Searching for SUSY Dark Matter at the LHC: finding the weak amongst the strong

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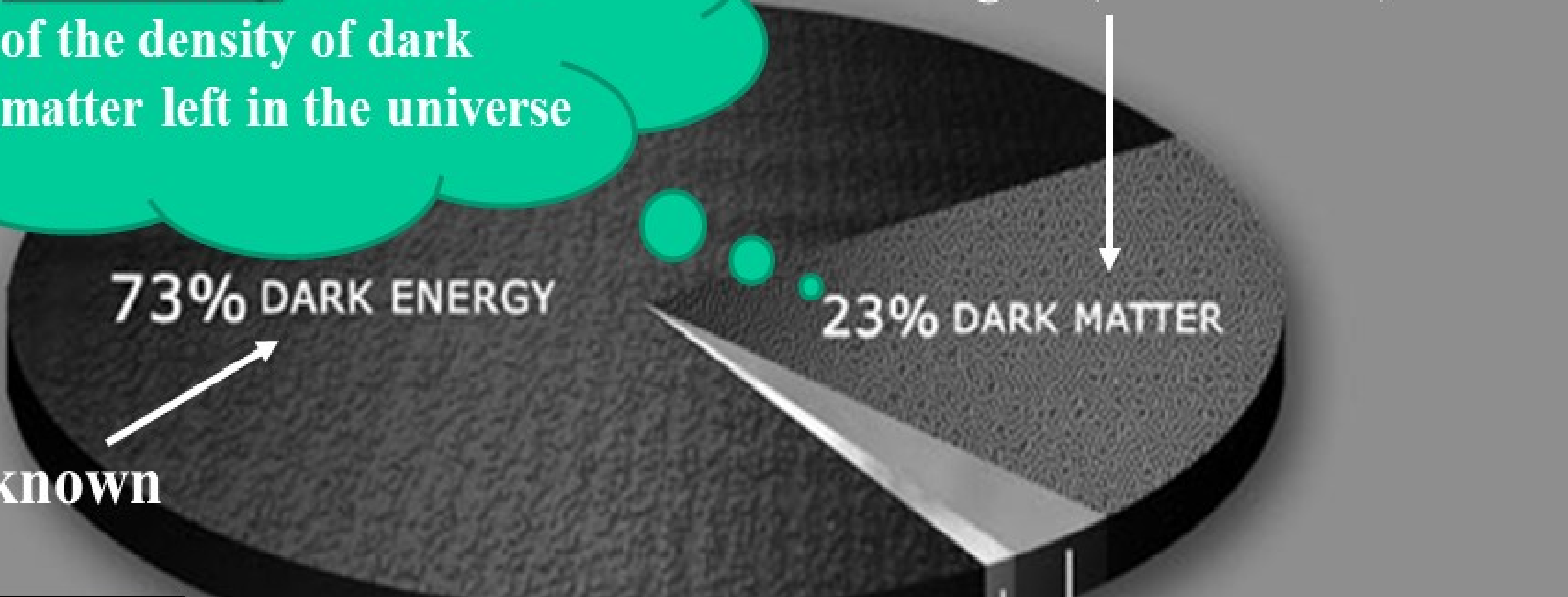
Content of the Universe

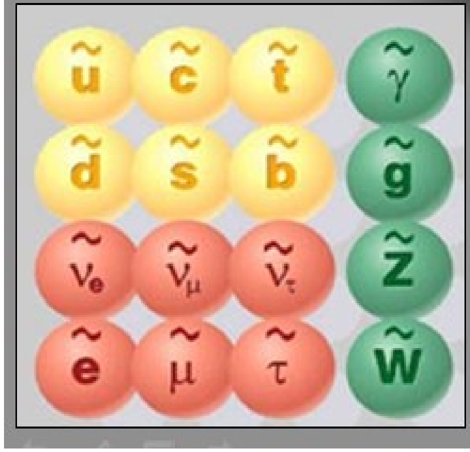
Relic Density: A measure of the density of dark matter left in the universe

Does not interact with light ("invisible")



Still Unknown

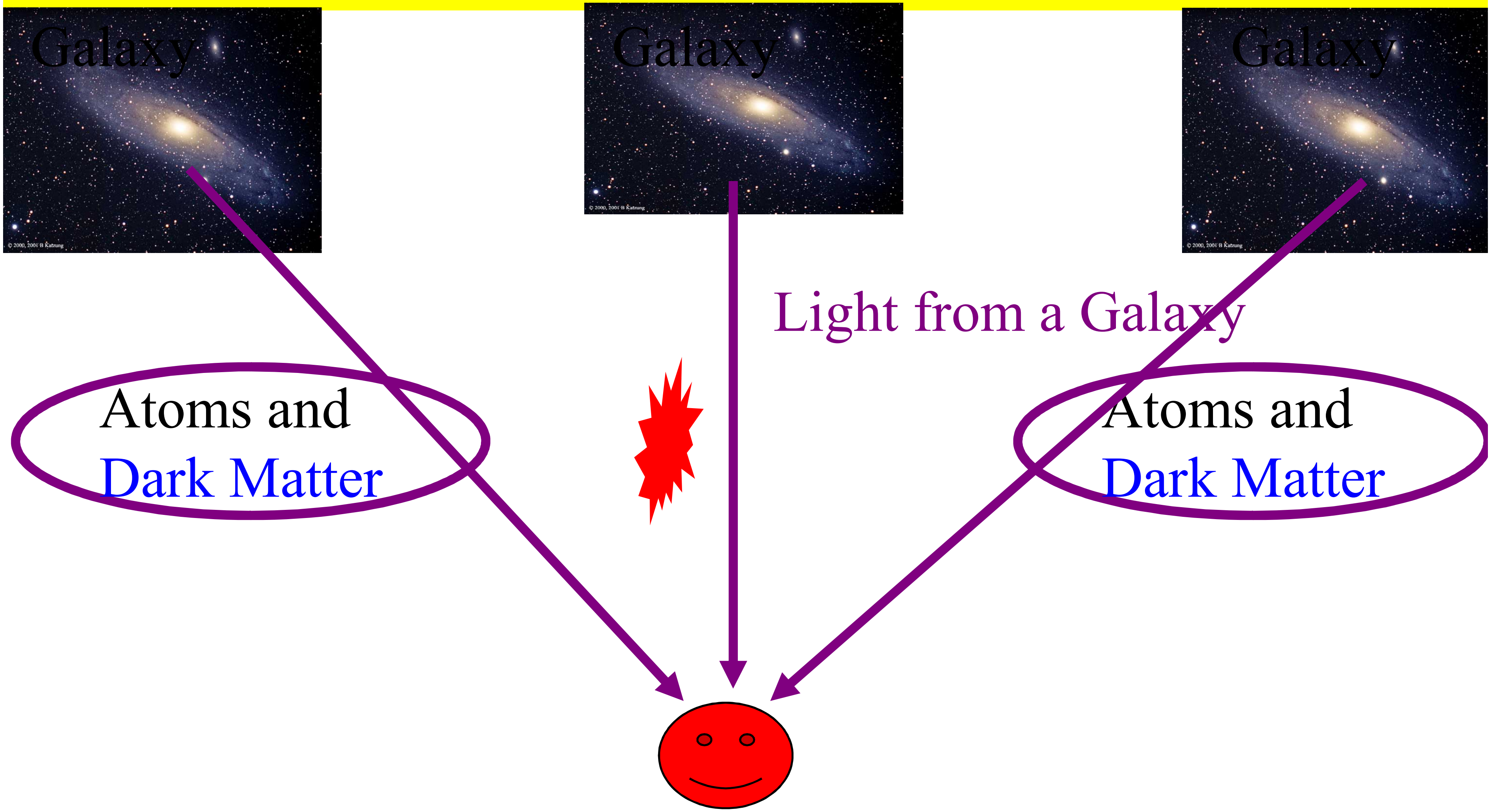
"Normal" Matter



- ❑ **Supersymmetry (SUSY)**
  - ❑ *Every SM fermion (boson) has a boson (fermion) superpartner*
- ❑ **SUSY extensions of the SM**
  - ❑ *Lightest Supersymmetric Particle (LSP) is a natural CDM candidate*

Evidence for Dark Matter

Colliding Galaxy Clusters



Galaxy

Galaxy

Galaxy

Light from a Galaxy

Atoms and
Dark Matter

Atoms and
Dark Matter

Blue (Dark Matter) is the mass as measured by gravitational lensing:

Pass through → Weakly

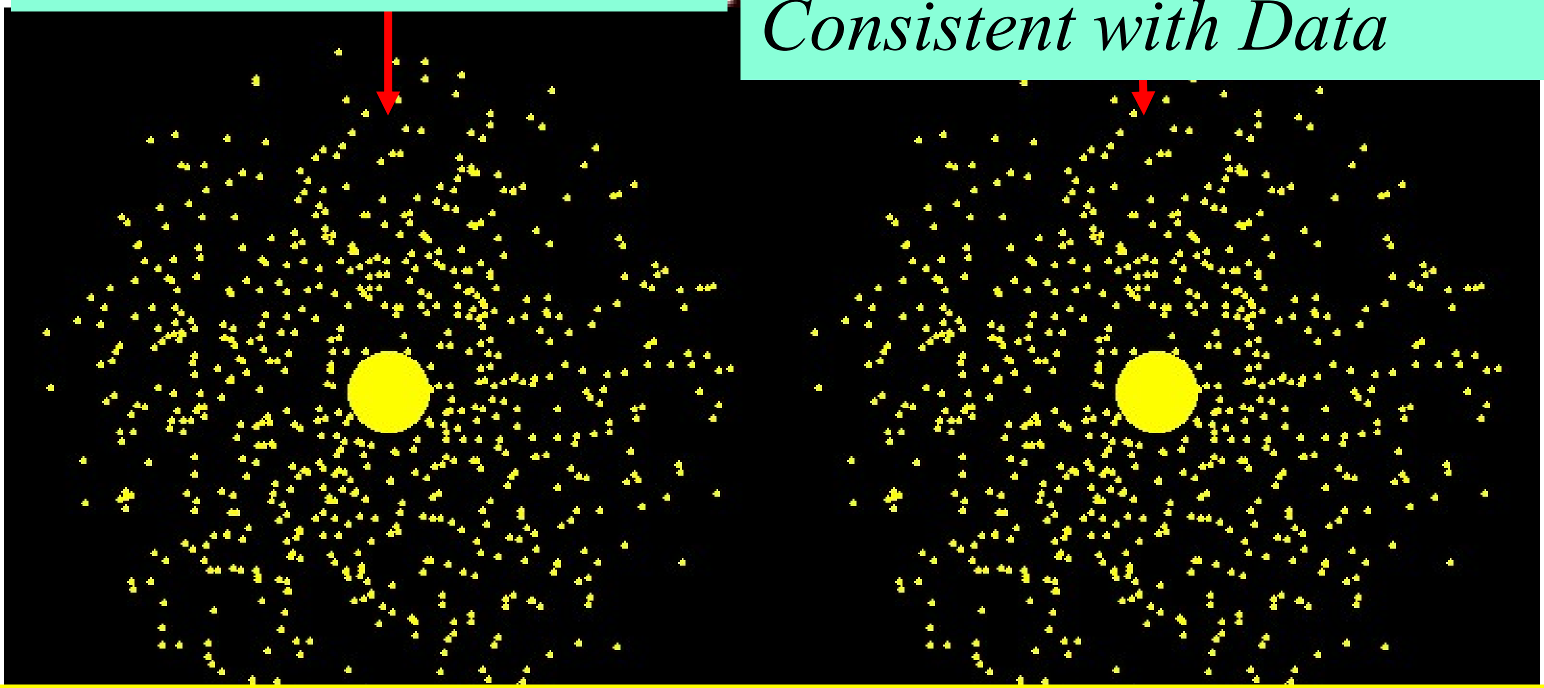
Intera

Red part from x-ray observations

Slowed→Particles with Standard Model

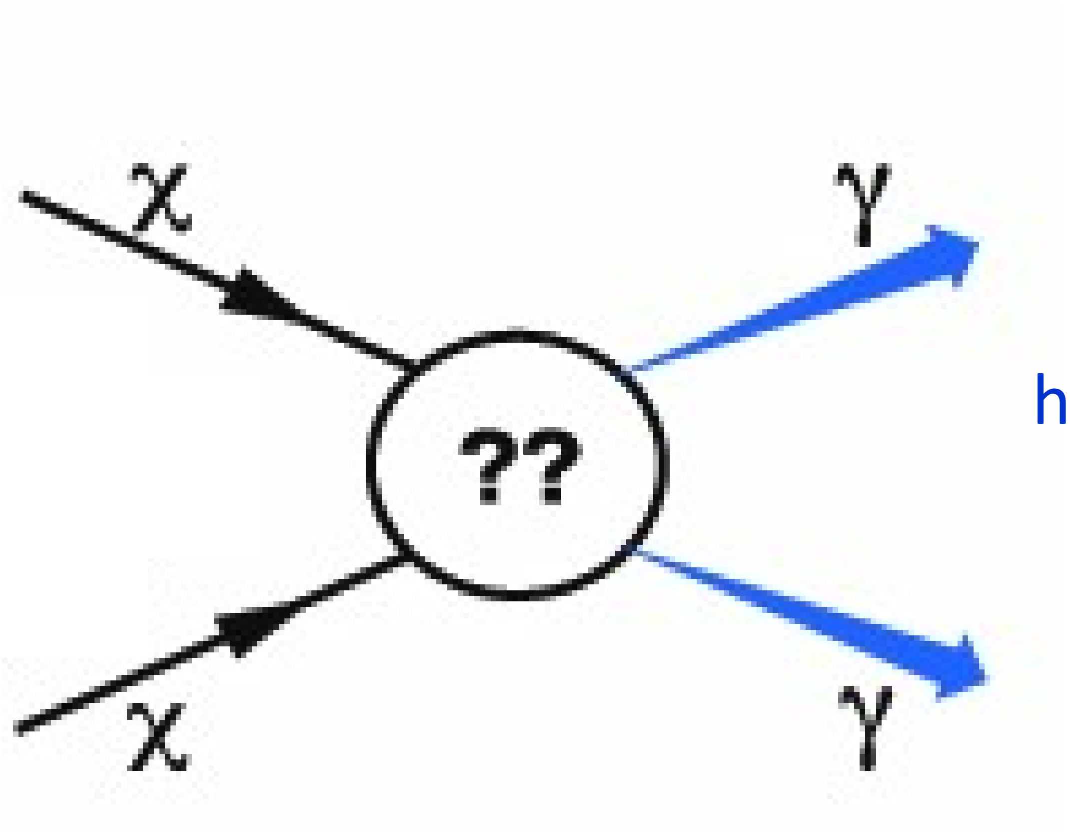
Simulation without Dark Matter

Simulation with Dark Matter Consistent with Data



Galaxy Rotation Simulation with and without Dark Matter

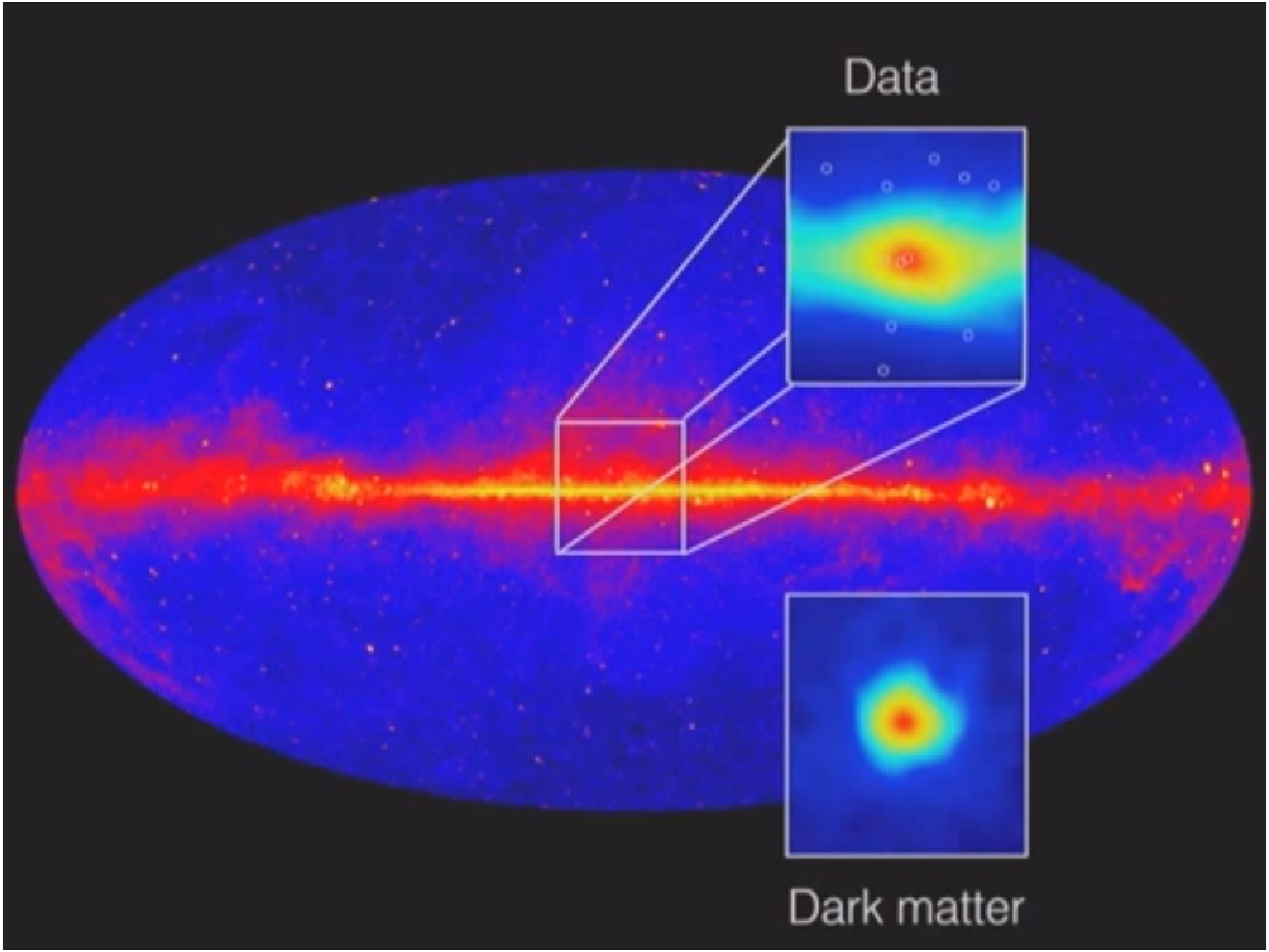
Dark Matter Annihilation



Dark Matter

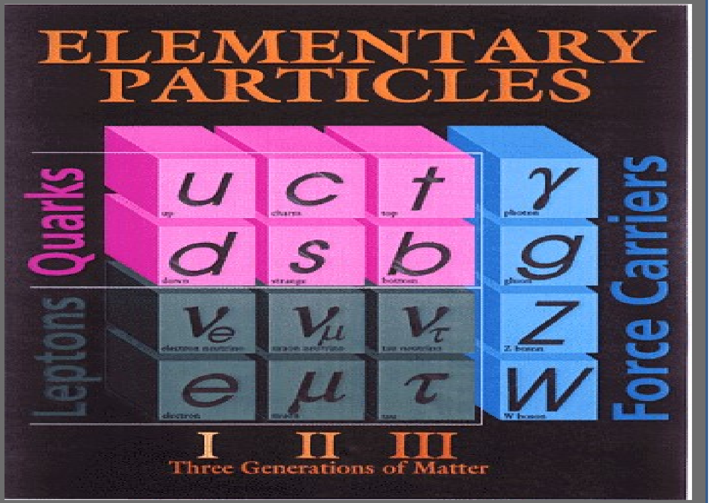
Dark Matter

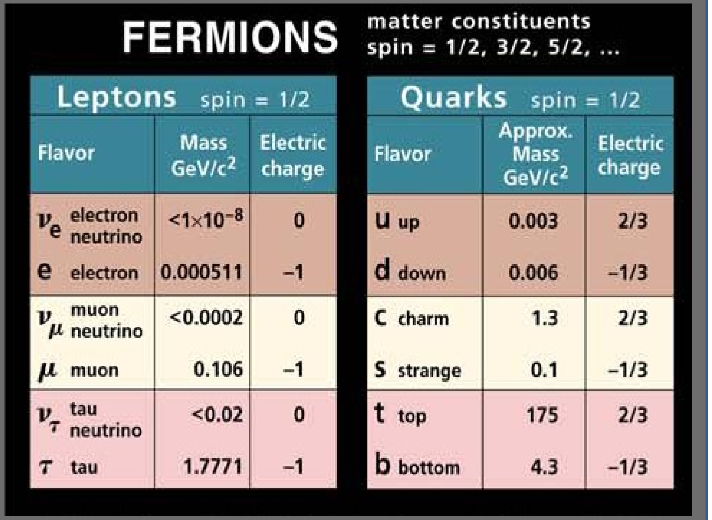
high-energy
light


Data
Dark matter

The Standard Model

- **Matter is composed of fermions**
  - Spin ½ particles
  - Leptons
    - Electric charge (electroweak interactions)
  - Quarks
    - Electric & color charge (strong interactions)
- **Bosons – mediate forces**
  - Integer spin particles
  - γ – electromagnetic interactions
  - Z/W – weak interactions
  - Gluon (g) – strong interactions
- **Other particles are made up of these fundamental particles**
- **Higgs boson**
  - → massive gauge bosons





FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

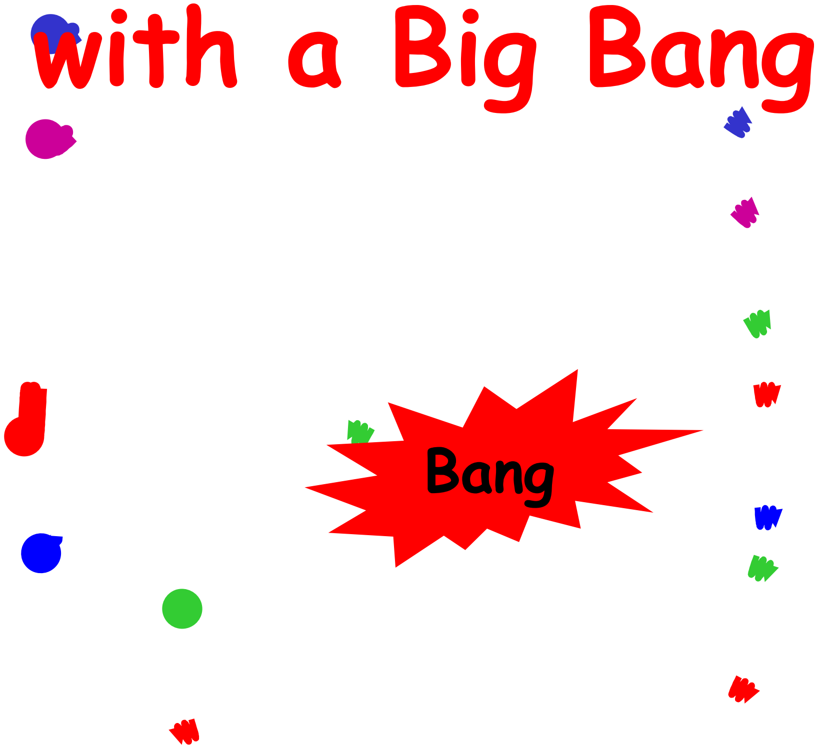
Flavor		Mass GeV/c²	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	–1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	–1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	–1

Quarks spin = 1/2

Flavor		Approx. Mass GeV/c²	Electric charge
u	up	0.003	2/3
d	down	0.006	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	175	2/3
b	bottom	4.3	–1/3

Artists Conception of the Big Bang

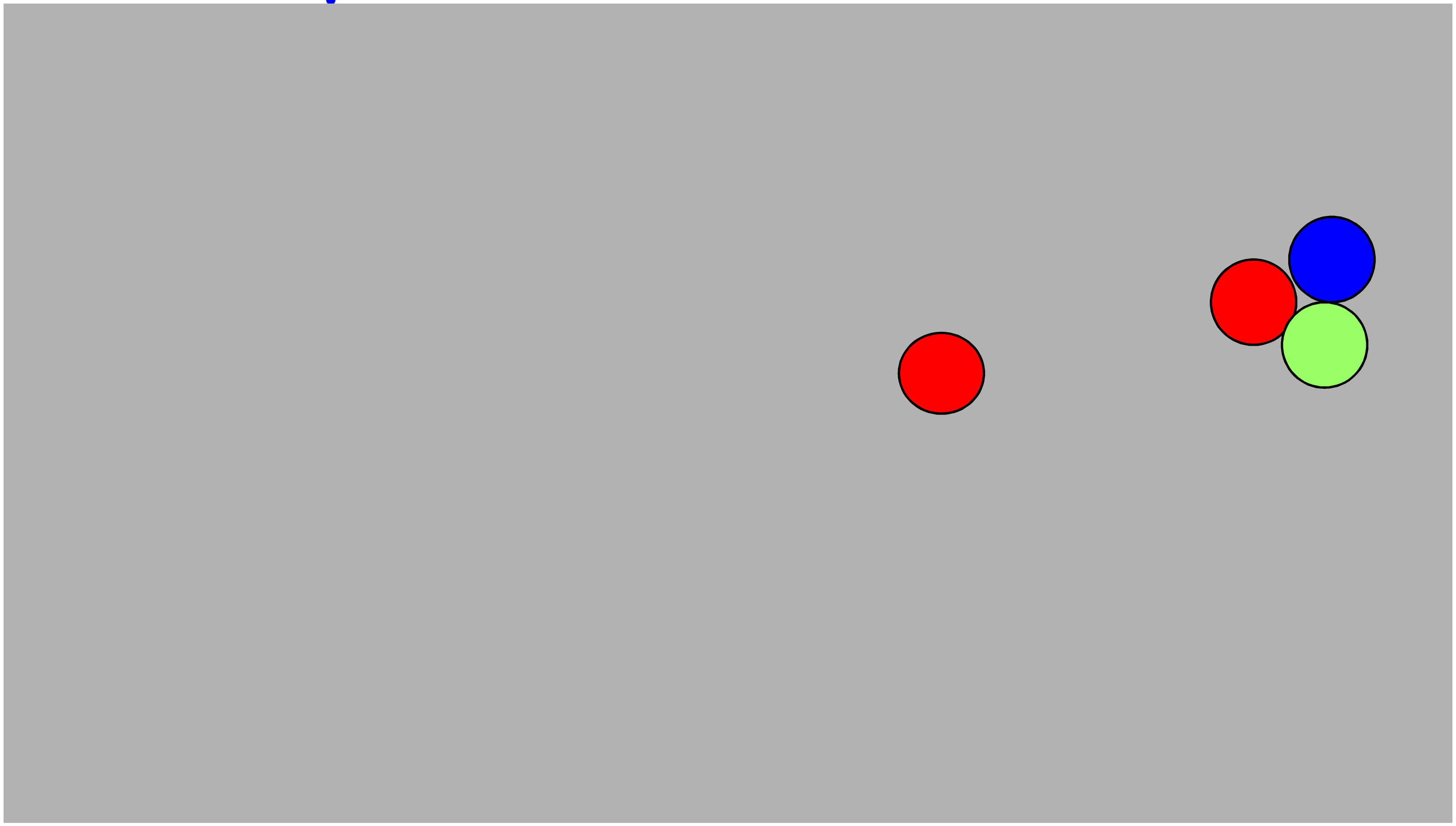
It all started 14 billion years ago with a Big Bang



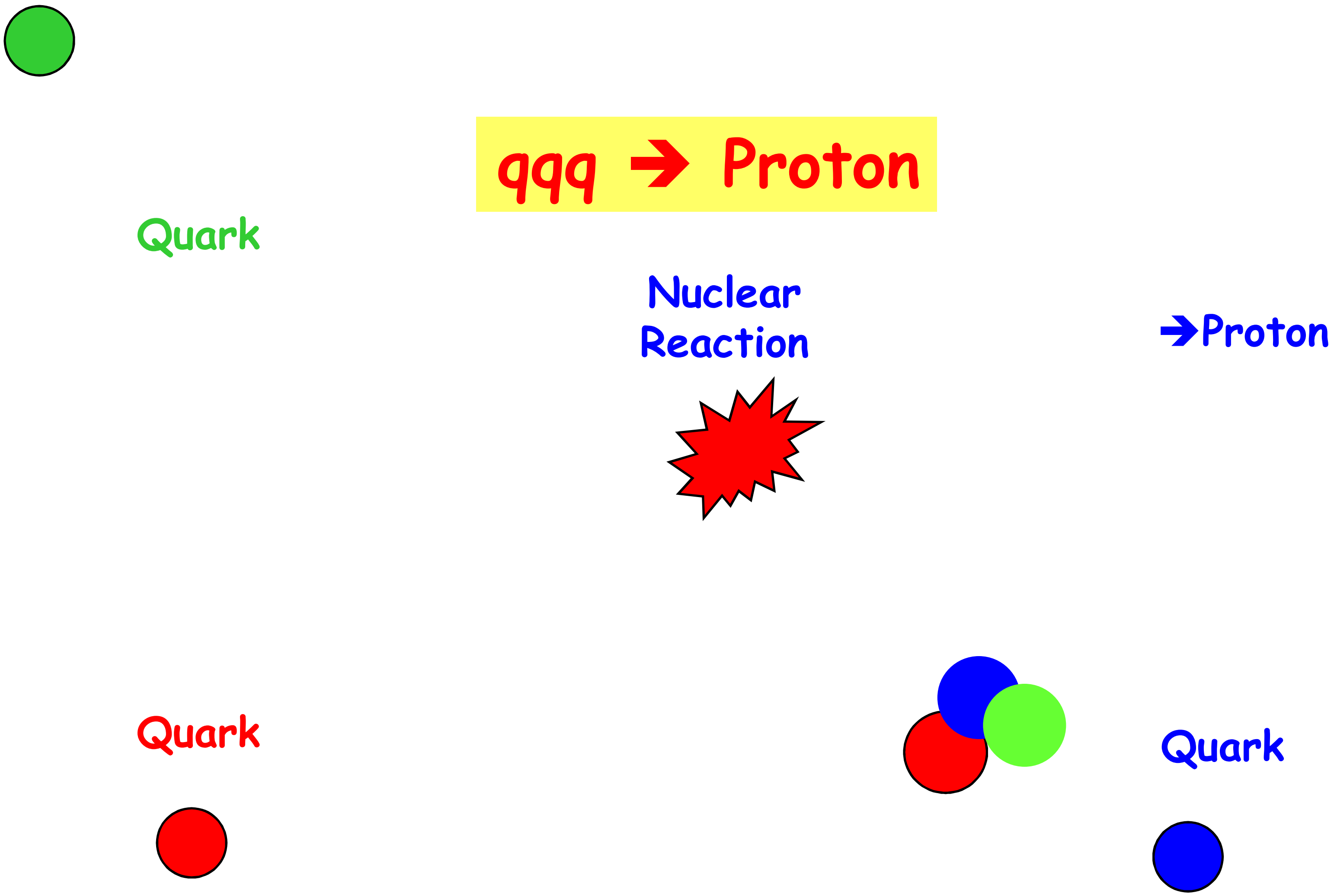
The very early Universe (<10^{-6} s)

Lots of free particles just hanging around…

Universe is so hot that quarks can't combine to make protons/neutrons



Later, Quarks Combine to Form Nucleons (10^{-6} s)



qqq → Proton

Quark

Nuclear Reaction

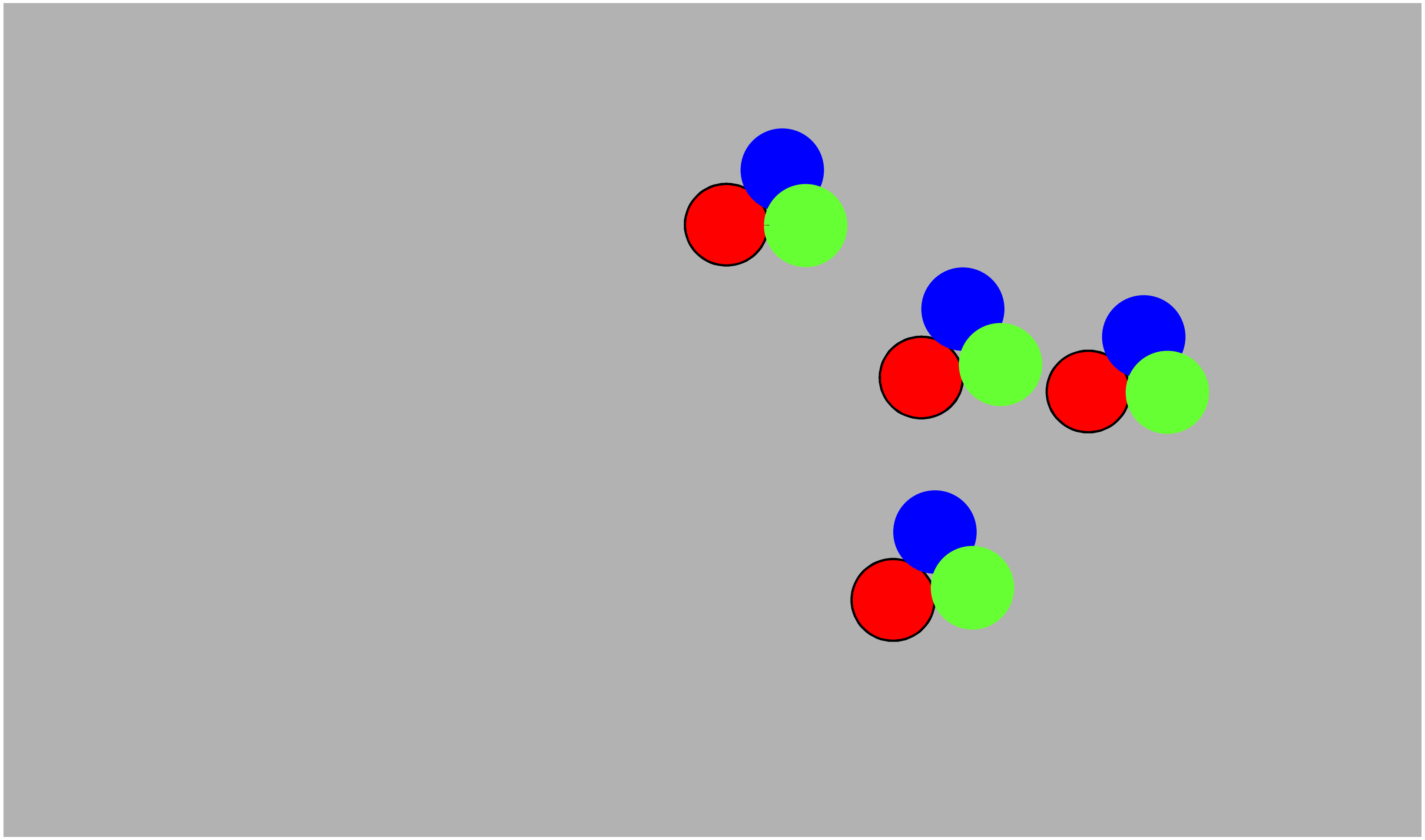
→Proton

Quark

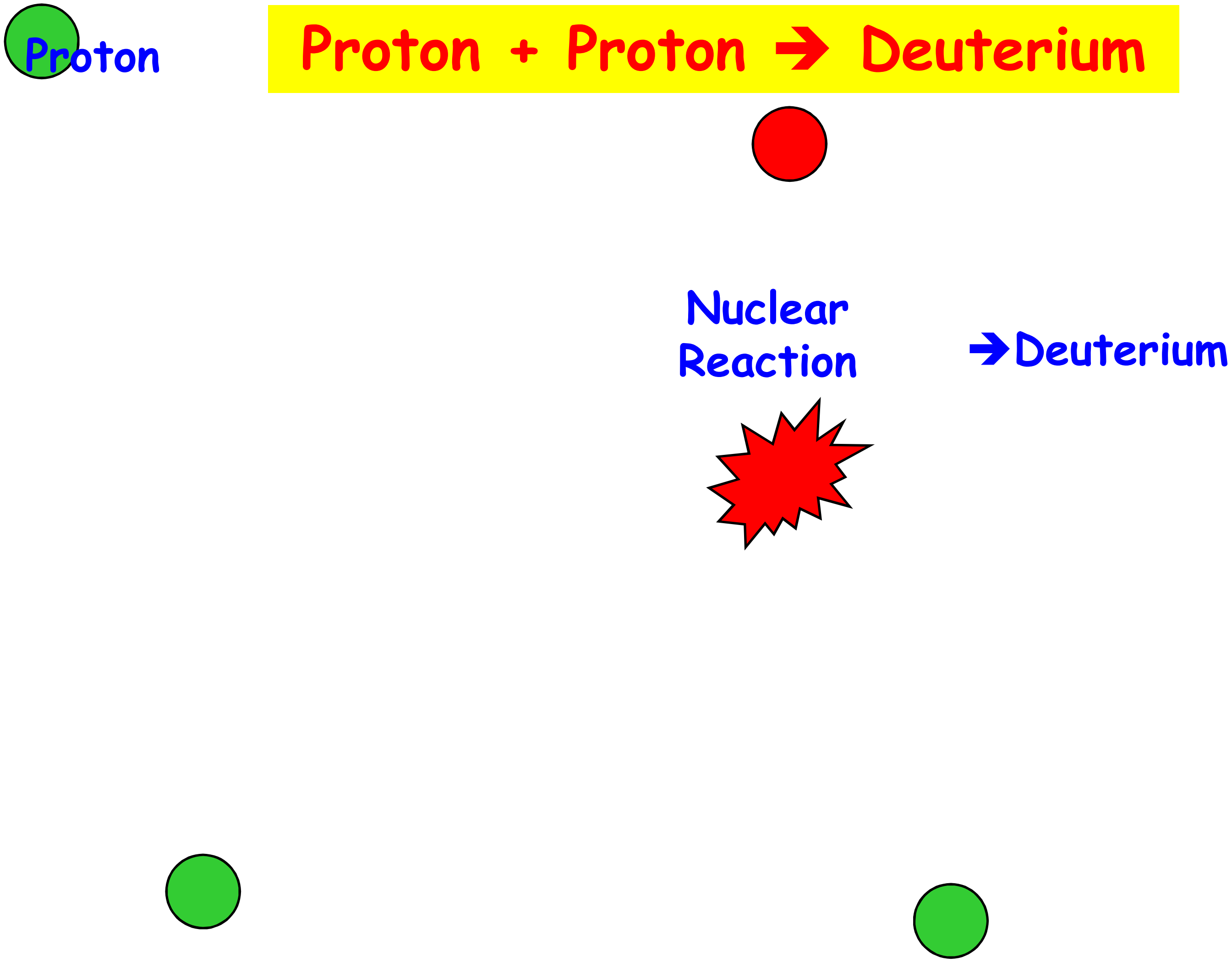
Quark

A Millionth of a Second after the Big Bang

The quarks have combined to form Protons and Neutrons



Create Heavier Nuclei (minutes)



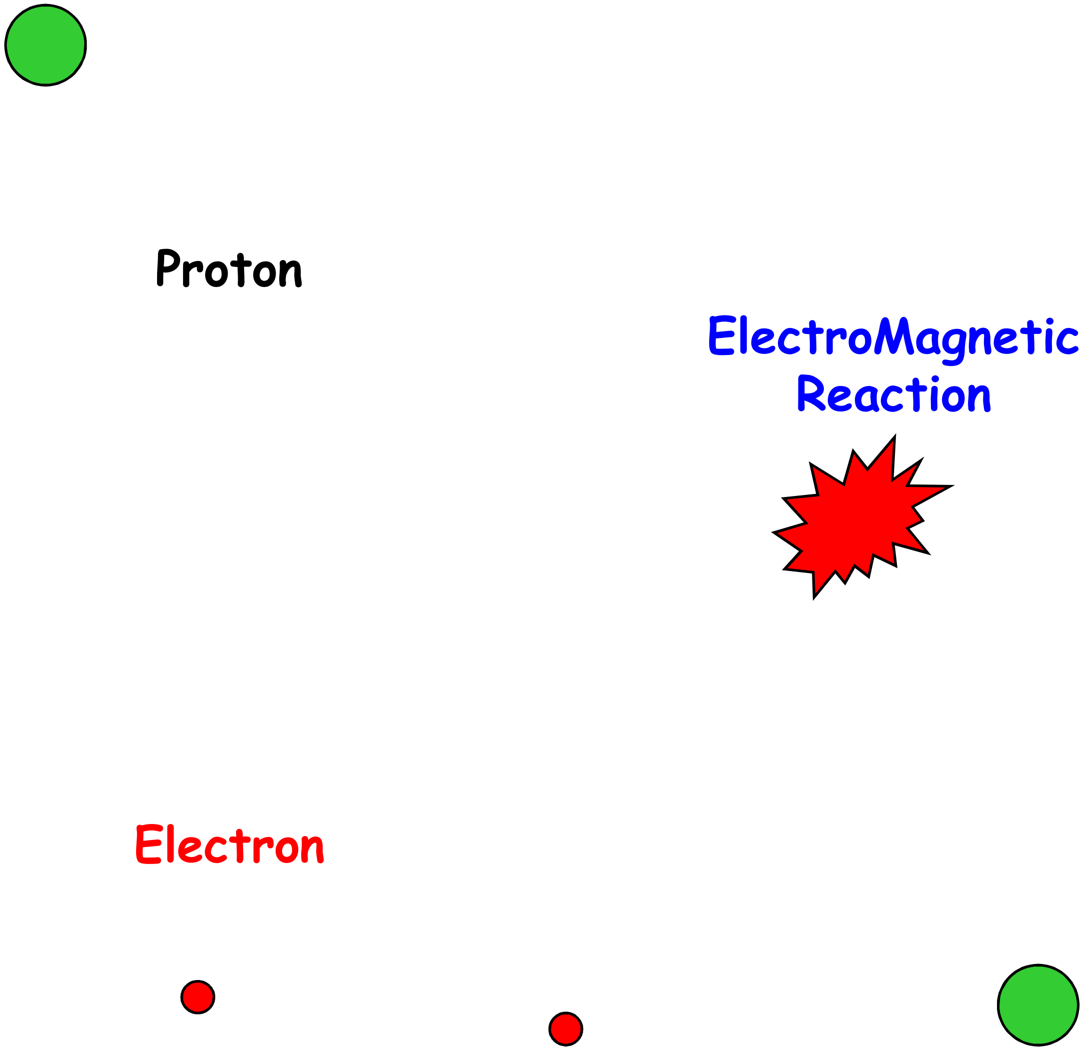
Proton

Proton + Proton → Deuterium

Nuclear Reaction

→Deuterium

A couple hundred thousand years later: Atoms



Proton

ElectroMagnetic
Reaction

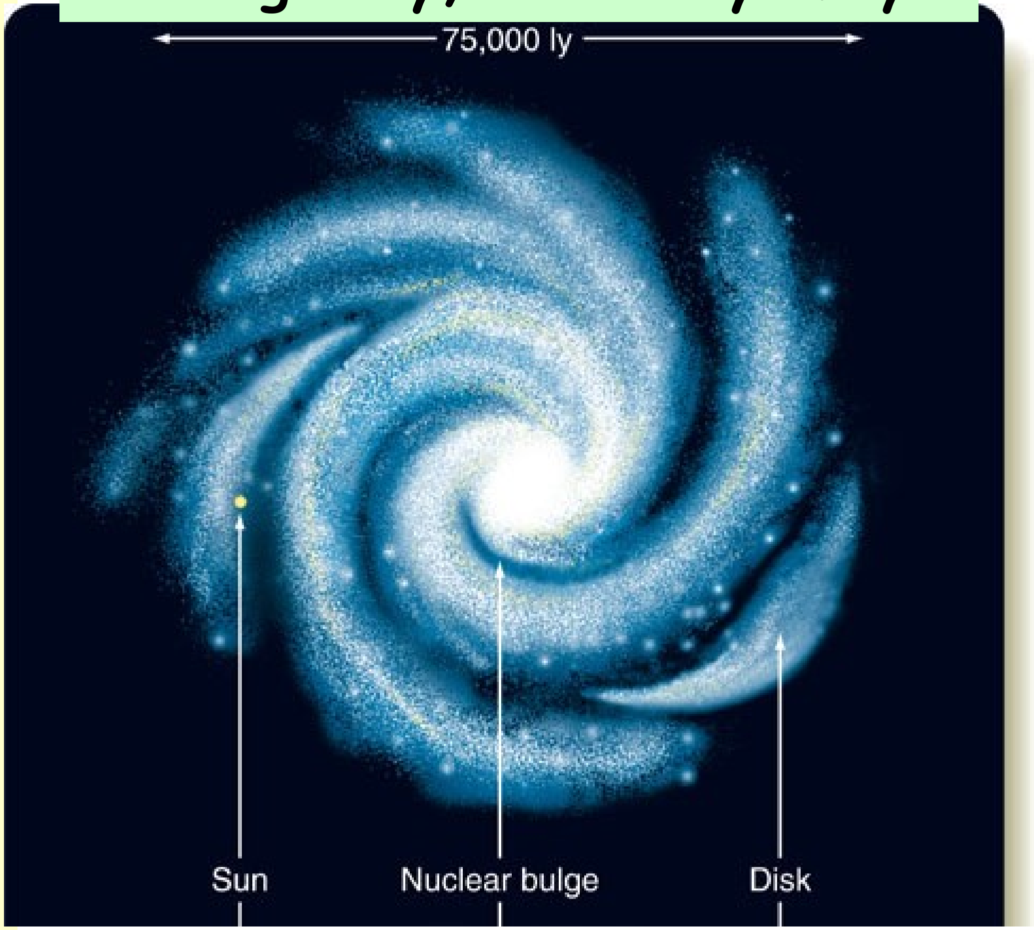
➔Hydrogen
Atom

Electron

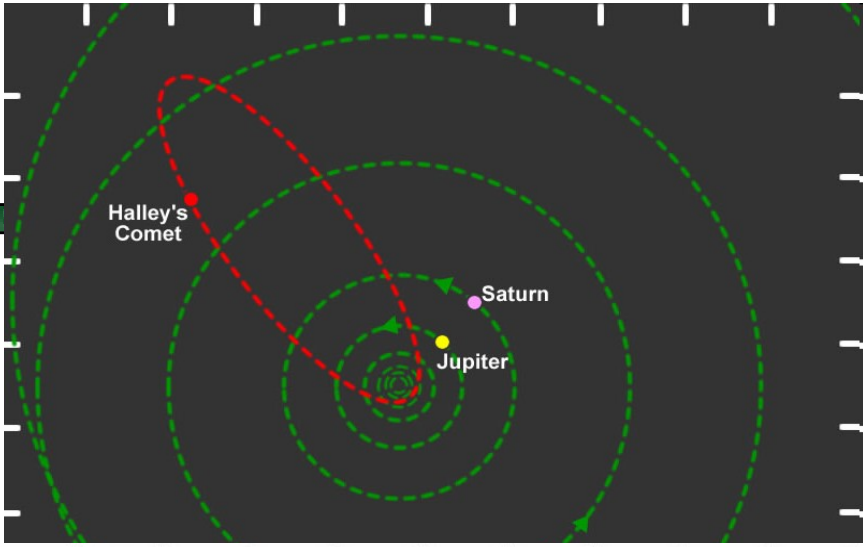
Wait a Billion Years

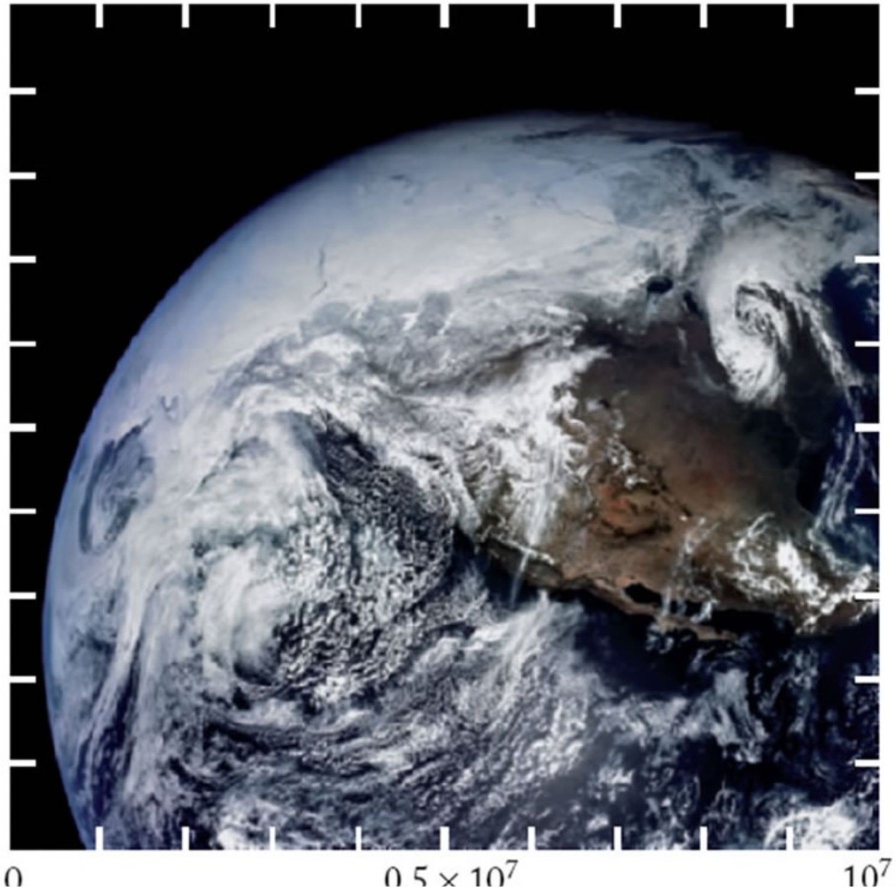
After about half a billion years, because of gravity, atoms combine to form the first stars and galaxies

Our galaxy, the Milky Way



After about 9 billion years our solar system and the Earth form

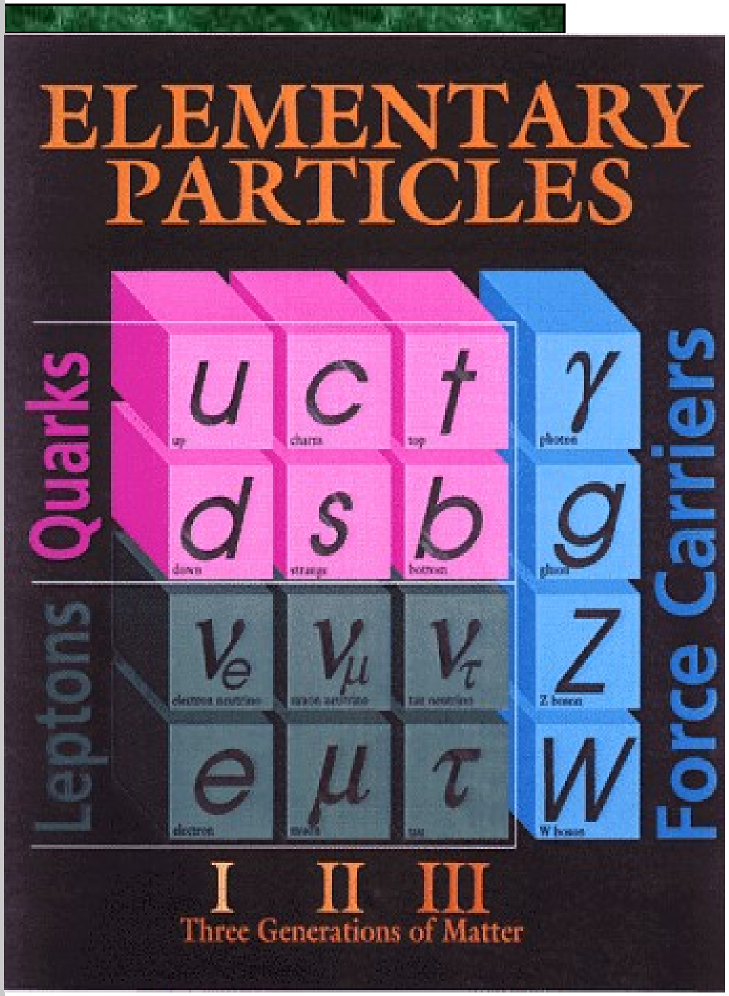




What does Dark Matter have to do with the Big Bang Theory?

The Known Particles

- No known particles have the properties of Dark Matter
- Other reasons to believe there are new fundamental particles to be discovered
  - For example, we just discovered the Higgs Boson
- Maybe Dark Matter is a New Particle!

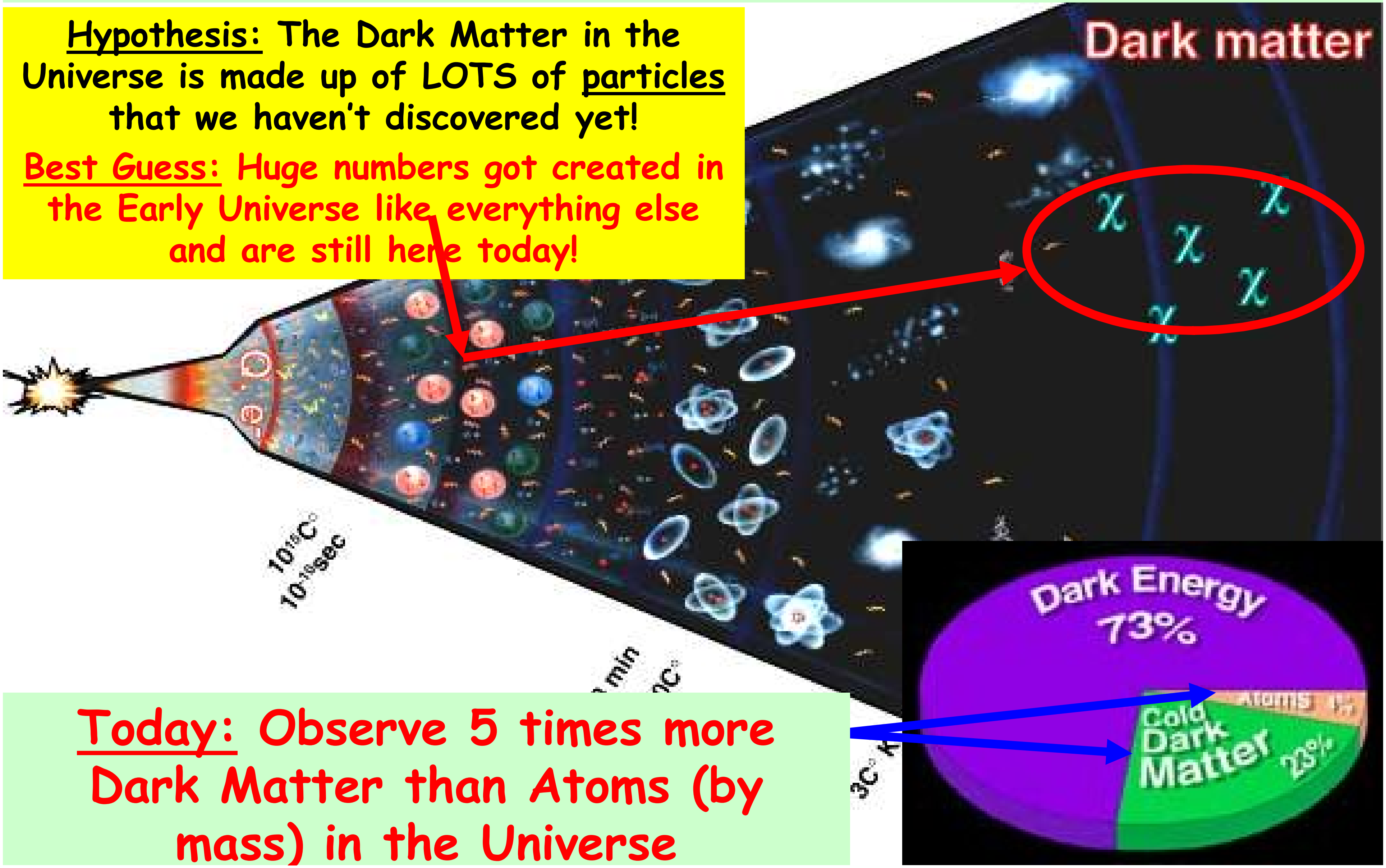


What IS the Dark Matter?

We don't know…

<u>Hypothesis:</u> The Dark Matter in the Universe is made up of LOTS of <u>particles</u> that we haven't discovered yet!

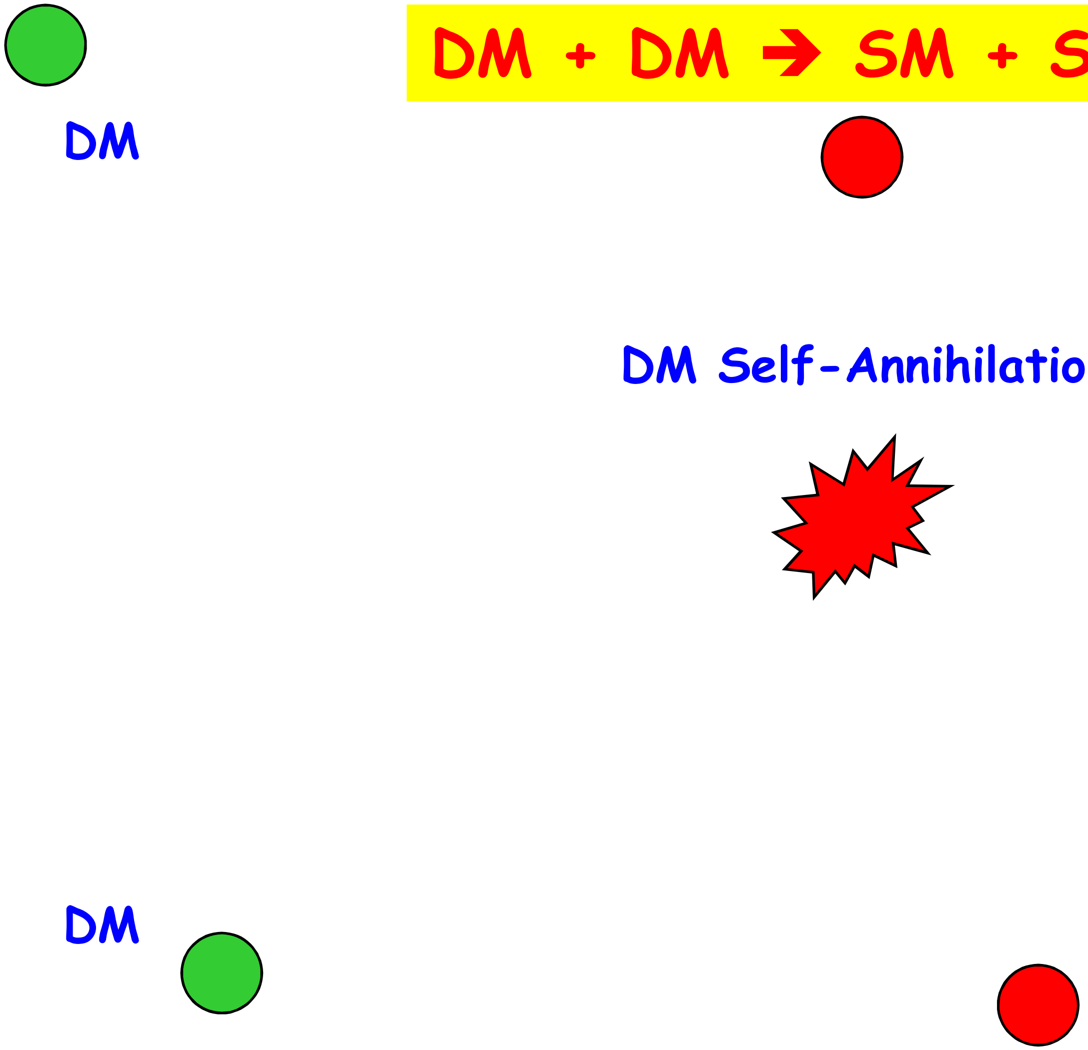
<u>Best Guess:</u> Huge numbers got created in the Early Universe like everything else and are still here today!



<u>Today:</u> Observe 5 times more Dark Matter than Atoms (by mass) in the Universe

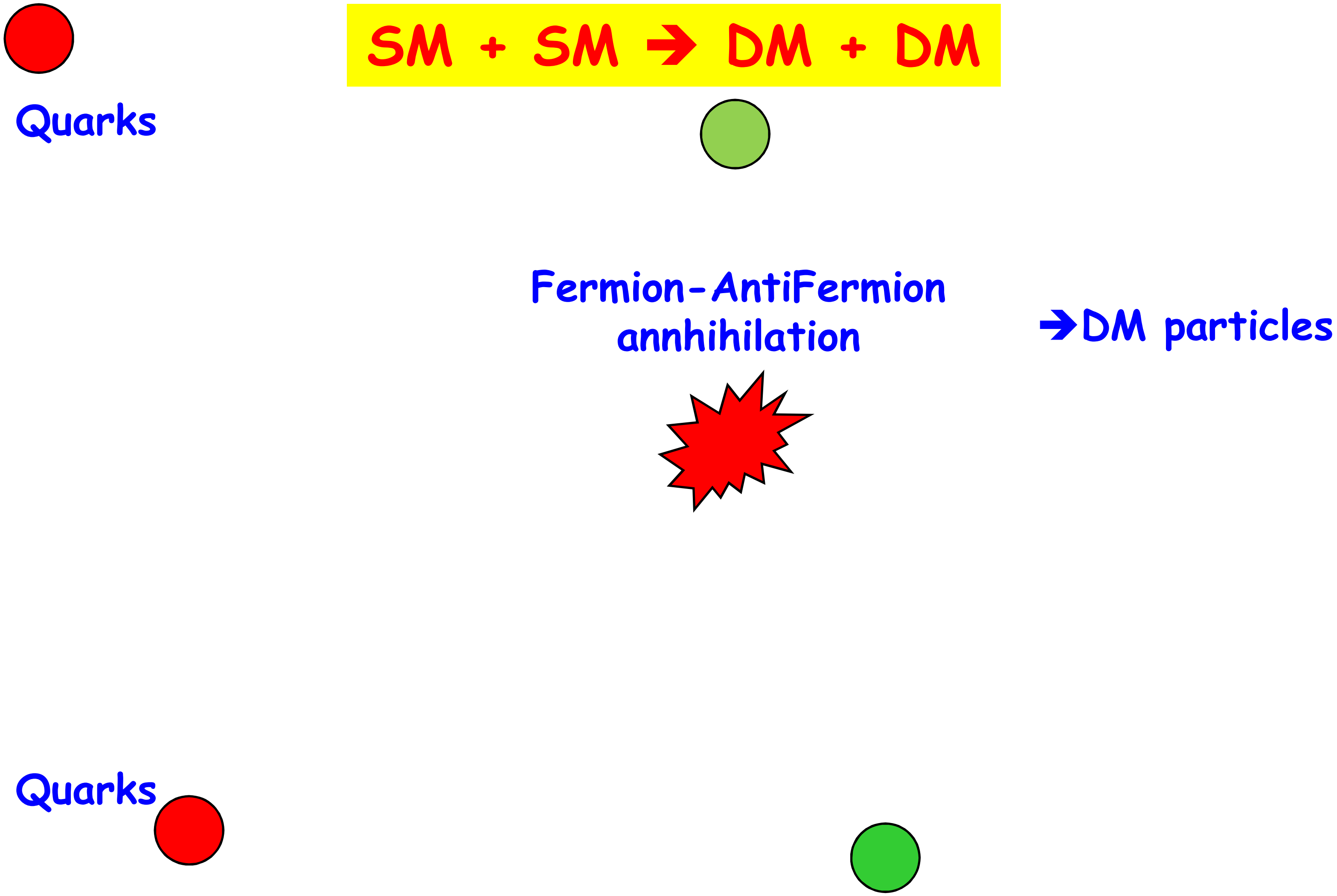
Constructing DM Relic Density

DM + DM → SM + SM



Constructing DM Relic Density

SM + SM → DM + DM

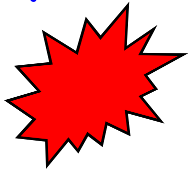


Universe Cools (less DM)

DM + DM → SM + SM

DM

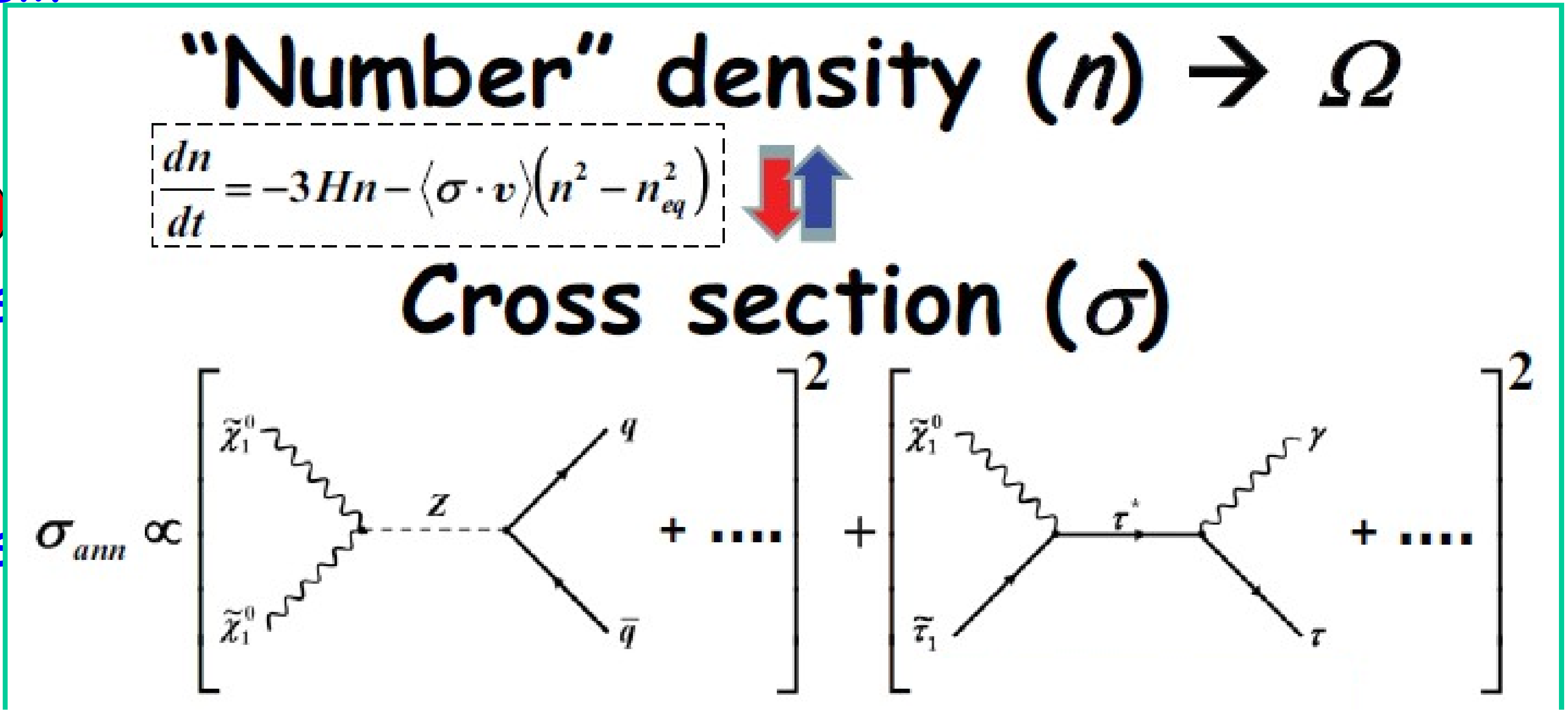
DM Self-Annihilation →SM particles



DM

S

S



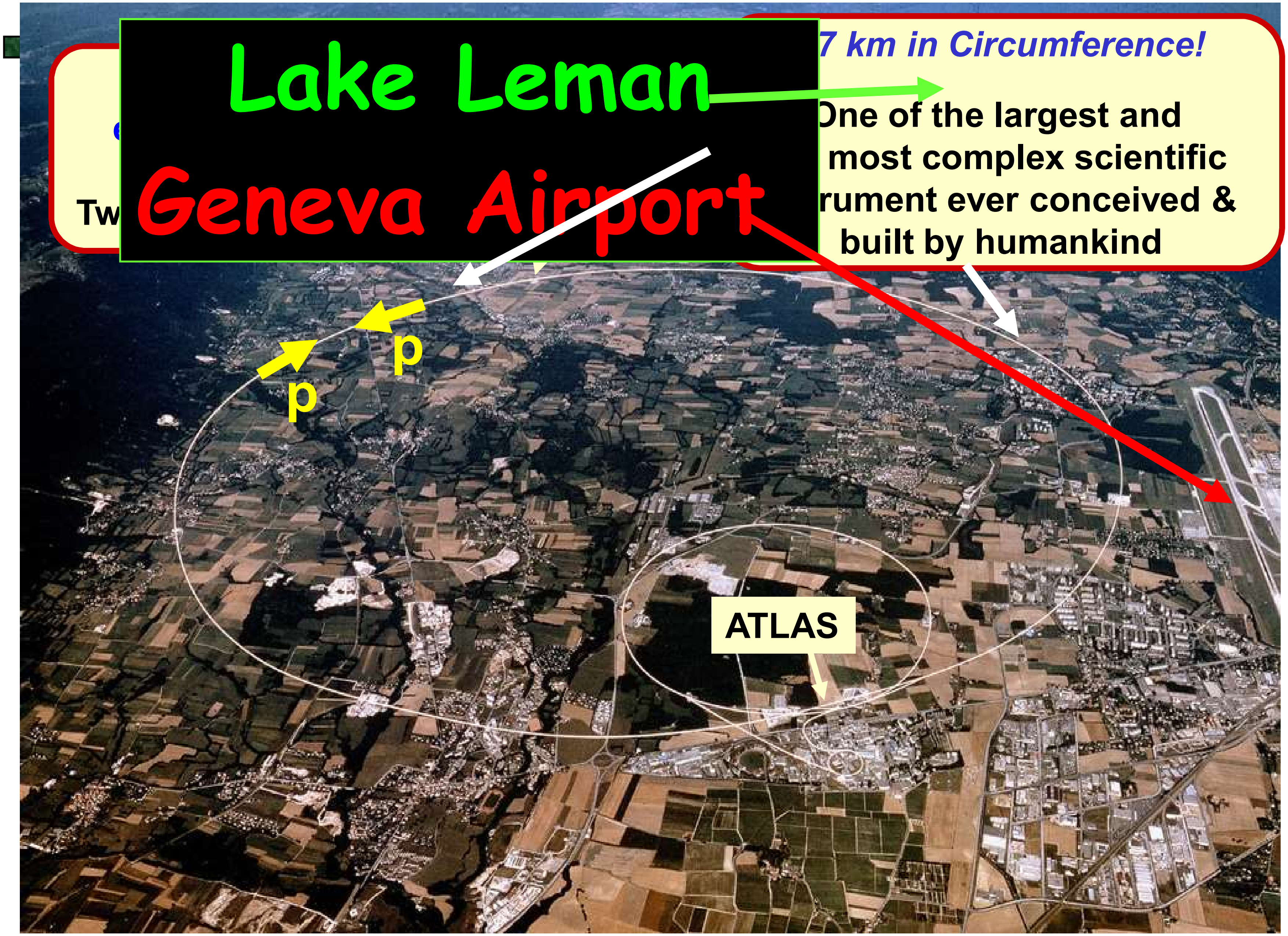
"Number" density (n) → Ω

$$\frac{dn}{dt} = -3Hn - \langle \sigma \cdot v \rangle \left(n^2 - n_{eq}^2 \right)$$

Cross section (σ)

$\sigma_{ann} \propto [\; \dots + \dots]^2 + [\; \dots + \dots]^2$

Aerial View of the LHC



7 km in Circumference!

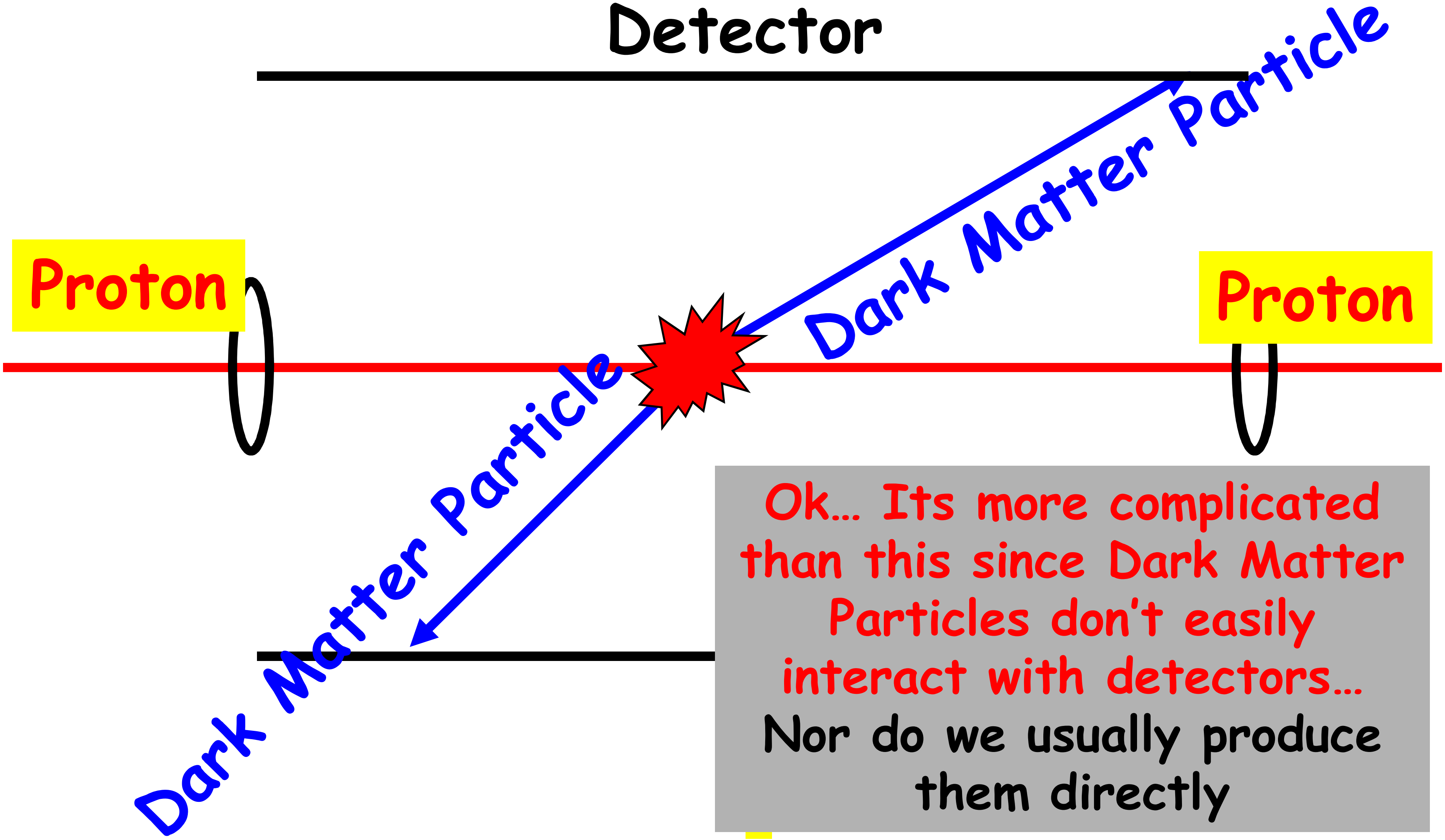
One of the largest and
most complex scientific
rument ever conceived &
built by humankind

Tw

More Expensive Dark Matter?

High Energy Collisions → Dark Matter Particles

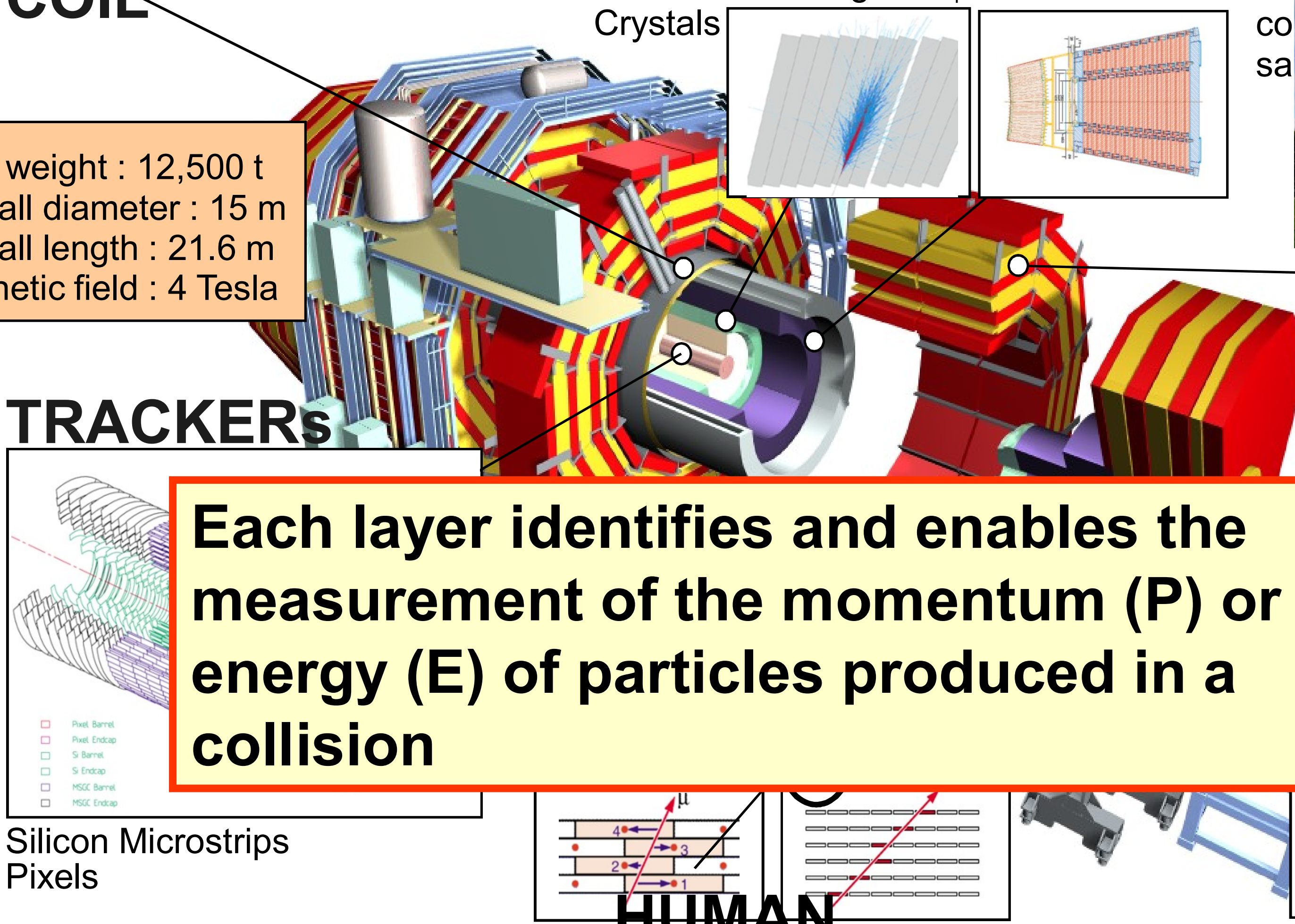
LHC → ≈1 ps after the Big Bang



Ok… Its more complicated than this since Dark Matter Particles don't easily interact with detectors…

Nor do we usually produce them directly

CMS Sub-Detectors



SUPERCONDUCTING COIL

CALORIMETERS

ECAL Scintillating $PbWO_4$ Crystals

HCAL Plastic scintil co sa

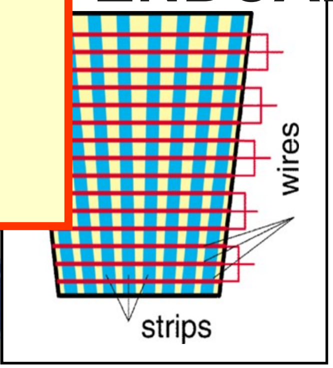
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

IRON YOKE

TRACKERs

Each layer identifies and enables the measurement of the momentum (P) or energy (E) of particles produced in a collision

MUON ENDCAPS



Silicon Microstrips
Pixels

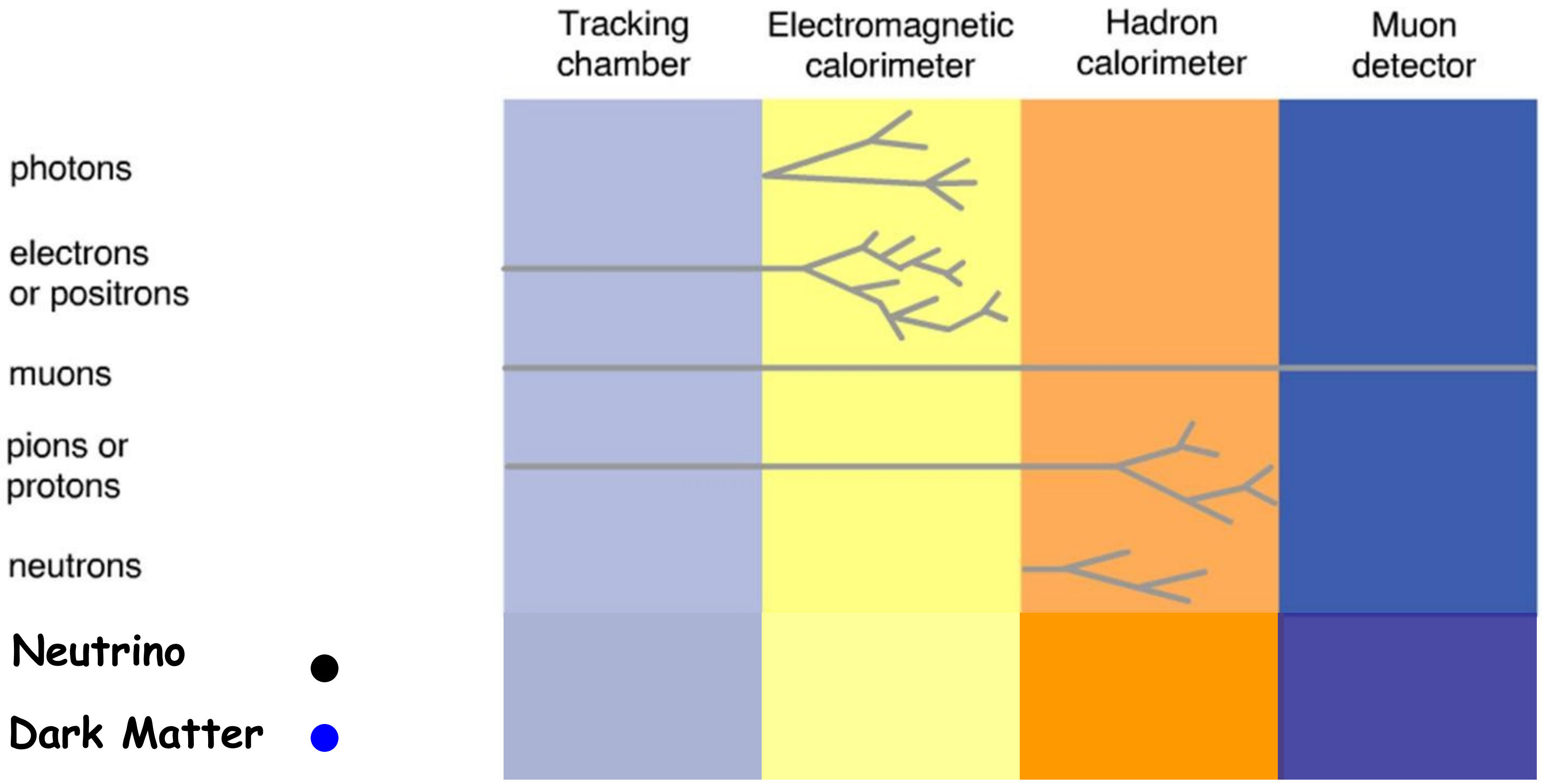
HUMAN

Drift Tube
Chambers

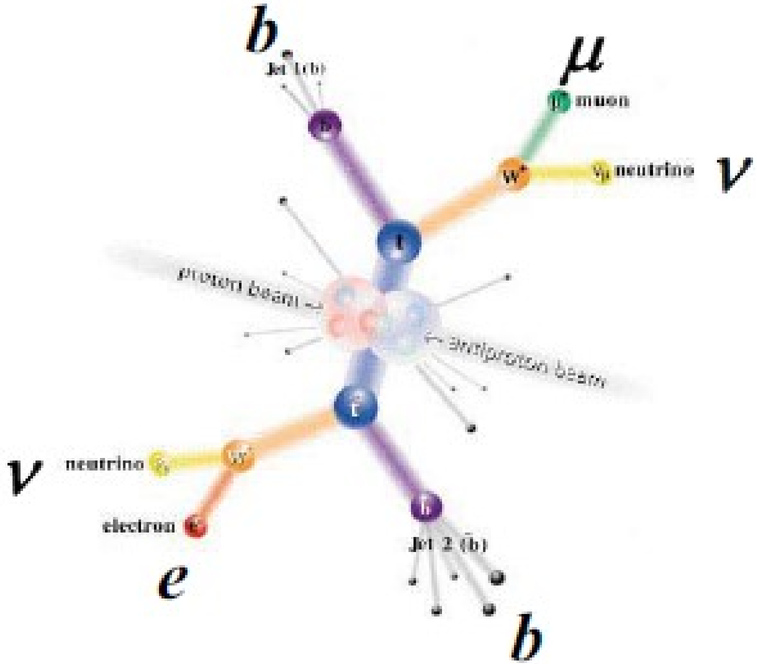
Resistive Plate
Chambers

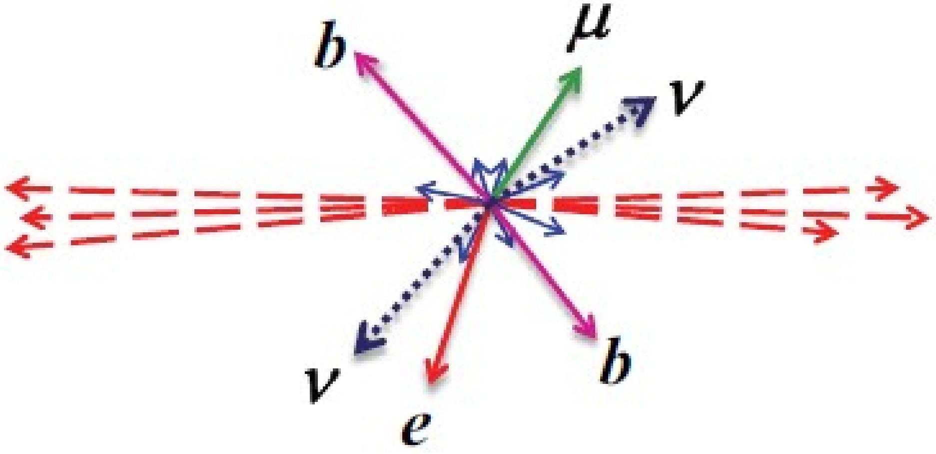
Cathode Strip Chambers
Resistive Plate Chambers

Neutrinos and Dark Matter Don't Interact with the Detectors



Missing Transverse Energy (MET)

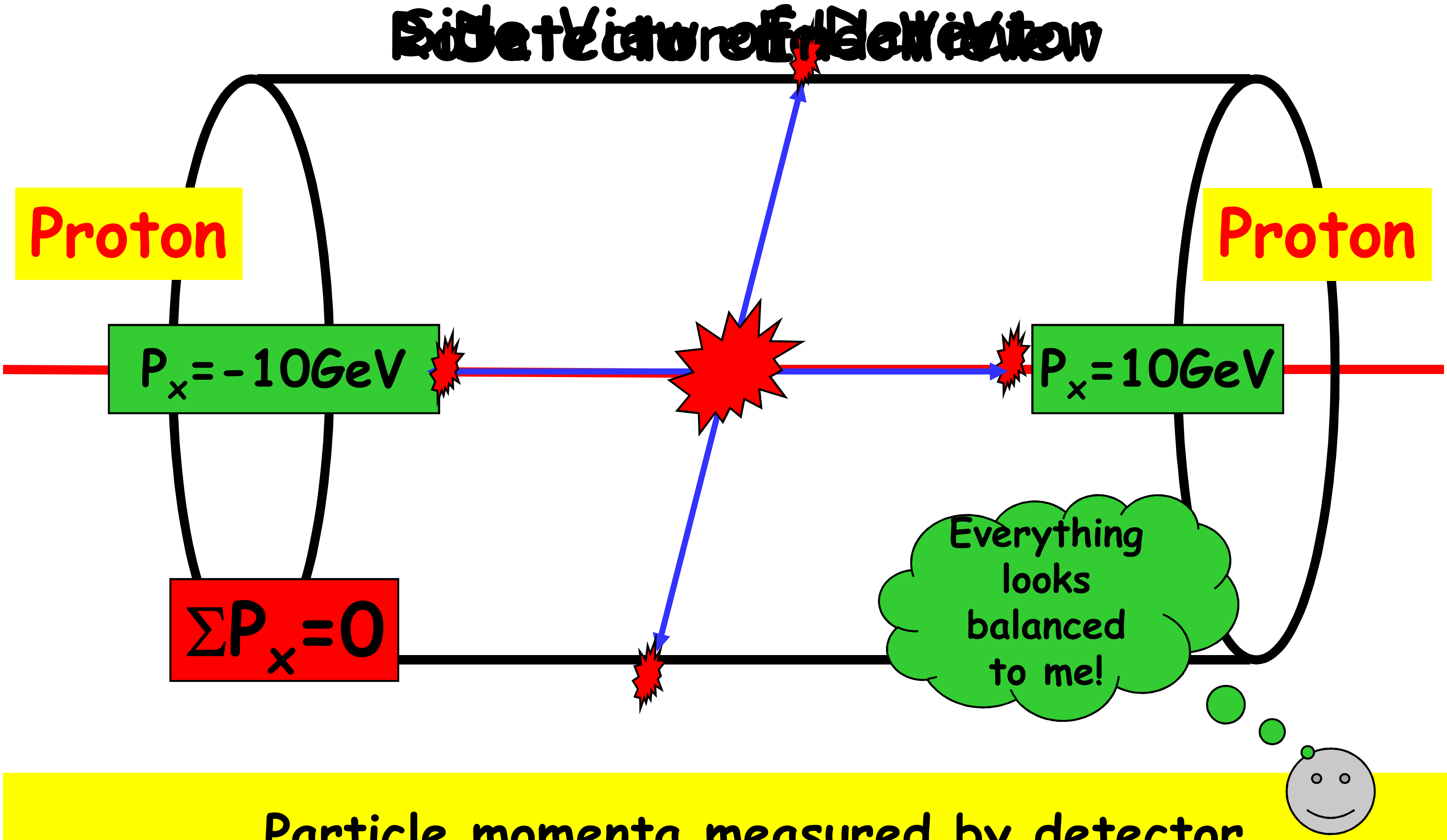




$$\sum_{\nu}\vec{p}+\sum_{visible}\vec{p}=\vec{0}\quad\Rightarrow\quad\sum_{\nu}\vec{p}\approx-\sum_{detected}\vec{p}\equiv\underbrace{\vec{p}}_{p\ \mathrm{slash}}$$

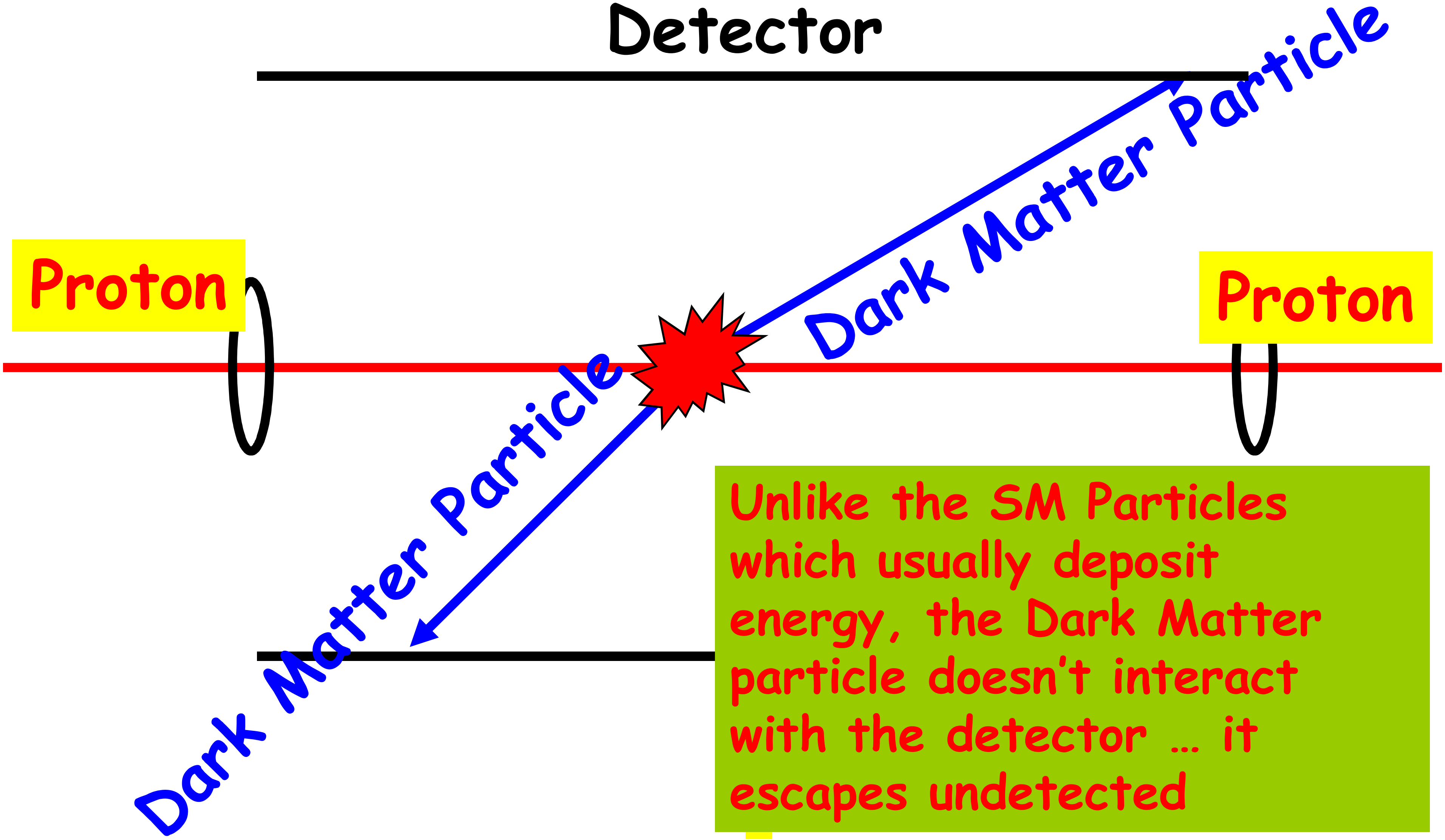
Experimentally, we measure a momentum imbalance in transverse plane and call it "missing transverse energy" ($E_{\mathrm{T}}^{\mathrm{miss}}$ or $\not{E}_{\mathrm{T}}$).

High Energy Collisions → Standard Model Particles



Particle momenta measured by detector

High Energy Collisions → Dark Matter Particles



Unlike the SM Particles which usually deposit energy, the Dark Matter particle doesn't interact with the detector … it escapes undetected

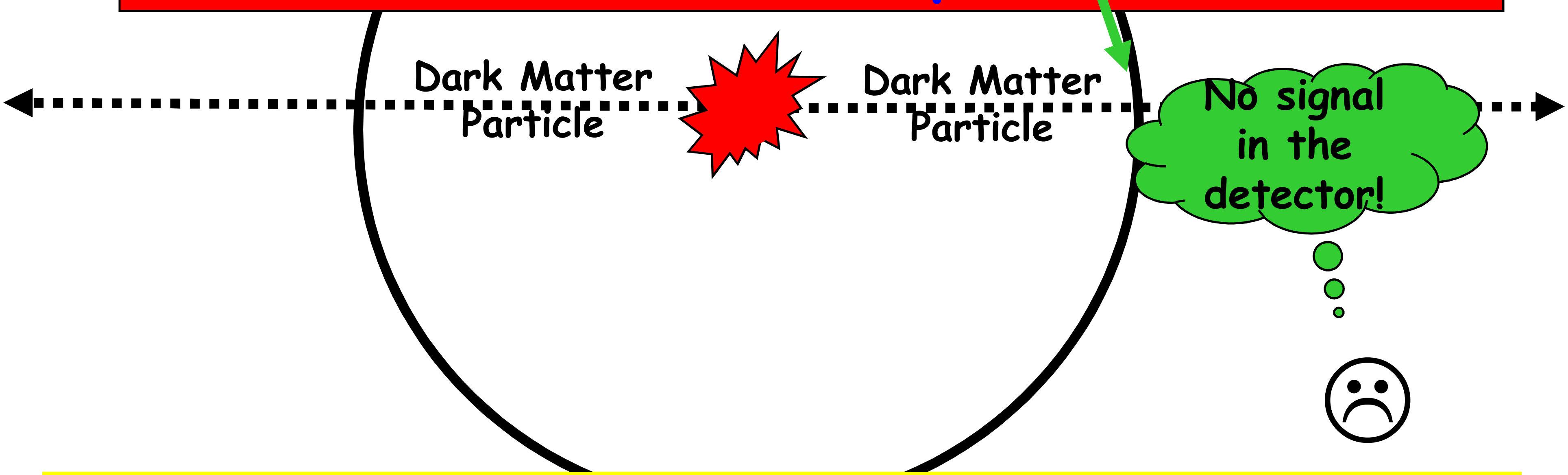
High Energy Collisions → Dark Matter Particles

$\Sigma P=0$ GeV

in the *x*-direction

→NO Missing Energy!

Similar to dominant QCD production at LHC



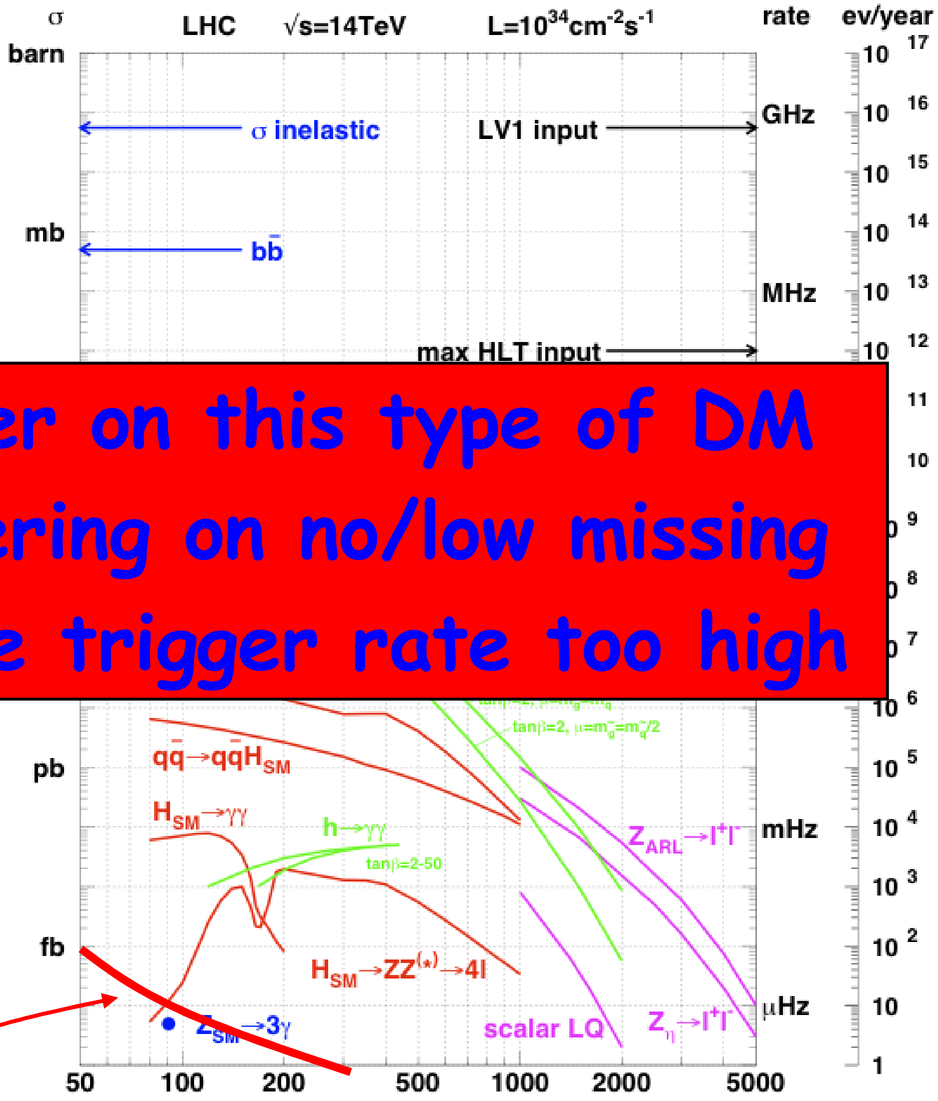
A Dark Matter particle doesn't interact with the detector

LHC Physics & Event Rates

- At design $L = 10^{34} cm^{-2}s^{-1}$
  - 1 GHz QCD jj events
  - 1 kHz W events
  - 10 Hz top events
  - 1 Hz SM Higgs events

→NO way to trigger on this type of DM topology since triggering on no/low missing momentum keeps the trigger rate too high

- Can store ~300 Hz
- Select in stages
  - Level-1 Triggers
    - 1 GHz to 100 kHz
  - High Level Triggers
    - 100 kHz to 300 Hz



D5 EFT, M*=2 TeV

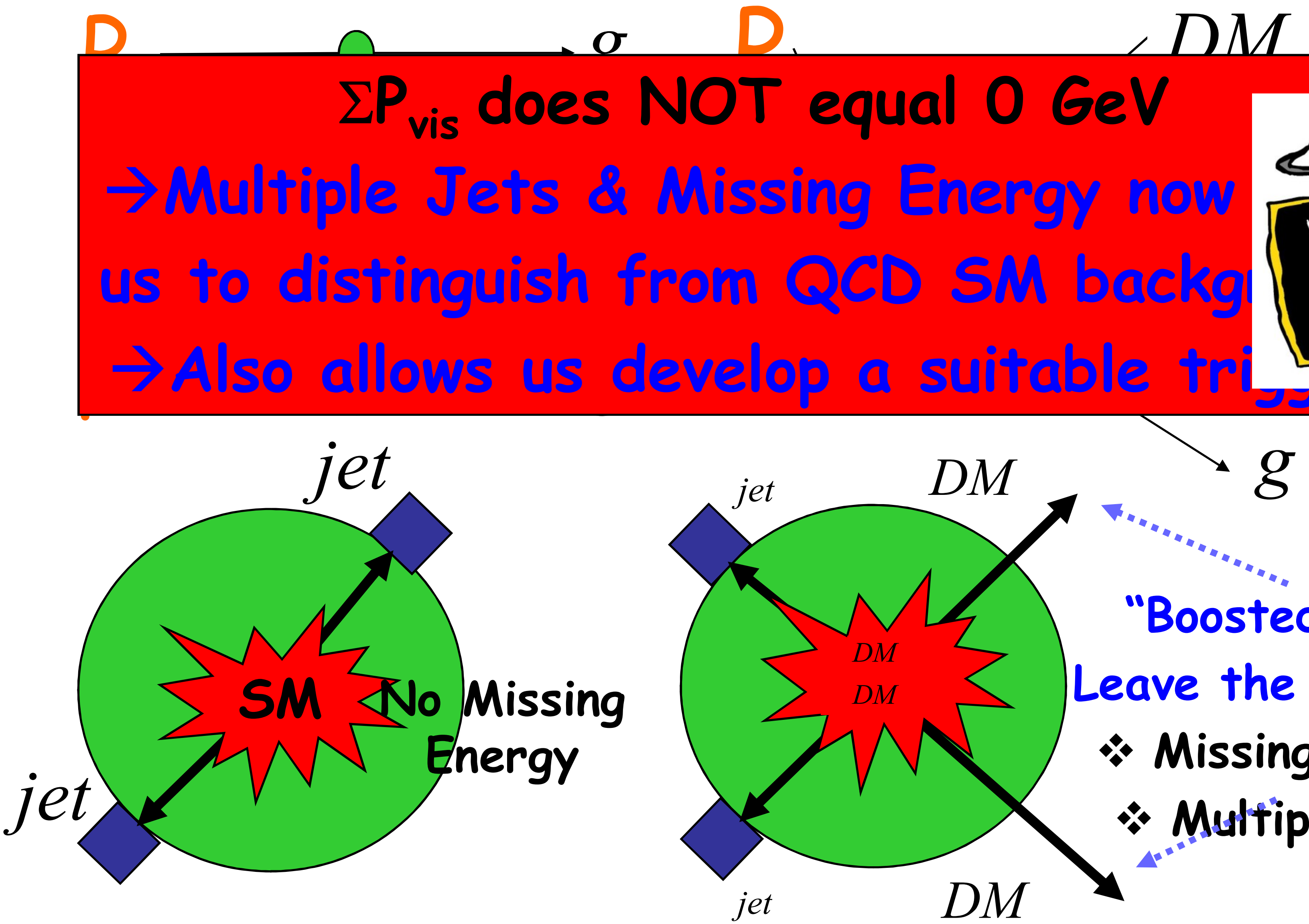
Standard Model: New Physics Model:

ΣP_{vis} does NOT equal 0 GeV

→Multiple Jets & Missing Energy now

us to distinguish from QCD SM backg

→Also allows us develop a suitable tri



"Boosted" DM

Leave the detector

- ❖ Missing Energy
- ❖ Multiple Jets

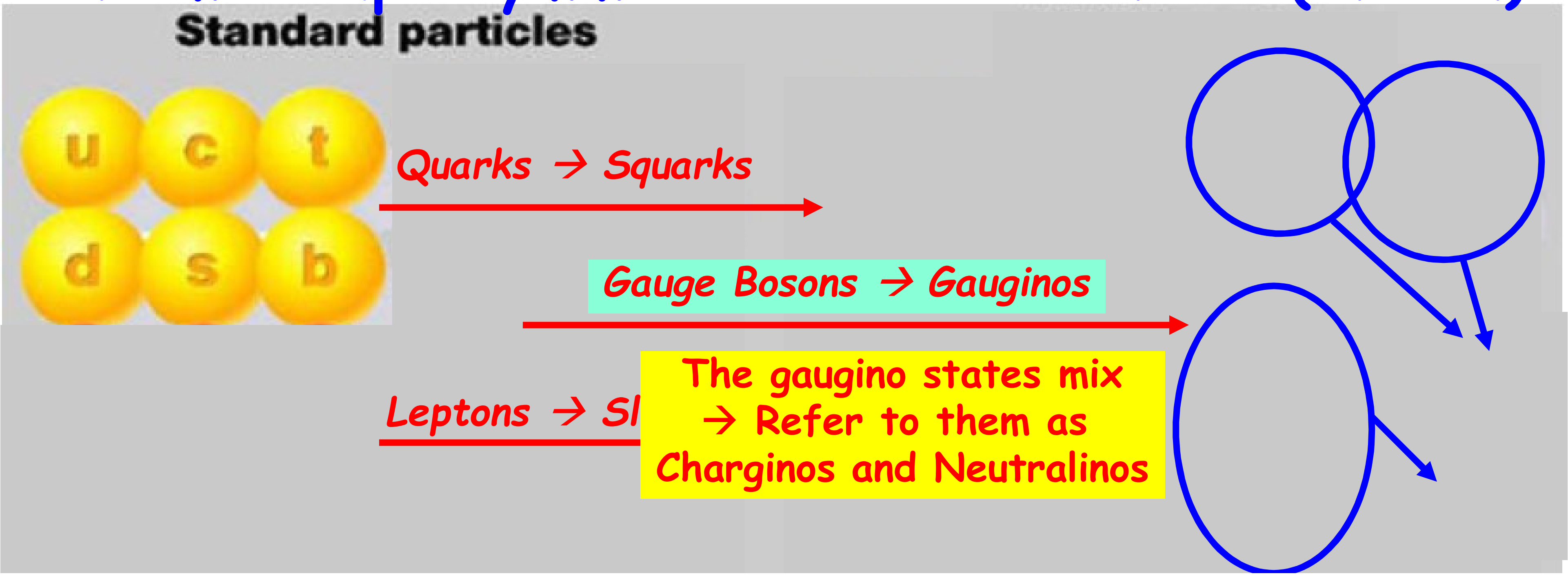
What is Supersymmetry?

Supersymmetry (SUSY) is a theory that postulates a symmetry between fermions and bosons

$$Q|\text{Boson}> \; = \; |\text{Fermion}>$$

$$Q|\text{Fermion}> \; = \; |\text{Boson}>$$

Minimal Supersymmetric Standard Model (MSSM)



Quarks → Squarks

Gauge Bosons → Gauginos

Leptons → Sl

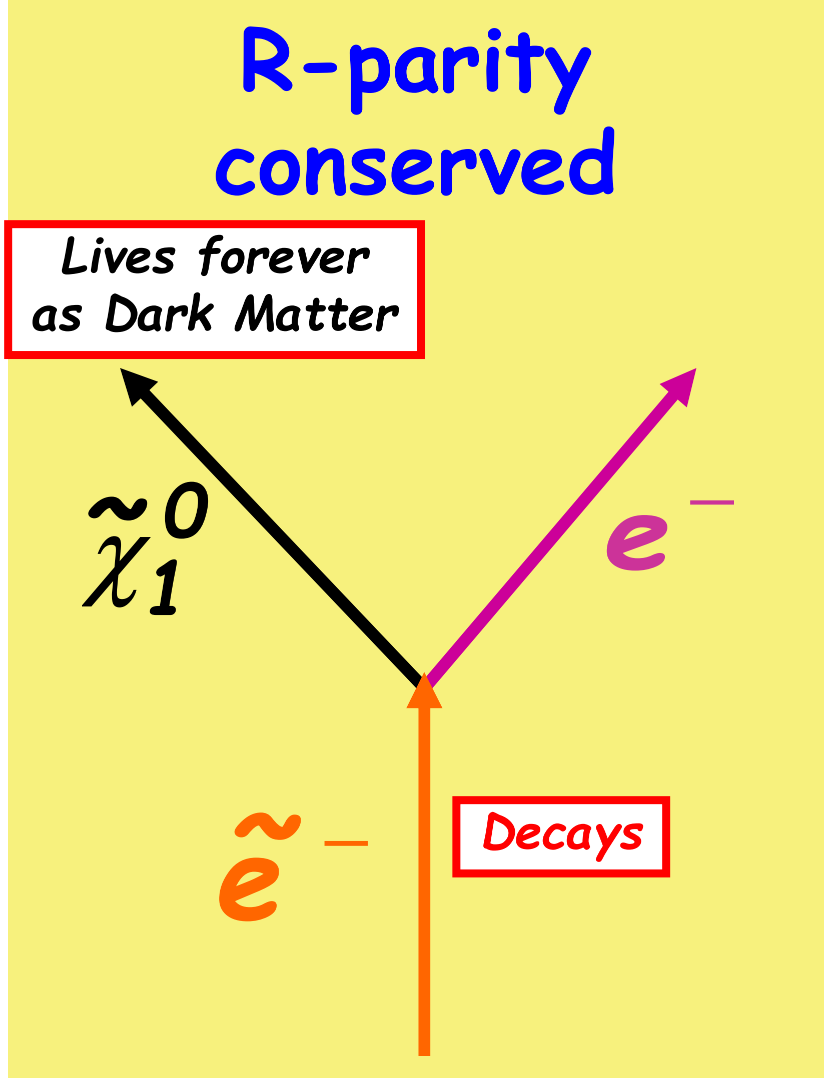
The gaugino states mix
→ Refer to them as
Charginos and Neutralinos

SUSY can provide a Dark Matter Candidate

If R-Parity is conserved then the lightest SUSY Particle can't decay and, if neutral

→Provides an excellent dark matter candidate

Provides the tie between Dark Matter, Cosmology and Particle Physics?



R-parity conserved

Lives forever as Dark Matter

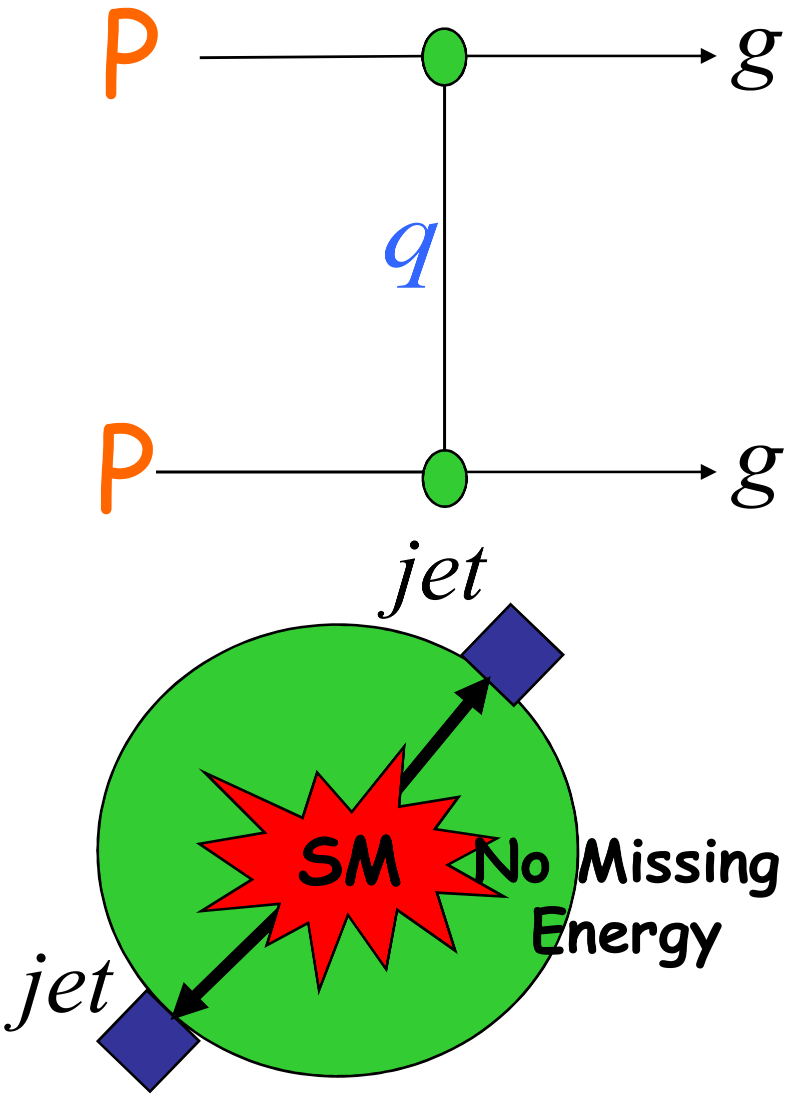
$\tilde{\chi}_1^0$

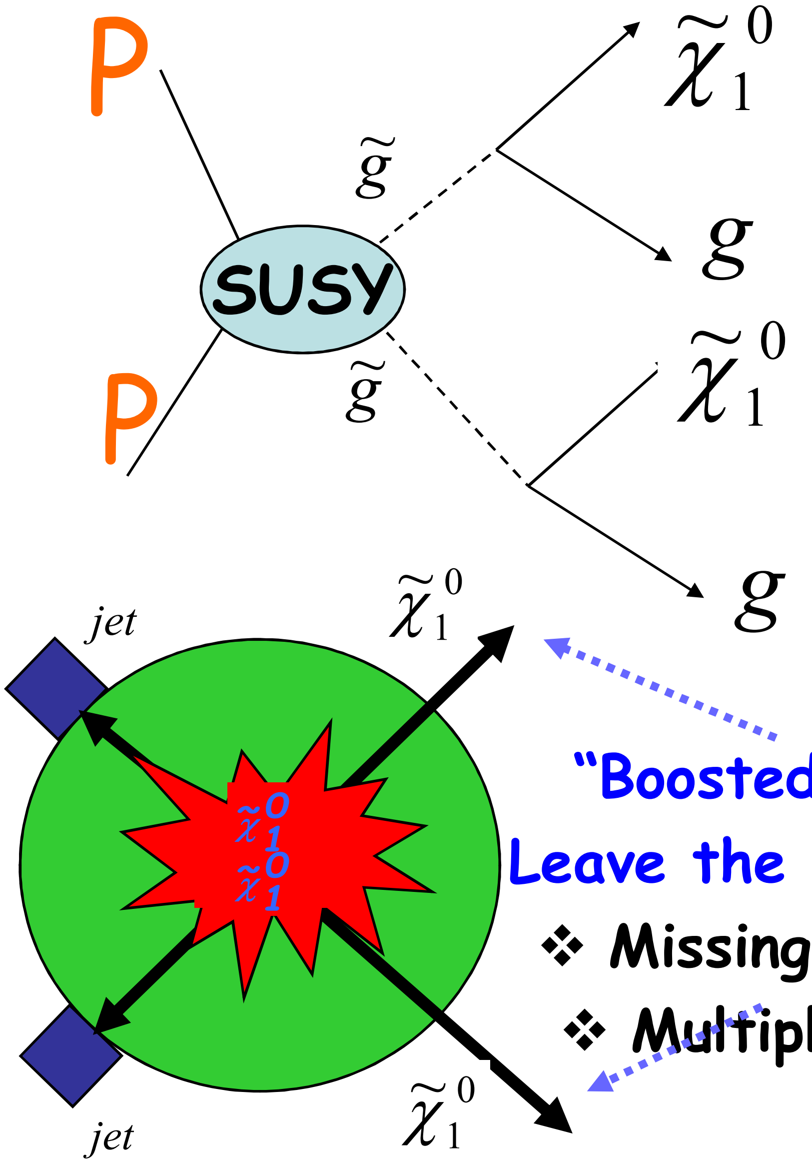
e^-

$\tilde{e}^-$

Decays

Standard Model: Supersymmetry:





"Boosted" DM

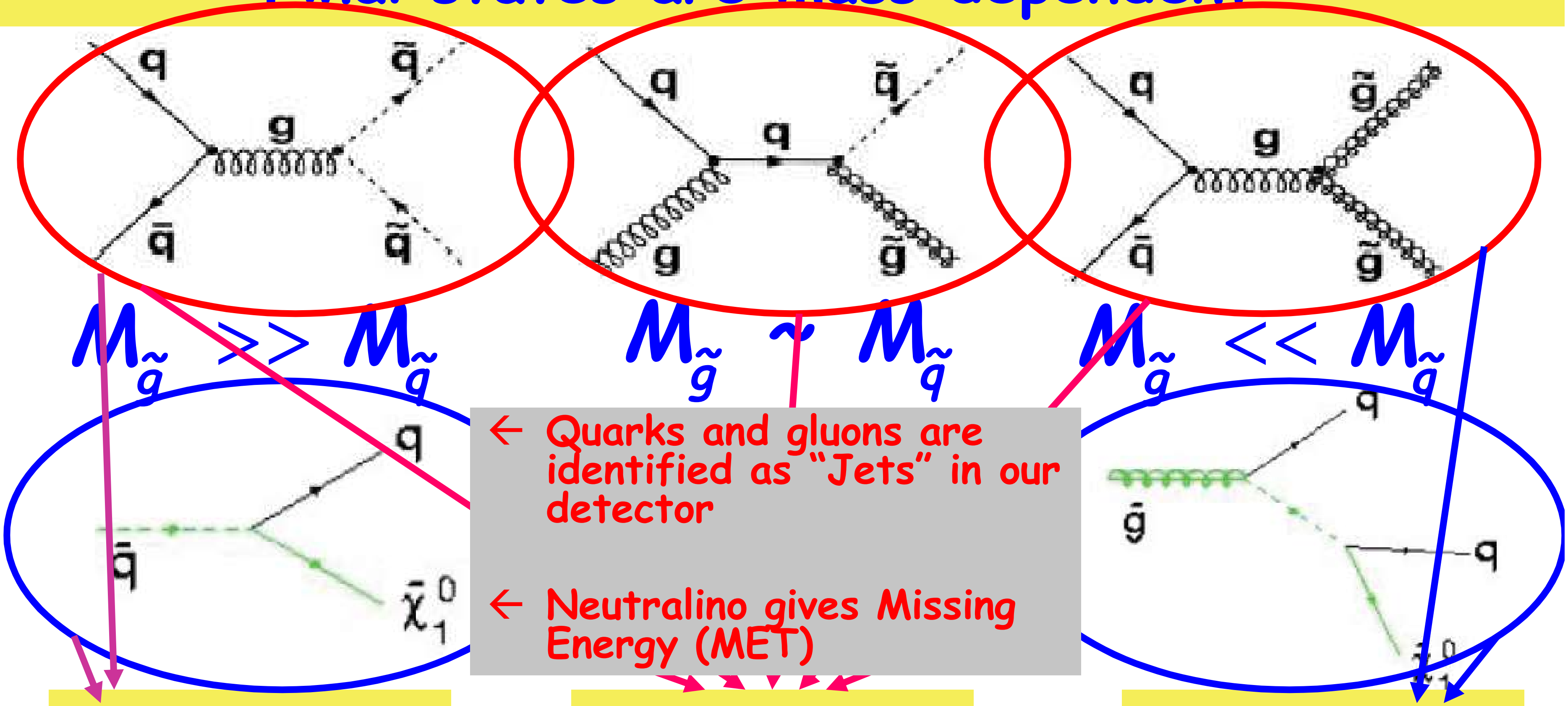
Leave the detector

- ❖ Missing Energy
- ❖ Multiple Jets

Squark and Gluino Searches in Multijet + Met

Example of important production diagrams

Final states are mass dependent



$M_{\tilde{g}} >> M_{\tilde{q}}$ $M_{\tilde{g}} \sim M_{\tilde{q}}$ $M_{\tilde{g}} << M_{\tilde{q}}$

← Quarks and gluons are identified as “Jets” in our detector

← Neutralino gives Missing Energy (MET)

2 jets + MET

3 jets + MET

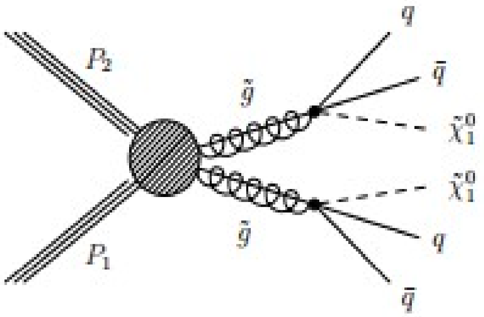
4 jets + MET

Multiple final states + Unified Analysis → best coverage

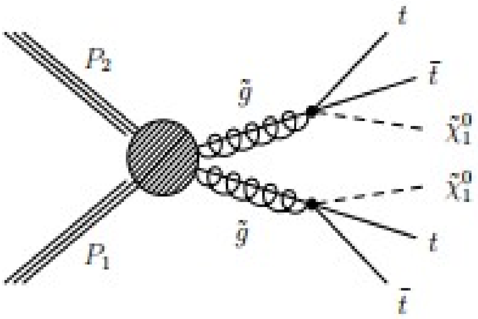
Looking for SUSY in Hadronic Final States

- Aiming for **direct** production of gluinos and squarks
  - Strong production → **high** σ
- **Largest** BR to SM quarks + LSP
  - **Many** jets/b-jets
  - High E_T^{miss}: scan the **tails**
- **Different** models → different topologies
  - Need to be sensitive to **many** possible final states

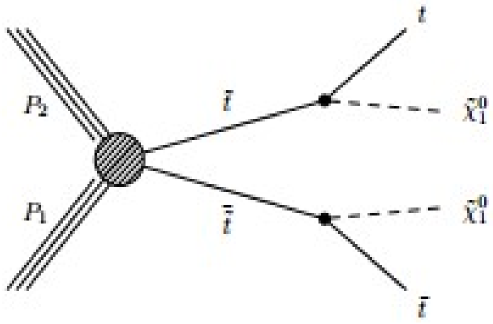
Some typical hadronic SUSY events:



4 jets + E_T^{miss}



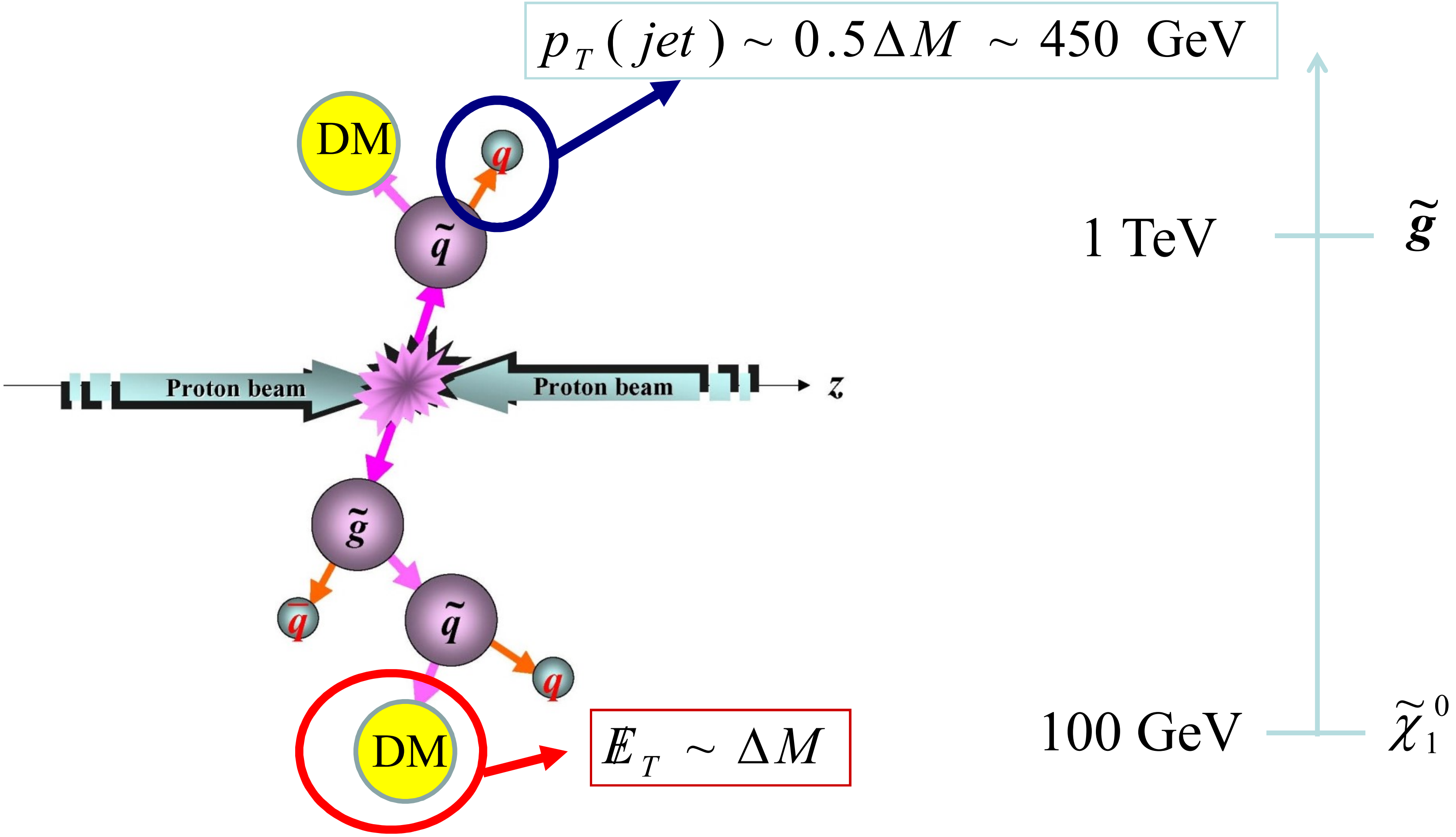
≤12 jets + E_T^{miss}
(4 b-jets)



≤6 jets + E_T^{miss}
(2 b-jets)

DM Signatures at LHC

$\tilde{g}, \tilde{q}$ **Production is dominant SUSY process at LHC (** $pp \to \tilde{q}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{g}$ **)**



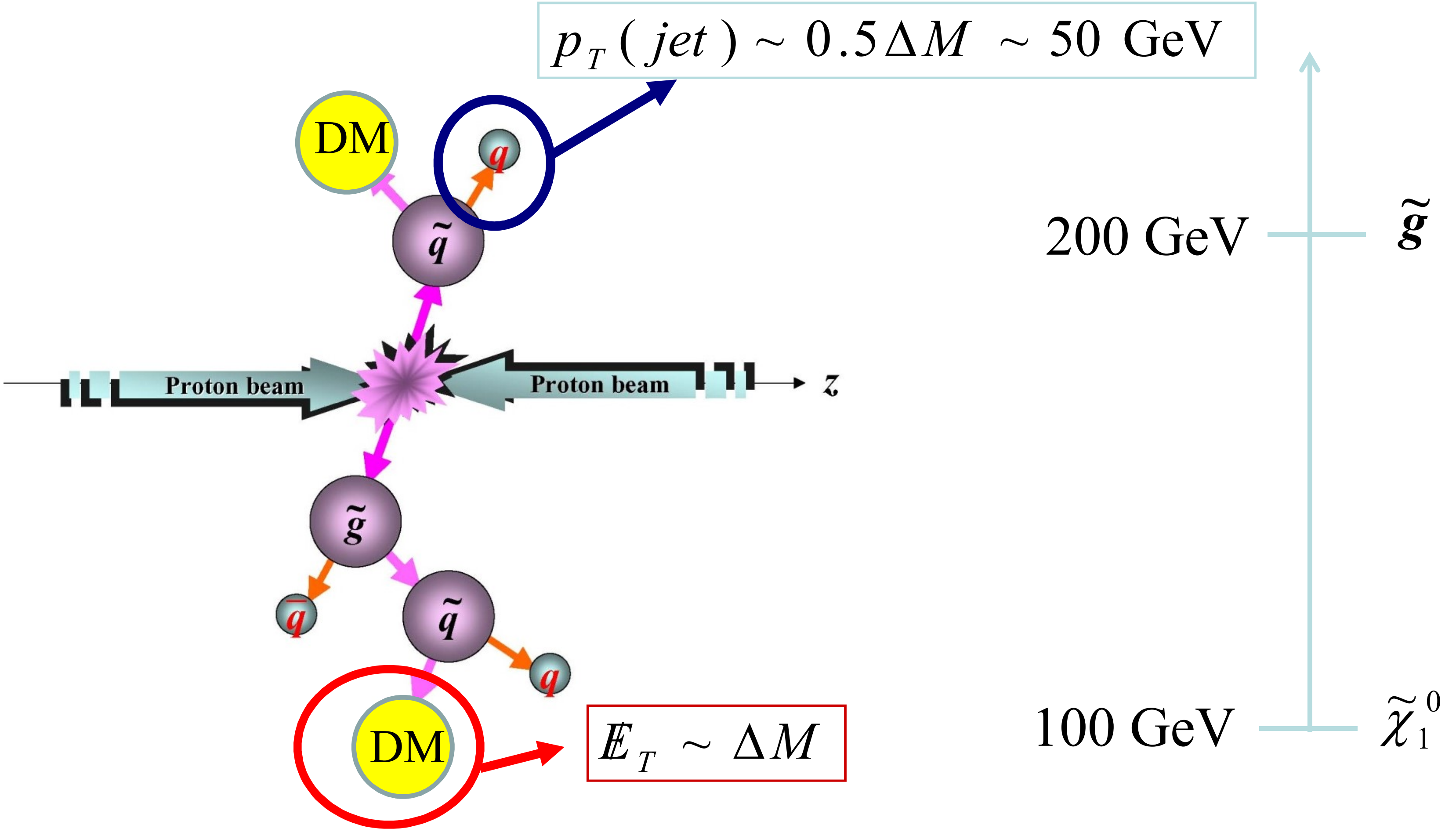
$p_T(jet) \sim 0.5\Delta M \sim 450\ \text{GeV}$

$\not{E}_T \sim \Delta M$

$$Jets + \not{E}_T$$

DM Signatures at LHC

$\tilde{g}, \tilde{q}$ **Production is dominant SUSY process at LHC** ($pp \to \tilde{q}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{g}$)



$p_T(jet) \sim 0.5\Delta M \sim 50$ GeV

$\not\!\!E_T \sim \Delta M$

$$Jets + \not\!\!E_T$$

Maintain as low thresholds as possible to be as inclusive

Four Independent Searches

- Historically, four CMS all-hadronic SUSY searches:

H_T and H_T^{miss}

SUS-16-014

12.9 fb^{-1} **NEW!**

M_{T2}

SUS-16-015

12.9 fb^{-1} **NEW!**

α_T

SUS-16-016

12.9 fb^{-1} **NEW!**

Razor

SUS-15-004

2.1 fb^{-1}

Common strategy:
veto leptons
look for lots of jets
and lots of E_T^{miss}

The Strategies at a Glance

- H_T and H_T^{miss}

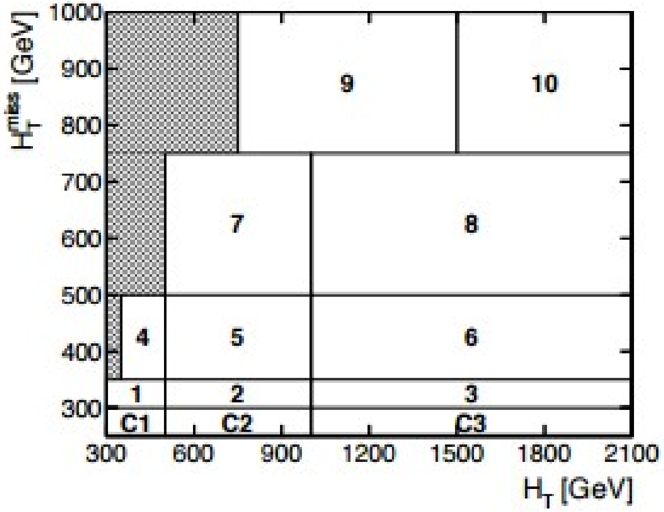
"A canonical jets+E_T^{miss} search"

Search variable: H_T^{miss}

Binned in jet and b-jet multiplicity (4×4):

N_j : 3-4, 5-6, 7-8, 9+
N_b : 0, 1, 2, 3+

In each of the 16 jet multiplicity regions bin in H_T and H_T^{miss}:



The Strategies at a Glance

- H_T and H_T^{miss}
- M_{T2}

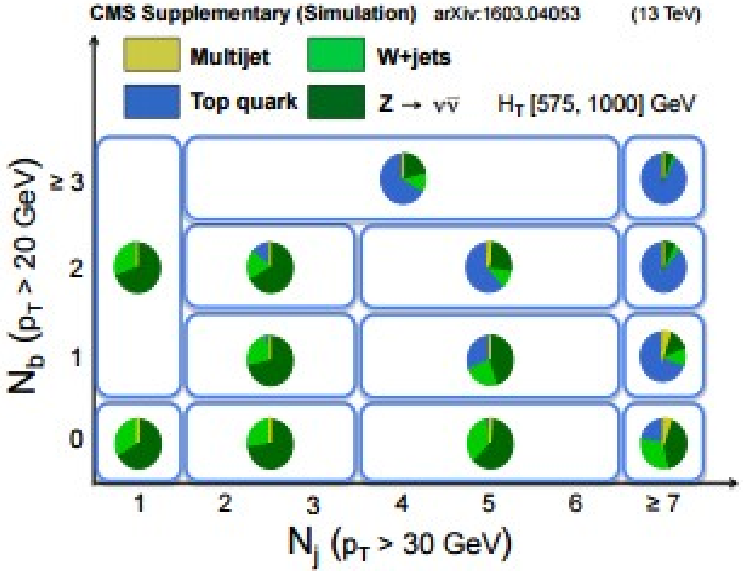
"Optimized for pair-produced new physics with WIMPs"

Search variable: M_{T2} ('stransverse mass', E_T^{miss}-like)

Binned in H_T, N_j and N_b

H_T : 200, 450, 575, 1000, 1500+ GeV
N_j : 1, 2-3, 4-6, 7+
N_b : 0, 1, 2, 3+

In each ($H_T \times N_j \times N_b$) region, look at **tails** of M_{T2}



The Strategies at a Glance

- H_T and H_T^{miss}
- M_{T2}
- α_T

"Maximal QCD rejection"

$$\alpha_T = \frac{E_{T\,j2}}{M_{T\,j1j2}} = \frac{\sqrt{E_{T\,j2}/E_{T\,j1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$

Search variable: H_T^{miss}

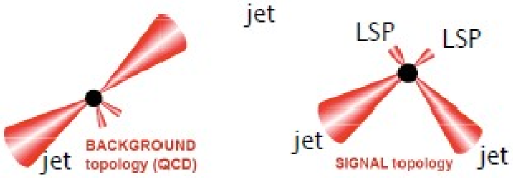
Trigger and preselection based on α_T variable

Require leading jet with $p_{T,1} > 100$ GeV

In dijet events:
$\alpha_T = p_{T,2} / M_T$

Depending on subleading jet, classify as:

- symmetrical ($p_{T,2} > 100$ GeV)
- asymmetrical ($40 < p_{T,2} < 100$ GeV)
- monojet ($p_{T,2} < 40$ GeV)



Binned in H_T, N_j and N_b

H_T : 200, 250, 300, 350, 400, 500, 600, 800+ GeV
N_j : 1, 2, 3, 4, 5+
N_b : 0, 1, 2, 3+

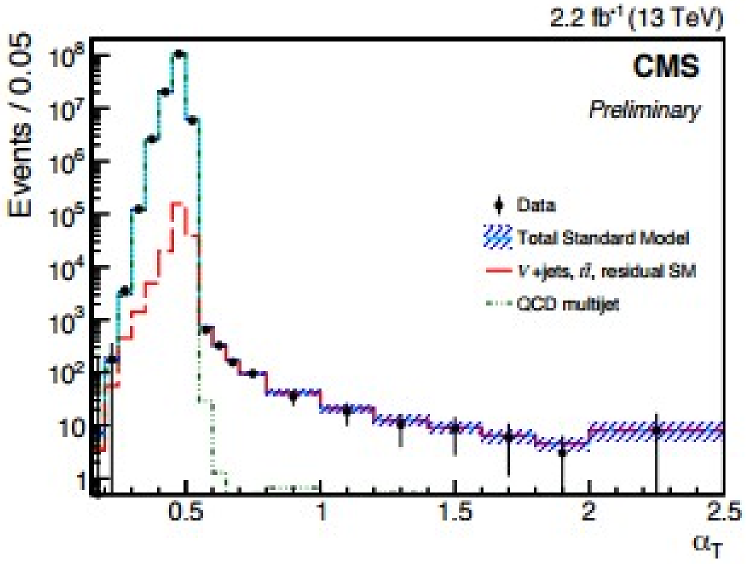
In each ($H_T \times N_j \times N_b$) region, look at **tails** of H_T^{miss}

Three Main Backgrounds

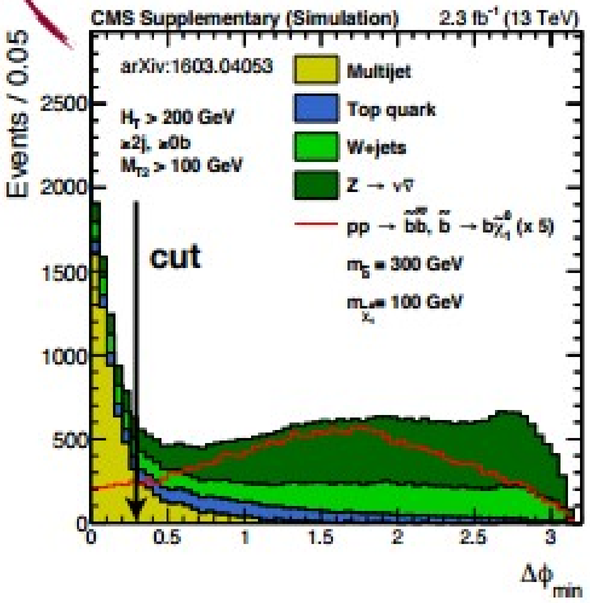
- **QCD** multijet events
  - **Instrumental** E_T^{miss}: mismeasurement of one of the jets
  - Typically pointing in the **direction** of a jet
- Events with **W→lv** decays ('lost lepton')
  - **Authentic** E_T^{miss} from neutrino
  - Out of acceptance, non-isolated, or mis-identified lepton; or hadronic τ
- Events with **Z→vv** decays ('invisible Z')
  - **Authentic** E_T^{miss} from neutrinos
  - Main **irreducible** background

Highest Cross-Section Background: QCD

- Search variables are ‘QCD-killers’
  - Tails mostly QCD-free



- **Further** suppression:
  - E_T^{miss} not pointing in direction of a jet
  - $E_T^{miss}/H_T^{miss} \sim 1$

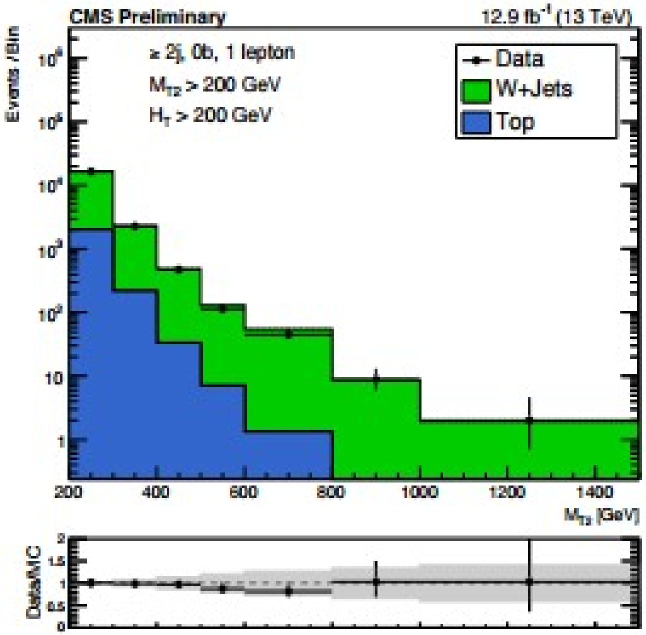


- **Residual** QCD evaluated from control regions
  - H_T/H_T^{miss} and M_{T2} : inverting $\Delta\phi(E_T^{miss}$,jet)
  - α_T : inverting E_T^{miss}/H_T^{miss}

‘Lost’ Lepton from W Decay

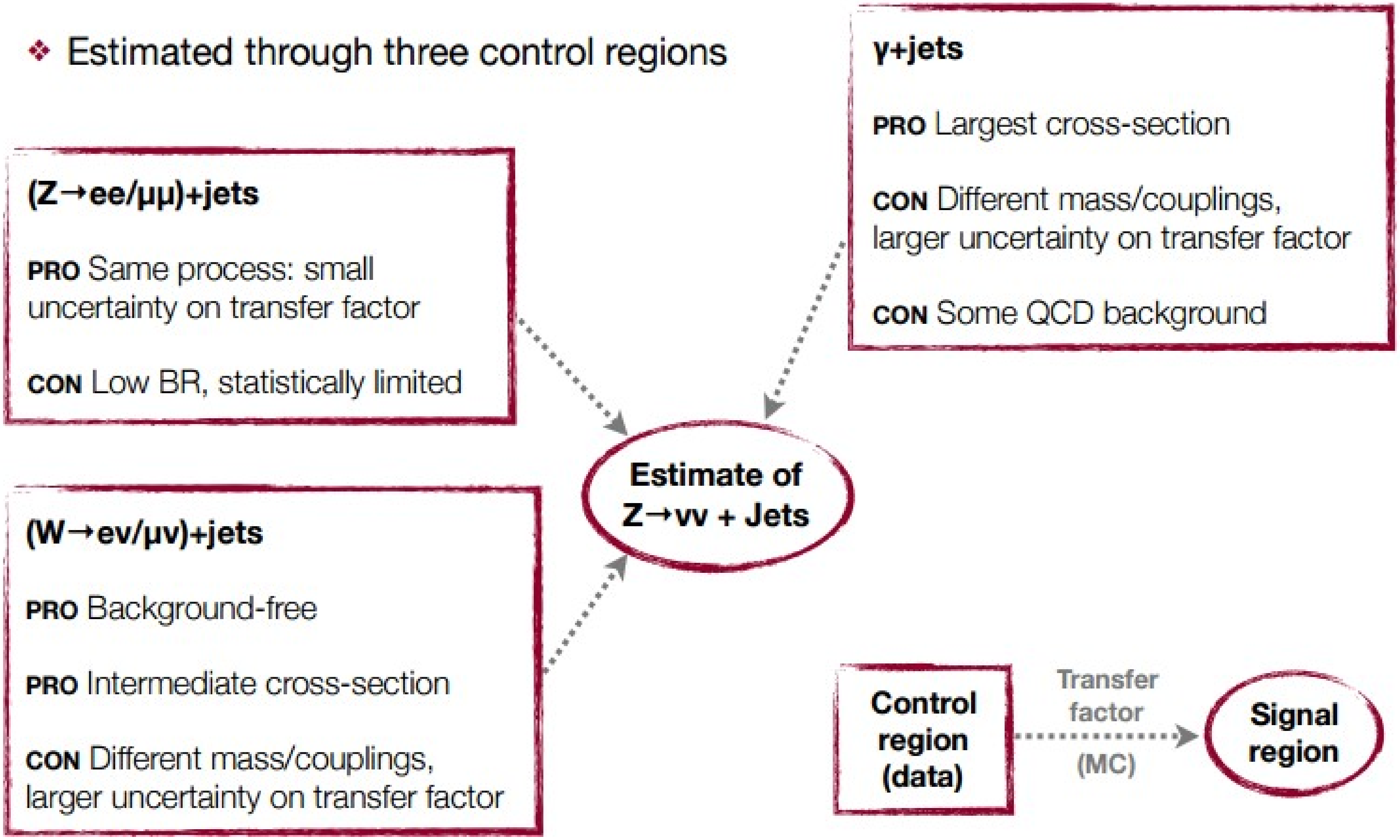
- **Main suppression**: tighten lepton veto
- Some residual events pass selection:
  - Outside of detector **acceptance**
  - **Non-isolated** leptons
  - Reconstruction/ID failures
- Data **control region** with exactly one e/μ
  - Then multiply by probability of ‘losing’ it

Example:
M_{T2} in single-lepton control region (lepton removed)



Main Irreducible Background: $Z\to\nu\nu$ + Jets

- Estimated through three control regions



$(Z\to ee/\mu\mu)$+jets

PRO Same process: small uncertainty on transfer factor

CON Low BR, statistically limited

$(W\to e\nu/\mu\nu)$+jets

PRO Background-free

PRO Intermediate cross-section

CON Different mass/couplings, larger uncertainty on transfer factor

γ+jets

PRO Largest cross-section

CON Different mass/couplings, larger uncertainty on transfer factor

CON Some QCD background

Estimate of $Z\to\nu\nu$ + Jets

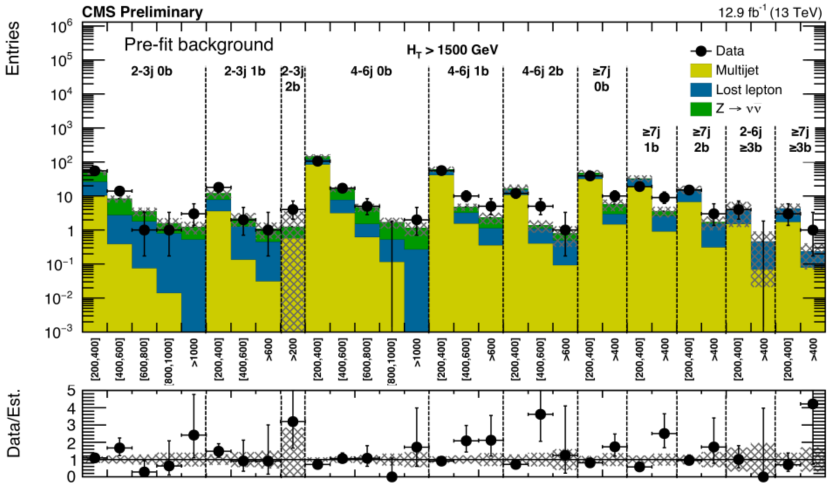
Control region (data)

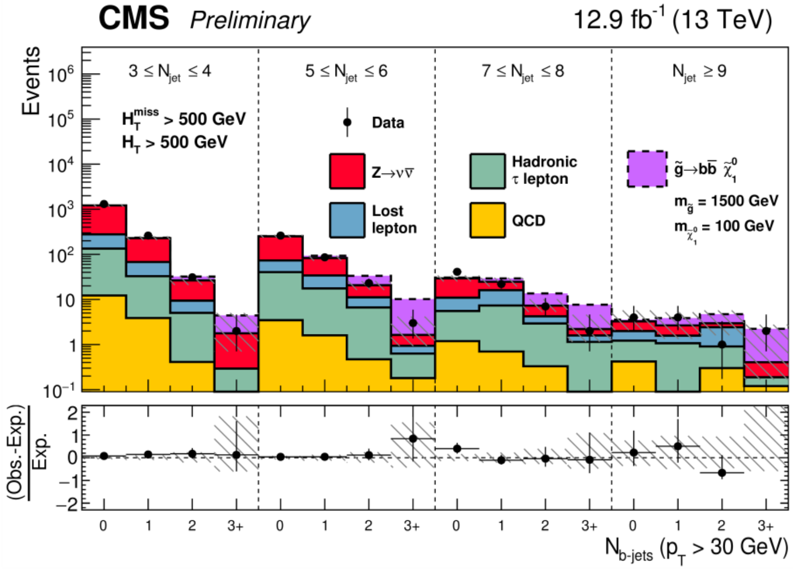
Transfer factor

(MC)

Signal region

Unified Squark/Gluino Search





HT/HTmiss

MT2

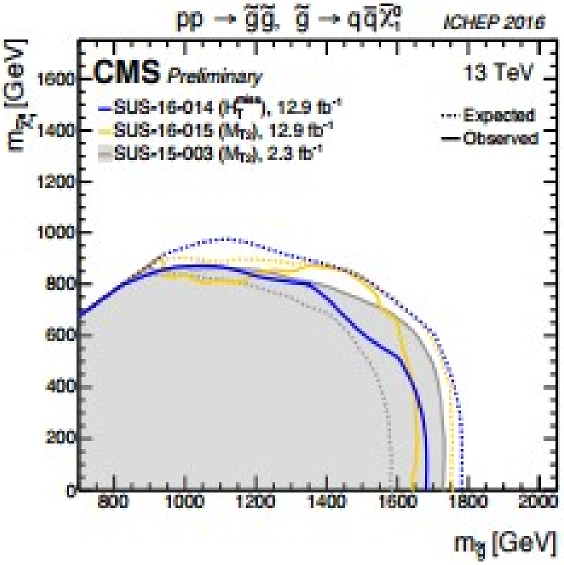
Set Cross Section Limits

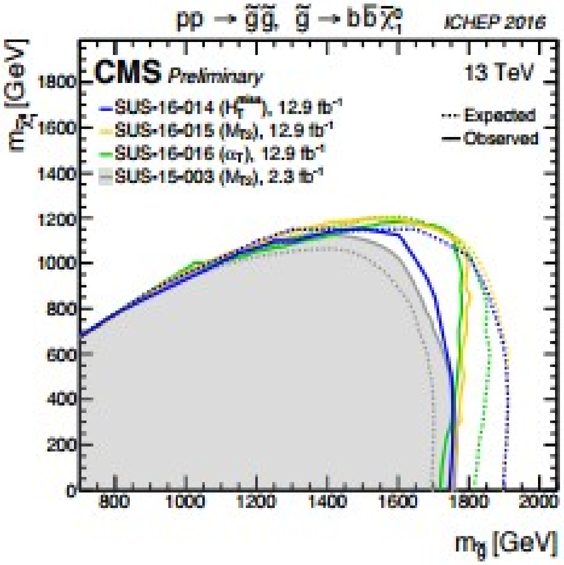
No evidence for new physics

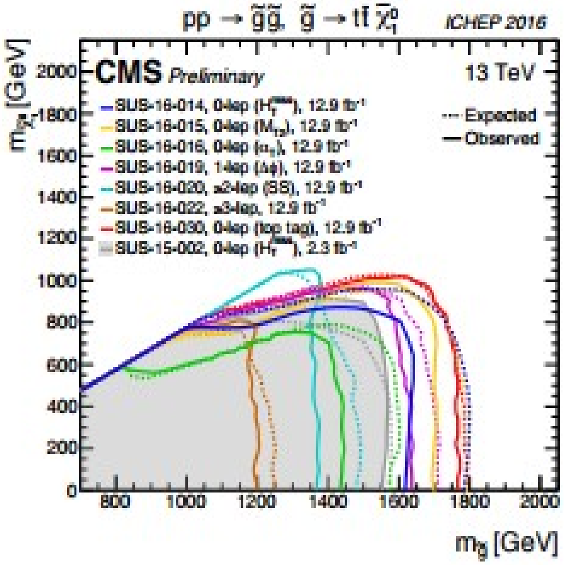
As with most CMS results, there are comparable ATLAS results which I won't touch on

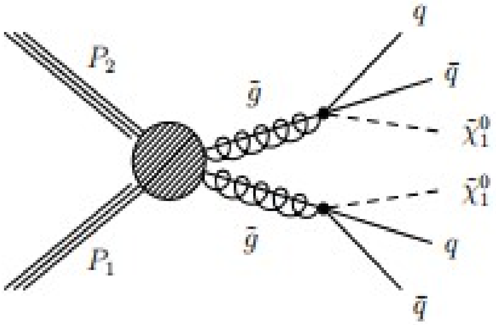
Limits on Direct Gluino Production

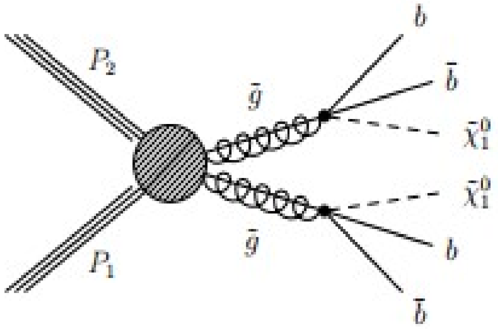
- Excluding **gluinos** up to 1.75 TeV and **neutralinos** up to 1.2 TeV

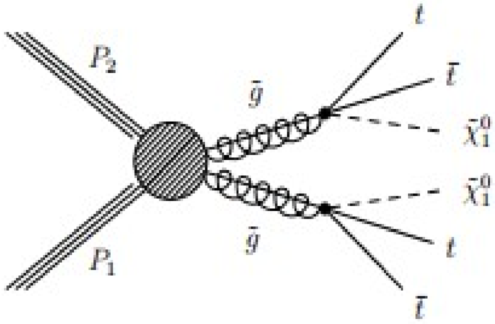






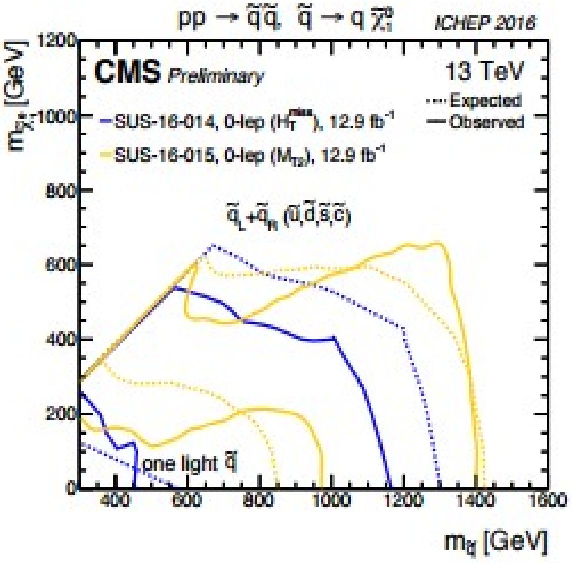


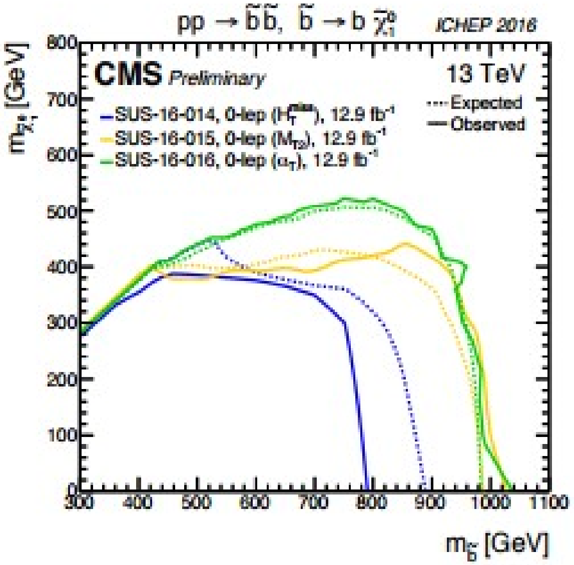


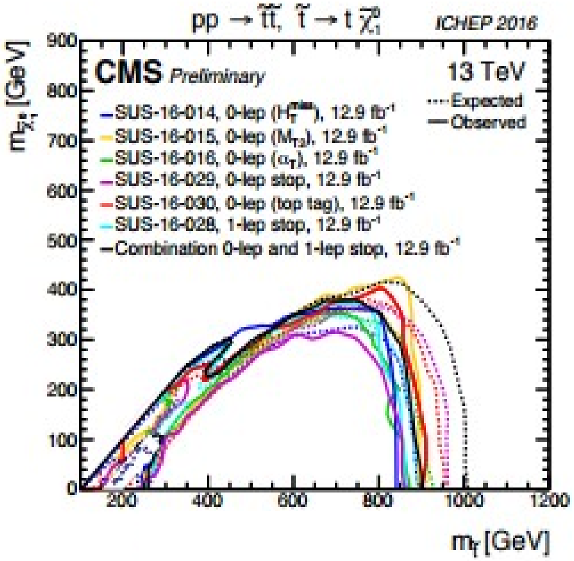


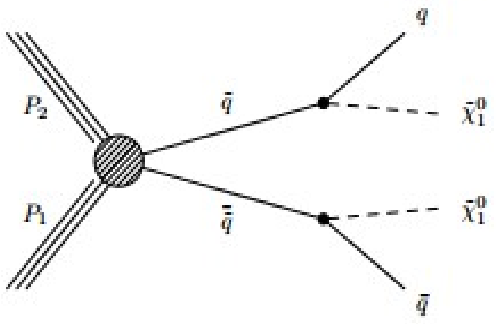
Limits on Direct Squark Production

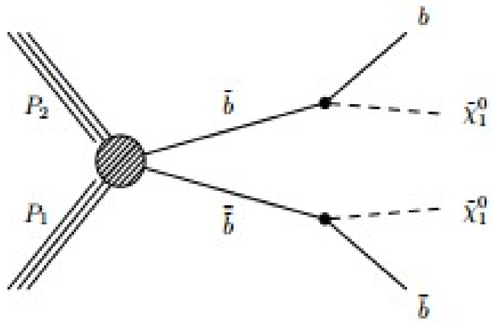
- Excluding **squarks (stops)** up to 1.4 (0.9) TeV and **neutralinos** up to 500 GeV

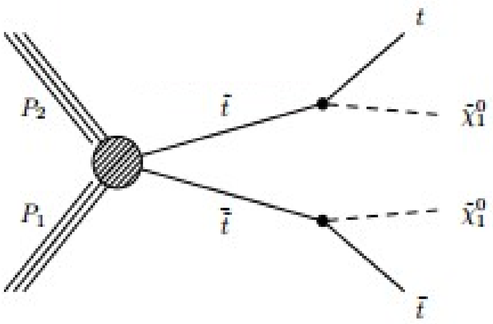










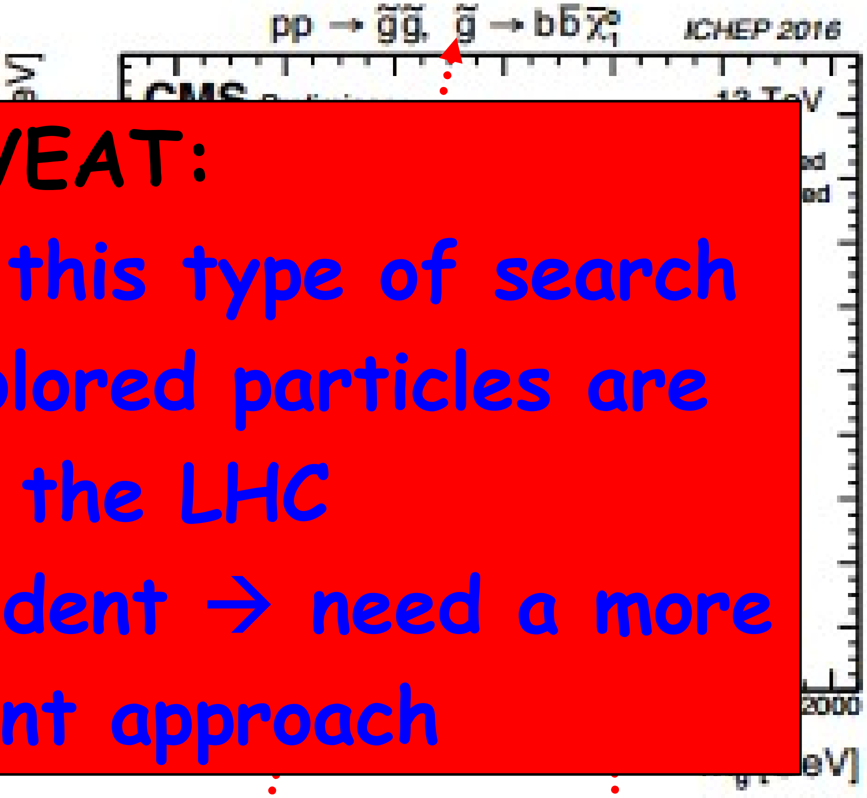


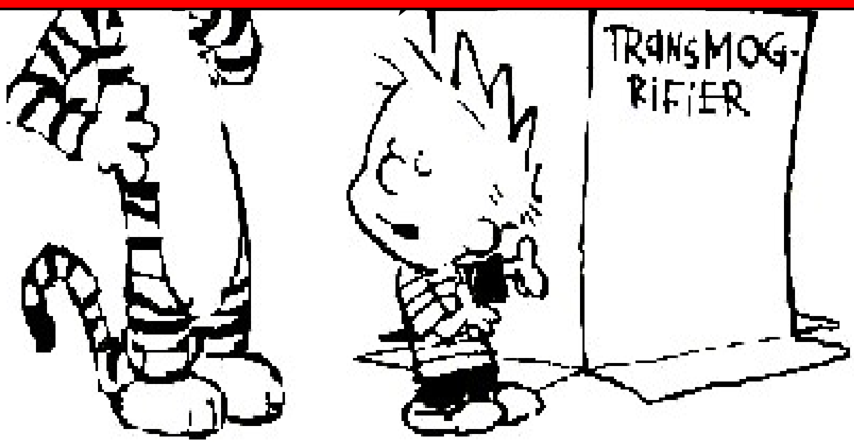
More limits…

HUGE CAVEAT:

→Can only probe DM in this type of search if these new heavier colored particles are accessible at the LHC

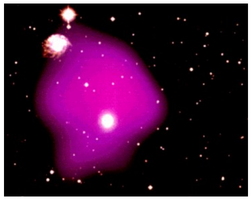
→Extremely model dependent → need a more model independent approach

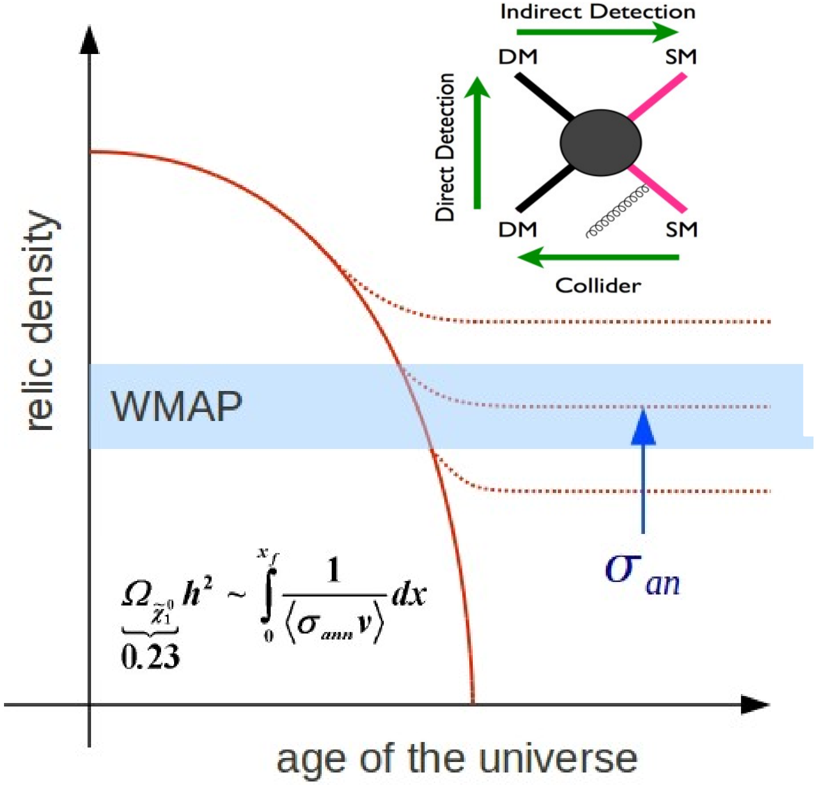




M(DM) < 1 TeV excluded
when M(gluino) < 1.7 TeV

Particle Physics & Cosmology





$$\underbrace{\Omega_{\tilde\chi_1^0} h^2}_{0.23} \sim \int_0^{x_f} \frac{1}{\langle \sigma_{ann} v \rangle} dx$$

℞ to Probe Ωh^2

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

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

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

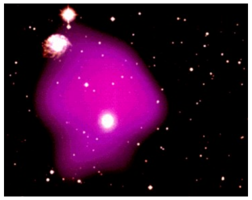
$M_1 << M_2, \mu \Rightarrow \tilde\chi_1^0 \approx \tilde B$ → *pure Bino*

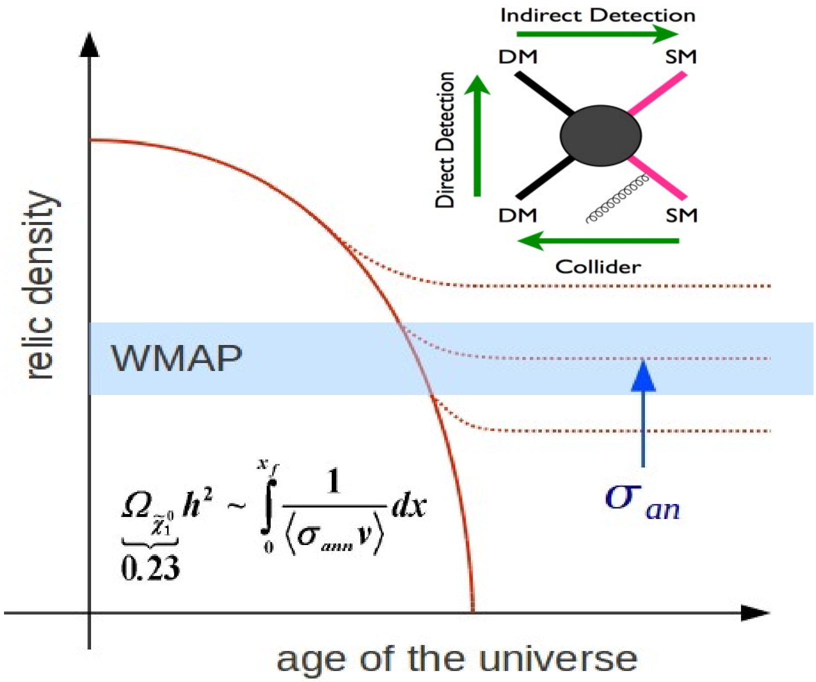
$M_2 << M_1, \mu \Rightarrow \tilde\chi_1^0 \approx \tilde W$ → *pure Wino*

$\mu << M_1, M_2 \Rightarrow \tilde\chi_1^0 \approx \tilde H_h + \tilde H_d$ → *pure Higgsino*

The identity of dark matter is one of the most profound questions at the interface of particle physics and cosmology.

VBF DM → Cosmology





- LSP has large Wino/Higgsino component
  - LSP annihilation cross section is too large to fit observed DM relic density
- LSP is mostly Bino
  - LSP annihilation cross section is too small to fit observed DM relic density

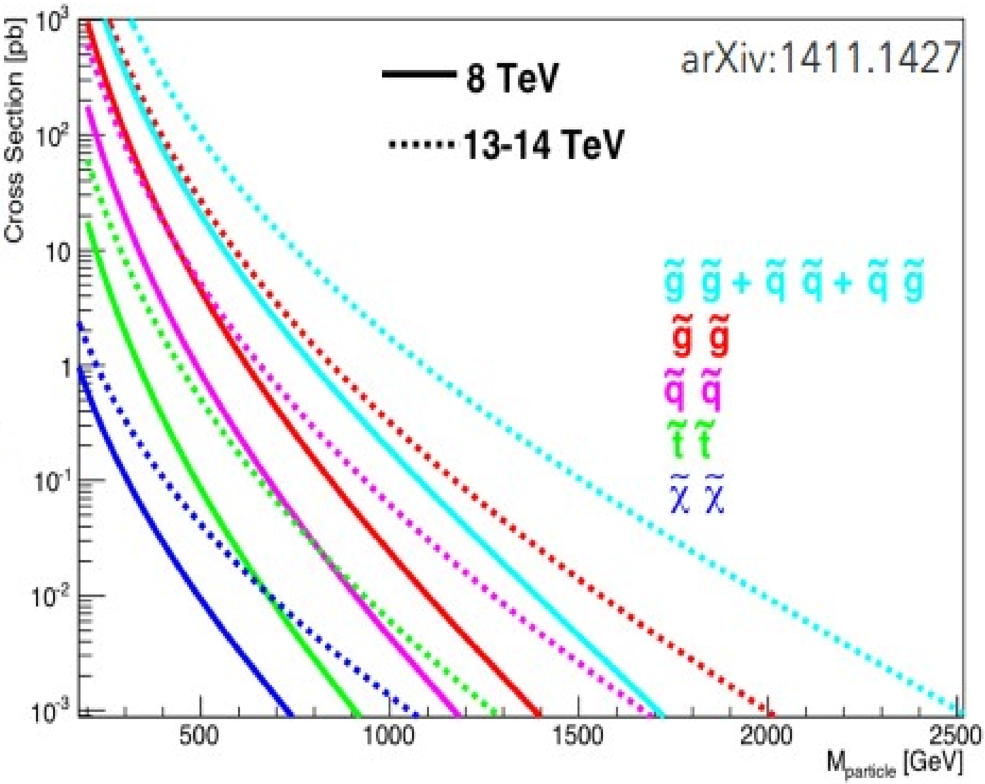
Some problems can be solved if the DM is non-thermal. For thermal DM, some problems can be solved by adding coannhilation, resonance effects, etc.

Determining the composition of the LSP for a given mass is *very important* to understand early universe cosmology

MOTIVATION

Most of the LHC SUSY searches focus on **strong production**, with larger cross section.

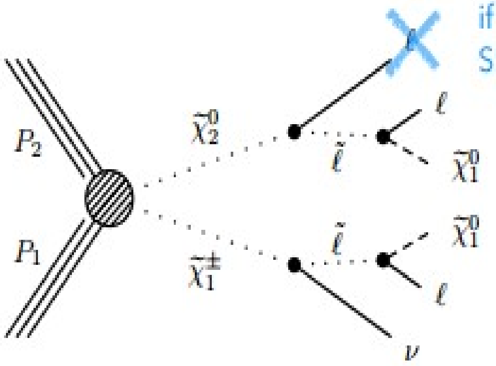
Current searches probe masses o squarks and gluinos up to ~1.75 TeV.



Heavy squarks and gluinos may **favour models with direct EWK production of charginos, neutralinos and sleptons** with low hadronic activity associated, and these could be the only accessible SUSY production at the LHC.

Charginos and neutralinos will decay then to sleptons or W, Z, h bosons.

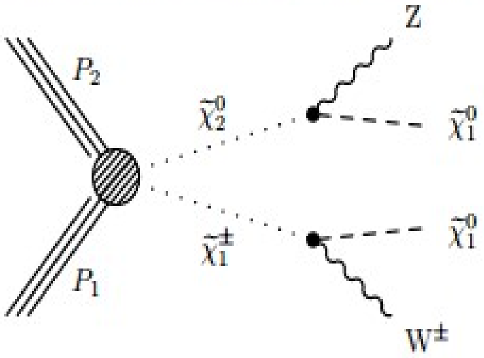
ELECTROWEAK SUSY PRODUCTION @CMS



if one missed:
SS channel

light sleptons and sneutrinos, different mass splittings

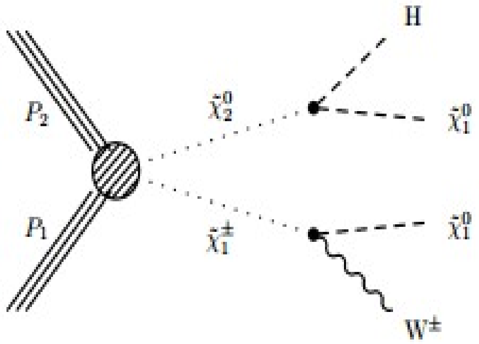
multi-lepton (2L same-sign/3L)



heavy sleptons, decays to W/Z

multi-lepton (3L)
(soft) opposite-sign (see M. Dünser's talk)

heavy sleptons, decays to W and H.

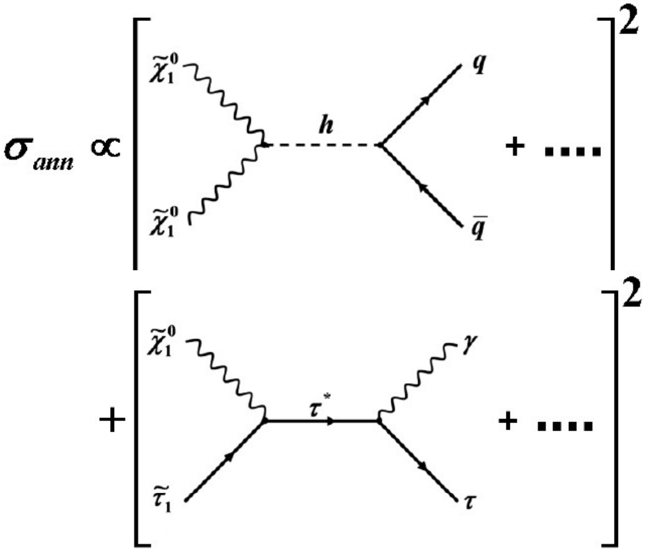


1l + H(bb) (A. Apresyan's talk)
multi-lepton 3L (H to WW)

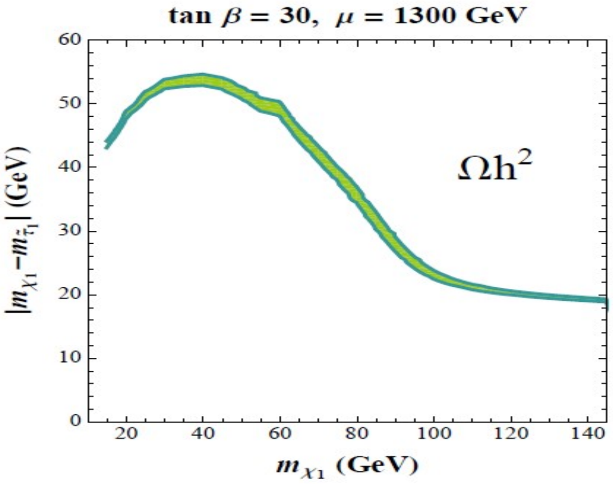
Multiple final states are needed to enhance sensitivity and cover as many corners of the phase space as possible.

Why 3^{rd} Generation SUSY?

- Cosmological Motivation
  - Thermal bino DM scenario
    - LSP annihilation is not enough to provide the correct cold dark matter relic density
    - Near mass degeneracy between bino LSP and other SUSY particle (e.g. stau) allows ***coannihilation processes which contribute to the determination of the relic density***
    - WMAP constrains on the relic density constrain ΔM = M(Stau) – M(LSP) < 50 GeV
  - Coannihilation of the LSP with e.g. stau provide ***the correct DM relic density***
  - Left/right-handed sfermion mixing proportional to mass of SM partners
    - ***Stau mass eigenstates lighter than other sparticles ("naturalness")***

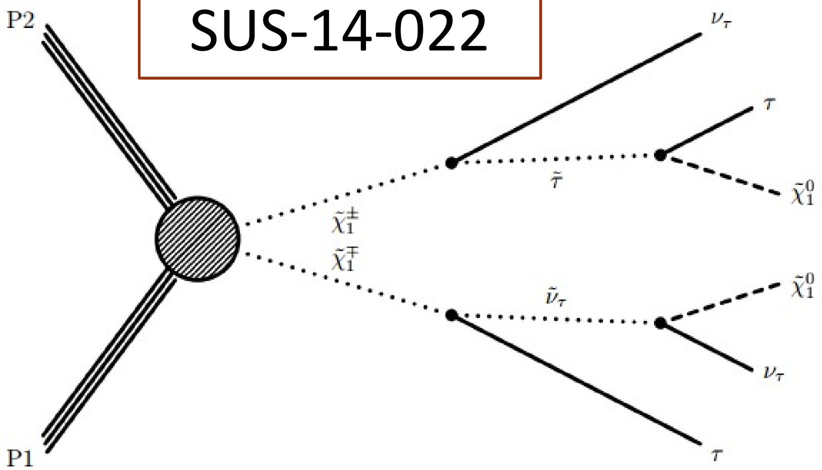


http://arxiv.org/pdf/1205.5842v1.pdf

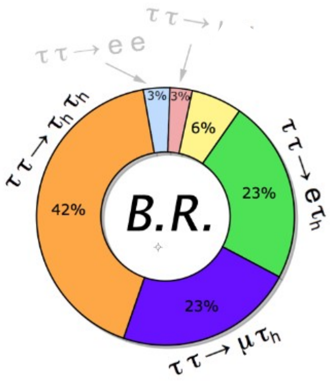

tan β = 30, μ = 1300 GeV

Opposite-sign Di-tau Search

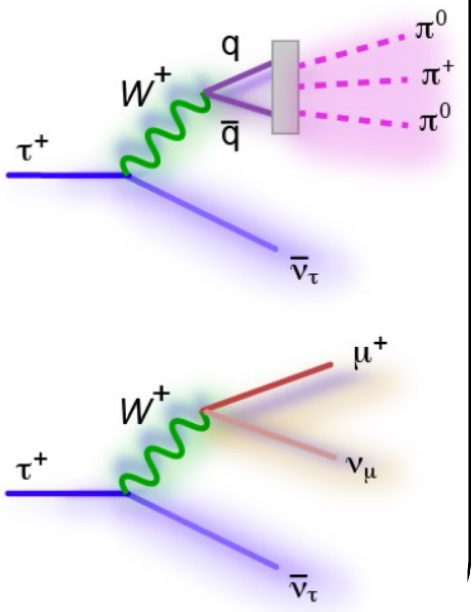
SUS-14-022



- OS chargino production
- Baseline Selections
  - At least one opposite-sign tau pair
  - $e\tau_h$: $p_T(e/\tau_h) > 25/25$ GeV, $|\eta| < 2.1/2.3$
  - $\mu\tau_h$: $p_T(\mu/\tau_h) > 20/25$ GeV, $|\eta| < 2.1/2.3$
  - $\tau_h\tau_h$: $p_T(\tau_h) > 45$ GeV, $|\eta| < 2.1$
  - $m(\tau_1\tau_2)$>15 GeV & Z-mass veto
  - Veto events w/ extra e/μ & b's (in some cases)
  - MET > 30 GeV, $M_{T2} > 40$ GeV
  - $\min\{\Delta\phi(\tau_h/\text{jet},\text{MET})\} > 1$
- Signal Regions
  - $\tau_h\tau_h$: $M_{T2} > 90$ GeV (SR1);
    $M_{T2} < 90$ GeV + $\Sigma m_T^{\tau h} > 250$ GeV (SR2)
  - $e\tau_h/\mu\tau_h$: $M_{T2} > 90$ GeV & $m_T^{\tau h} > 200$ GeV (SR3/SR4)



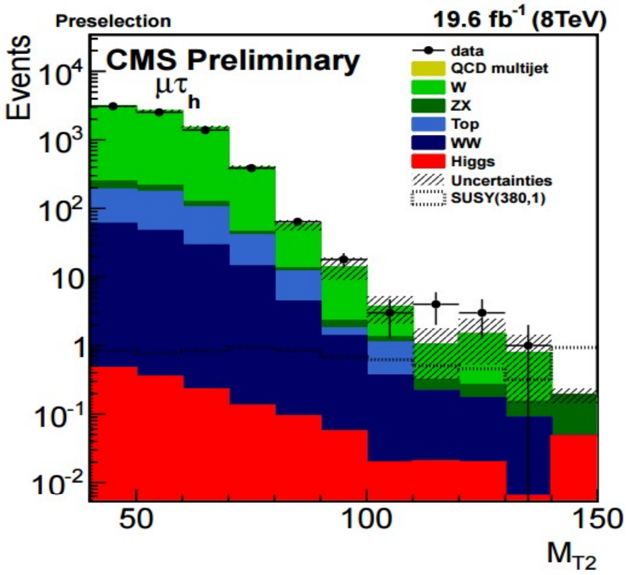
Tau decay modes

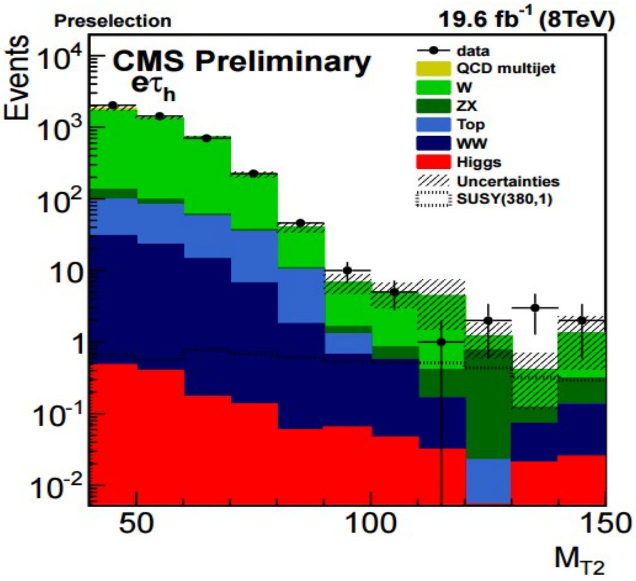


Opposite-sign Di-tau Search

SUS-14-022

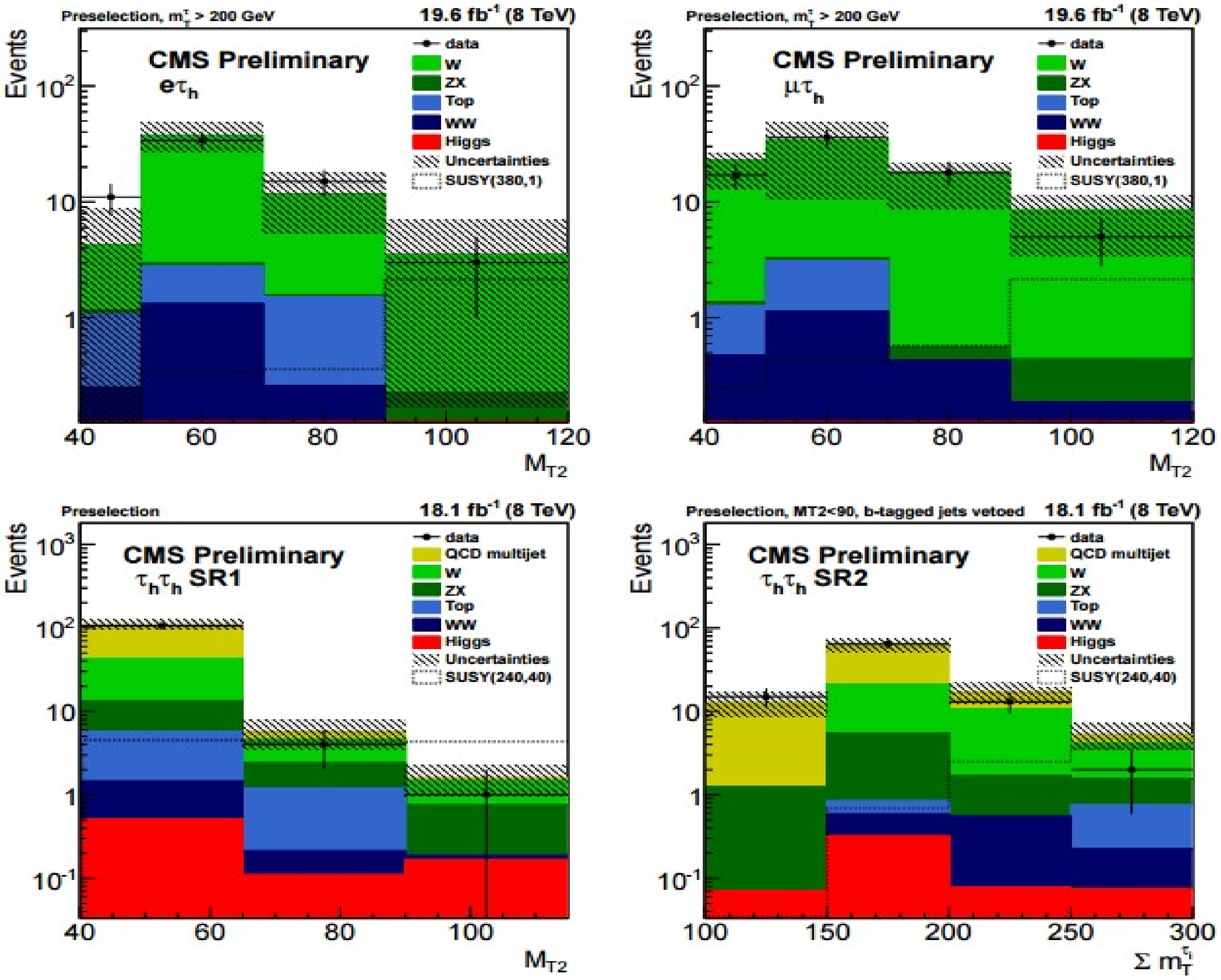
- Backgrounds
  - Top pair, W+jets, QCD, Z+jets, VV, Higgs
- Estimate of Real Tau Backgrounds
  - Z→$\tau\tau$: validate good modeling by MC using control samples w/ low M_{T2} & near Z-mass
  - Other small BGs taken from simulation
- Estimate of “Fake” Tau Background
  - $l\tau_h$: measure fake rate in fake/jet dominated control sample (MET < 30 GeV)
  - $\tau_h\tau_h$: Signal-like “fake” dominated control sample using SS non-iso $\tau_h\tau_h$ is weighted using transfer factor to go from non-iso SS to isolated OS $\tau_h\tau_h$, measured at low M_{T2}/mT





Opposite-sign Di-tau Search

No excess above the SM predictions in any signal region

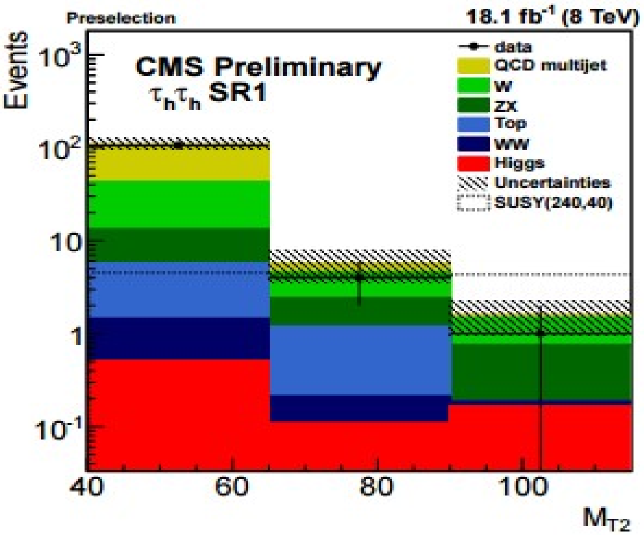


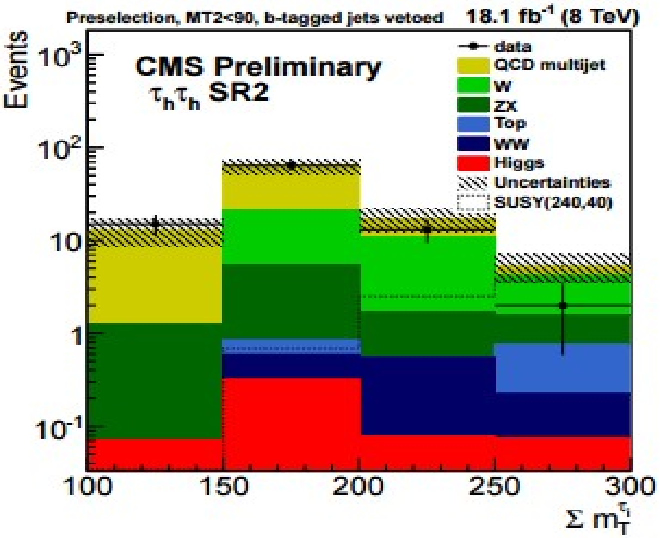
Opposite-sign Di-tau Search

No excess above the SM predictions in any signal region

	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$ SR1	$\tau_h\tau_h$ SR2
Z+jets	$0.19 \pm 0.04 \pm 0.03$	$0.25 \pm 0.06 \pm 0.04$	$0.56 \pm 0.07 \pm 0.12$	$0.81 \pm 0.56 \pm 0.18$
$t\bar{t}$, VV, Higgs	$0.03 \pm 0.03 \pm 0.02$	$0.19 \pm 0.09 \pm 0.09$	$0.19 \pm 0.03 \pm 0.09$	$0.75 \pm 0.35 \pm 0.38$
W+jets	$3.30 \pm 3.35 \pm 0.56$	$8.15 \pm 4.59 \pm 1.53$	$0.72 \pm 0.11 \pm 0.57$	$2.58 \pm 0.35 \pm 1.25$
QCD multijet	-	-	$0.13 \pm 0.06 \pm 0.21$	$1.15 \pm 0.39 \pm 0.74$
SM Total	$3.52 \pm 3.35 \pm 0.56$	$8.59 \pm 4.59 \pm 1.53$	$1.60 \pm 0.15 \pm 0.62$	$5.29 \pm 0.70 \pm 1.51$
Observed	3	5	1	2

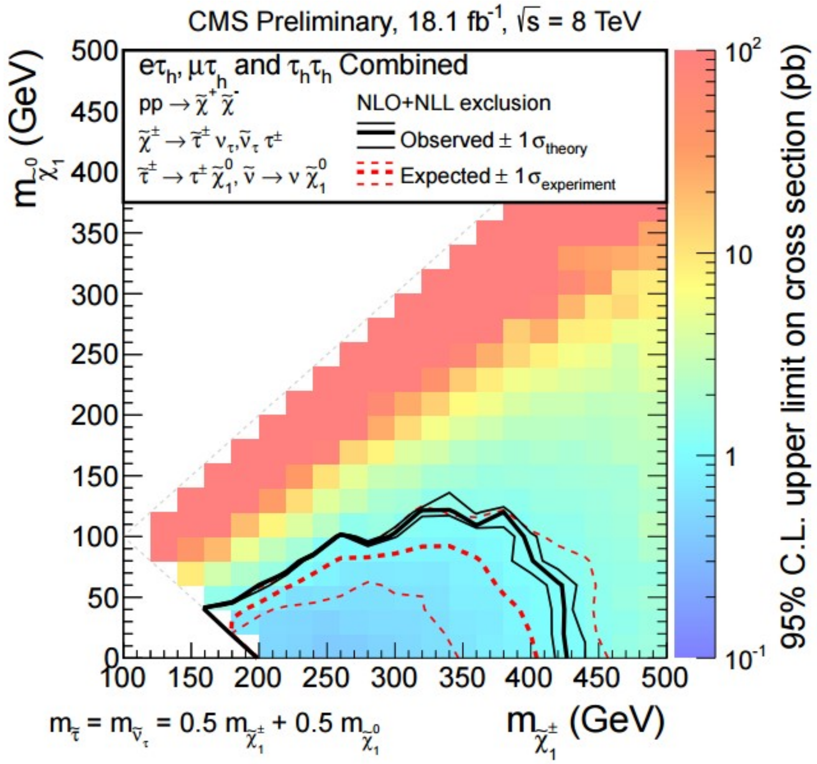
Fully hadronic ditau is the most sensitive channel

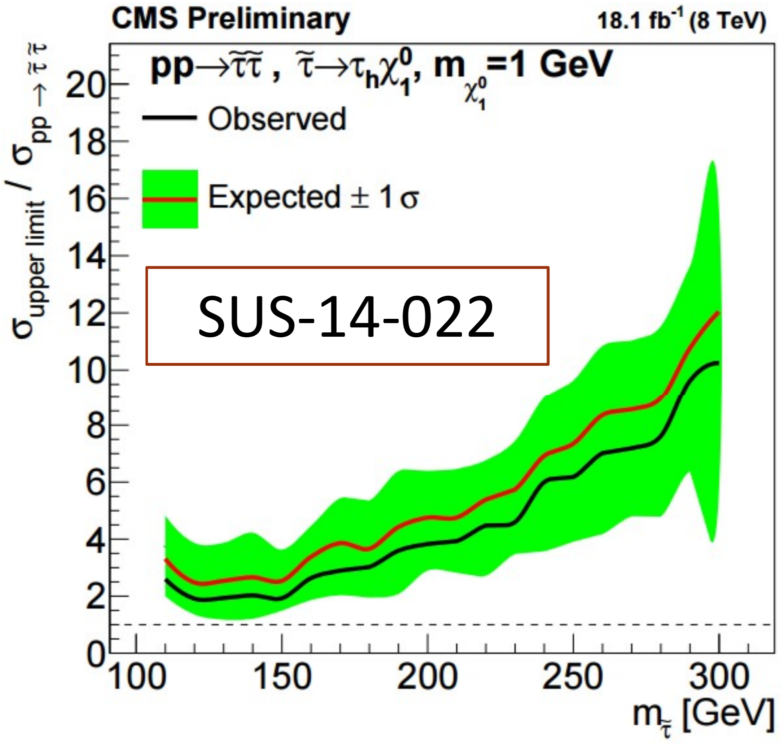




Opposite-sign Di-tau Search

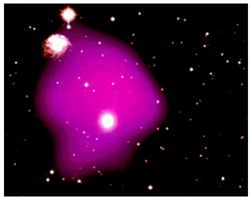
- No significant excess above SM predictions in any signal region





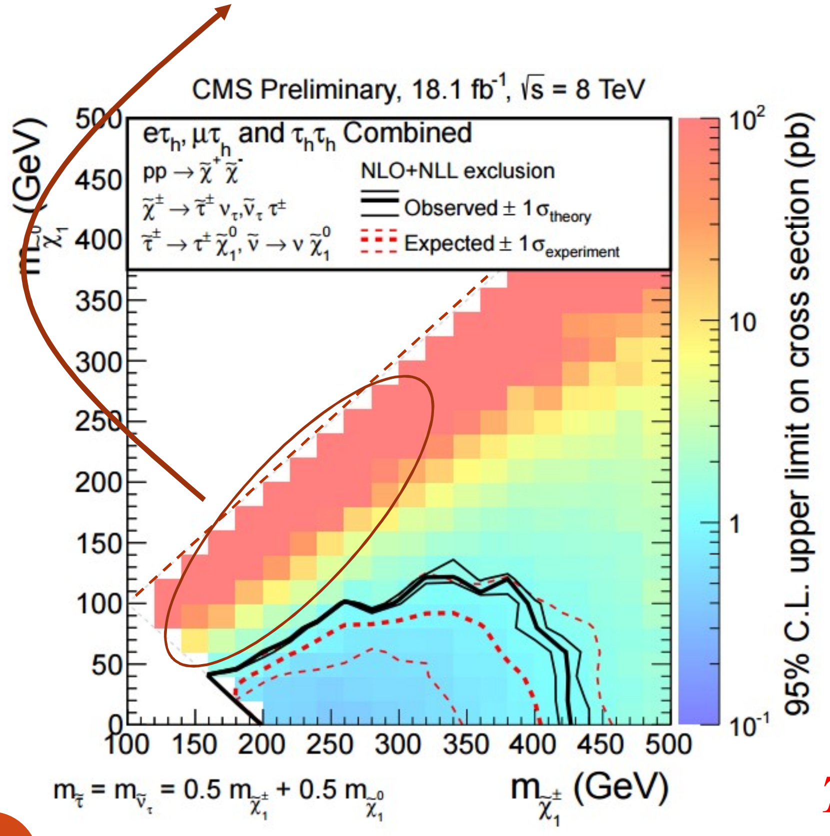
- ***M(chargino) up to ~ 420 GeV excluded for massless LSP***
  - ***No exclusion on M(chargino) for ΔM < 150 GeV***
  - ***Direct stau production remains difficult to probe***

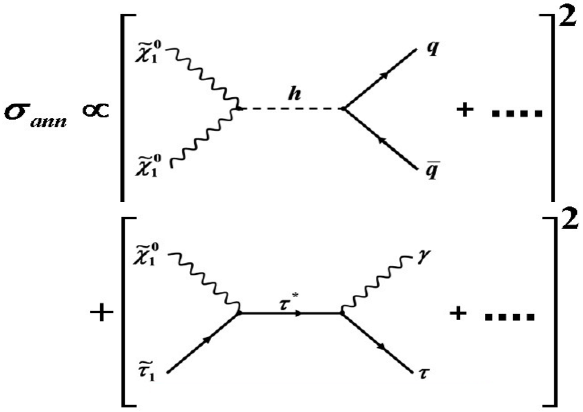
3rd gen & Compressed



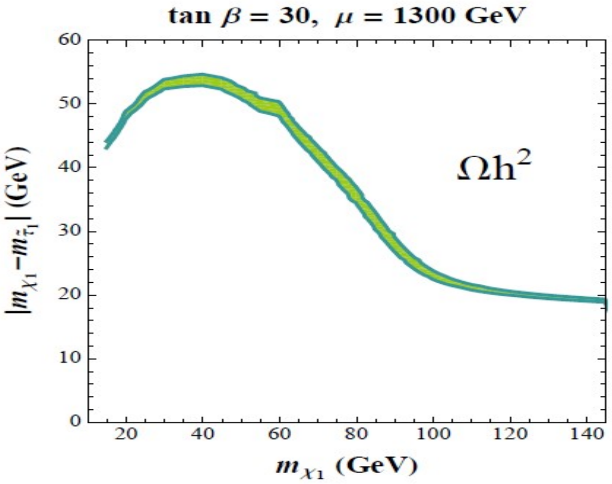
No sensitivity in cases with 3rd gen and compressed spectra

Can be important for cosmology



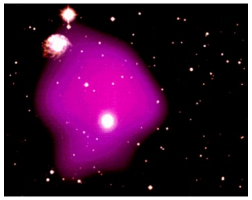


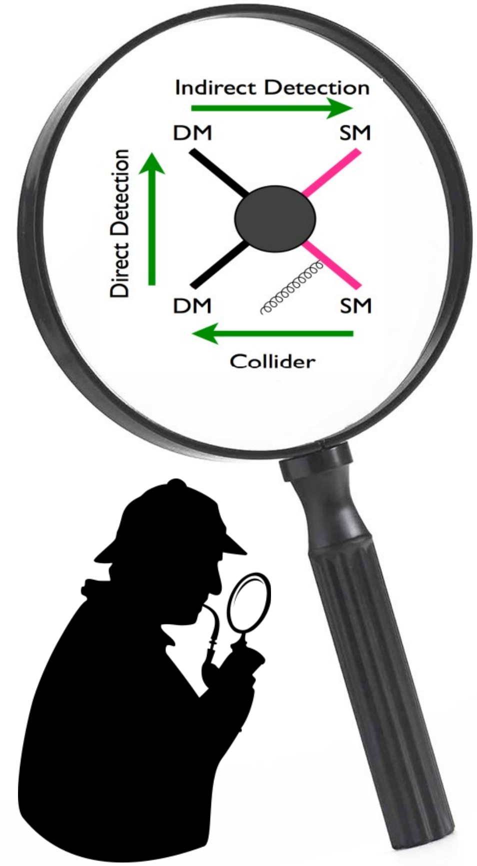
http://arxiv.org/pdf/1205.5842v1.pdf



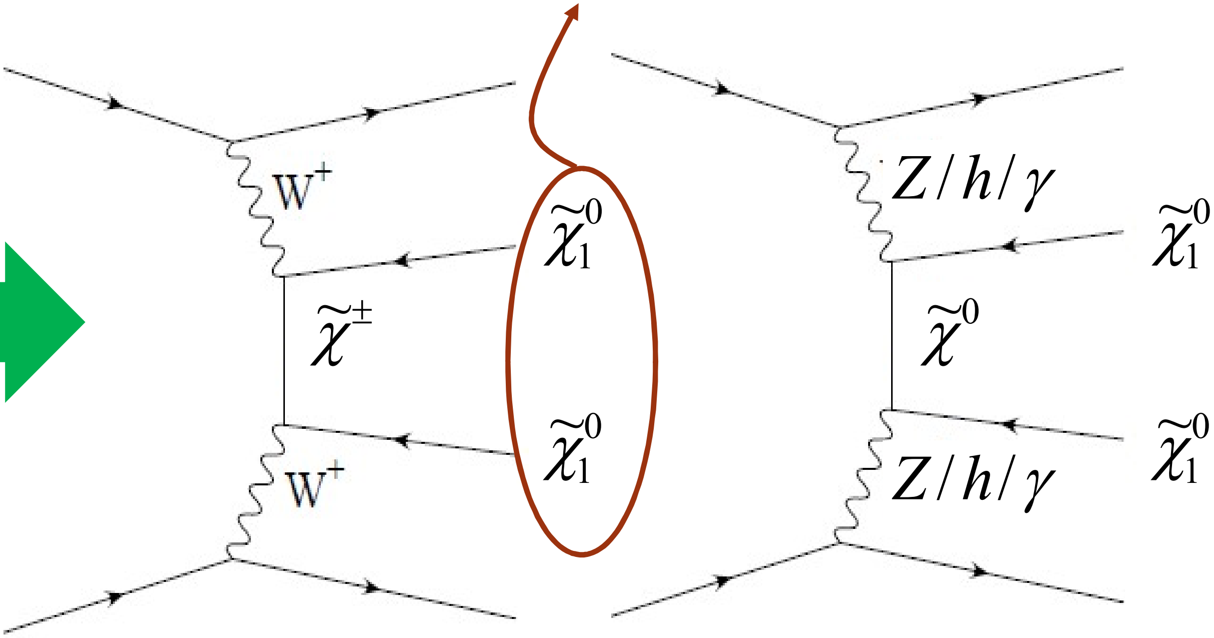
Tackling these scenarios is a very tall tall task at the LHC

Probing SUSY DM with VBF

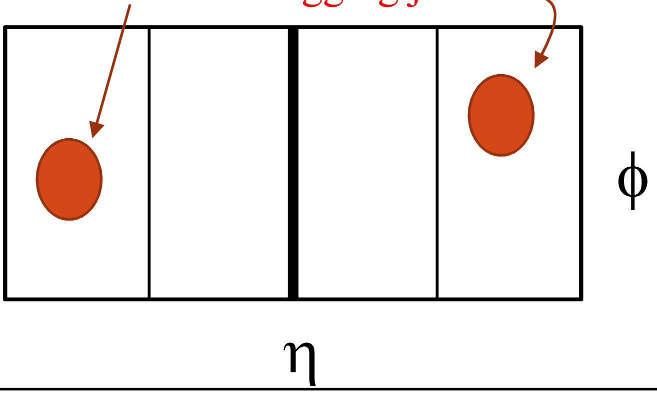




Cold dark matter candidate

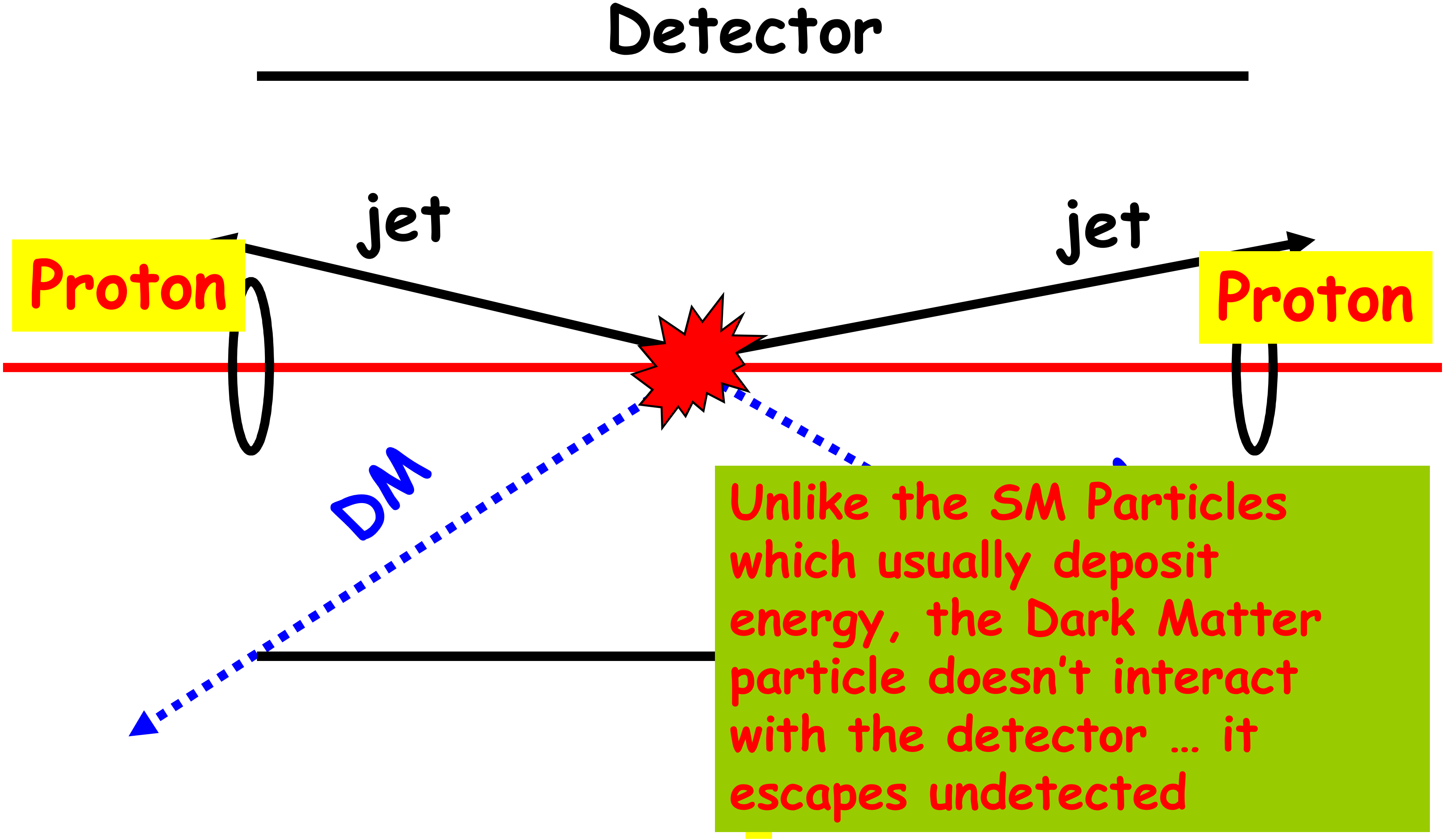


Forward tagging jets



MET + jj

Dark Matter Production by VBF



Unlike the SM Particles which usually deposit energy, the Dark Matter particle doesn't interact with the detector … it escapes undetected

ΣP=-200 GeV

in the *x*-direction

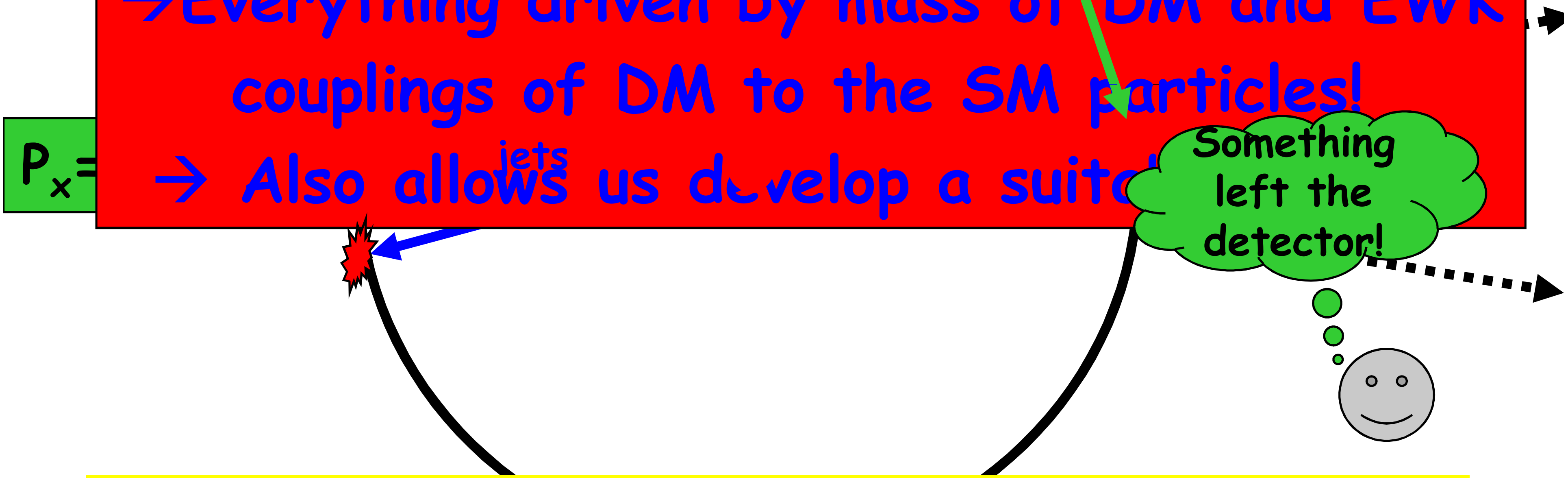
→Boosted DM means Missing En

→Dijet masses ~ few TeV!

Smoking Gun for Dark Matter

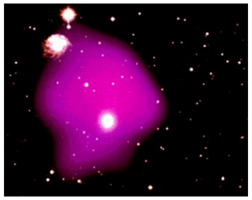
→Everything driven by mass of DM and EWK couplings of DM to the SM particles!

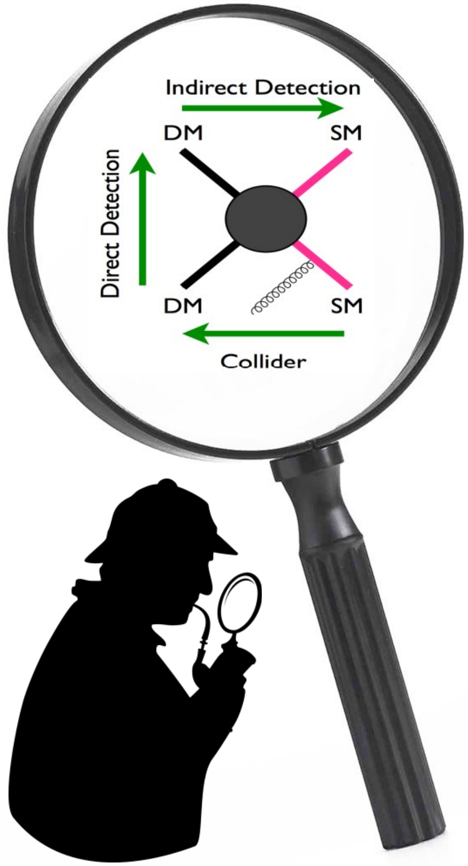
→ Also allows us develop a suit



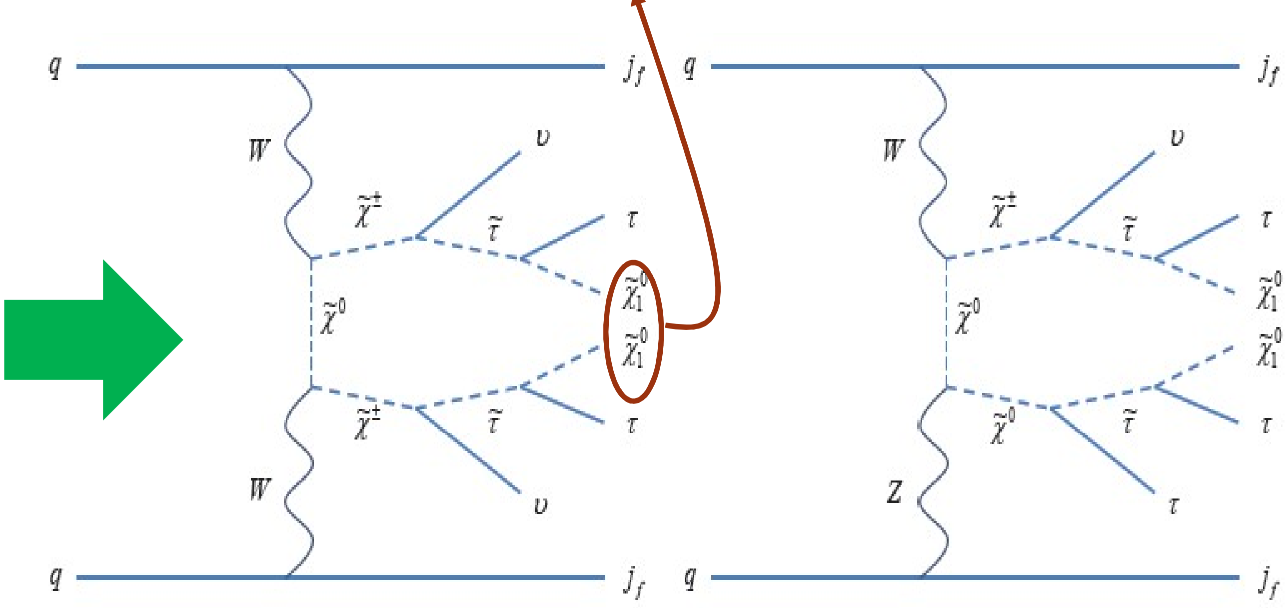
SM Particle Deposits energy, but the Dark Matter particles don't interact with the detector

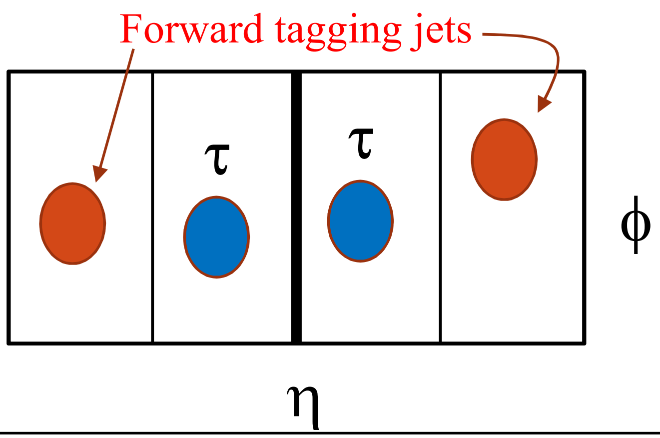
Probing EWK SUSY with VBF





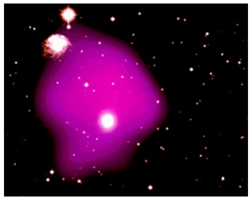
Cold dark matter candidate





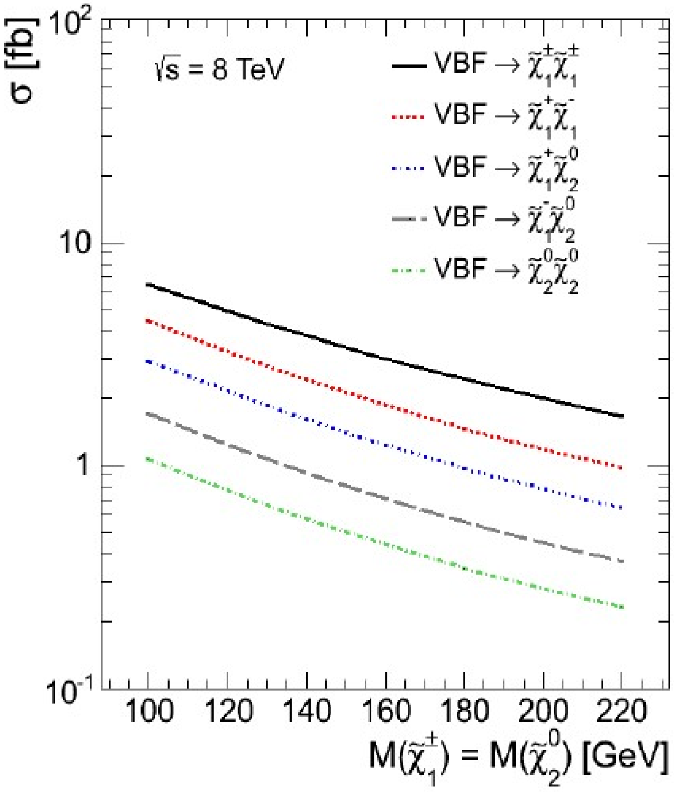
MET + jj + leptons

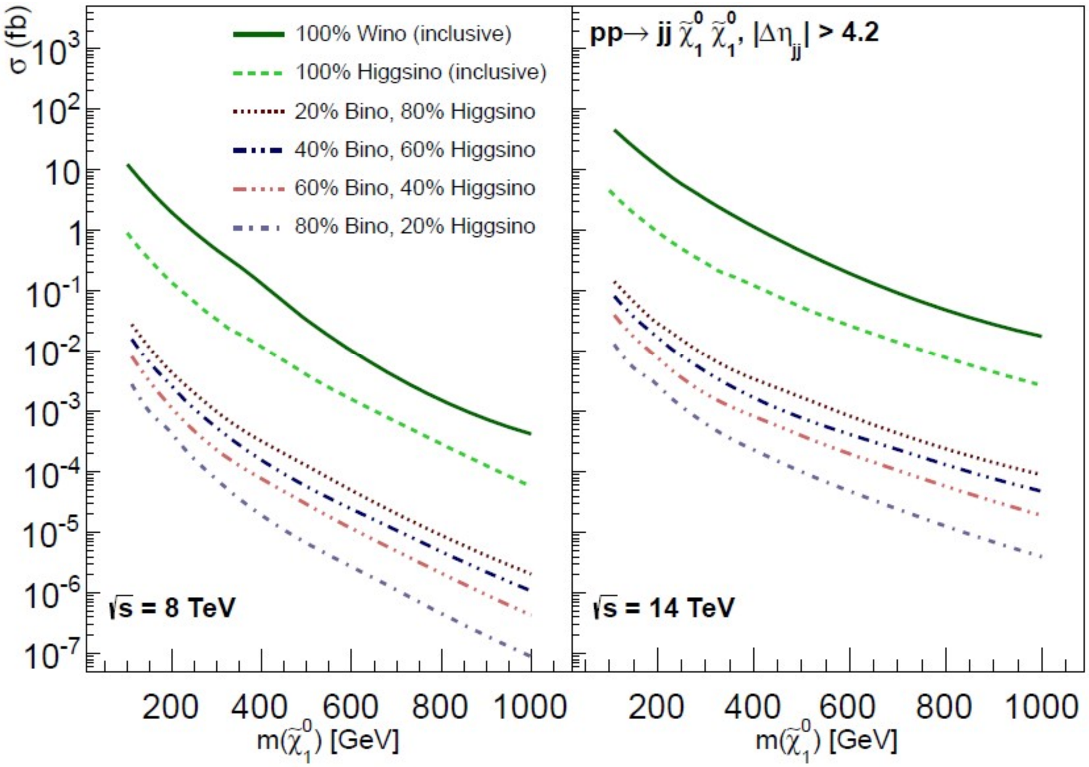
Probing DM with VBF



http://arxiv.org/pdf/1210.0964v2.pdf

http://arxiv.org/pdf/1304.7779v1.pdf

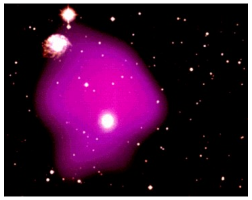


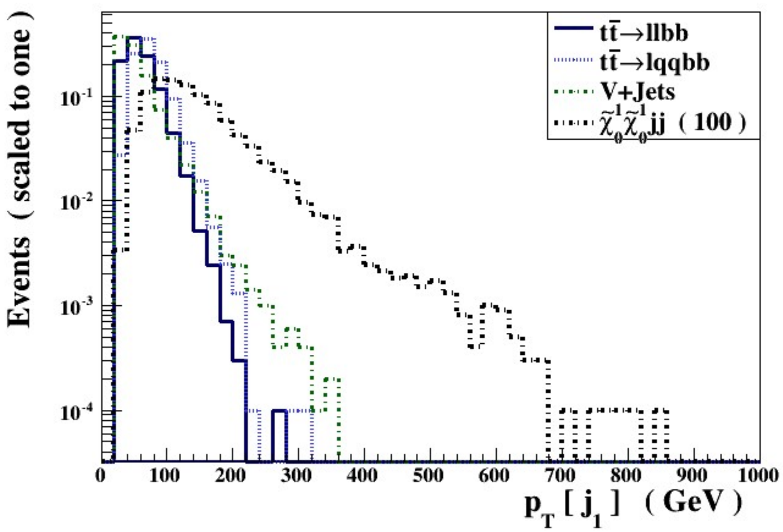


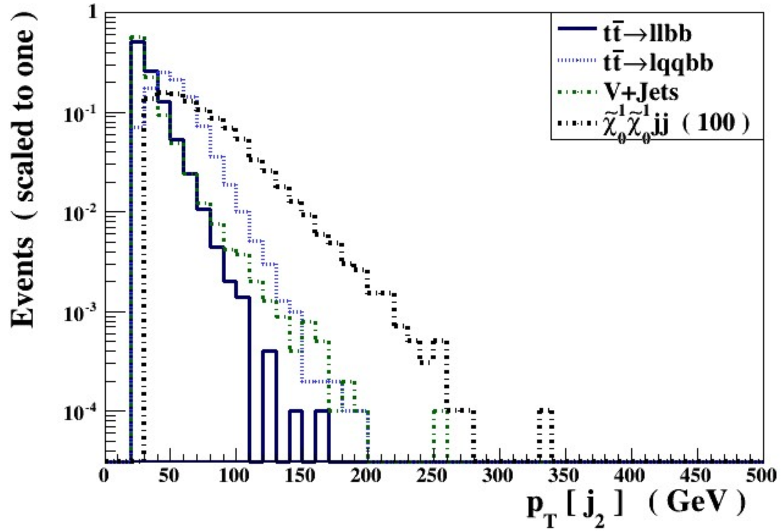
MET + jj + leptons

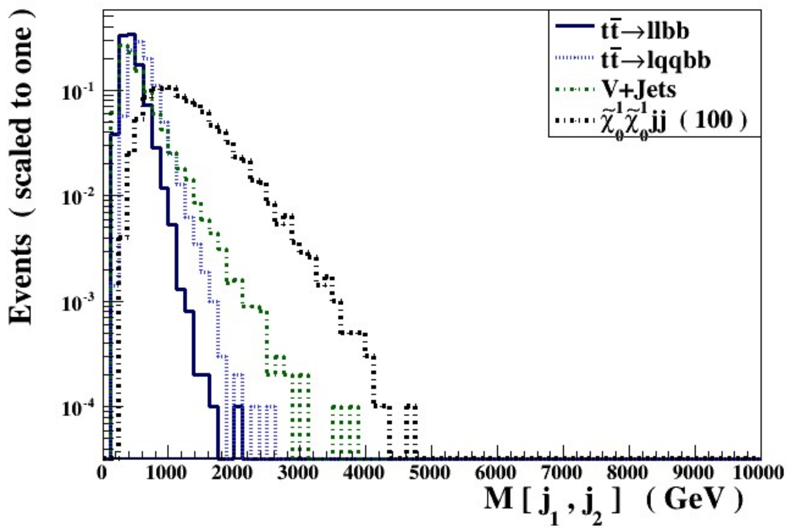
MET + jj

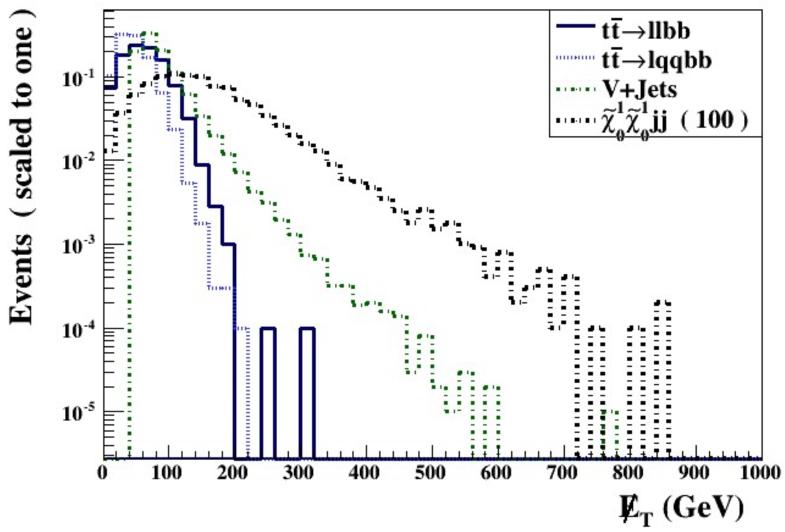
VBF SUSY Kinematics



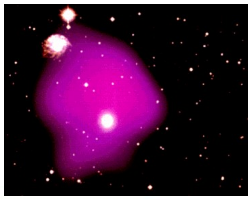




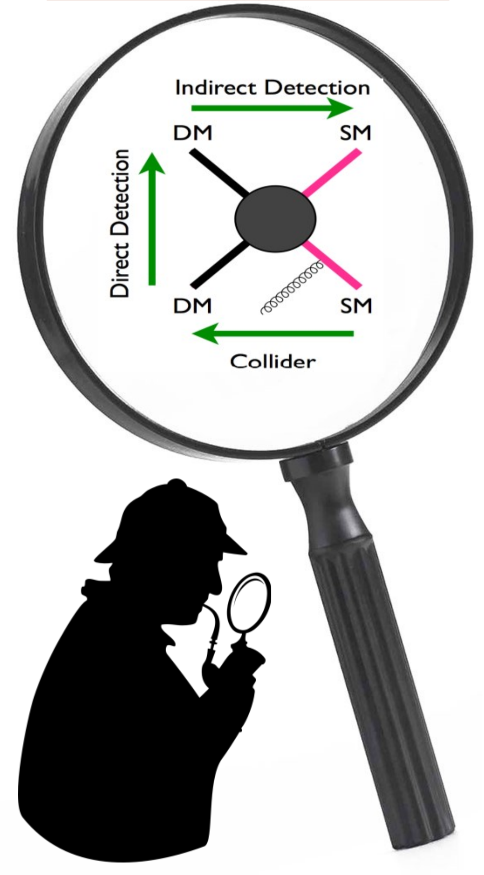


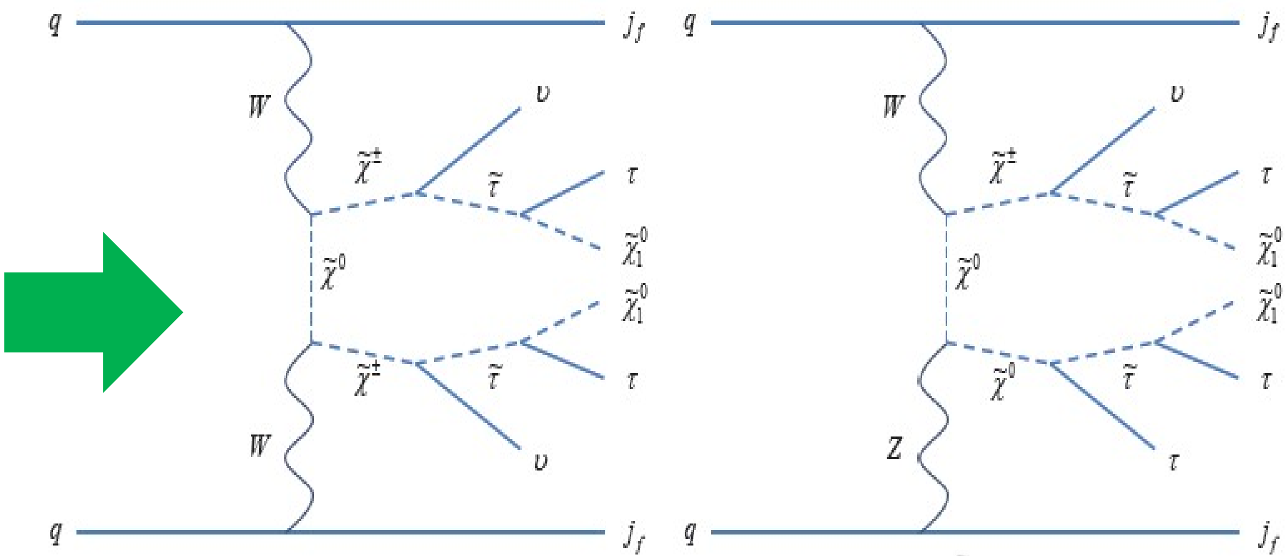


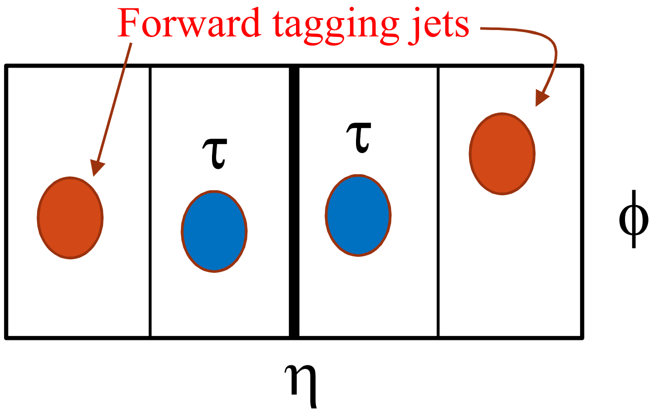
First Ever VBF SUSY Search!

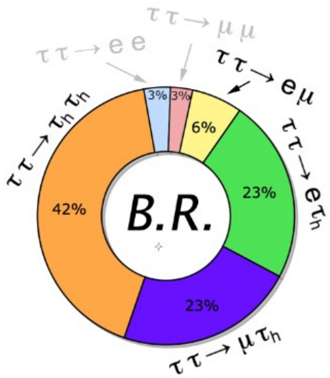


SUS-14-005









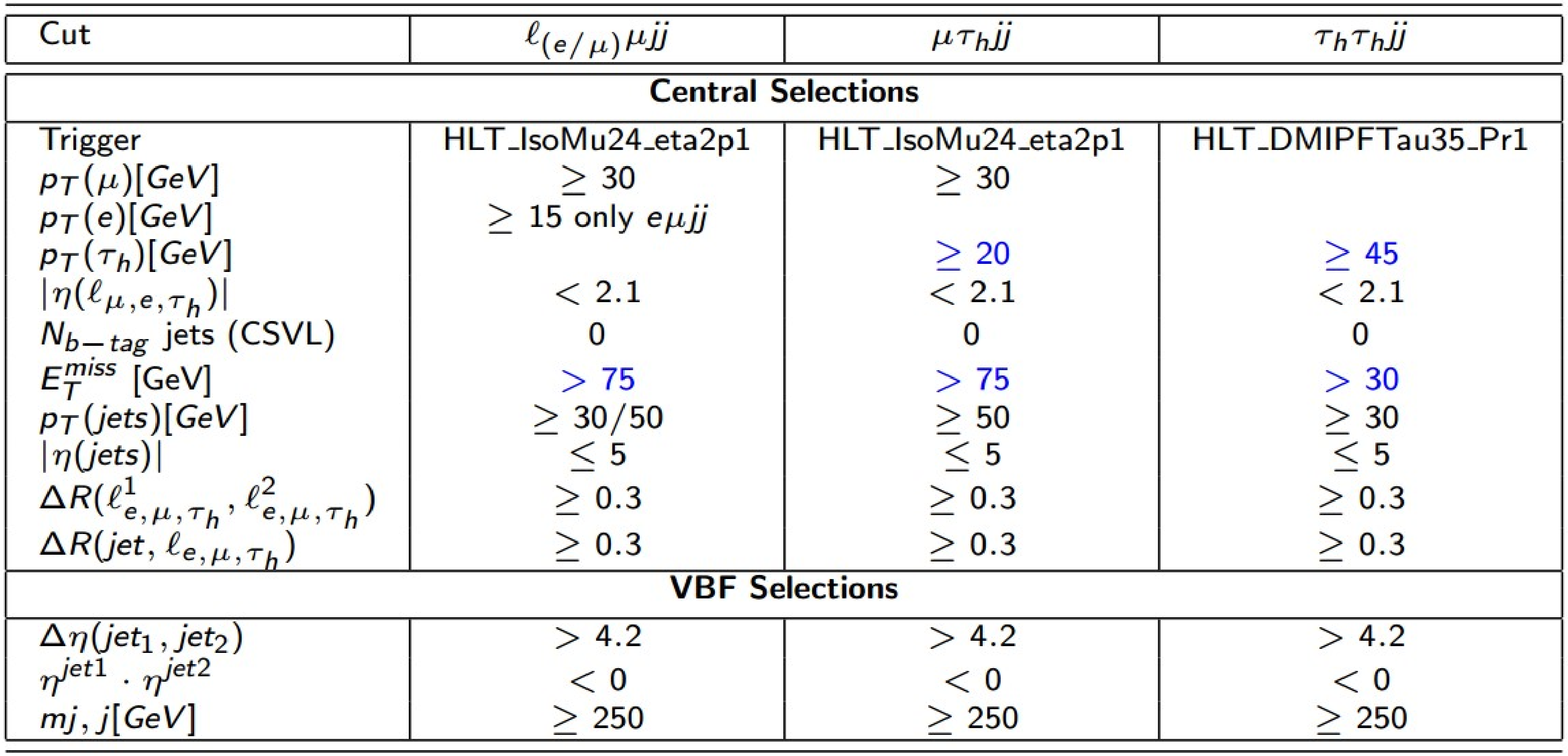
MET + ττ + leptons

8 final states considered: μμjj, eμjj, $\mu\tau_h$jj, $\tau_h\tau_h$jj (OS & LS)

μ/e channels use a single muon trigger; $\tau_h\tau_h$jj channels use a ditau trigger

First Ever VBF SUSY Search!

Summary of event selection criteria for all channels



Cut	$\ell_{(e/\mu)}\mu jj$	$\mu\tau_h jj$	$\tau_h\tau_h jj$
Central Selections			
Trigger	HLT_IsoMu24_eta2p1	HLT_IsoMu24_eta2p1	HLT_DMIPFTau35_Pr1
$p_T(\mu)[GeV]$	≥ 30	≥ 30	
$p_T(e)[GeV]$	≥ 15 only $e\mu jj$		
$p_T(\tau_h)[GeV]$		≥ 20	≥ 45
$\lvert\eta(\ell_{\mu,e,\tau_h})\rvert$	< 2.1	< 2.1	< 2.1
N_{b-tag} jets (CSVL)	0	0	0
E_T^{miss} [GeV]	> 75	> 75	> 30
$p_T(jets)[GeV]$	$\geq 30/50$	≥ 50	≥ 30
$\lvert\eta(jets)\rvert$	≤ 5	≤ 5	≤ 5
$\Delta R(\ell^1_{e,\mu,\tau_h}, \ell^2_{e,\mu,\tau_h})$	≥ 0.3	≥ 0.3	≥ 0.3
$\Delta R(jet, \ell_{e,\mu,\tau_h})$	≥ 0.3	≥ 0.3	≥ 0.3
VBF Selections			
$\Delta\eta(jet_1, jet_2)$	> 4.2	> 4.2	> 4.2
$\eta^{jet1} \cdot \eta^{jet2}$	< 0	< 0	< 0
$mj, j[GeV]$	≥ 250	≥ 250	≥ 250

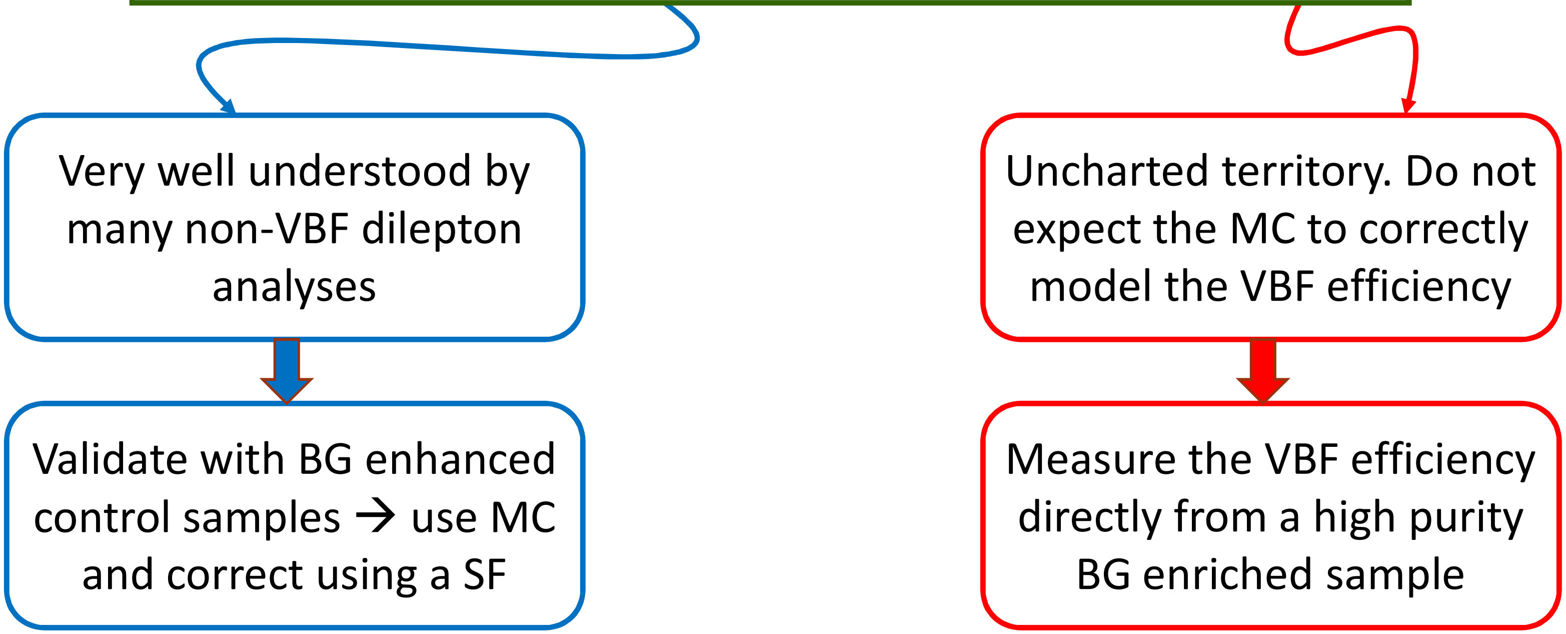
Perform a fit of the entire M_{jj} spectrum (shape based search)

SUS-14-005

VBF SUSY BG Estimation

- As a general rule of thumb, the basic strategy/approach is:

$$N_{\mathrm{BG}}^{\mathrm{Data}} = N_{\mathrm{BG}}^{\mathrm{MC}}(\mathrm{central}) \cdot SF_{\mathrm{central}}^{\mathrm{CR1}} \cdot \epsilon_{\mathrm{VBF}}^{\mathrm{CR2}}(m_{jj})$$



Very well understood by many non-VBF dilepton analyses

Validate with BG enhanced control samples → use MC and correct using a SF

Uncharted territory. Do not expect the MC to correctly model the VBF efficiency

Measure the VBF efficiency directly from a high purity BG enriched sample

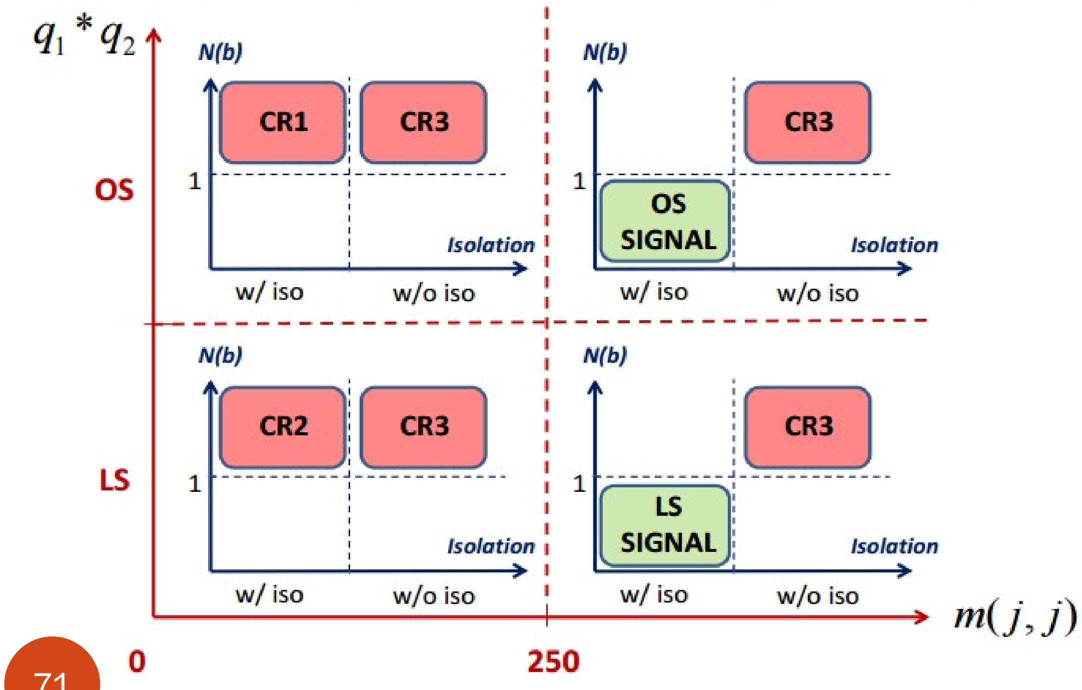
- Main part of the strategy is how to measure the VBF efficiency
    - CRs chosen so signal contamination is negligible
- Small BGs taken from MC with single SF and systematics based on level of agreement between MC and data M_{jj} shapes

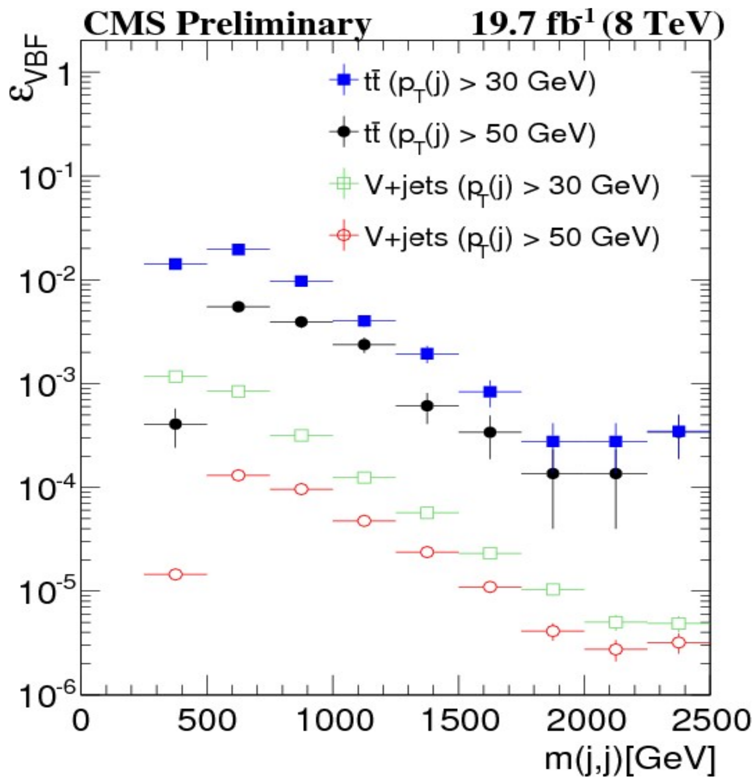
VBF SUSY BG Estimation

1. CR1: $SF^{\mathrm{CR1}}_{\mathrm{central}}$ for central selections for OS events.
2. CR2: $SF^{\mathrm{CR2}}_{\mathrm{central}}$ for central selections for LS events.
3. CR3: measure VBF efficiency and dijet mass shape from data.

SUS-14-005

Top Pair Background Estimation & Validation/Closure Strategy





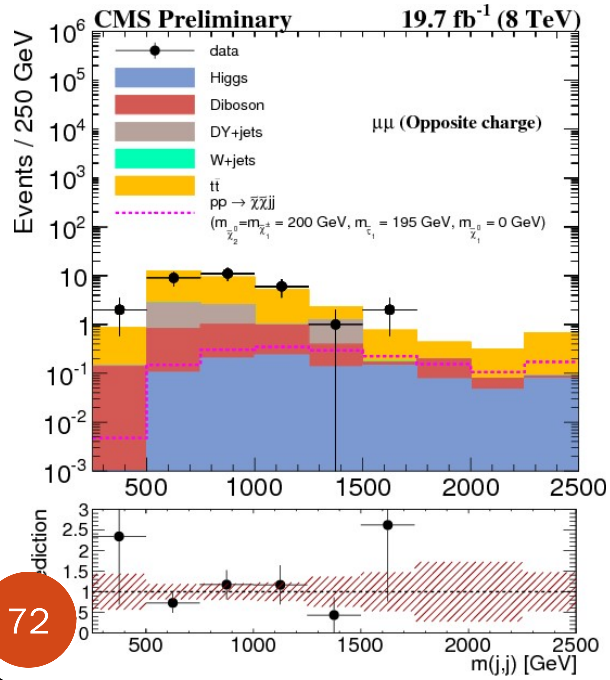
VBF SUSY Search Results

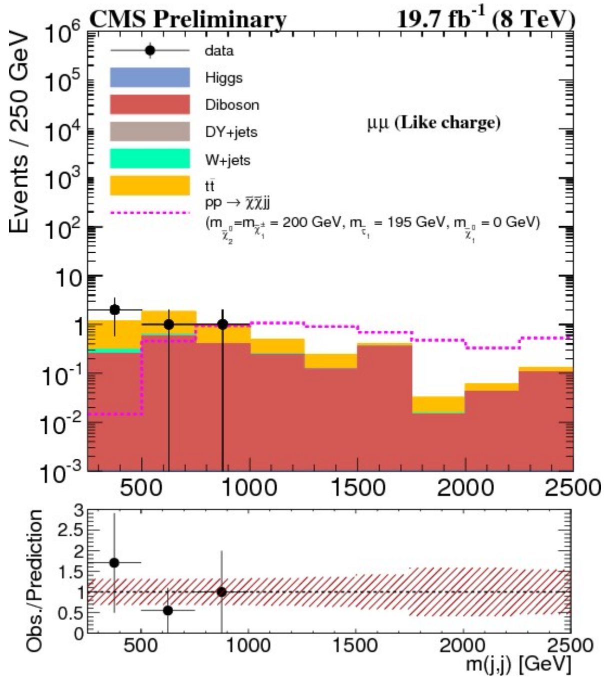
Yields in OS Signal Regions

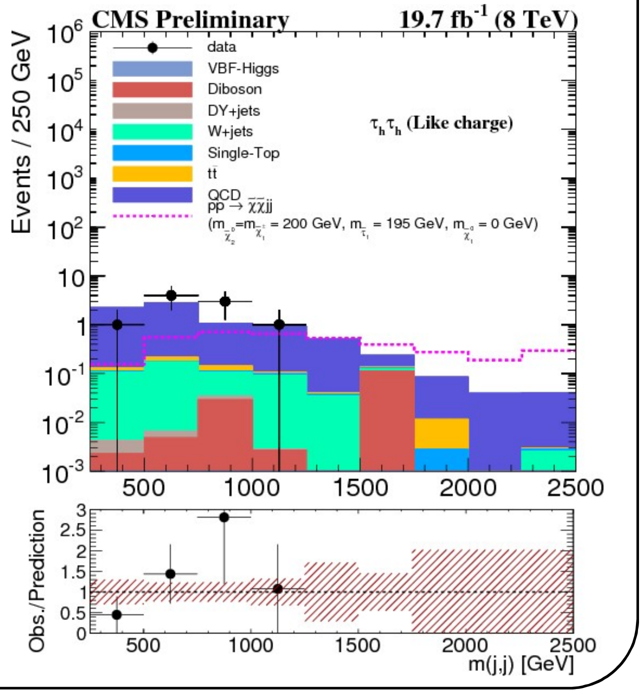
Process	$\mu^\pm\mu^\mp jj$	$e^\pm\mu^\mp jj$	$\mu^\pm\tau_h^\mp jj$	$\tau_h^\pm\tau_h^\mp jj$
DY + jets	4.3 ± 1.7	$3.7\pm^{2.1}_{1.9}$	19.9 ± 2.9	12.3 ± 4.4
W + jets	< 0.01	$4.2\pm^{3.3}_{2.5}$	17.3 ± 3.0	2.0 ± 1.7
VV	2.8 ± 0.5	3.1 ± 0.7	2.9 ± 0.5	0.5 ± 0.2
$t\bar{t}$	24.0 ± 1.7	$19.0\pm^{2.3}_{2.4}$	11.7 ± 2.8	–
QCD	–	–	–	6.3 ± 1.8
Higgs	1.0 ± 0.1	1.1 ± 0.5	–	1.1 ± 0.1
VBF Z	–	–	–	0.7 ± 0.2
Total	32.2 ± 2.4	$31.1\pm^{4.6}_{4.1}$	51.8 ± 5.1	22.9 ± 5.1
Observed	31	22	41	31

Yields in LS Signal Regions

Process	$\mu^\pm\mu^\pm jj$	$e^\pm\mu^\pm jj$	$\mu^\pm\tau_h^\pm jj$	$\tau_h^\pm\tau_h^\pm jj$
DY + jets	< 0.01	$0\pm^{1.7}_{0}$	0.5 ± 0.2	< 0.01
W + jets	$0.1 \pm 8.2 \times 10^{-4}$	$0\pm^{3.0}_{0}$	9.3 ± 2.3	0.5 ± 0.1
VV	2.1 ± 0.3	$1.9\pm^{0.4}_{0.2}$	1.1 ± 0.2	$0.1 \pm 6.5 \times 10^{-2}$
$t\bar{t}$	3.1 ± 0.1	$3.5\pm^{0.7}_{0.9}$	6.7 ± 2.8	$0.1 \pm 1.2 \times 10^{-2}$
Single top	–	–	–	< 0.1
QCD	–	–	–	7.6 ± 0.9
Higgs	–	–	–	< 0.01
Total	5.4 ± 0.3	$5.4\pm^{3.5}_{0.9}$	17.6 ± 3.8	8.4 ± 0.9
Observed	4	5	14	9



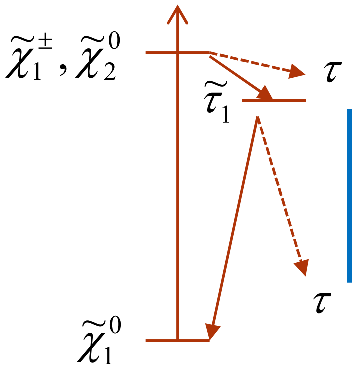




VBF SUSY Search Results

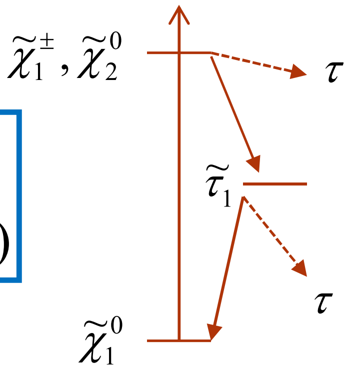
$$m(\tilde{\chi}_1^{\pm}) - m(\tilde{\tau}_1) = 5\,\mathrm{GeV}$$

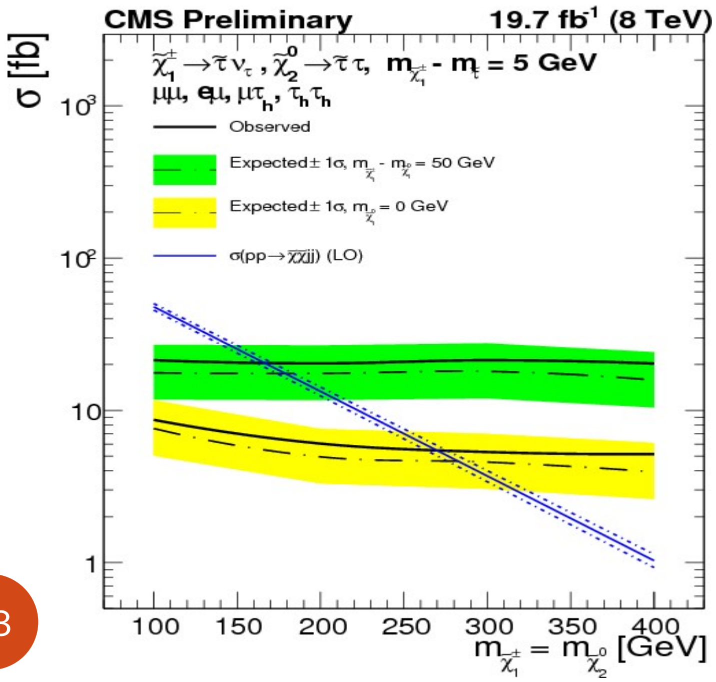
$$m(\tilde{\tau}_1) = \frac{1}{2} m(\tilde{\chi}_1^{\pm}) + \frac{1}{2} m(\tilde{\chi}_1^{0})$$

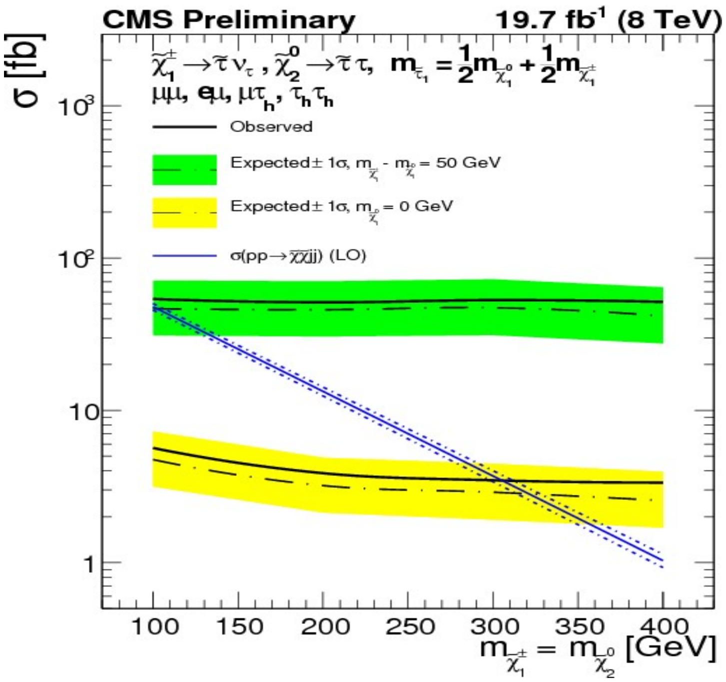


$$m(\tilde{\chi}_1^{0}) = 0\,\mathrm{GeV}\ (\text{large mass gap})$$

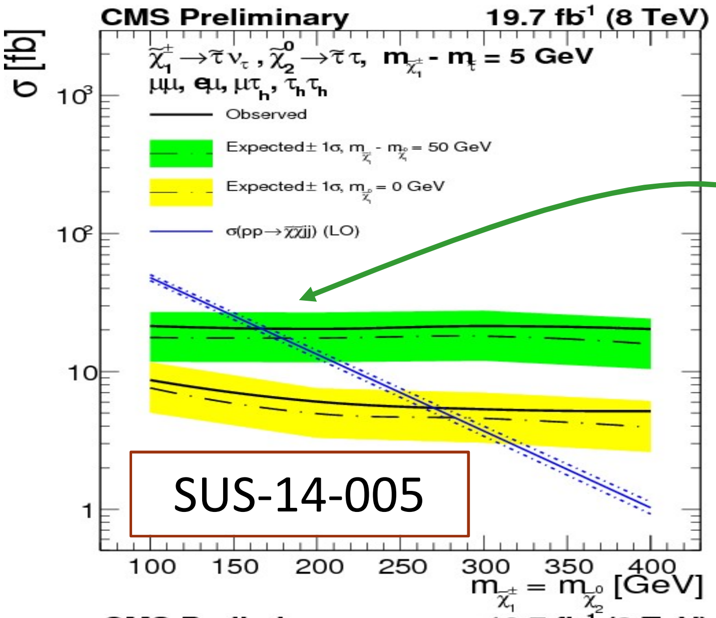
$$m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^{0}) = 50\,\mathrm{GeV}\ (\text{compressed})$$



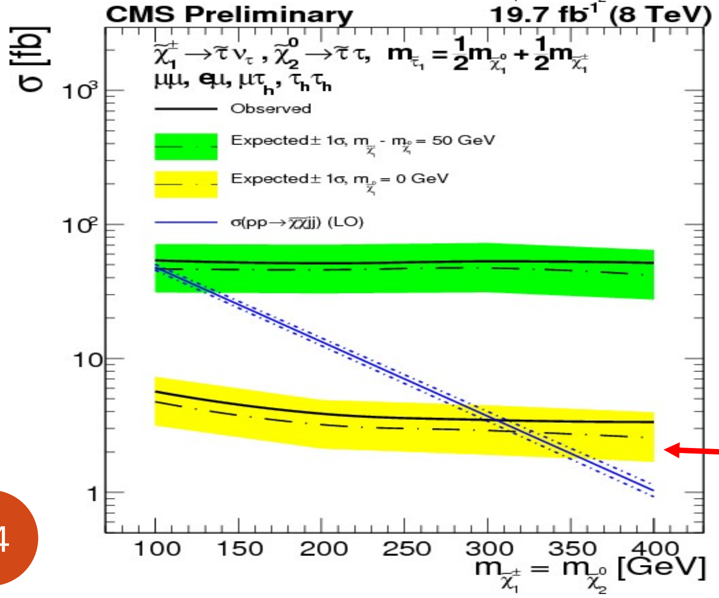




VBF SUSY Search Results

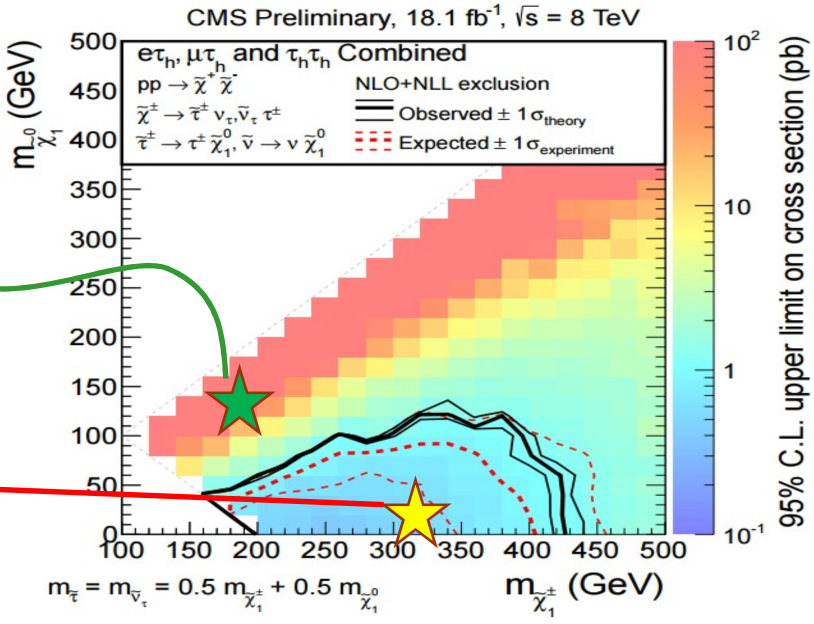


SUS-14-005



VBF SUSY search nicely complements other searches for EWK SUSY sector

Sensitivity to compressed regions difficult to probe with other searches



VBF Dark Matter Search

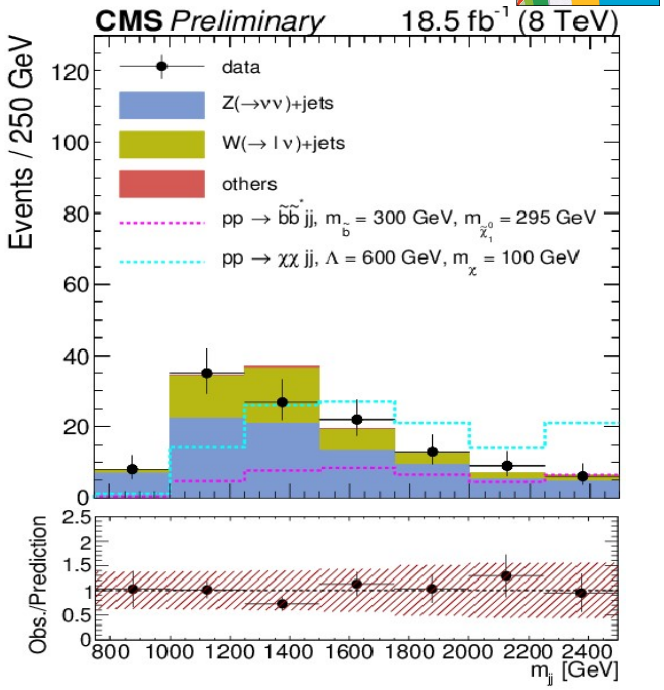
SUS-14-019

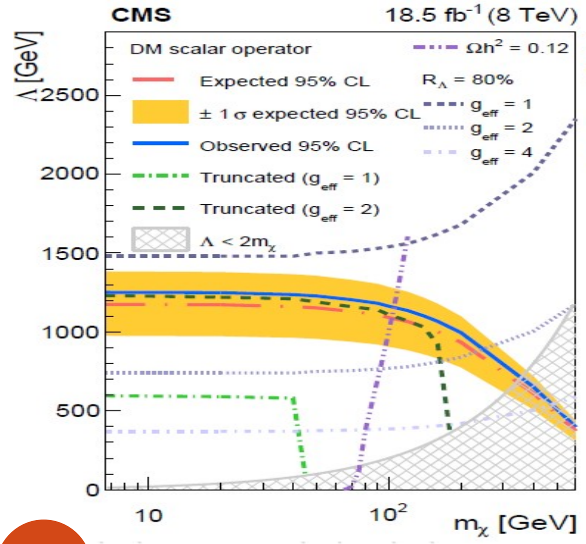
Trigger: MET65+VBFDiJet35

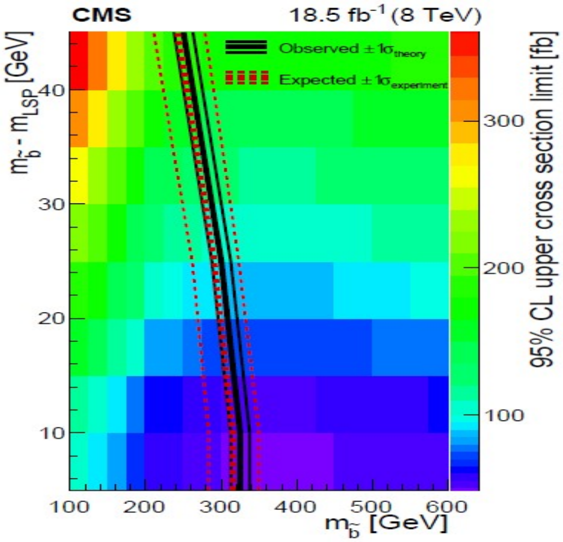
Selection: Two jets (p_T>50 GeV with $\eta_1\eta_2<0$; large rapidity gap $|\eta_1-\eta_2|>4.2$ and invariant mass m_{12}>750 GeV; no b-tag); MET>250 GeV; veto further jets (p_T>30 GeV)

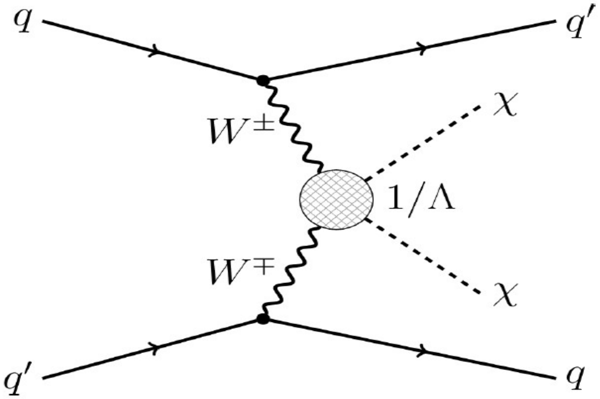
Dominant bgs: $(Z \to \nu\nu) + \text{jets}$ & $(W^\pm \to l^\pm\nu) + \text{jets}$ estimated from data

Interpretation in models with DM production via contact interaction and $\tilde{b}\tilde{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$ production with $m_{\tilde{b}} - m_{\tilde{\chi}_1^0} = 5$ GeV









First search for direct DM production via VBF!

Most stringent limits on compressed colored sector with 8 TeV data

Conclusions

- The LHC has performed a broad and deep set of searches for SUSY
  - Unfortunately, no sign of new physics
- Many Colombian collaborators in this room have played a key/lead role!
- If our understanding of Cosmology and Particle Physics are correct, a major discovery may be just around the corner!