 Hz
- Trigger system decides if the event is interesting to be stored for offline analysis
  → rejection power of $10^6$

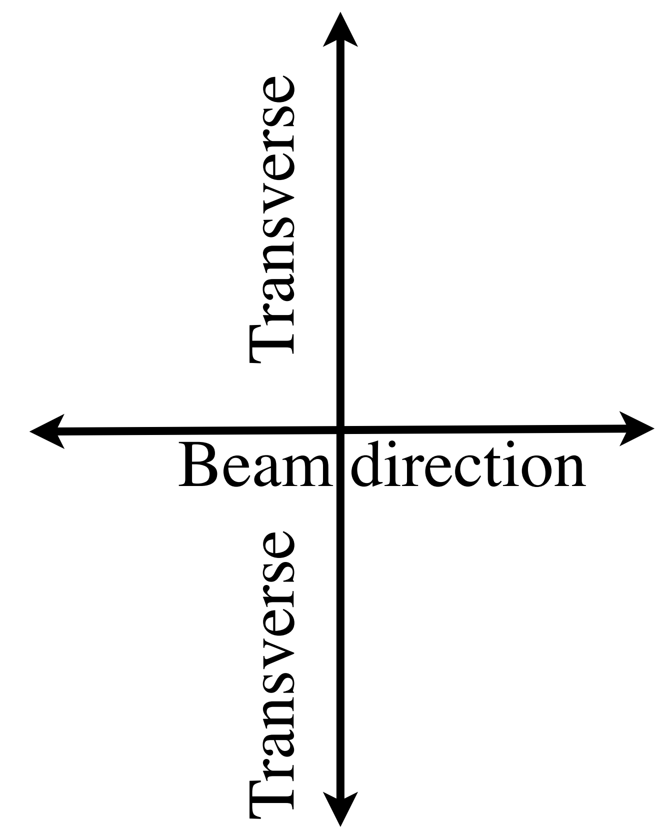
CMS has a two step process :

- Level-1 Trigger : dedicated hardware processors
  - rate reduction : 40 MHz → 100 kHz
  - time allotted : <1 micro-sec
- High Level Trigger : detailed processing of events selected by Level-1
  - rate reduction : 100 kHz → 100 Hz

# New Physics @ LHC

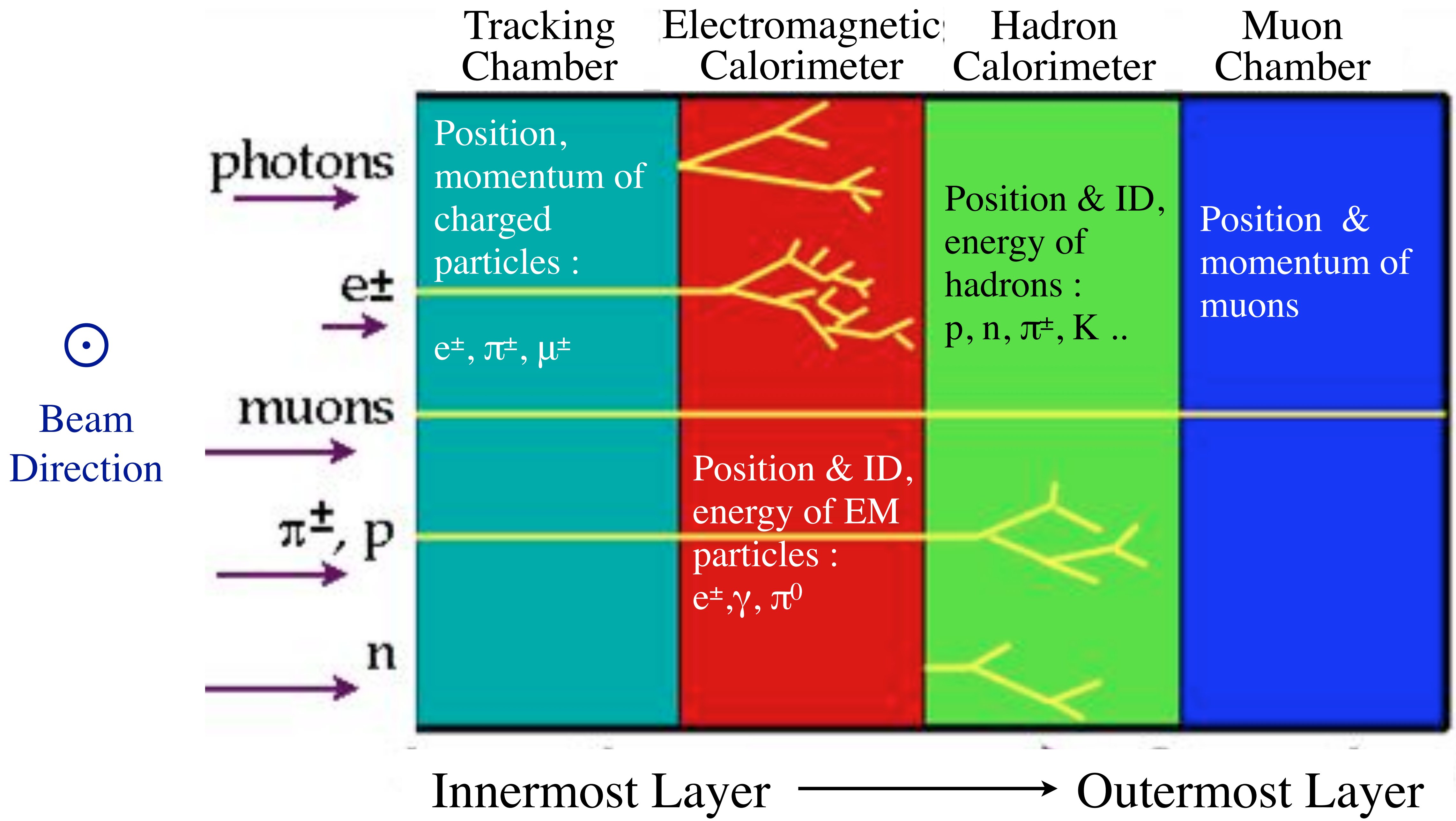
New particles can be produced in collisions of particles at high energies.




- Interactions between the constituent partons.
- As the LHC operating energy increases, massive states can be produced at higher energy thresholds : $M_{new} = \sqrt{s}$ (centre-of-mass energy)
  - 7 TeV → 8 TeV → 13 TeV
- Multiple production channels (strong, electroweak) : gg, qq', qg, WW ...

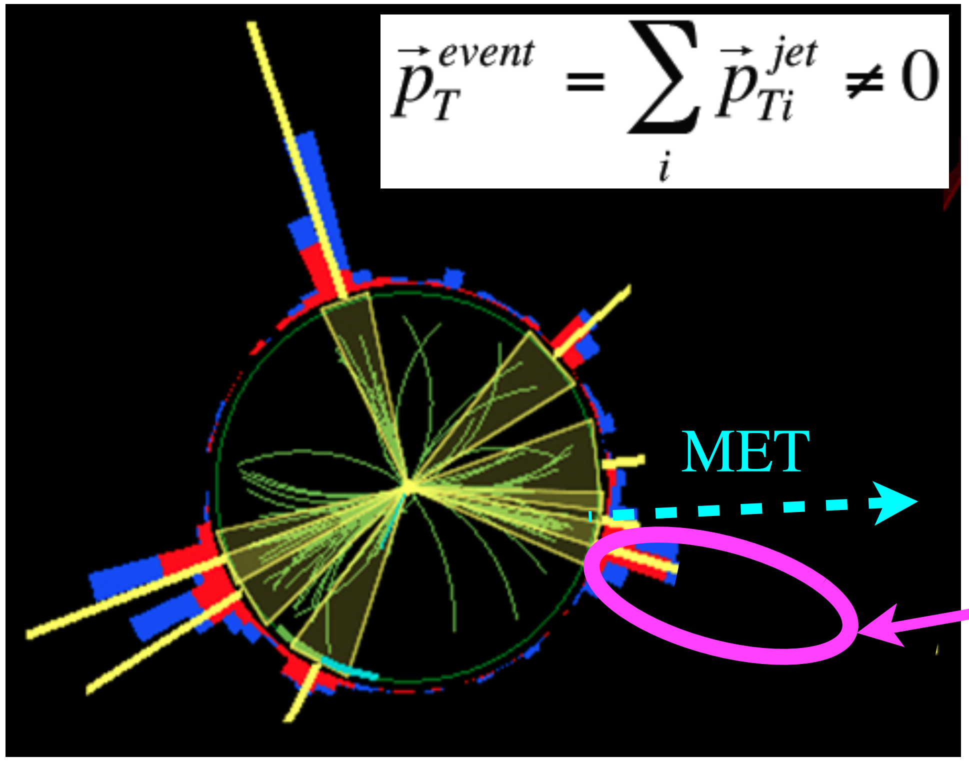
# A Generic HEP Detector & Event Reconstruction

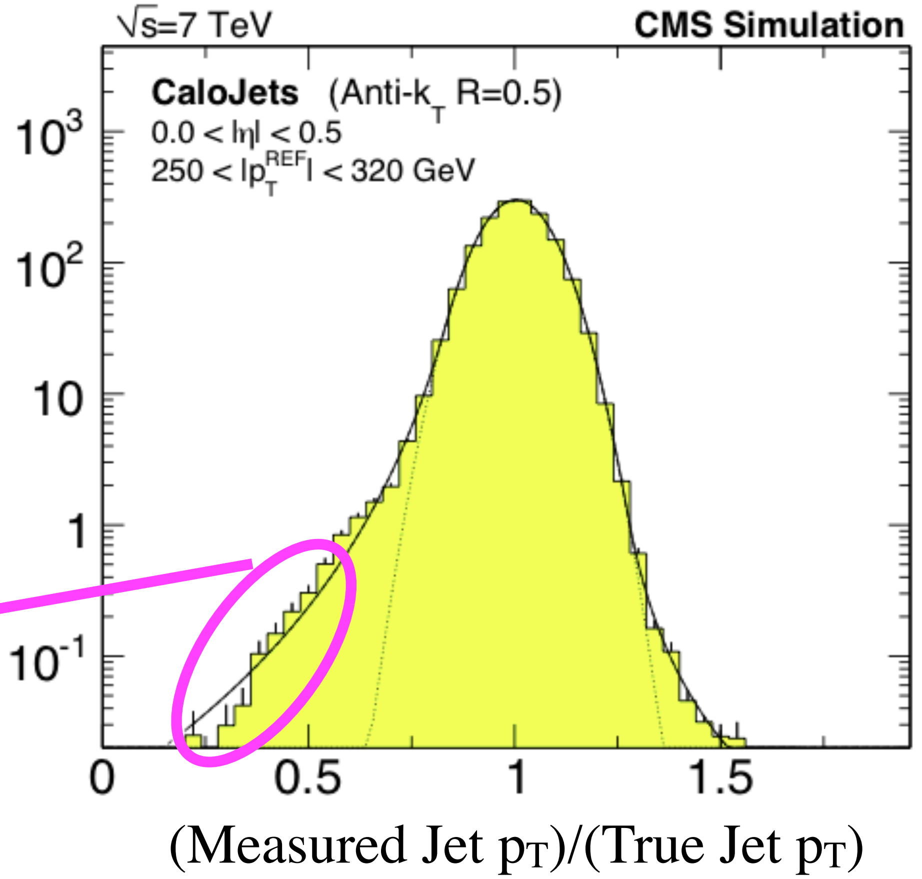



Reconstruct all the stable particles : electrons, photons, muons, charged and neutral hadrons

# (Fake) MET

**Mis-**measurement of jets can result in fake missing transverse momentum.




Detector response < 1 → mimic signature of a ν or $\tilde{\chi}_1^0$

Understanding jet $p_T$ resolution is very important to control the QCD multijet background.