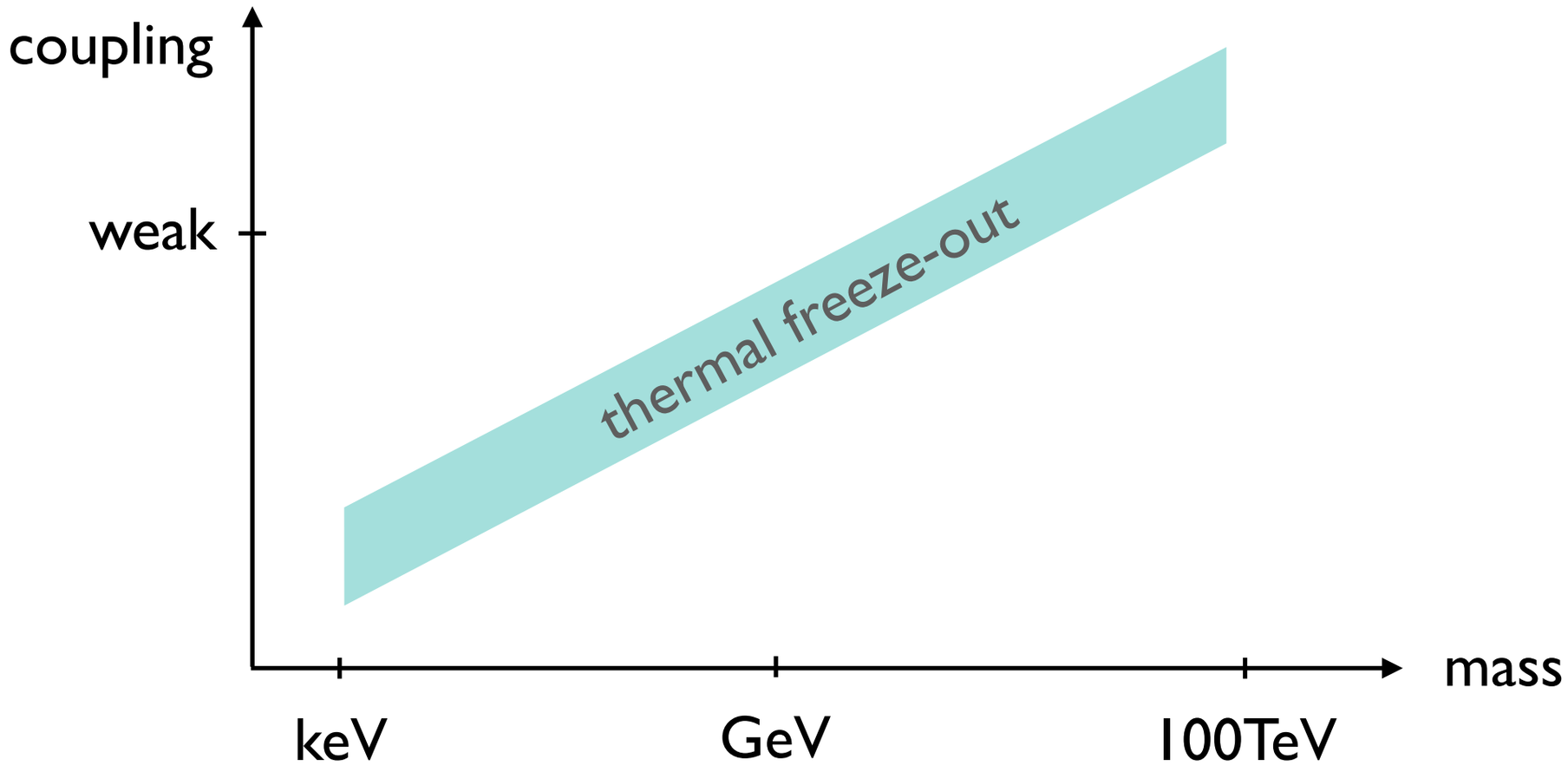
ISAPP School 2024, Bad Liebenzell

Accelerator-based Dark Matter searches

Jan Heisig

Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Dark matter as a thermal relic



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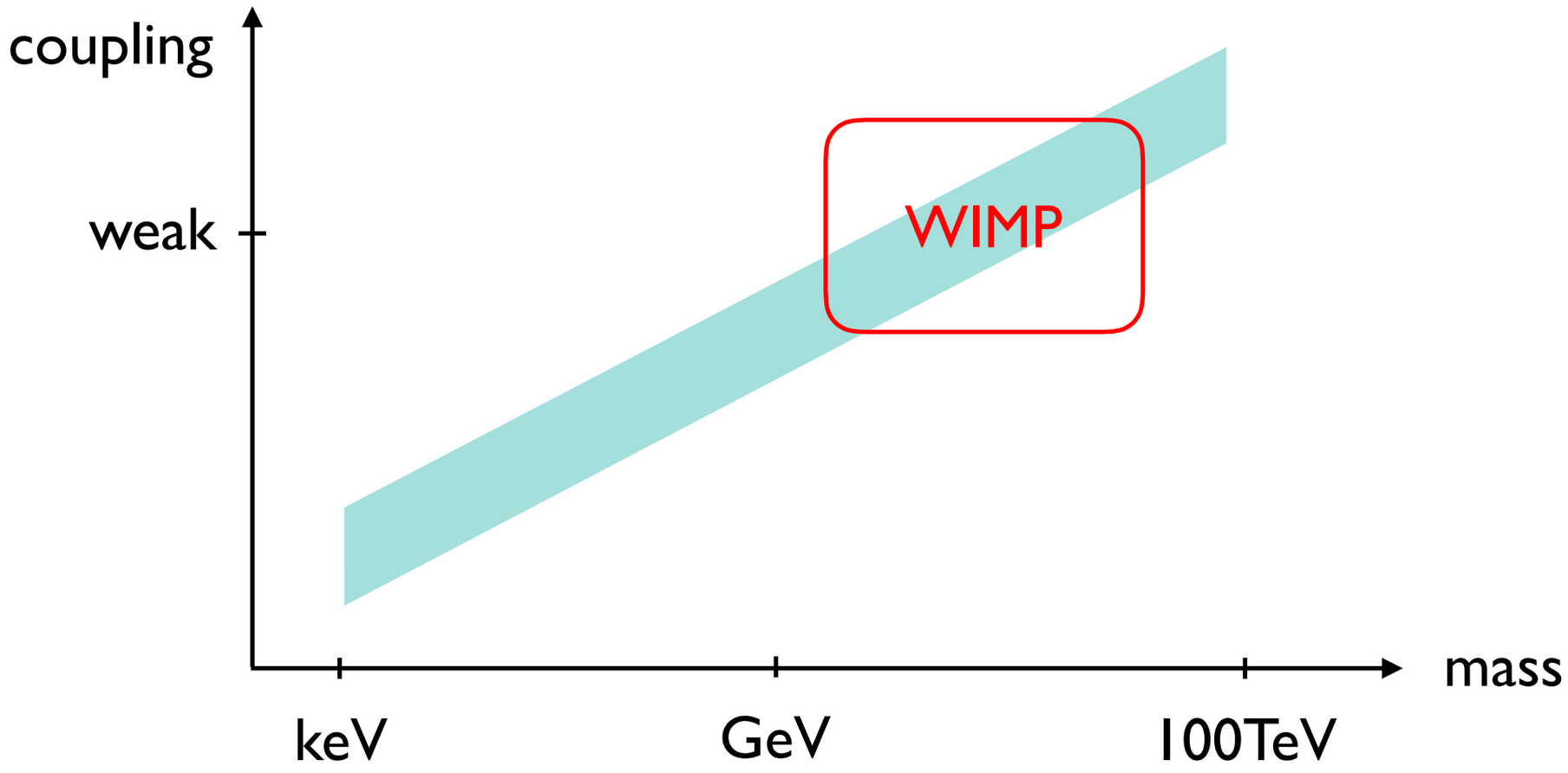

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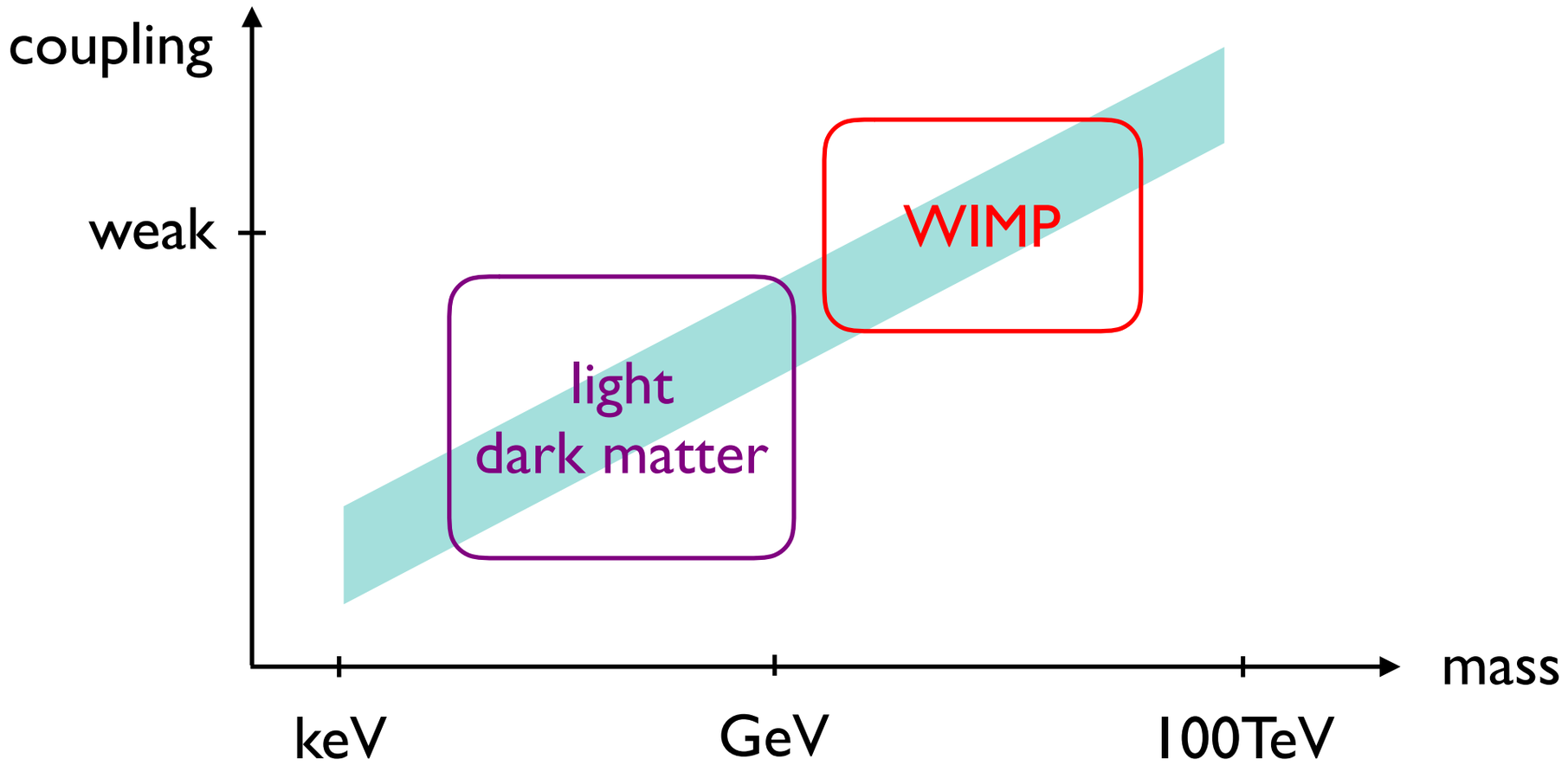

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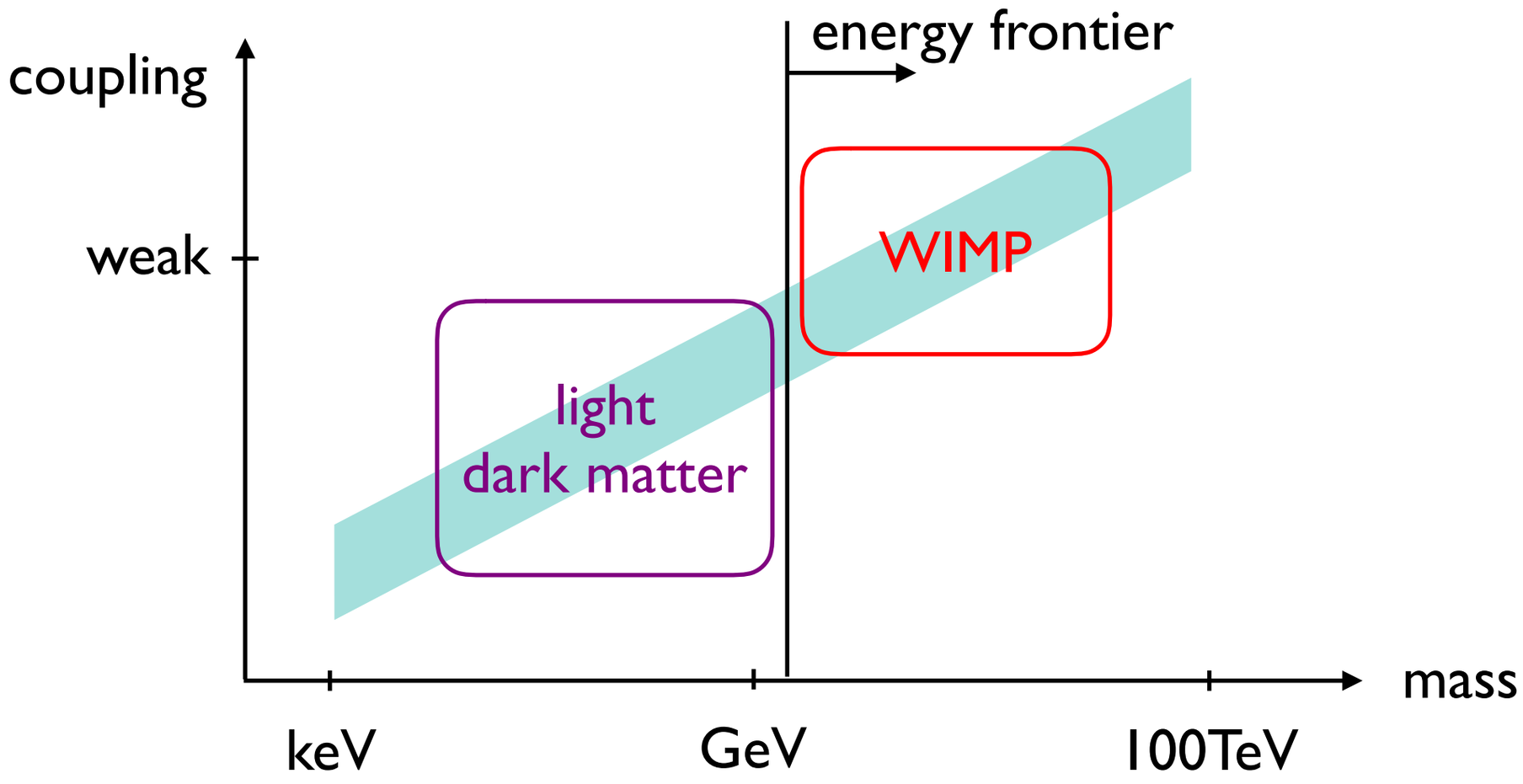

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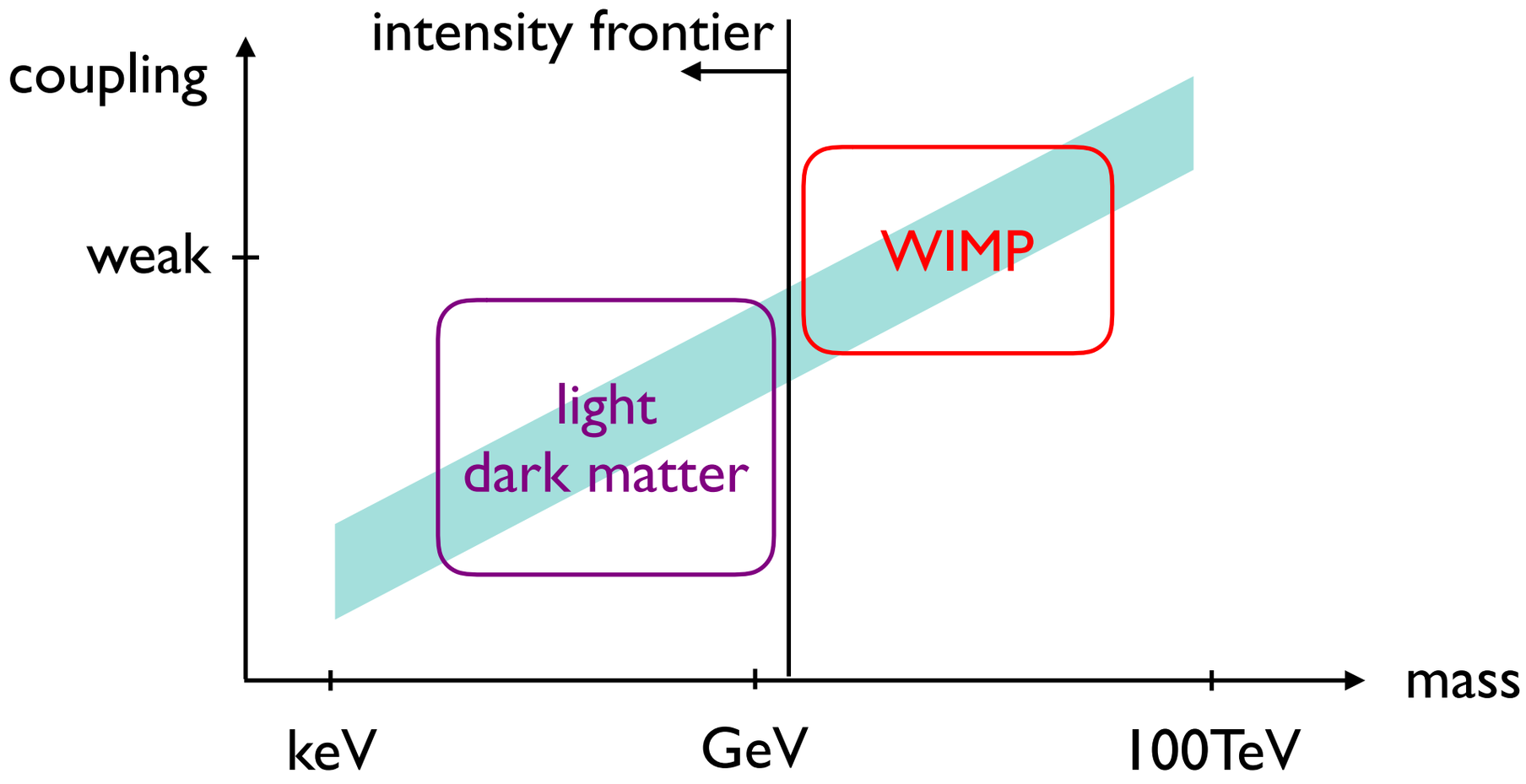
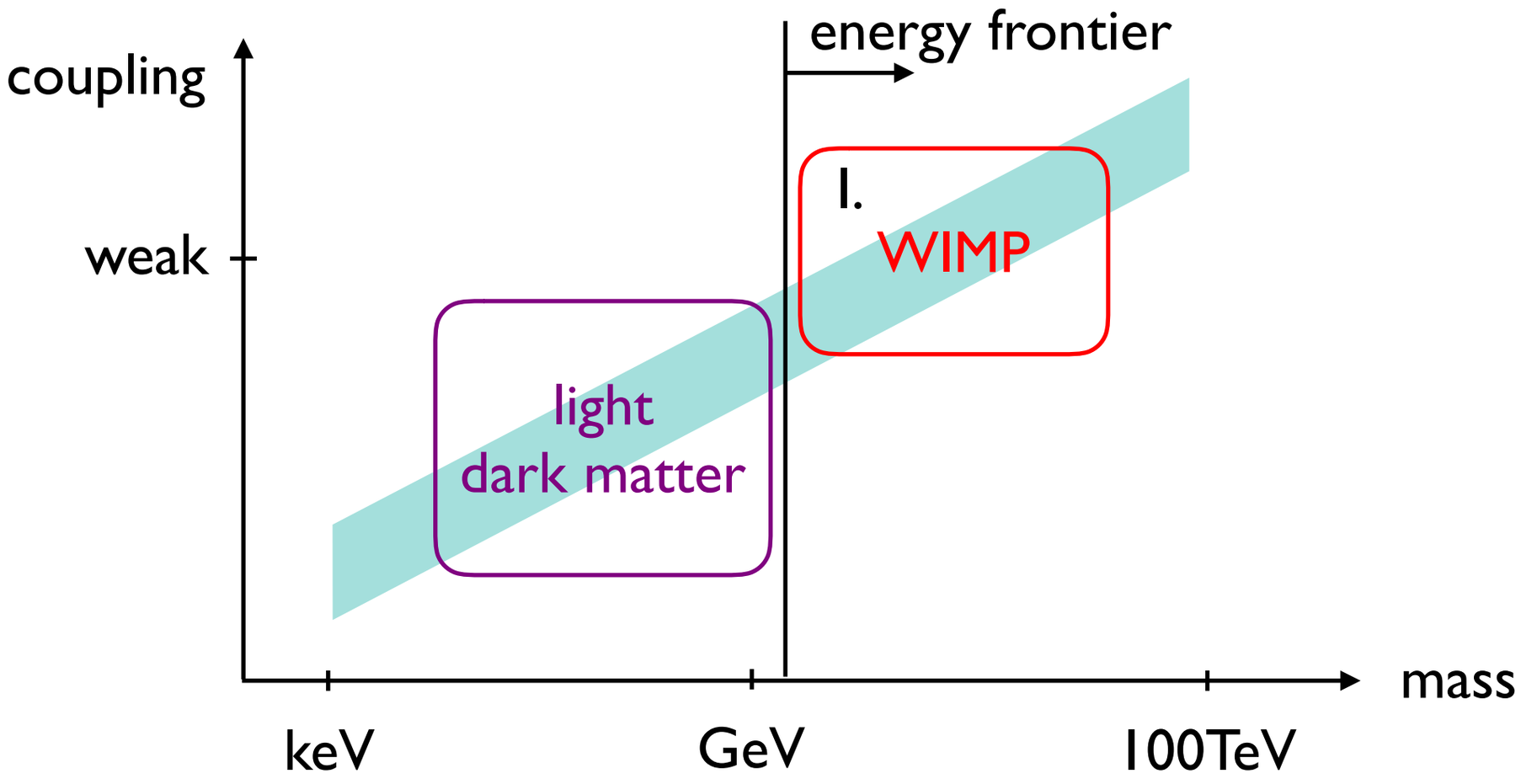


Dark matter as a thermal relic – outline



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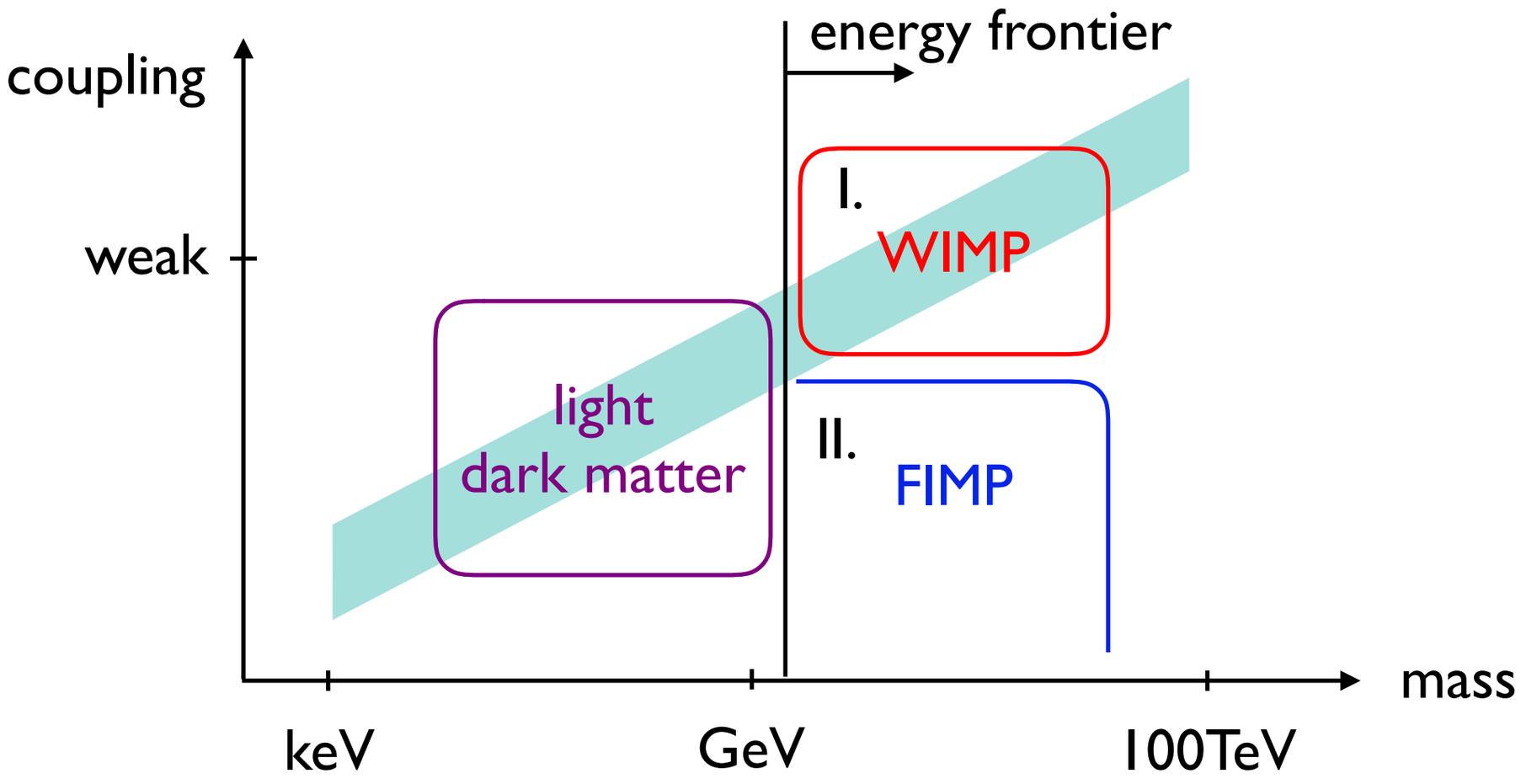
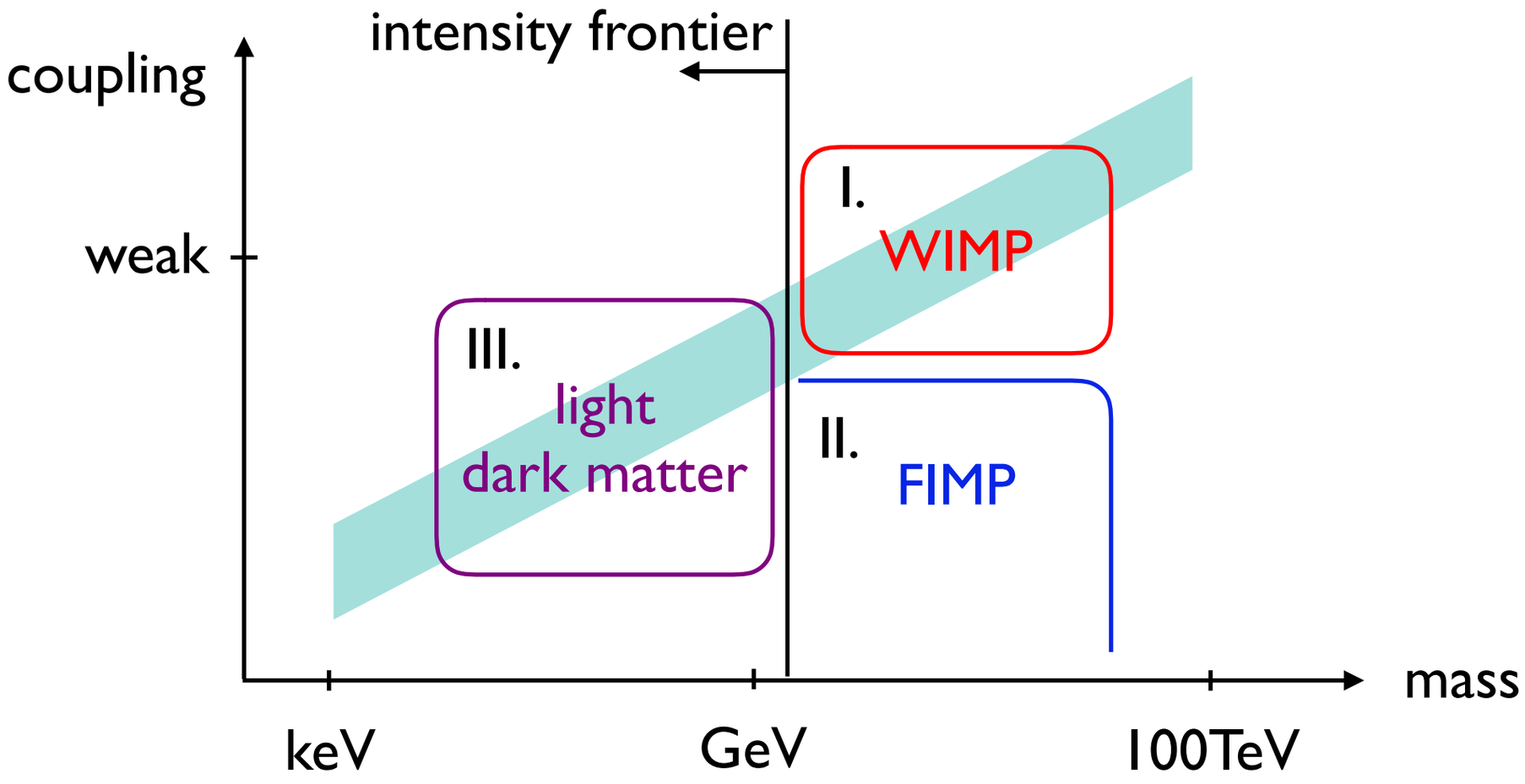


Dark matter as a thermal relic – outline



I. Searches for WIMPs

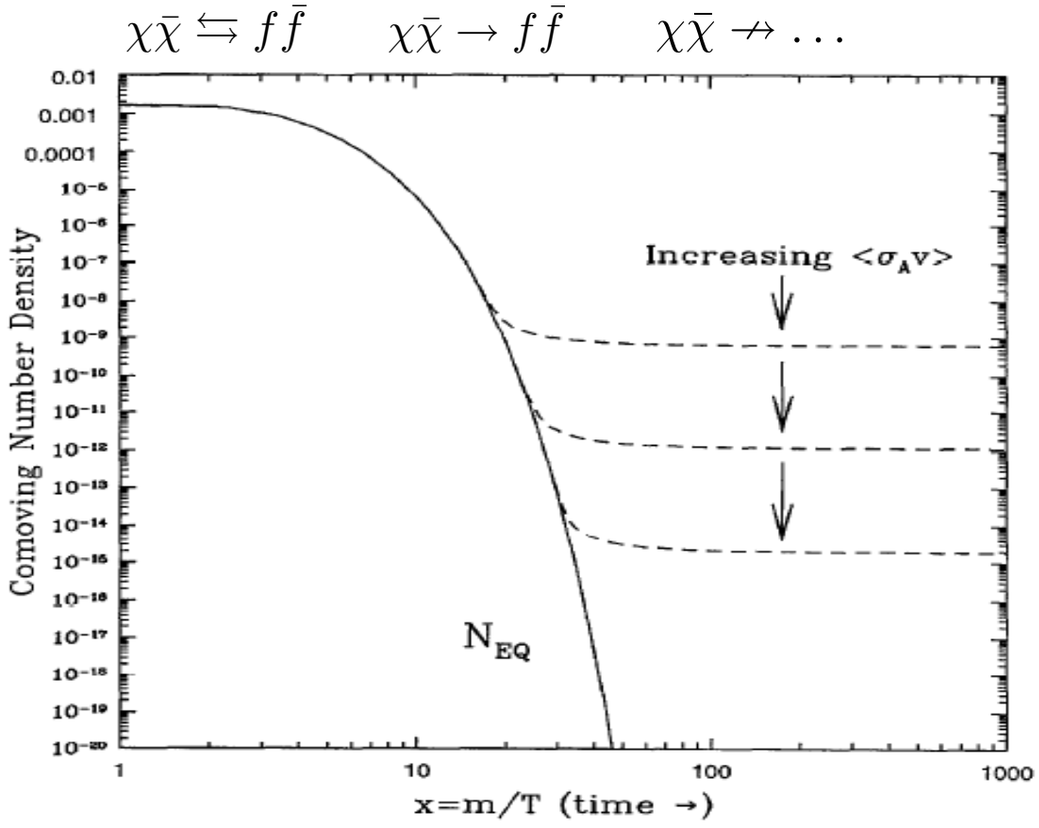
Weakly Interacting Massive Particle (WIMP)

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

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

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

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



Marco's lecture

Weakly Interacting Massive Particle (WIMP)

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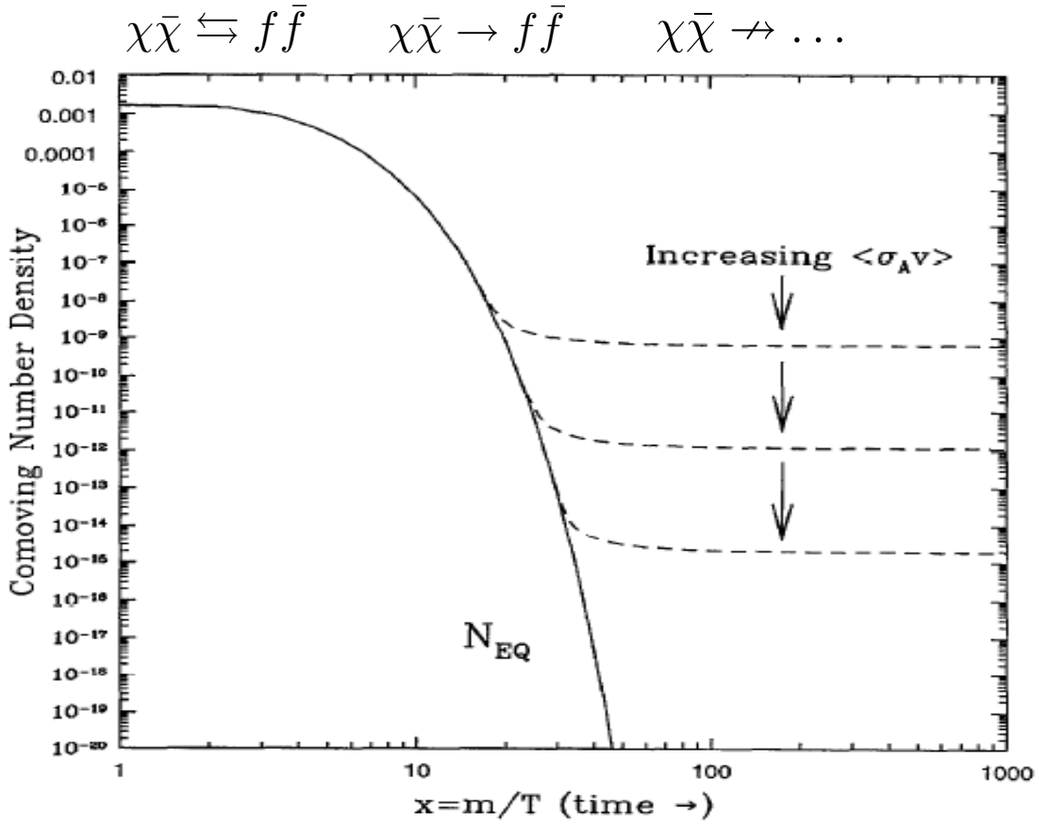
$$\Rightarrow \langle \sigma_{\mathrm{ann}} v \rangle \simeq 3 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}$$

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

Nicely fulfilled by:

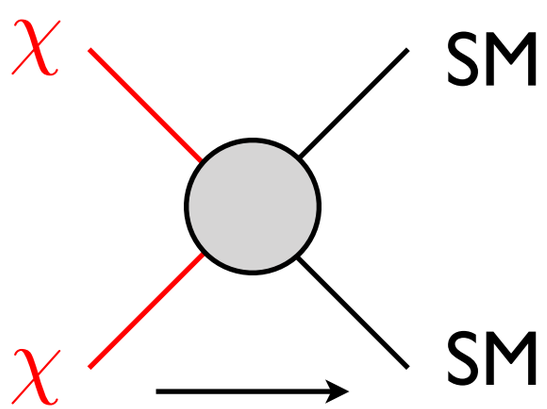
- weak-scale (toTeV) mass
- weak coupling strength



Marco's lecture

WIMP dark matter searches

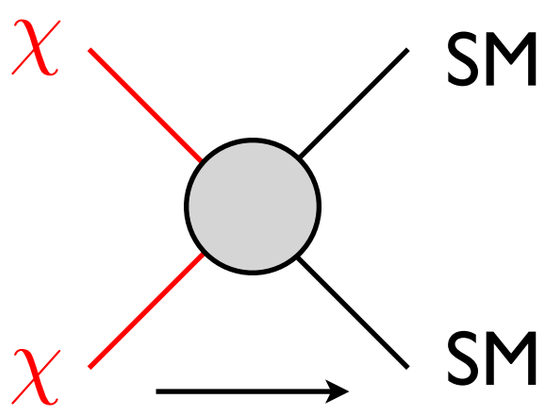
Indirect detection



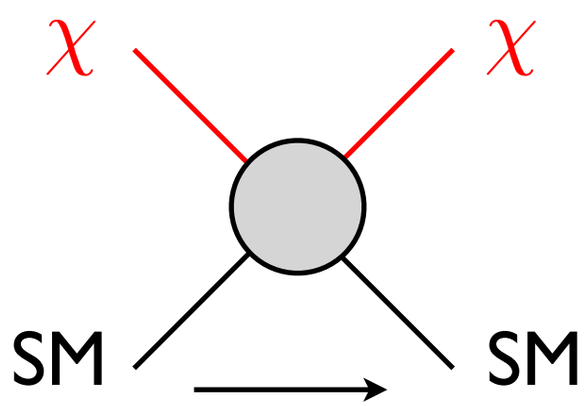
Elisa's lecture

WIMP dark matter searches

Indirect detection



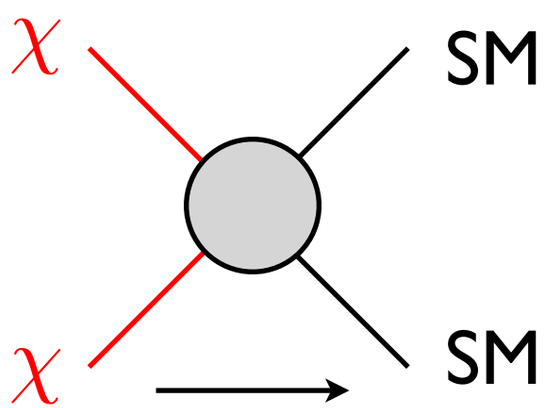
Direct detection



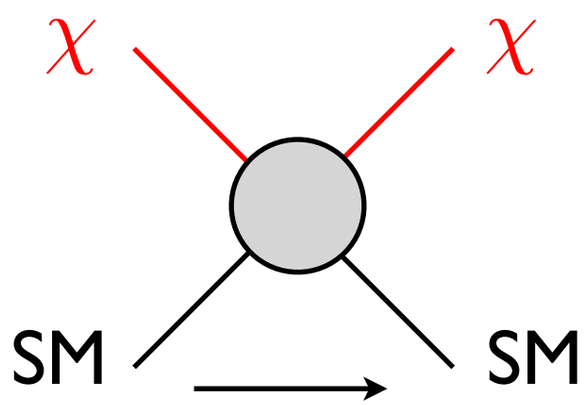
Belina's lecture

WIMP dark matter searches

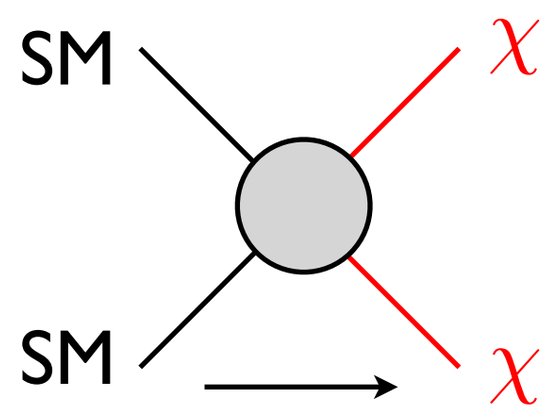
Indirect detection



Direct detection



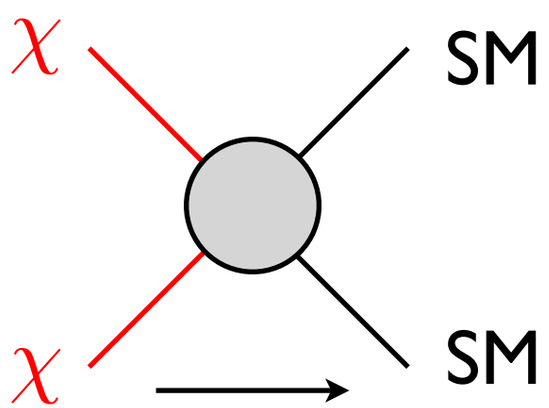
Production



This lecture

WIMP dark matter searches

Indirect detection



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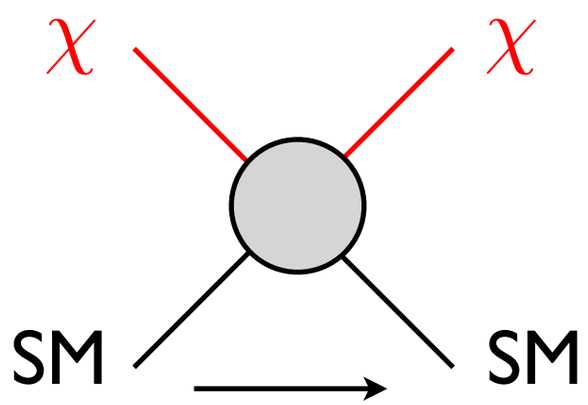

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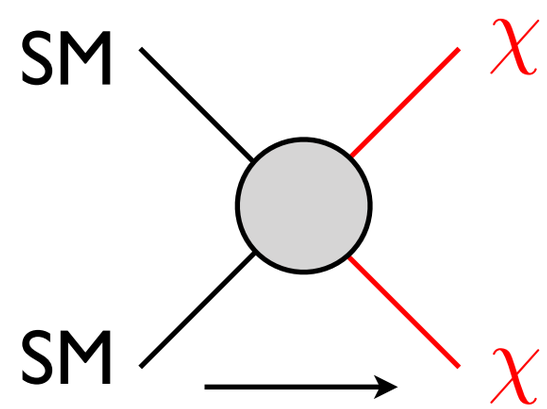
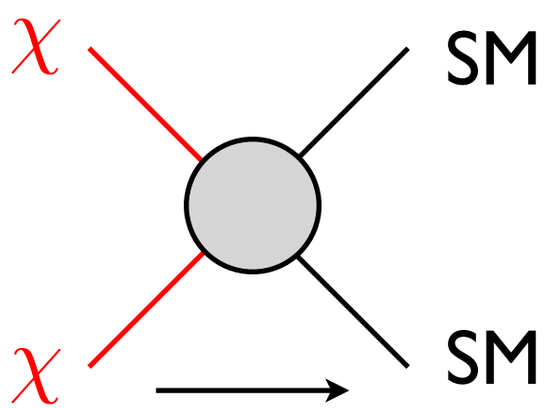


Amount of DM in probed environments

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

WIMP dark matter searches

Indirect detection



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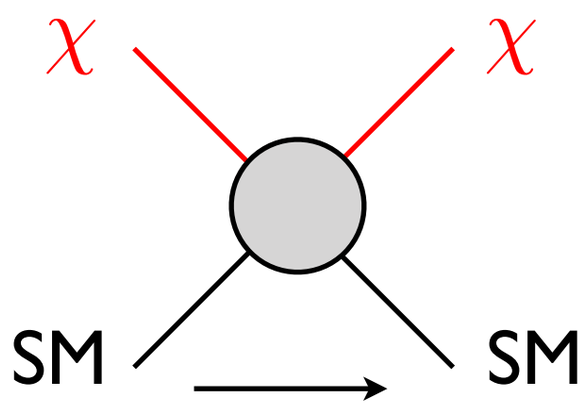

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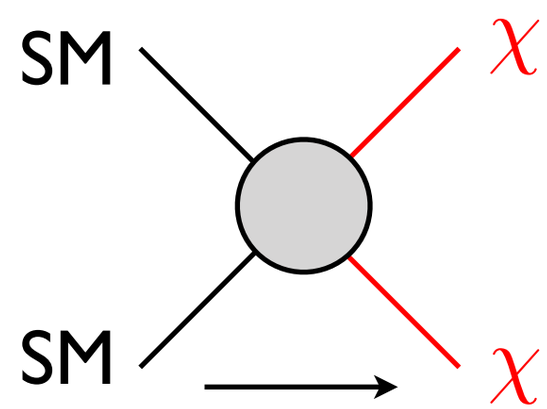


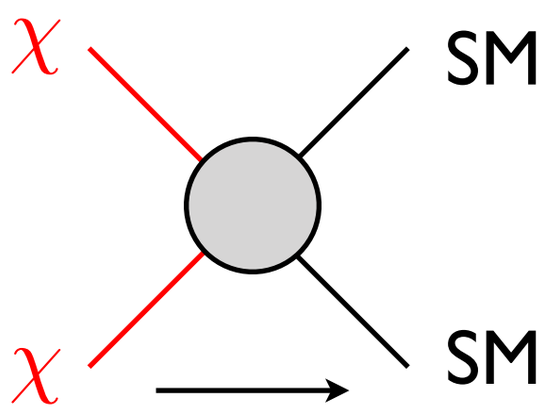
Amount of DM in probed environments

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

Independent test

WIMP dark matter searches

Indirect detection



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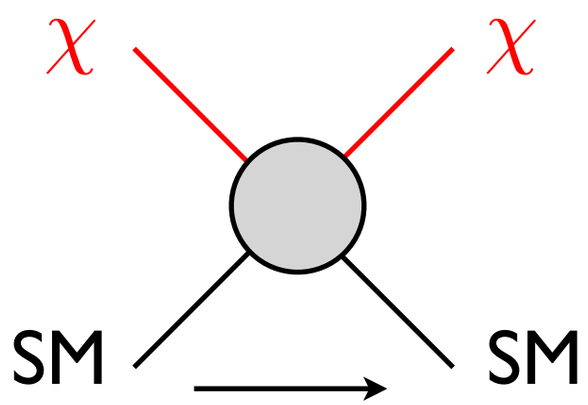

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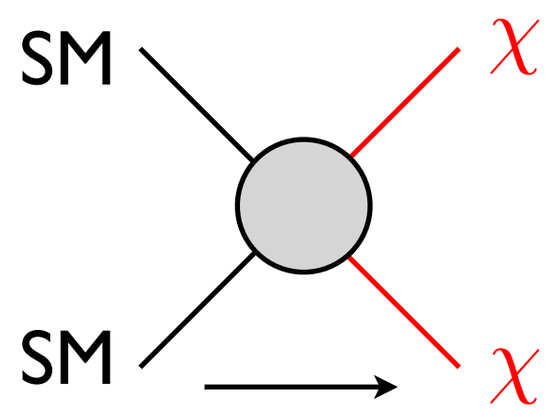

Amount of DM in probed environments

Independent test

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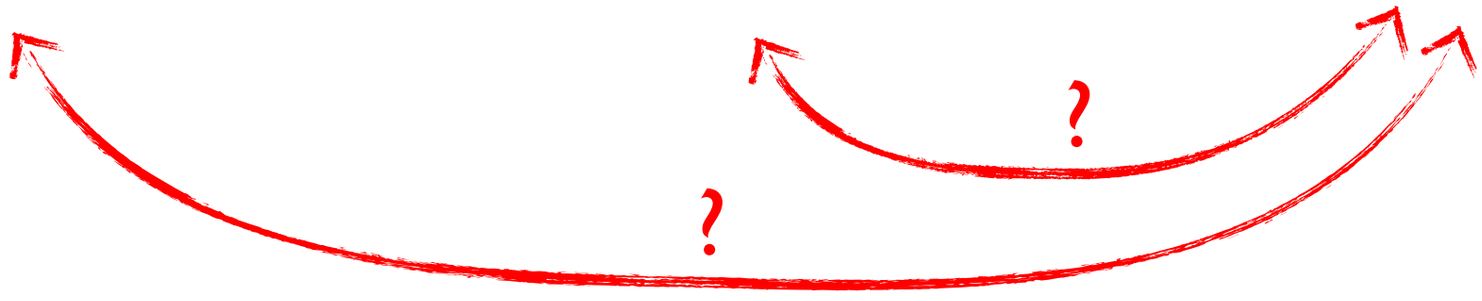
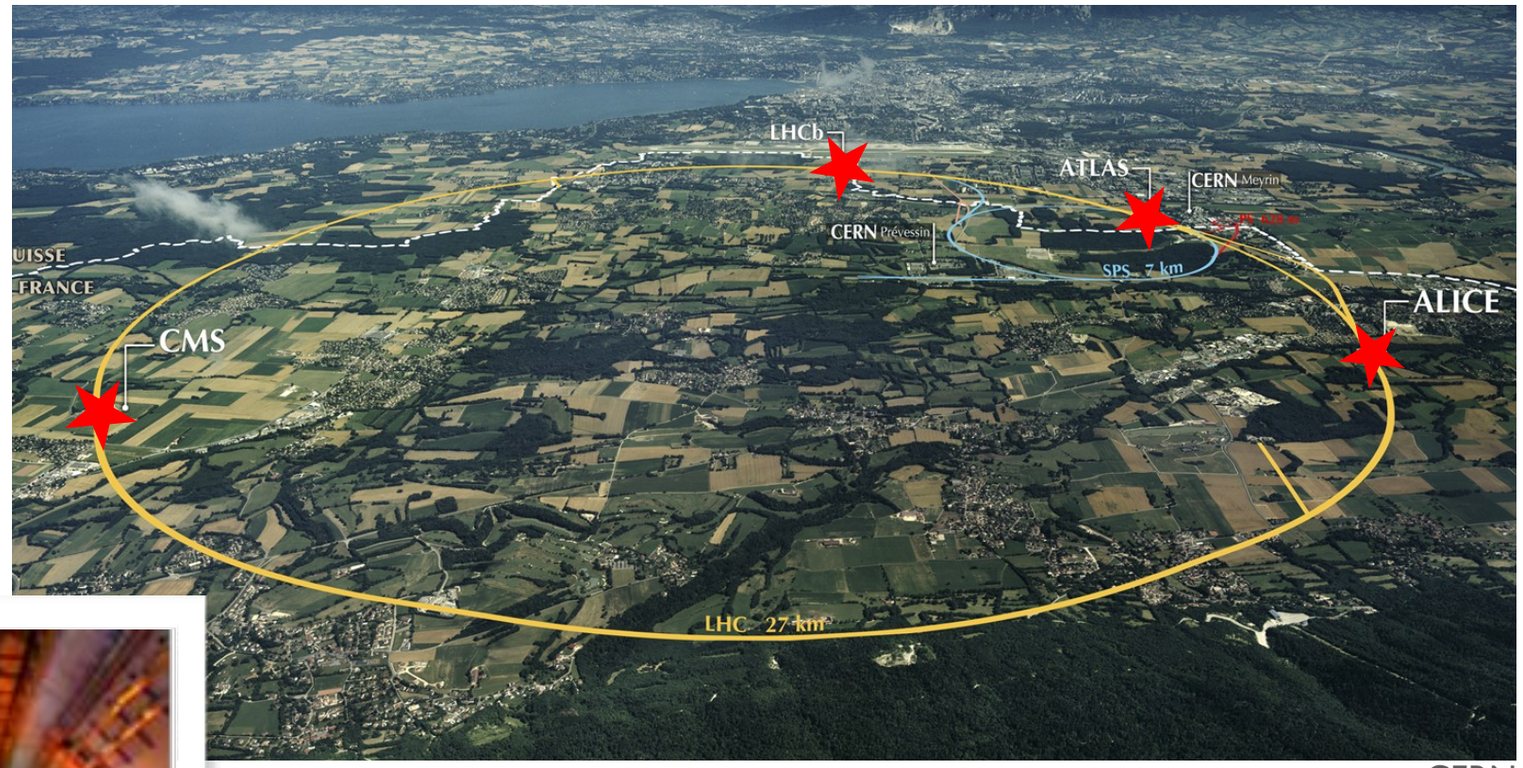


Large Hadron Collider (LHC)

Proton-proton collisions
at 13.6 TeV CM energy



CERN

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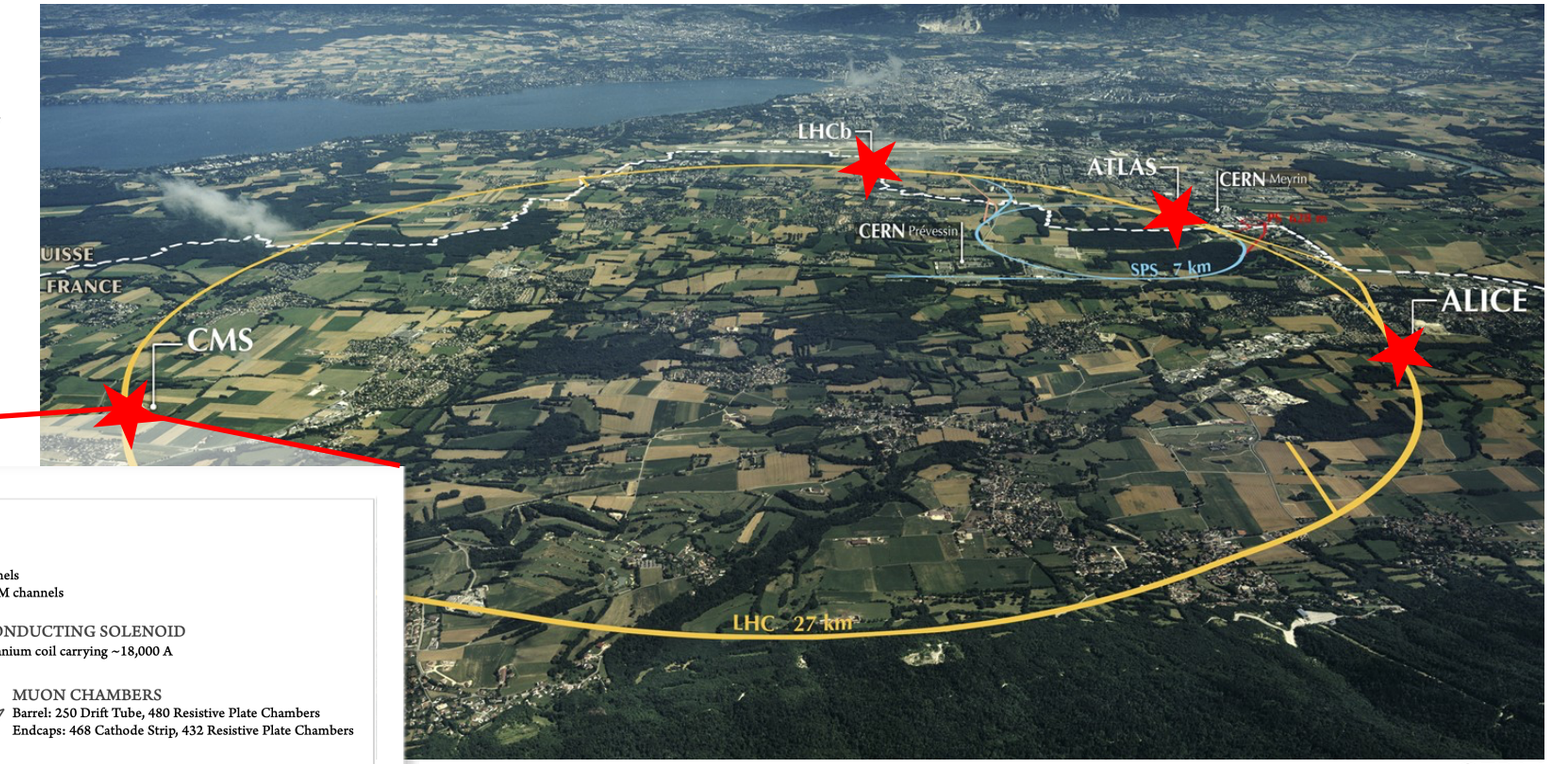

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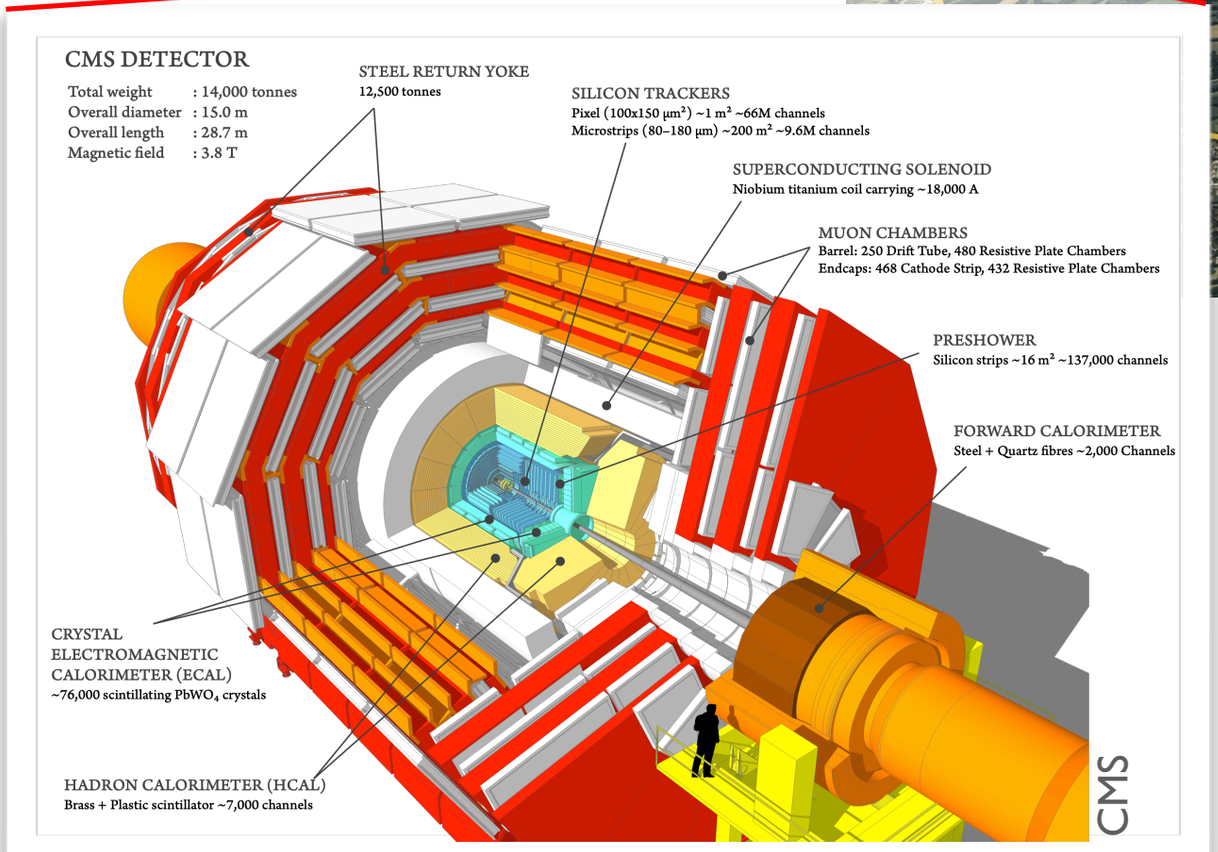

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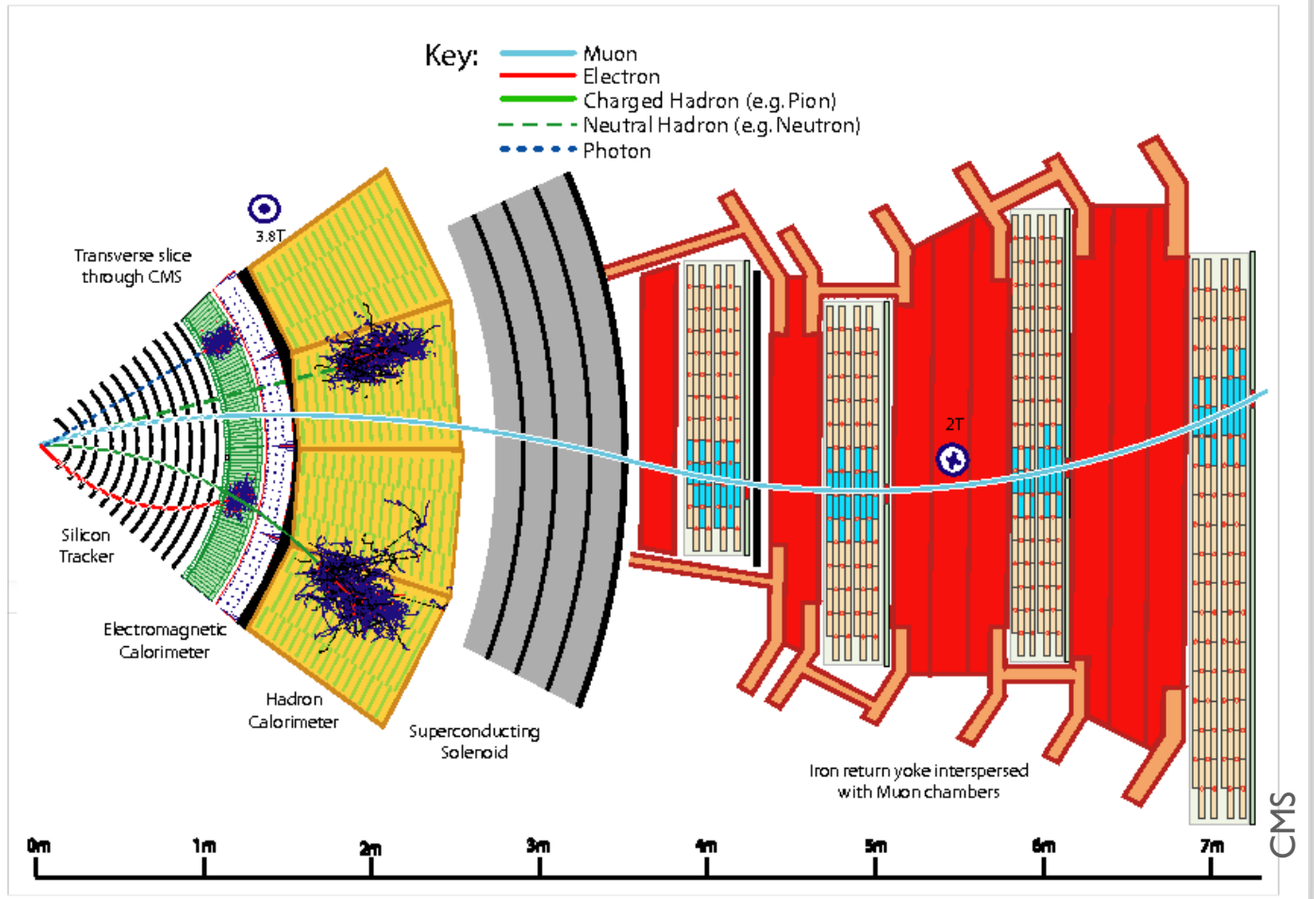
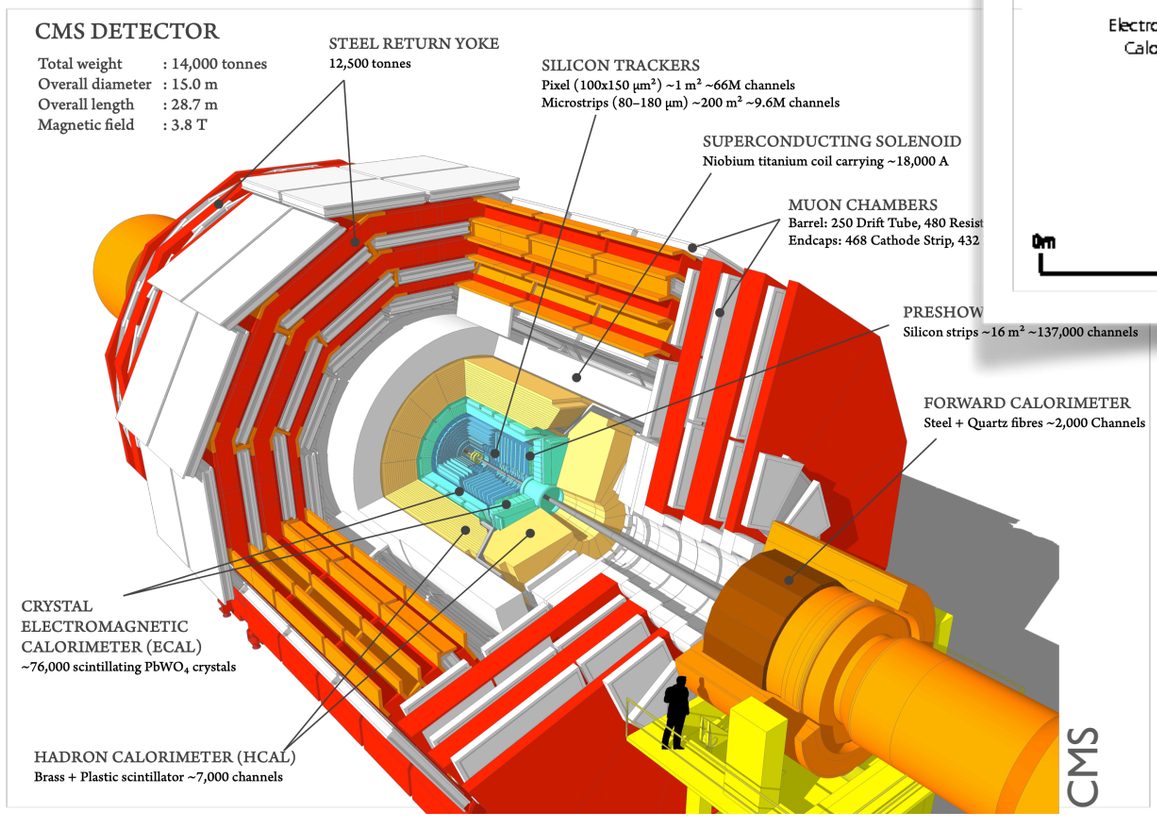


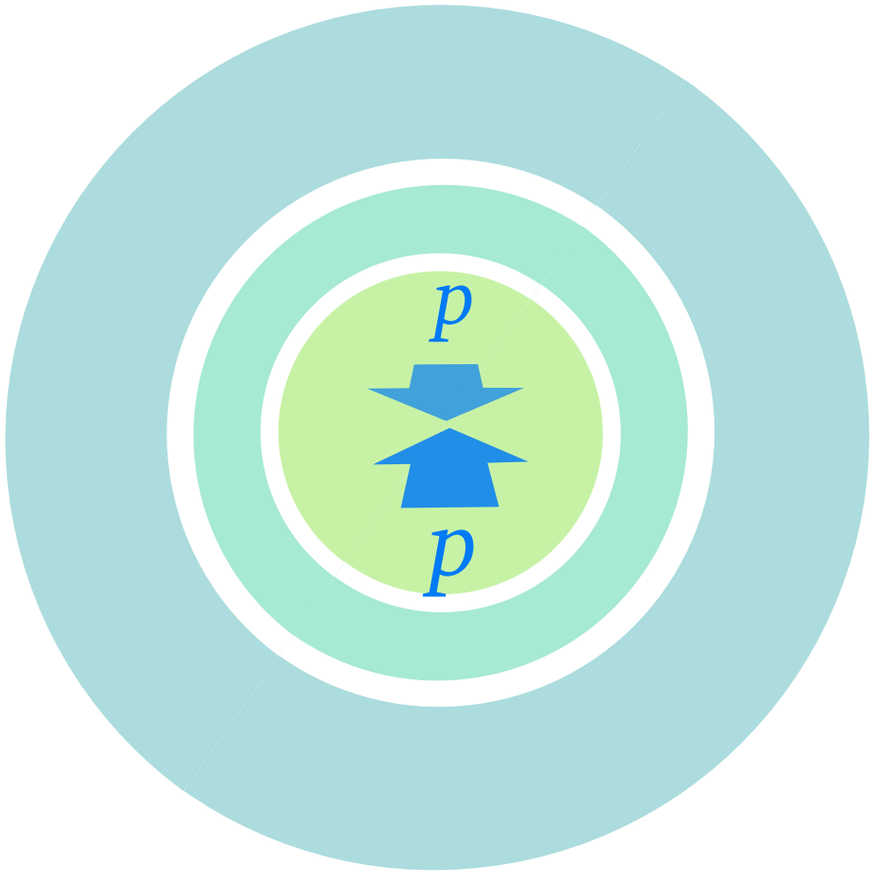


WIMPs at the LHC

schematic detector
head-on view:

WIMPs at the LHC

schematic detector
head-on view:



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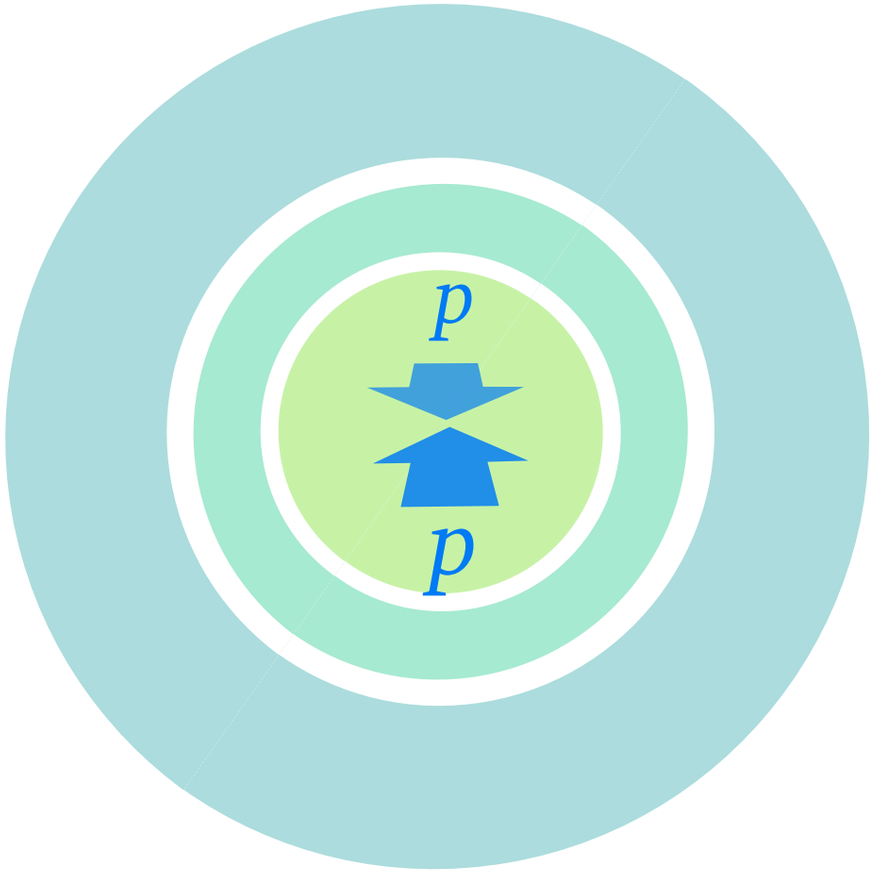
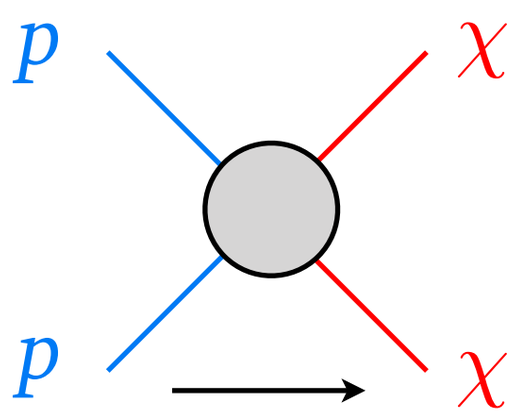


DM production



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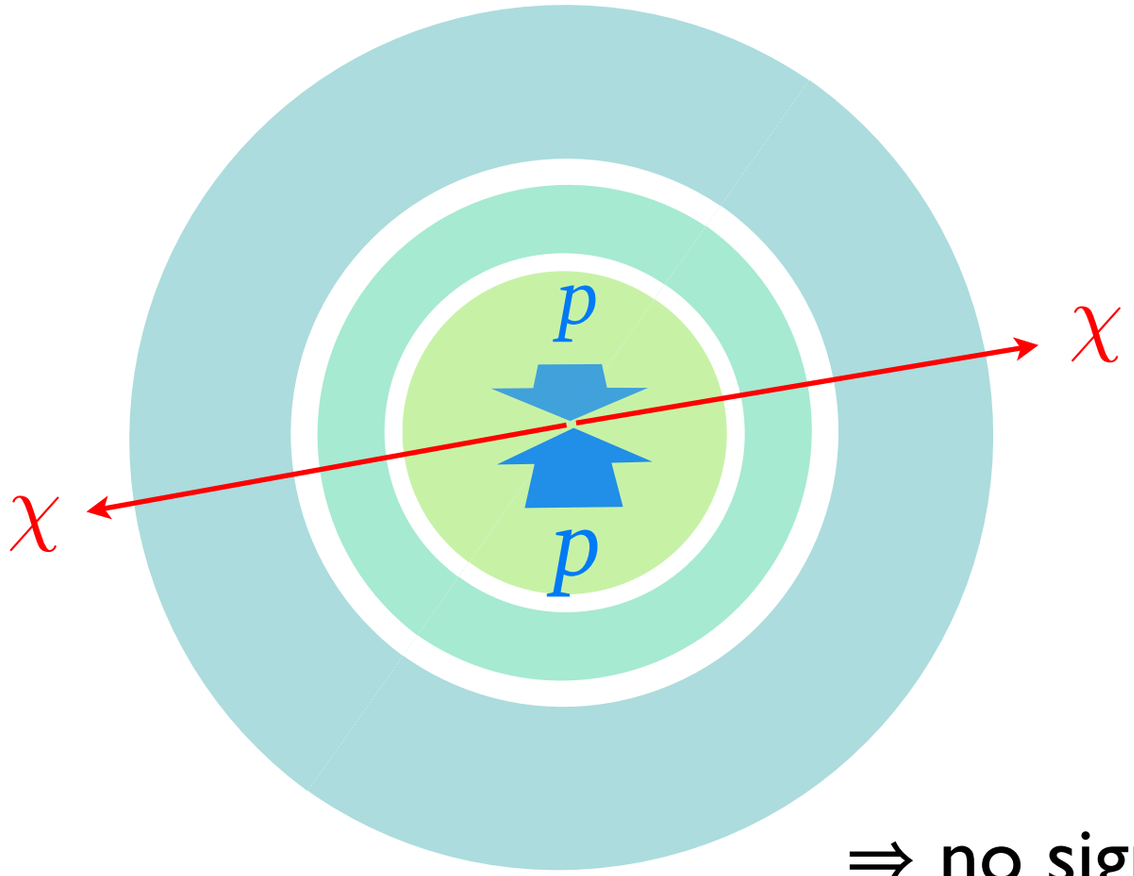

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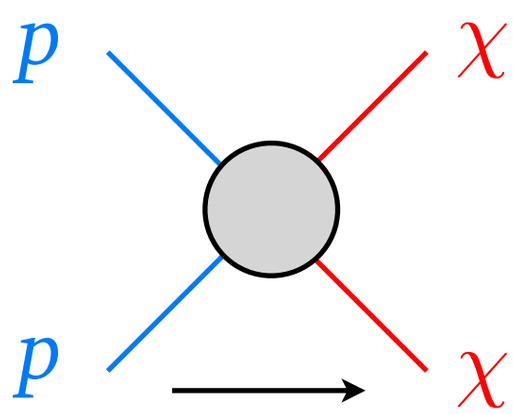

⇒ no signal

WIMPs at the LHC

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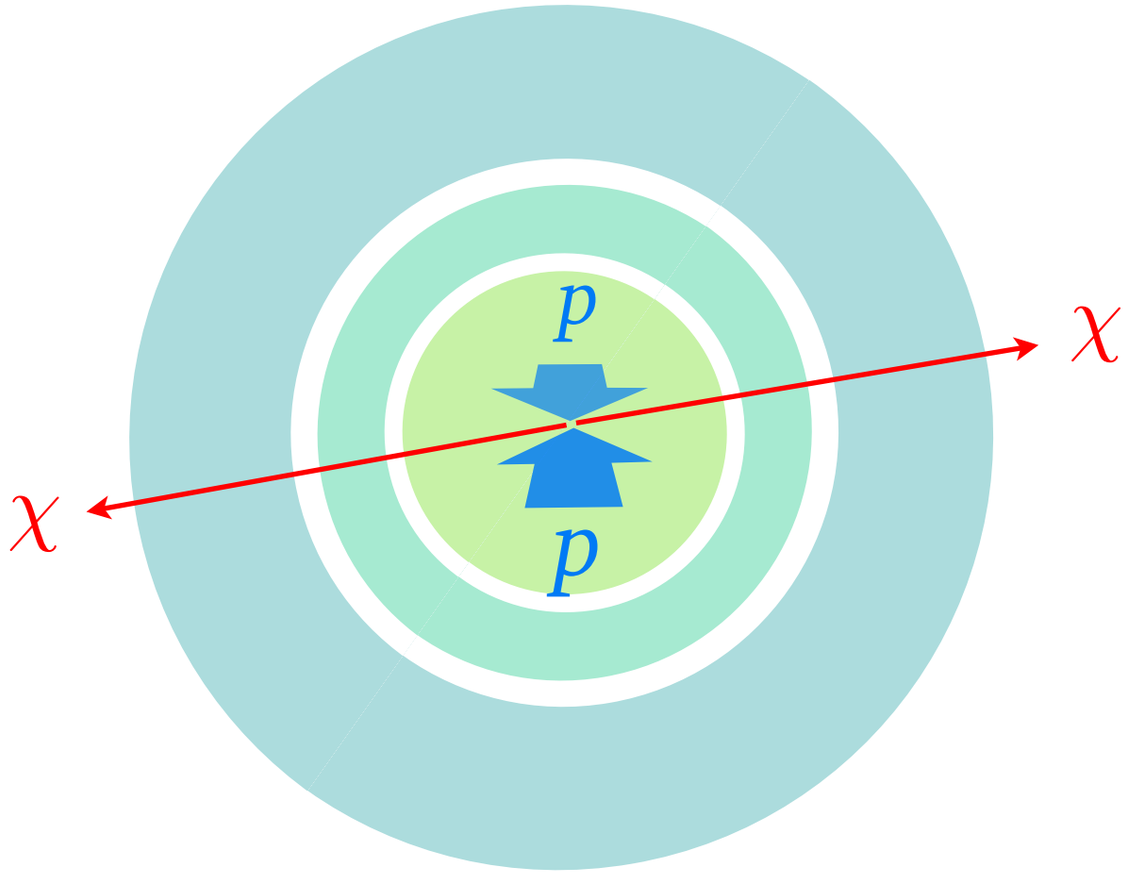
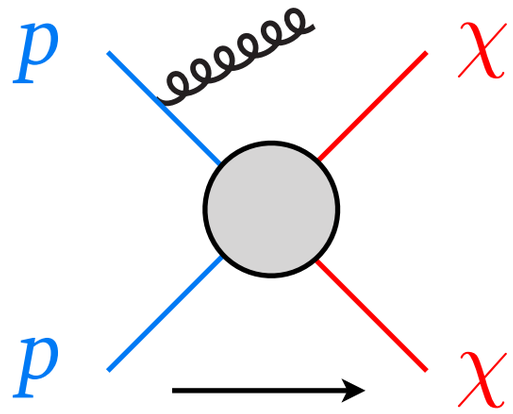


DM production

+ initial state radiation (ISR)



WIMPs at the LHC

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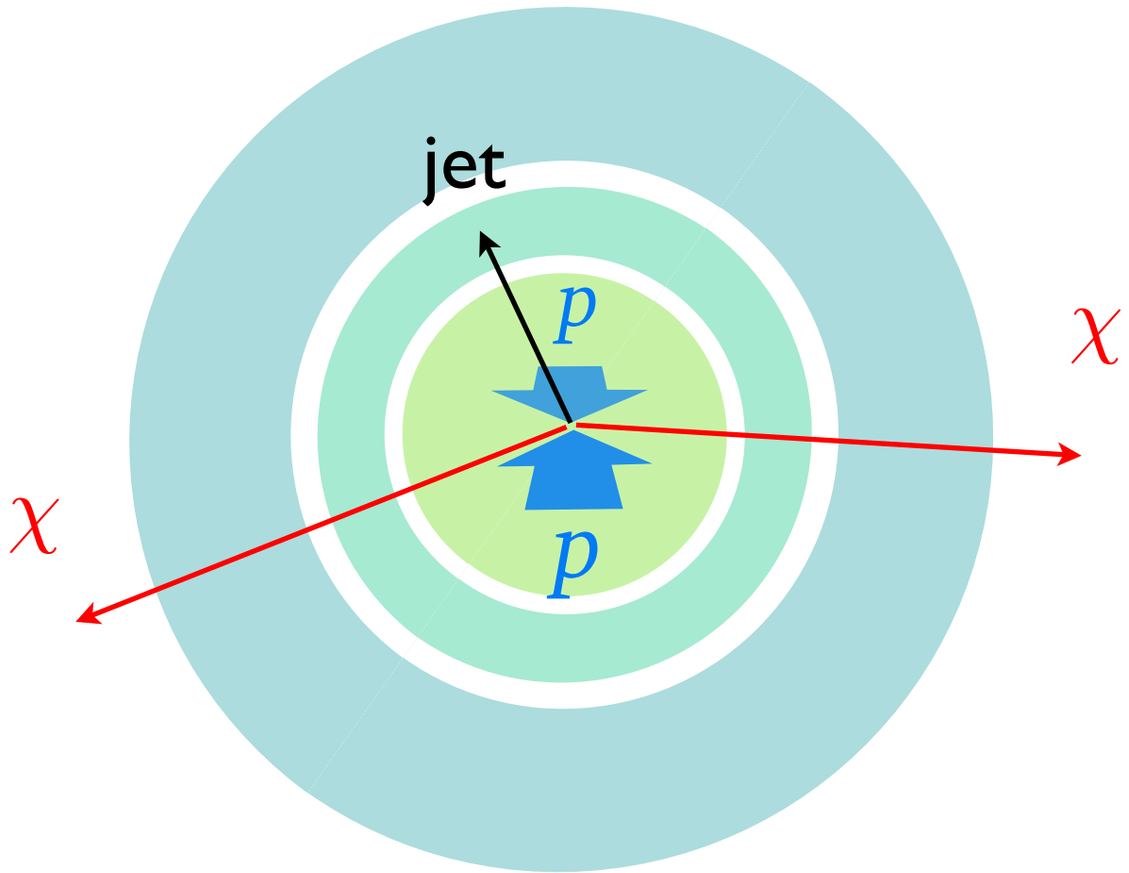

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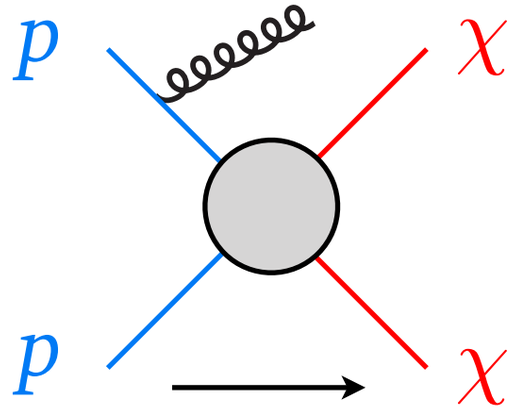

WIMPs at the LHC

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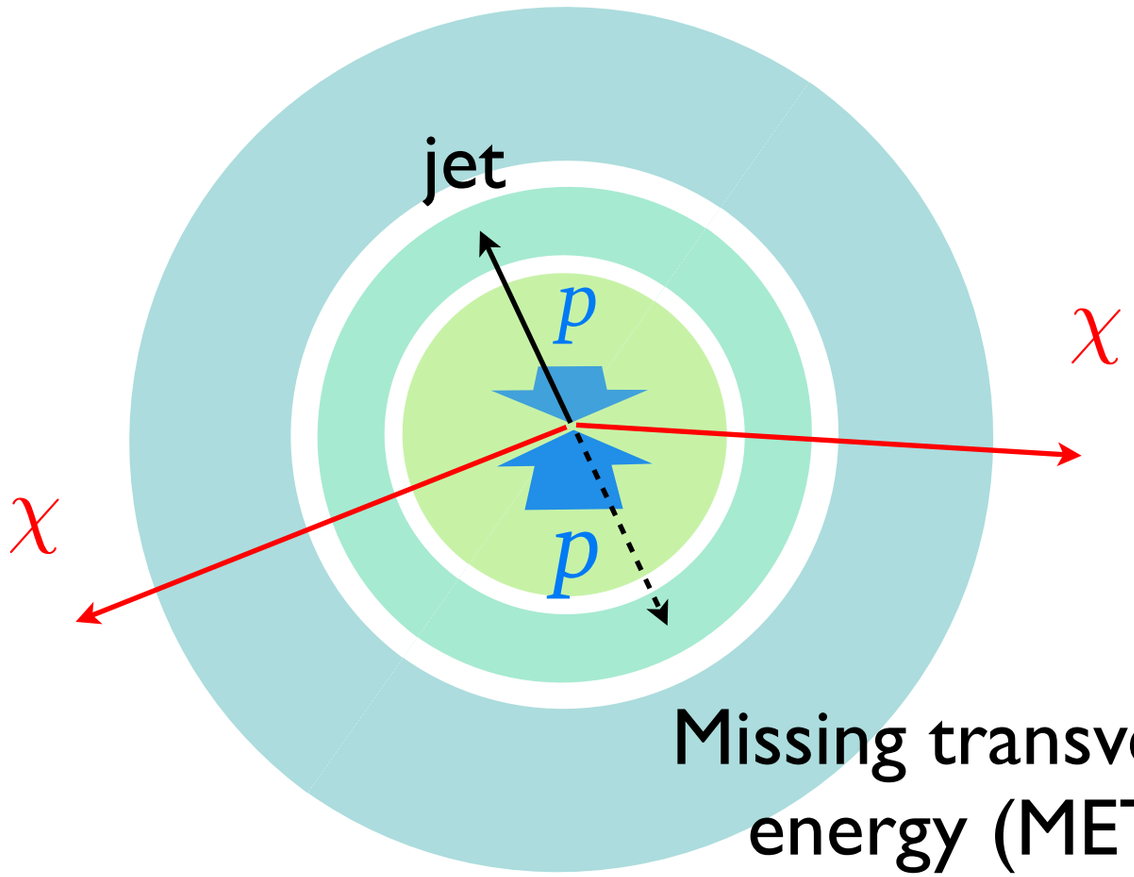
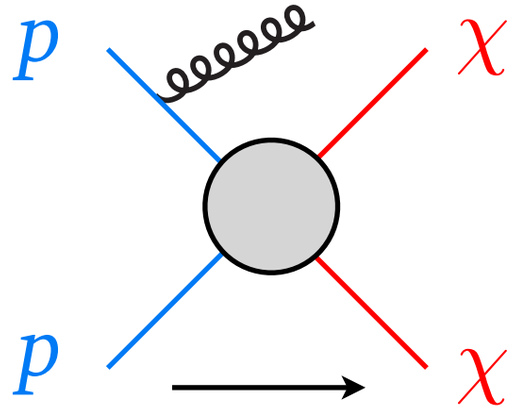


Missing transverse
energy (MET)

DM production
+ initial state radiation (ISR)



WIMPs at the LHC

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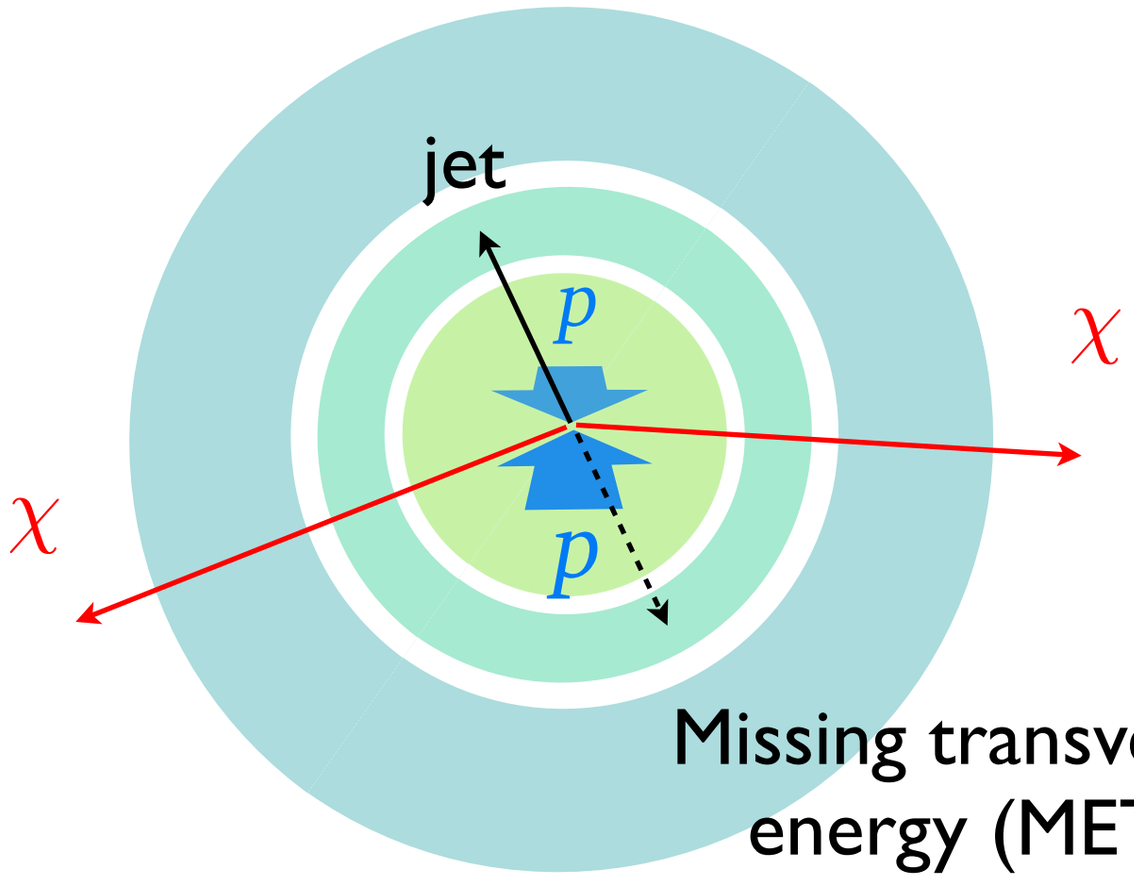

DM production
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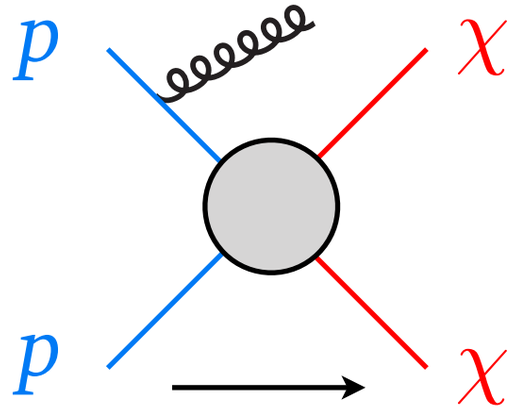


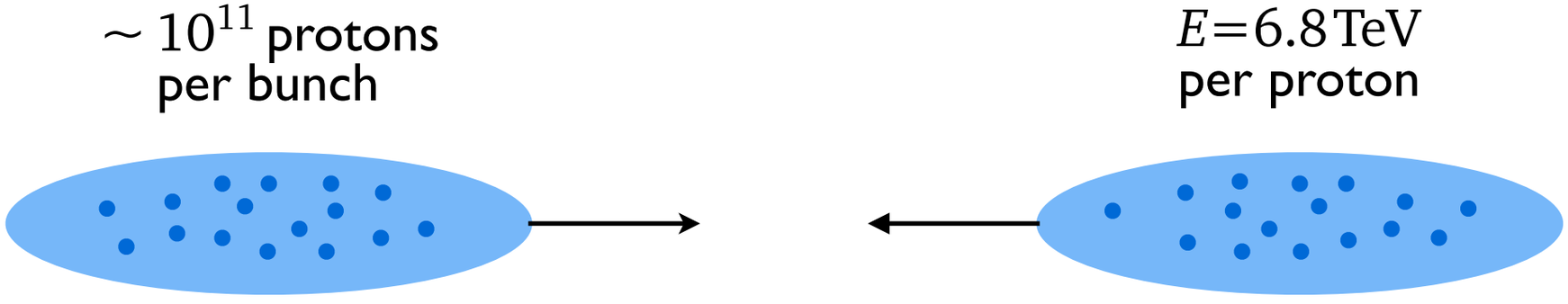
Missing transverse
energy (MET)

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

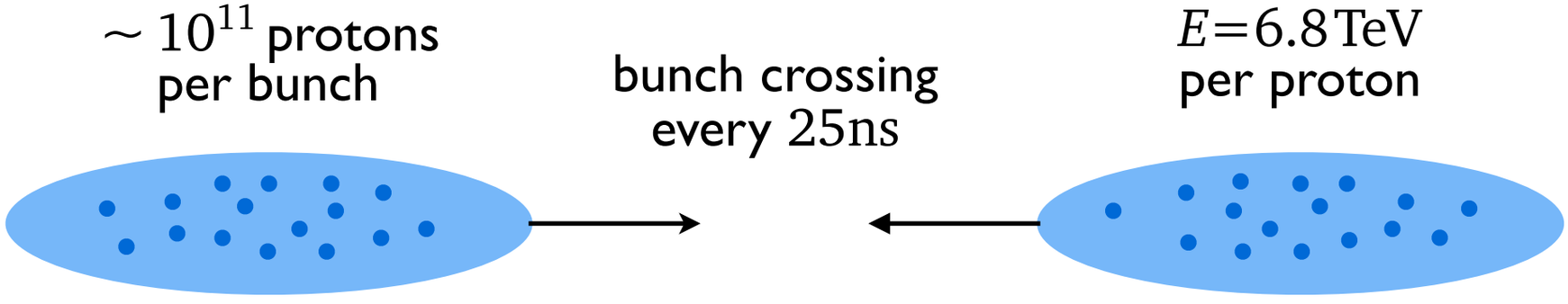
Proton collisions at the LHC

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

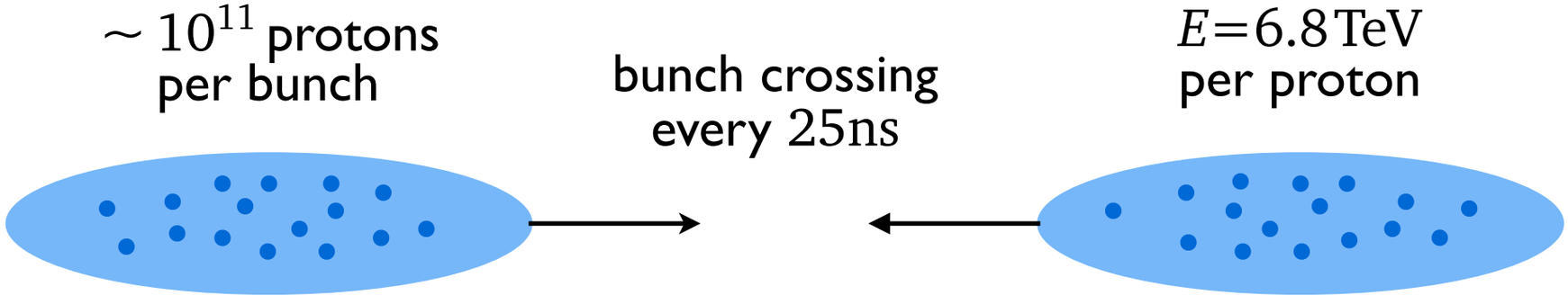
Proton collisions at the LHC



Proton collisions at the LHC

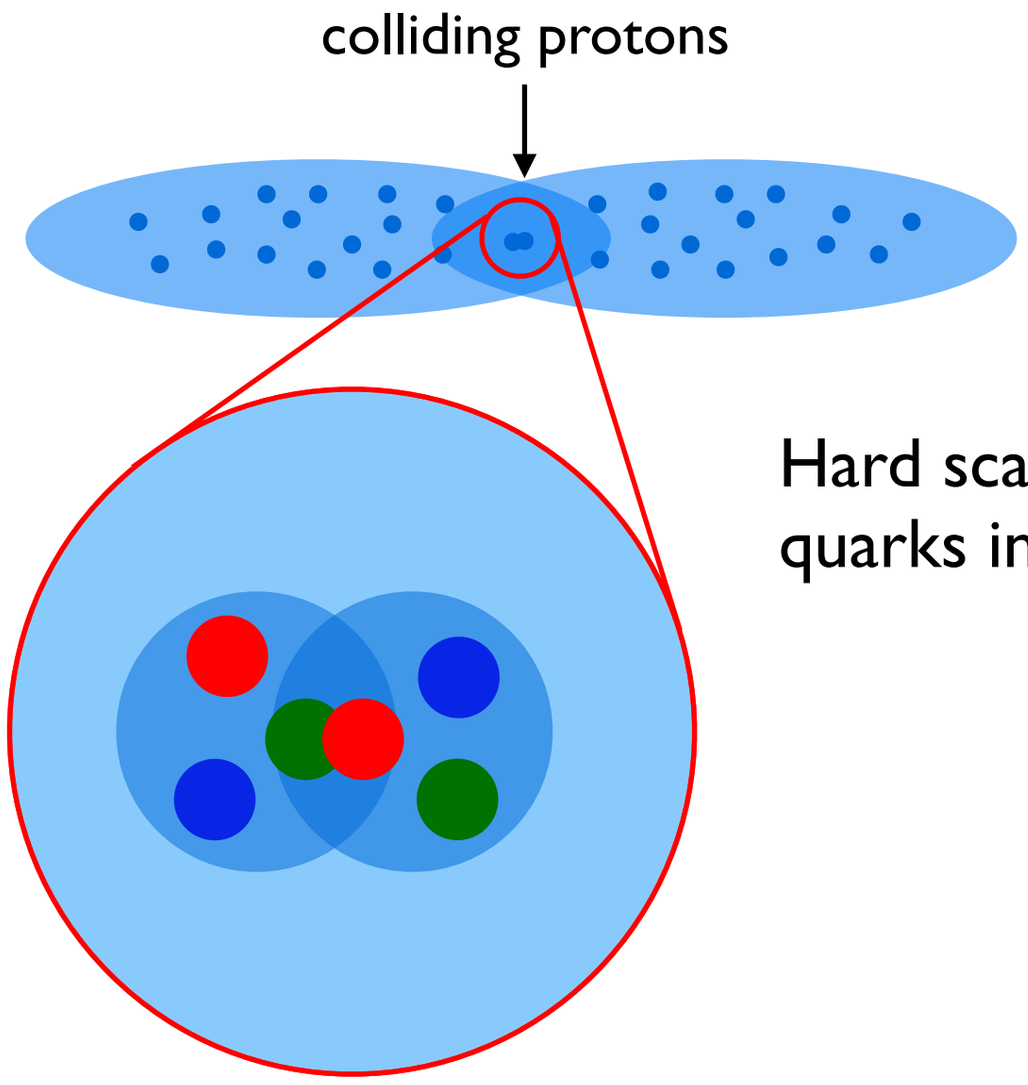


Proton collisions at the LHC



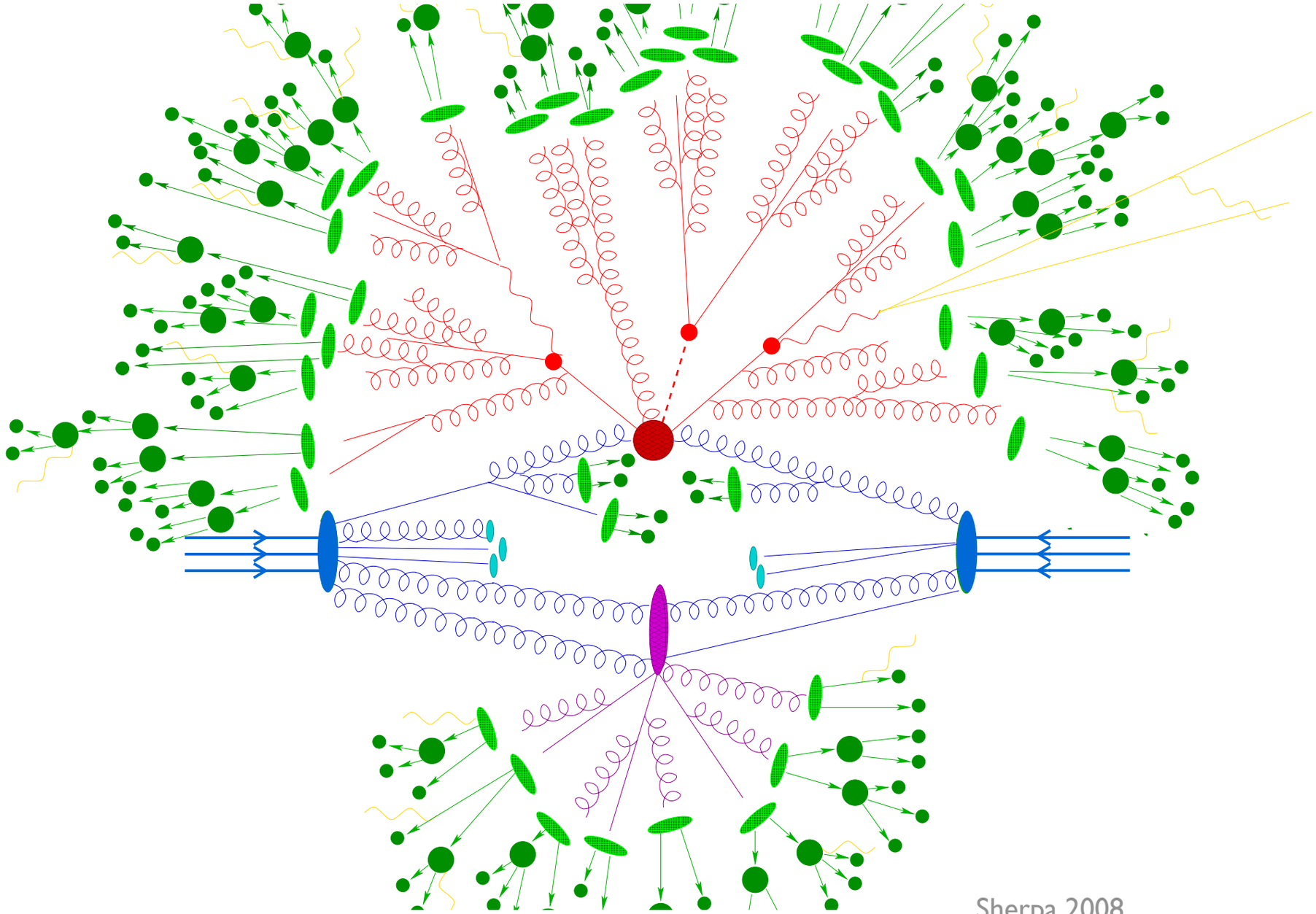
Most of the time, nothing interesting happens
$\Rightarrow$ trigger recording of events

Proton collisions at the LHC



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

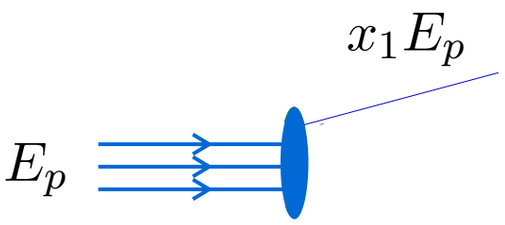
Proton collisions at the LHC

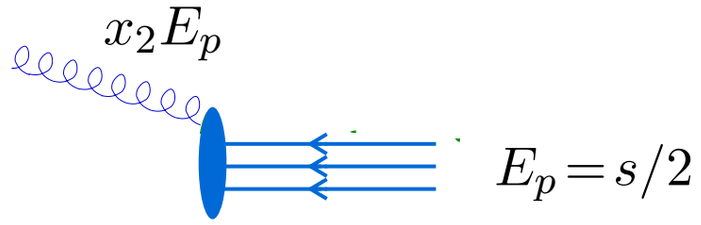


Sherpa 2008

Proton collisions at the LHC

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

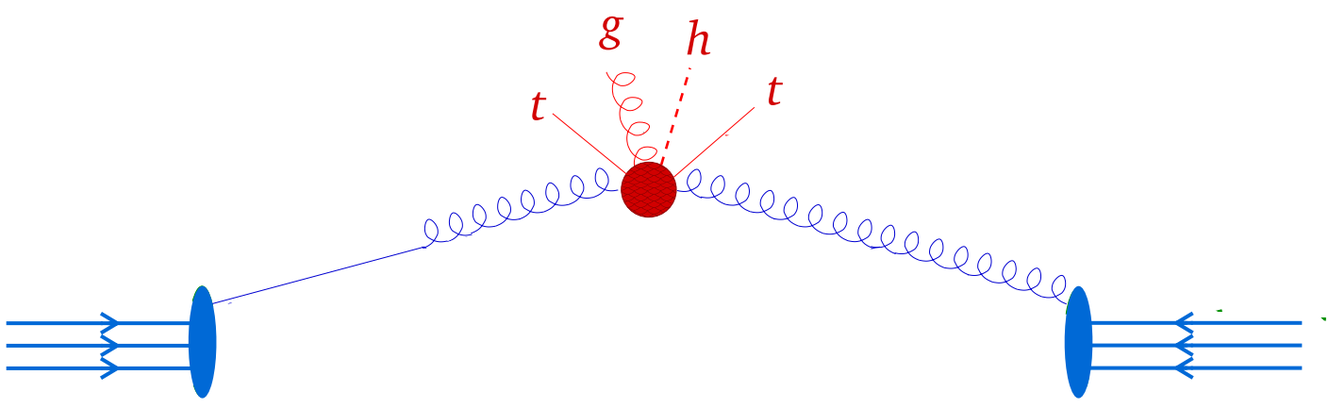




Sherpa 2008

Proton collisions at the LHC

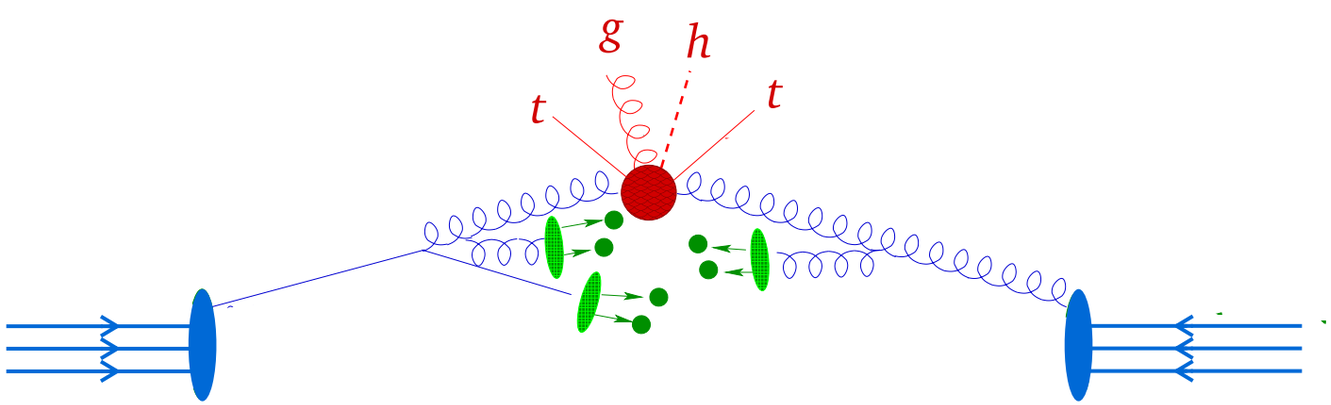
- Parton distributions
- Hard scattering



Sherpa 2008

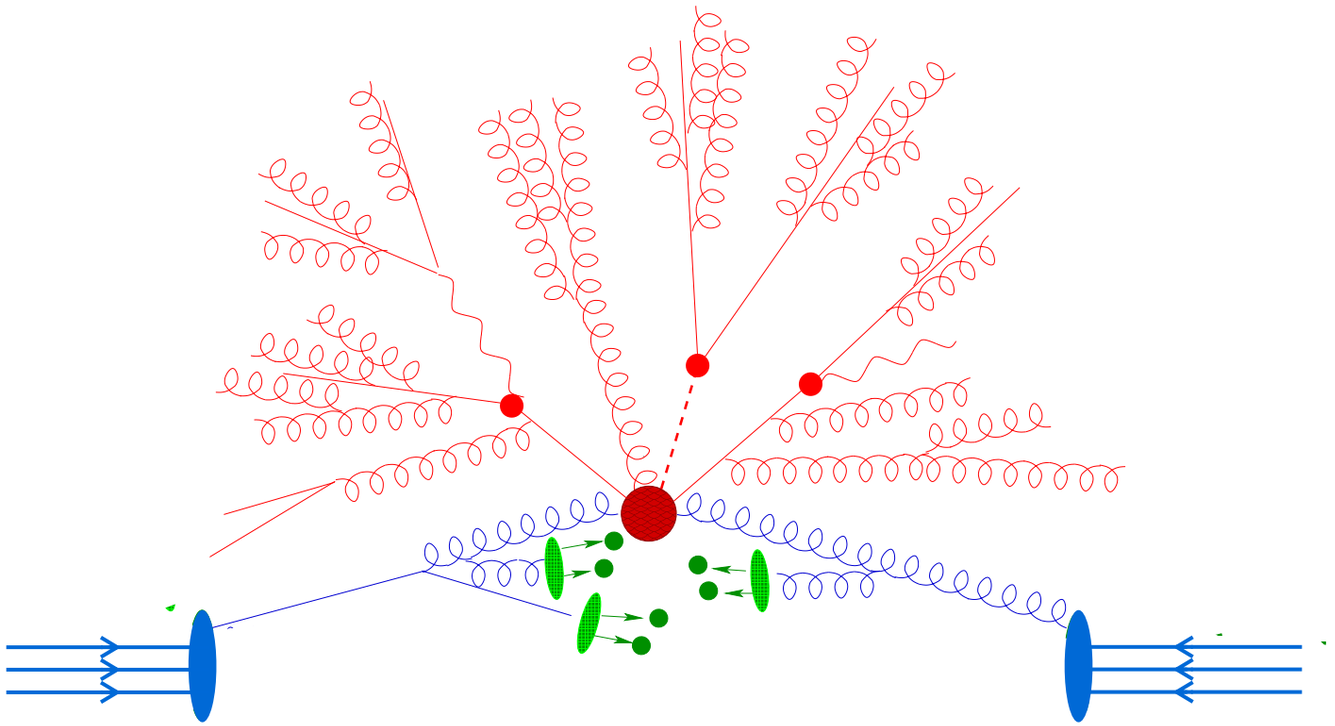
Proton collisions at the LHC

- 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

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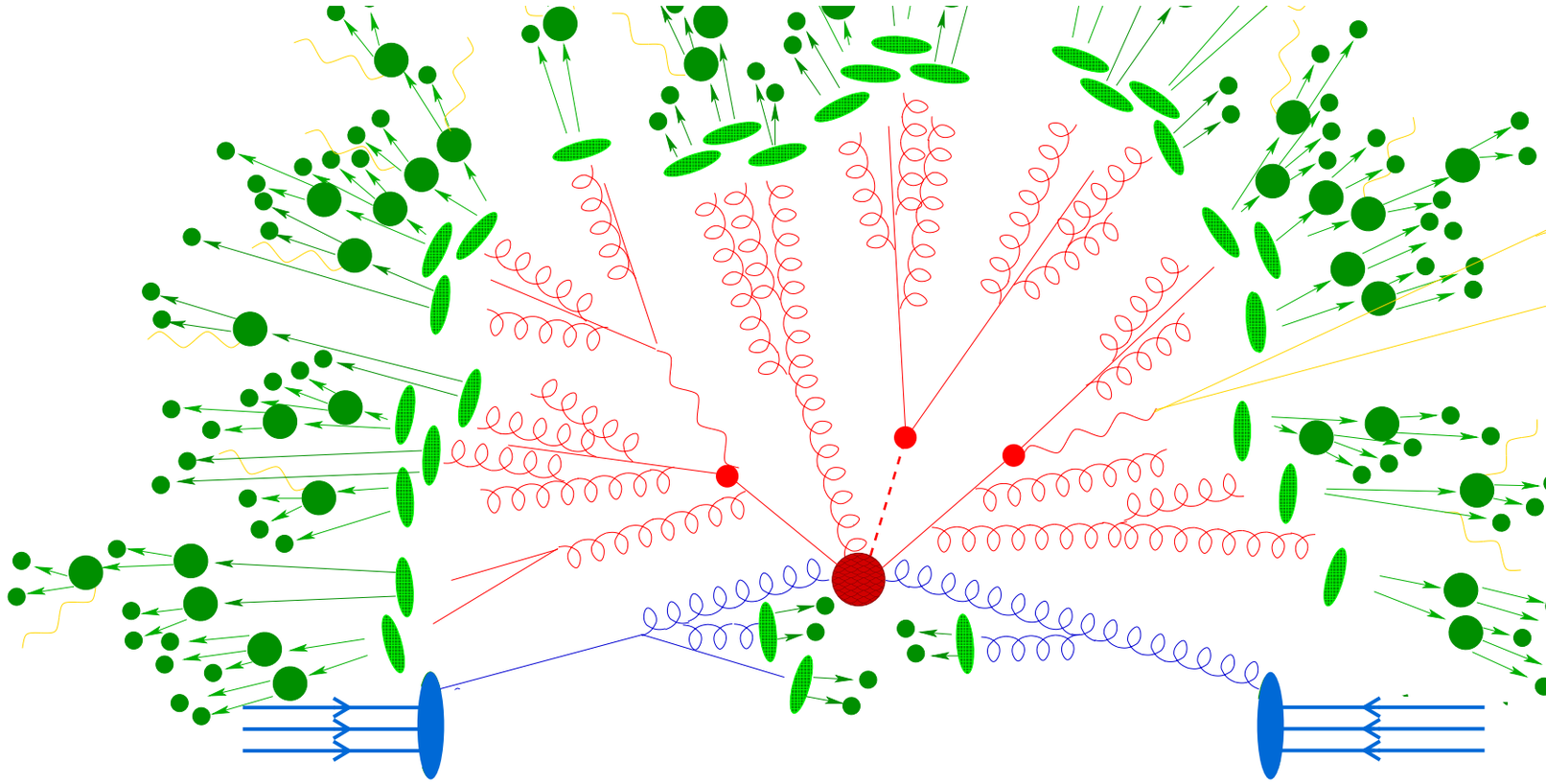

- Parton distributions
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Sherpa 2008

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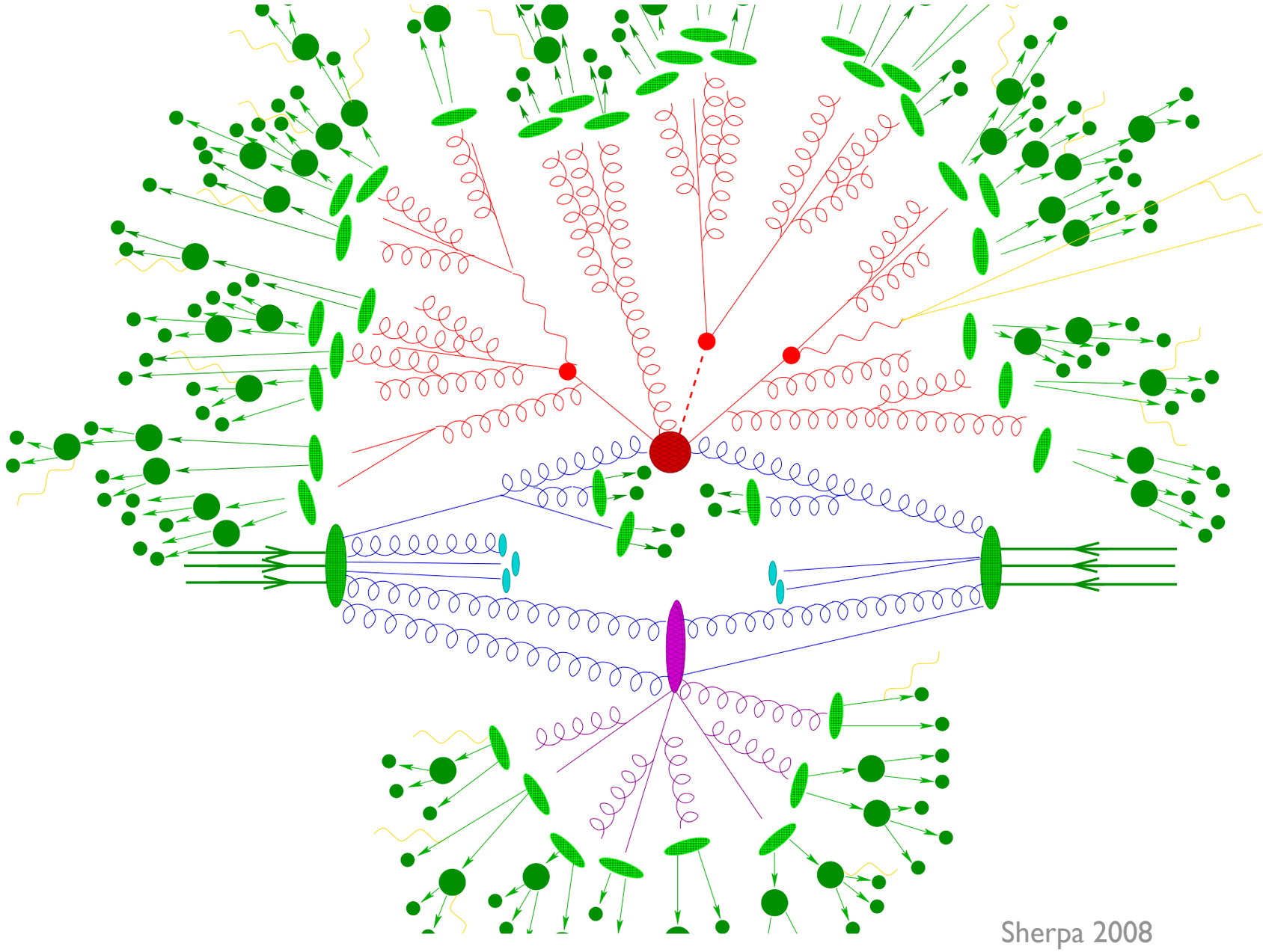

Sherpa 2008

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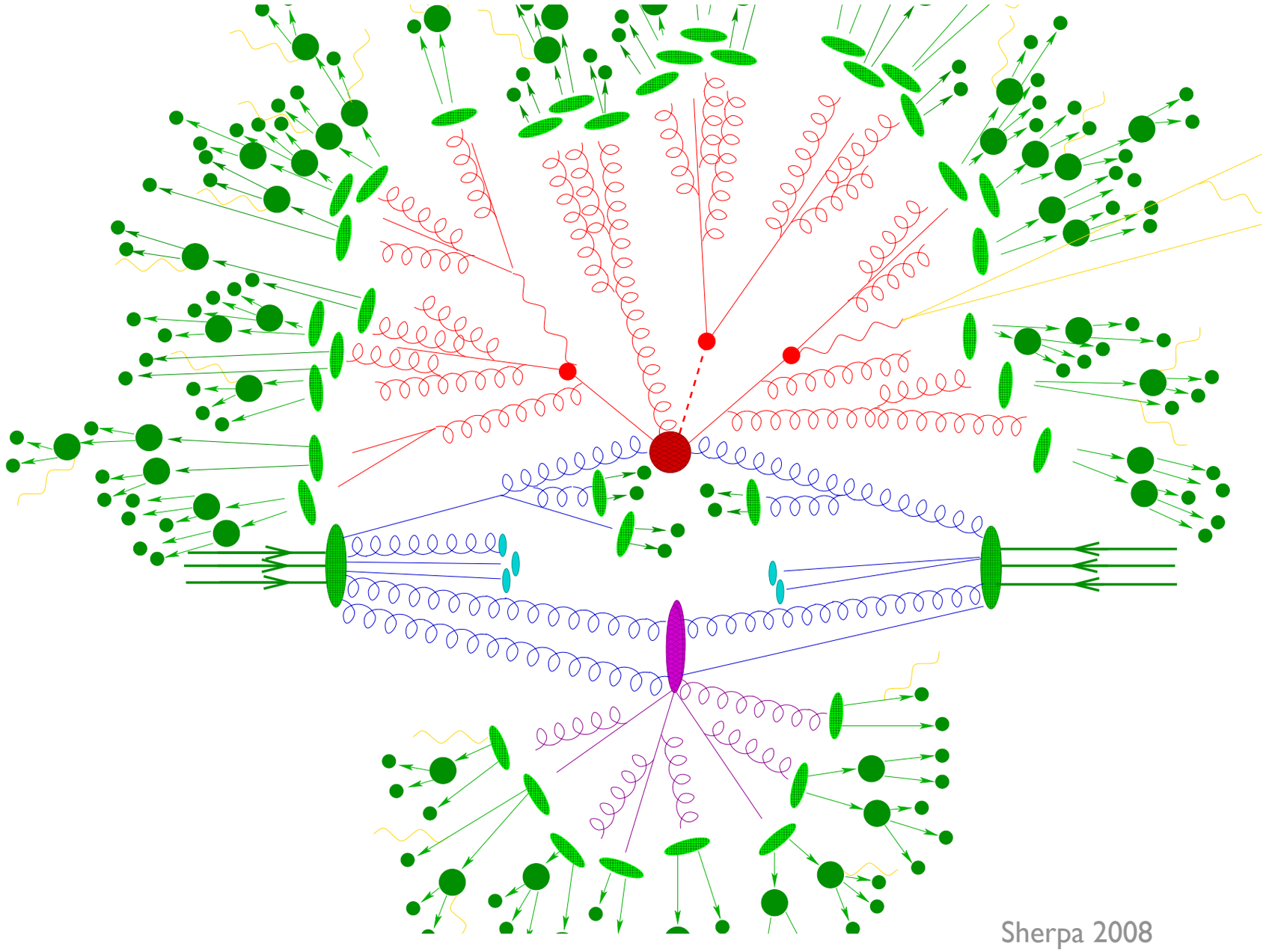
Proton collisions at the LHC



Sherpa 2008

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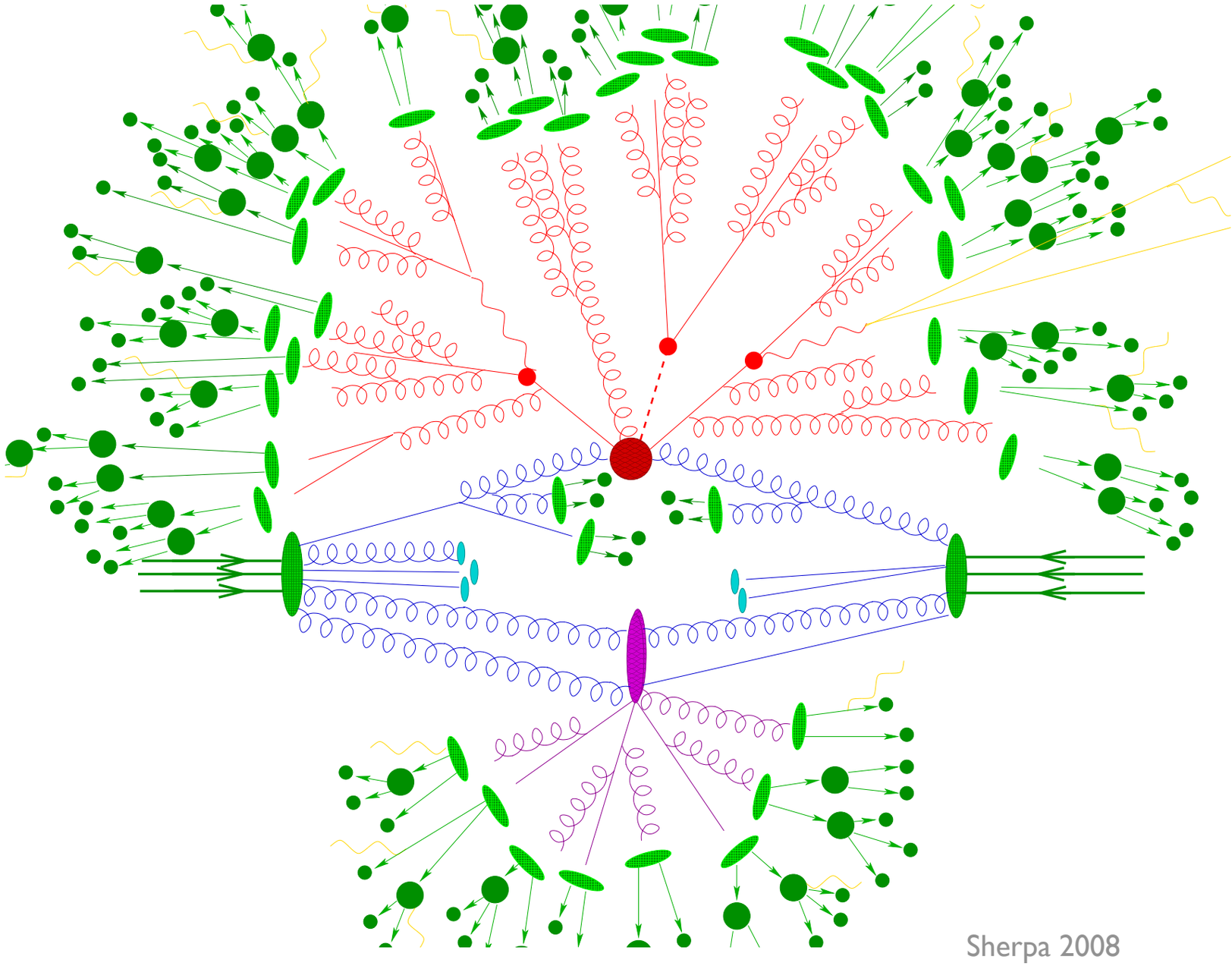
↑

Monte Carlo
event generators

Proton collisions at the LHC



Sherpa 2008

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Monte Carlo event generators:

e.g. Pythia, Herwig, Sherpa, Powheg;

MadGraph, MCFM, Whizard

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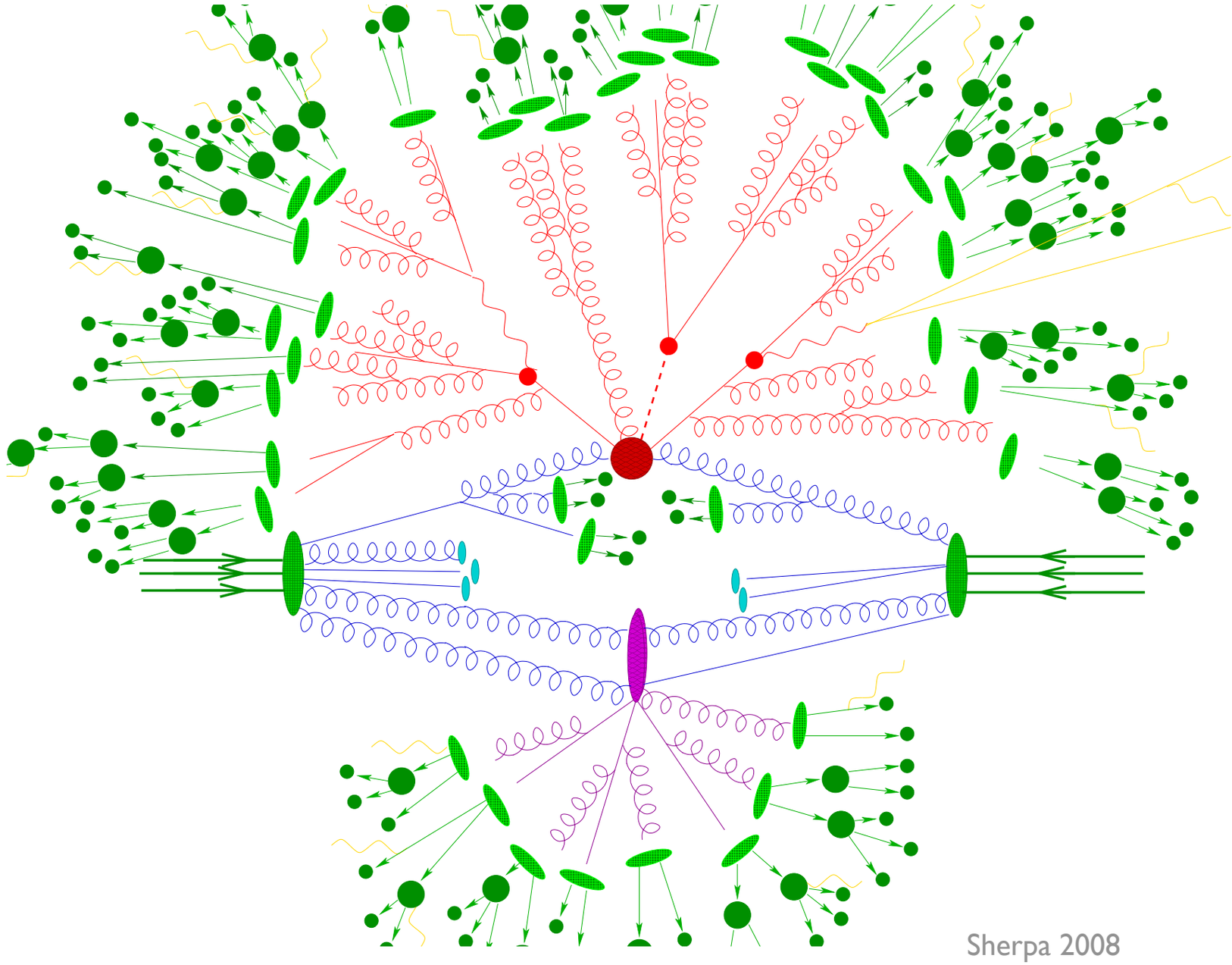

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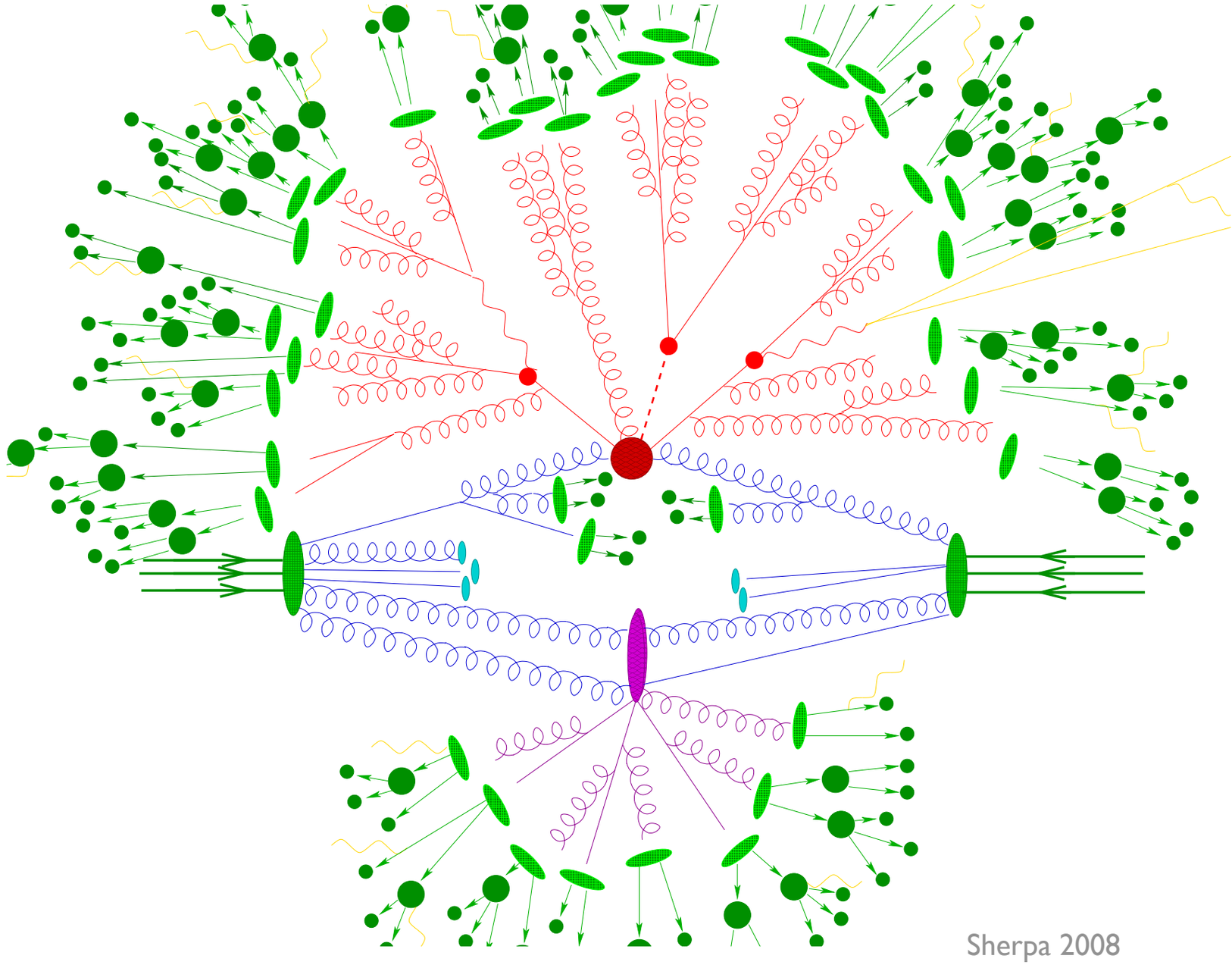

Sherpa 2008

- Parton distributions
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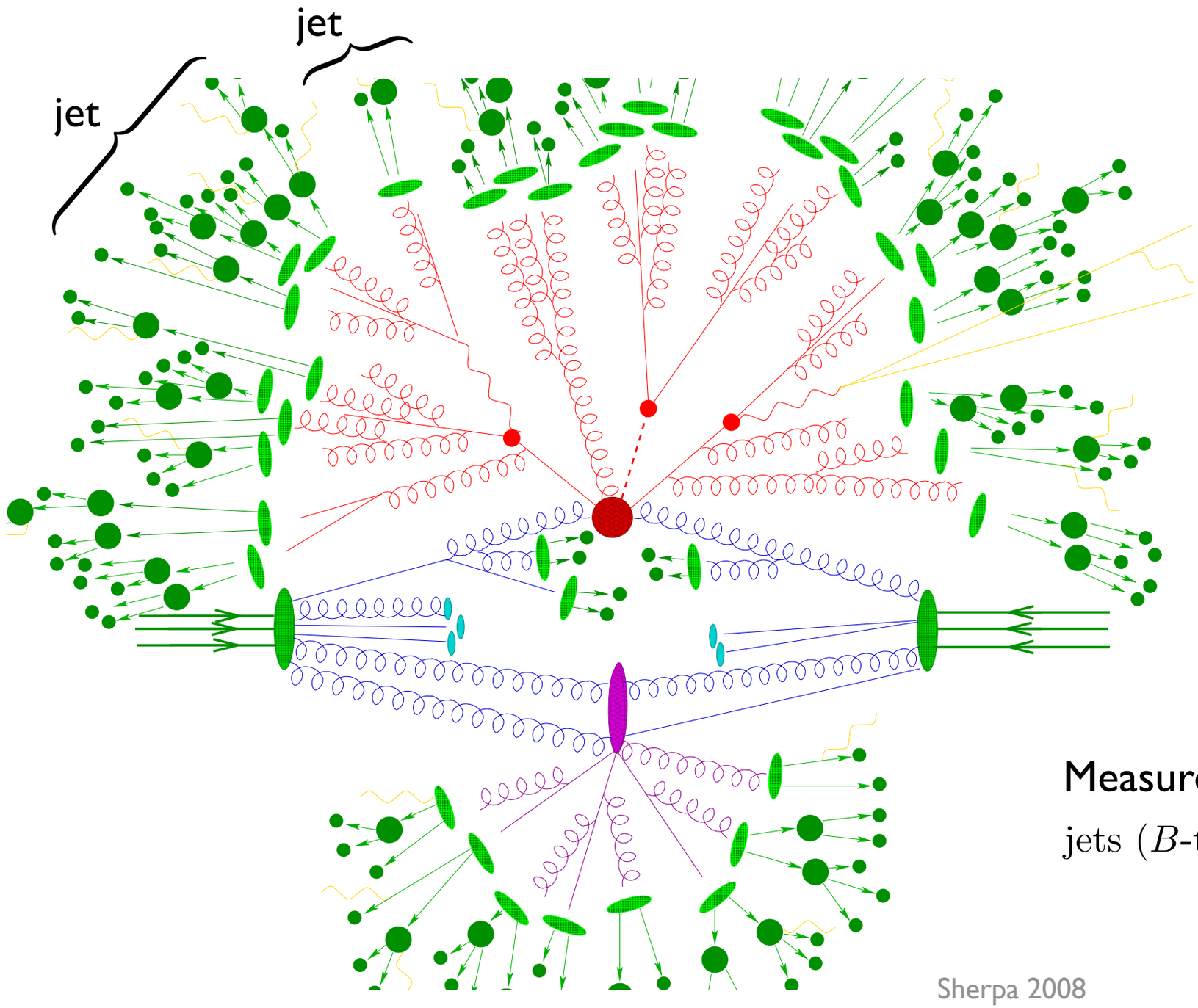
Proton collisions at the LHC



- Parton distributions
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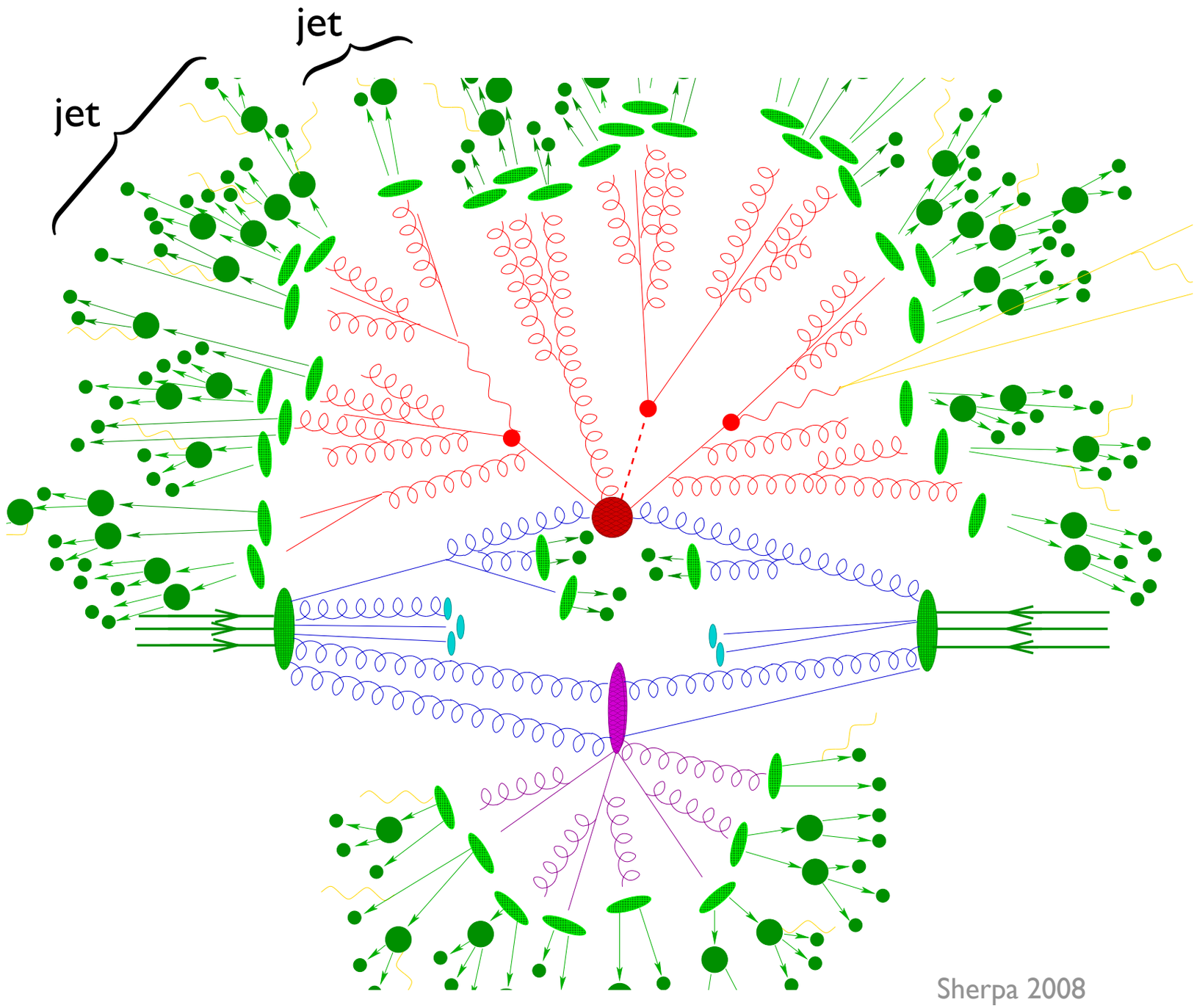
- Jet clustering

Measured objects in an event:

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

Sherpa 2008

Proton collisions at the LHC



Sherpa 2008

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- Apply search cuts

Signal over background?

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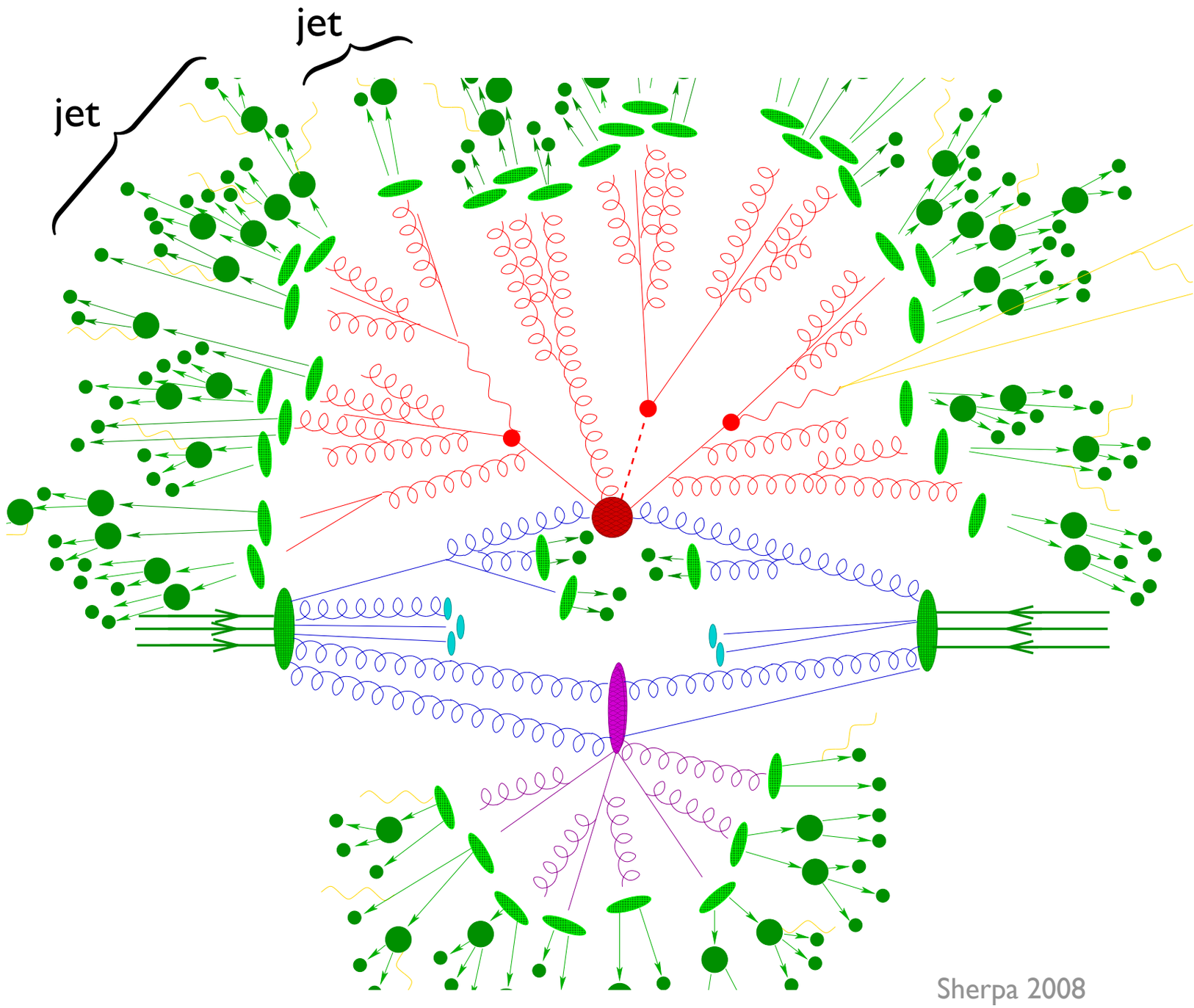

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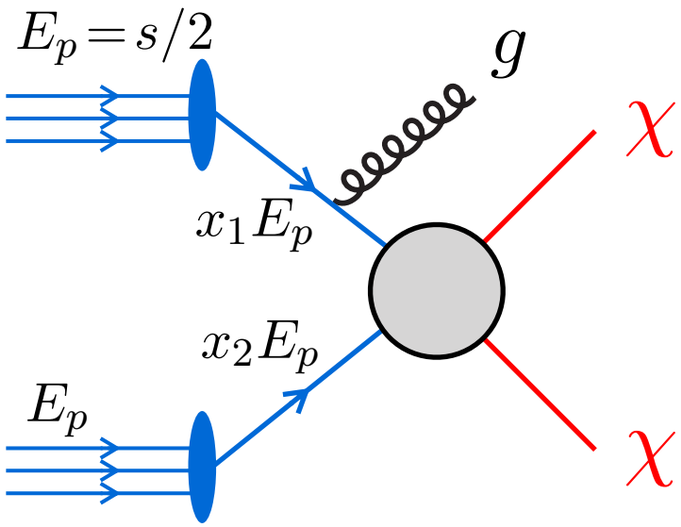
Signal over background?

MadAnalysis, CheckMate, SModelS, …

WIMP dark matter production cross section



$$\hat{s} = x_1 x_2 s$$

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

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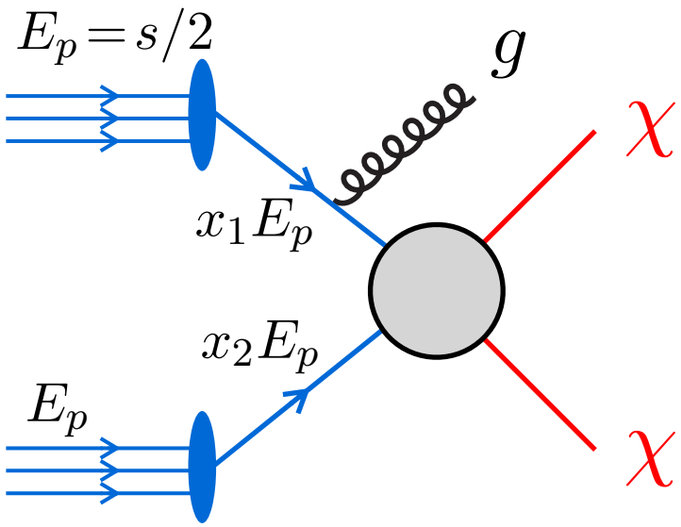

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$$2m_\chi + E_{\text{jet}}$$

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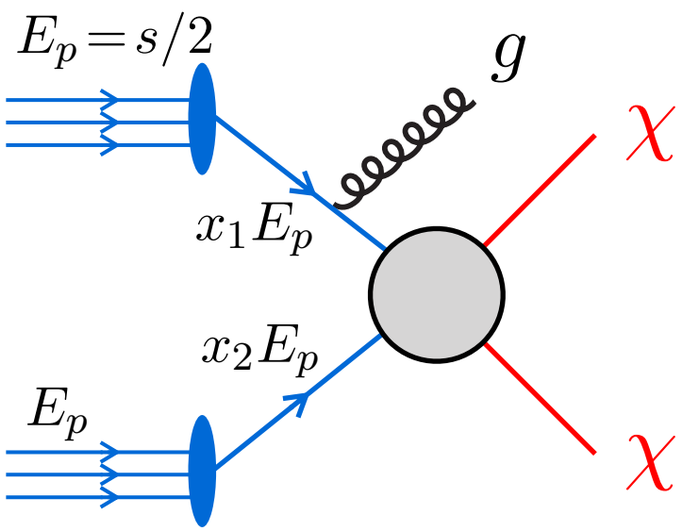

$2m_\chi + E_{\text{jet}}$

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

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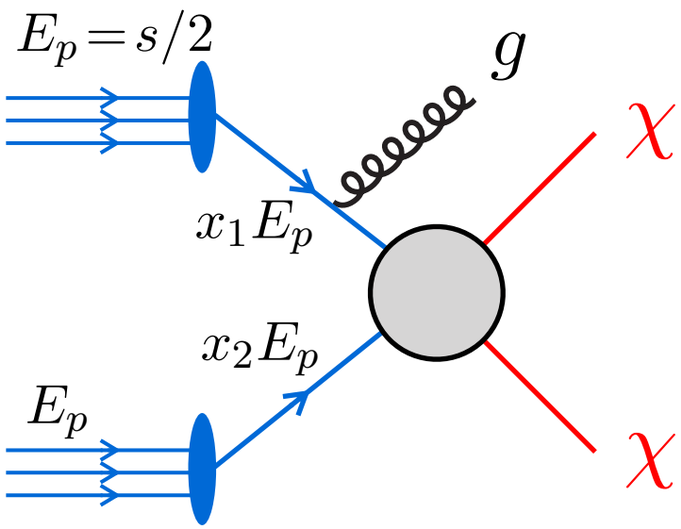

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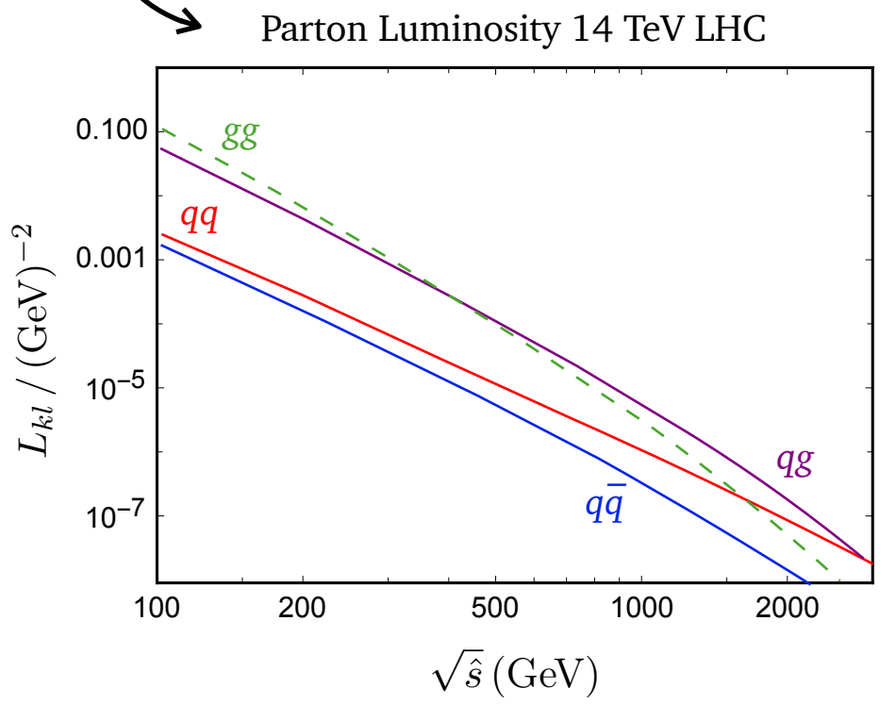

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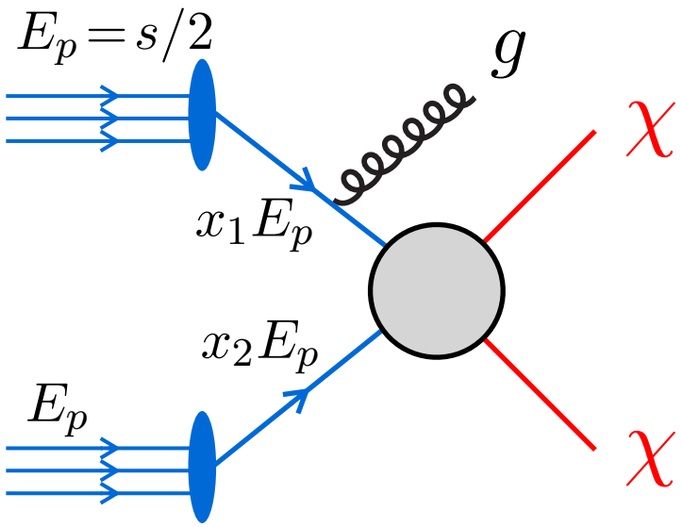

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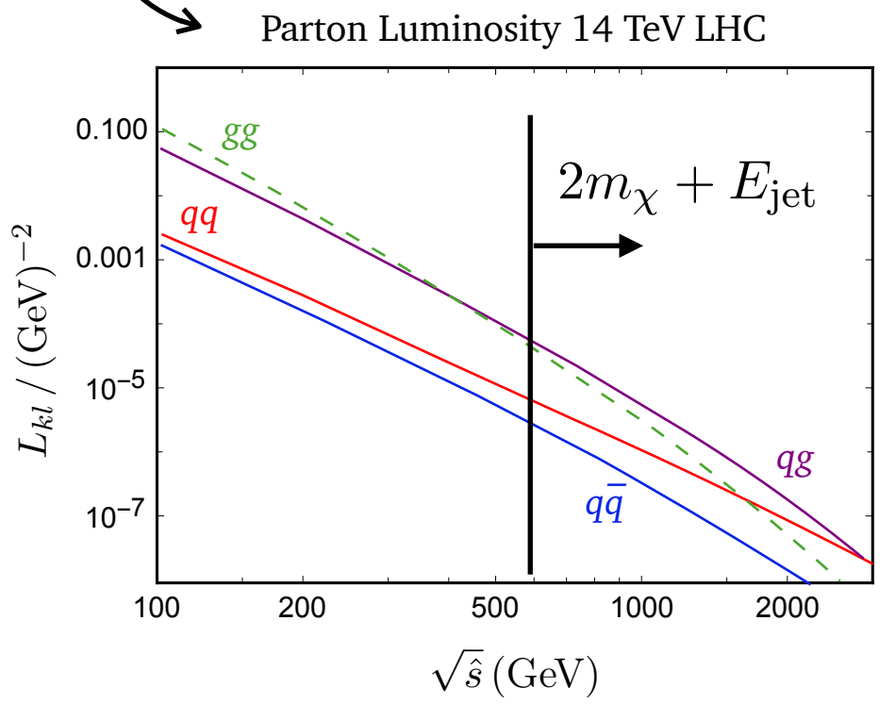

WIMP dark matter production – background

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
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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
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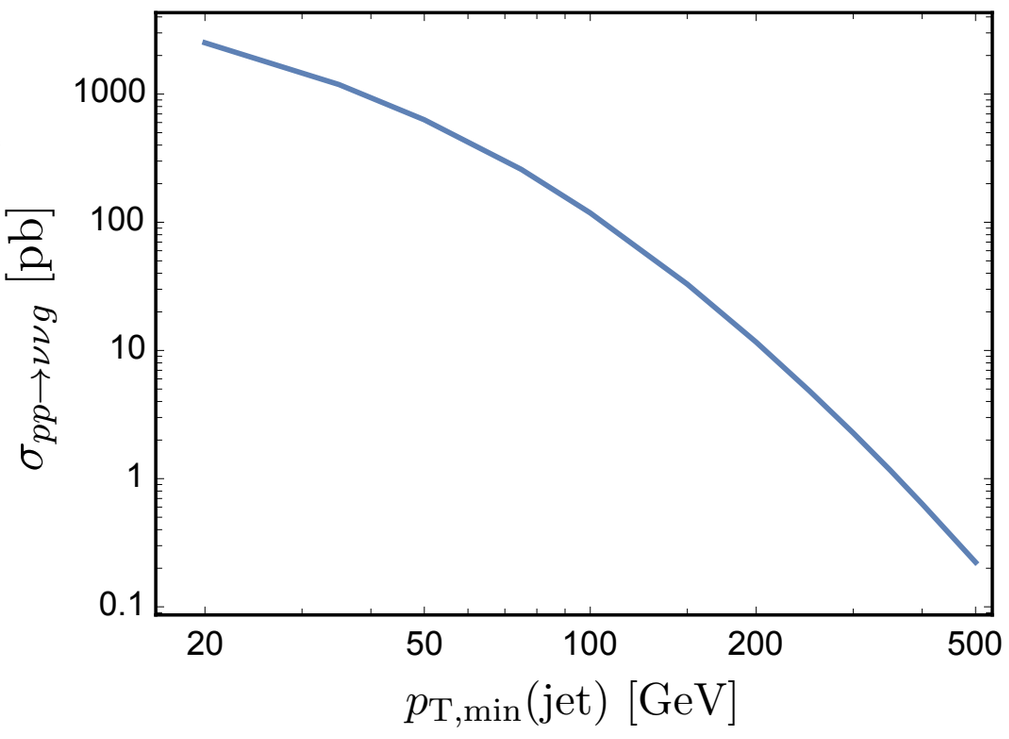

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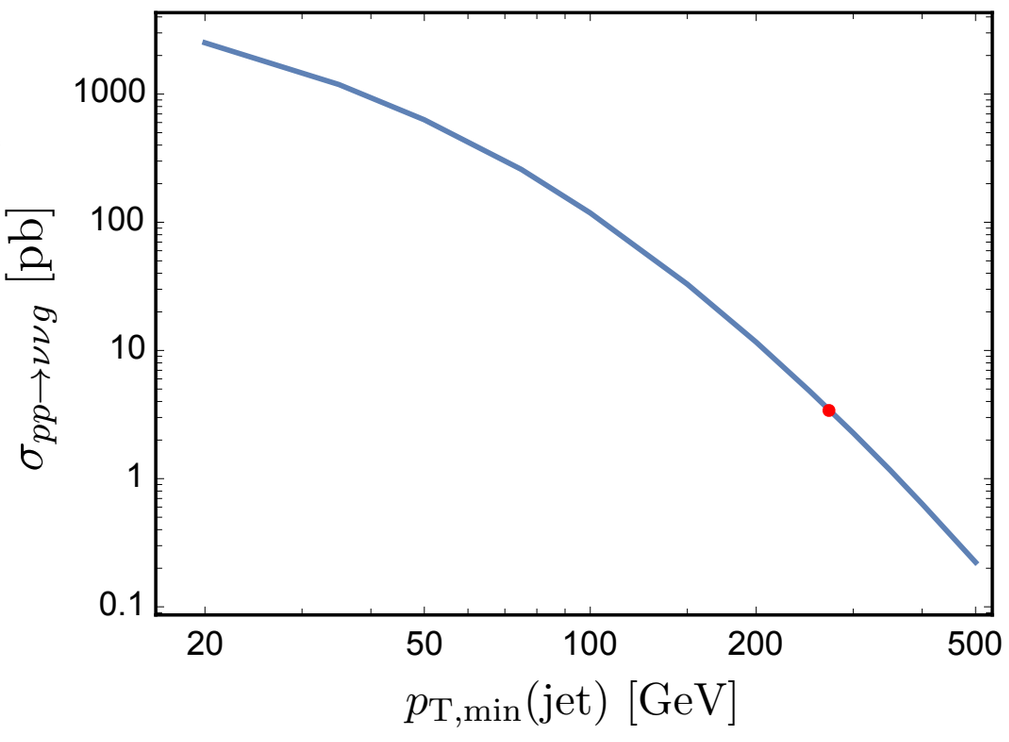


$$\sigma_{pp\to\nu\nu g}(p_{\mathrm{T}}^{\mathrm{jet}} > 250\mathrm{GeV}) \sim \text{few pb}$$

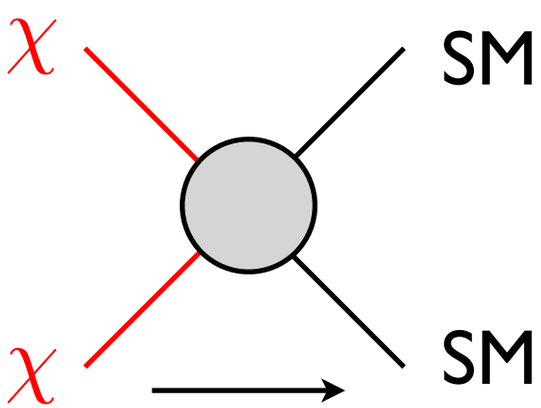
$$\Rightarrow B \sim 100\,\mathrm{fb}^{-1} \times 1000\,\mathrm{fb} \sim 10^5$$

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

systematics become dominant

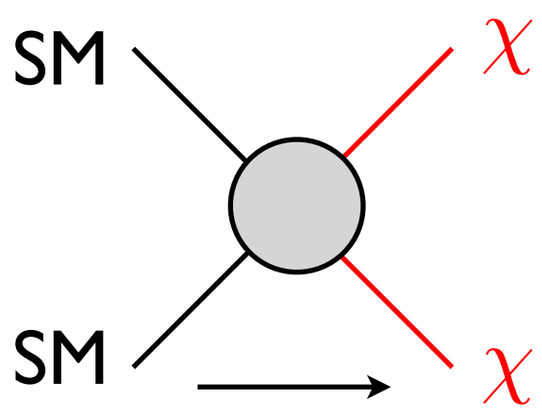
WIMP dark matter searches

Freeze-out



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

Production



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WIMP dark matter searches

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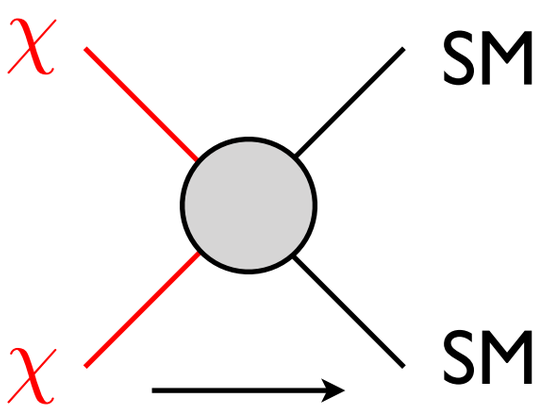

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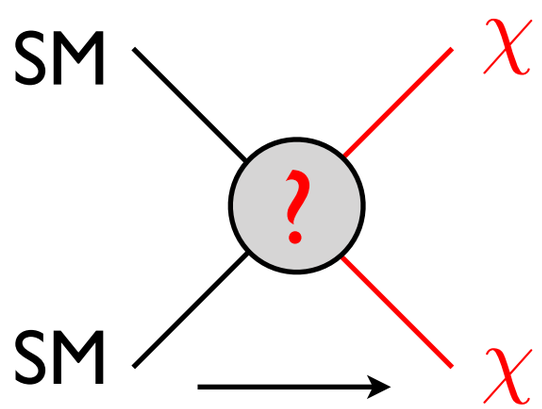

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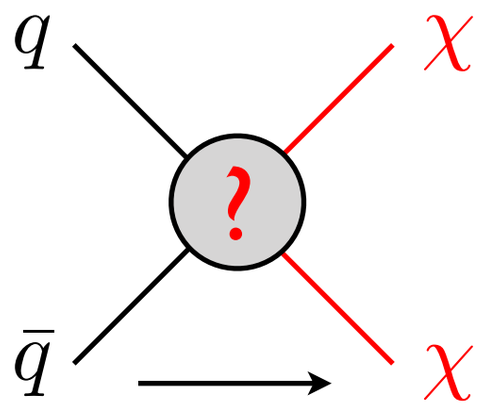
Effective field theory (EFT)



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

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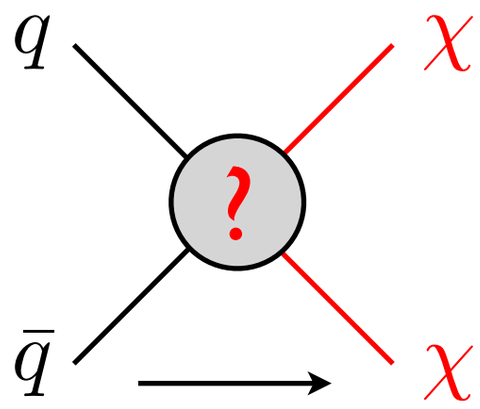

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Problem at LHC: Typical limit on Λ around TeV ~ energies of collisions

$\Rightarrow$ EFT not valid [Busoni *et al* 1307.2253, Buchmueller *et al* 1308.6799, …]

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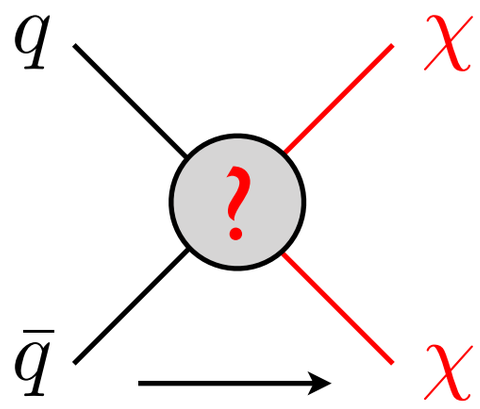

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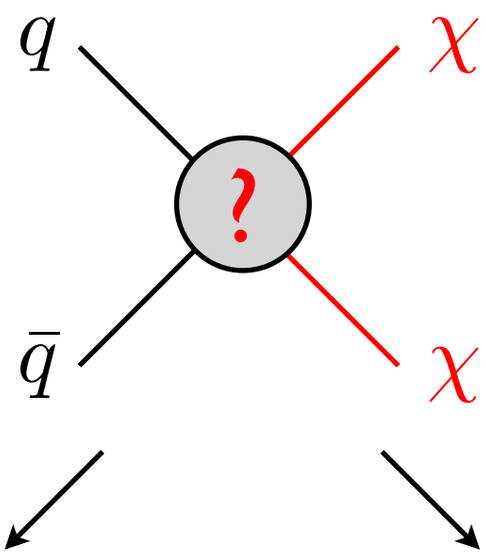
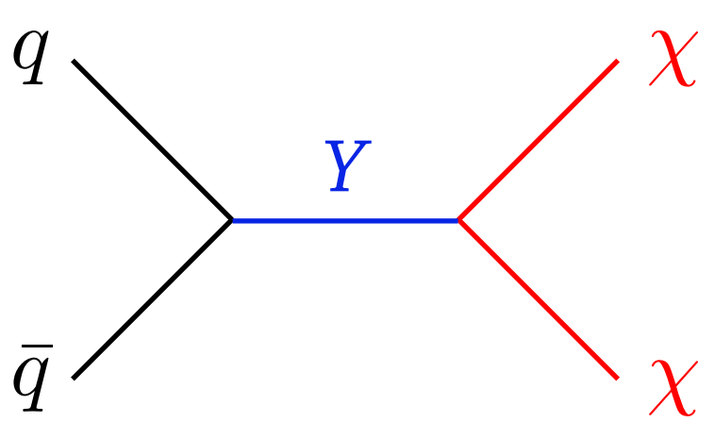
$\Rightarrow$ EFT not valid [Busoni *et al* 1307.2253, Buchmueller *et al* 1308.6799, …]

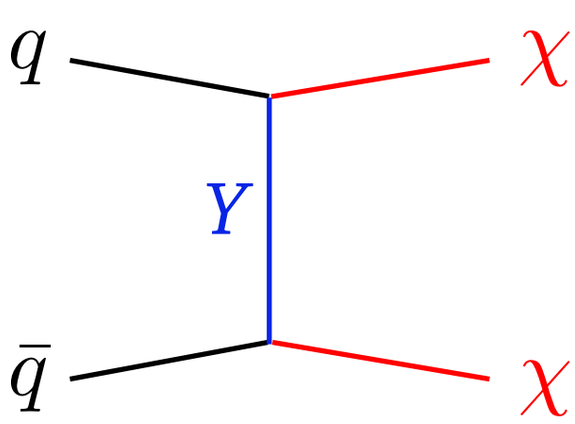
$$\frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M^2} \qquad \Lambda^2 \sim \hat{s} \;\Rightarrow \begin{cases} M^2 \lesssim \hat{s} & \text{perturbative} \\ M^2 \gg \Lambda^2 & g \gg 1 \end{cases}$$

Beyond effective field theory – simplified models



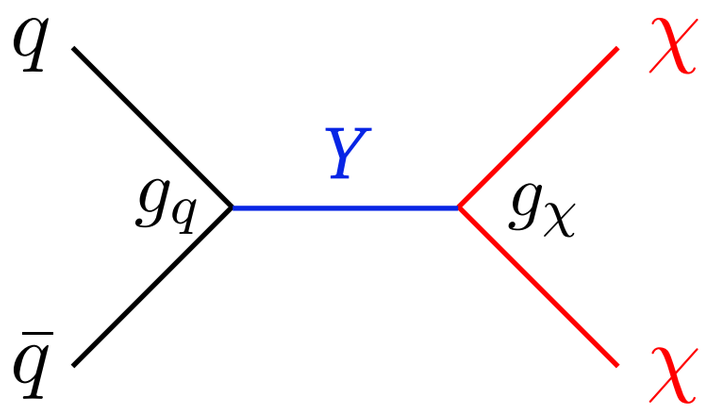


s-channel mediator



t-channel mediator

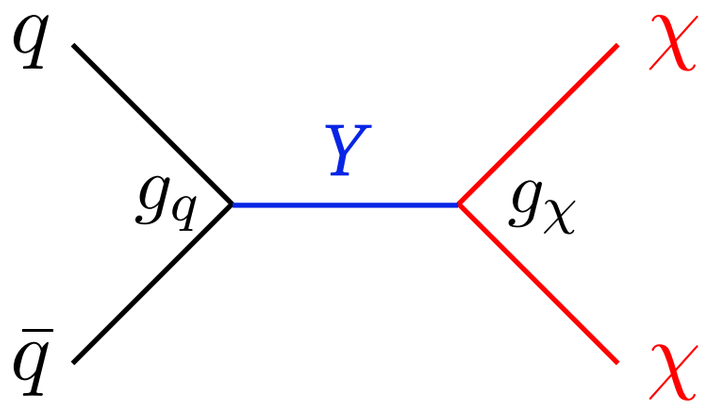
Simplified models: s-channel mediator



- 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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- 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

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]

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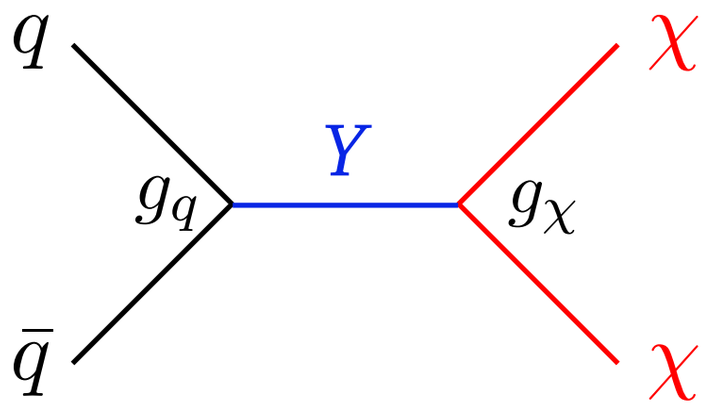

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$$\mathcal{L} \supset g_q Z'^\mu \sum_q \bar{q}\gamma_\mu\gamma^5 q + g_\chi Z'^\mu \bar{\chi}\gamma_\mu\gamma^5\chi \quad \text{axial-vector}$$

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

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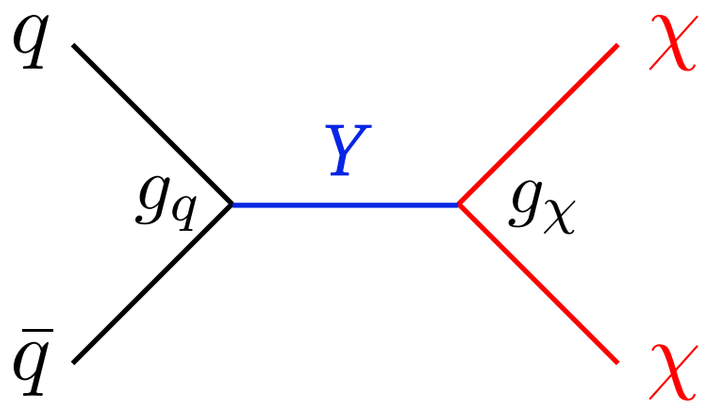

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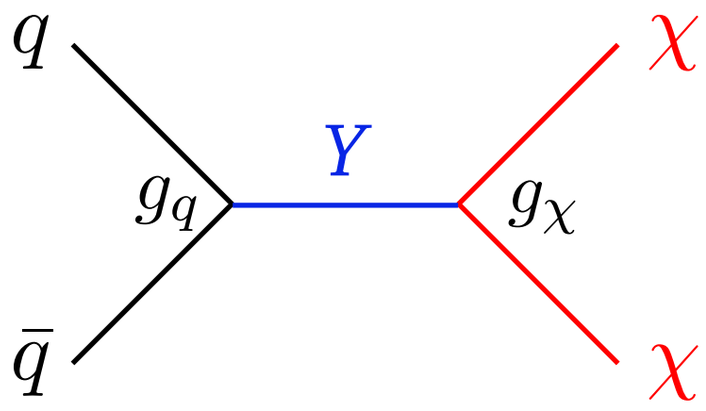
$$\mathcal{L} \supset g_q a \sum_q y_q \bar{q} \gamma^5 q + g_\chi a \bar{\chi} \gamma^5 \chi \qquad \text{pseudo-scalar}$$

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

Simplified models: s-channel mediator



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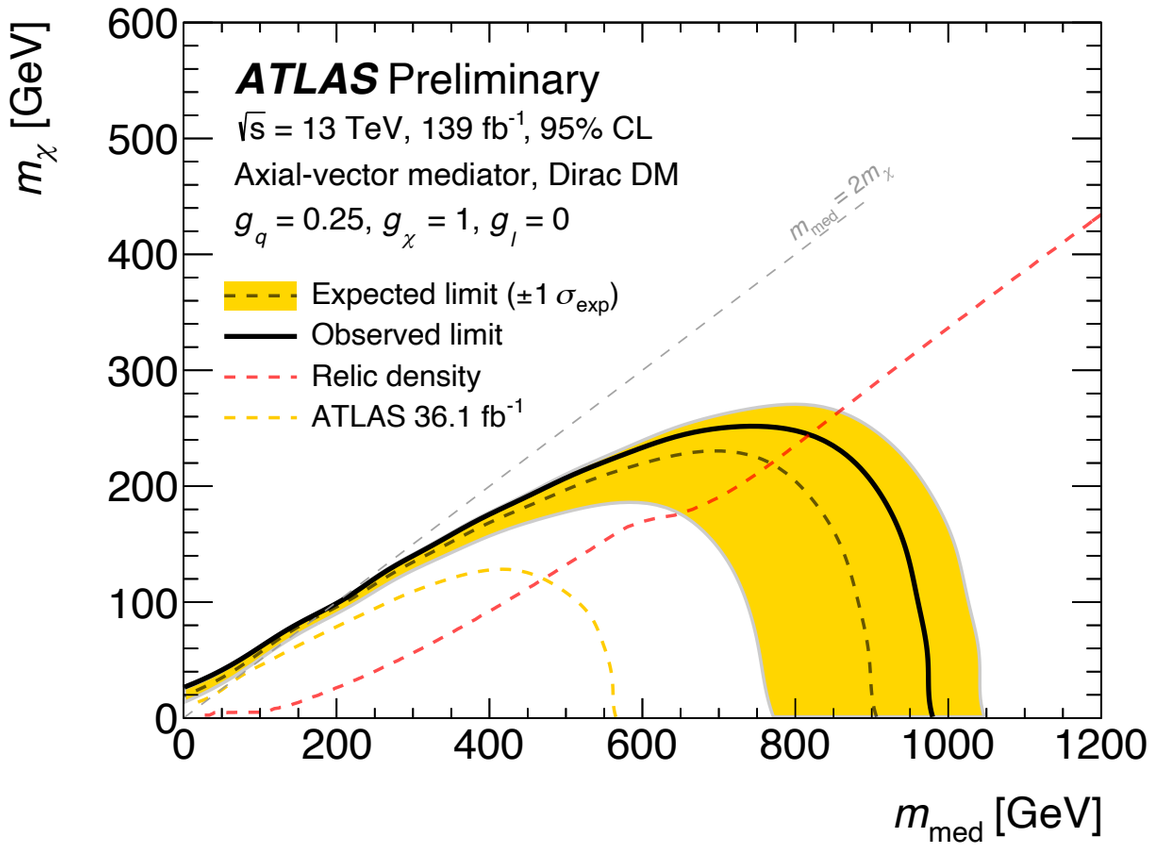
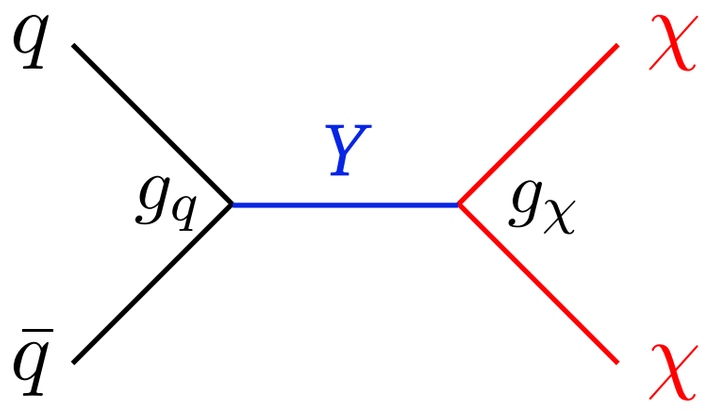


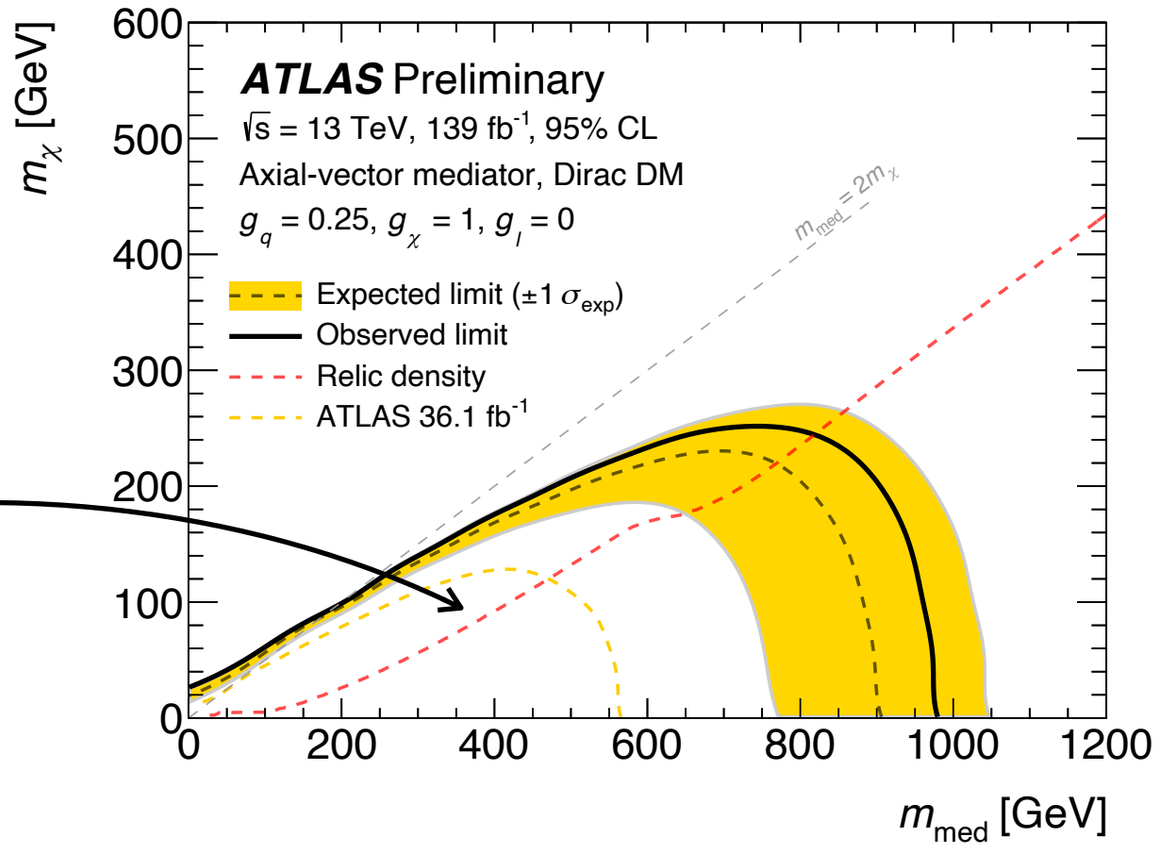
Simplified models: s-channel mediator



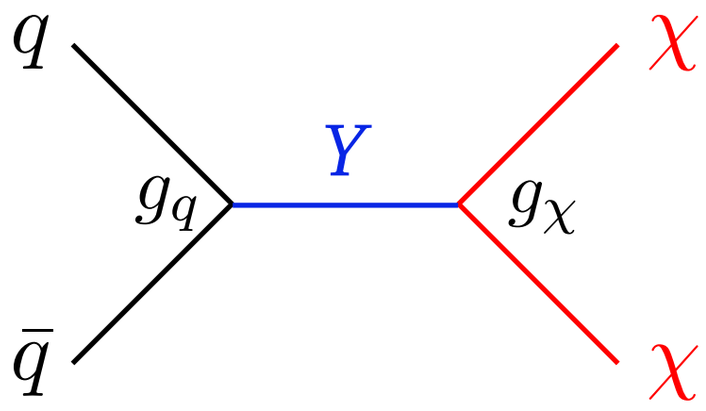
- Y could be scalar or vector
- Four free parameters (at least)

  m_χ, m_Y, g_q, g_χ

Relic density



Simplified models: s-channel mediator



- Y could be scalar or vector
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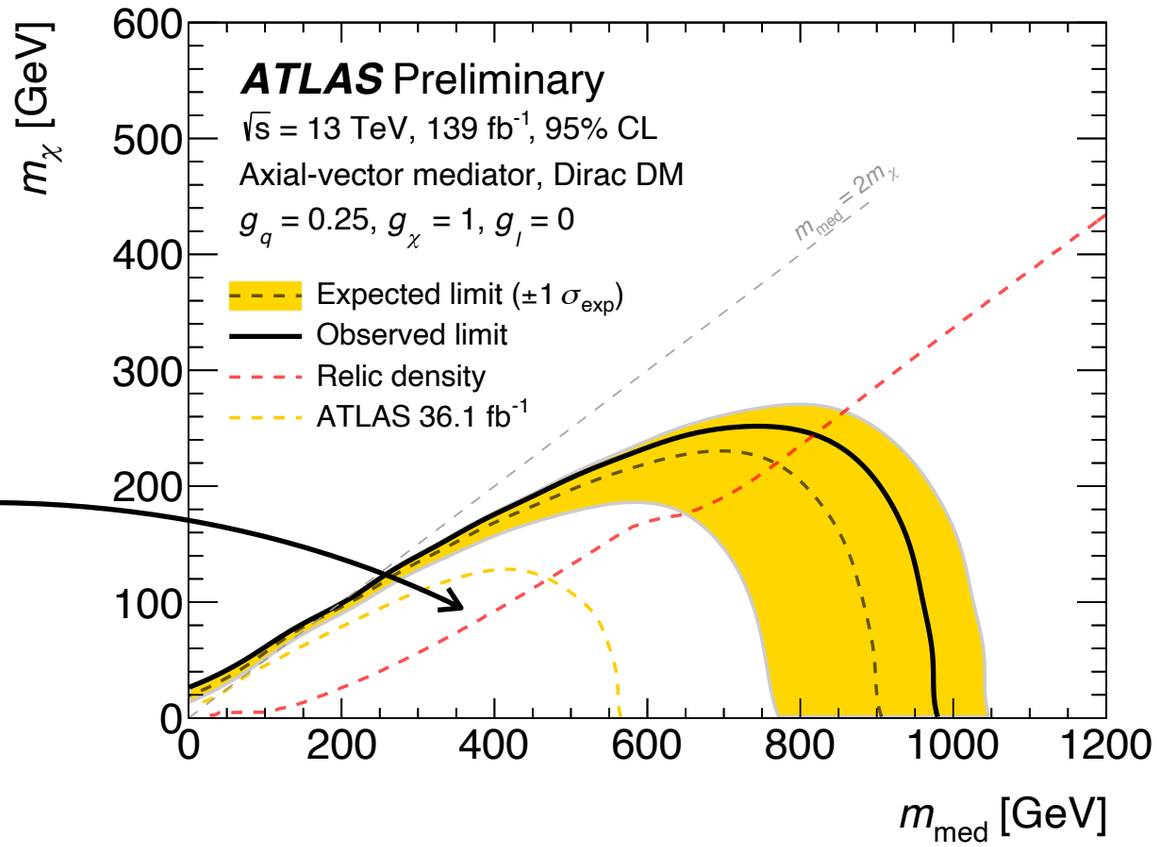
  m_χ, m_Y, g_q, g_χ

Relic density

Mapping onto operators for direct detection

[Dent et al 1505.03117]

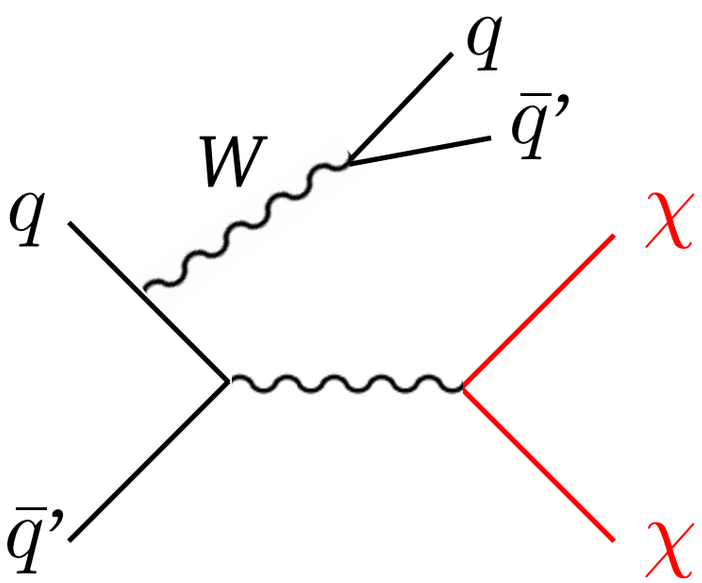


Consistency within s-channel mediator models

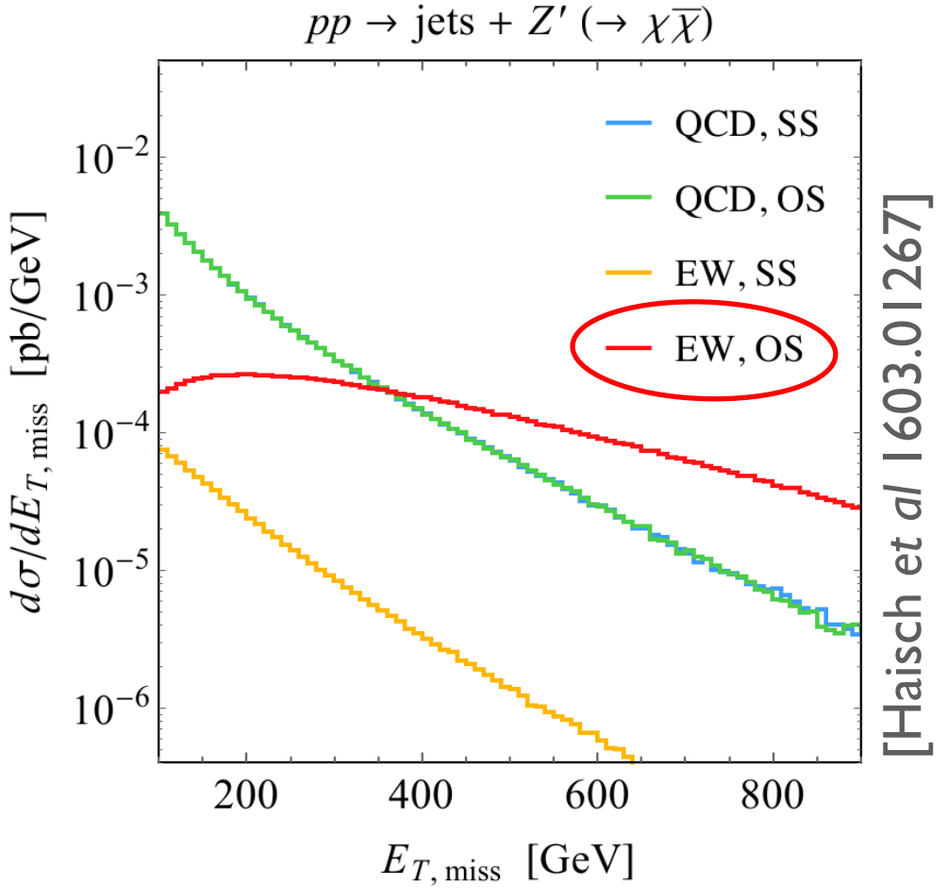
- Not all choices are theoretically consistent
- E.g. simplified models respecting the symmetries of the broken SU(3) x $U(1)_{em}$, but not SU(3) x SU(2) x $U(1)_Y$

[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]

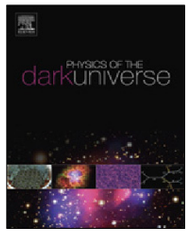
Consistency within s-channel mediator models

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

Contents lists available at ScienceDirect

Physics of the Dark Universe

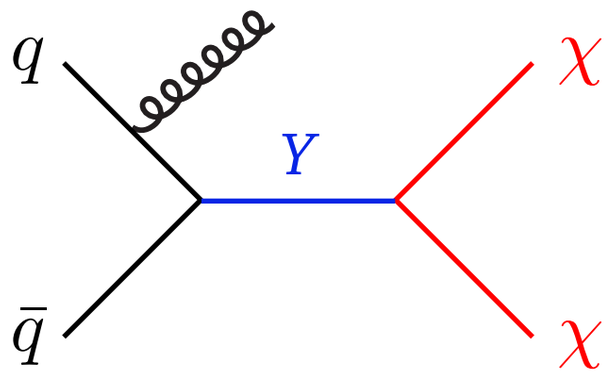
journal homepage: www.elsevier.com/locate/dark



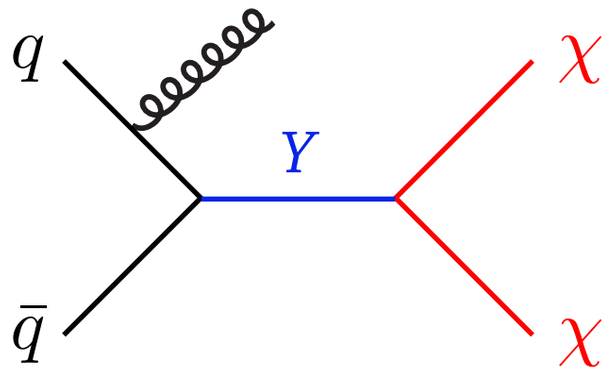
LHC Dark Matter Working Group: Next-generation spin-0 dark matter models

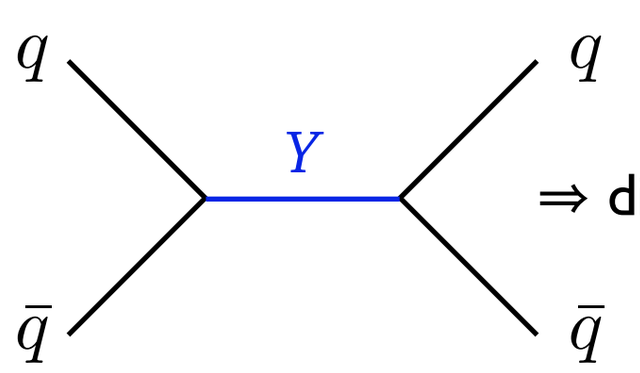
Tomohiro Abe [1,2], Yoav Afik [3], Andreas Albert [4], Christopher R. Anelli [5], Liron Barak [6], Martin Bauer [7], J. Katharina Behr [8], Nicole F. Bell [9], Antonio Boveia [10,a], Oleg Brandt [11], Giorgio Busoni [9], Linda M. Carpenter [10], Yu-Heng Chen [8], Caterina Doglioni [12,a], Alison Elliot [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



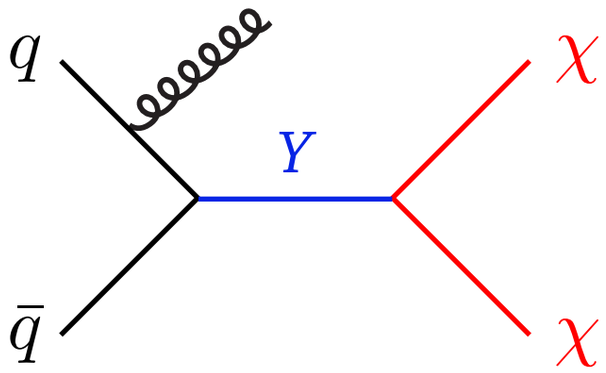
Signatures beyond MET

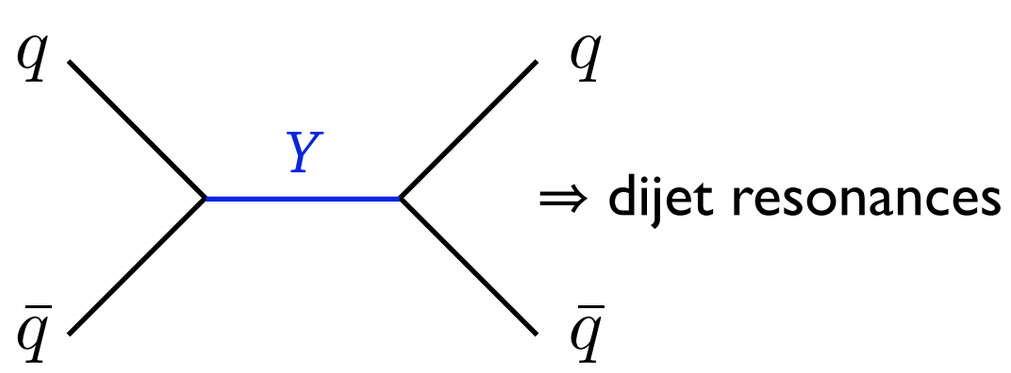


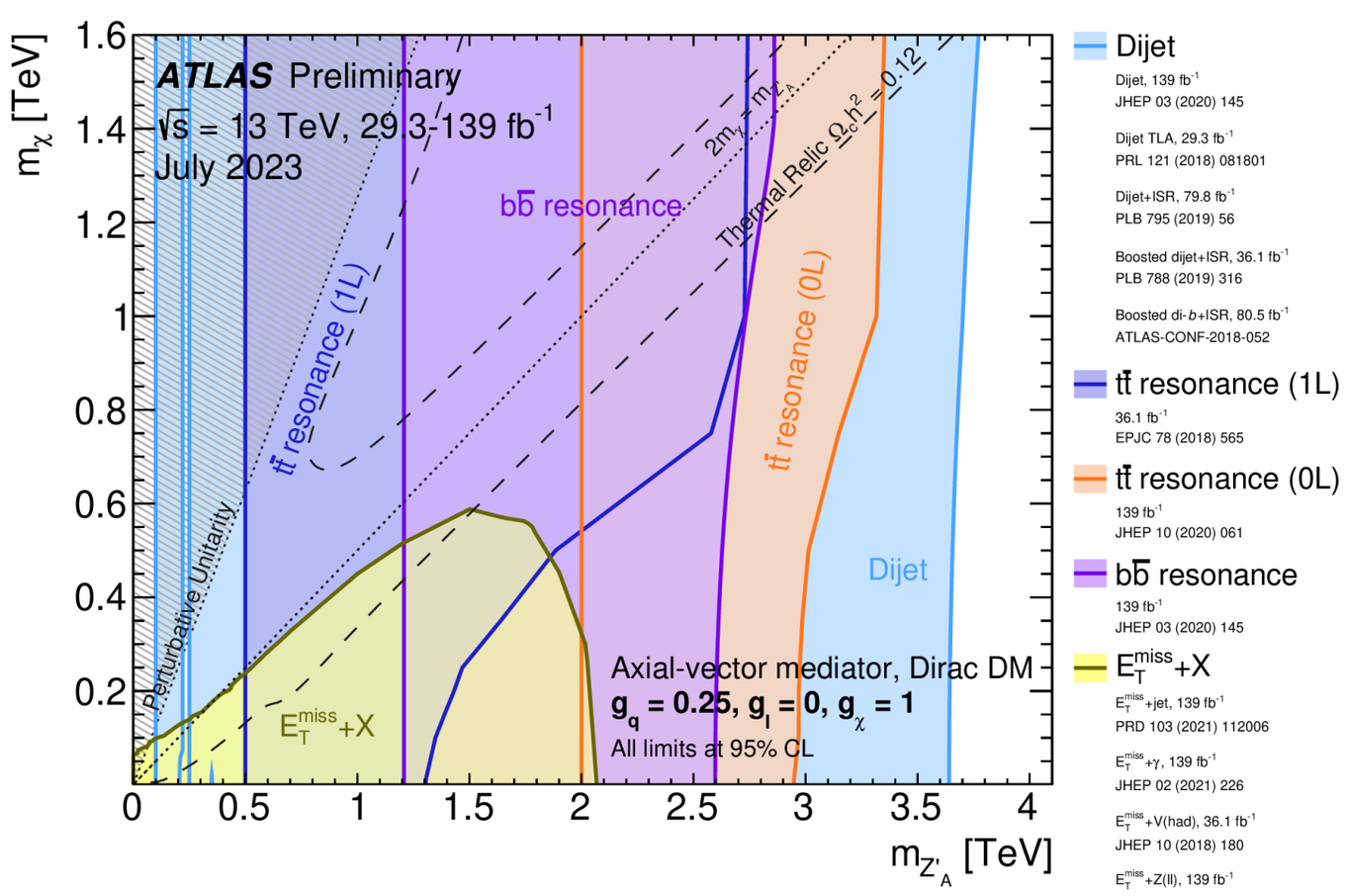


$\Rightarrow$ dijet resonances

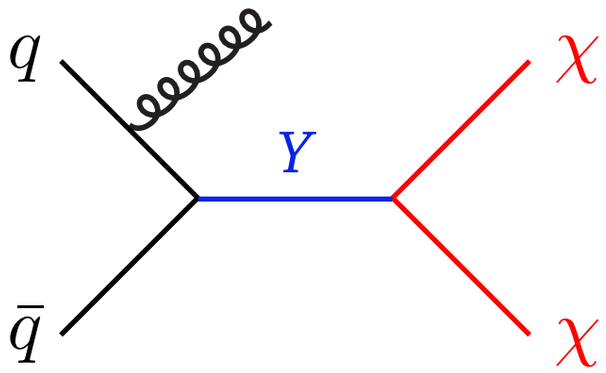
Signatures beyond MET

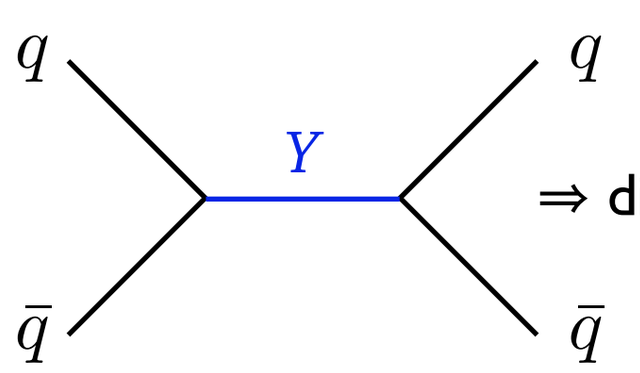




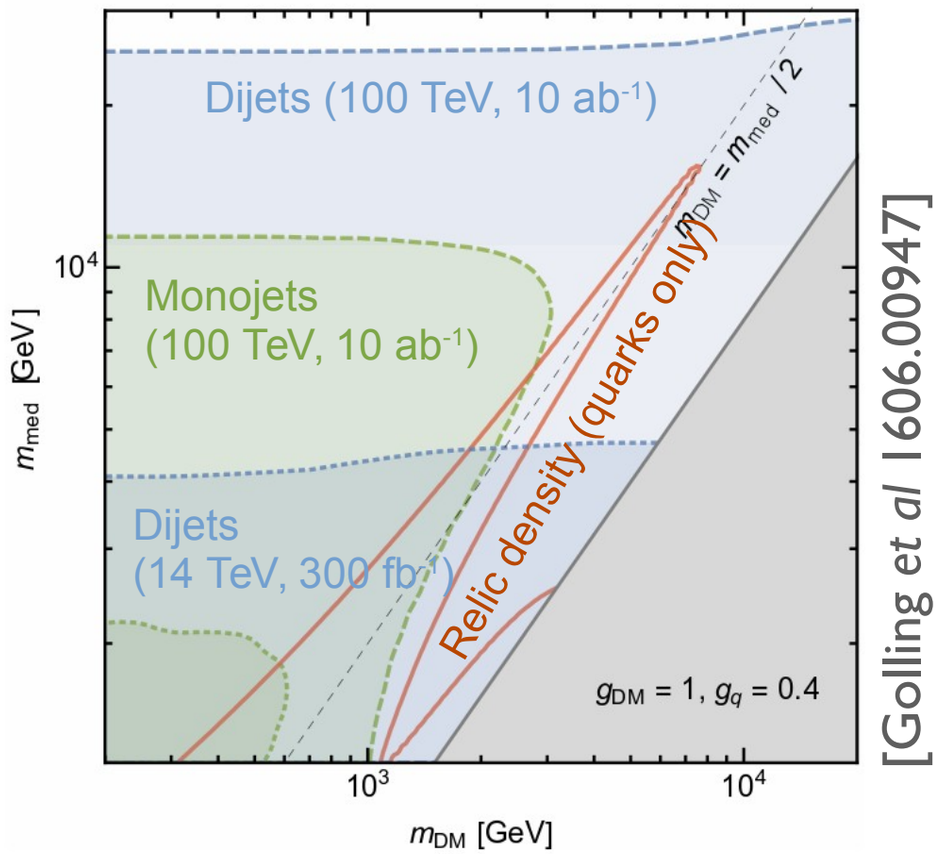


Signatures beyond MET



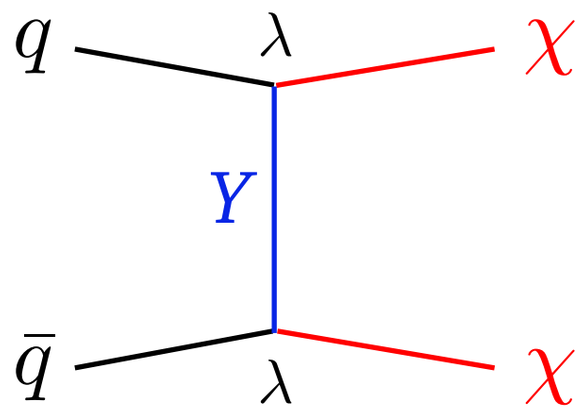


⇒ dijet resonances



[Golling *et al* 1606.00947]

Simplified models: t-channel mediator

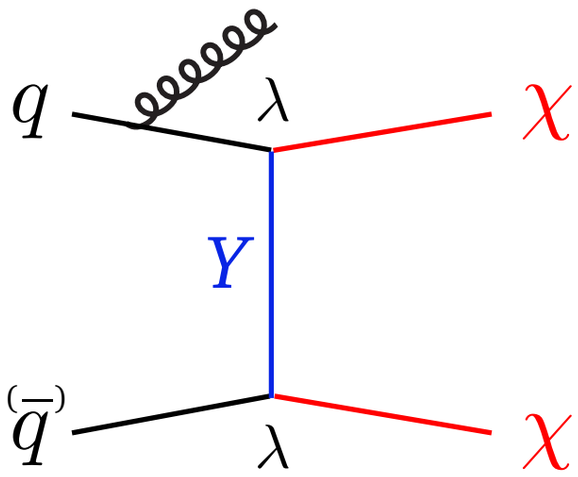


- Y could be scalar or fermion
- Three free parameters (at least): m_χ, m_Y, λ
- Dark matter gauge singlet ⇒ Y same quantum numbers as Y
- Dark matter stabilised by Z_2 symmetry: both X and Y odd (SM particles are even)
- $m_Y > m_\chi$
- Examples:

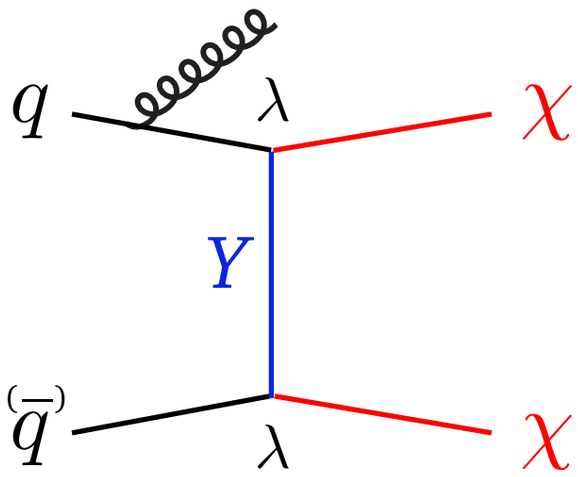
$$\mathcal{L} \supset \lambda Y^\dagger \bar{\chi} P_R q + \text{h.c.} \qquad \text{Scalar mediator}$$

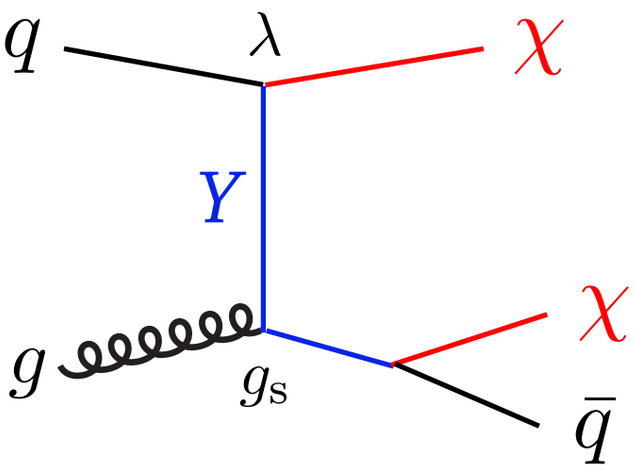
$$\mathcal{L} \supset \lambda \bar{Y} P_R q S + \text{h.c.} \qquad \text{Fermion mediator}$$

Simplified models: t-channel mediator

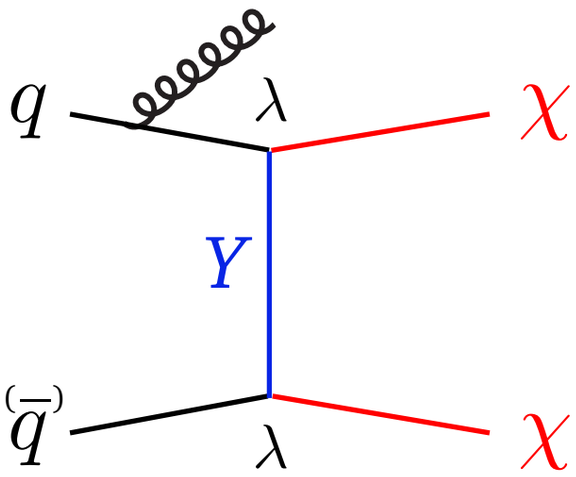


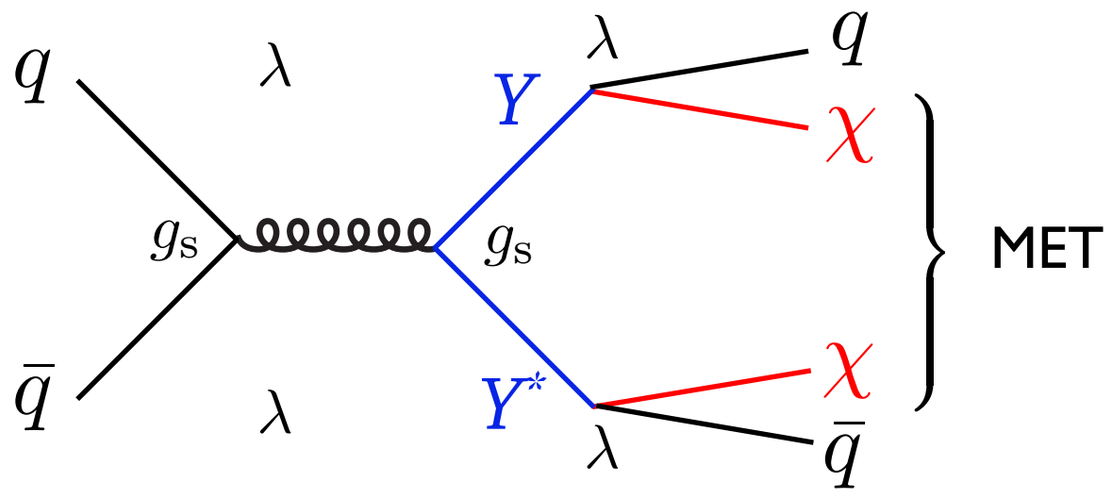
Simplified models: t-channel mediator

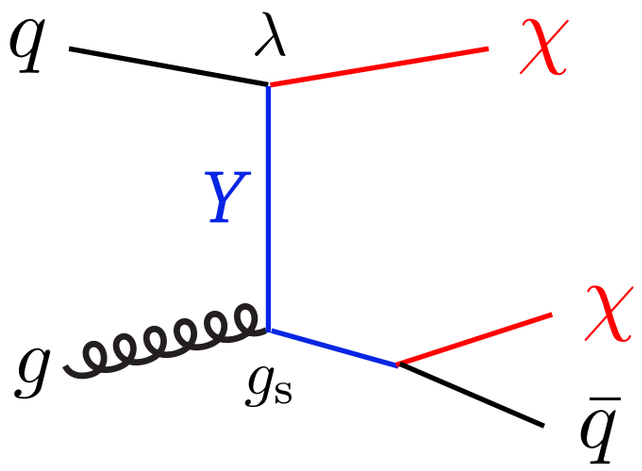




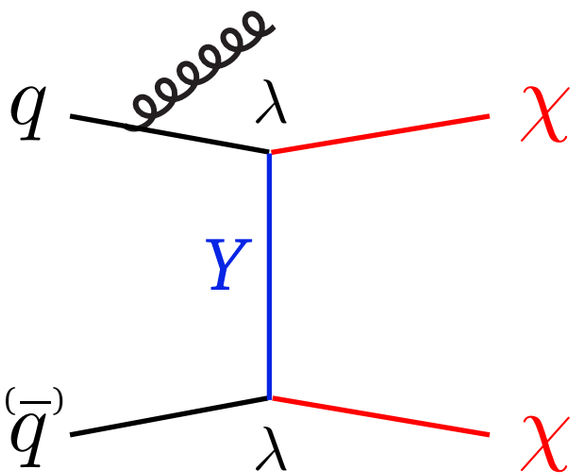
Simplified models: t-channel mediator

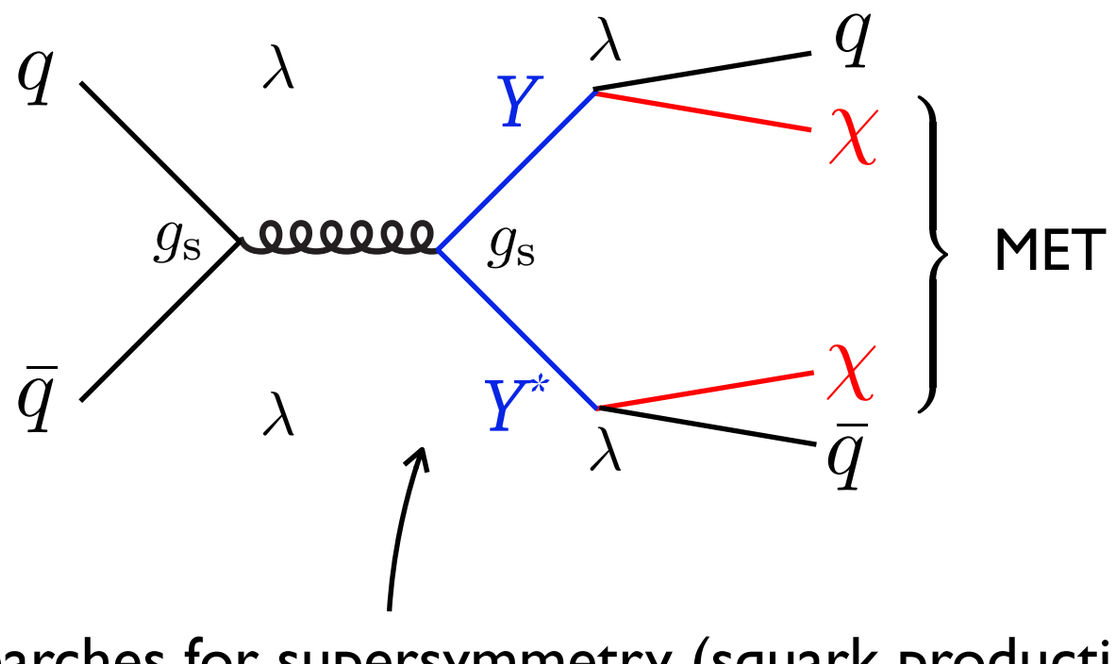


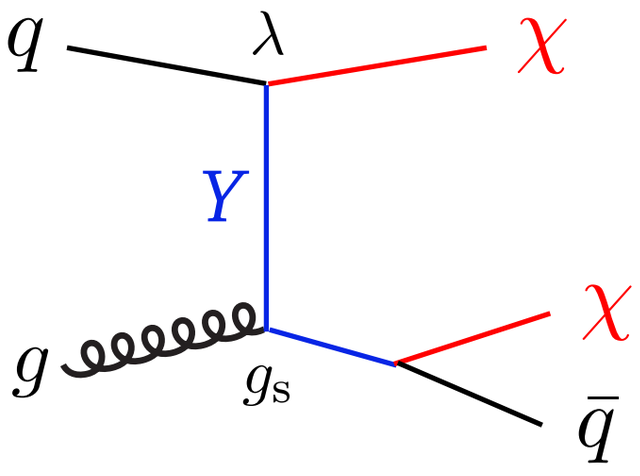




t-channel mediator models – signatures

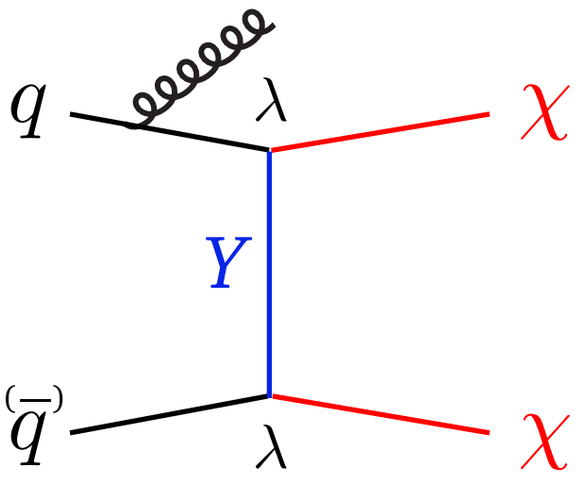


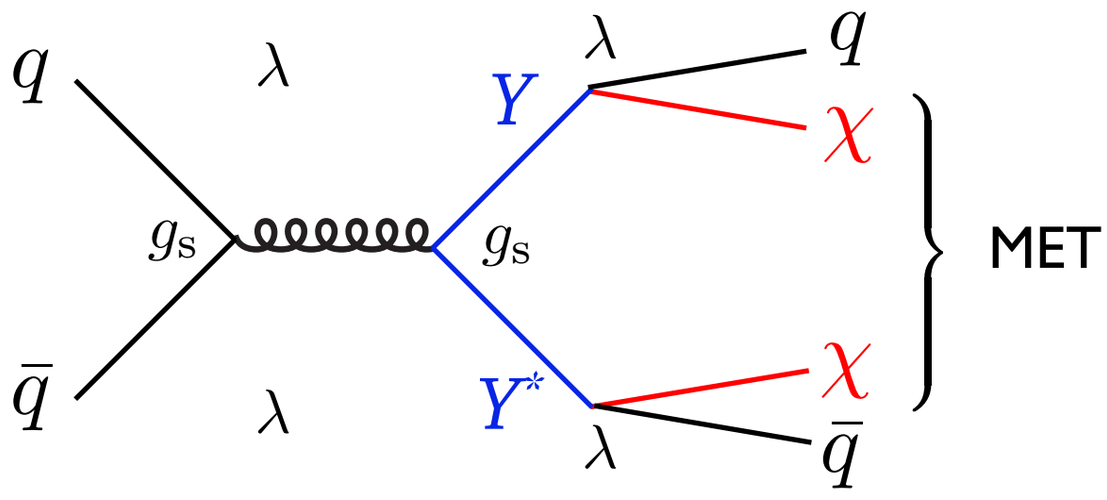


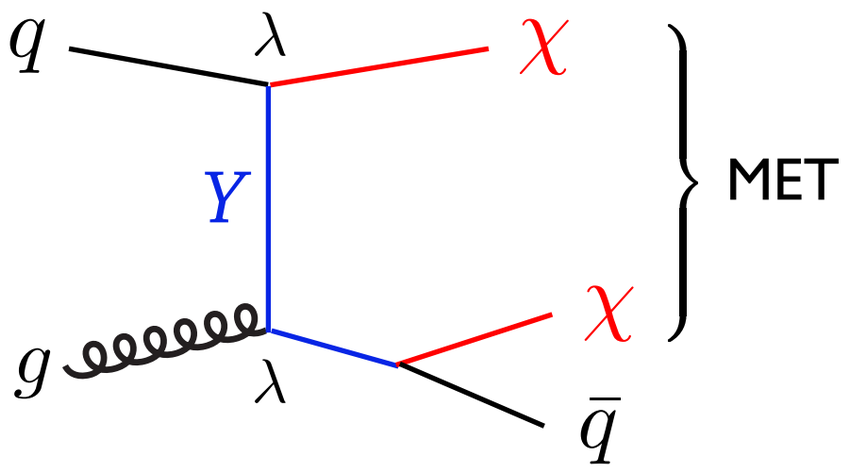


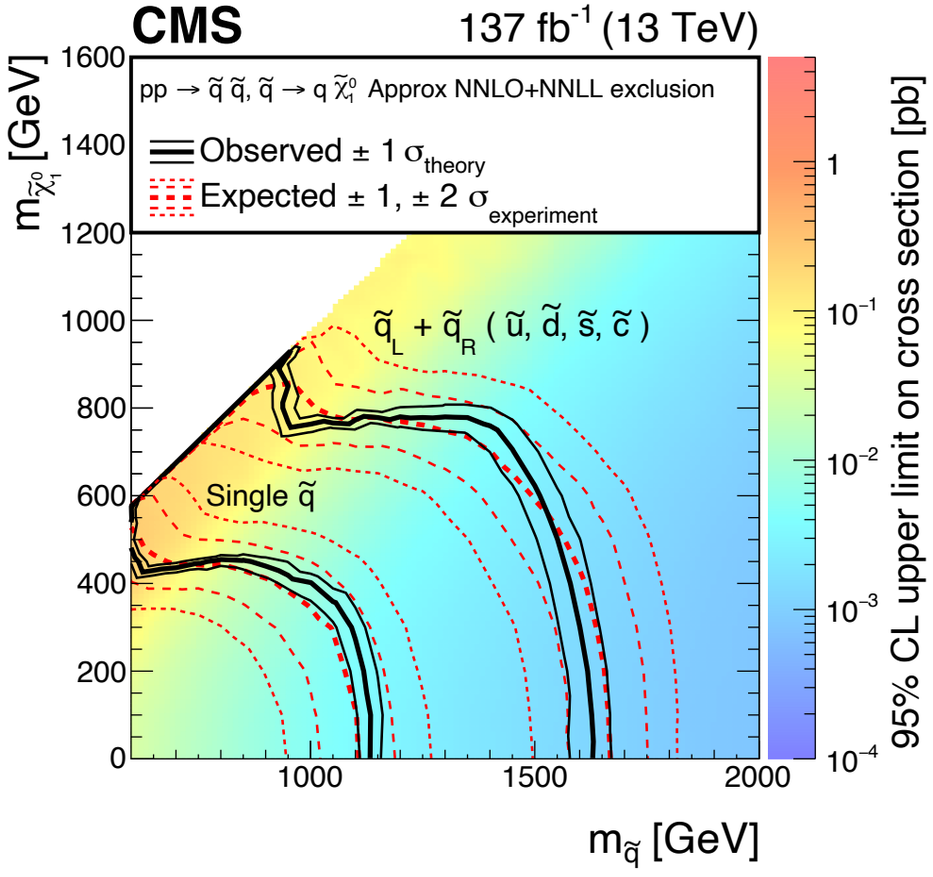
Searches for supersymmetry (squark production)

t-channel mediator models – signatures

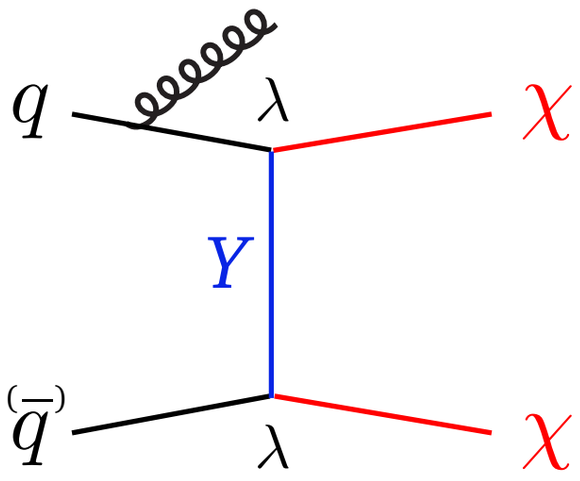


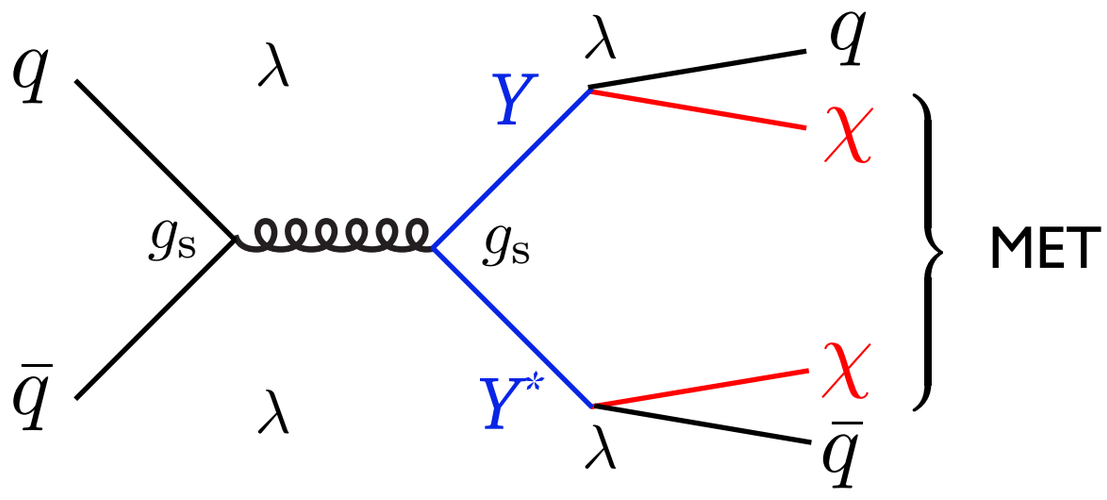


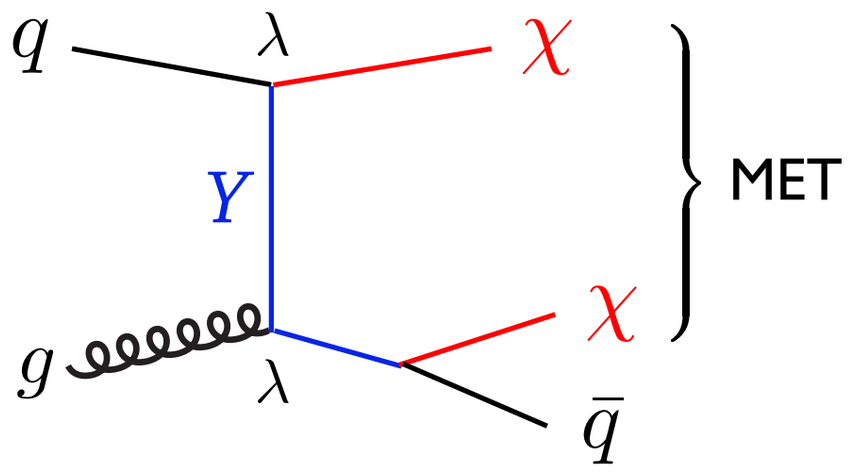


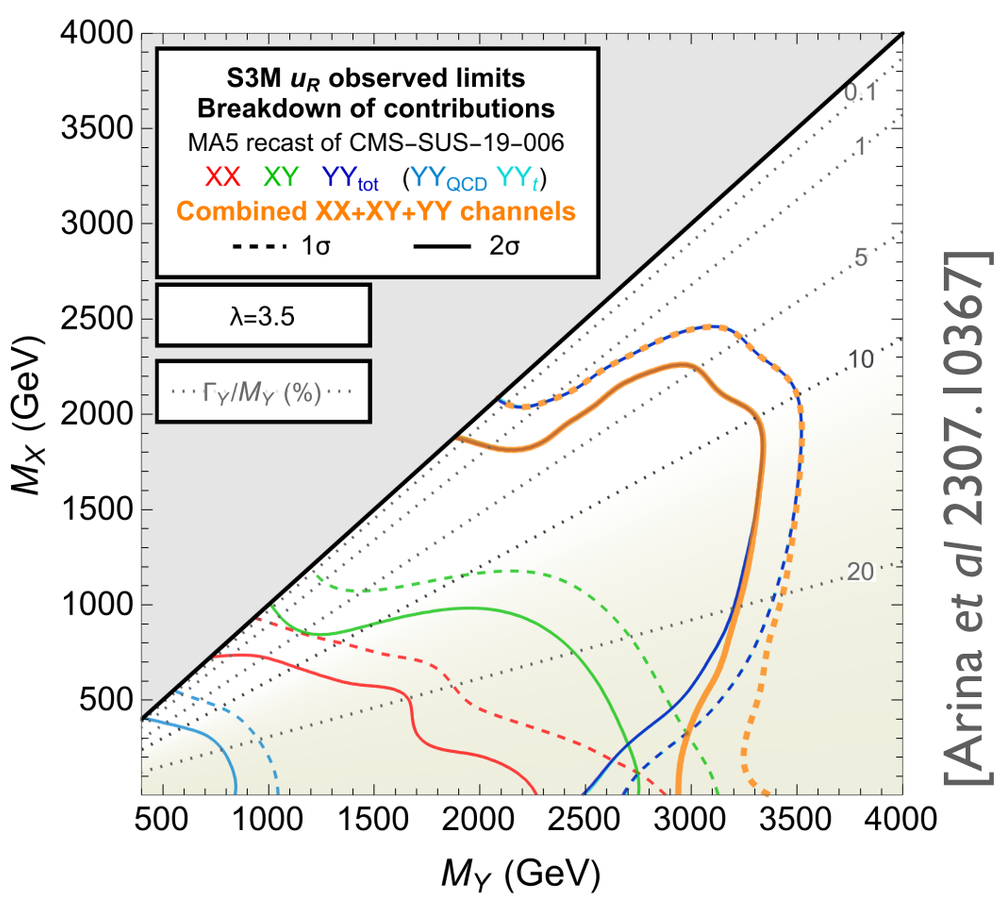


t-channel mediator models – signatures

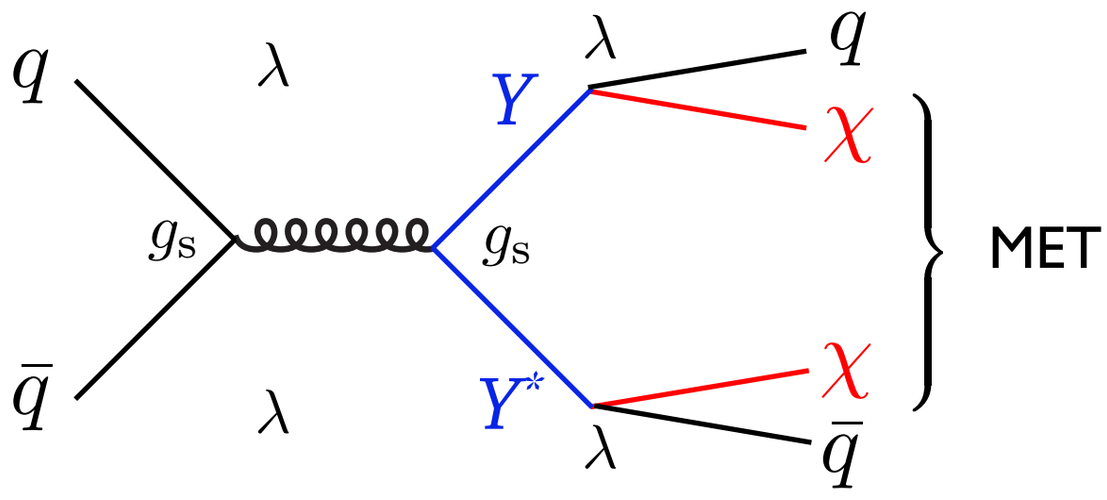


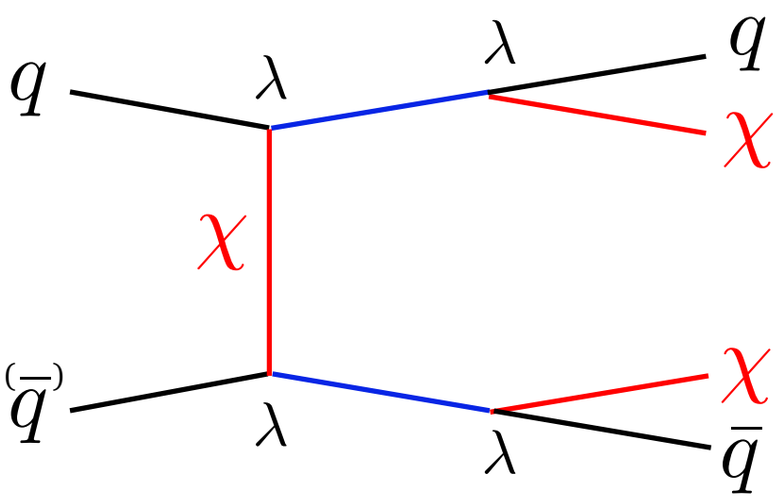


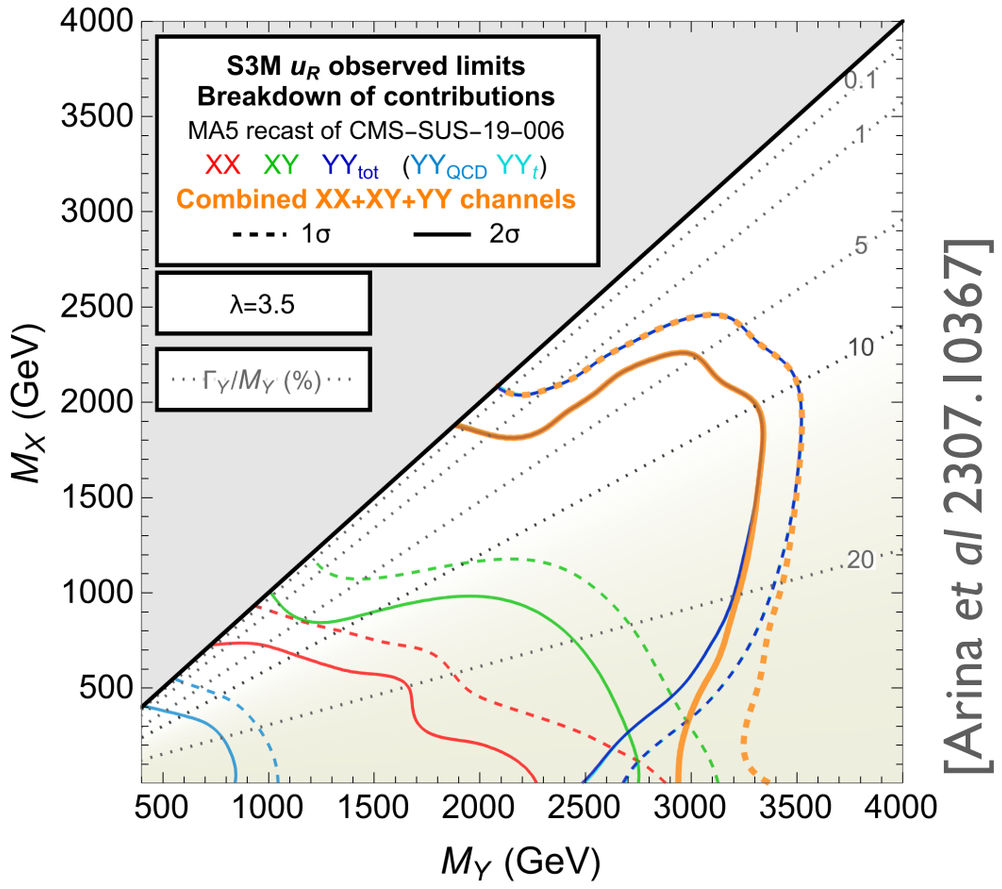




t-channel mediator models – signatures







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