Hidden Valley phenomenology: from colliders to cosmology

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Faculty of Physics

based on: H. Beauchesne, E. Bertuzzo, G^{2}dC and Z. Tabrizi, JHEP1808(2018)101, [1712.07160]
H. Beauchesne, E. Bertuzzo and G^{2}dC, JHEP 1904(2019)118, [1809.10152]
H. Beauchesne and G^{2}dC, [19xx.xxxxx]

GGI workshop - Next Frontier in the search for DM - 4th September 2019

Outline

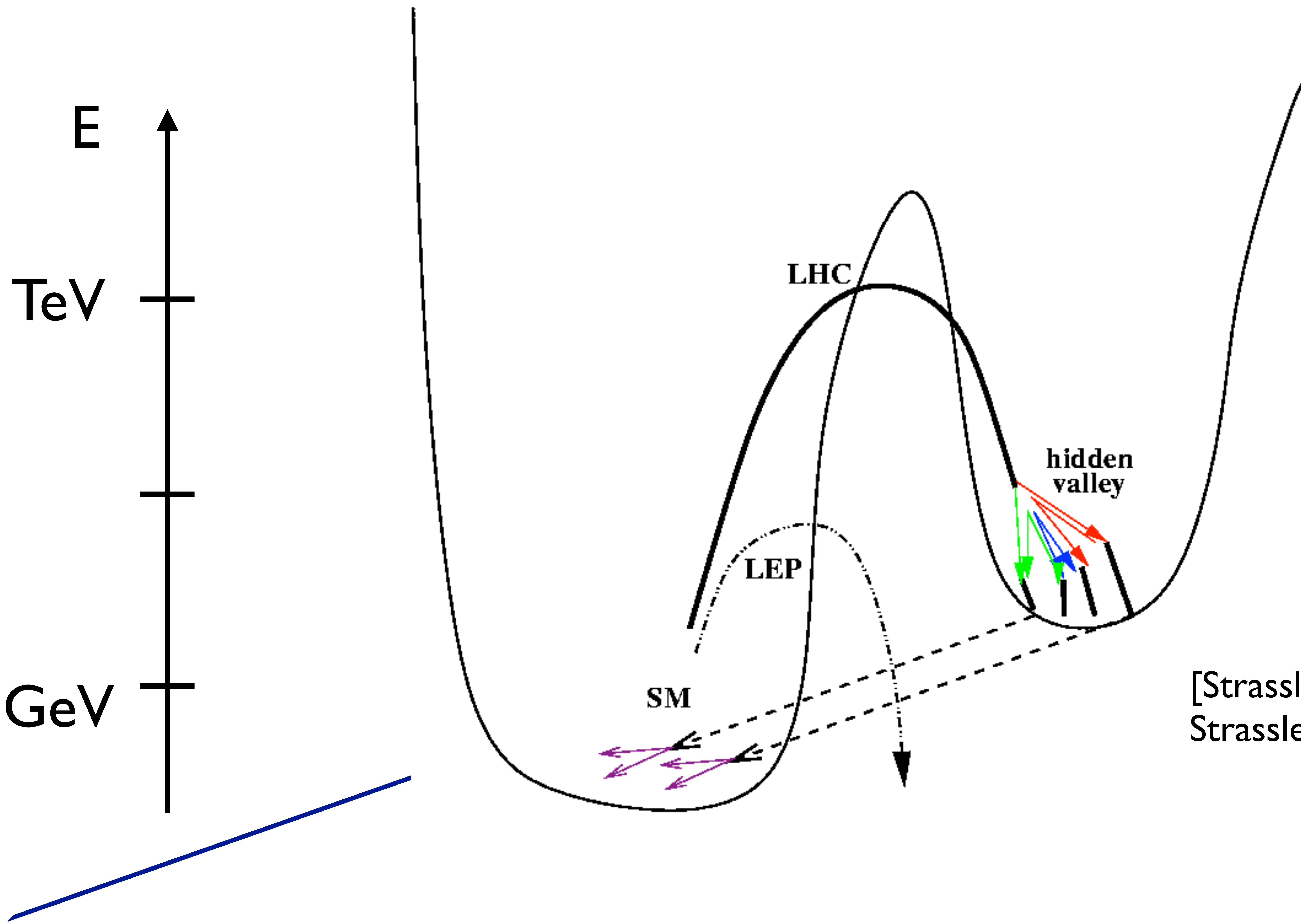
- Introduction and motivation
- Collider
  1. Signatures
  2. Models
  3. Constraints

- Dark Matter
  1. Production mechanisms
  2. Benchmark models constraints

- Conclusions

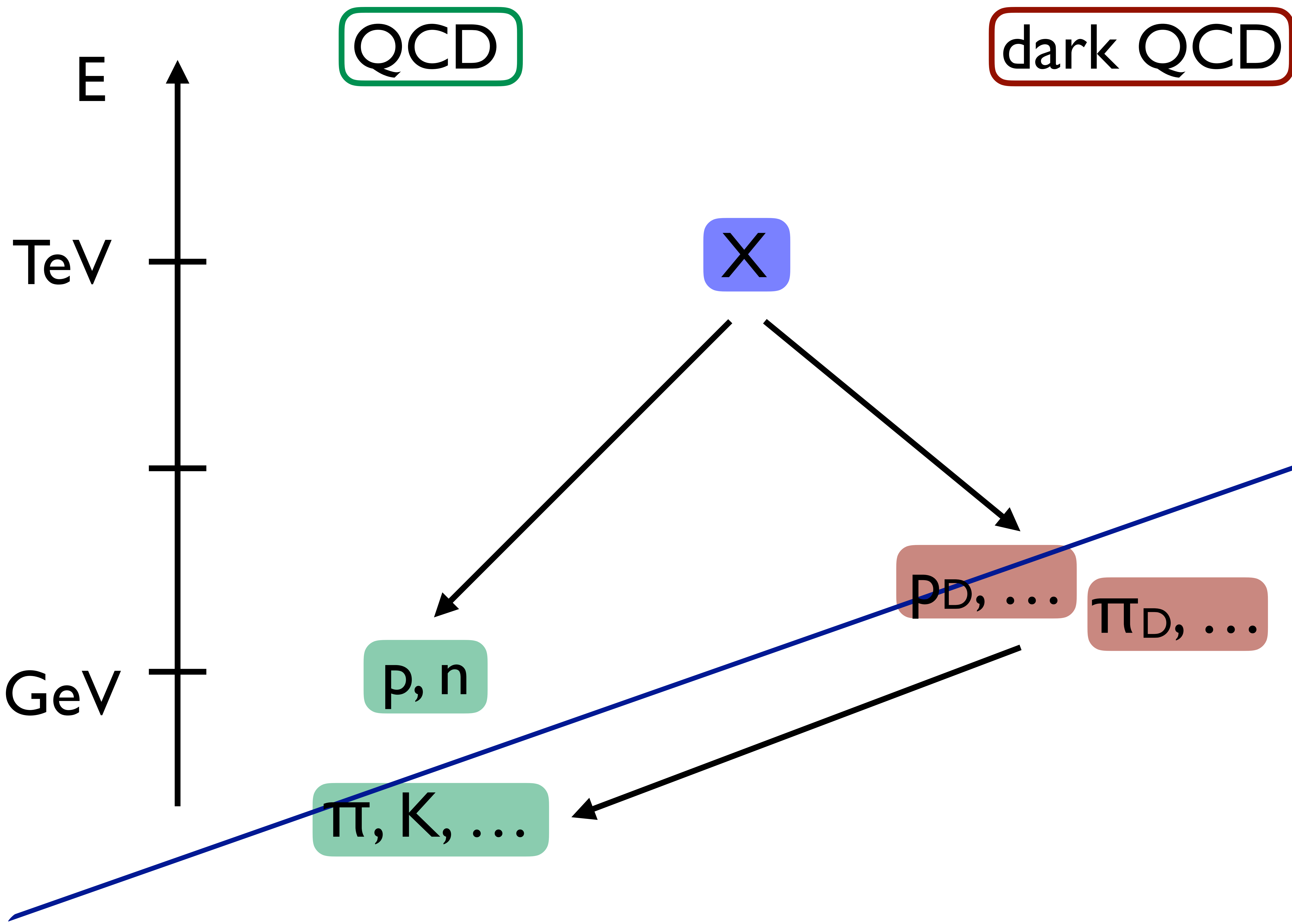
Introduction

Introduction



[Strassler, Zurek '06, Strassler '08]

Introduction

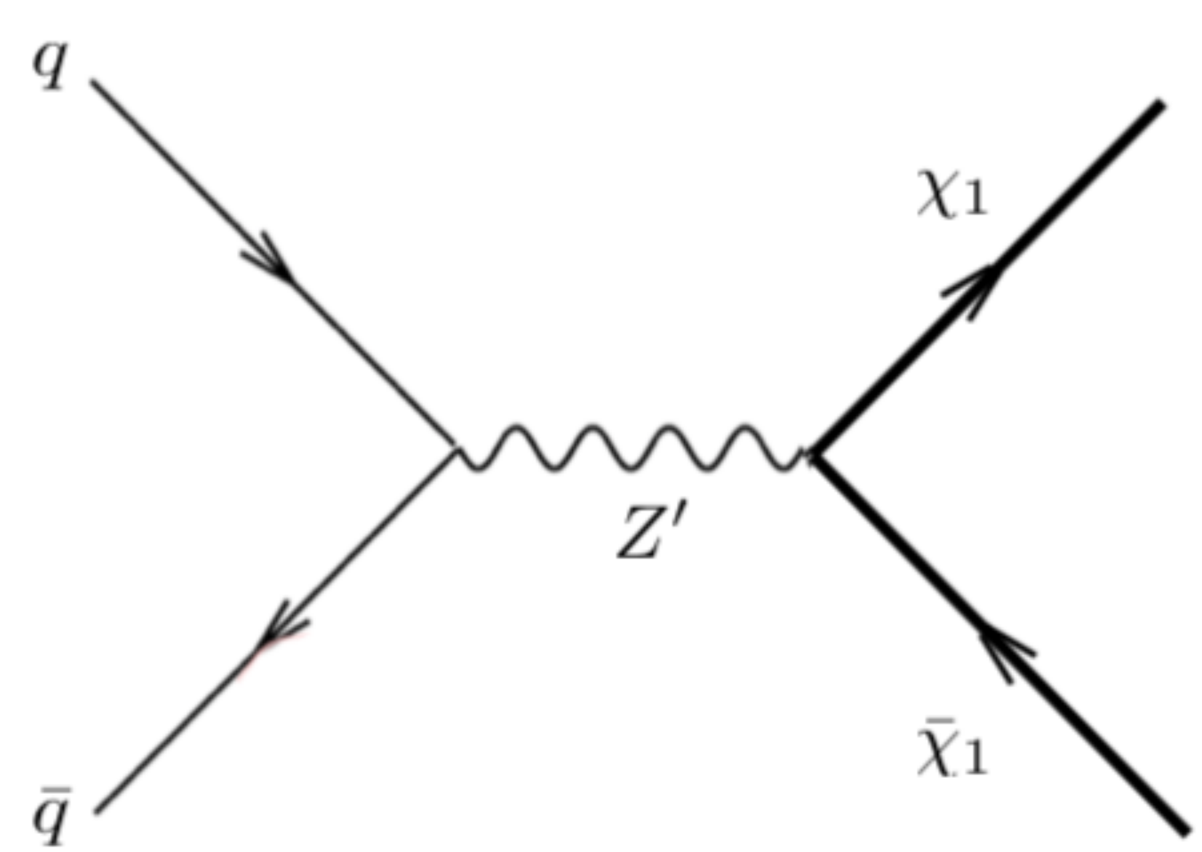


1) SU(N) dark sector;
2) neutral dark quarks;
3) confinement scale Λ;
4) dark mesons can be unstable or long lived.

Motivation

[Strassler, Zurek '06,
Han et al. '07, Strassler '08,
Baumgart et al. '09, Seth '11,
Chan et al. 11, …,
Cohen et al '15, '17, …]

Spin one mediators are very well studied.



Motivation

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Cohen et al '15, '17, …]

Spin 0 and 1/2 mediators well motivated:

Motivation

Spin 0 and 1/2 mediators well motivated:

Twin Higgs UV completions

[Chacko et al. '05]

$$SU(6)\times SU(4)\supset SU(3)_A\times SU(3)_B\times SU(2)_A\times SU(2)_B$$

$$Q_L=(6,\bar{4})=\begin{pmatrix} q_A & \tilde{q}_A \\ \tilde{q}_B & q_B \end{pmatrix}=\begin{pmatrix} (3,2,1,1) & (3,1,1,2) \\ (1,2,3,1) & (1,1,3,2) \end{pmatrix}$$

$$T_R=(\bar{6},1)=\begin{pmatrix} t_A \\ t_B \end{pmatrix}=\begin{pmatrix} (\bar{3},1,1,1) \\ (1,1,\bar{3},1) \end{pmatrix}$$

$$yHQ_LT_R+\text{h.c.}$$

$$M(\tilde{q}^c_A\tilde{q}_A+\tilde{q}^c_B\tilde{q}_B)$$

top contribution to the Higgs potential is finite at one loop

Motivation

Spin 0 and 1/2 mediators well motivated:

Folded SUSY

[Burdman et al. '06]

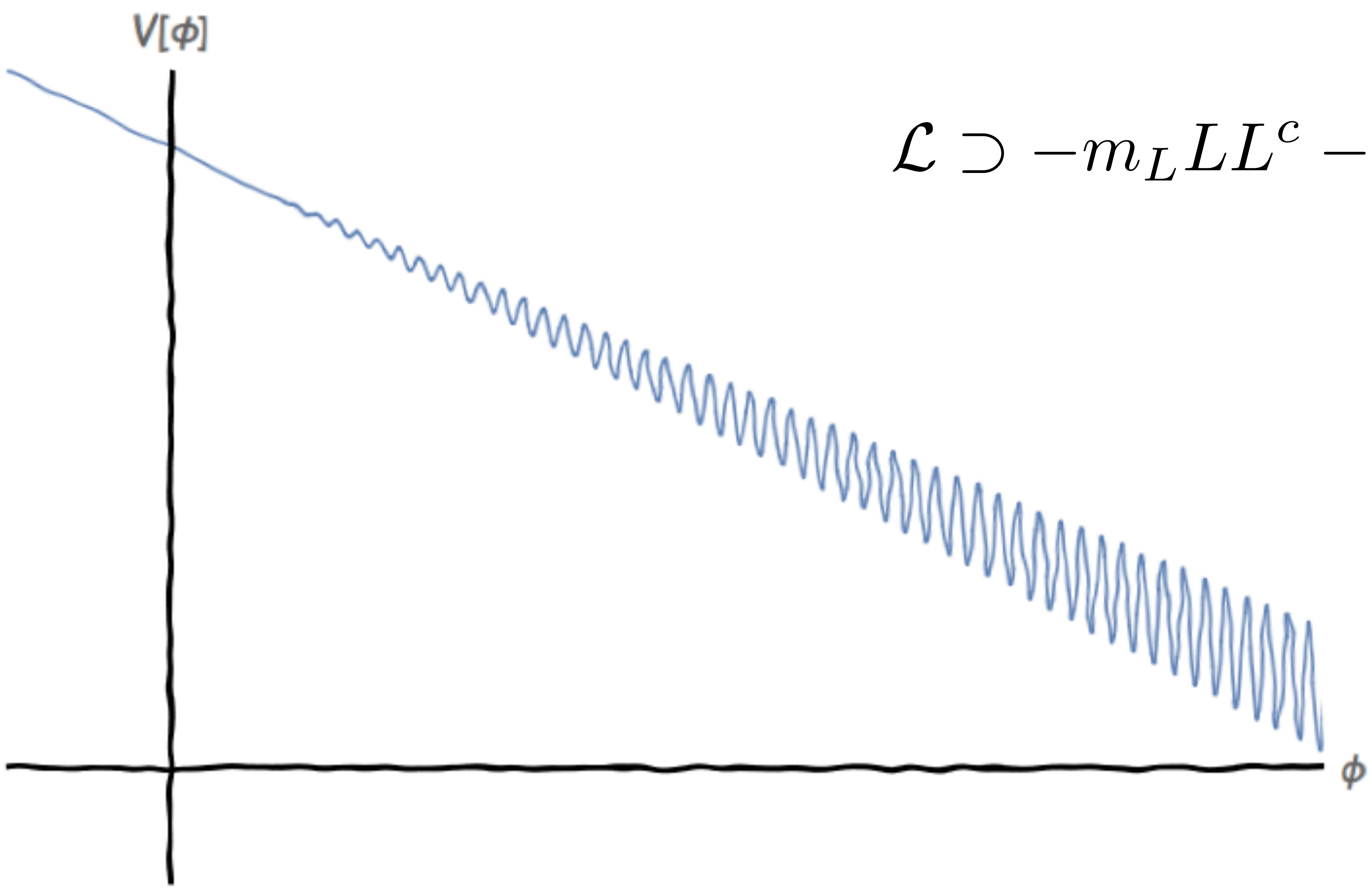
Scalar top partners charged under a mirror SU(3).

Motivation

Spin 0 and 1/2 mediators well motivated:

Relaxion

[Graham et al. '15]



$$\mathcal{L} \supset -m_L L L^c - m_N N N^c - y H L N^c - \tilde{y} H^\dagger L^c N + \text{h.c.}$$

Motivation

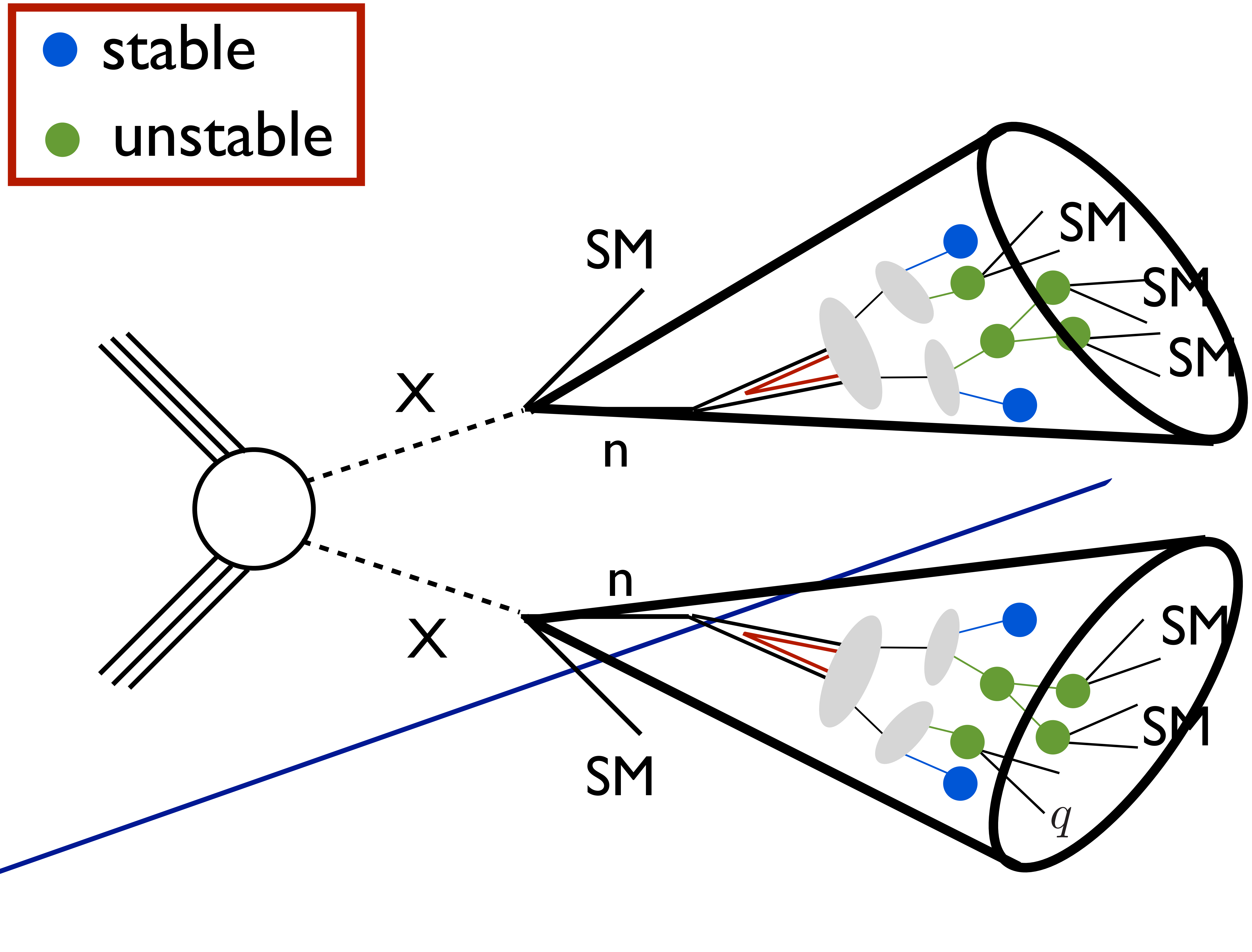
Hidden Valley models can have DM candidates:

1. Asymmetric DM: GeV scale
   [Kaplan, Luty & Zurek '09, Kim & Zurek '13, …]
2. Non-WIMP scenarios: MeV - GeV scale
   [Bhattachrya et al. '13, Cline et al. '13, Hochberg et al '14, …, Beauchesne, Bertuzzo & G^{2}dC '18, Beauchesne & G^{2}dC, in prep.]
3. …

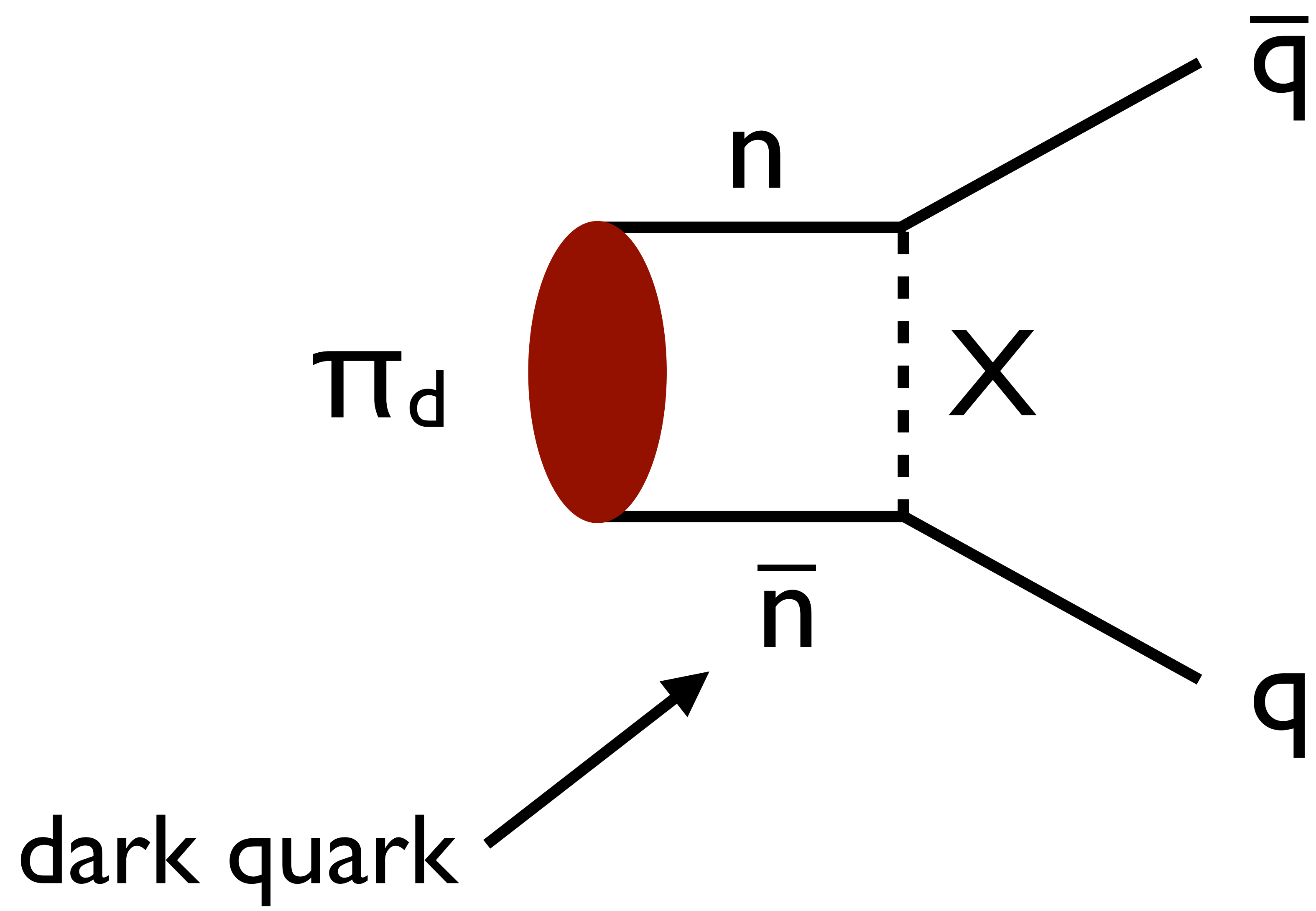
second part of the talk

Signatures

Signatures



Signatures



$$\tau_0 = \Gamma^{-1}(\pi_d \to \bar{q}q) \approx \frac{1}{\lambda^4}\left(\frac{m_X}{\mathrm{TeV}}\right)^4 \left(\frac{\mathrm{GeV}}{f_{\pi_d}}\right)^2 \left(\frac{0.1\,\mathrm{GeV}}{m_{\mathsf{n}}}\right)^2 \left(\frac{\mathrm{GeV}}{m_{\pi_d}}\right) \mathrm{cm}$$

Signatures

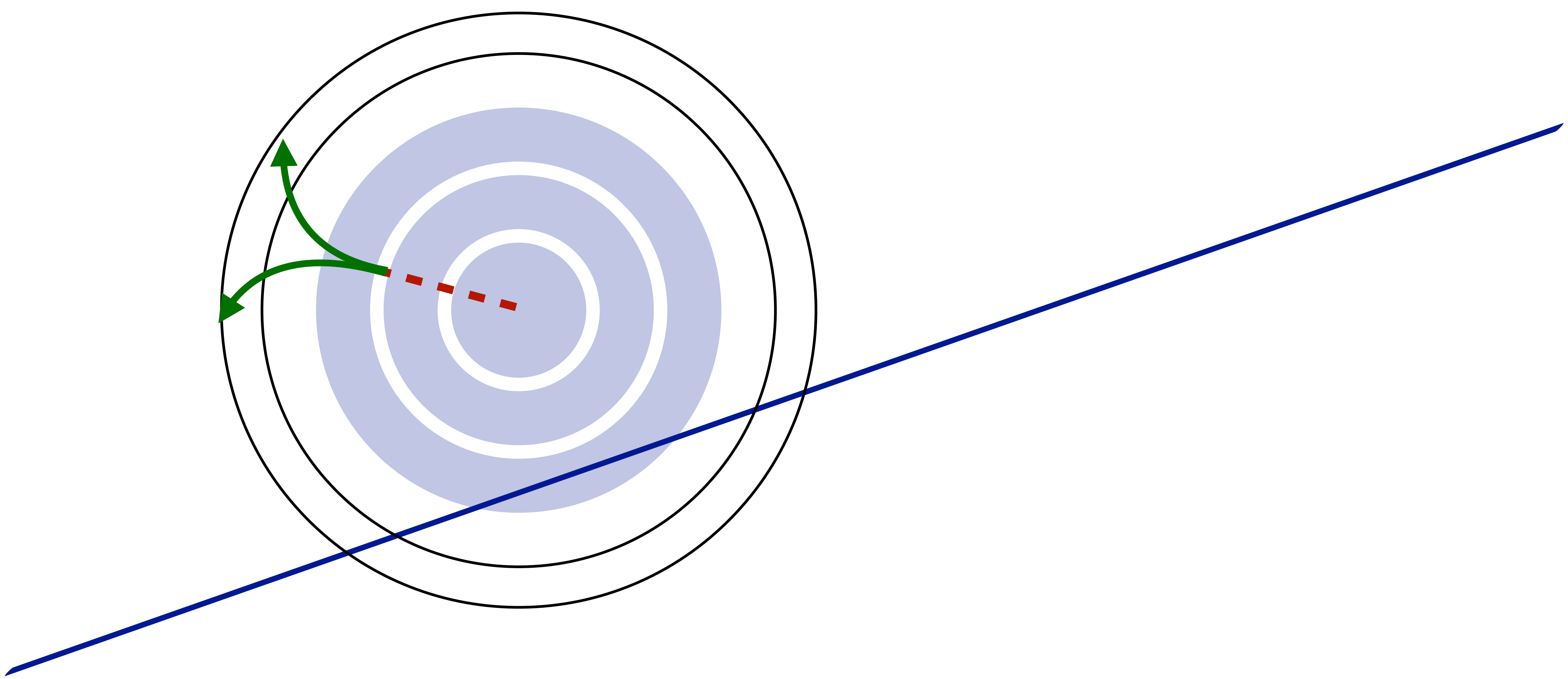
Stable dark hadrons on collider scales

Dark hadrons leads to MET:
SUSY with R-parity searches

Signatures

Dark hadrons decaying inside the detector

Displaced vertices



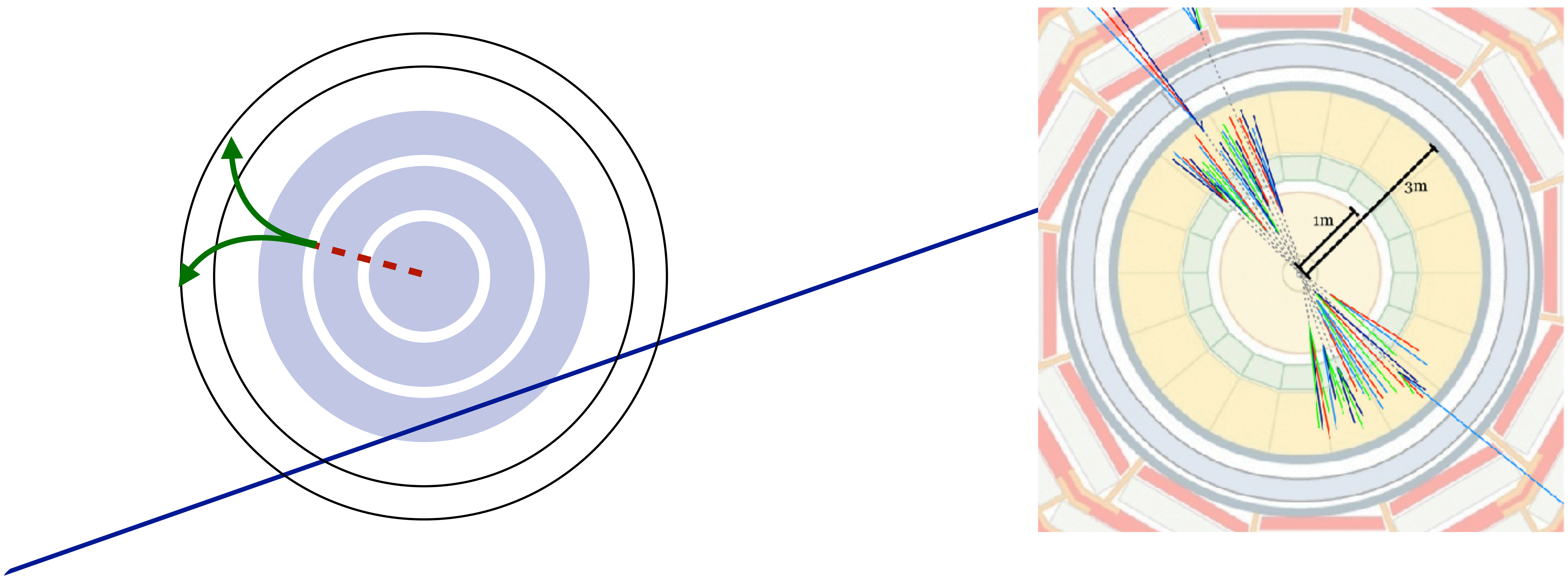
Signatures

Dark hadrons decaying inside the detector

[Schwaller et al. ’15]

Displaced vertices

Emerging jets



Signatures

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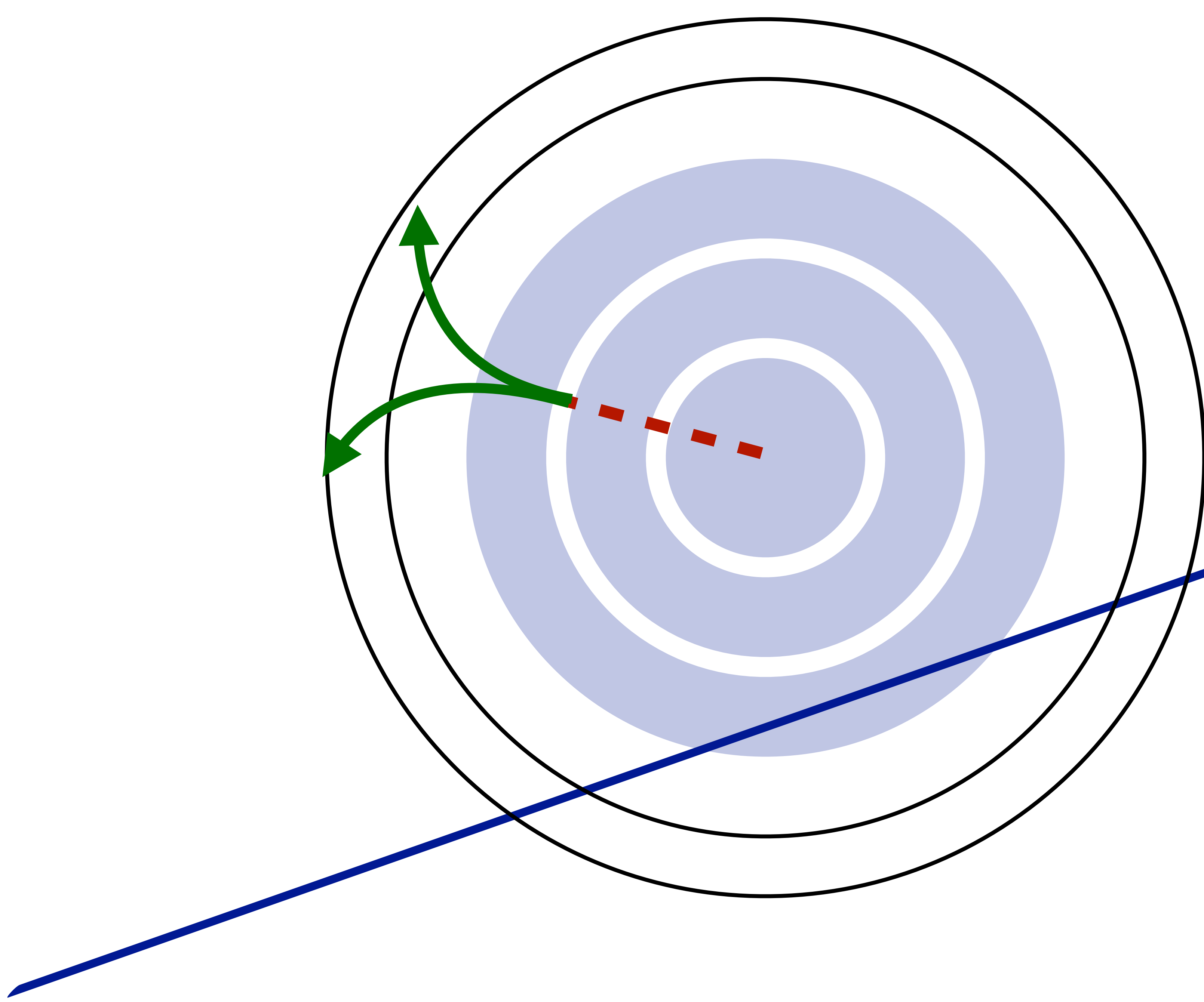
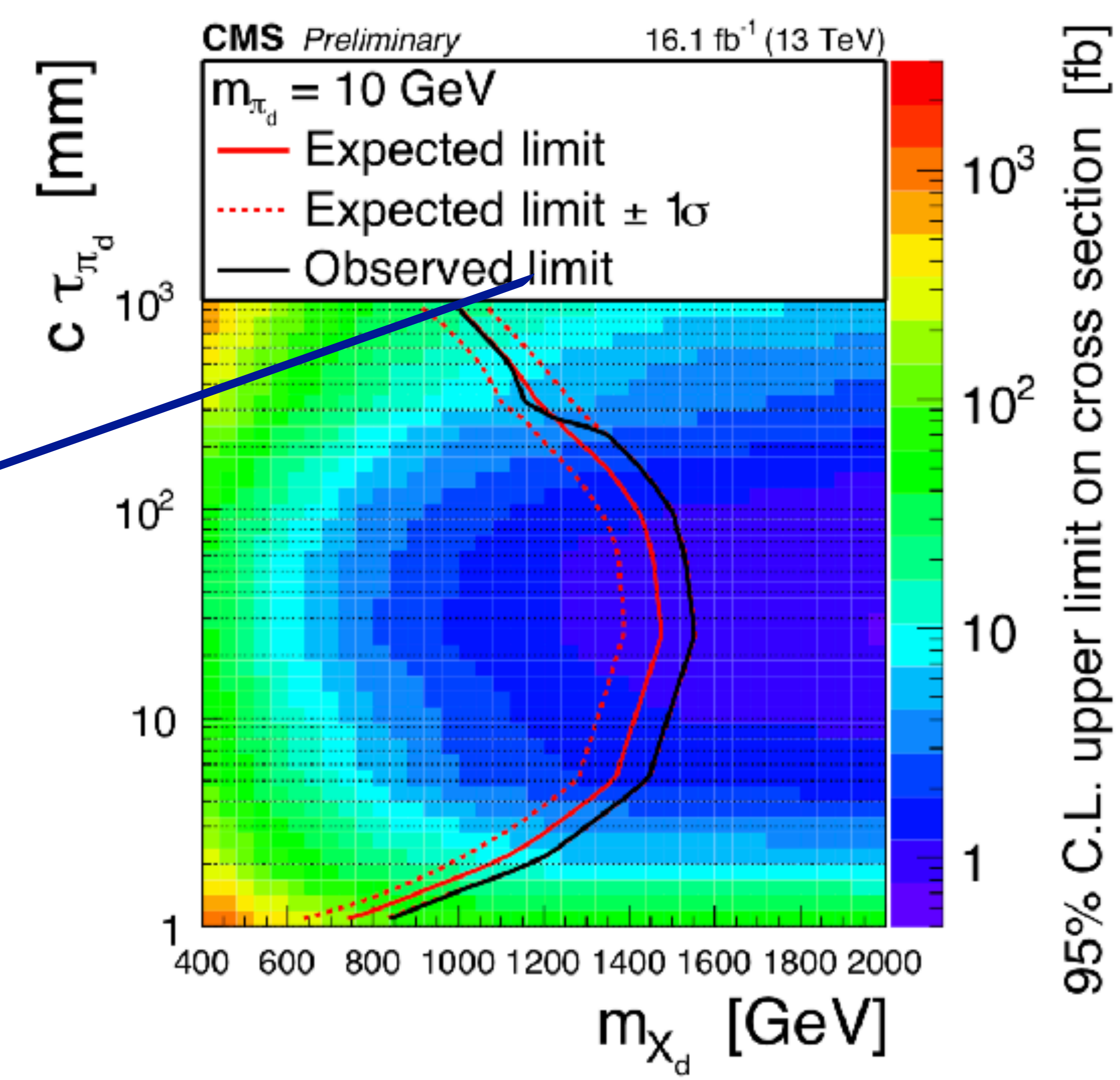


Emerging jets

[Schwaller et al. '15, CMS-PAS-EXO-18-001]

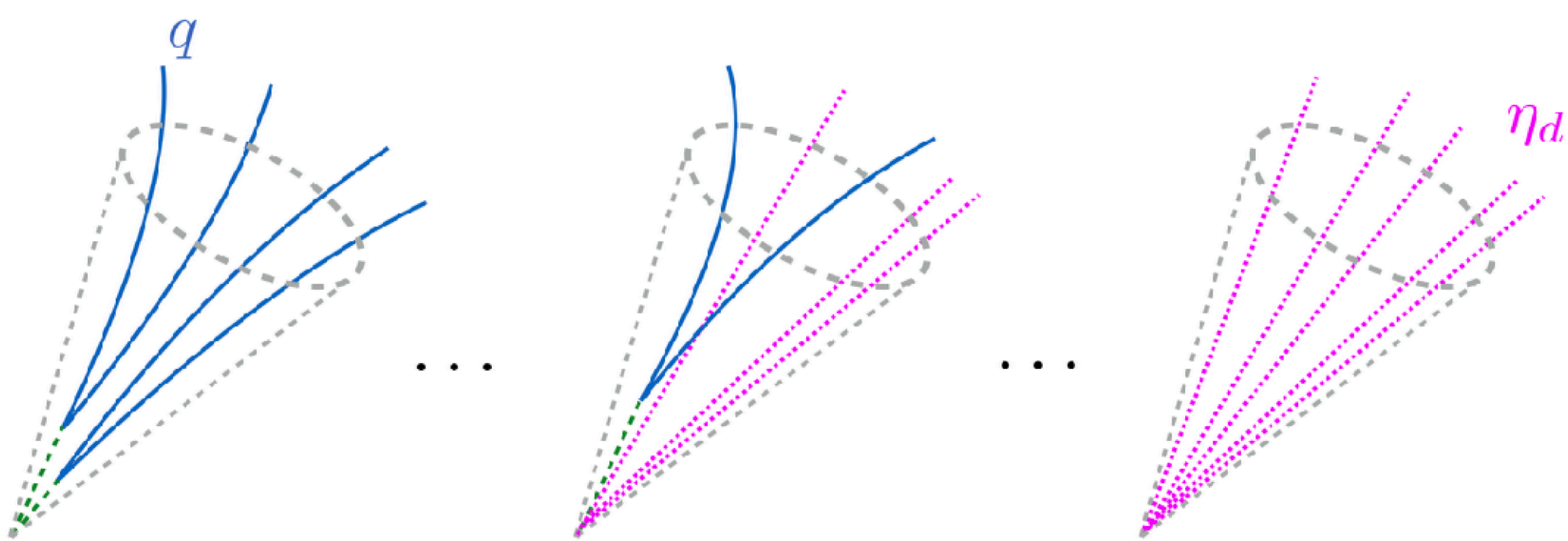


Signatures

Dark hadrons decaying promptly

[Cohen et al. '15, Cohen et al.'17]

Semivisible jets



Signatures

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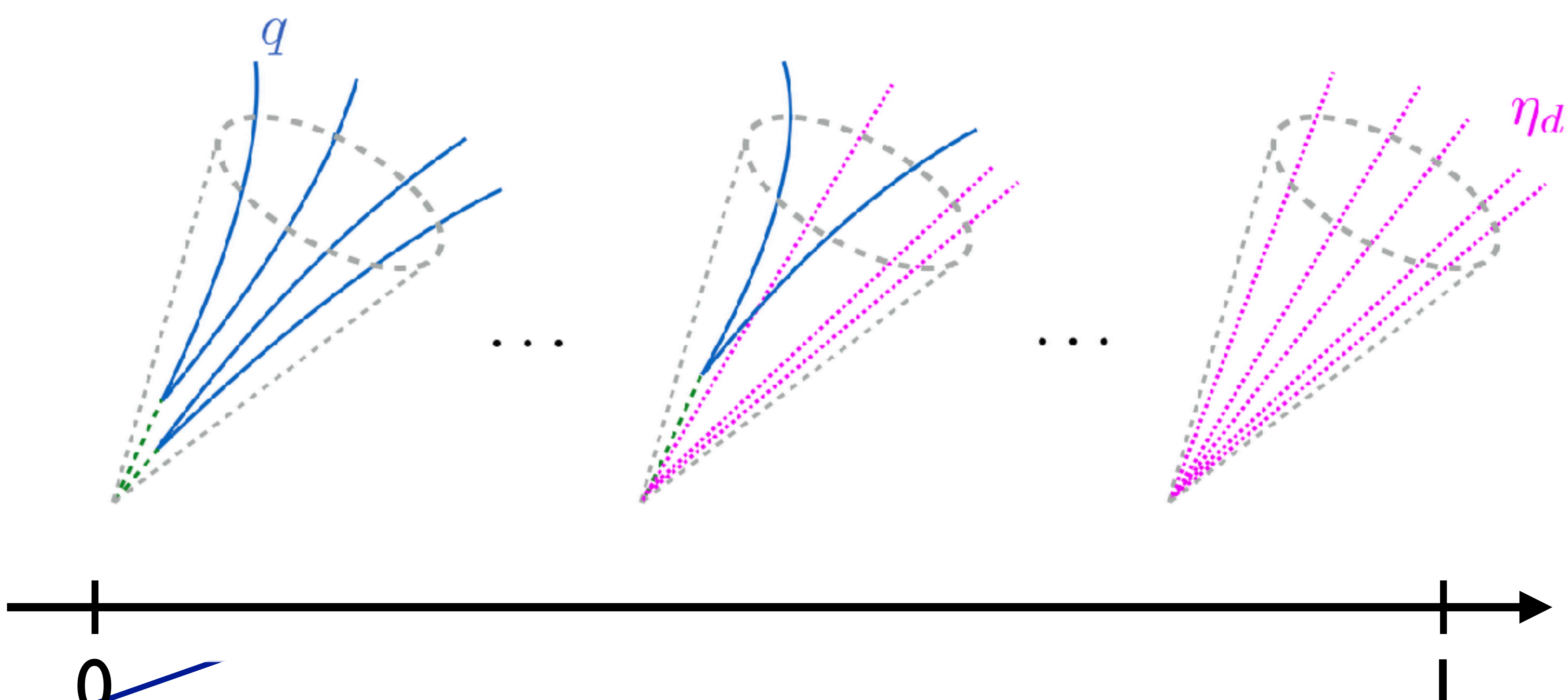
Semivisible jets



r_{inv} = average fraction of energy transmitted to MET

Signatures

Dark hadrons decaying promptly

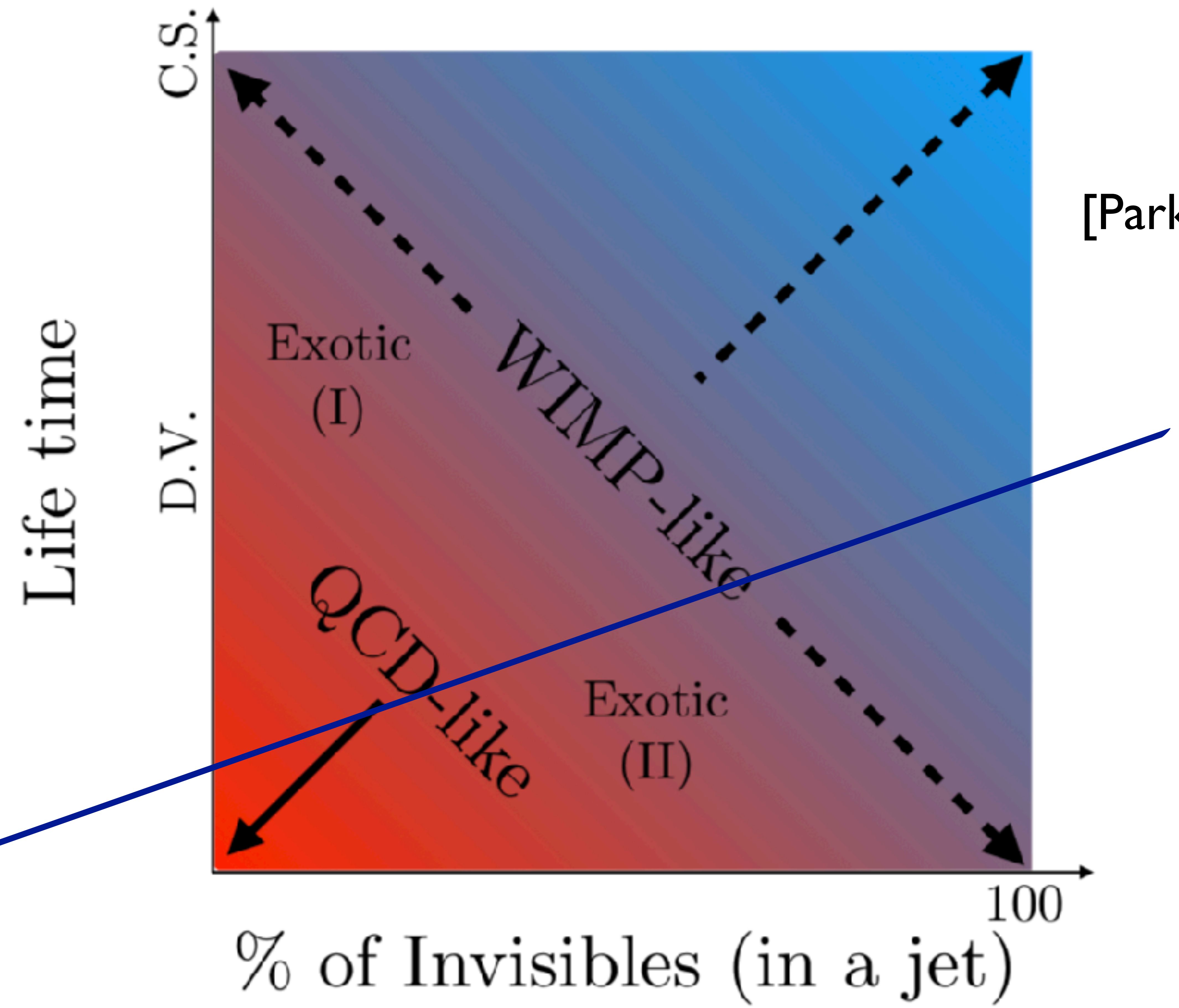
Semivisible jets

Example:

- many dark quarks generation n_i;
- one mediator communicates with one n_i;
- there is a U(1) symmetry associated to each n_i;
- the mesons $\bar{n}_i n_j$ are unstable only for i=j.

Signatures

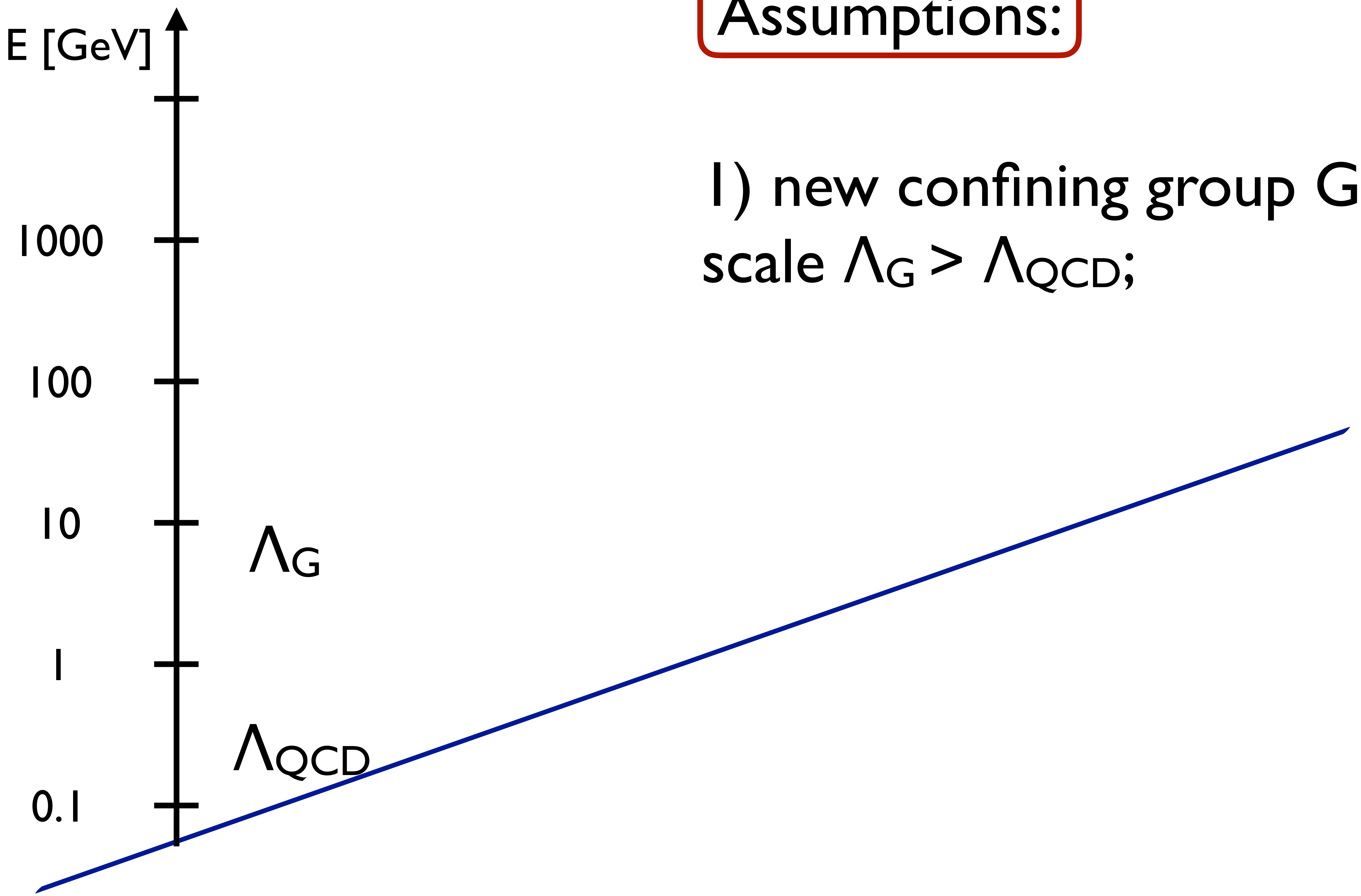
Several combinations



[Park and Zhang, '17]

General setup

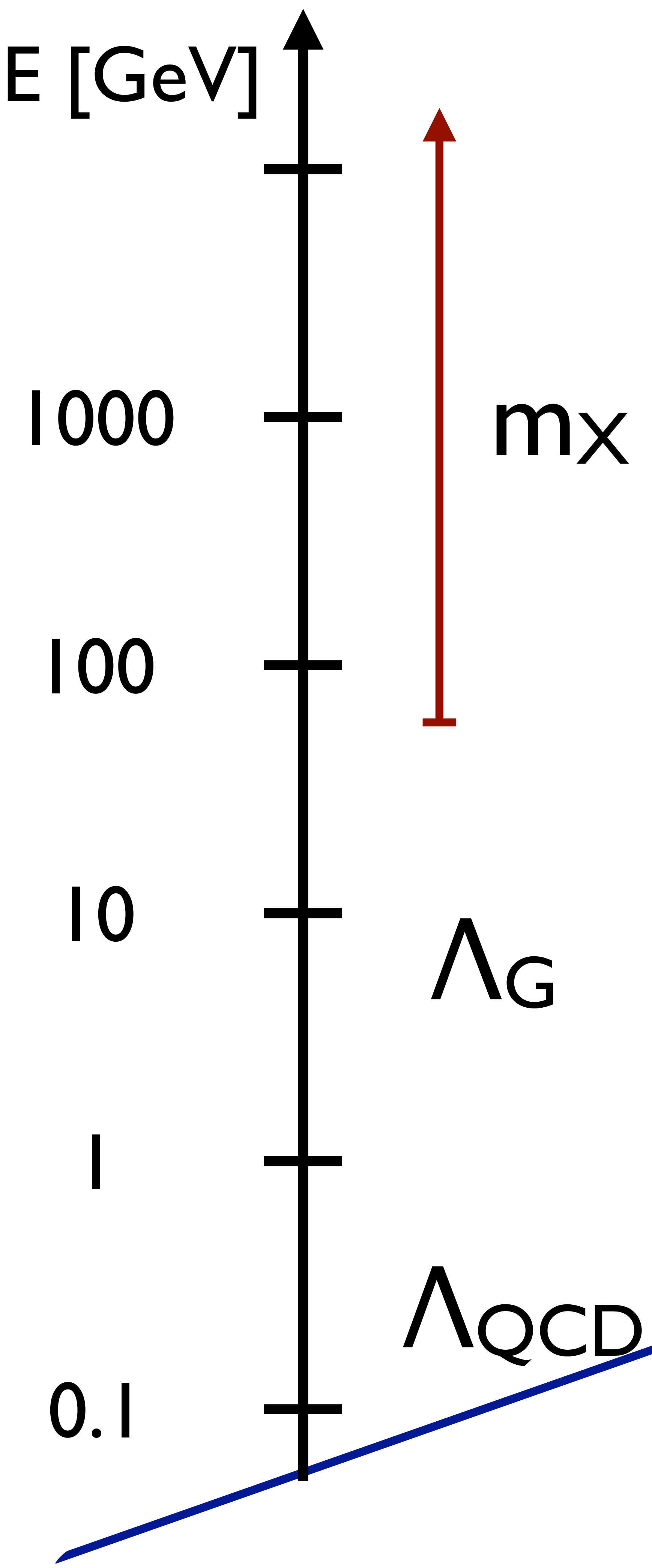
General setup



Assumptions:

1) new confining group G with confinement scale $\Lambda_G > \Lambda_{QCD}$;

General setup

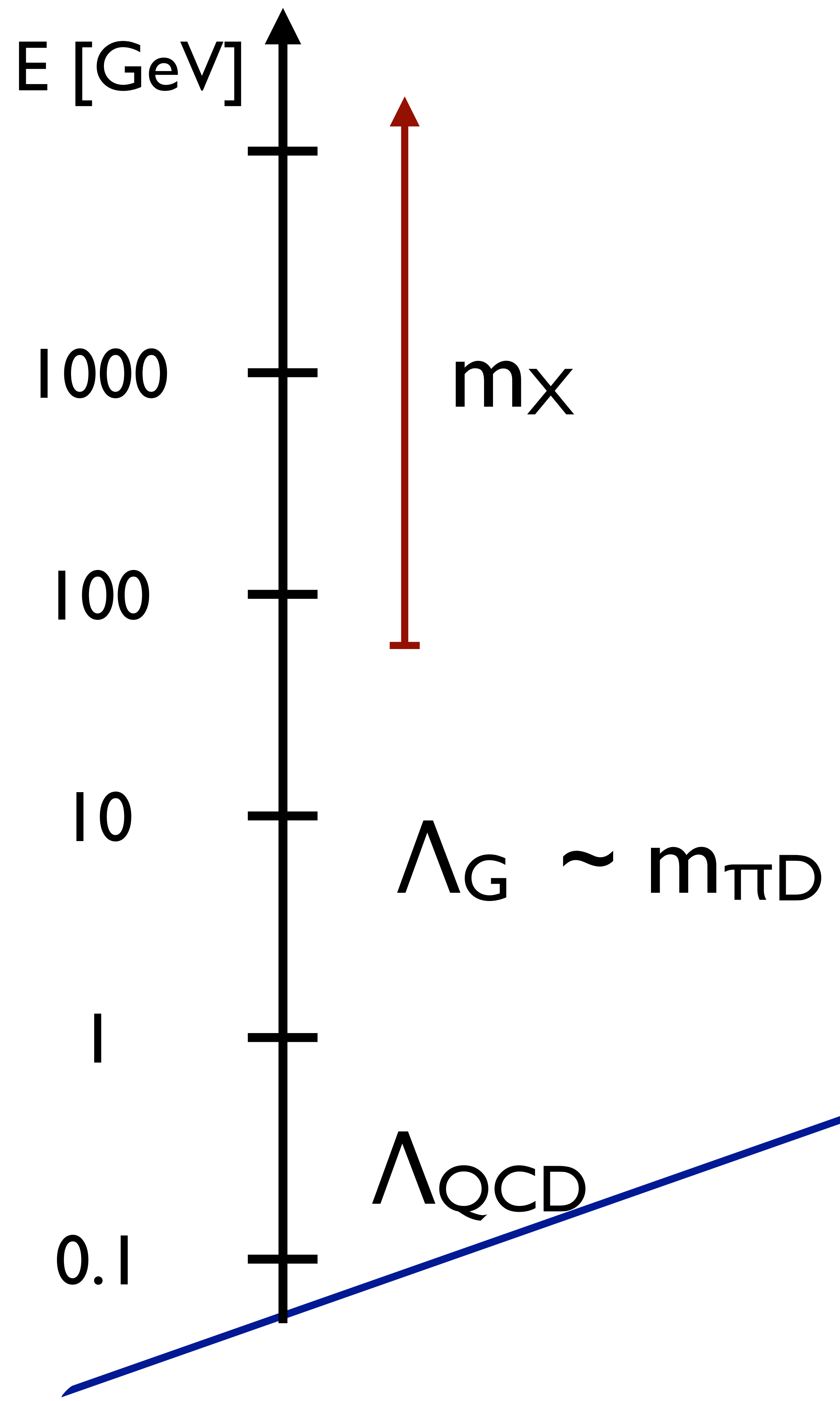


Assumptions:

1) new confining group G with confinement scale $\Lambda_G > \Lambda_{QCD}$;

2) one mediator X (scalar or fermion), charged under G and G_{SM};

General setup



Assumptions:

1) new confining group G with confinement scale $\Lambda_G > \Lambda_{QCD}$;

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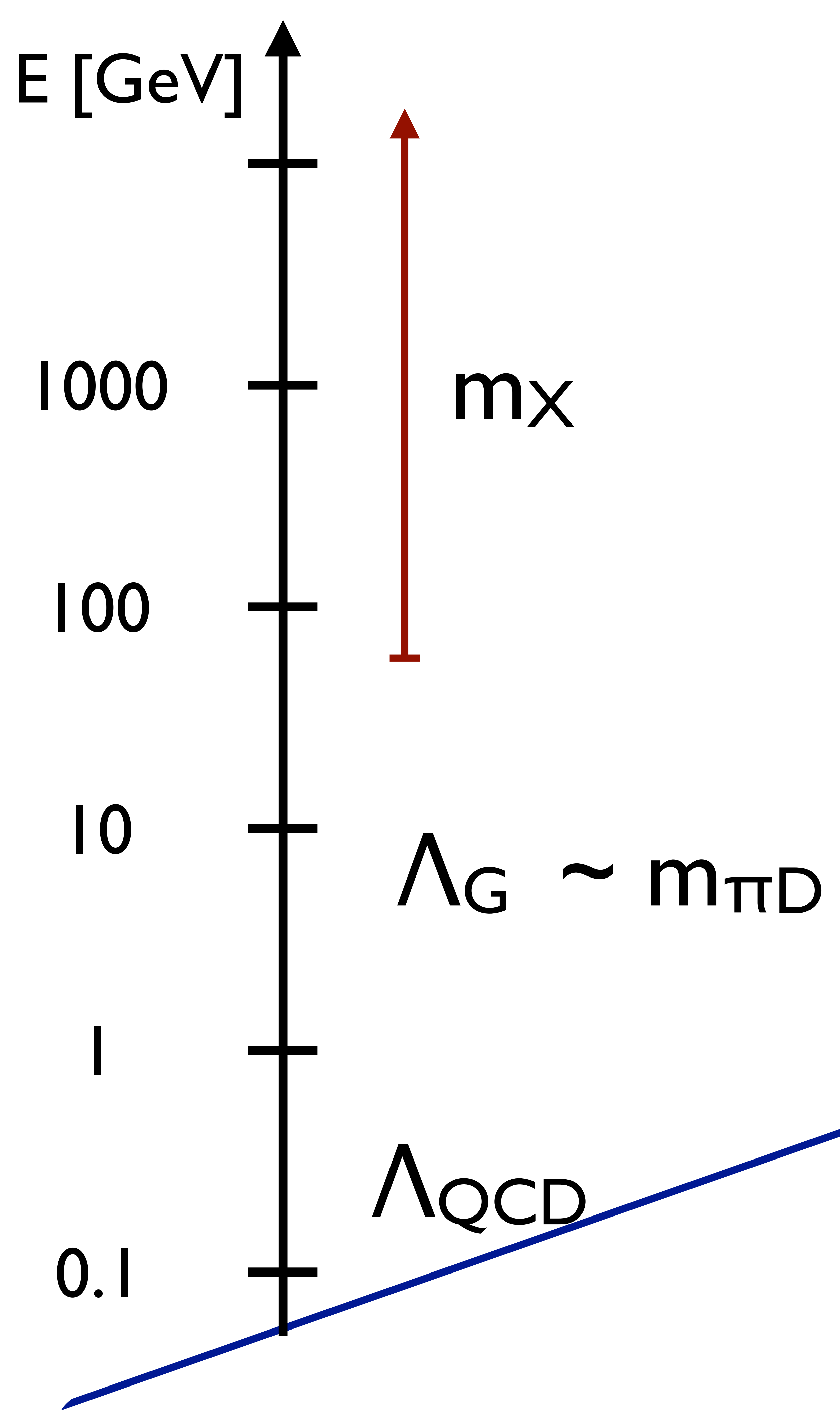
3) dark (s)quark n charged only under G.

General setup



Assumptions:

1) new confining group G with confinement scale $\Lambda_G > \Lambda_{QCD}$;

2) one mediator X (scalar or fermion), charged under G and G_{SM};

3) dark (s)quark n charged only under G.

Semivisible jets:

- originate from X decay
- have large multiplicity
- are very boosted

General setup

Mediator decays

X → for general gauge numbers →

- kinetic terms
- mass terms
- $XX^\dagger|H|^2$
- $XX^\dagger|n|^2$

→ ~~$U(1)_X$ symmetry mediator stable~~

General setup

Spontaneous breaking

Leads to uneaten Goldstone, leads to cosmological problems and challenge EWPT

Not ruled out but problematic

Explicit breaking

Introduce d=4 operators that explicitly break $U(1)_X$.

Ignore operators that preserve Z_N symmetry.

Finite number of operators classified in 5 categories (I will discuss only 2).

Case 1

Case I

scalar or fermion

Qi, Ui, Di

dark quark

$$\lambda\, n^{\dagger} \bar{X} P_{L/R} \Psi + \text{h.c.}$$

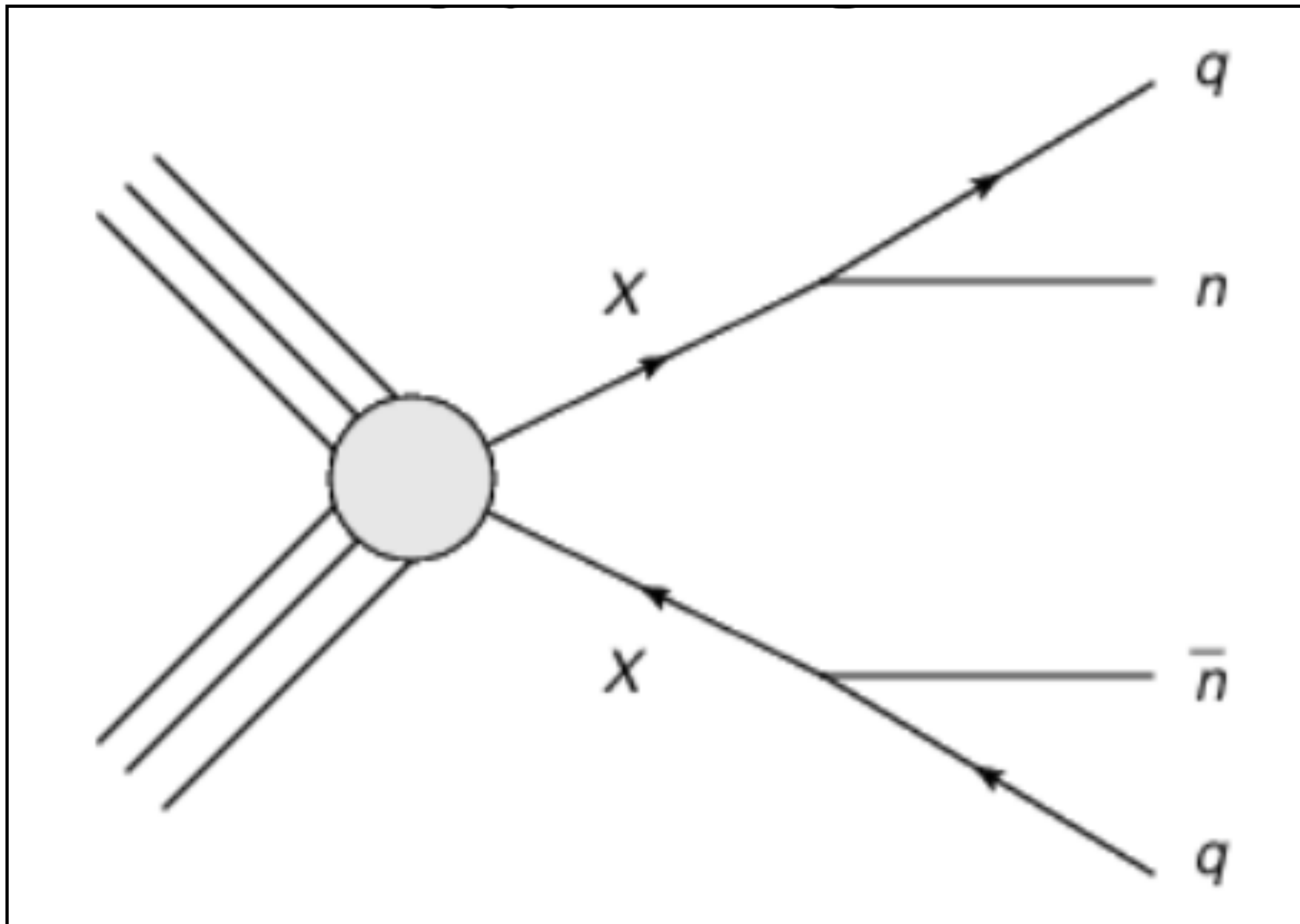
flavour?
[Renner, Schwaller '18]

coupling **mediator**

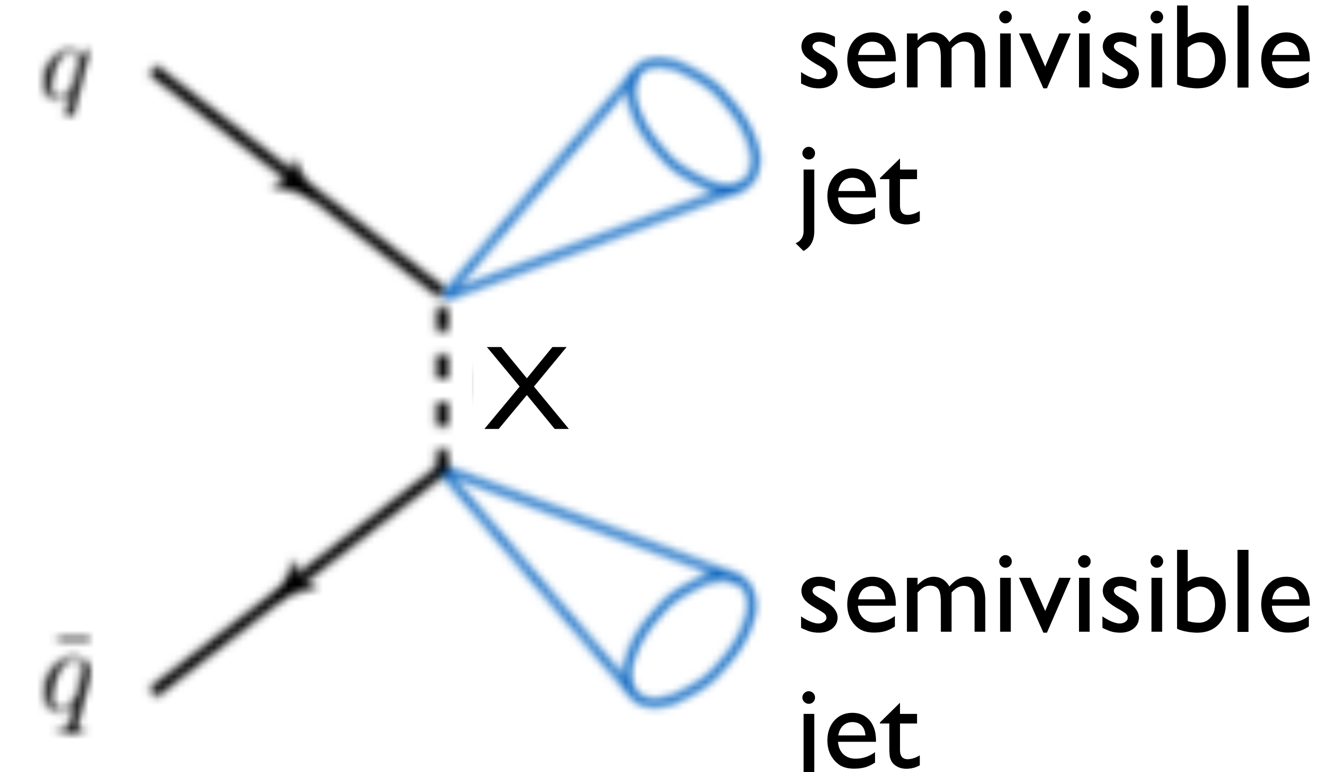
fermion or scalar

Case I

$$\lambda \, n^\dagger \bar{X} P_L q_L + \text{h.c.}$$



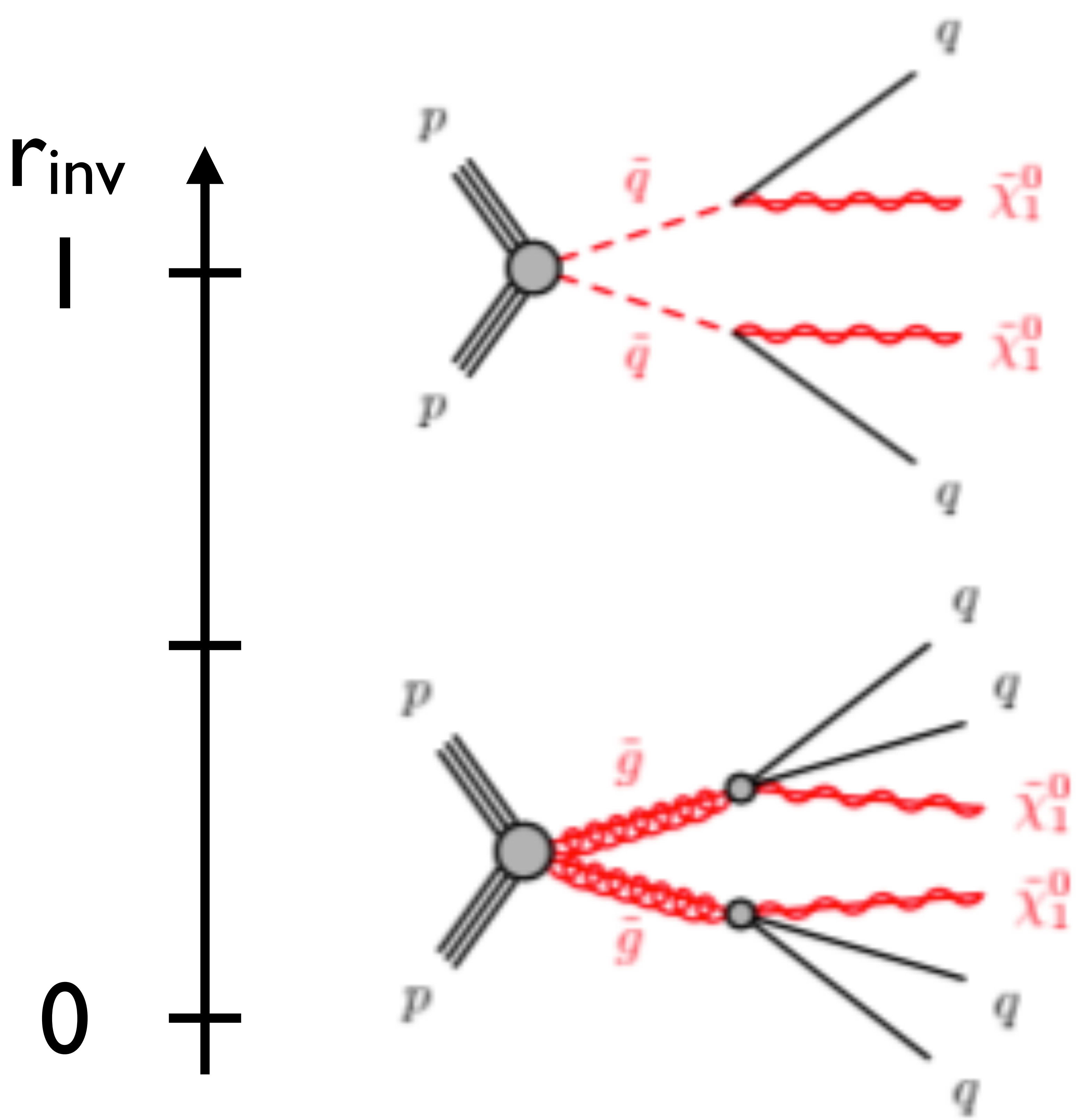
We take λ<<1 in order to avoid effects on the cross section and suppress



[Cohen et al. '17]

Case I

Large r_{inv}: first two generations



[ATLAS-CONF-2017-022]

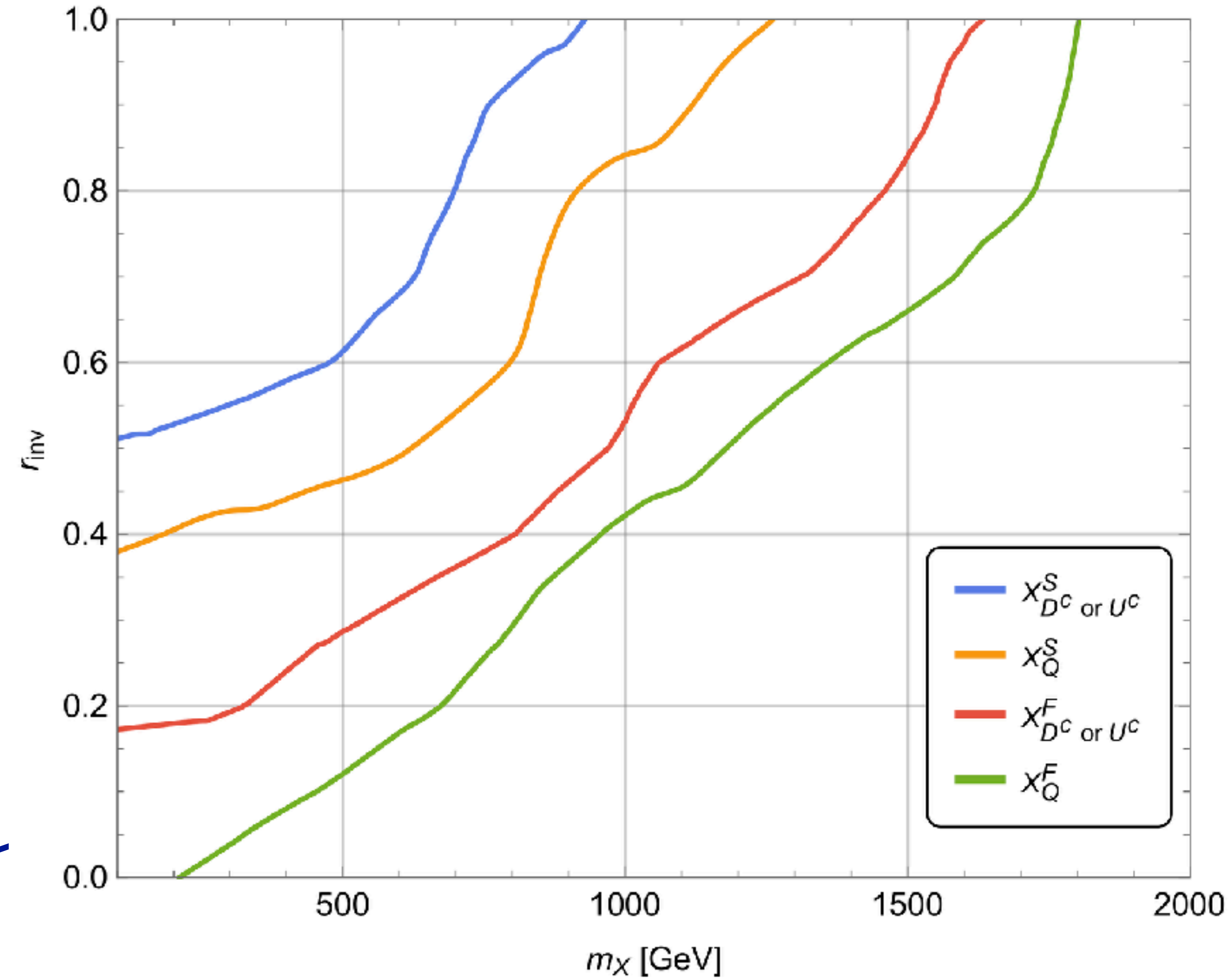
13 TeV, 36 fb^{-1}

2 or 3 jets + MET, cut on M_{eff}, cut on MET $\lesssim$ 250 GeV

4 or 5 jets + MET, cut on M_{eff}, cut on MET $\lesssim$ 250 GeV

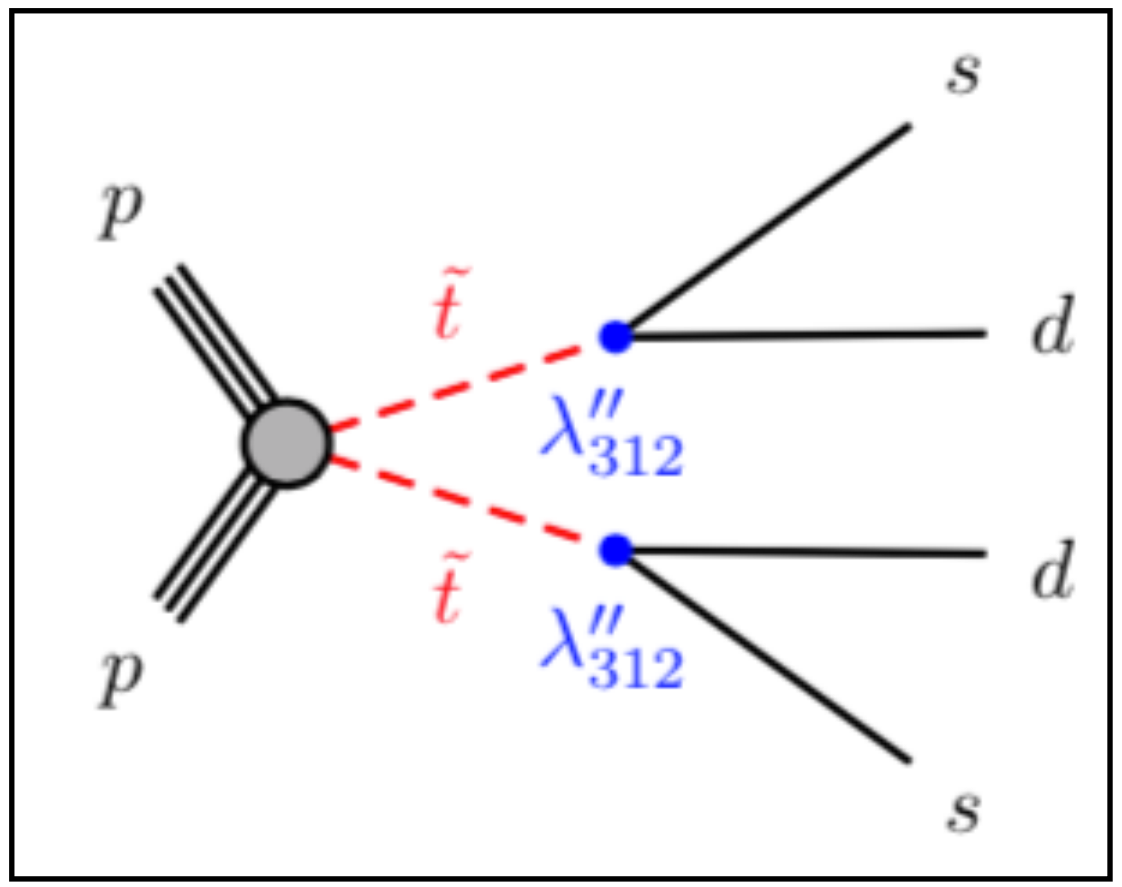
Case I

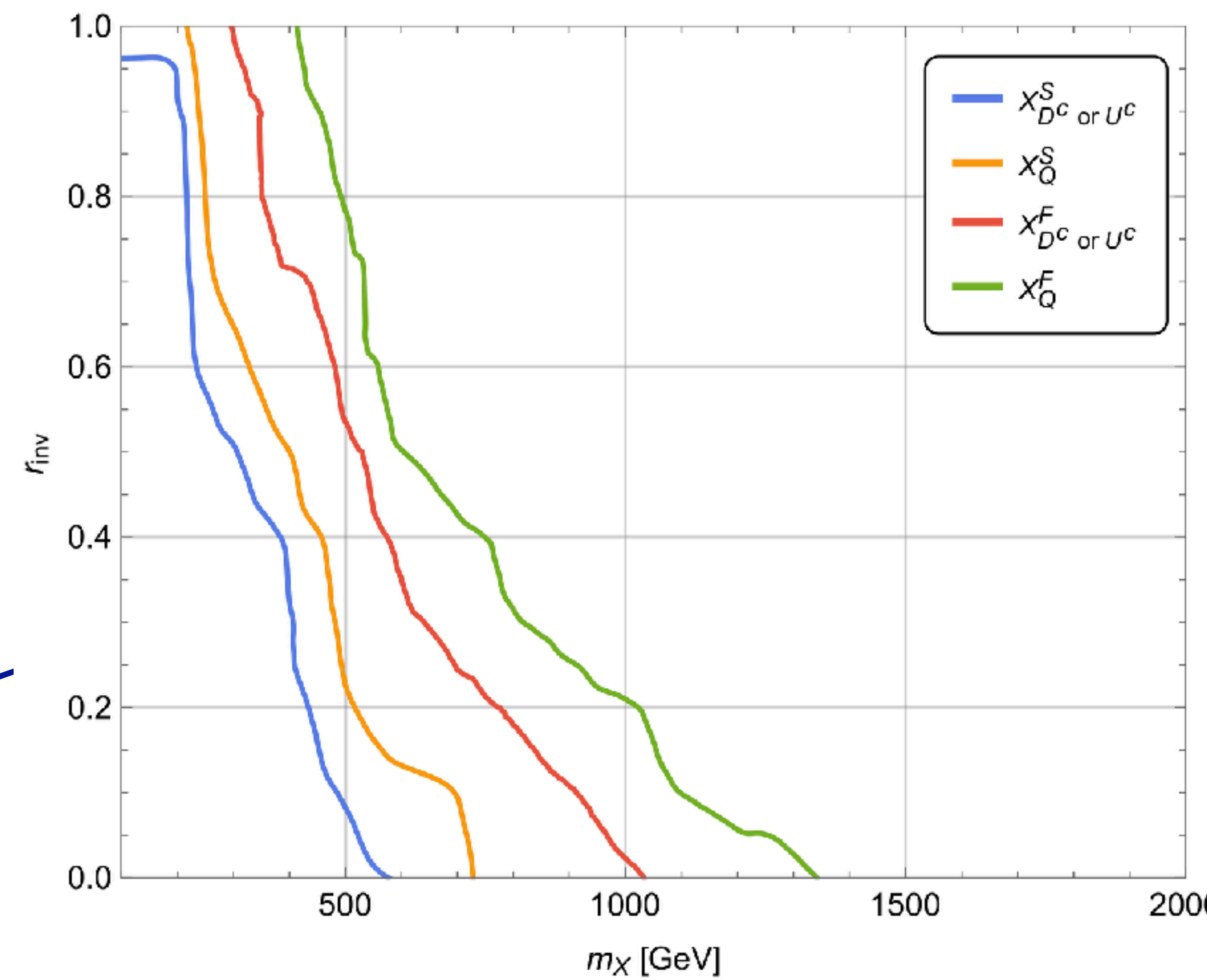
Large r_{inv}: first two generations



Case I

Small r_{inv}: first two generations





[ATLAS-CONF-2017-025]   13 TeV, 36 fb^{-1}

> 4 jets + reconstruct the dijet pairs

Case II

Case II

scalar or fermion

L_i, E_i

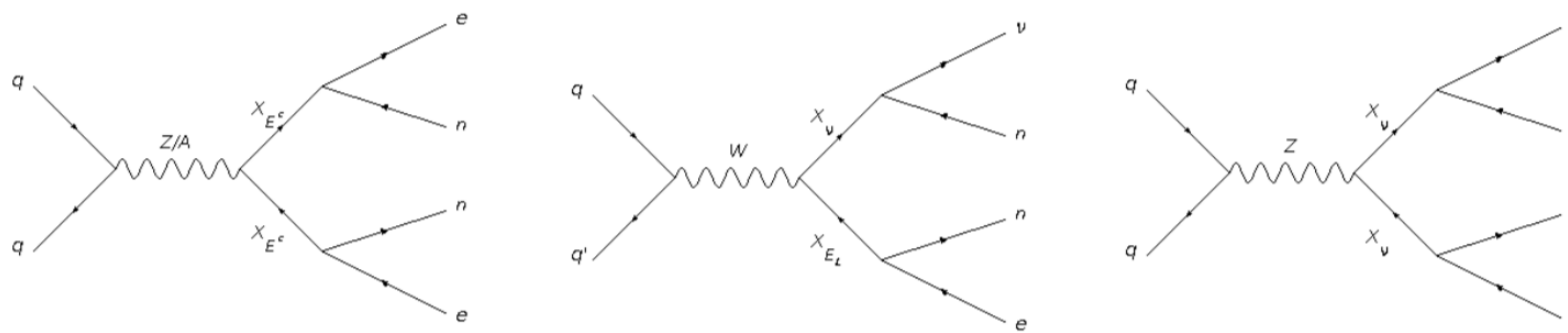
dark quark

$$\lambda \, n^\dagger \bar{X} P_{L/R} \Psi + \text{h.c.}$$

coupling **mediator**

fermion or scalar

Case II

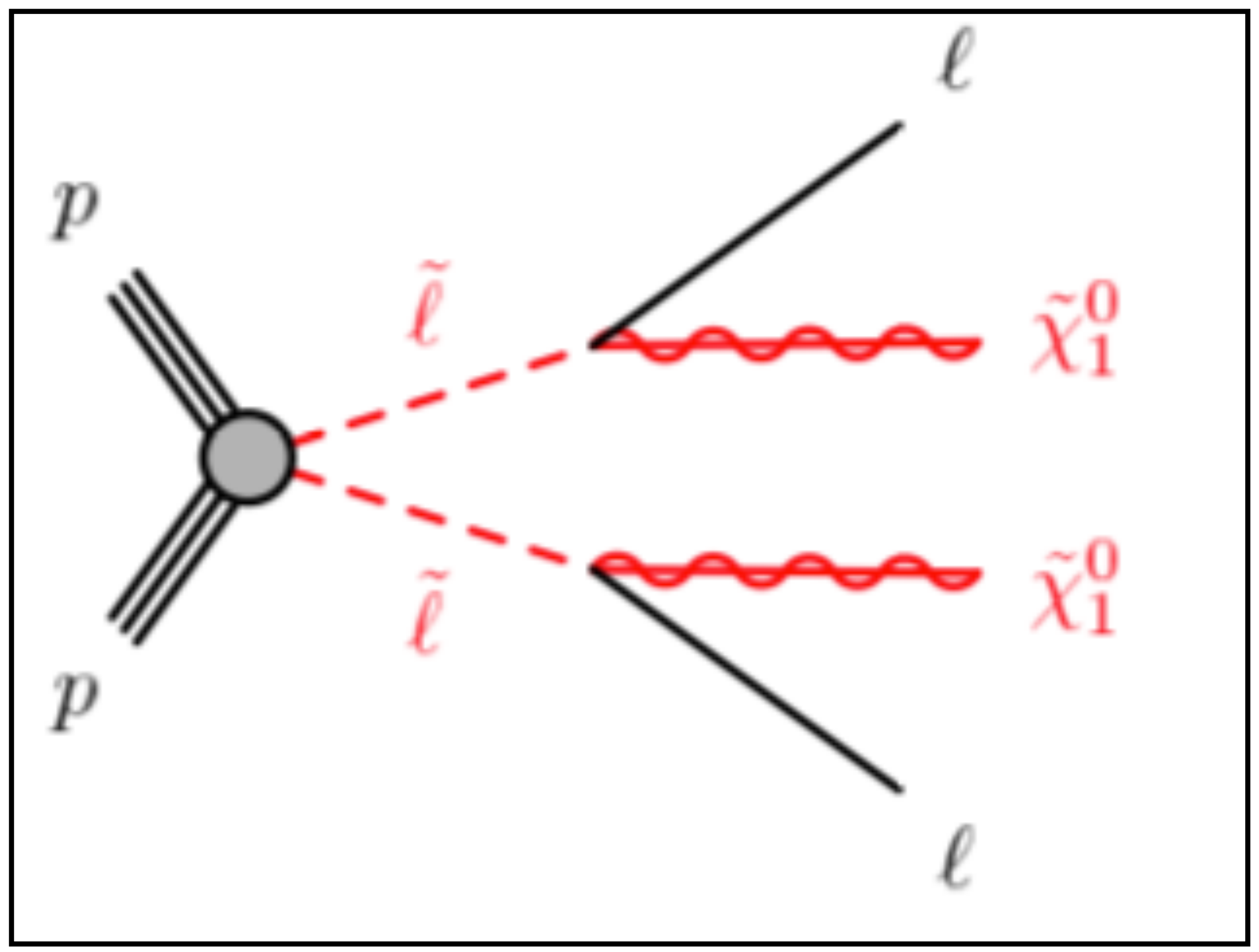


Possible signatures at hadron colliders:

1) 2 charged leptons, 2 semivisible jets and MET
2) 1 charged lepton, 2 semivisible jets and more MET
3) 0 charged leptons, 2 semivisible jets and even more MET

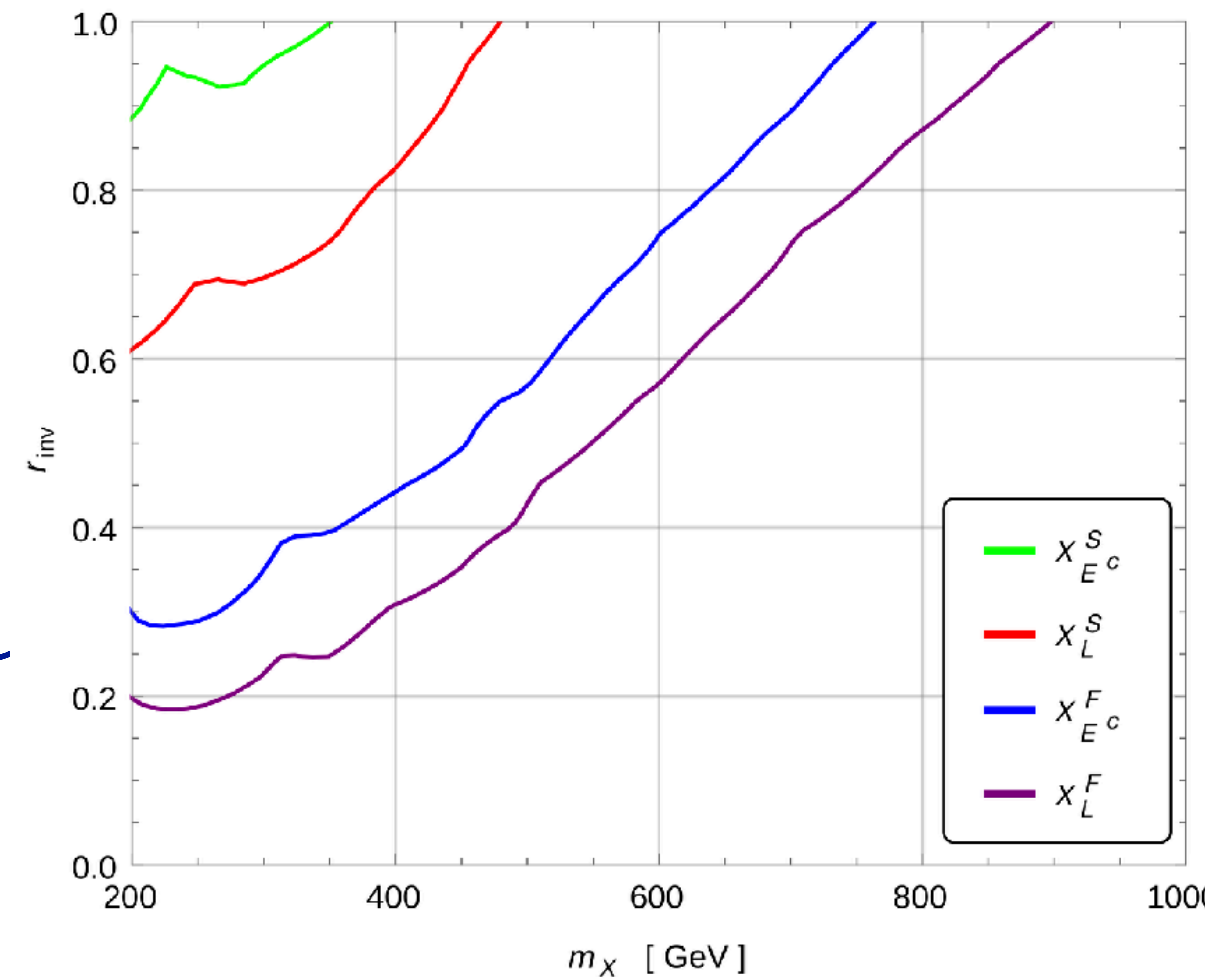
Case II

Large r_{inv}: first two generations



[ATLAS-CONF-2017-039]   13 TeV, 36 fb^{-1}

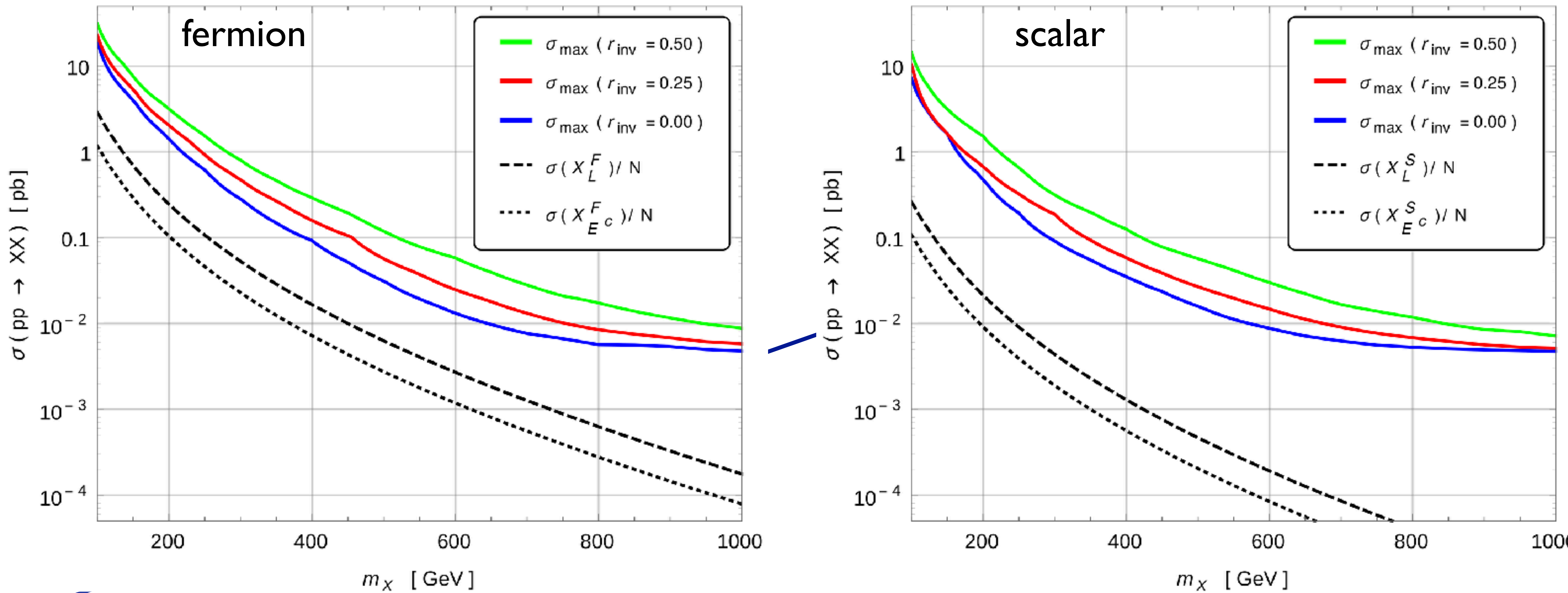
2 same flavour leptons
+ jet veto (p_T > 60 GeV)



Case II

Small r_{inv}

[CMS-PAS-EXO-16-043], 13 TeV, 2.6 fb^{-1}, requires 2 electrons and > 1 jet



Case II

Small r_{inv}

[Opal collaboration, hep-ex/0305053], 595 pb^{-1} at (189-208) GeV

$r_{inv}=0$

Mediator	Generation	$SU(2)$ [GeV]	$SU(3)$ [GeV]	$SU(4)$ [GeV]
X_L^F	1	104	104	104
	2	104	104	104
	3	103	104	104
$X_{E^c}^F$	1	103	104	104
	2	104	104	104
	3	103	103	104
X_L^S	1	93	95	96
	2	98	99	100
	3	91	93	95
$X_{E^c}^S$	1	93	95	96
	2	98	99	100
	3	90	93	94

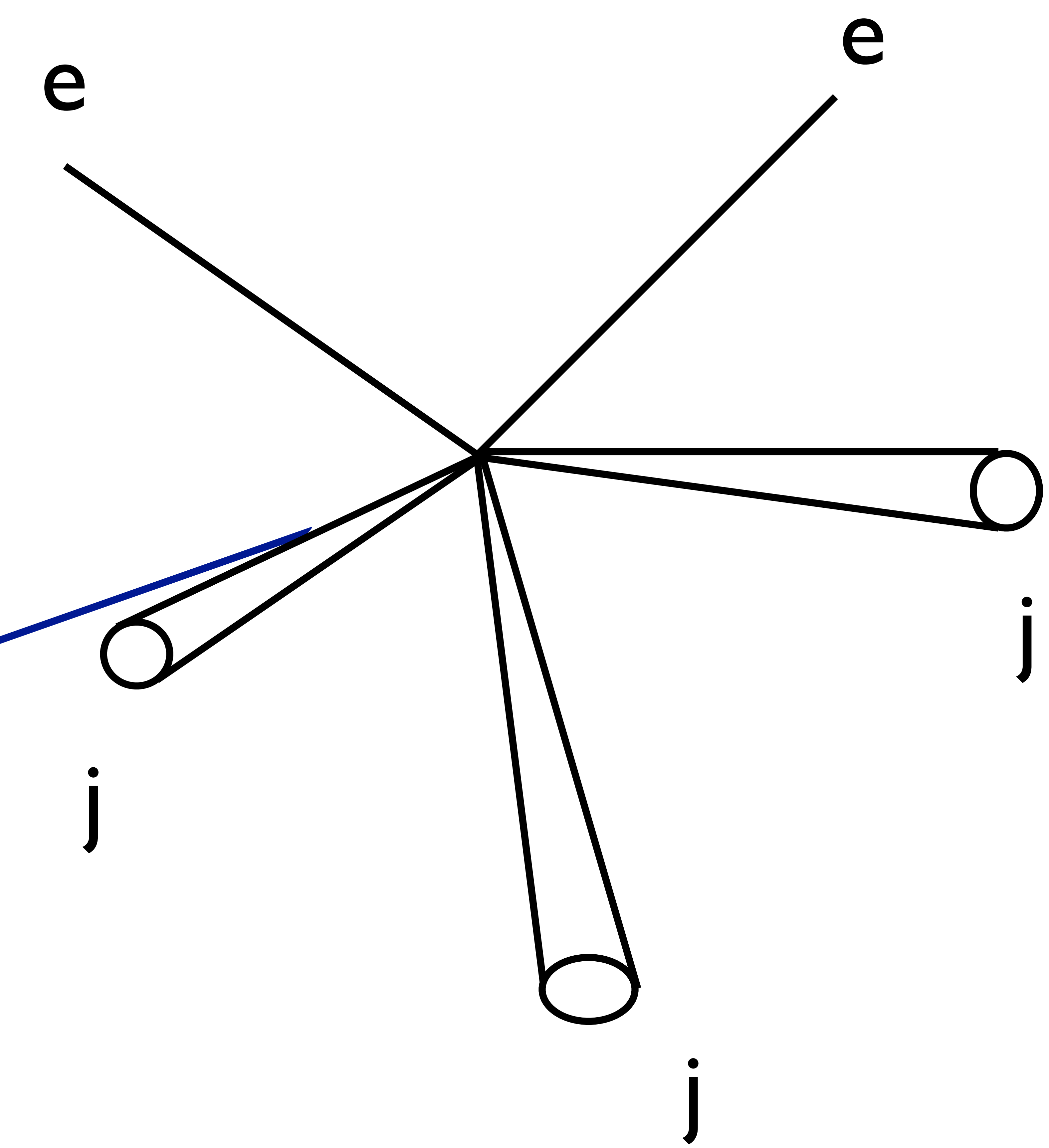
Case II

Intermediate r_{inv}

Modify [ATLAS-CONF-2017-039]* and require:

1) presence of exactly 2 leptons;
2) presence of at least 2 jets;
3) minimum values for m_{ll}, m_{T2} and MET;

Main background: $t\bar{t}$ production

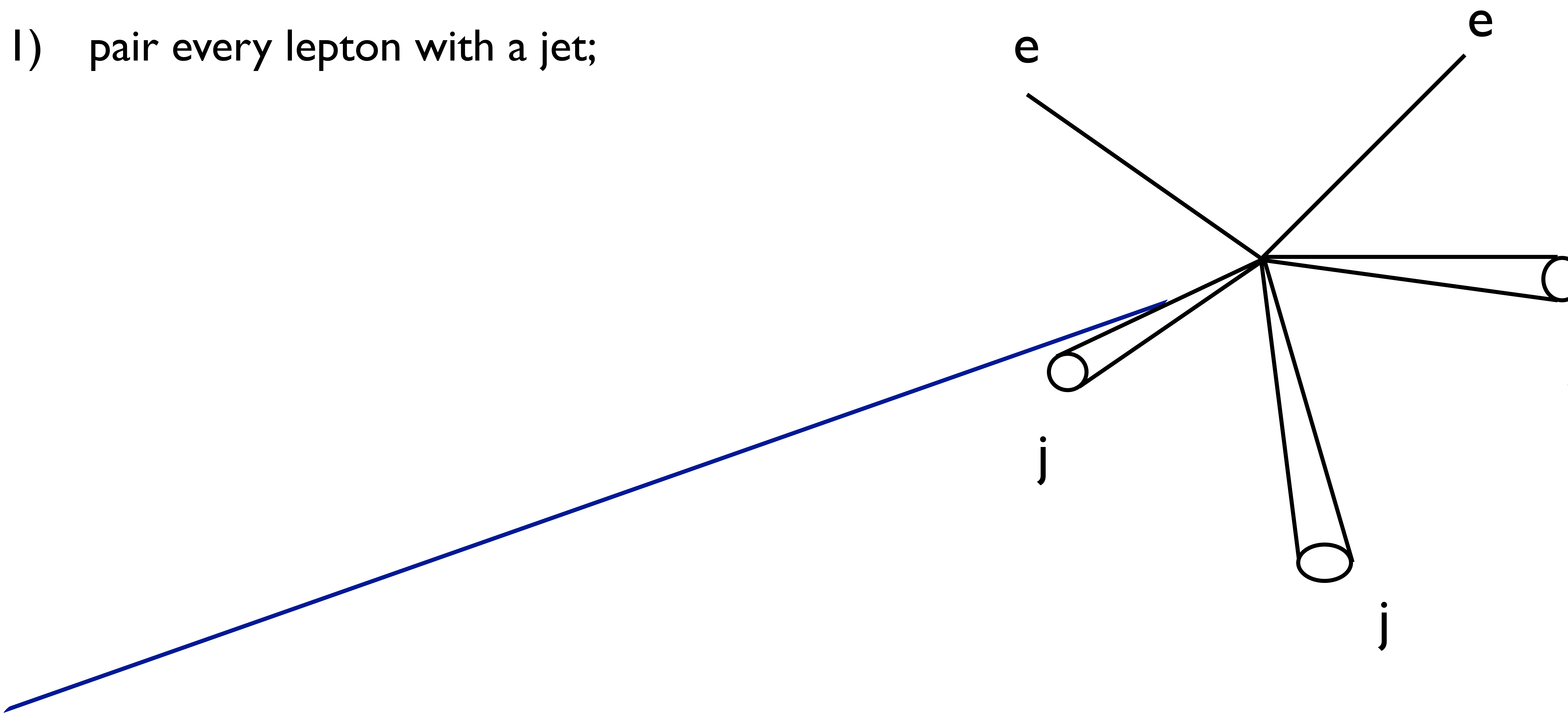


* slepton search

Case II

Intermediate r_{inv}

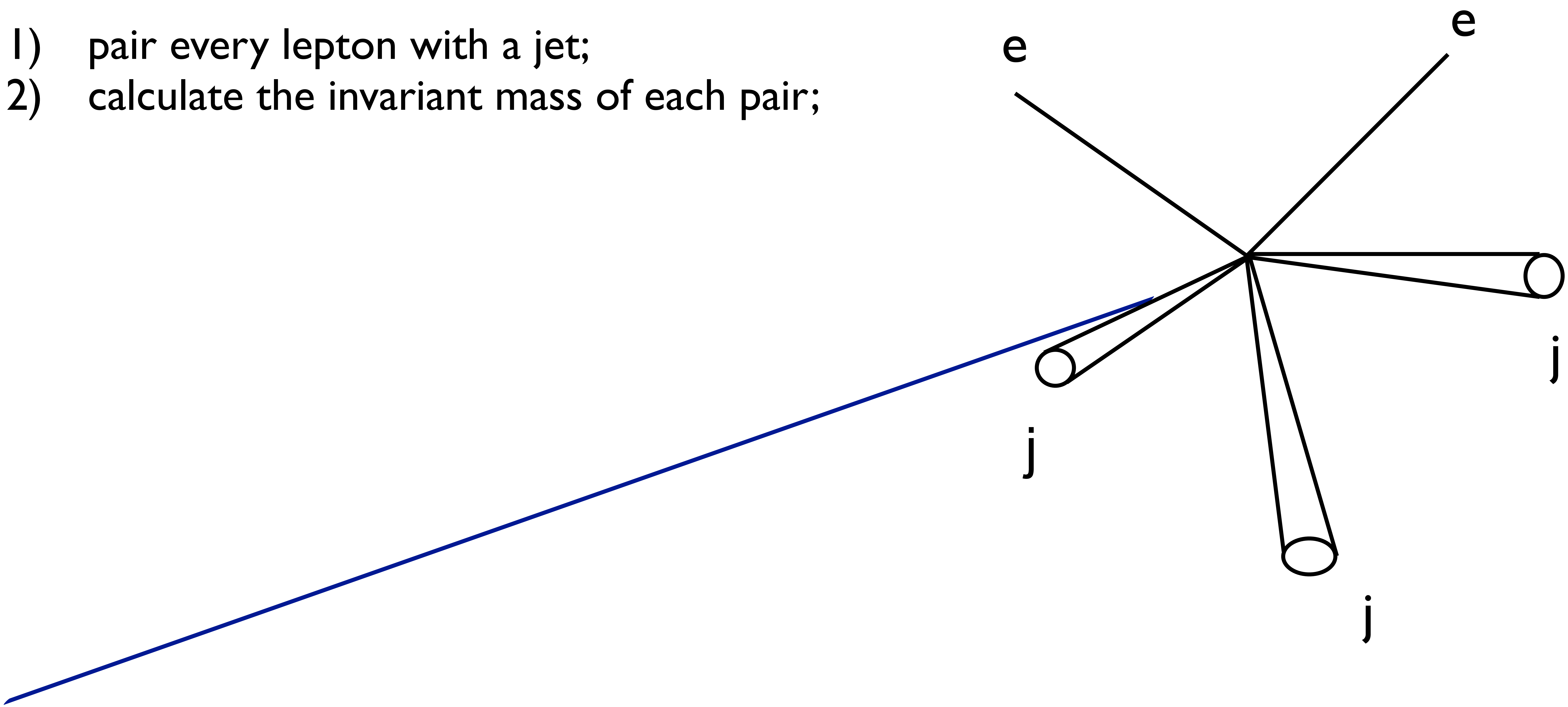
1) pair every lepton with a jet;



Case II

Intermediate r_{inv}

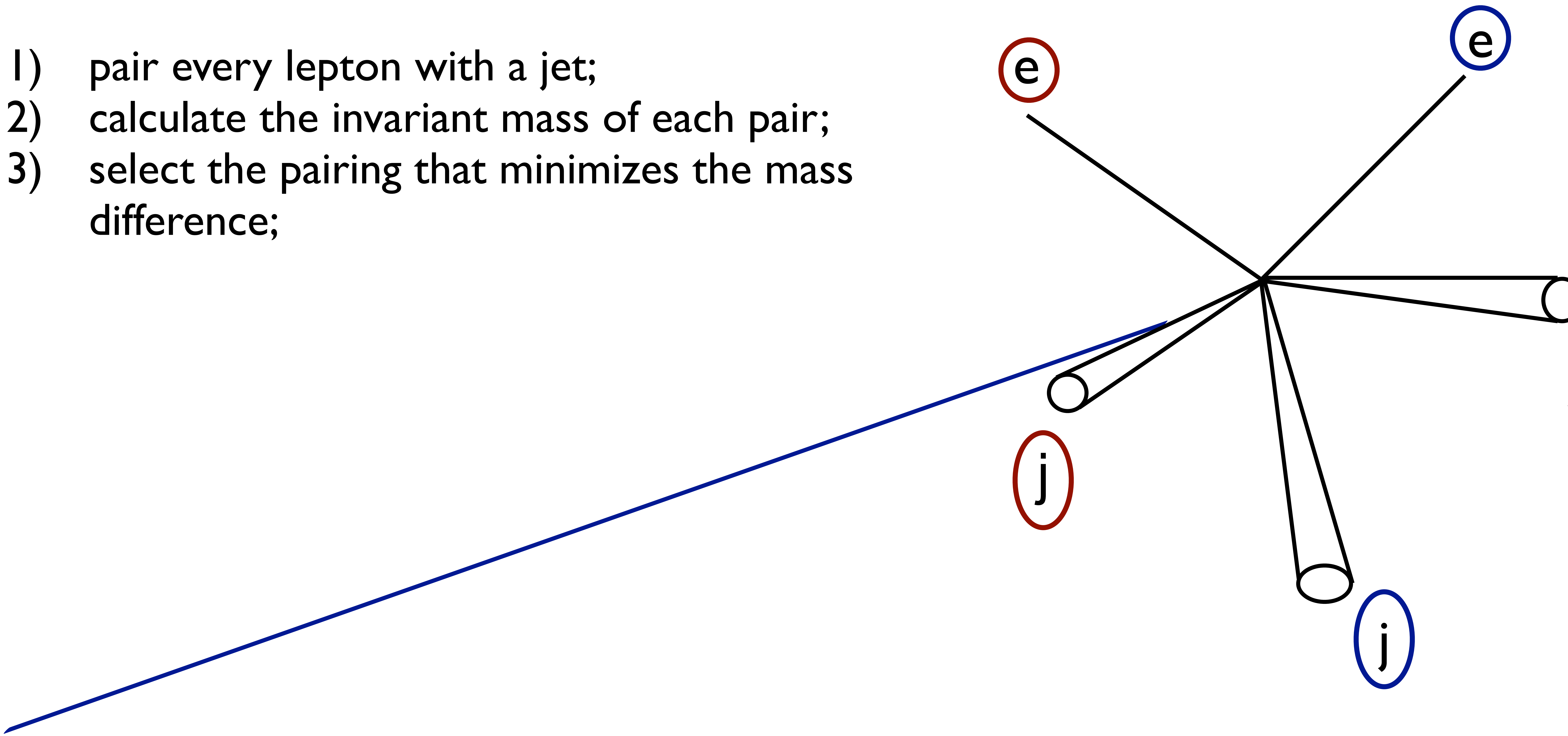
1) pair every lepton with a jet;
2) calculate the invariant mass of each pair;



Case II

Intermediate r_{inv}

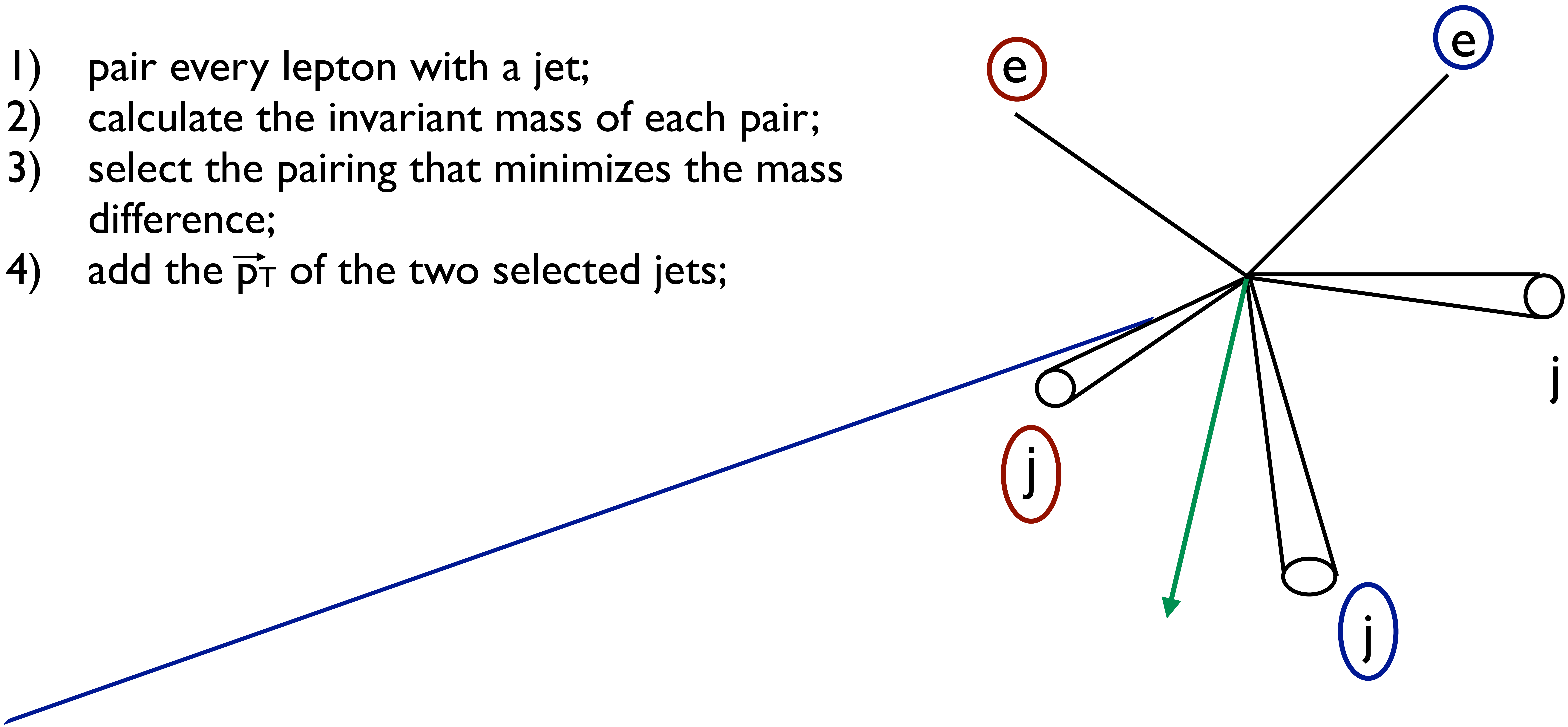
1) pair every lepton with a jet;
2) calculate the invariant mass of each pair;
3) select the pairing that minimizes the mass difference;



Case II

Intermediate r_{inv}

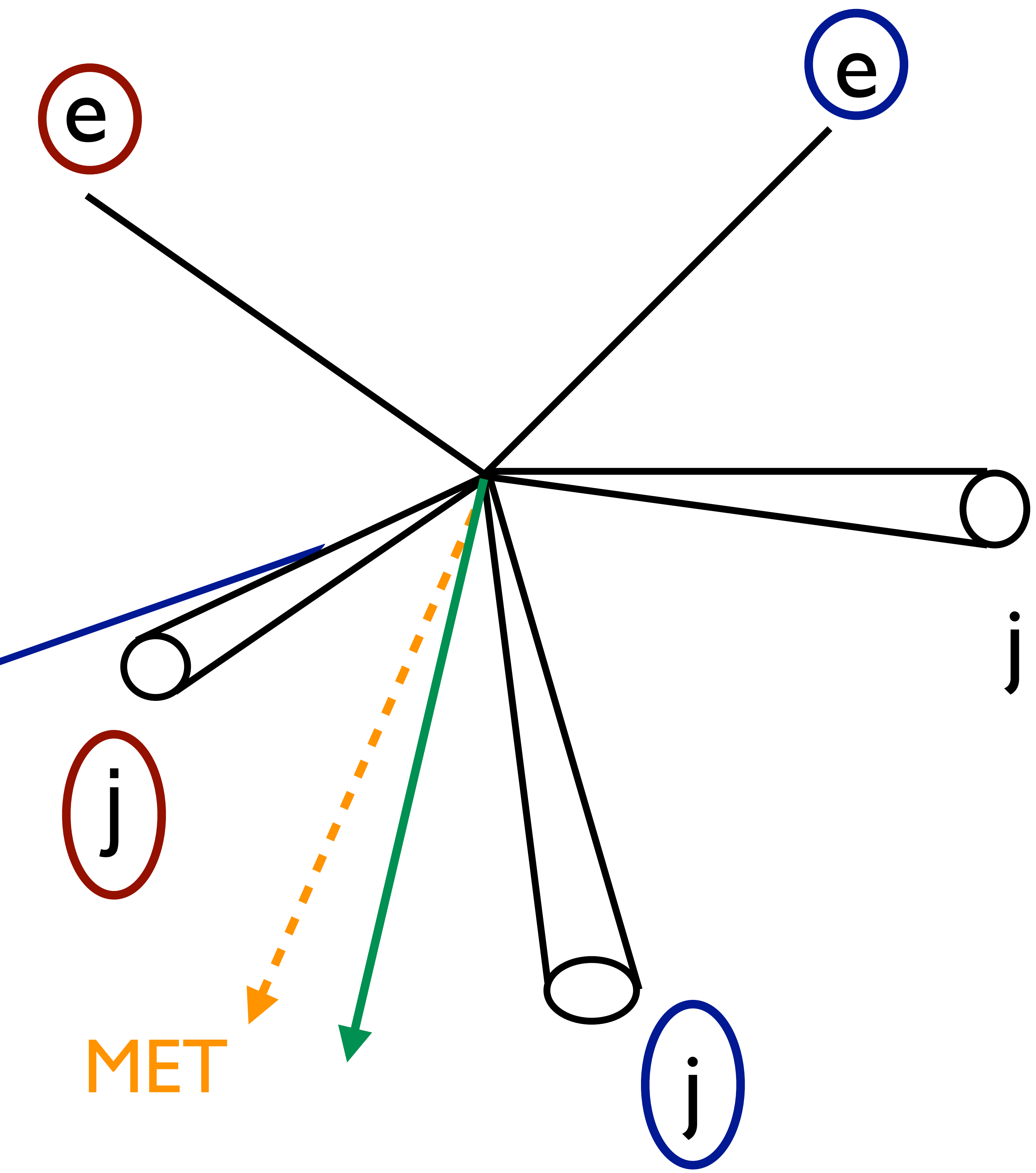
1) pair every lepton with a jet;
2) calculate the invariant mass of each pair;
3) select the pairing that minimizes the mass difference;
4) add the $\vec{p}_T$ of the two selected jets;



Case II

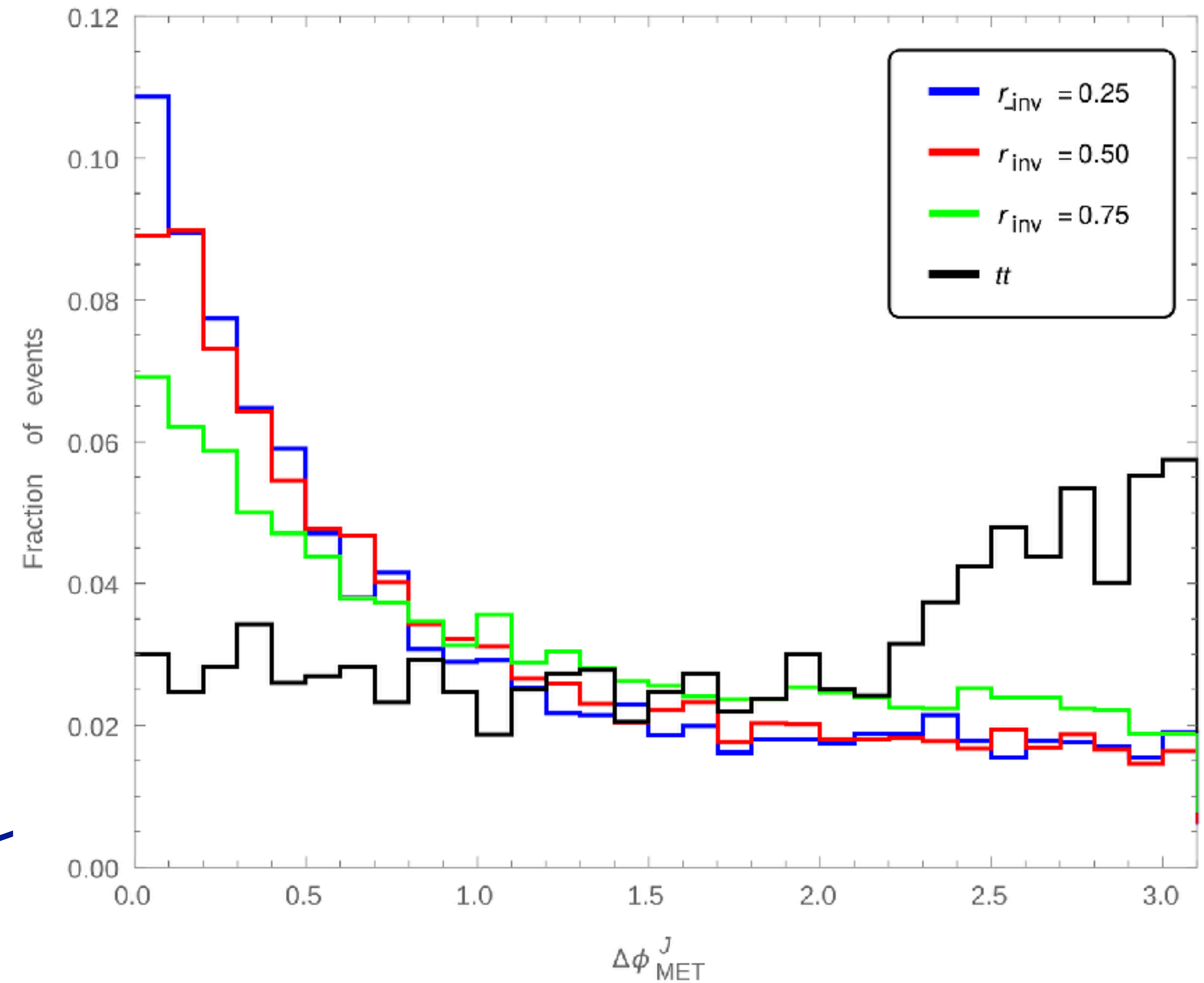
Intermediate r_{inv}

1) pair every lepton with a jet;
2) calculate the invariant mass of each pair;
3) select the pairing that minimizes the mass difference;
4) add the $\vec{p}_T$ of the two selected jets;
5) define $\Delta\Phi^{j}_{MET}$ the difference between the azimuthal angle of the $\vec{p}_T$ and the direction of the MET;



Case II

Intermediate r_{inv}



Dark mesons DM

The model

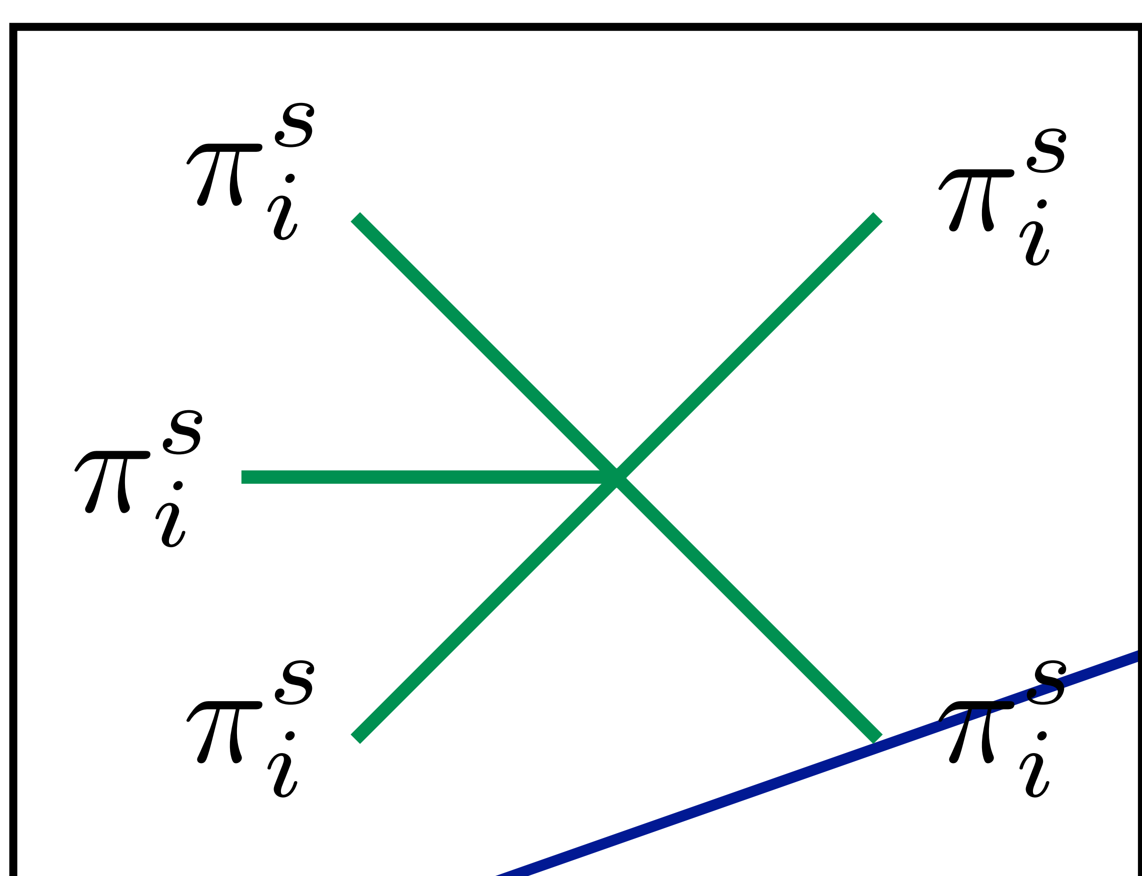
two unstable dark pions

$$\Pi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi_1^u + \frac{1}{\sqrt{6}}\pi_2^u & \pi_1^s & \pi_2^s \\ \bar{\pi}_1^s & -\frac{1}{\sqrt{2}}\pi_1^u + \frac{1}{\sqrt{6}}\pi_2^u & \pi_3^s \\ \bar{\pi}_2^s & \bar{\pi}_3^s & -\sqrt{\frac{2}{3}}\pi_2^u \end{pmatrix}$$

three stable dark pions

The model

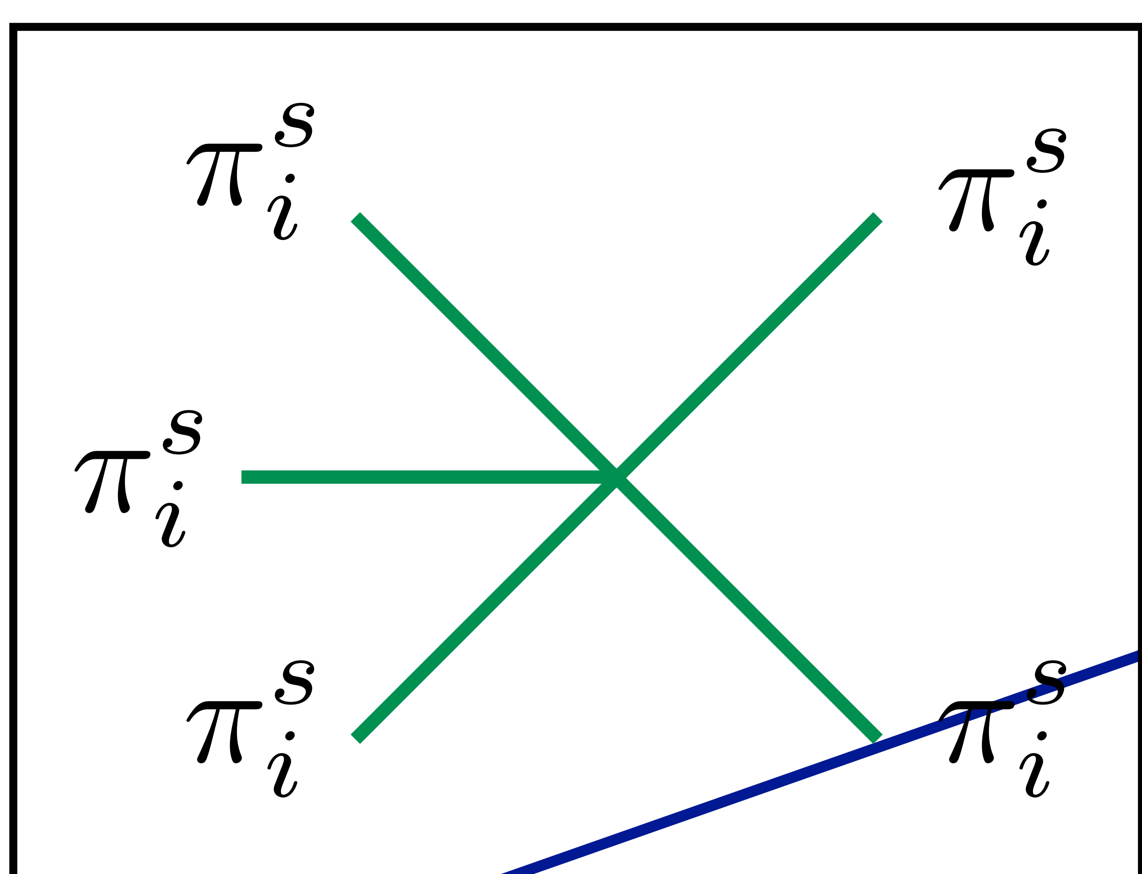
$$\mathcal{L} \supset \frac{2N_c}{15\pi^2 f_{\pi_D}^5}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}[\Pi\partial_\mu\Pi\partial_\nu\Pi\partial_\rho\Pi\partial_\sigma\Pi]$$

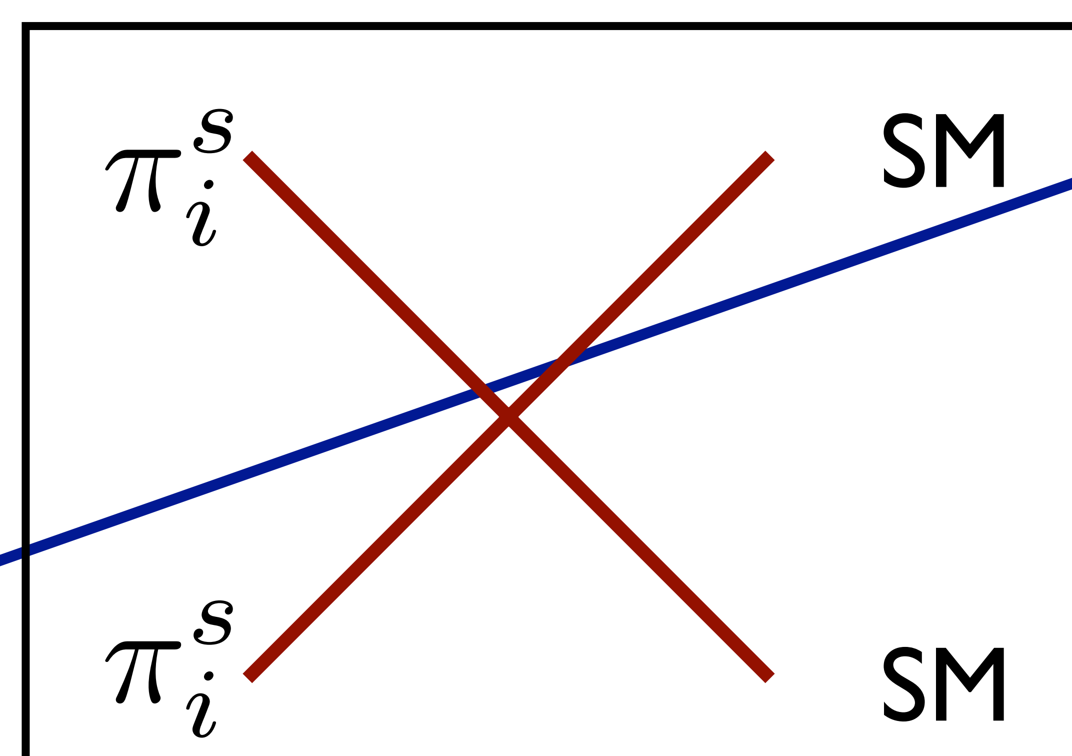


The model

$$\mathcal{L} \supset \frac{2N_c}{15\pi^2 f_{\pi_D}^5}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}[\Pi\partial_\mu\Pi\partial_\nu\Pi\partial_\rho\Pi\partial_\sigma\Pi] + i\frac{\lambda^2}{m_X^2}(\pi_i^s\partial_\mu\bar{\pi}_i^s - \bar{\pi}_i^s\partial_\mu\pi_i^s)\bar{f}\gamma^\mu f$$

NB: qualitative Lagrangian, some terms have missing numerical factors, momentum dependence, etc. etc.





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$$+ g_i\bar{\pi}_i^s\pi_i^s\bar{\pi}_j^u\pi_k^u$$

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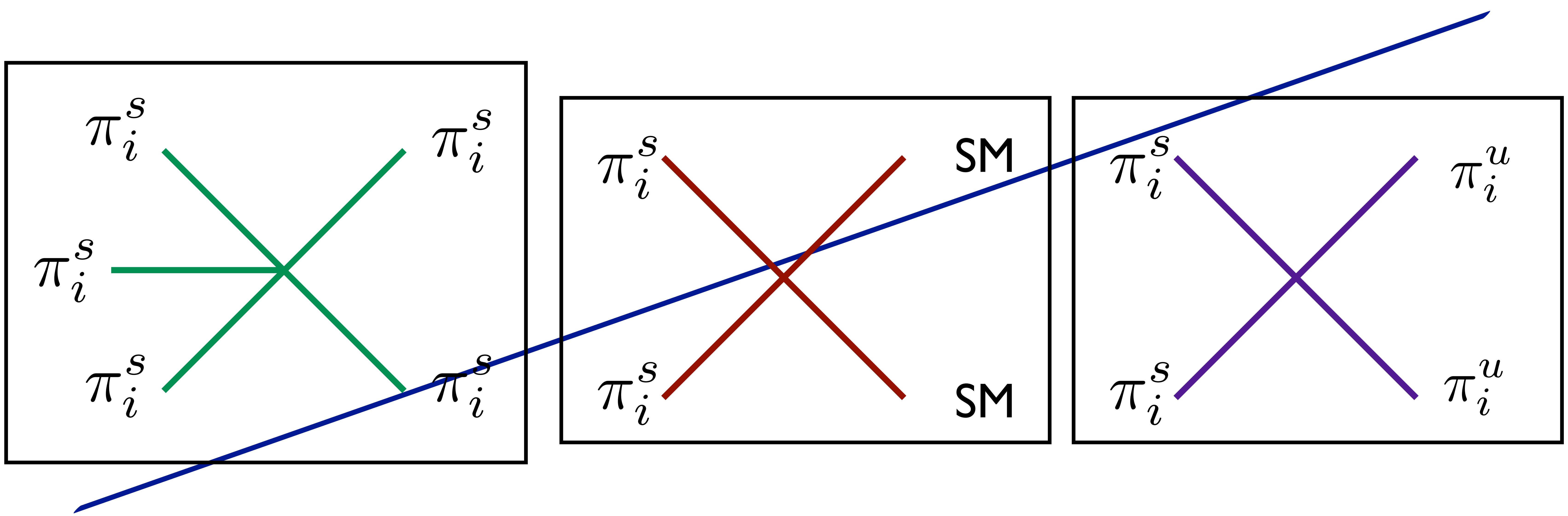

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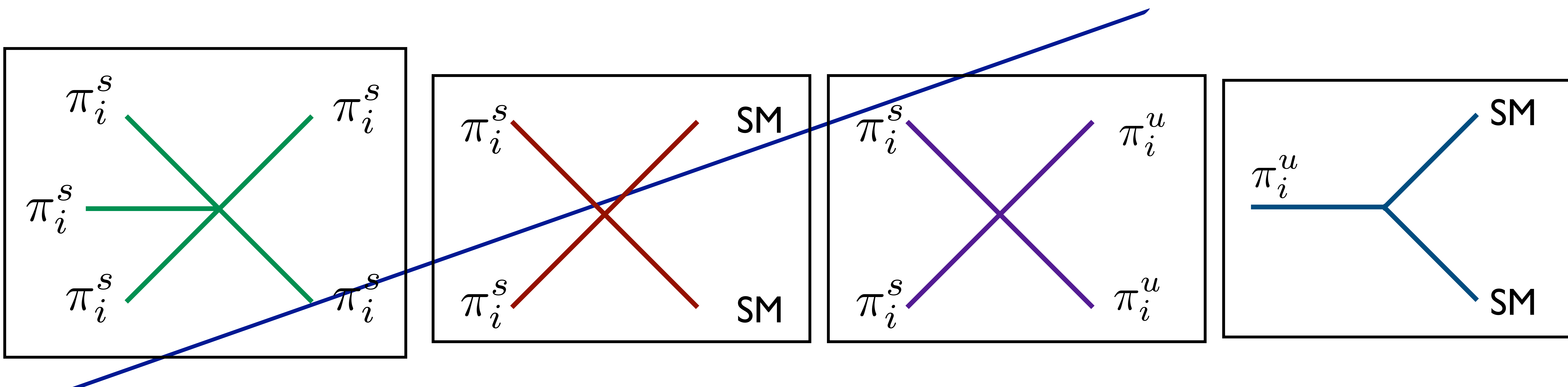
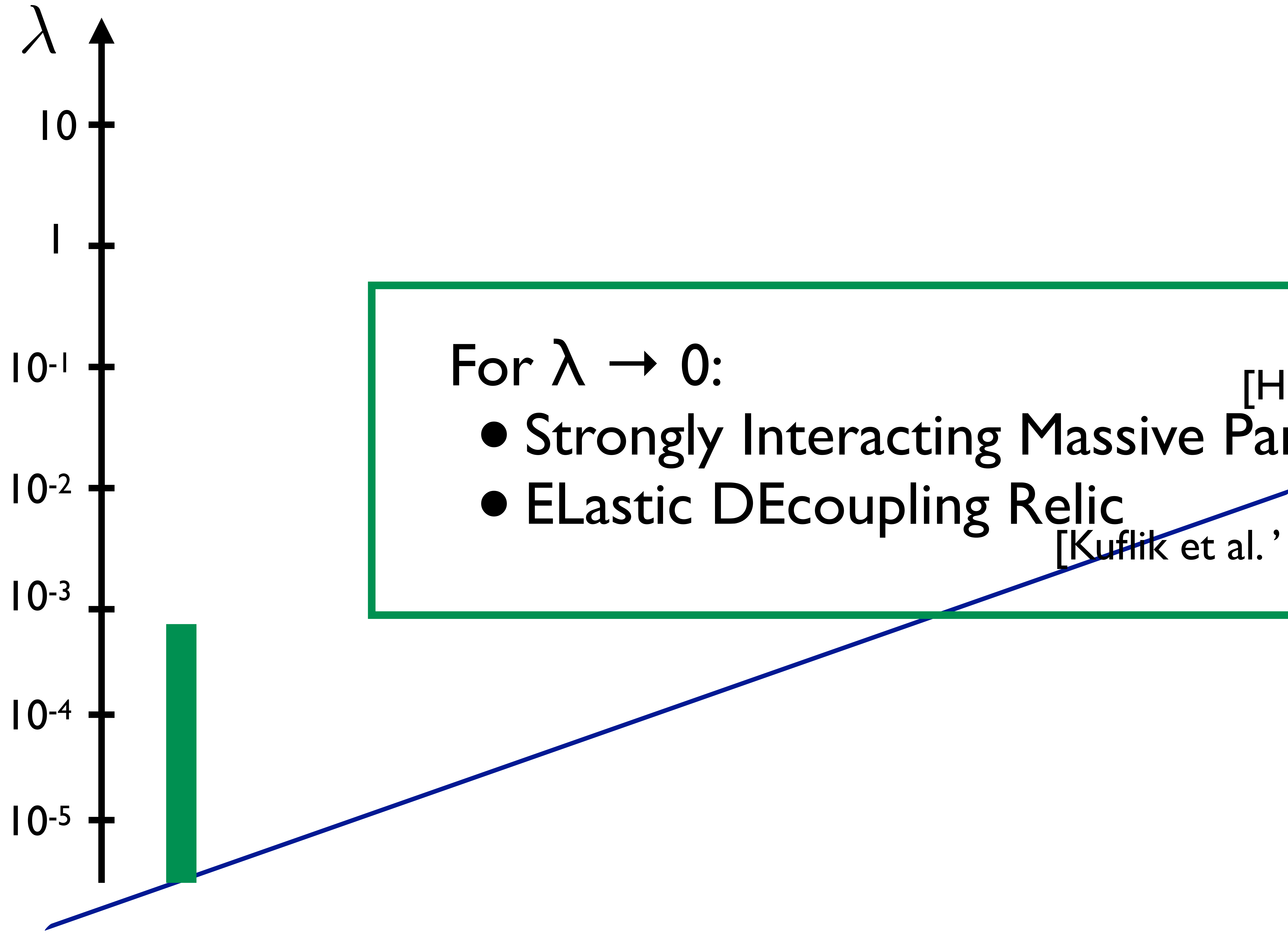
$$+ g_i\bar{\pi}_i^s\pi_i^s\bar{\pi}_j^u\pi_k^u + \frac{f_{\pi_D}\lambda^2}{m_X^2}\partial_\mu\pi_i^u\bar{f}\gamma^\mu f + \ldots$$

NB: qualitative Lagrangian, some terms have missing numerical factors, momentum dependence, etc. etc.



DM production mechanism



For $\lambda \to 0$:

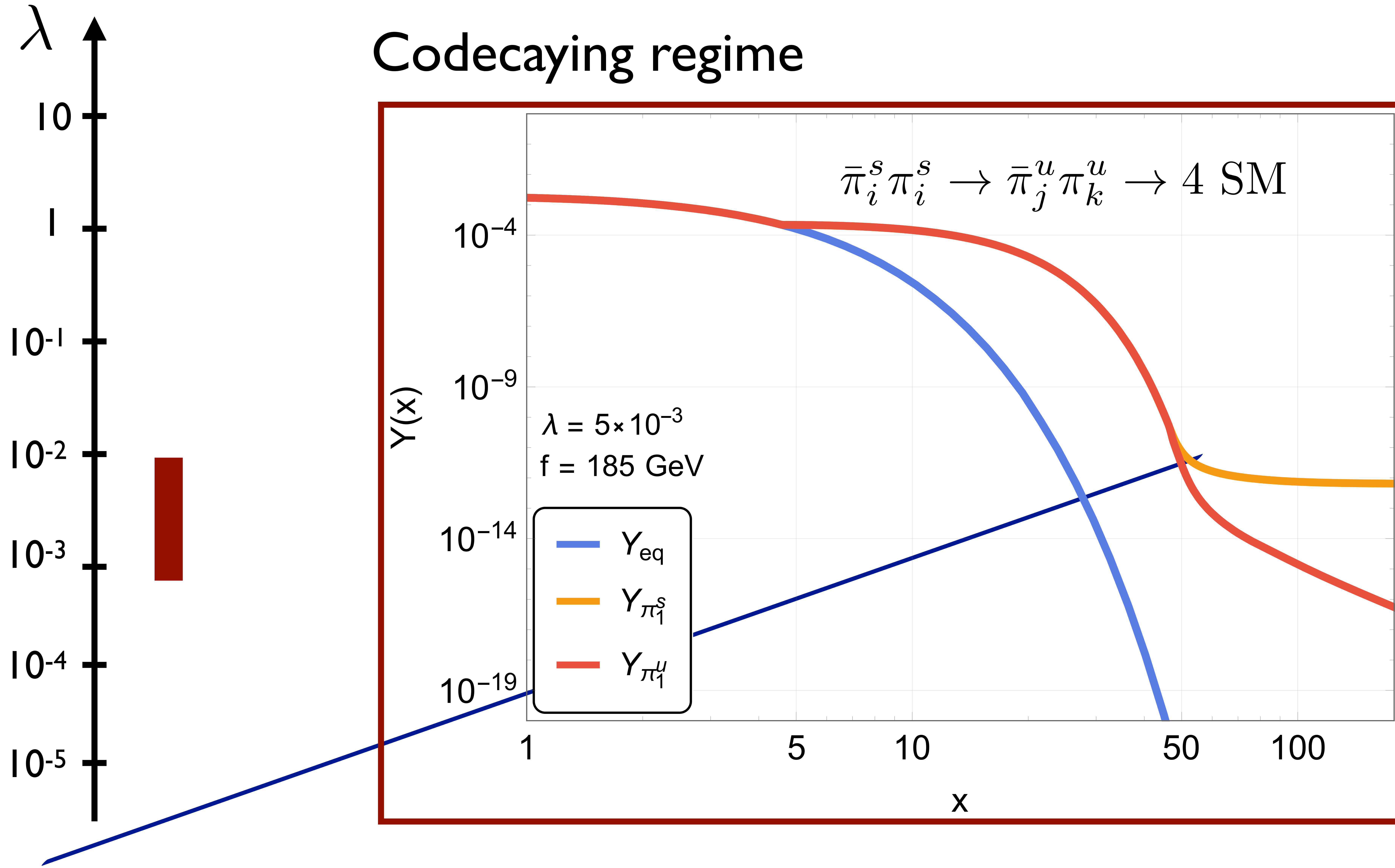
[Hochberg et al. '14,…]

- Strongly Interacting Massive Particle
- ELastic DEcoupling Relic

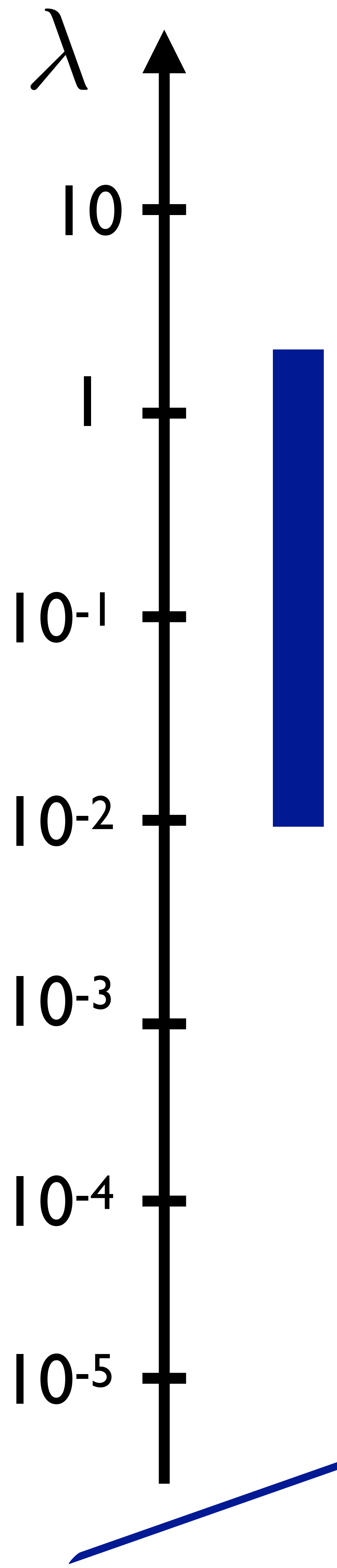
[Kuflik et al. '15,…]

DM production mechanism

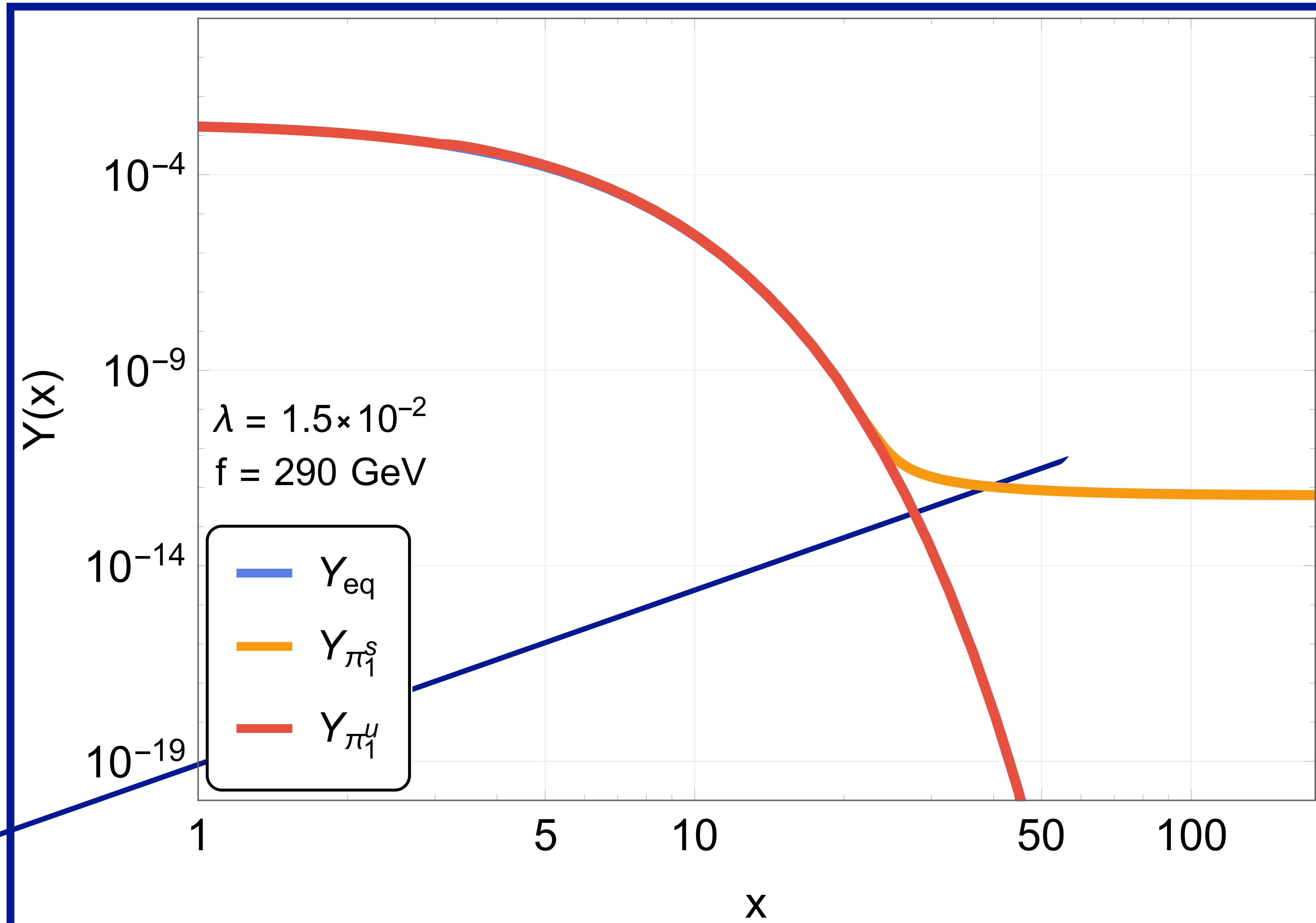
Codecaying regime



DM production mechanism

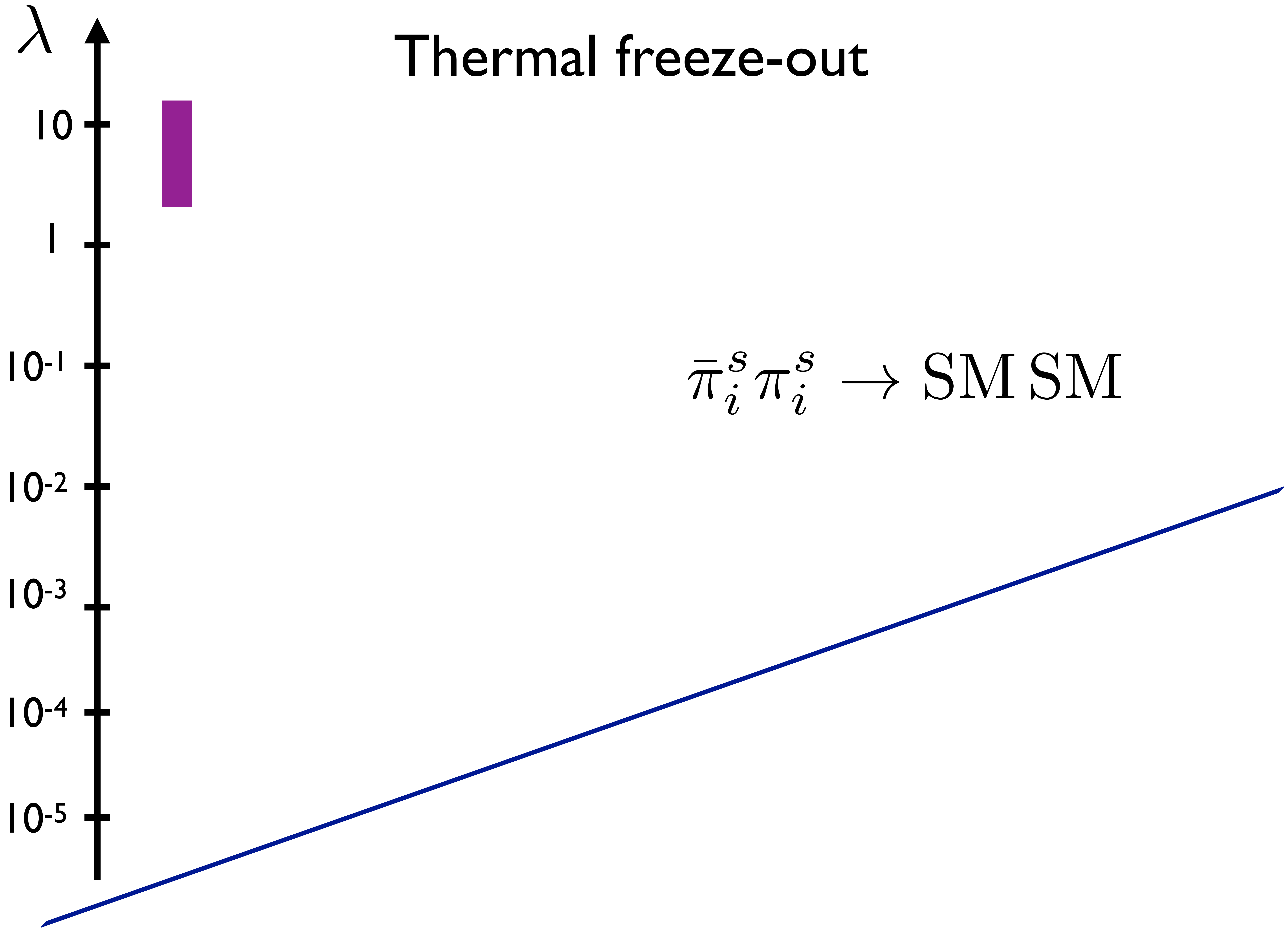


Coupling independent regime



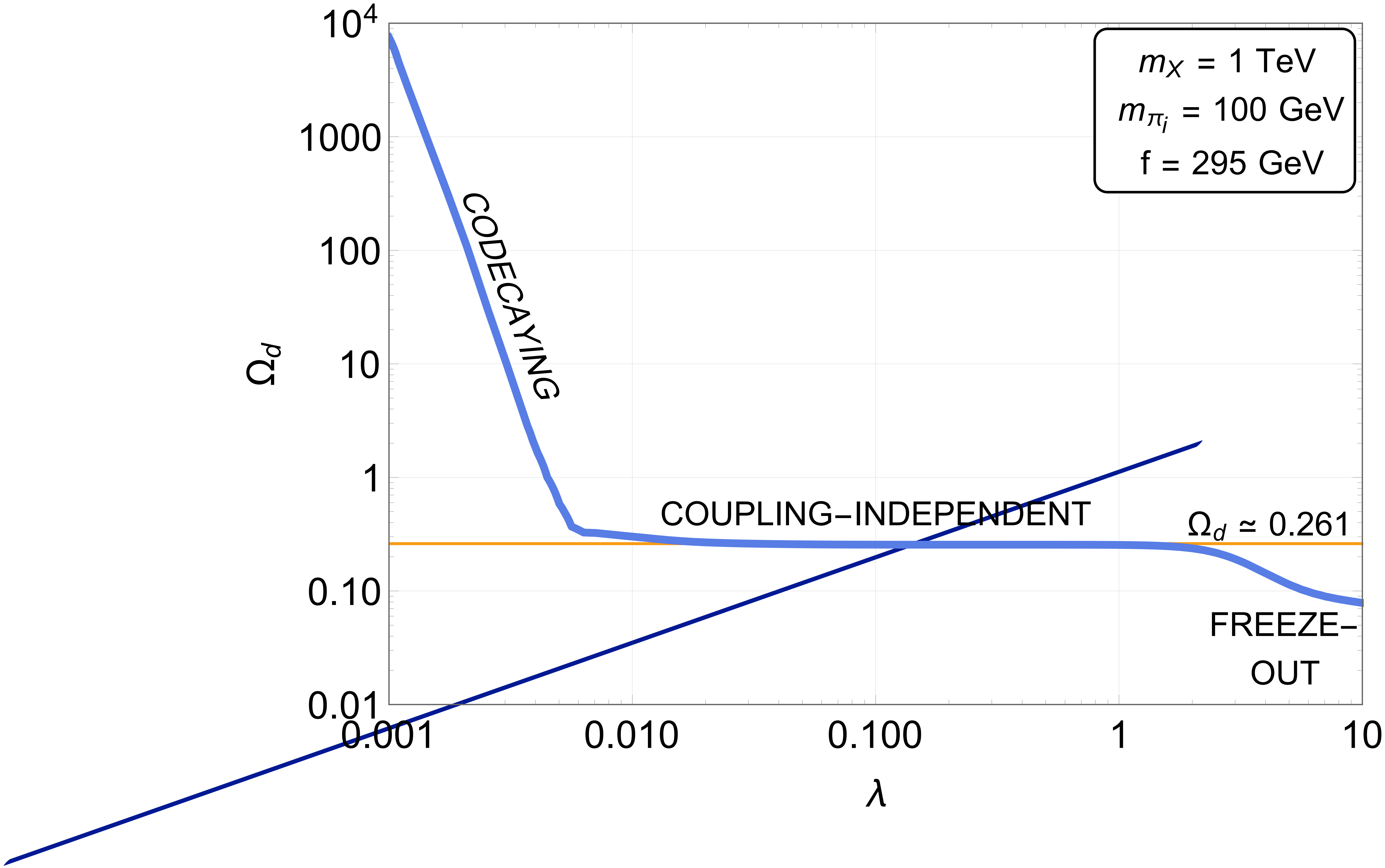
DM production mechanism

Thermal freeze-out



$$\bar{\pi}_i^s \pi_i^s \to \mathrm{SM}\,\mathrm{SM}$$

DM production mechanism



Overview of constraints

Direct Detection

Xenon1T bounds [Xenon Coll. '17]

Running effects [Crivellin et al. '14, D'Eramo et al. '15, '16]

Indirect Detection

Cascade decays: [Elor et al. '15]

1) CMB from Planck [Planck Coll. '15]

2) dwarf galaxies from Fermi-LAT [Fermi Coll. '15]

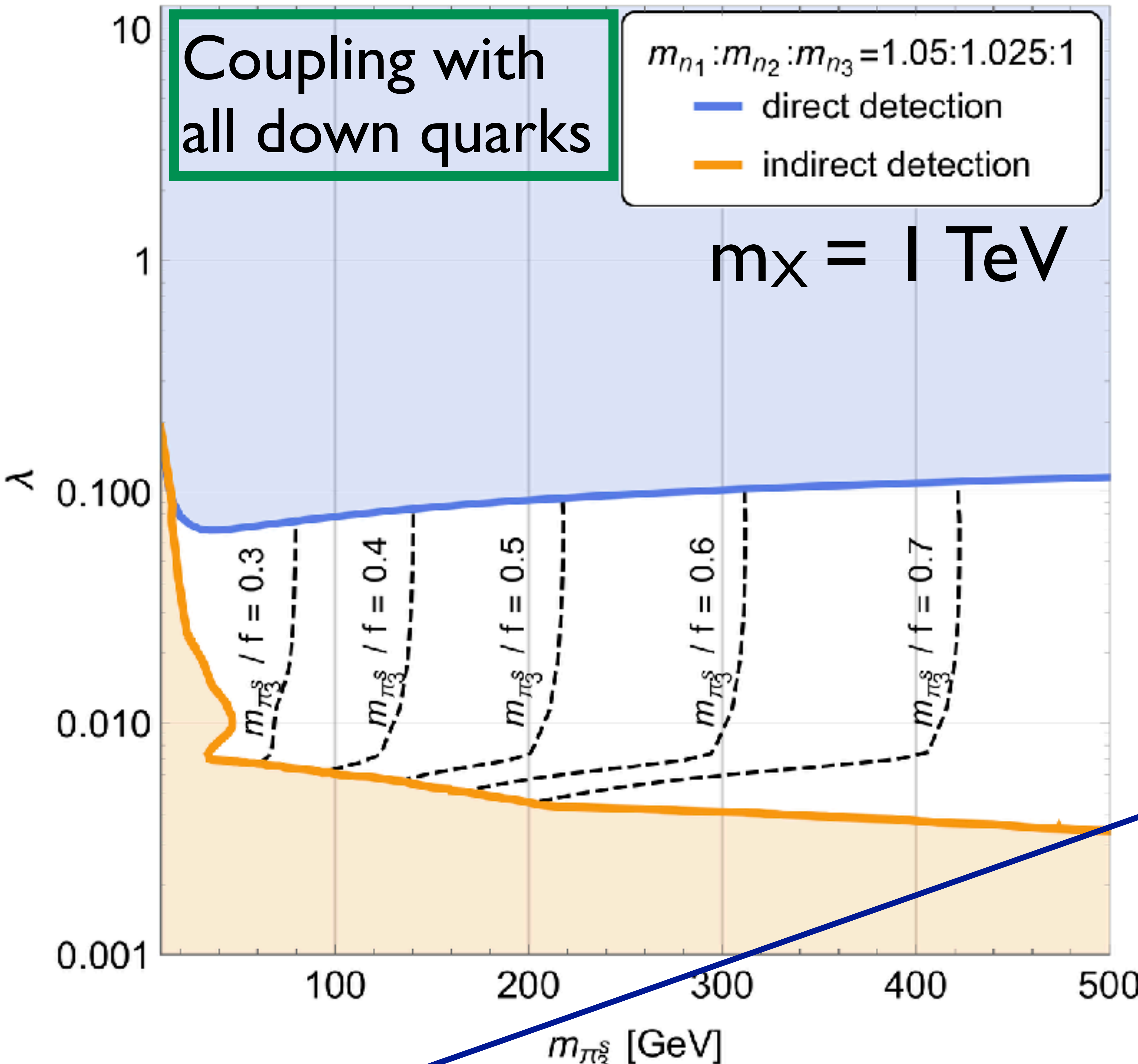
3) Positrons from AMS [AMS Coll. '14]

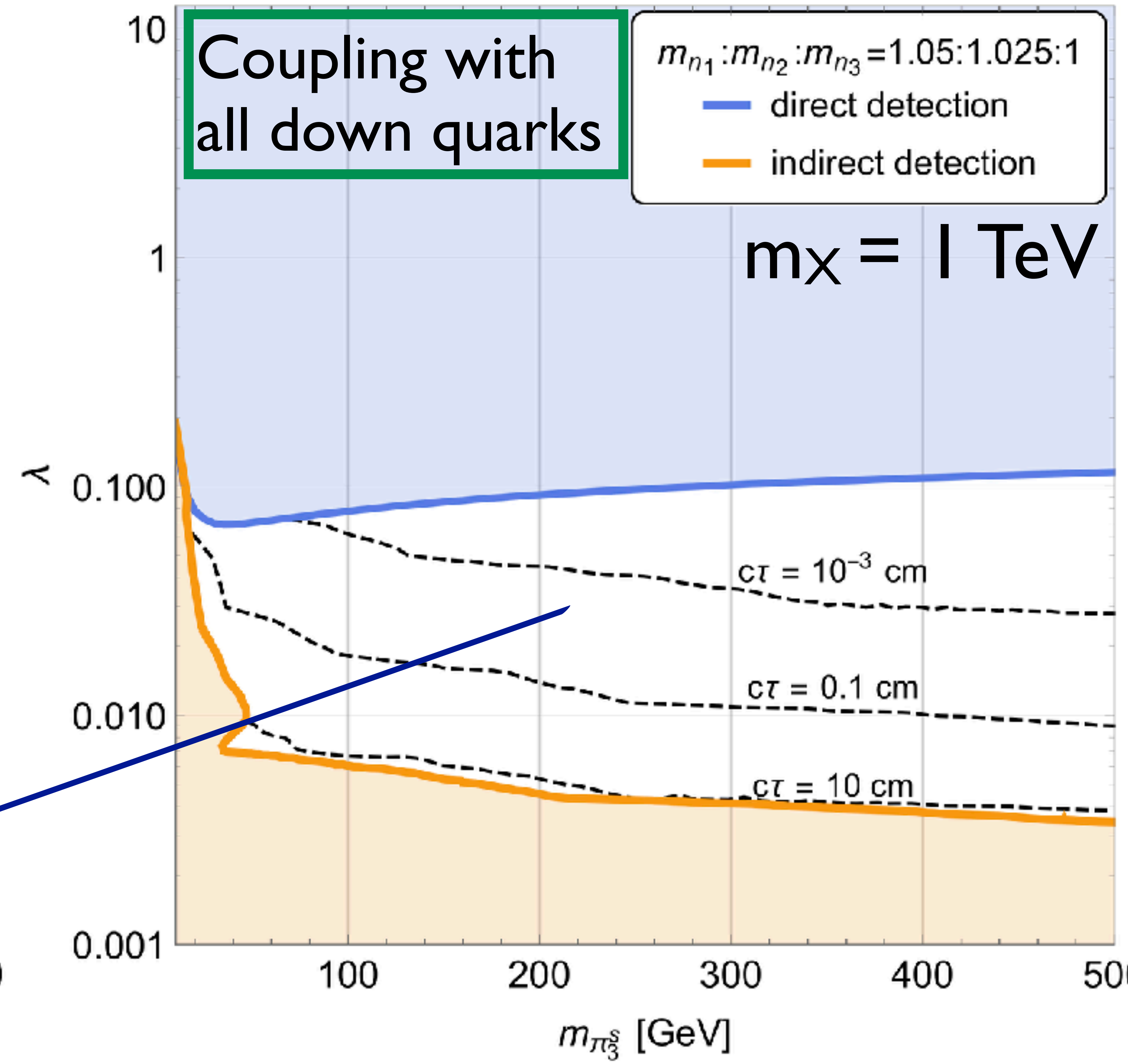
Benchmark model

$$\lambda^S_{D^c_{ijk}} (X^S_{D^c_k})^\dagger \bar{n}_i P_R D^c_j + h.c.$$

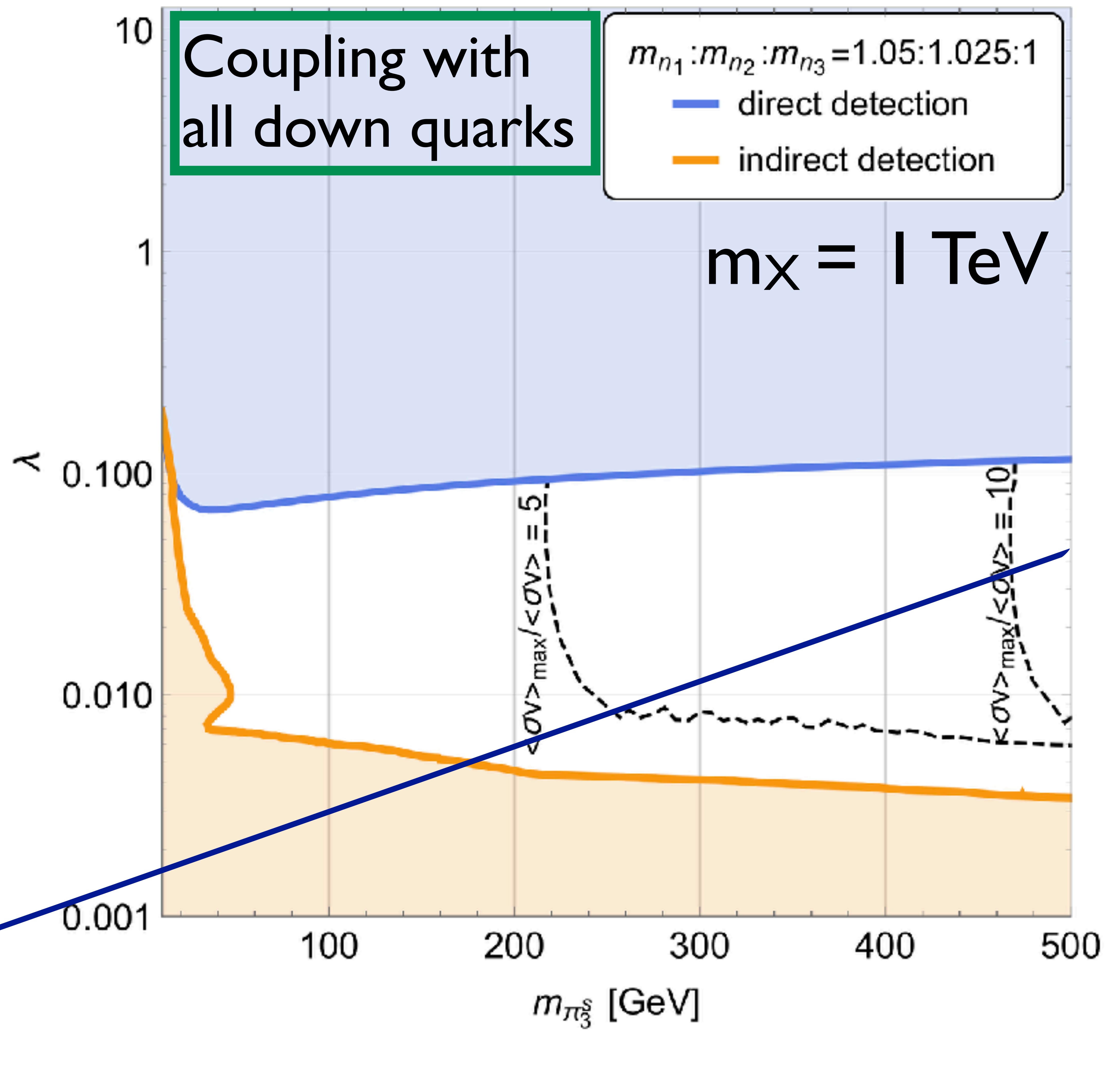
$$\lambda^S_{D^c_{ijk}} = \lambda \delta_{i1} \delta_{jk}$$

Benchmark model





Benchmark model



Conclusions

Conclusions

- Hidden confining dark sectors arise in many new physics models (Twin Higgs, Folded SUSY, Relaxion, DM) and lead to interesting collider signatures, such as emerging/semivisible jets.
- Current collider searches are not optimised to look for semivisible jets, leaving large part of the parameter space unconstrained.
- Stable Dark Mesons of confining sectors can be suitable DM candidates. Their parameter space can be mapped to possible exotic signatures at colliders and future indirect detection experiments.