Dark Matter
Beam & Detector

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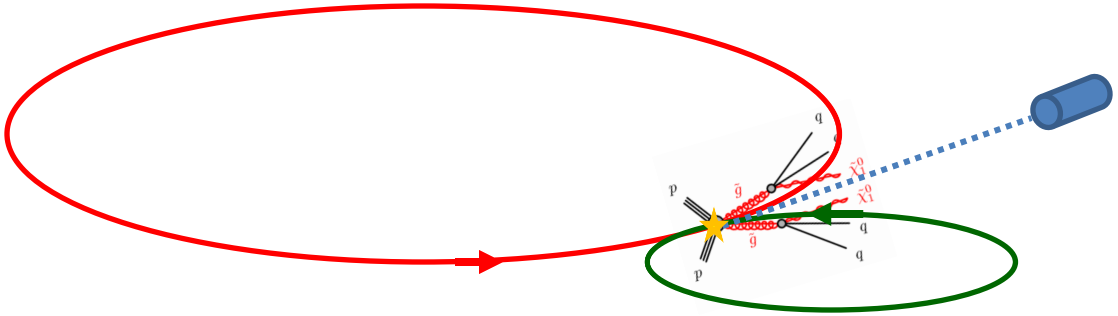
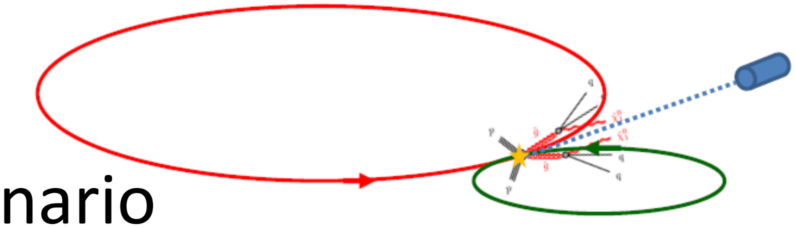


Motivation

- Dark Matter is arguably the most convincing evidence and the most important application of BSM physics
  - controlled DM production and detection under laboratory conditions would be a major breakthrough!

- Motivations for a dedicated DM experiment at FCC
  - next step if compelling signal is observed at LHC Run-2
  - scenarios where dark matter is invisible for ATLAS & CMS but visible with a dedicated DM detector
  - bread & butter neutrino physics in the TeV regime (?)

Overview



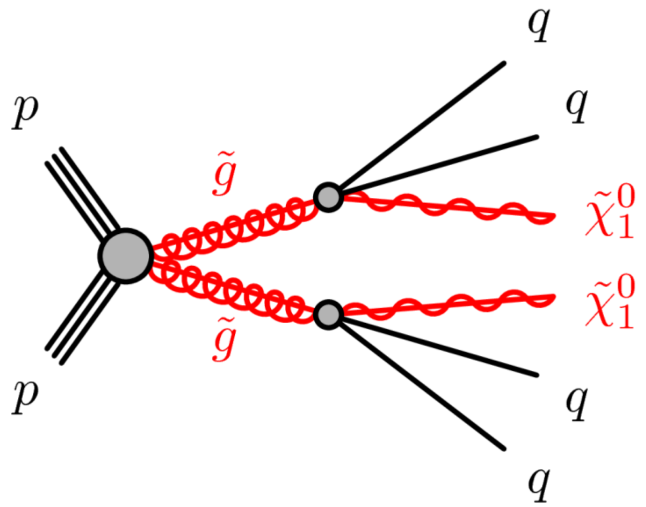
- dark matter production
  - DM flux in explicit SUSY scenario
  - symmetric vs asymmetric colliders
- dark matter detection
  - inelastic qχ and qν cross-sections
  - expected signal yields
  - neutrino background rejection

Thanks to George Azuelos and Zach Marshall for help with MadGraph+Pythia!!

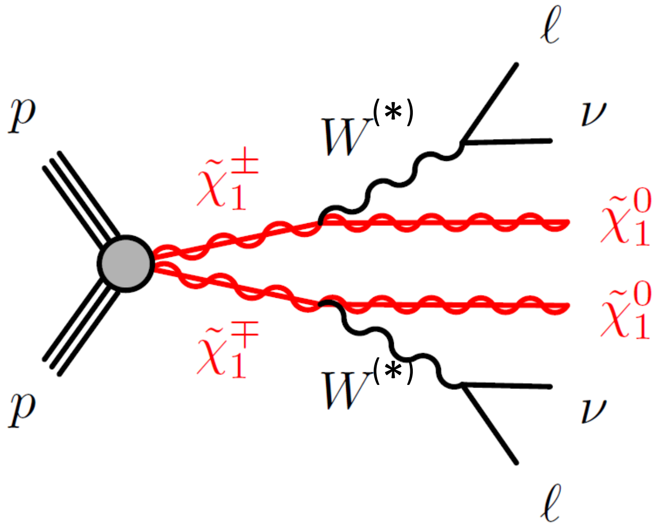
Update from initial presentation on Nov 18th :
https://indico.cern.ch/conferenceDisplay.py?confId=283785

Dark Matter production at pp collider

For today, assuming: WIMP dark matter = SUSY neutralino (χ^0_1)

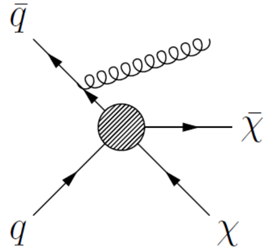


strong production



electroweak production

More DM models shall be considered (*e.g.* effective contact operators)



$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}, \qquad \text{(vector, } s\text{-channel)} \qquad (1)$$

$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}, \qquad \text{(axial vector, } s\text{-channel)} \qquad (2)$$

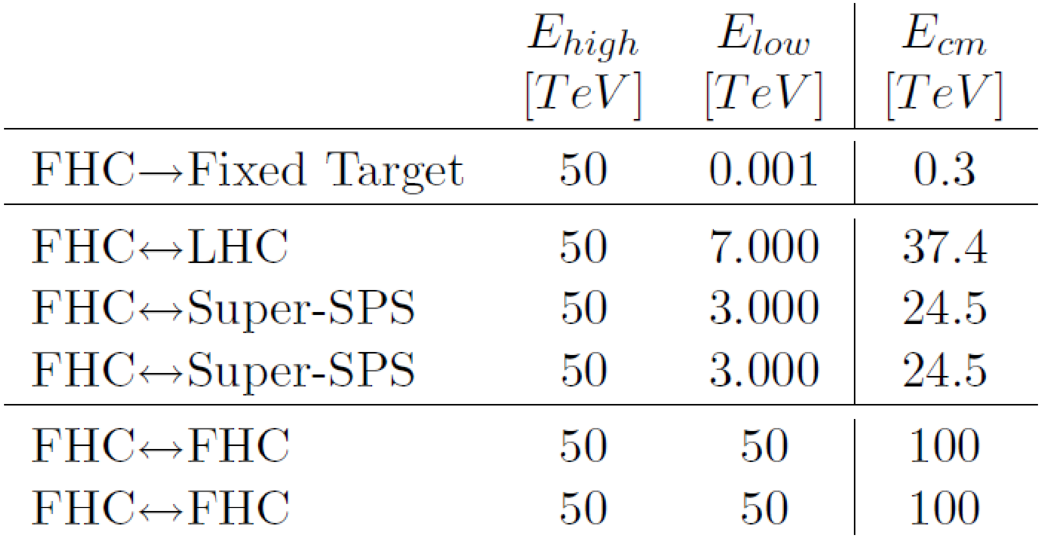
$$\mathcal{O}_t = \frac{(\bar{\chi}P_R q)(\bar{q}P_L\chi)}{\Lambda^2} + (L \leftrightarrow R), \qquad \text{(scalar, } t\text{-channel)} \qquad (3)$$

Explicit benchmark SUSY scenario

- Model #9515 from pMSSM scan [arXiv:1307.8444]
  - survive all experimental constraints to date
  - dark matter relic density compatible with WMAP
    - “Well-Tempered” bino-higgsino scenario
  - fine-tuning < 1% (i.e. “natural” SUSY)
  - dominated by electroweak production
  - probably discoverable in Run-2
    - m_N1 = 79.3 GeV
    - m_C1 = 105.6 GeV
    - m_N2 = 118.4 GeV
    - m_N3 = 138.9 GeV

Alternative models dominated by strong production will also be considered for next presentation…

Collider Configuration Options

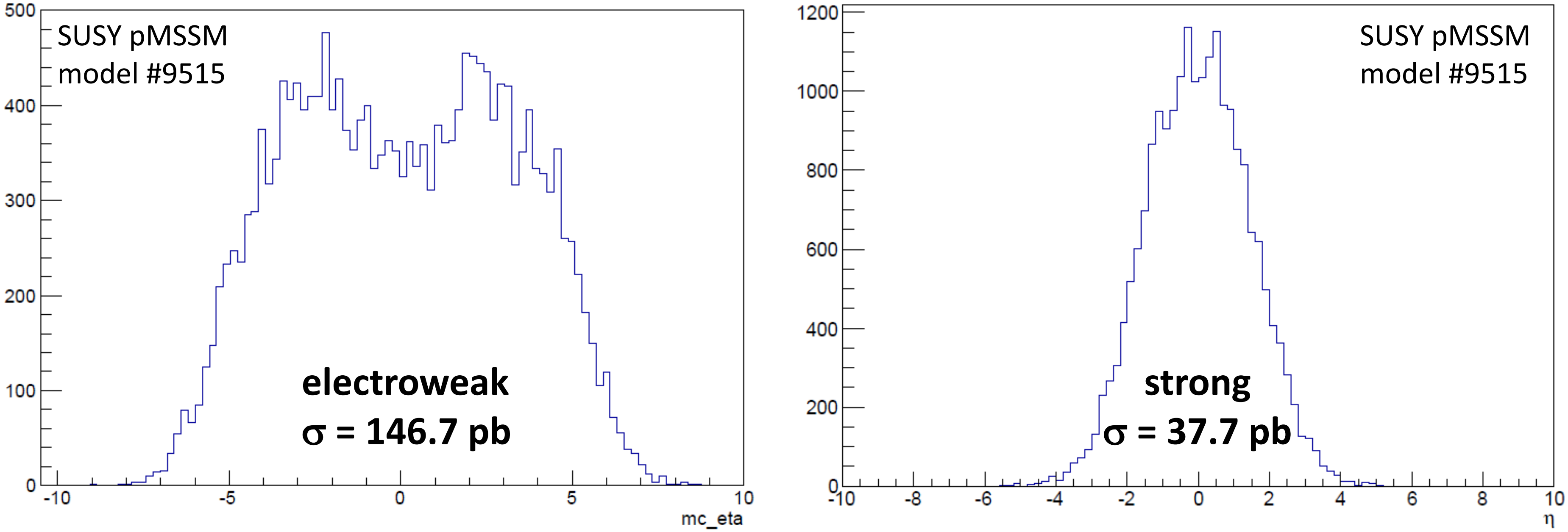


	E_{high} $[TeV]$	E_{low} $[TeV]$	E_{cm} $[TeV]$
FHC→Fixed Target	50	0.001	0.3
FHC↔LHC	50	7.000	37.4
FHC↔Super-SPS	50	3.000	24.5
FHC↔Super-SPS	50	3.000	24.5
FHC↔FHC	50	50	100
FHC↔FHC	50	50	100

- Fixed Target has insufficient E_{cm}
- Symmetric or Asymmetric colliders look promising

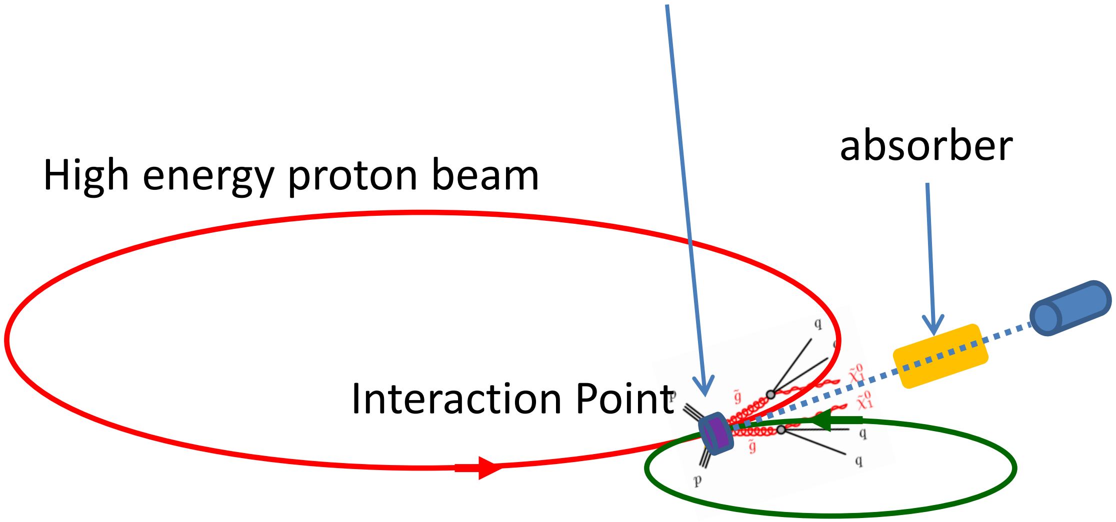
Symmetric collider

Pseudo-rapidity of χ^0_1 dark matter produced by symmetric pp collisions @ E_{CM}=100 TeV



detector position (z)	detector eta range (radius= 1m - 10m)		electroweak coverage	strong coverage
15m	η=1.19	η=3.40	22% (40%)	20%
35m	η=1.97	η=4.25	22% (33%)	9%
60m	η=2.49	η=4.79	20% (27%)	4%
100m	η=3.00	η=5.30	18% (22%)	2%

Asymmetric Collider



near detector (TeV physics with boosted center of mass frame?)

absorber

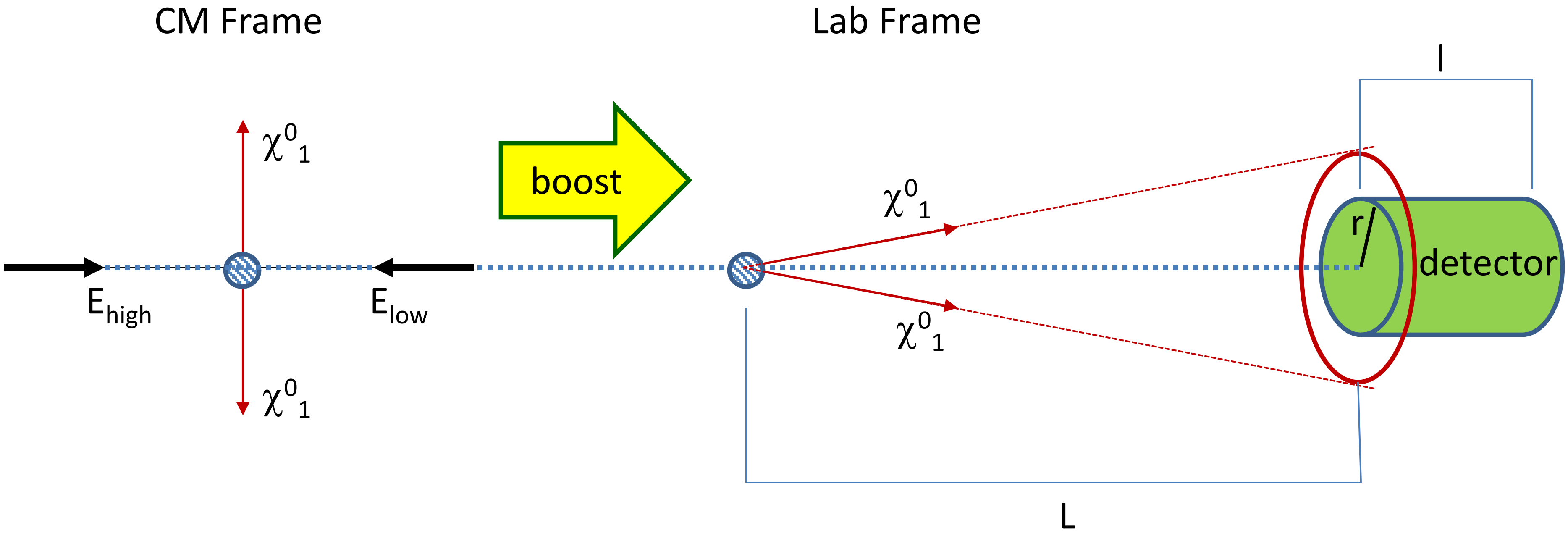
High energy proton beam

far detector(s)
- dark matter
- neutrinos

Interaction Point

Low energy proton beam

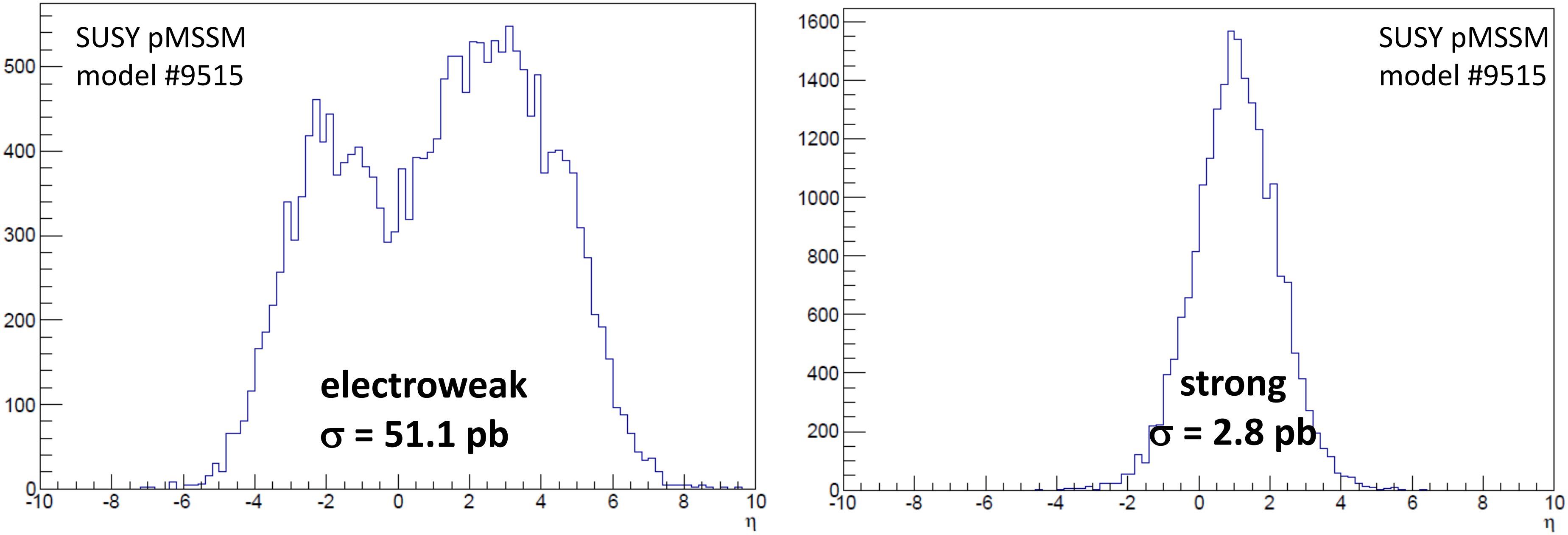
Boosted center of mass frame



Angular coverage depends on boost (E_{high}, E_{low}), distance (L) and radius (r).
Detection efficiency depends on depth (l).

Asymmetric collider: FHC↔LHC

Pseudo-rapidity of χ^0_1 dark matter produced by asymmetric pp collisions @ E_{CM}=37.4 TeV



detector position (z)	detector eta range (radius= 1m - 10m)		electroweak coverage	strong coverage
15m	η=1.19	η=3.40	28% (53%)	42% (44%)
35m	η=1.97	η=4.25	28% (43%)	21% (21%)
60m	η=2.49	η=4.79	26% (37%)	10% (10%)
100m	η=3.00	η=5.30	24% (29%)	4% (4%)

Asymmetric *vs* Symmetric

Flux on detector for $\mathscr{L}=10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and pMSSM model #9515

	electroweak production		**strong production**	
	symmetric **FHC↔FHC**	**asymmetric** **FHC↔LHC**	**symmetric** **FHC↔FHC**	**asymmetric** **FHC↔LHC**
cross-section	147 pb	51 pb	38 pb	3 pb
neutralino flux	2.9 χ/s	1.0 χ/s	0.8 χ/s	0.06 χ/s
coverage	18-40%	24-53%	2-20%	4-44%
flux on detector	0.5-1.2 χ/s	0.2-0.5 χ/s	0.02-0.2 χ/s	0.03 – 0.3 χ/s

Note: the WIMP-detector cross-section downstream has a strong energy dependence which is not yet taken into account.

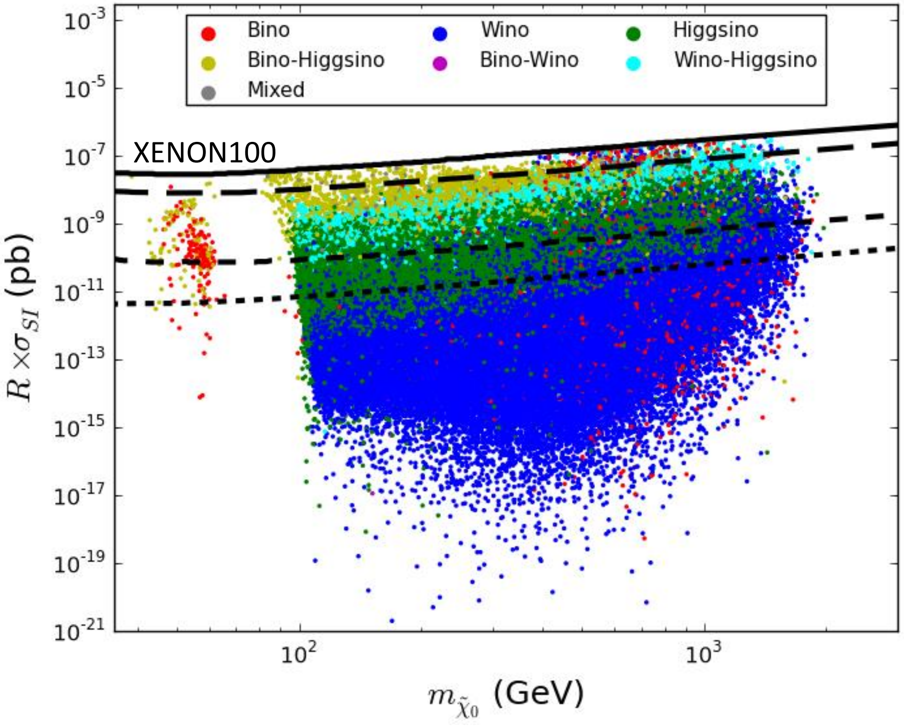
$\Rightarrow$ this will probably favor an asymmetric configuration

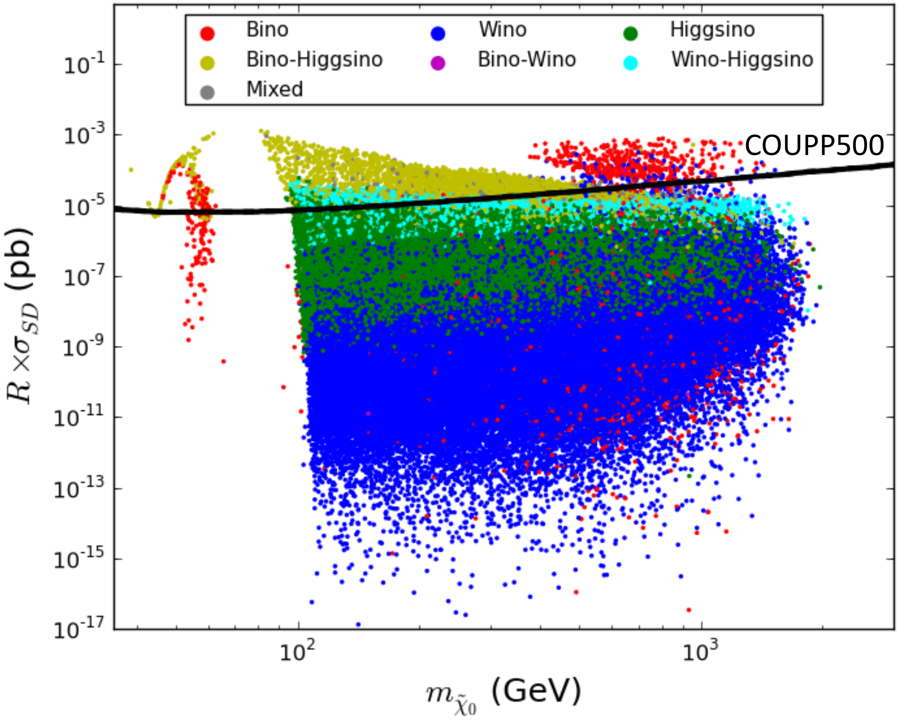
Dark Matter Detector

in the TeV regime…

WIMP-nucleon cross-section @ keV

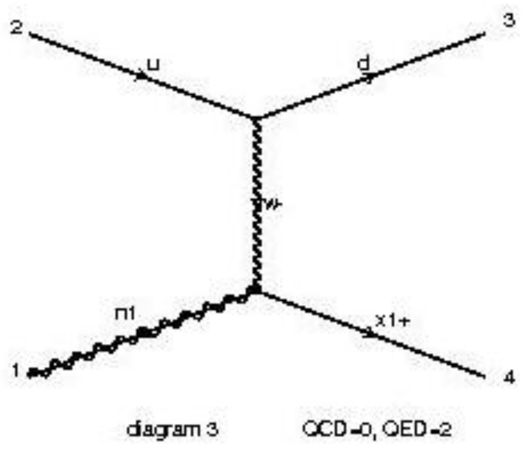
arXiv:1305.6921

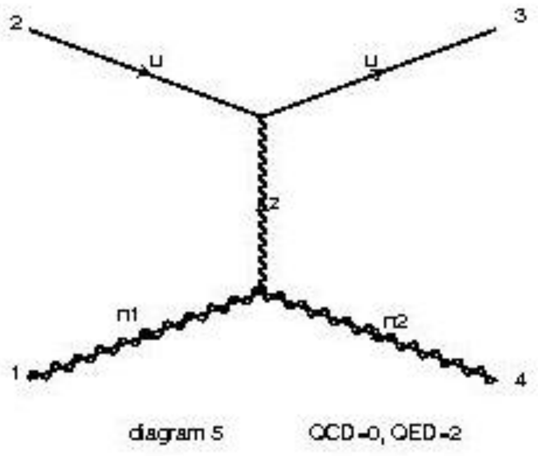


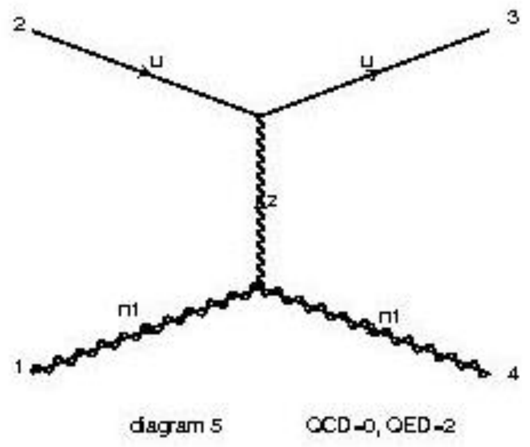


- WIMP interactions provoke nucleus recoils in the keV regime, with $\sigma < 10^{-3}$ pb

WIMP-nucleon cross-section @ TeV







σ = 17.5 pb

σ = 4.5 pb

σ = 1.0 pb

pMSSM model #9515 at 43 TeV (FHC↔LHC)

Parton interactions leaving W$^{(*)}$+jet and Z$^{(*)}$+jet signatures!

- larger (energy-dependent) cross-sections
- completely different detector design

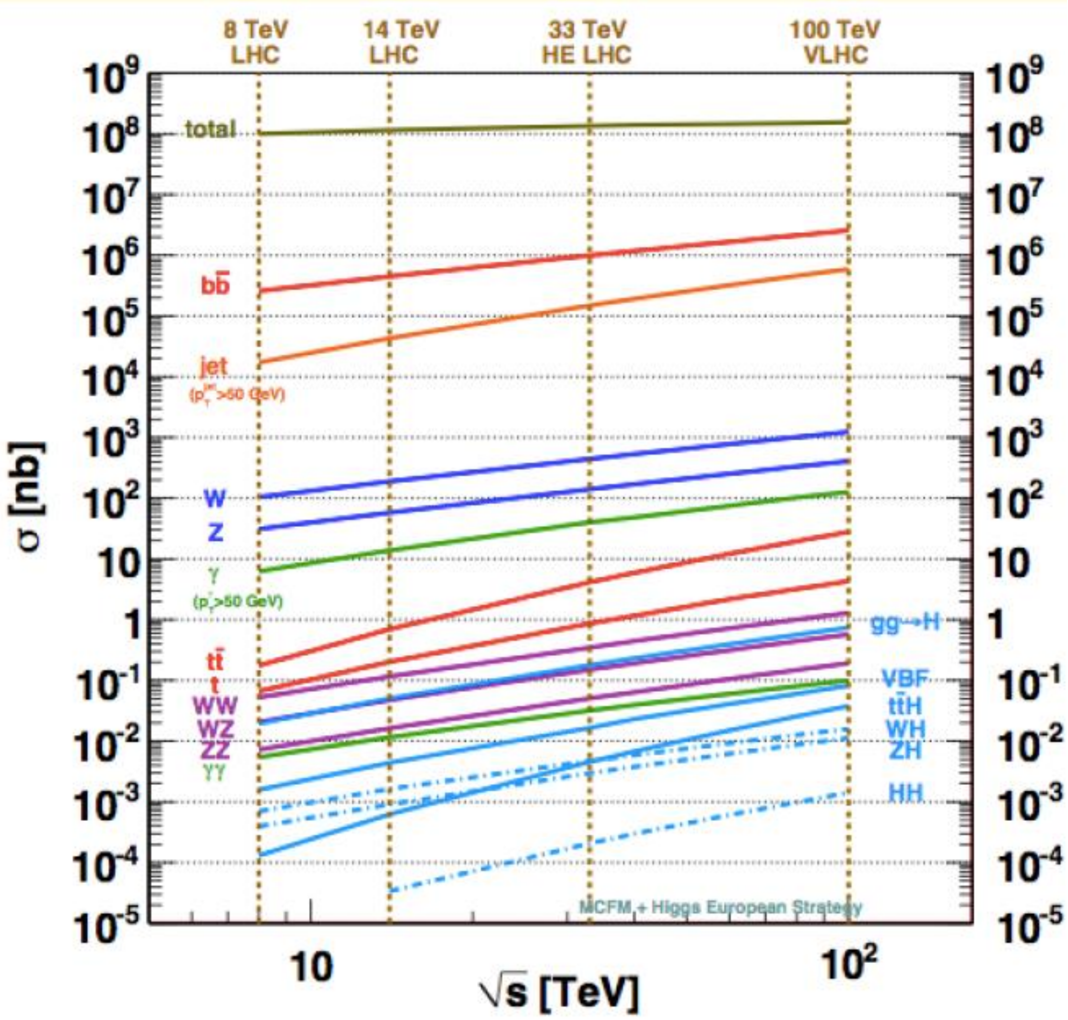
Neutrino Flux

The inclusive neutrino cross-section is basically equal to the total pp cross-section:

- $\sigma_\nu = \sim 10^8$ nb

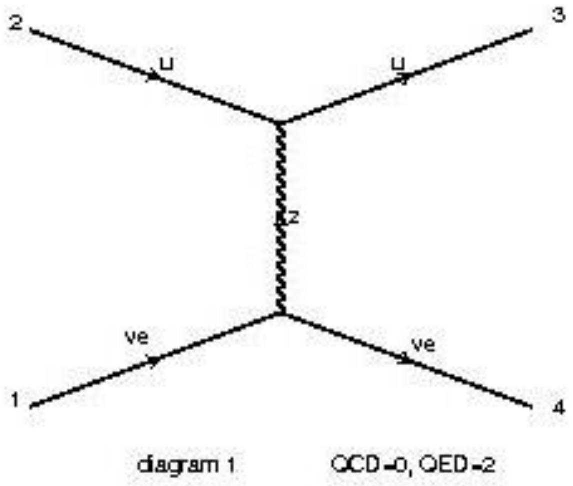
Flux for $\mathscr{L} = 10^{34}$ cm^{-2}s^{-1} :

- $\sim 10^{12}$ neutrinos/s



Neutrino interaction with detector

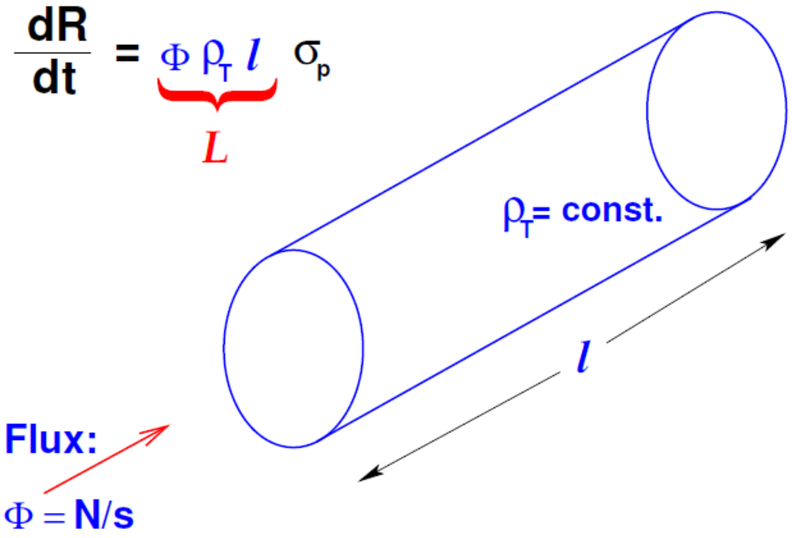
- Cross-sections @ 43 TeV (FHC↔LHC)
  - – ν_e: 46.0 pb
  - – ν_μ: 46.0 pb
  - – ν_τ: 47.0 pb
  - – anti-ν_e: 48.8 pb
  - – anti-ν_μ: 48.8 pb
  - – anti-ν_τ: 46.3 pb



Energy dependence of WIMP & neutrino interactions with detector

- WIMP (model #9515):
  - σ = 23 @ 43 TeV (asymmetric FHC↔LHC)
  - σ = 11 pb @ 27 TeV
  - σ = 2 pb @ 12 TeV
  - σ = 10^{-7} pb @ 2 TeV (symmetric FHC)
- Electron neutrino (SM):
  - σ = 46 @ 43 TeV (asymmetric FHC↔LHC)
  - σ = 30 pb @ 27 TeV
  - σ = 12 pb @ 12 TeV
  - σ = 0.08 pb @ 2 TeV (symmetric FHC)

Interaction Rate



$$\frac{dR}{dt} = \underbrace{\Phi \, \rho_T \, l}_{L} \; \sigma_p$$

For 10m detector made of copper:

- $\rho = 5.4 \times 10^{24}$ nucleons cm^{-3}

WIMP (model #9515) @ FHC↔LHC

- $\Phi = 0.5$ s^{-1}
- $\sigma = 23$ pb
- rate = 2 hits/year

Neutrinos @ FHC↔LHC

- $\Phi = 10^{12}$ s^{-1}
- $\sigma = 47$ pb
- rate = ~200k hits/second (?!)

To-do:

- consider different SUSY model with much stronger production cross-section
- in any case, neutrino background will be overwhelming!
  $\Rightarrow$ can we exploit it for neutrino physics?

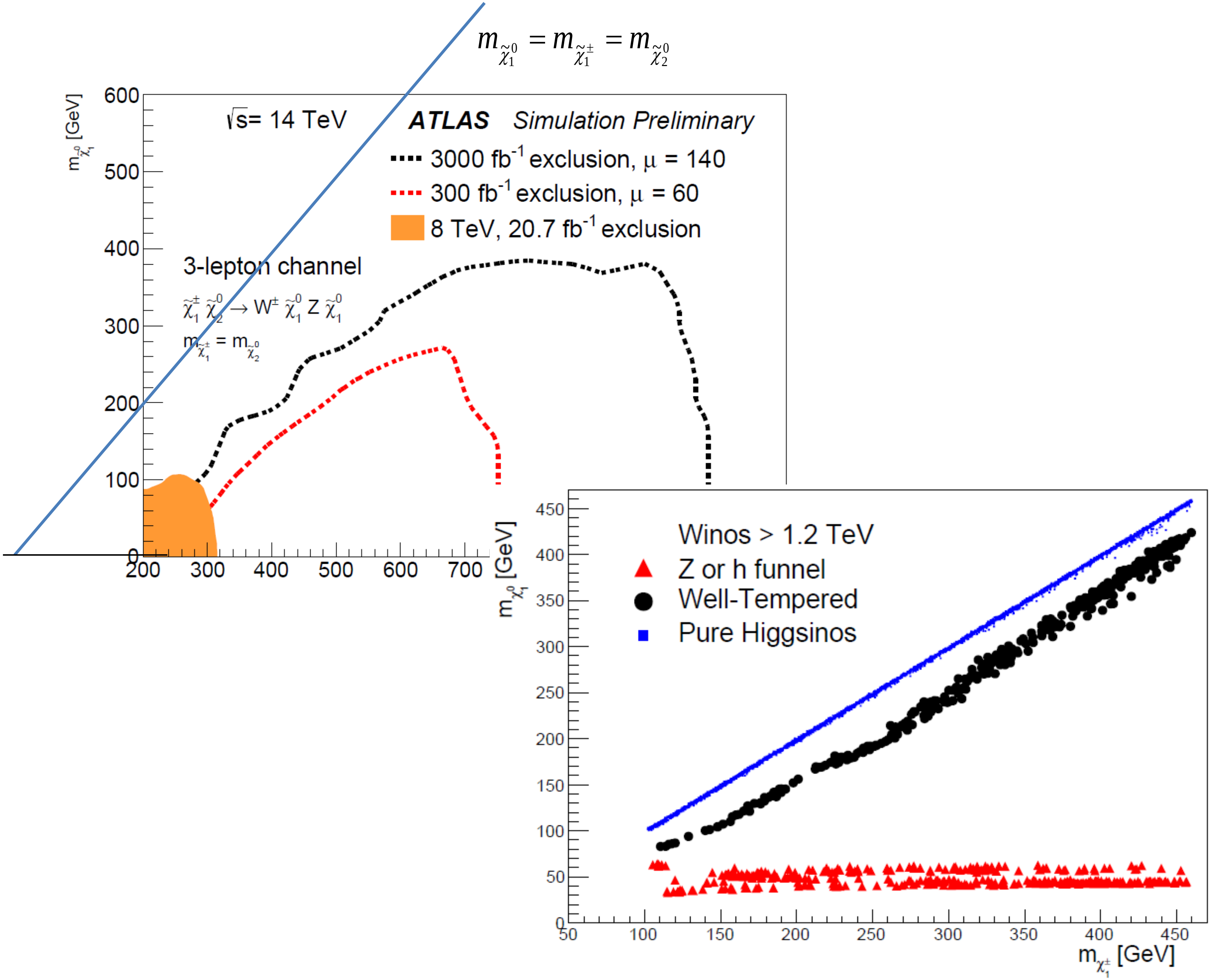
Thoughts about detector requirements

- Didn’t spend enough time on this yet…
- Detector will need to have:
  - largest amount of material to increase WIMP rate
  - largest possible surface to increase geometric coverage
  - ability to identify signal jets
- WIMP *vs* neutrino separation will be challenging
  - identify WIMP from unique Z* and W* signature
  - maybe use time-of-flight information?
    - for neutralino masses of 50 GeV – 1 TeV:
      - $\Delta_{TOF}(\nu,\chi)$ = 0.1 – 45 picosecond for distance of 60 meters
      - $\Delta_{TOF}(\nu,\chi)$ = 1.9 – 755 picosecond for distance of 1000 meters

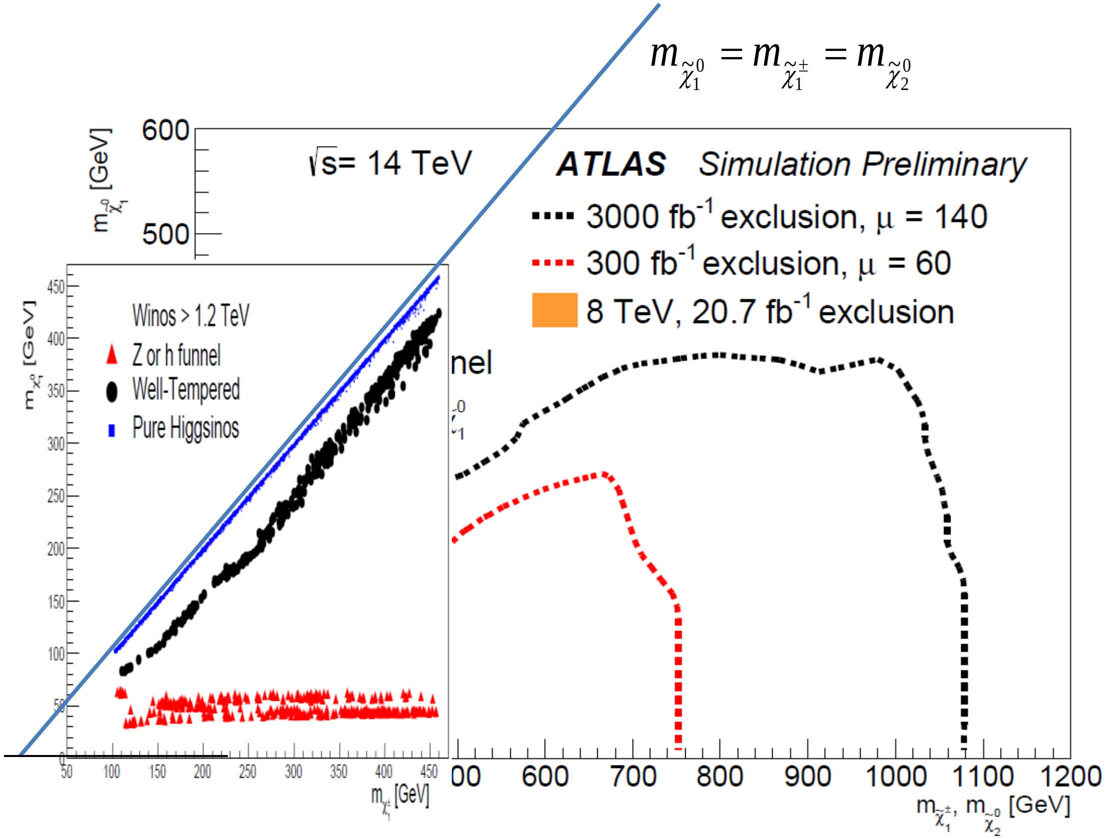
Summary & Outlook

- Started to explore the concept of Dark Matter Beam experiments in the context of FHC
  - symmetric or asymmetric colliders are compared
    - large neutrino flux: interesting study for itself?
  - used an explicit benchmark SUSY model
    - getting sufficient WIMP flux is challenging
      - more models will be studied
  - parton interaction of WIMP & ν with detector
    - strong energy dependence of the cross-section
      - neutrino: jet signature
      - WIMP: W*+jet and Z*+jet signature
  - a new type of dark matter detector design is required

Backup Material



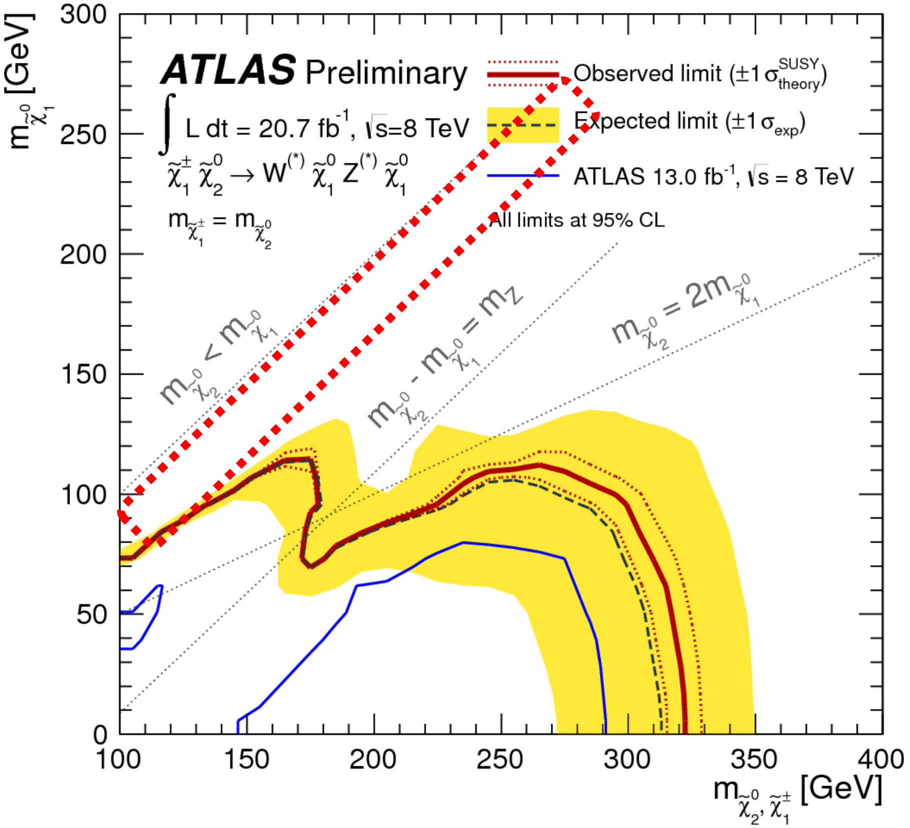
$$m_{\tilde{\chi}_1^0} = m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_2^0}$$

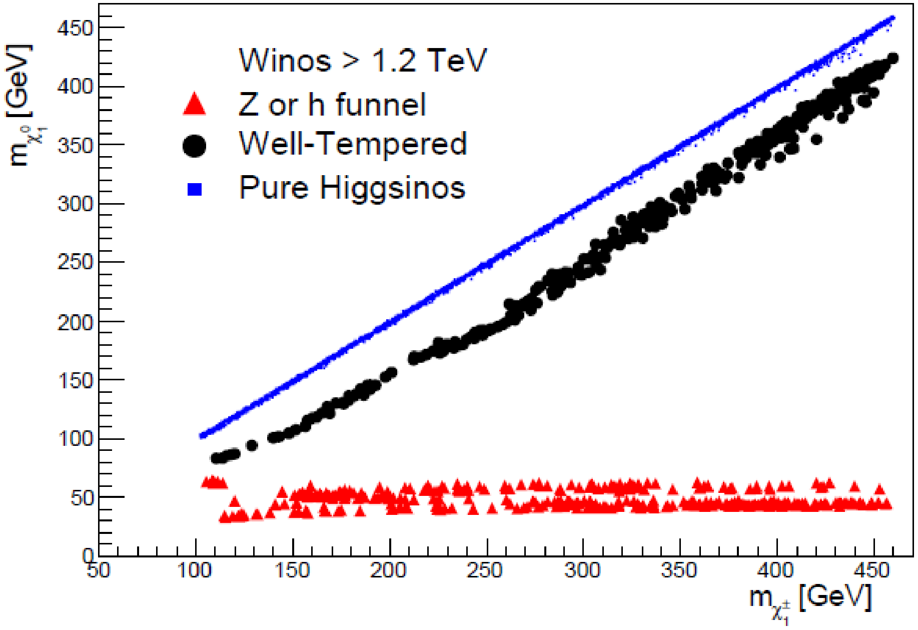


$$m_{\tilde\chi_1^0} = m_{\tilde\chi_1^\pm} = m_{\tilde\chi_2^0}$$

“Invisible” SUSY scenarios

electroweak production



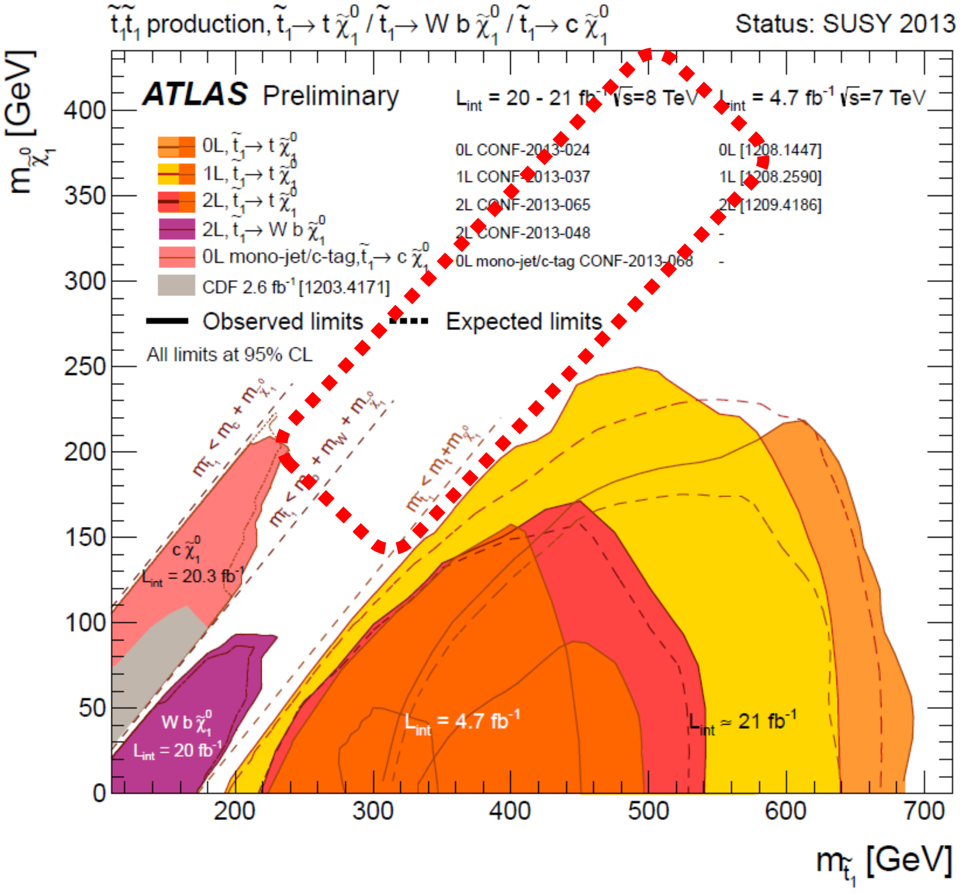


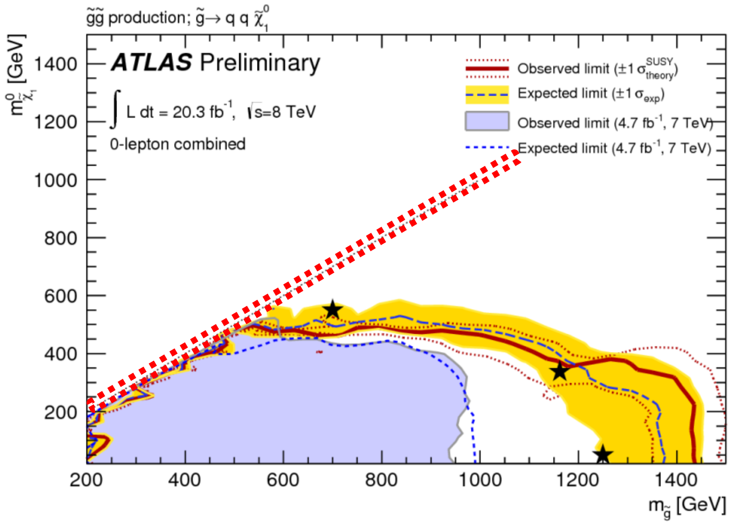
So-called “compressed scenarios” with small ΔM(initial SUSY particle, LSP) could be invisible in ATLAS/CMS but observable with a dark matter detector.

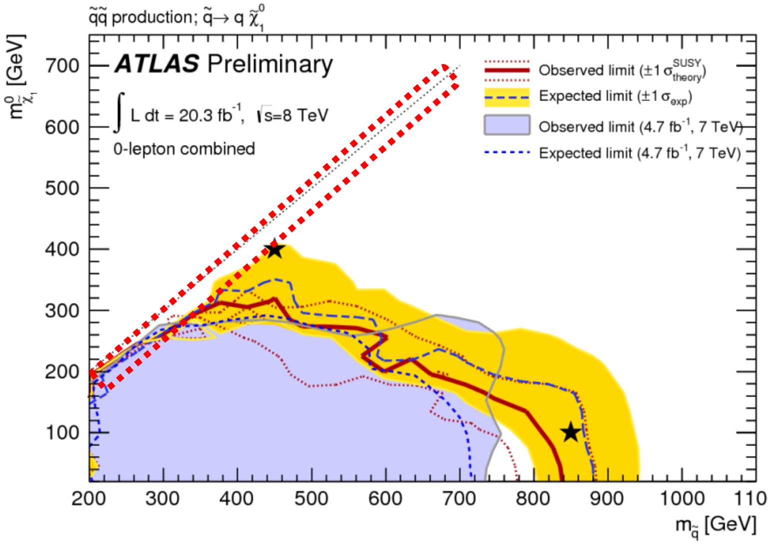
*limits assume largest (pure Wino) cross-section

“Invisible” SUSY scenarios

strong production







So-called “compressed scenarios” with small ΔM(initial SUSY particle, LSP) could be invisible in ATLAS/CMS but observable with a dark matter detector.

*limits assume 100% Branching Fraction