Search for branons in hadronic final states in proton-proton collisions at sqrt(s) = 13 TeV

Outline

- Motivations
- Presentation of the branon model
- Branon phenomenology
- The mono-jet and mono-V analysis
- Simulations and results

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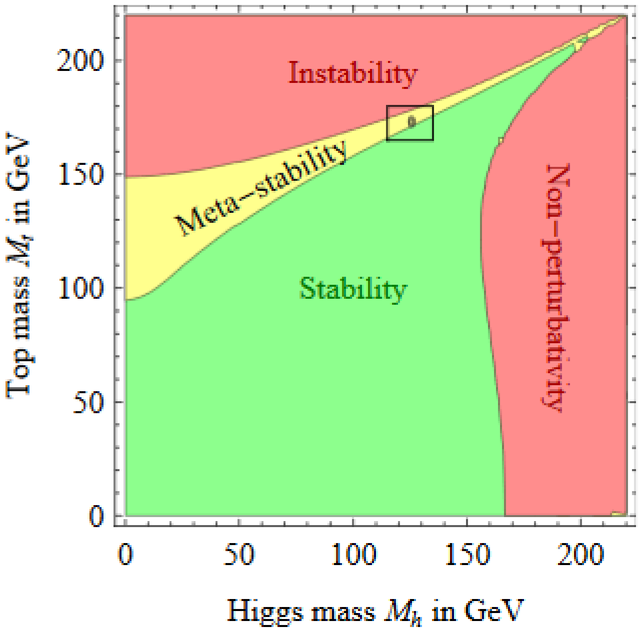
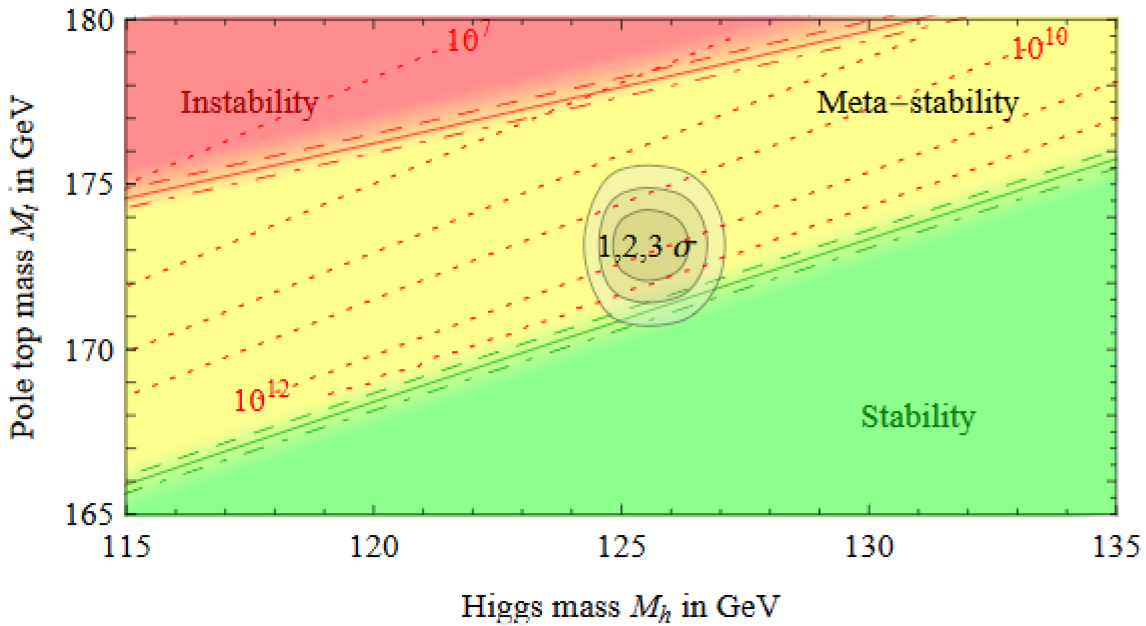
The hierarchy problem

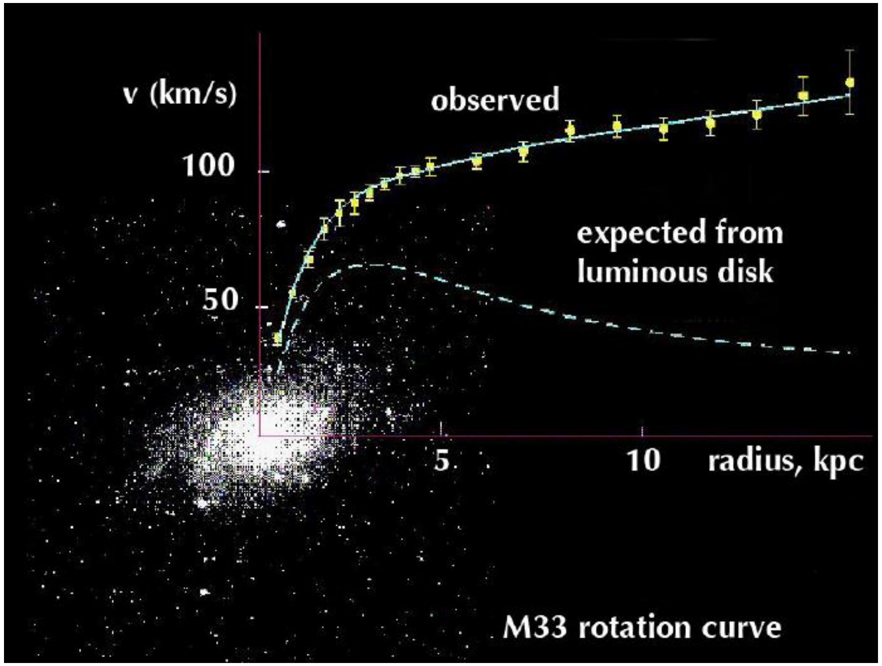
- Why the Electroweak scale is not Planck scale ?





The Dark Matter problem

➢ What is Dark Matter ?



- Galaxies rotation curves
- …

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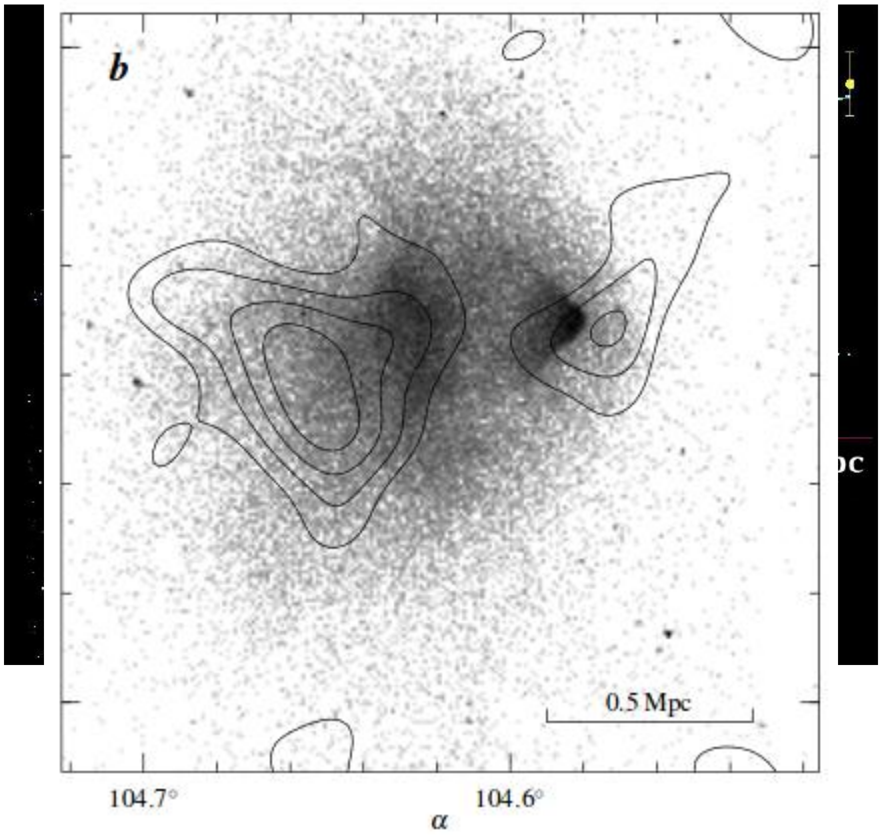

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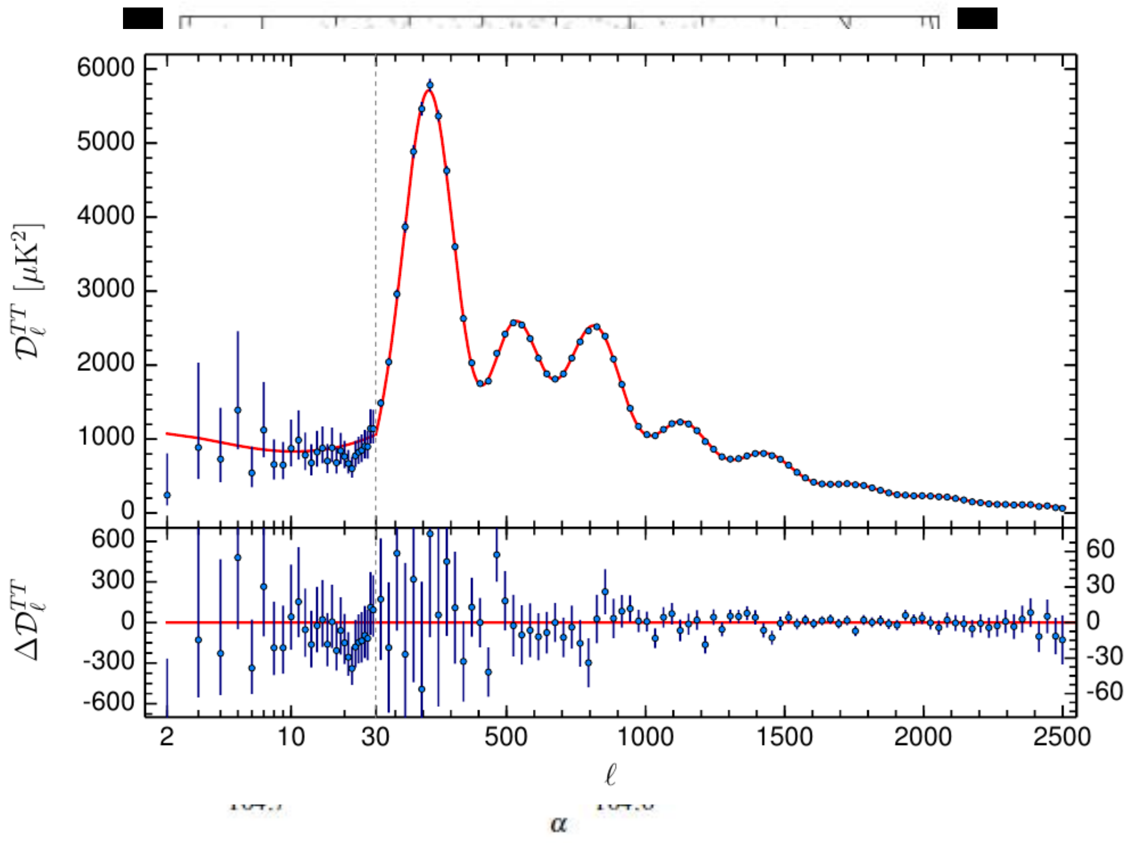

- Galaxies rotation curves
- Galaxy cluster collisions
- Cosmic Microwave Background
- …

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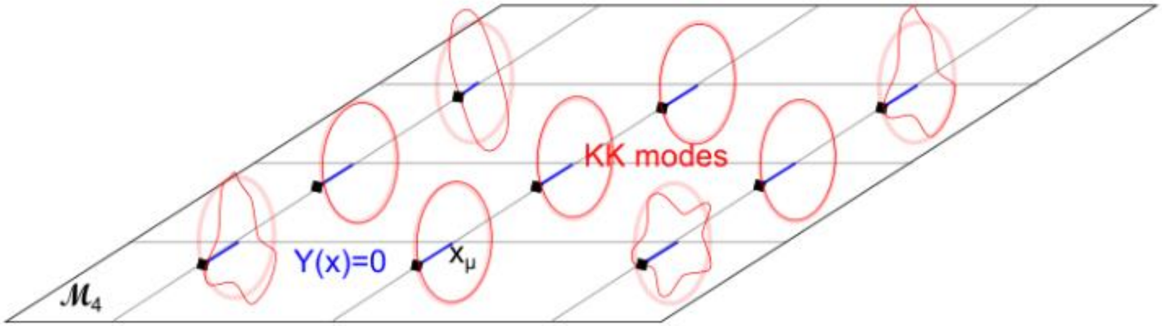
Branon model

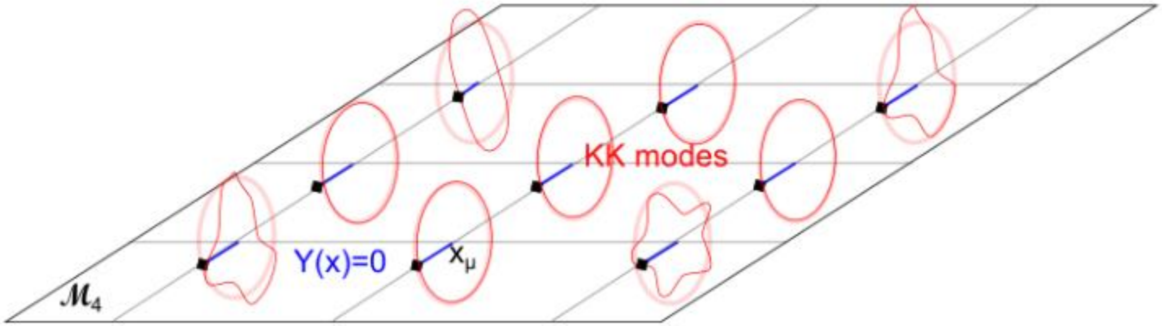
- Based on extra-dimension ADD model (Arkani, Dimopoulos & Dvali)



- Gravity leaks in the extra-dimension
- SM particles are confined into a rigid brane
- The Planck mass can be made arbitrarily small : $M_p^2 \approx M_D^{D-2} R^d$
- Solution to Hierarchy problem + DM candidate : KK-graviton

Branon model

- Based on extra-dimension ADD model



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Planck mass on the brane

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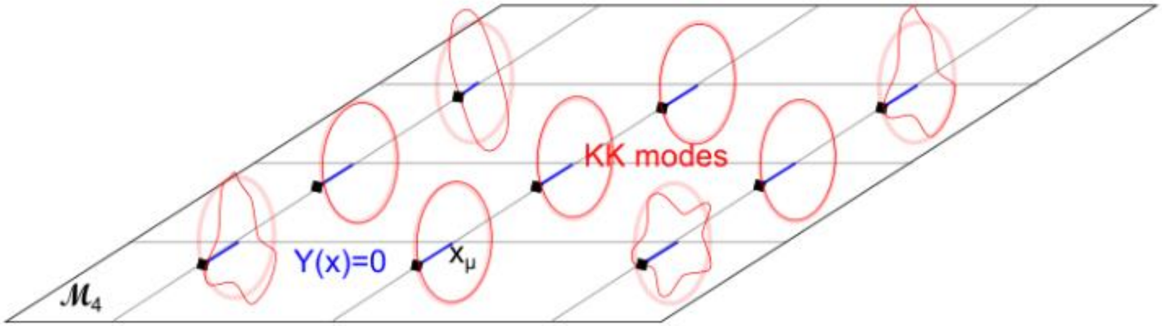

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Planck mass

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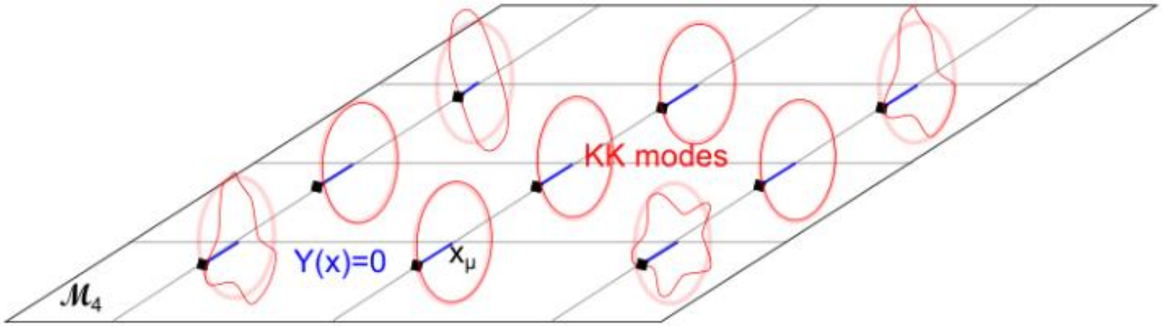

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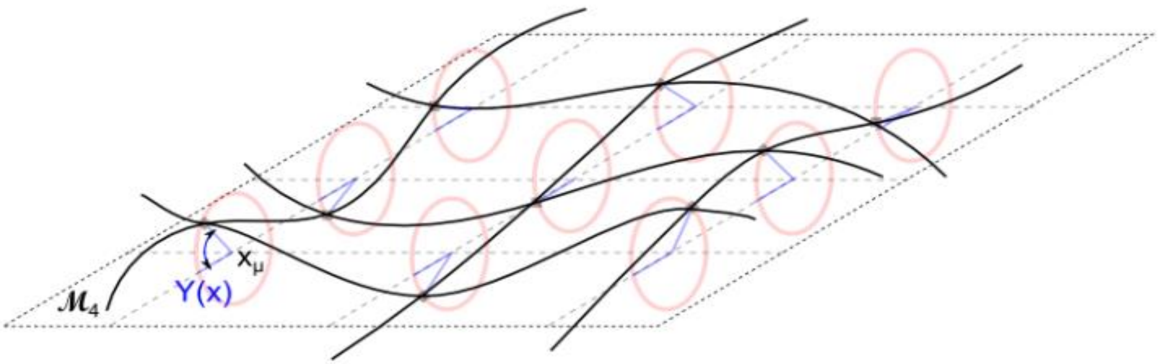
Planck mass on the brane

Planck mass

Typical size of extra dimensions

Branon model

- Suppose the brane is flexible and can move along the extra-dimension



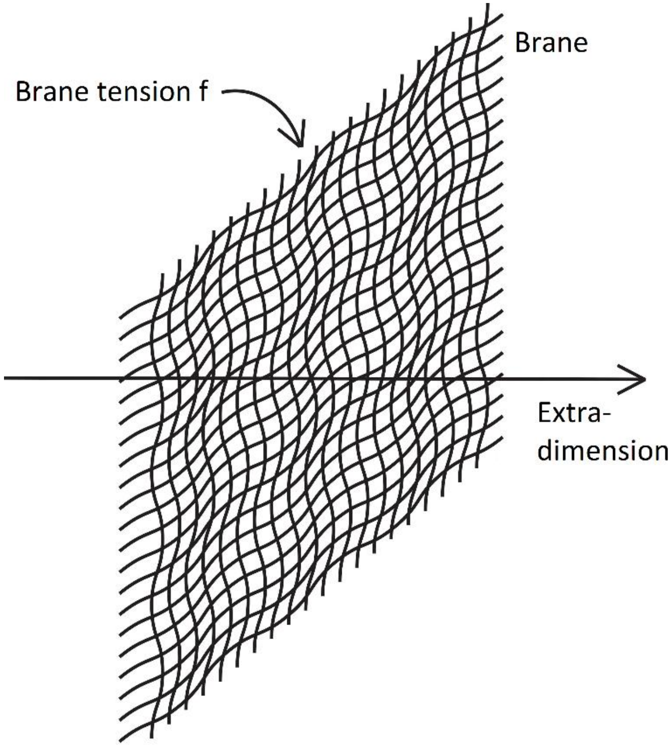
- General action : $$\mathcal{S}_B = -f^4 \int_{\mathcal{M}_4} d^4x \sqrt{\tilde{g}}$$

- f is the brane tension : scale of perturbations on the brane

- $\tilde{g}$ is the induced metric on the brane

Branon model

- The presence of the brane breaks space-time symmetries.
- Each broken space-time symmetry produces a stable Goldstone boson, called branon.
- A priori, family of N branons
- N is degenerated with f → N=1 here



Branon model

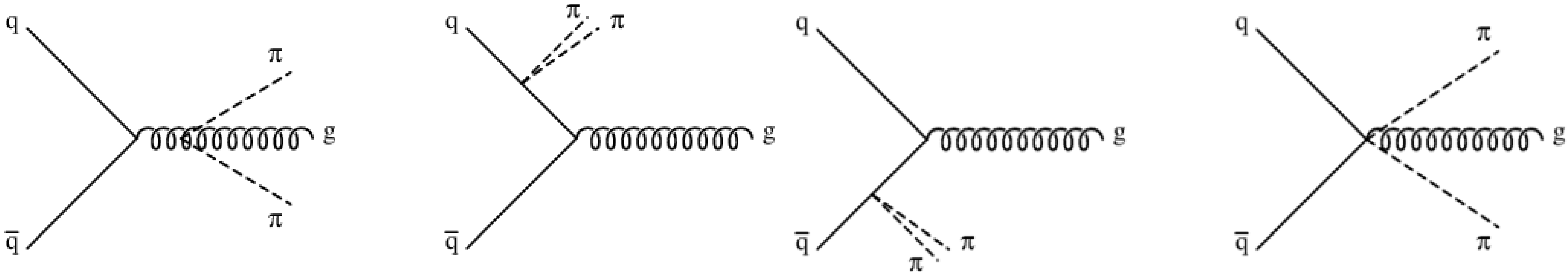
The general free branon (field π) action is given by :

$$S_\pi = \frac{1}{2}\int_{\mathcal{M}_4} d^4x(\delta_{\alpha\beta}\partial_\mu\pi^\alpha\partial^\mu\pi^\beta - M^2_{\alpha\beta}\pi^\alpha\pi^\beta)$$

The branons are also coupled to SM vie the energy-momentum tensor :

$$S_{SM/\pi} = \frac{1}{8f^4}\int_{\mathcal{M}_4} d^4x(4\delta_{\alpha\beta}\partial_\mu\pi^\alpha\partial_\nu\pi^\beta - \eta_{\mu\nu}M^2_{\alpha\beta}\pi^\alpha\pi^\beta)T^{\mu\nu}_{SM}$$

Example of process producing two branons along with a gluon :



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Mass term

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Brane tension

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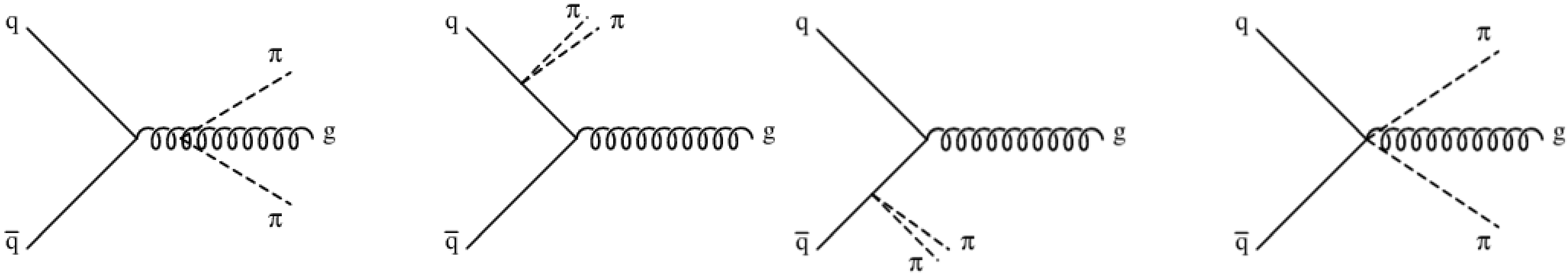

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Mass term

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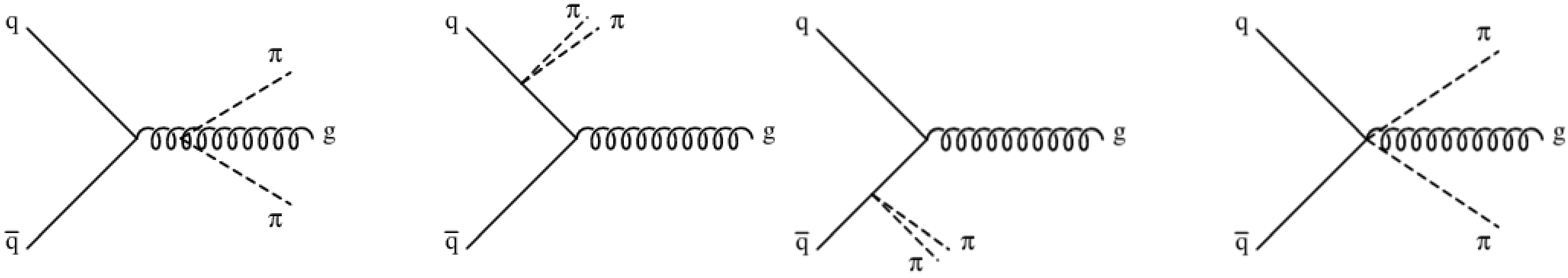

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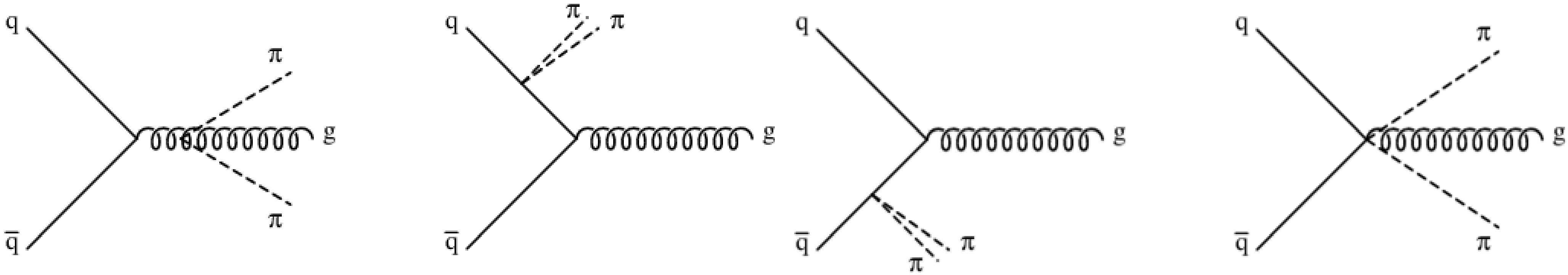
Brane tension

pair

pair

Example of process producing two branons along with a gluon :



Branon model - summary

- ADD model provides an answer for hierarchy problem
- If there are extra-dimensions there must be branons
- Branon can be produced at collider
  - Direct coupling to SM particles via energy-momentum tensor
  - 2 parameters : the branon's mass M and the brane tension f
  - The cross-sections are suppressed by $1/f^8$
  - Branons are pair produced
  - When f is low, branon production can dominate over KK graviton production
- Branon is a scalar that can be Dark Matter candidate

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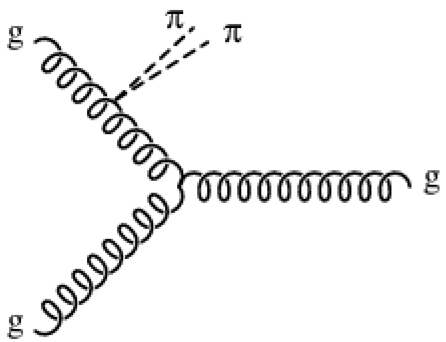
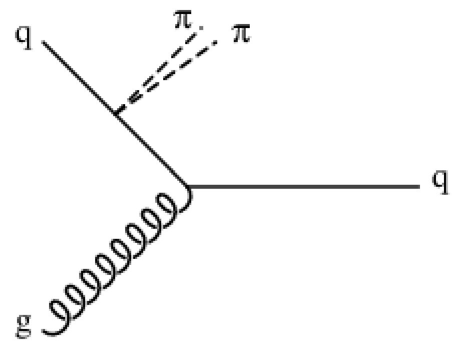
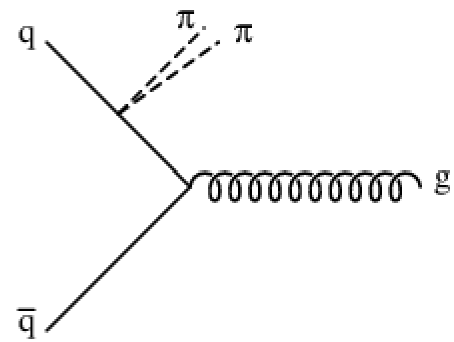
Branon phenomenology

- At LHC, QCD is everywhere : monojet final state is very interesting
  - Two main channels for this study :

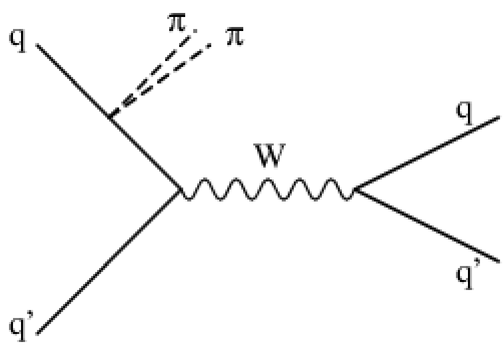
Mono-jet :

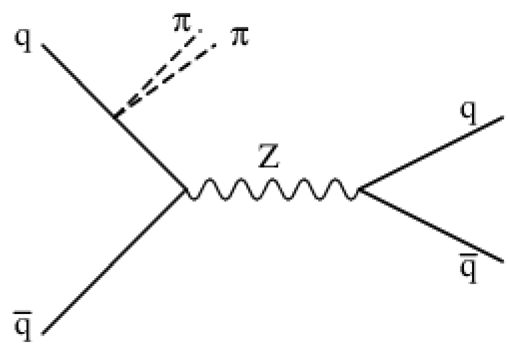






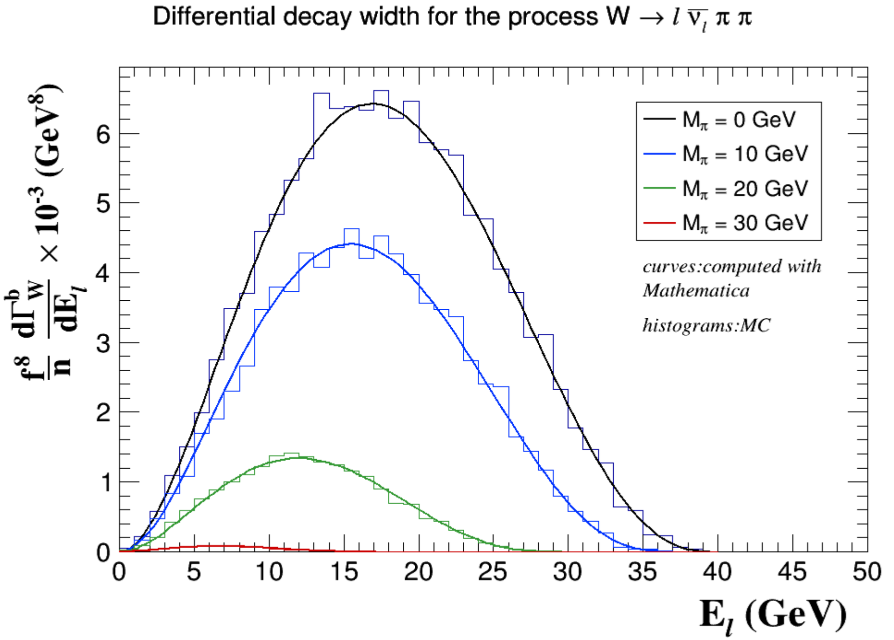
Mono-V :

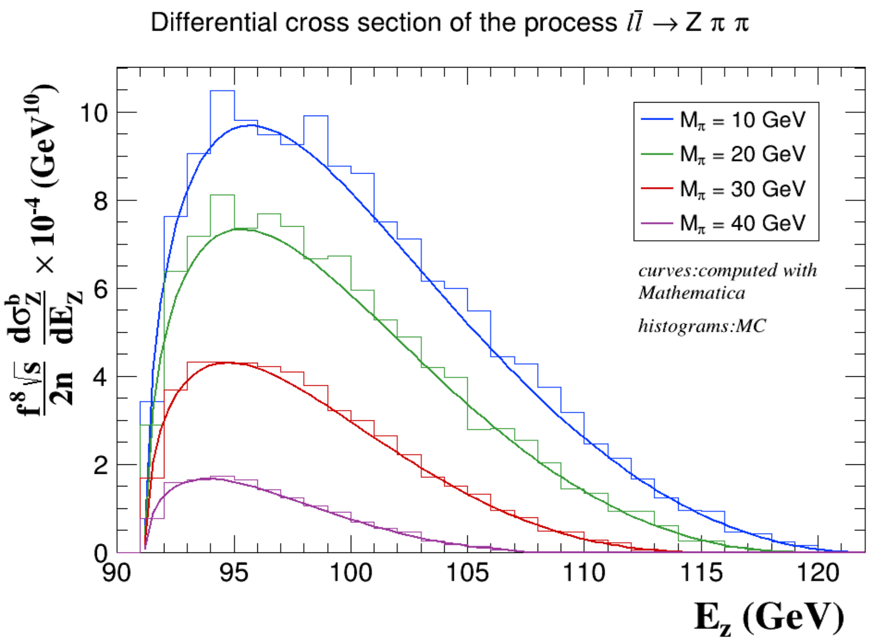




Branon phenomenology

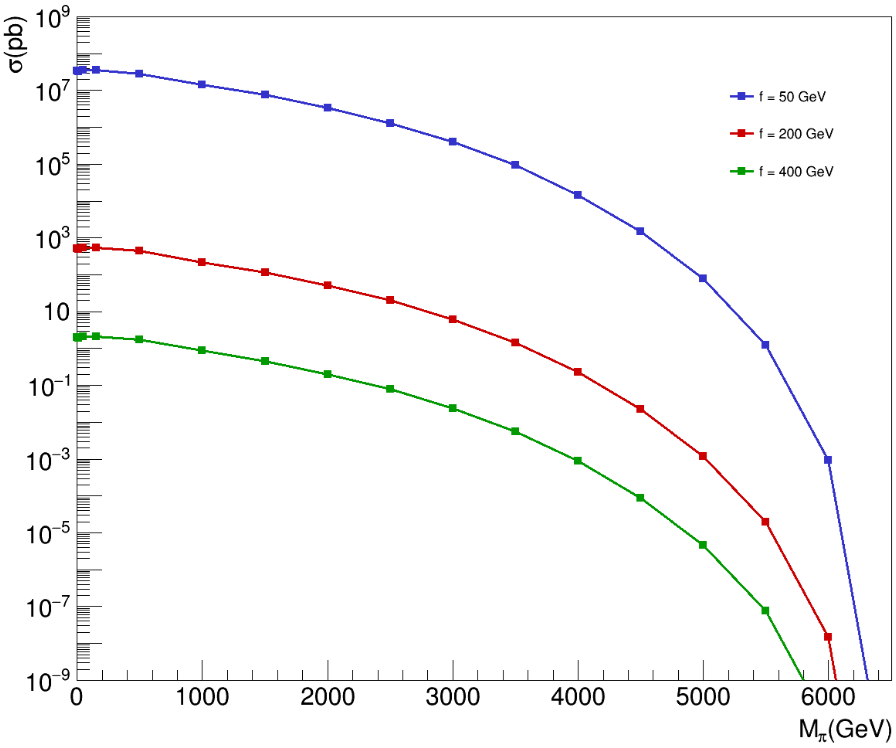
- The branon model have been implemented in FeynRules.
- Monte-Carlo production with MadGraph at parton level.
- Hadronization with Pythia8.
- Validation in W/Z production channels, base on results from Phys.Rev. D67 (2003) 075010 :



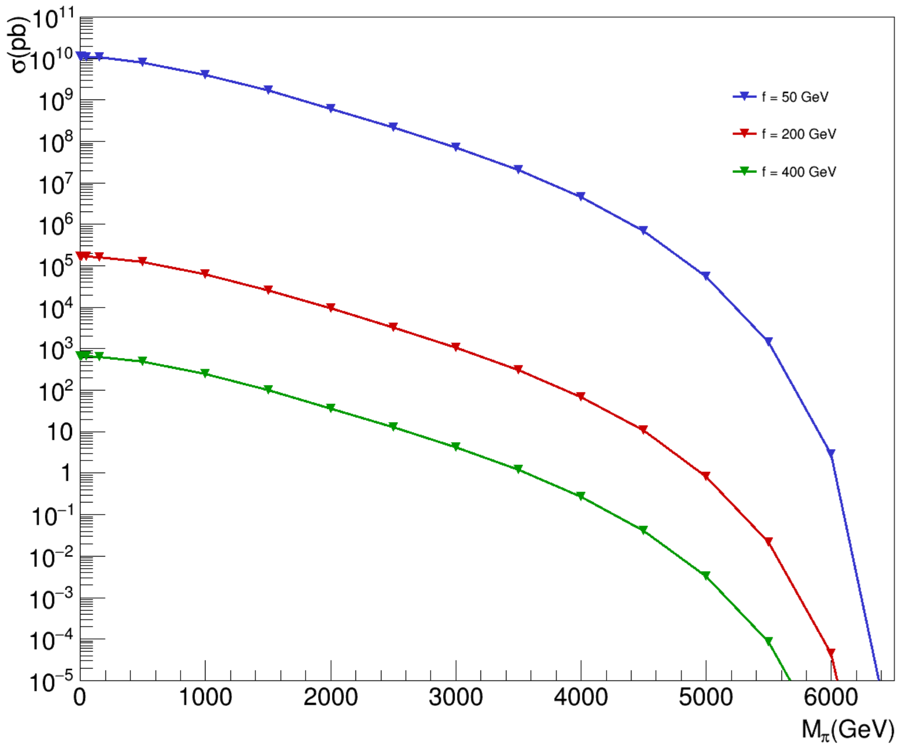


Branon phenomenology

- PDF : LHAPDF-263000, sqrt(s)= 13TeV



$$pp \to W + \pi\pi$$



$$pp \to jet + \pi\pi$$

- Results in mono-Z and mono-W production channel are similar

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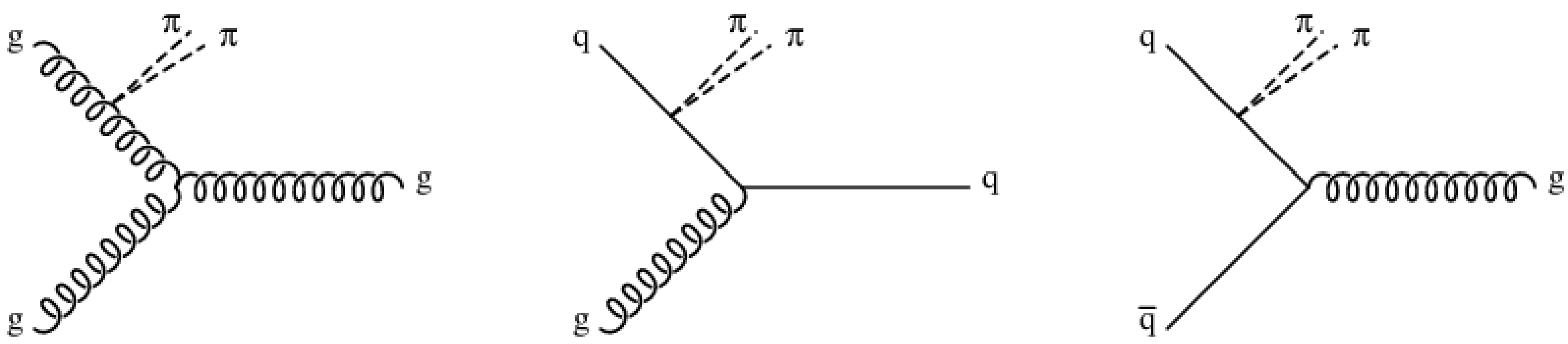
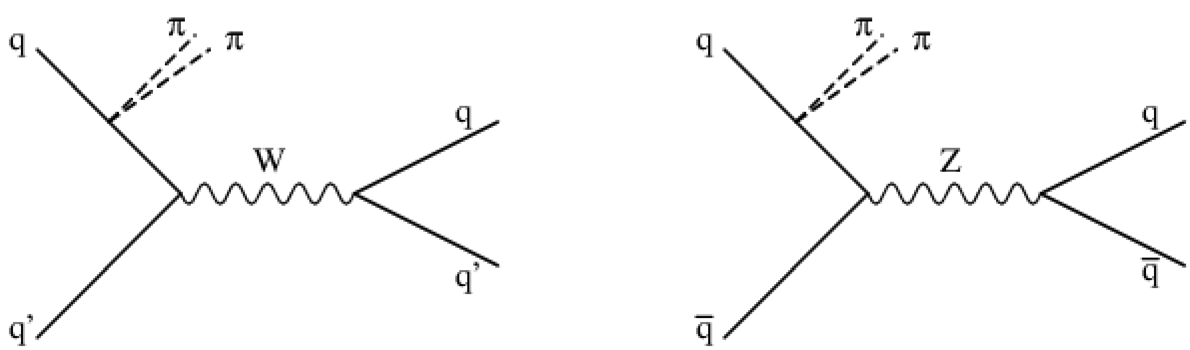
Mono-jet :



Mono-V :



Branon phenomenology

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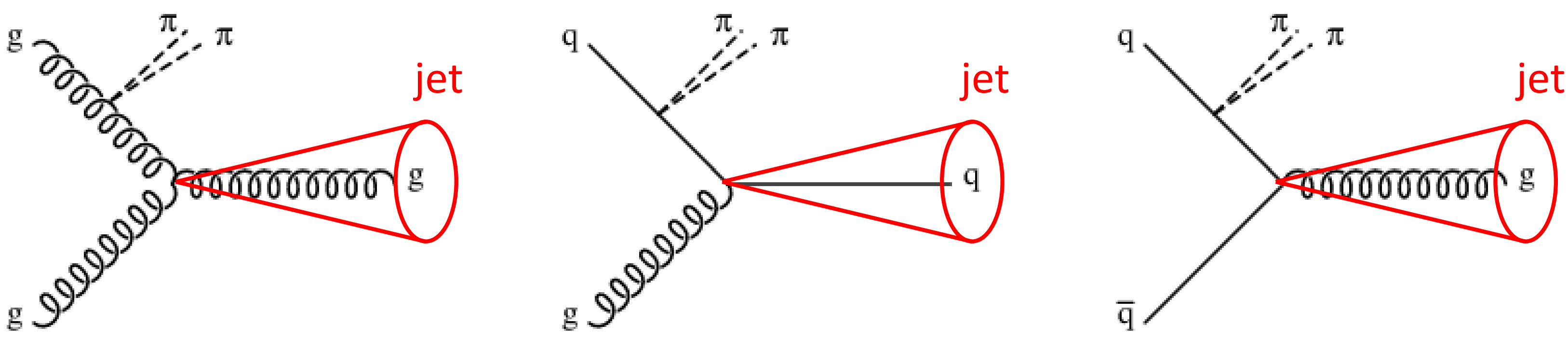
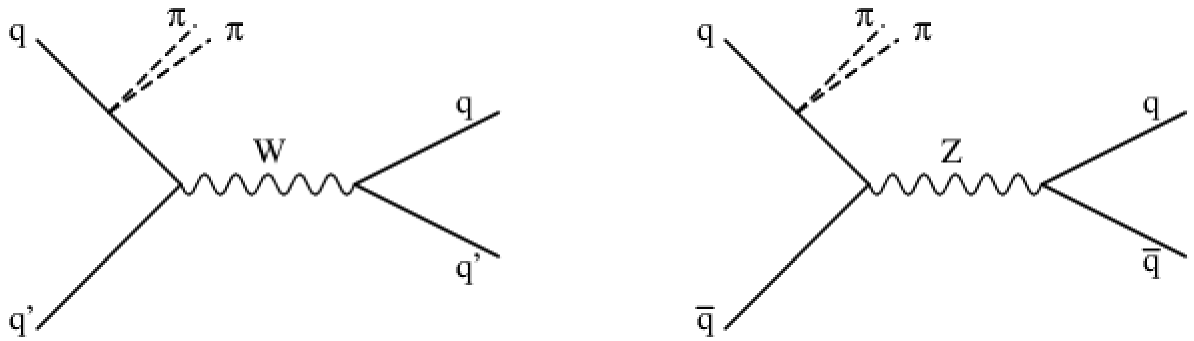
Mono-jet :



Mono-V :



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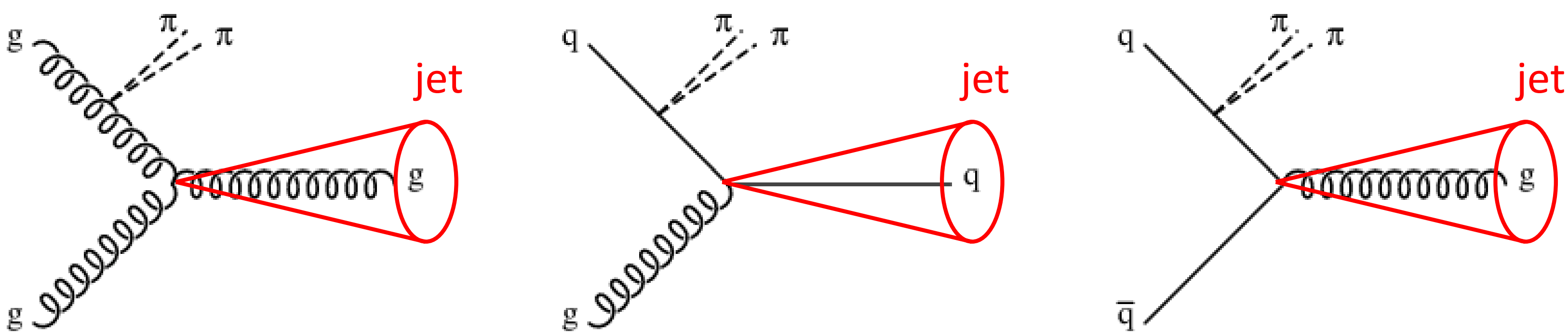
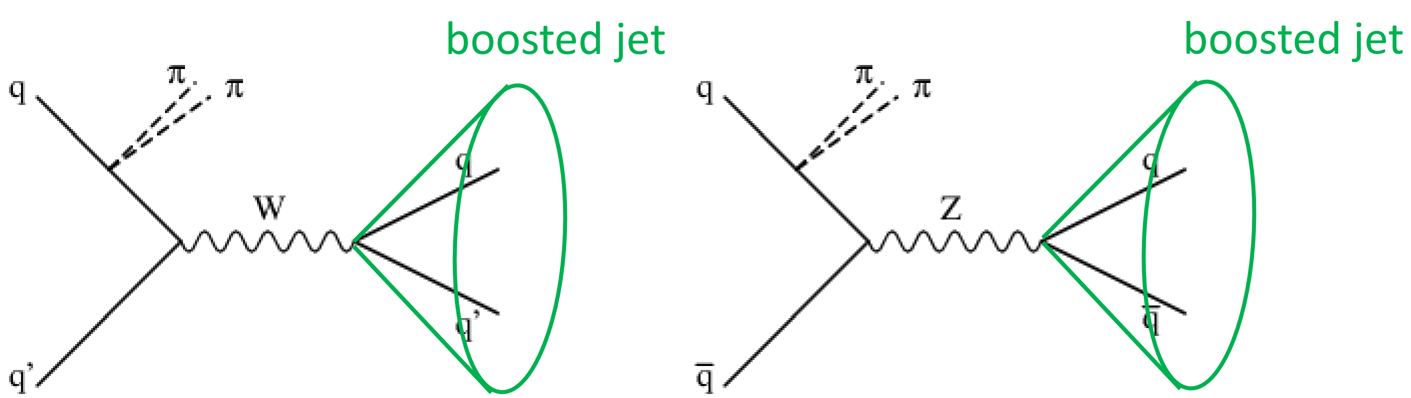
Mono-jet :



Mono-V :



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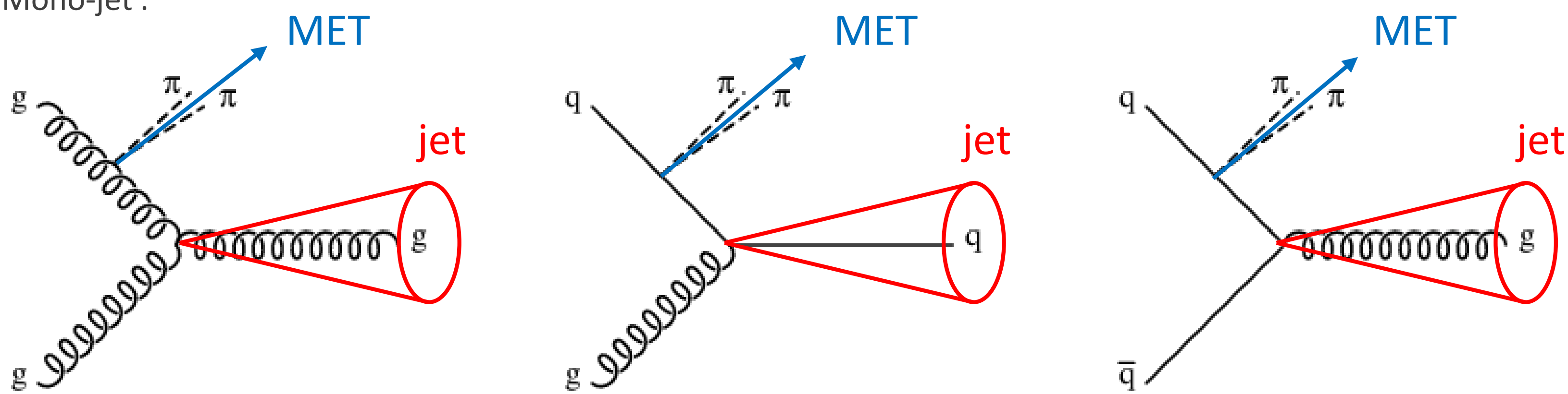

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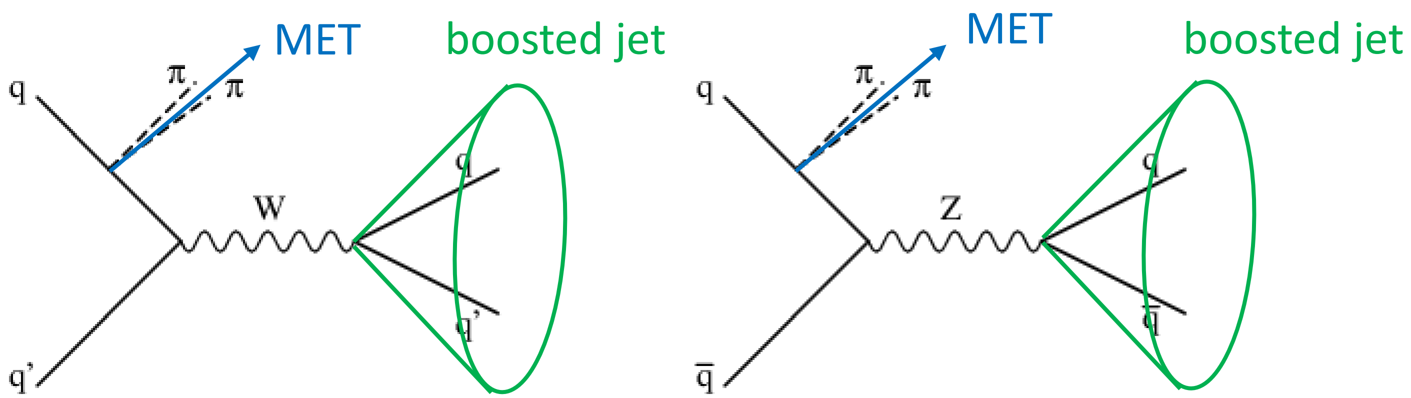


DM search in monojet and monoV channels

- Search for events with >1 jets and significant MET
- Two channels : mono-jet and mono-V
- Backgrounds considered :

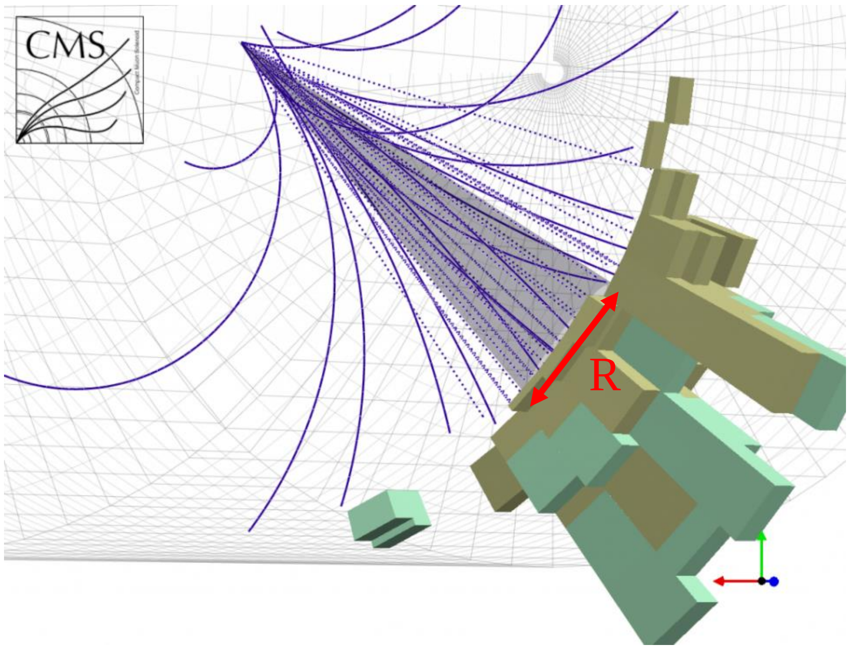
Estimated from data :
- Z(νν)+jets
- W(ℓν)+jets
- QCD

Estimated from MC :
- Z(ℓℓ)+jets
- γ+jets
- top
- Dibosons

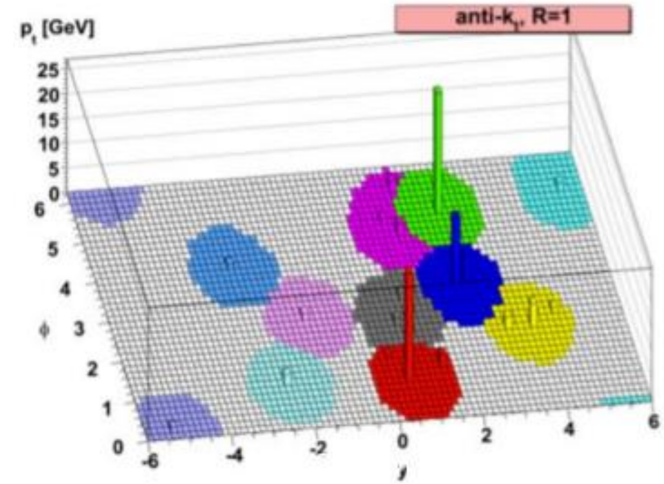
- Use of kinematically similar control regions to estimate backgrounds from data

Physics objects

- Jets clustering :

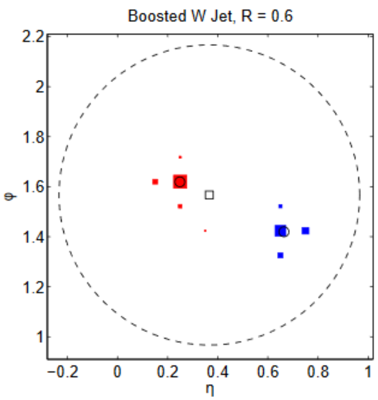
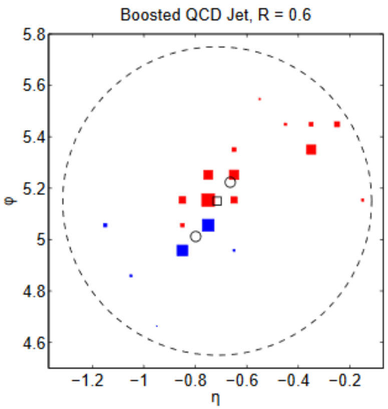


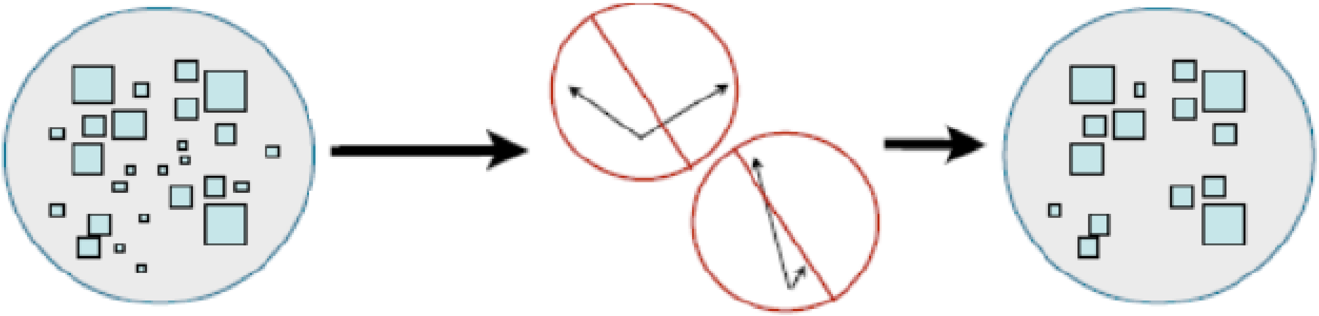
- In the detector, many collimated tracks
- Originated from a single parton
- Reconstructed as a single jet



Physics objects

- Usual jets : $\Delta R = 0.4$
- Boosted jets : $\Delta R = 0.8$ → substructure variables

N-subjettiness : distinguish between  and 

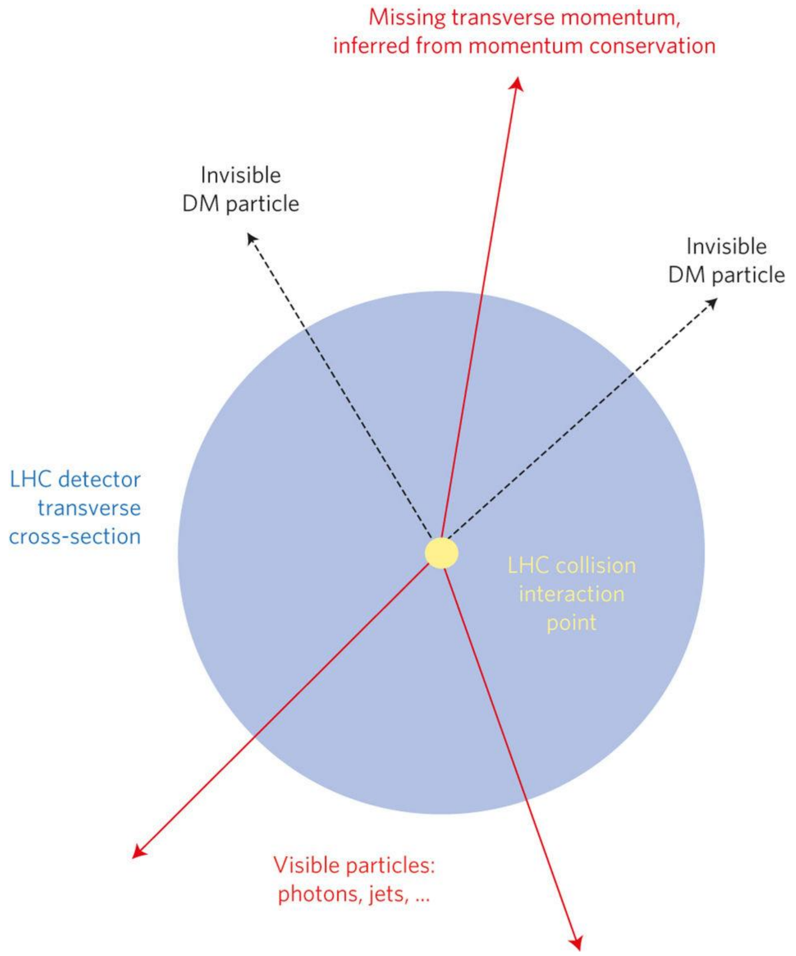
Pruned mass : 

- Possible to do V-tagging

Physics objects

➢ Important tool to study particles that don't interact in the detector : Missing Transverse Energy

$$\vec{E}_{T,Type-I}^{miss} = -\sum_{jet} \vec{p}_{T,jet}^{JEC} - \sum_{i \in uncl.} \vec{p}_{T,i}$$



Signal regions selection

- Search for monojet and mono-V as two disjoint channels
- Two categories of selections :

Mono-V

- Leading jet :
  - $\Delta R=0.8$
  - $p_T>250$ GeV
- MET>250 GeV
- V-tagging selection :
  - N-subjettiness variable < 0.6
  - $65<m_{pruned}<105$ GeV

- Veto on leptons
- Veto on b-jets (remove ttbar)
- $\Delta\varphi$(jets,MET)>0.5 (remove QCD)

Mono-jet

- Leading jet :
  - $\Delta R=0.4$
  - $p_T>100$ GeV
- MET>200 GeV

- Veto on leptons
- Veto on b-jets (remove ttbar)
- $\Delta\varphi$(jets,MET)>0.5 (remove QCD)

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Selection efficiencies - monojet category

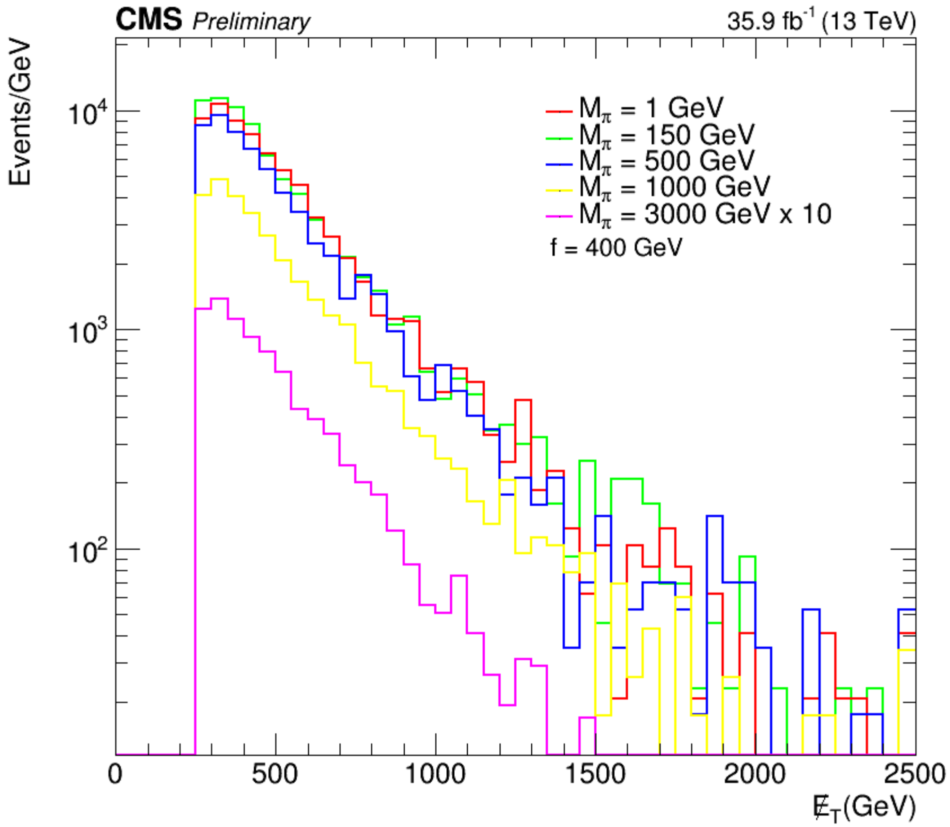
Mass (GeV)	Monojet	MonoW	MonoZ
1	41,42%	15,92%	15,41%
10	41,29%	15,72%	15,65%
50	41,45%	15,67%	15,57%
150	41,67%	15,84%	15,45%
500	43,45%	15,96%	15,53%
1000	46,01%	16,49%	15,96%
3000	49,29%	15,66%	15,57%
5000	46,44%	10,86%	10,37%
6000	20,09%	03,60%	03,95%
6400	0,03%	0,04%	0,05%

Selection efficiencies - monoV category

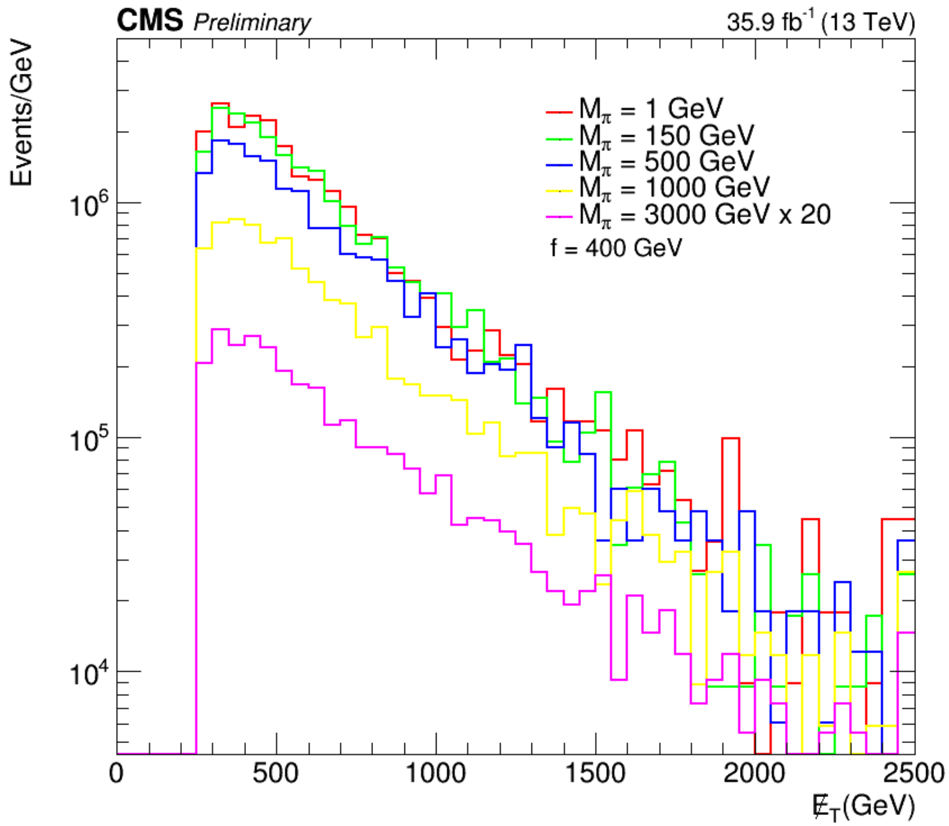
Mass (GeV)	Monojet	MonoW	MonoZ
1	02,71%	06,46%	06,19%
10	02,82%	06,25%	06,07%
50	02,75%	06,24%	06,11%
150	02,76%	06,21%	06,14%
500	02,95%	06,51%	06,25%
1000	03,20%	06,62%	06,64%
3000	03,47%	06,62%	06,61%
5000	03,57%	04,44%	04,32%
6000	0,96%	0,80%	0,77%
6400	0,007%	0,01%	0,01%

Monte-Carlo generation

- MET distributions in the mono-V category :



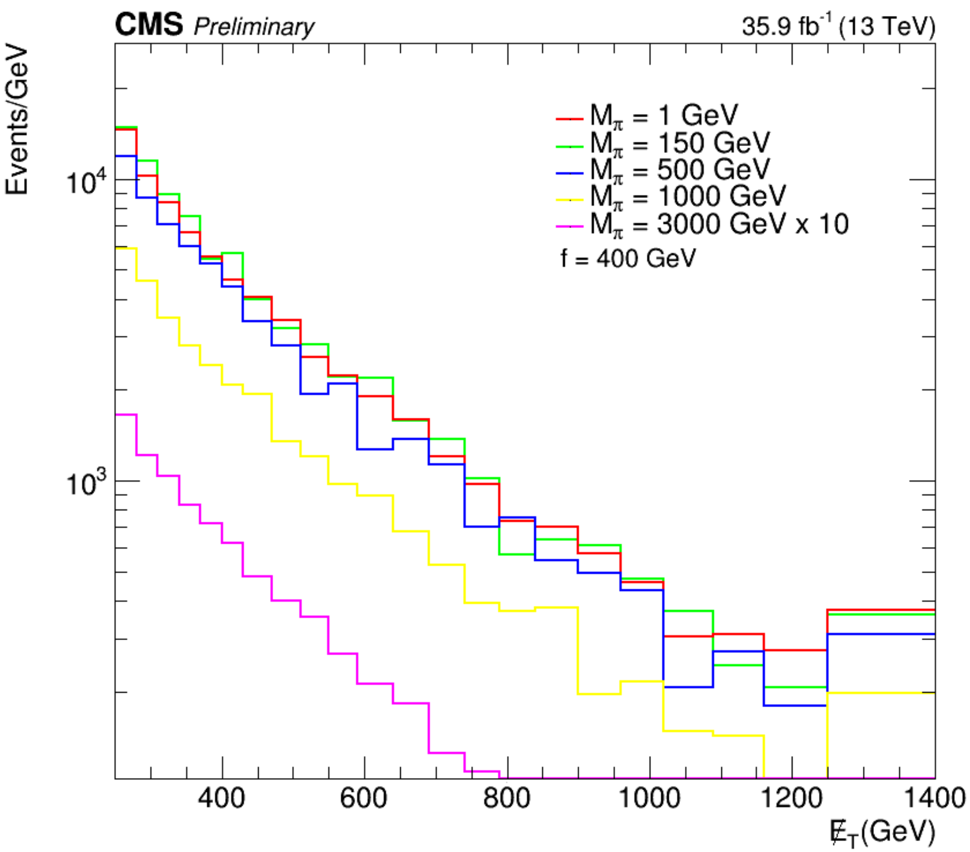
MonoW channel



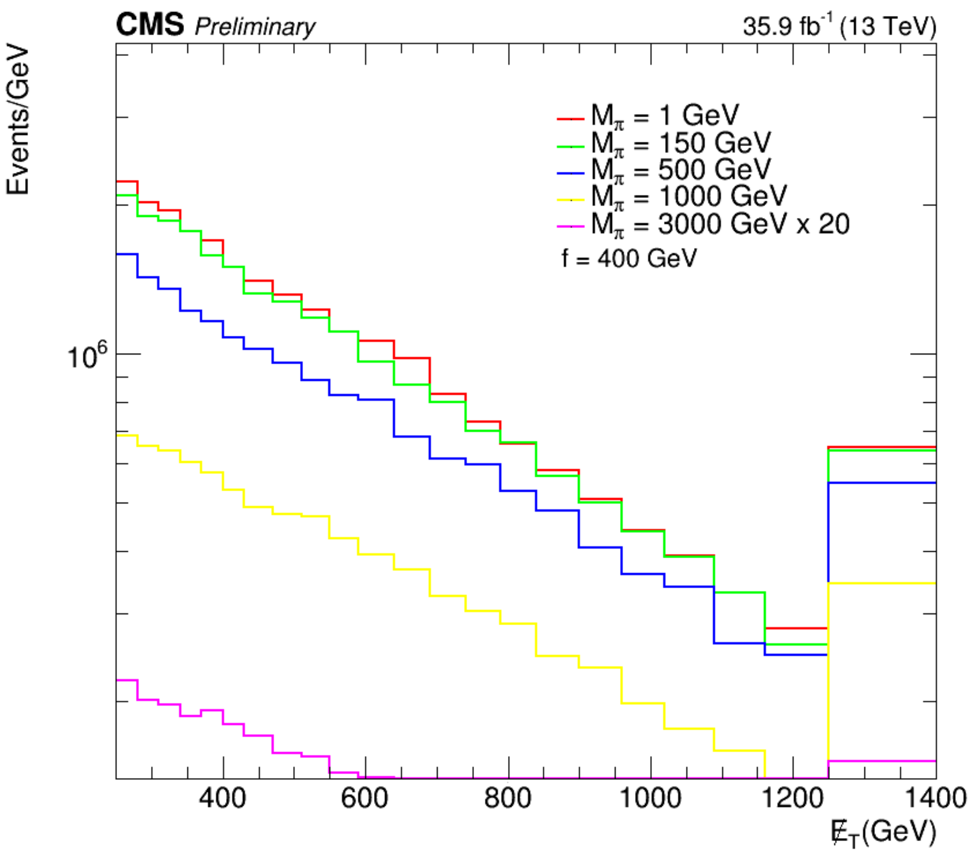
Monojet channel

Monte-Carlo generation

➢ MET distributions in the mono-jet category :



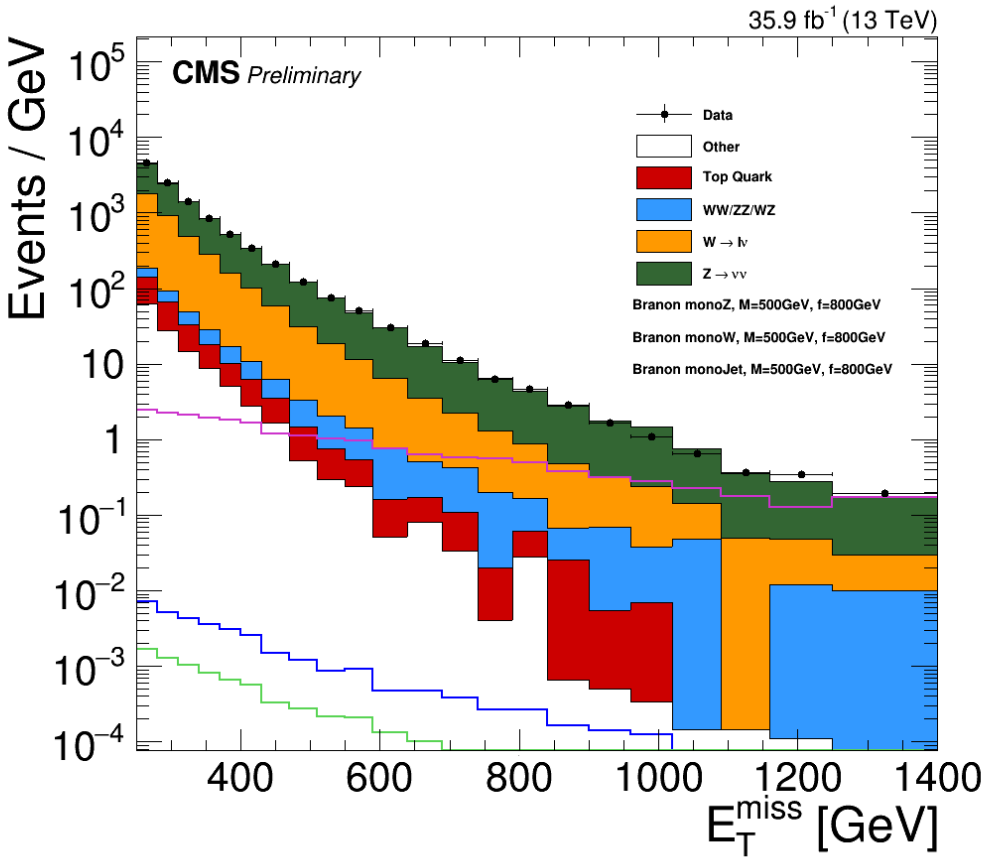
MonoW channel



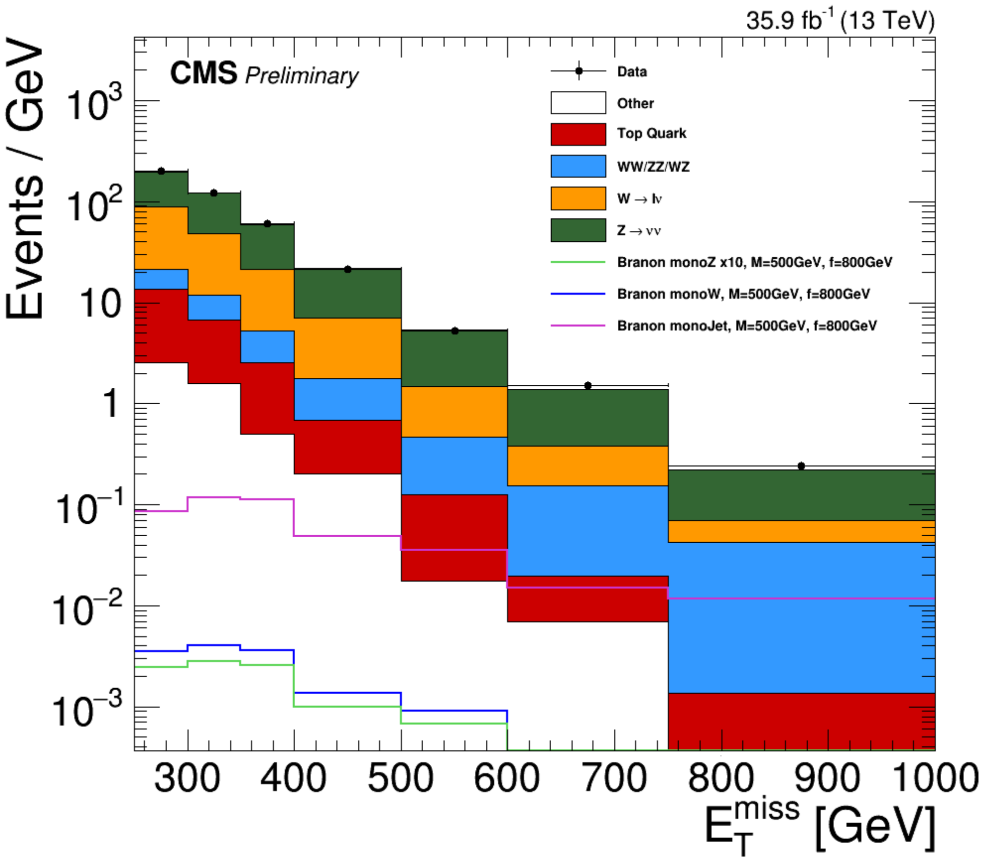
Monojet channel

Comparison with background

- MET distribution of signal compared to background in the two categories, with ICHEP data :



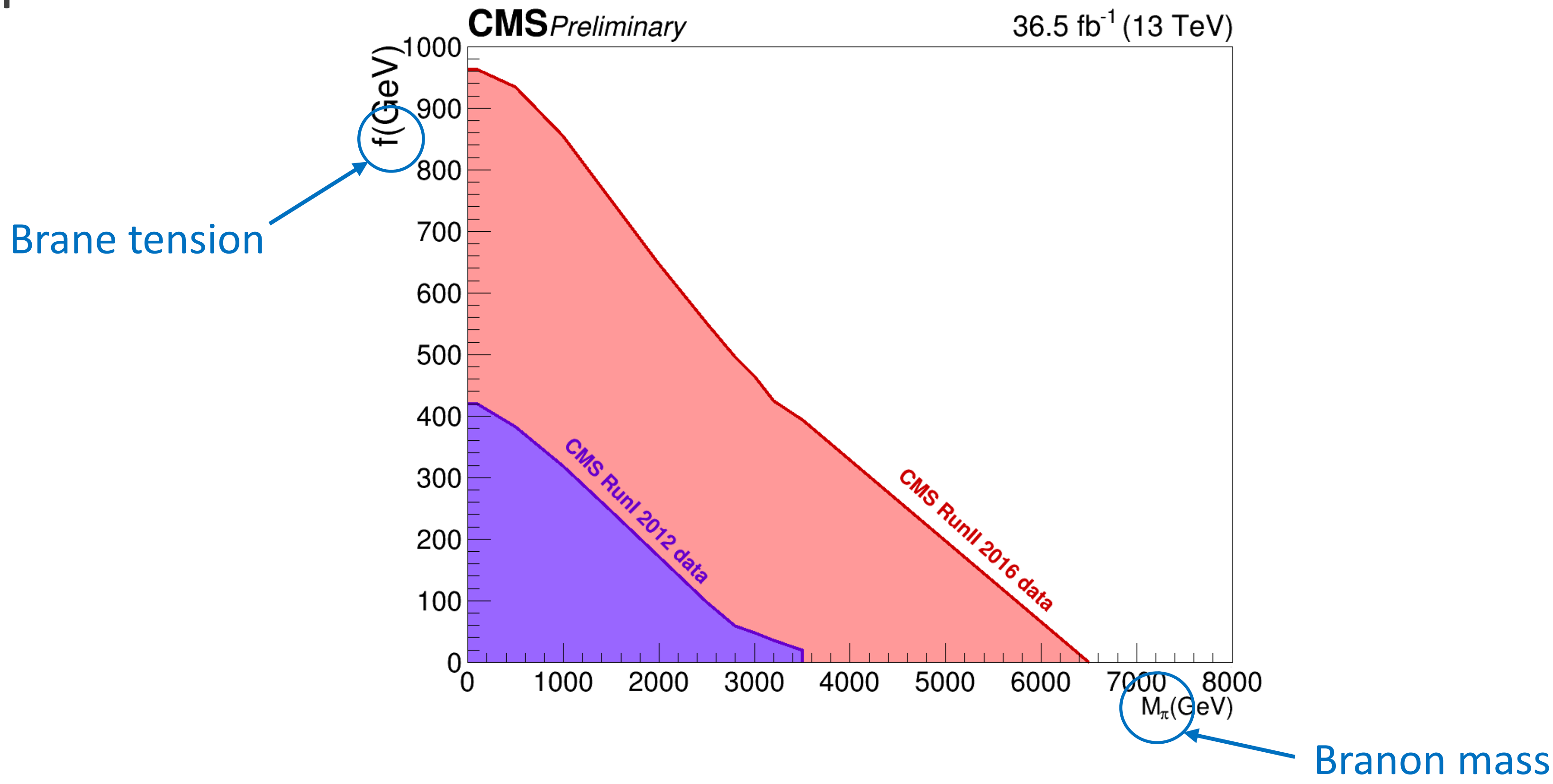
Monojet category



MonoV category

Projected limit

- Observed limit not public yet
- Projected result obtained by extrapolating previous result at 8TeV in monophoton channel



Perspectives

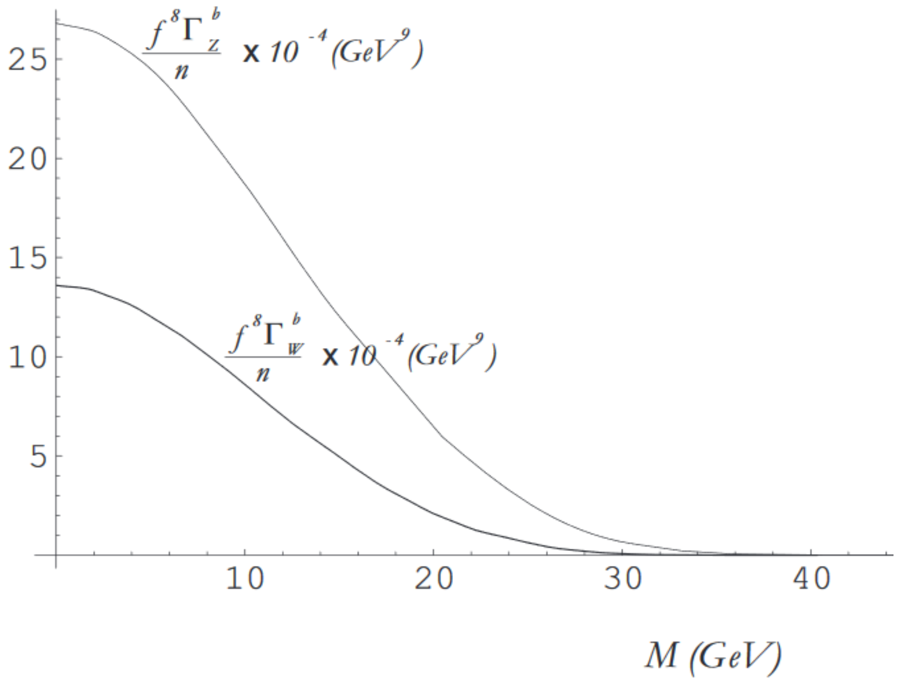
- Objectif : Discover branons (if not, constraint the model as much as possible)

- Make the limit obtained with 2016 data public
- Do the analysis with 2017 data
- Build a branon dedicated analysis in these channels
- Use other data to extract the most we can from branon model (ex: DM relic density)

Thank you !

MC production

Partial decay width of Z/W decaying in two fermions and two branons :



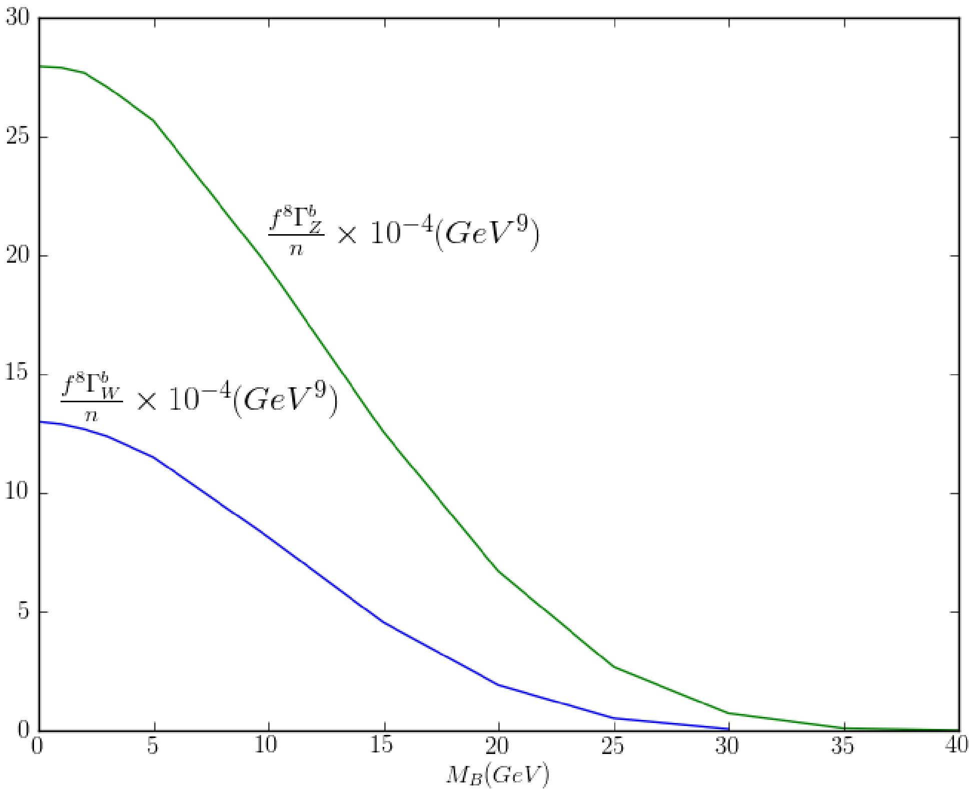
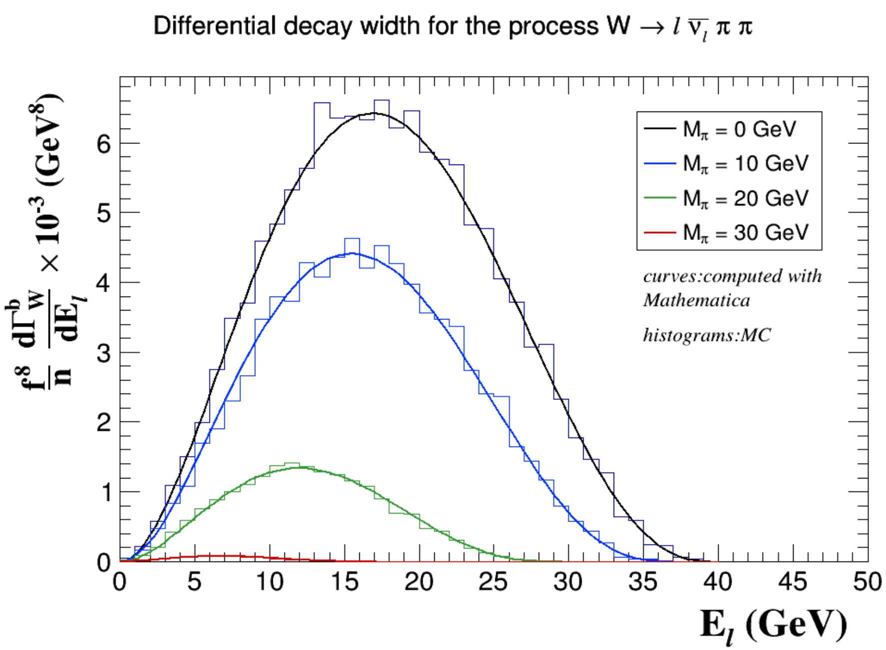


Figure 1: $W^{\pm}$ and Z widths as a function of the branon mass. Both plots correspond to a single channel. We have extracted the dependence on the brane tension and the number of branons in the factor f^8/n.

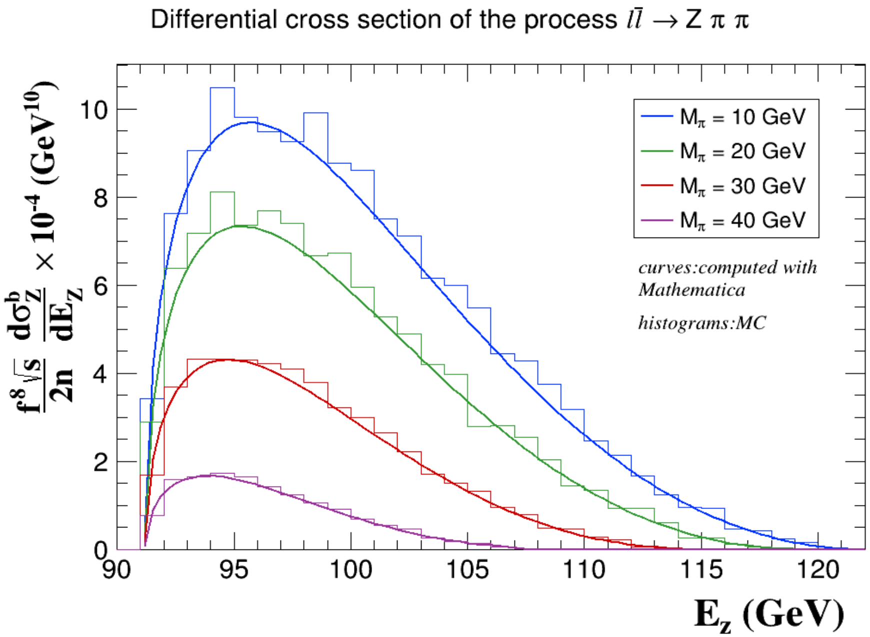
MC production

$$
\begin{aligned}
s &= 2p_1^0 p_2^0 (1-\cos\theta), \\
t &= M_Z(M_Z - 2p_1^0), \\
u &= M_Z(M_Z - 2p_2^0),
\end{aligned}
$$

$$
\begin{aligned}
\frac{d\Gamma_Z^b}{d^3\overrightarrow{p_1}\, d^3\overrightarrow{p_2}} &= \frac{|h|^2}{4\pi}\, \frac{2M_Z n}{61440 f^8 3\pi^6 t^2 u^2 (M_Z^2 - t)(M_Z^2 - u)(M_Z^2 - s)^2} \\
& \sqrt{1 - \frac{4M^2}{k^2}}\{20M^2 M_Z^2 (2k^2 - 5M^2) t^2 u^2 (M_Z^2(2s - k^2) + tu) \\
&+ (k^2 - 4M^2)^2 \{stu(s(k^2 + M_Z^2) + 4tu)(2s(k^2 + M_Z^2) + t^2 + u^2) \\
&+ (t^2 + u^2)(2s + 2k^2 + M_Z^2) M_Z^8 \\
&- [6s(t^3 + u^3) + 6s^2(t^2 + u^2 - tu) + 3tu(t-u)^2 + t^4 + u^4] M_Z^6 \\
&+ M_Z^4 [2s^3(2(t^2 + u^2) - 5tu) + 2s^2(3(t^3 + u^3) - 5tu(t+u)) \\
&+ s(2(t^4 + u^4) + tu(t^2 + u^2 - 8tu)) + tu(t^3 + u^3 - 7tu(t+u))] \\
&- M_Z^2 [s^4(t-u)^2 - 8t^3u^3 + 2s^3(t^3 + u^3 - 2tu(t+u)) \\
&+ 2stu(t^3 + u^3 - 3tu(t+u)) \\
&+ s^2(t^4 + u^4 + tu(t^2 + u^2 - 14tu))]\}\}
\end{aligned}
$$



MC production

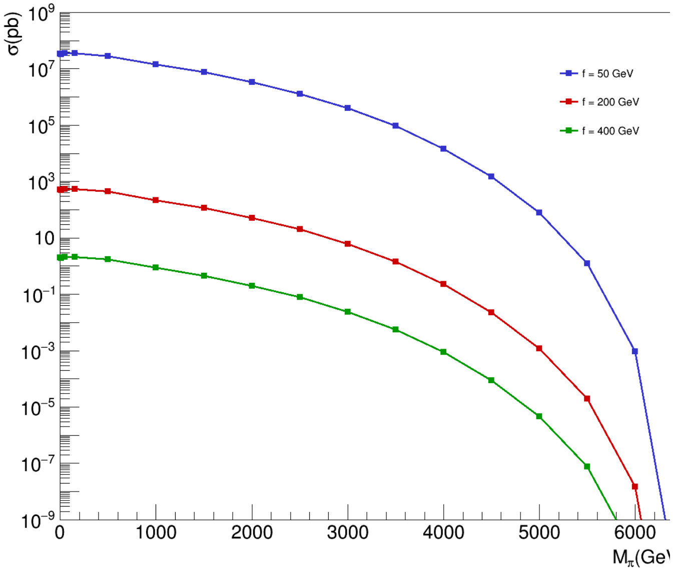


$$
\begin{aligned}
\frac{d\sigma_A}{dx\,d\cos\theta} = {} & \frac{|h|^2}{4\pi}\frac{(c_V^2+c_A^2)n}{122880 f^8\pi^2(s-M_a^2)^2}\sqrt{1-\frac{4M^2}{s(1-x)+M_a^2}} \\
& \sqrt{s(sx^2-4M_a^2)}\{5M^2M_a^2(2(s(1-x)+M_a^2)-5M^2) \\
& \{8M_a^2+(sx^2-4M_a^2)\sin^2\theta\} \\
+ {} & \frac{2(s(1-x)+M_a^2-4M^2)^2}{(4M_a^2(M_a^2+s(1-x))+s(sx^2-4M_a^2)\sin^2\theta)^2} \\
& \{16M_a^2(s(1-x)+M_a^2)^2[10M_a^6+M_a^4s(9-5x) \\
+ {} & 2M_a^2s^2(4-3x+x^2)+s^3(1-x)] \\
- {} & 2[40M_a^{12}-2M_a^{10}s(-112+40x+5x^2) \\
+ {} & 4M_a^8s^2(78-70x-3x^2+5x^3)+s^6x^2(-2+4x-3x^2+x^3) \\
+ {} & M_a^6s^3(216-272x+6x^2+66x^3-11x^4) \\
+ {} & M_a^4s^4(96-184x+62x^2+44x^3-21x^4+x^5) \\
+ {} & M_a^2s^5(8-16x-12x^2+42x^3-29x^4+6x^5)]\sin^2\theta \\
+ {} & s(sx^2-4M_a^2)^2[7M_a^6+M_a^4s(17-7x)+M_a^2s^2(1-2x) \\
+ {} & s^3(3(1-x)+2x^2)]\sin^4\theta - s^2(sx^2-4M_a^2)^3(s-M_a^2)\sin^6\theta\}
\end{aligned}
$$

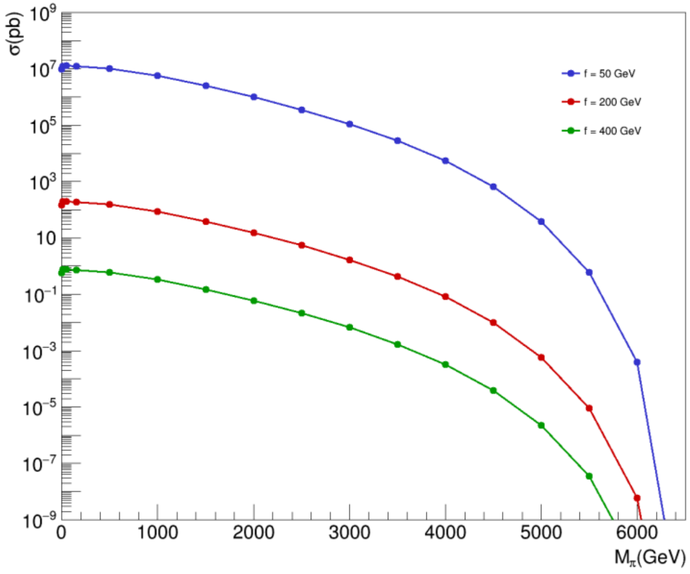
$$
\begin{aligned}
t &= -\sqrt{s}(q_0-|\vec{q}|\cos(\theta))+M_a^2 \\
u &= -\sqrt{s}(q_0+|\vec{q}|\cos(\theta))+M_a^2 \\
k^2 &= s(1-x)+M_a^2 \\
q_0 &= \frac{x\sqrt{s}}{2} \\
|\vec{q}| &= \frac{1}{2}\sqrt{sx^2-4M_a^2}
\end{aligned}
$$

MC production

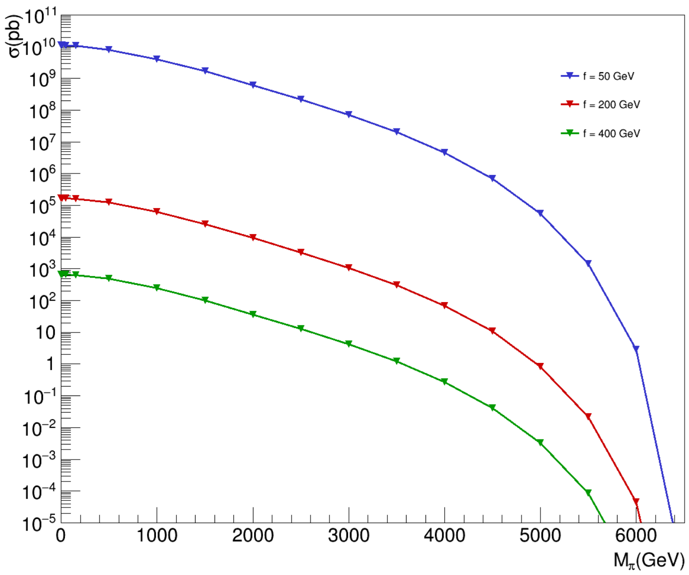
- PDF : LHAPDF-263000, sqrt(s)= 13TeV



$$pp \rightarrow W + \pi\pi$$



$$pp \rightarrow Z + \pi\pi$$



$$pp \rightarrow jet + \pi\pi$$

MC production

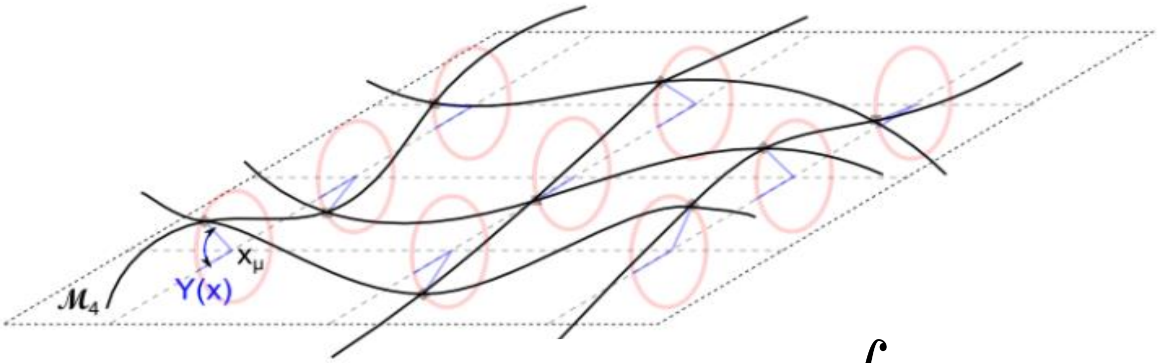
- Three production channels : mono-W, mono-Z, monojet
- Mono-jet channel : 100k events
- Mono-W and Mono-Z channel : 50k events
- 10 mass points, $M_\pi = 1$ to 6400 GeV, to cover all the allowed kinematical region, no need to produce for several f values

Substructure variables

$$\tau_N = \frac{\sum_i k_{T,i} \min\left(R_{1i}, R_{2i} ... R_{ni}\right)}{\sum_i k_{T,i} R}$$

Branon model

- Suppose the brane is flexible and can move along the extra-dimension



- General action (Nambu-Goto) : $$\mathcal{S}_B = -f^4 \int_{\mathcal{M}_4} d^4x \sqrt{\tilde{g}}$$
- f is the brane tension and $\tilde{g}$ is the induced metric on the brane.
- See :
  - Sundrum PRD59 (1999) 085009
  - Dobado, Maroto NPB592 (2001) 203
  - Cembranos, Dobado, Maroto PRD65 (2002) 026005

Branon model

- ADD model provides an answer for hierarchy problem
- Branon can be produced at collider
  - Direct coupling to SM particles via energy-momentum tensor
  - 2 types of couplings : derivative coupling and mass term ; and the coupling strength is controlled by $1/f^8$
  - Branons are pair produced
  - 2 parameters : the branon's mass M and the brane tension f
  - When $f<M_{D,}$ branon pair production can dominate over KK graviton production
  - (see PRD88 (2013) 075021)
- Branon is a scalar that can be Dark Matter candidate
  - DM model with no mediator
  - (see Cembranos, Dobado, Maroto with PRL90 (2003) 241301, PRD68 (2003) 103505, PRD69 (2004) 043509)

DM search in monojet and monoV channels

➢ Backgrounds considered : Z(νν)+jets