

Dark Matter at a Future Hadron Collider

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Future Circular Collider Study Kickoff Meeting



UNIVERSITÉ
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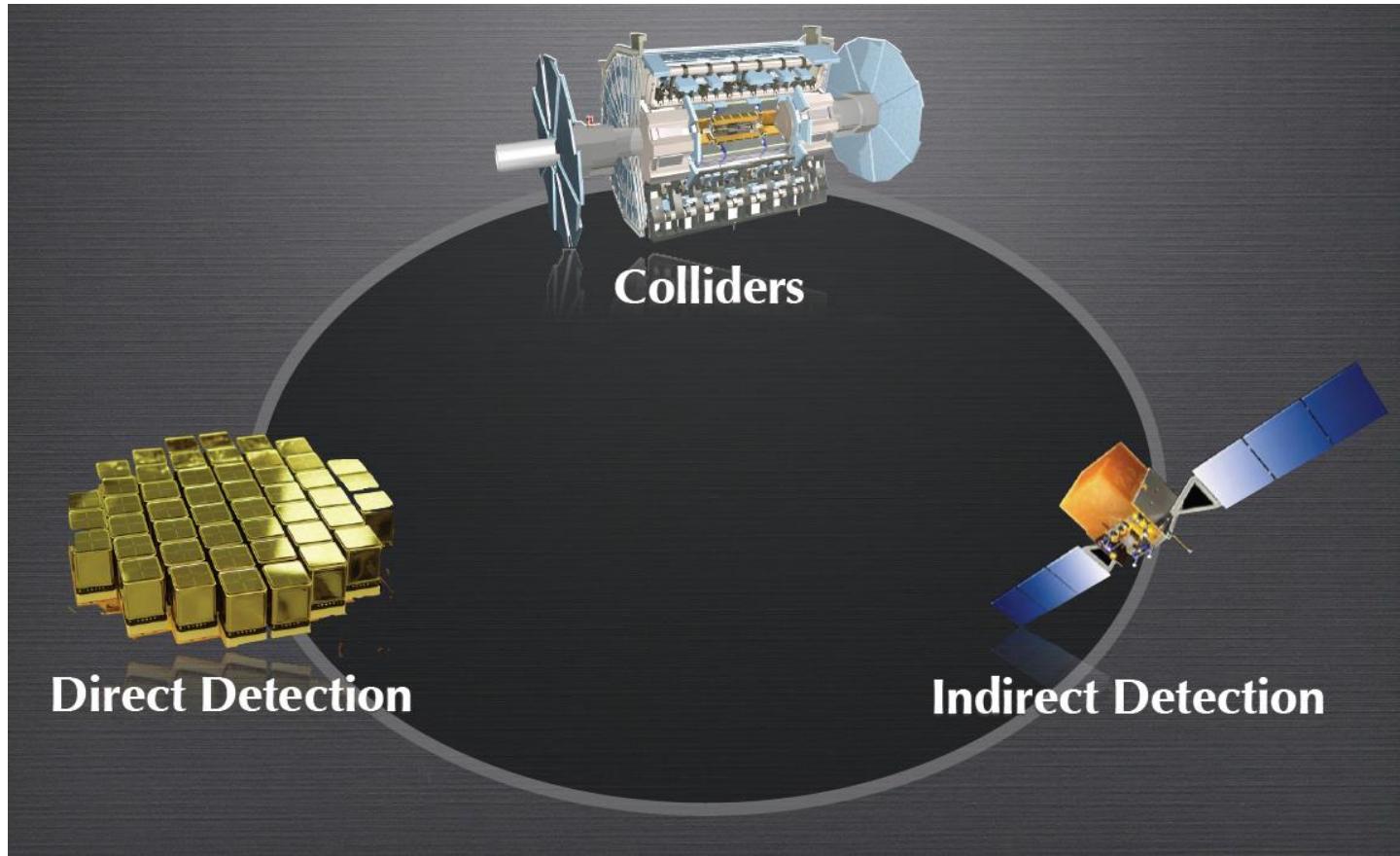


Overview

- Introduction: dark matter at colliders
- Searches for electroweak SUSY with E_T^{miss}
- Dark matter beam & detector

Disclaimer: all results are very preliminary!

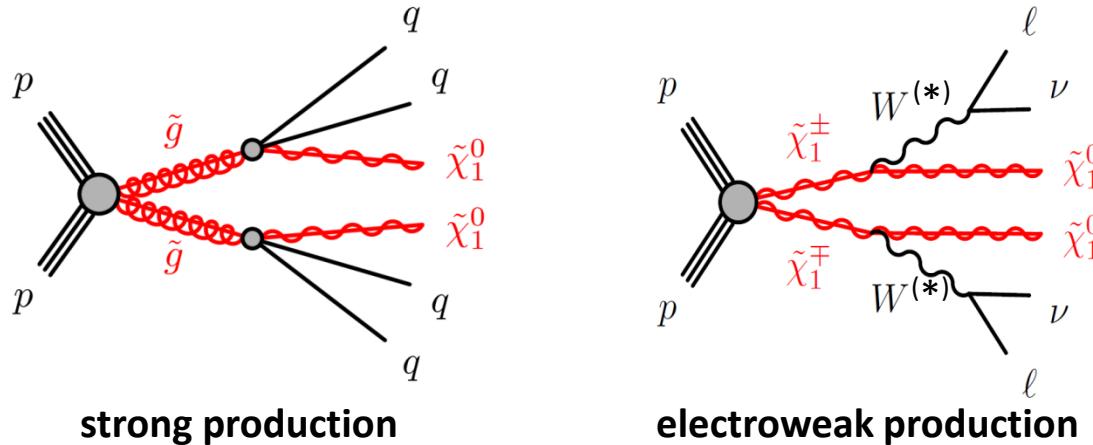
Complementary Dark Matter Searches



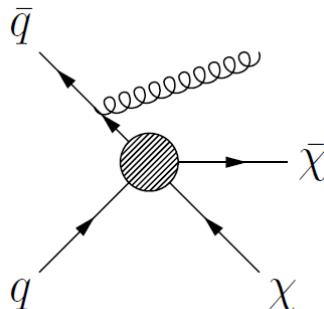
credits: G. Bertone

Dark Matter production at pp collider

SUSY: lightest neutralino ($\tilde{\chi}_1^0$) is WIMP dark matter candidate



Effective Contact Operators



$$\mathcal{O}_V = \frac{(\bar{\chi} \gamma_\mu \chi)(\bar{q} \gamma^\mu q)}{\Lambda^2}, \quad (1)$$

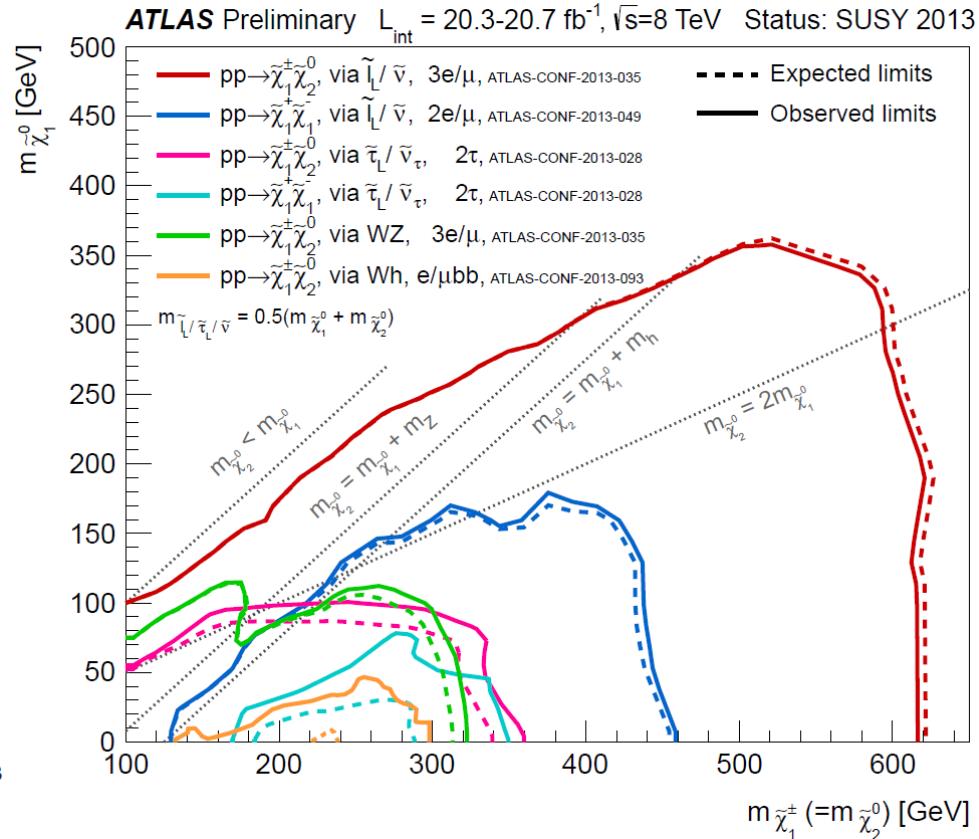
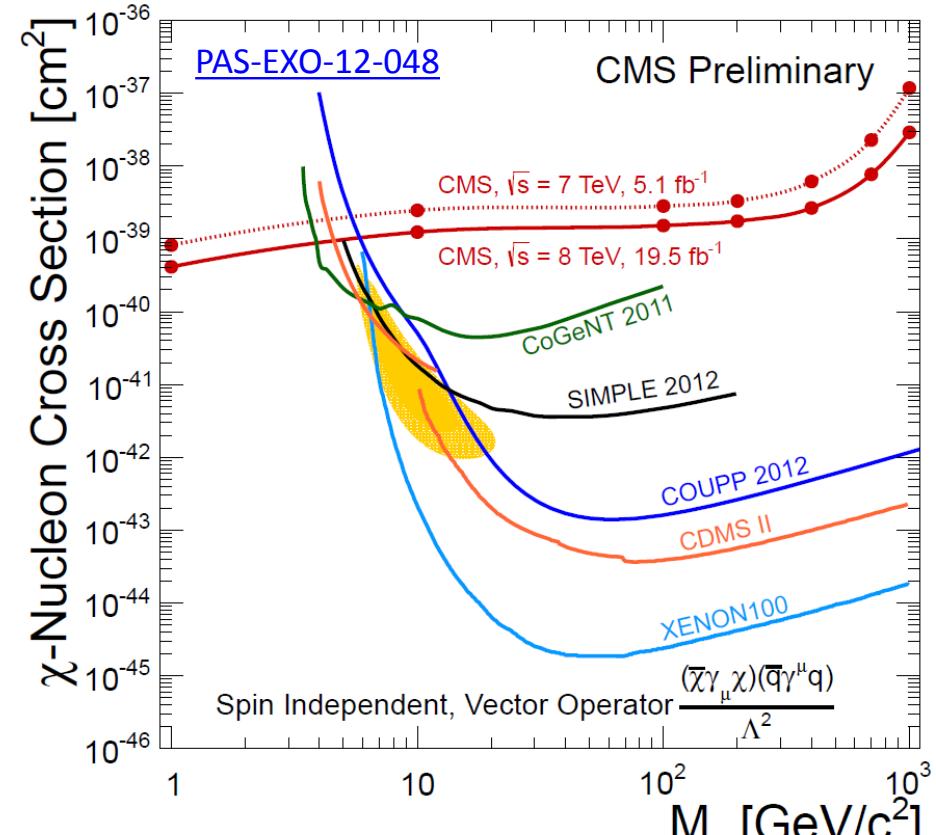
$$\mathcal{O}_A = \frac{(\bar{\chi} \gamma_\mu \gamma_5 \chi)(\bar{q} \gamma^\mu \gamma_5 q)}{\Lambda^2}, \quad (2)$$

$$\mathcal{O}_t = \frac{(\bar{\chi} P_R q)(\bar{q} P_L \chi)}{\Lambda^2} + (L \leftrightarrow R), \quad (3)$$

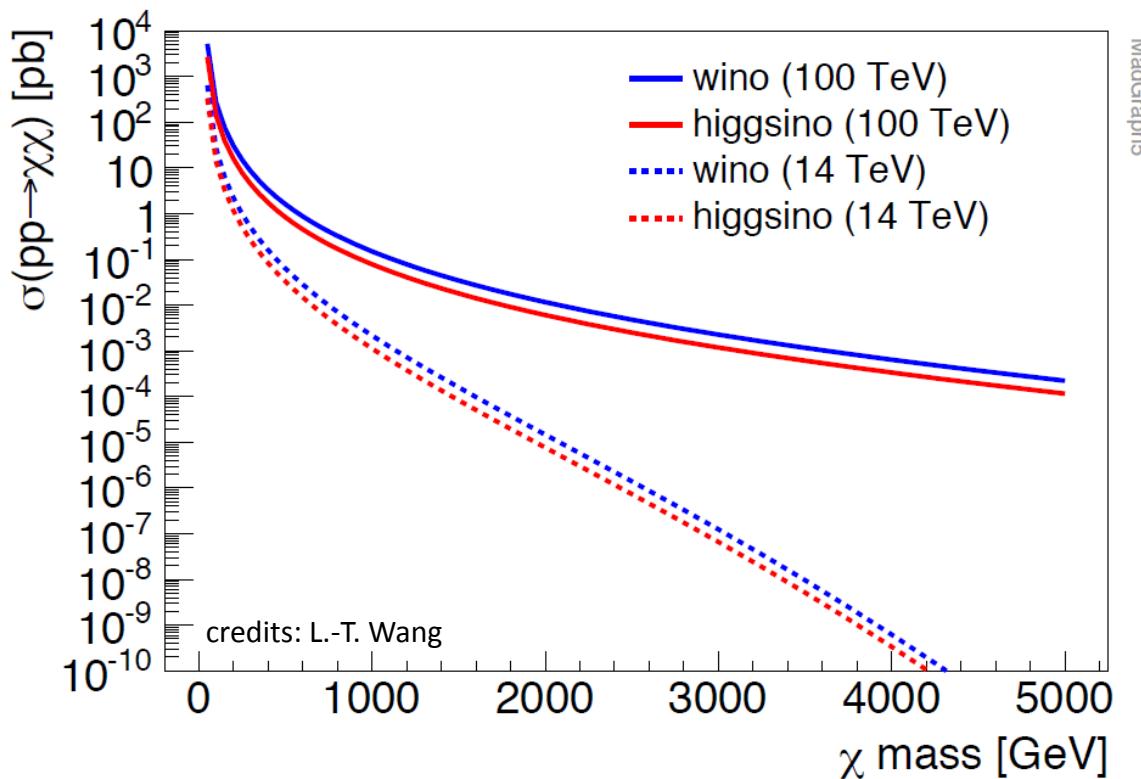
[Phys. Rev. D85 \(2012\) 056011](#)

Assumption: “heavy messenger”

Results from LHC @ 8 TeV



Electroweak SUSY @ 100 TeV

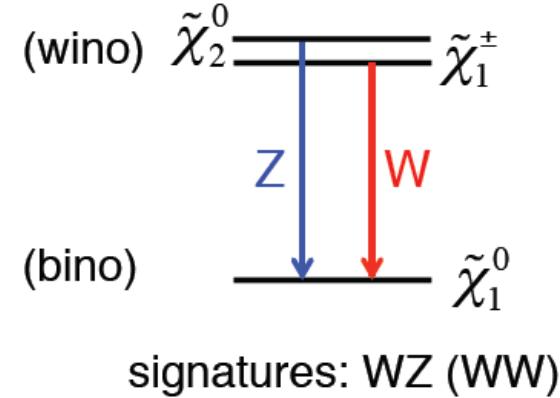
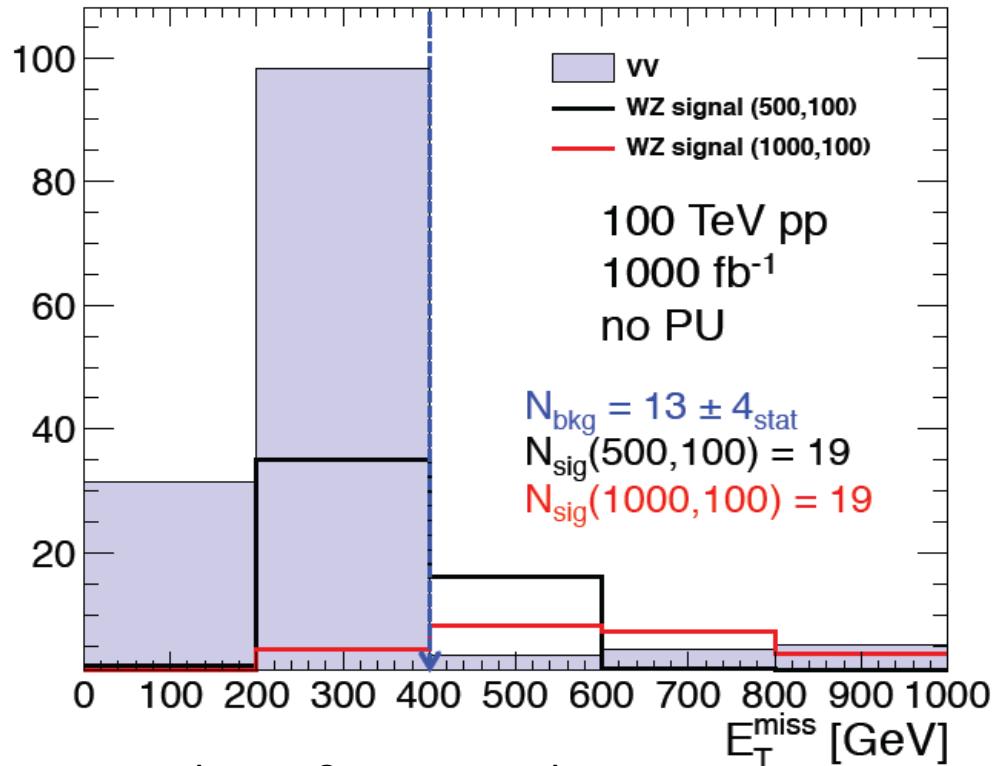


Expecting large improvements!

A few studies already:

- [BSM physics opportunities at 100 TeV](#)
- [LPC meeting on future 100 TeV proton collider](#)

$\chi^0_2 \chi^\pm_1 \rightarrow 3 \text{ leptons} + E_T^{\text{miss}}$ @ 100 TeV



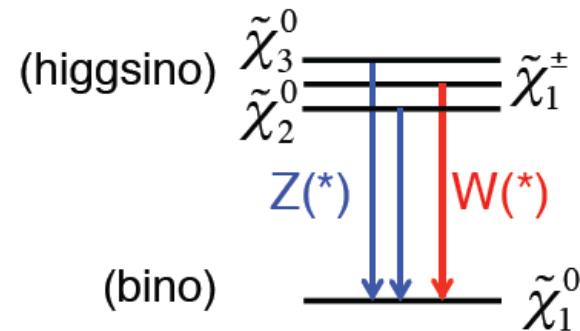
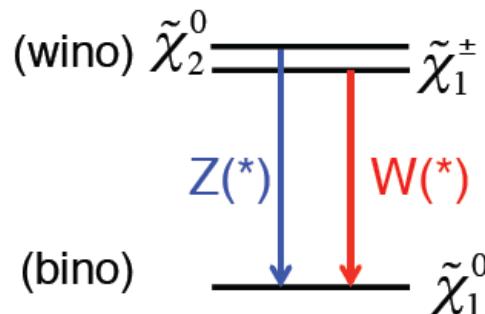
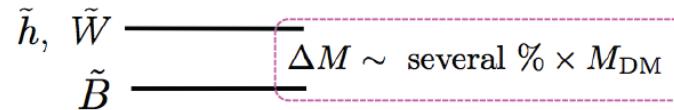
Benchmark simplified model
used by ATLAS & CMS for Run-1.

- Simple cut & count analysis
 - require: exactly 3 leptons ($p_T > 20$ GeV), large E_T^{miss} , jet veto, $M_T >> m_W$
 - main background: WZ+jet
- Signal MC: privately produced pythia8+Delphes with no pile-up
- Background MC: [100 TeV Snowmass](#) Delphes samples
- Preliminary studies look promising for ~1 TeV winos in this scenario

Interesting electroweak SUSY models (I)

Well-Tempered Neutralino

a “realistic” dark matter scenario.

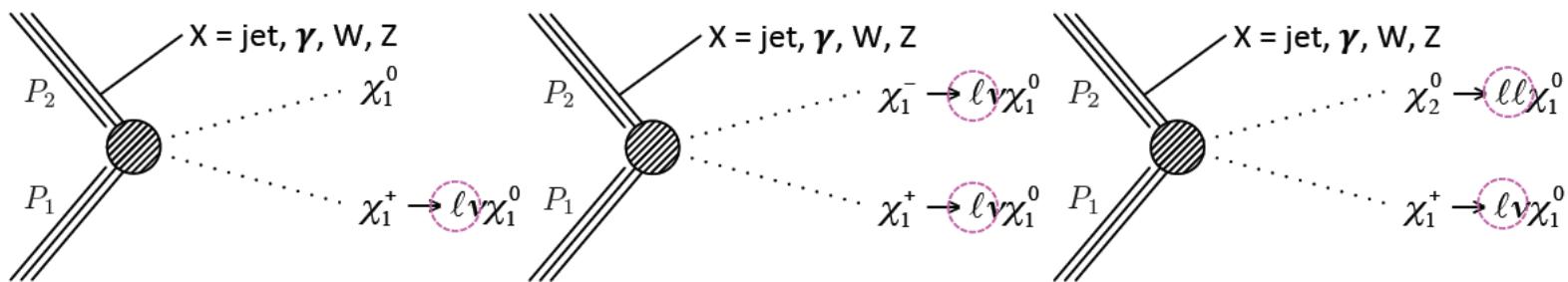
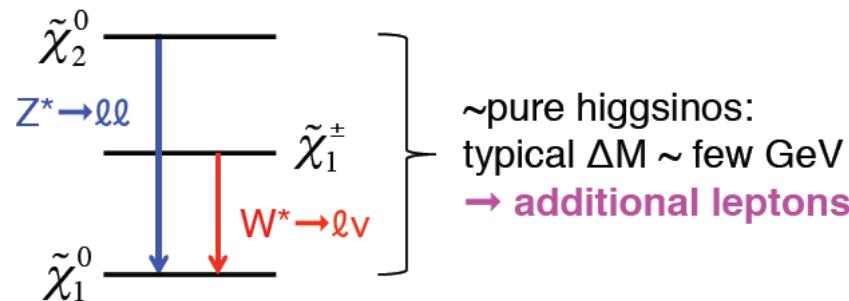


- The “well-tempered neutralino” scenario requires small ΔM values
- Extend WZ search to off-shell W/Z bosons with lower p_T leptons (also softer E_T^{miss} , so more challenging)

Interesting electroweak SUSY models (II)

Pure Higgsino scenario

motivated by SUSY naturalness.

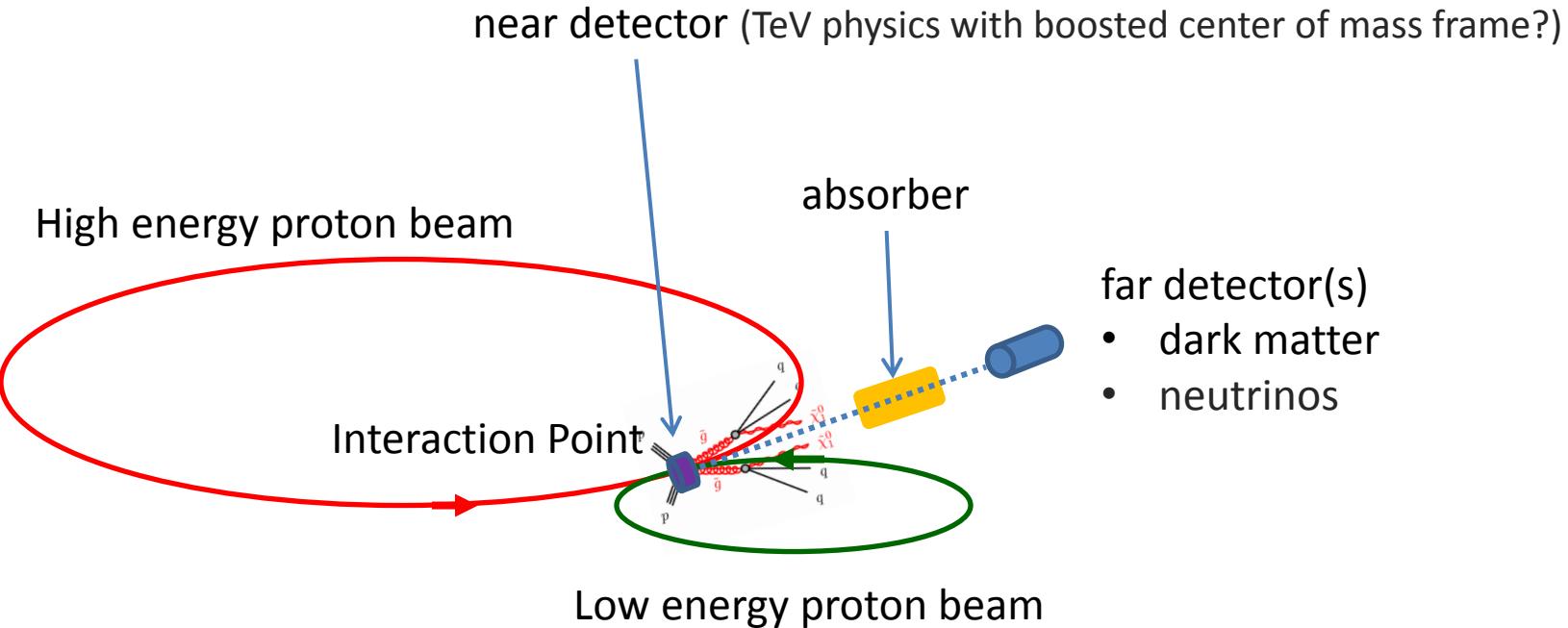


- Augment mono-X searches with additional leptons to improve sensitivity to wino & higgsino DM?
 - Probe as low in lepton p_T as possible to target small ΔM

Dark Matter Detector @ FHC

- Assume that dark matter (DM) is produced by the future collider, study the possibility of adding a new type of detector to perform a direct observation of DM interaction with ordinary matter
 - controlled DM production and detection under laboratory conditions!
 - unique unambiguous identification of dark matter
 - direct detection from space: don't know the origin of the observed signal
 - E_T^{miss} signature: don't know the nature of the un-detected particle(s)
 - if successful, such a detector would allow:
 - absolute measurement of dark matter interaction cross-section
 - possible measurement of dark matter mass from time-of-flight
 - possibly find scenarios where dark matter is invisible for ATLAS & CMS but visible through direct detection
 - bread & butter neutrino physics in the TeV regime
- Two possible experimental setups:
 - symmetric collider
 - asymmetric collider producing a dark matter beam

DM Beam from Asymmetric Collider

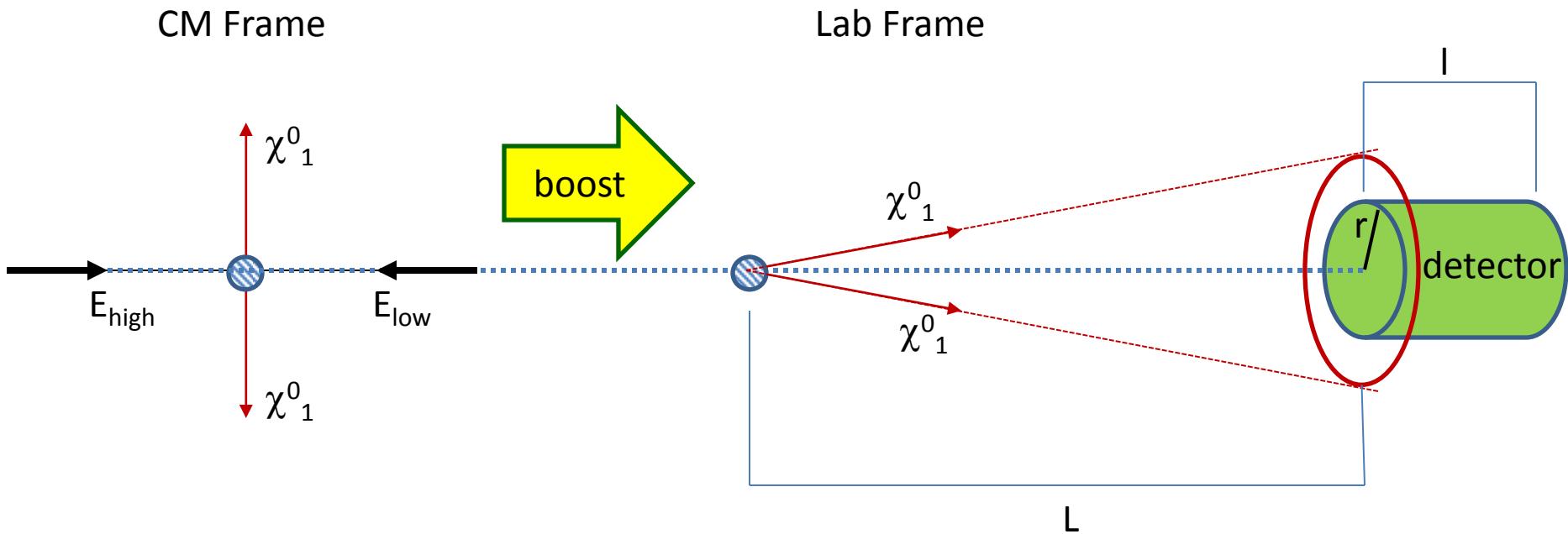


	E_{high} [TeV]	E_{low} [TeV]	E_{cm} [TeV]
FHC→Fixed Target	50	0.001	0.3
FHC↔LHC	50	7.000	37.4
FHC↔Super-SPS	50	3.000	24.5

insufficient E_{cm}

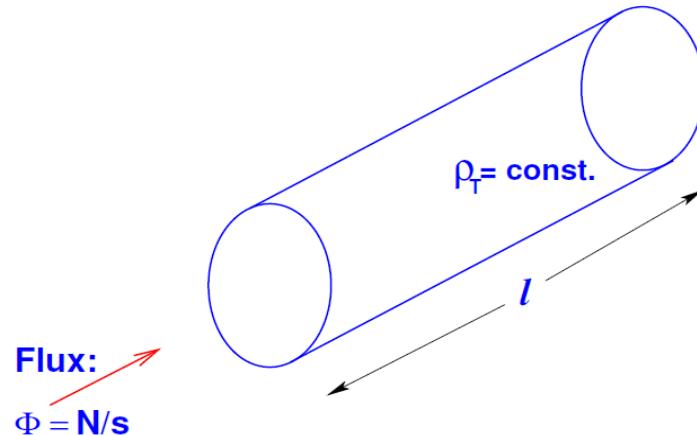
} promising!

Boosted center of mass frame



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

Dark Matter Interaction Rate



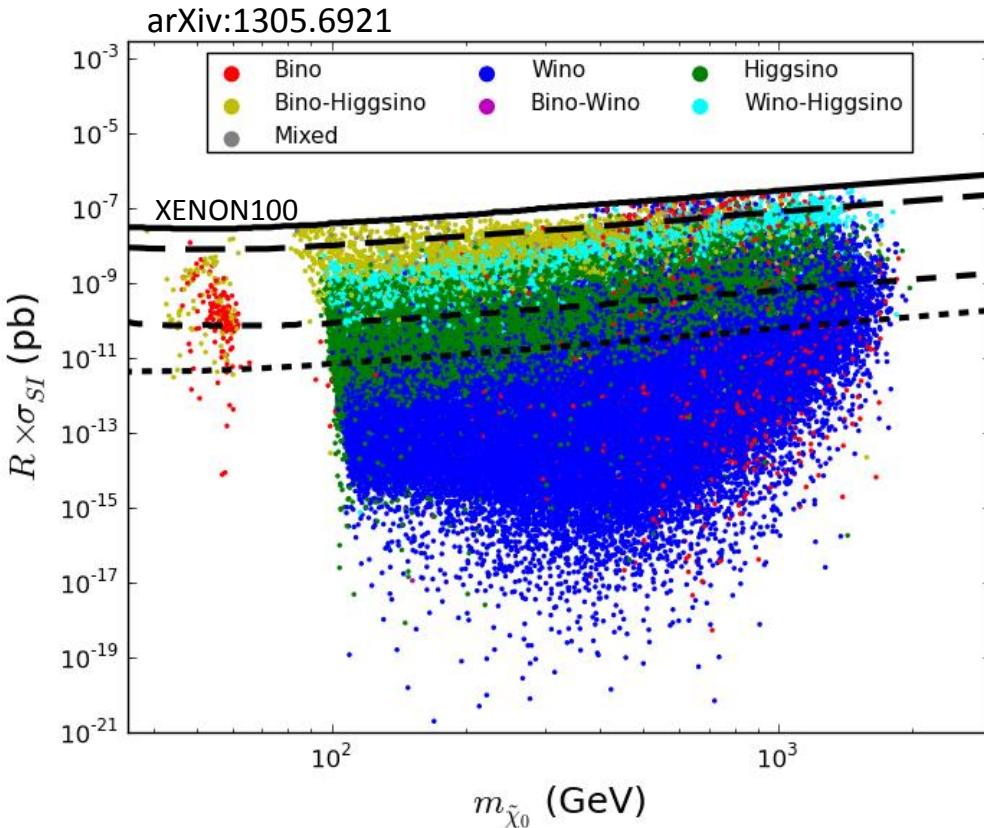
Number of dark matter signal hits on detector:

$$N_{\text{hits}} = \Phi_{\text{tot}}(E_{\text{CM}}) \cdot A \cdot l \cdot \rho_T \cdot \sigma_\chi(E_\chi) \cdot t$$

total DM flux from collider center-of-mass collider energy geometric acceptance of DM detector DM interaction cross-section time
w.r.t. detector

symmetric collider: more E_{CM} , less E_χ
asymmetric collider: less E_{CM} , more E_χ

Direct detection of DM from space



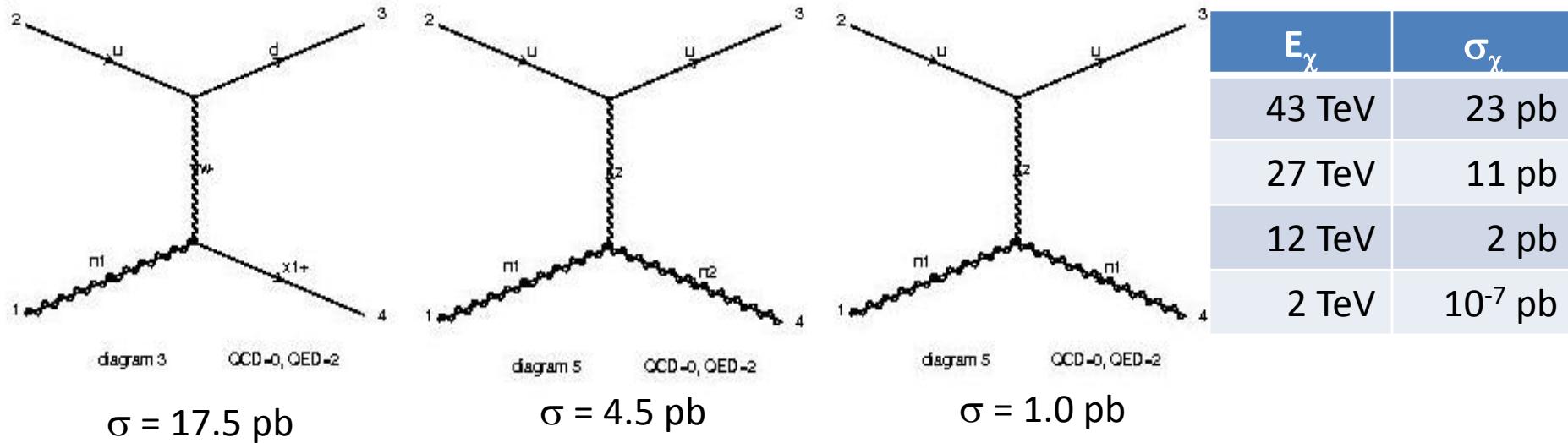
Dark Matter from space:

- Flux: $\Phi \approx 10^5 \text{ cm}^{-2}\text{s}^{-1}$
- Speed: $\sim 300 \text{ km/s}$
- Energy: $\sim 100 \text{ keV}$
- $\sigma_\chi = 10^{-8} - 10^{-15} \text{ pb}$

Large flux but tiny cross-sections.

Faint signal from nucleus recoil,
requiring ultra-low backgrounds.

Direct detection of DM from collider

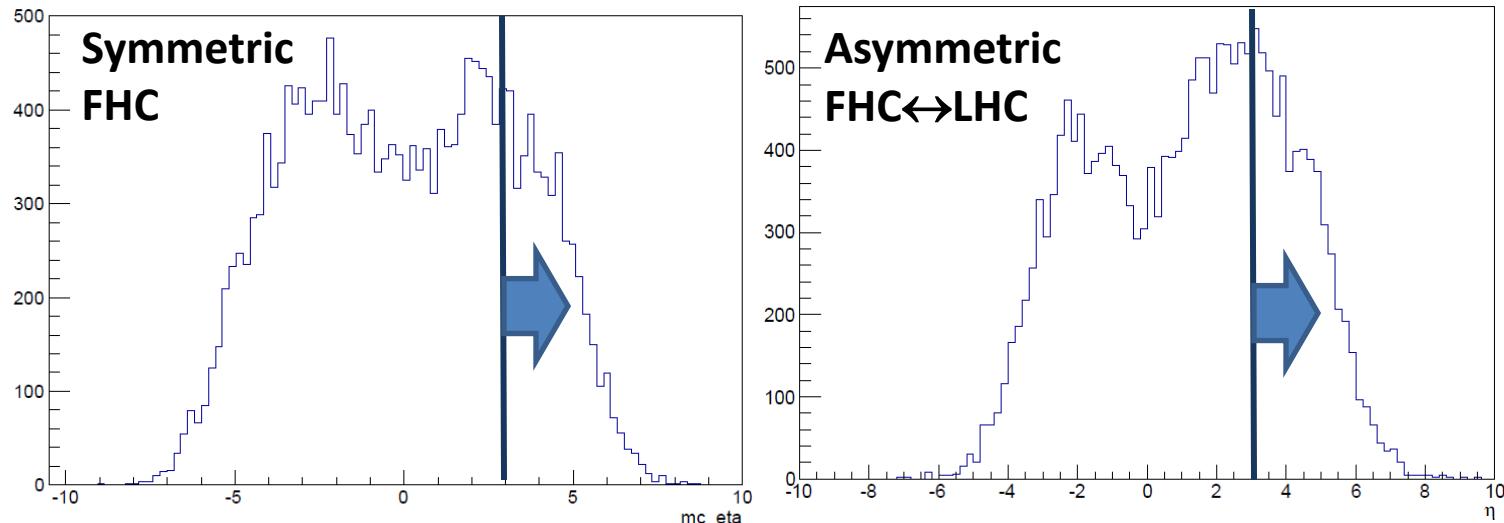


pMSSM model #9515 at 43 TeV (FHC \leftrightarrow LHC), see 1307.8444 and backup.

Inelastic parton interaction: jet, $W^{(*)}+j$, $Z^{(*)}+j$ signatures!

- dramatic cross-section increase w.r.t. nucleus recoil
 - strong energy dependence
- completely different detector design
 - look for jets + leptons instead of nucleus recoil

Symmetric vs Asymmetric Collider



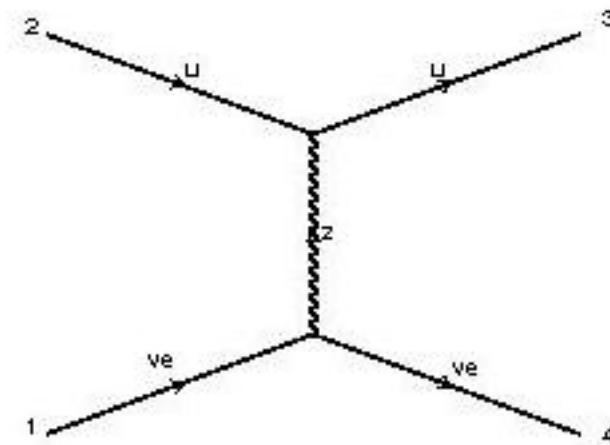
	symmetric FHC	asymmetric FHC↔LHC
collider luminosity	$10^{36} \text{ cm}^{-2}\text{s}^{-1}$	$10^{36} \text{ cm}^{-2}\text{s}^{-1}$
collider E_{cm}	100 TeV	37.4 TeV
SUSY production cross-section	147 pb	51 pb
detector acceptance (100m)	22%	29%
dark matter energy at detector	$\sim 2 \text{ TeV}$	$\sim 43 \text{ TeV}$
dark matter cross-section (σ_χ)	10^{-7} pb	23 pb
χ^0_1 in detector (10m copper)	3x10 ⁻⁹ signal hit/day	0.3 signal hit/day

Neutrino Background

- Challenging neutrino background in DM detector
- The inclusive neutrino cross-section is basically equal to the total pp cross-section!
 - orders of magnitude larger than dark matter flux
- Neutrino cross-section in detector also somewhat larger than neutralino
- Signature: mono-jet
 - but not $W^{(*)}+j$ or $Z^{(*)}+j$

E_ν	σ_ν
43 TeV	46 pb
27 TeV	30 pb
12 TeV	12 pb
2 TeV	0.08 pb

MadGraph5, electron neutrino



DM Detector Requirements

- Seems to require a new detector concept, with:
 - largest amount of material to increase WIMP rate
 - largest possible surface to increase geometric coverage
 - ability to identify signal jets
 - ability to identify leptons
 - ultra-precise timing
- Main background: neutrinos from collider
 - lepton identification: Z^*+j and W^*+j signature unique to dark matter
 - Time-Of-Flight: heavy χ_1^0 travel slower than nearly massless ν
 - TOF info could also be used for DM mass measurement
 - $\Delta_{\text{TOF}}(\nu, \chi) = 0.2 - 75$ picosecond ($m_\chi = 0.05 - 1$ TeV, detector at 100 m)
 - question: what is the technological limit on fast timing?
- Other backgrounds:
 - reduced with timing and direction with respect to collider

Summary

- FHC can be used to search for dark matter
- Searches for electroweak SUSY with E_T^{miss}
 - preliminary studies look promising for $\sim 1 \text{ TeV}$ winos
- Dark Matter beam and detector
 - DM production and detection in the laboratory
 - asymmetric collider seems necessary
 - sufficient E_{CM} for neutralino flux
 - maximize DM beam energy for cross-section in detector
 - dark matter signature: $W^{(*)} + \text{jet}$ and $Z^{(*)} + \text{jet}$
 - pointing towards a new detector concept

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
 - $m_{N1} = 79.3 \text{ GeV}$
 - $m_{C1} = 105.6 \text{ GeV}$
 - $m_{N2} = 118.4 \text{ GeV}$
 - $m_{N3} = 138.9 \text{ GeV}$

Many alternative models will be considered in future updates...