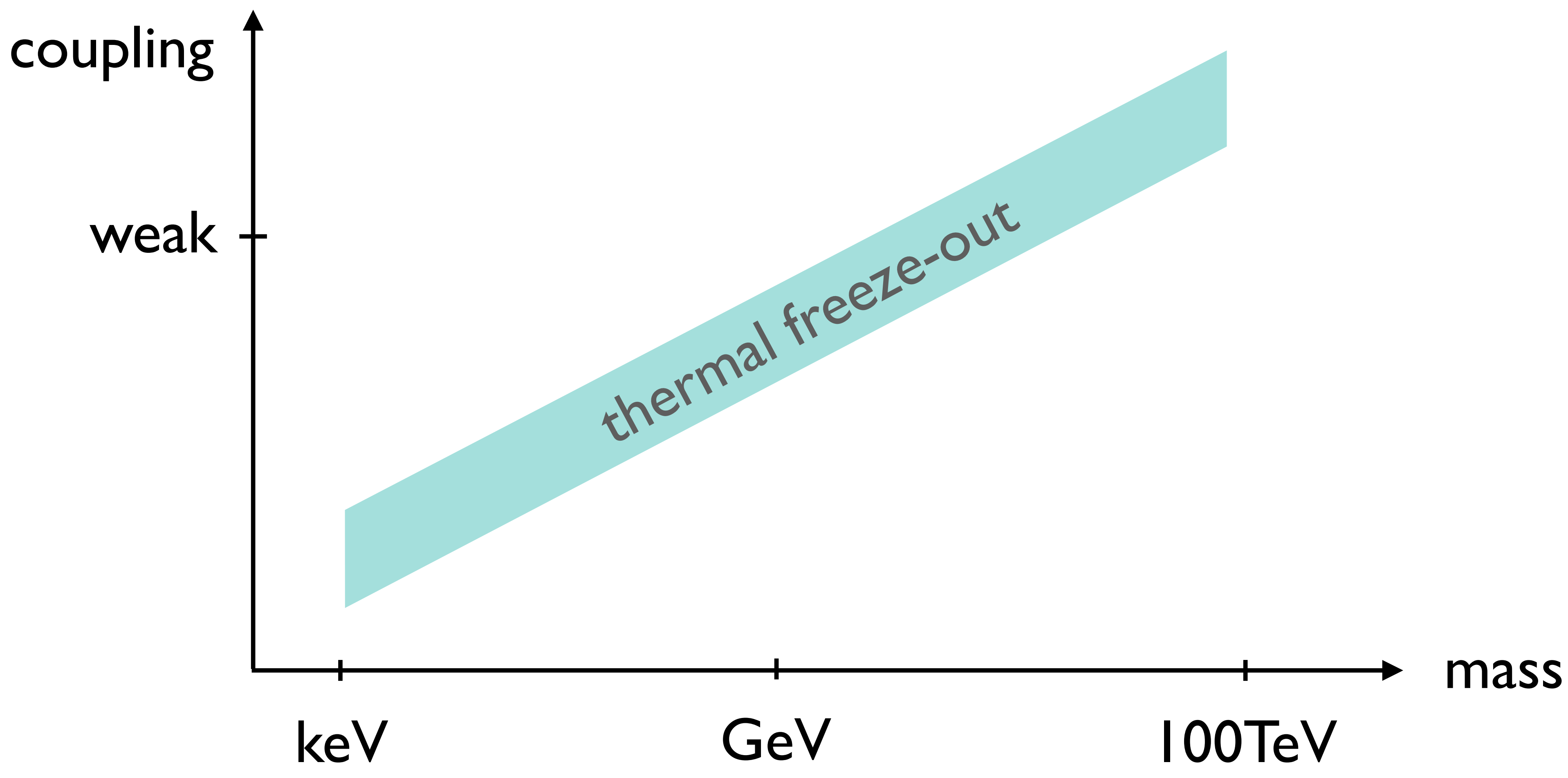
ISAPP School 2024, Bad Liebenzell

Accelerator-based Dark Matter searches

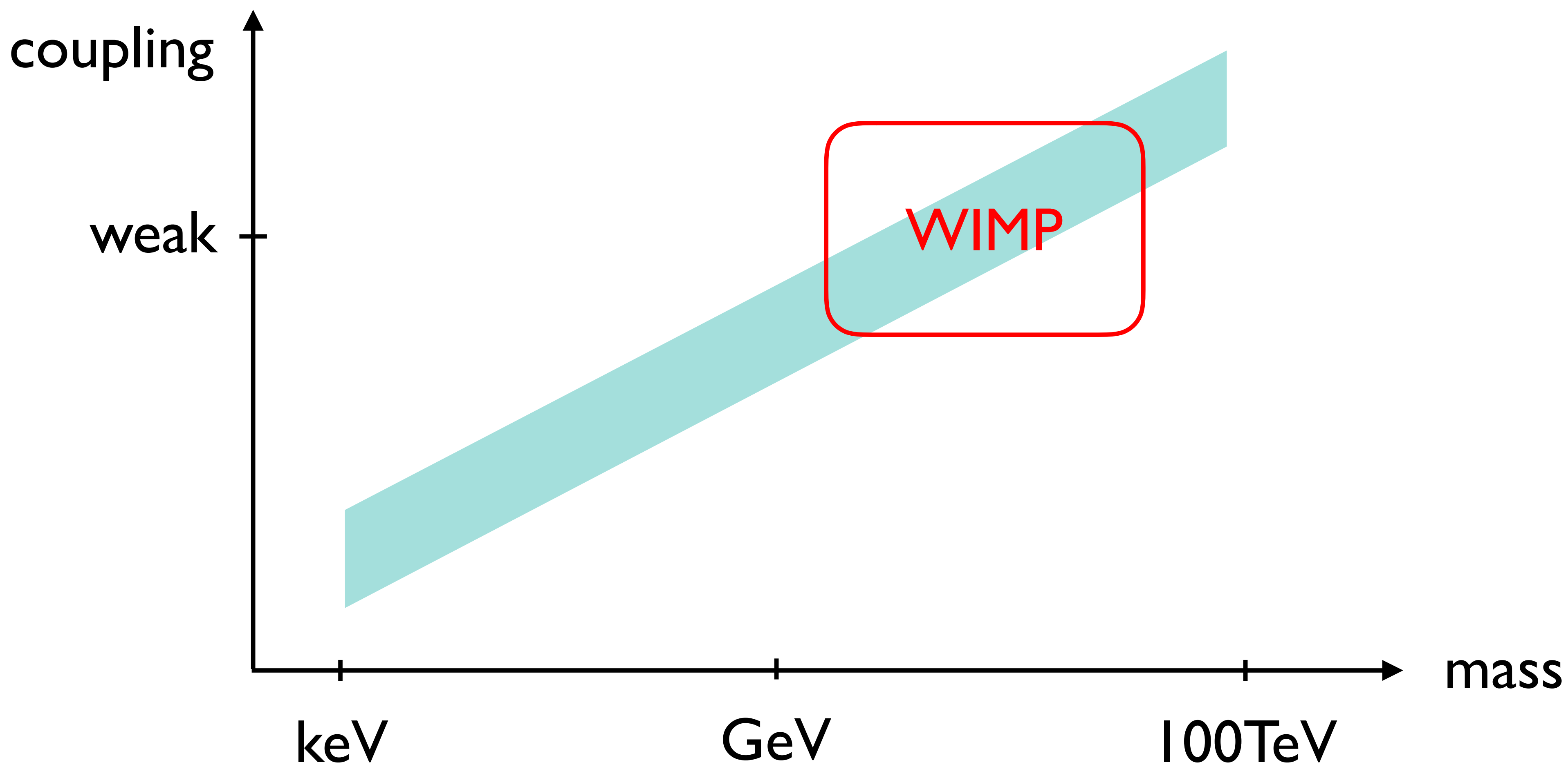
Jan Heisig

TTK Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Dark matter as a thermal relic



Dark matter as a thermal relic



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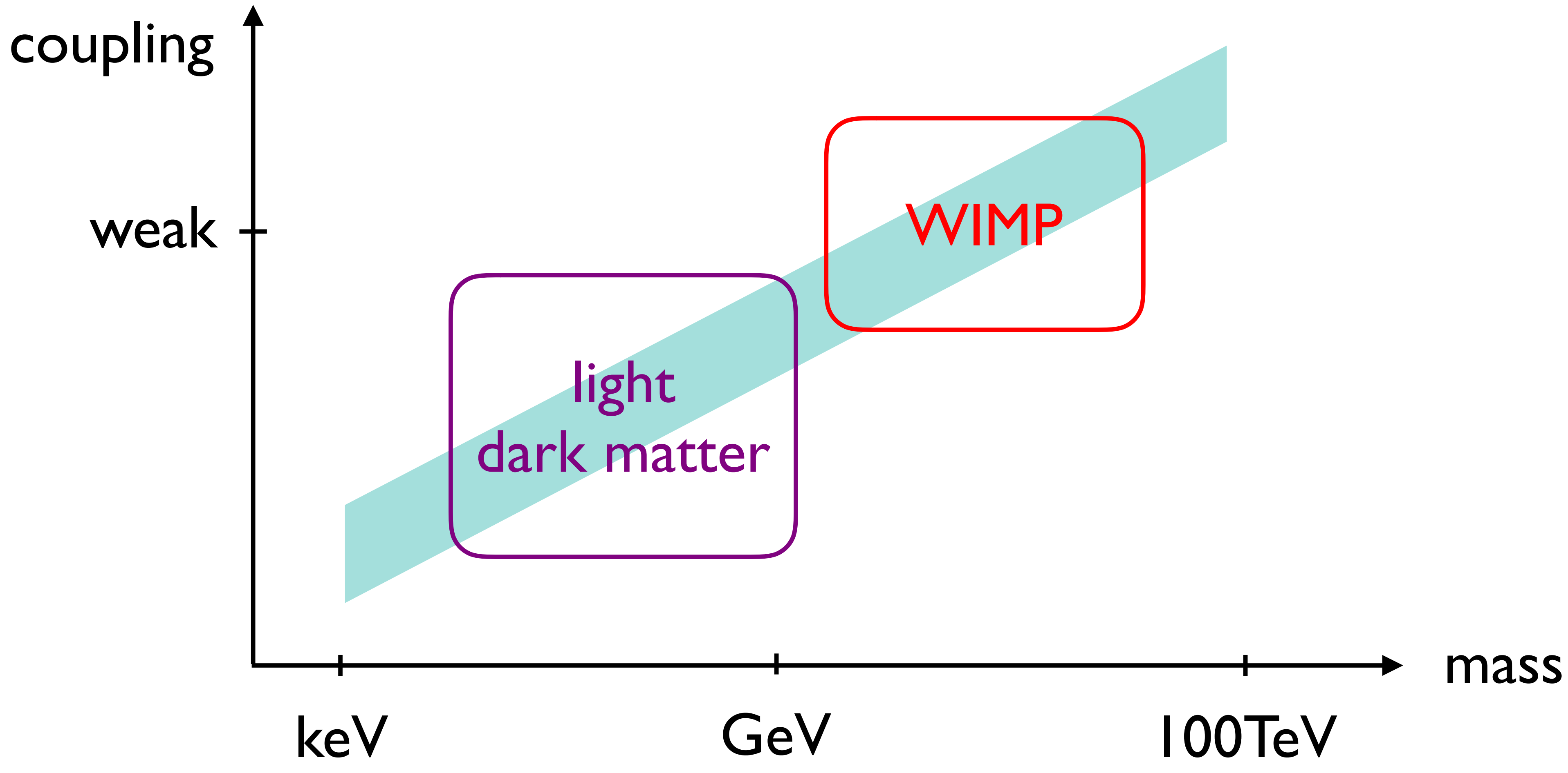

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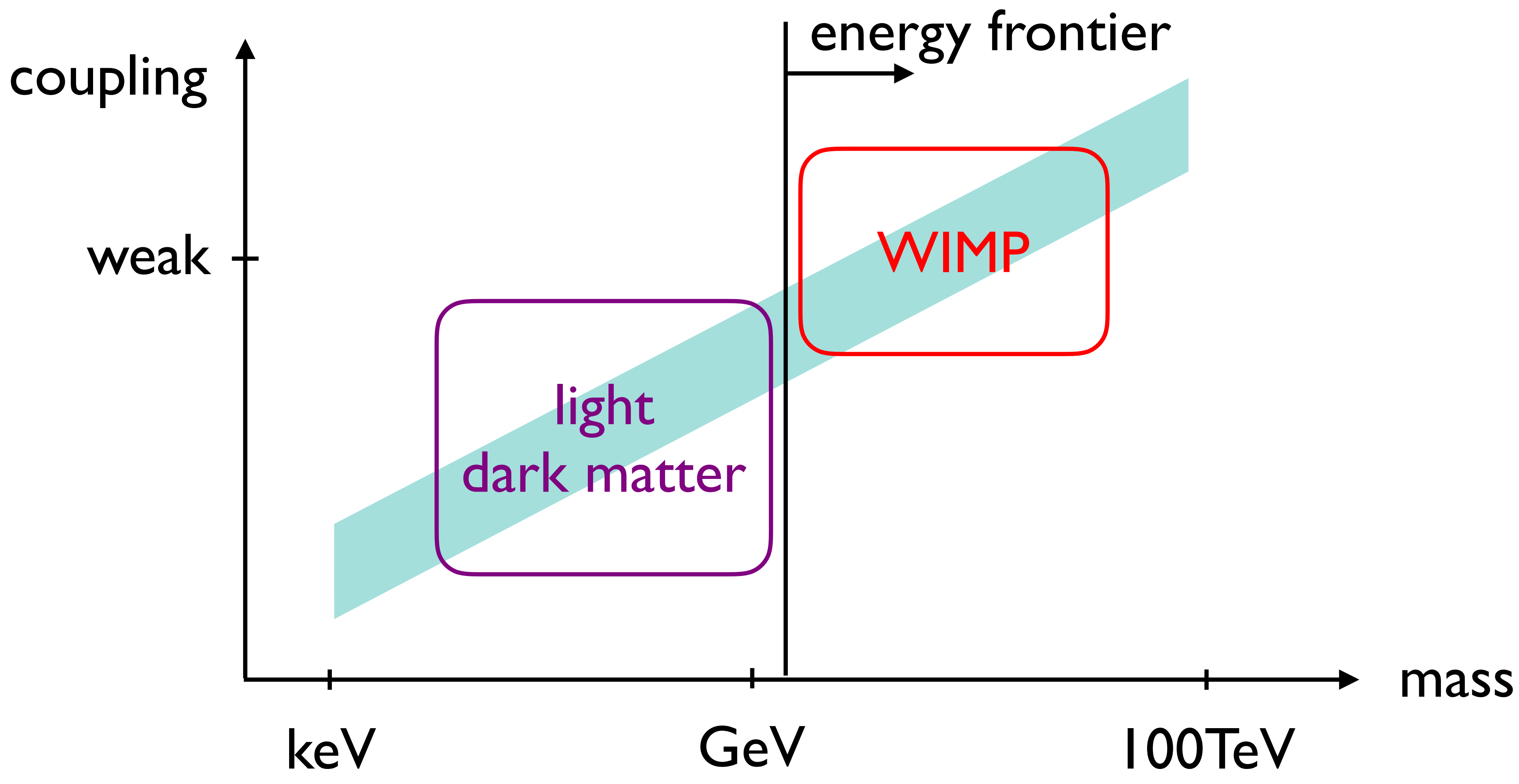

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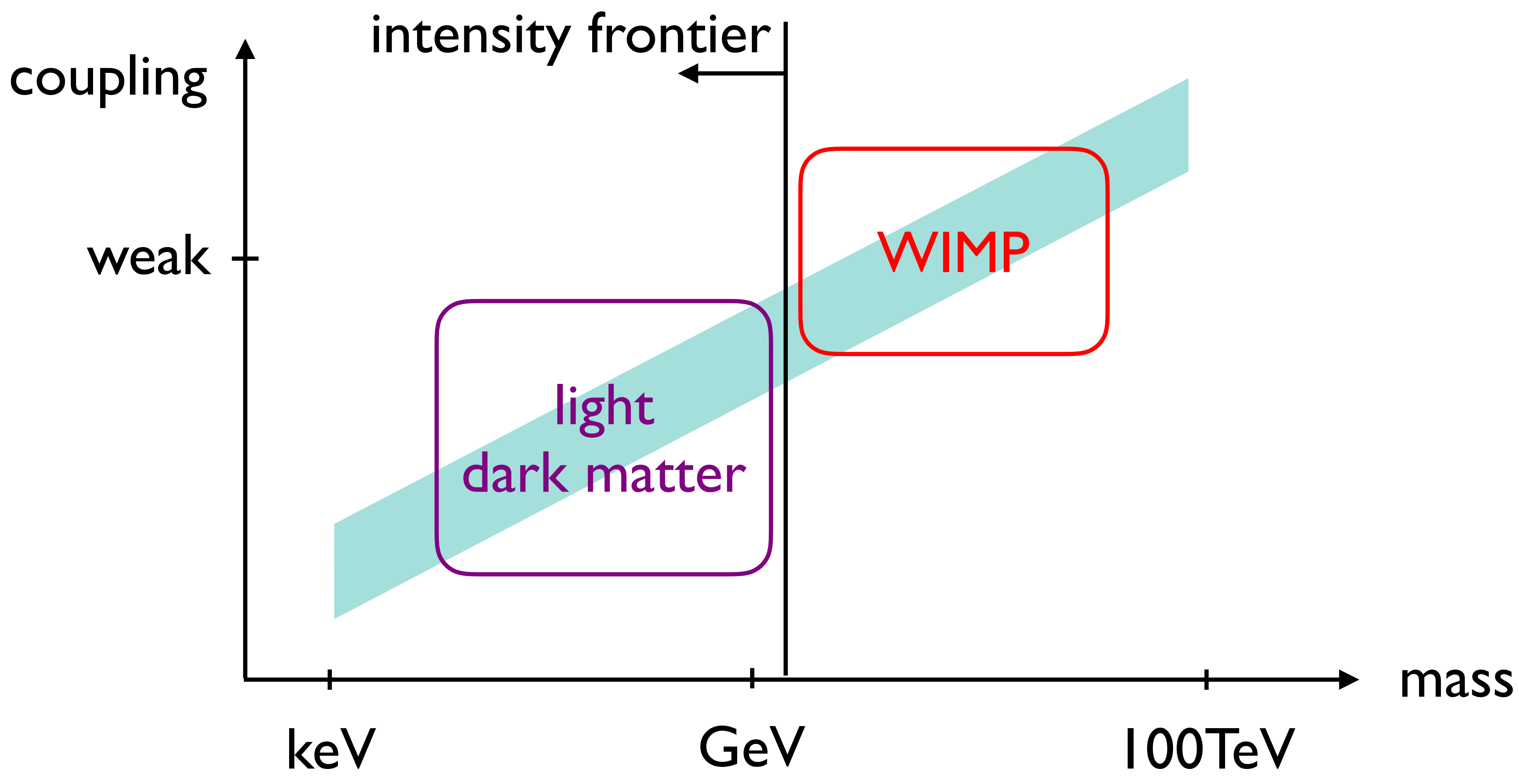
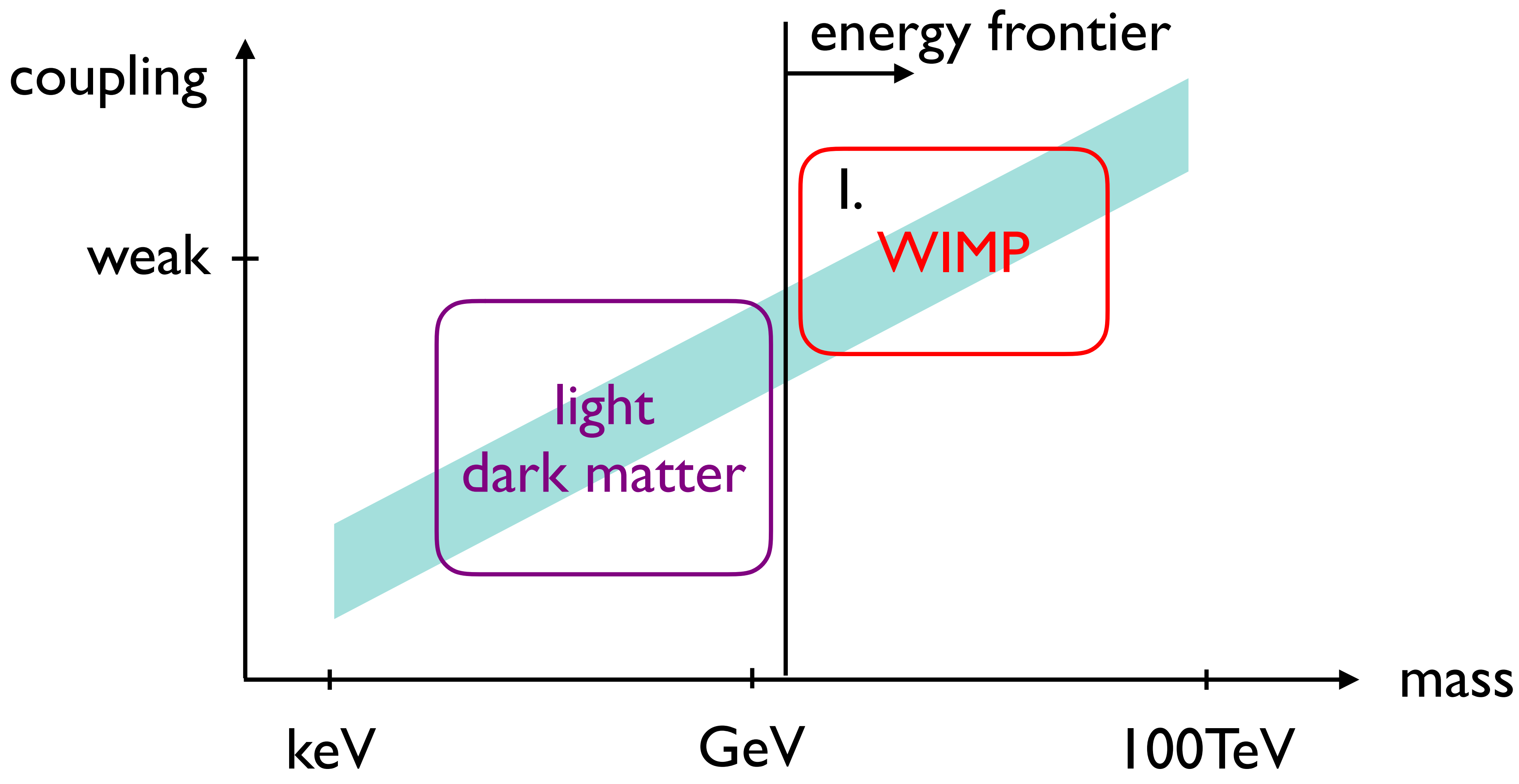


Dark matter as a thermal relic – outline



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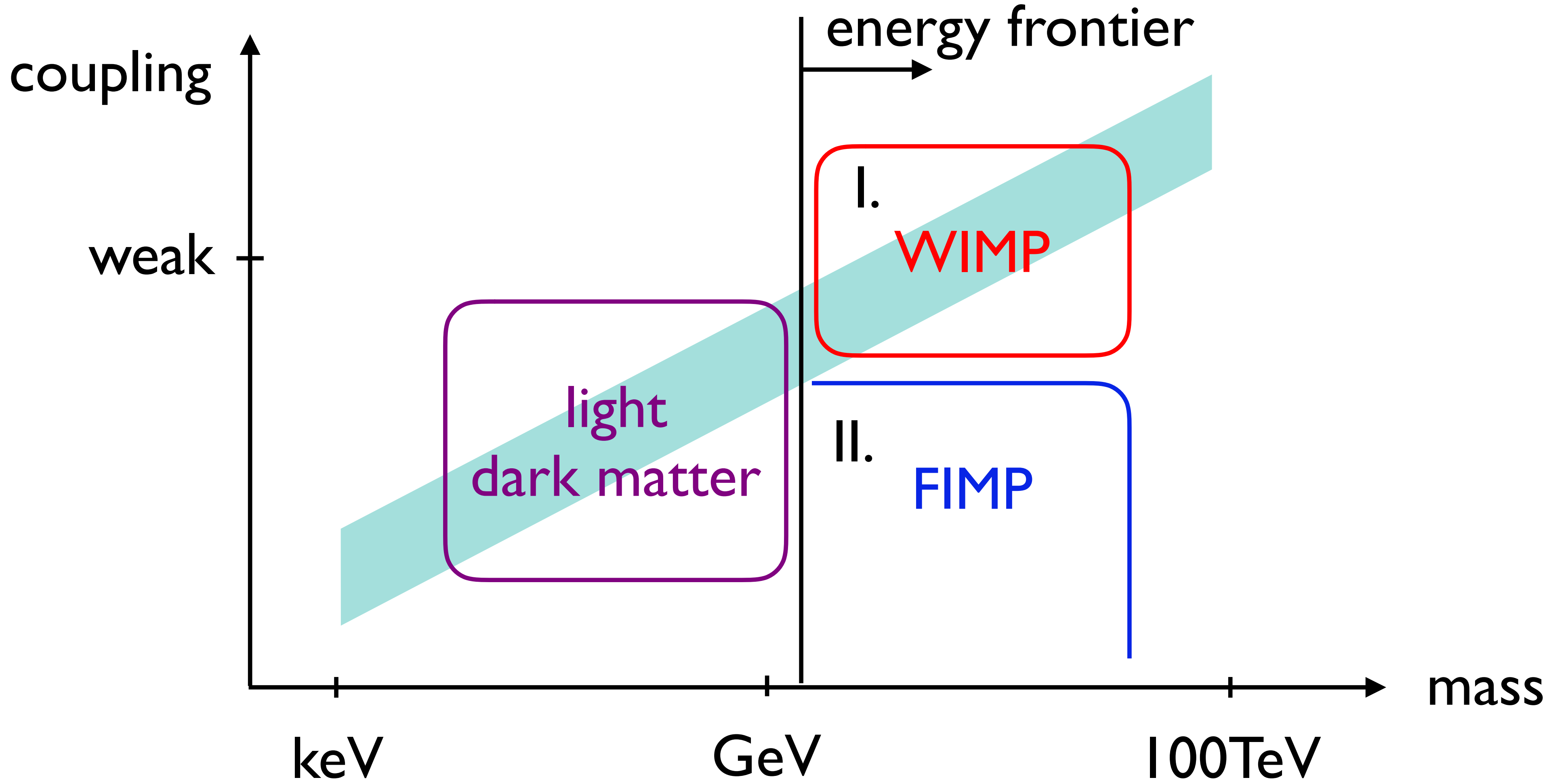
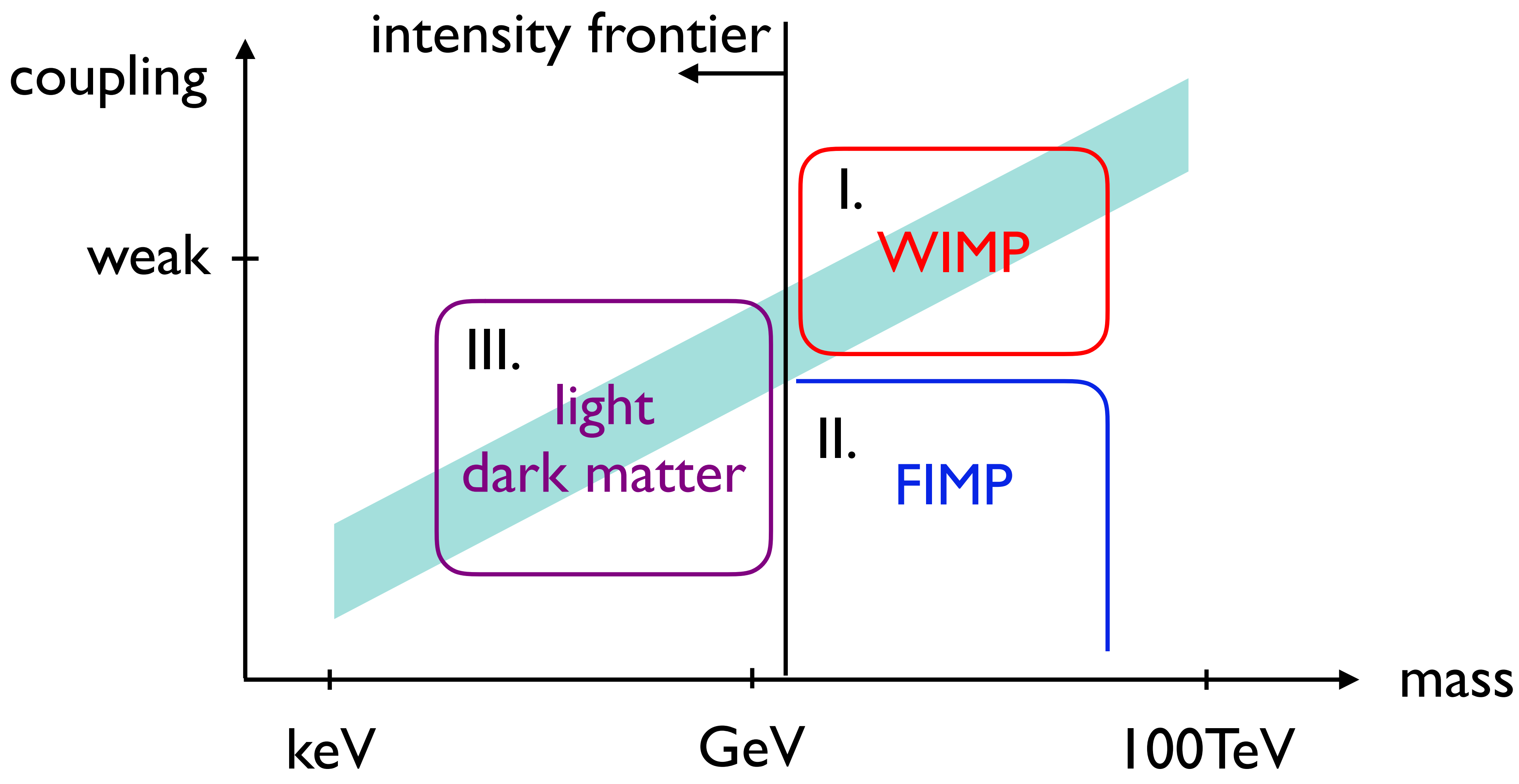


Dark matter as a thermal relic – outline



I. Searches for WIMPs

Weakly Interacting Massive Particle (WIMP)

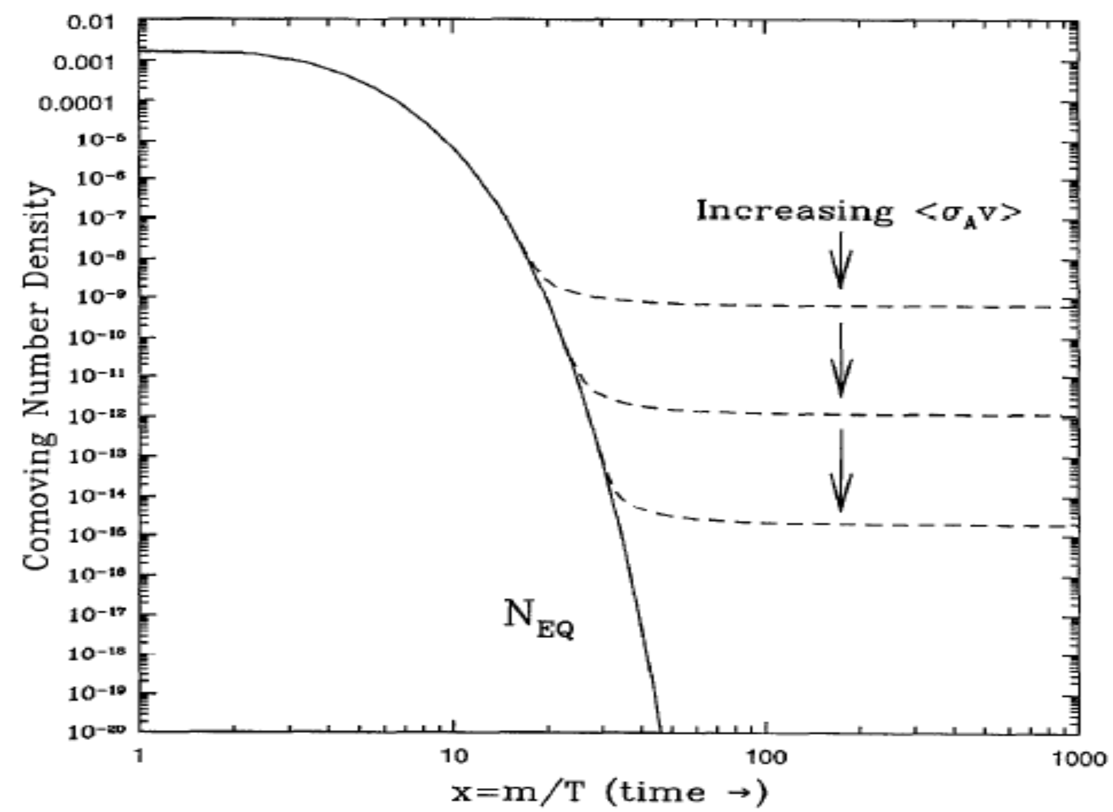
- Color- and electrically neutral
- Thermal relic from freeze-out:

$$\Omega \simeq \frac{0.6 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_{\mathrm{ann}} v \rangle} \stackrel{!}{=} 0.26$$

$$\Rightarrow \langle \sigma_{\mathrm{ann}} v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

$$\sim \frac{1}{(20\,\mathrm{TeV})^2}$$

$\chi\bar{\chi} \leftrightarrows f\bar{f}$ $\chi\bar{\chi} \rightarrow f\bar{f}$ $\chi\bar{\chi} \nrightarrow \ldots$



Marco's lecture

Weakly Interacting Massive Particle (WIMP)

- Color- and electrically neutral
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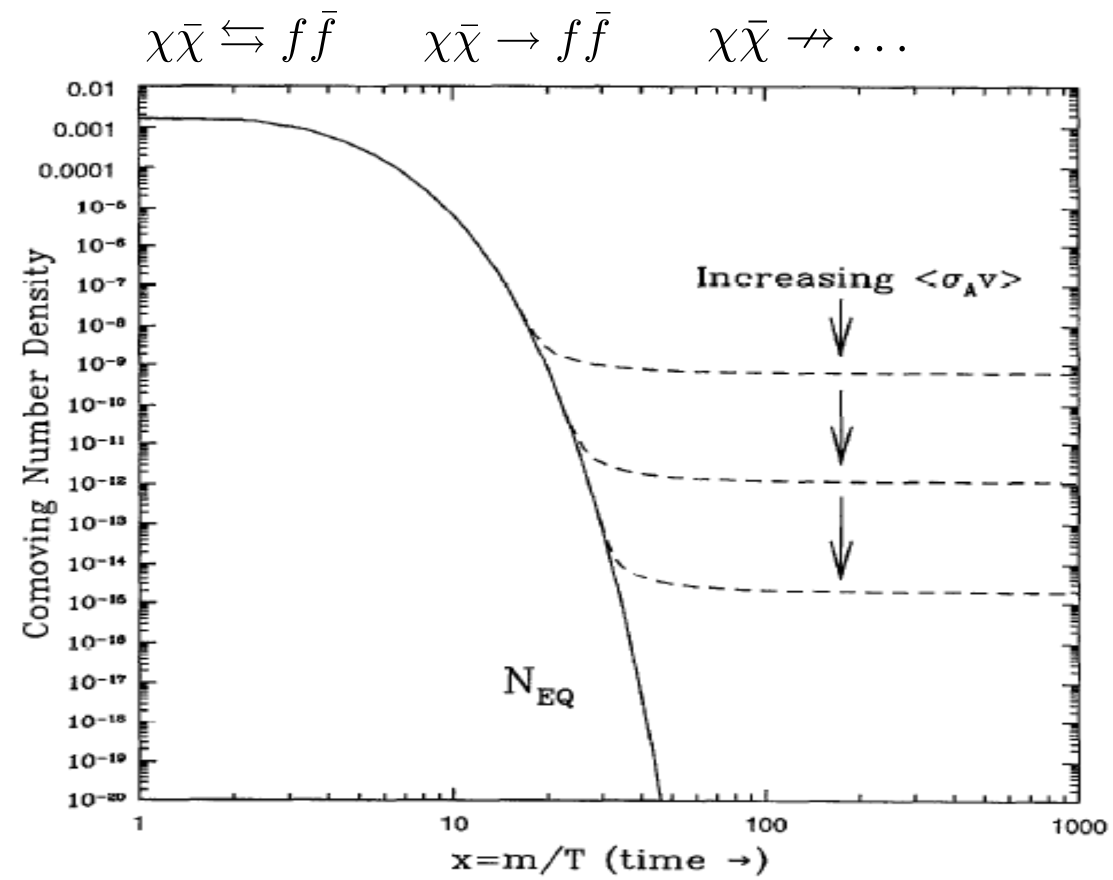
$$\Rightarrow \langle \sigma_{\mathrm{ann}} v \rangle \simeq 3 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}$$

$$\sim \frac{1}{(20\,\mathrm{TeV})^2}$$

Nicely fulfilled by:

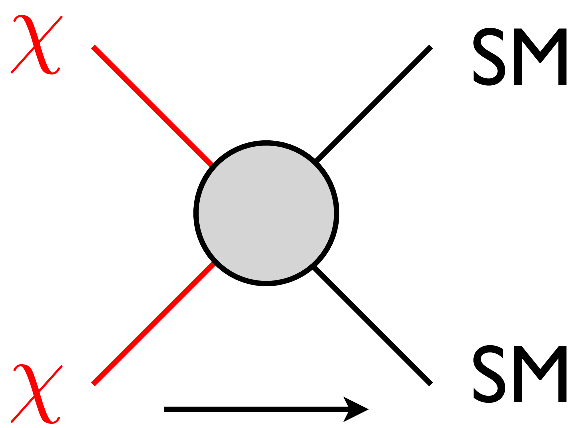
- weak-scale (toTeV) mass
- weak coupling strength



Marco's lecture

WIMP dark matter searches

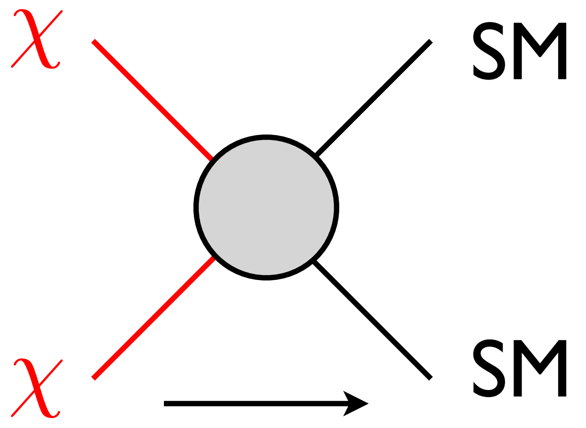
Indirect detection



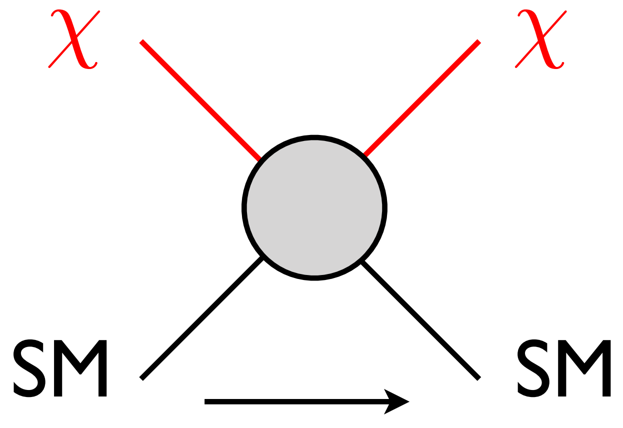
Elisa's lecture

WIMP dark matter searches

Indirect detection

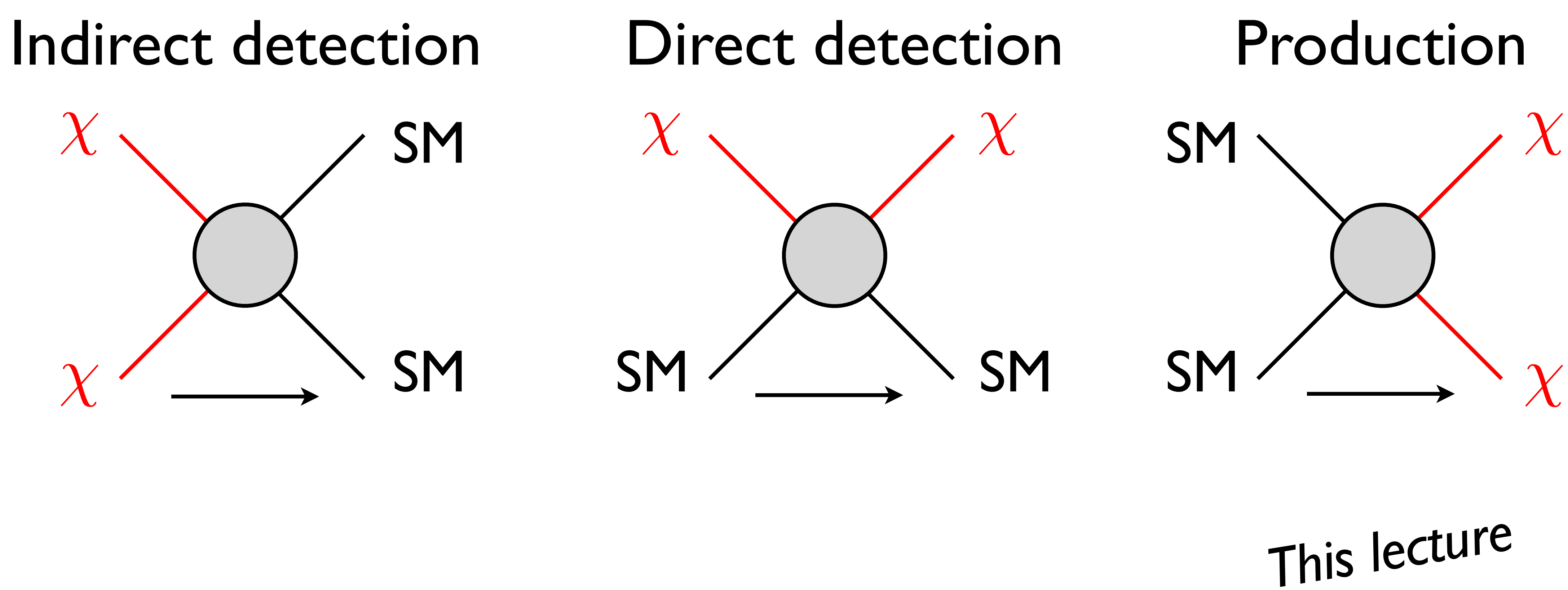


Direct detection



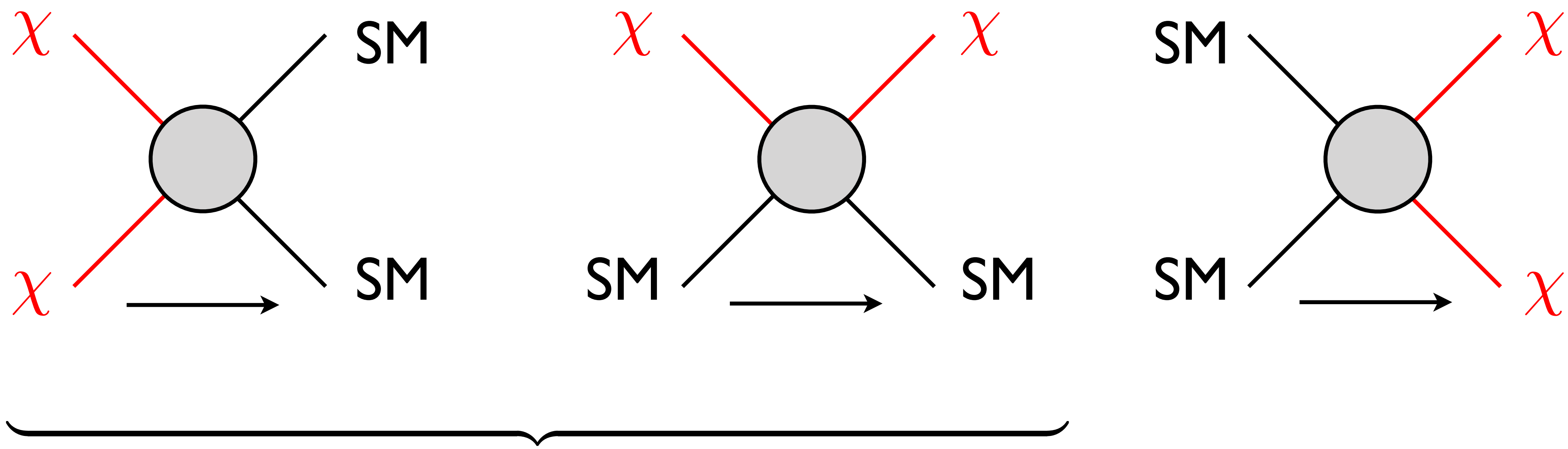
Belina's lecture

WIMP dark matter searches



WIMP dark matter searches

Indirect detection | Direct detection | Production

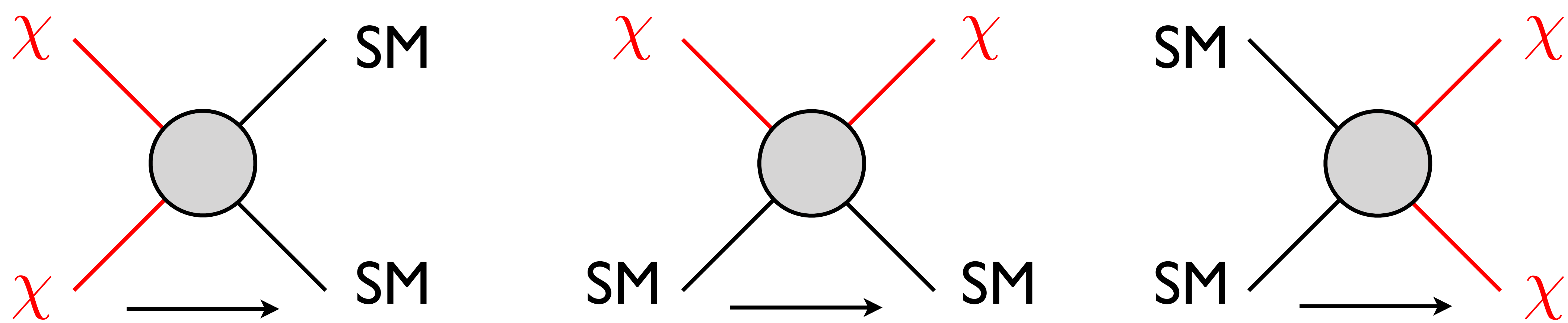


Amount of DM in probed environments

ρ^2_{probe} ρ_{probe}

WIMP dark matter searches

Indirect detection | Direct detection | Production



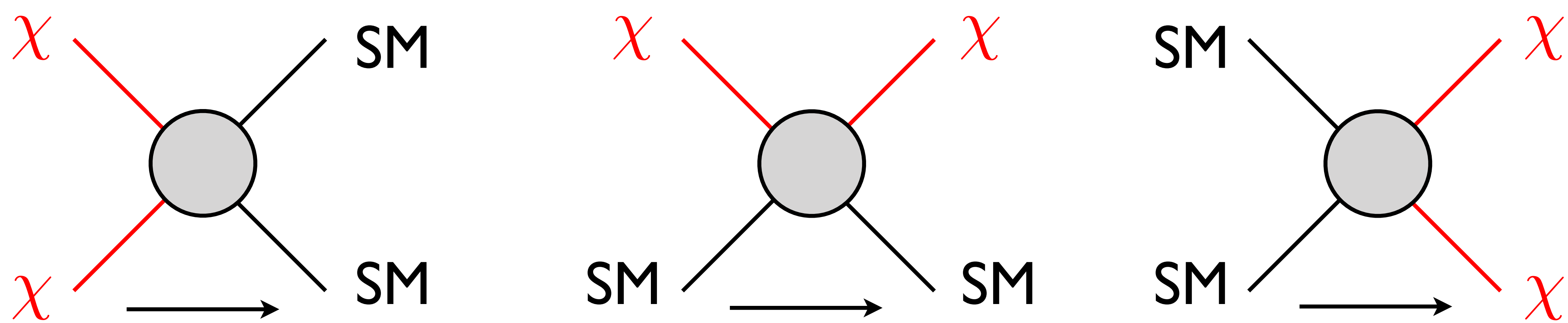
Amount of DM in probed environments

ρ^2_{probe} | ρ_{probe}

Independent test

WIMP dark matter searches

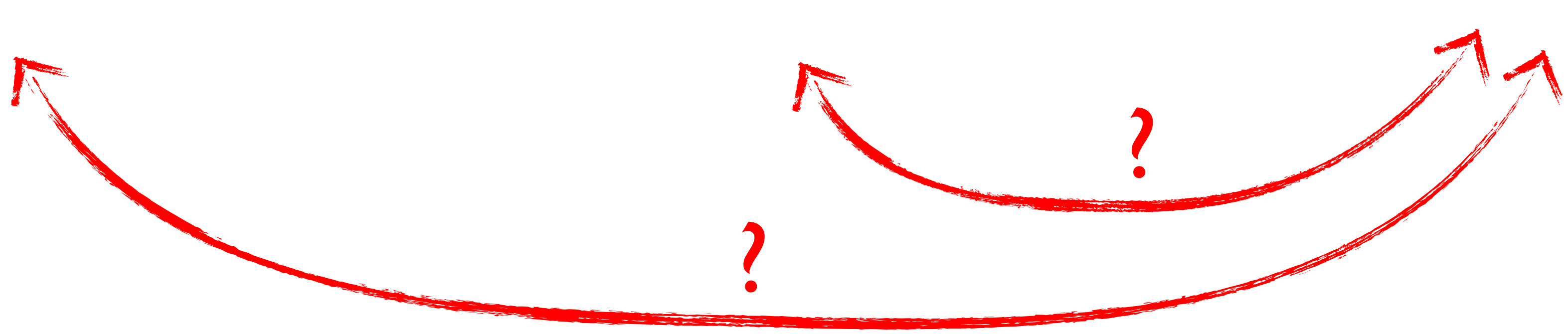
Indirect detection | Direct detection | Production



Amount of DM in probed environments

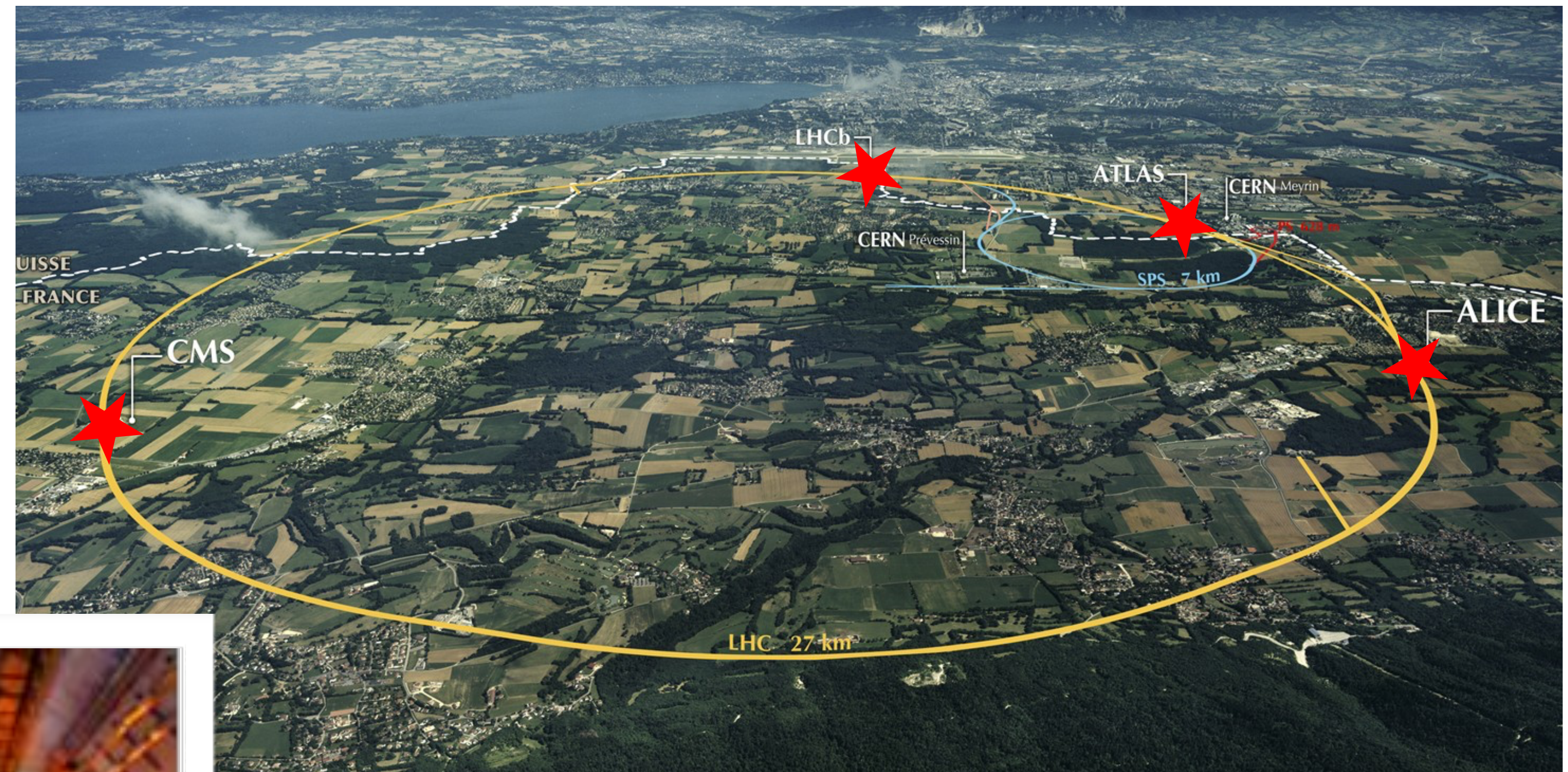
$\rho^2_{\rm probe}$ $\rho_{\rm probe}$

Independent test



Large Hadron Collider (LHC)

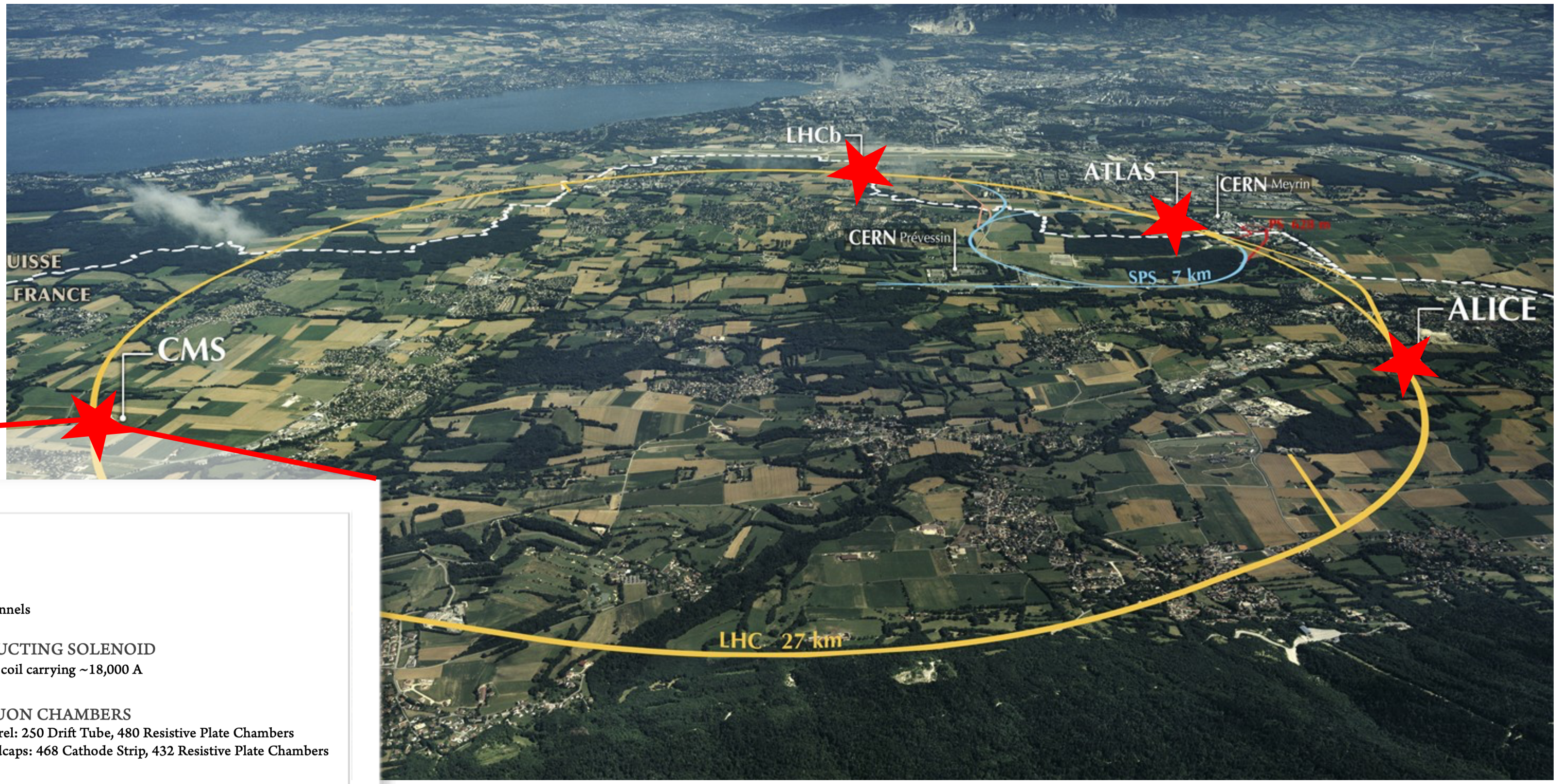
Proton-proton collisions
at 13.6 TeV CM energy



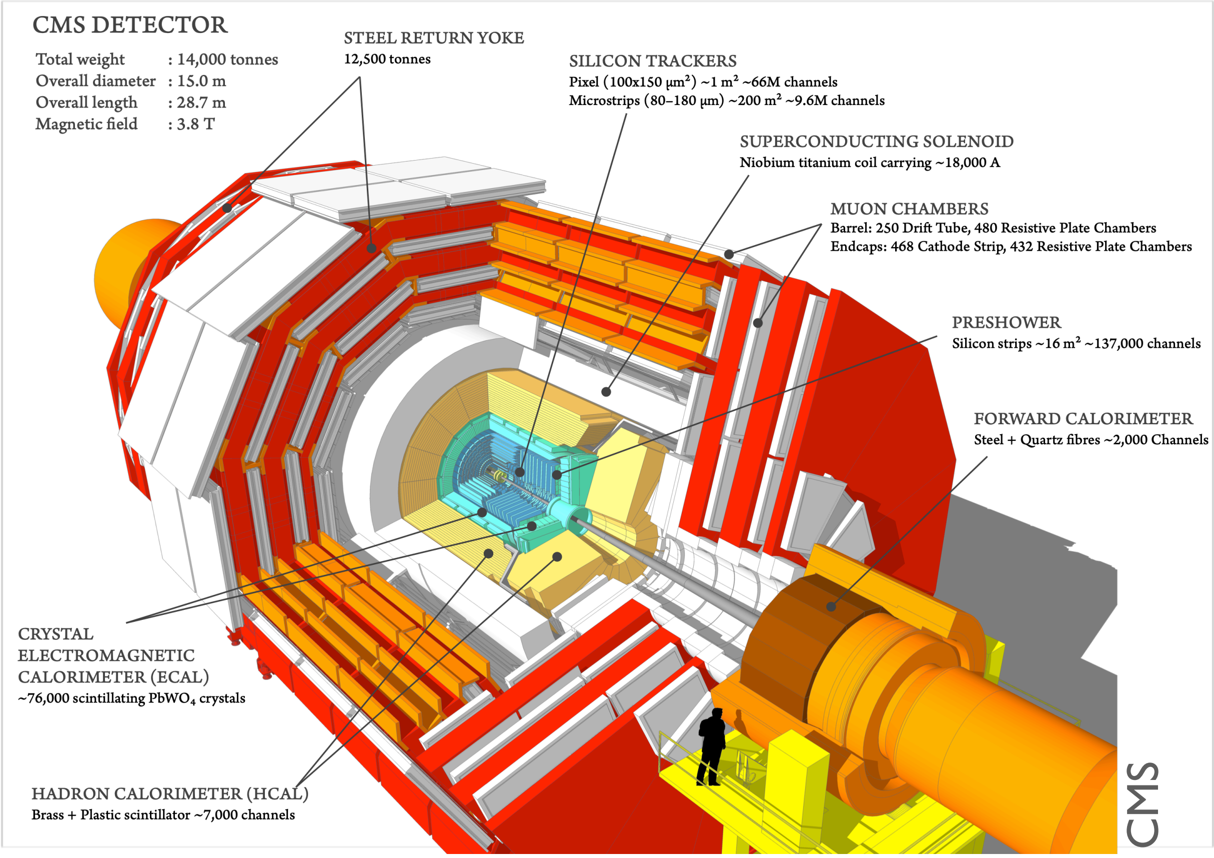
CERN

Large Hadron Collider (LHC)

Proton-proton collisions at 13.6 TeV CM energy



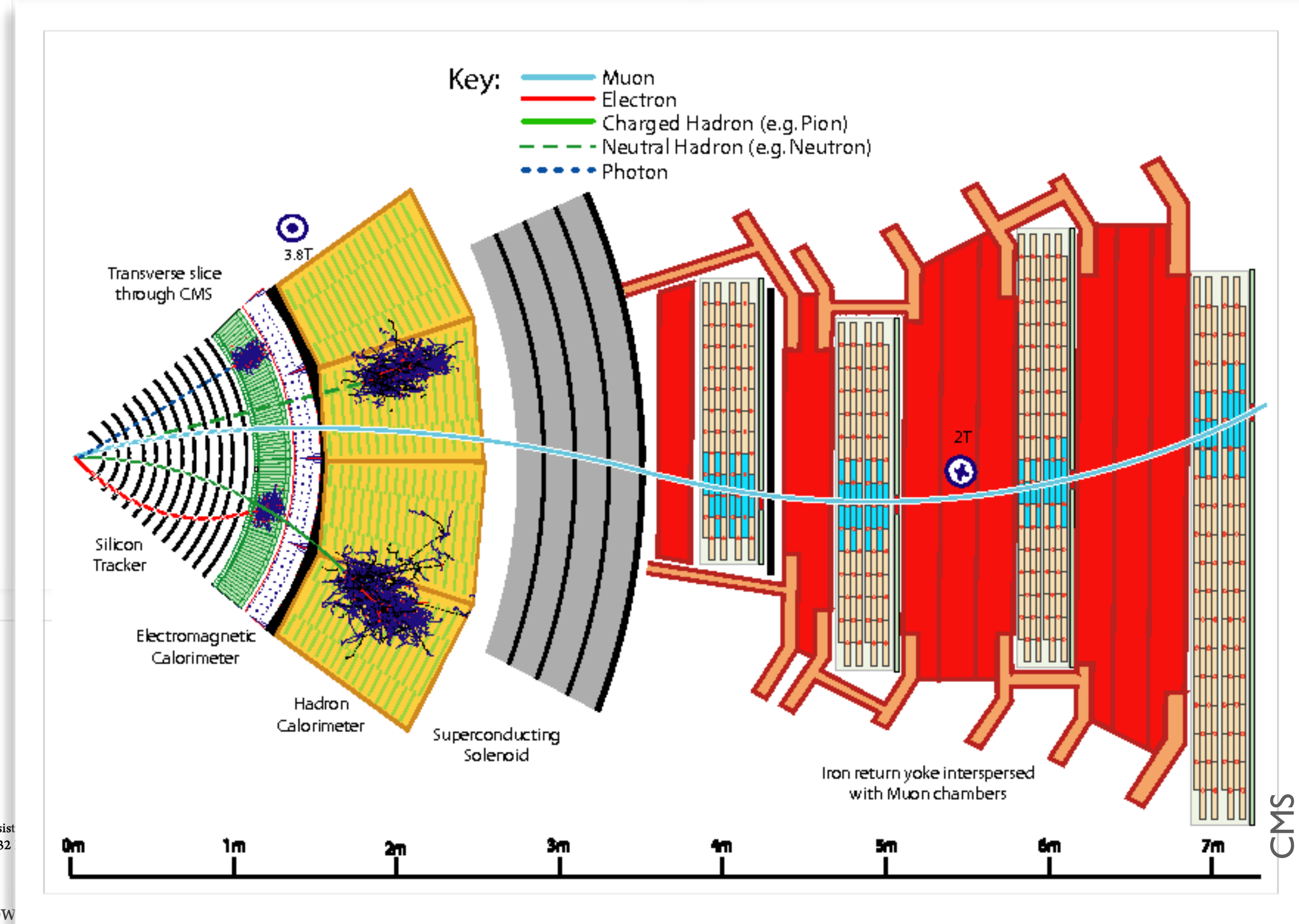
CERN

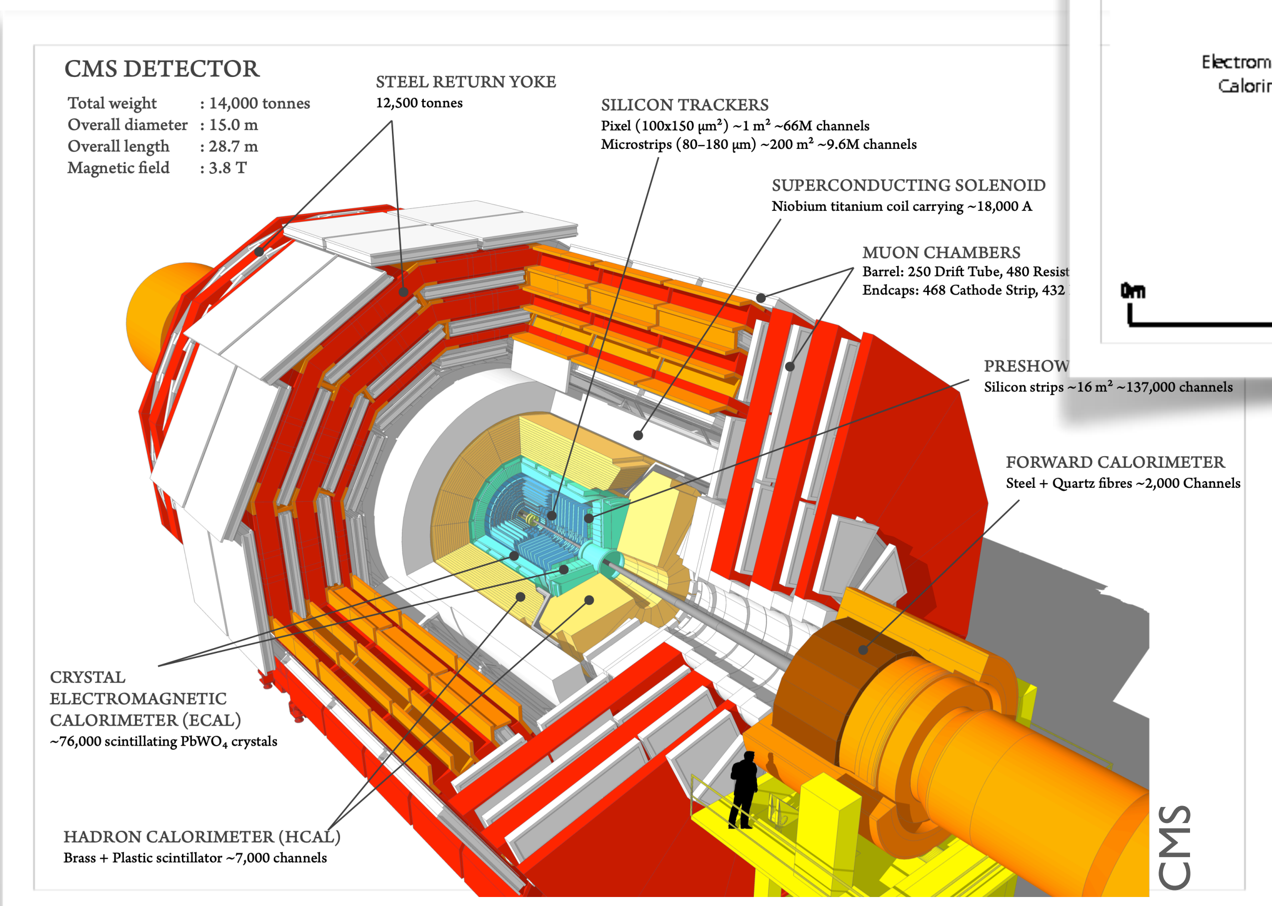


CMS

Large Hadron Collider (LHC)

Proton-proton collisions
at 13.6 TeV CM energy



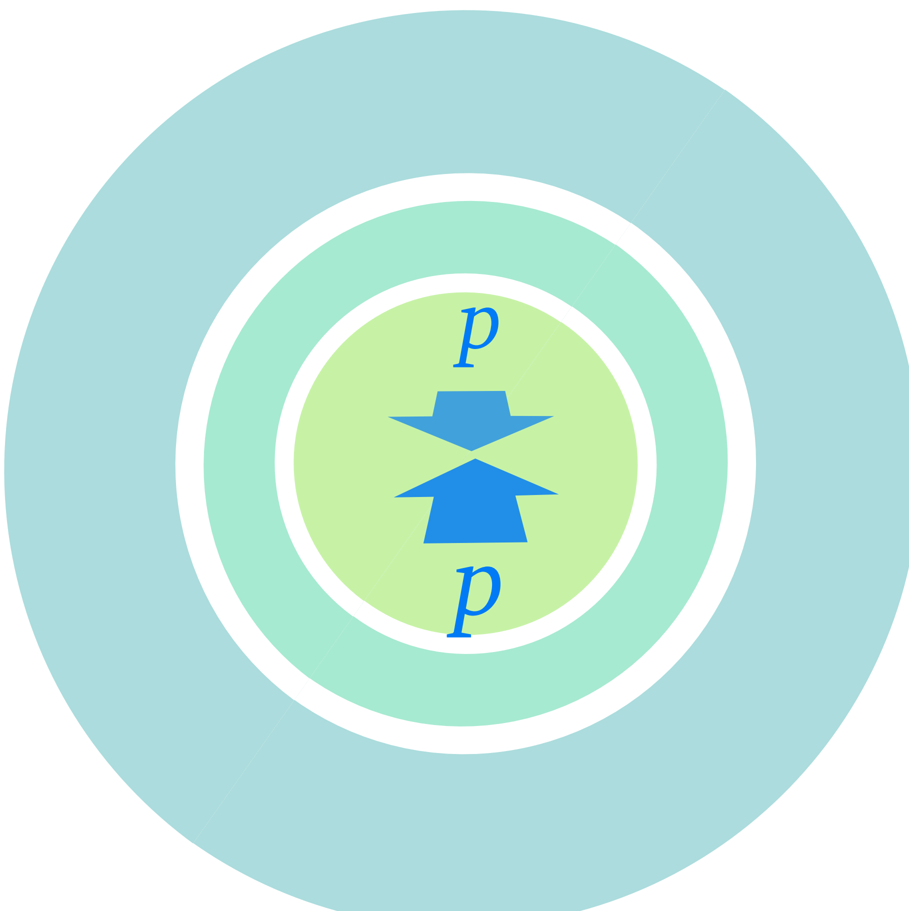


WIMPs at the LHC

schematic detector
head-on view:

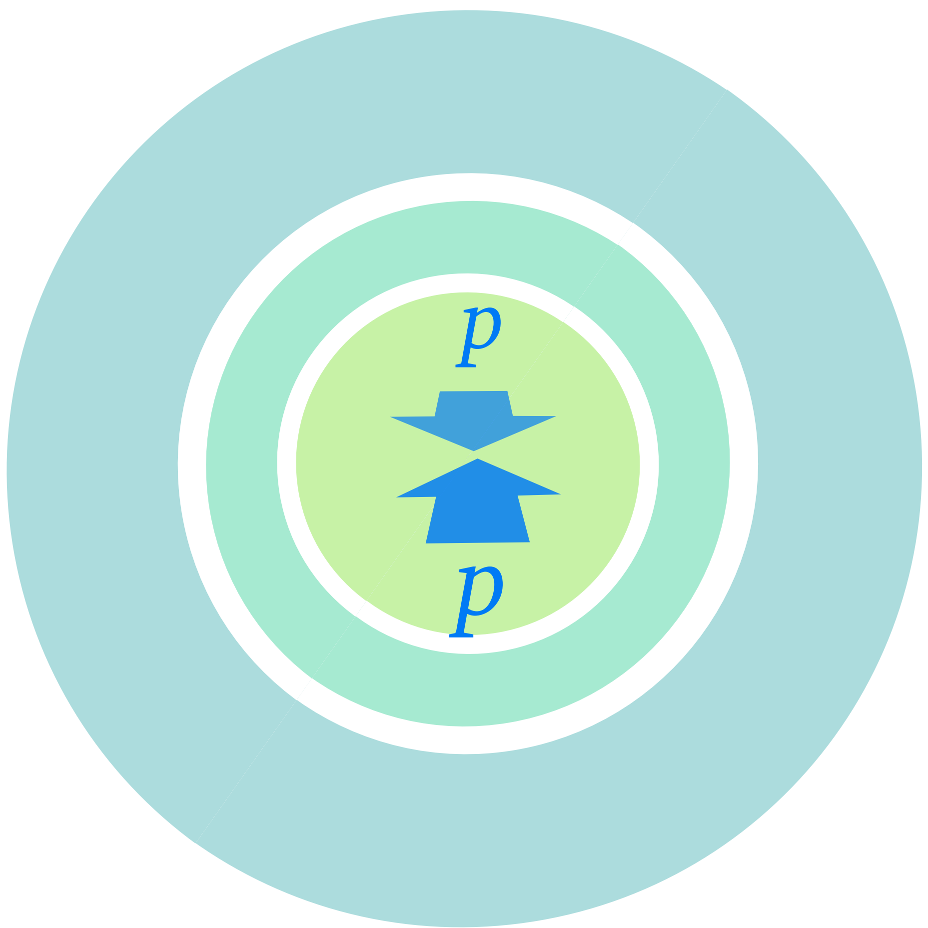
WIMPs at the LHC

schematic detector
head-on view:

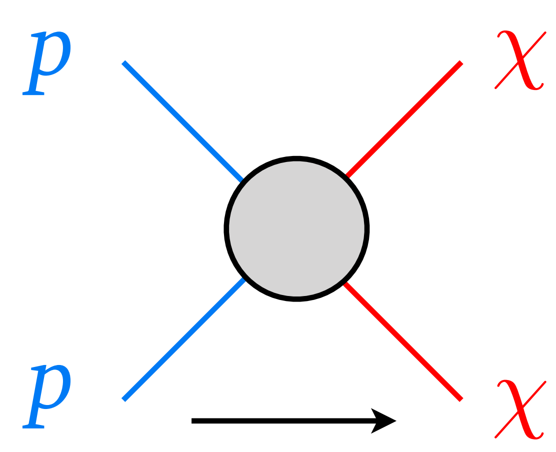


WIMPs at the LHC

schematic detector
head-on view:



DM production



WIMPs at the LHC

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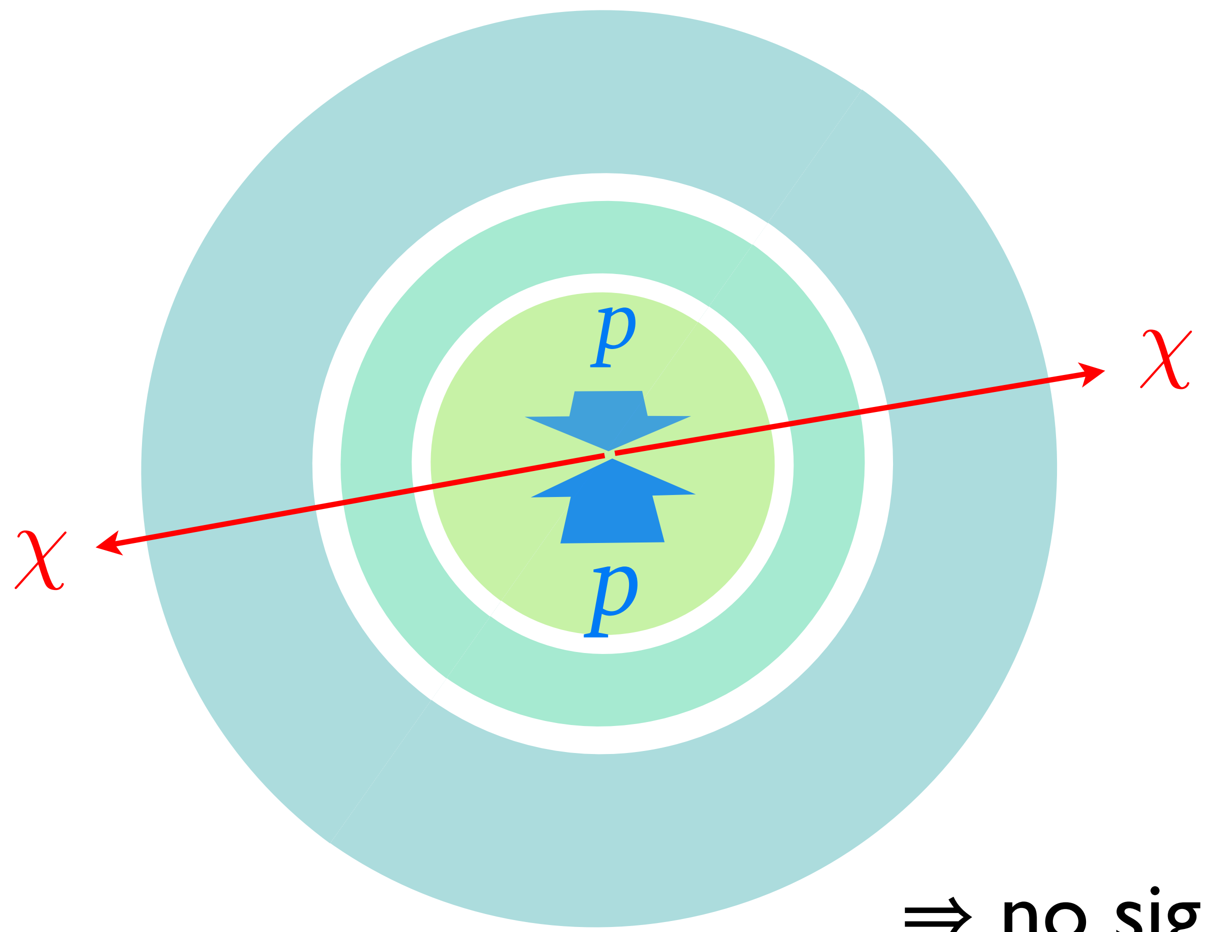
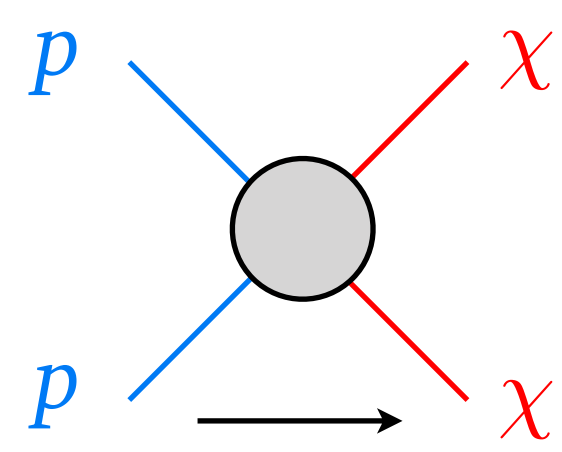
head-on view:



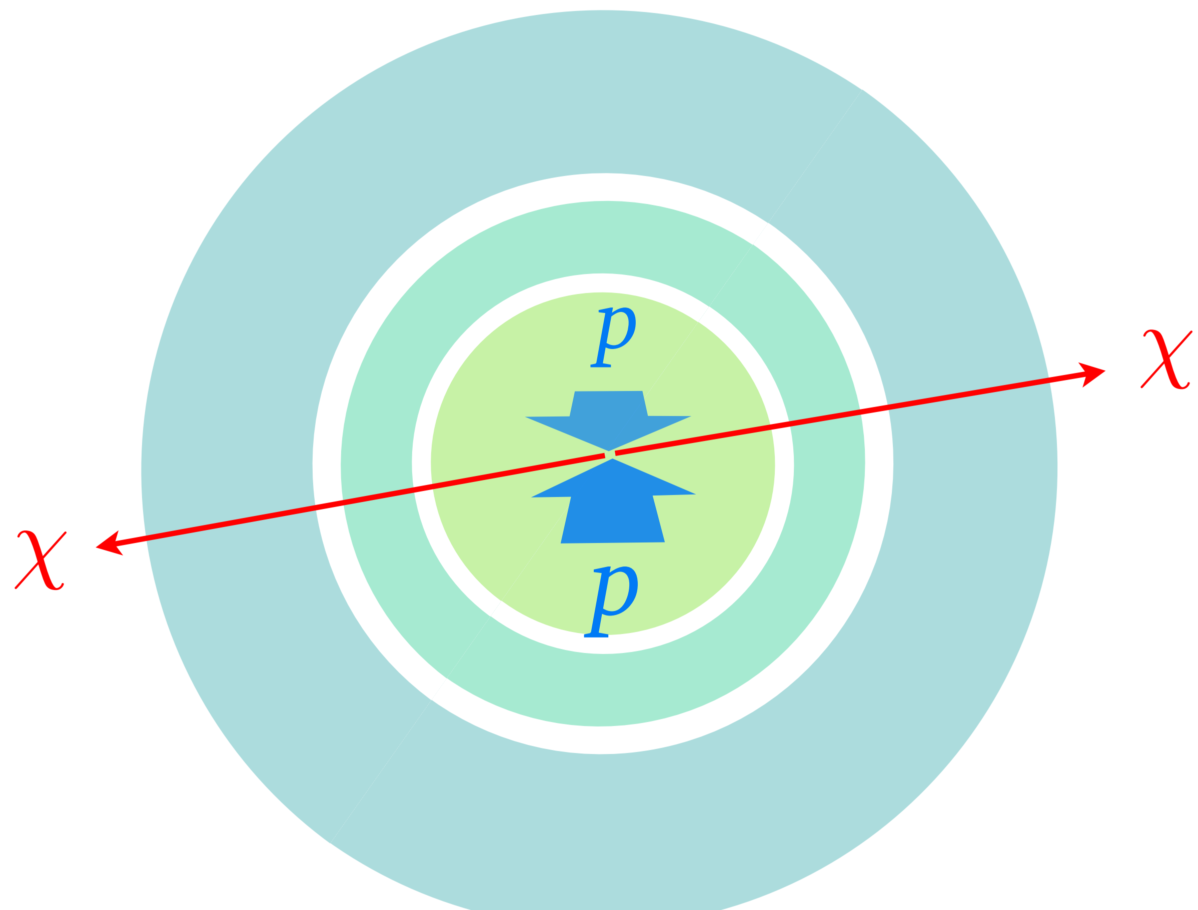
DM production



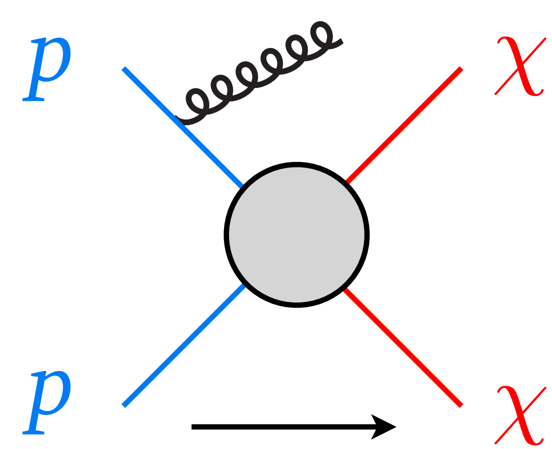
$\Rightarrow$ no signal

WIMPs at the LHC

schematic detector
head-on view:

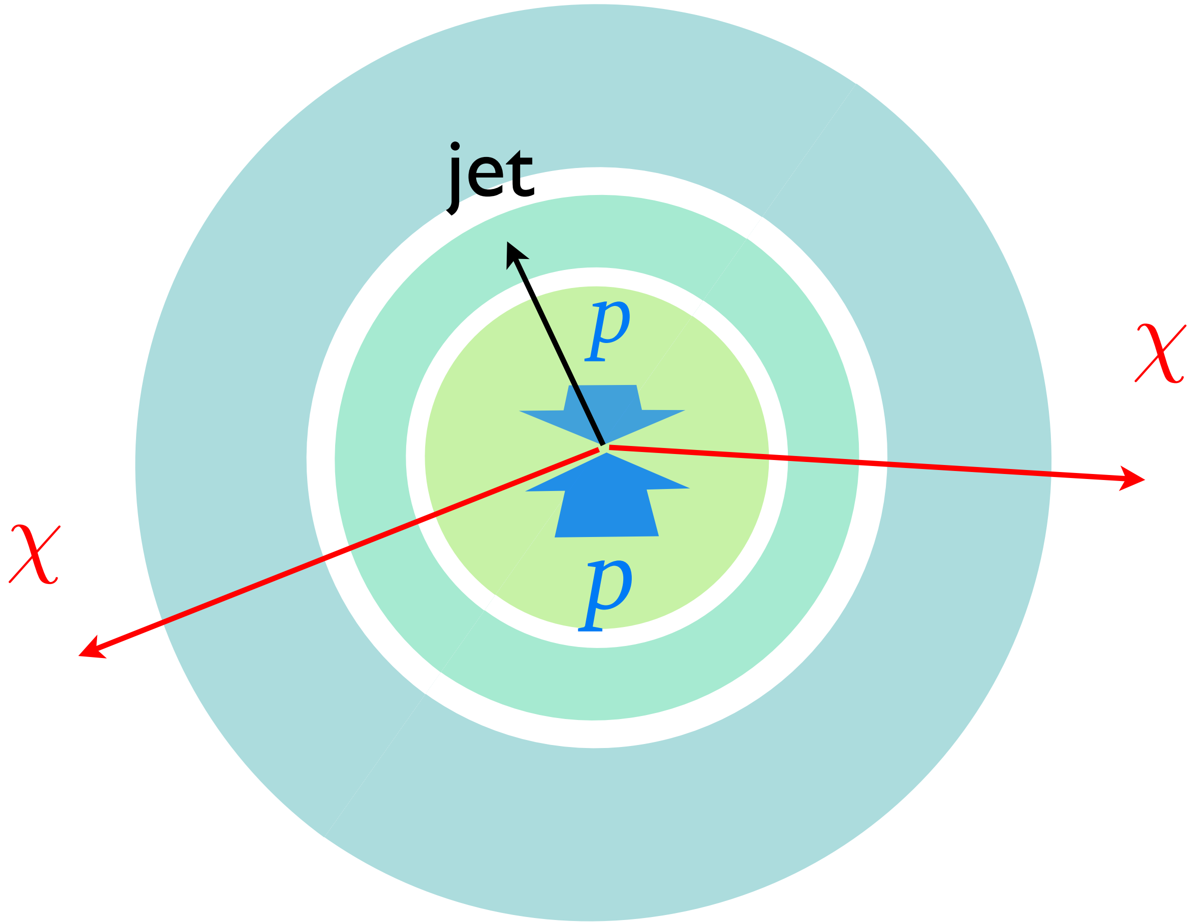


DM production
+ initial state radiation (ISR)



WIMPs at the LHC

schematic detector
head-on view:



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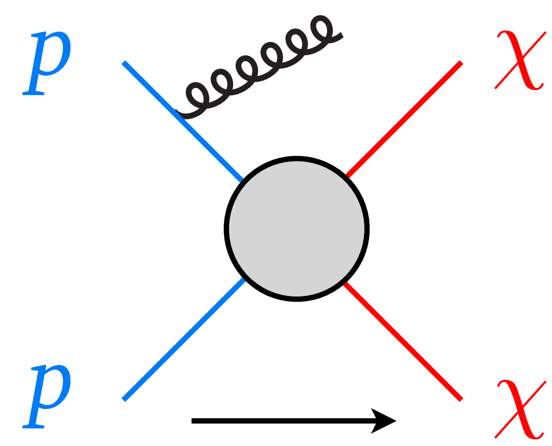
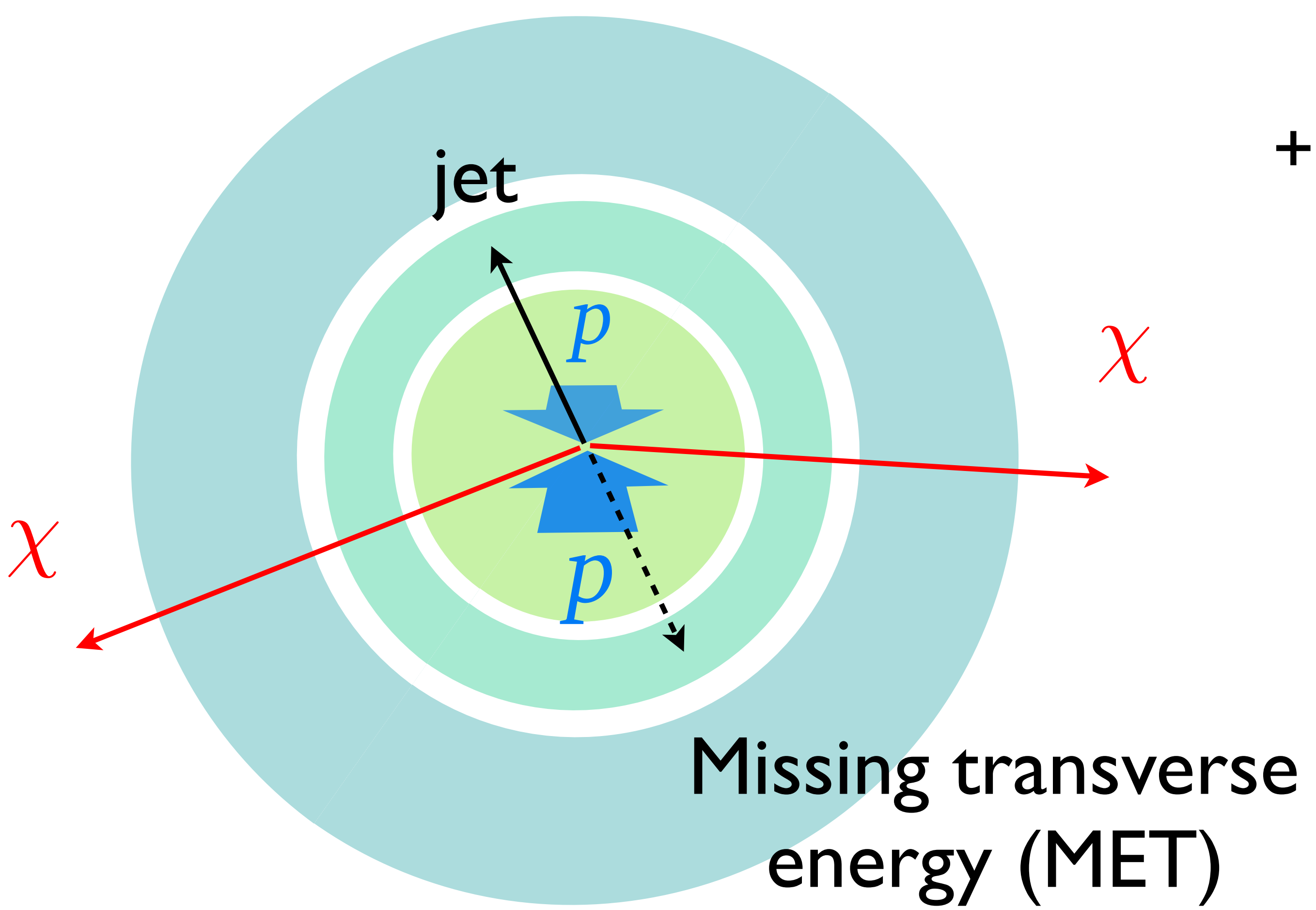


WIMPs at the LHC

schematic detector head-on view:



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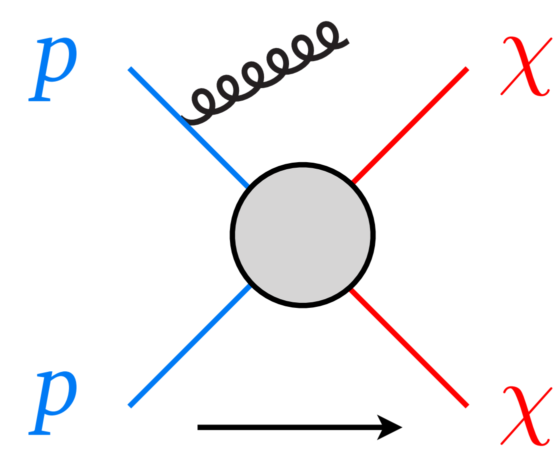
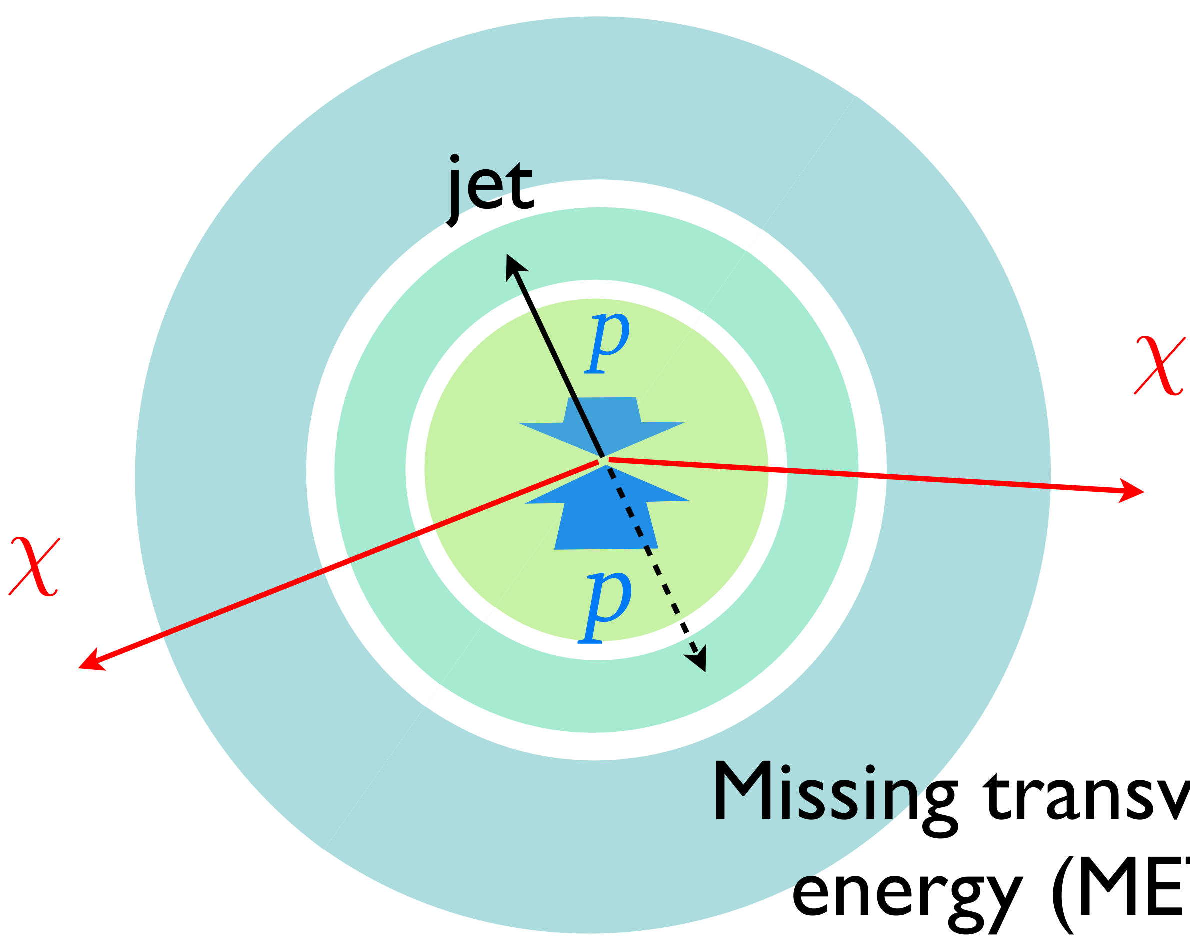


WIMPs at the LHC

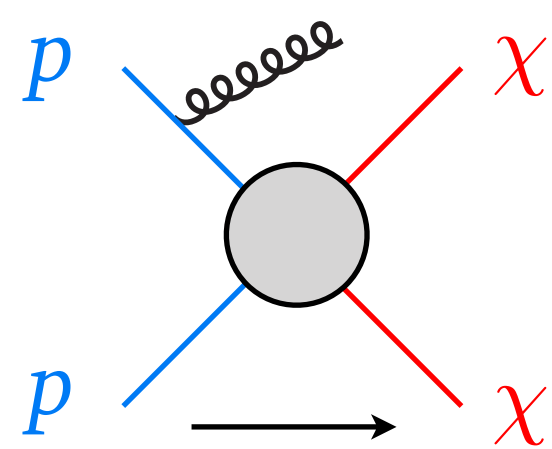
schematic detector
head-on view:



Missing transverse energy (MET)

$$\not{E}_{\mathrm{T}} = p_{\mathrm{T}}^{\mathrm{jet}}$$

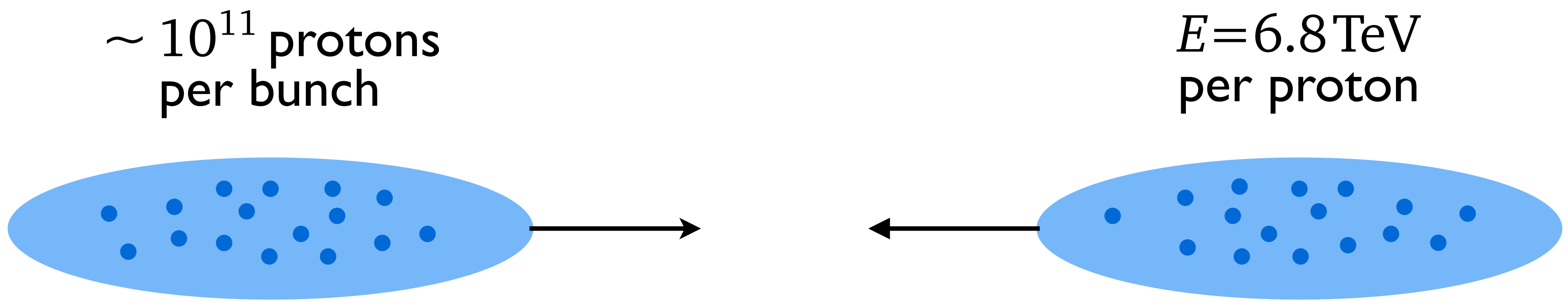
DM production
+ initial state radiation (ISR)



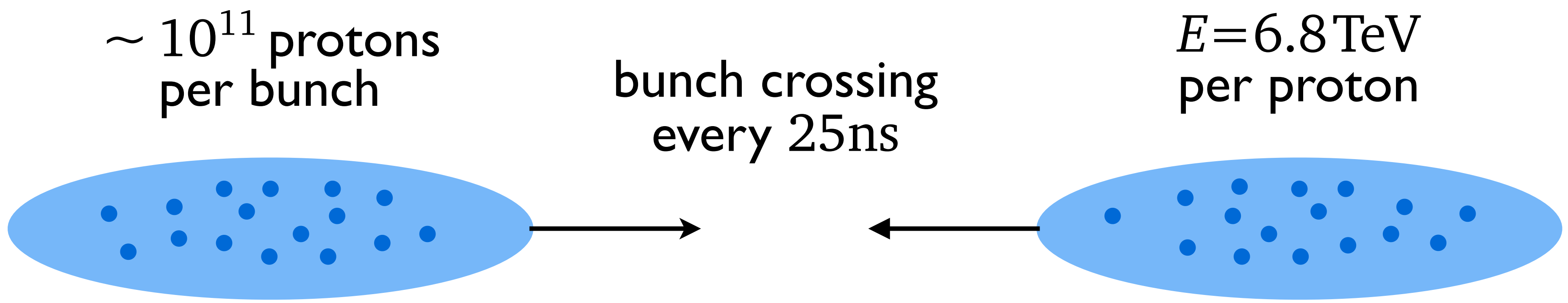
Proton collisions at the LHC

$\sim 10^{11}$ protons
per bunch

Proton collisions at the LHC



Proton collisions at the LHC



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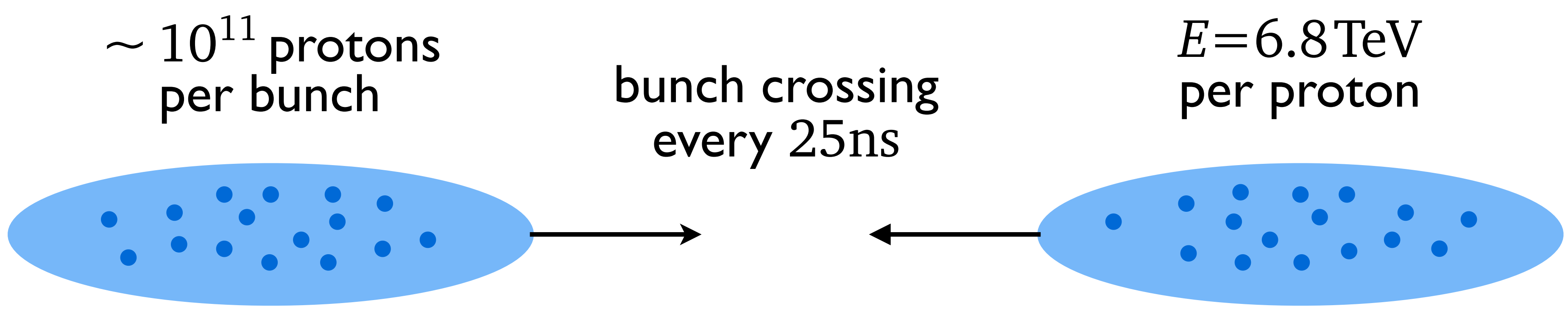
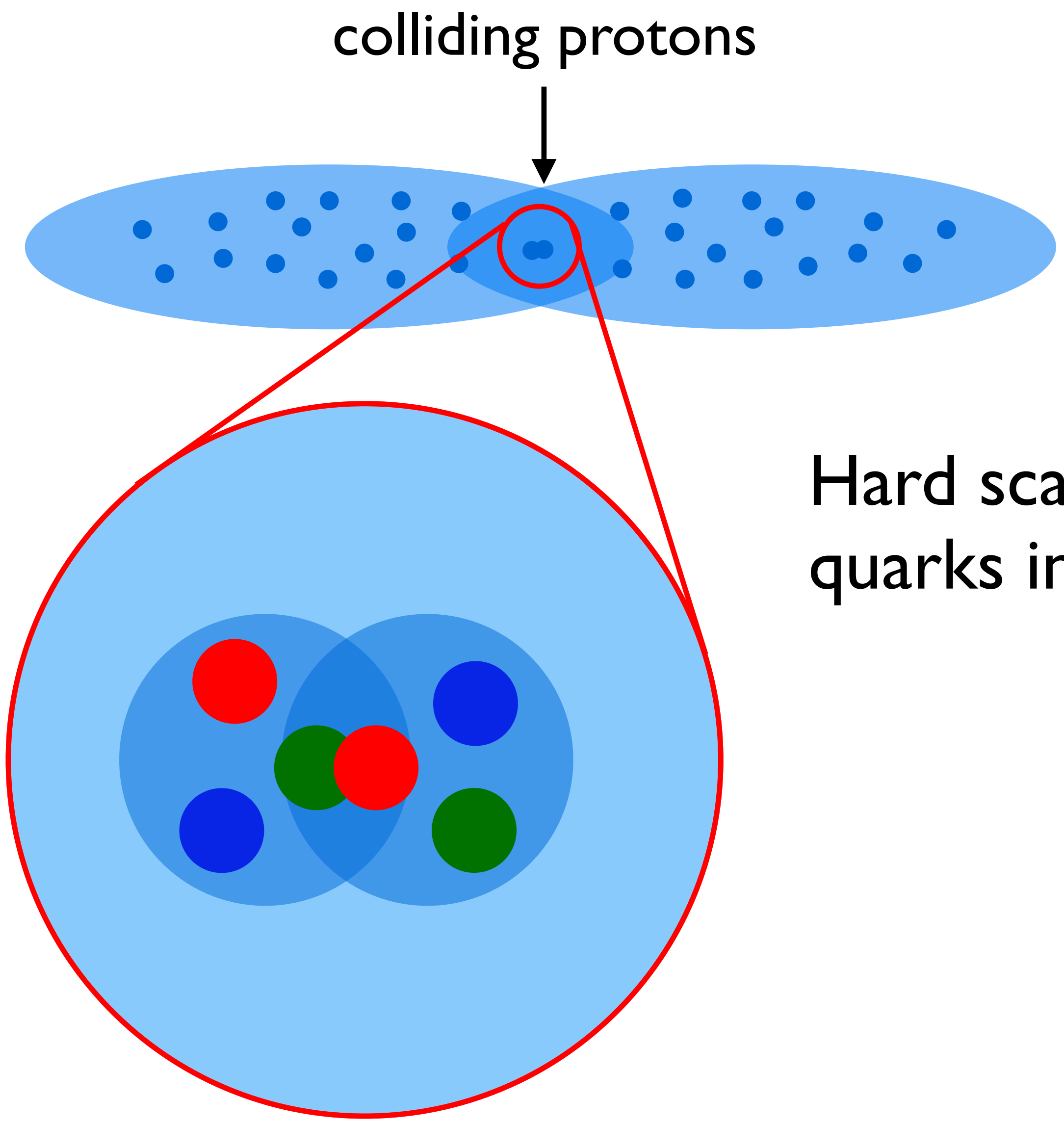


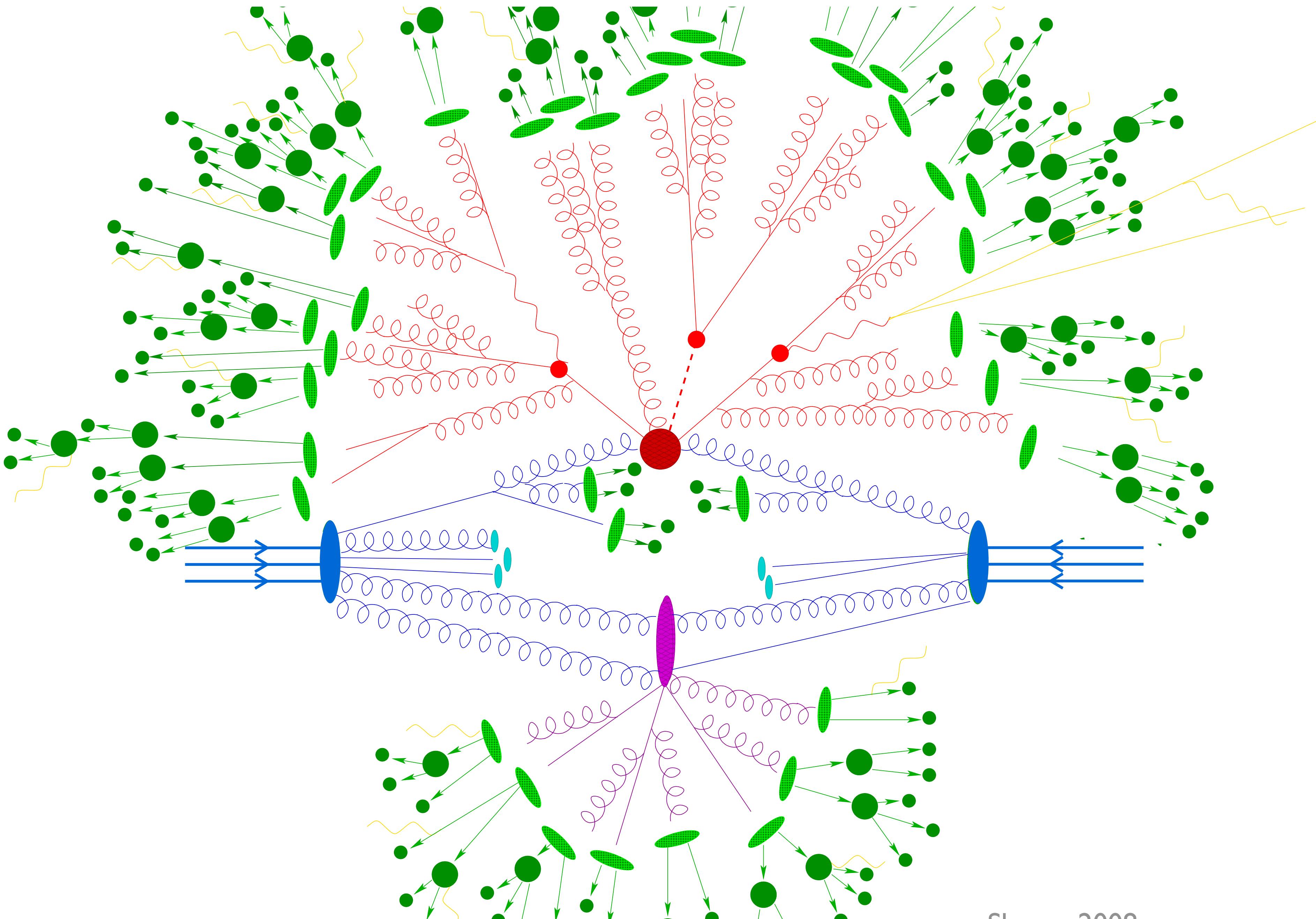
Most of the time, nothing interesting happens
$\Rightarrow$ trigger recording of events

Proton collisions at the LHC



Hard scattering ($|q| \sim$ GeV–TeV) : quarks in protons collide

Proton collisions at the LHC



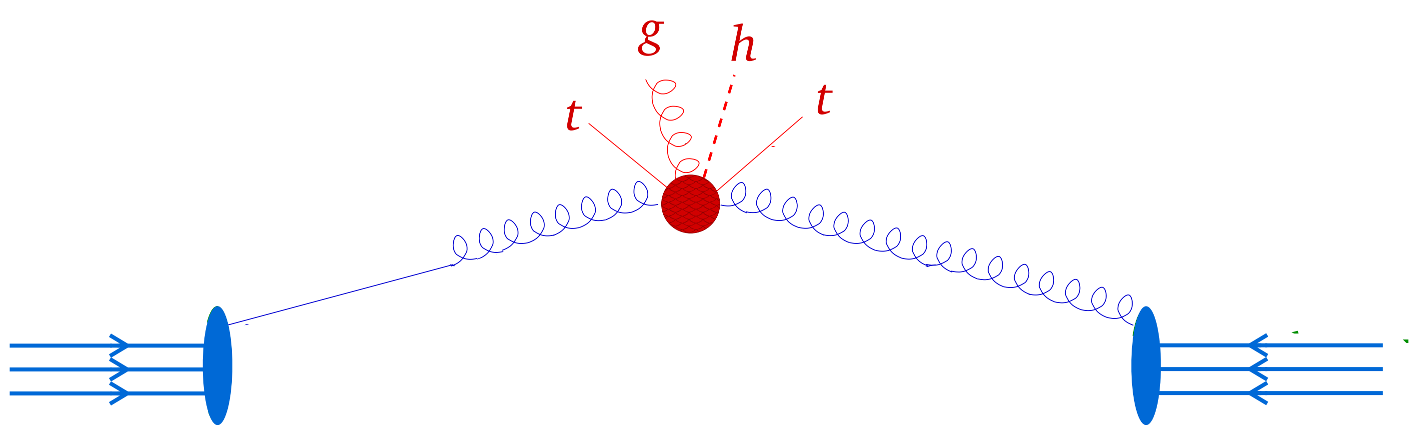
Sherpa 2008

Proton collisions at the LHC

- Parton distributions
  $f(x, \mu_F)$

Sherpa 2008

Proton collisions at the LHC

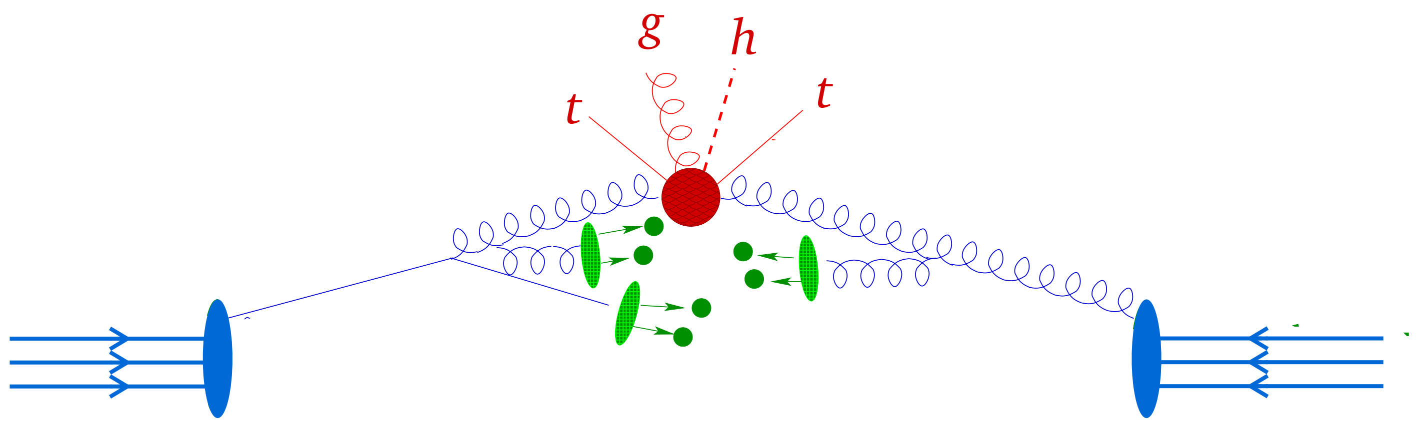


- Parton distributions
- Hard scattering

Sherpa 2008

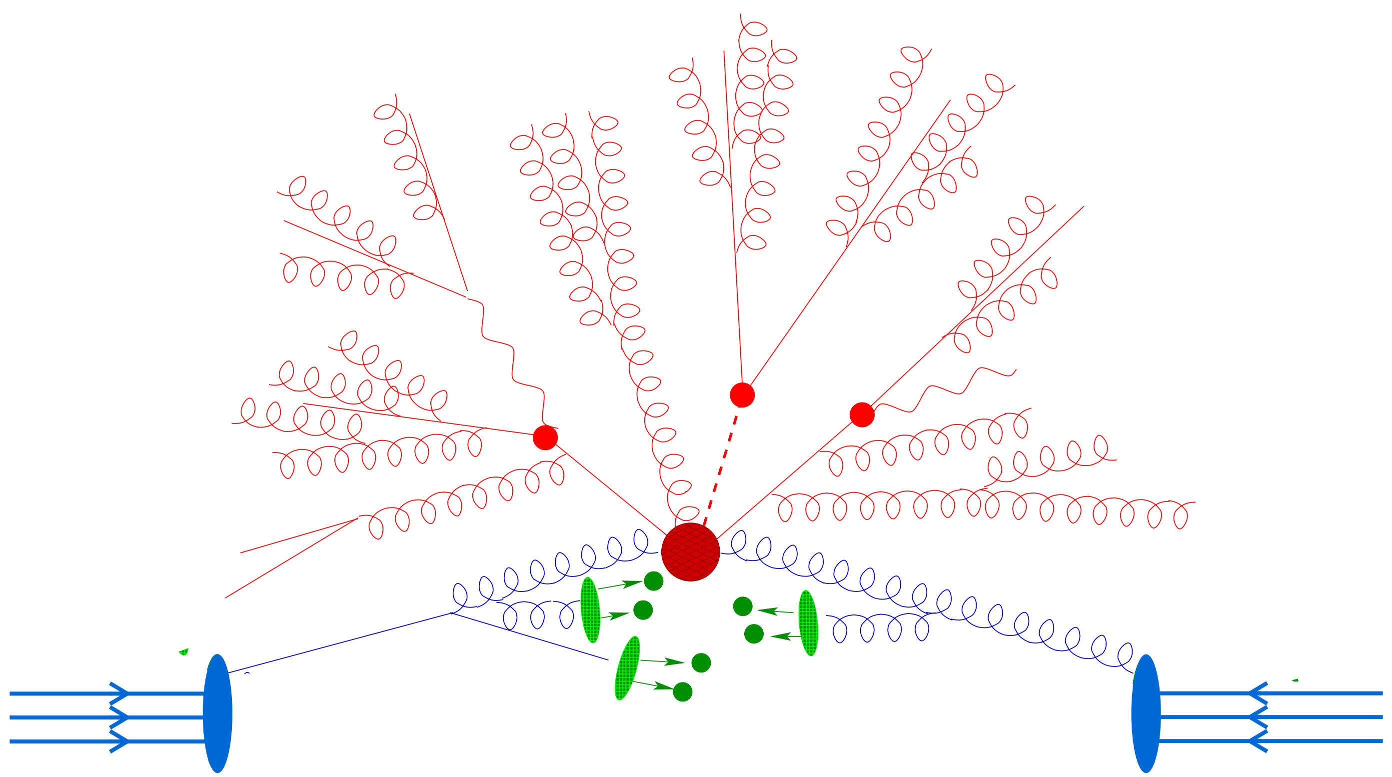
Proton collisions at the LHC

- Parton distributions
- Hard scattering
- Initial state radiation



Sherpa 2008

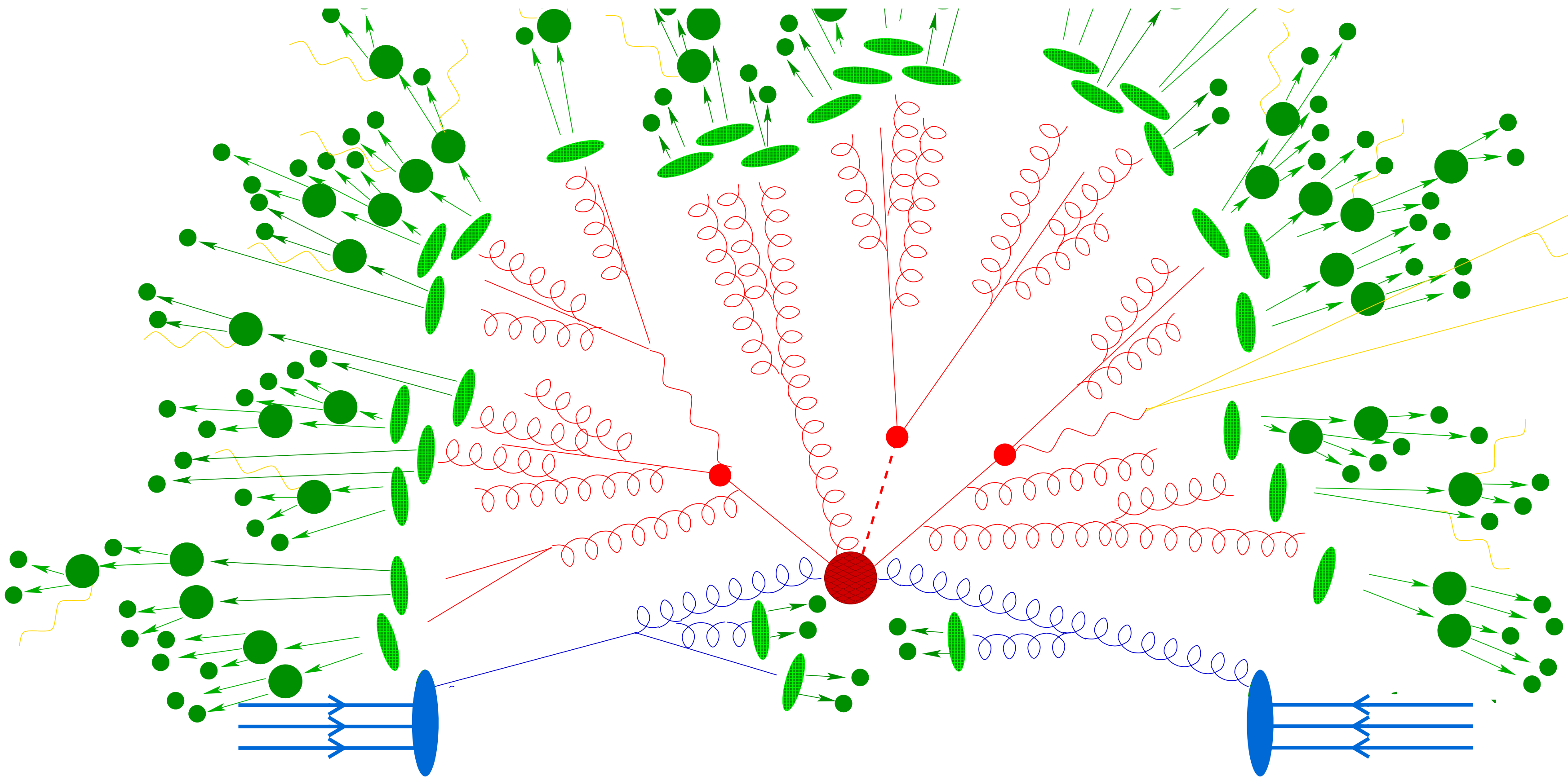
Proton collisions at the LHC



- Parton distributions
- Hard scattering
- Initial state radiation
- Final state radiation

Sherpa 2008

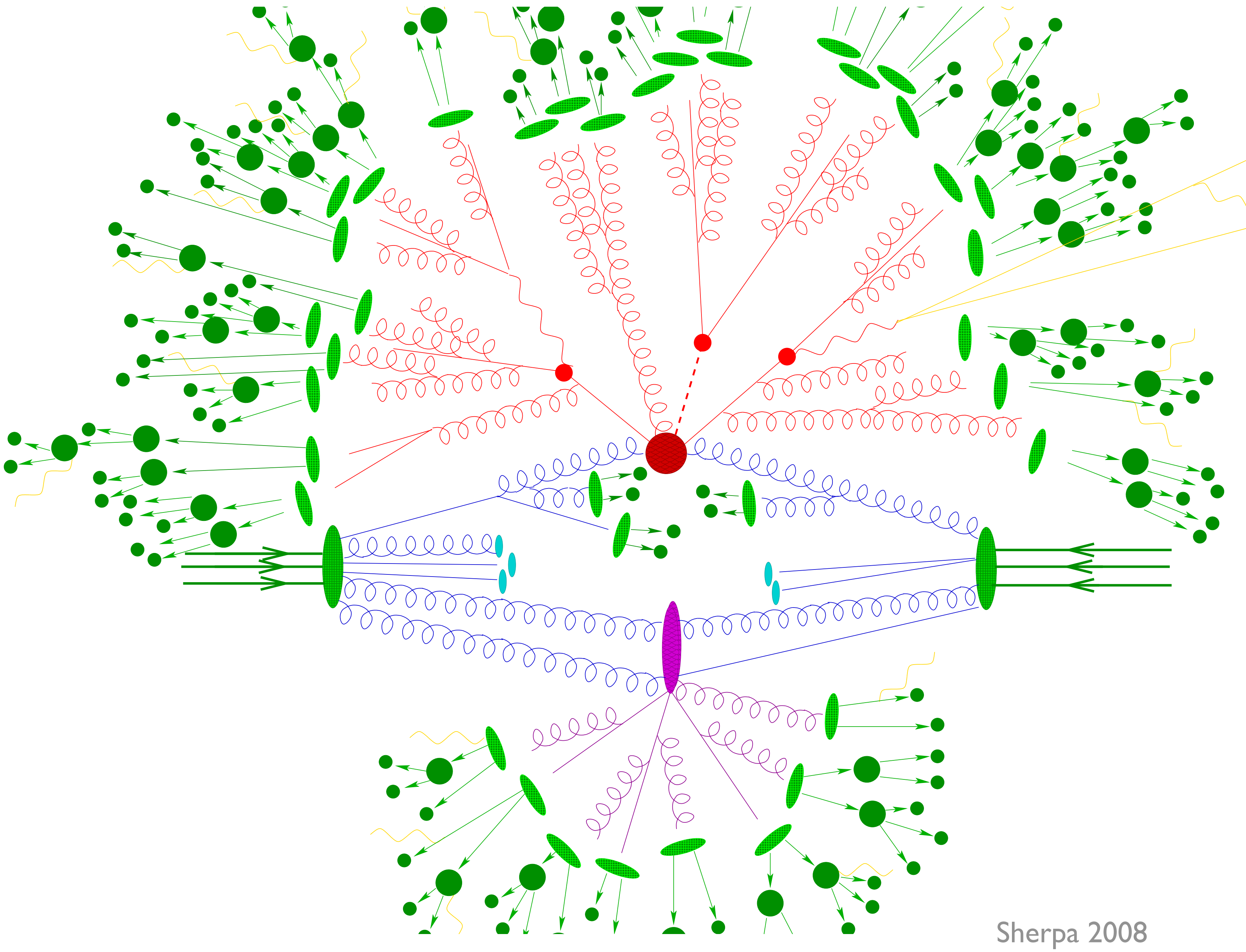
Proton collisions at the LHC



- Parton distributions
- Hard scattering
- Initial state radiation
- Final state radiation
- Hadronization & decay

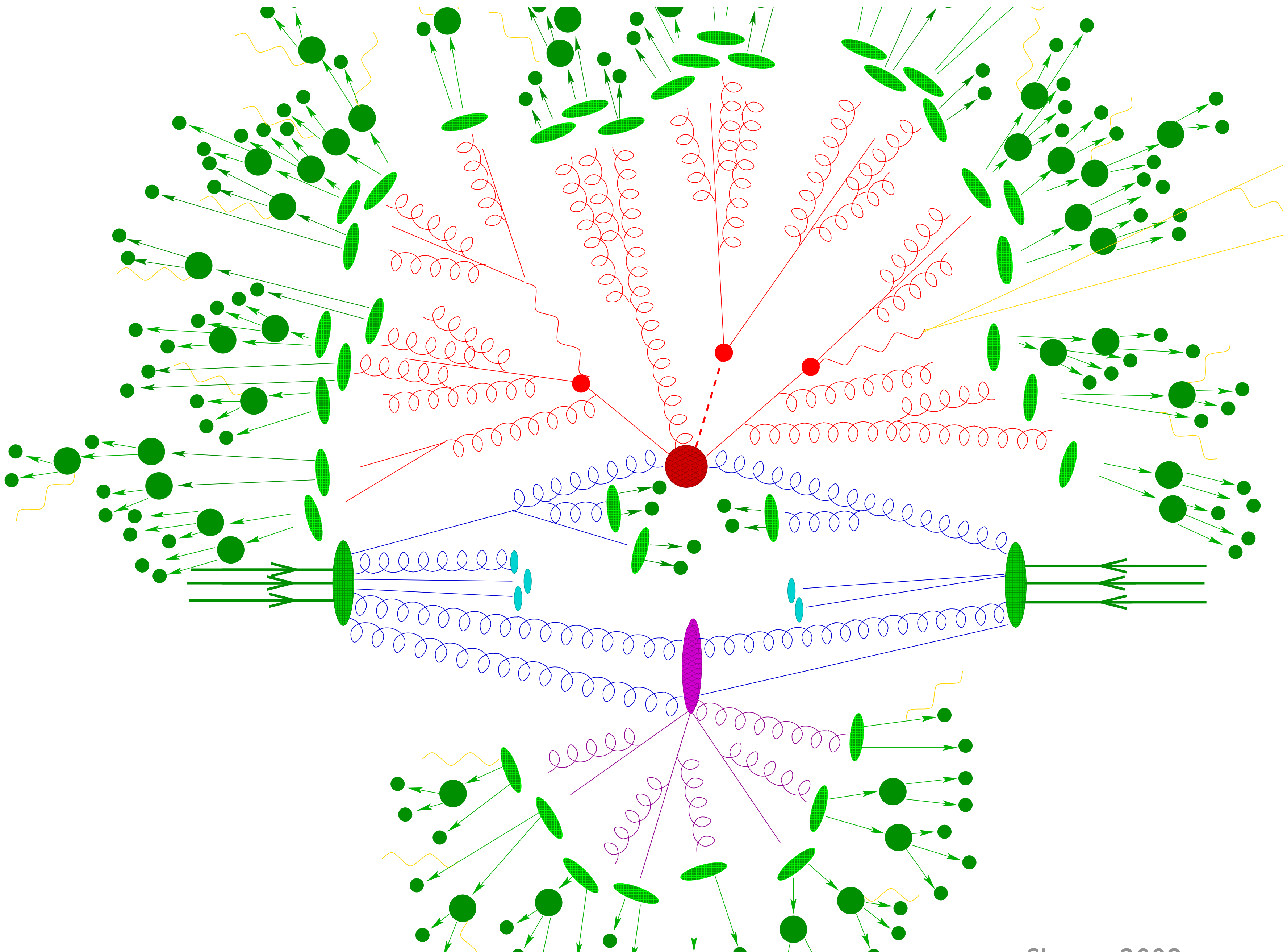
Sherpa 2008

Proton collisions at the LHC



- Parton distributions
- Hard scattering
- Initial state radiation
- Final state radiation
- Hadronization & decay
- Secondary interactions

Proton collisions at the LHC

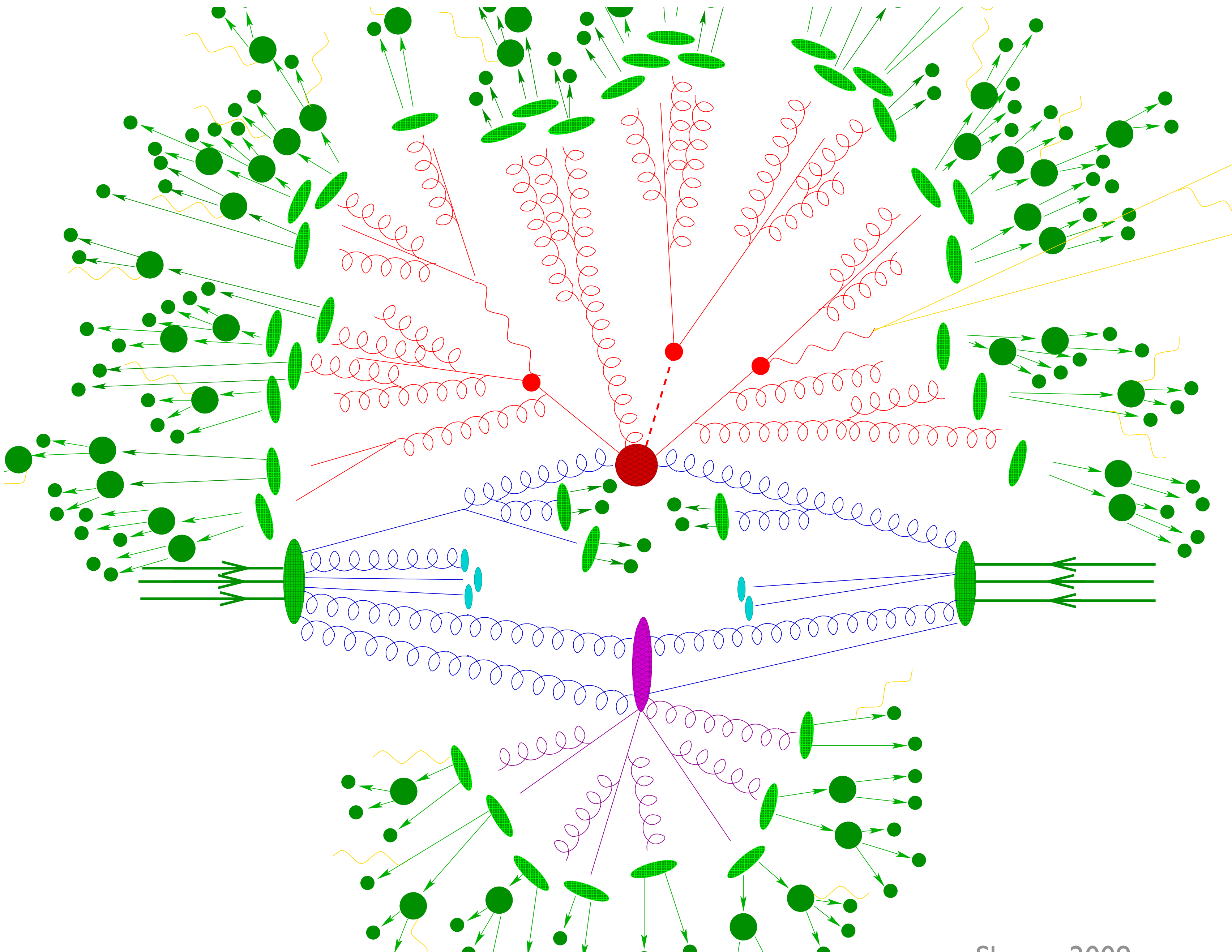


- Parton distributions
- Hard scattering
- Initial state radiation
- Final state radiation
- Hadronization & decay
- Secondary interactions

↑

Monte Carlo event generators

Proton collisions at the LHC



Sherpa 2008

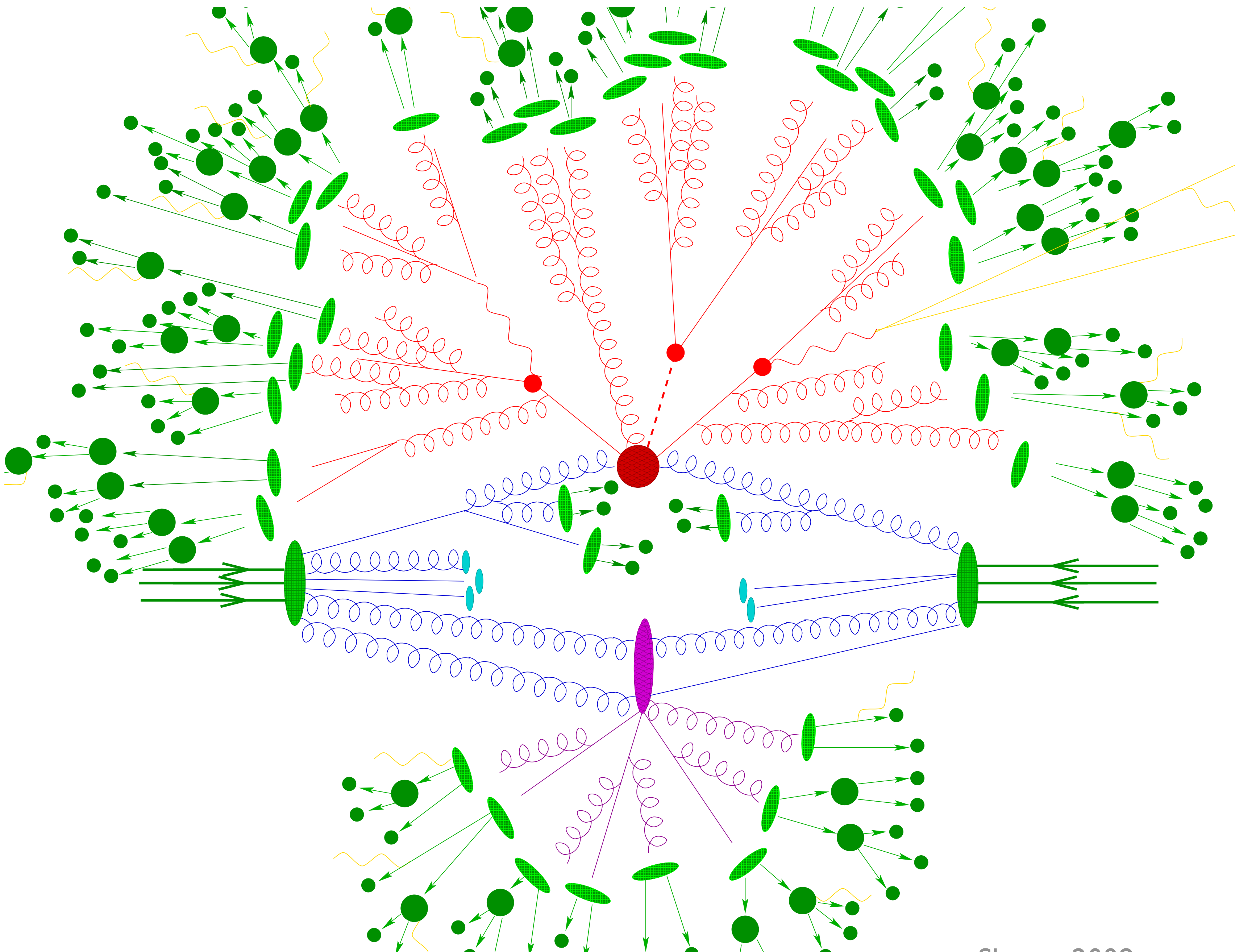
- Parton distributions
- Hard scattering
- Initial state radiation
- Final state radiation
- Hadronization & decay
- Secondary interactions

↑

Monte Carlo
event generators:

e.g. Pythia, Herwig,
Sherpa, Powheg;
MadGraph, MCFM,
Whizard

Proton collisions at the LHC



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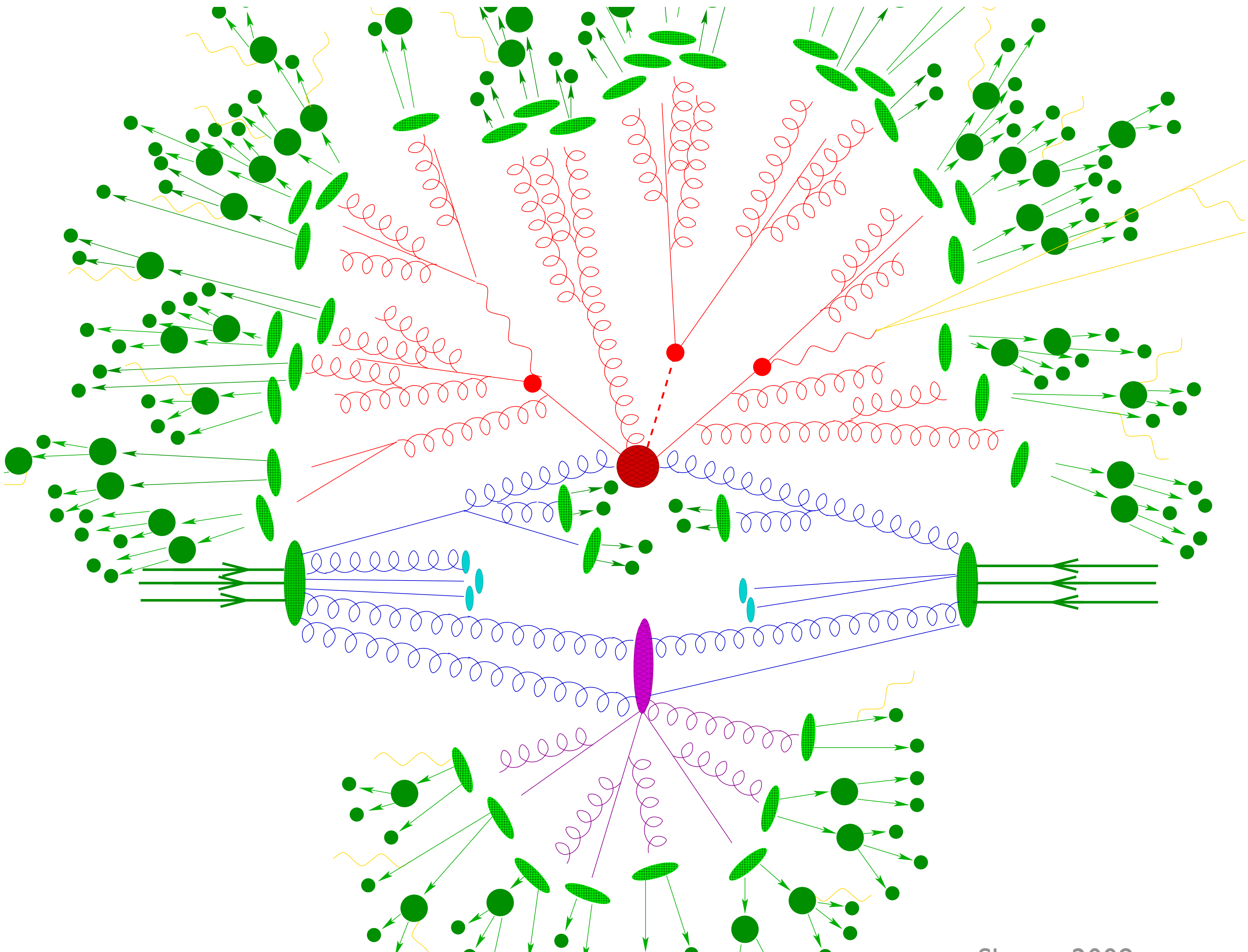
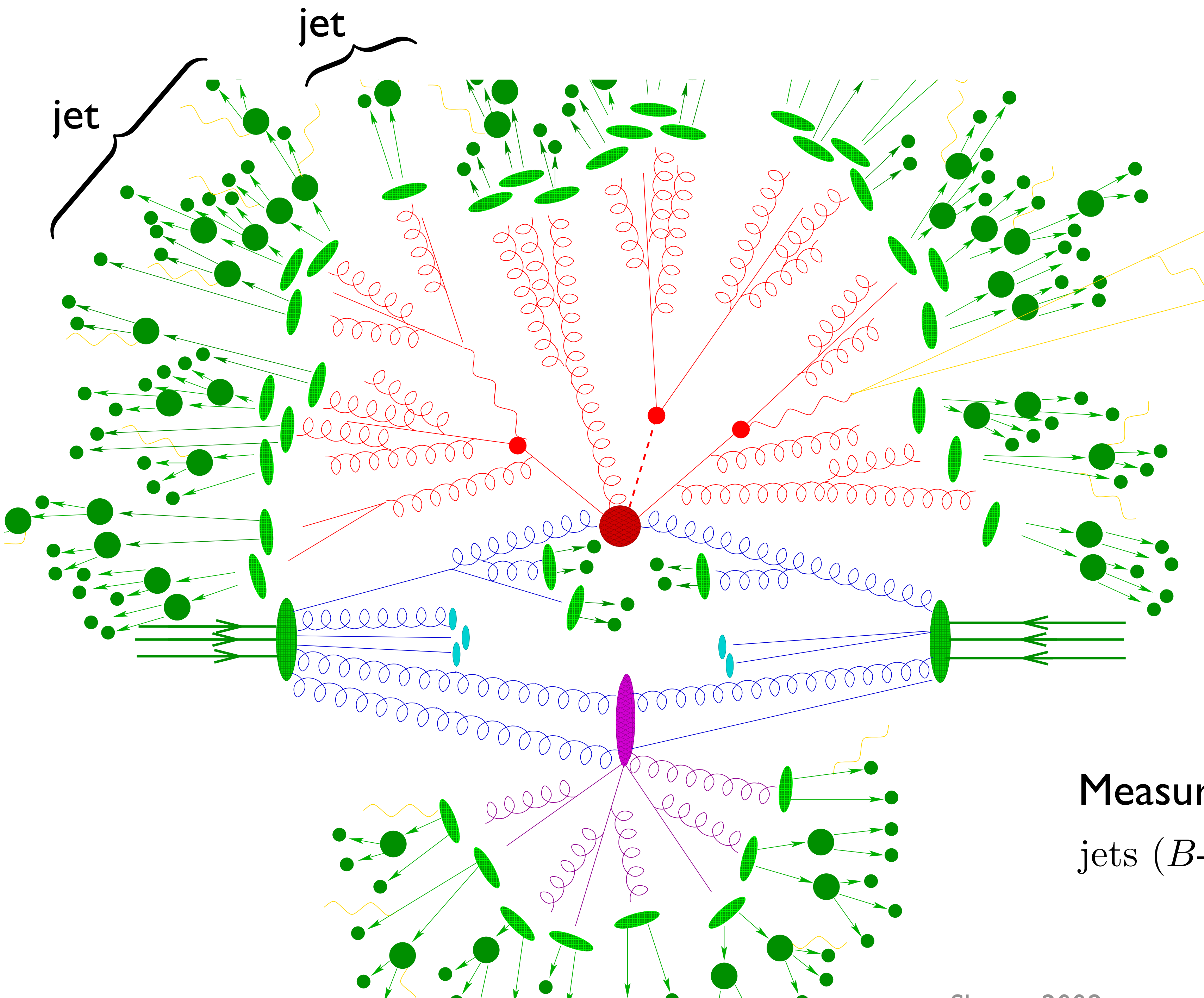
Proton collisions at the LHC



Sherpa 2008

- Parton distributions
- Hard scattering
- Initial state radiation
- Final state radiation
- Hadronization & decay
- Secondary interactions
- Detector simulation

Proton collisions at the LHC



Sherpa 2008

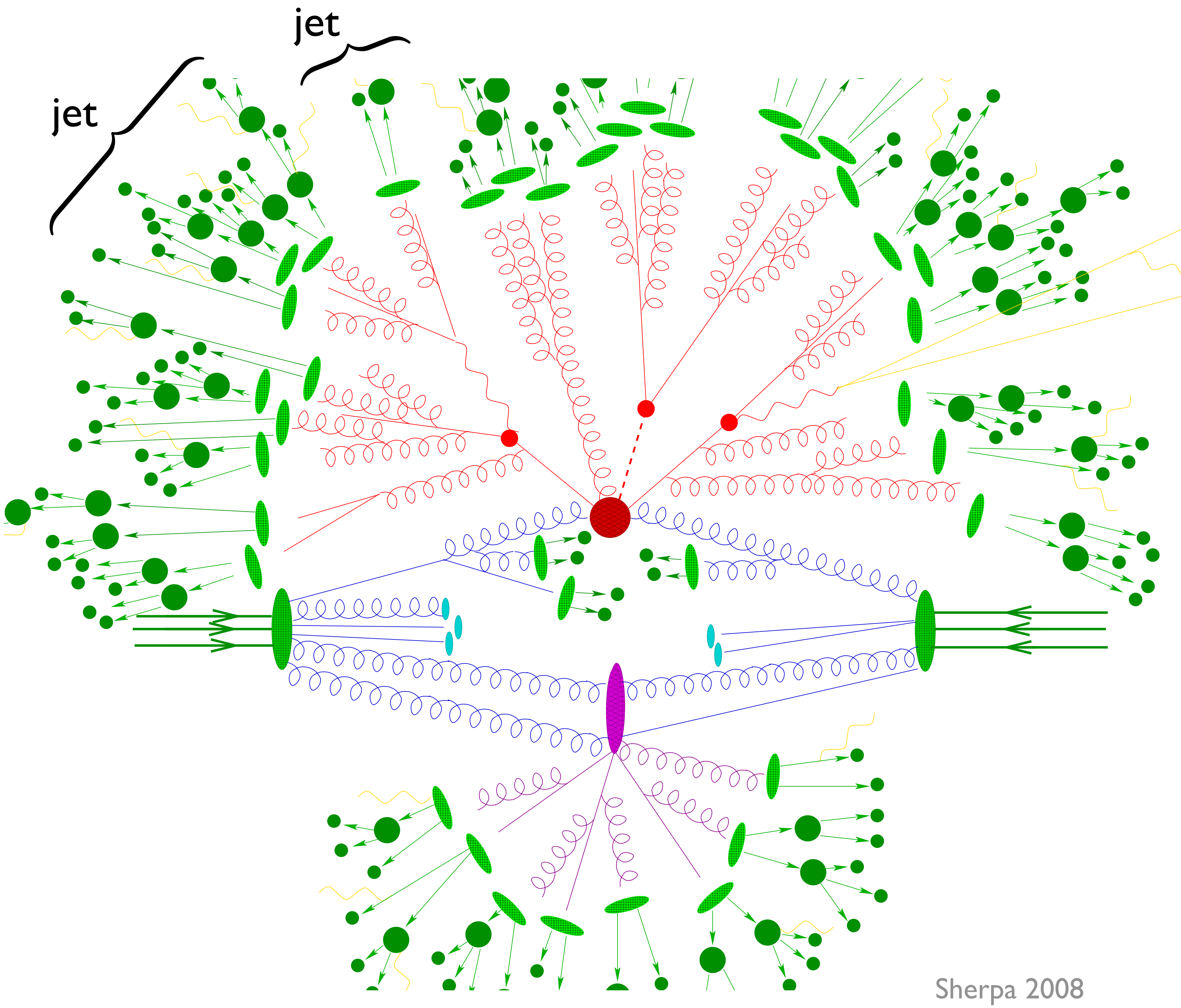
- Parton distributions
- Hard scattering
- Initial state radiation
- Final state radiation
- Hadronization & decay
- Secondary interactions

- Detector simulation
- Jet clustering

Measured objects in an event:

jets (B-tag, τ-tag), γ, $e^{\pm}$, $\mu^{\pm}$, MET

Proton collisions at the LHC

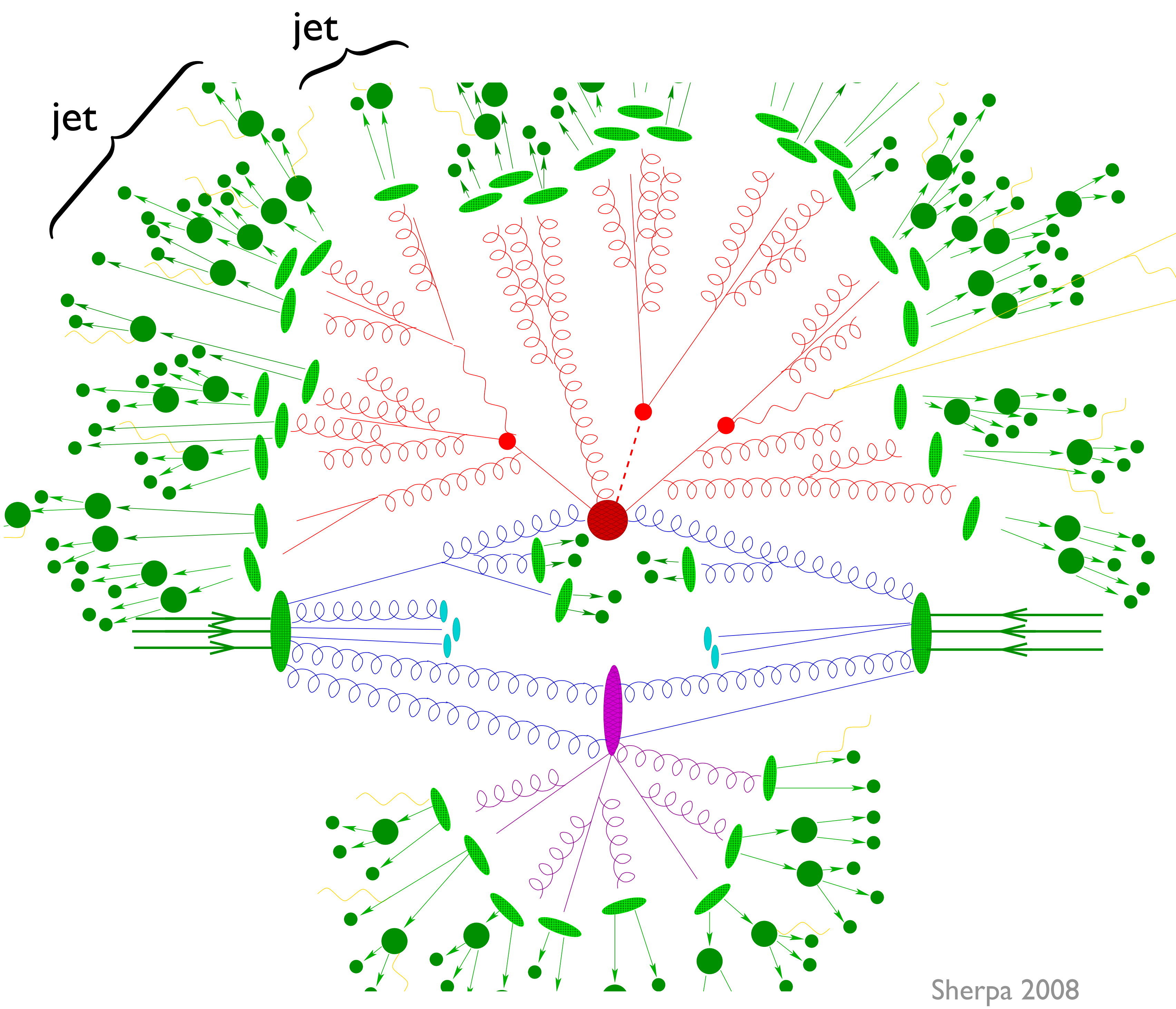


- Parton distributions
- Hard scattering
- Initial state radiation
- Final state radiation
- Hadronization & decay
- Secondary interactions

- Detector simulation
- Jet clustering
- Apply search cuts

Signal over background?

Proton collisions at the LHC



- Parton distributions
- Hard scattering
- Initial state radiation
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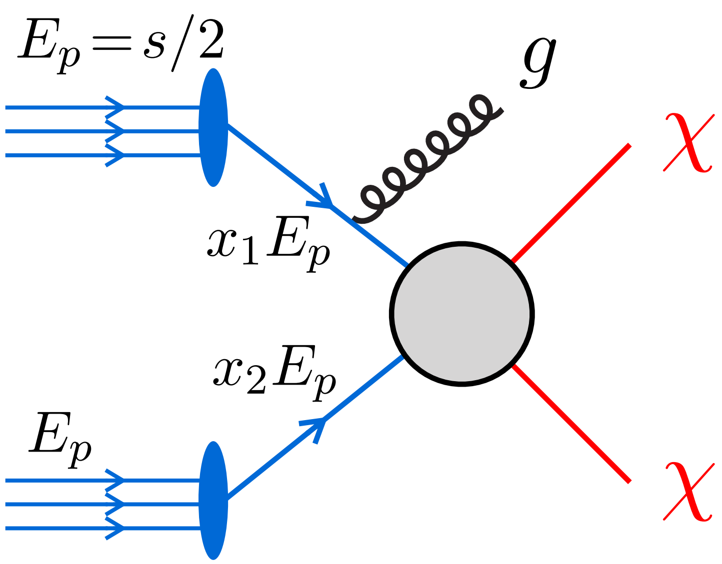
Signal over background?

MadAnalysis, CheckMate, SModelS, …

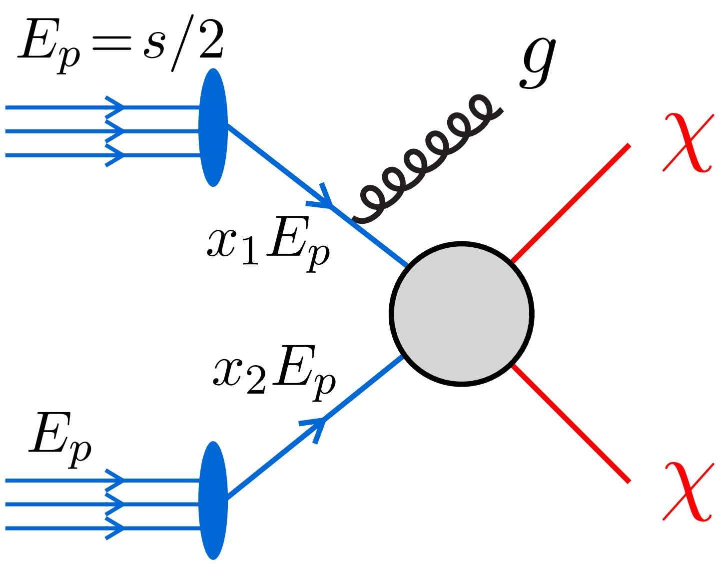
WIMP dark matter production cross section



$\hat{s} = x_1 x_2 s$

$$\sigma_{pp\to\chi\chi g} = \sum_{k,l} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \; f_k(x_1)\, f_l(x_2)\; \sigma_{kl\to\chi\chi g}(\hat{s})\; \Theta_{\text{thresh.}}$$

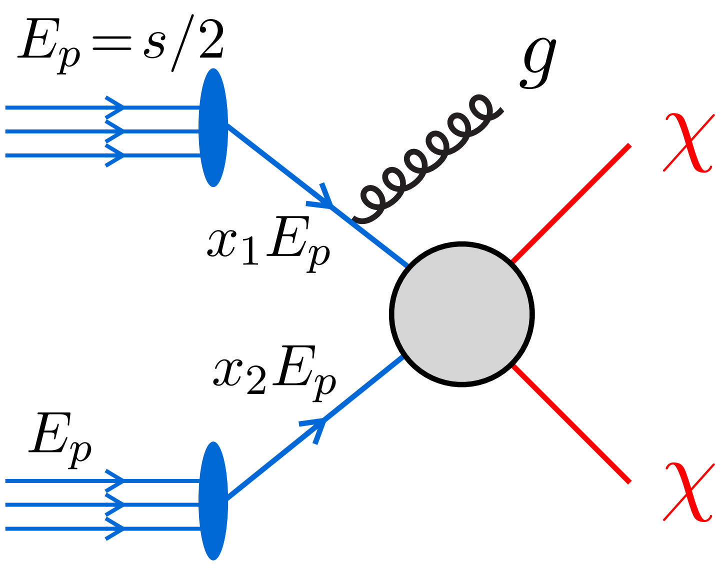
WIMP dark matter production cross section



$$\sigma_{pp\to\chi\chi g} = \sum_{k,l} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \; f_k(x_1)\, f_l(x_2)\; \sigma_{kl\to\chi\chi g}(\hat{s})\; \Theta_{\text{thresh.}}$$

$2m_\chi + E_{\text{jet}}$

WIMP dark matter production cross section

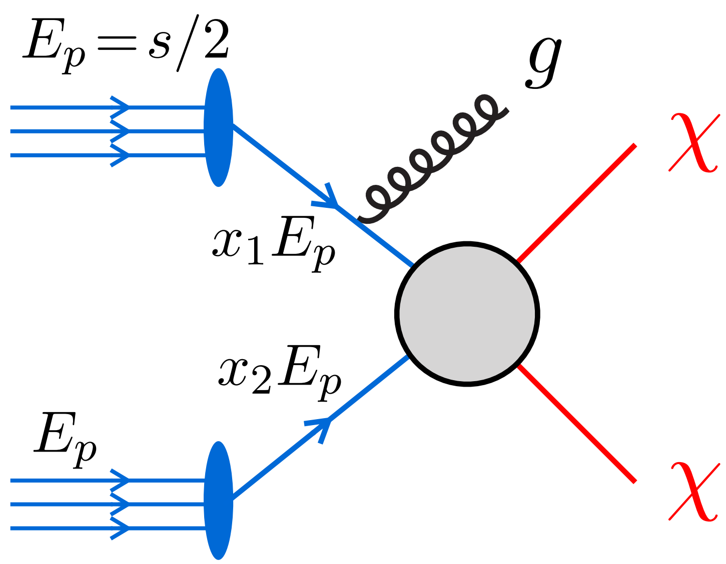


$2m_\chi + E_{\rm jet}$ ↓

$$\sigma_{pp\to\chi\chi g} = \sum_{k,l} \int_0^1 {\rm d}x_1 \int_0^1 {\rm d}x_2 \; f_k(x_1)\, f_l(x_2)\; \sigma_{kl\to\chi\chi g}(\hat{s})\; \Theta_{\rm thresh.}$$

$$= \sum_{k,l} \int_{s_{\rm thresh.}}^{s} {\rm d}\hat{s}\, L_{kl}(\hat{s}) \times \sigma_{kl\to\chi\chi g}(\hat{s})$$

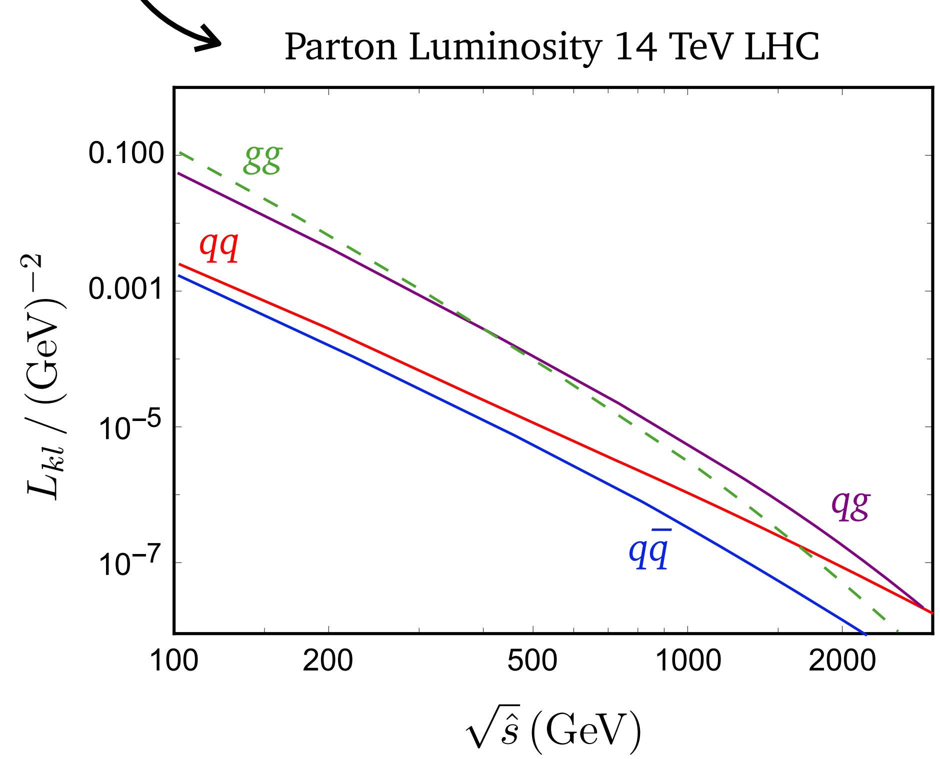
WIMP dark matter production cross section



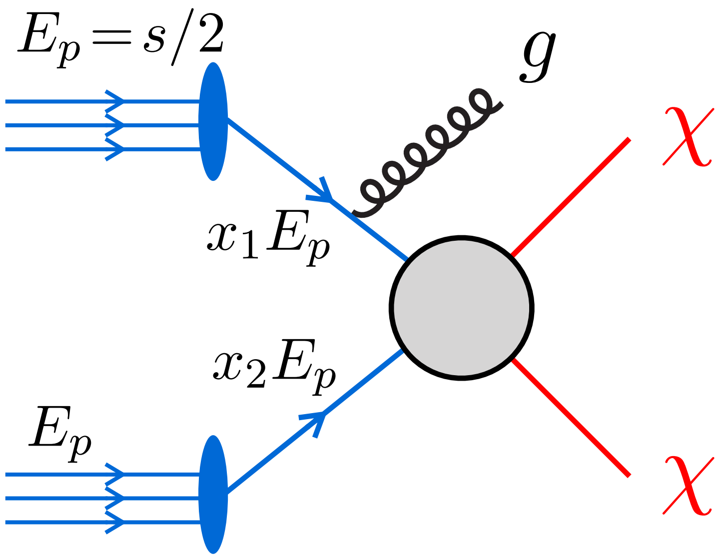
$2m_\chi + E_{\rm jet}$

$$\sigma_{pp\to\chi\chi g} = \sum_{k,l} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \; f_k(x_1)\, f_l(x_2)\; \sigma_{kl\to\chi\chi g}(\hat{s})\; \Theta_{\rm thresh.}$$

$$= \sum_{k,l} \int_{s_{\rm thresh.}}^{s} \mathrm{d}\hat{s}\, L_{kl}(\hat{s}) \times \sigma_{kl\to\chi\chi g}(\hat{s})$$



WIMP dark matter production cross section



$2m_\chi + E_{\text{jet}}$

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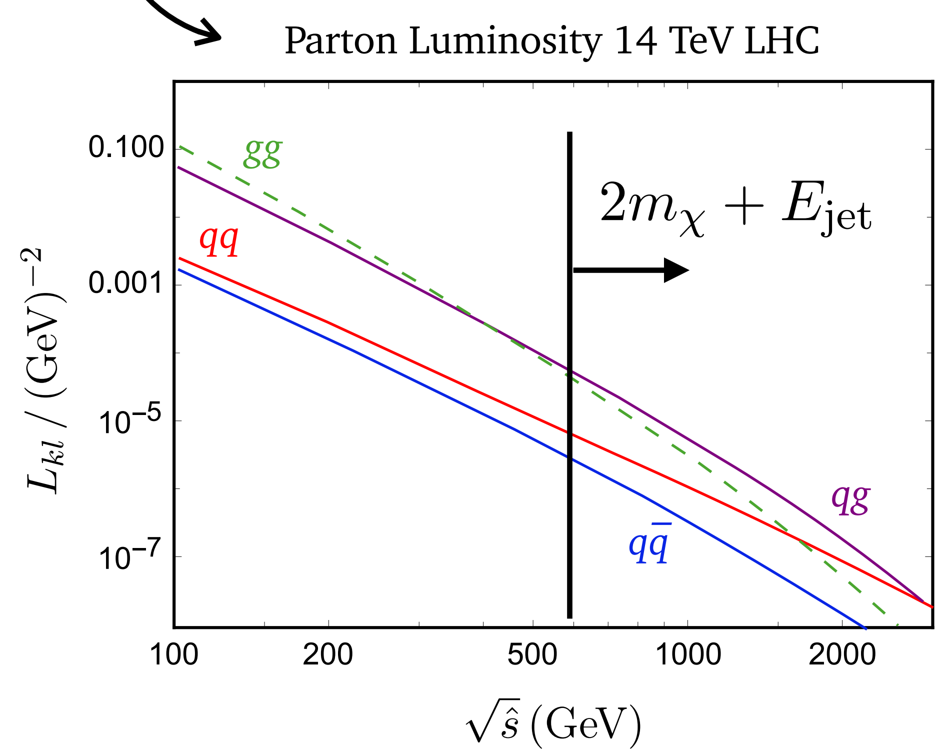

WIMP dark matter production – background

Leading background for MET searches:

- Z+jets, $Z \to \nu\nu$
- W+jets, $W \to \ell\nu$
- $t\bar{t}$, $t \to bW \to b\ell\nu$
- QCD mismeasured jets

WIMP dark matter production – background

Leading background for MET searches:

• Z+jets, $Z \to \nu\nu$	irreducible
• W+jets, $W \to \ell\nu$	
• $t\bar{t}$, $t \to bW \to b\ell\nu$	
• QCD mismeasured jets	instrumental

WIMP dark matter production – background

Leading background for MET searches:

- Z+jets, $Z \to \nu\nu$ — irreducible
- W+jets, $W \to \ell\nu$ — } depends on search
- $t\bar{t}$, $t \to bW \to b\ell\nu$ — } depends on search
- QCD mismeasured jets — instrumental

WIMP dark matter production – background

Leading background for MET searches:

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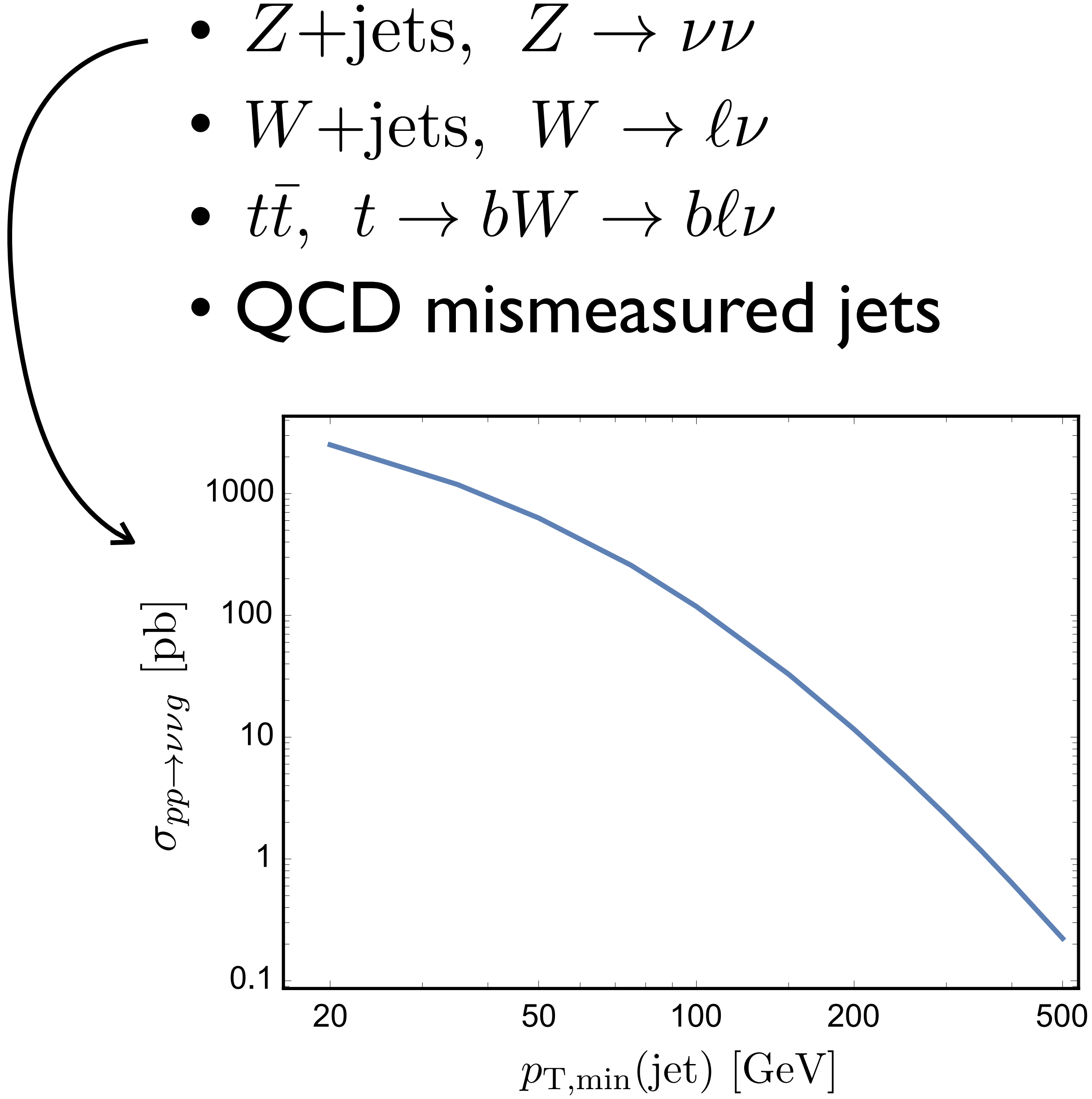

WIMP dark matter production – background

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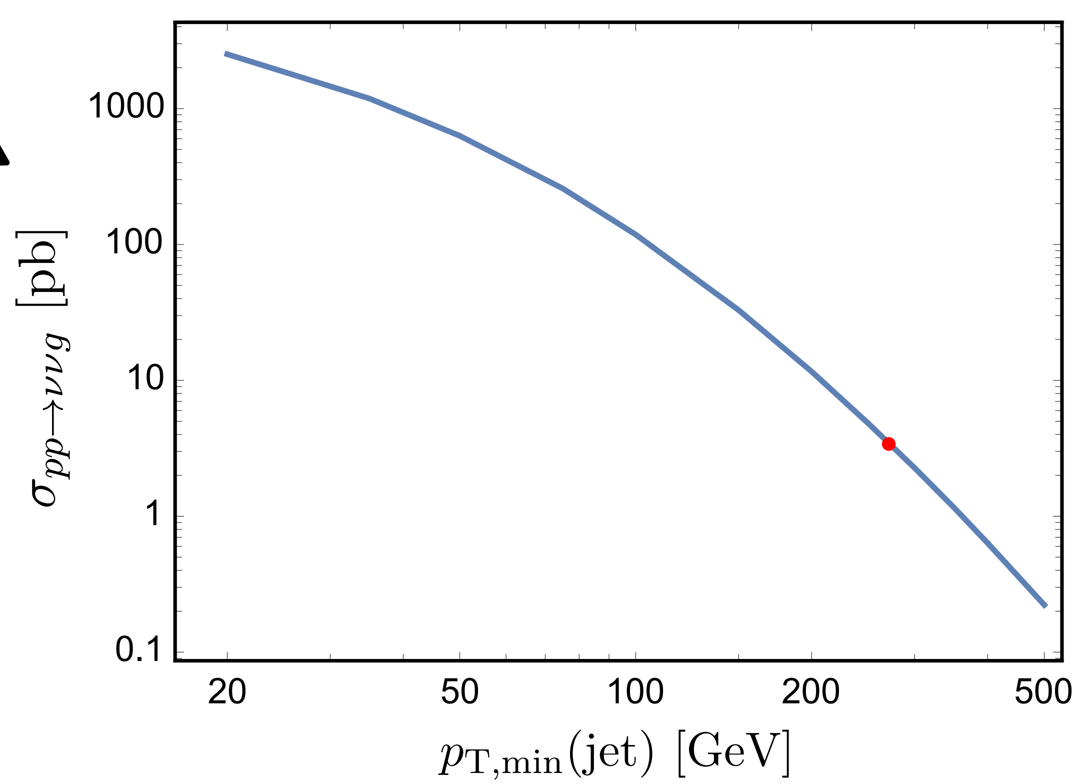


$$\sigma_{pp\to\nu\nu g}(p_{\mathrm{T}}^{\mathrm{jet}} > 250\mathrm{GeV}) \sim \text{few pb}$$

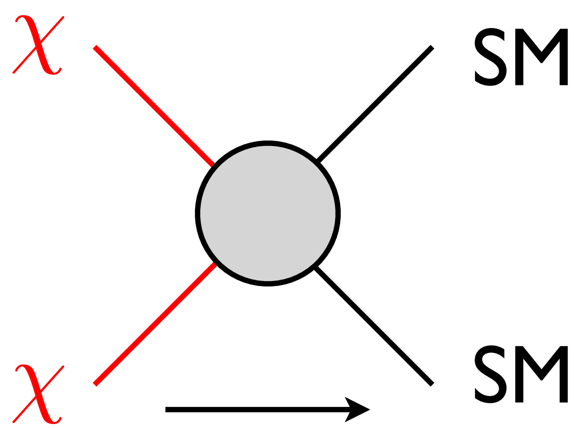
$$\Rightarrow B \sim 100\,\mathrm{fb}^{-1} \times 1000\,\mathrm{fb} \sim 10^5$$

$$\frac{S}{\sqrt{B}} \simeq 2 \quad \Rightarrow \quad S \sim 10^3$$

systematics become dominant

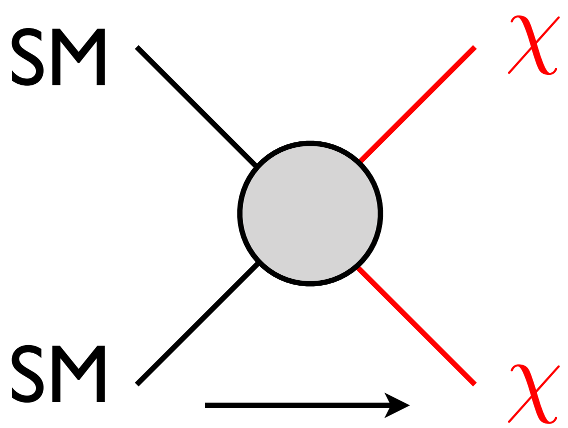
WIMP dark matter searches

Freeze-out



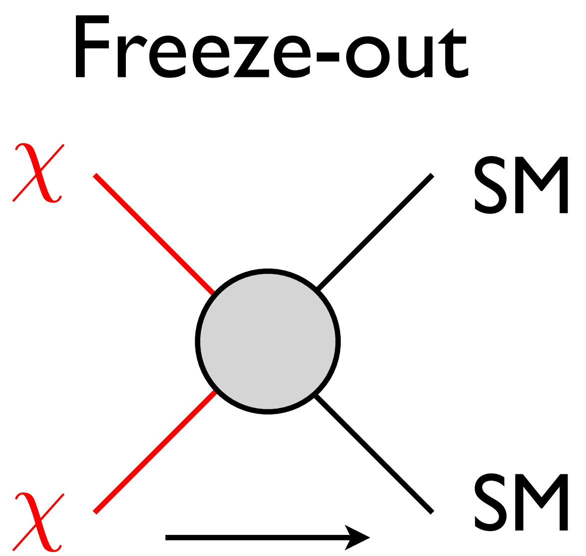
$\langle \sigma v \rangle \sim 10^{-26} \mathrm{cm}^3/\mathrm{s}$

Production

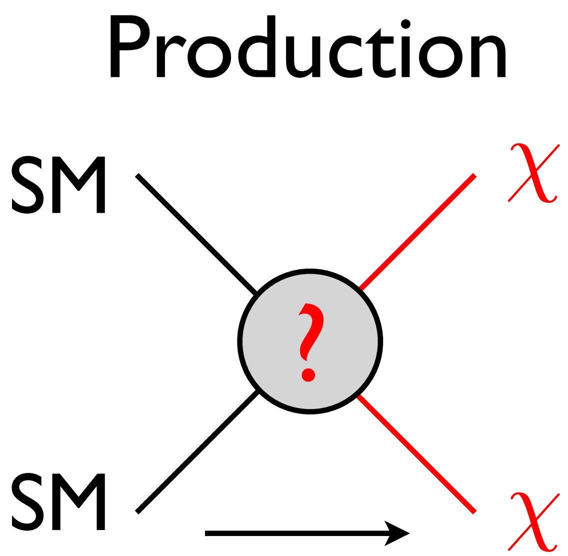


$\sigma \sim \mathrm{pb}$

WIMP dark matter searches

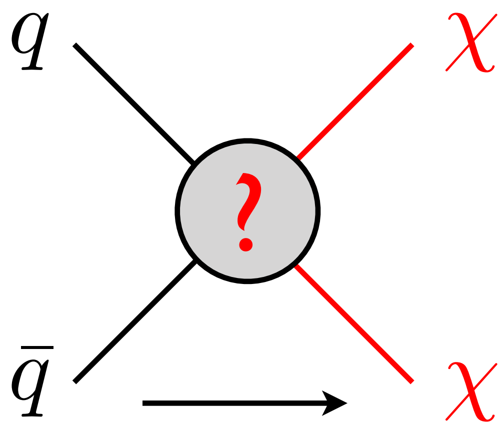


$\langle \sigma v \rangle \sim 10^{-26} \mathrm{cm}^3/\mathrm{s}$



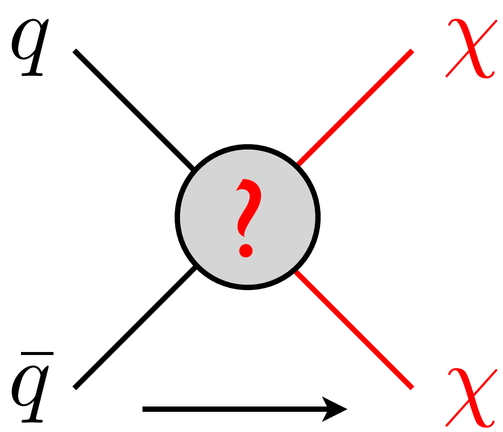
$\sigma \sim \mathrm{pb}$

Effective field theory (EFT)



$$\sim \frac{1}{\Lambda^2}(\bar{q}q)(\bar{\chi}\chi)\,, \;\; \frac{1}{\Lambda^2}(\bar{q}\gamma^\mu\gamma^5 q)(\bar{\chi}\gamma_\mu\gamma^5\chi)\,, \;\ldots$$

Effective field theory (EFT)

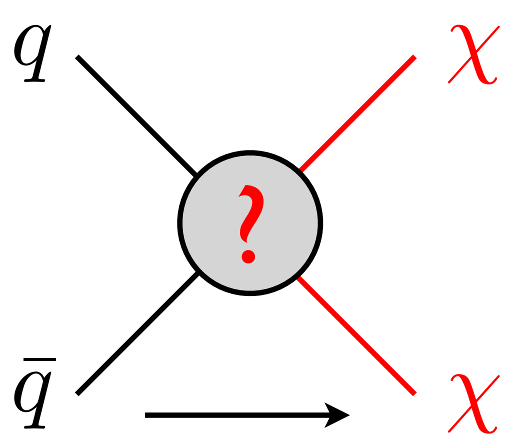


$$\sim \frac{1}{\Lambda^2}(\bar{q}q)(\bar{\chi}\chi)\,, \quad \frac{1}{\Lambda^2}(\bar{q}\gamma^\mu\gamma^5 q)(\bar{\chi}\gamma_\mu\gamma^5\chi)\,, \ldots$$

Problem at LHC: Typical limit on Λ around TeV ~ energies of collisions

⇒ EFT not valid [Busoni *et al* 1307.2253, Buchmueller *et al* 1308.6799, …]

Effective field theory (EFT)

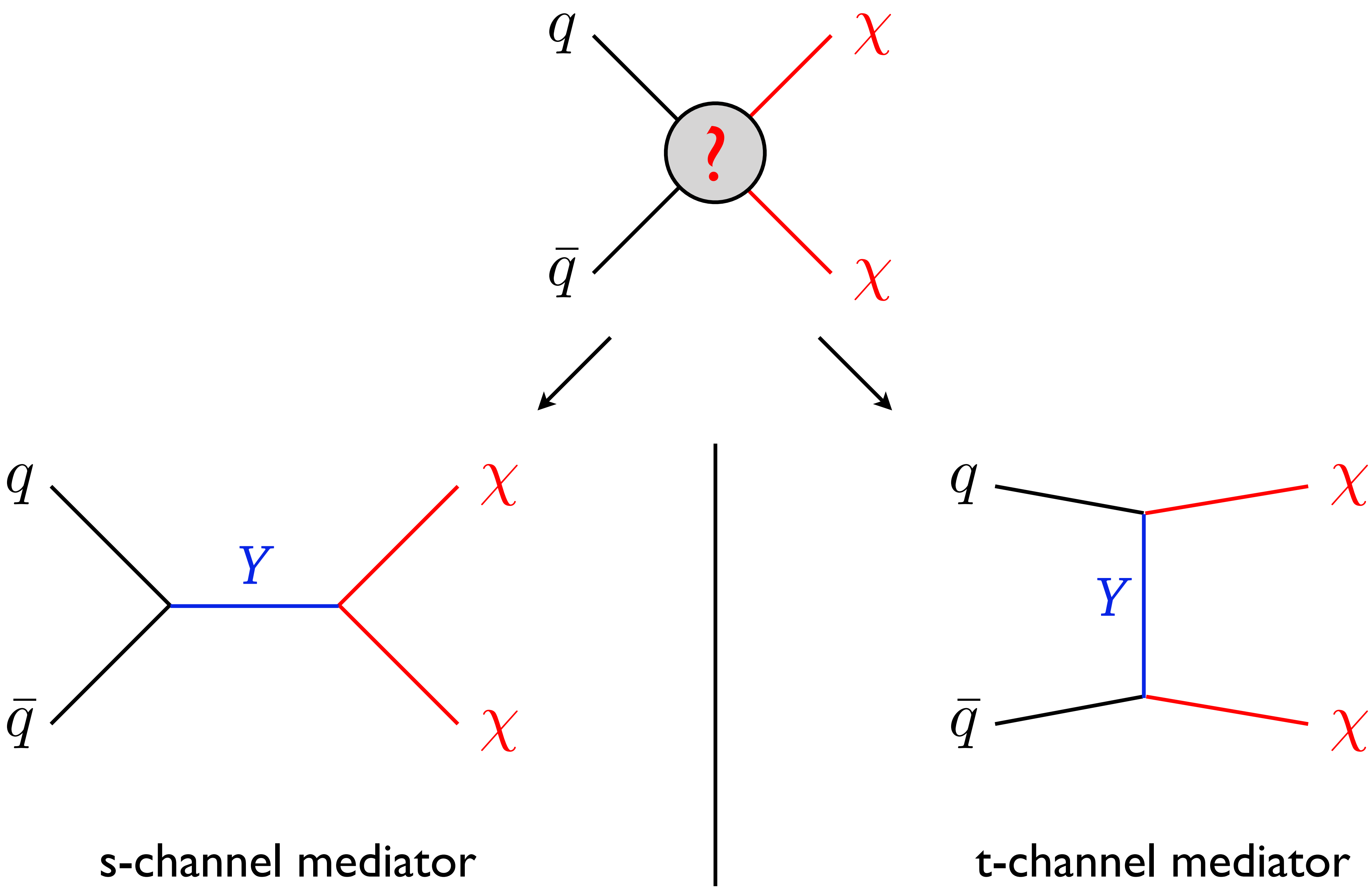


$$\sim \frac{1}{\Lambda^2}(\bar{q}q)(\bar{\chi}\chi)\,,\quad \frac{1}{\Lambda^2}(\bar{q}\gamma^\mu\gamma^5 q)(\bar{\chi}\gamma_\mu\gamma^5\chi)\,,\ \ldots$$

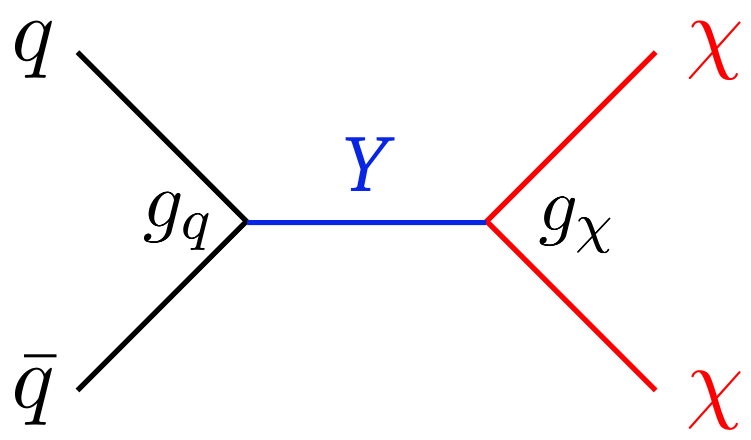
Problem at LHC: Typical limit on Λ around TeV ~ energies of collisions
⇒ EFT not valid [Busoni *et al* 1307.2253, Buchmueller *et al* 1308.6799, …]

$$\frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M^2} \qquad \Lambda^2 \sim \hat{s} \;\Rightarrow\; \begin{cases} M^2 \lesssim \hat{s} & \text{perturbative} \\ M^2 \gg \Lambda^2 & g \gg 1 \end{cases}$$

Beyond effective field theory – simplified models

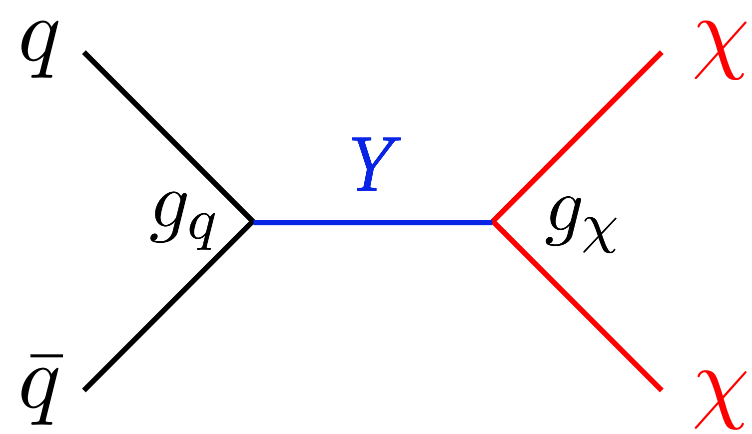


Simplified models: s-channel mediator



- Y could be scalar or vector
- Four free parameters (at least)
  m_χ, m_Y, g_q, g_χ

Simplified models: s-channel mediator



- Y could be scalar or vector
- Four free parameters (at least)
  m_χ, m_Y, g_q, g_χ
- The LHC DM Working Group compiled lists of simplified models

[Boveia *et al* 1603.04156]

Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter

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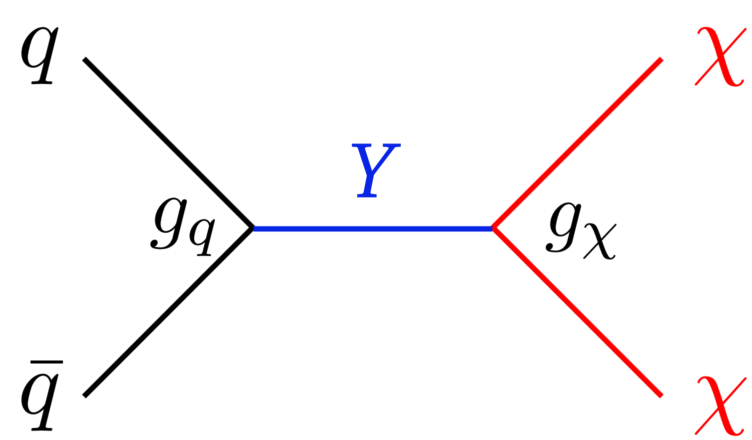
Antonio Boveia,[1,*] Oliver Buchmueller,[2,*] Giorgio Busoni,[3]
Francesco D'Eramo,[4] Albert De Roeck,[1,5] Andrea De Simone,[6]
Caterina Doglioni,[7,*] Matthew J. Dolan,[3] Marie-Helene Genest,[8]
Kristian Hahn,[9,*] Ulrich Haisch,[10,11,*] Philip C. Harris,[1]
Jan Heisig,[12] Valerio Ippolito,[13] Felix Kahlhoefer,[14,*]
Valentin V. Khoze,[15] Suchita Kulkarni,[16] Greg Landsberg,[17]
Steven Lowette,[18] Sarah Malik,[2] Michelangelo Mangano,[11,*]
Christopher McCabe,[19,*] Stephen Mrenna,[20] Priscilla Pani,[21]
Tristan du Pree,[1] Antonio Riotto,[11] David Salek,[19,22]
Kai Schmidt-Hoberg,[14] William Shepherd,[23] Tim M.P. Tait,[24,*]
Lian-Tao Wang,[25] Steven Worm[26] and Kathryn Zurek[27]

Simplified models: s-channel mediator

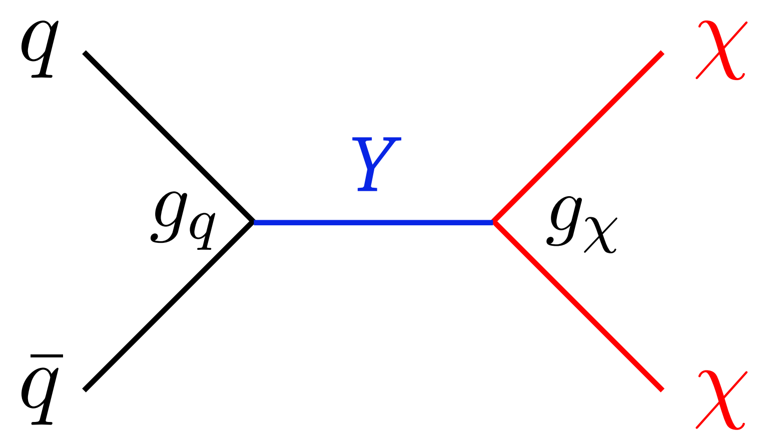


- Y could be scalar or vector
- Four free parameters (at least)
  m_χ, m_Y, g_q, g_χ

$$\mathcal{L} \supset g_q Z'^{\mu} \sum_q \bar{q}\gamma_\mu\gamma^5 q \,+\, g_\chi Z'^{\mu}\bar{\chi}\gamma_\mu\gamma^5\chi$$ axial-vector

$$\mathcal{L} \supset g_q Z'^{\mu} \sum_q \bar{q}\gamma_\mu q \,+\, g_\chi Z'^{\mu}\bar{\chi}\gamma_\mu\chi$$ vector

Simplified models: s-channel mediator

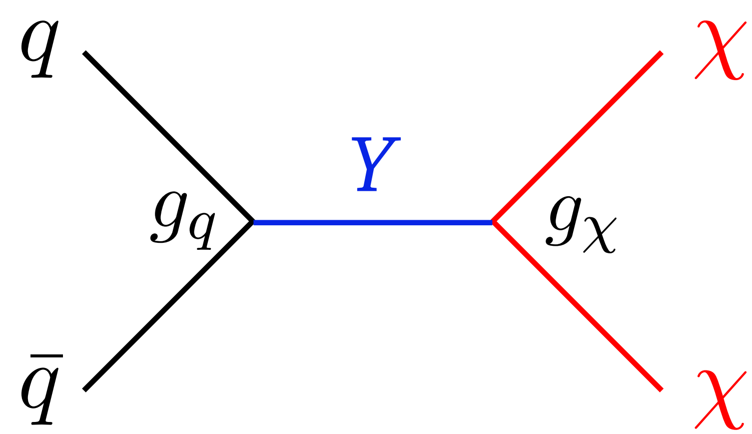


- Y could be scalar or vector
- Four free parameters (at least)
  m_χ, m_Y, g_q, g_χ

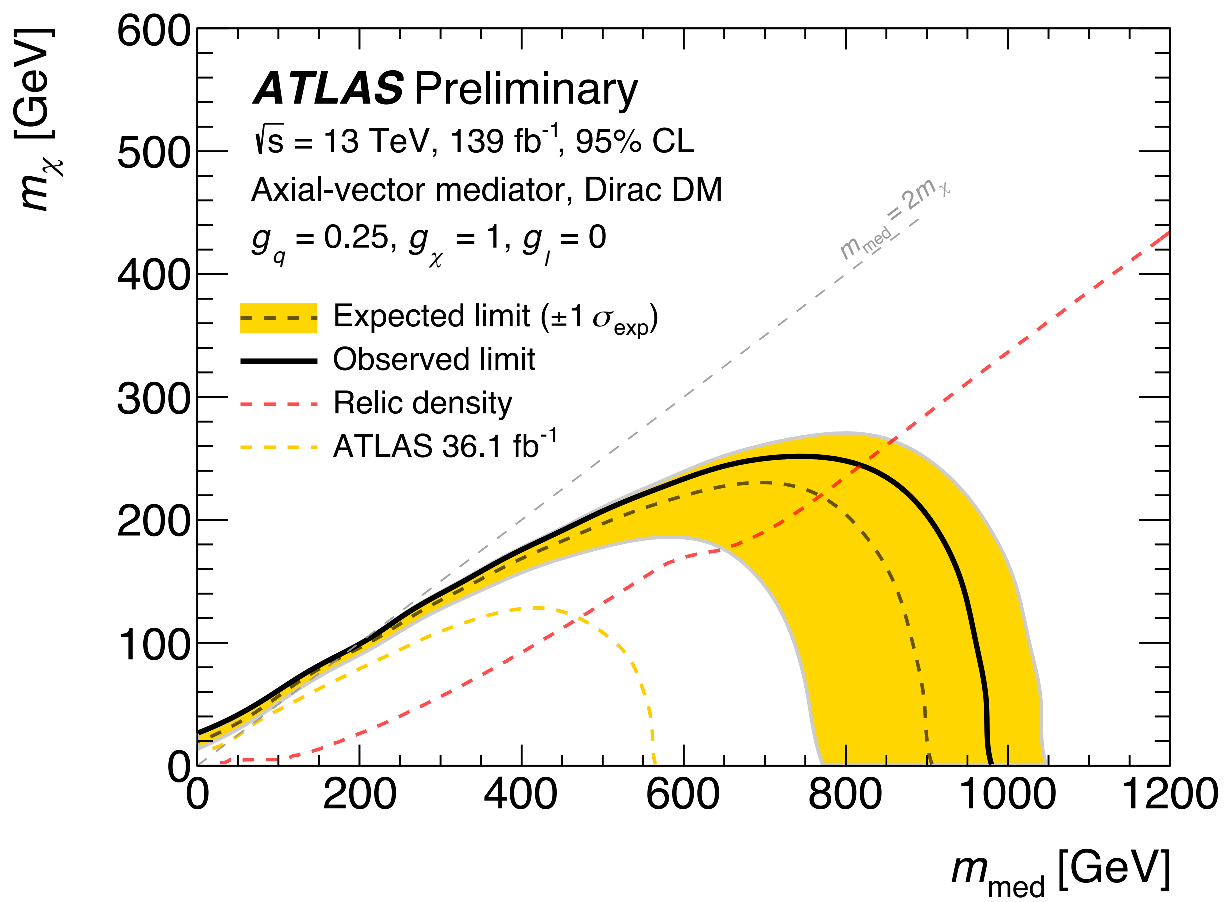
$$\mathcal{L} \supset g_q a \sum_q y_q \bar{q} \gamma^5 q \, + \, g_\chi a \bar{\chi} \gamma^5 \chi$$ pseudo-scalar

$$\mathcal{L} \supset g_q \phi \sum_q y_q \bar{q} q \, + \, g_\chi \phi \bar{\chi} \chi$$ scalar

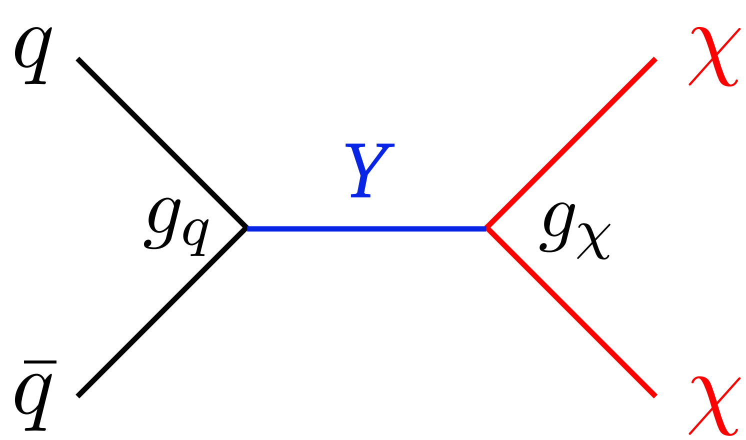
Simplified models: s-channel mediator



- Y could be scalar or vector
- Four free parameters (at least) m_χ, m_Y, g_q, g_χ



Simplified models: s-channel mediator



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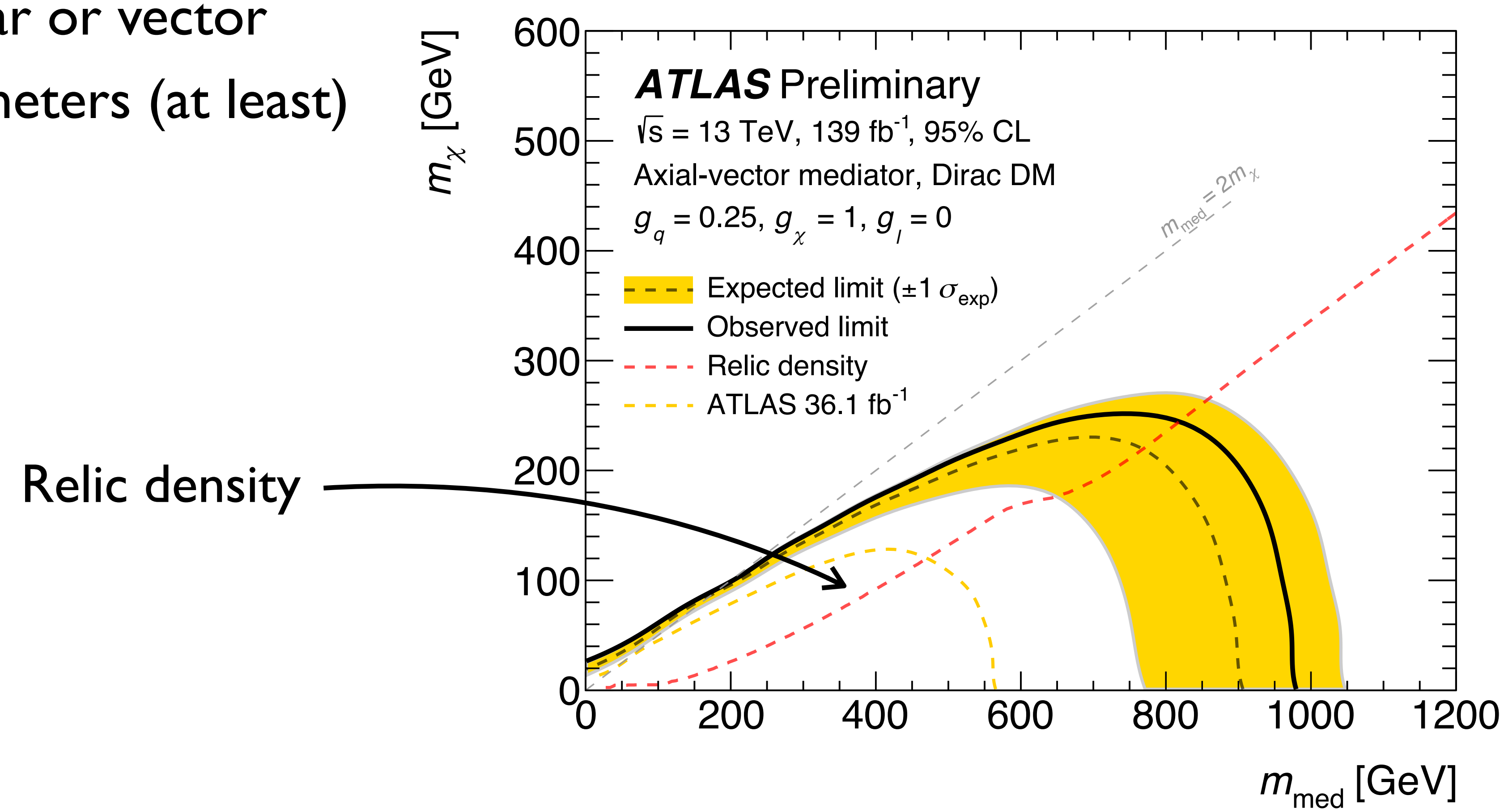
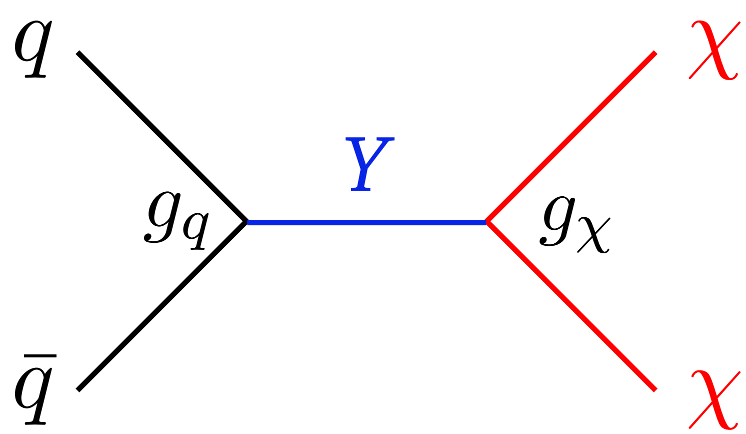


Simplified models: s-channel mediator

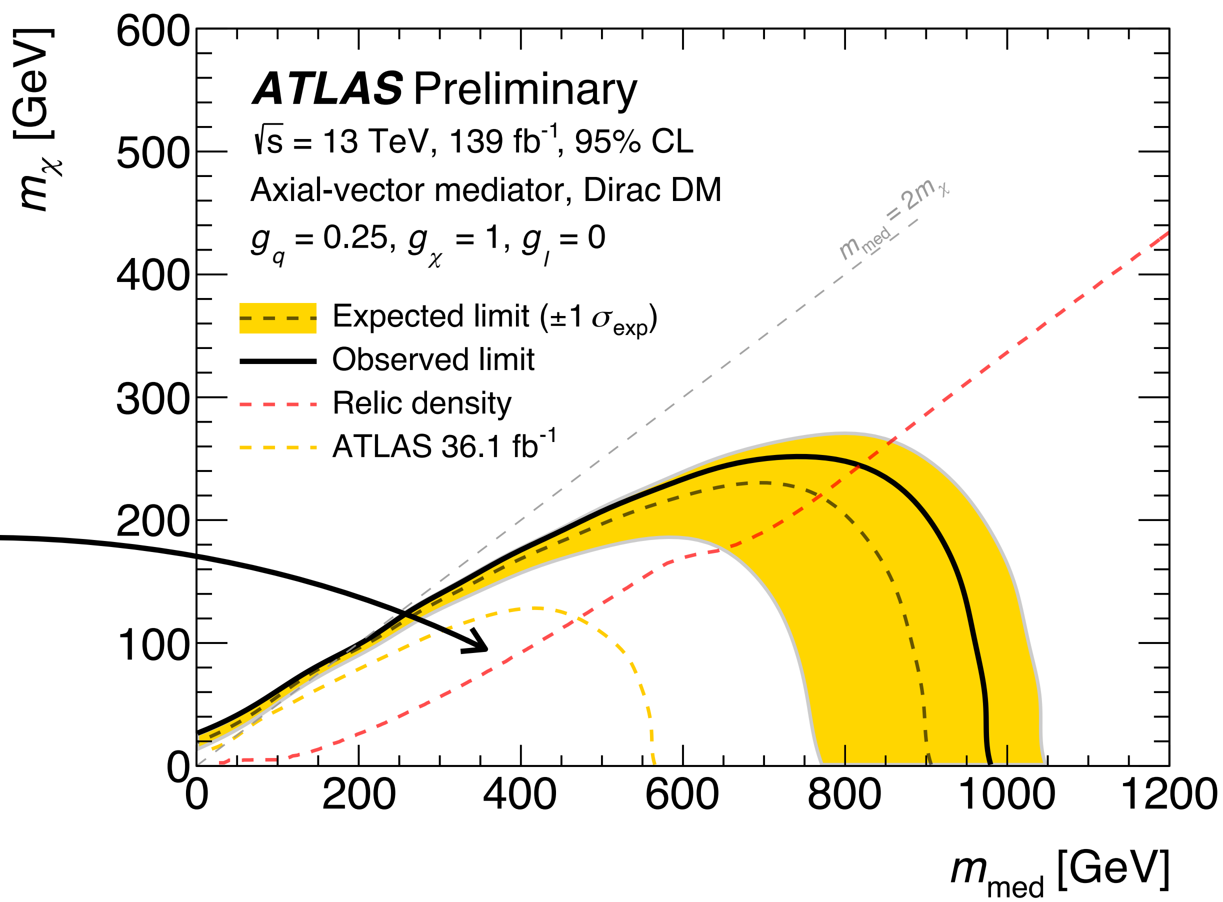


- Y could be scalar or vector
- Four free parameters (at least)
  m_χ, m_Y, g_q, g_χ

Relic density

Mapping onto operators for direct detection

[Dent et al 1505.03117]

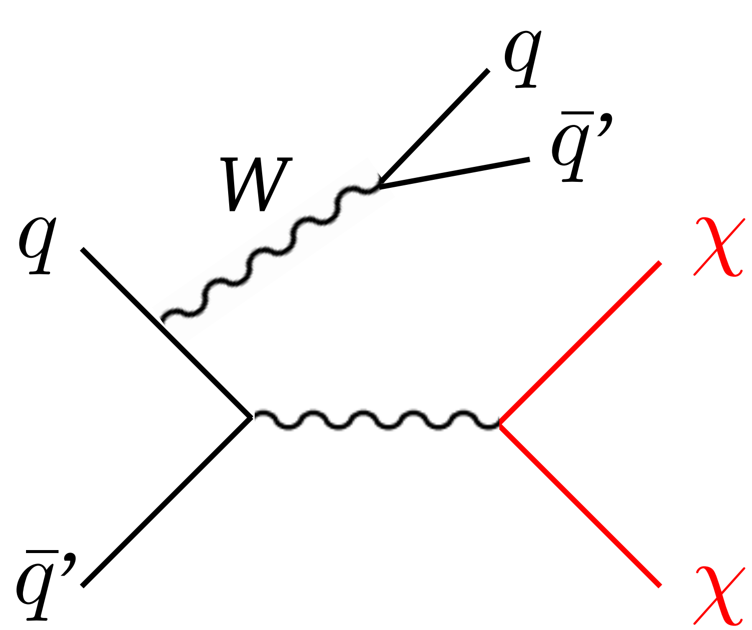


Consistency within s-channel mediator models

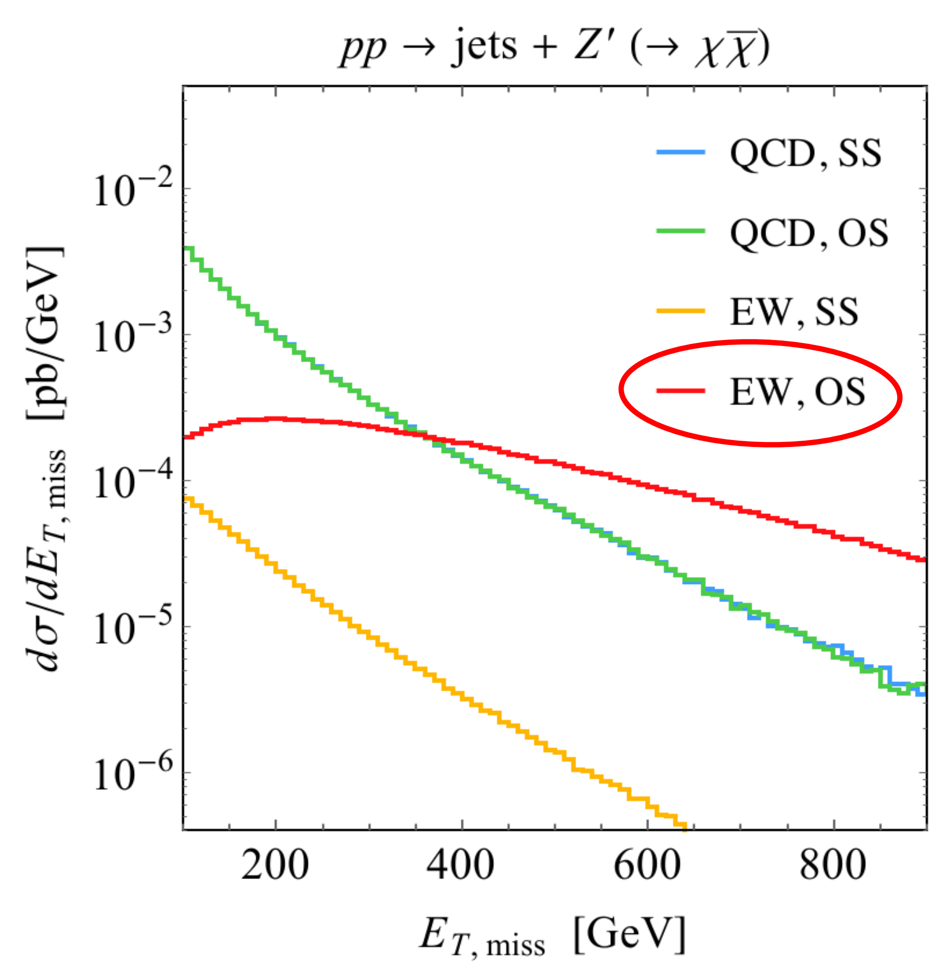
- Not all choices are theoretically consistent
- E.g. simplified models respecting the symmetries of the broken SU(3) x $U(1)_{em}$, but not SU(3) x SU(2) x $U(1)_Y$

[Bell *et al* 1512.00476]

Spin-1 mediators with different couplings to up- and down-quarks:



violation of perturbative unitarity



[Haisch *et al* 1603.01267]

Consistency within s-channel mediator models

- Not all choices are theoretically consistent
- Additional structure required, e.g. $2\mathrm{HDM}+a$ [Abe *et al* 1810.09420]
  $\Rightarrow$ point to new signatures

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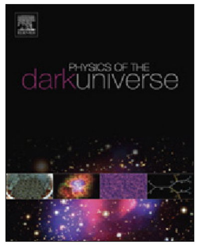
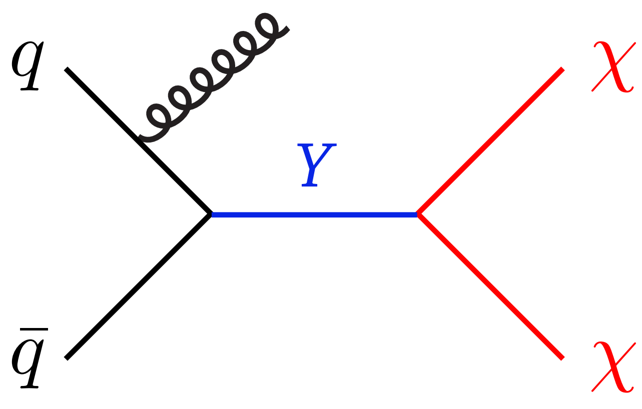


LHC Dark Matter Working Group: Next-generation spin-0 dark matter models

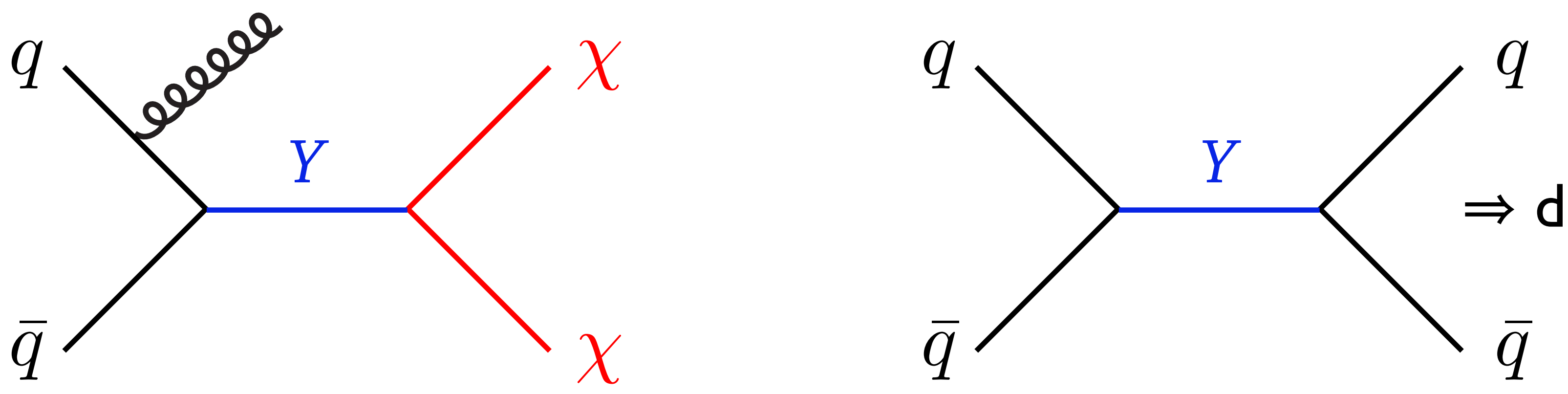
Check for updates

Tomohiro Abe [1,2], Yoav Afik [3], Andreas Albert [4], Christopher R. Anelli [5], Liron Barak [6], Martin Bauer [7], J. Katharina Behr [8], Nicole F. Bell [9], Antonio Boveia [10,a], Oleg Brandt [11], Giorgio Busoni [9], Linda M. Carpenter [10], Yu-Heng Chen [8], Caterina Doglioni [12,a], Alison Elliot [13], Motoko Fujiwara [14], Marie-Helene Genest [15], Raffaele Gerosa [16], Stefania Gori [17], Johanna Gramling [18], Alexander Grohsjean [8], Giuliano Gustavino [19], Kristian Hahn [20,a], Ulrich Haisch [21,22,23,a,*], Lars Henkelmann [11], Junji Hisano [2,14,24], Anders Huitfeldt [25], Valerio Ippolito [26], Felix Kahlhoefer [27], Greg Landsberg [28], Steven Lowette [29,a], Benedikt Maier [30], Fabio Maltoni [31], Margarete Muehlleitner [32], Jose M. No [33,34], Priscilla Pani [8,35], Giacomo Polesello [36], Darren D. Price [37], Tania Robens [38,39], Giulia Rovelli [40], Yoram Rozen [3], Isaac W. Sanderson [9], Rui Santos [41,42], Stanislava Sevova [43], David Sperka [44], Kevin Sung [20], Tim M.P. Tait [17,a], Koji Terashi [45], Francesca C. Ungaro [9], Eleni Vryonidou [23], Shin-Shan Yu [46], Sau Lan Wu [47], Chen Zhou [47]

Signatures beyond MET

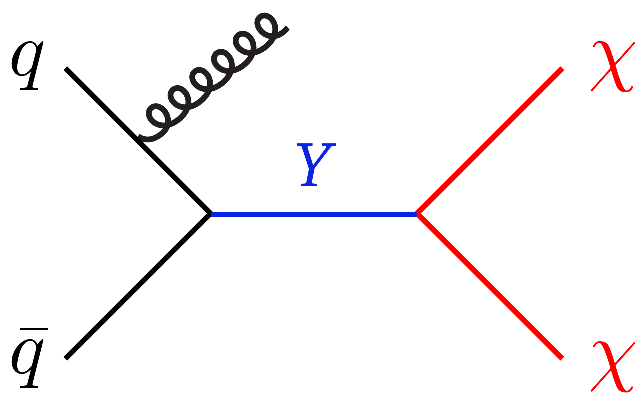


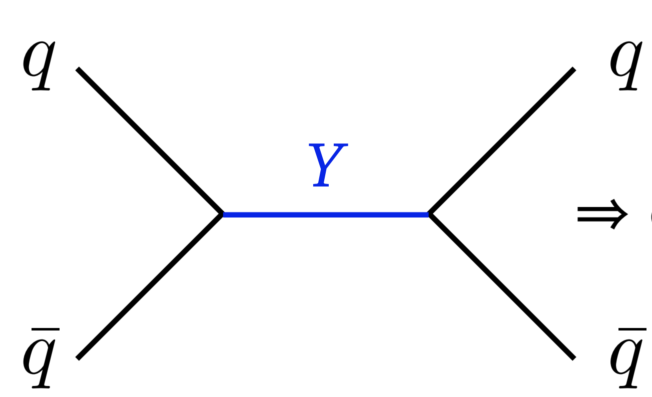
Signatures beyond MET



⇒ dijet resonances

Signatures beyond MET





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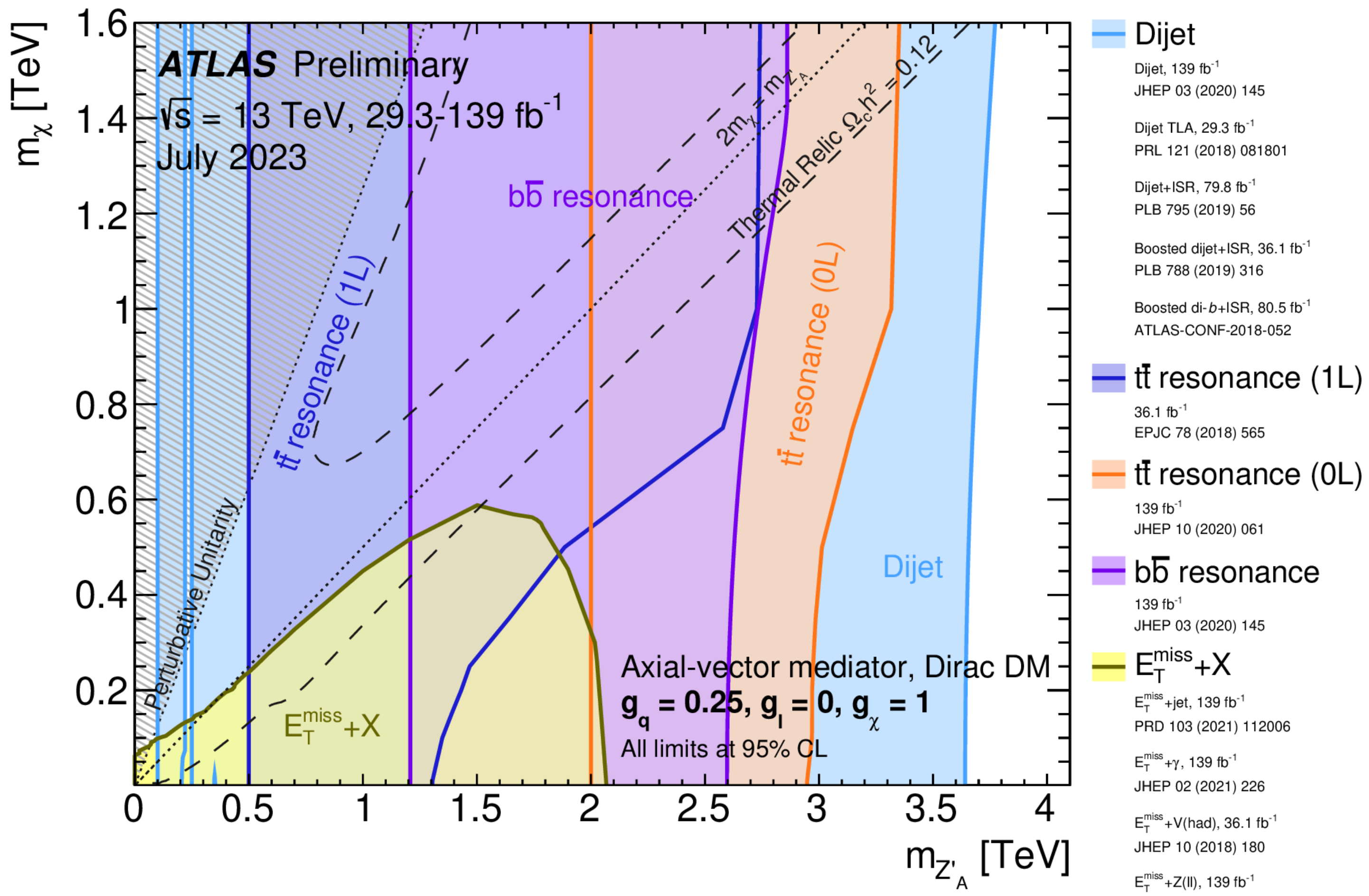
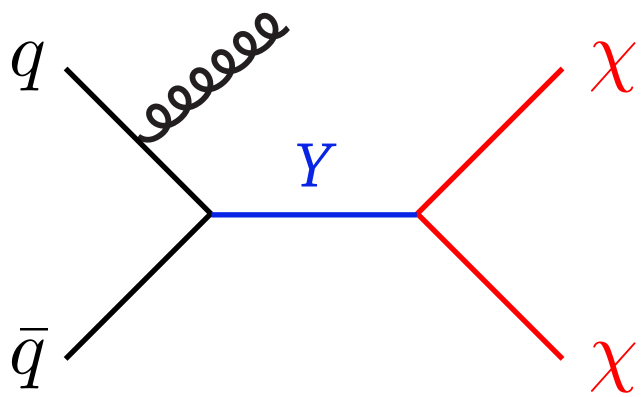
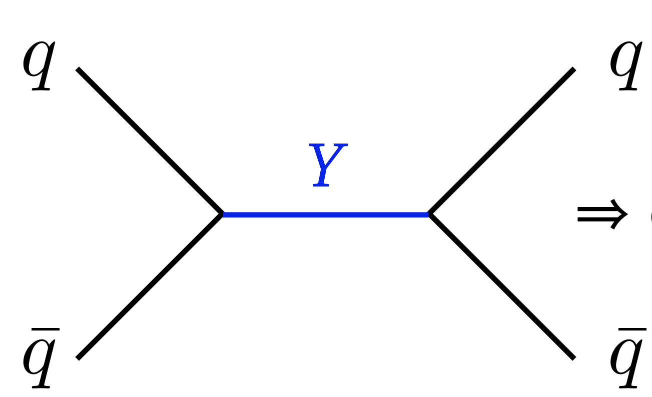


Signatures beyond MET





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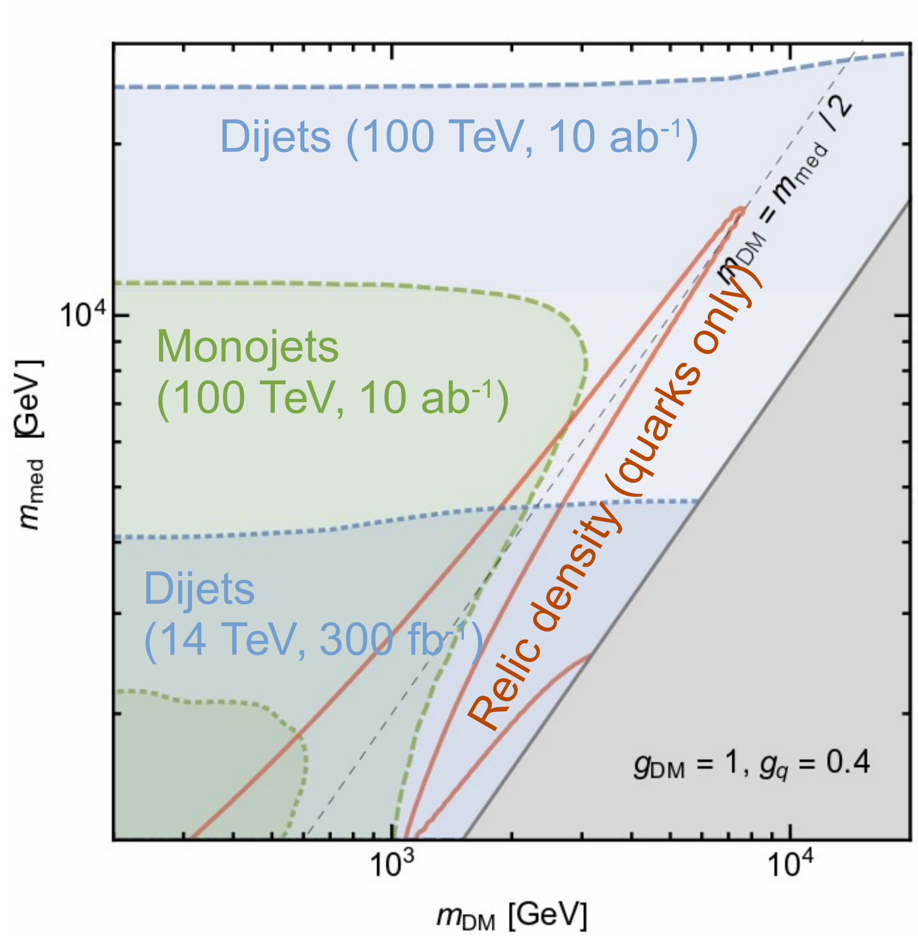
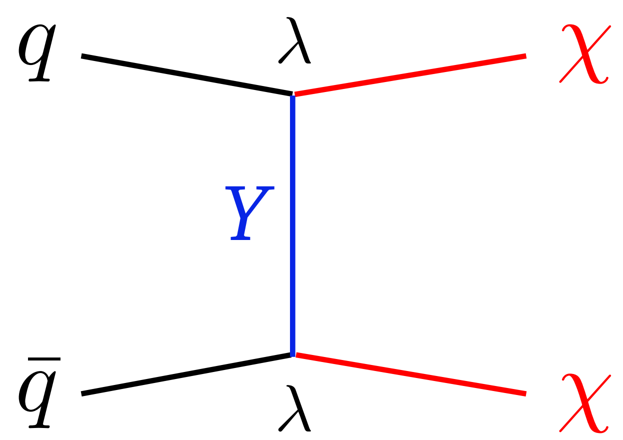


[Golling *et al* 1606.00947]

Simplified models: t-channel mediator

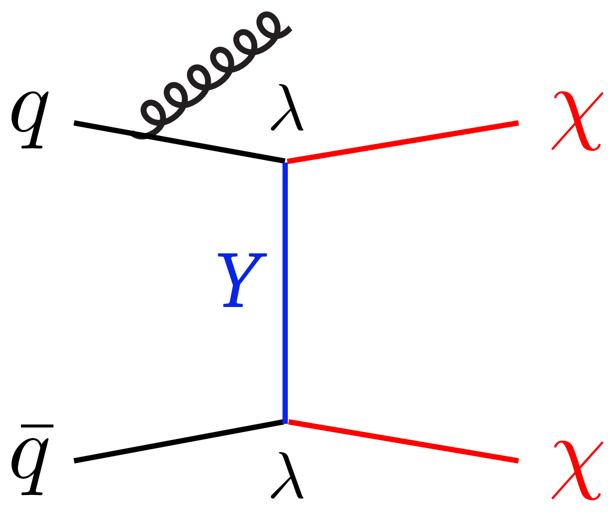


- Y could be scalar or fermion
- Three free parameters (at least): m_χ, m_Y, λ
- Dark matter gauge singlet $\Rightarrow Y$ same quantum numbers as Y
- Dark matter stabilised by Z_2 symmetry: both X and Y odd (SM particles are even)
- $m_Y > m_\chi$
- Examples:

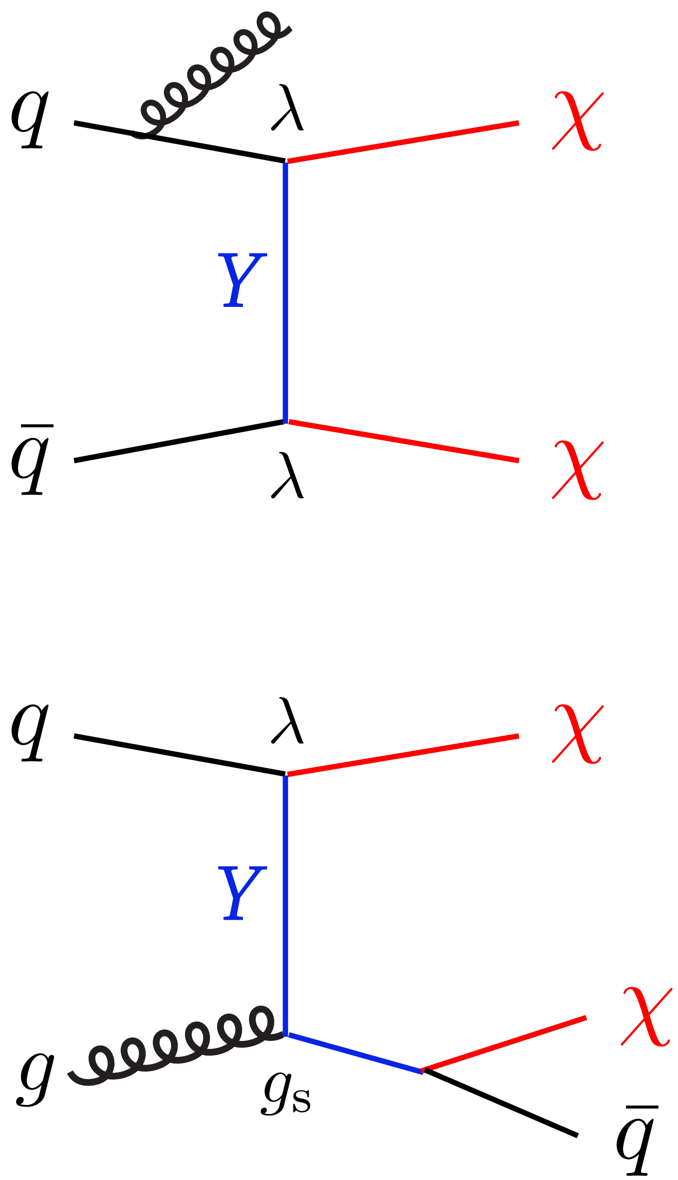
$$\mathcal{L} \supset \lambda Y^\dagger \bar{\chi} P_R q + \text{h.c.}$$ Scalar mediator

$$\mathcal{L} \supset \lambda \bar{Y} P_R q S + \text{h.c.}$$ Fermion mediator

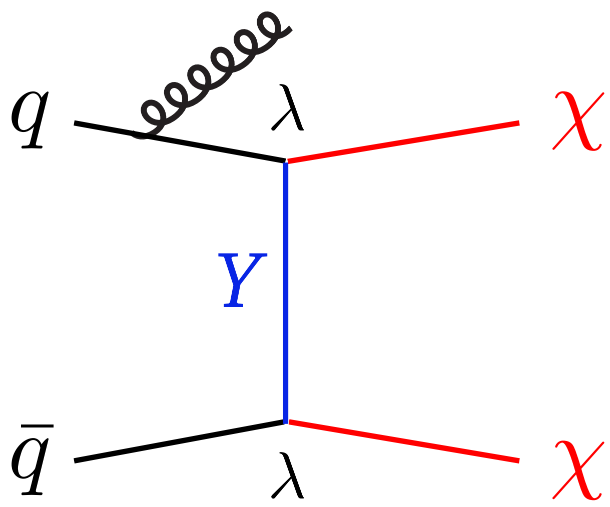
Simplified models: t-channel mediator

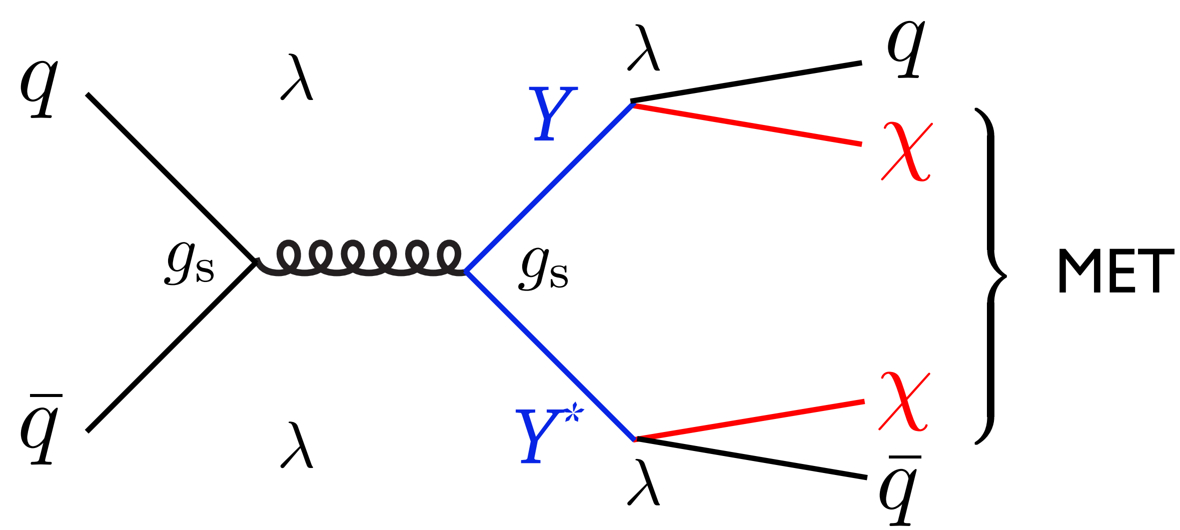


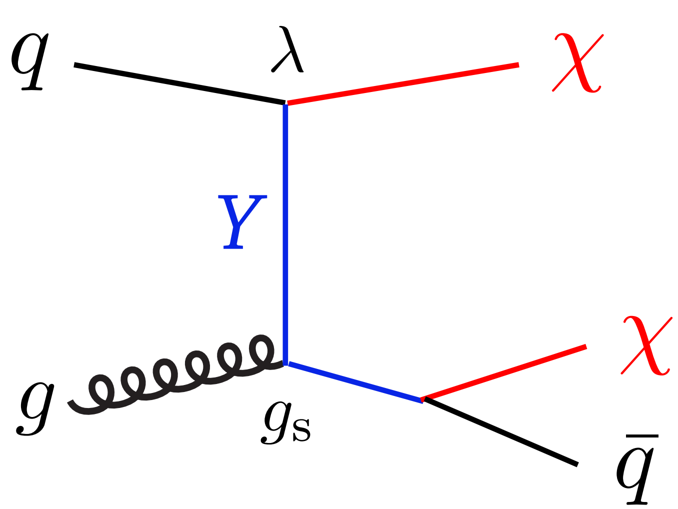
Simplified models: t-channel mediator



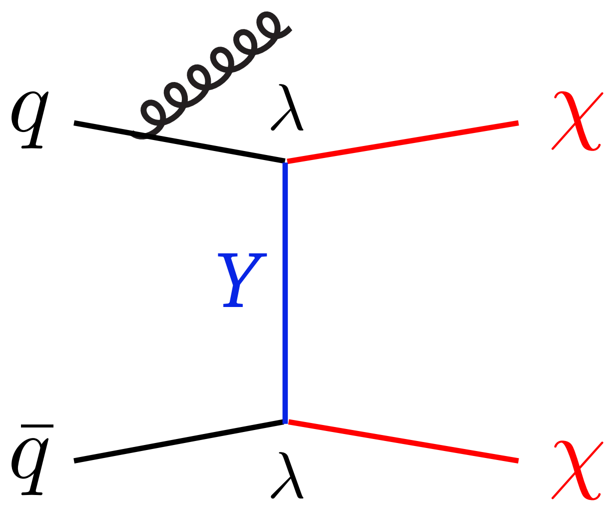
Simplified models: t-channel mediator

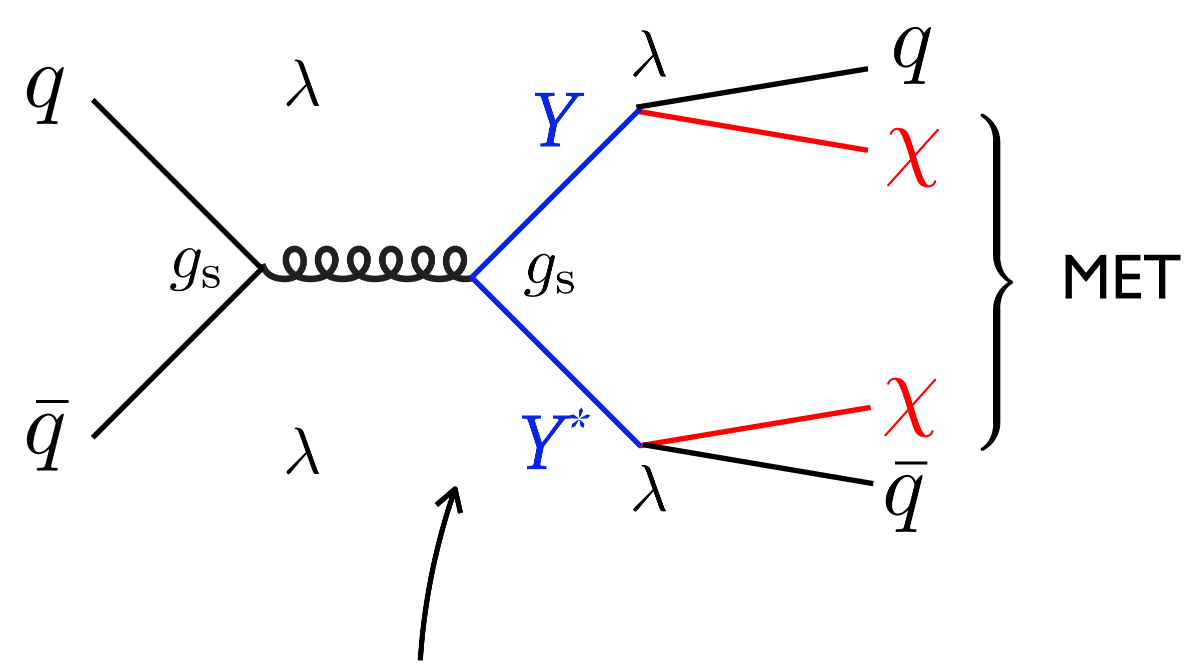




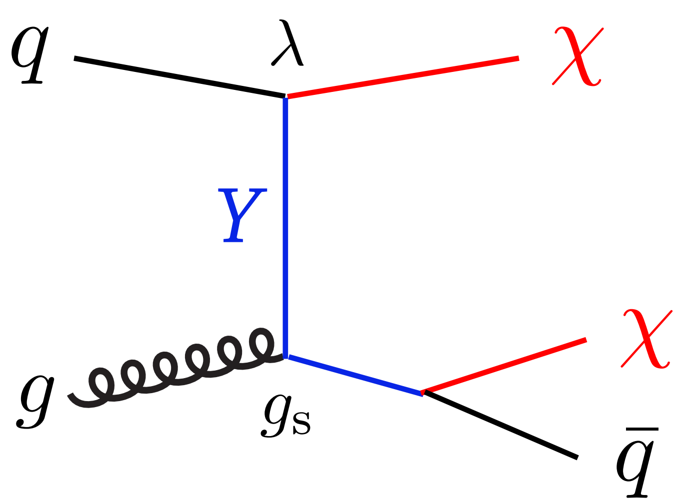


t-channel mediator models – signatures

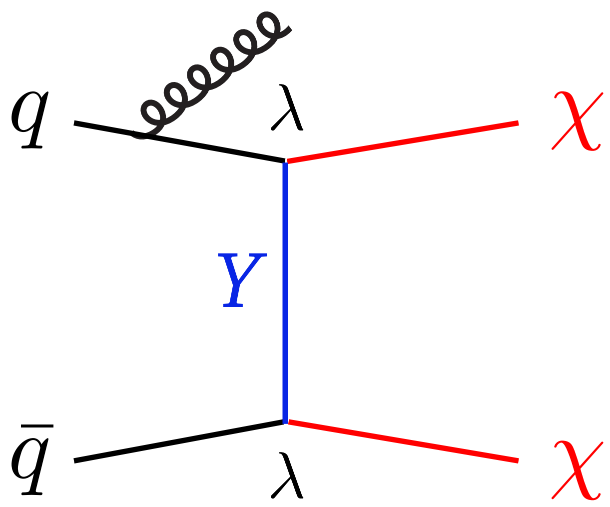


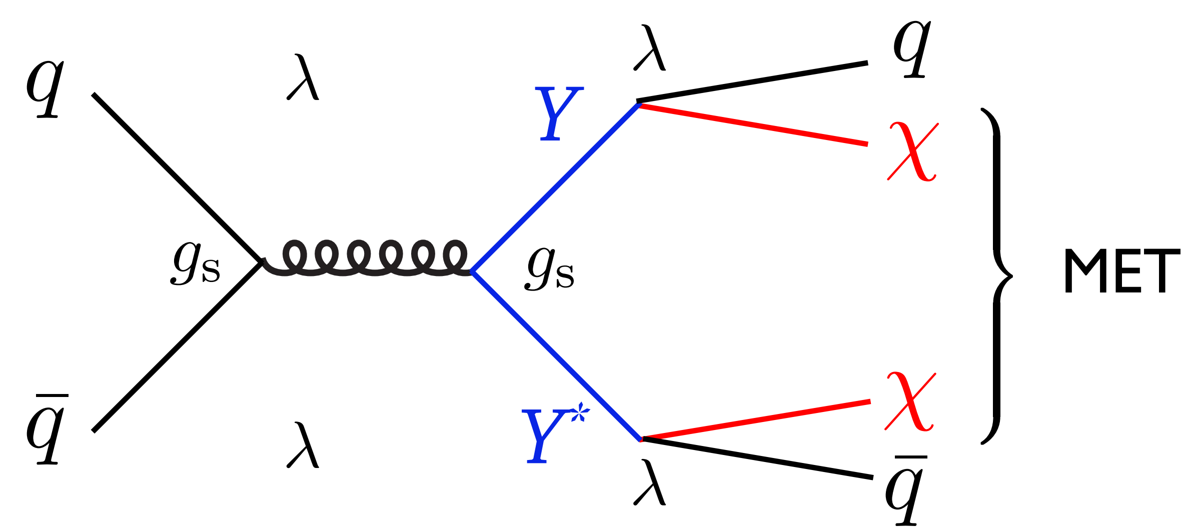


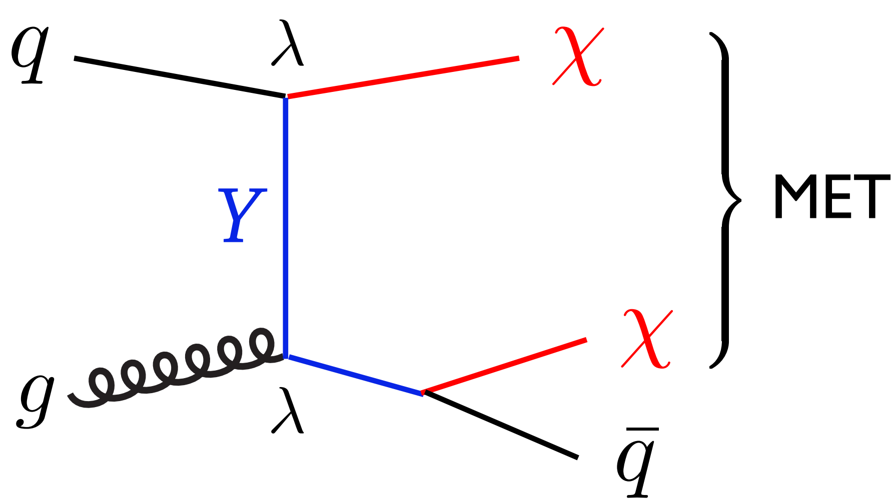
Searches for supersymmetry (squark production)

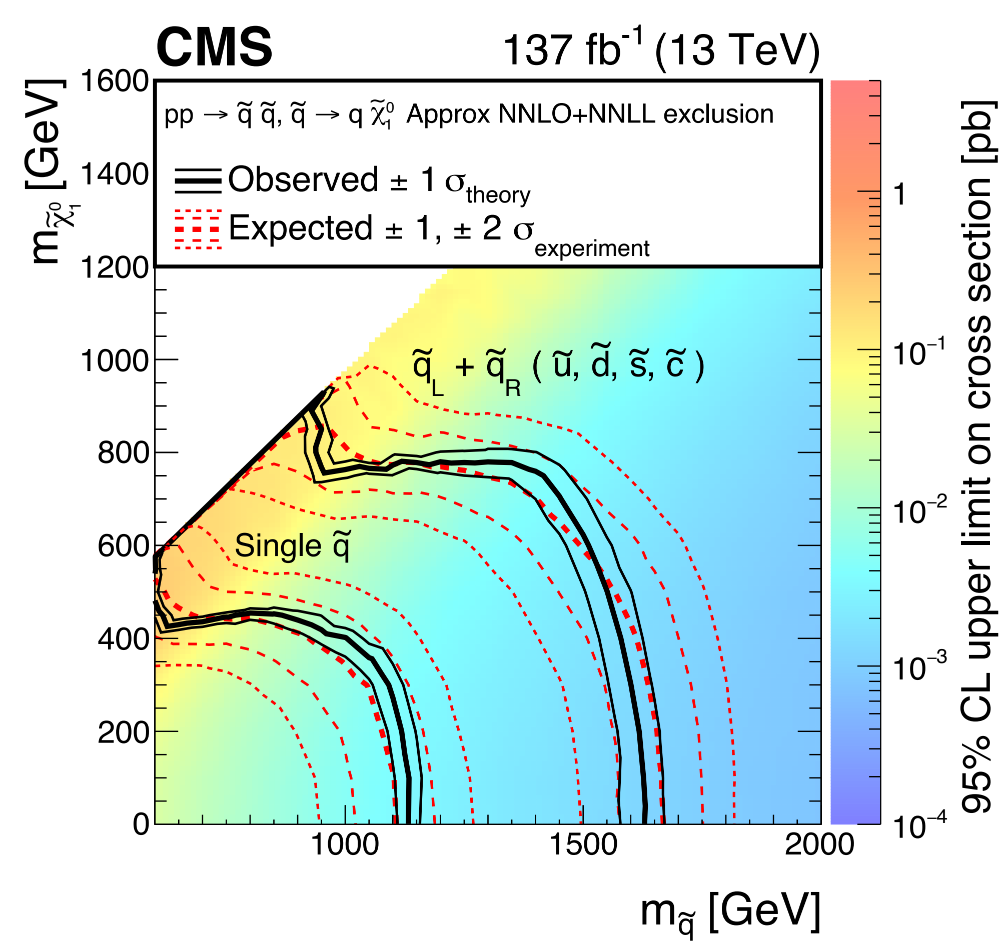


t-channel mediator models – signatures

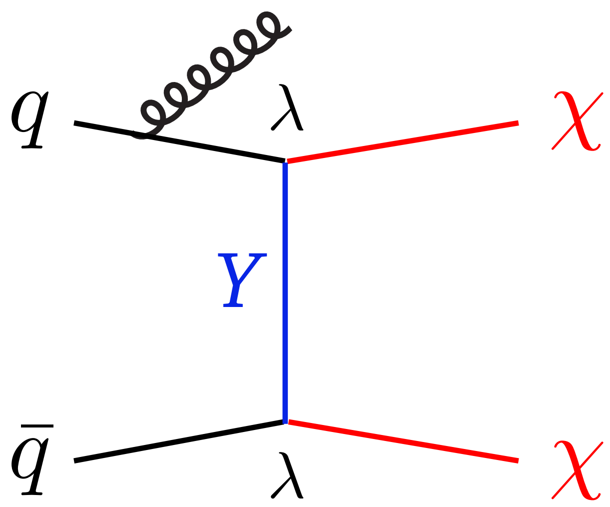


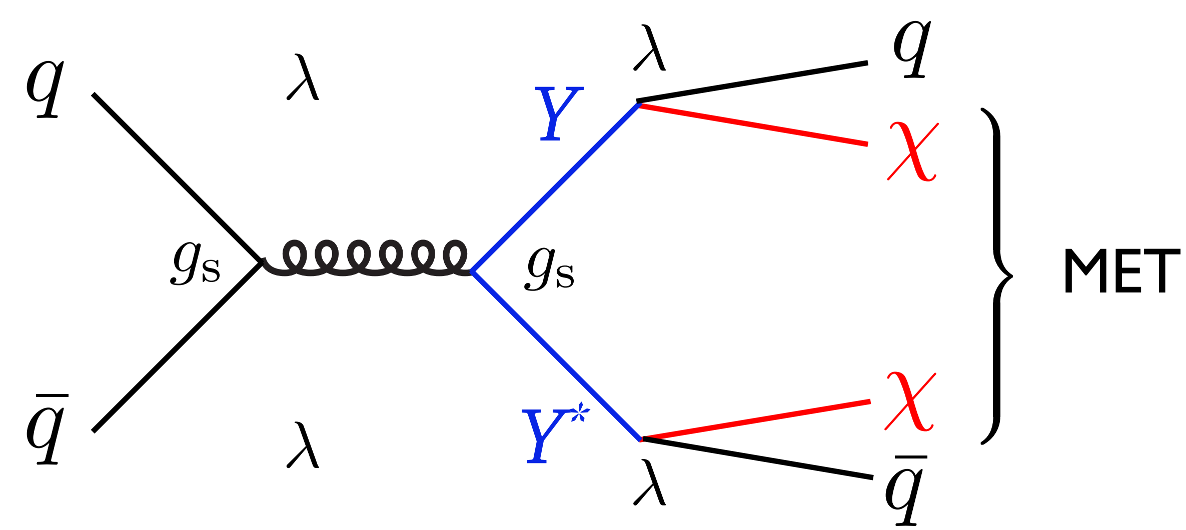


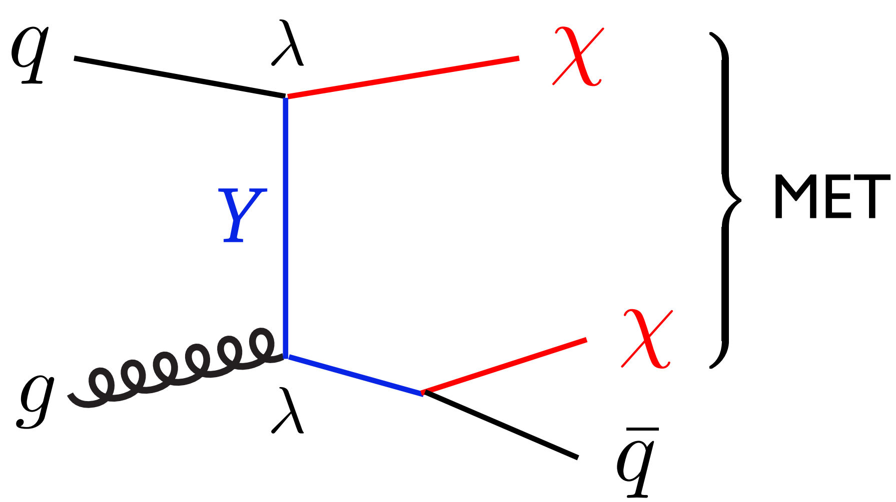


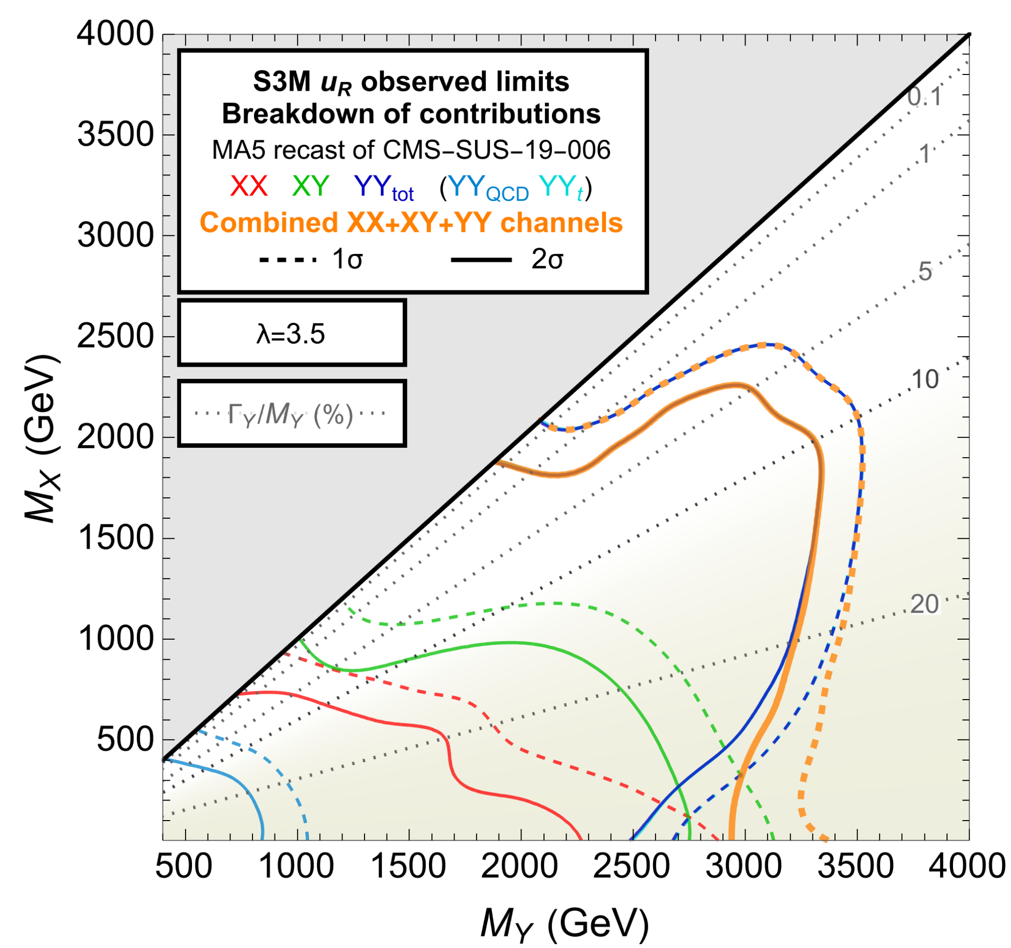


t-channel mediator models – signatures



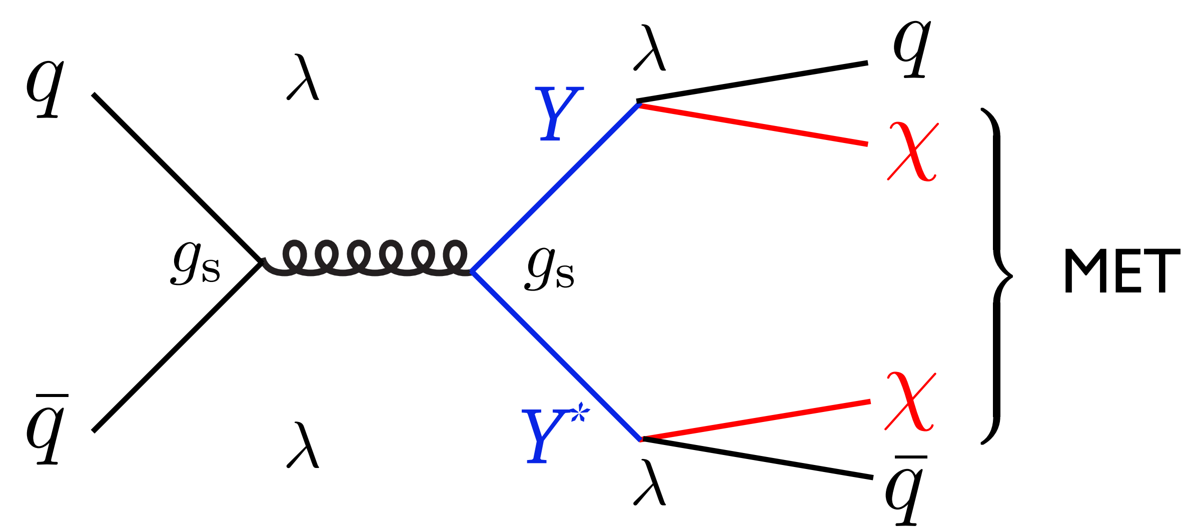


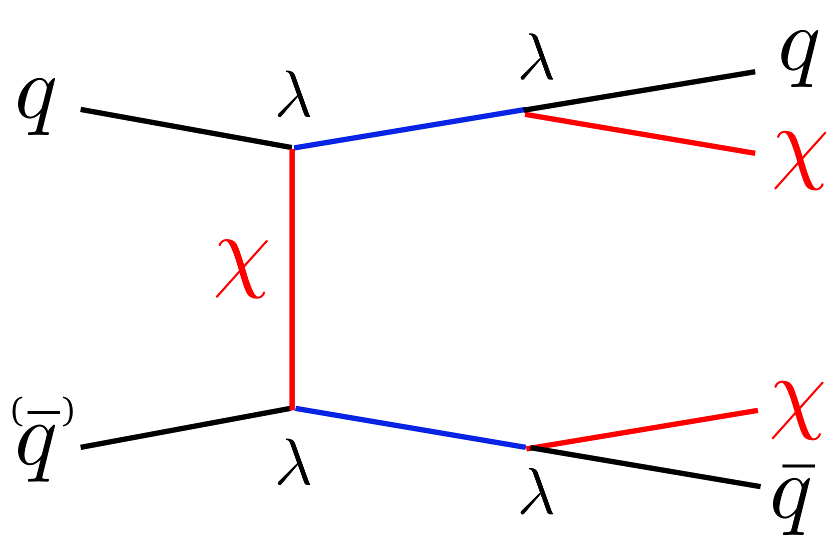


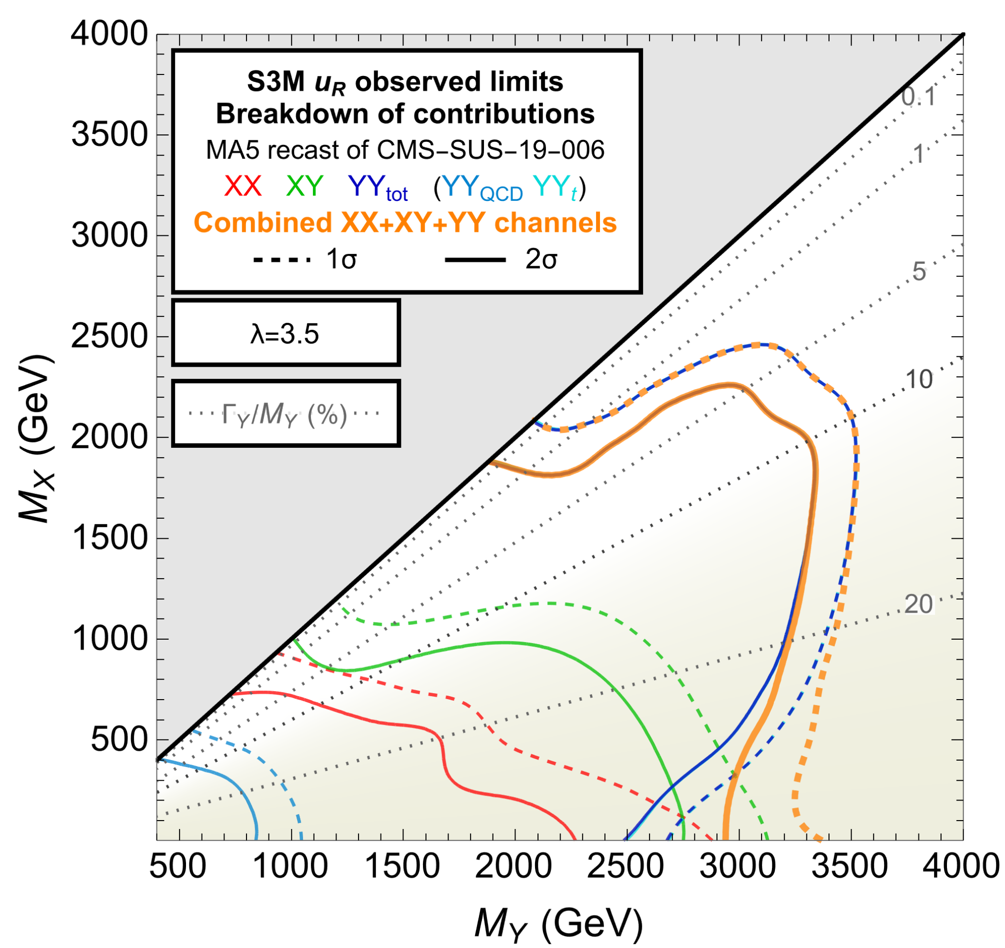


[Arina *et al* 2307.10367]

t-channel mediator models – signatures



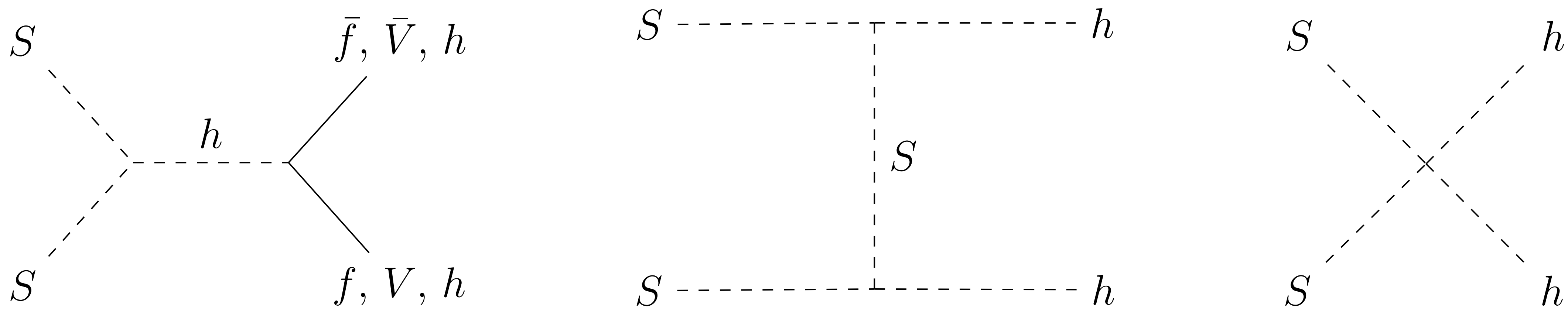




[Arina *et al* 2307.10367]

Higgs portal dark matter

$$\mathcal{L} \supset \lambda\, H^\dagger H S^2 \quad \sim \frac{1}{2}\lambda\, h^2 S^2 + \lambda\, v\, h S^2$$



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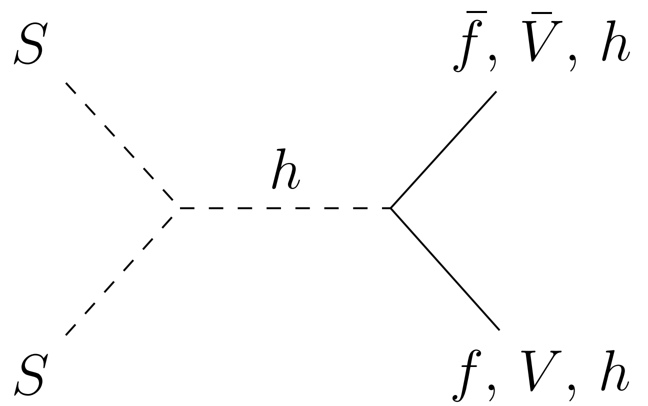
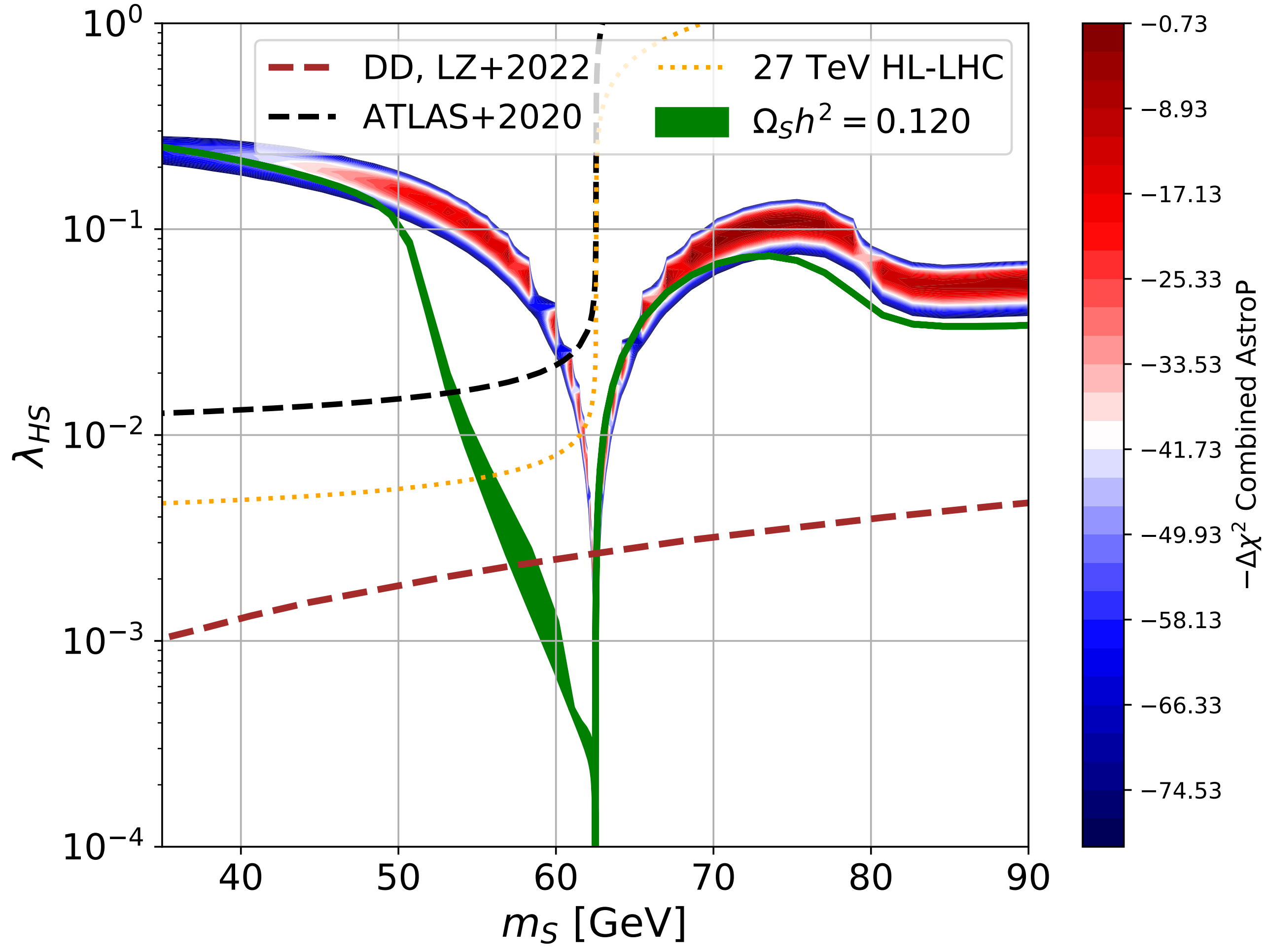




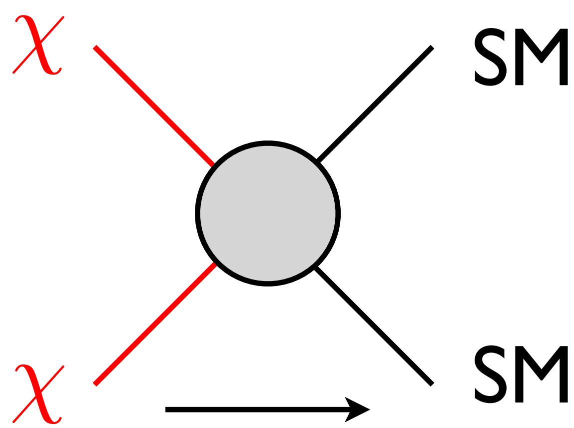
Summary on WIMP dark matter searches at LHC

- WIMP invisible, detectable via missing energy
- Proton collisions: steeply falling parton luminosity
- Irreducible background from neutrinos
- EFT not suitable for LHC ⇒ simplified models (or more complex models)
- Often mediator searches more promising
- MET signal still important for establishing dark matter

II. Searches for Feebly Interacting Massive Particles (FIMPS)

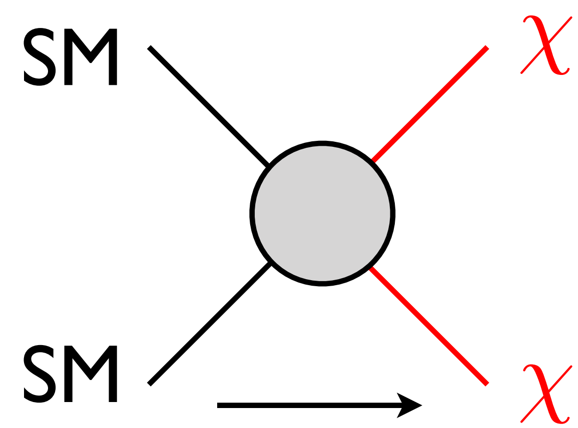
FIMP dark matter production?

WMP freeze-out



$\langle \sigma v \rangle \sim 10^{-26} \mathrm{cm}^3/\mathrm{s}$

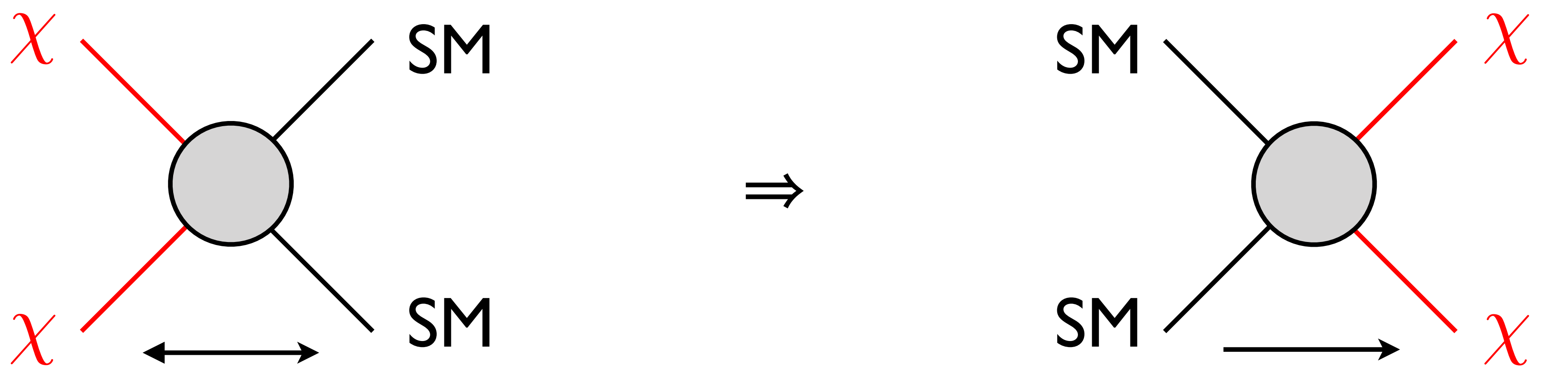
WIMP production



$\sigma \sim \mathrm{pb}$

FIMP dark matter production?

Feeble couplings ⇒ No signal at LHC



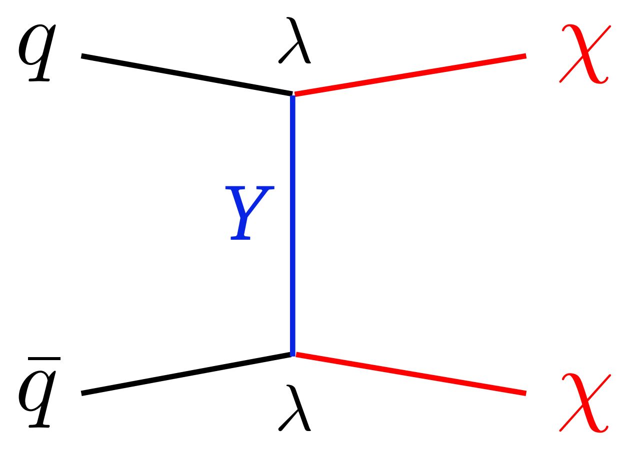
$\Gamma \ll H$ $\qquad$ $\sigma\,\mathcal{L} \ll 1$

[Kahlhoefer 1801.07621]

However, if some part of new physics sector thermalises, those particles may be produced

Feeble coupling to dark matter ⇒ long-lived particles

Simplified models: t-channel mediator

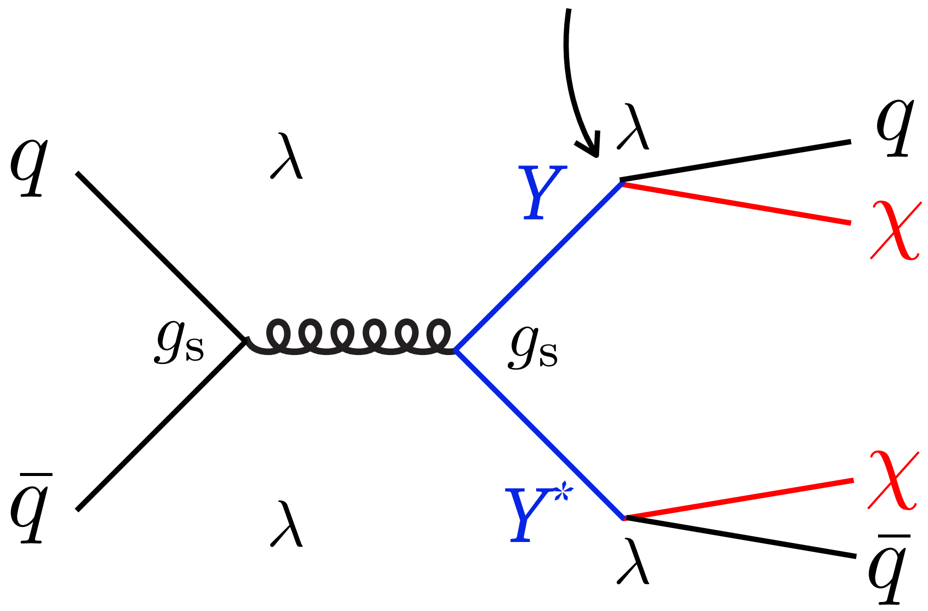


- Y could be scalar or fermion
- Three free parameters (at least): m_χ, m_Y, λ
- Dark matter gauge singlet $\Rightarrow$ Y same quantum numbers as Y
- Dark matter stabilised by Z_2 symmetry: both X and Y odd (SM particles are even)
- $m_Y > m_\chi$
- Examples:

$$\mathcal{L} \supset \lambda Y^\dagger \bar{\chi} P_R q + \text{h.c.}$$ Scalar mediator

Simplified models: t-channel mediator

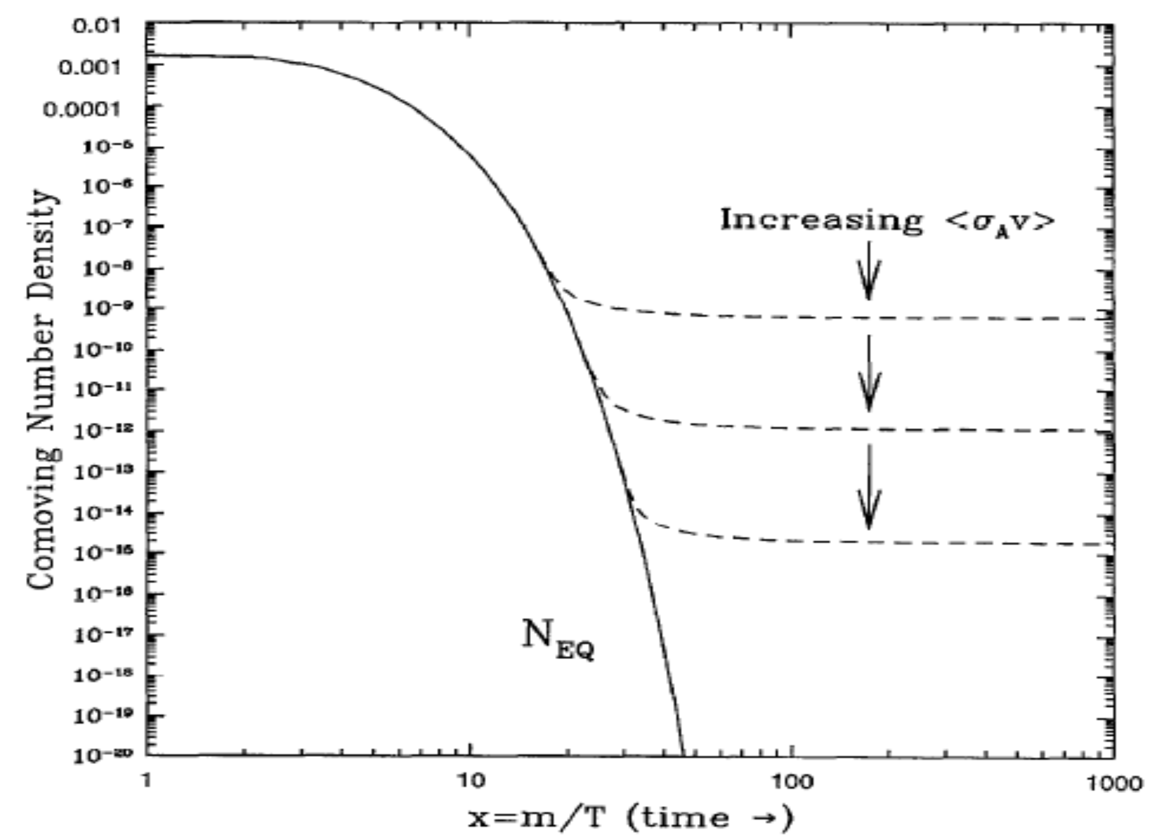
Assumption in WIMP regime: Y decays promptly, $c\tau_Y \ll 1\,\mathrm{mm}$



t-channel mediator decay

Assumption in WIMP regime: Y decays promptly, $c\tau_Y \ll 1\,\mathrm{mm}$

$\chi\bar{\chi} \leftrightarrows f\bar{f}$ $\chi\bar{\chi} \to f\bar{f}$ $\chi\bar{\chi} \nrightarrow \ldots$



t-channel mediator decay

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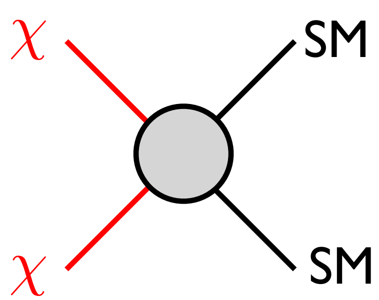
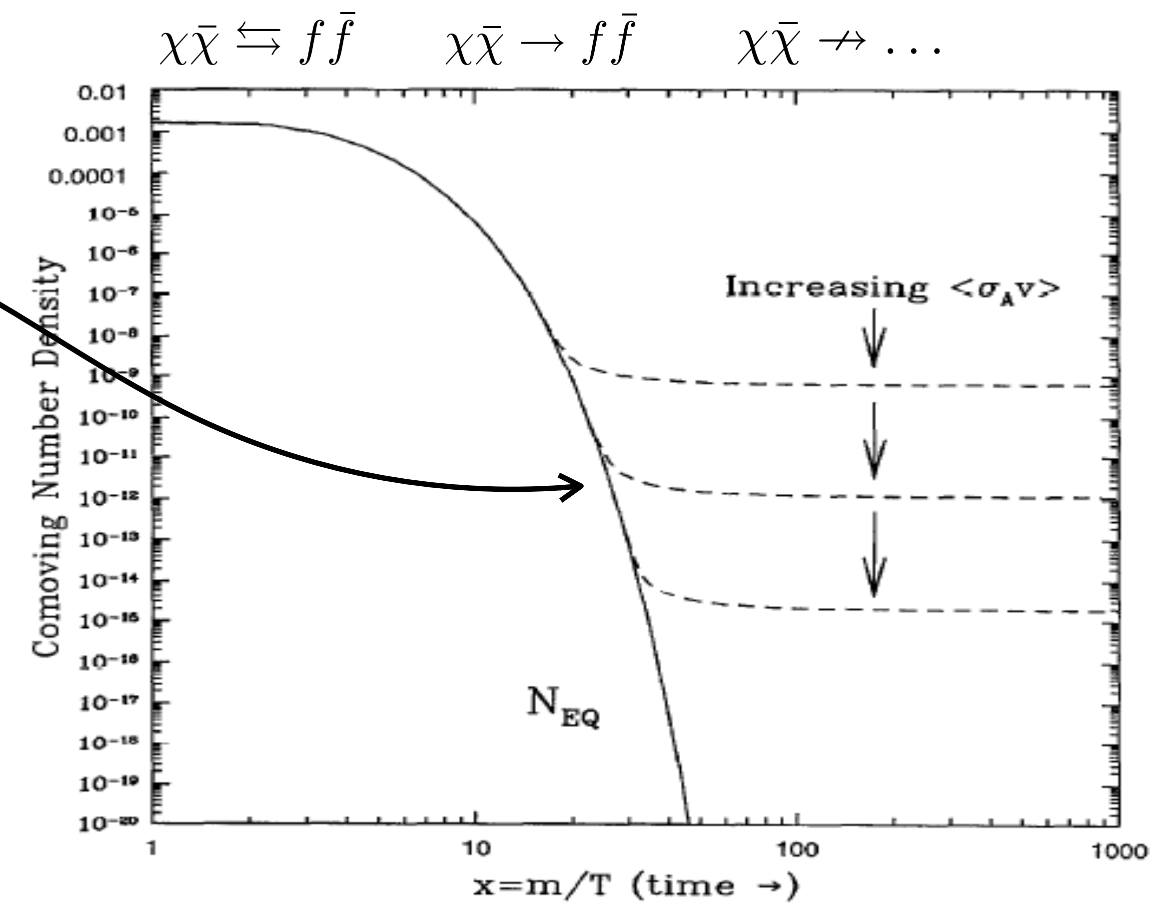
Freeze-out condition:



$\Gamma_{\rm ann} \sim H$



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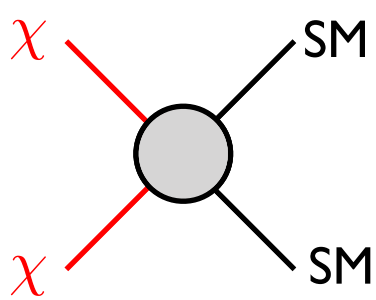
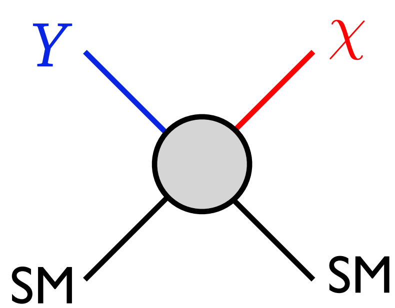
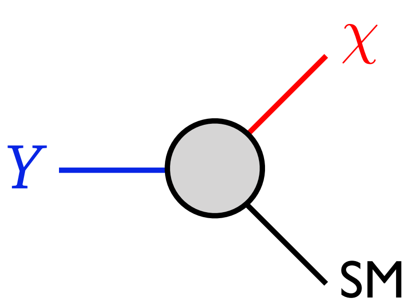


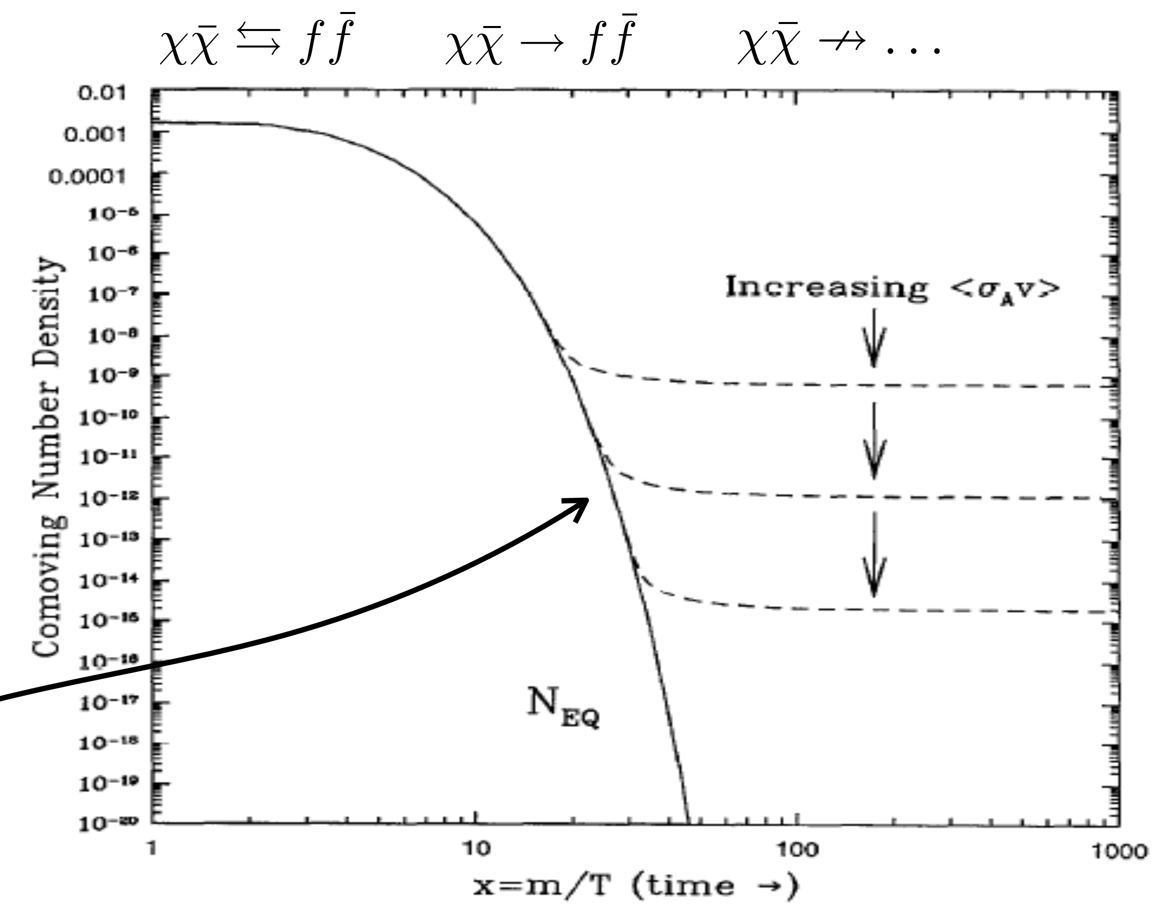
$\Gamma_{\mathrm{ann}} \sim H$



$\Rightarrow$



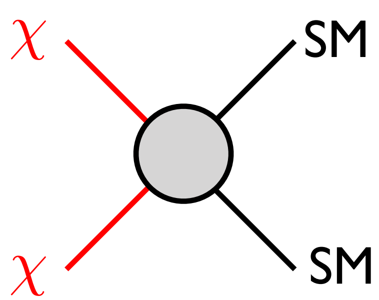
$\Gamma_{\mathrm{con}} \ggg H$



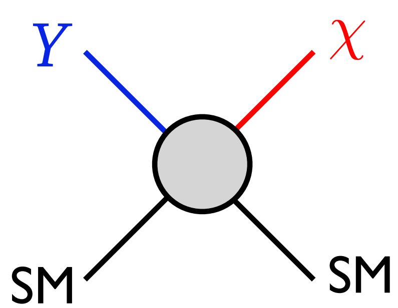
t-channel mediator decay

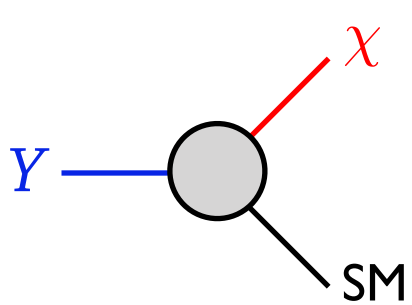
Assumption in WIMP regime: Y decays promptly, $c\tau_Y \ll 1\,\mathrm{mm}$

Freeze-out condition:



$\Gamma_{\mathrm{ann}} \sim H$

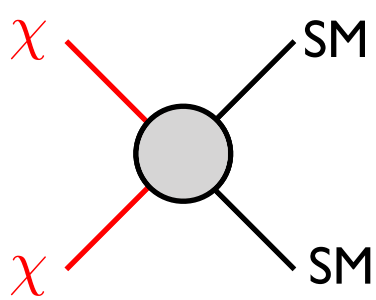




$\Rightarrow$ $\Gamma_{\mathrm{con}} \ggg H \quad \Rightarrow \quad c\tau \lll H^{-1}(T_{\mathrm{fo}}) \sim 10\,\mathrm{cm}\left(\frac{T_{\mathrm{fo}}}{30\,\mathrm{GeV}}\right)^{-2}$

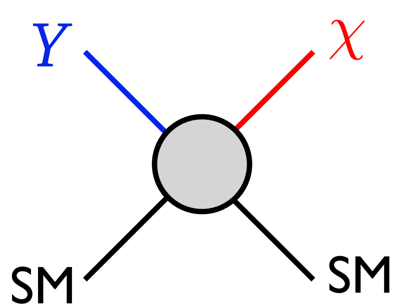
t-channel mediator decay

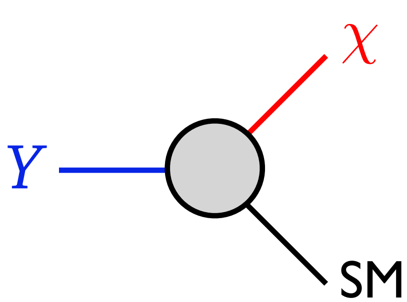
Feeble couplings:



$$\Gamma_{\rm ann} \lll H$$

⇒





two cases:

Non-thermalised:

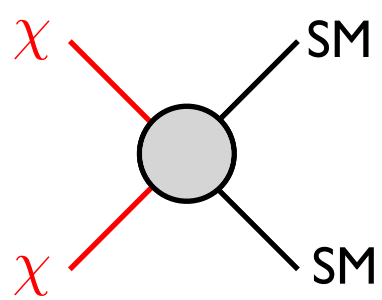
$$\Gamma_{\rm con} \ll H \qquad c\tau \gg H^{-1}(T_*) \sim 10\,{\rm cm}\left(\frac{T_*}{30\,{\rm GeV}}\right)^{-2}$$

'Just' thermalised:

$$\Gamma_{\rm con} \sim H \qquad c\tau \sim H^{-1}(T_*) \sim 10\,{\rm cm}\left(\frac{T_*}{30\,{\rm GeV}}\right)^{-2}$$

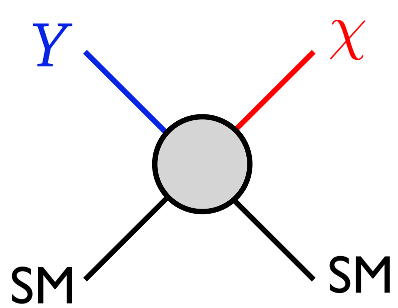
t-channel mediator decay

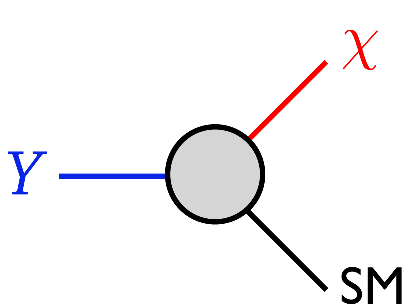
Feeble couplings:



$\Gamma_{\rm ann} \lll H$

⇒ Long-lived particles (LLPs) at colliders!





two cases:

Non-thermalised:

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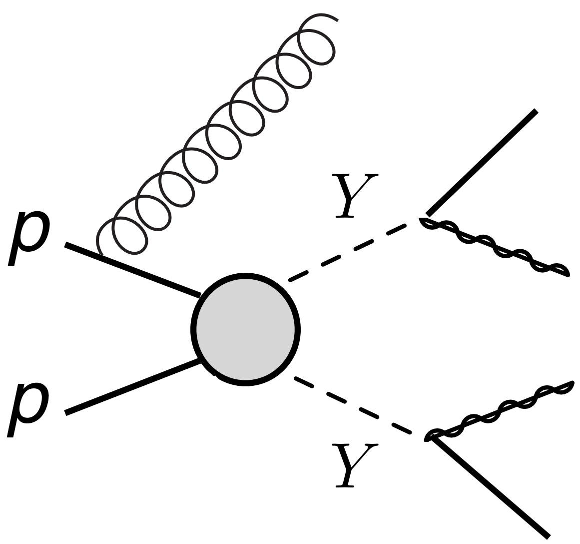
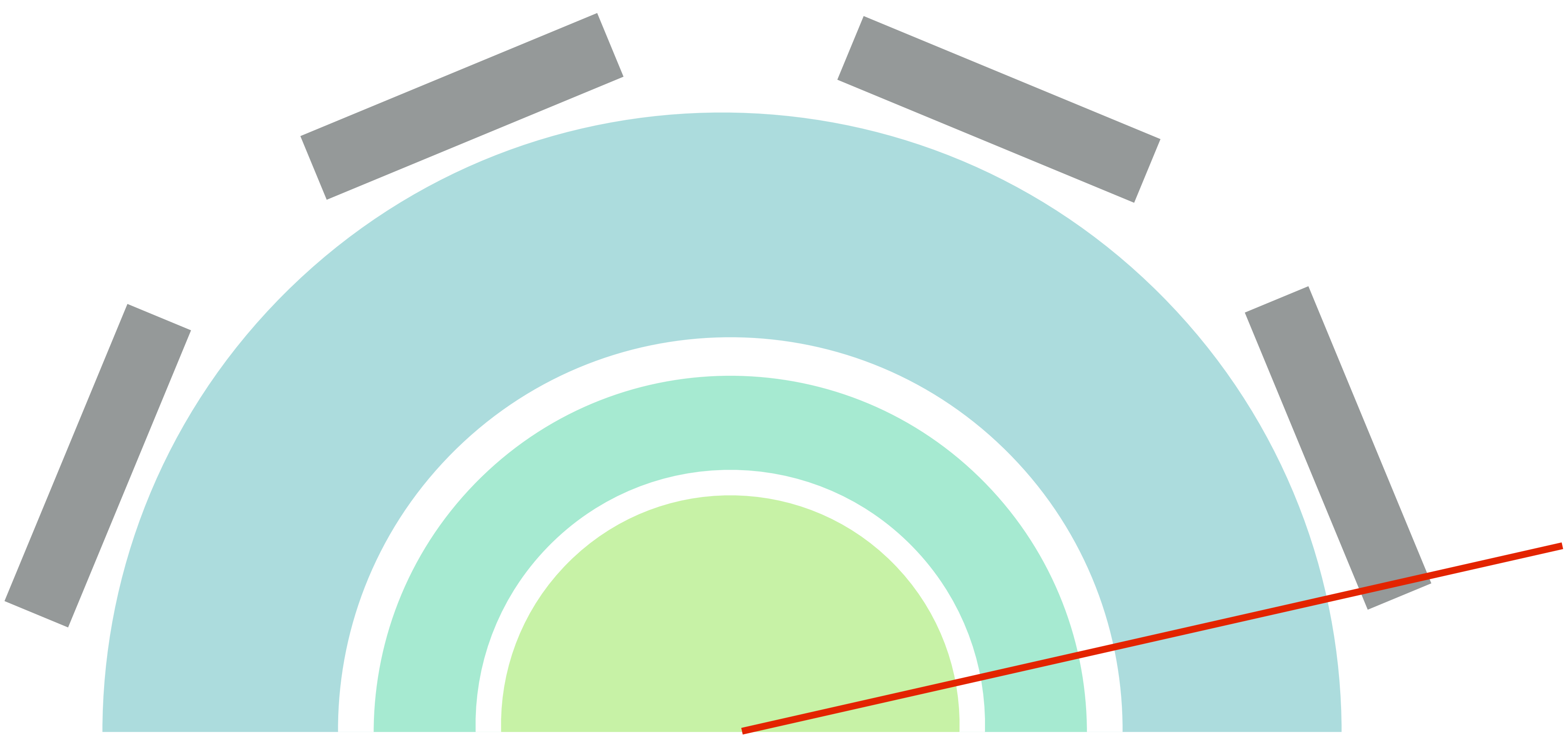
'Just' thermalised:

$$\Gamma_{\rm con} \sim H \qquad c\tau \sim H^{-1}(T_*) \sim 10\,{\rm cm}\left(\frac{T_*}{30\,{\rm GeV}}\right)^{-2}$$

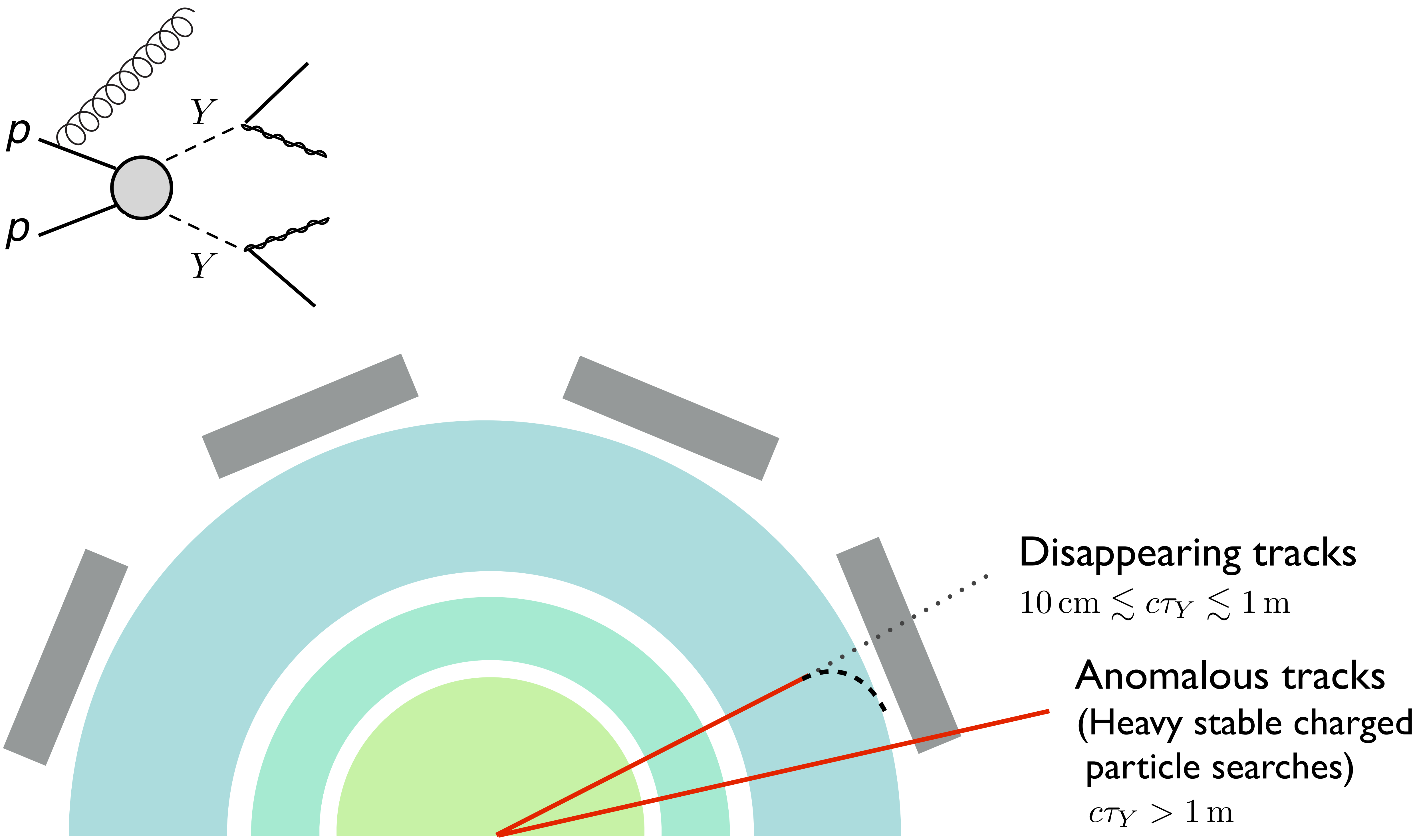
Long-lived particle signatures



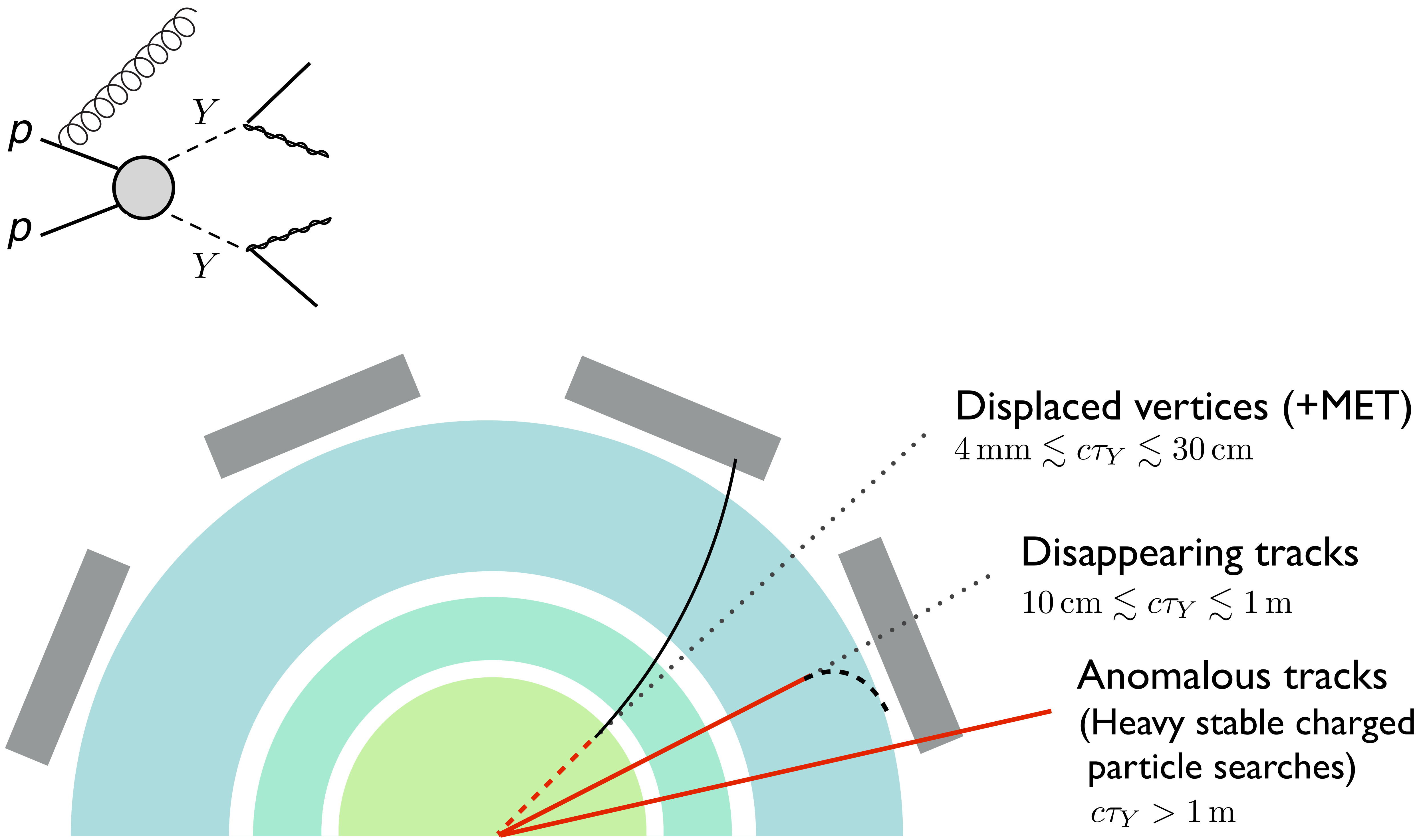


Anomalous tracks
(Heavy stable charged particle searches)
$c\tau_Y > 1\,\mathrm{m}$

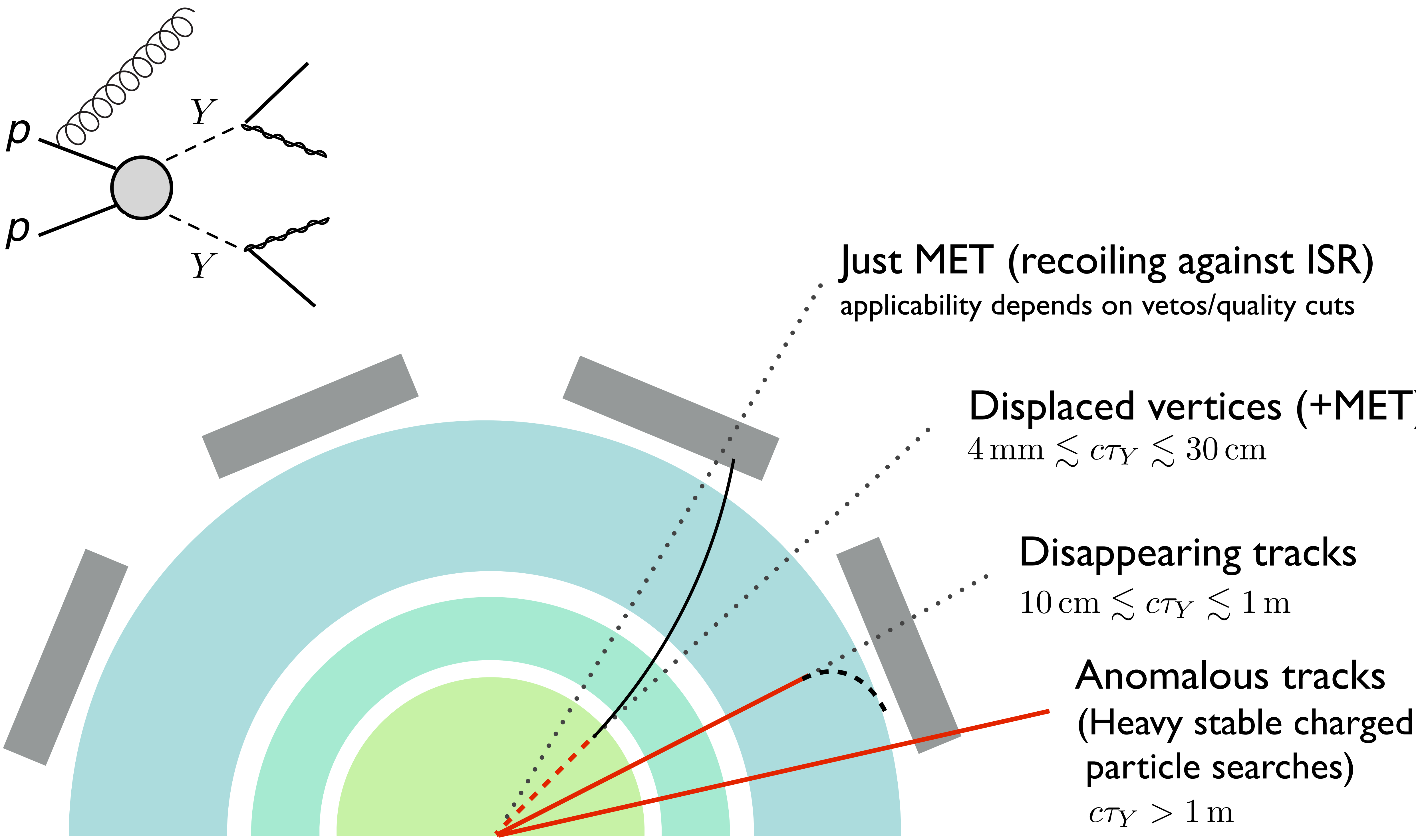
Long-lived particle signatures



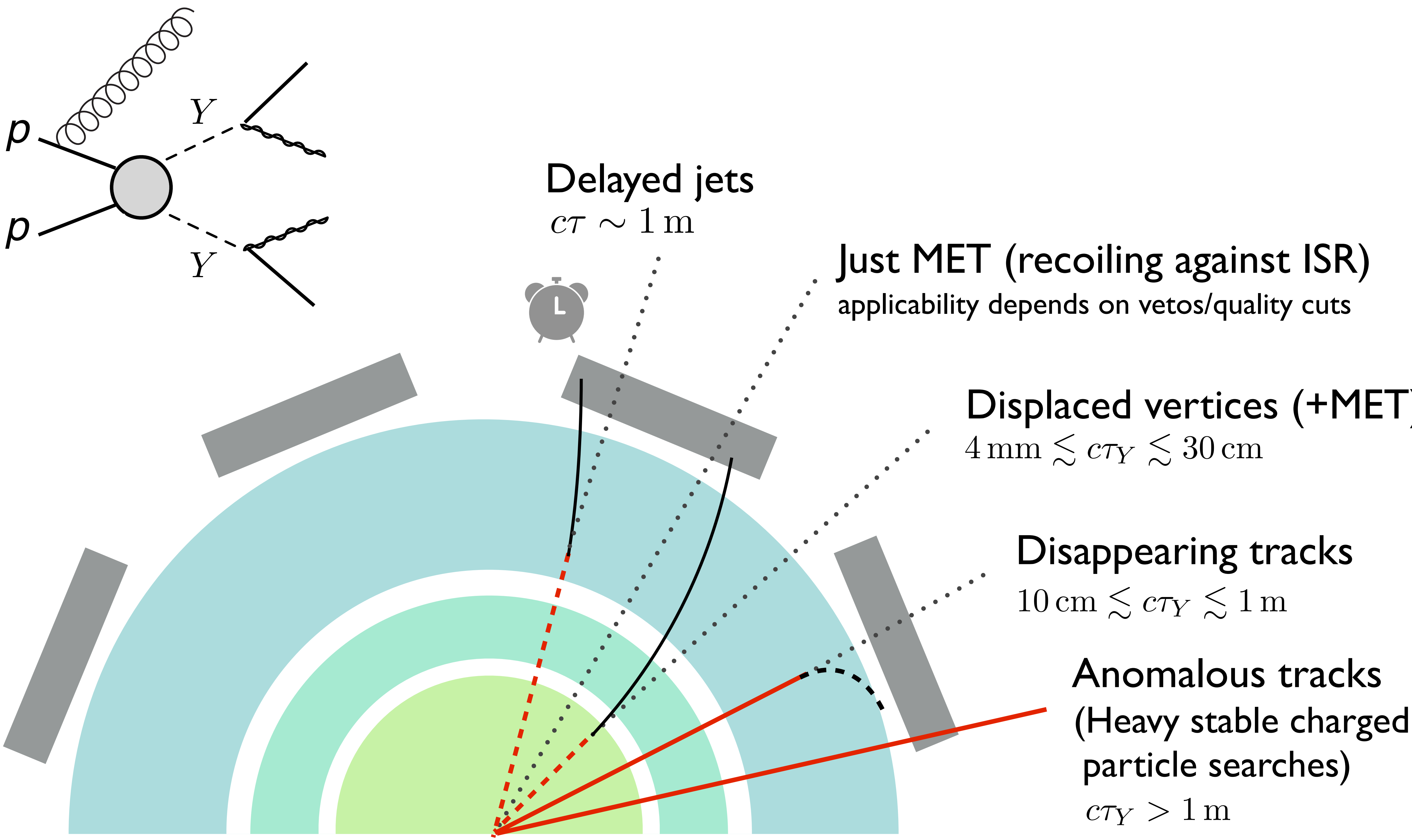
Long-lived particle signatures



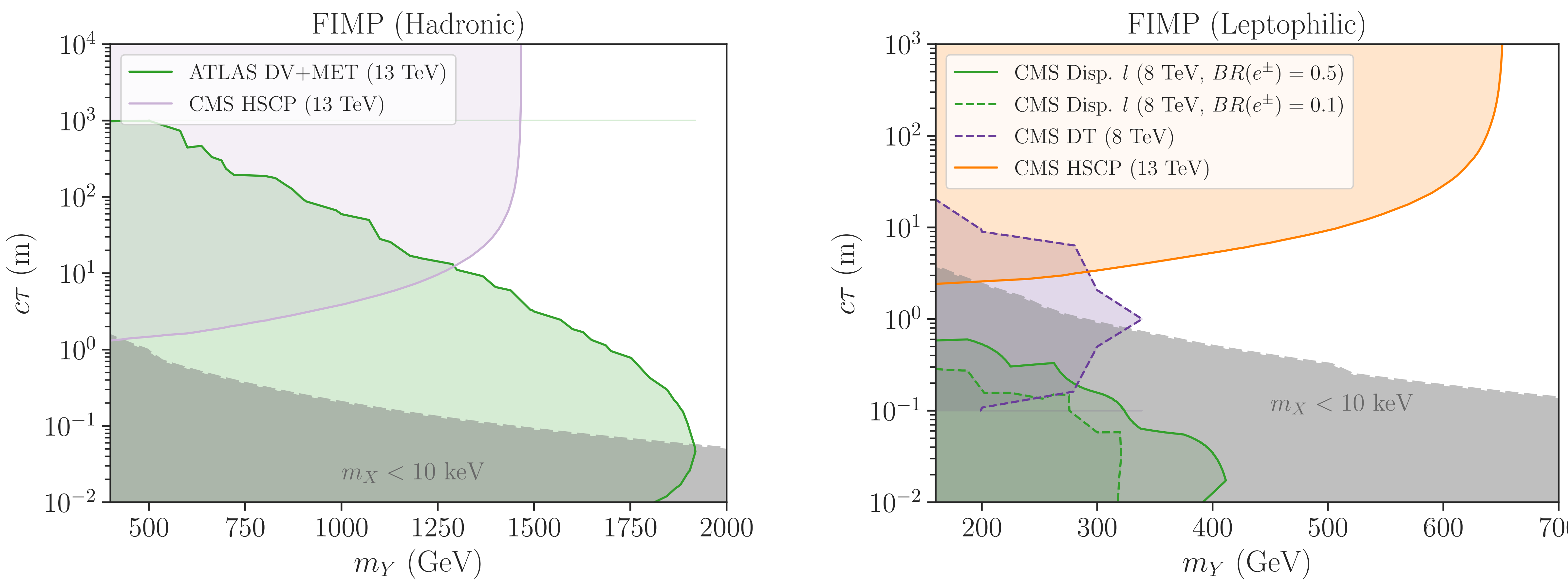
Long-lived particle signatures



Long-lived particle signatures

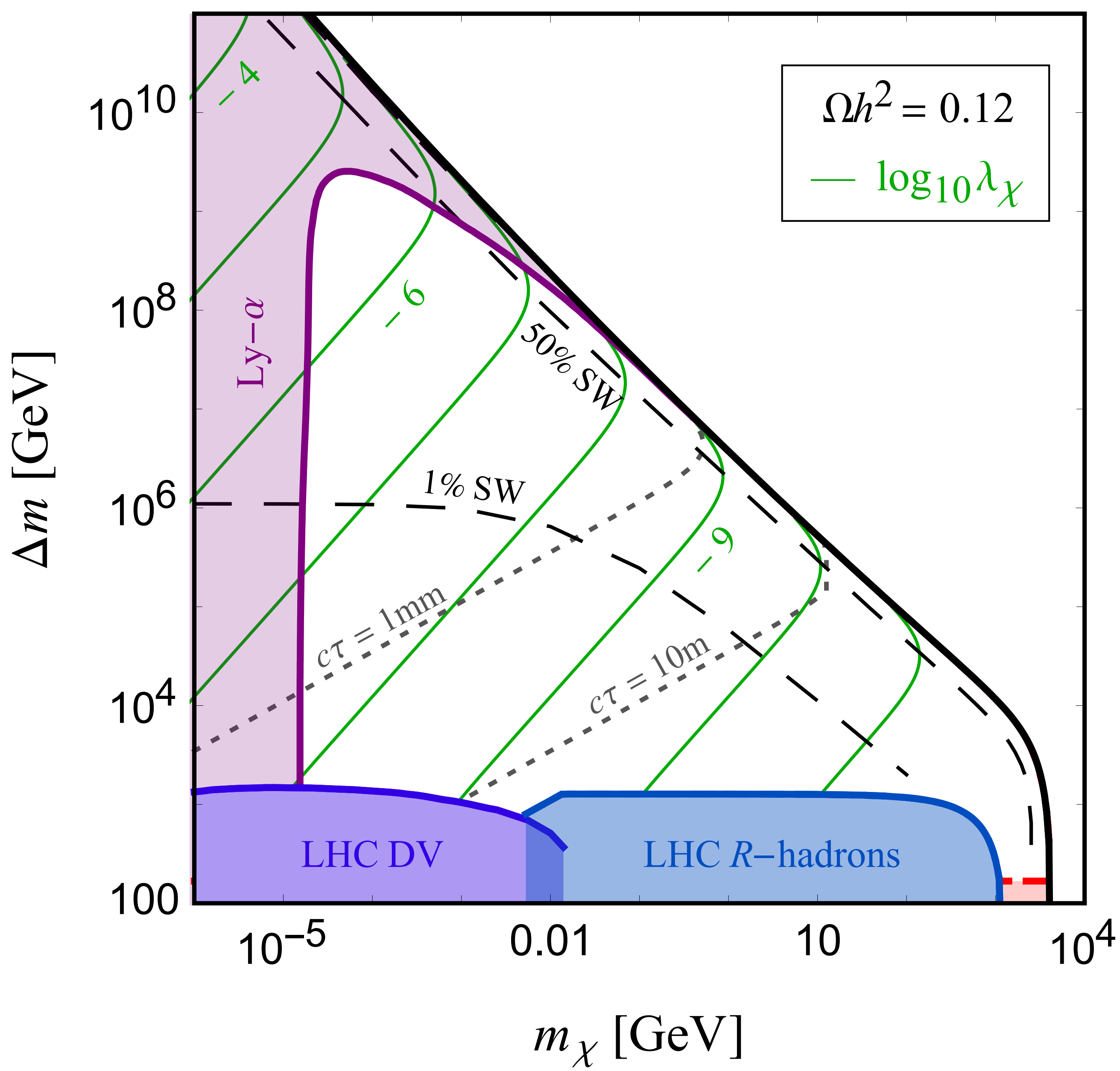


Non-thermalized dark matter: long-lived particle constraints



[Bélanger et *al.* 1811.05478]

Non-thermalized dark matter: viable parameter space

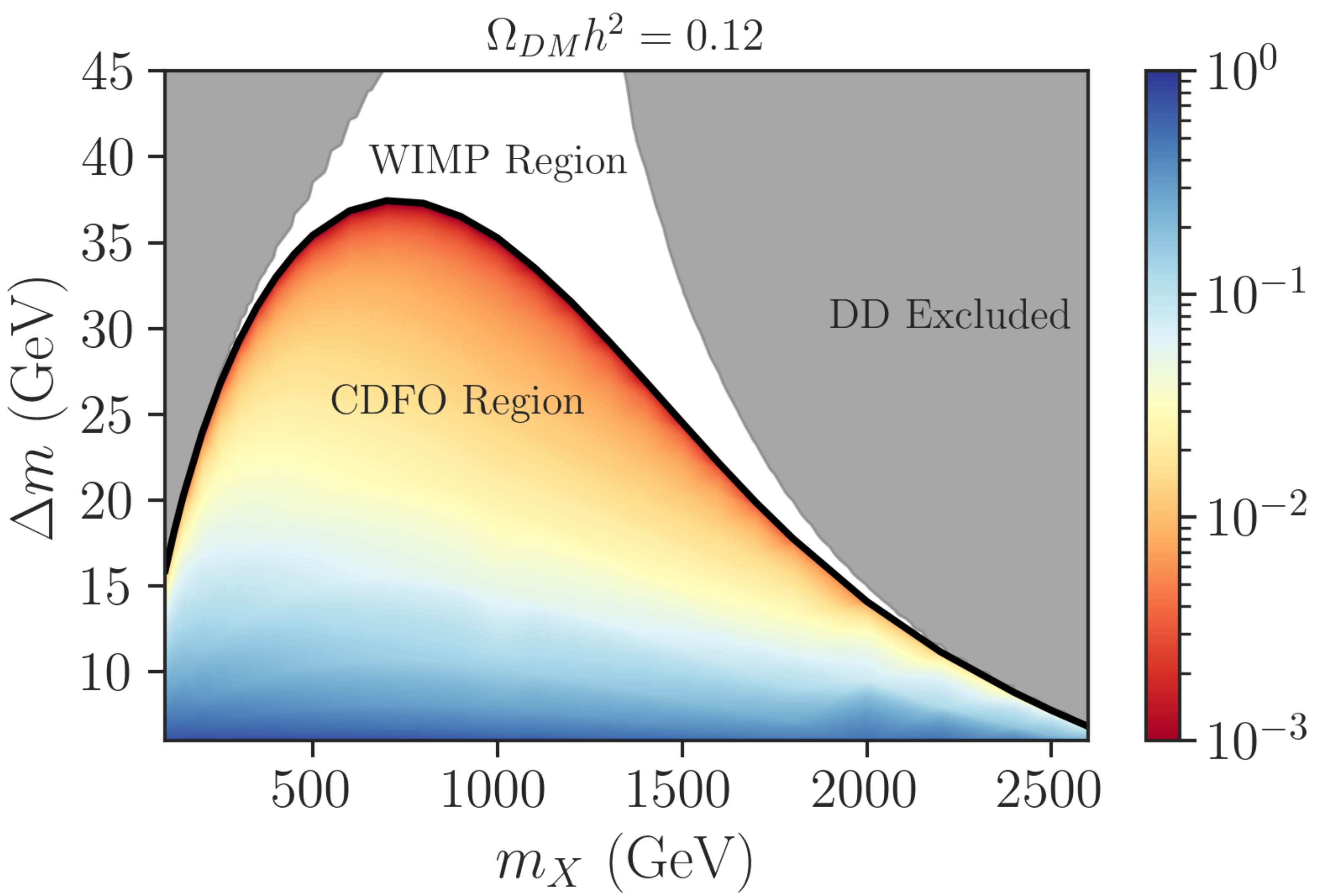


[Decant *et al.* 2111.09321]

‘Just’ thermalised case

Conversion-driven freeze-out (CDFO):

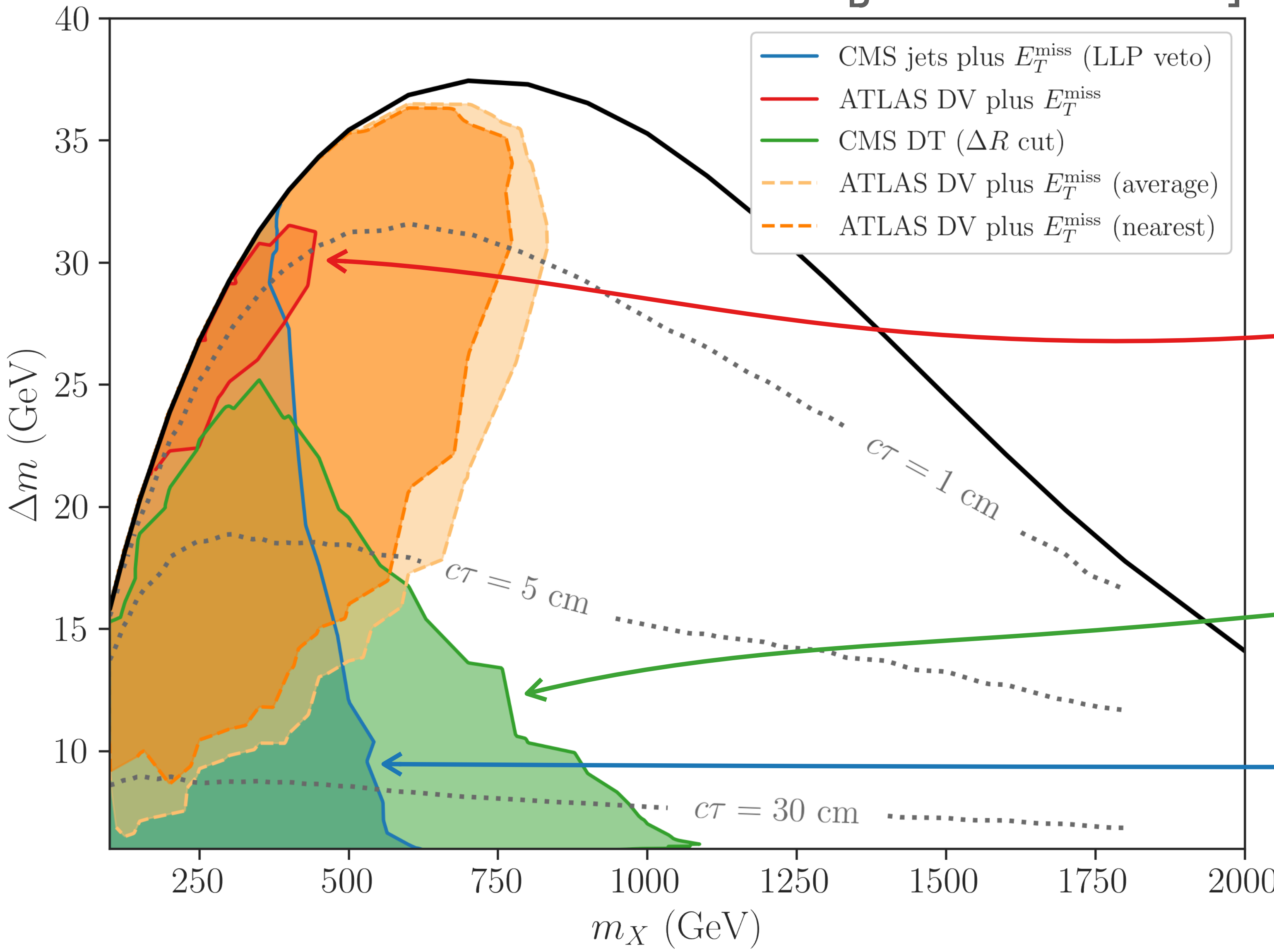
[Garny *et al* 1705.09292; D’Agnolo *et al* 1705.08450]



[JH *et al* 2404.16086]

Current LHC constraints

[JH *et al* 2404.16086]

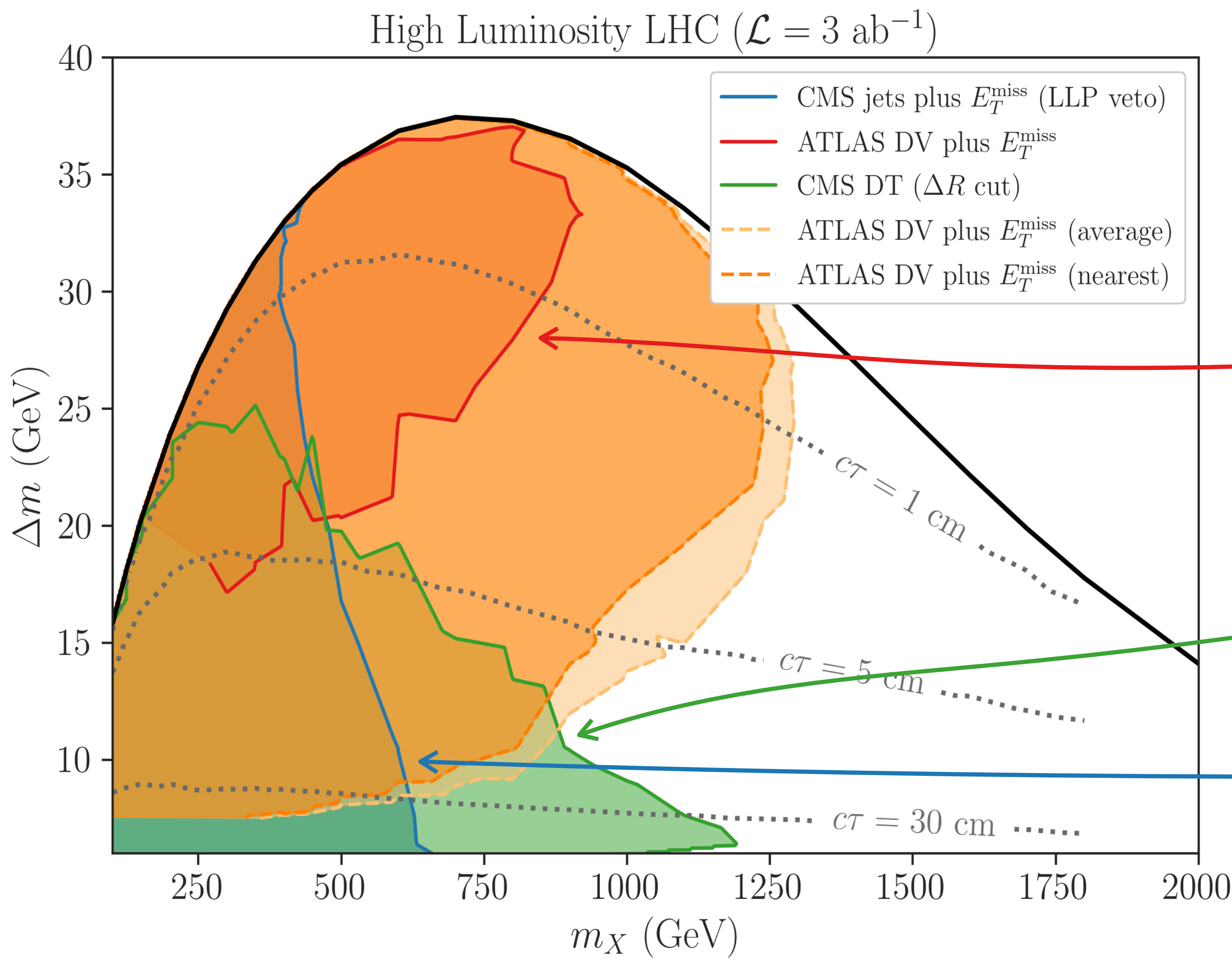


Displaced vertices (+MET)
$4\,\mathrm{mm} \lesssim c\tau_Y \lesssim 30\,\mathrm{cm}$

Disappearing tracks
$10\,\mathrm{cm} \lesssim c\tau_Y \lesssim 1\,\mathrm{m}$

MET search

HL-LHC projections



Displaced vertices (+MET)

$4\,\text{mm} \lesssim c\tau_Y \lesssim 30\,\text{cm}$

Disappearing tracks

$10\,\text{cm} \lesssim c\tau_Y \lesssim 1\,\text{m}$

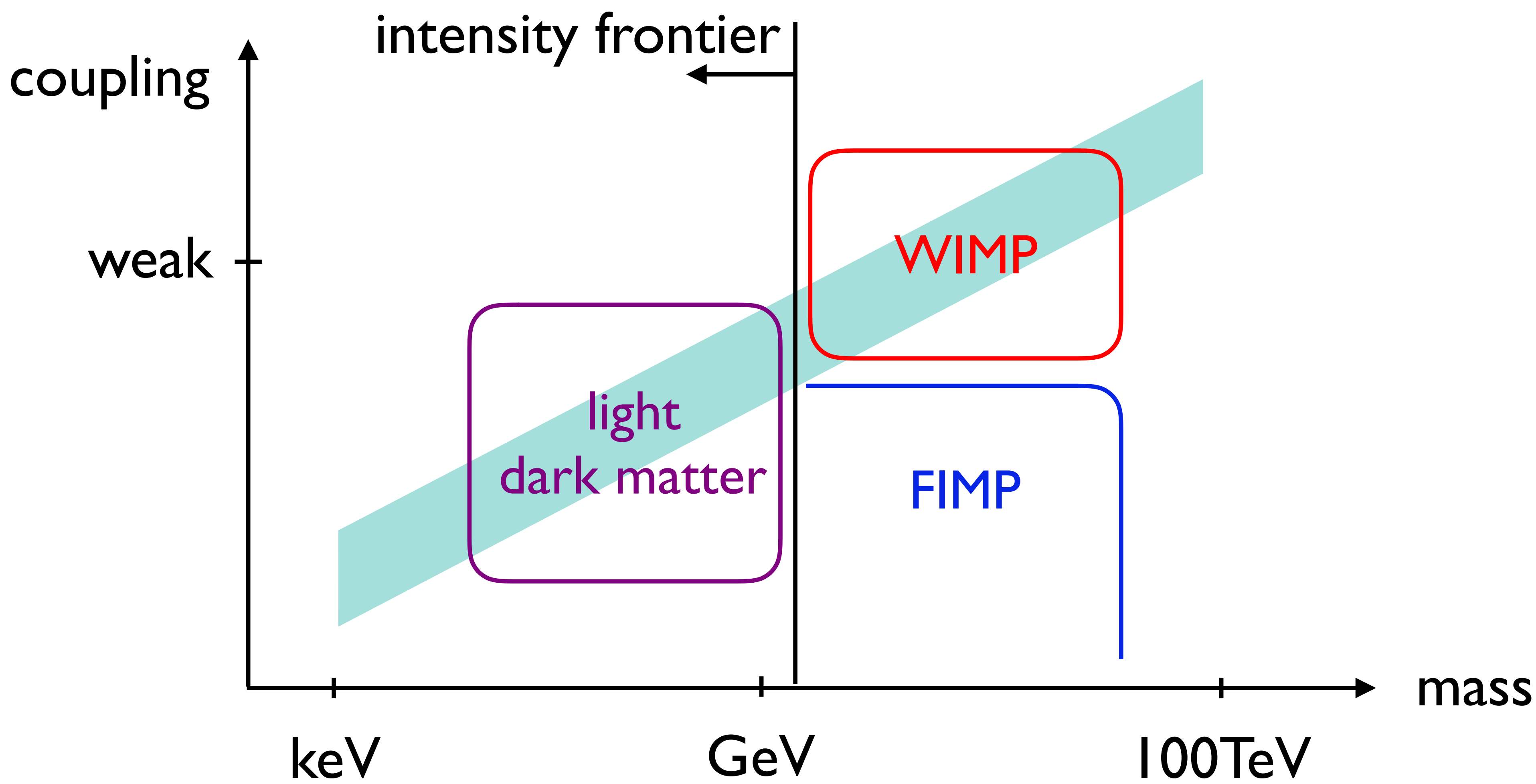
MET search

Summary on FIMP dark matter searches at LHC

- FIMPs not directly produced in collisions
- But from decay of other new physics states
- Feeble coupling $\Rightarrow$ long-lived particle
- Prominent low-background searches, statistically limited
- Promising channels at HL-LHC

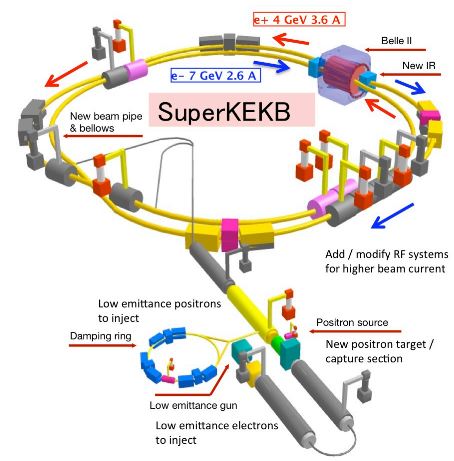
III. Searches for light dark matter

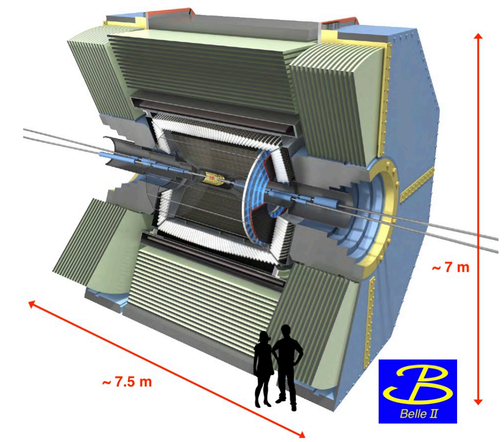
Dark matter as a thermal relic



Intensity frontier

- ‘Low’-energy e^+e^--colliders: BarBar, Belle-II



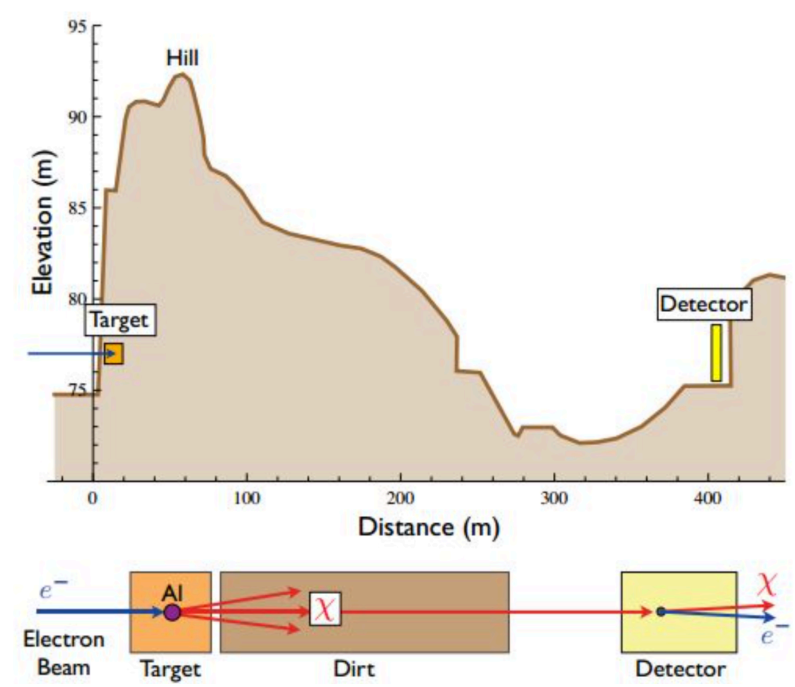


- Fixed target experiments

  Electron beams: E137, E141(SLAC), E774 (Fermilab), NA64e (CERN), HPS (JLab)

  Proton beams: CHARM, NA62 (CERN), nu-Cal

  …



Dark photon model

Massive dark photon A'_μ coupling to hyper charge:

$$\mathcal{L} \supset -\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu} \to \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

Induces interaction to matter current:

$$\mathcal{L}_{\rm int} \supset -e\epsilon J^\mu A'_\mu$$

⇒ dark photon interacts with SM fermions just as a photon but suppressed by ϵ.

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Induces interaction to matter current:

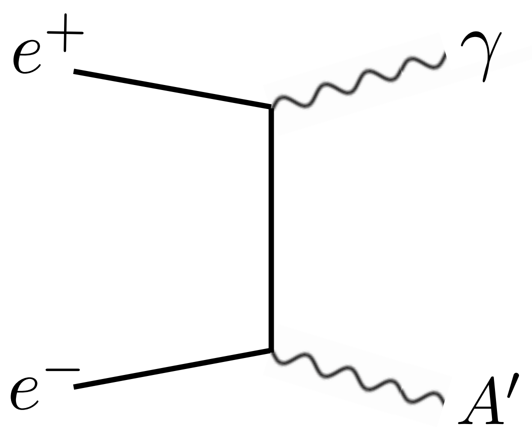
$$\mathcal{L}_{\rm int} \supset -e\epsilon J^\mu A'_\mu$$

⇒ dark photon interacts with SM fermions just as a photon
but suppressed by ϵ.

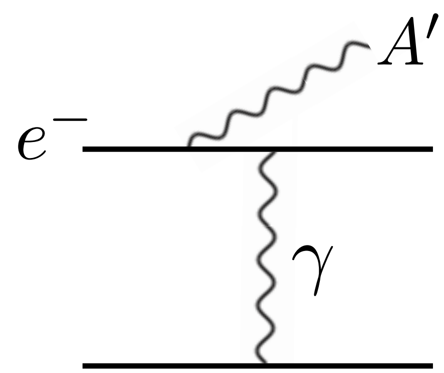
Interaction to dark matter, e.g.:

$$\mathcal{L}_{A'\chi} = -g_\chi A'_\mu \bar{\chi}\gamma^\mu \chi$$

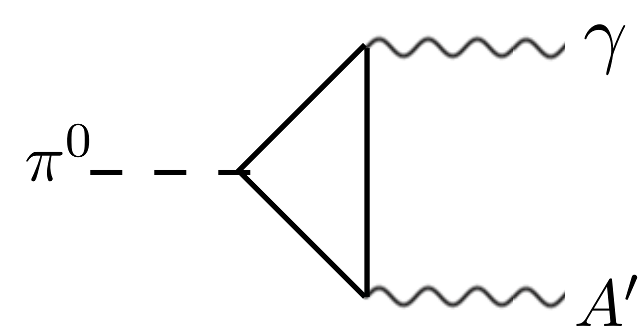
Dark photon production channels



e^+e^--collisions

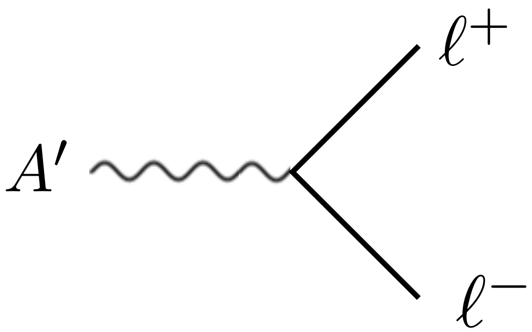


bremsstrahlung
in material

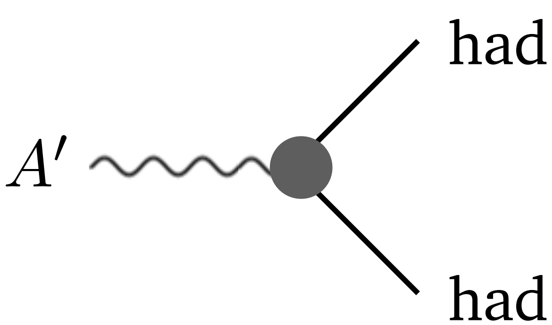


in decays of
pions

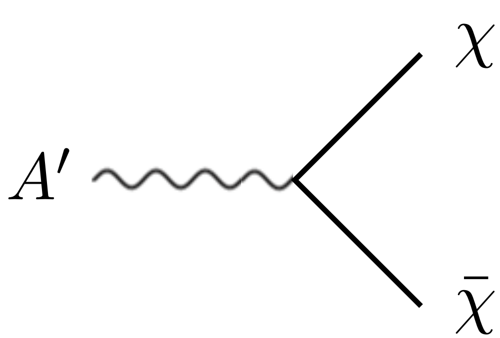
Dark photon decay channels

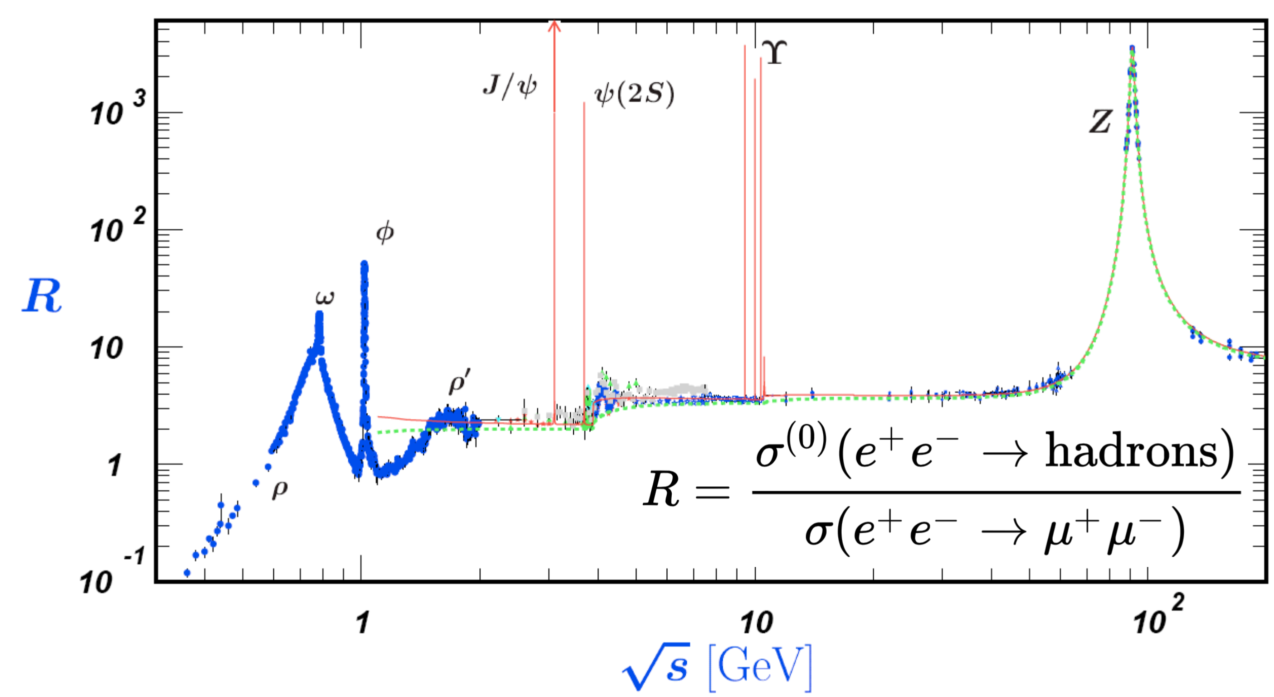


$$\Gamma_{\ell^+\ell^-} \sim \epsilon^2 \alpha m_{A'} \times (\text{phase-space})$$

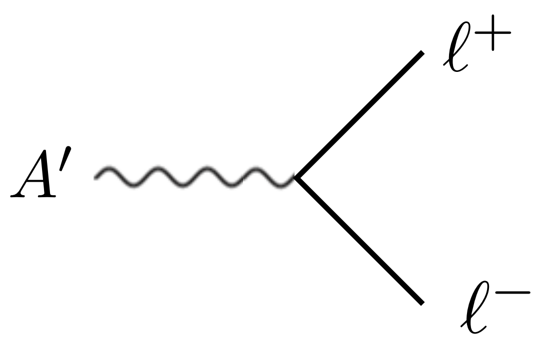


$$\Gamma_{\text{had}} = \Gamma_{\mu^+\mu^-}\, R(\sqrt{s} = m_{A'})$$

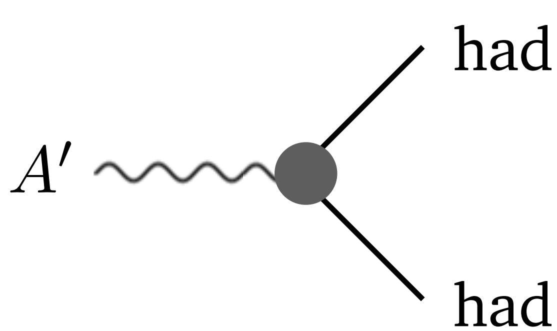




Dark photon decay channels



$$\Gamma_{\ell^+\ell^-} \sim \epsilon^2 \alpha m_{A'} \times (\text{phase-space})$$



$$\Gamma_{\text{had}} = \Gamma_{\mu^+\mu^-} \, R(\sqrt{s} = m_{A'})$$

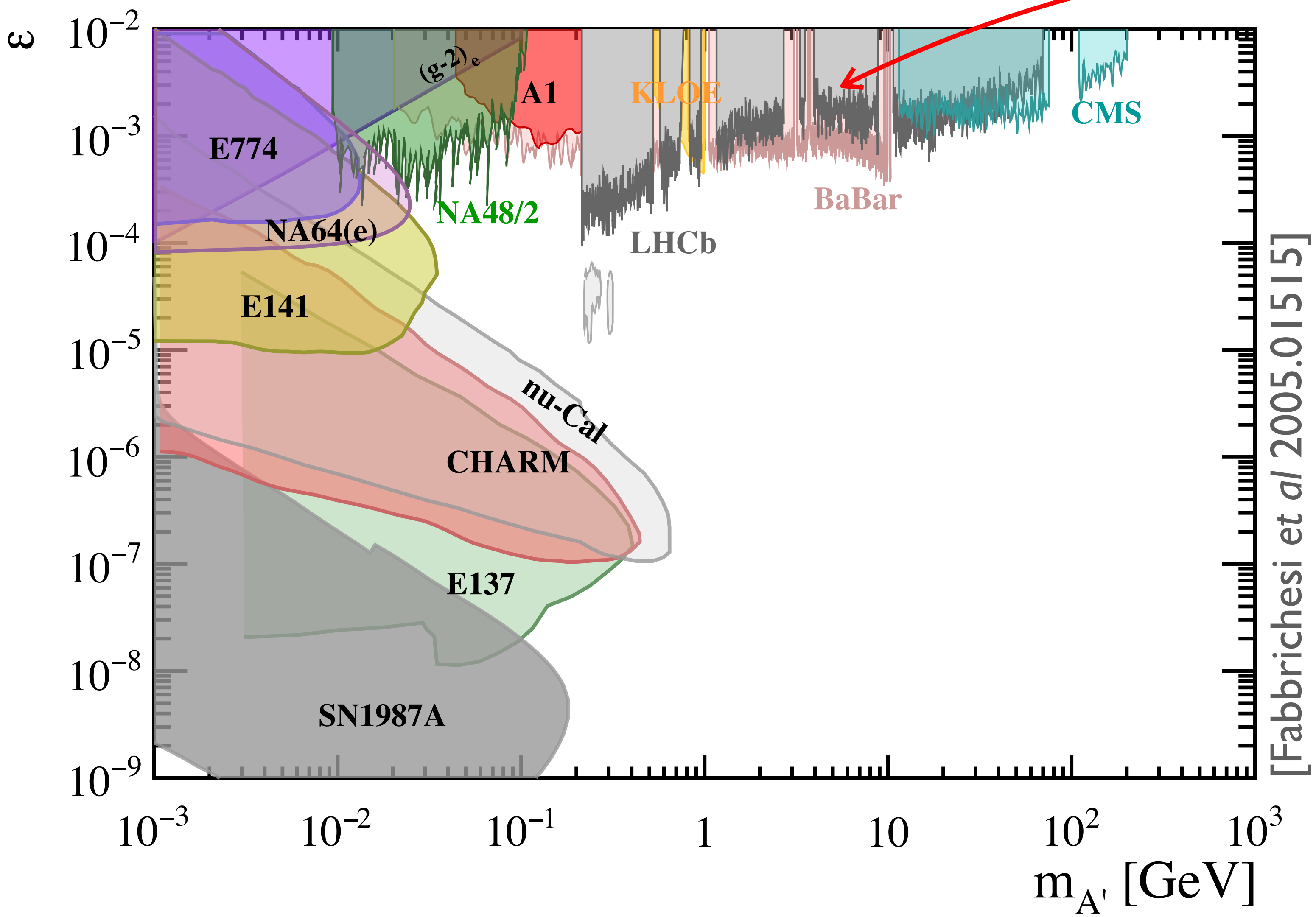
$m_{A'} = 10\,\text{MeV}$

$\epsilon = 10^{-3}$:
$c\tau \sim 6 \times 10^{-6}\,\text{m}$
(prompt)

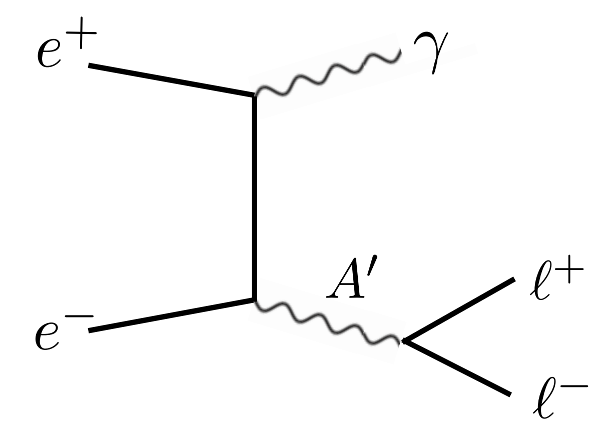
$\epsilon = 10^{-6}$:
$c\tau \sim 6\,\text{m}$
(metastable)

Dark photon searches

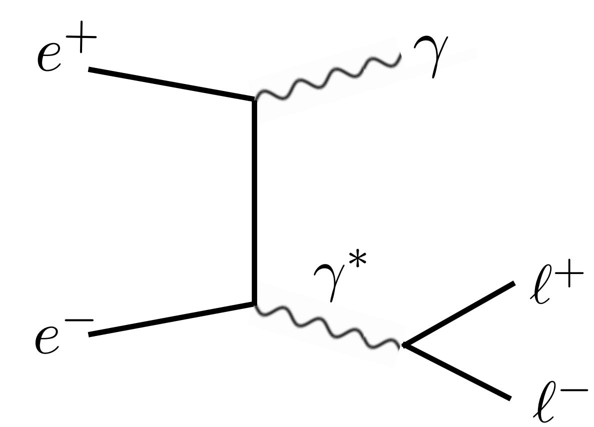
Decay into leptons:



Prompt searches



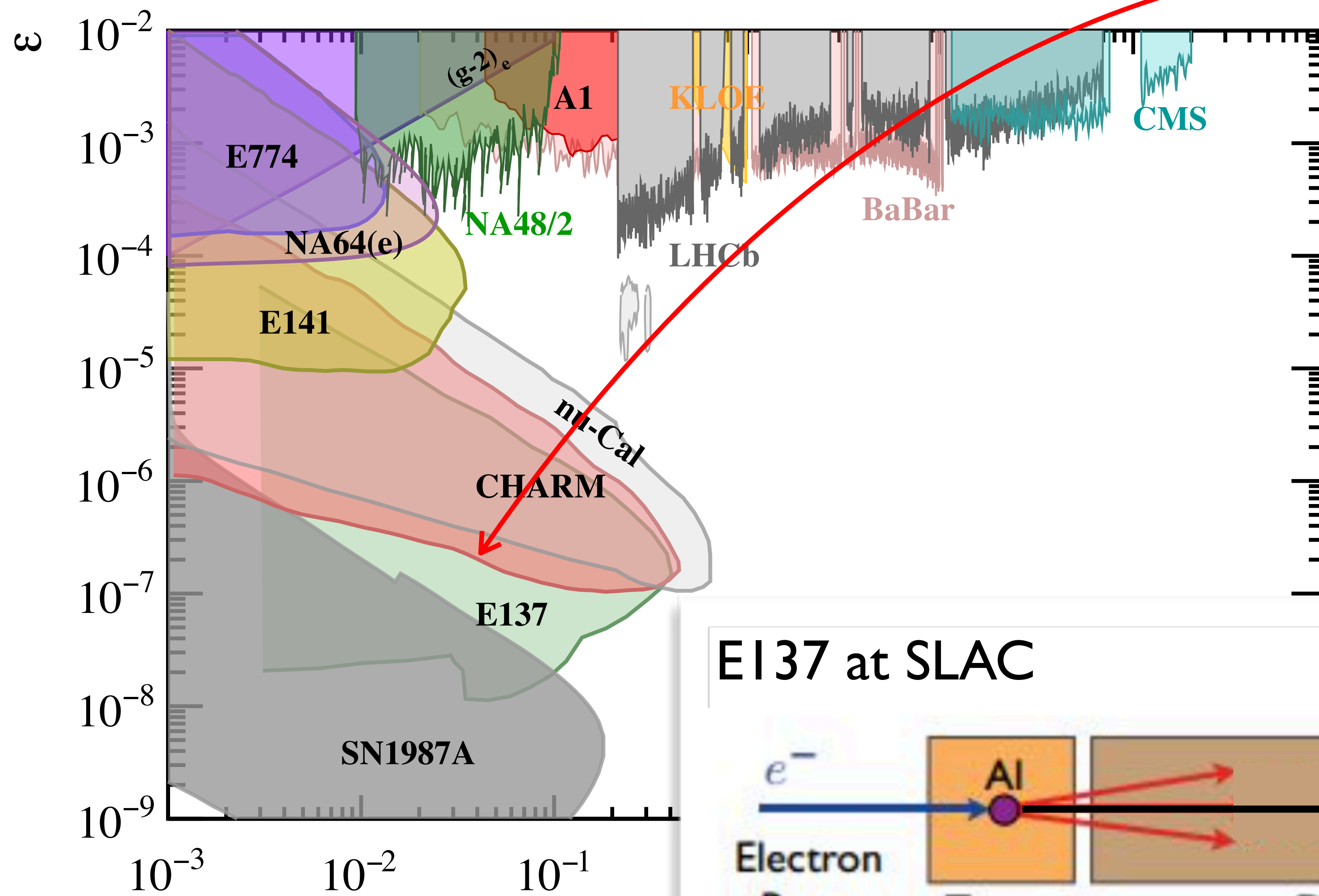
Irreducible background:



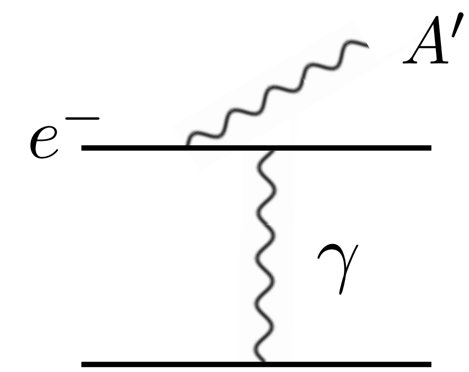
Limited by resolution of $m_{\ell^+\ell^-}$

Dark photon searches

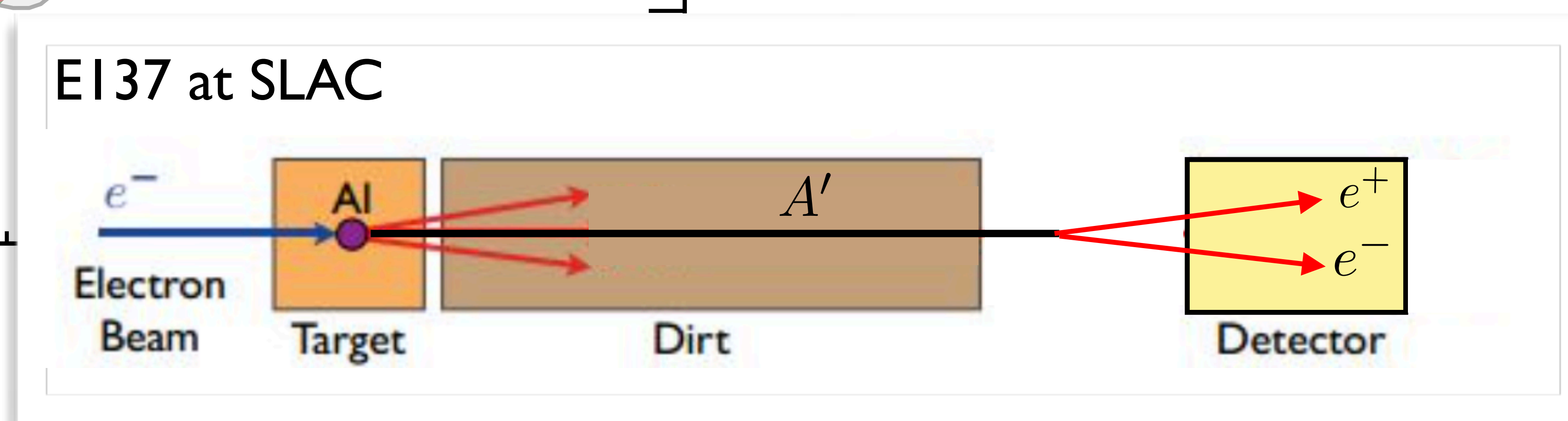
Decay into leptons:



Long-lived searches

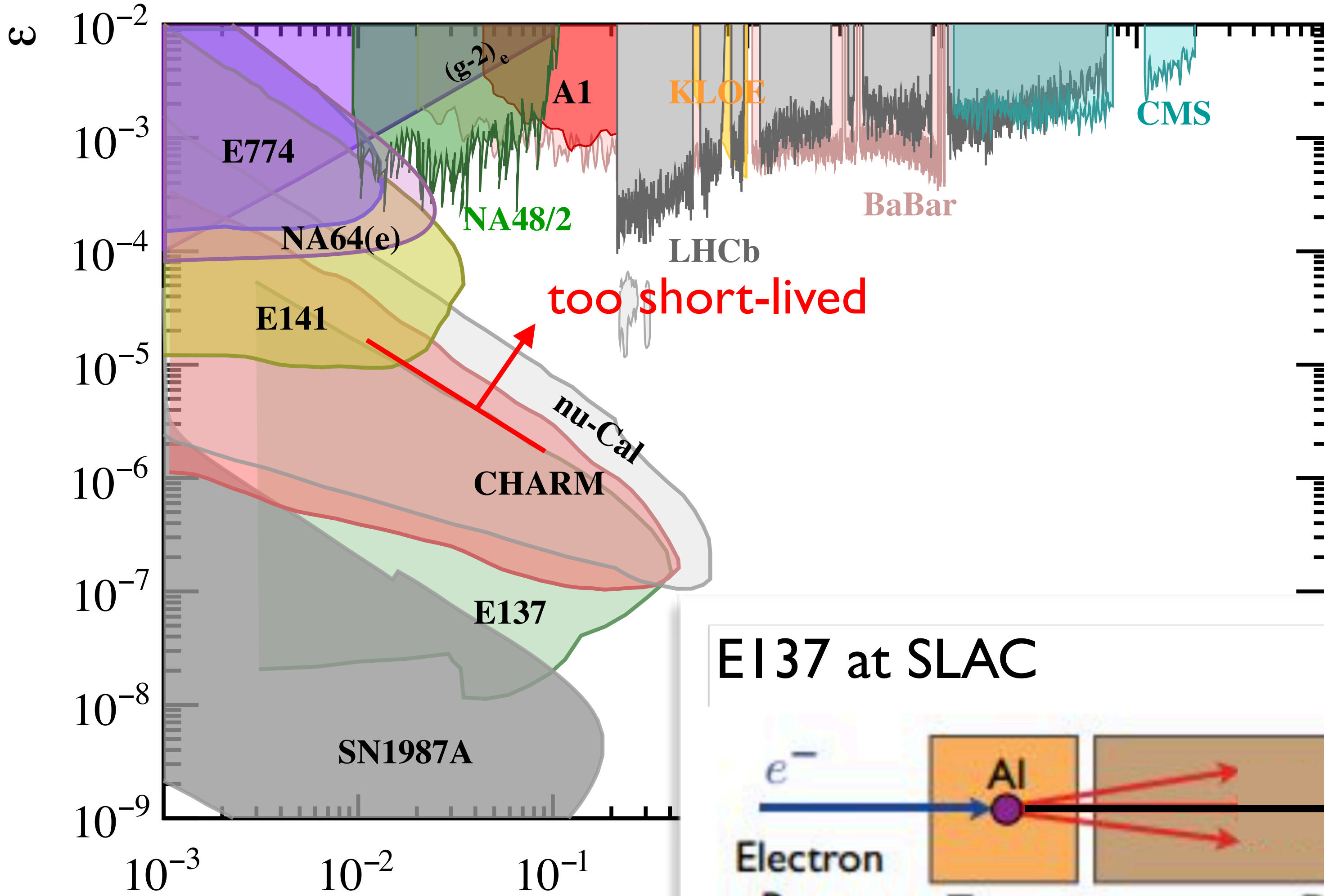


Coherent interaction with nuclei of fixed target

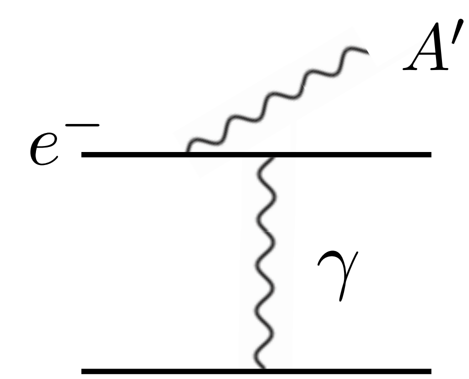


Dark photon searches

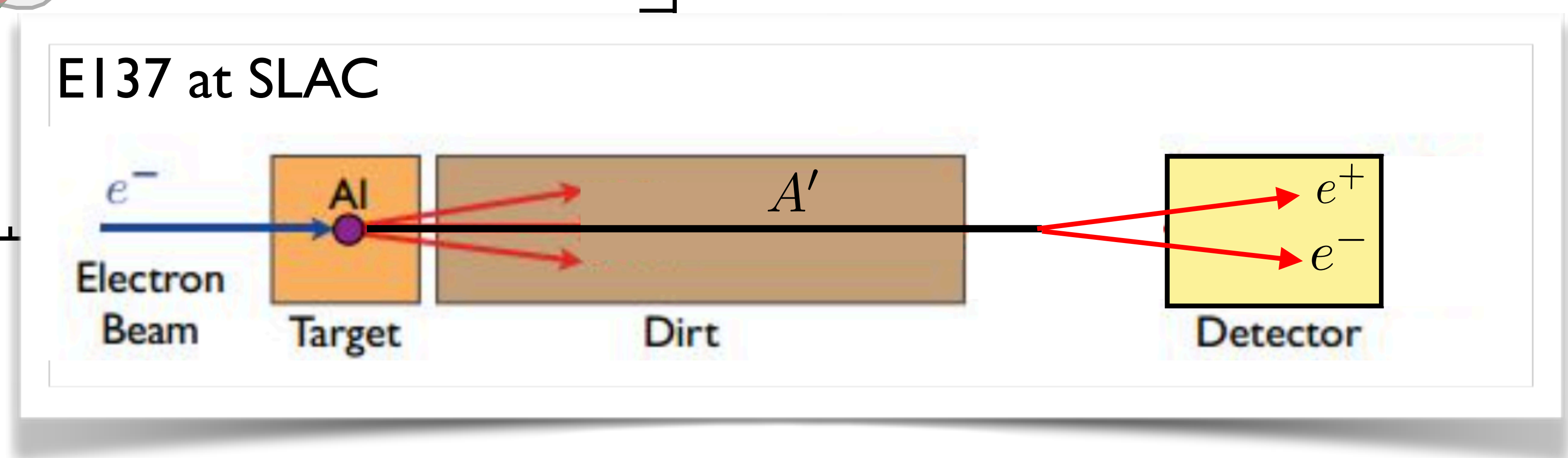
Decay into leptons:



Long-lived searches

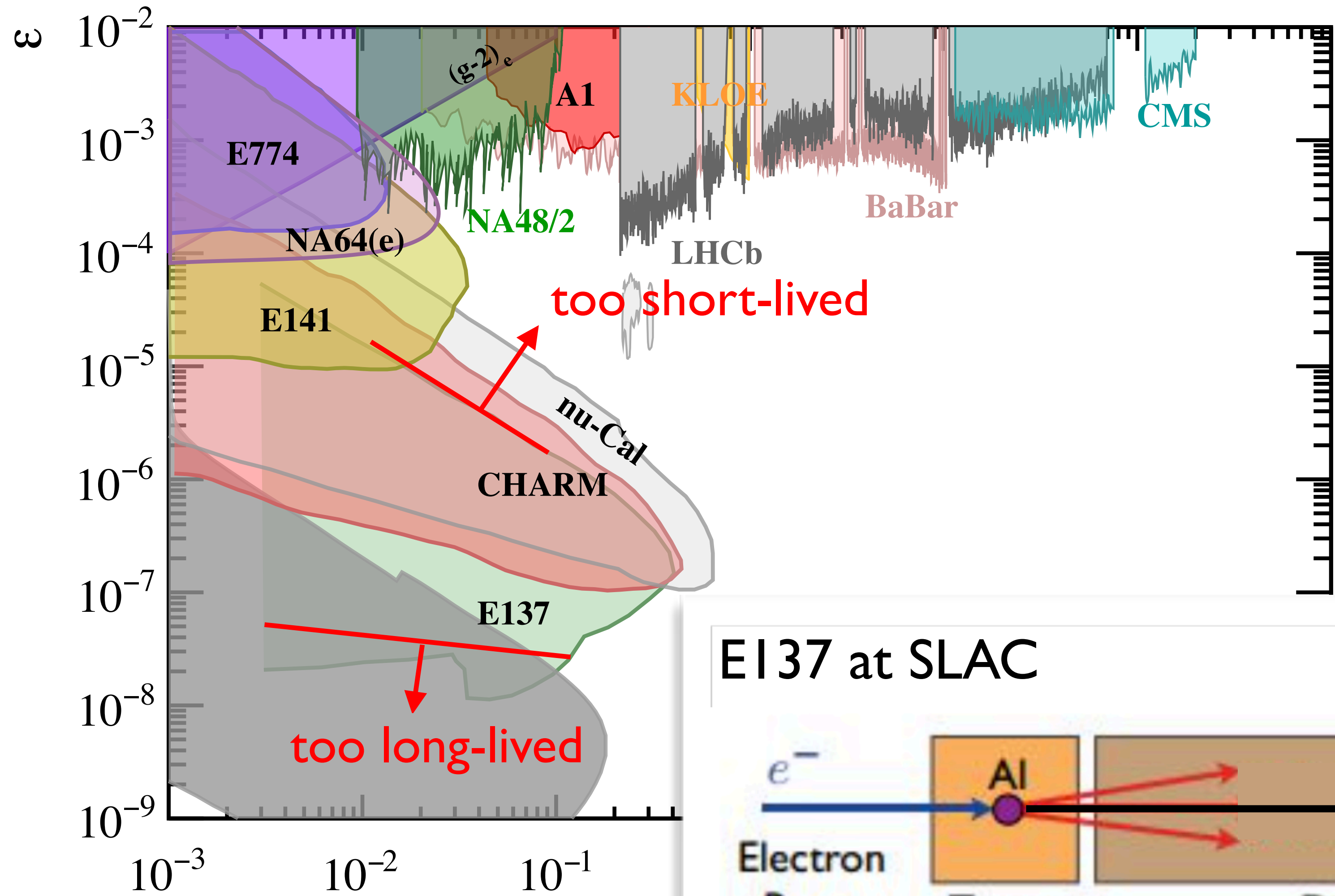


Coherent interaction with nuclei of fixed target

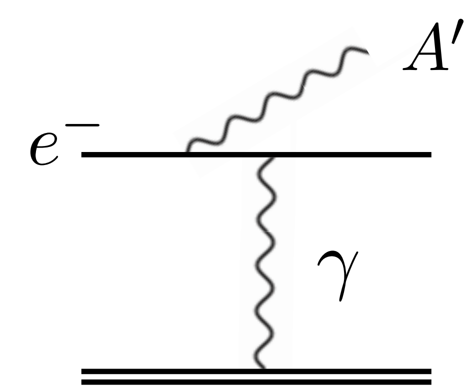


Dark photon searches

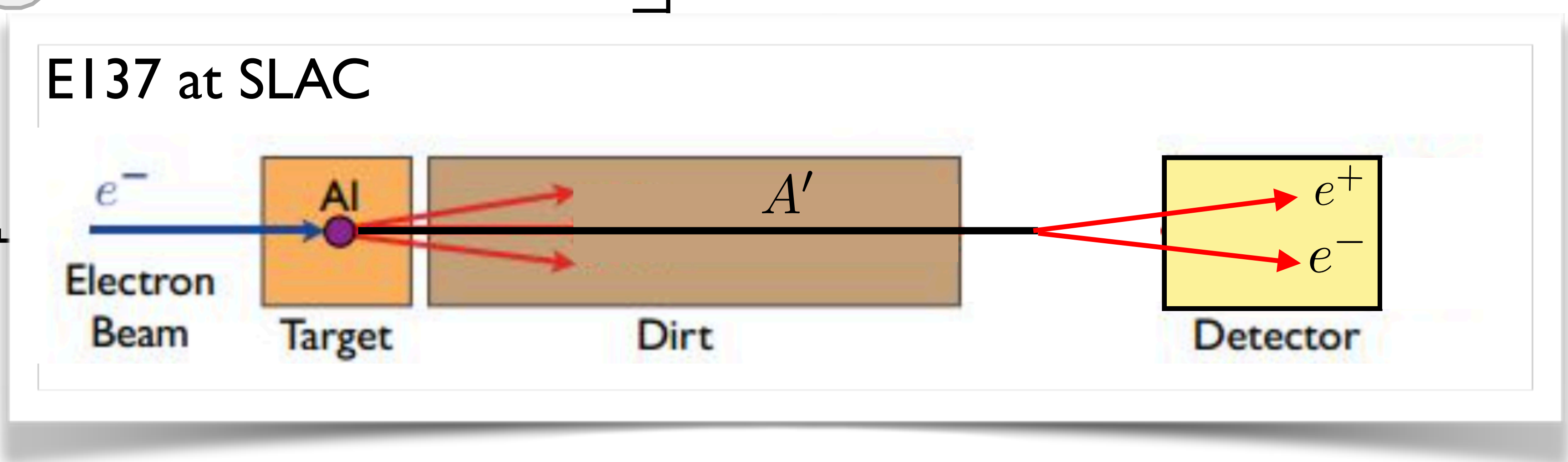
Decay into leptons:



Long-lived searches

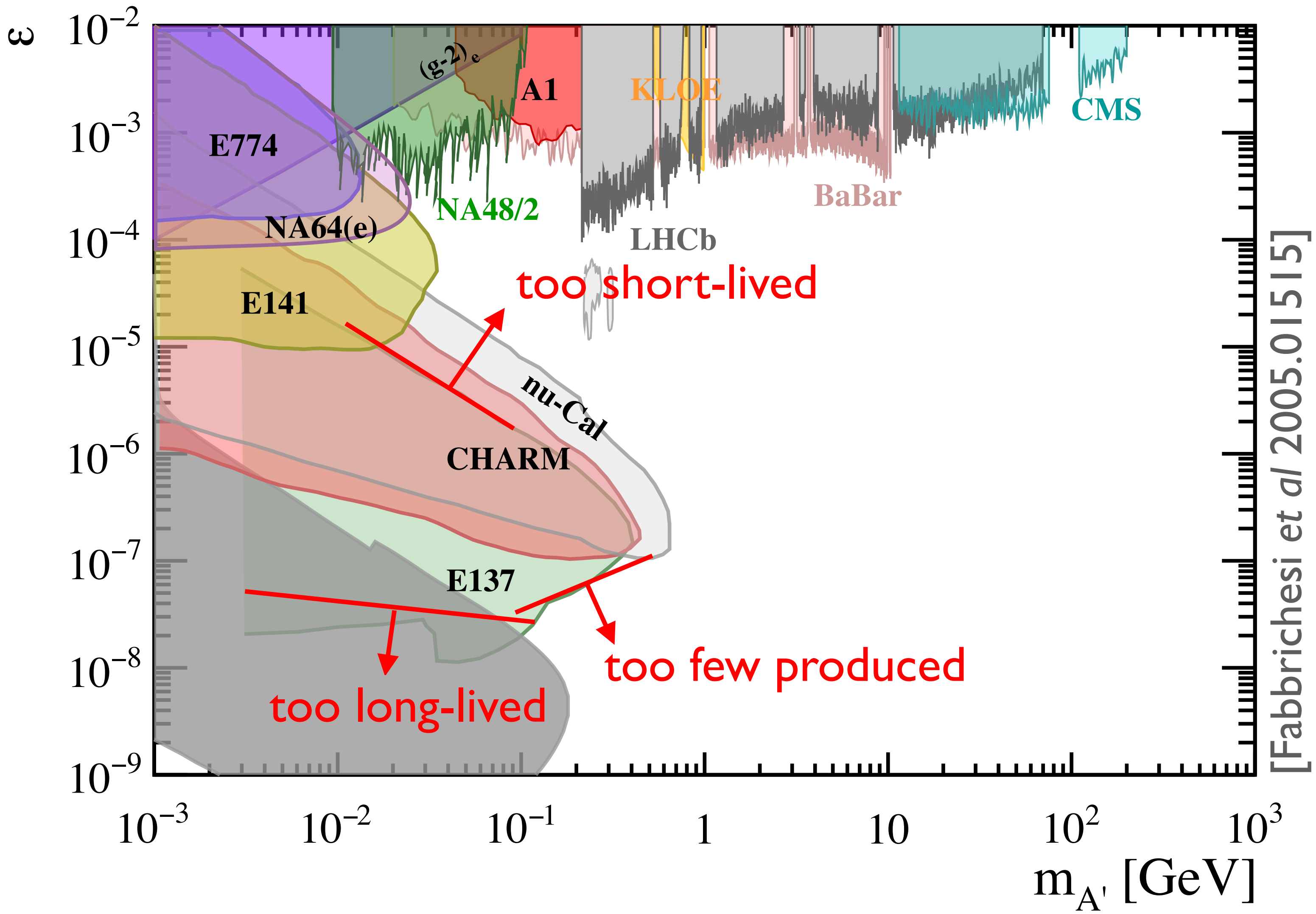


Coherent interaction with nuclei of fixed target

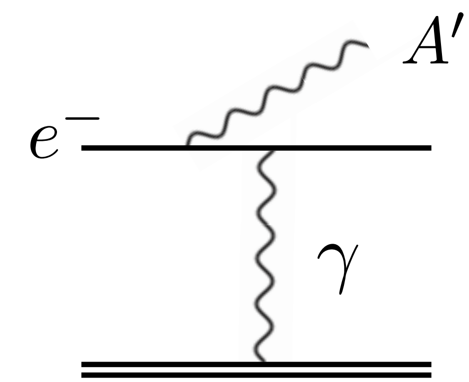


Dark photon searches

Decay into leptons:



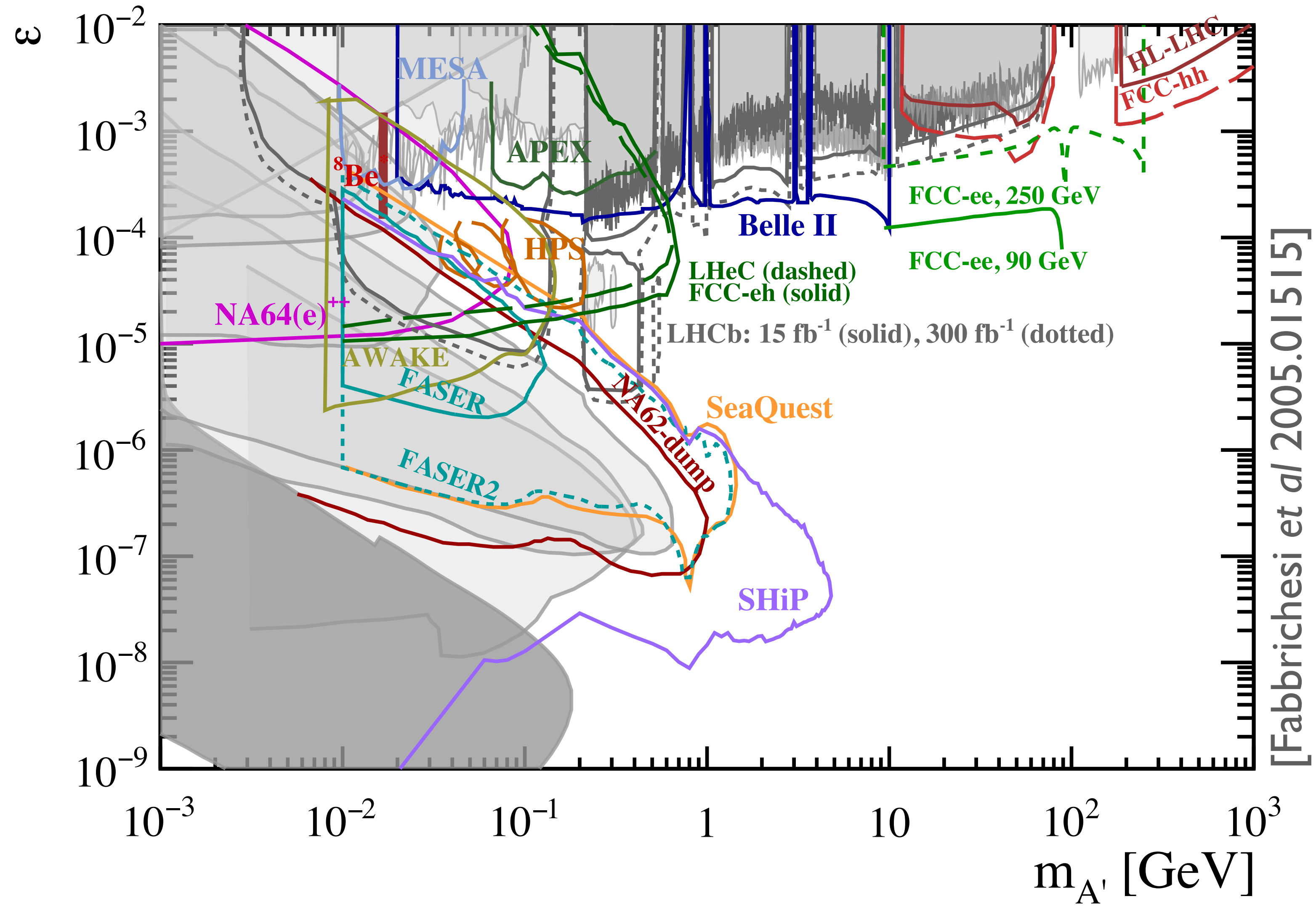
Long-lived searches



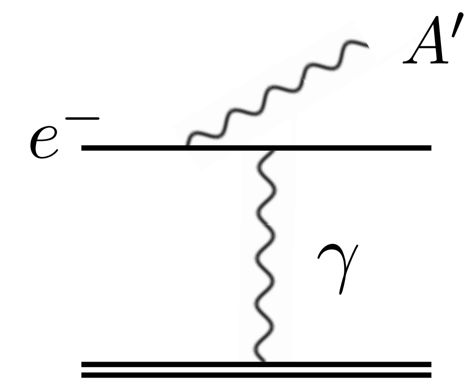
Coherent interaction with nuclei of fixed target

Dark photon searches

Decay into leptons:



Long-lived searches



Coherent interaction with nuclei of fixed target

Dark photon model

Massive dark photon A'_μ coupling to hyper charge:

$$\mathcal{L} \supset -\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu} \to \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

Induces interaction to matter current:

$$\mathcal{L}_{\rm int} \supset -e\epsilon J^\mu A'_\mu$$

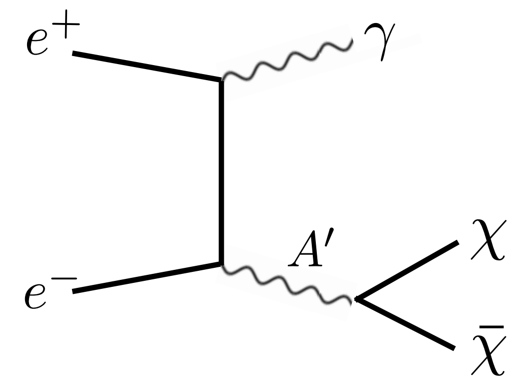
⇒ dark photon interacts with SM fermions just as a photon but suppressed by ϵ.

Interaction to dark matter, e.g.:

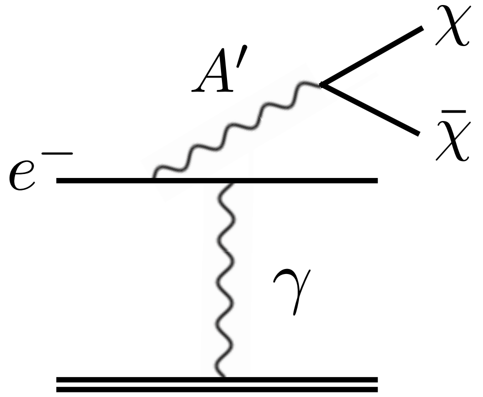
$$\mathcal{L}_{A'\chi} = -g_\chi A'_\mu \bar{\chi}\gamma^\mu \chi$$

Dark matter searches

- Missing energy strategy:

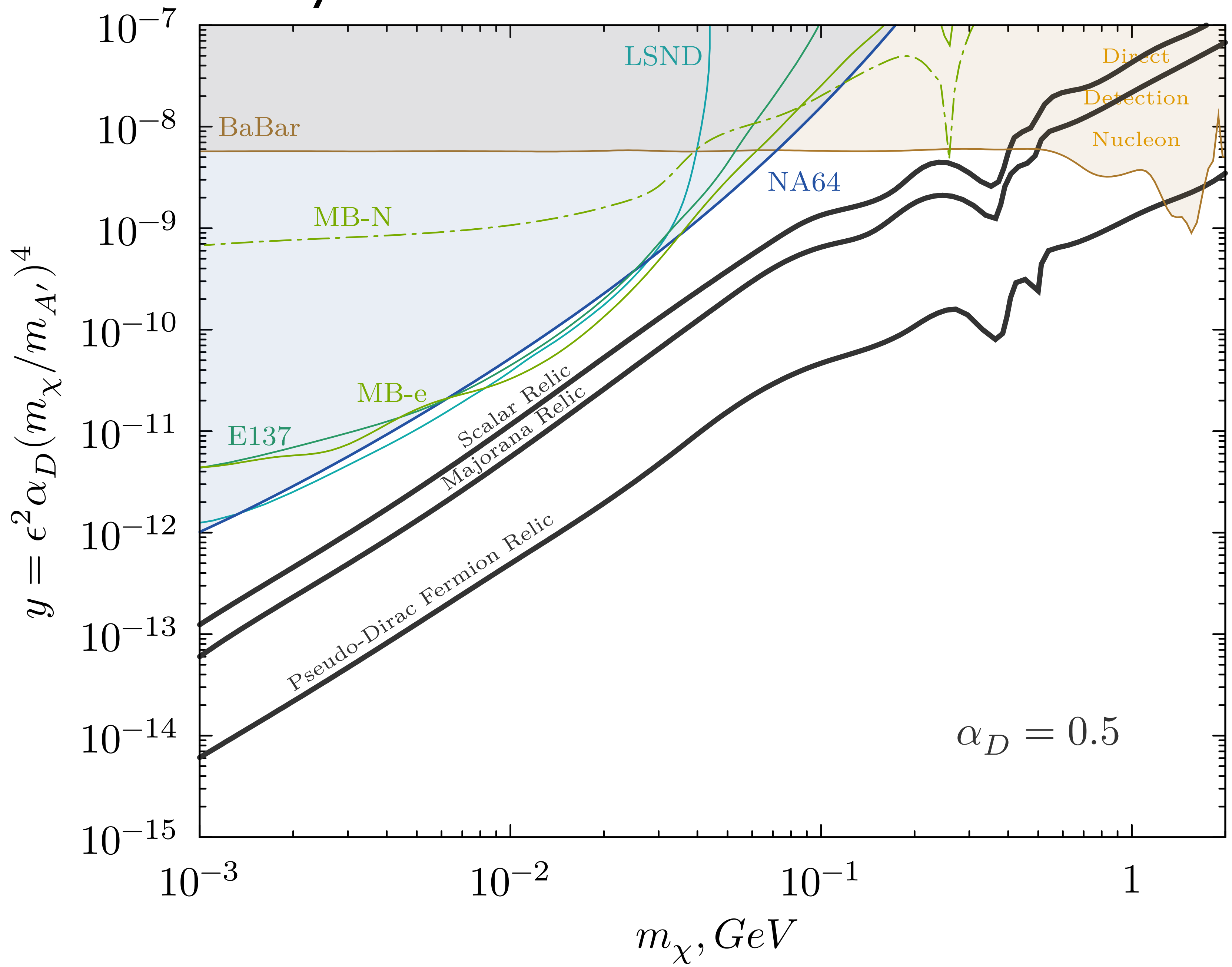


- Dark matter detection:



Dark matter searches

Decay into dark matter:



[1906.00176]

Summary on light dark matter searches

- Common benchmark: dark photon, kinetic mixing
- Lifetime range from prompt to long-lived
- Intensity frontier: B-factories and fixed target experiments
- Prompt searches background-limited
- Long-lived searches luminosity- and baseline-limited
- Fixed target experiments: dark matter search beyond missing energy