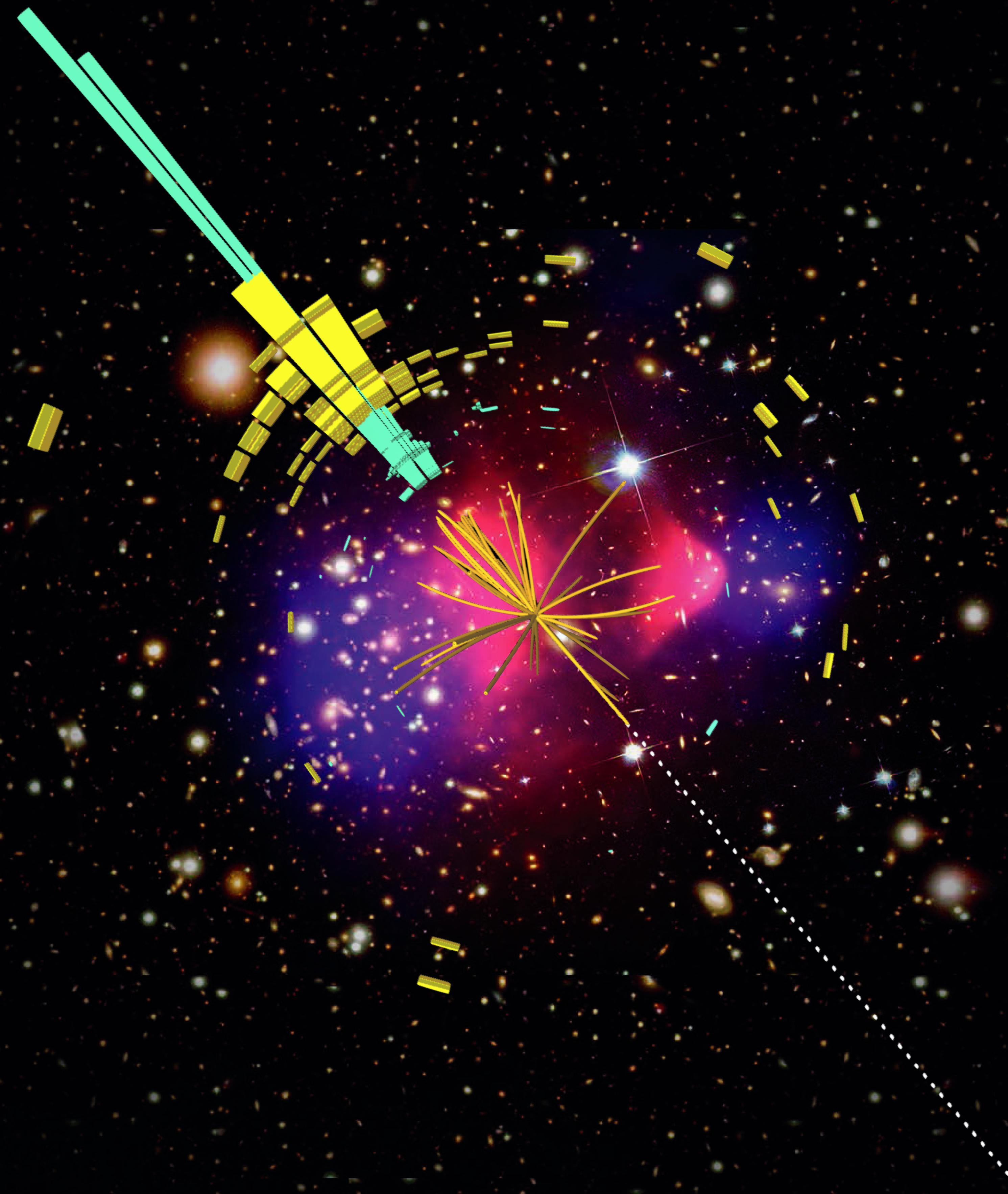
# Dark Matter at the LHC

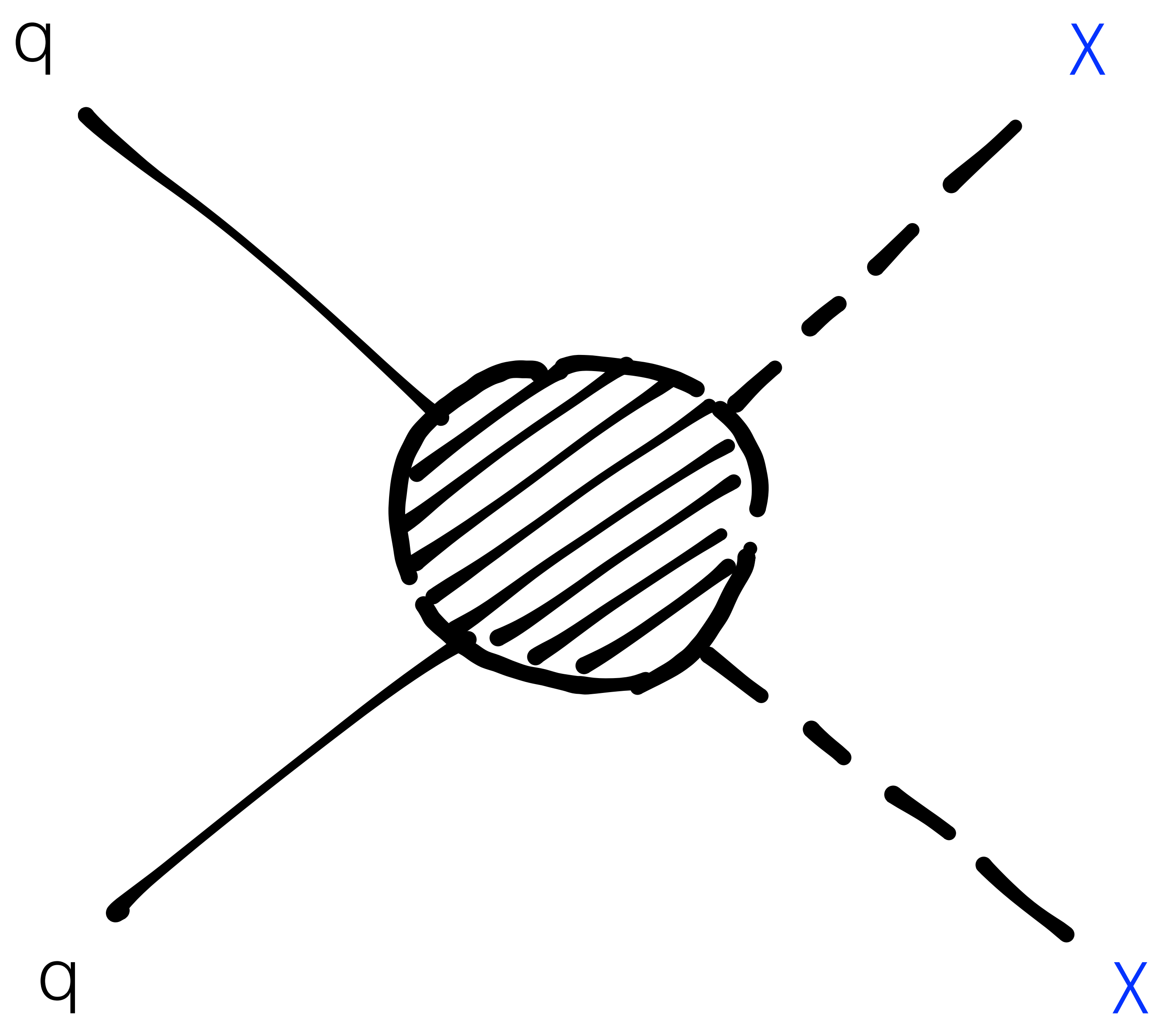
## In search for the invisible …



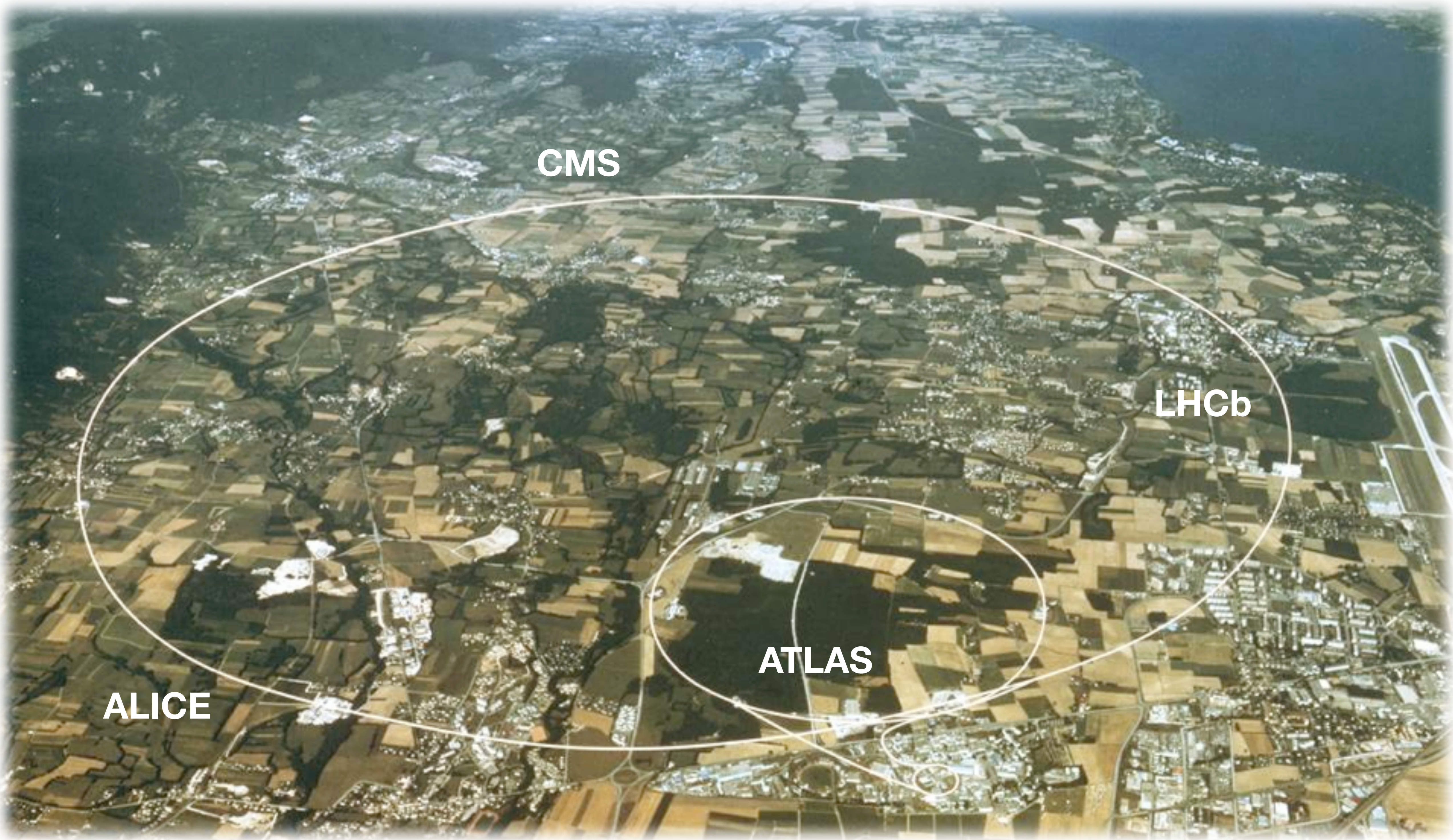
Hans-Christian Schultz-Coulon
Kirchhoff-Institut für Physik

International Summer School
on Astroparticle Physics
Heidelberg, Mai 2019

# DM Production at the LHC



# The Large Hadron Collider



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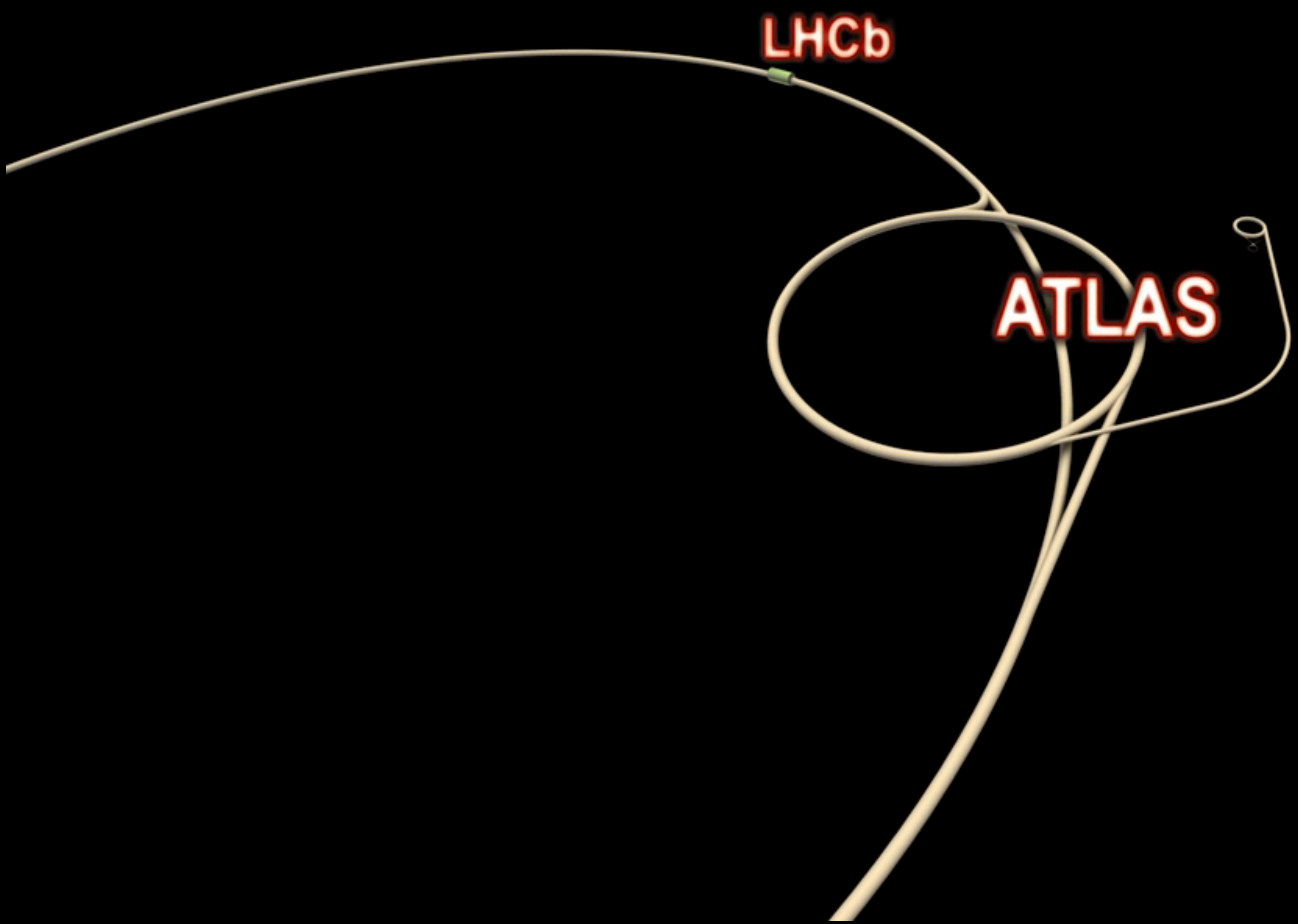

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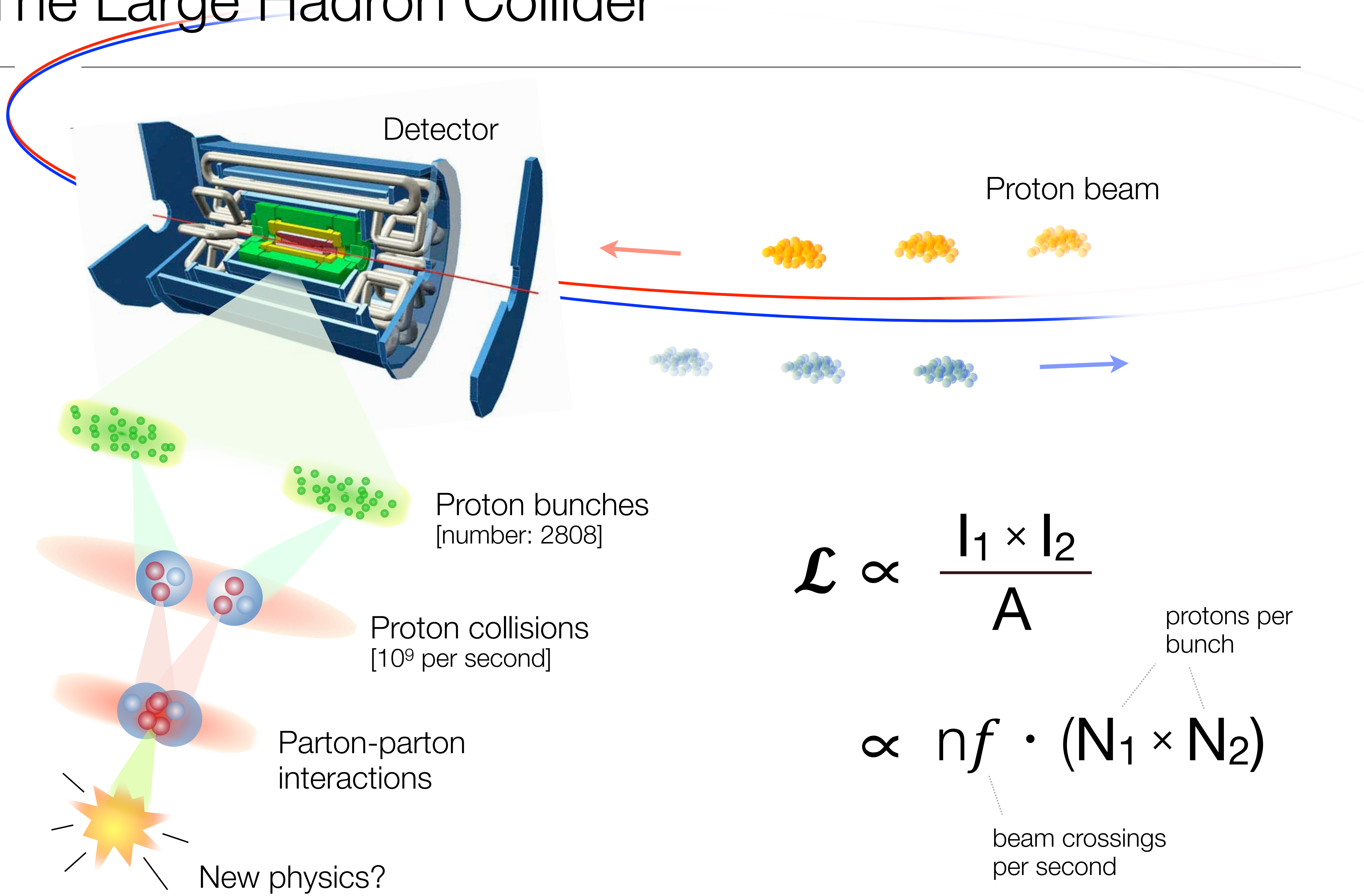
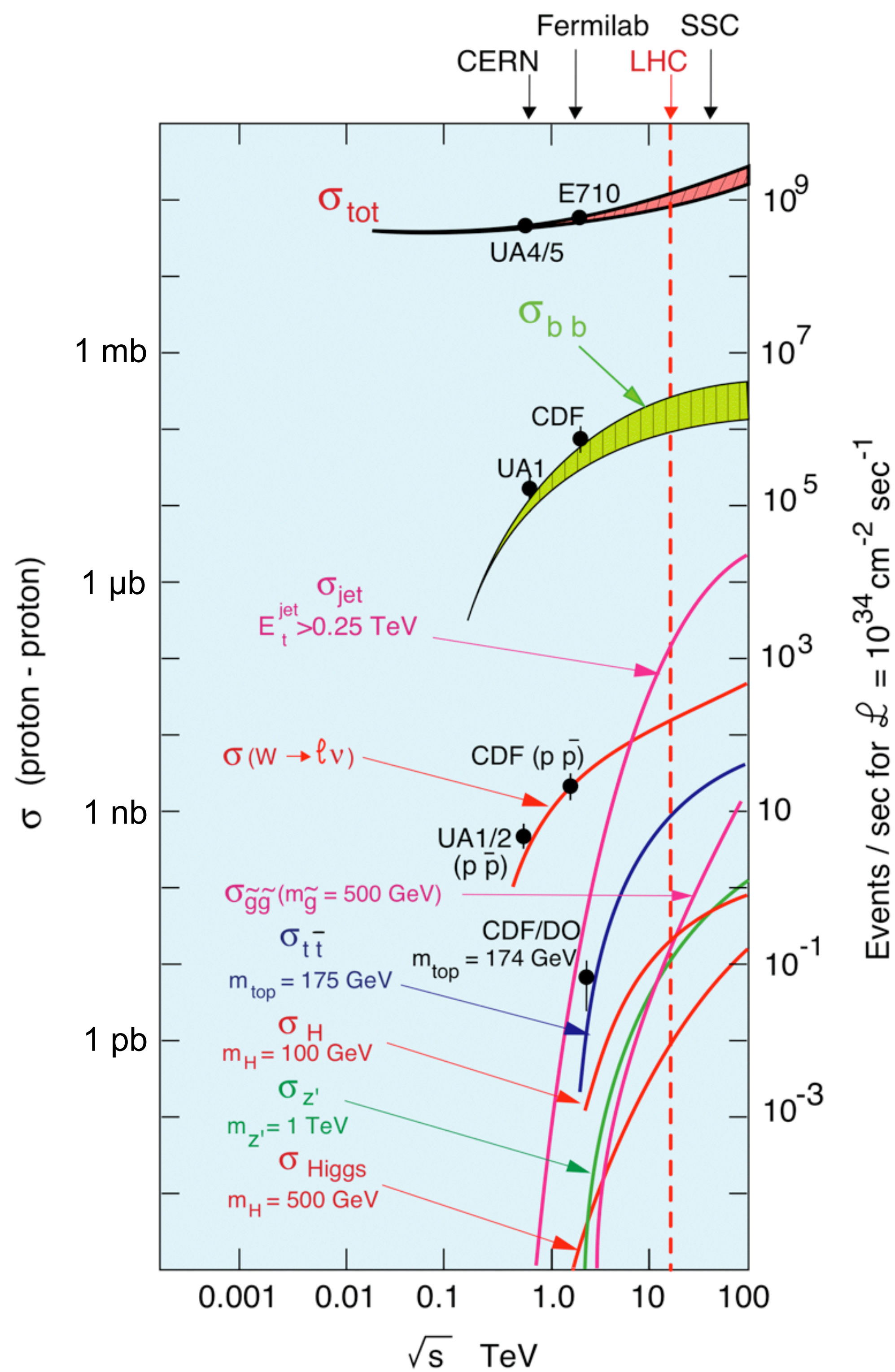



$$\mathcal{L} \propto \frac{I_1 \times I_2}{A}$$

$$\propto nf \cdot (N_1 \times N_2)$$

# LHC Cross Sections and Event Rates




13 Orders of Magnitude

Event Rate

Luminosity

Cross Section

$$\dot{N} = \mathcal{L} \cdot \sigma$$

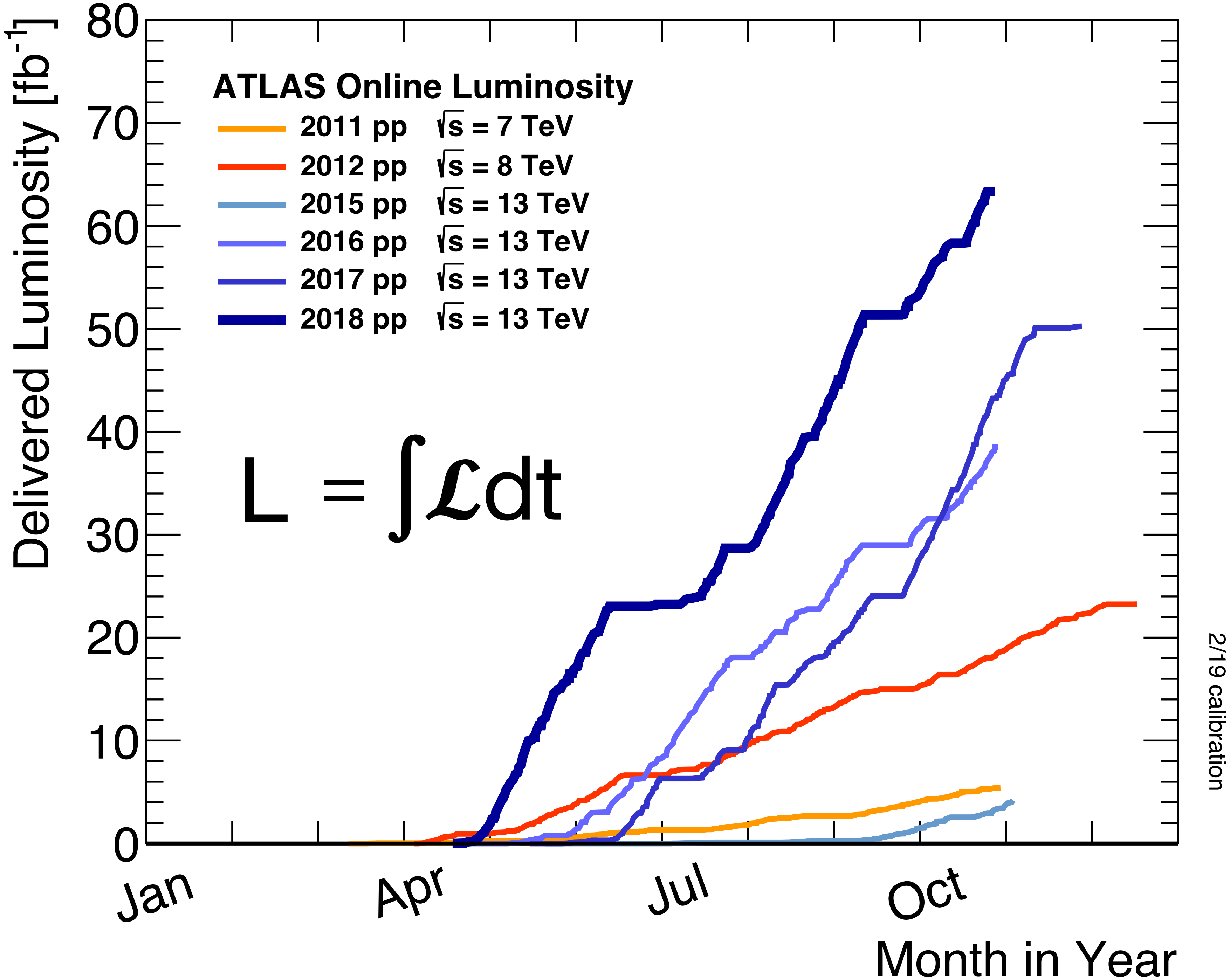
with

$$\mathcal{L} \propto \frac{I_1 \times I_2}{A}$$

product of beam currents

cross-sectional area of the beam

# Run-2 Performance



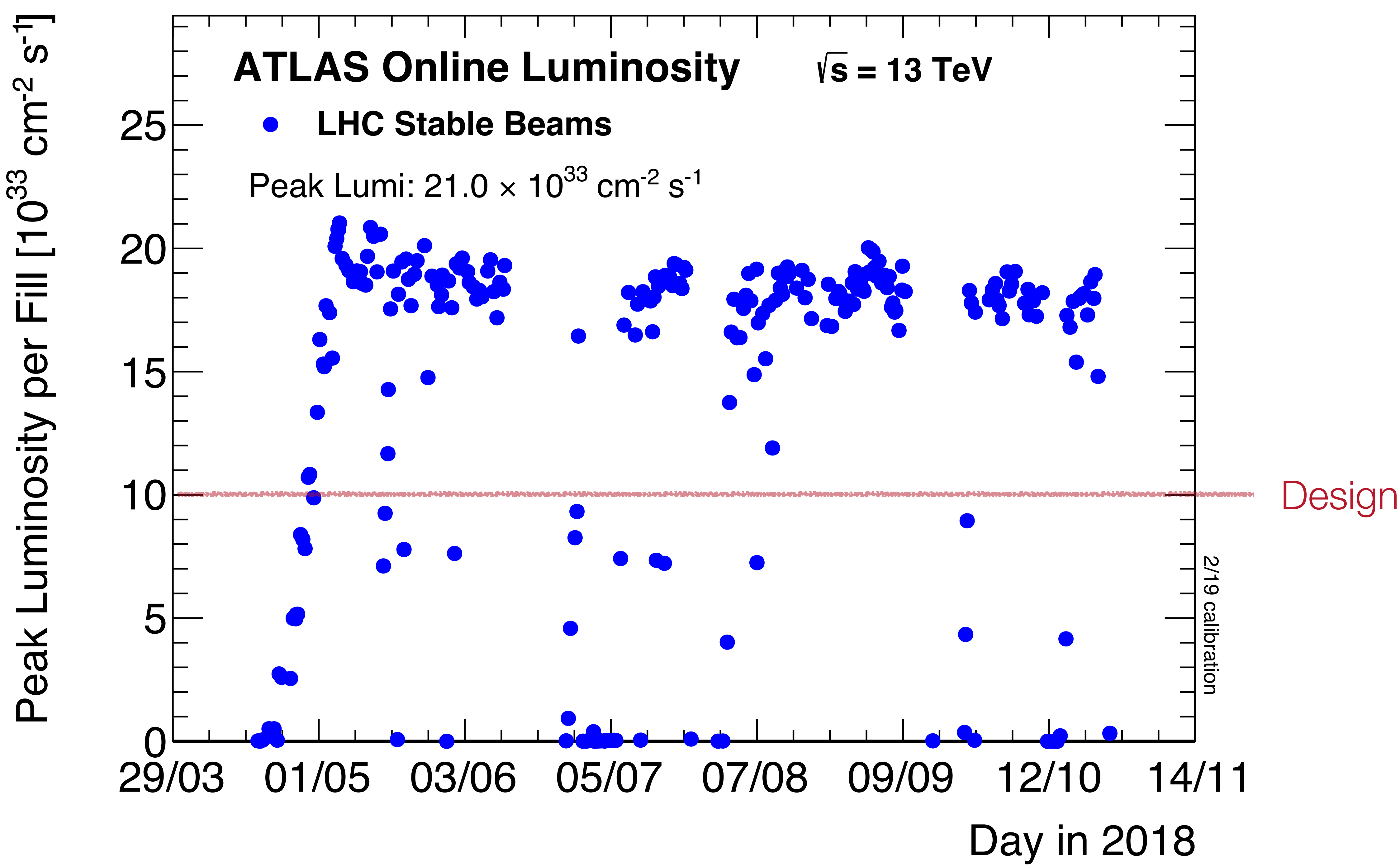

Luminosities:
[recorded]

2011: 5.1 $fb^{-1}$
2012: 21.3 $fb^{-1}$

2015: 3.9 $fb^{-1}$
2016: 35.6 $fb^{-1}$
2017: 46.9 $fb^{-1}$

2018: 60.6 $fb^{-1}$

# Run-2 Performance

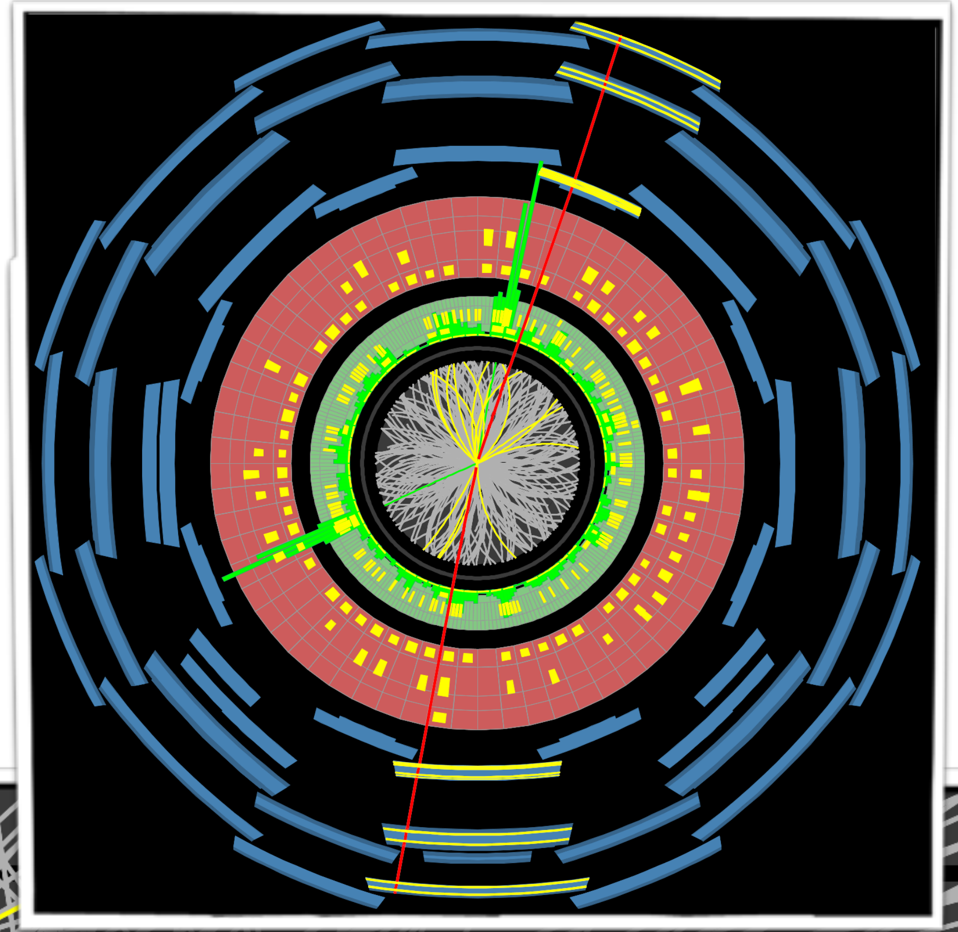


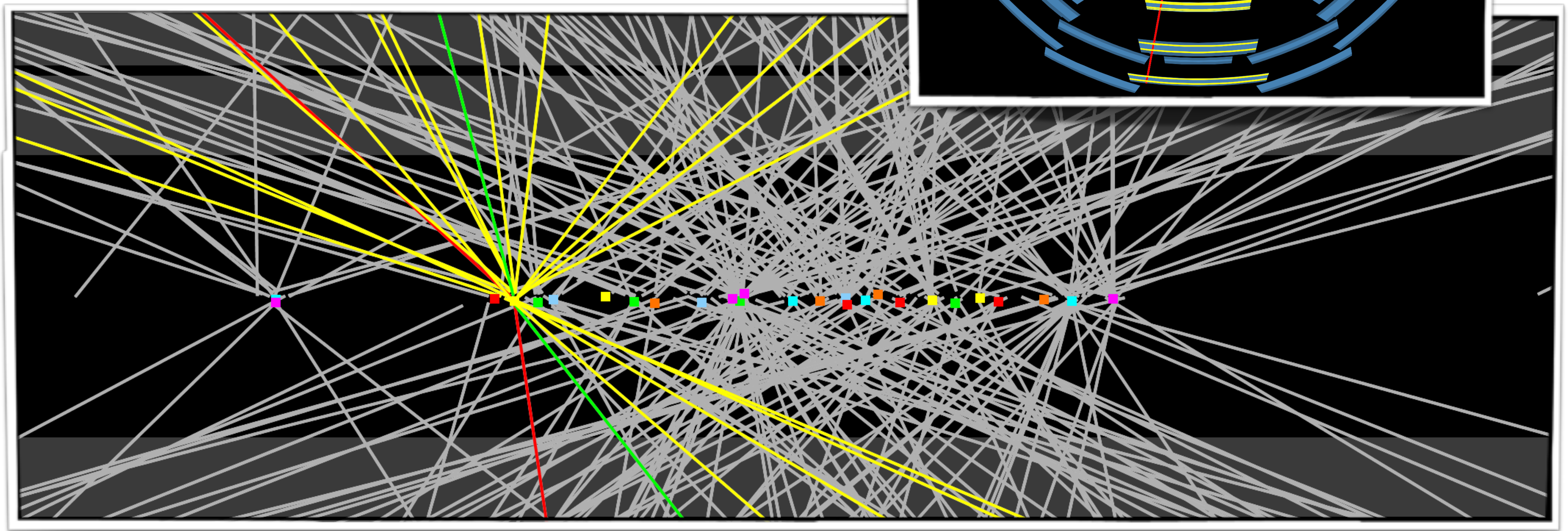
# Run-2 Performance

ATLAS Event
with 25 pileup vertices

[$\sqrt{s}$ = 13 TeV; 2016 Data]

H ➛ ZZ ➛ ee μμ candidate event





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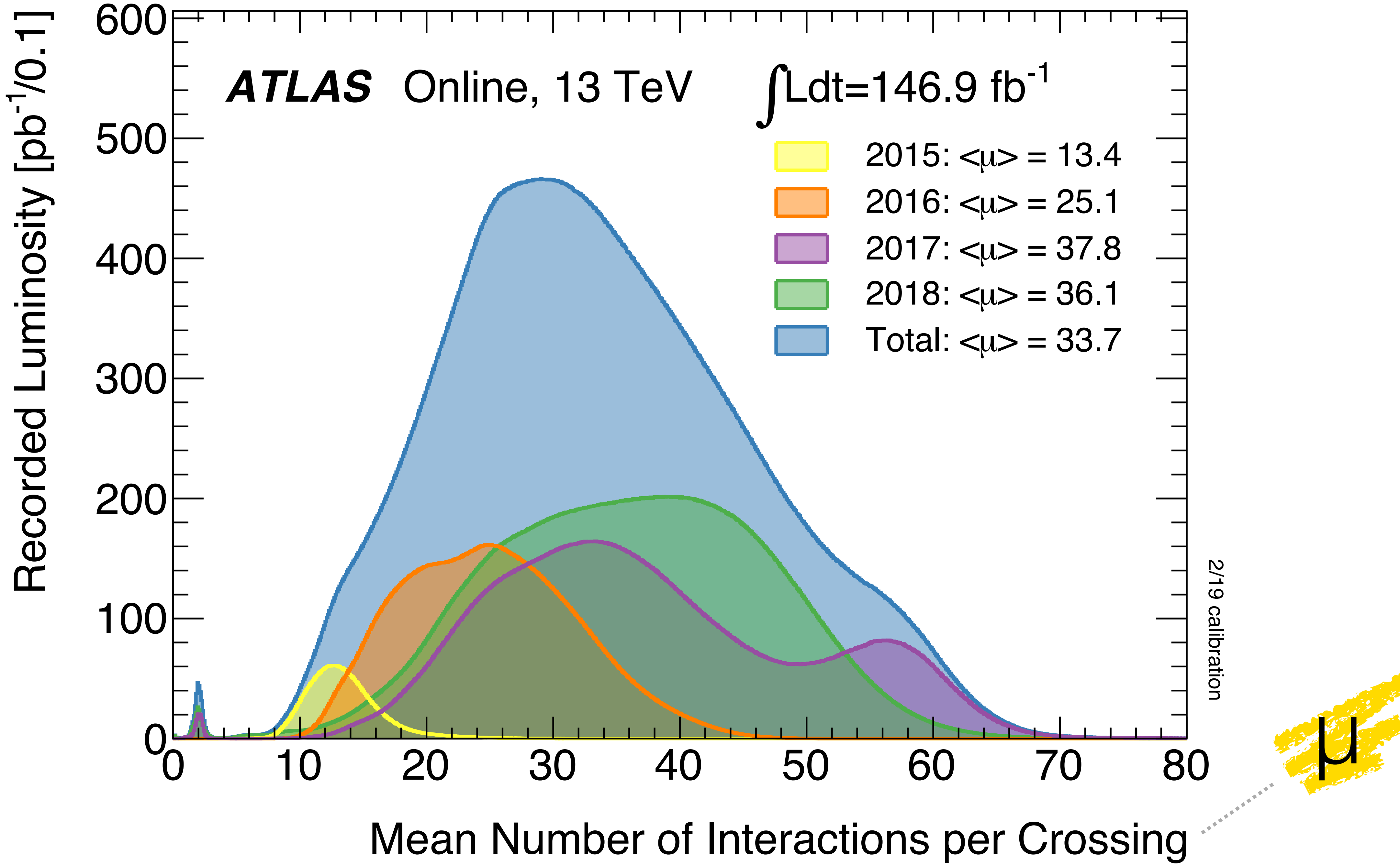
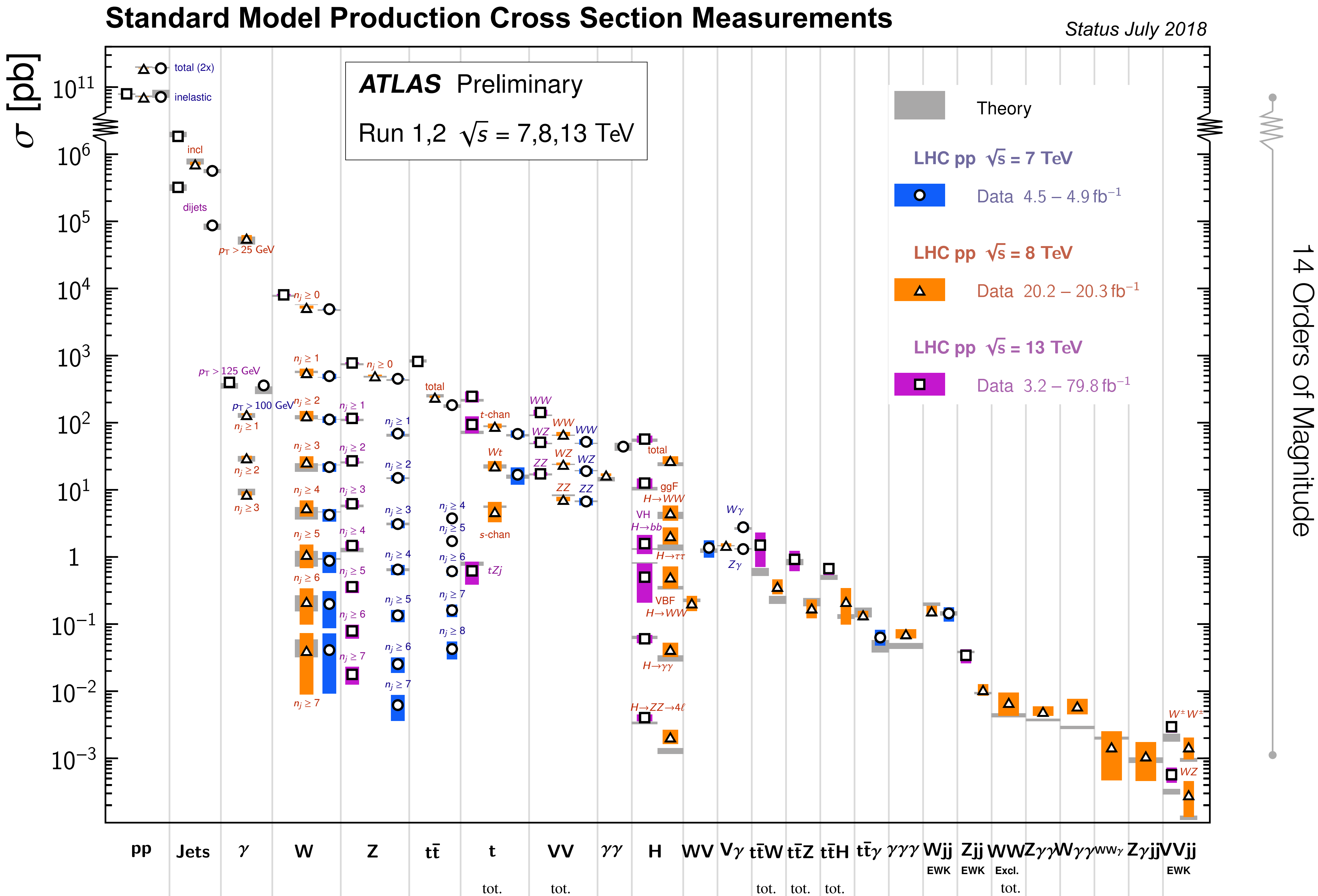


# Standard Model Measurements



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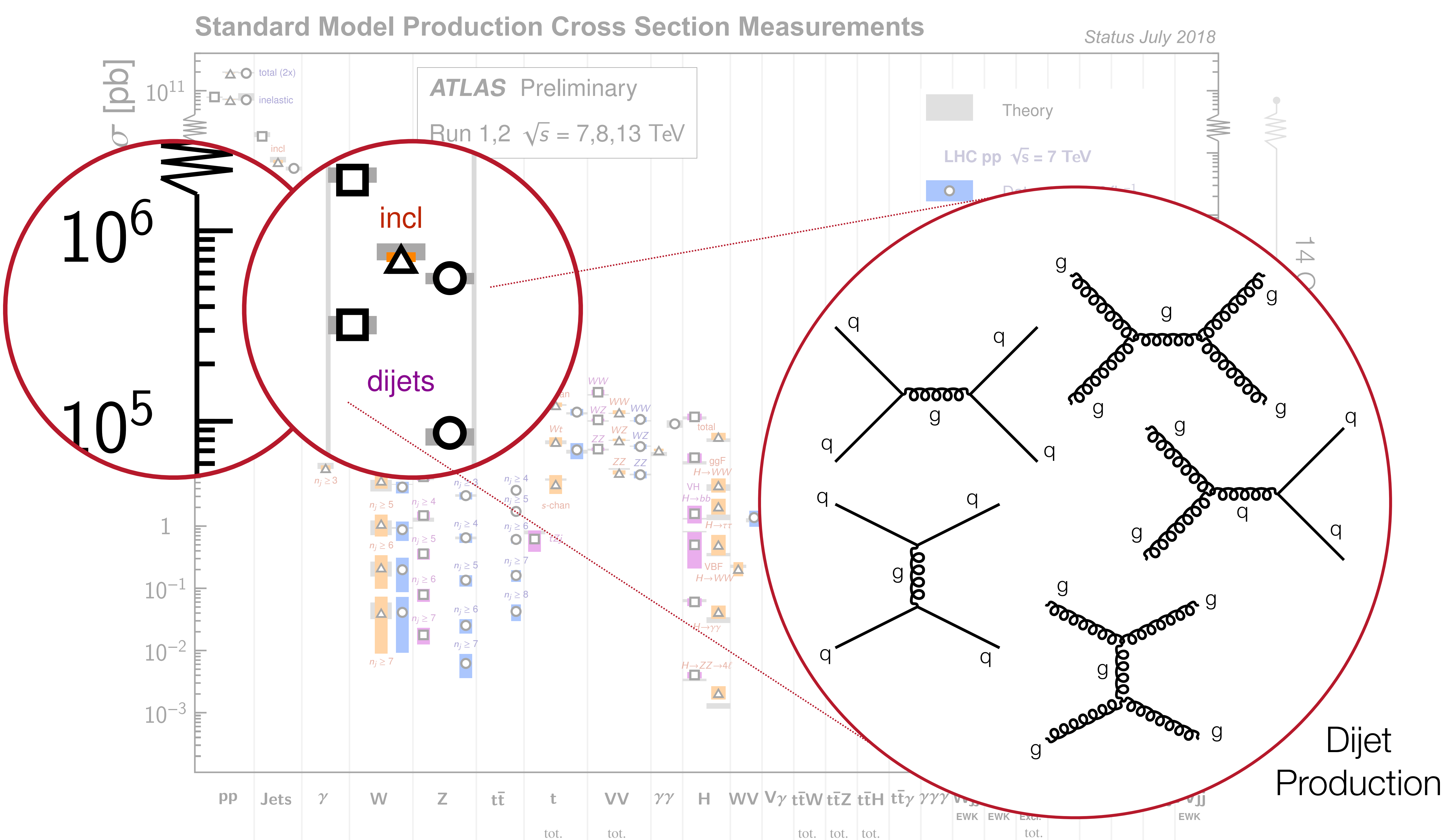

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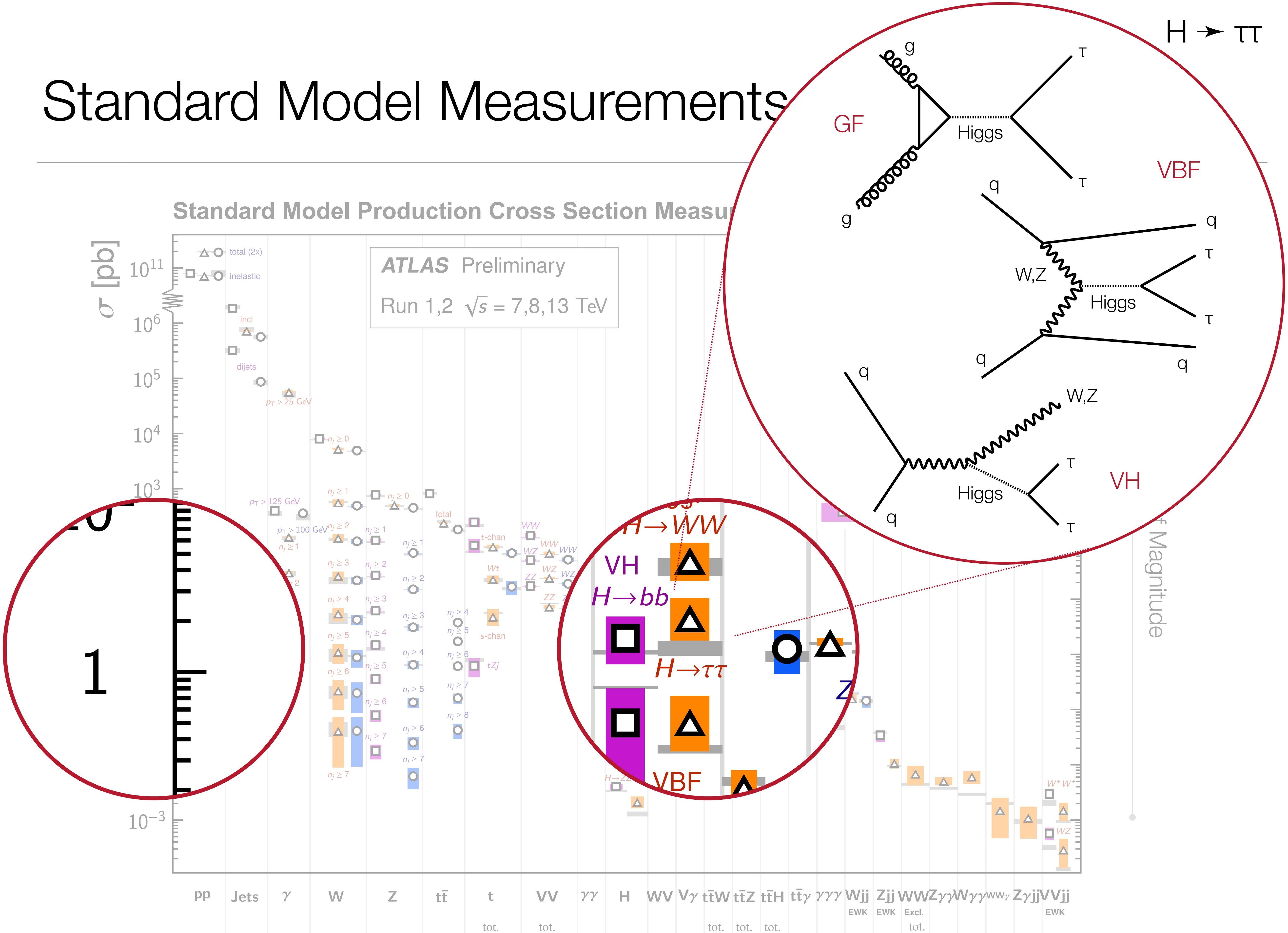

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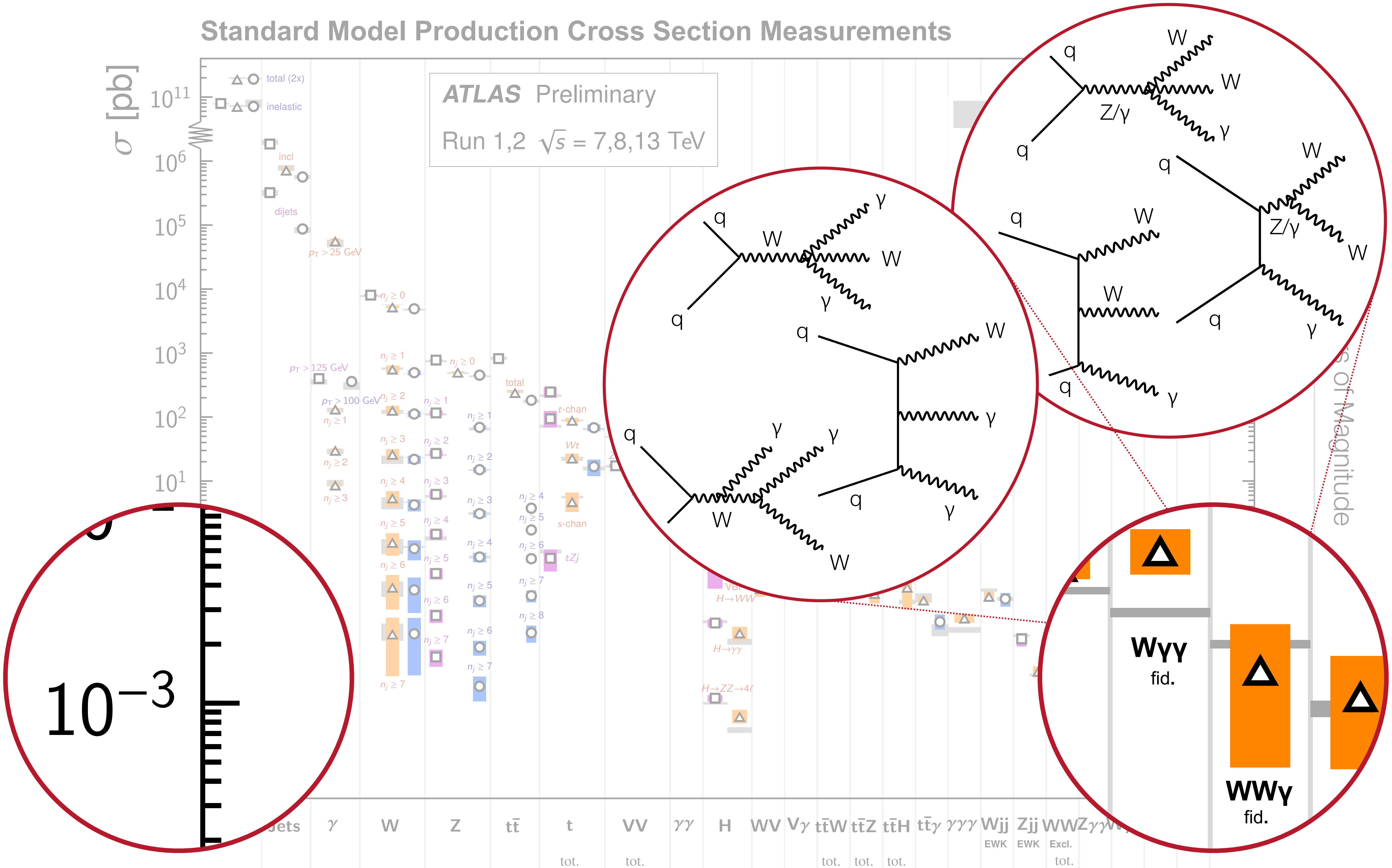

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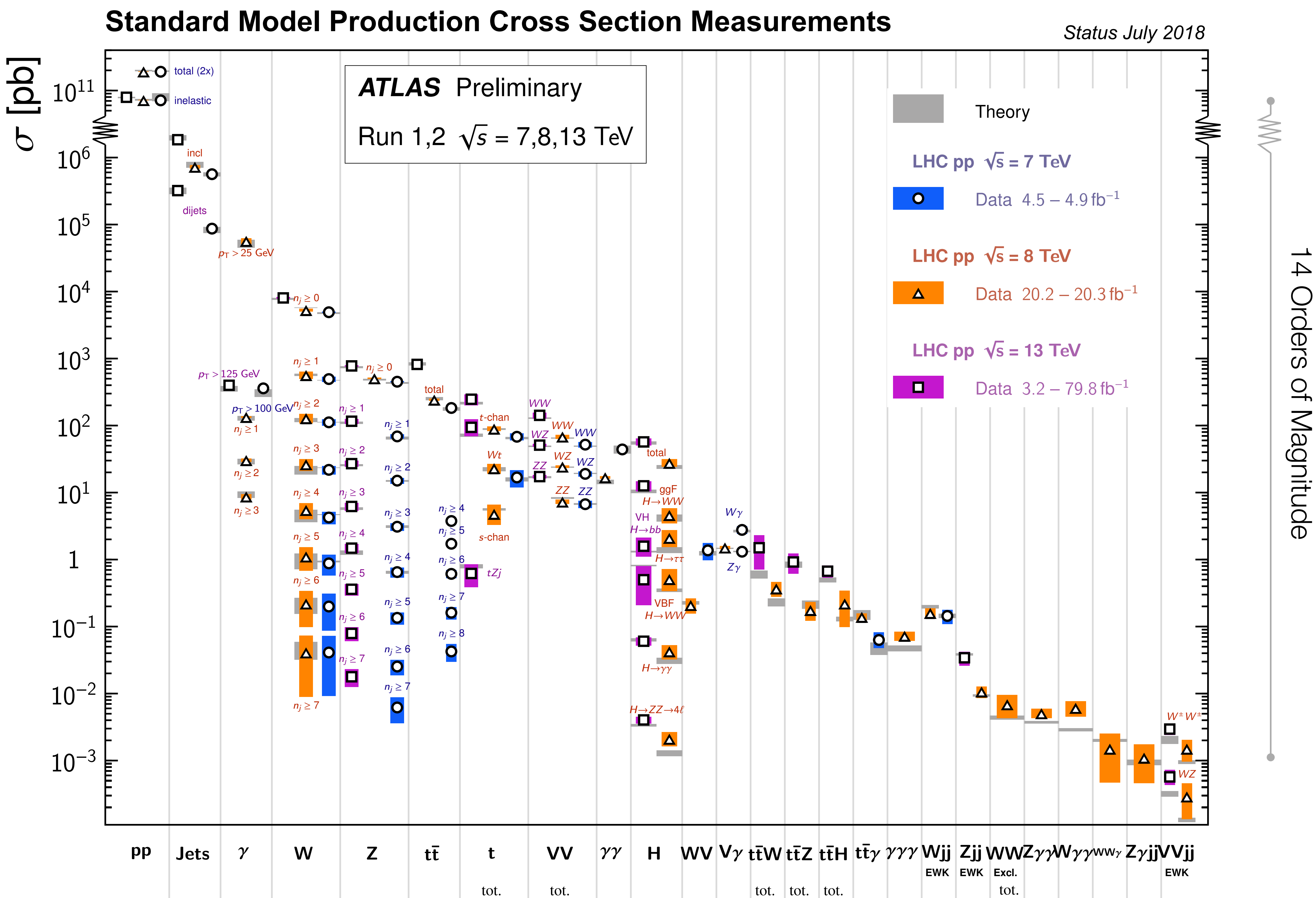


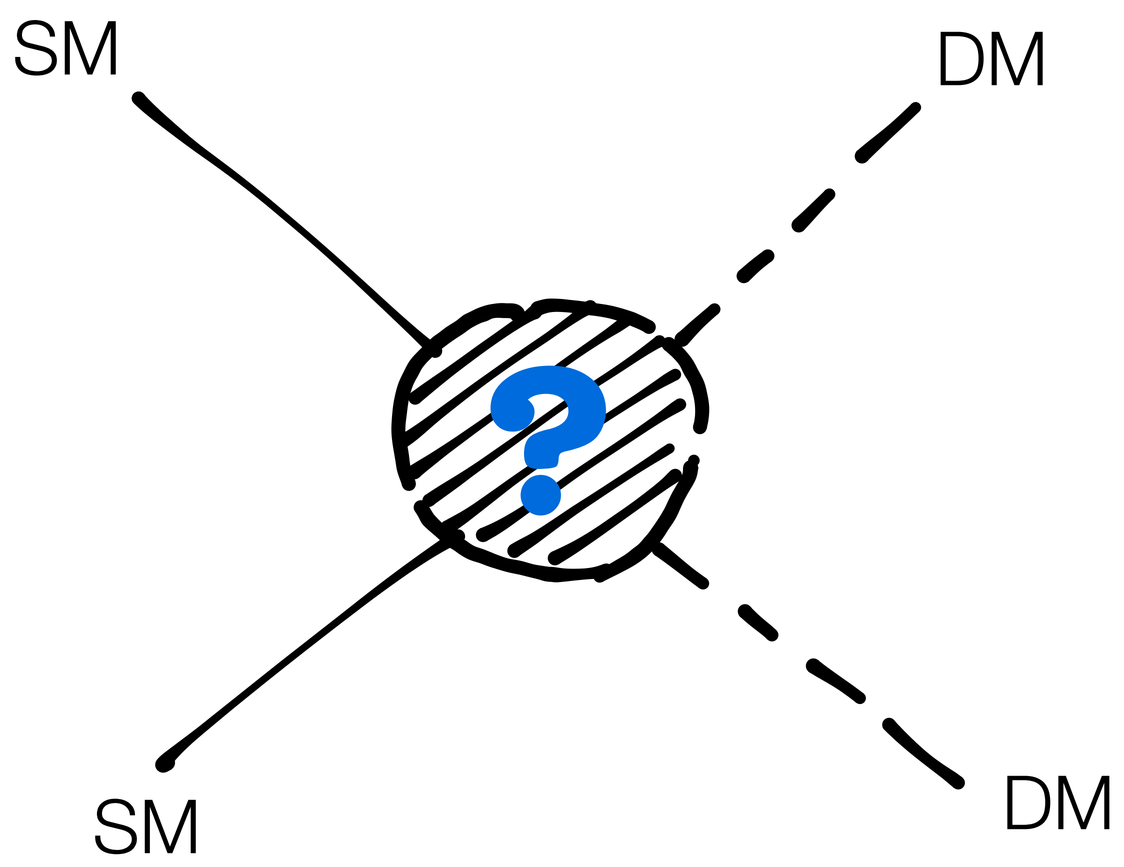
# Missing Energy Signatures

Assumption:

Dark Matter thermally produced in early Universe

Requires weak interaction between DM and SM particles

Candidates: WIMPs
[Weakly Interacting Massiv Particles]

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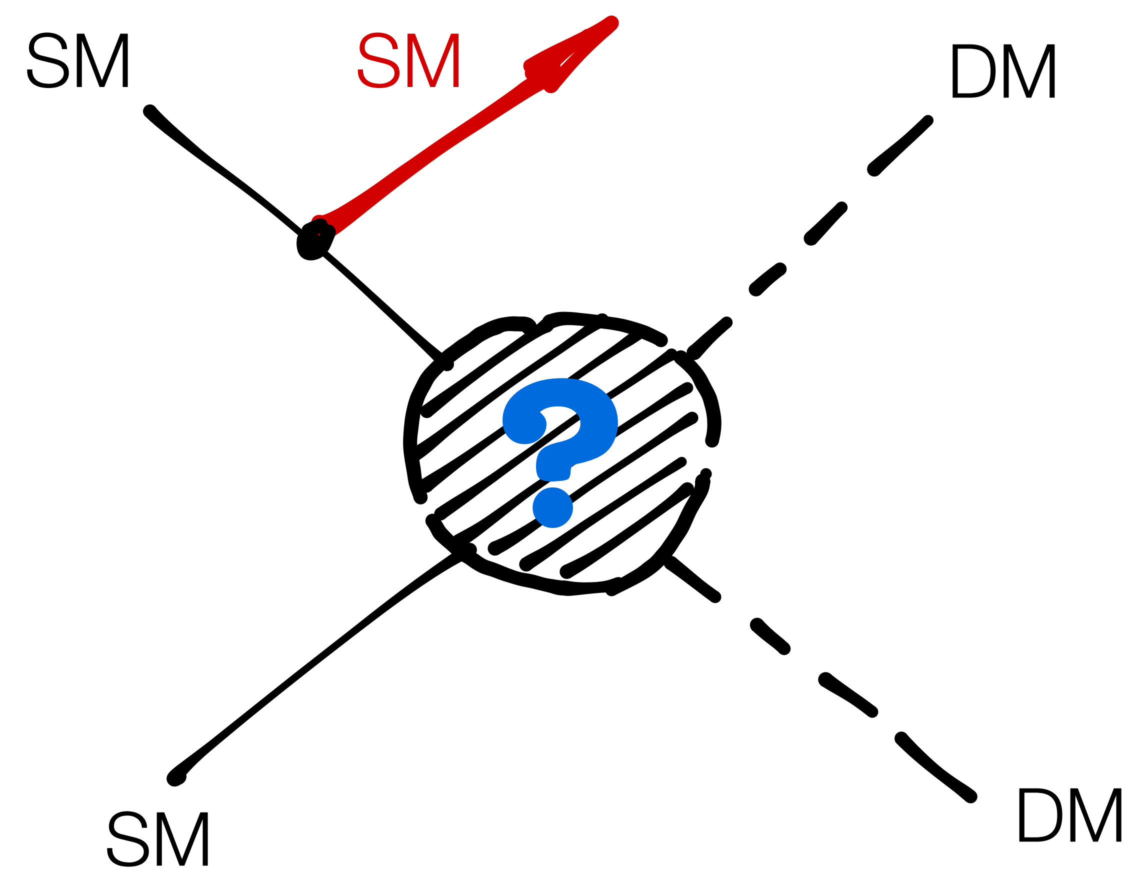
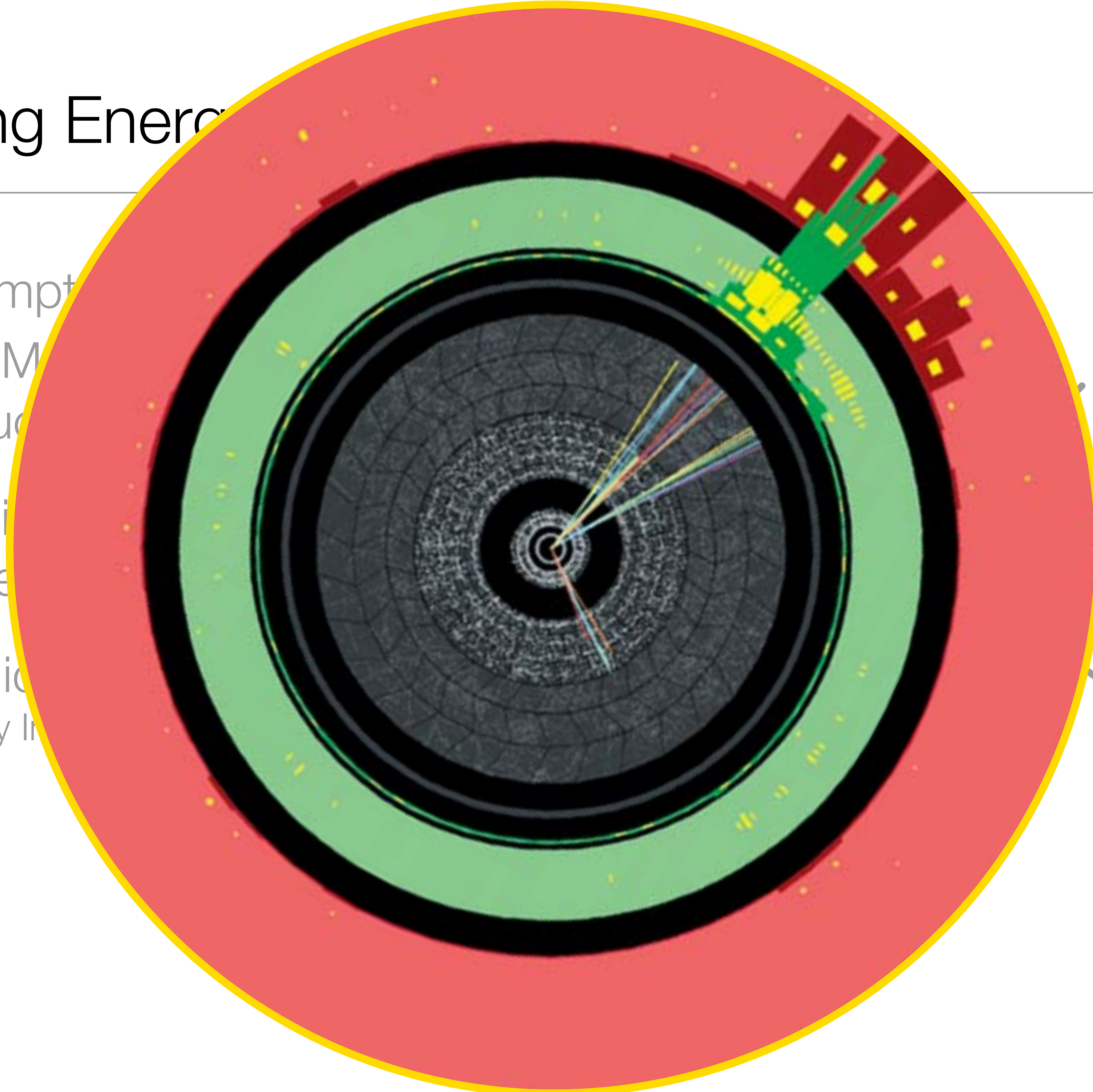



# Missing Energ

Assumpt
Dark M
produc

Requi
betwe

Candid
[Weakly I



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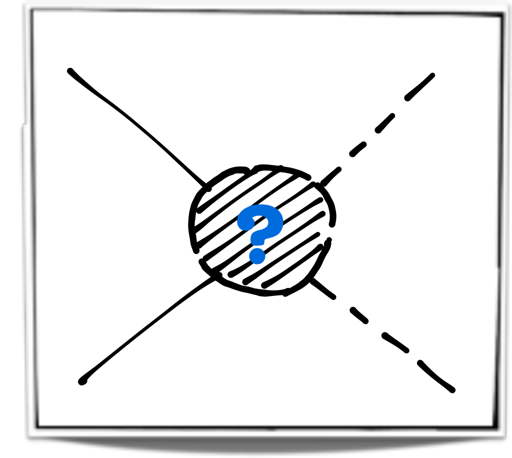


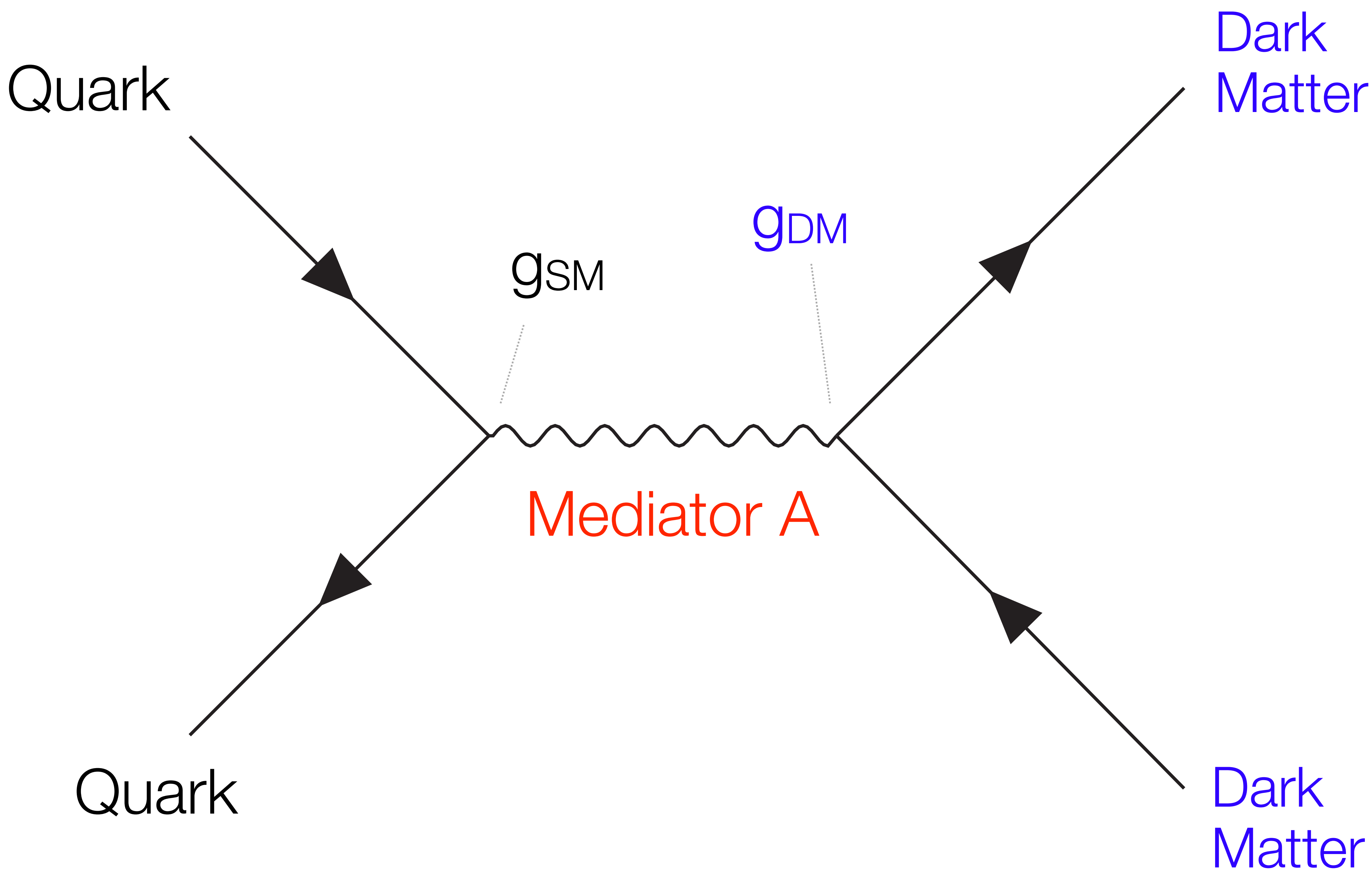

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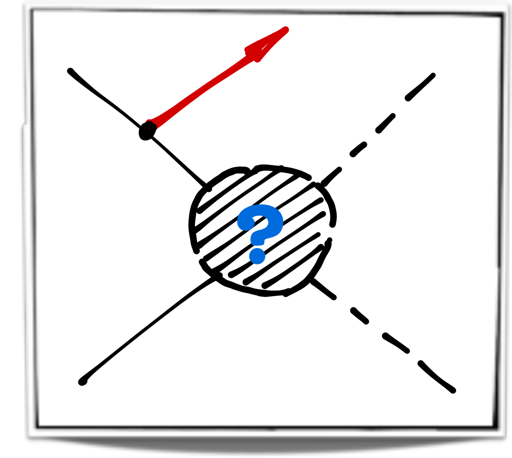
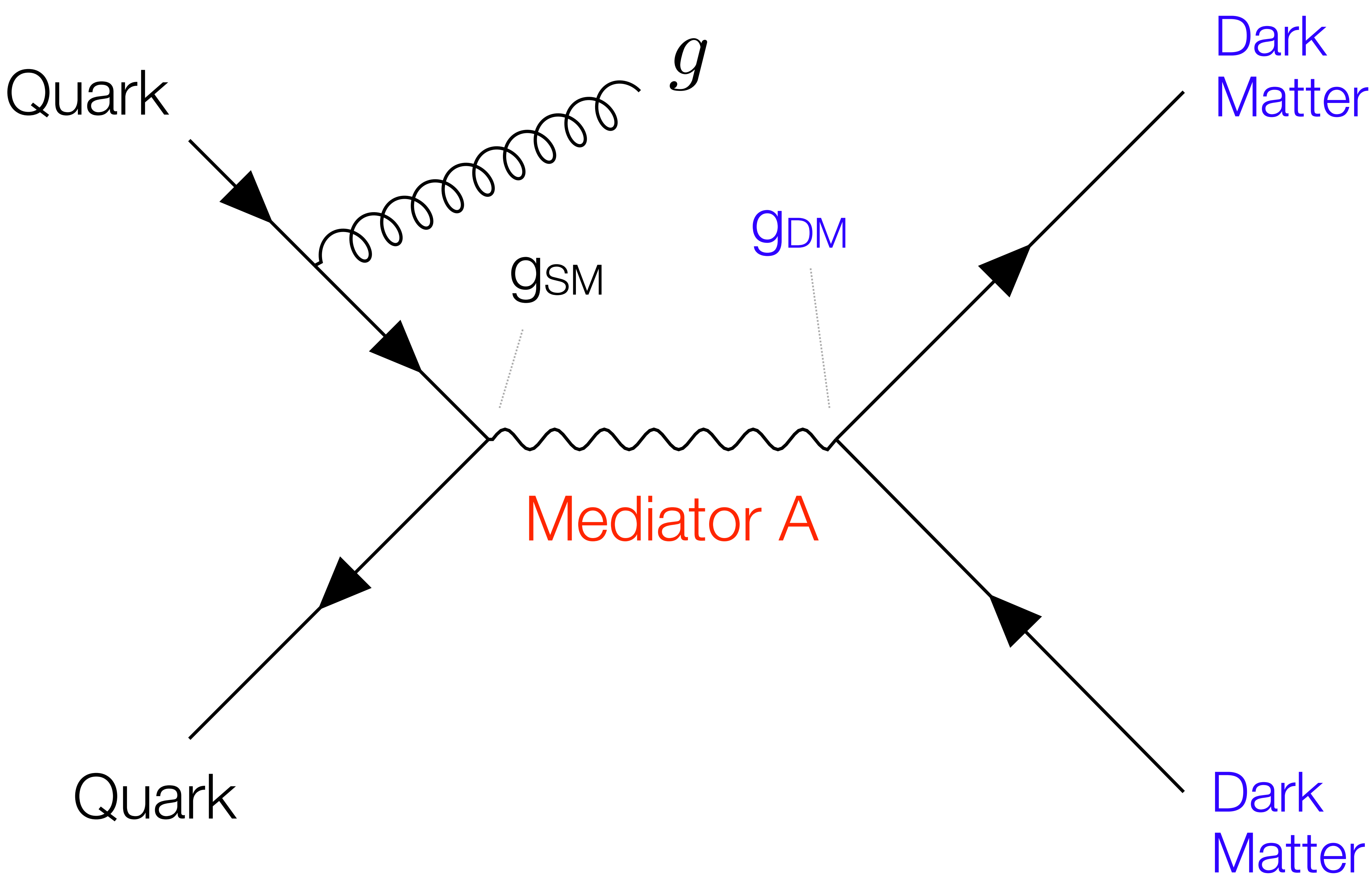
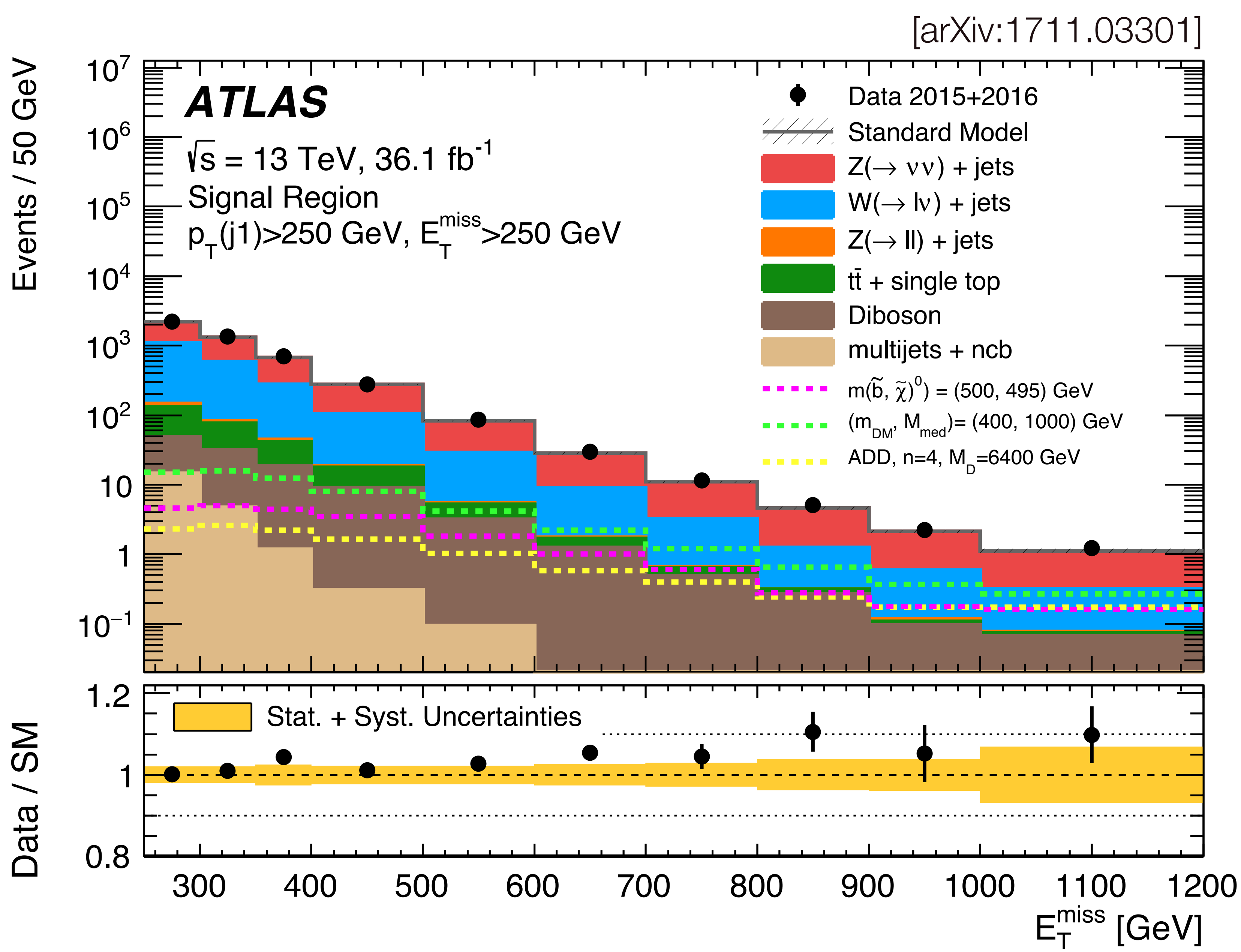
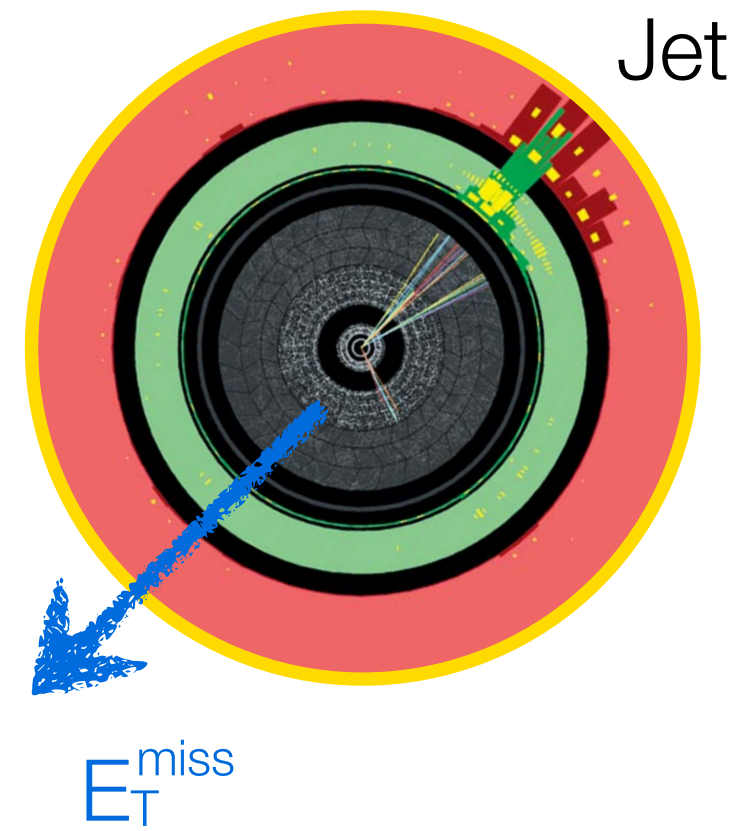




# ATLAS Monjet-Search



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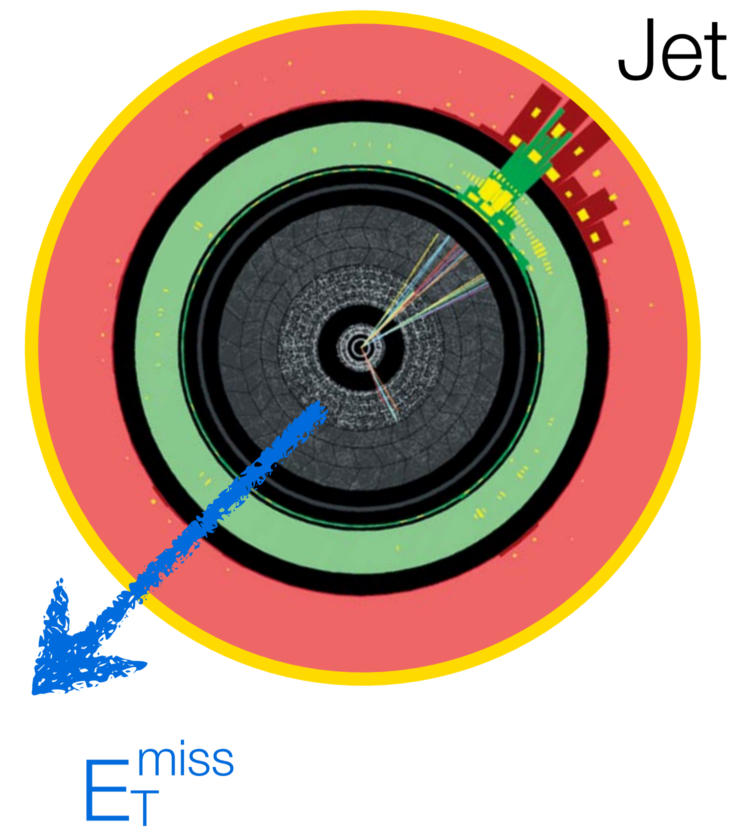
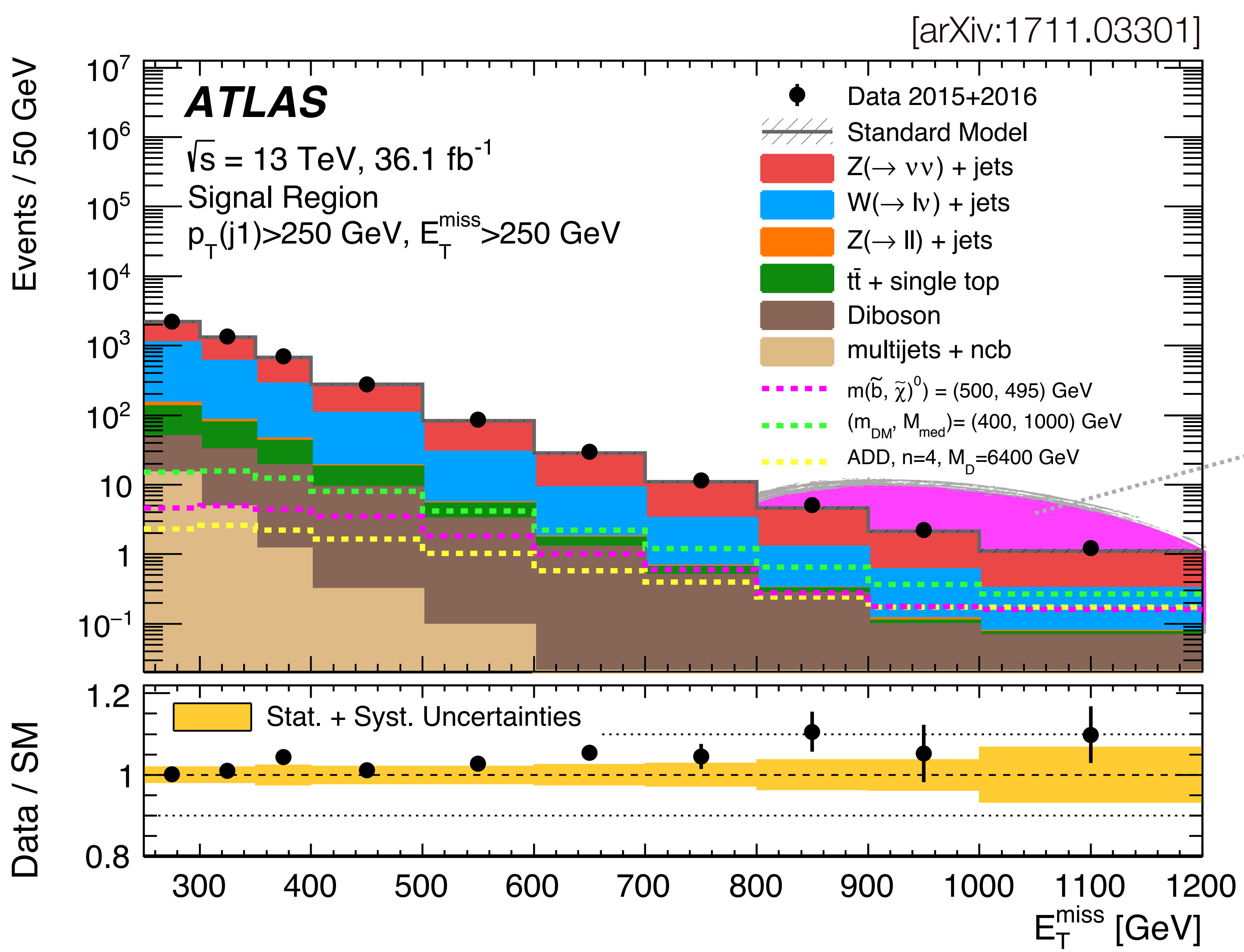


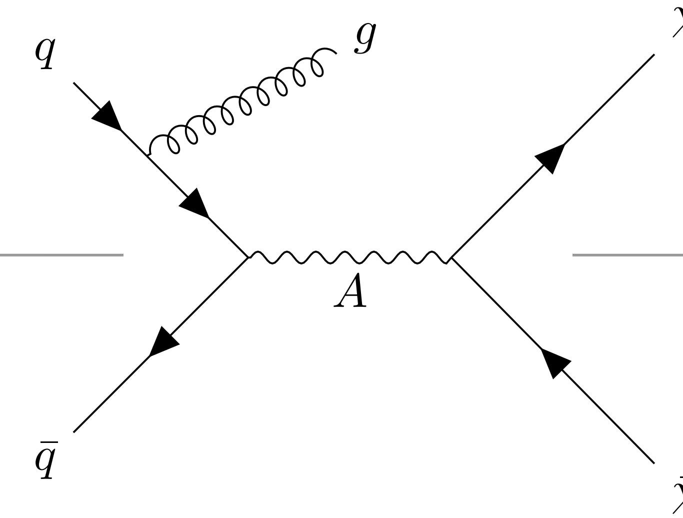



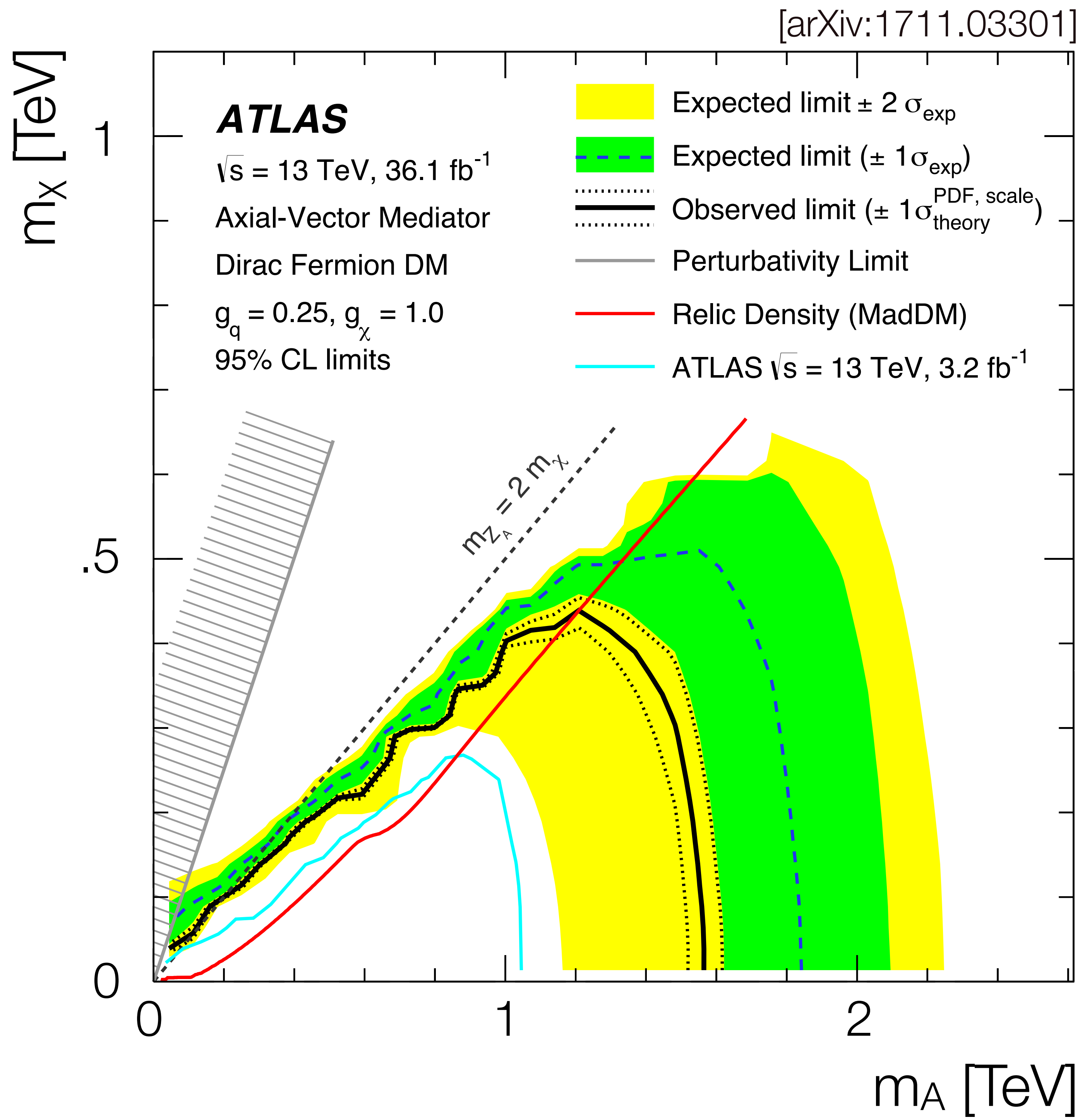

DM-Signal

Depends on

- Mass of DM-particle
- Mass of Mediator
- Couplings

# ATLAS Monjet-Search

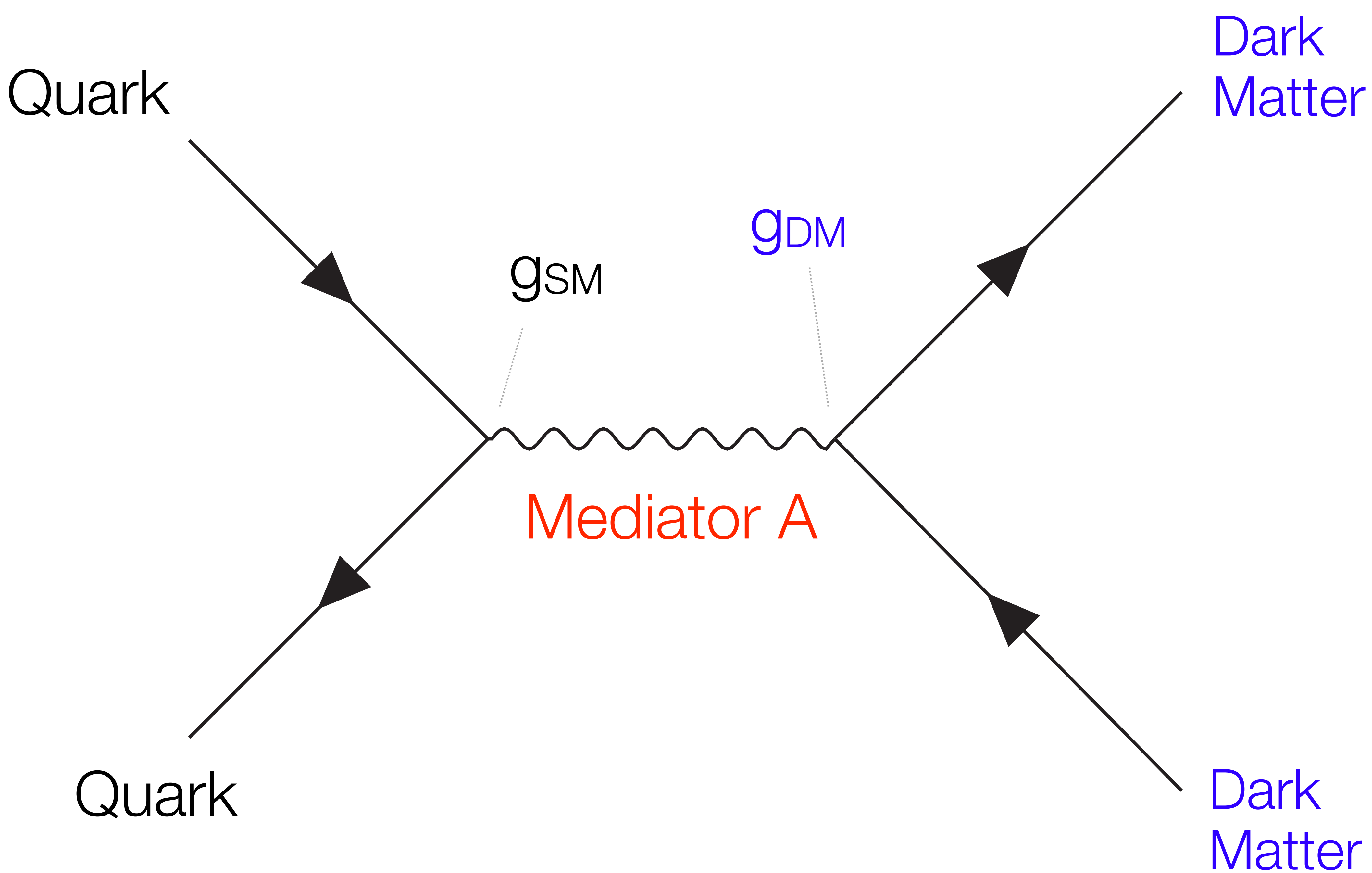



$g_{SM} = 0.25$ [$g_q$]
$g_{DM} = 1.00$ [$g_\chi$]

$m_A$ : Mediator mass
$m_\chi$ : DM mass

# Dijet Resonance Searches



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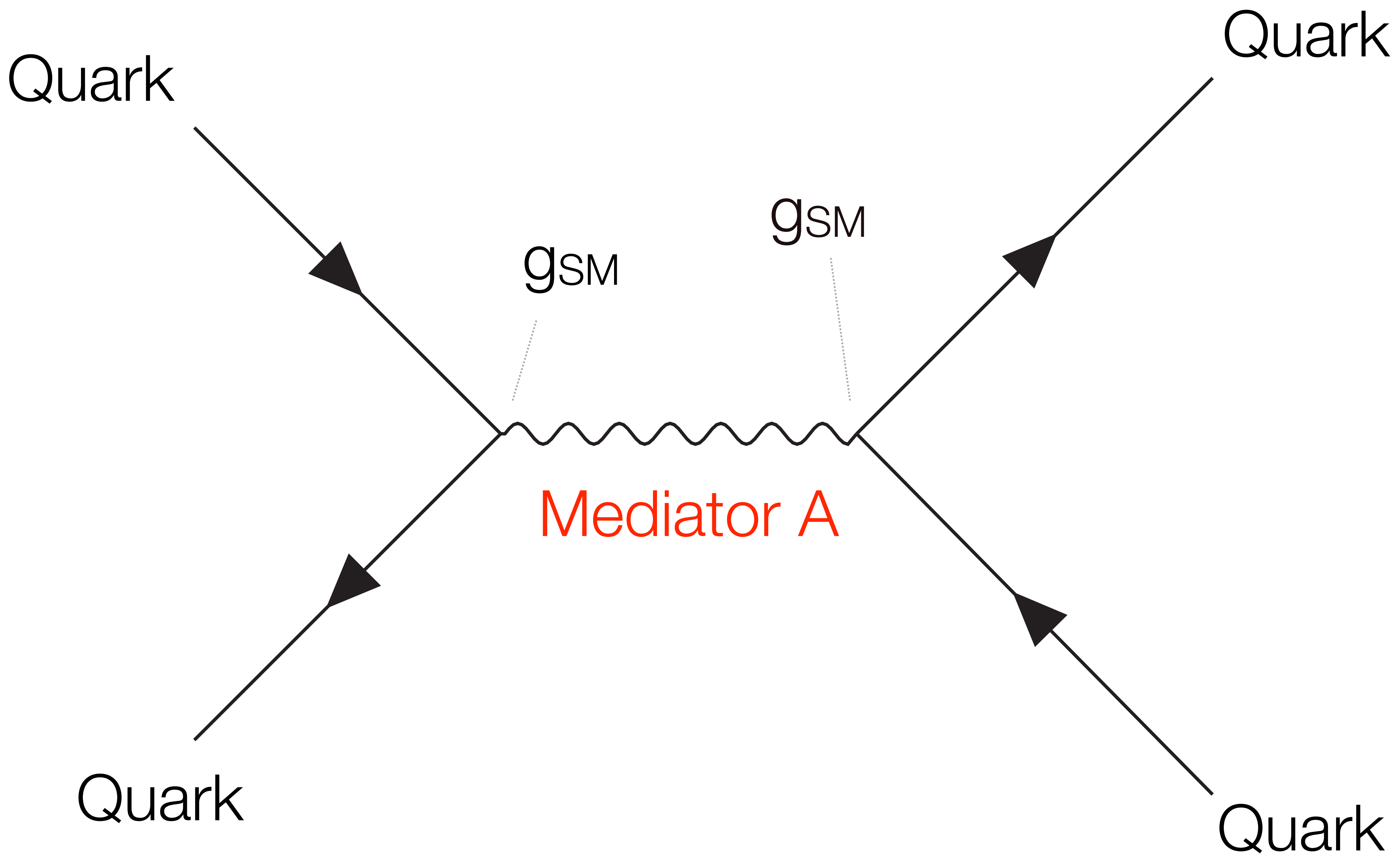

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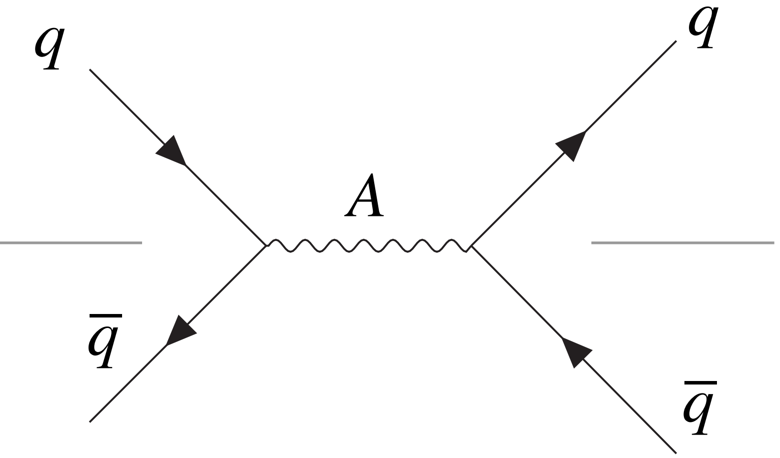
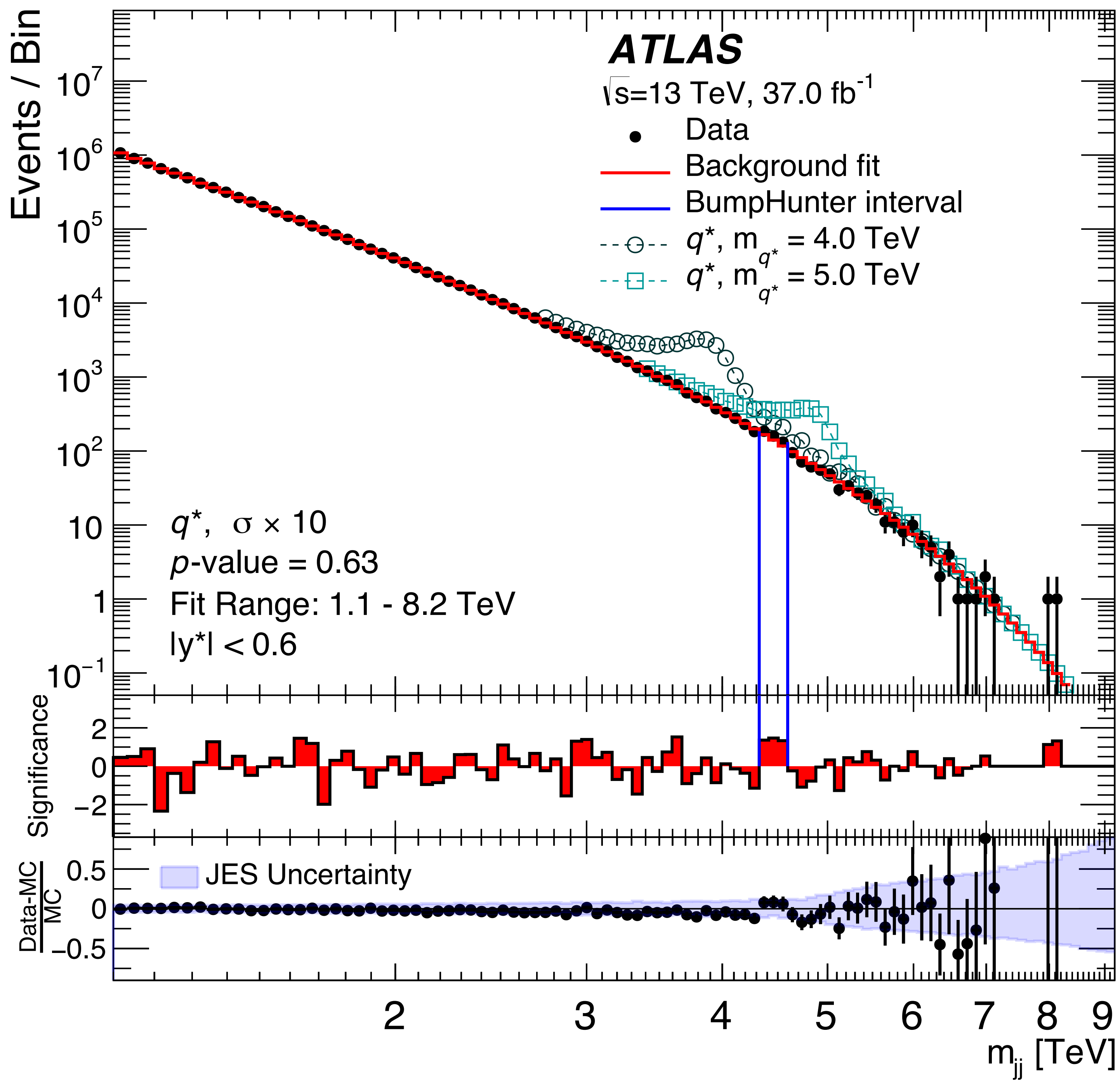



[arXiv:1703.09127]




## Dijet searches at high energy

2 ➝ 2 processes
well described by QCD …

Any deviation from SM
implies new physics …

e.g.

| | |
|---|---|
| quantum black holes | > 8.7 TeV |
| excited quarks | > 5.6 TeV |
| heavy SM-like W’ | > 2.9 TeV |
| excited W* bosons | > 3.3 TeV |
| leptophobic Z’ | |
| contact interactions | |
| … | |

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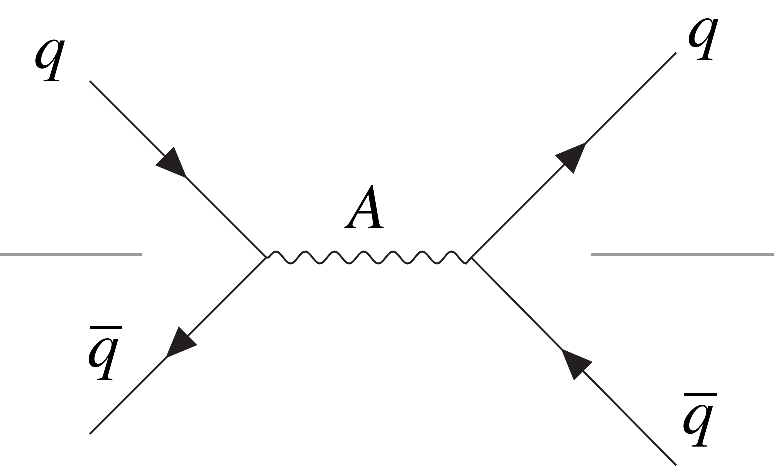
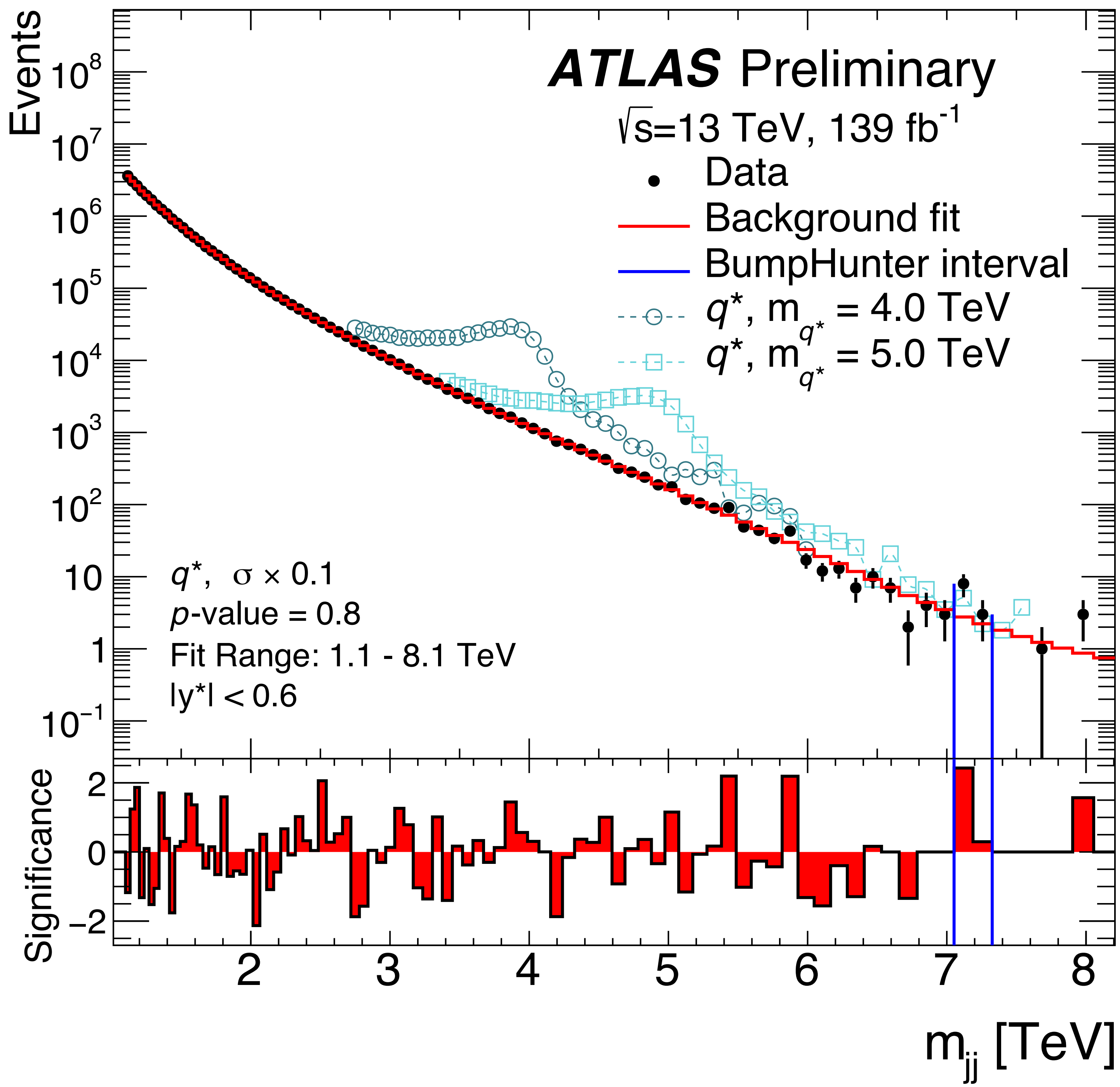



[ATLAS-CONF-2019-007]

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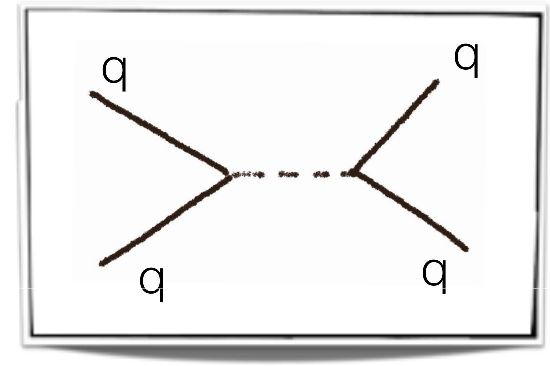
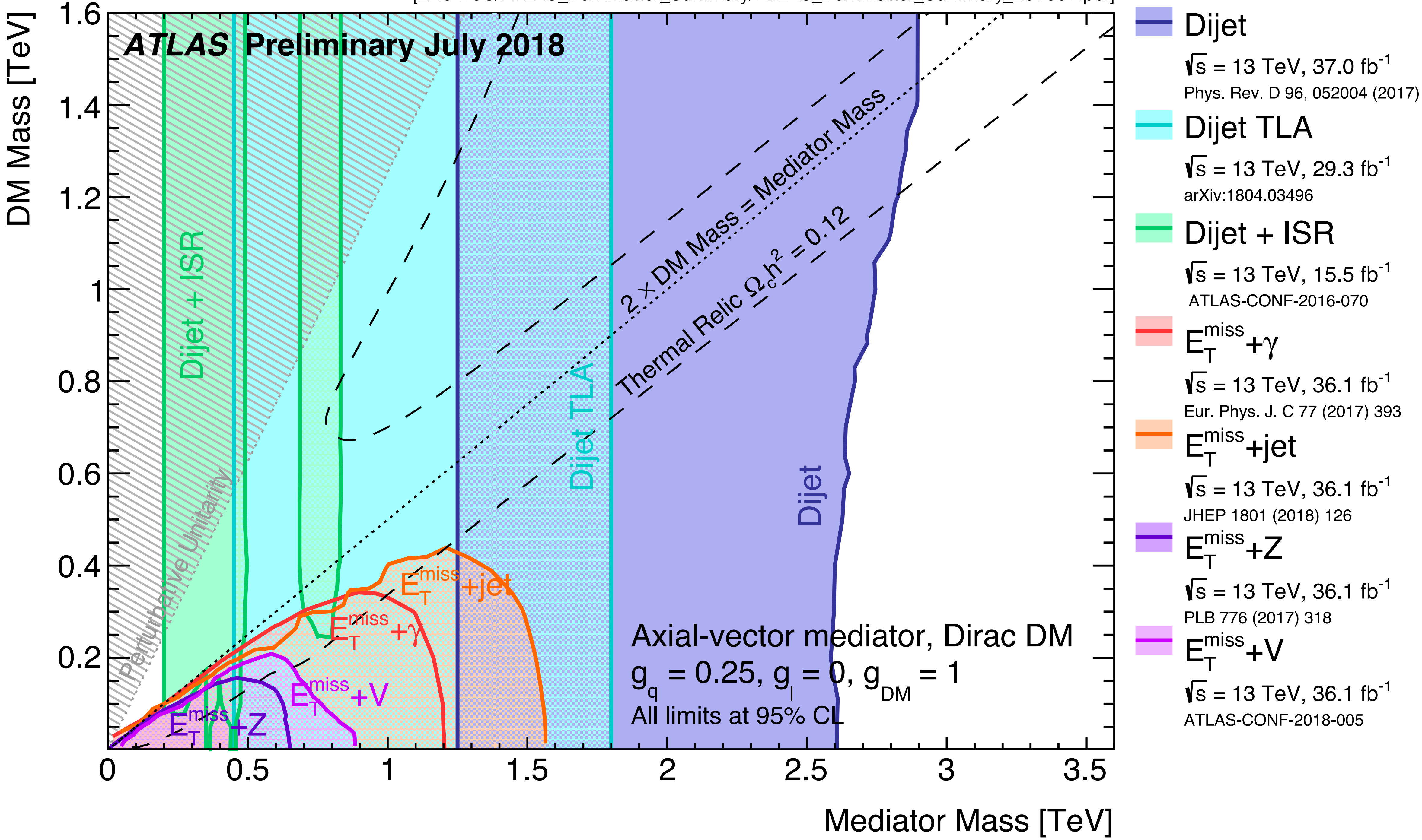
# Dijet Resonance Searches

+ TLA




[EXOTICS/ATLAS_DarkMatter_Summary/ATLAS_DarkMatter_Summary_201807.pdf]



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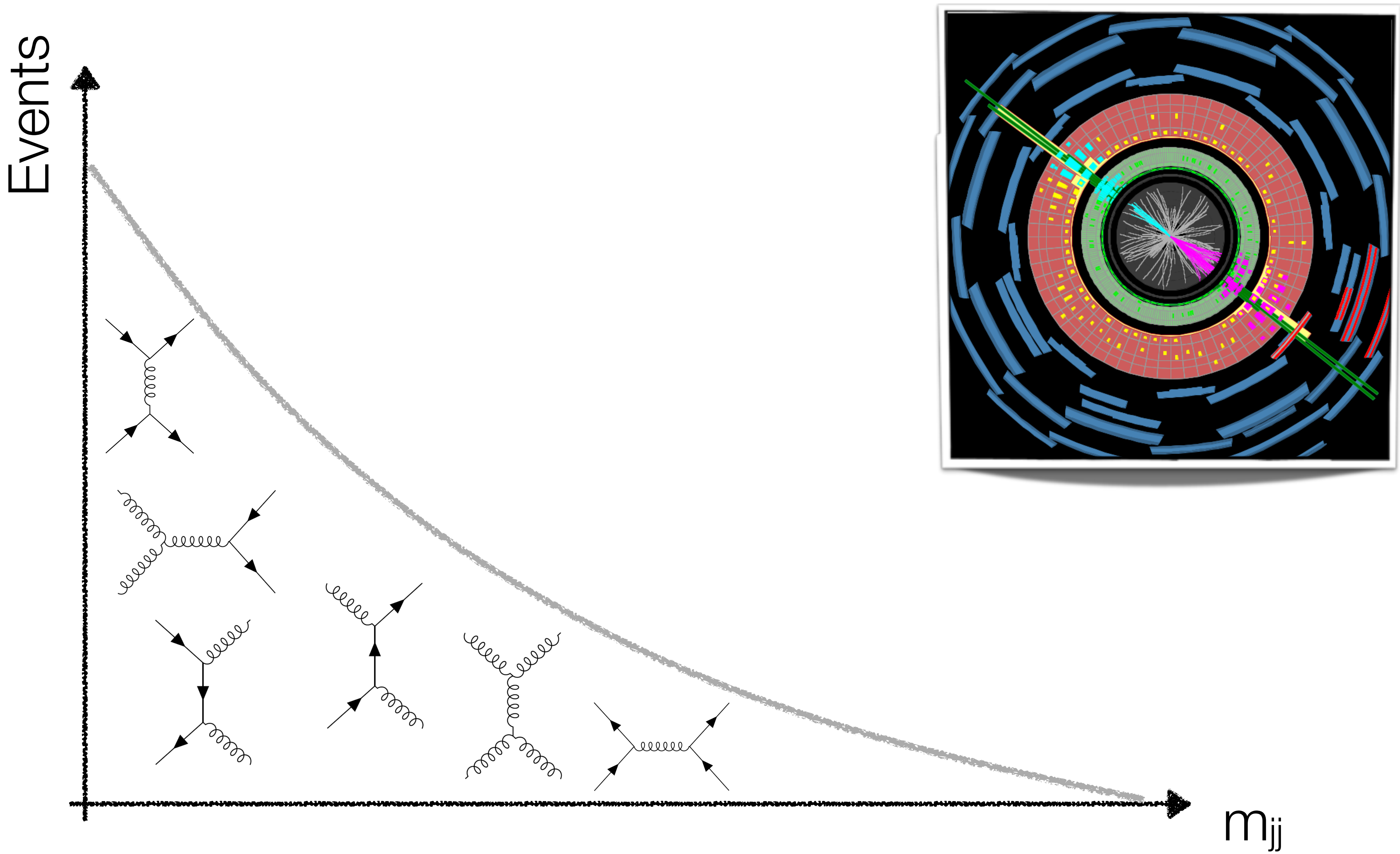


[courtesy Hanno Meyer zu Theenhausen]

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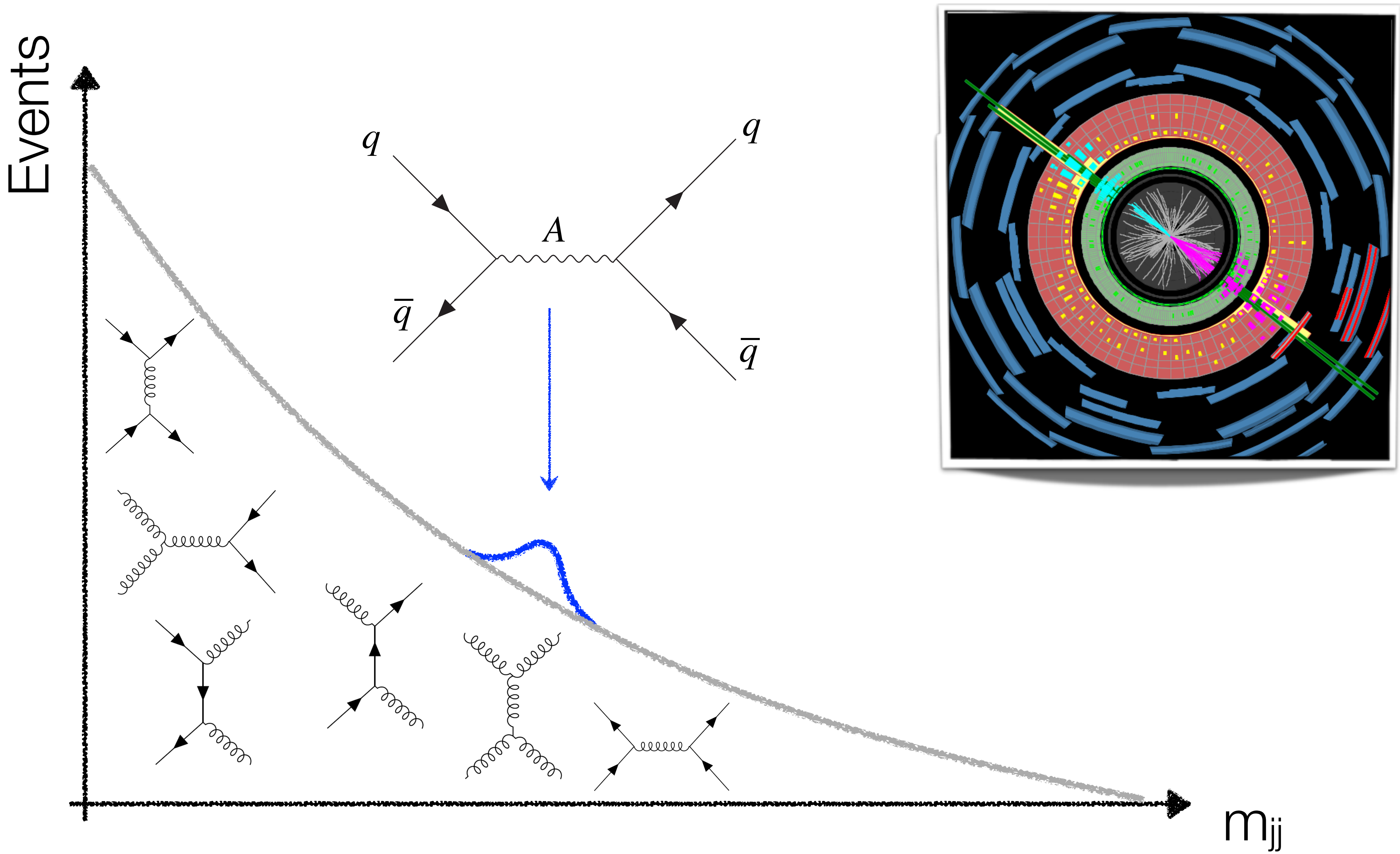



[courtesy Hanno Meyer zu Theenhausen]

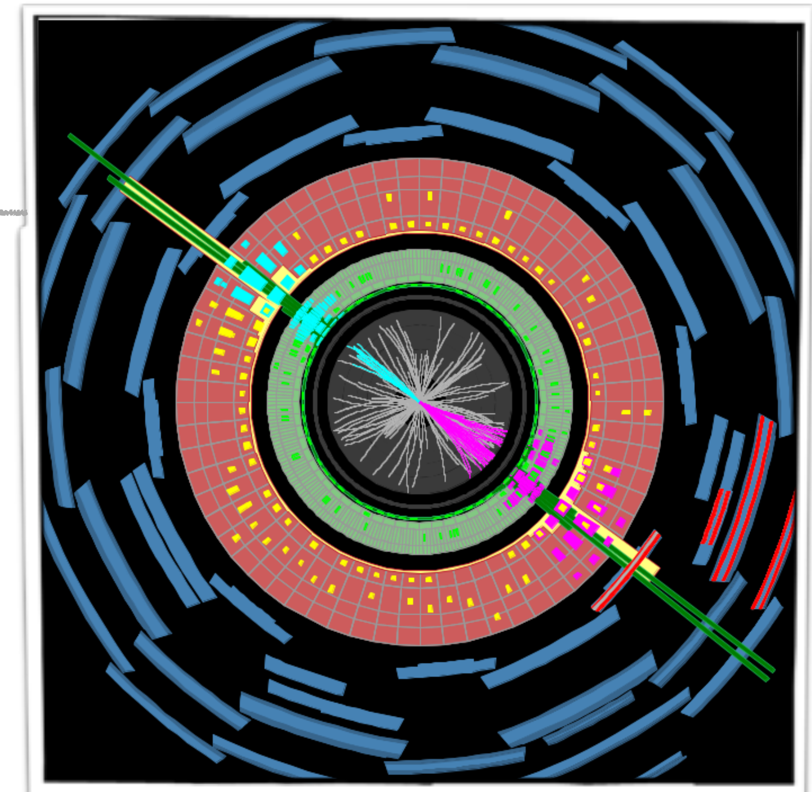
# TLA Dijet Resonance Search

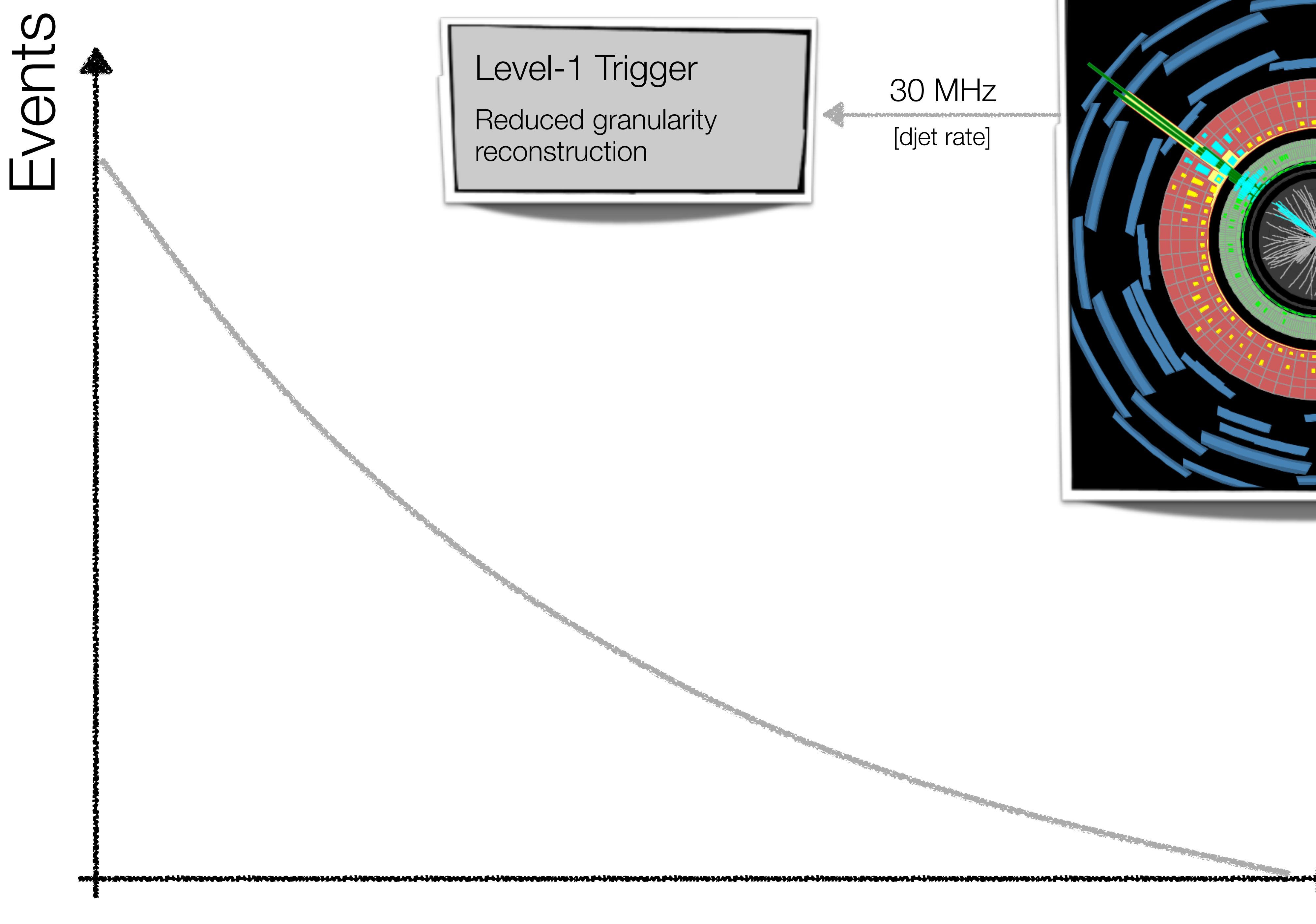
Level-1 Trigger

Reduced granularity reconstruction

30 MHz

[djet rate]






$m_{jj}$

[courtesy Hanno Meyer zu Theenhausen]

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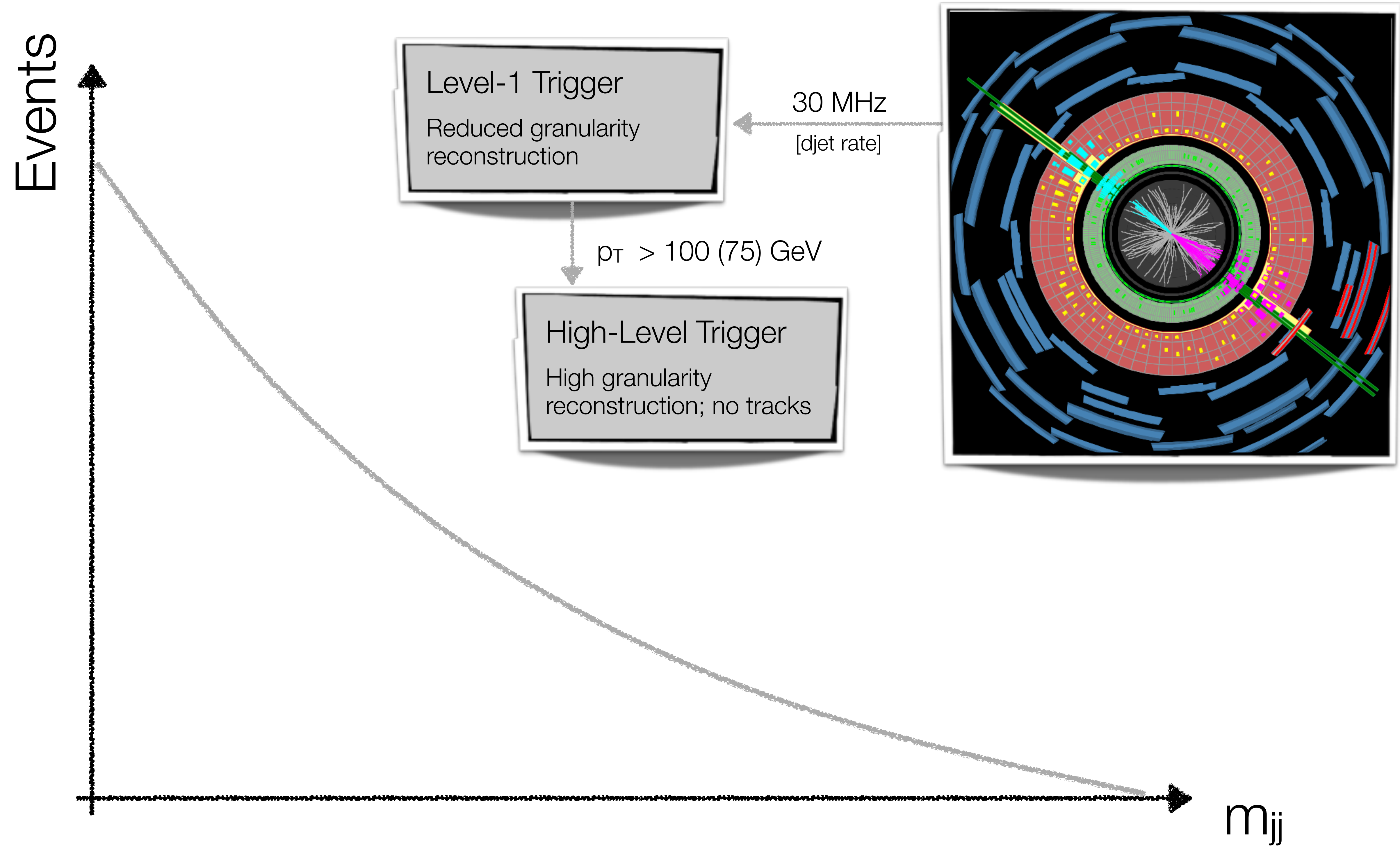


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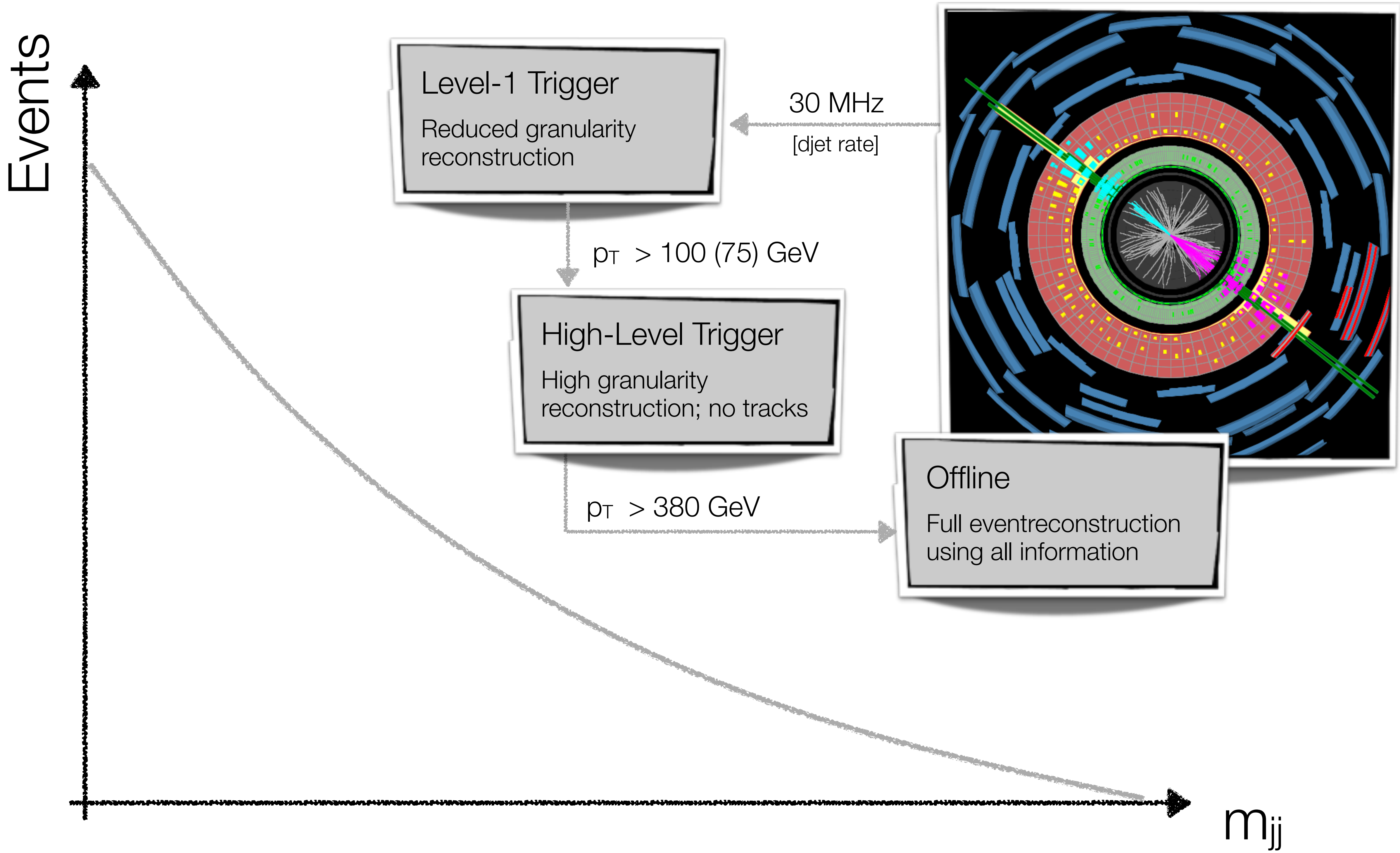


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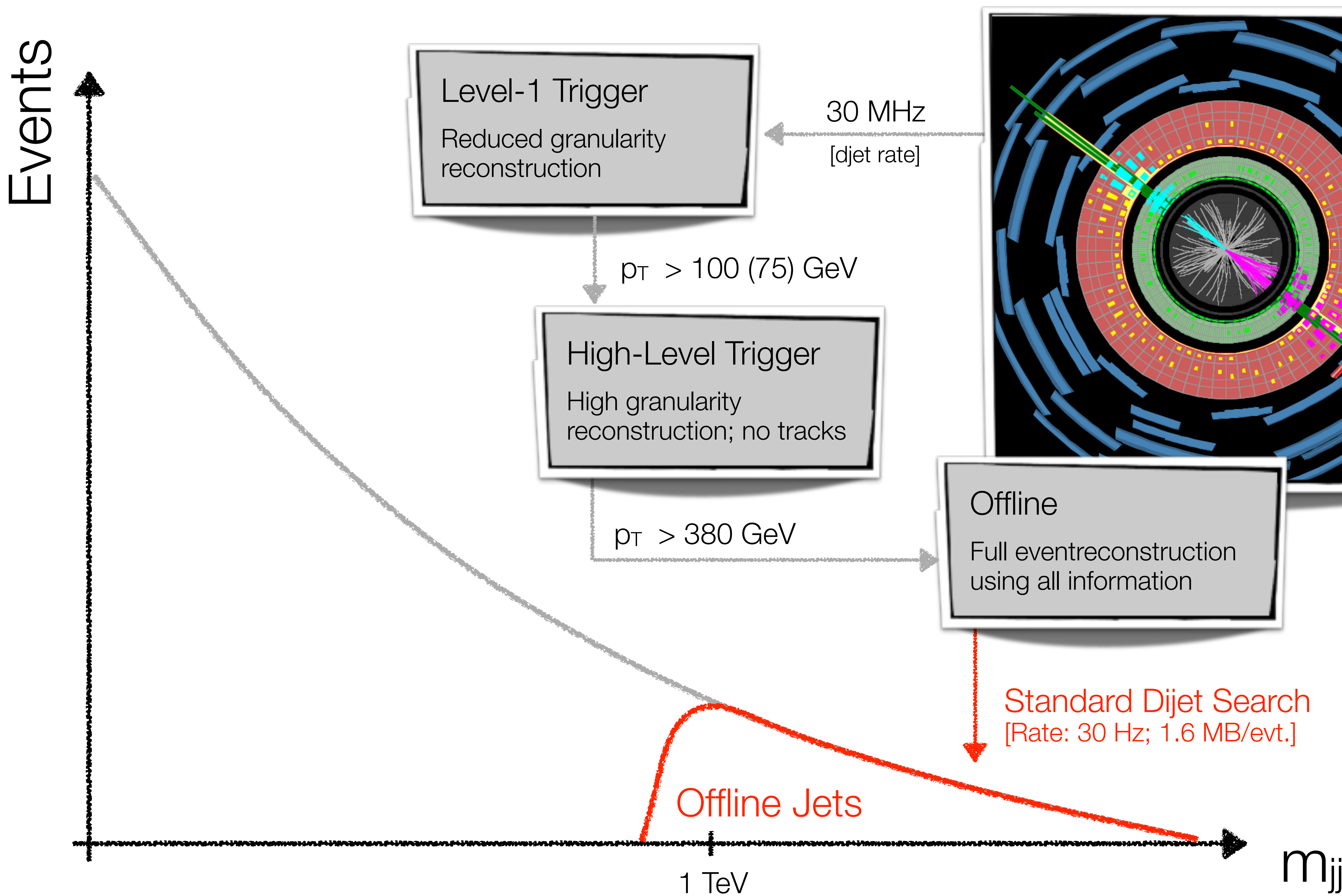


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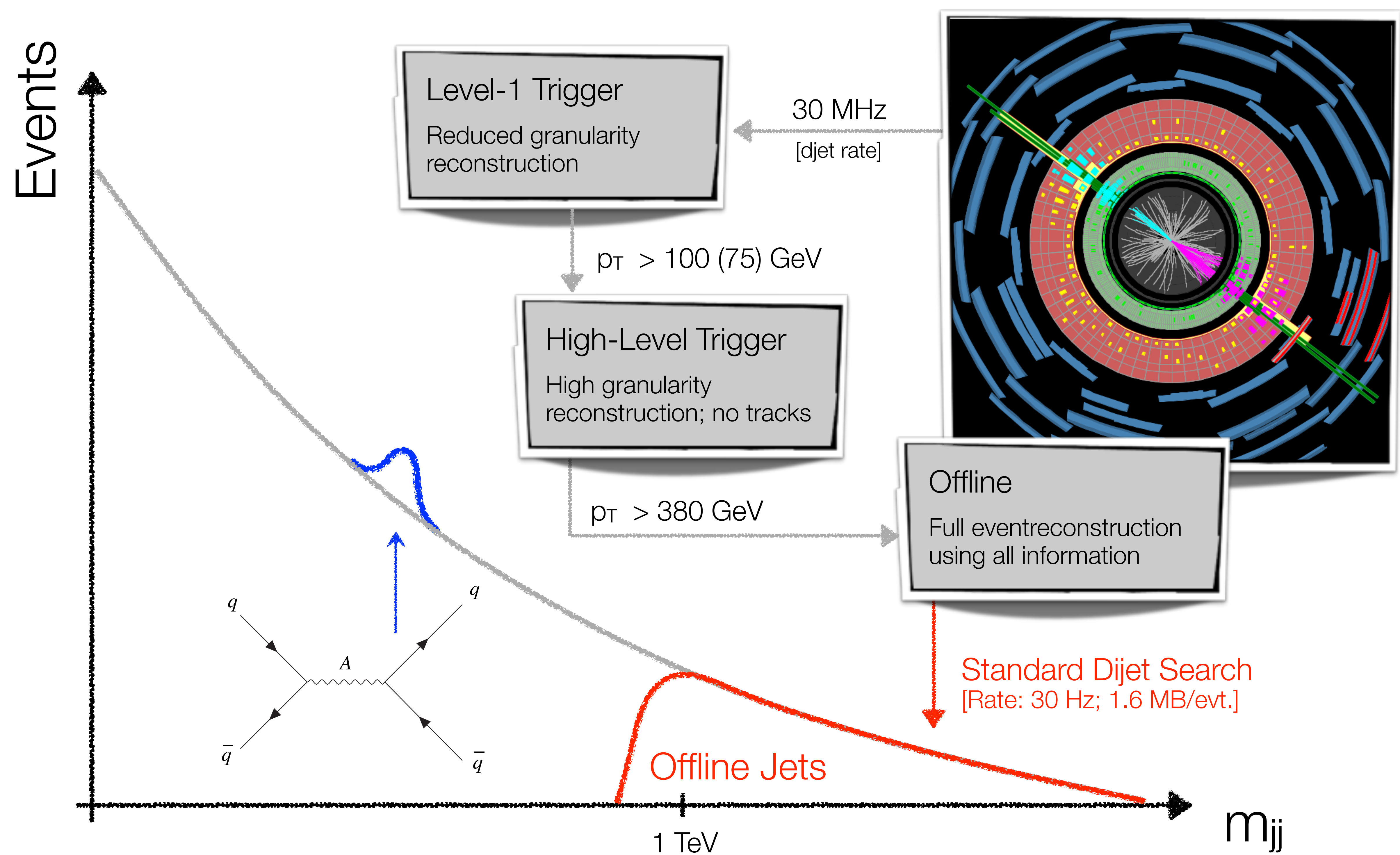


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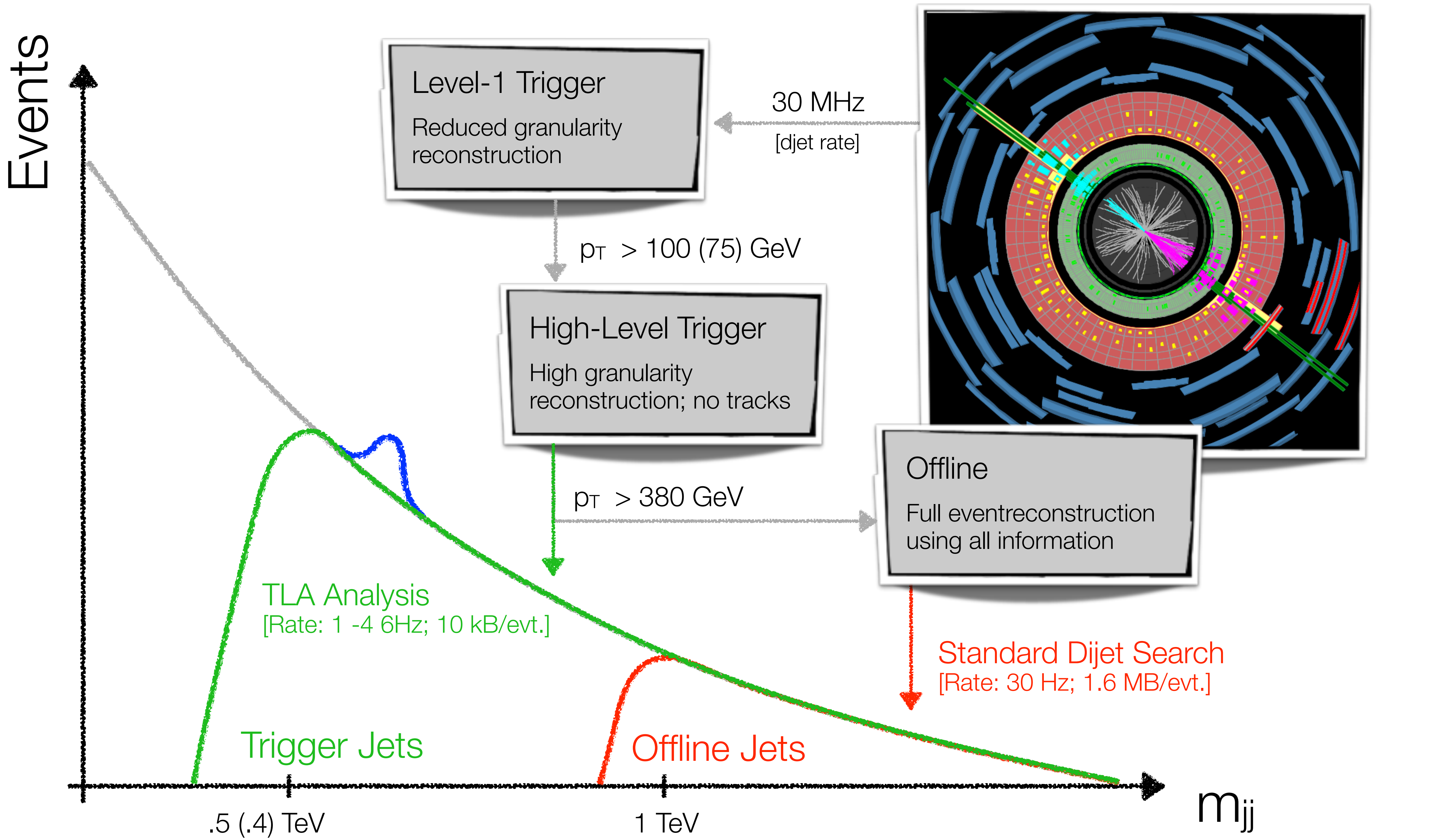


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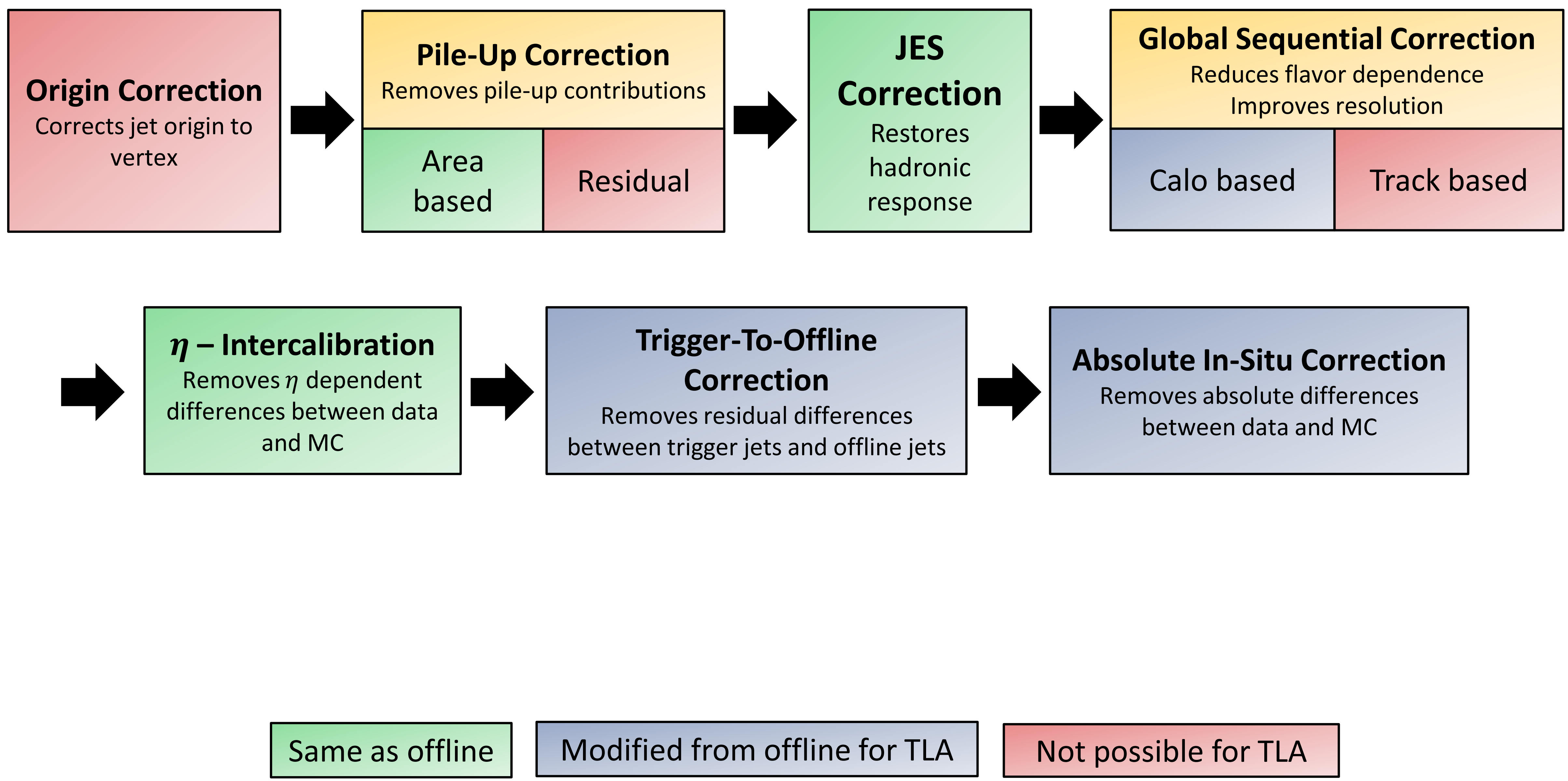
# TLA Jet Calibration

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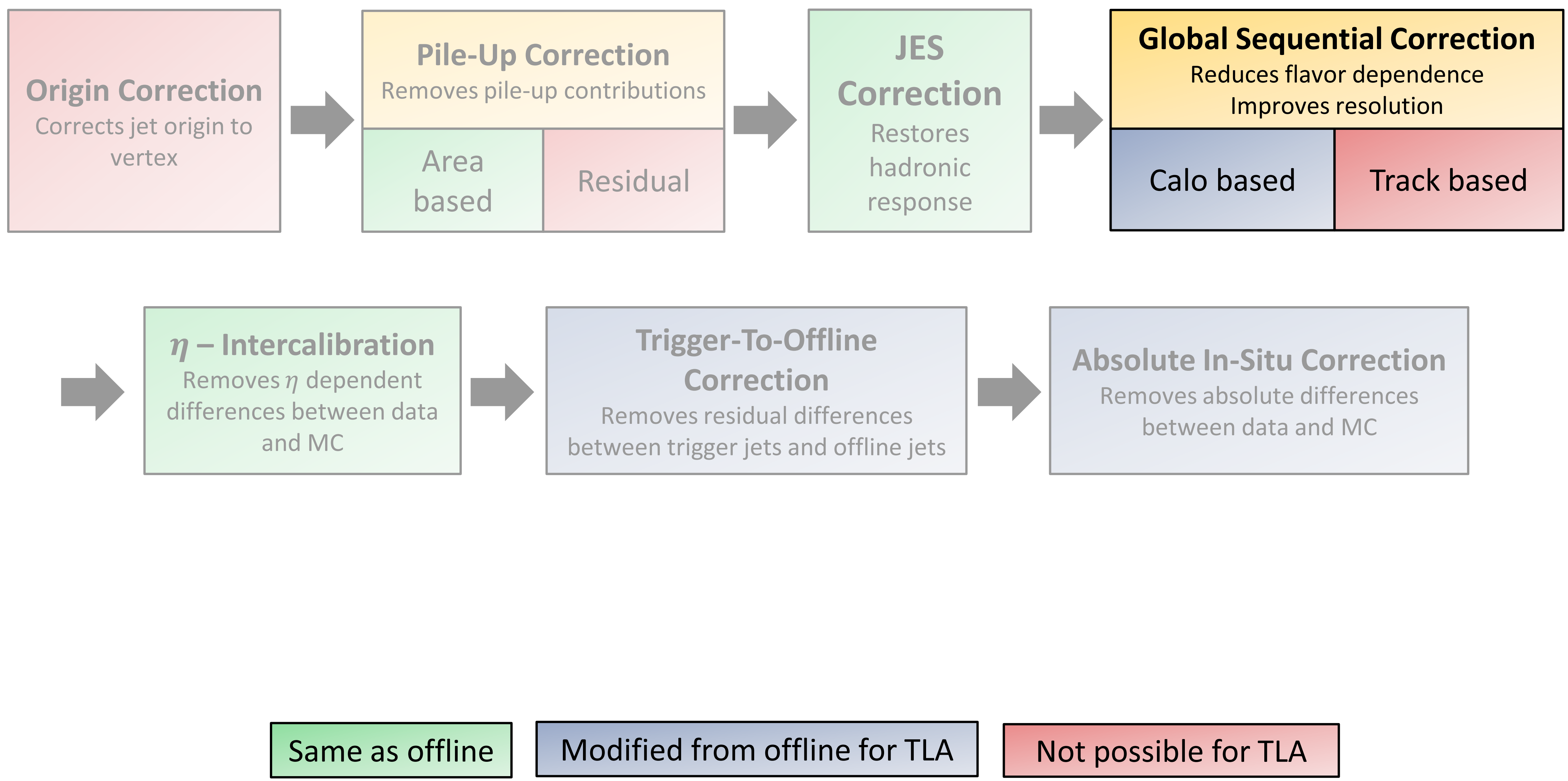


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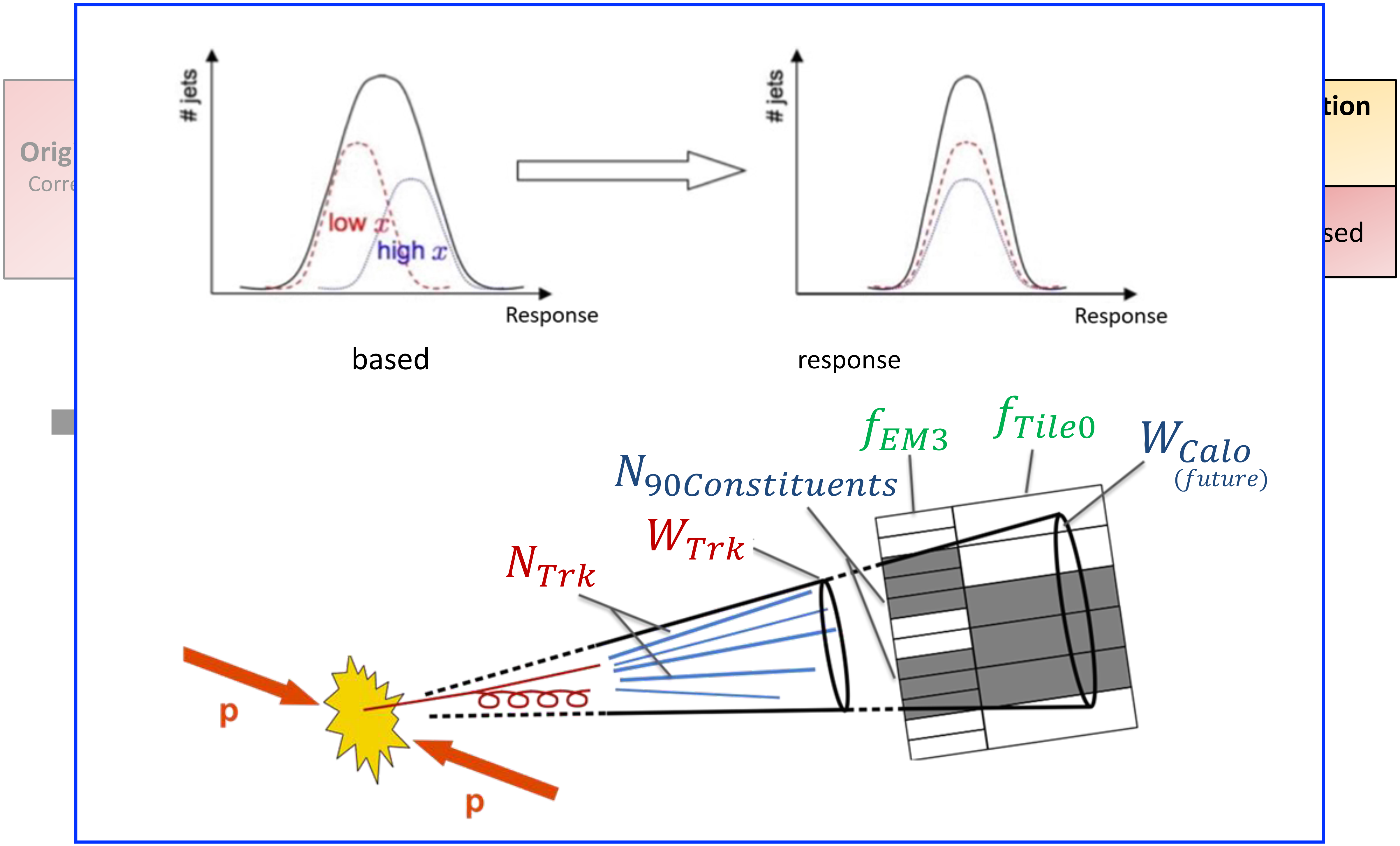


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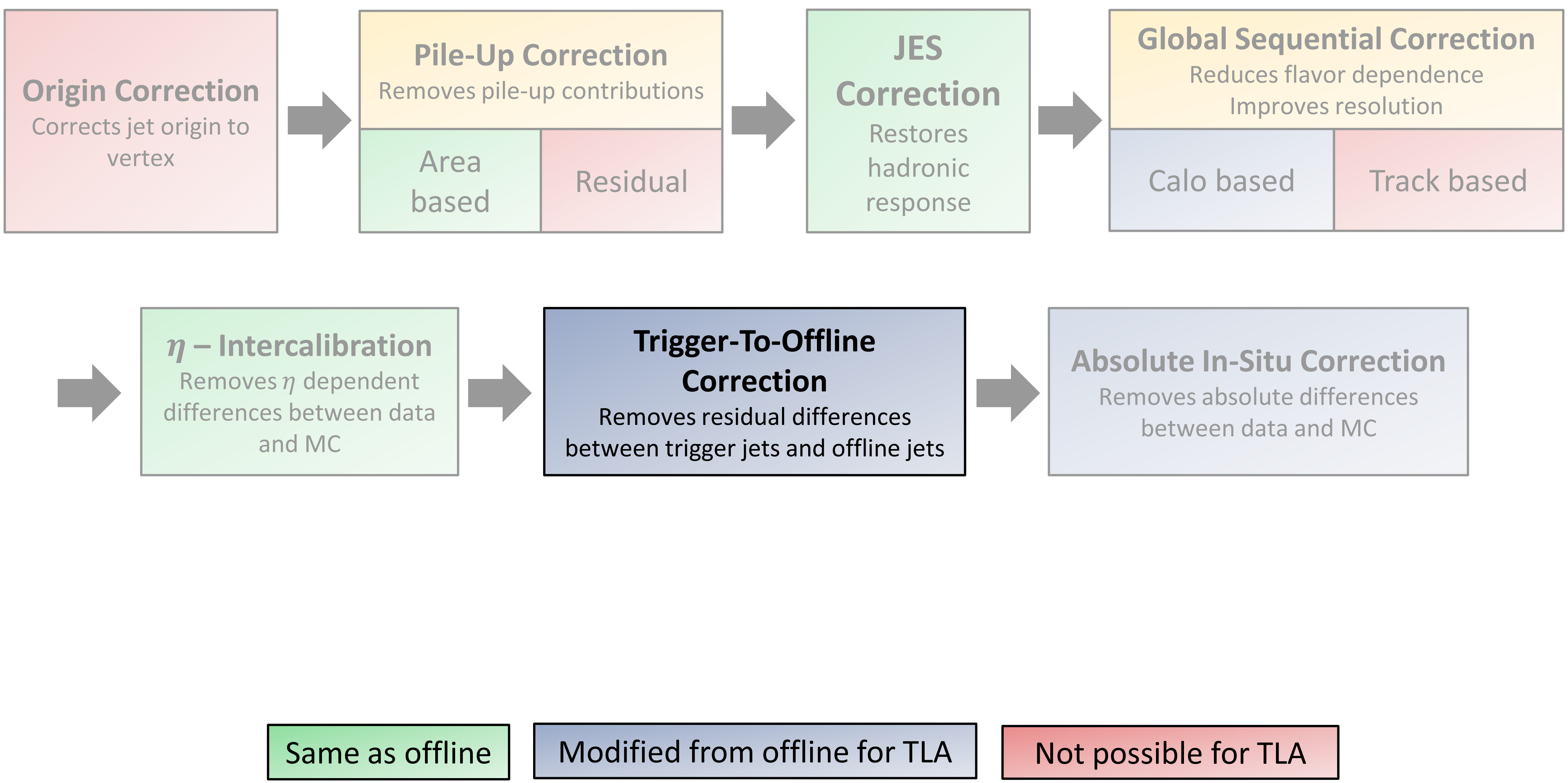


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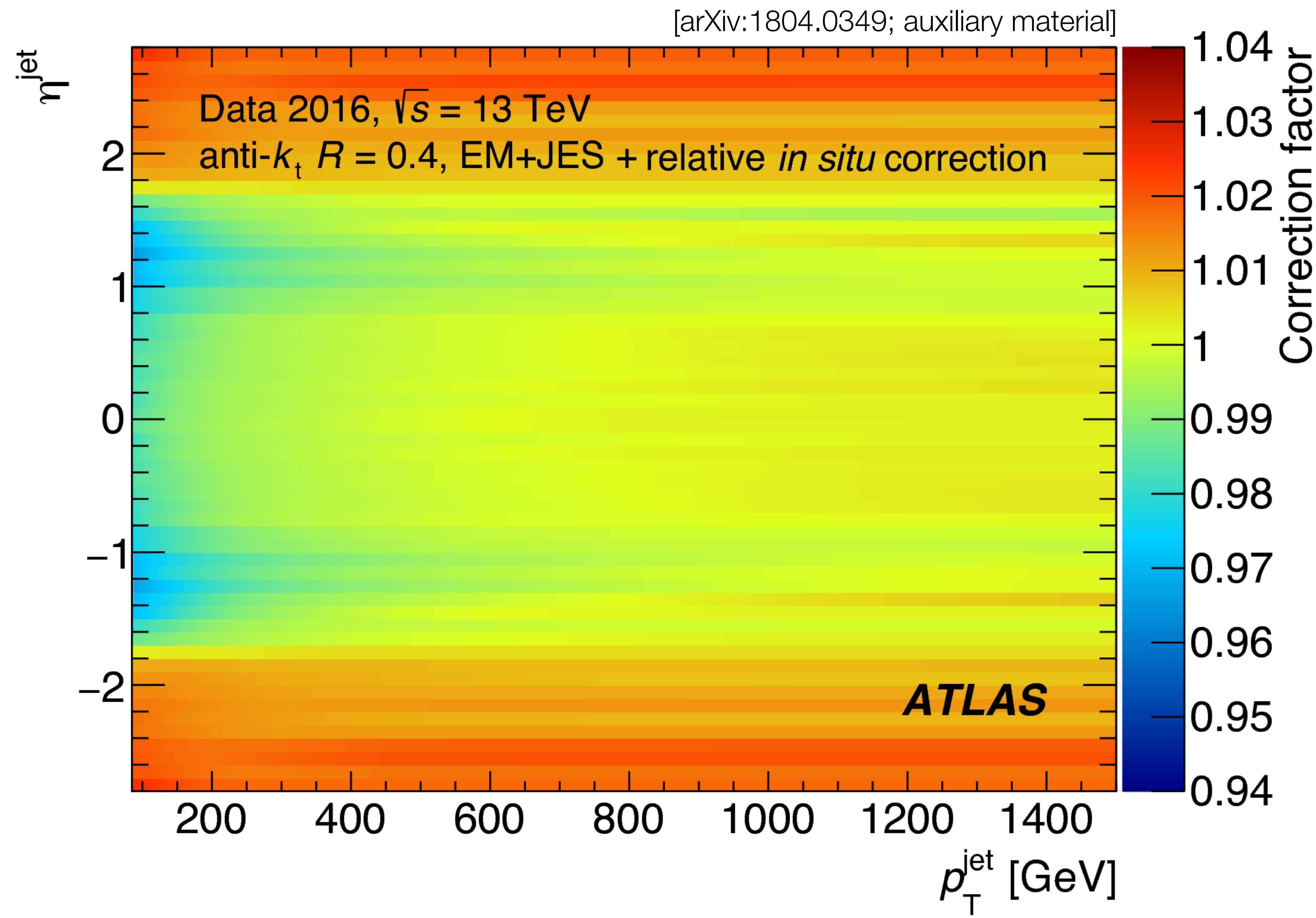


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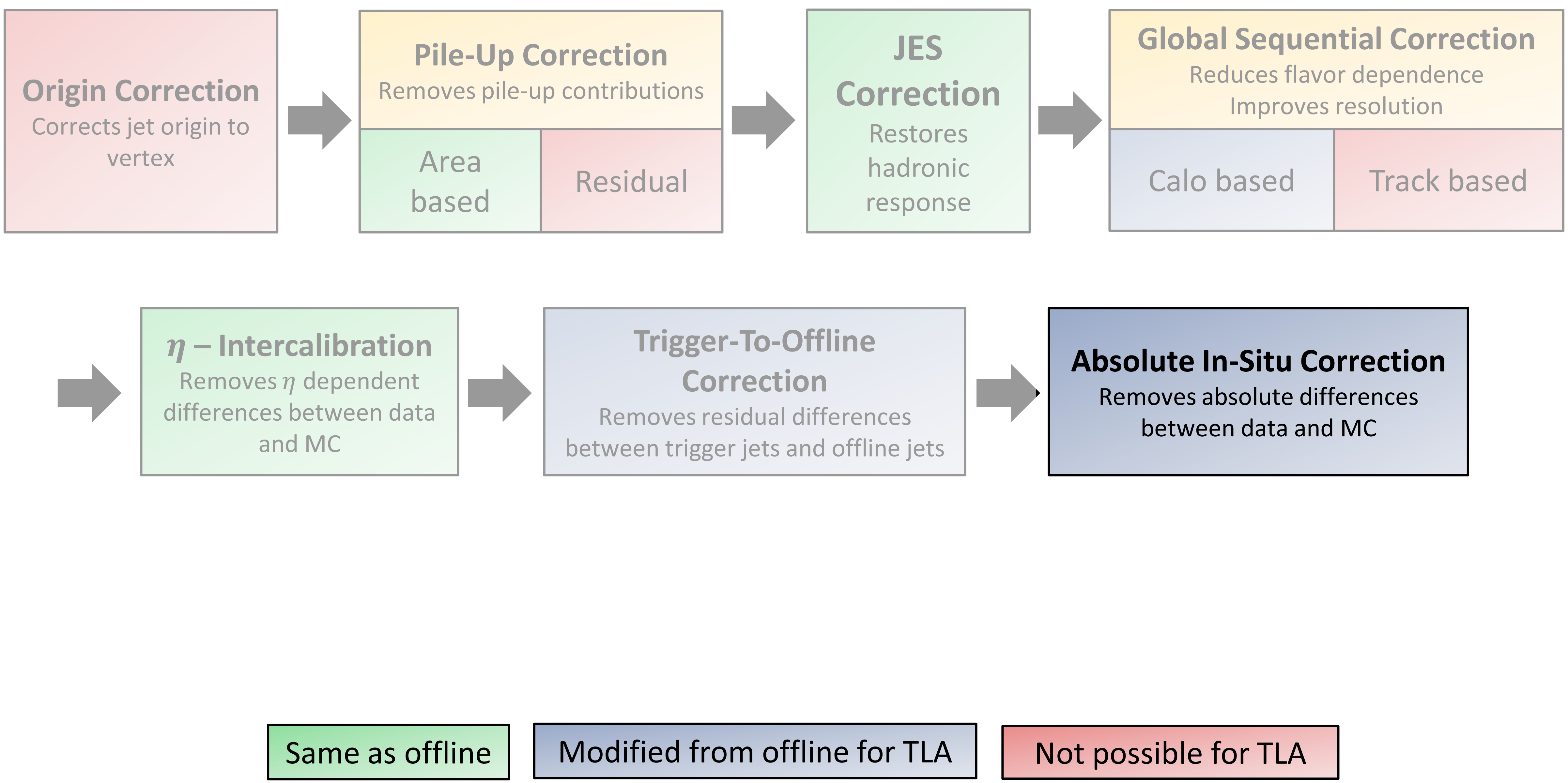


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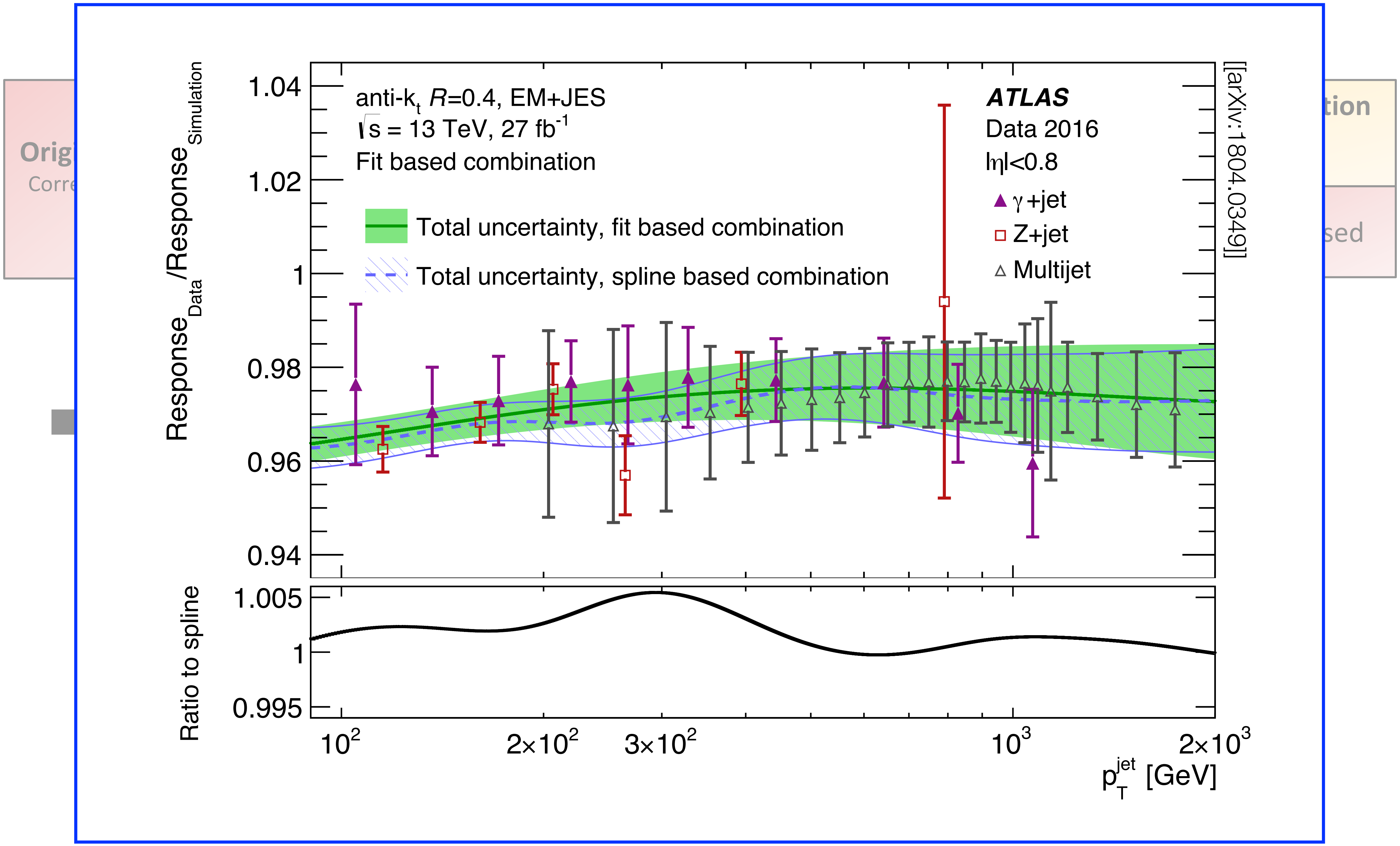


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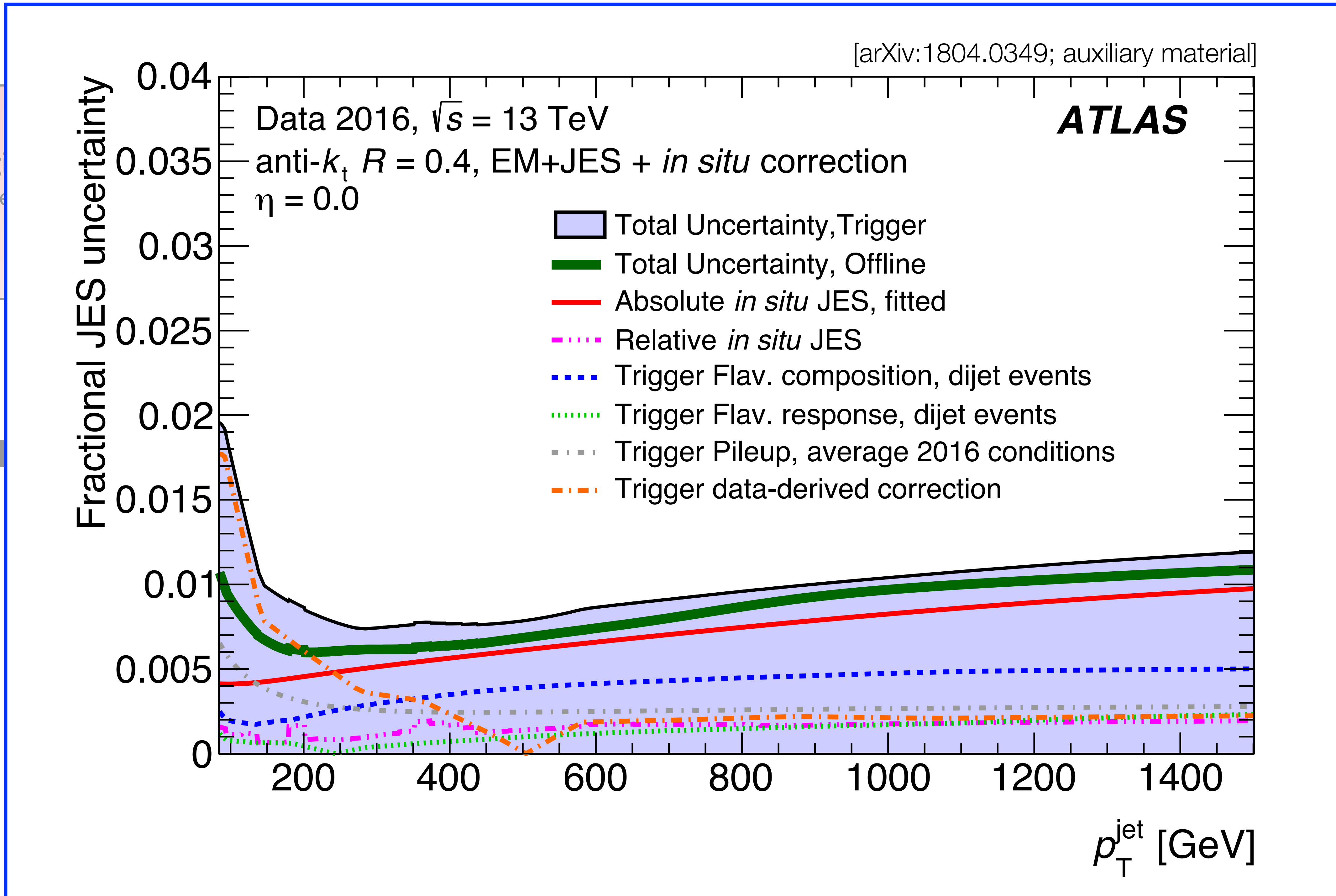
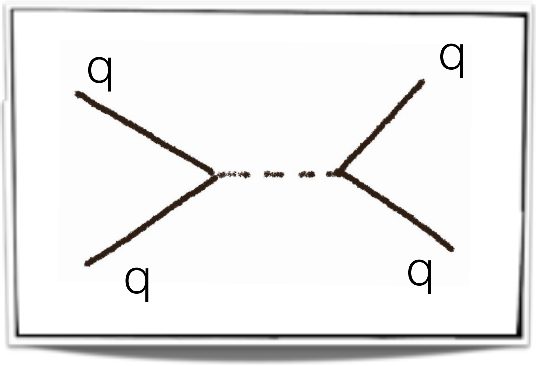


# TLA Analysis Results




Dijet searches
at low energy

Trigger Object Level
Analysis [aka TLA]

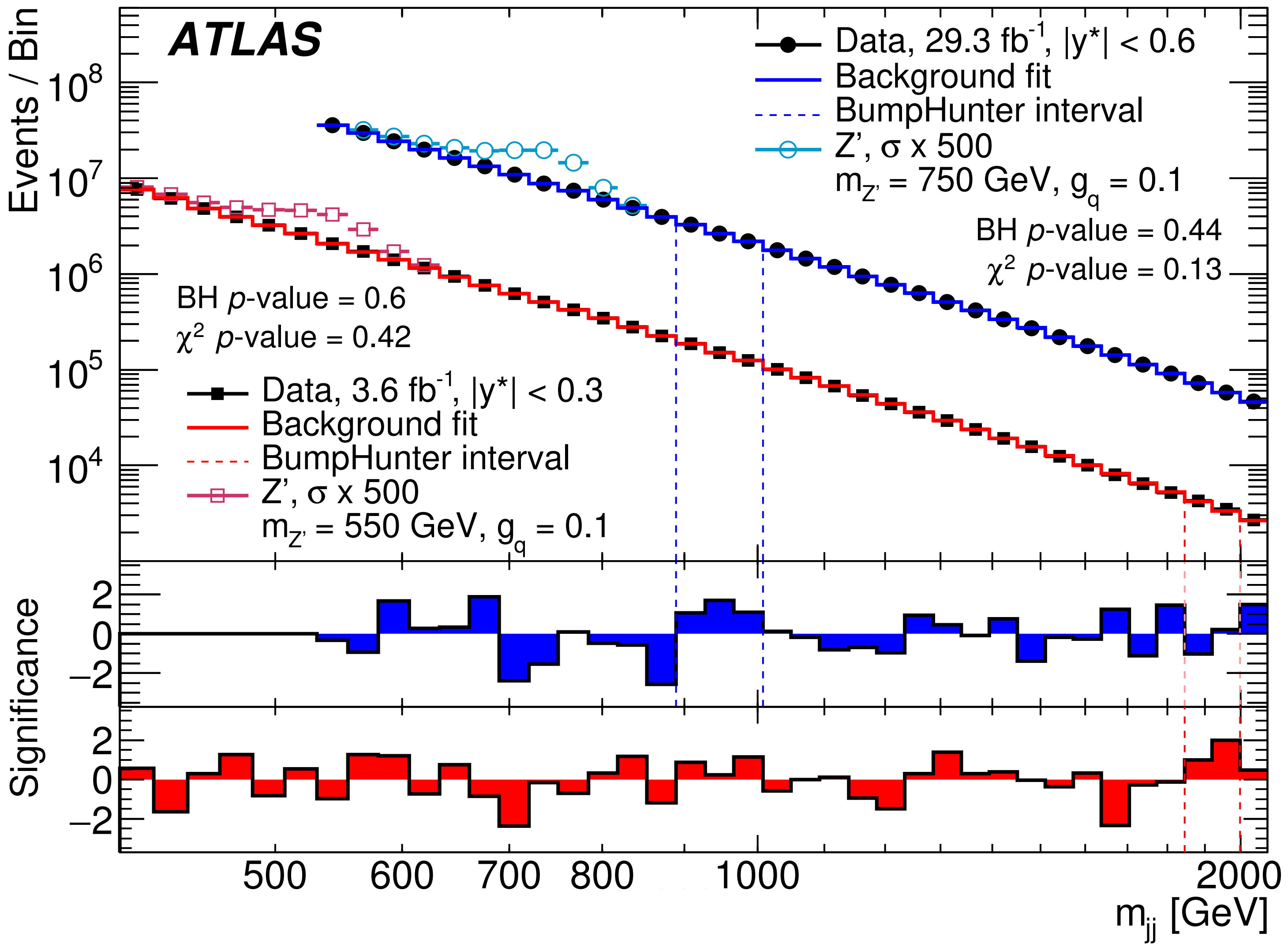
Measure:

Dijet mass spectrum
from 400 to 1000 GeV

Search for localized excess
using BumpHunter

Analysis requires
dedicated jet calibration …

[arXiv:1804.0349]



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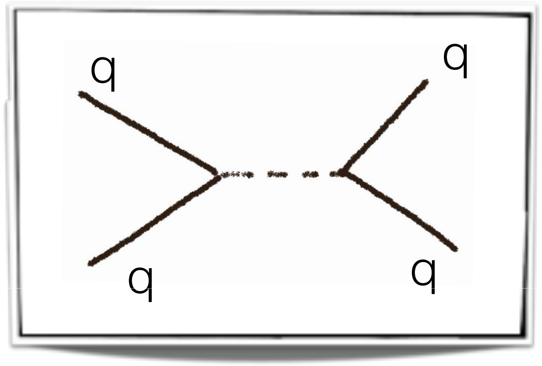
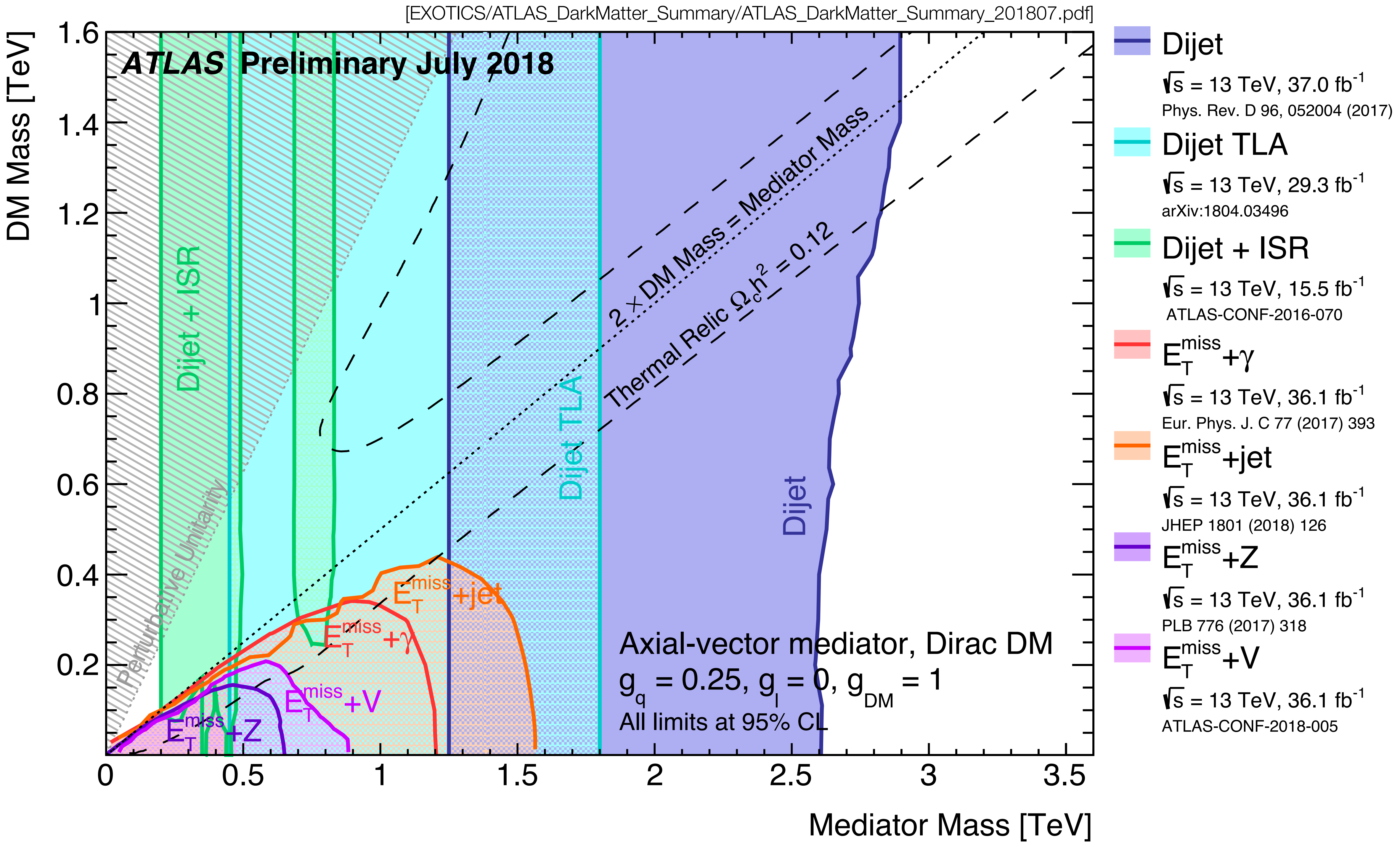
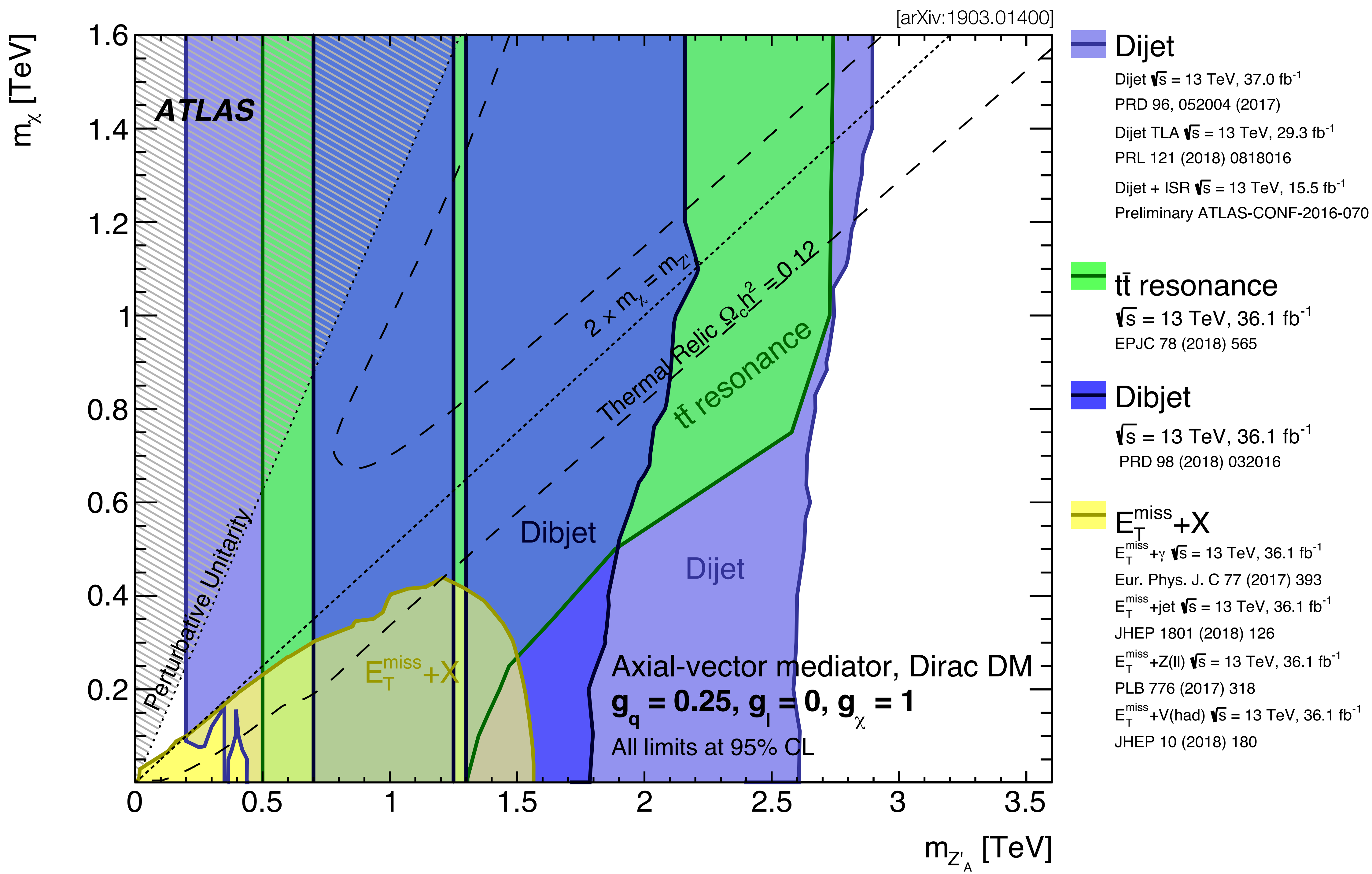


# Recent ATLAS Dark Matter Summary Paper



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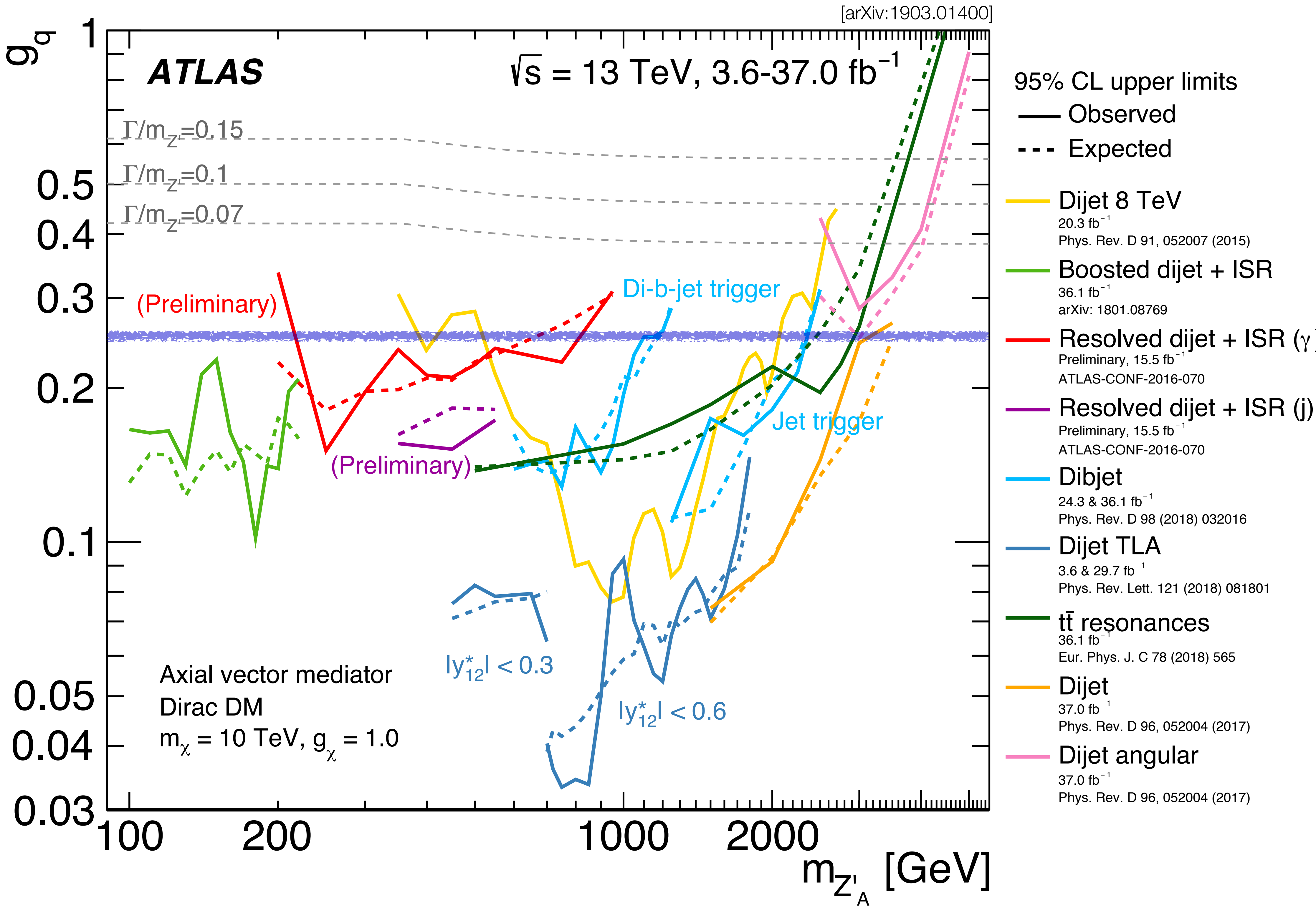

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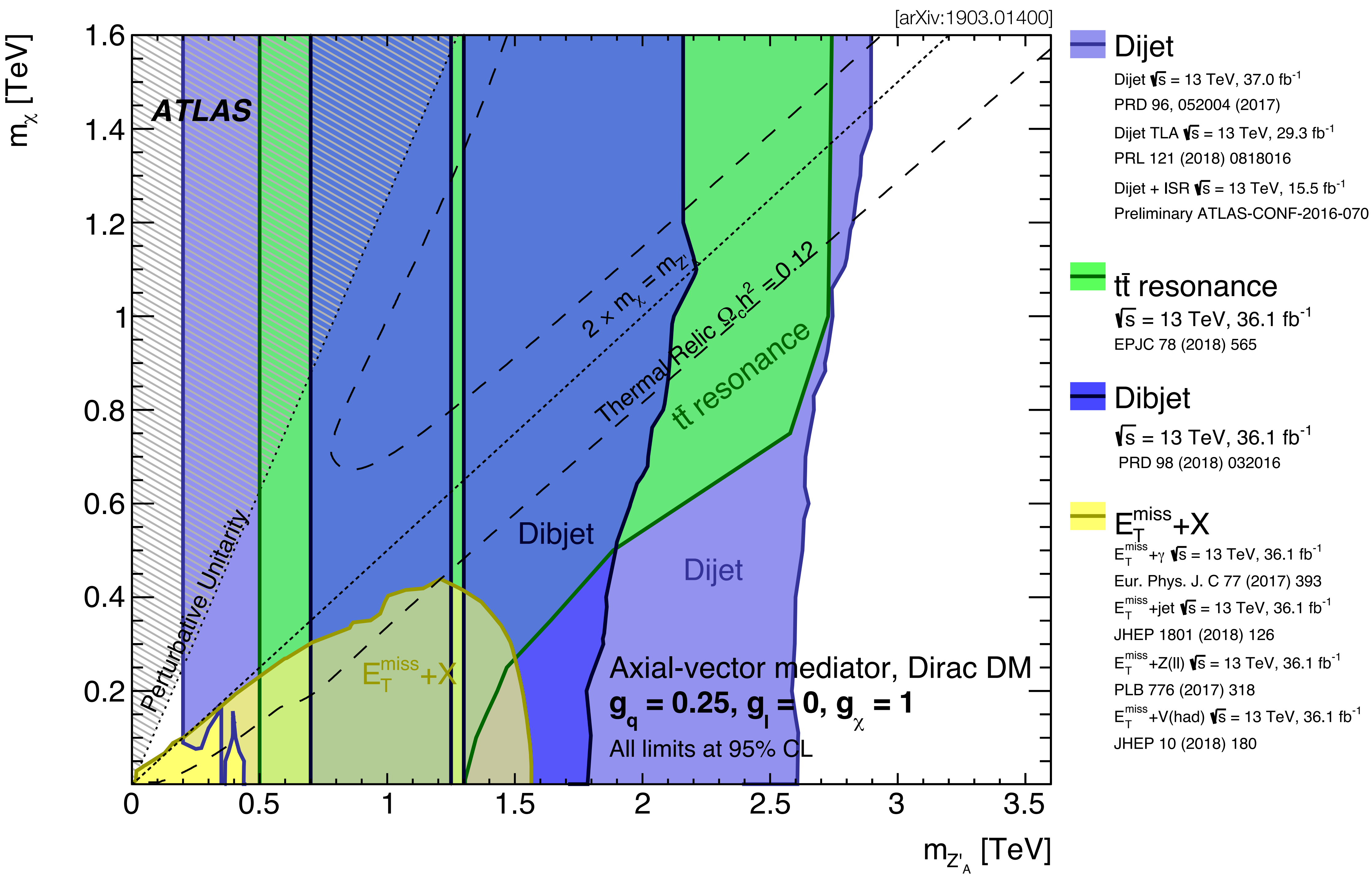

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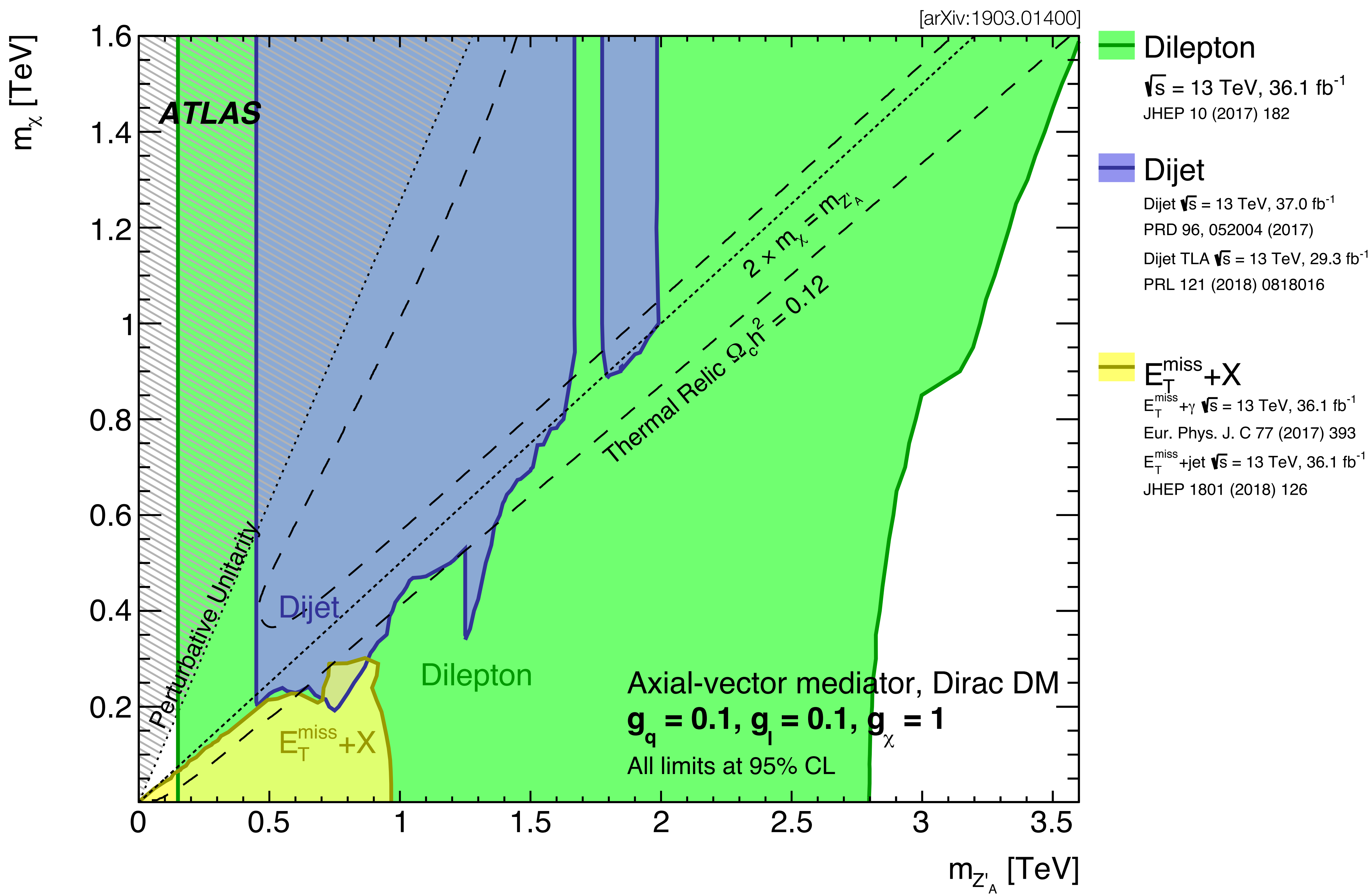
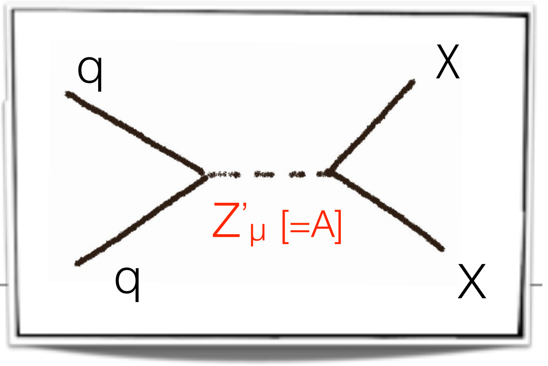


# Vector vs. Axial-Vector Models




$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q$$

$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma_5 q$$

[from arXiv:1603.04156]

LHC Recommendation on DM Search Presentation

$$\Gamma^{\chi\bar{\chi}}_{\text{vector}} = \frac{g^2_{\text{DM}} M_{\text{med}}}{12\pi} (1 - 4 z_{\text{DM}})^{1/2} (1 + 2 z_{\text{DM}})$$

$$\Gamma^{q\bar{q}}_{\text{vector}} = \frac{g^2_q M_{\text{med}}}{4\pi} (1 - 4 z_q)^{1/2} (1 + 2 z_q)$$

$$\Gamma^{\chi\bar{\chi}}_{\text{axial-vector}} = \frac{g^2_{\text{DM}} M_{\text{med}}}{12\pi} (1 - 4 z_{\text{DM}})^{3/2}$$

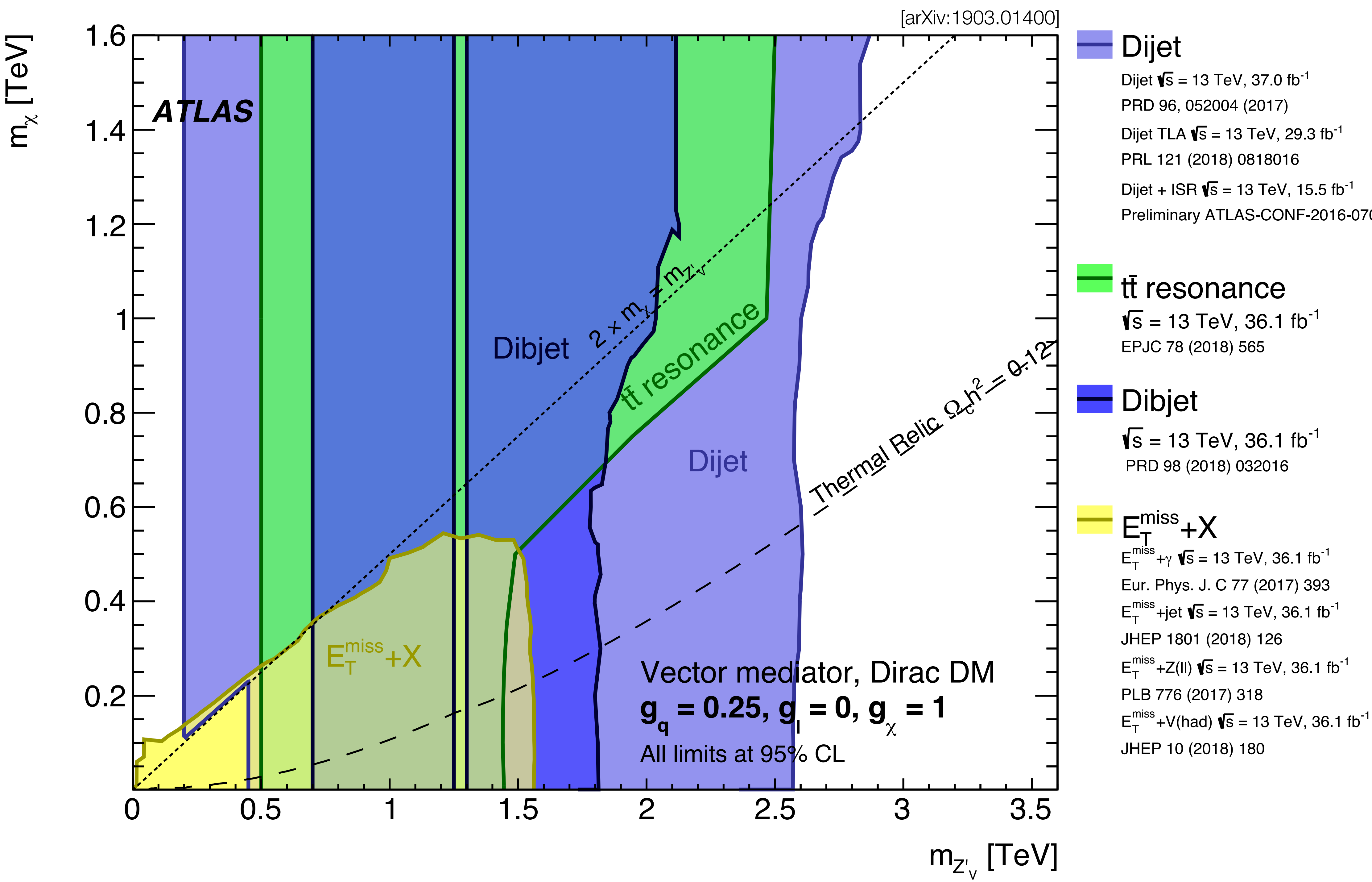
$$\Gamma^{q\bar{q}}_{\text{axial-vector}} = \frac{g^2_q M_{\text{med}}}{4\pi} (1 - 4 z_q)^{3/2}$$

Partial decay widths

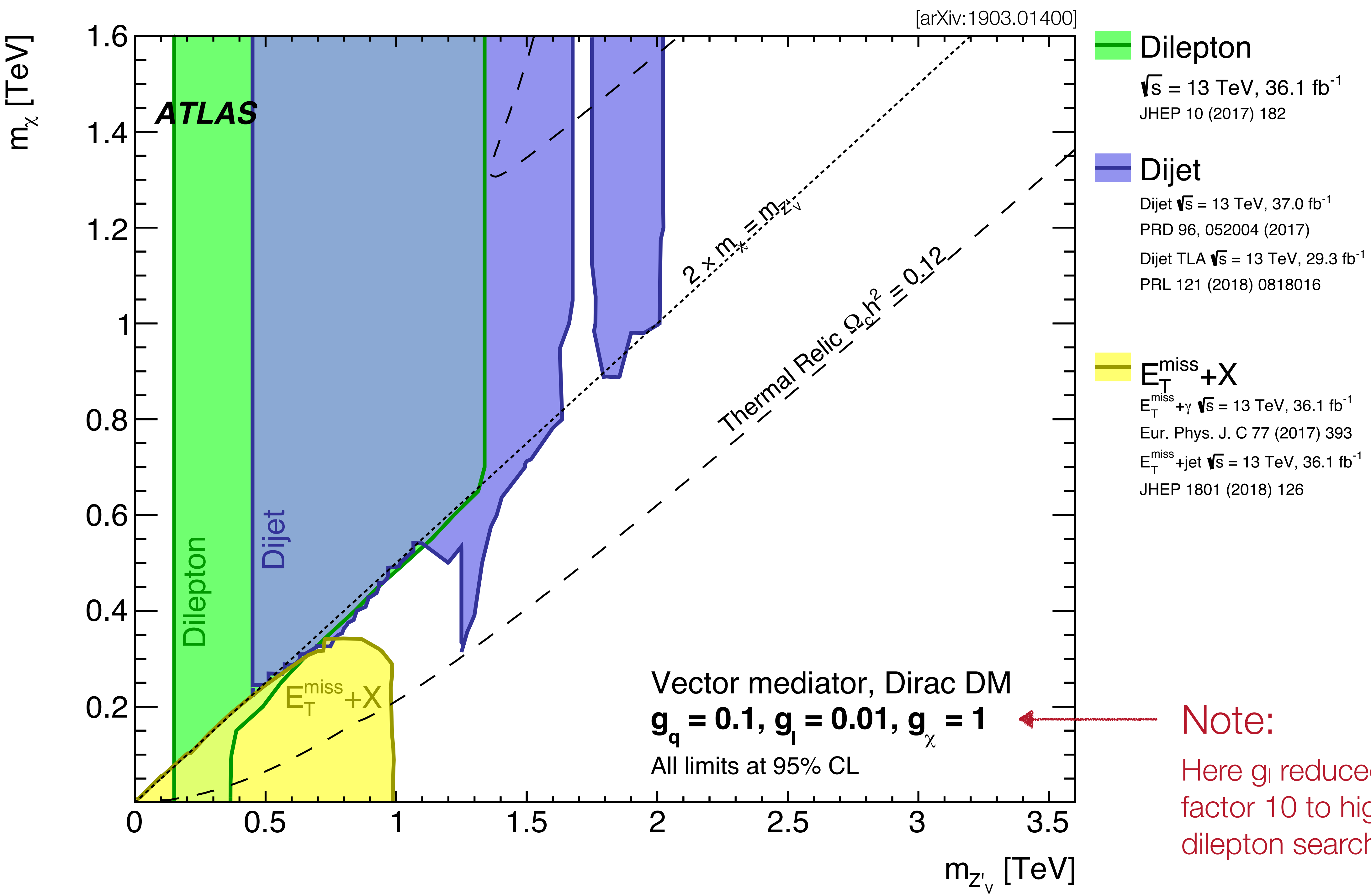
with

$$z_{\text{DM},q} = m^2_{\text{DM},q}/M^2_{\text{med}}$$

# Recent ATLAS Dark Matter Summary Paper



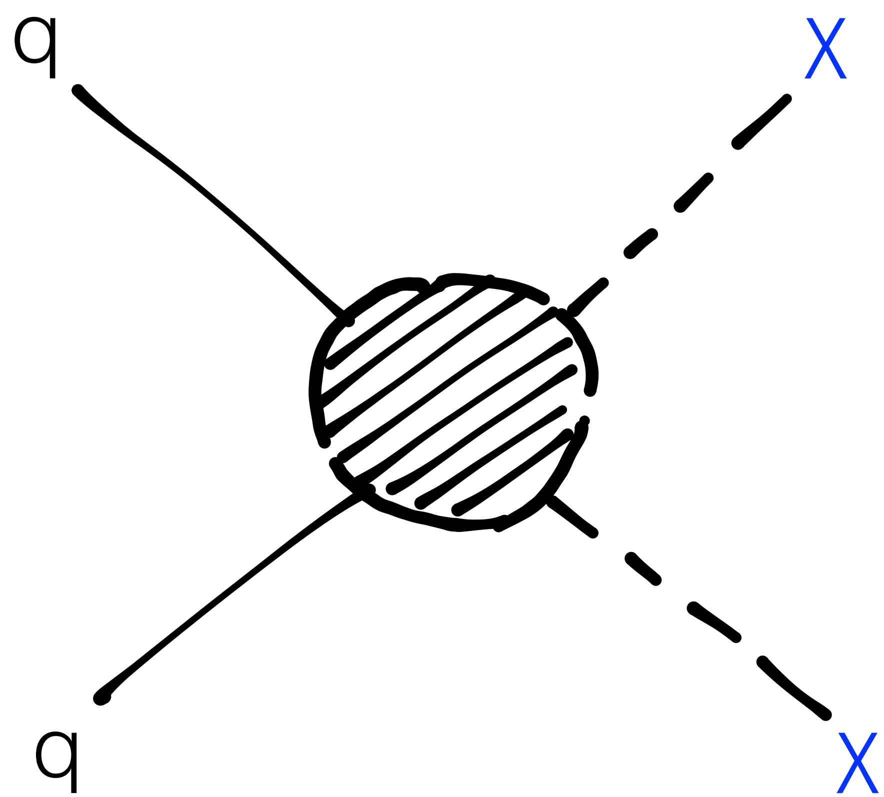
# Recent ATLAS Dark Matter Summary Paper



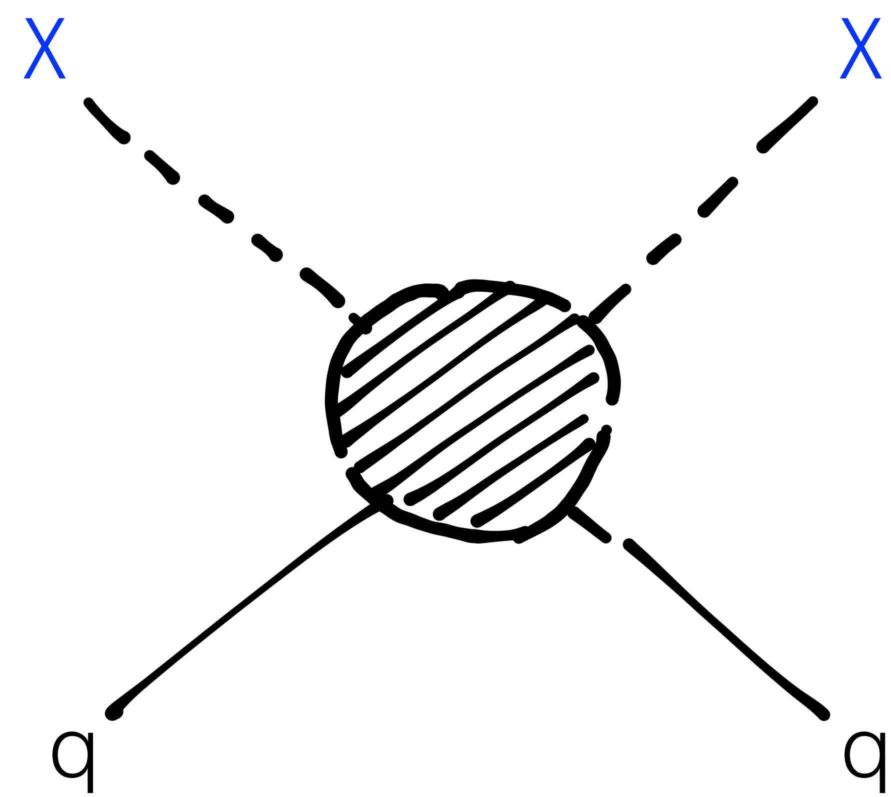

Note:

Here $g_l$ reduced by factor 10 to highlight dilepton search sensitivity

# Comparing with Direct Searches




LHC DM Production




Direct Detection

# Comparing with Direct Searches

## LHC DM Searches

$$\sigma_{\chi N}^{\rm SI} = \frac{f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4}$$

$$f(g_q) = 3 g_q$$

$$\sigma_{\chi N}^{\rm SD} = \frac{3 f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4}$$

$$f^{p,n}(g_q) = \Delta_u^{(p,n)}\, g_u + \Delta_d^{(p,n)}\, g_d + \Delta_s^{(p,n)}\, g_s$$

$$f(g_q) = 0.32 g_q$$

## Direct Detection

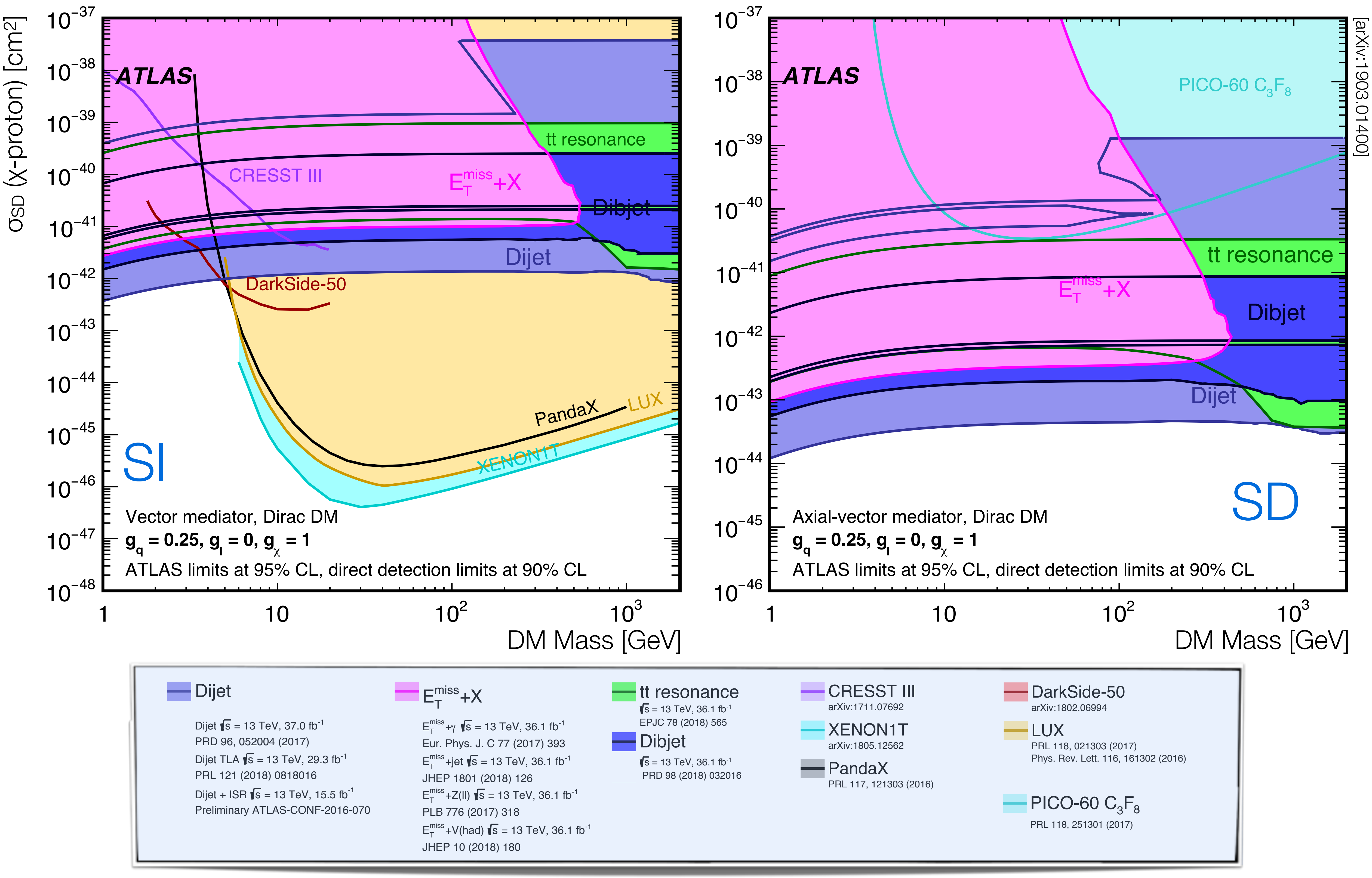
$$\frac{d\sigma^{\rm SI}}{dq^2} = \frac{\sigma_{\chi N}^{\rm SI}}{2\mu_N^2 v^2}\, A^2$$

$$\frac{d\sigma^{\rm SD}}{dq^2} = \frac{\sigma_{\chi N}^{\rm SD}}{3\mu_N^2 v^2} \frac{\pi}{2J+1} S_N(q)$$

| | |
|---|---|
| $\sigma^{SI}_{\chi N}, \sigma^{SD}_{\chi N}$ | : χ-nucleon cross section |
| v | : WIMP velocity |
| $\mu_{n\chi,N}$ | : reduced WIMP-nucleus mass |
| $g_{q,DM}$ | : couplings to quarks, DM |
| $M_{Med}$ | : Mediator mass |
| $\Delta_q$ | : quark spin-content |
| J | : total angular momentum |
| $S_N$ | : axial-vector structure factor |

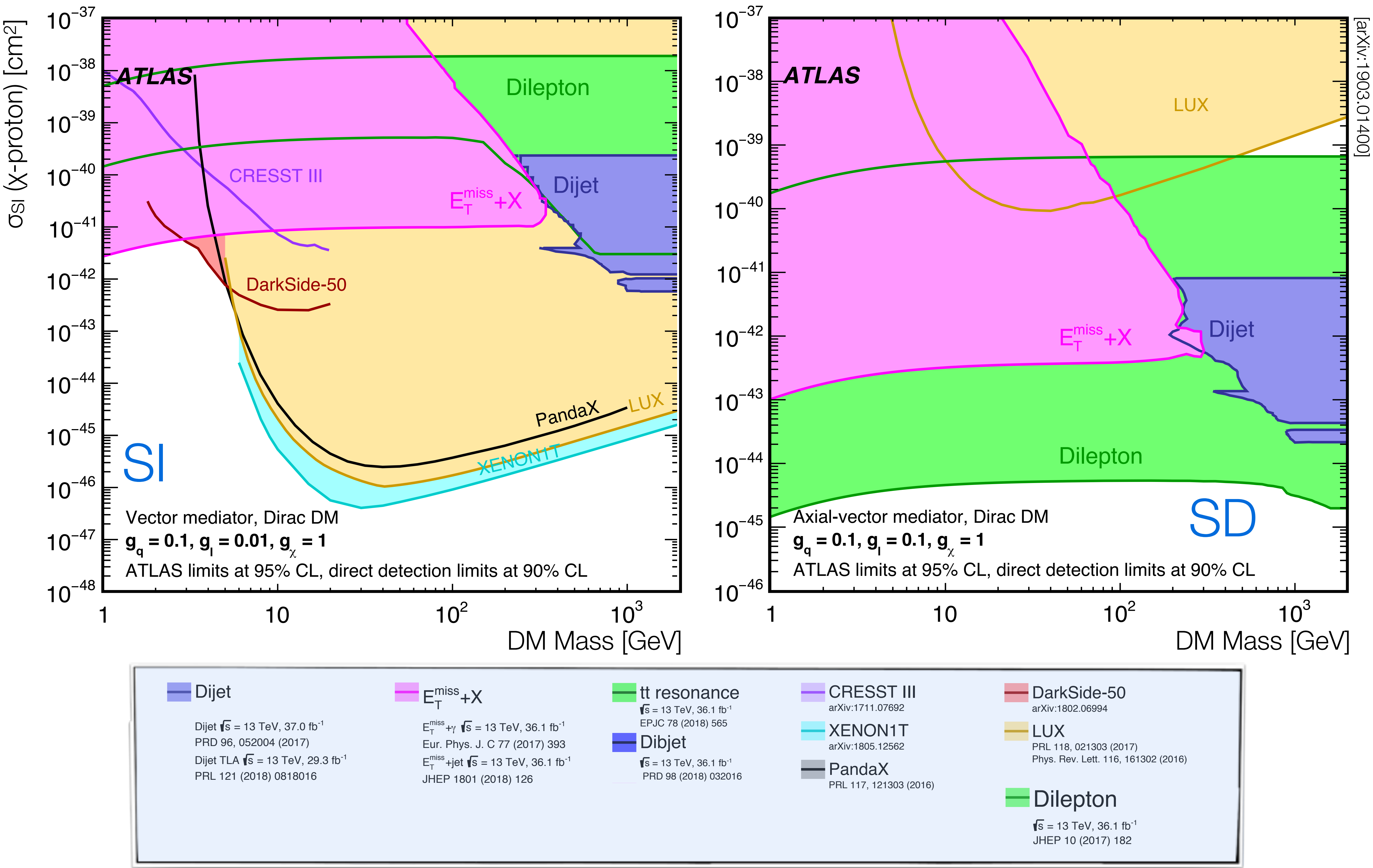
# DM Simplified Model Exclusion

$g_q = 0.25$
$g_{lep} = 0.00$
$g_{DM} = 1.00$



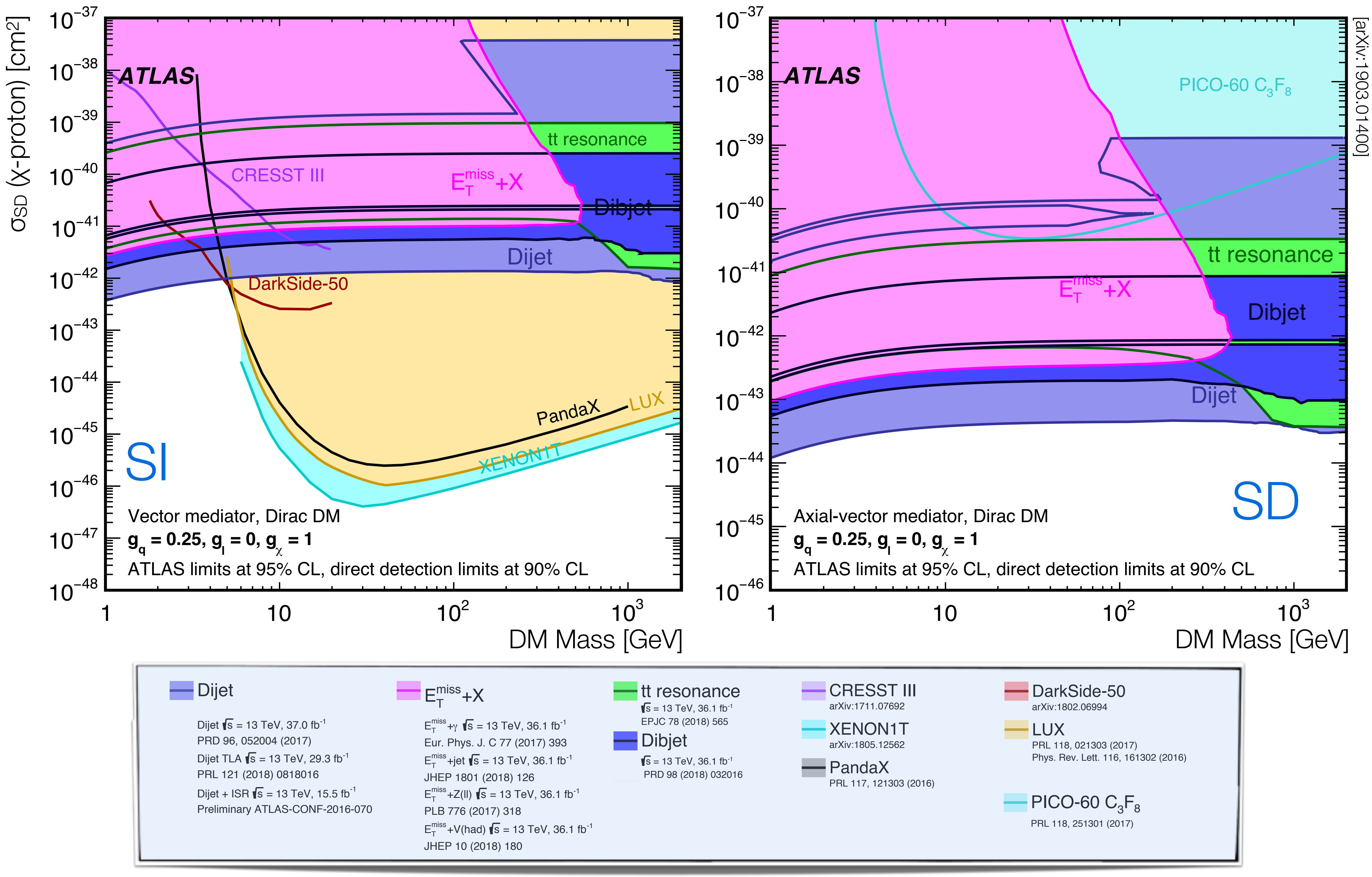
# DM Simplified Model Exclusion

$g_q = 0.10$
$g_{lep} = 0.01/0.10$
$g_{DM} = 1.00$

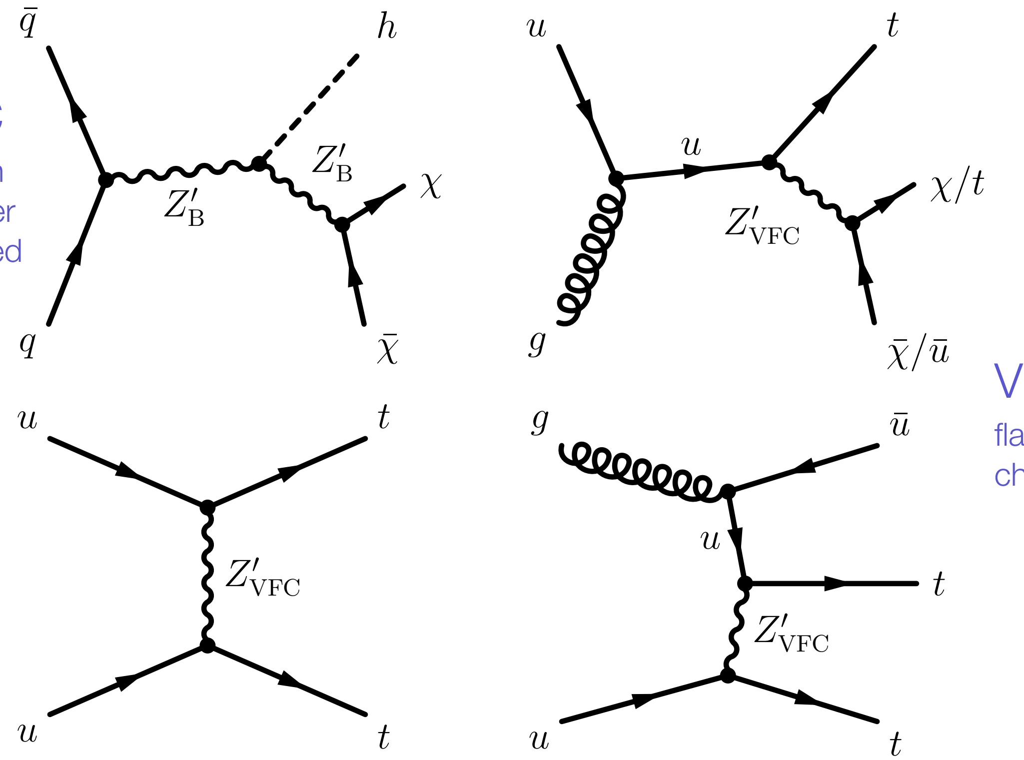


# DM Simplified Model Exclusion

$g_q = 0.25$
$g_{lep} = 0.00$
$g_{DM} = 1.00$

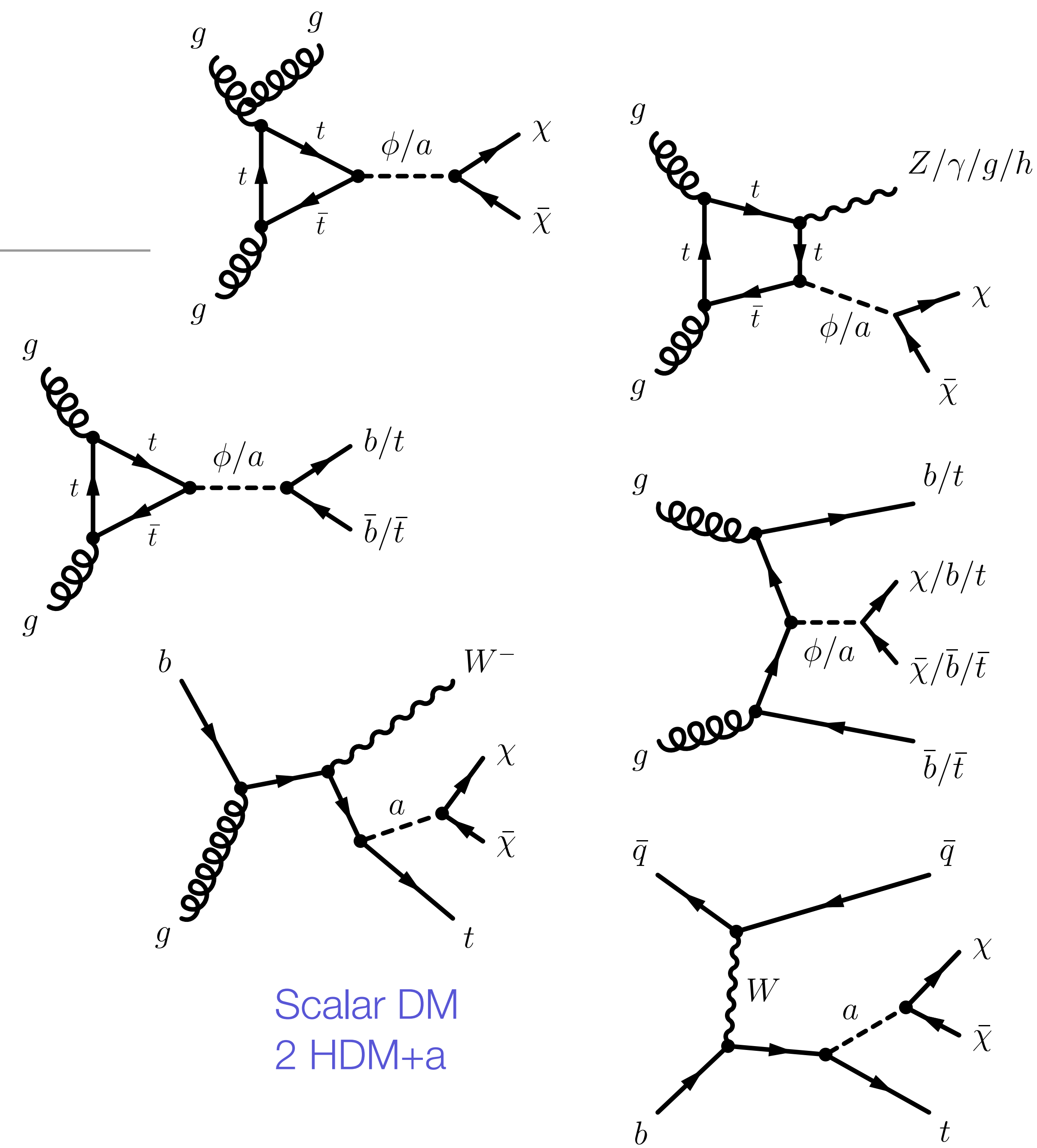


# More Dark Matter Models

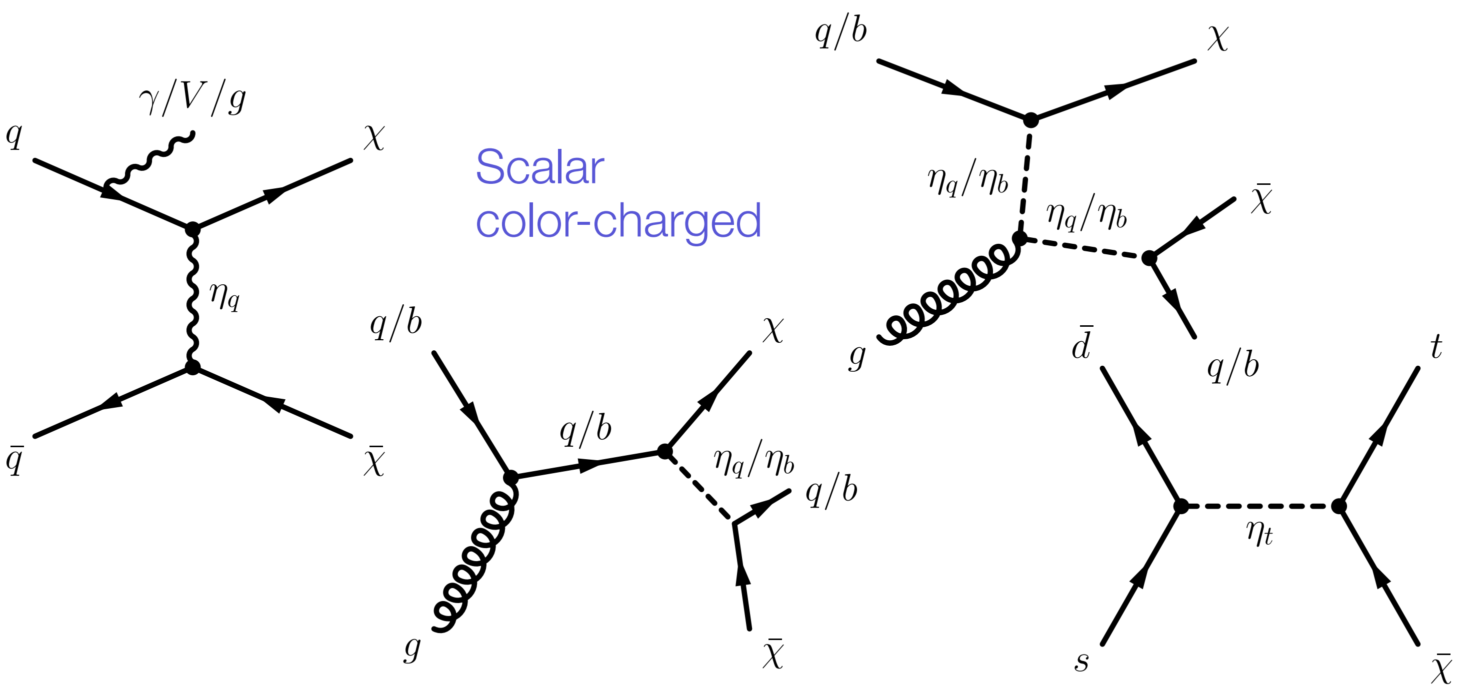



VBC
baryon
number
charged

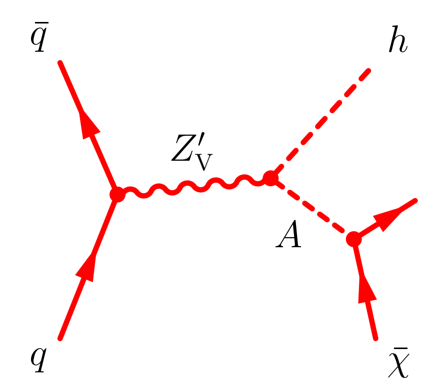
VFC
flavour
changing




Scalar DM
2 HDM+a




Scalar
color-charged




Z’-2HDM

…

# Mono-Higgs DM Search

Maybe
DM-Production not simple …
with the Higgs playing a special role

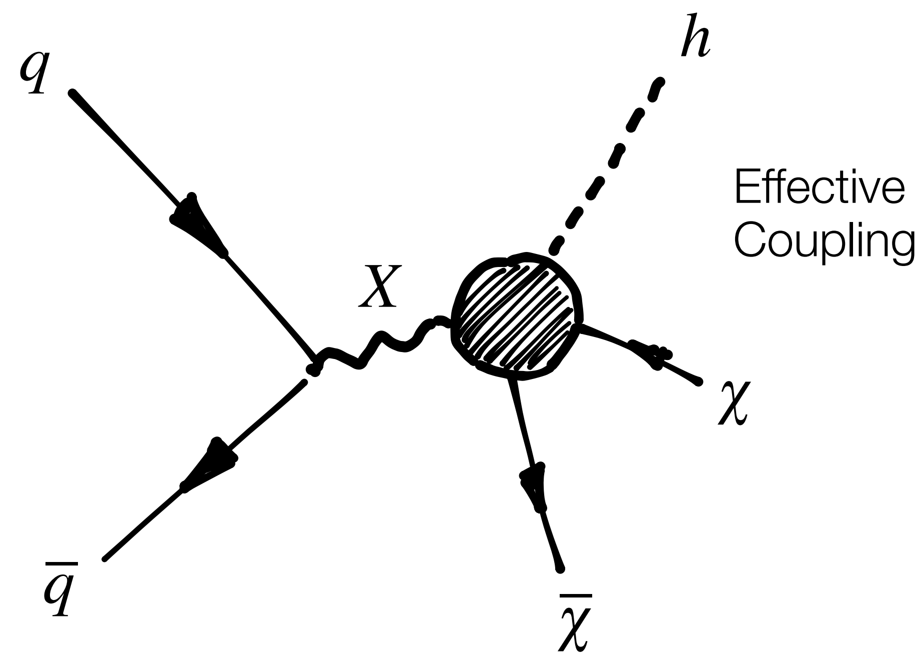
Interesting signatures:

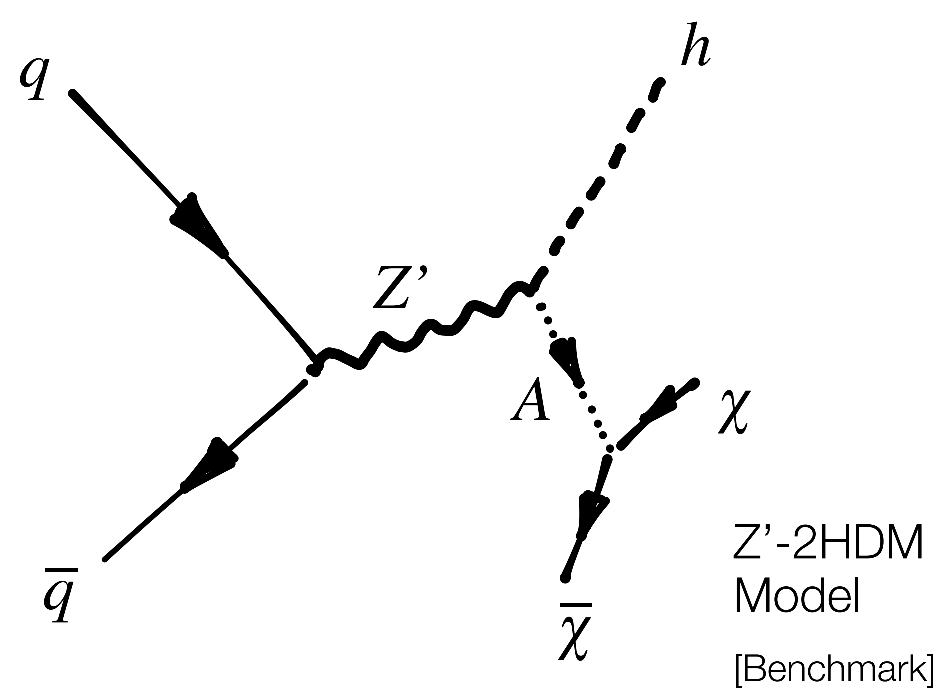
Invisible Higgs
Mono-Higgs

Mono-Higgs:

Directly probes
DM production mechanism …

Search for: H(➛bb,γγ) + $E_{T,miss}$



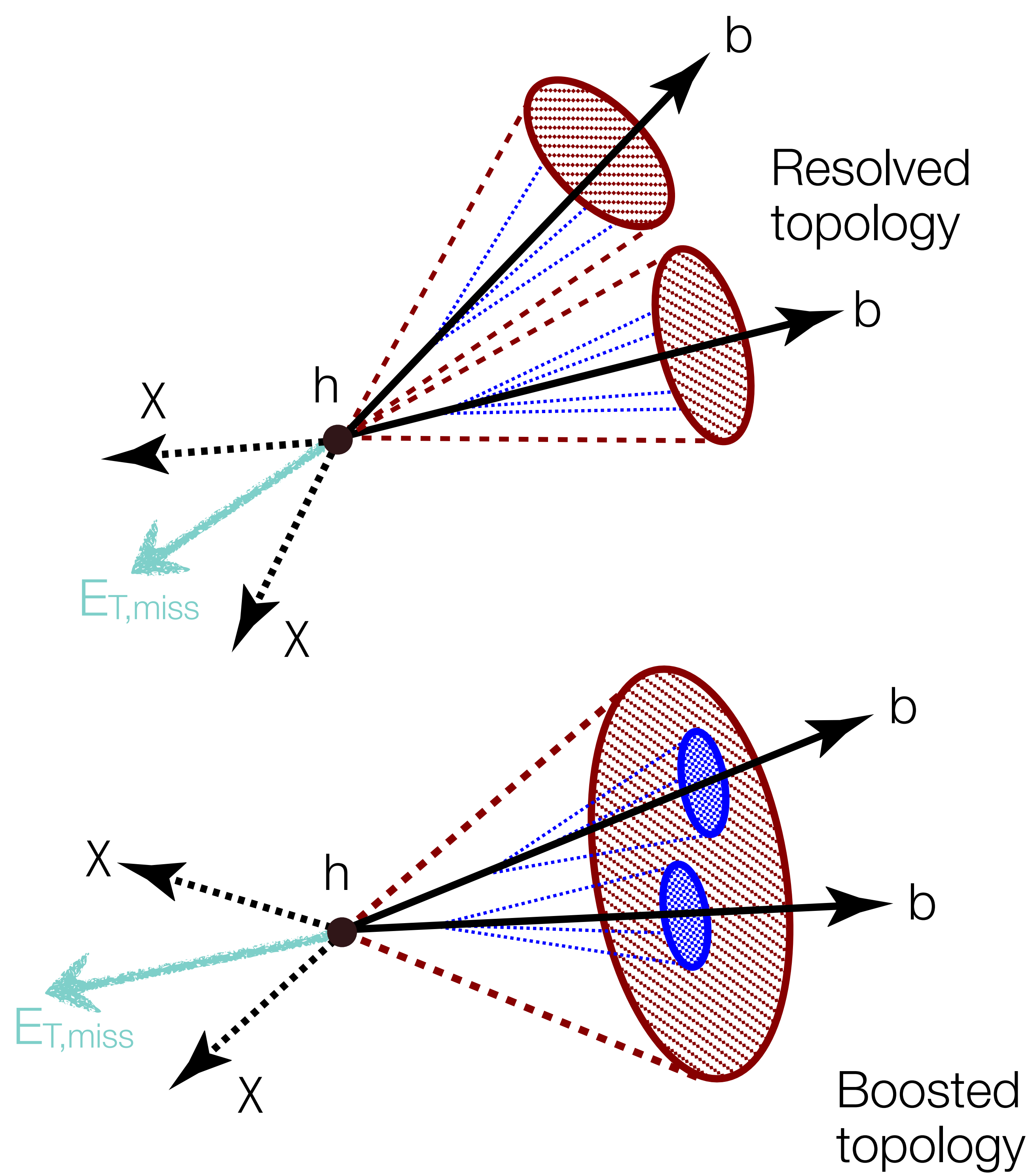
# Mono-Higgs DM Search

Signature:

Missing Energy
Jets with tagged b-Quarks
Dijet mass $m_{bb} = m_{Higgs}$

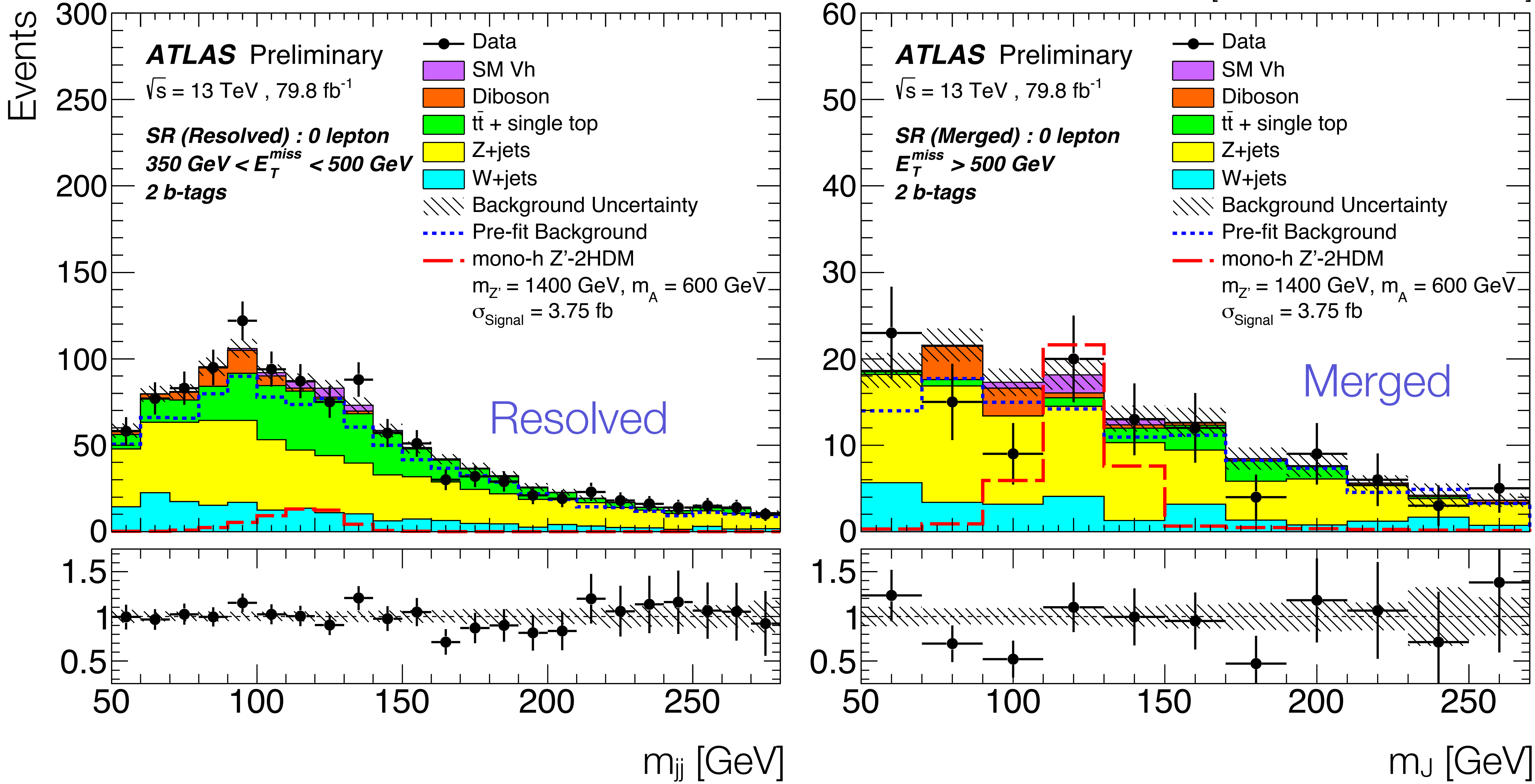
Potentially expect:
Highly boosted Higgs

Investigate
boosted topologies …

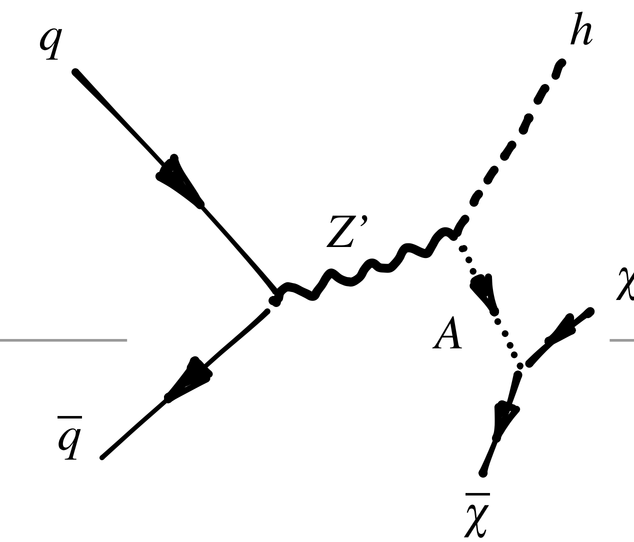


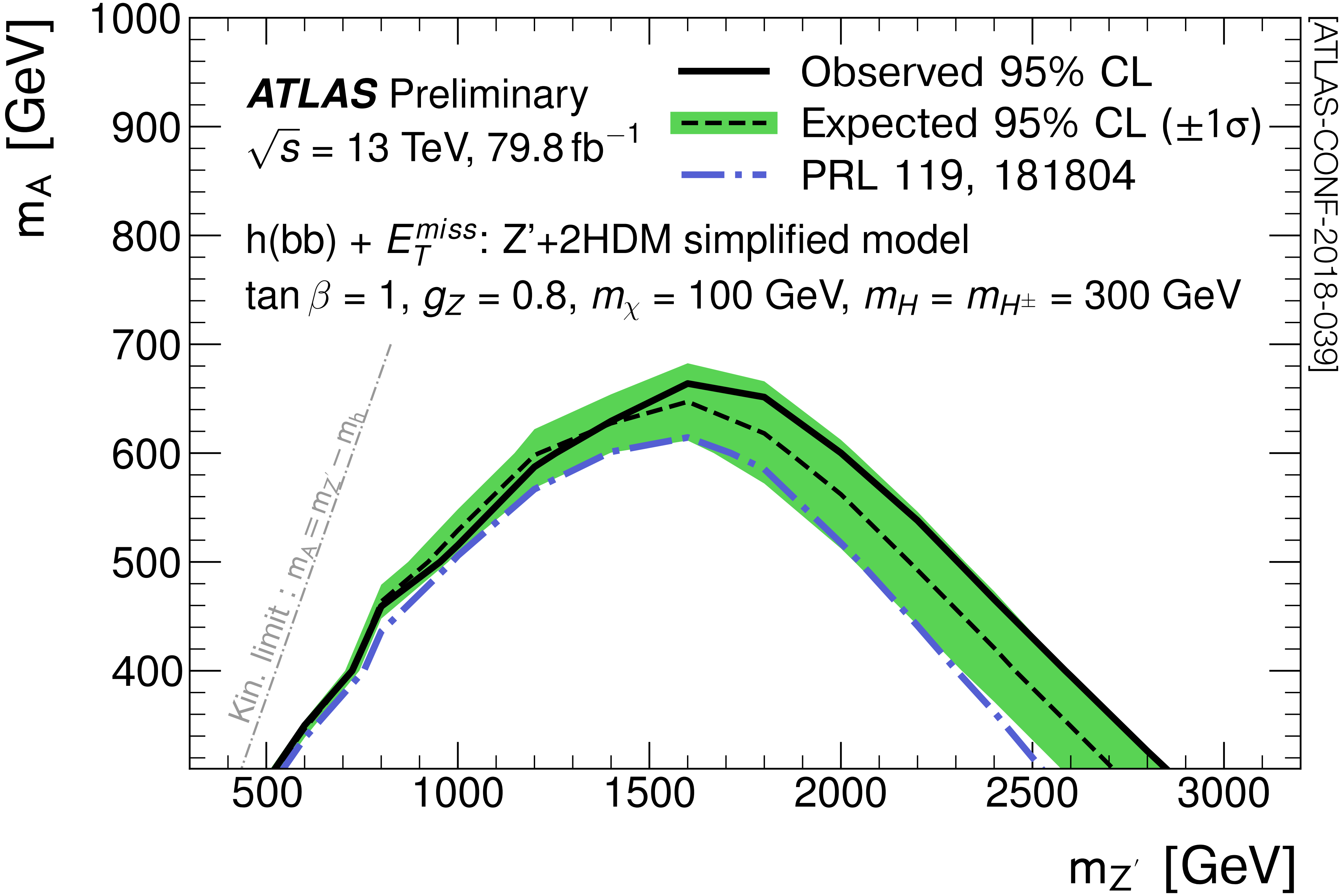
# Mono-Higgs DM Search

[ATLAS-CONF-2018-039]

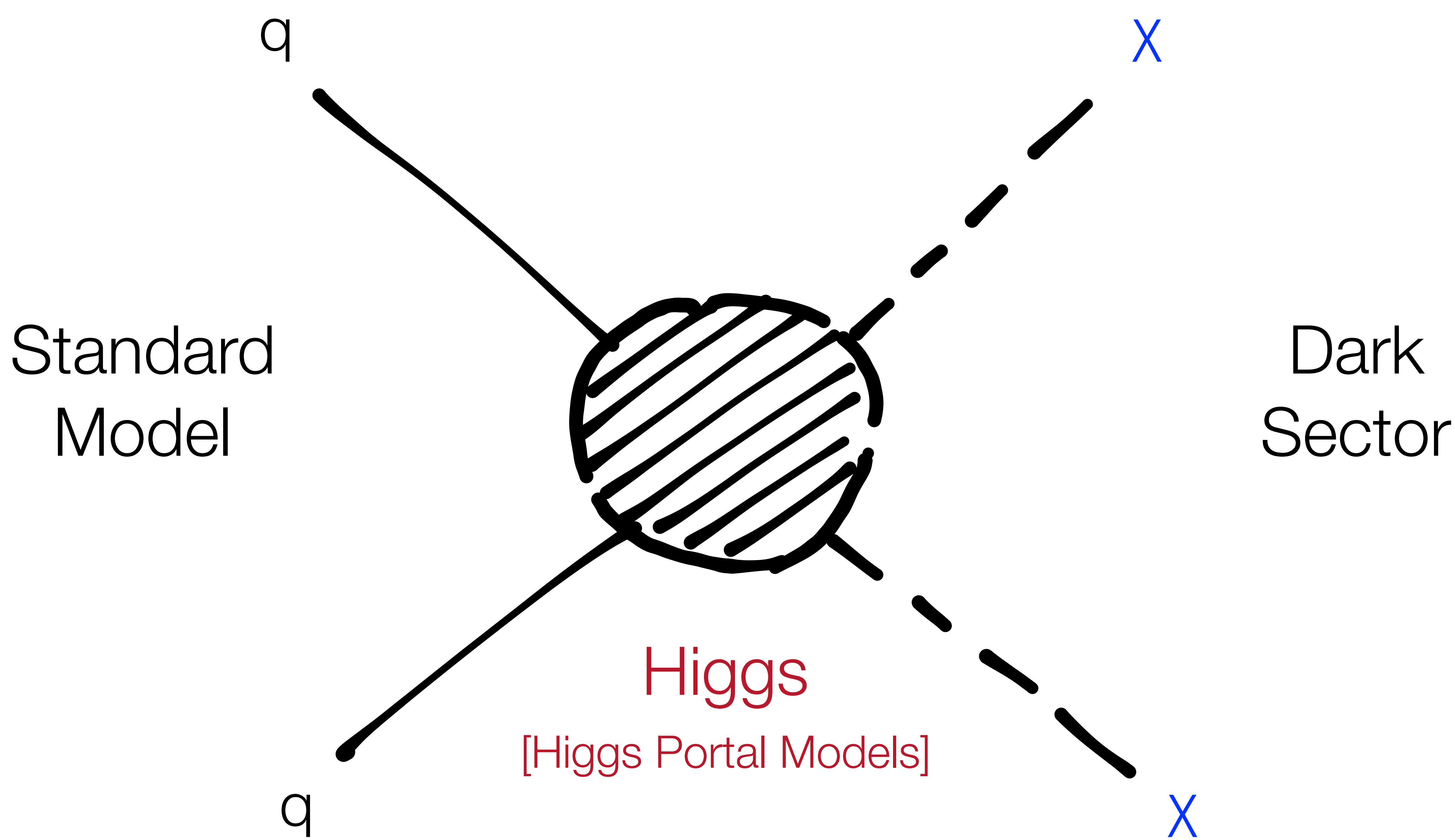


# Mono-Higgs DM Search

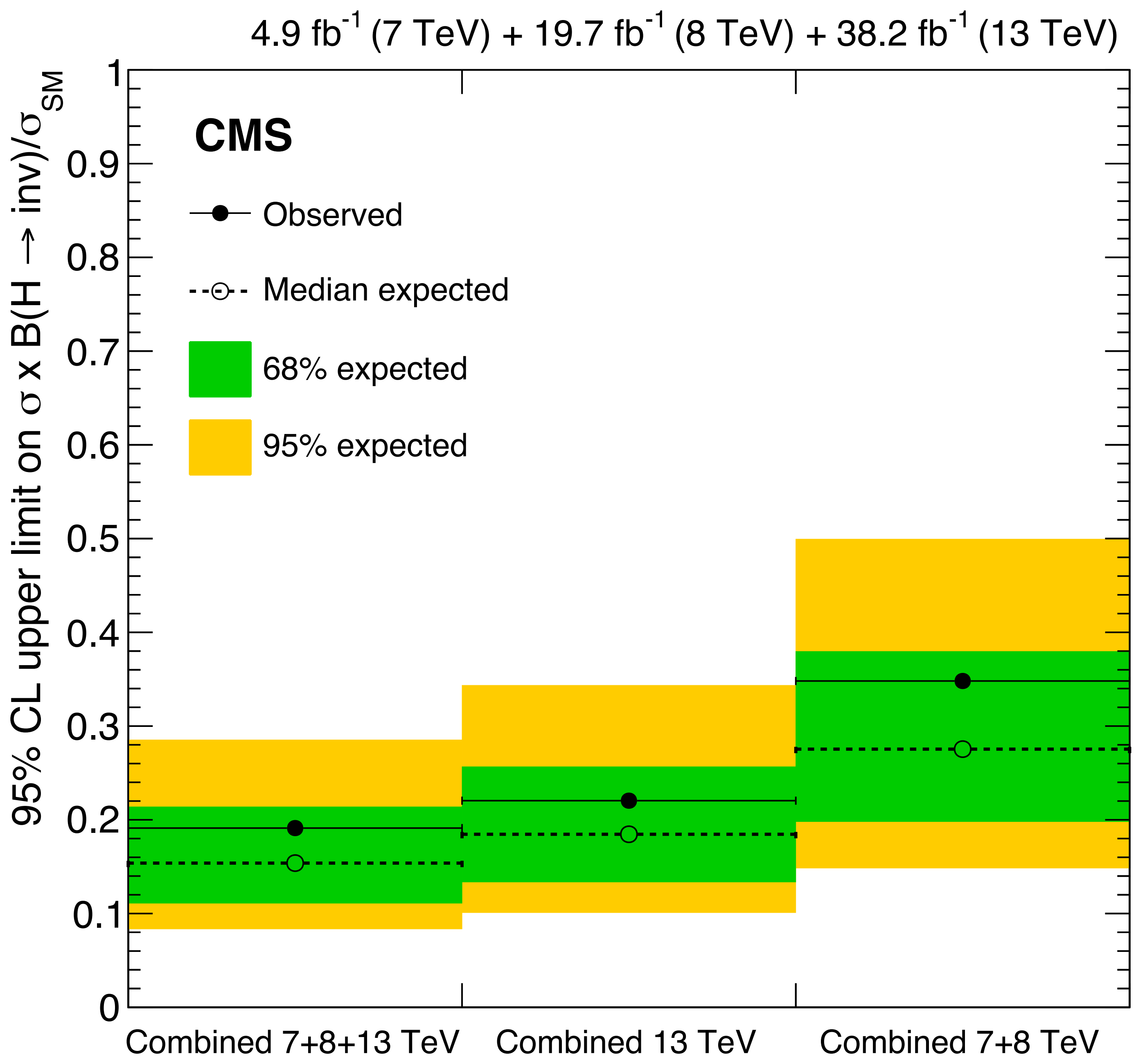


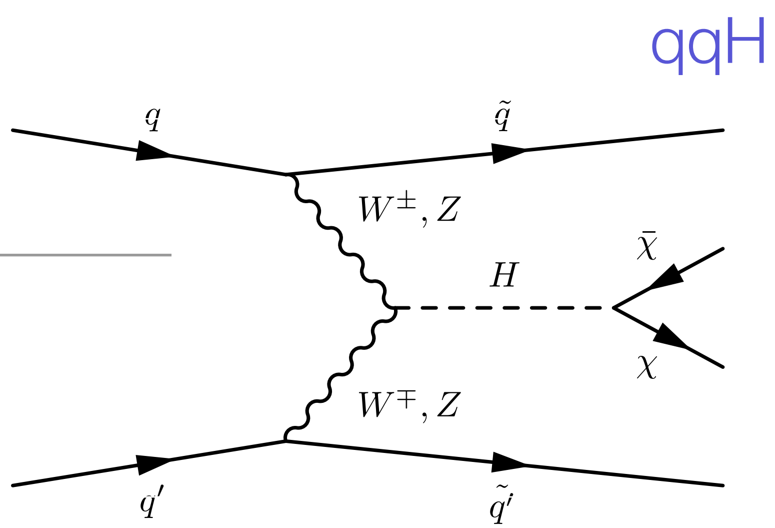



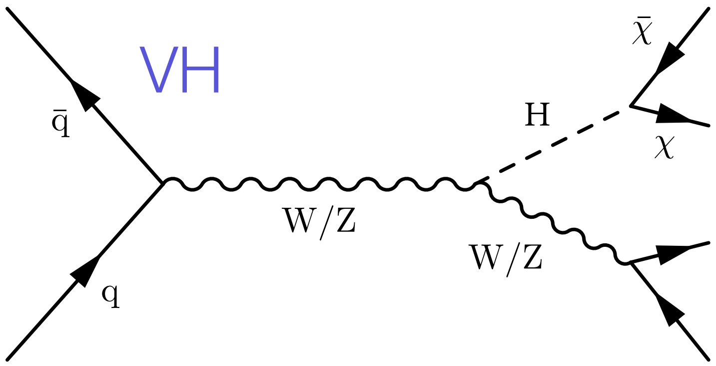
# Higgs-to-Invisible Searches

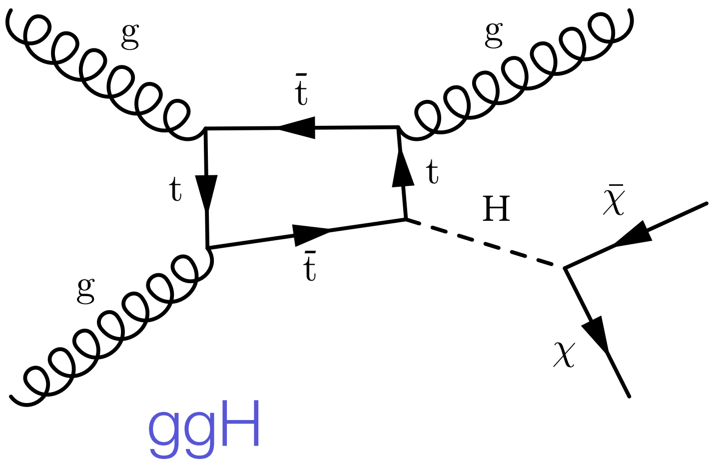


# Higgs-to-Invisible Searches

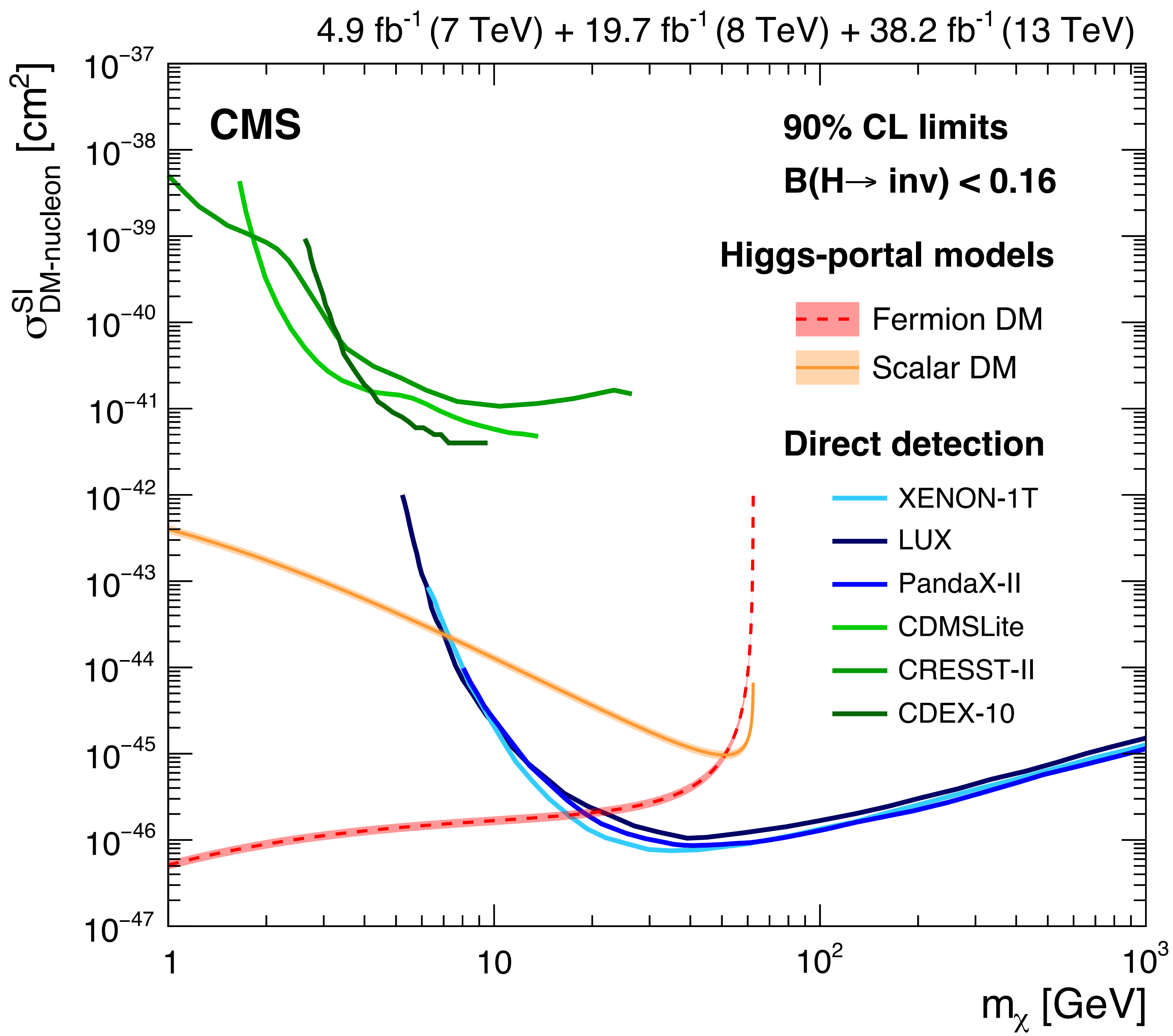


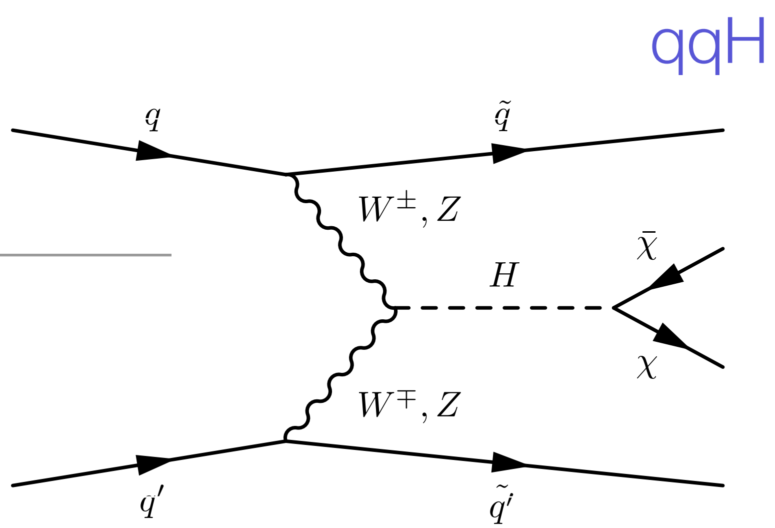



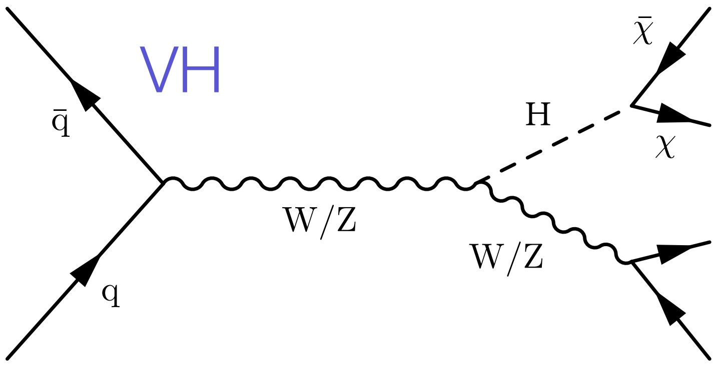



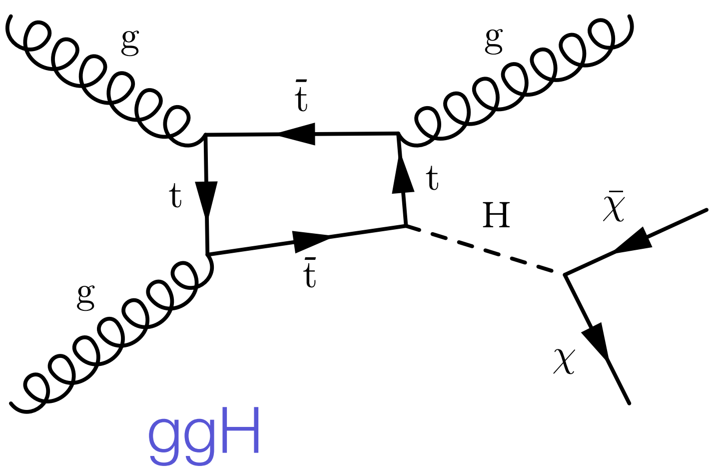



# Higgs-to-Invisible Searches

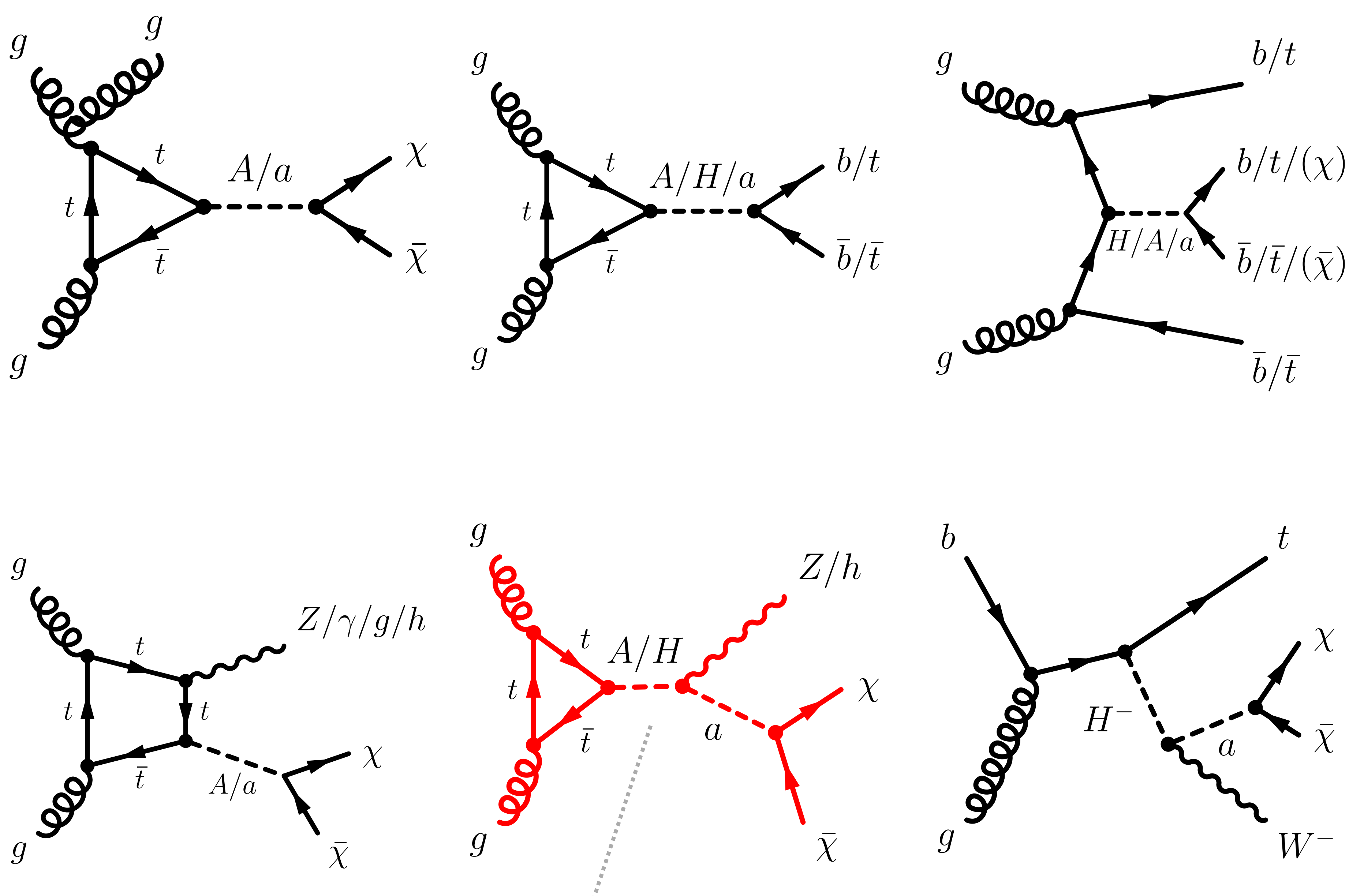


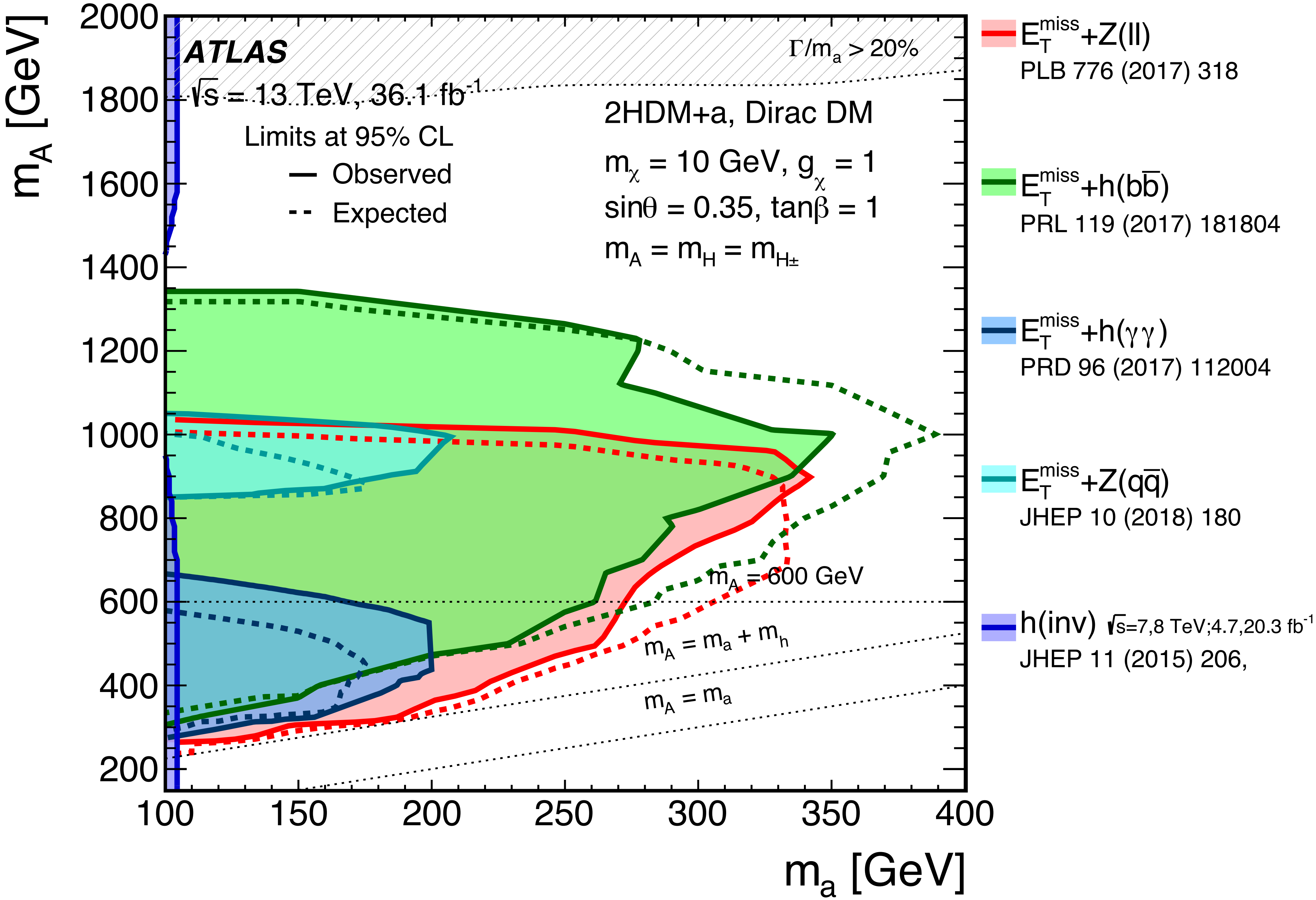



# 2HDM with Pseudo-Scalar Mediator

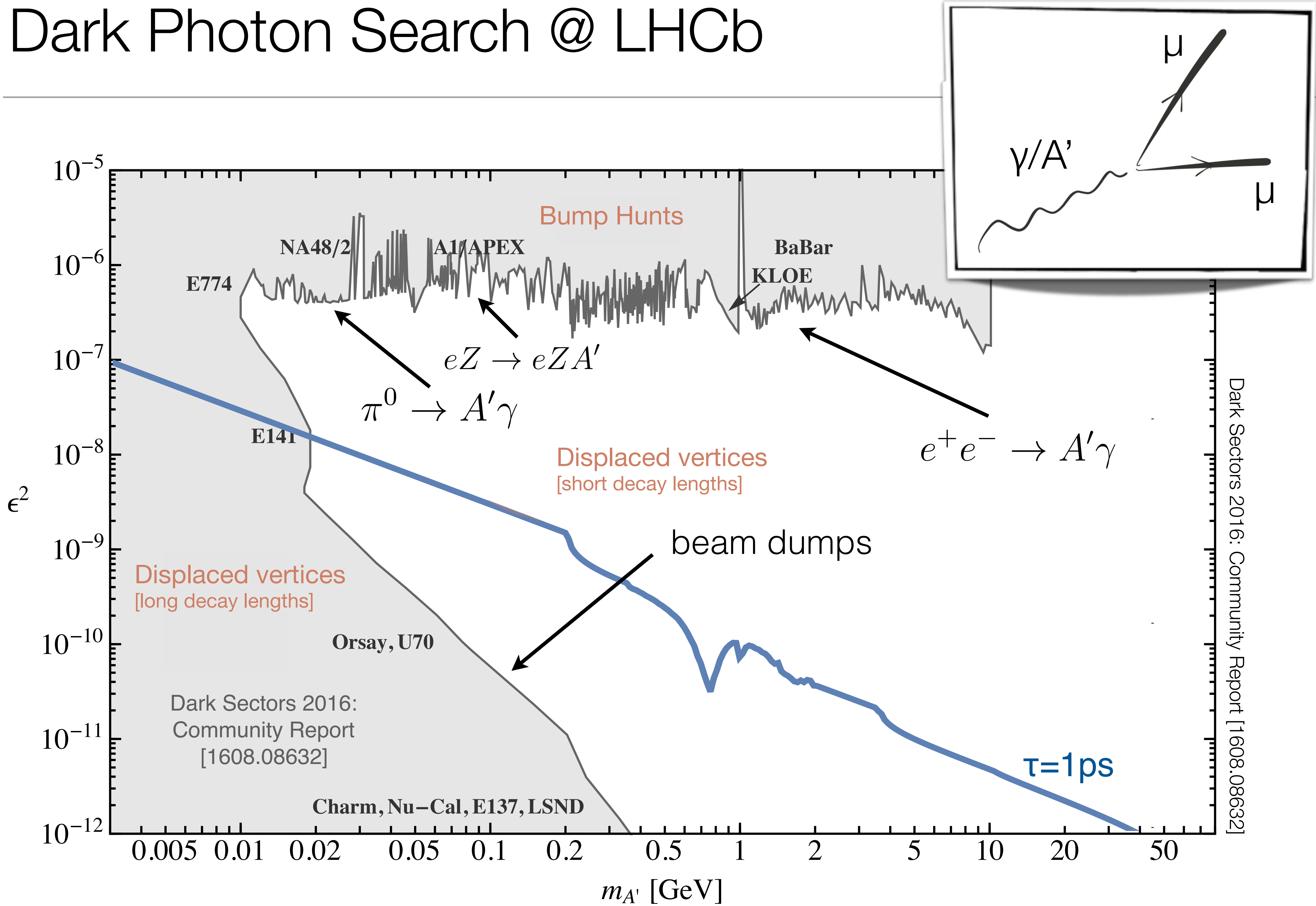



resonant
enhancement possible

# 2HDM with Pseudo-Scalar Mediator



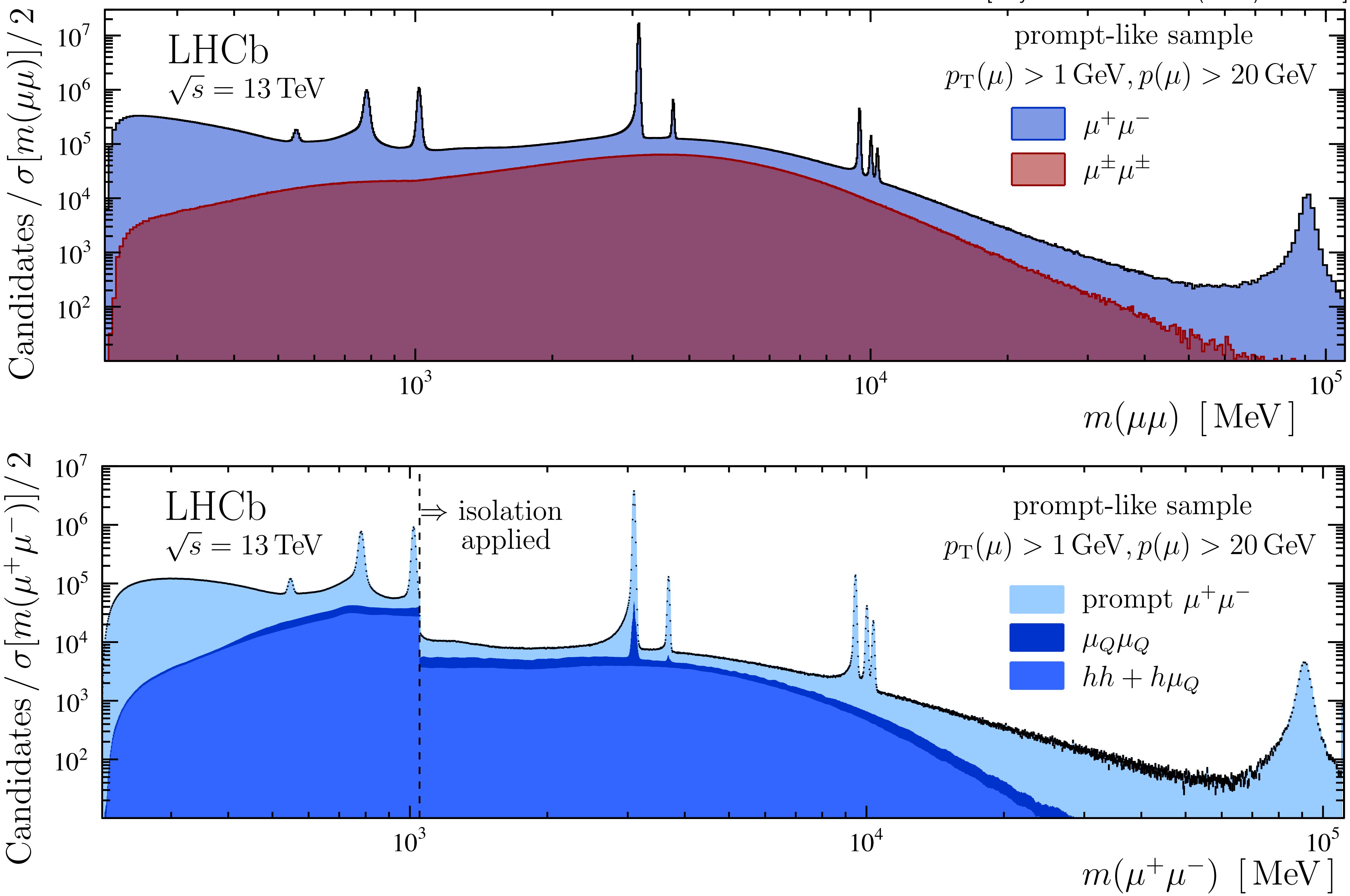
# Dark Photon Search @ LHCb



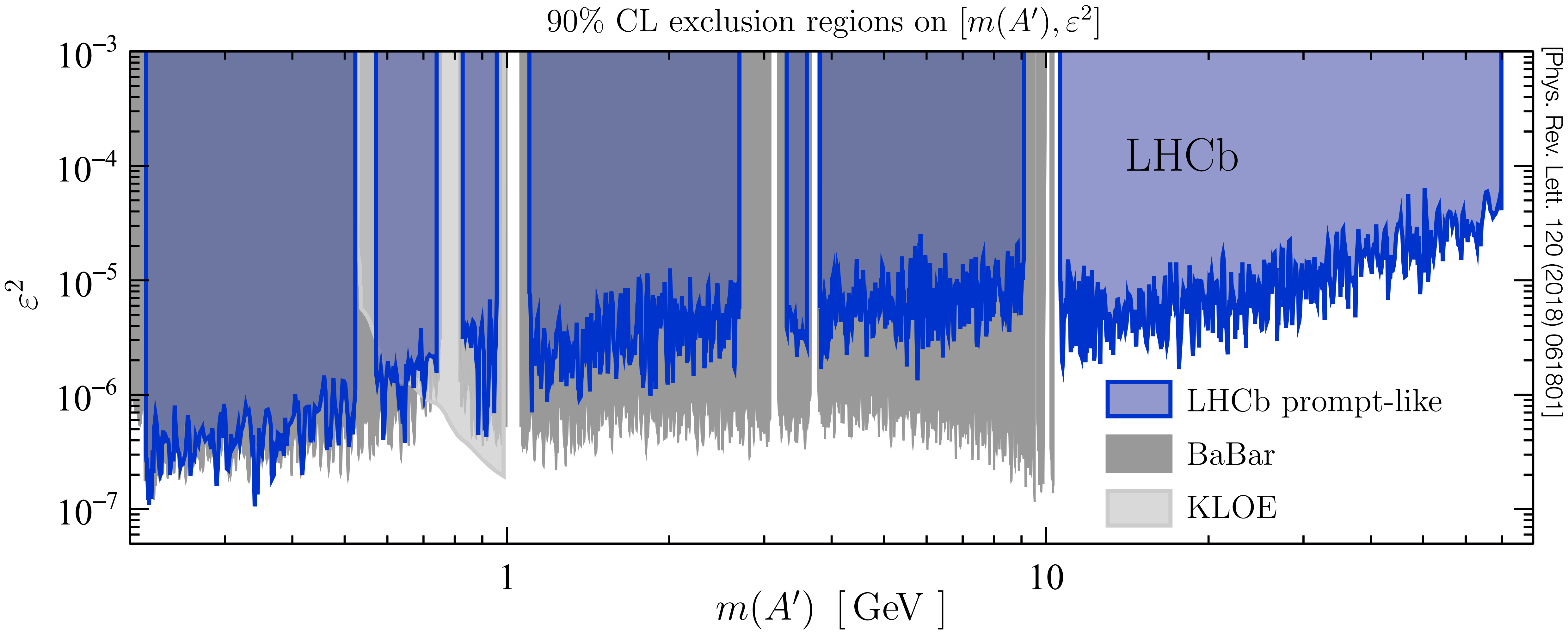

courtesy Mike Williams (via F.L. Redi)

# Dark Photon Search @ LHCb

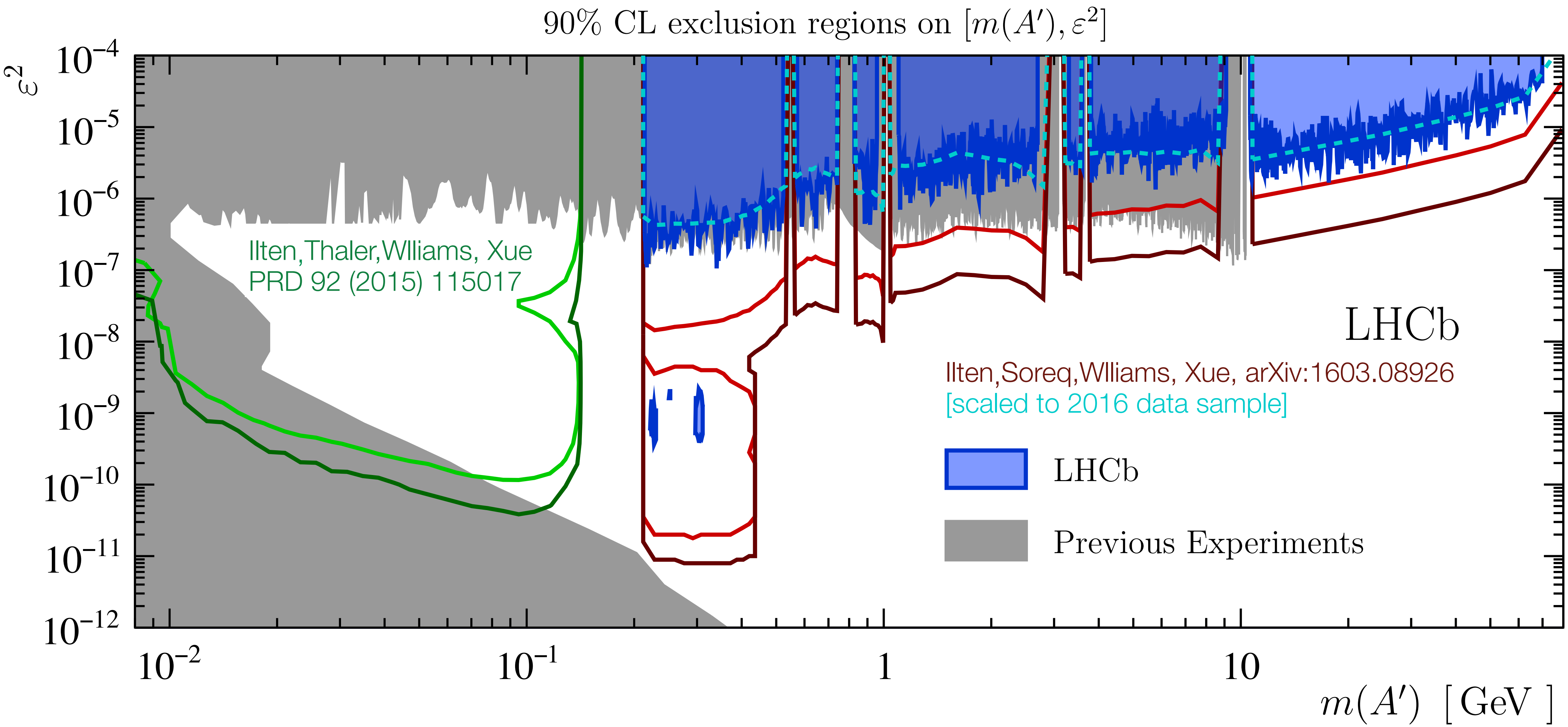
[Phys. Rev. Lett. 120 (2018) 061801]



# Dark Photon Search @ LHCb



# Dark Photon Search @ LHCb




courtesy F.L. Redi




PhD Comics
Dark Matters - A Tales
from the Road Comic