Dark Matter @ 100 TeV

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w/help from
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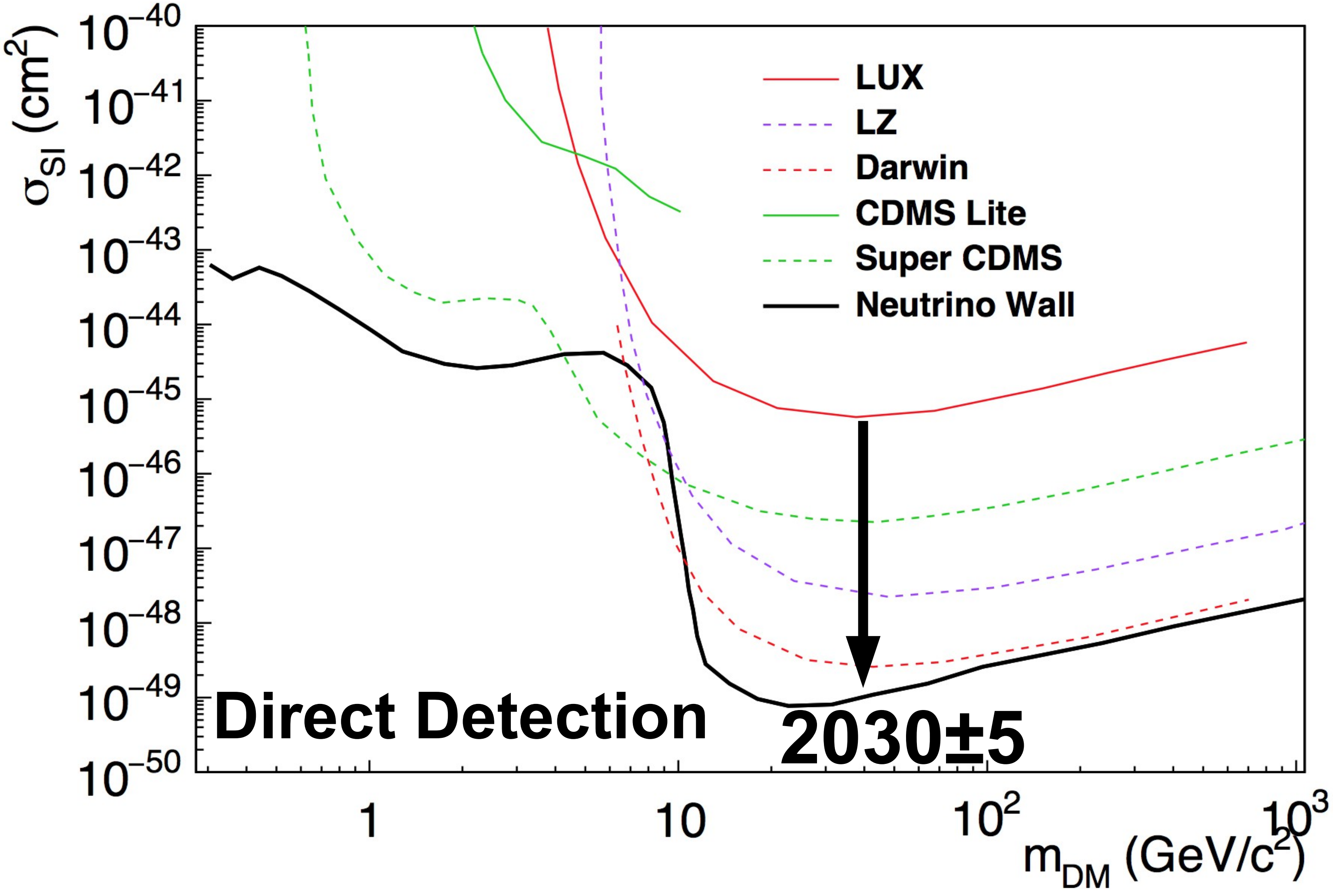
Dark Matter searches not @ collider

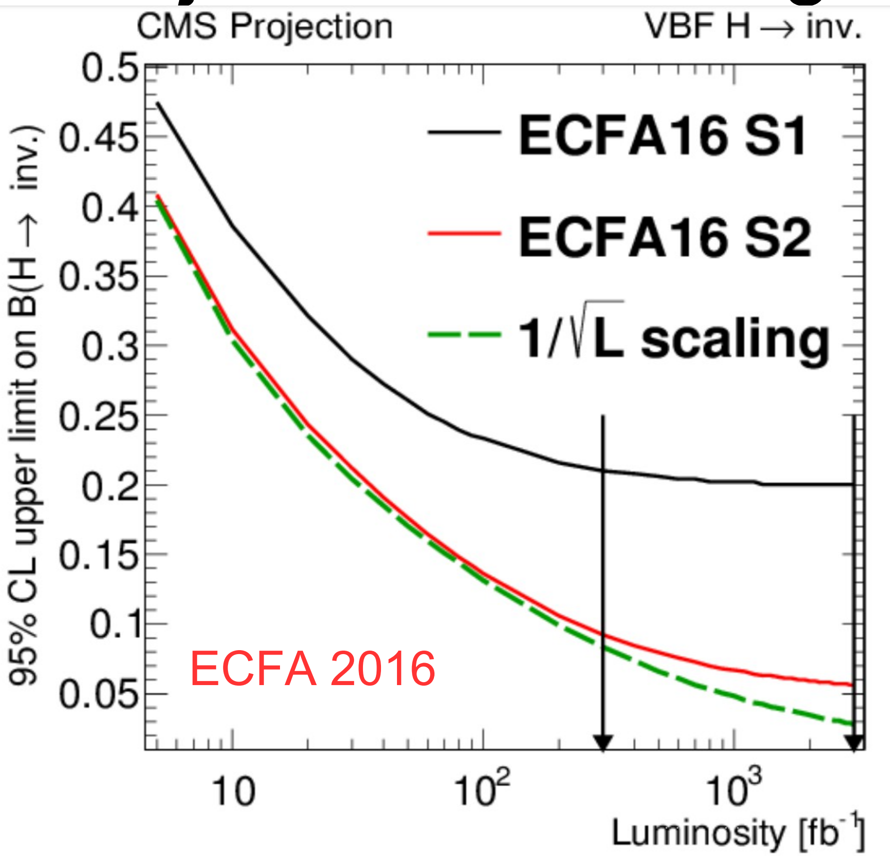
Dark matter searches not at colliders have clear benchmarks

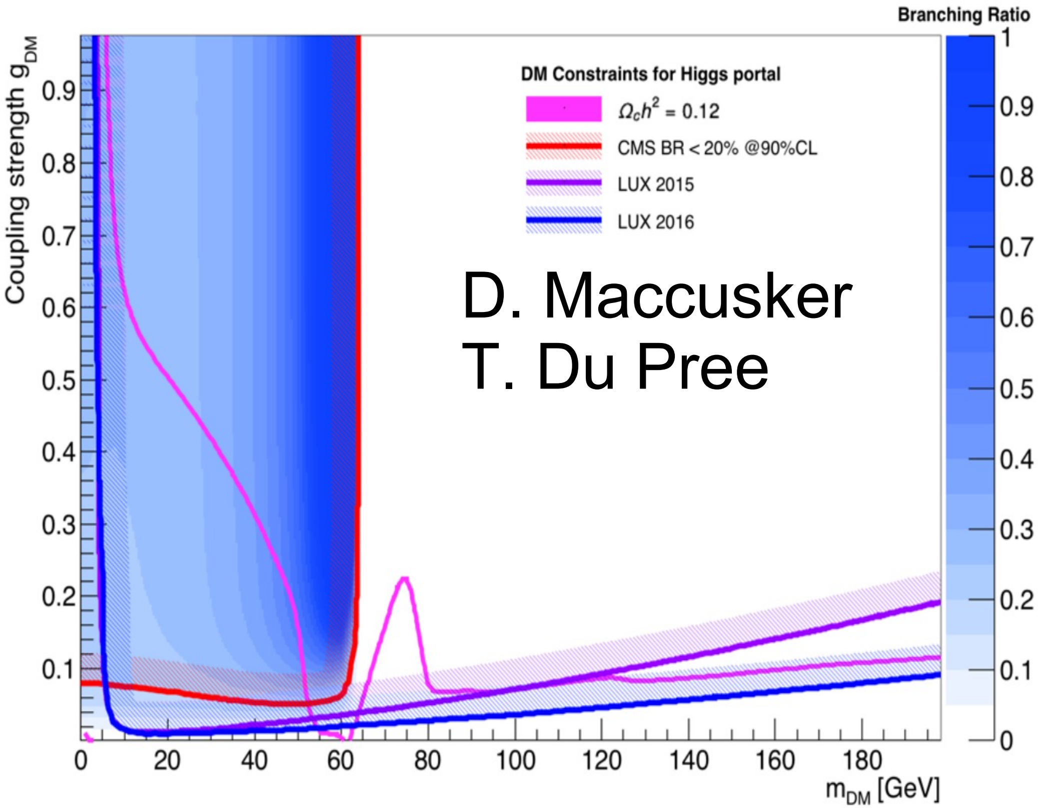


Goal: get to the Neutrino background wall

Full Scaling expected Scaling

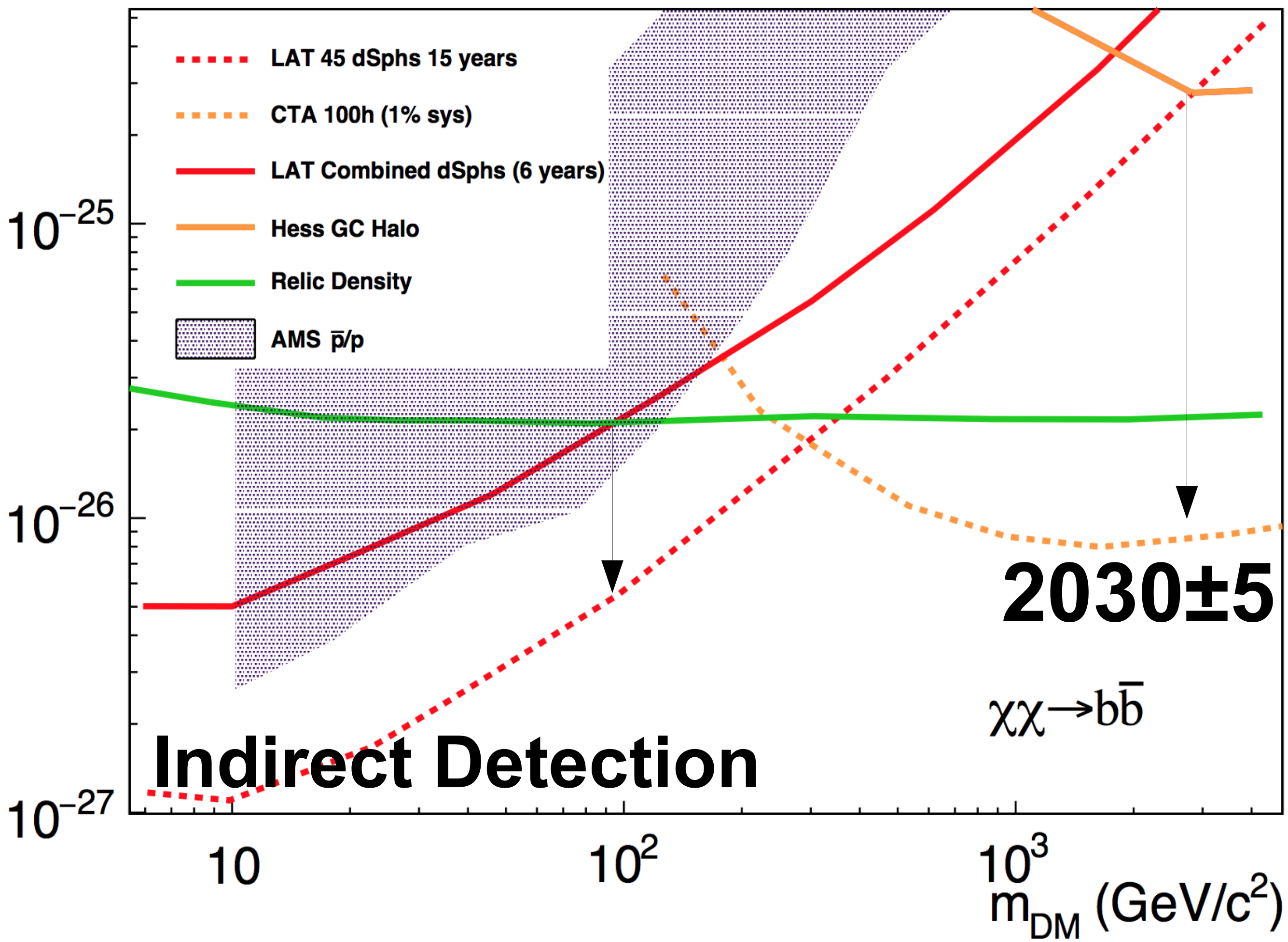
- Projections at LHC go to <3%





	ECFA16 S1	ECFA16 S2	$1/\sqrt{L}$ scaling
300 fb^{-1}	0.210	0.092	0.084
3000 fb^{-1}	0.200	0.056	0.028

Dark Matter searches not @ collider



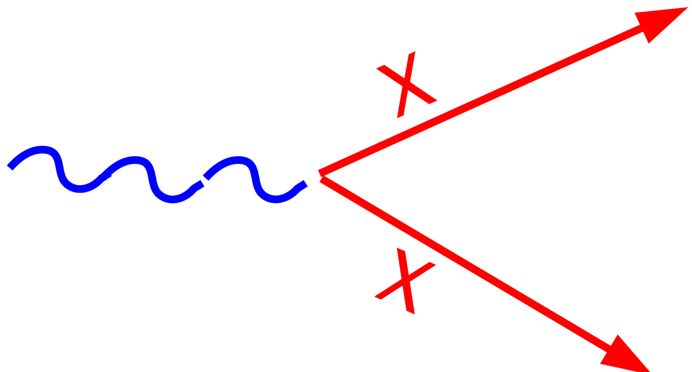
Goal: get to the Relic density

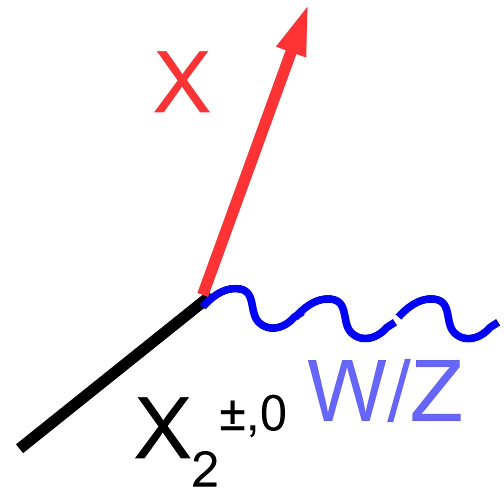
Question:

- Whats the simplest way to present LHC results in the context of Dark Matter?

Question:

- Whats the simplest way to present LHC results in the context of Dark Matter?
- Answer:
  - $\sigma_{Invisible}$





- Assumes dark matter coupling to standard model
  - $\mathcal{L} = g_{DM}\bar{\chi}\chi Y$ → Mediator + SM interactions
  - $\mathcal{L} = g_{SM}\gamma_{\mu}\bar{\chi}_i\chi_j V^{\mu}$ → SM mediator + SM interactions

Dark Matter

Adding Dark Matter

- What drives dark matter interaction is production
  - Take the approach that this is defined by the mediator

For a mediator search

- $\mathcal{L} = g_{DM}\chi\chi Y$

Z'^{μ} Spin 1

Uniform coupling to SM

$$\mathcal{L} = \mathcal{L} + g_{SM} Z'_{\mu} \bar{q} \gamma^{\mu} q$$

S Spin 0

Yukawa* couplings to SM

$$\mathcal{L} = \mathcal{L} + g_{SM} S \bar{q} q$$

Simplified Models 101

Vector

$$g_{\mathrm{DM}} Z'_\mu \bar{\chi} \gamma^\mu \chi$$

EWK style coupling
(equal to all quarks/leptons)

Axial vector

$$g_{\mathrm{DM}} Z''_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$$

EWK style coupling
(equal to all quarks/leptons)

Scalar

$$g_{\mathrm{DM}} S \, \bar{\chi} \chi$$

Yukawa style coupling
(Mass based coupling)

Pseudoscalar

$$g_{\mathrm{DM}} P \, \bar{\chi} \gamma^5 \chi$$

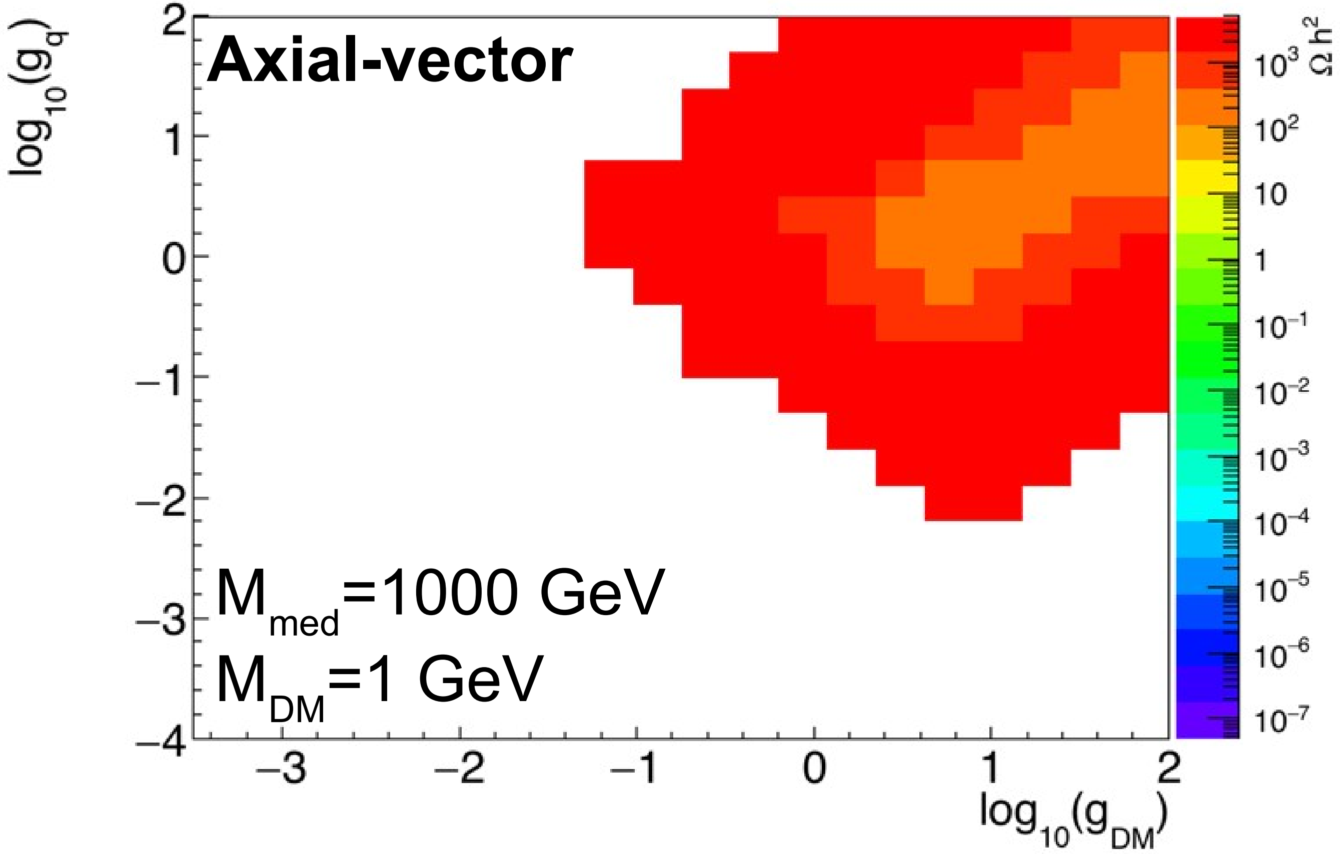
Yukawa style coupling
(Mass based coupling)

Establishing a collider benchmark

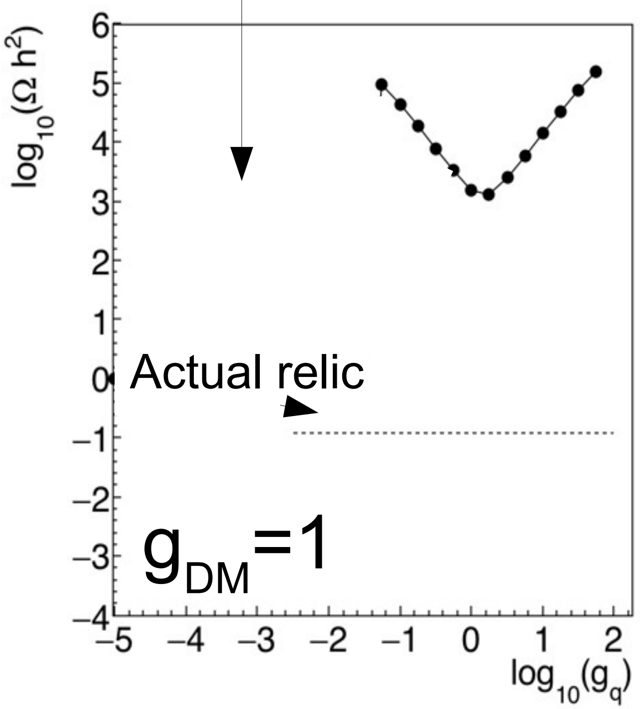
Relic Density??

Solving for the relic

- We can numerically solve for the solution



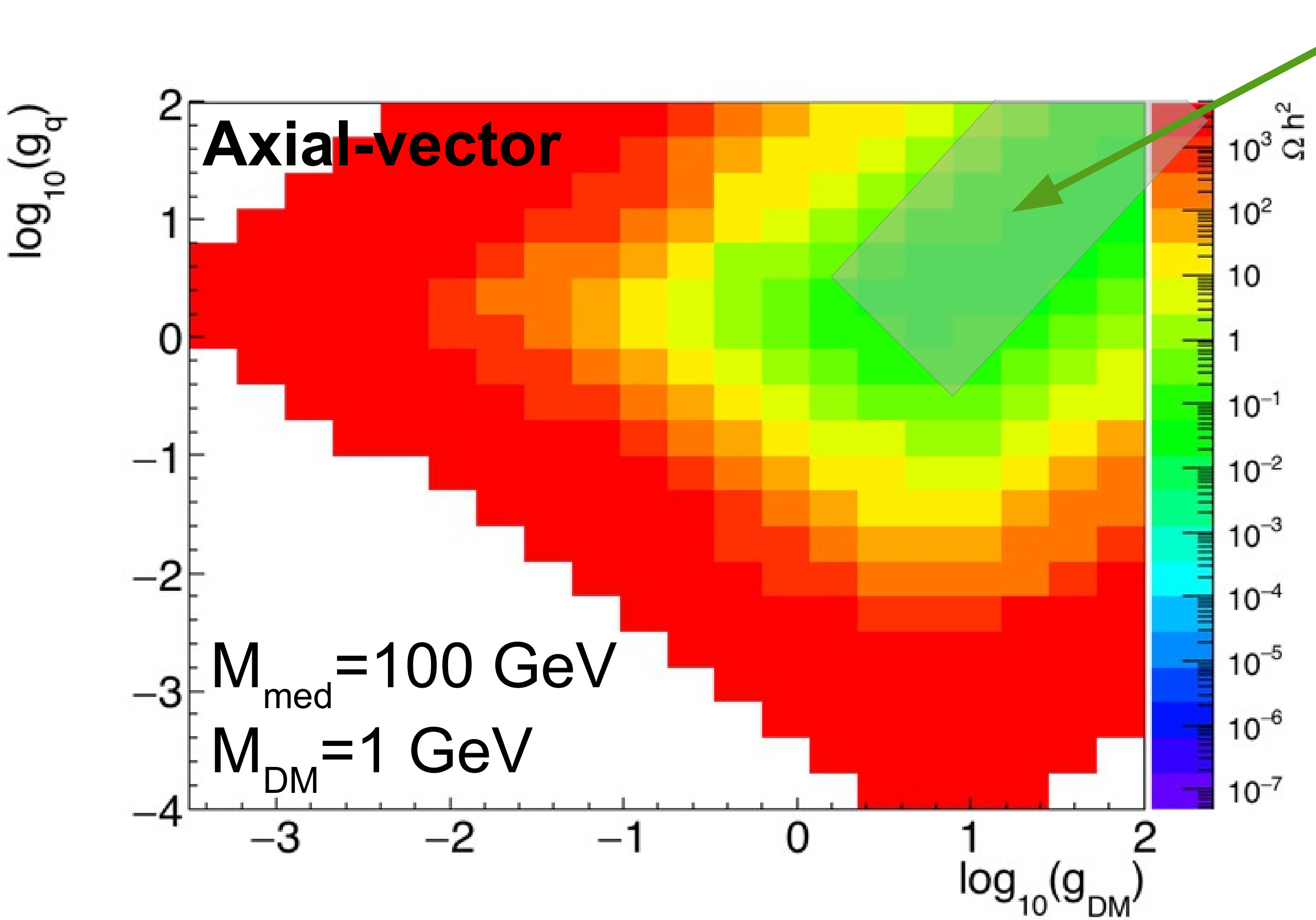
Fixing the DM coupling

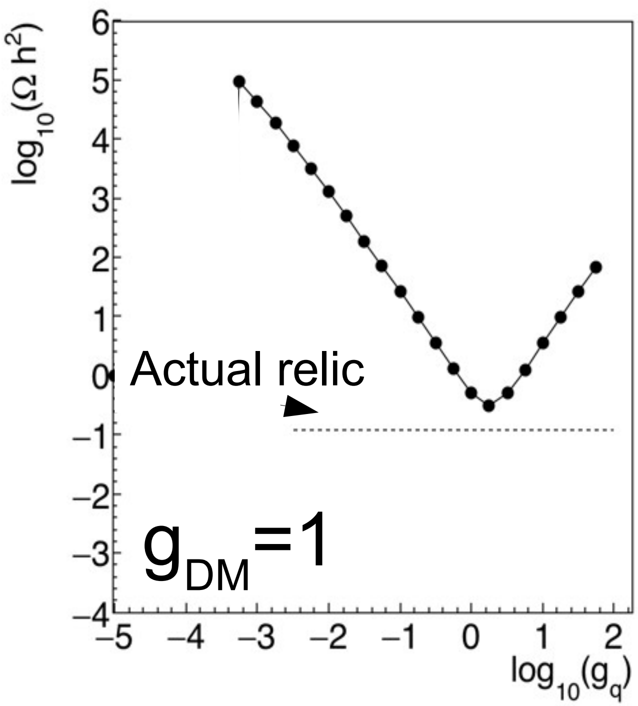


For a large mediator we have no allowed solution

Solving for the relic

- We can numerically solve for the solution



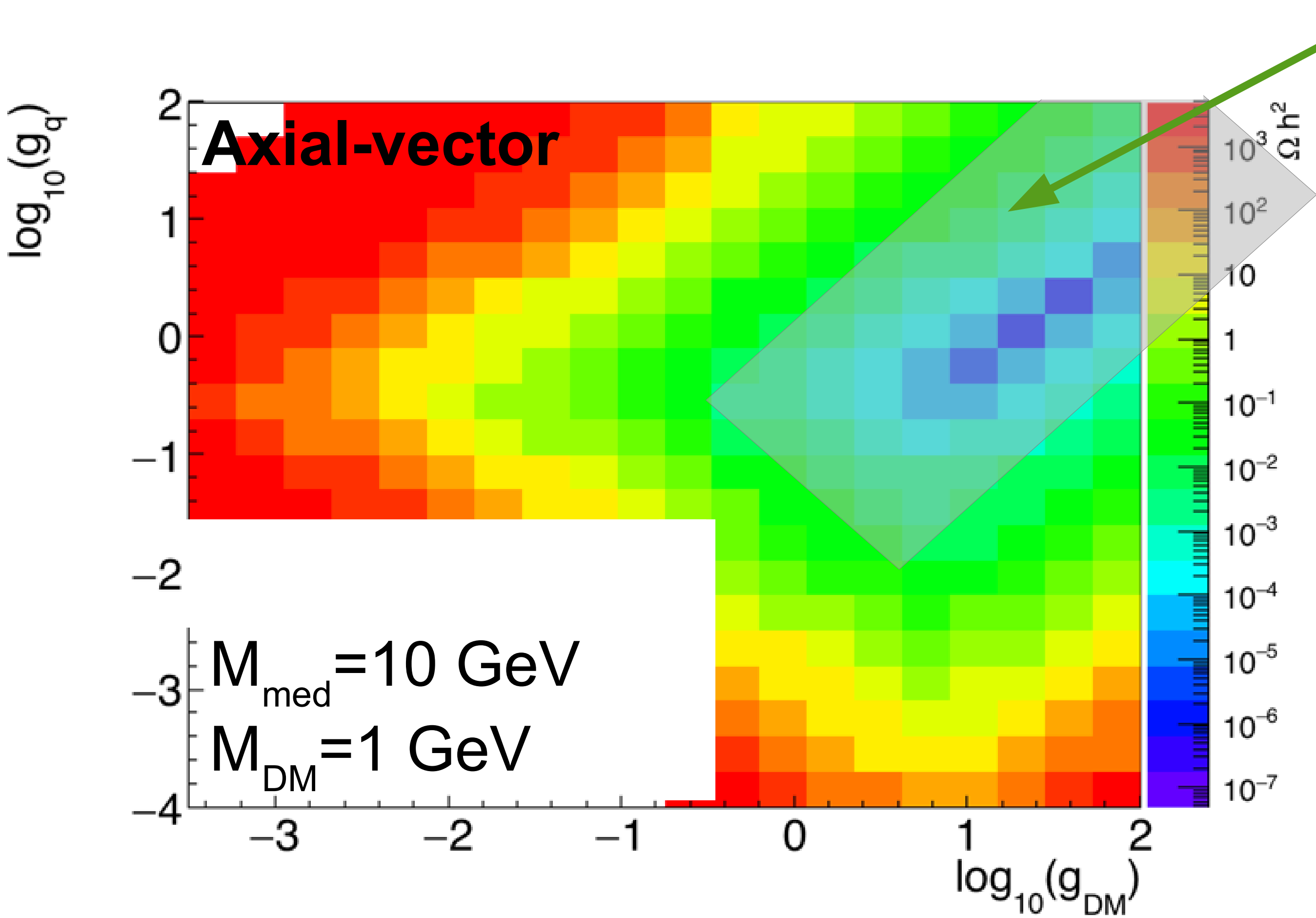


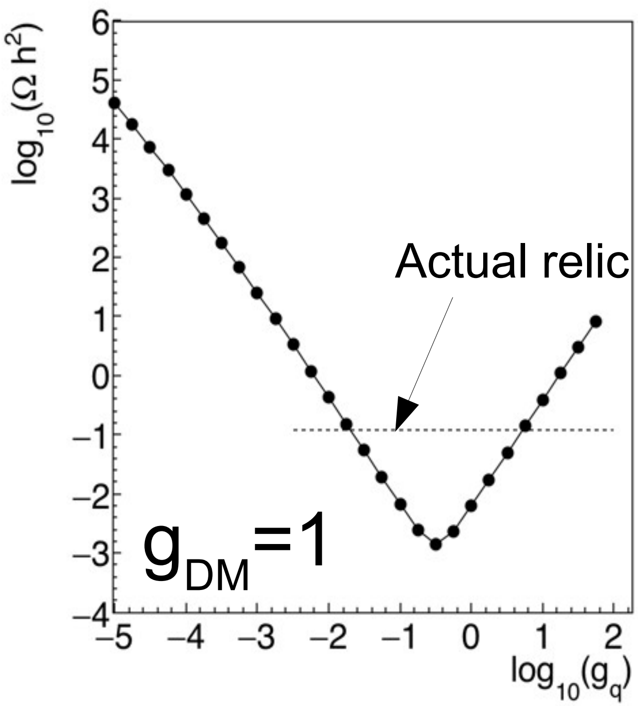
For smaller mediators allowed solution

Arxiv:1703.05703

Solving for the relic

- We can numerically solve for the solution





Arxiv:1703.05703

A common theme of DM talks

- Relic density is solved for a constant value of:

$$(g_q g_{DM})^2 = C$$

Hardest challenge

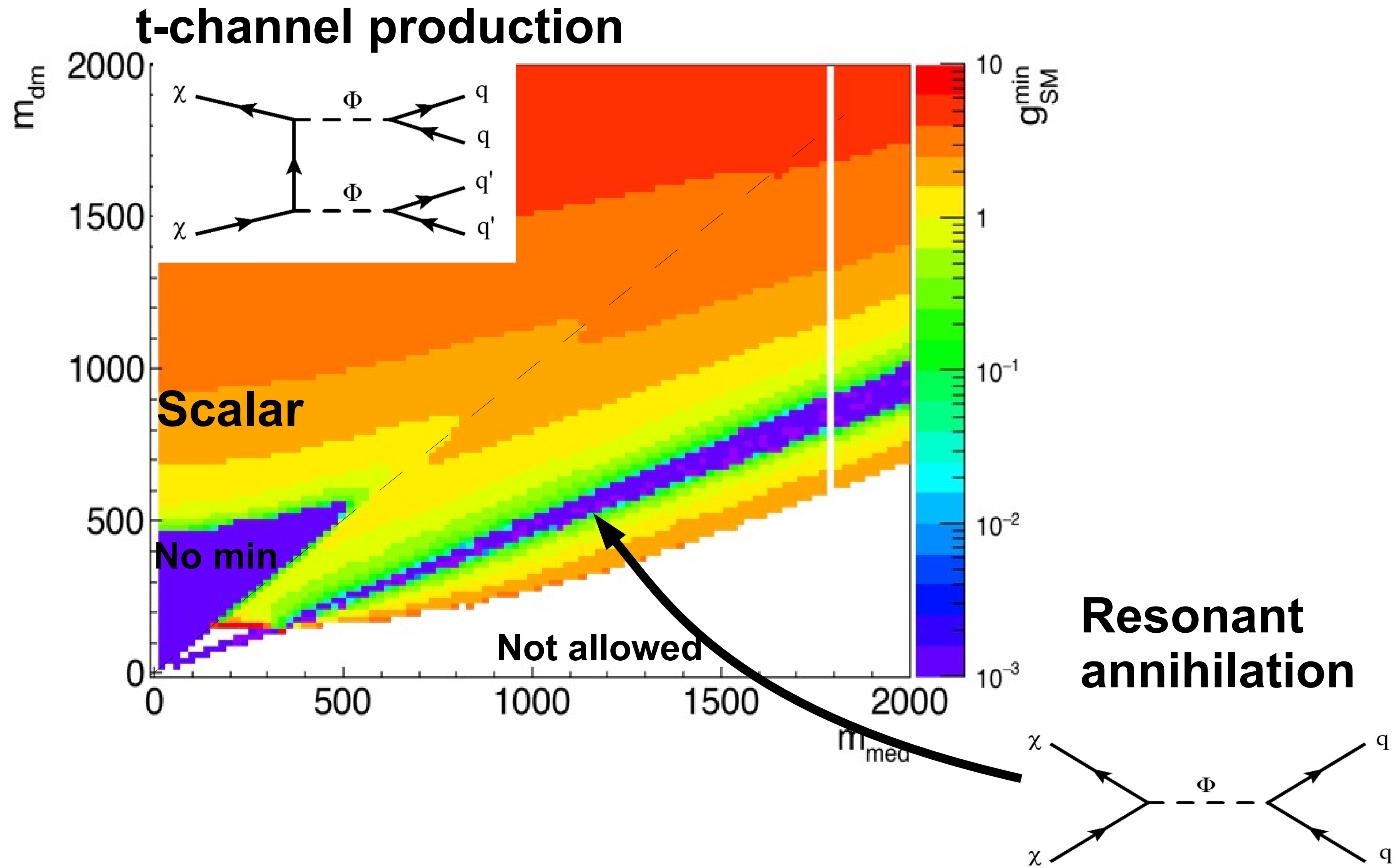
Set this to be large
still get right relic

Set this to be small
Weak coupling with the SM

Most challenging dark matter searches consist of :
strong dark sector coupled weakly to the visible sector

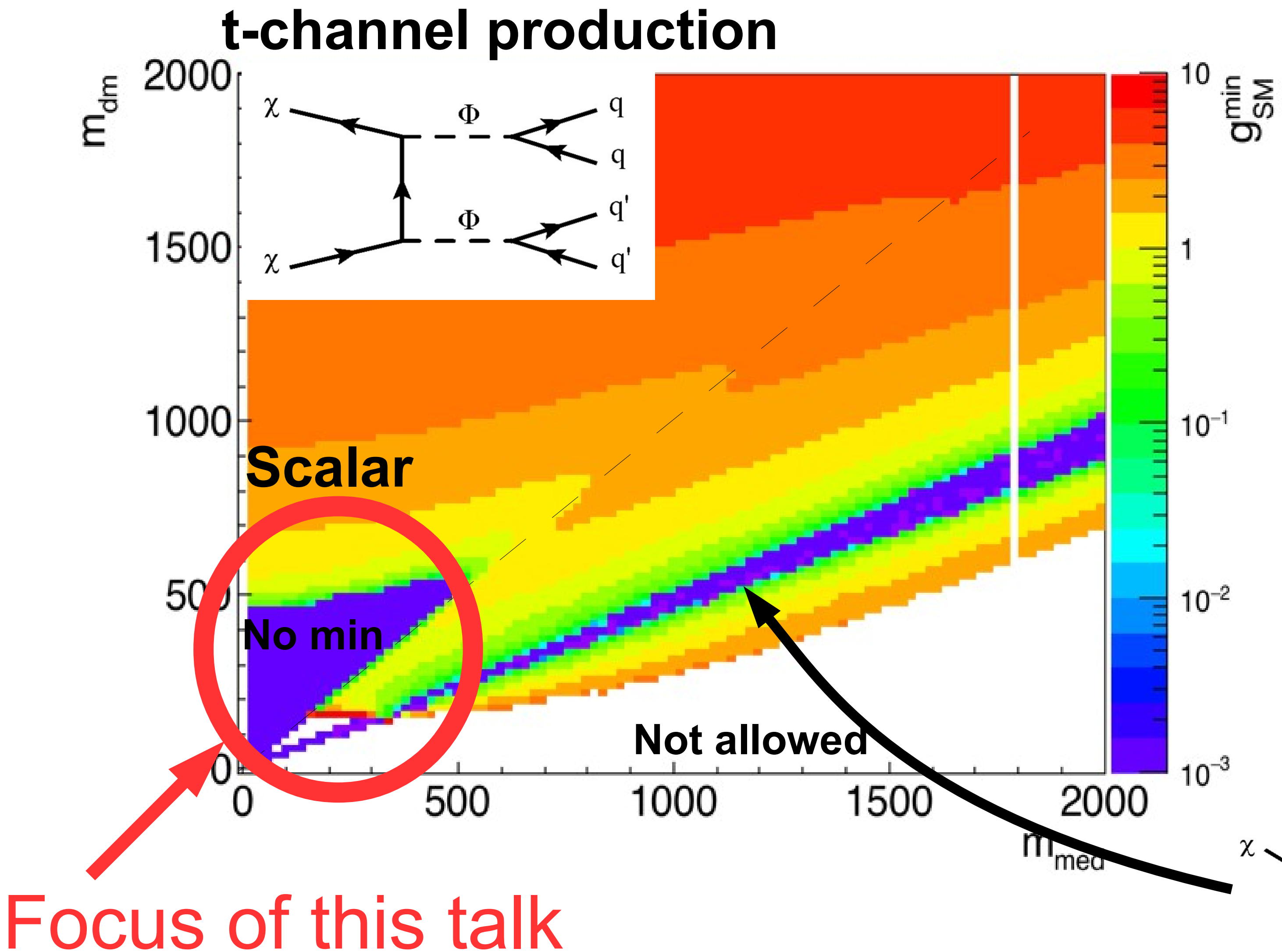
What is the smallest coupling?

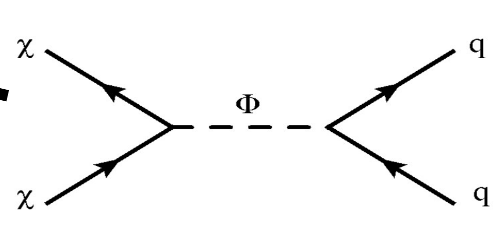
- For a dark sector coupling g_{DM}=1



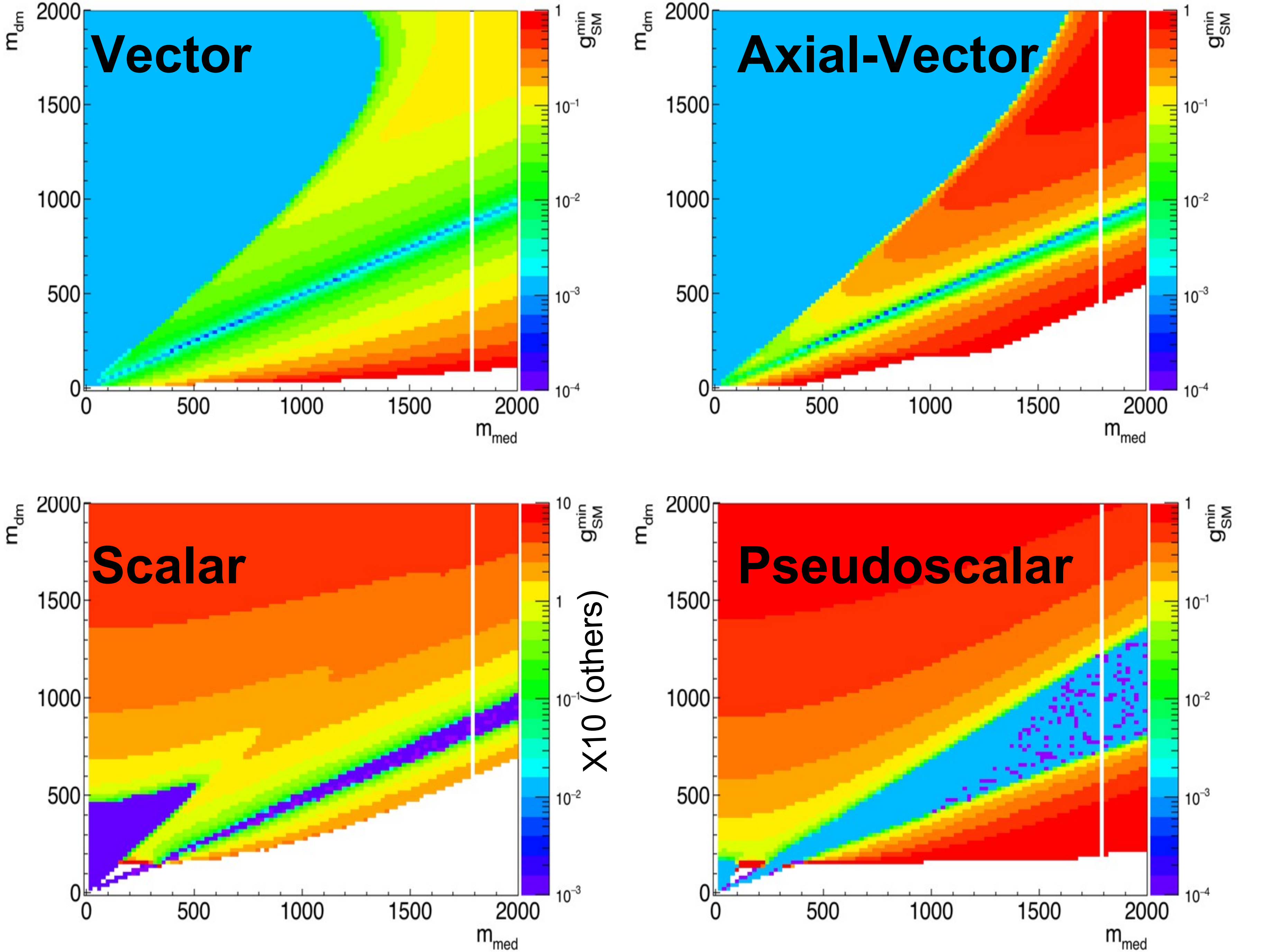
What is the smallest coupling?

- For a dark sector coupling g_{DM}=1





Min Couplings for all



Summary Benchmarks

- Spin 1 :
  - Aim to probe couplings down 0.01 for m_{Med} > 100 GeV
- Spin 0 :
  - Aim to probe couplings down 0.1 for m_{Med} > 300 GeV
  - Try to cover m_{Med} < 300 by any means possible

- In previous talks
  - Have shown for SM-like couplings @ 100 TeV can probe most/if not all phase space
  - A few tough to reach places exist
    - This talk will focus on how far we can push these

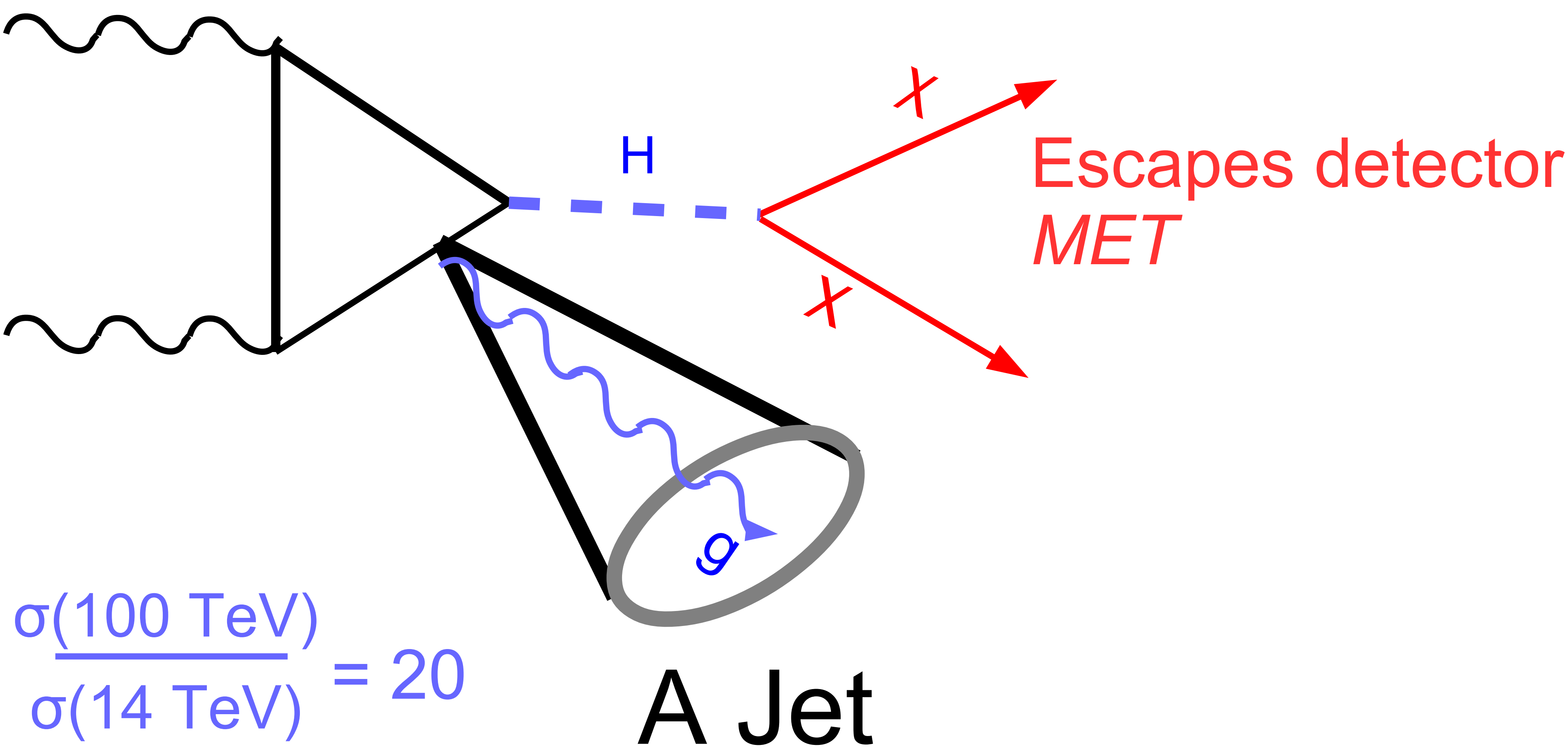
Using the Luminosity

FCC-hh as Higgs Production tool

- Rate of Higgs production at 100 TeV is very large
  - 800 Higgs events per pb
- Focus of this talk :
  - Whats our sensitivity to H→Inv?
- H→Inv probes a large variety of models
  - Benchmark for exotic Higgs sensitivity
  - Benchmark for low mass scalars
- Fundamental question:
  - What are the advantages of such high rates

The Basic Monojet Search

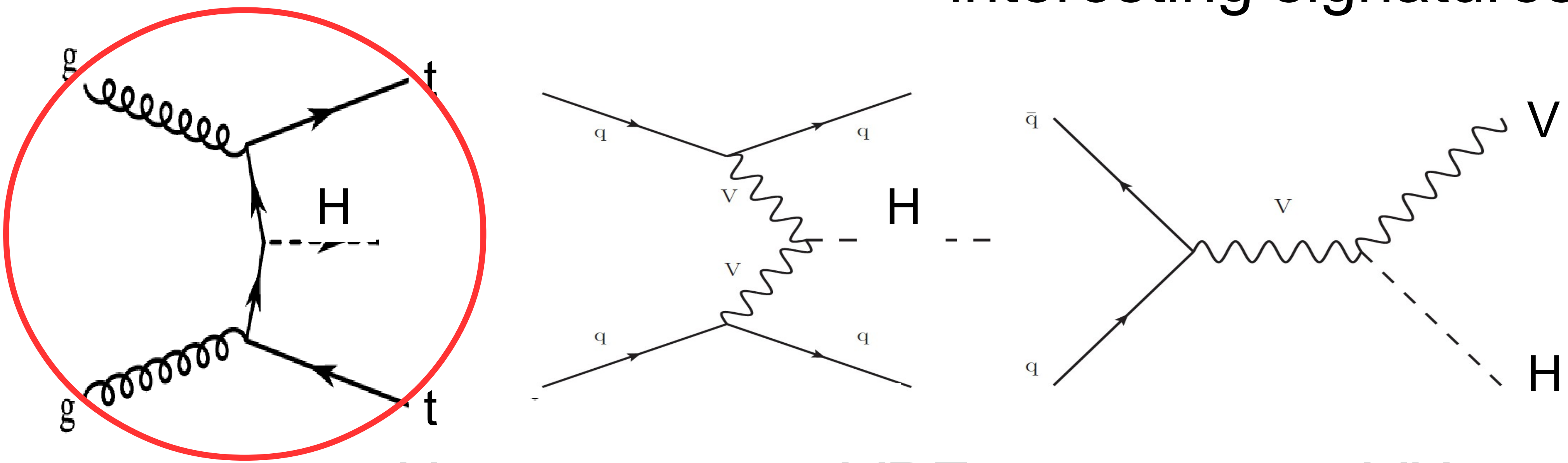
Escaping detector gives us signatures of *MET*



$$\frac{\sigma(100\ \text{TeV})}{\sigma(14\ \text{TeV})} = 20$$

Additional Probes

Higgs production has additional interesting signatures



	tt+H	VBF	VH
$\frac{\sigma(100\ \text{TeV})}{\sigma(14\ \text{TeV})}$	61	18	11

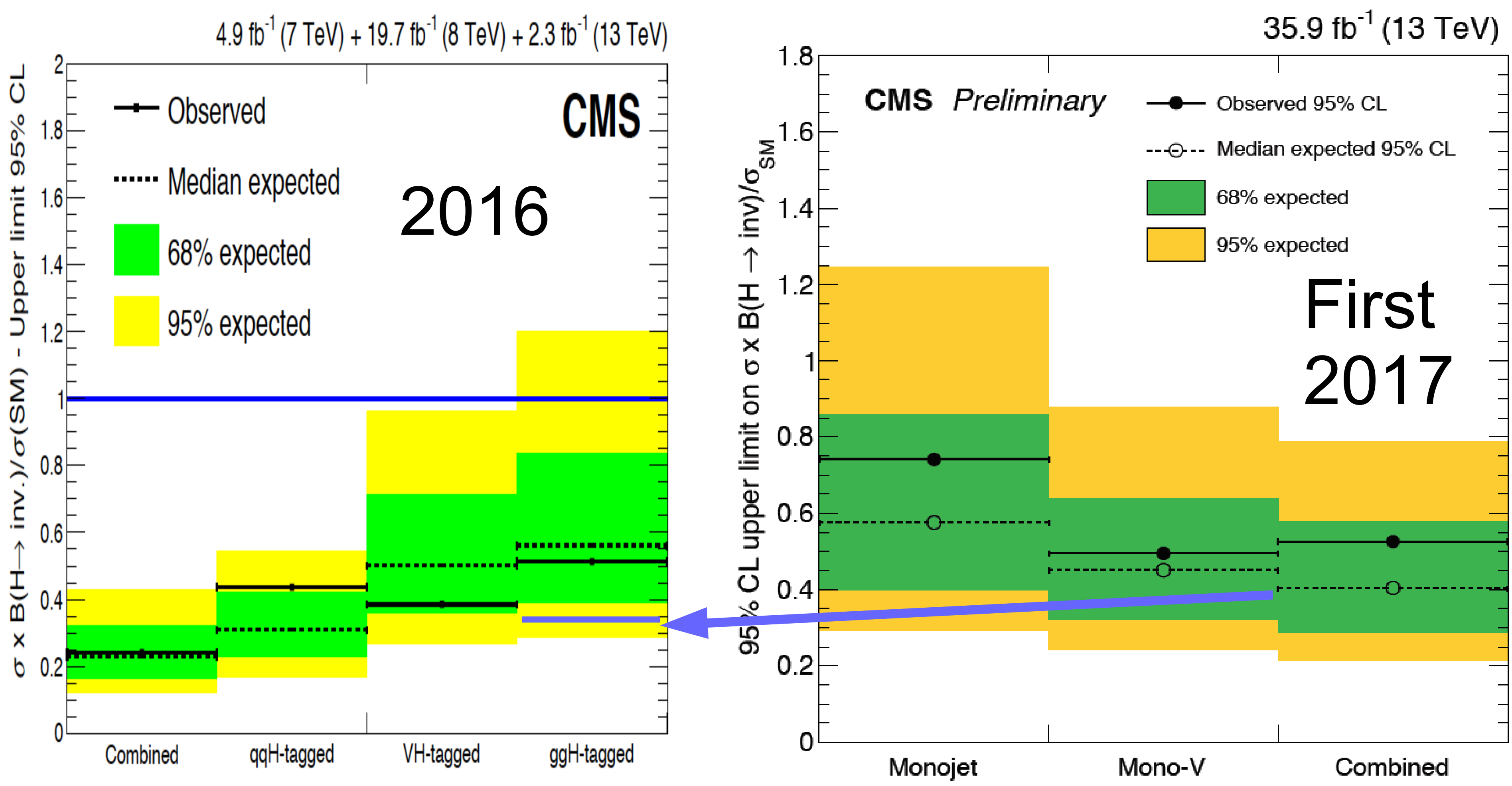
tt+H has a very distinct initial state

Large cross section increase makes :

tt+H→Invisible the golden invisible channel

Current Higgs Invisible Search

- This model is the same as Higgs invisible search

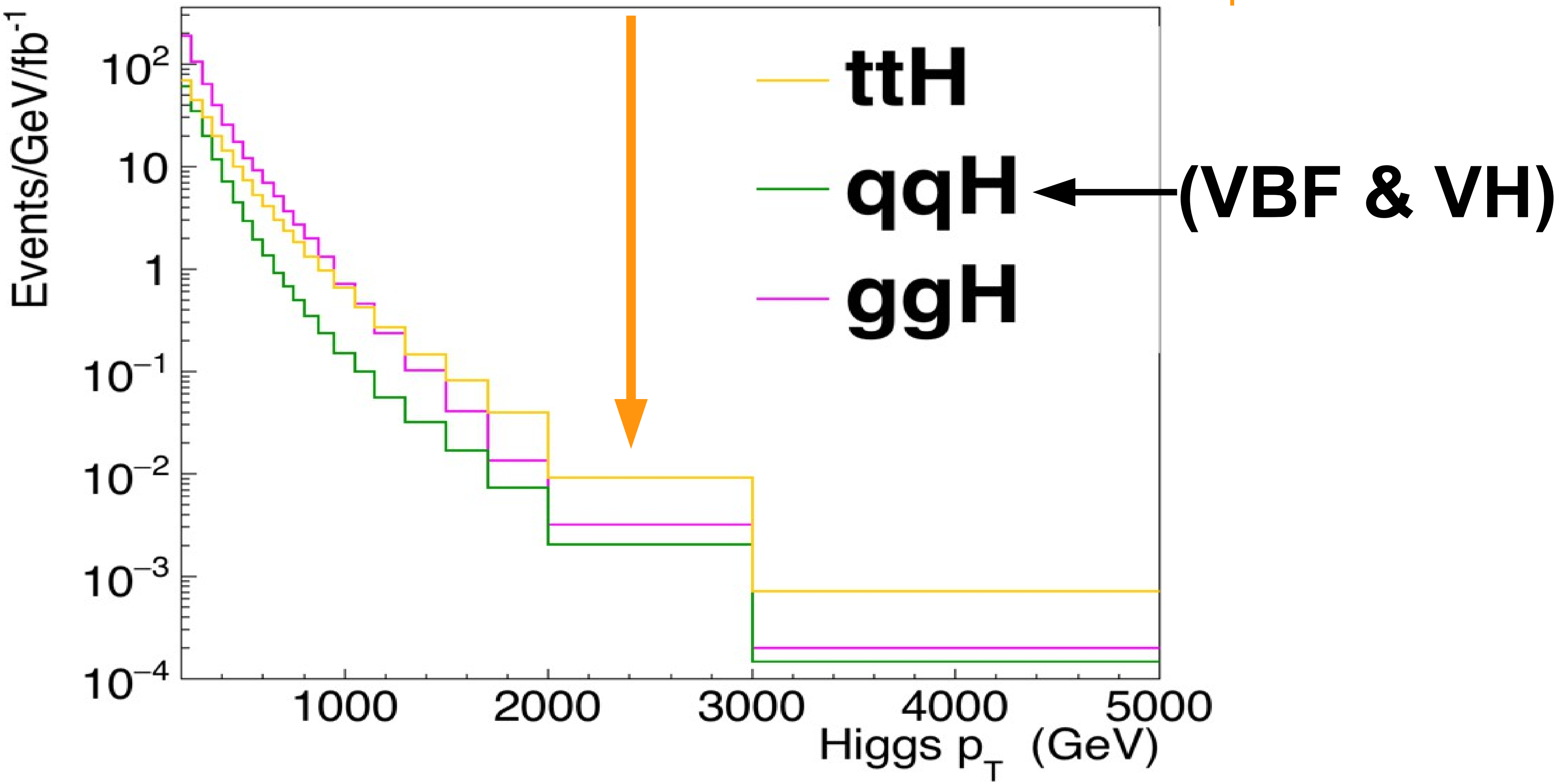


BR(H→Inv) < 24% (CMS) 25% (ATLAS)

Additional Observation

- One key feature MLM pointed out

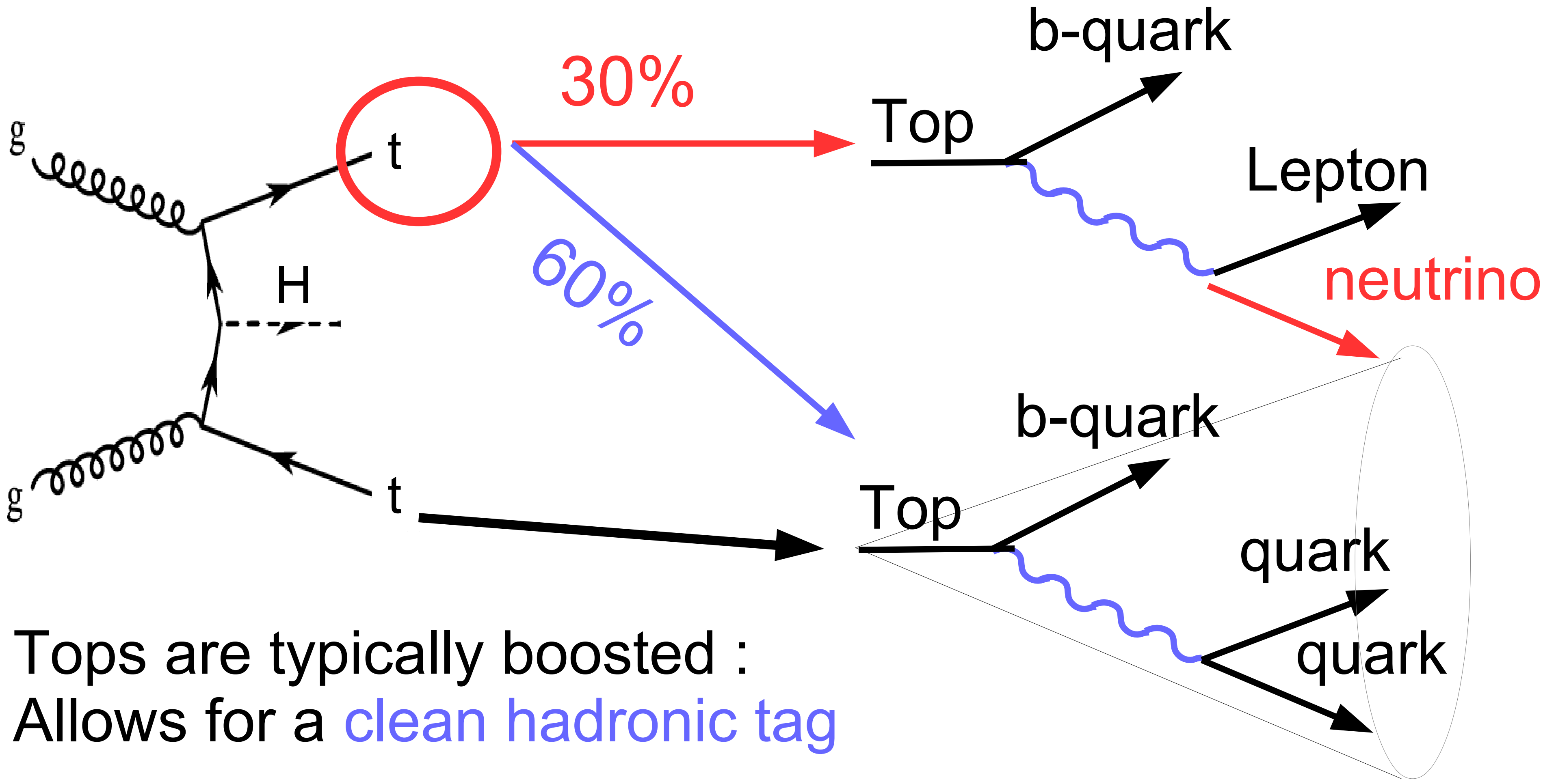
tt+H has a larger yield at high p_T



p_T spectra of Z & W bosons drops rapidly at high p_T

Inclusive ttH can be made relatively pure

Designing the tt+H Analysis



Tops are typically boosted :
Allows for a clean hadronic tag

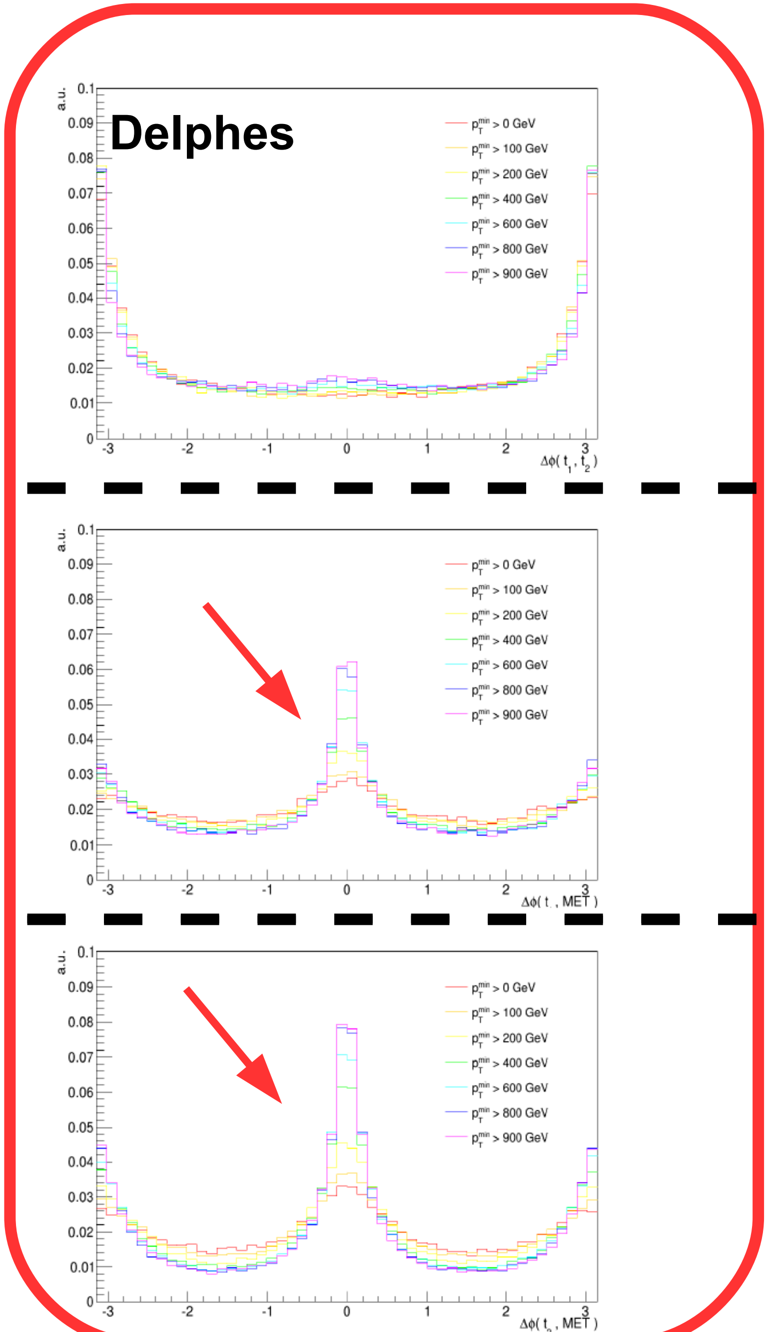
With leptonic decay can get higher purity

Here:
consider lepton w/another hadronic top jet

Background : SM tt

Signal : tt+H→Inv

Discrimination Purity



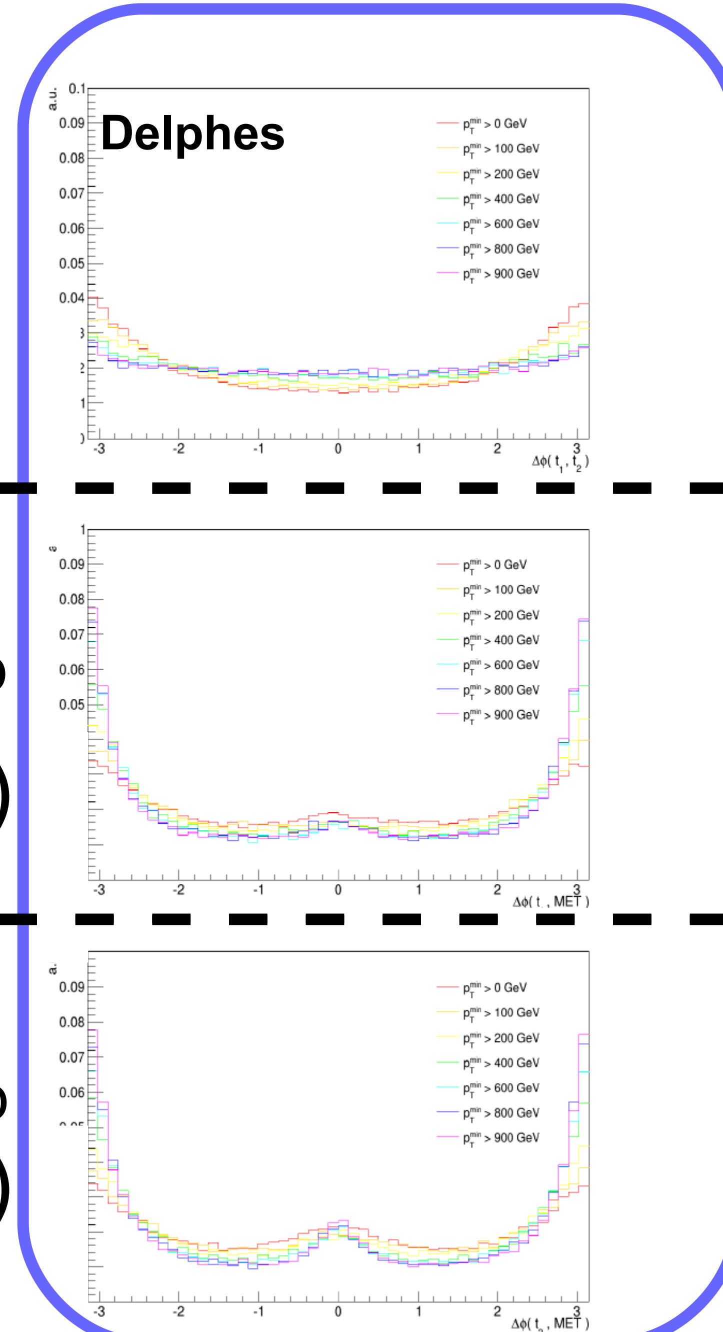
$\Delta\phi(t_1,t_2)$

Leading top

$\Delta\phi(t_1,\not{E}_T)$

Trailing top

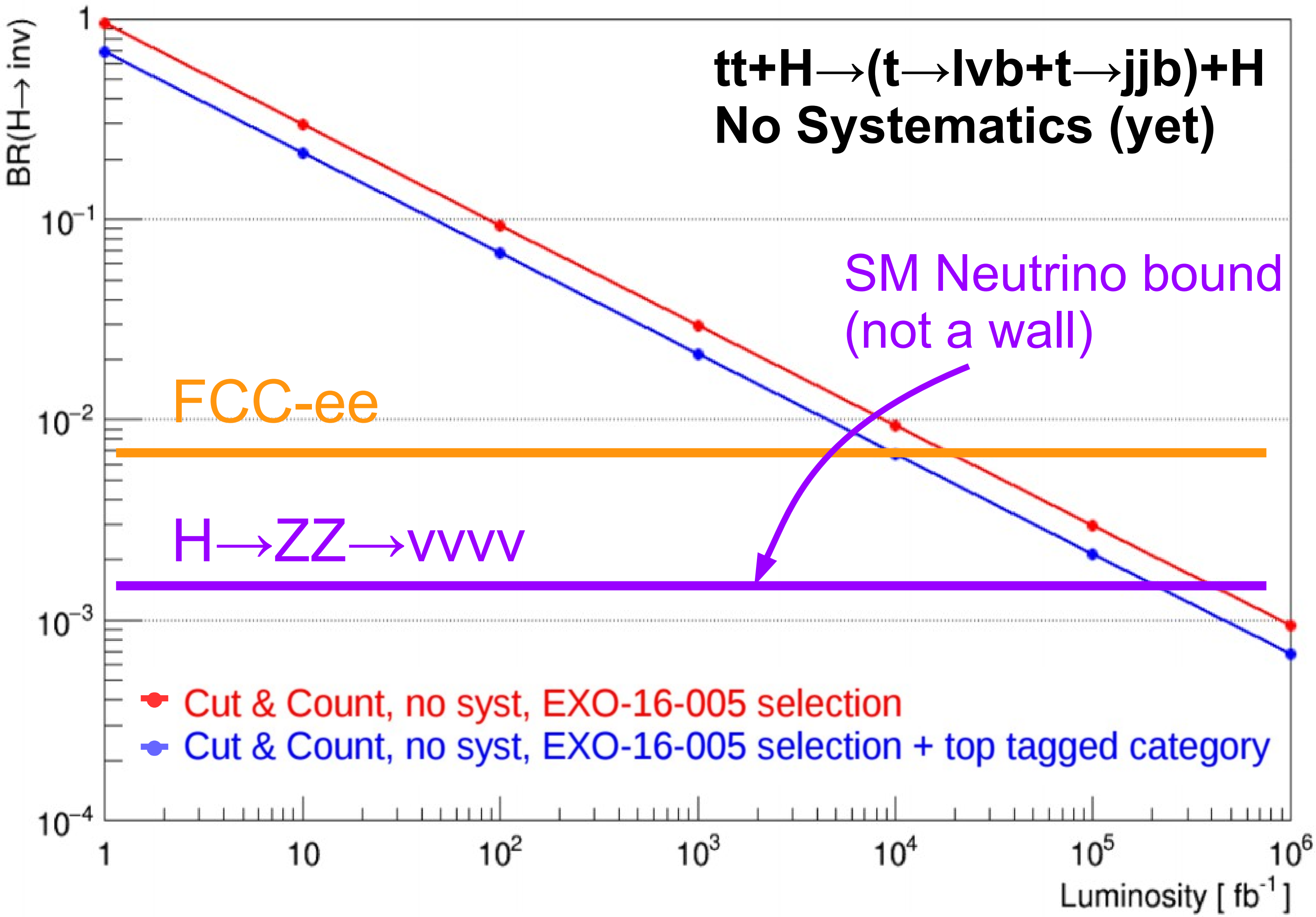
$\Delta\phi(t_2,\not{E}_T)$



Boosted tt+H analysis has an S/B of 1 to 1 (very pure)

Implications with a Pure category

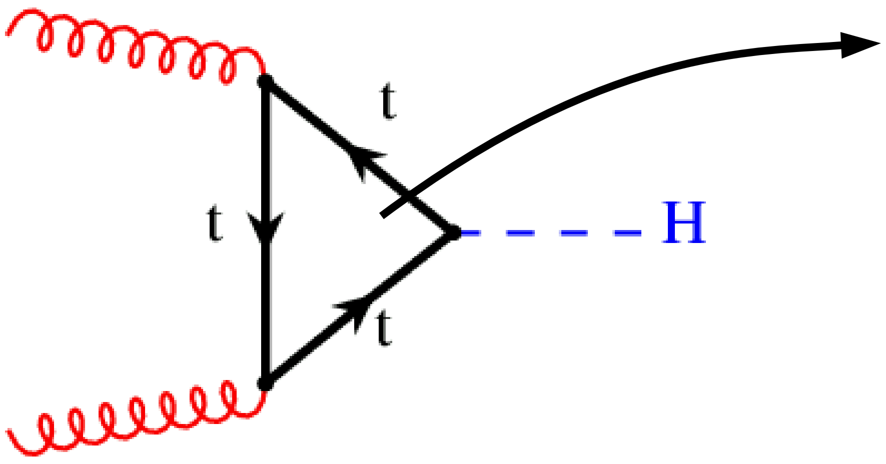
Currently considering semi-leptonic channel without systematics



Crosses both FCC bounds and SM H Invisible bound

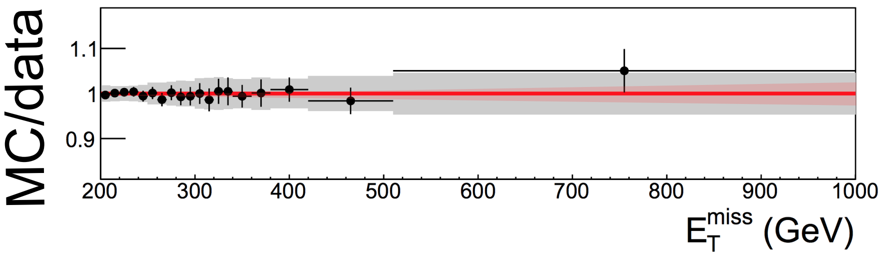
Monojet(s) analysis

- Consider an analysis :
  - Veto leptons for $|\eta| < 4.0$
  - Fit the MET spectrum
    - Predict the MET spectrum with the highest level of precision
- In MET tail S/B is 2-5%
  - Aim to just exploit low purity with very large yields

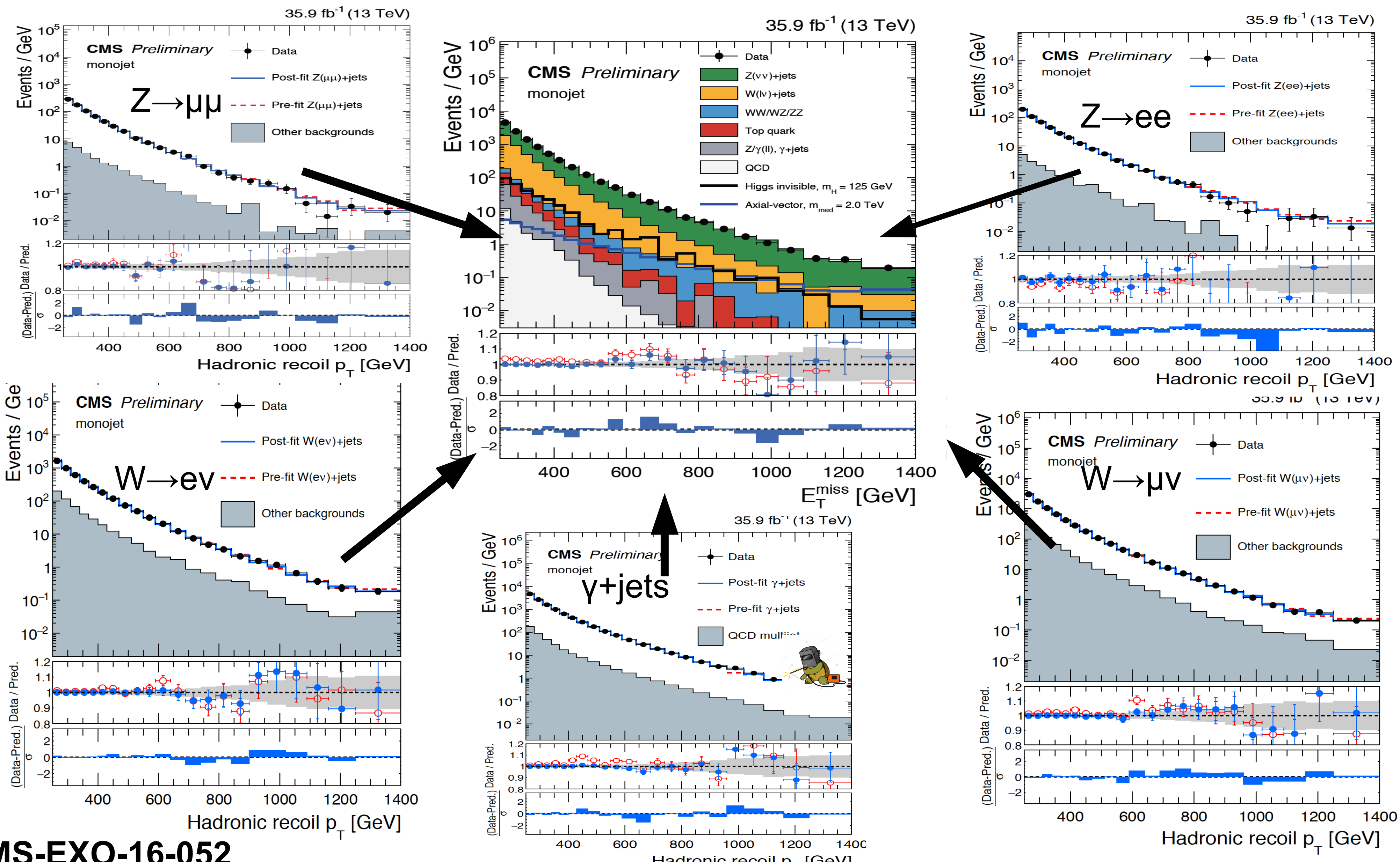


Finite top quark mass contribution crucial

Approximately known to NLO



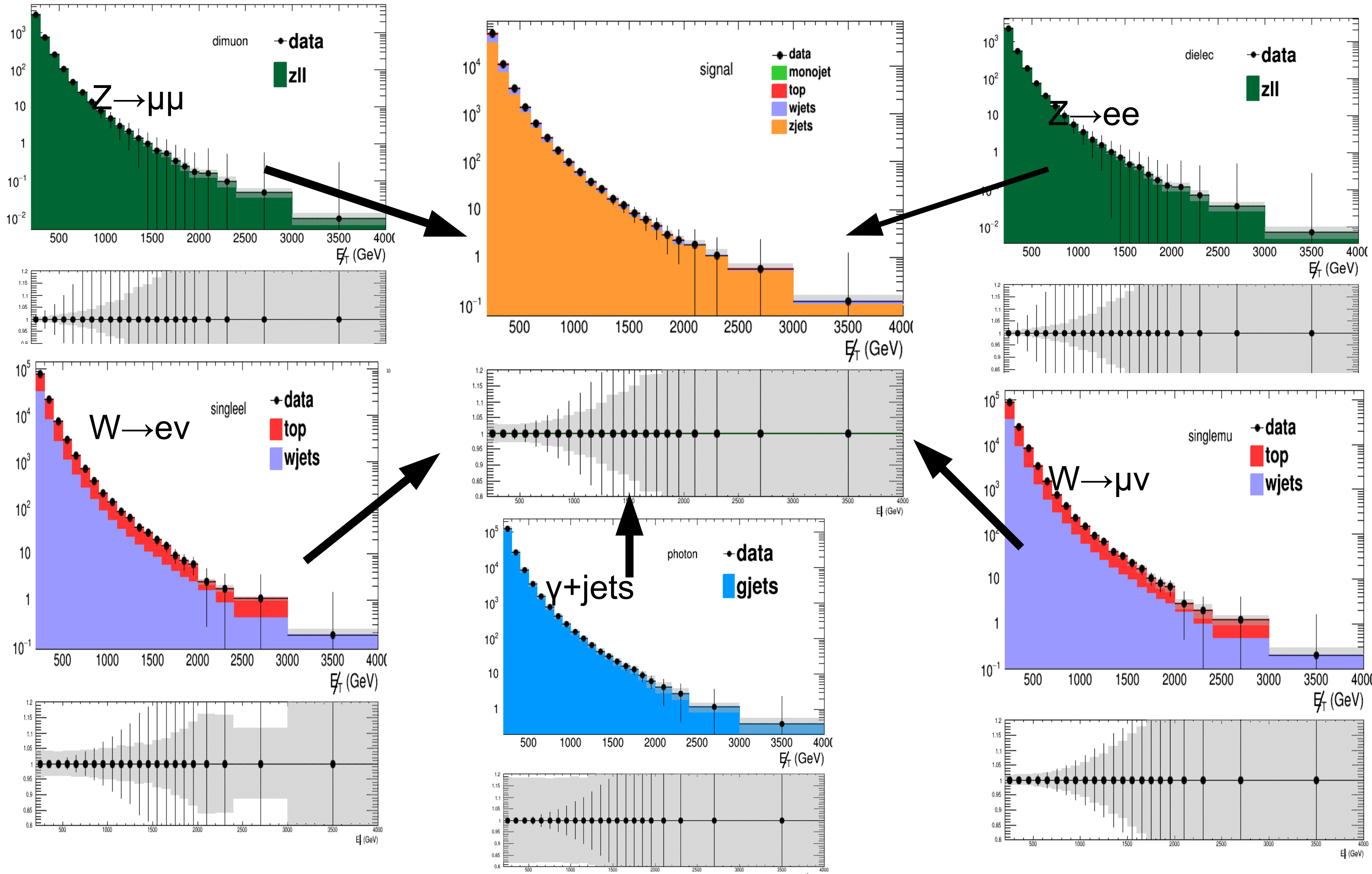
5 Control regions
15% uncertainty @ 1 TeV



CMS-EXO-16-052

Monojet analysis @ CMS

The same fitting scheme applies to 100 TeV

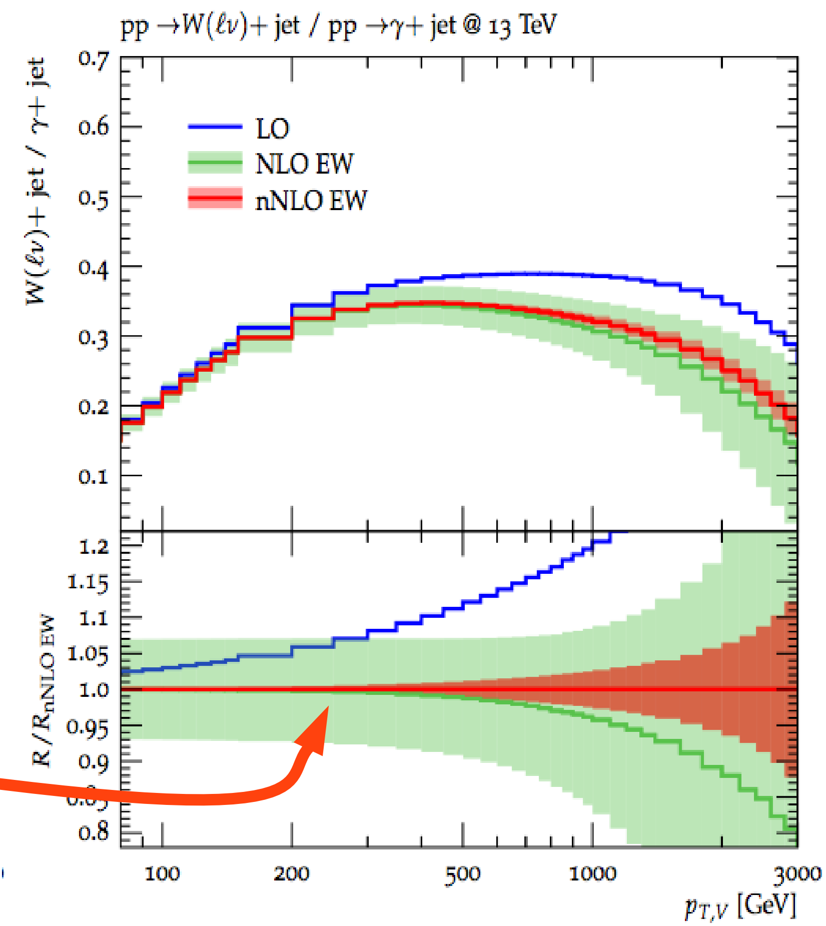


The foundation of this analysis

Going from γ or W → Z

Unc. → $$\frac{d\sigma^{\gamma(W)}}{dp_T} \Big/ \frac{d\sigma^{Z}}{dp_T}$$

- Key to this analysis ratios
  - Require best theoretical calculations
  - Current (N)NLO theoretical prescription brought additional ~40% on 36/fb analysis

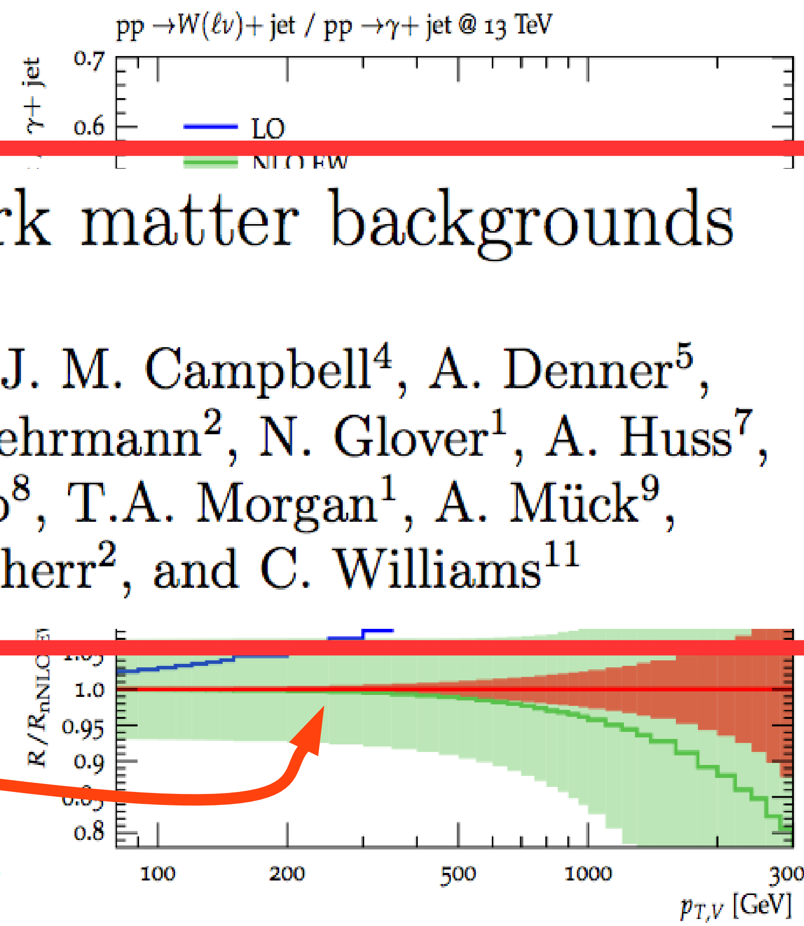


arxiv/1705.04664

The foundation of this analysis

Going from γ or W $\rightarrow$ Z

Unc. $\longrightarrow$ $\dfrac{d\sigma^{\gamma(W)}}{dp_T} \Big/ \dfrac{d\sigma^{Z}}{dp_T}$



Precise predictions for V+jets dark matter backgrounds

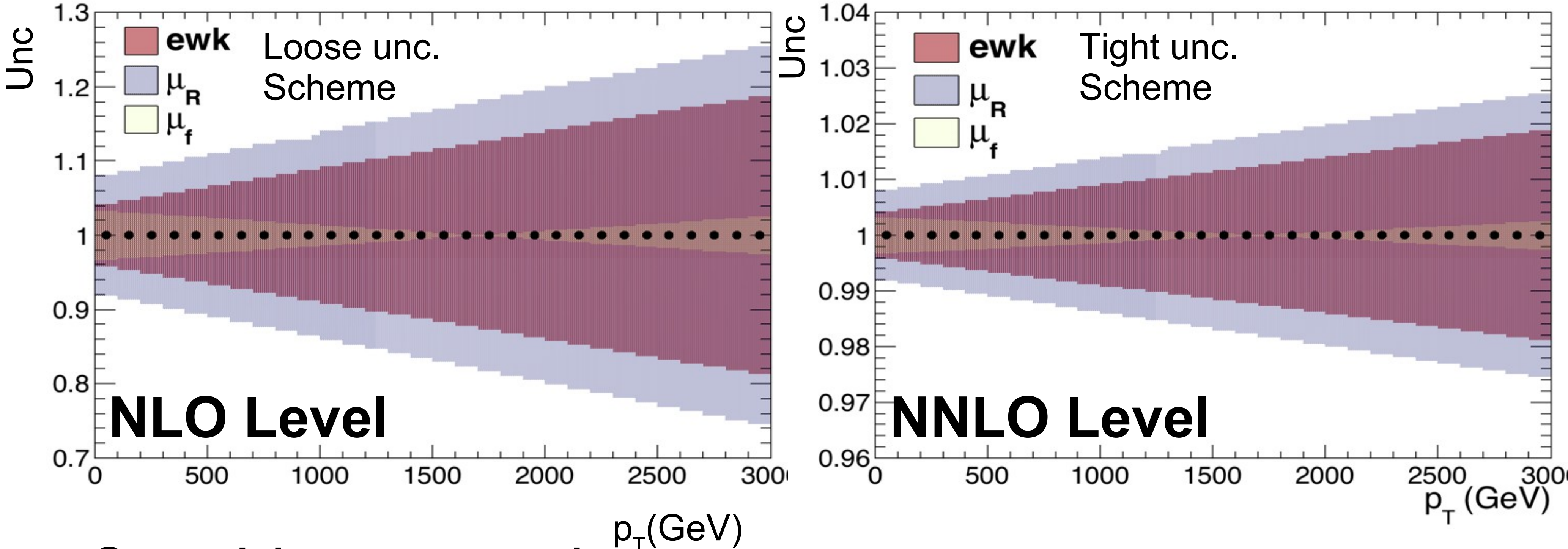
J. M. Lindert[1], S. Pozzorini[2], R. Boughezal[3], J. M. Campbell[4], A. Denner[5], S. Dittmaier[6], A. Gehrmann-De Ridder[2,7], T. Gehrmann[2], N. Glover[1], A. Huss[7], S. Kallweit[8], P. Maierhöfer[6], M. L. Mangano[8], T.A. Morgan[1], A. Mück[9], F. Petriello[3,10], G. P. Salam*[8], M. Schönherr[2], and C. Williams[11]

prescription brought additional ~40% on 36/fb analysis

arxiv/1705.04664

Benchmarks for this study

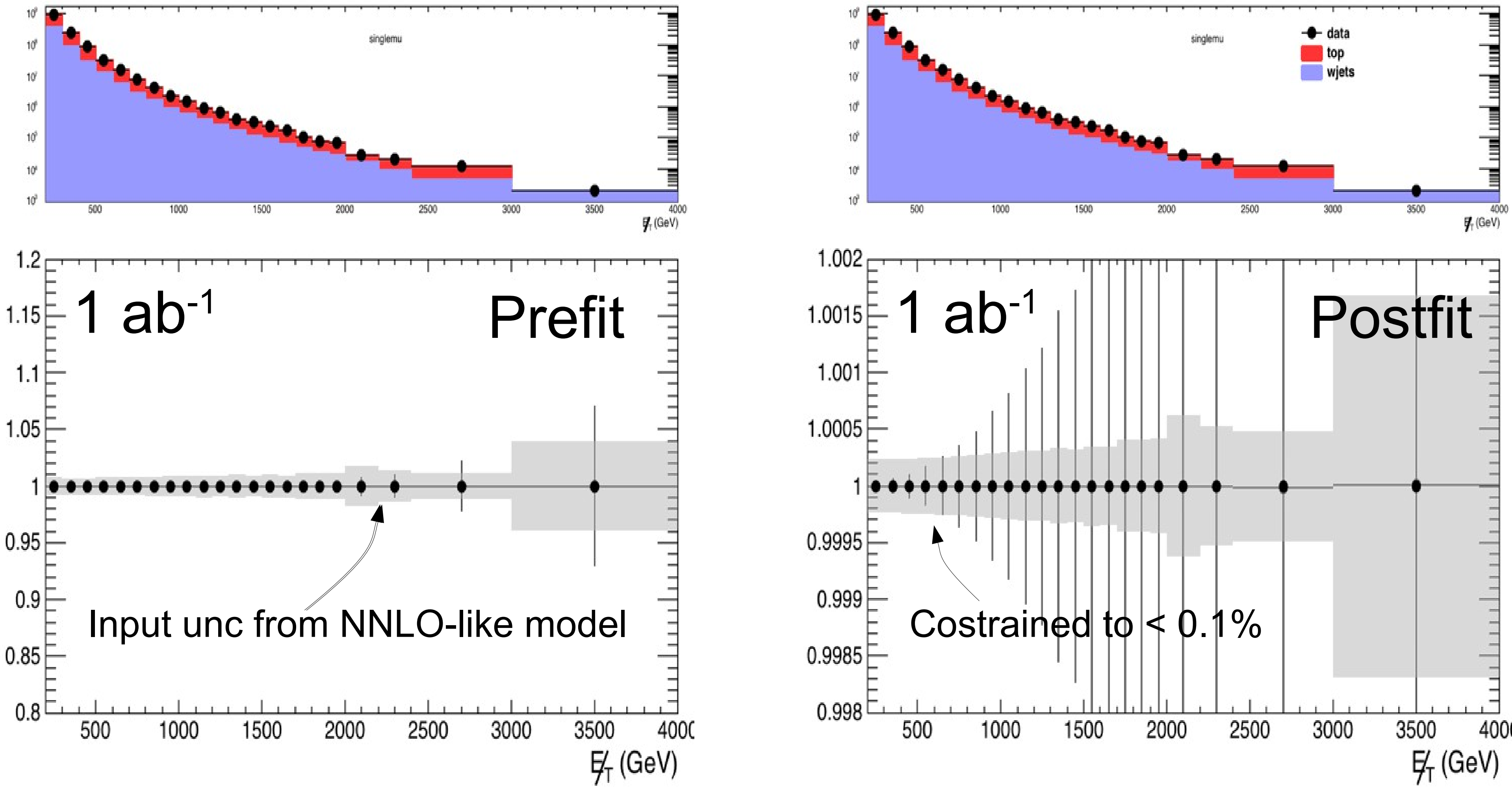
- What are reasonable uncertainty choices



- Consider two options :
  - A Loose uncertainty →Comparable to NLO
  - A Tight uncertainty →Comparable to NLO
- Using : 0.5%/0.25%/5% e/μ/τ efficiency & 1% lumi

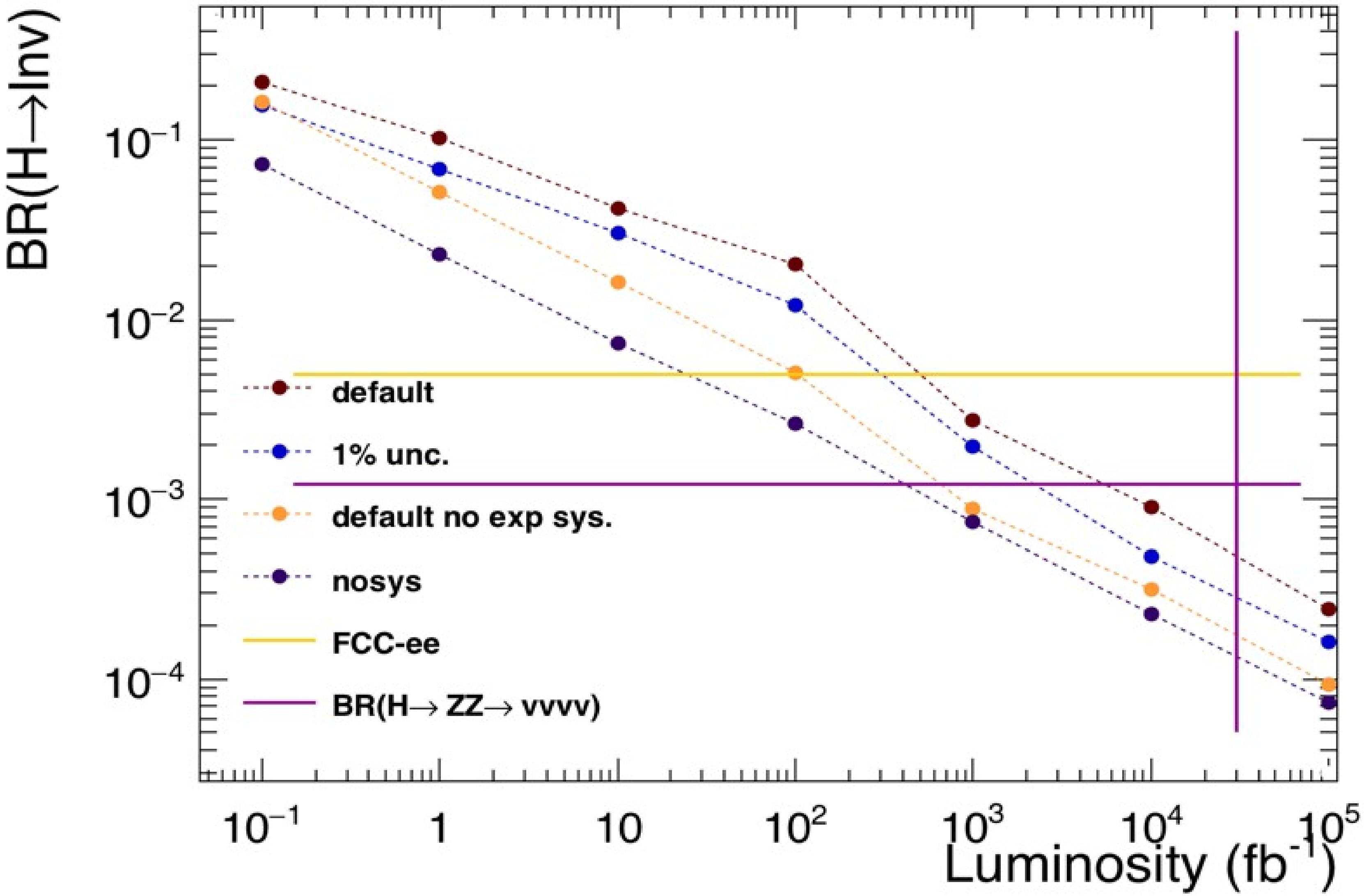
What is the precision?

- Can probe a few % effects (NNLO precision)



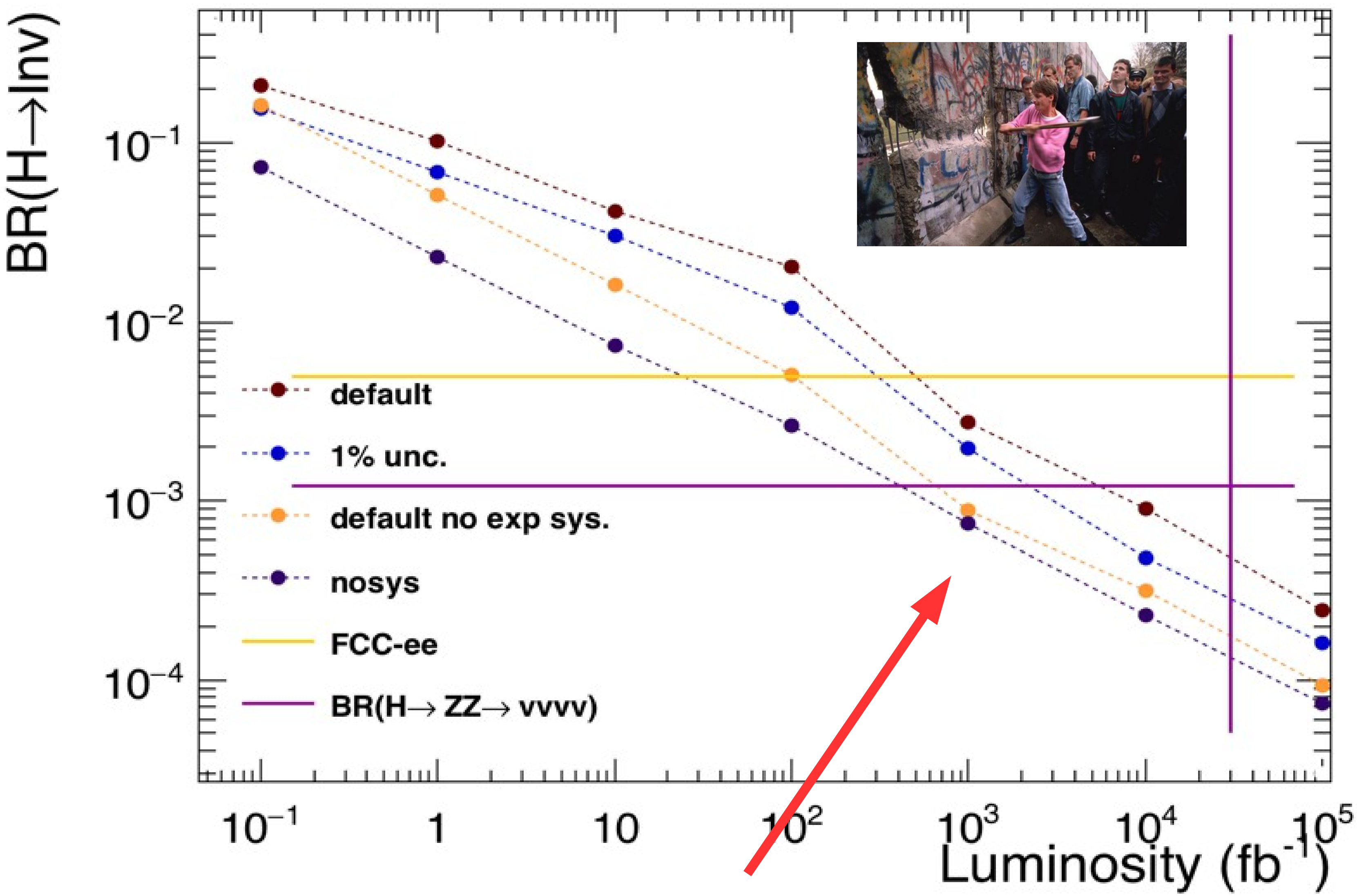
Through this scheme we can probe boson pT to 10^{-4} level

How do things scale?



Cross the SM neutrino wall at FCC with < 1 ab^{-1}

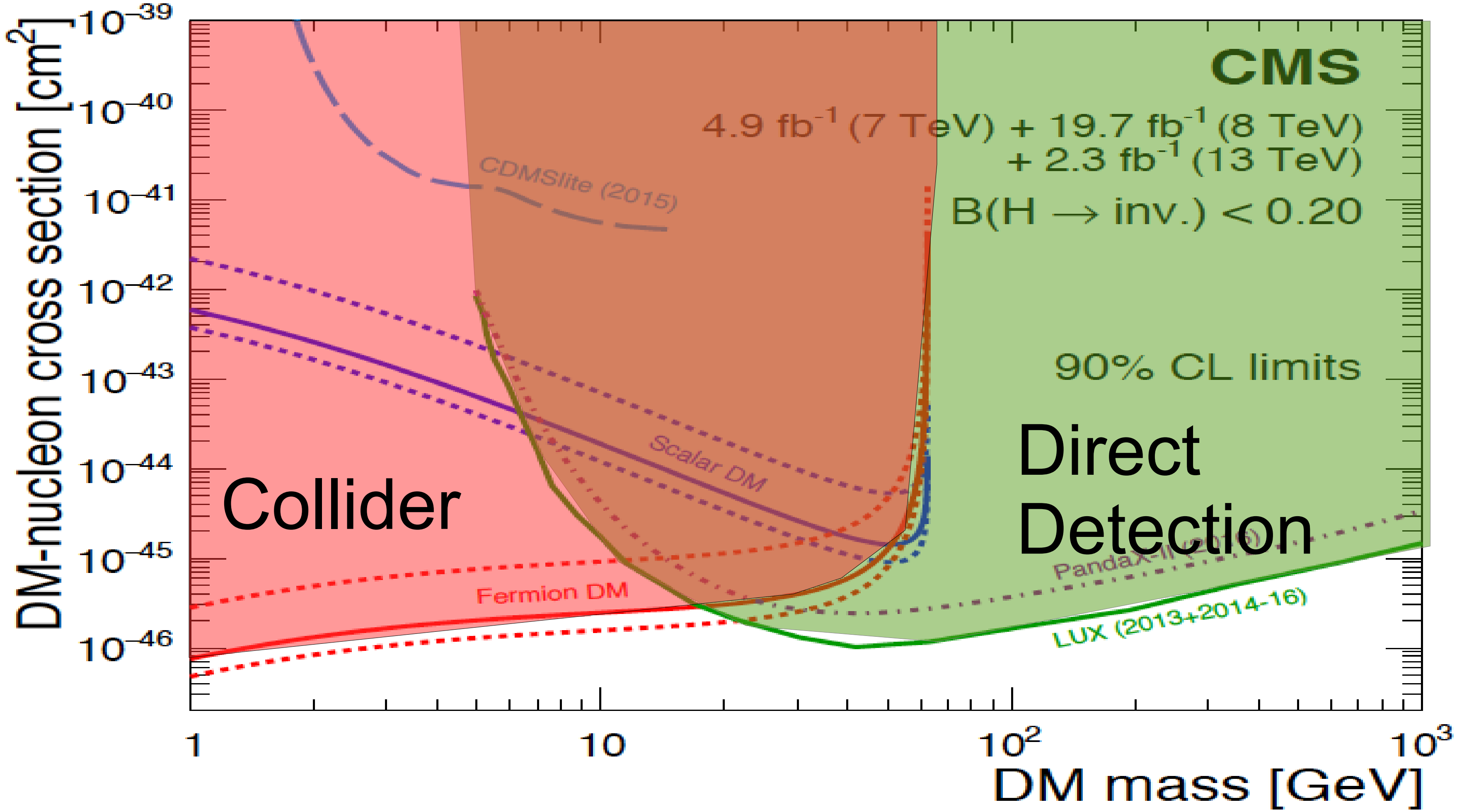
How do things scale?



There is no systematics wall

Current Bounds

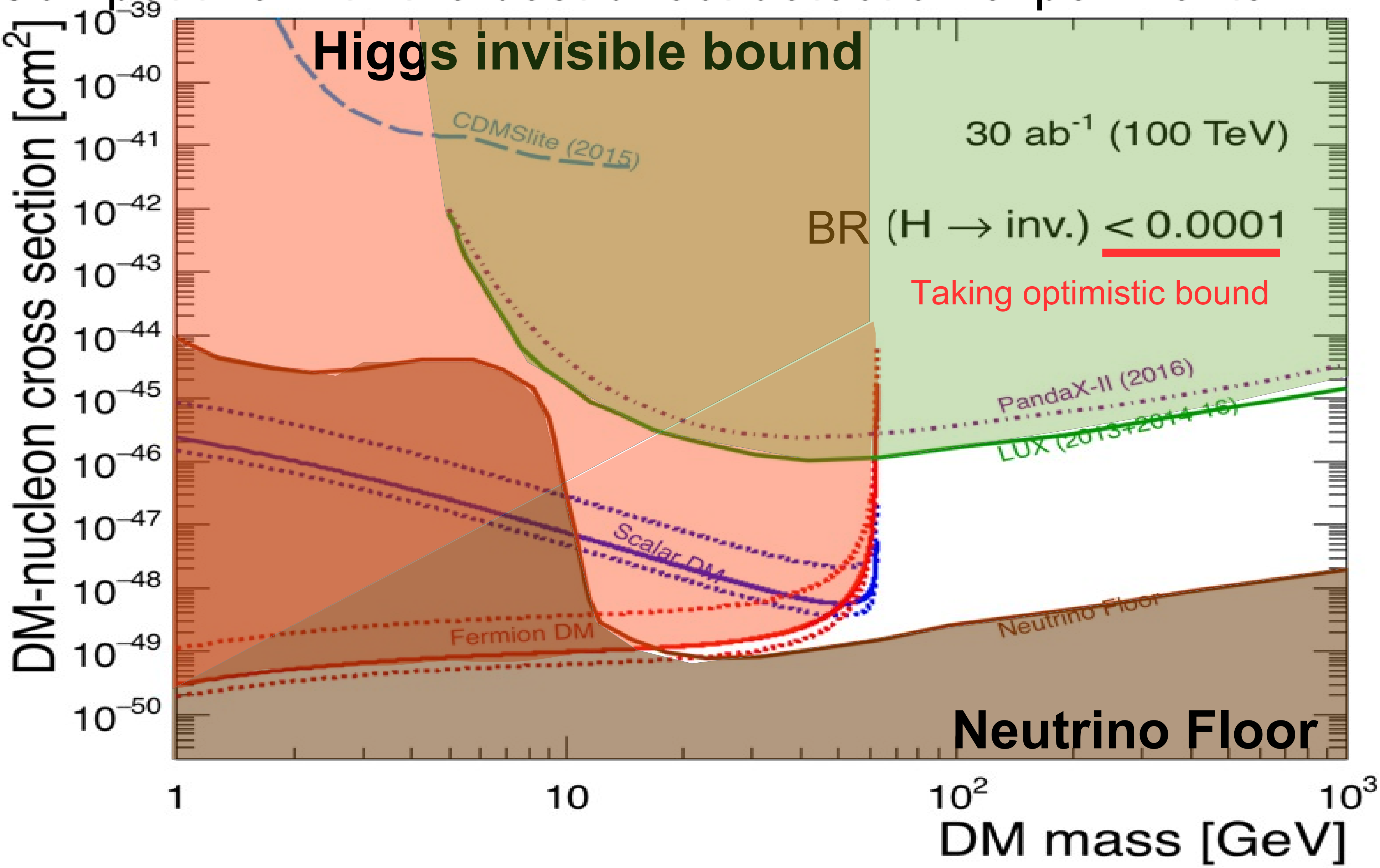
- Higgs to invisible :
  - Direct detection and collider are head to head



Competitive with the best direct detection experiments

Future Bounds

Competitive with the best direct detection experiments

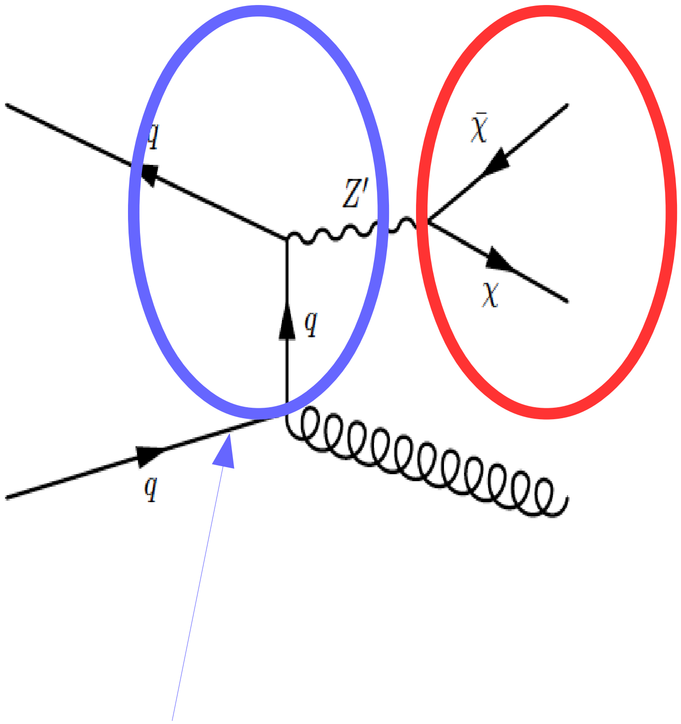


Higgs invisible of 10^{-4} corresponds to g_{SM} from 10^{-3} to 10^{-2}

Beyond Invisible Searches

What else?

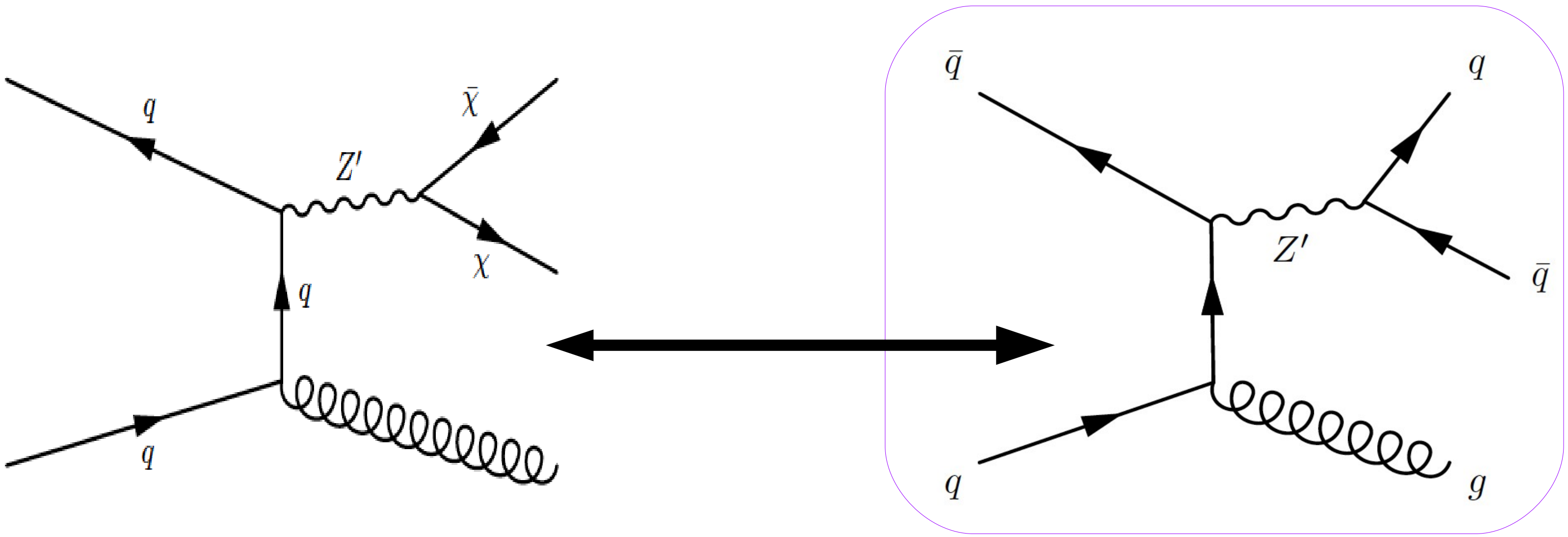
- Without loss of generality we also have dijets



Mediator is coupling to quarks and to Dark matter

What else?

- Without loss of generality we also have dijets

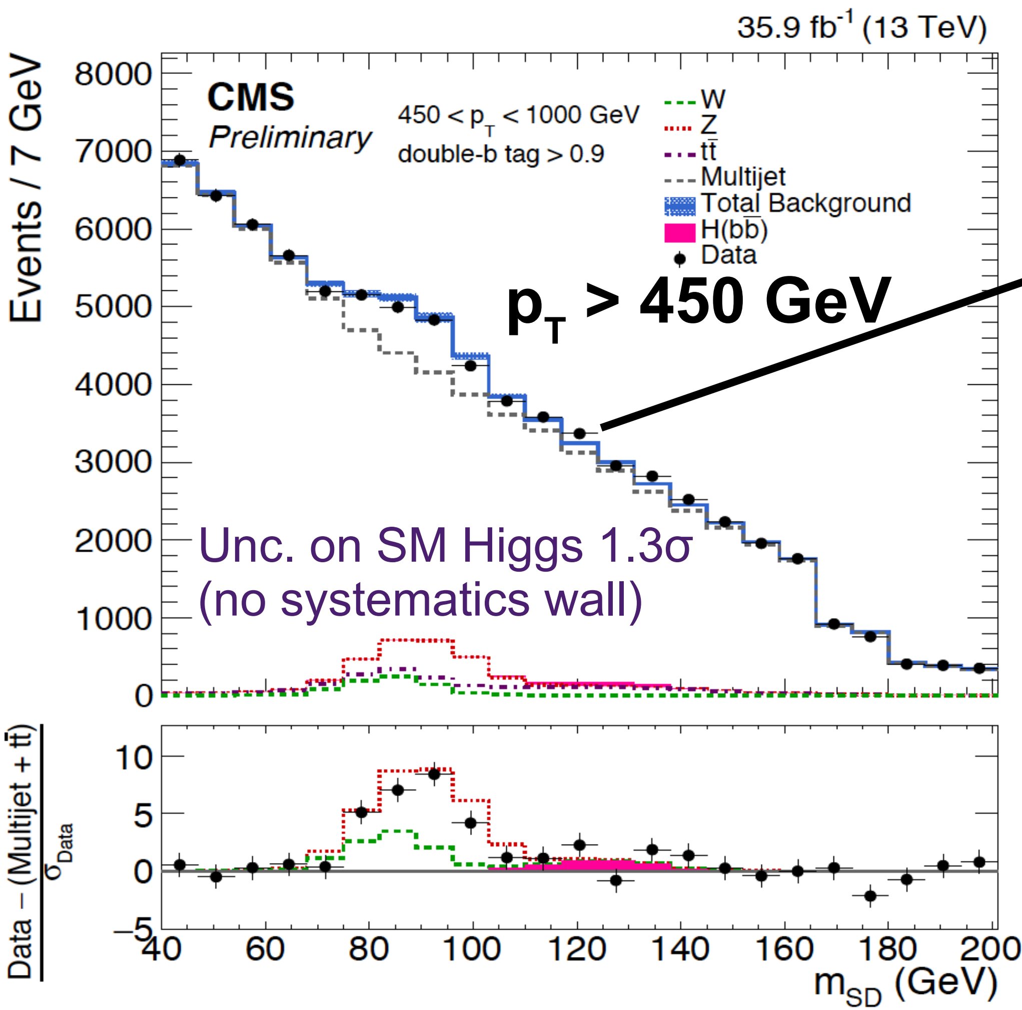


This is a dijet+ISR search

Mediator is coupling to quarks and to Dark matter
Mediator can decay to quarks

Just beginning to search directly

- Technique for tagging high p_T objects in its infancy



First result for high p_T
"Visible Higgs"
Came out this week

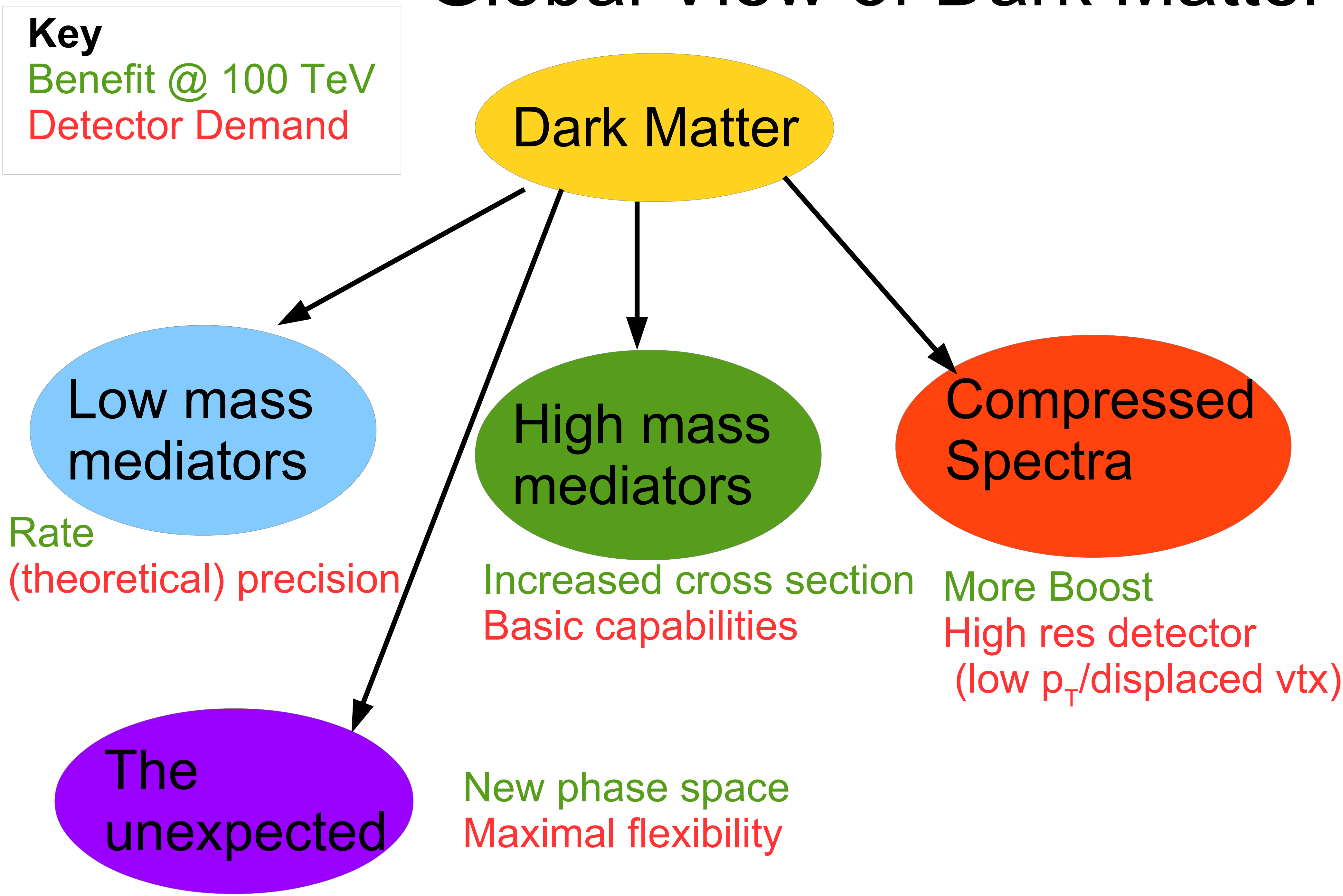
Can exploit same ideas
From invisible to probe
Higgs production
w/small couplings

To full FCC-hh gives BR(H→bb) sensitivity 10^{-3}

CMS-HIG-17-010

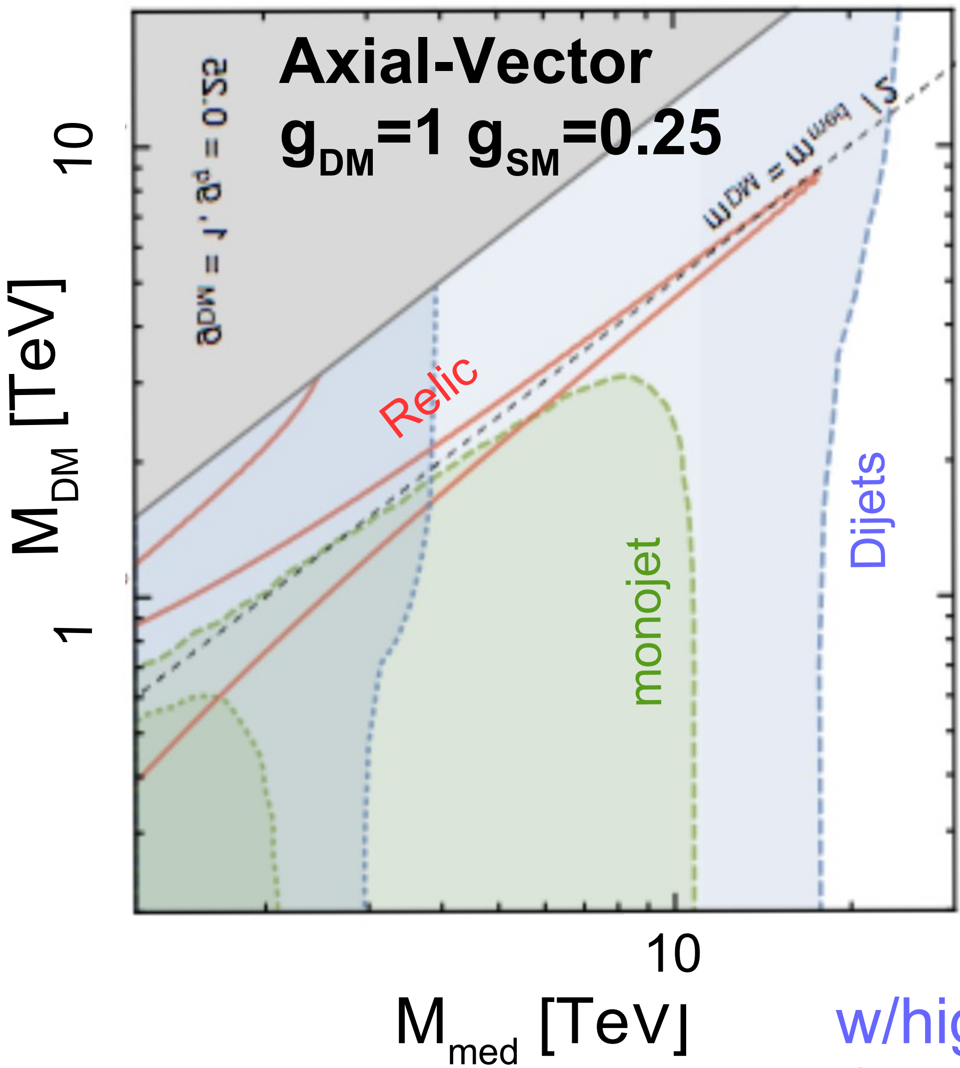
Other Dark Matter

Global View of Dark Matter



High Mass Reach

- Probing High mass reach



Model	Collider	(In)Direct	Relic
Vector	15 TeV	>100 TeV	70 TeV
Axial	15 TeV	6 TeV	8 TeV
Scalar	3.5 TeV	3 TeV	6 TeV
Pseudo	4 TeV	1 TeV?	40 TeV

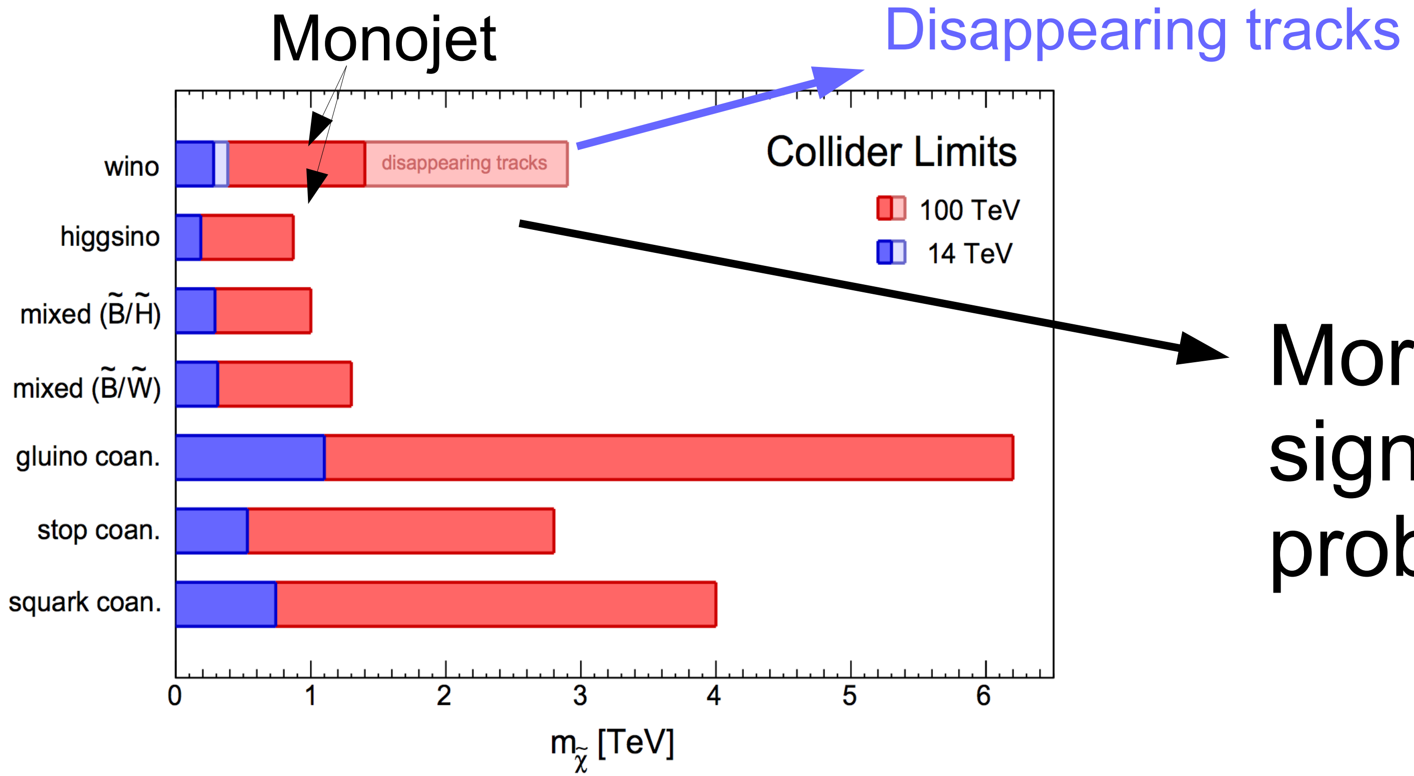
100 TeV bounds

Bounds from other methods

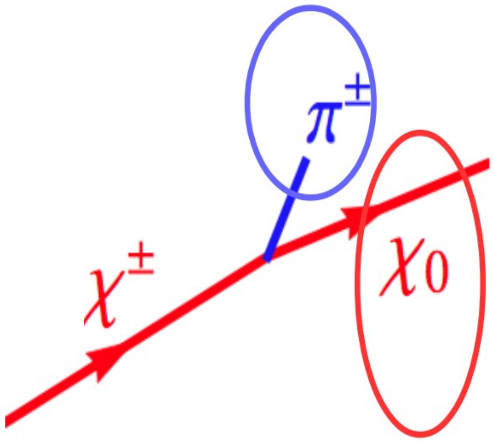
Relic density

w/high mass mediators searches
Cover large most(if not all) allowed space)

More striking signatures



More striking signatures can be probed



With compressed scenarios can have :

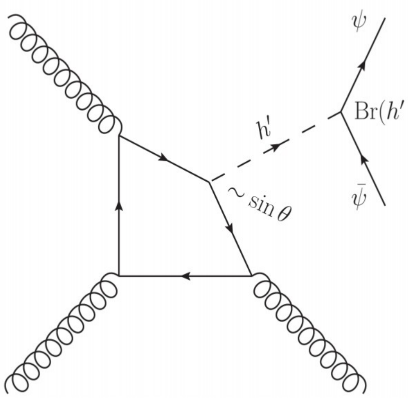
Disappearing Tracks

Low p_T leptons (< 10 GeV)

Displaced vertices

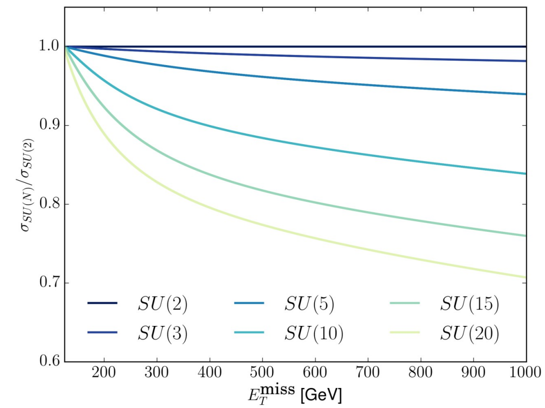
More exotic searches

- Can consider extended QCD sectors

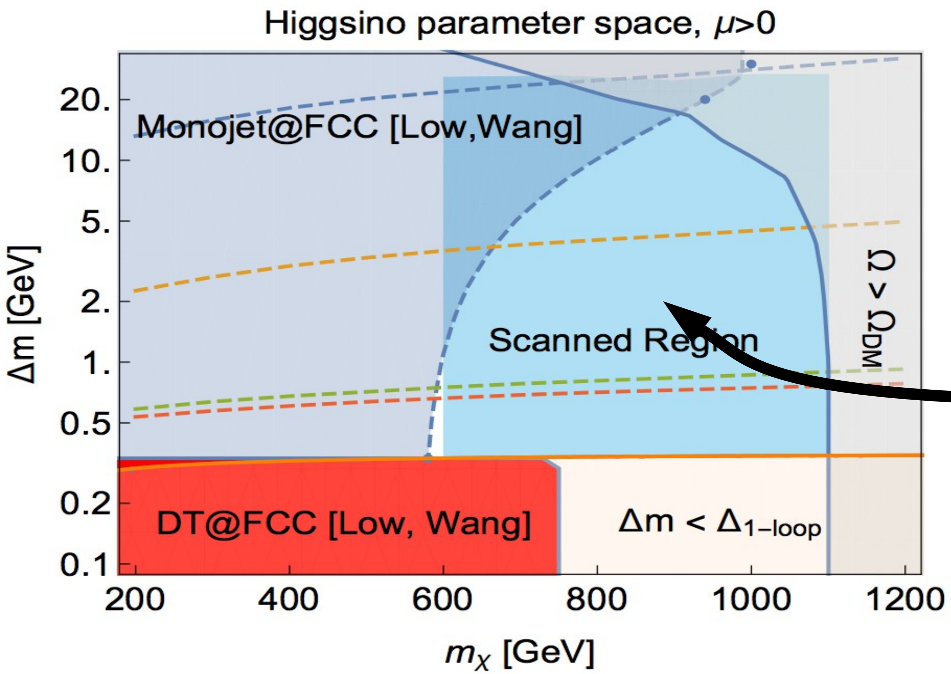


Can recast Higs monojet

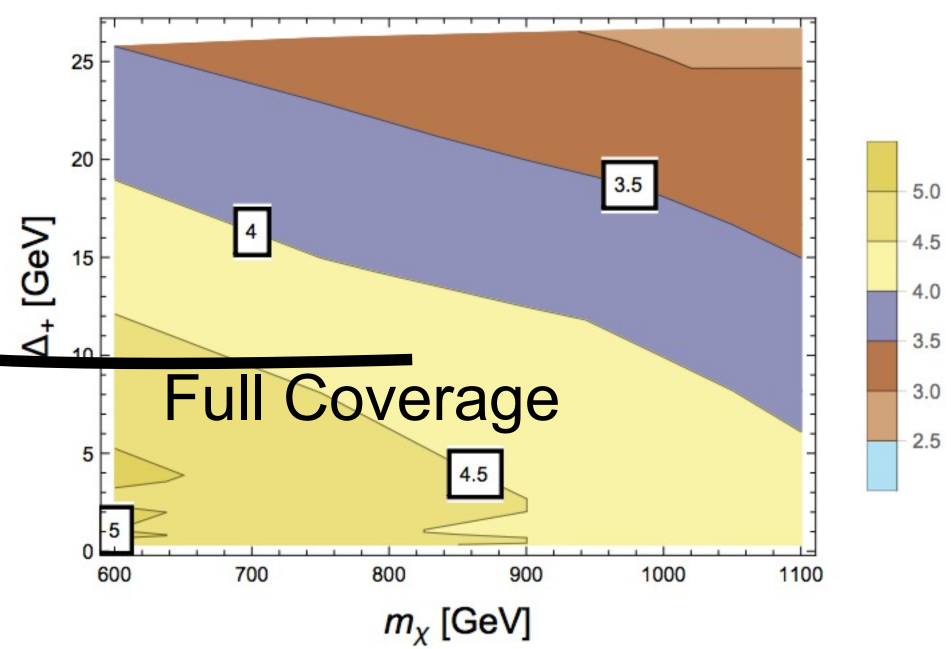
Invisible search for SU(N) QCD



- Exending compressed spectra to mono-Z



Full Coverage



https://indico.cern.ch/event/550509/contributions/2413850/attachments/1399186/2134448/Zurita_F

Spectrum of Dark matter

- Deep understanding of monojet extends to many models

- Additional searches extend to
  - Disappearing track
  - Mono-Z
  - Displaced jets
  - ...More exotic

Final State	Analysis	section
jet+MET	Wino, Higgsino DM	4.3.1 - 4.3.4
jet+MET	Higgs Portal	4.3.5
jet+MET	Simplified Vector/Axial	4.4.1 - 4.4.3
jet+MET	Simplified Scalar/Pseudo	4.4.1 - 4.4.3
jet+MET	Gluion/stop coannihalation	4.5.1
VBF jets +MET	Wino, Higgsino DM	4.3.1 - 4.3.2
VBF jets +MET	Higgs Portal	4.3.5
photon+MET	Wino	4.3.2
Disappearing tracks	Wino,Higgsino	4.3.1 - 4.3.2
Disappearing tracks	Fiveplet DM	4.3.3
Disappearing tracks	Relic-Neutralino	4.3.4
lepton+γ+MET	Relic-Neutralino	4.3.4
$Z_D \to ll$+$(Z_D \to ll)$	Dark Photons	4.4.4, 4.6.3
displaced jets	Dark QCD/Hidden Valley	4.6.2
long lived charged particle	Super-WIMPS/Gravitino	4.6.4
dijet	Simplified Vector/Axial	4.4.1 - 4.4.3

Table 5: Overview of the final states and the associated model, with a link to the respective section.

Conclusions

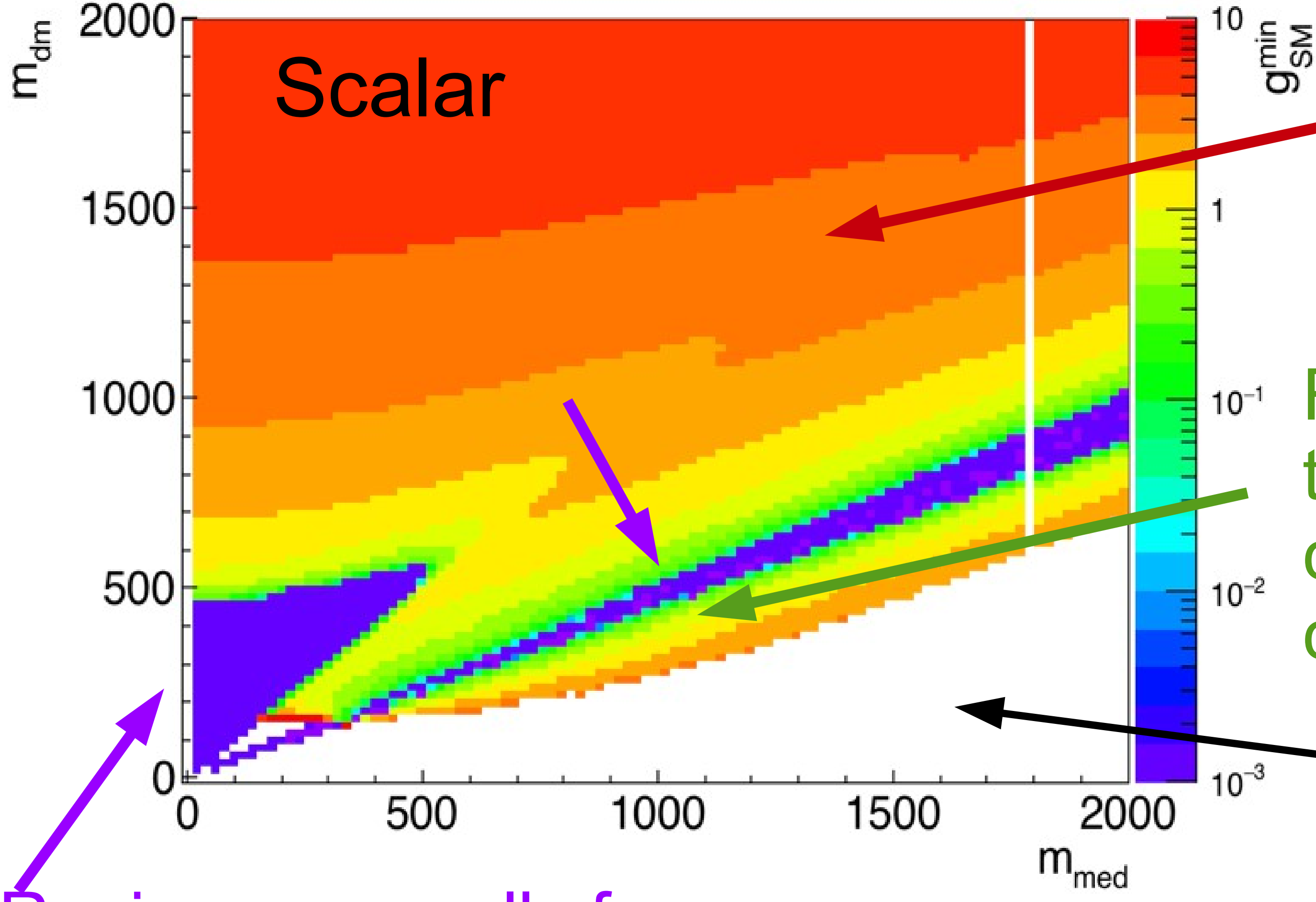
- A key aspect to FCC-hh is incredible rate
  - Allows us to probe Higgs invisible beyond neutrino wall
  - Extends Higgs invisible search well beyond FCC-ee
  - Extends to SM Higgs invisible
    - Gives us a signal we can calibrate
  - Higgs invisible bound translated to low mass scalar
    - Probes most of the allowed minimal coupling phase space

- Dark matter at FCC-hh
  - Four part study in High rate/High Mass/Exotics
  - In all cases: capability to exceed or match all other exp.

Thanks!

What do we conclude?

- What is driving the results is the coupling



Regions that generally overclose

Regions we can try to probe with current or future colliders

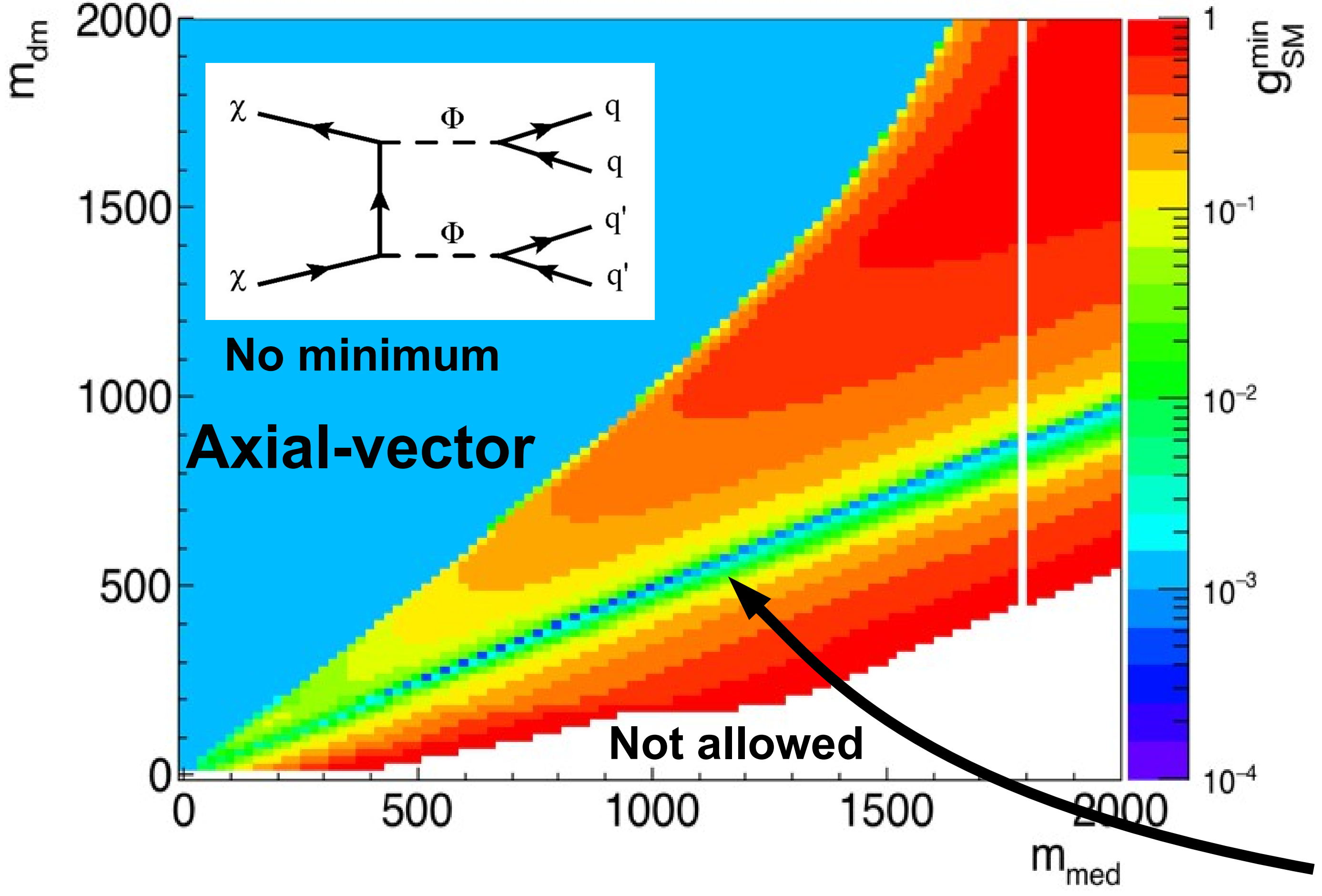
Regions that are forbidden

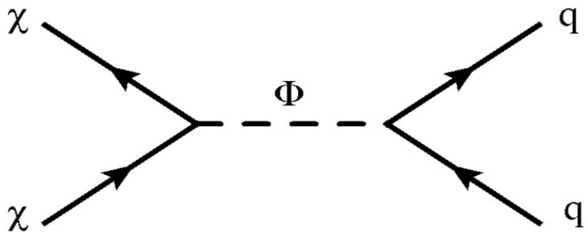
Regions generally free Of relic constraints

Aim for $0.1 < g_{SM} < 3$

Min couplings

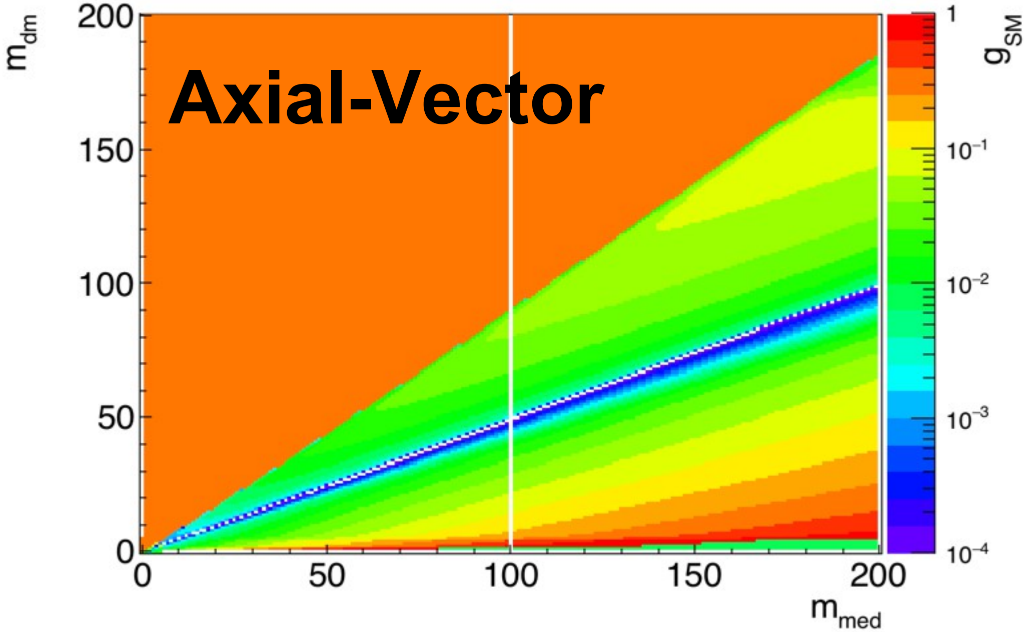
- Can split the solution to the max and min coupling
  - In this case we fix g_{DM}=1 (product $g_q g_{DM}$ defines bound)

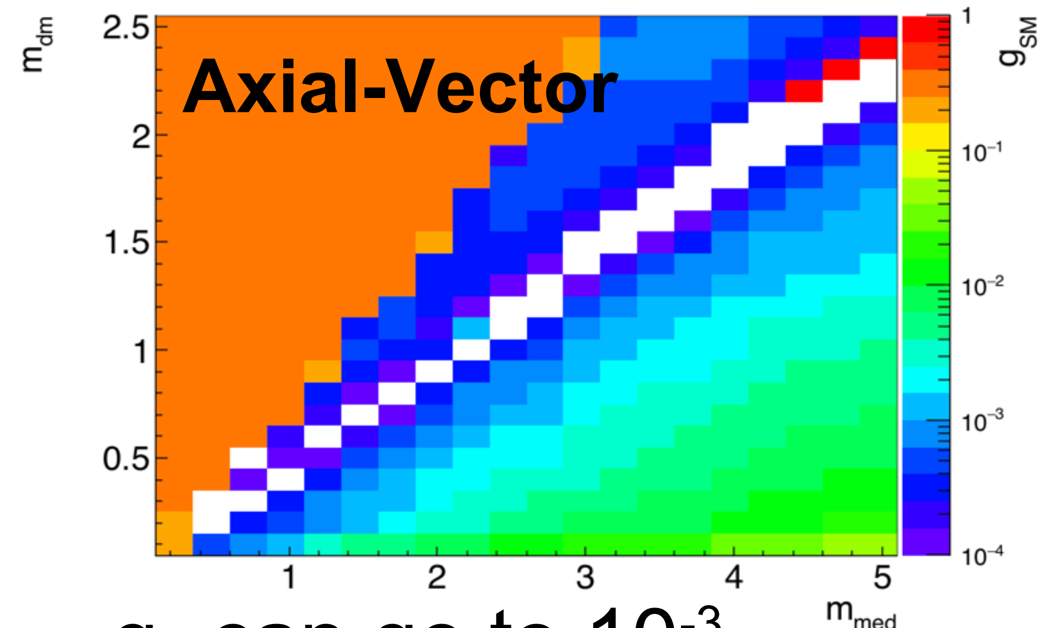




What about at low mass?

- Coupling becomes a real challenge



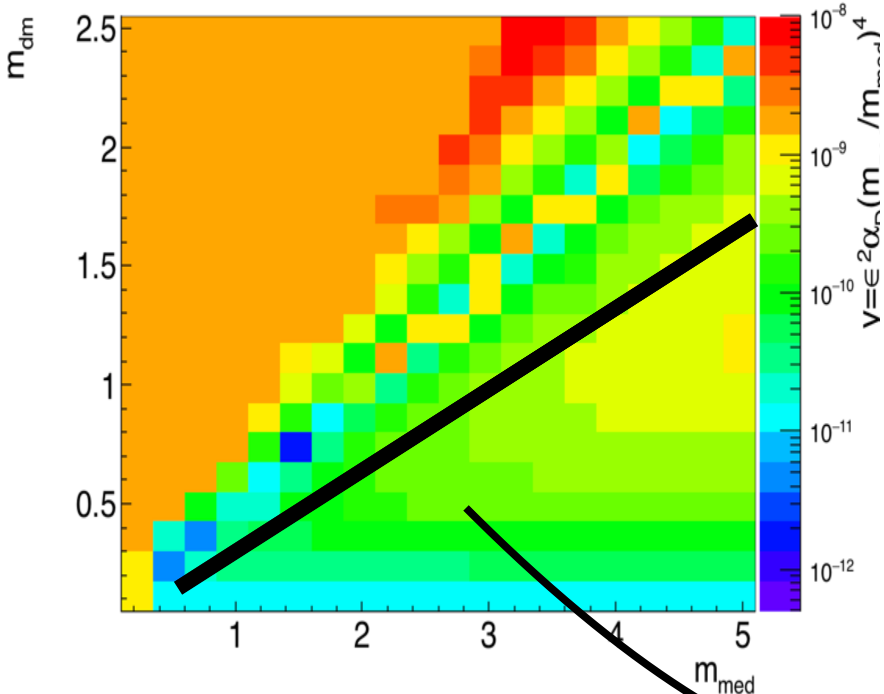


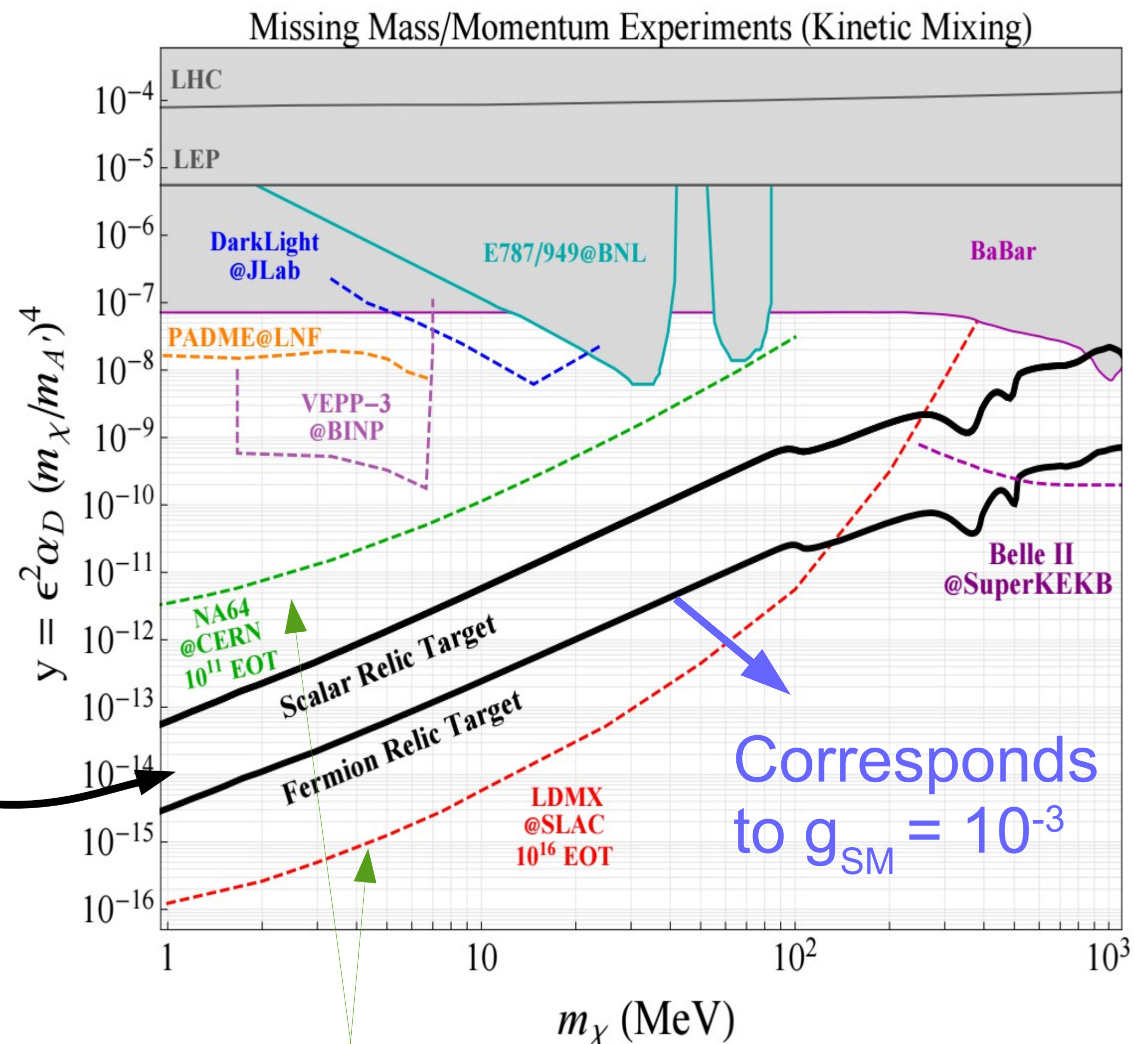
g_q can go to 10^{-3}

At low masses we can have very small couplings

However we have more strategies

@low mass aim is for low couplings





Consider a diagonal projection $m_{DM}/m_{MED} = 1/3$

Corresponds to $g_{SM} = 10^{-3}$

Reach of a few proposed beam dump experiements

Can probe the interesting region

Preserving Generality?

To compare with other (low energy) searches :
split by spin dependence

$$\mathcal{L}' = g_{DM}\chi\chi Y$$

Spin 1

Z'^{μ} Vector

$$\mathcal{L}' = \mathcal{L}' + g_{SM} Z'_{\mu}\bar{q}\gamma^{\mu}q$$

γ^5

Z'^{μ} Axial-Vector

$$\mathcal{L}' = \mathcal{L}' + g_{SM} Z'_{\mu}\bar{q}\gamma^{\mu}\gamma^5 q$$

Spin 0

S Scalar

$$\mathcal{L}' = \mathcal{L}' + g_{SM} S\bar{q}q$$

γ^5

P Pseudoscalar

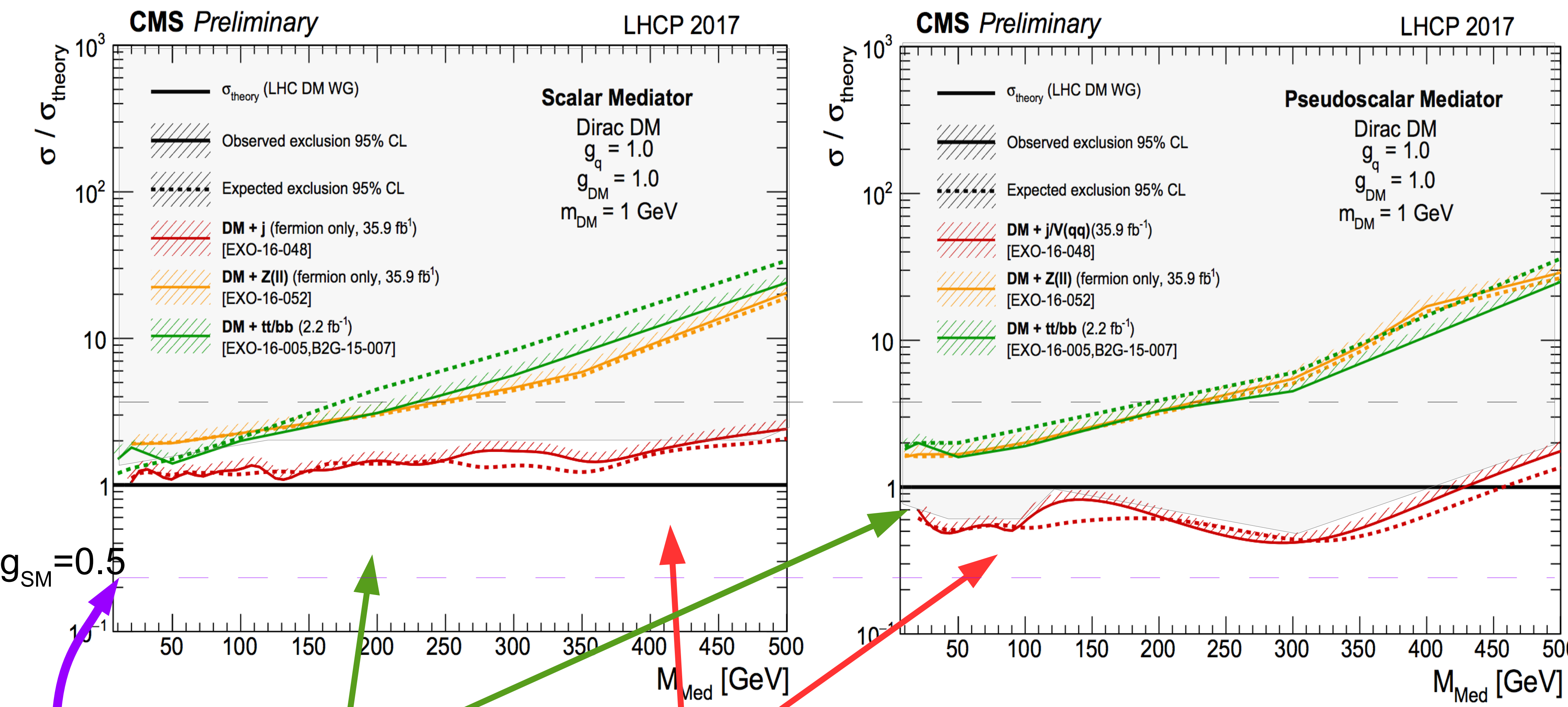
$$\mathcal{L}' = \mathcal{L}' + g_{SM} P\bar{q}\gamma^5 q$$

Strategy of searches in LHC does not change much
Interpretation agains Direct Detection/Indirect Changes a lot

Monojet search
Straddling SM and BSM

No EWSB

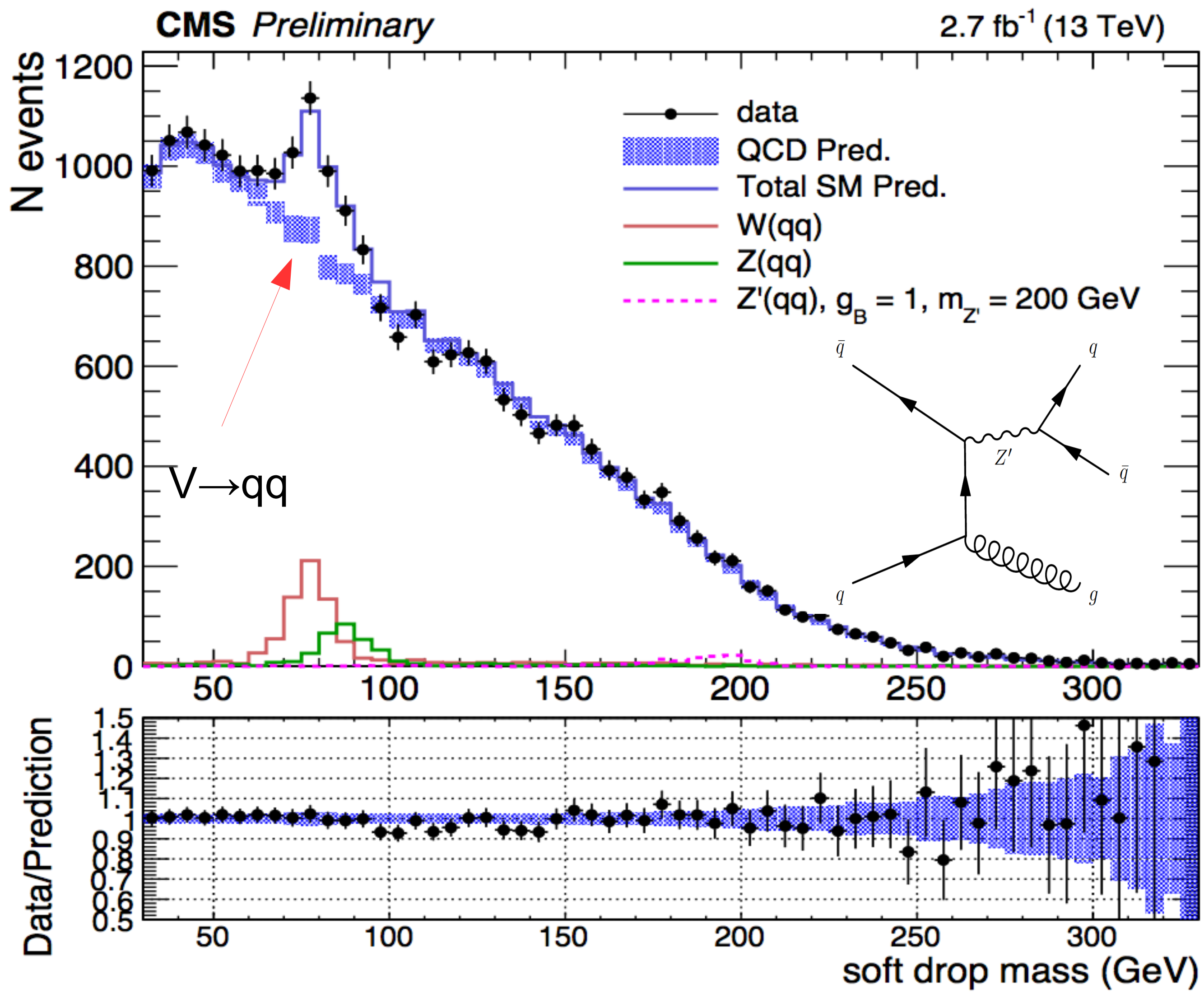
Comparing all channels

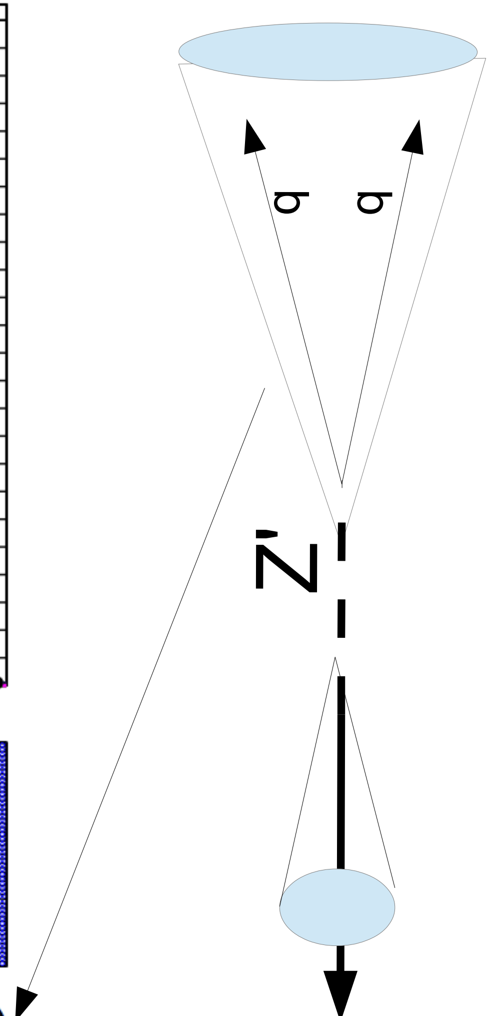


tt+DM($2fb^{-1}$) and monojet drive the combination

Not far from an intermediate benchmark of $g_{SM} = 0.5$

Going all the way down



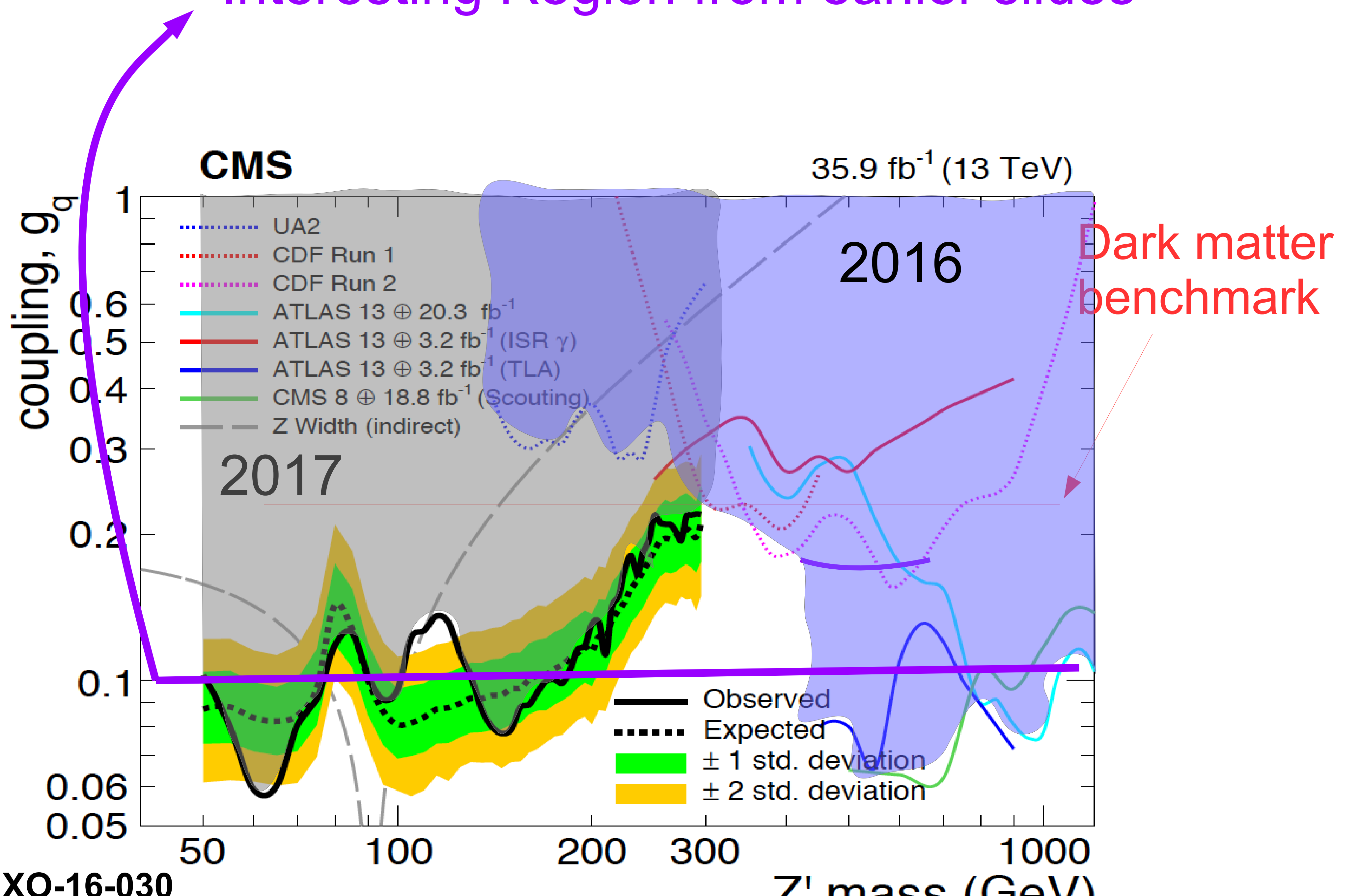


Fat jet + ISR

For this plot we invented a new substructure var

arXiv:1603.00027

Interesting Region from earlier slides

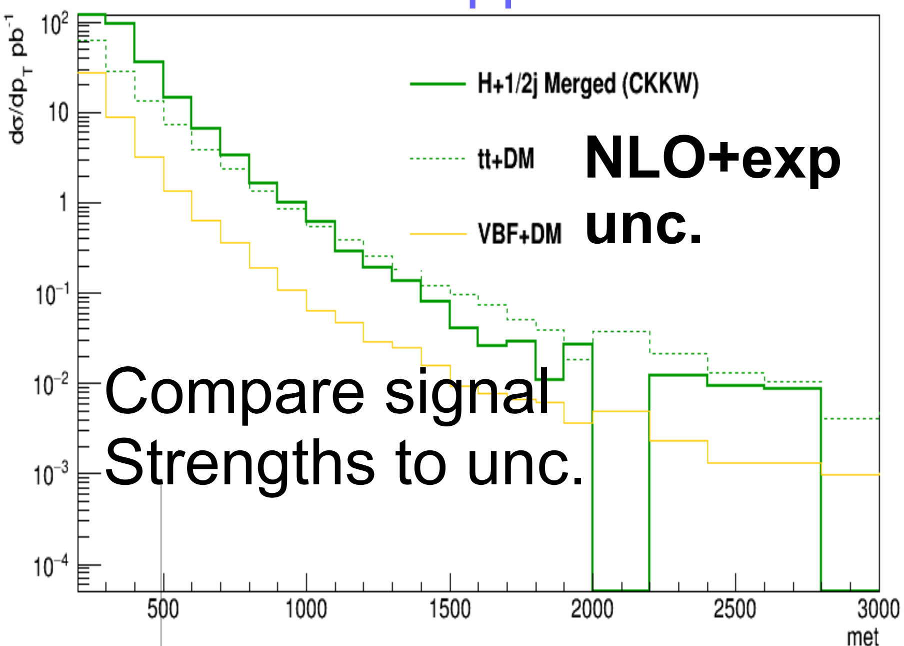


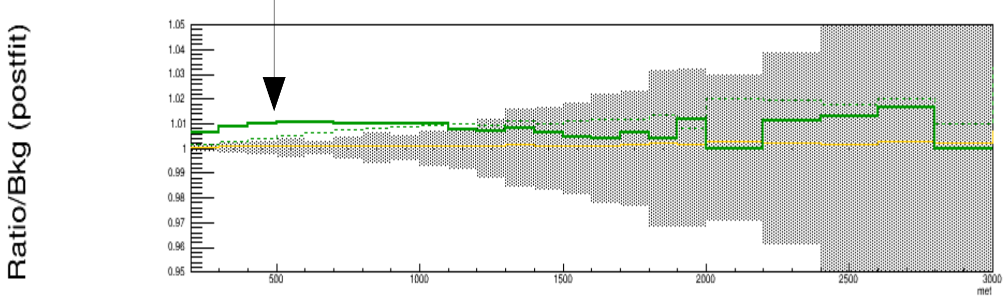
EXO-16-030
EXO-17-001

Where are we most sensitive?

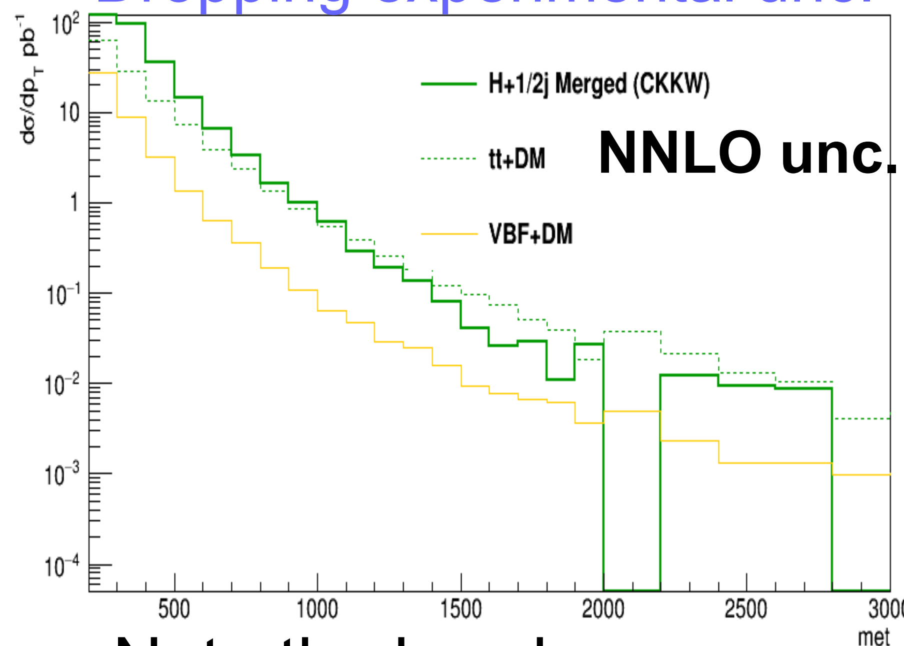
- 10 fb^{-1} : Signal sensitivity to unceratinty

Current approach

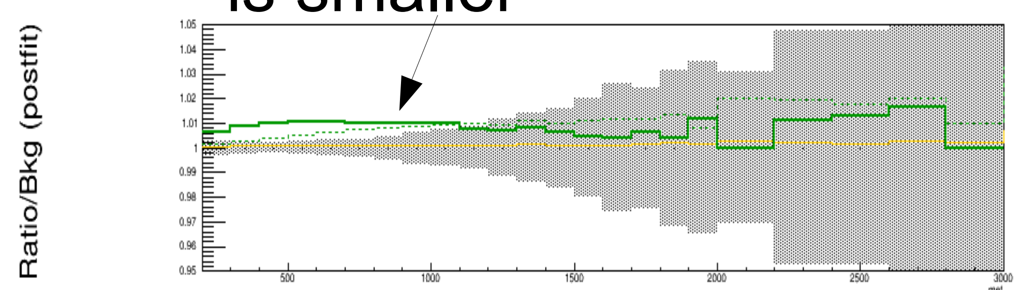




Dropping experimental unc.



Note the band is smaller

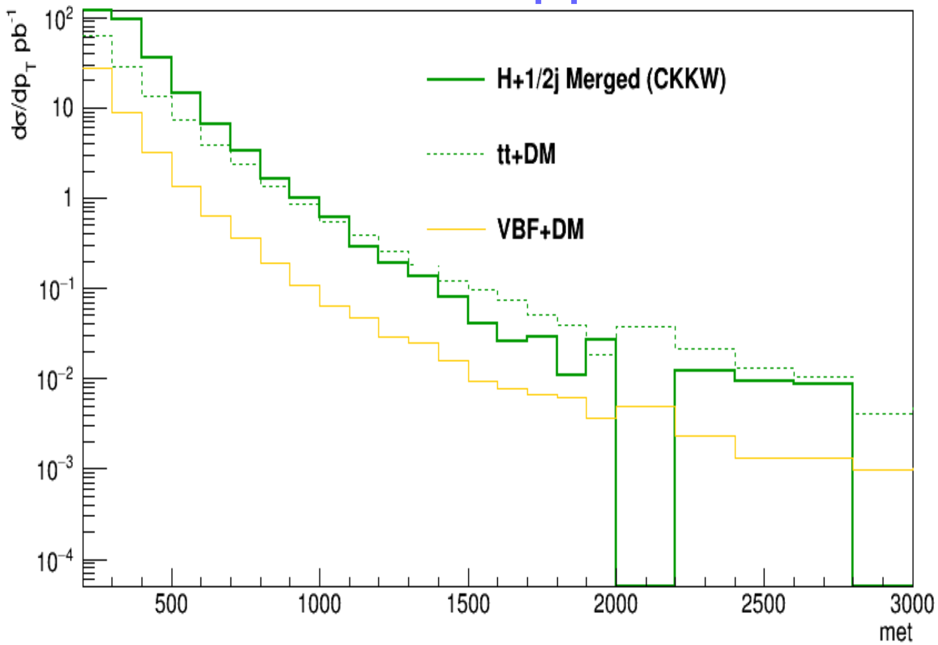


Postfit uncertainty band (using all constraints)

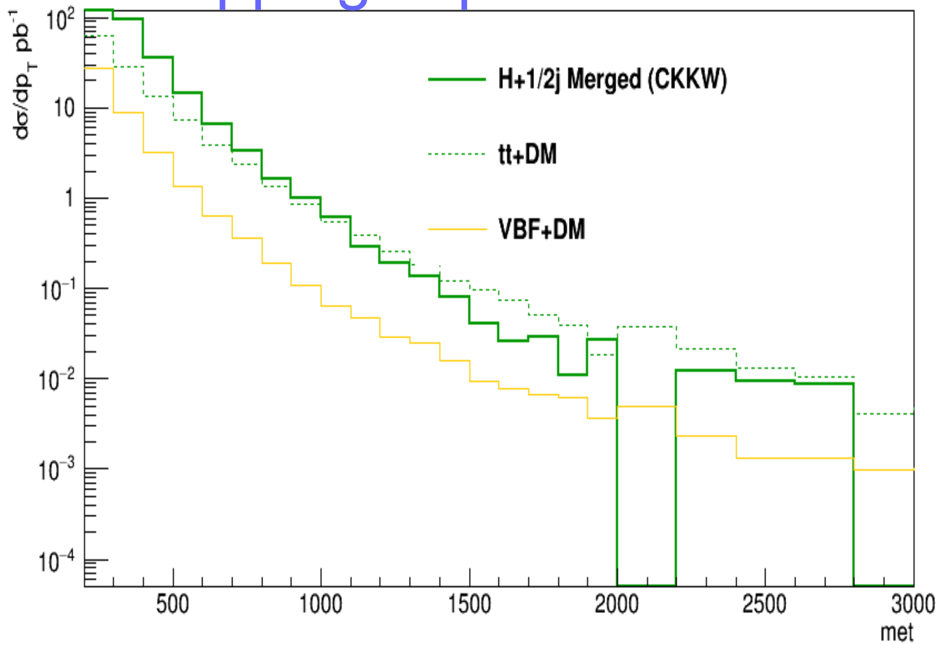
Where are we most sensitive?

- 10 fb^{-1}: Changing ratio to Bin/postfit unc. σ

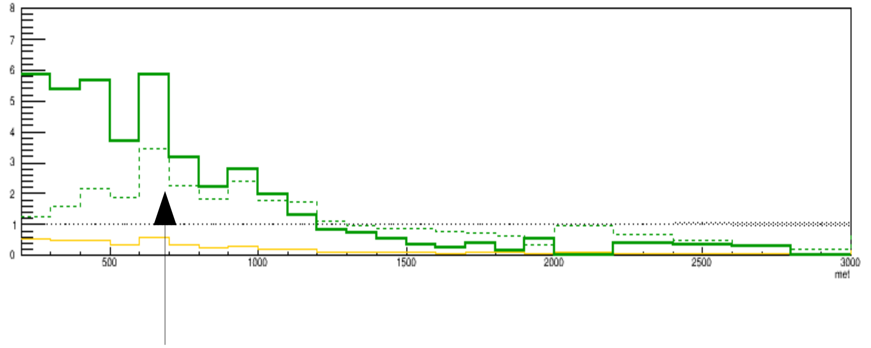
Current approach

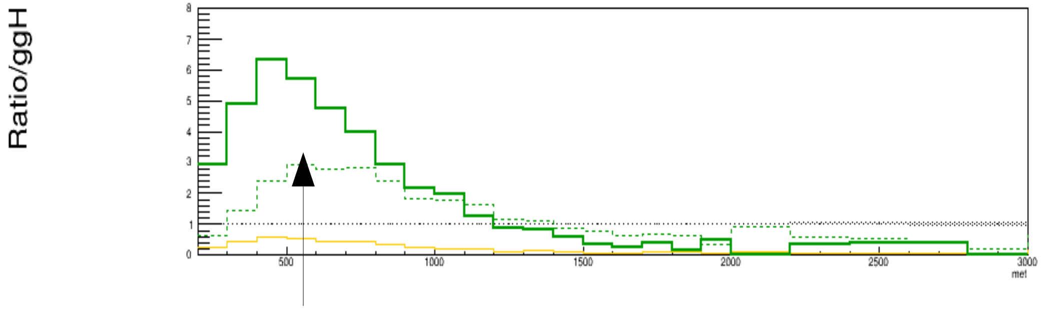


Dropping experimental unc.

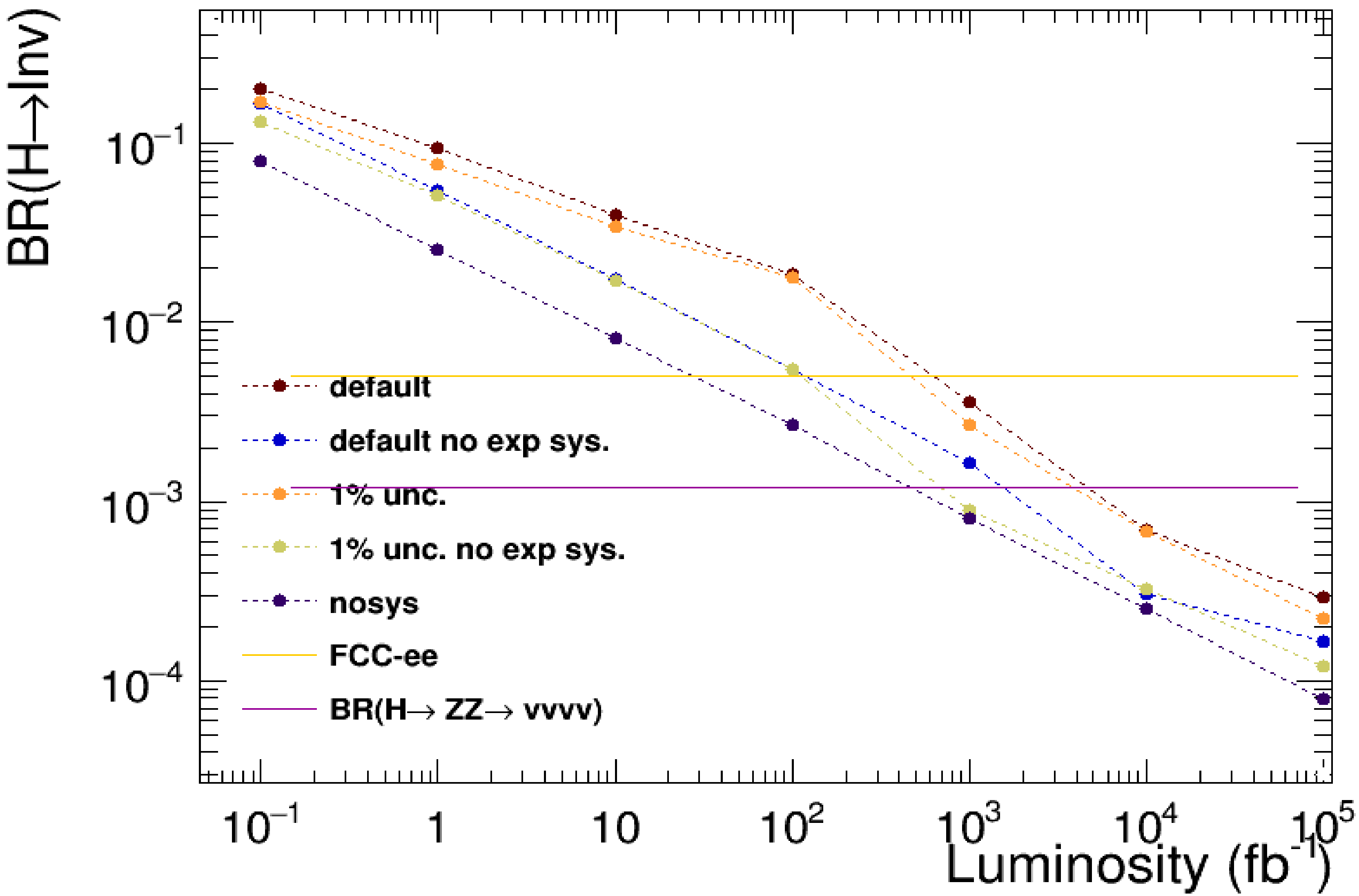


In both cases monojet dominates tt+H signal for sensitivity





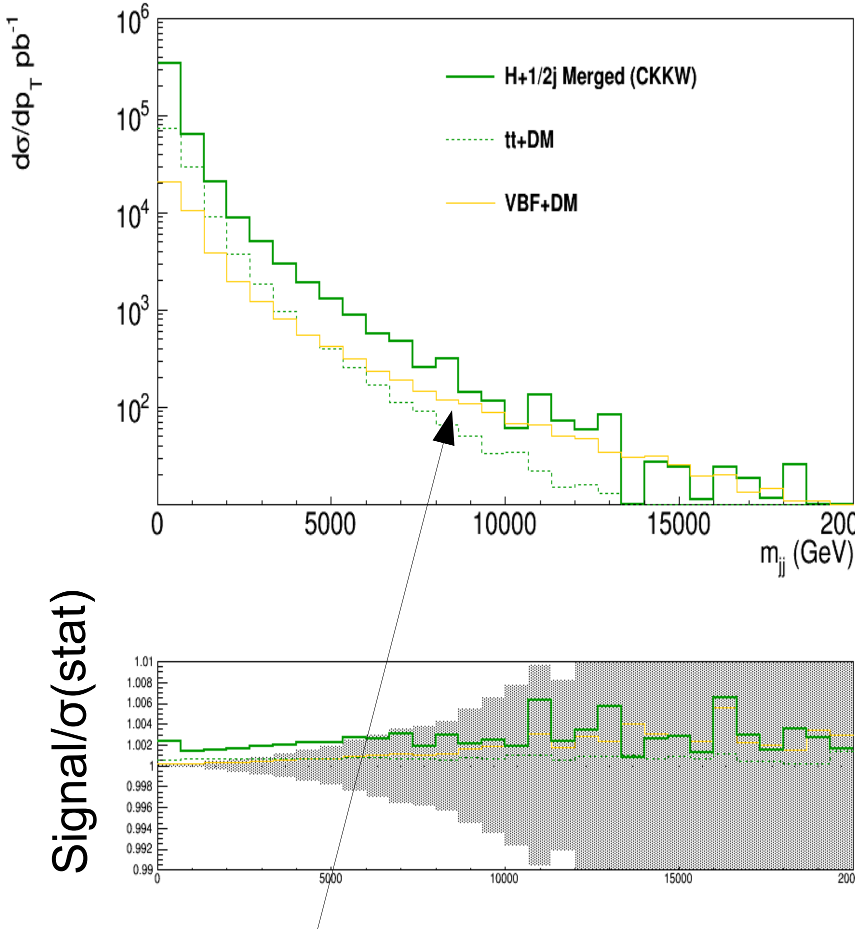
How do things scale?

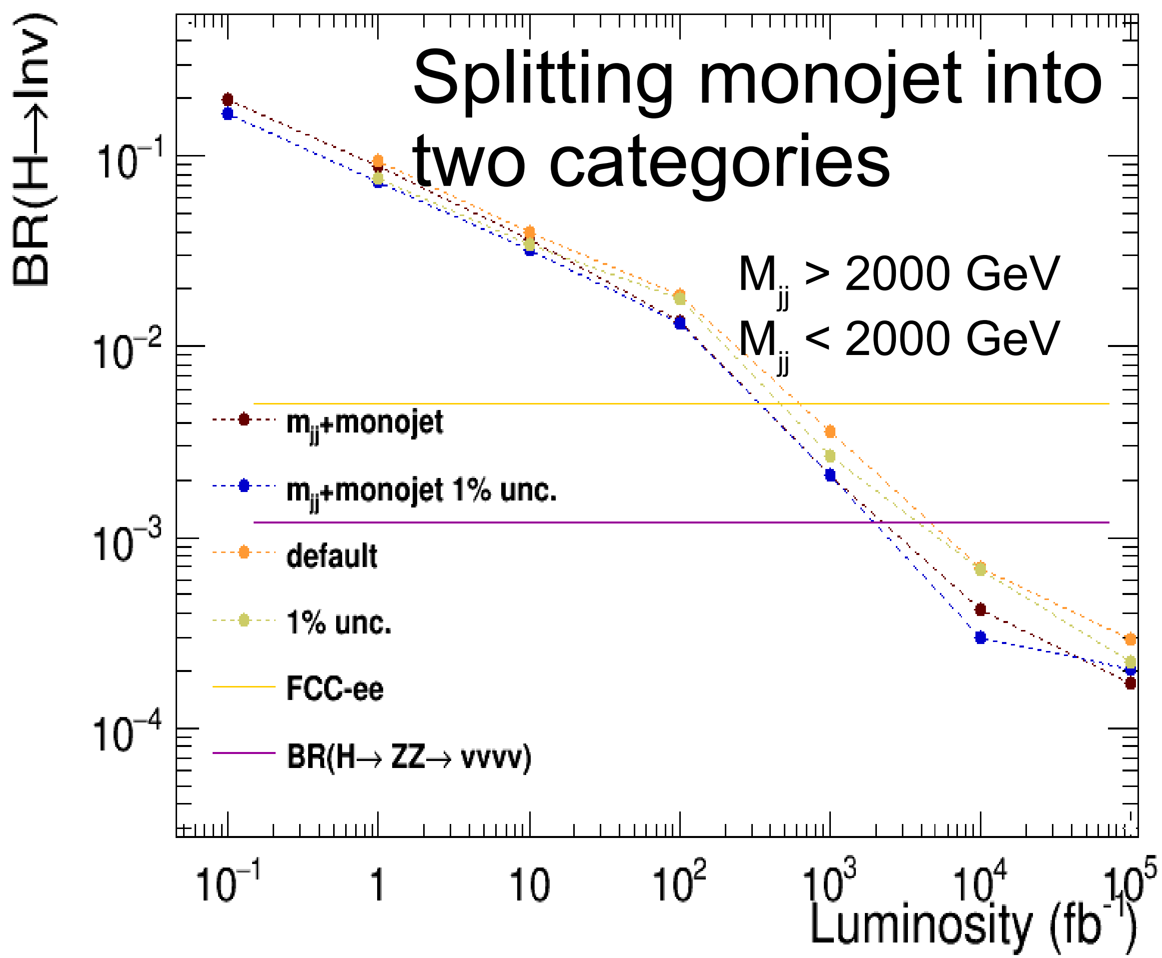


Cross the SM neutrino wall at FCC with < 1 ab^{-1}

Can we extend things?

- Can consider targetting the VBF final state?

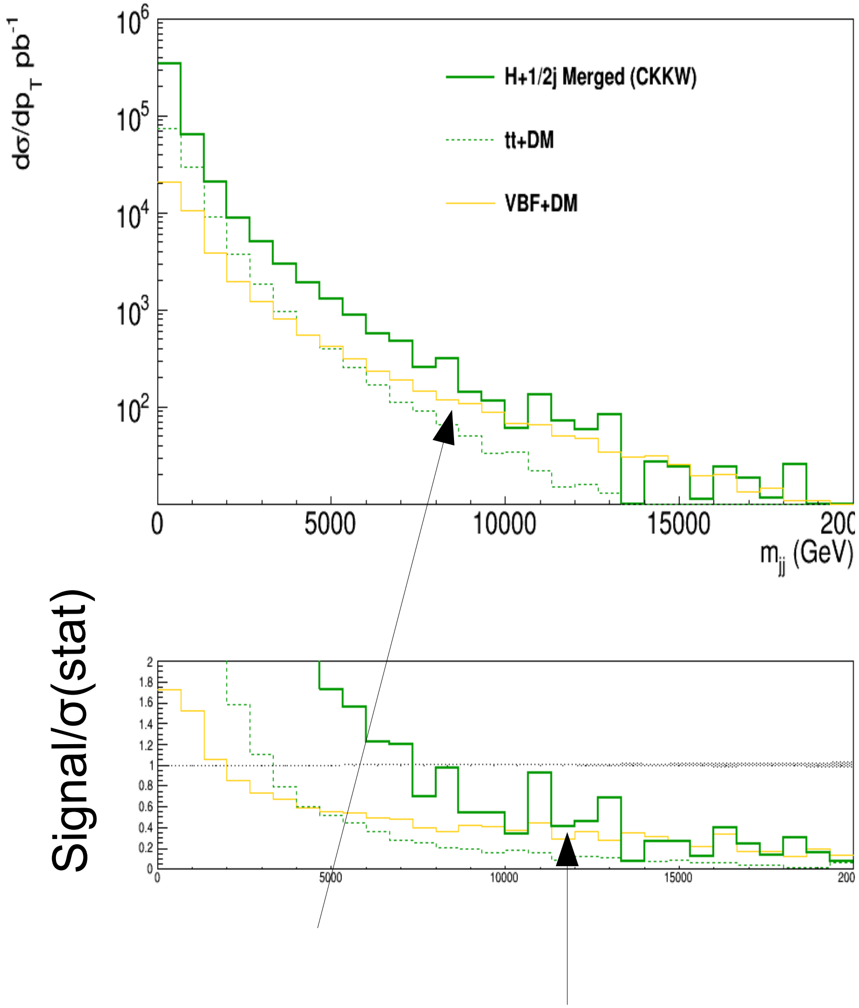


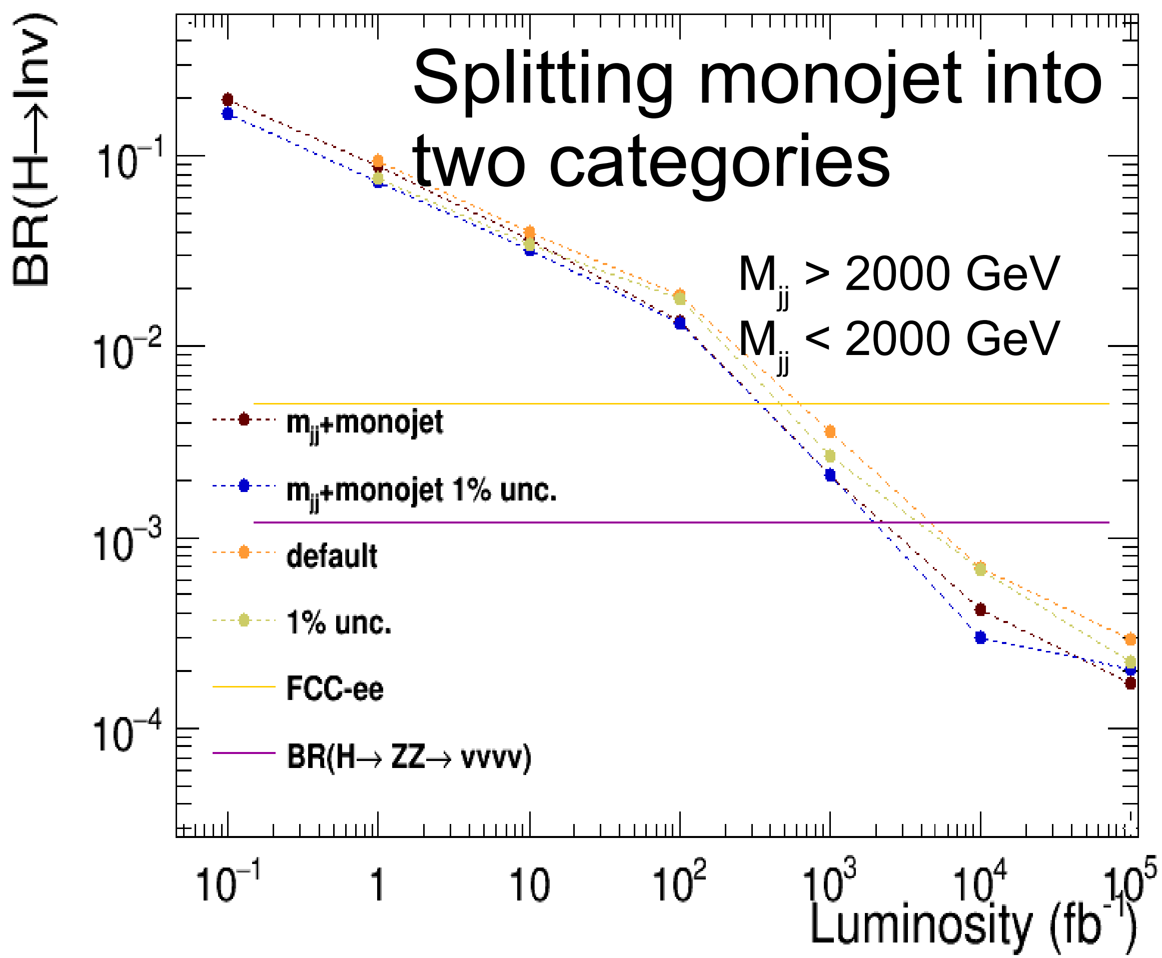


At high mjj purity for VBF can become quite high

Can we extend things?

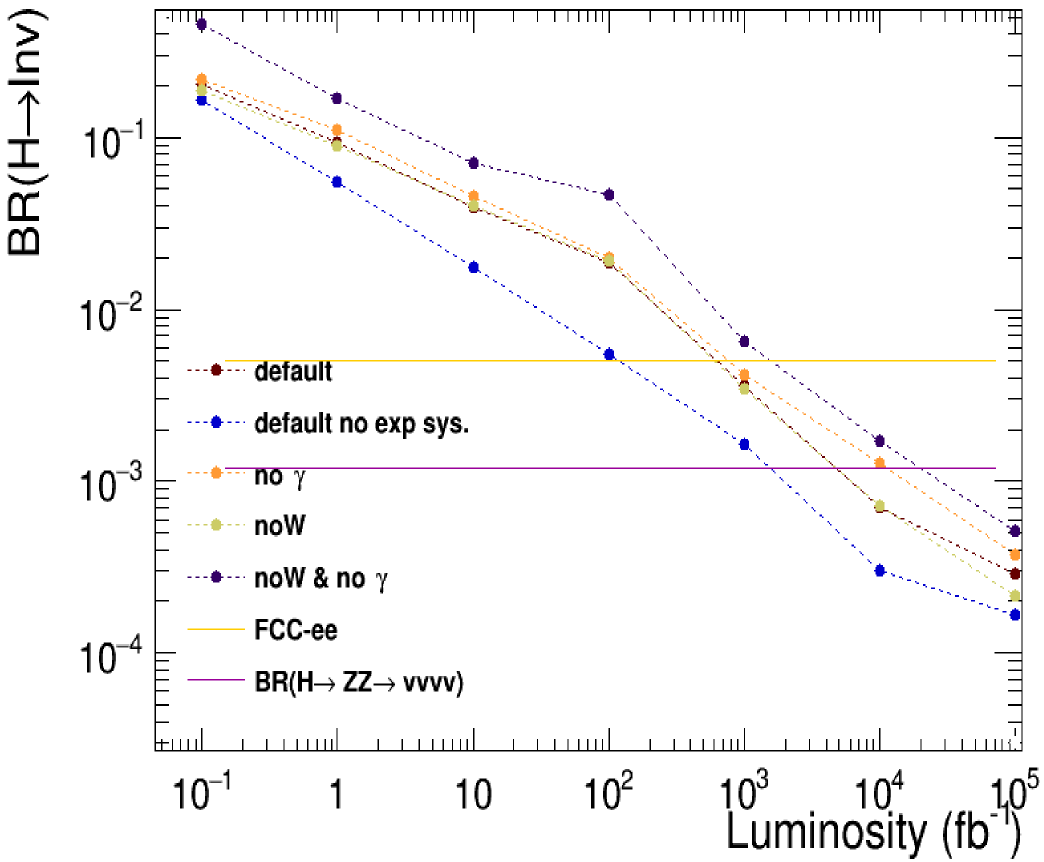
- Can consider targetting the VBF final state?

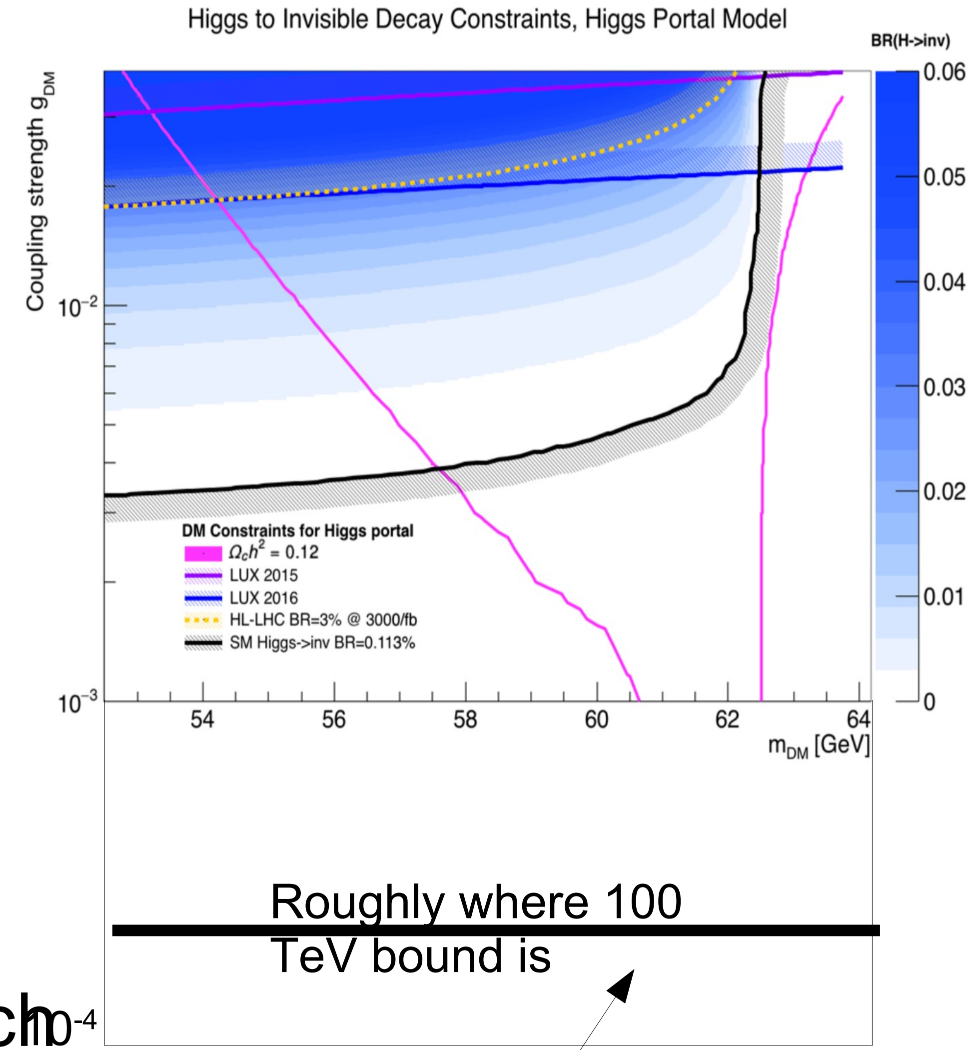




Note the broad sensitive region

What is the impact?





Relying on the Z boson gives a substantial reduction in the search

Equivalent mass splitting to be < 1 GeV (given relic)

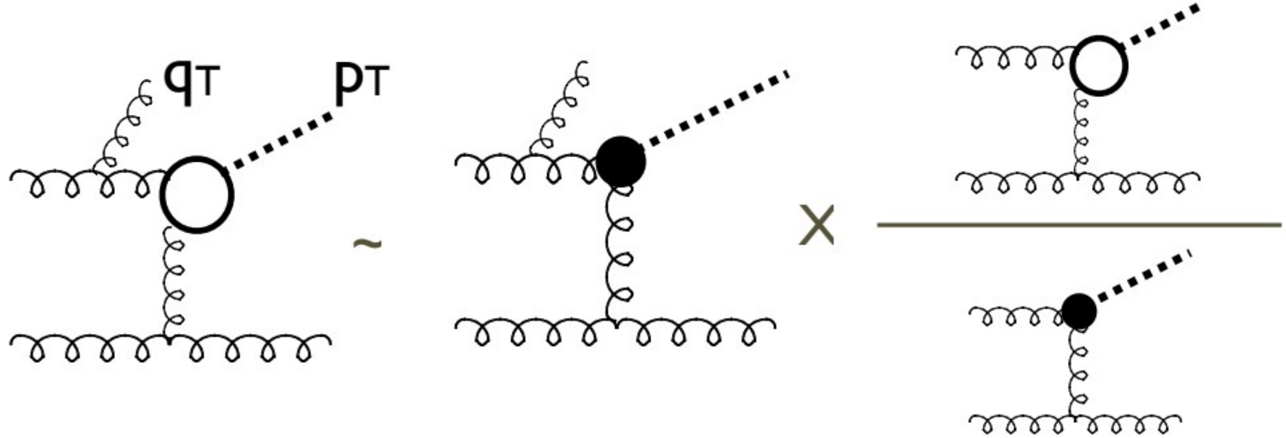
Conclusion

- Currently investigating H→Invisible
  - Monojet and tt+H are the dominant productions
  - Modern approach allows for scaling of limits
    - Result scales with luminosity
    - Systematic choice is critical for search
- Improving the search:
  - Better understanding of the Higgs p_T needed
- For Higgs Invisible we find that :
  - We can reach the neutrino wall SM H→Invisible
    - Best BR(H→Invisible) < $1\text{-}2 \times 10^{-4}$

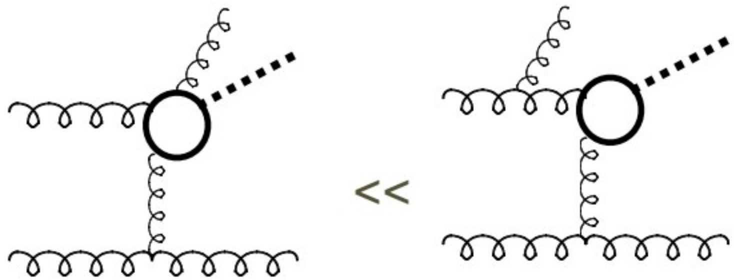
Justification for this approximation:

For $q_T < p_T$

(a)

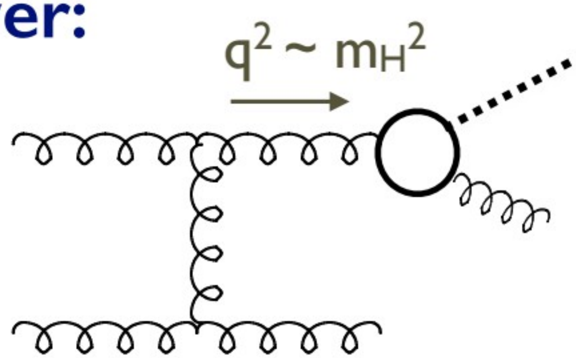


(b)

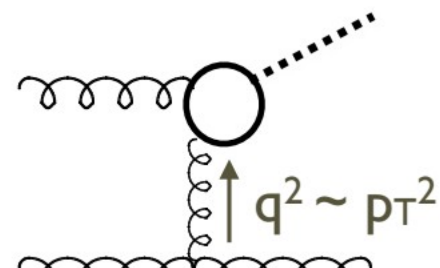


From Michelangelo Mangano

However:

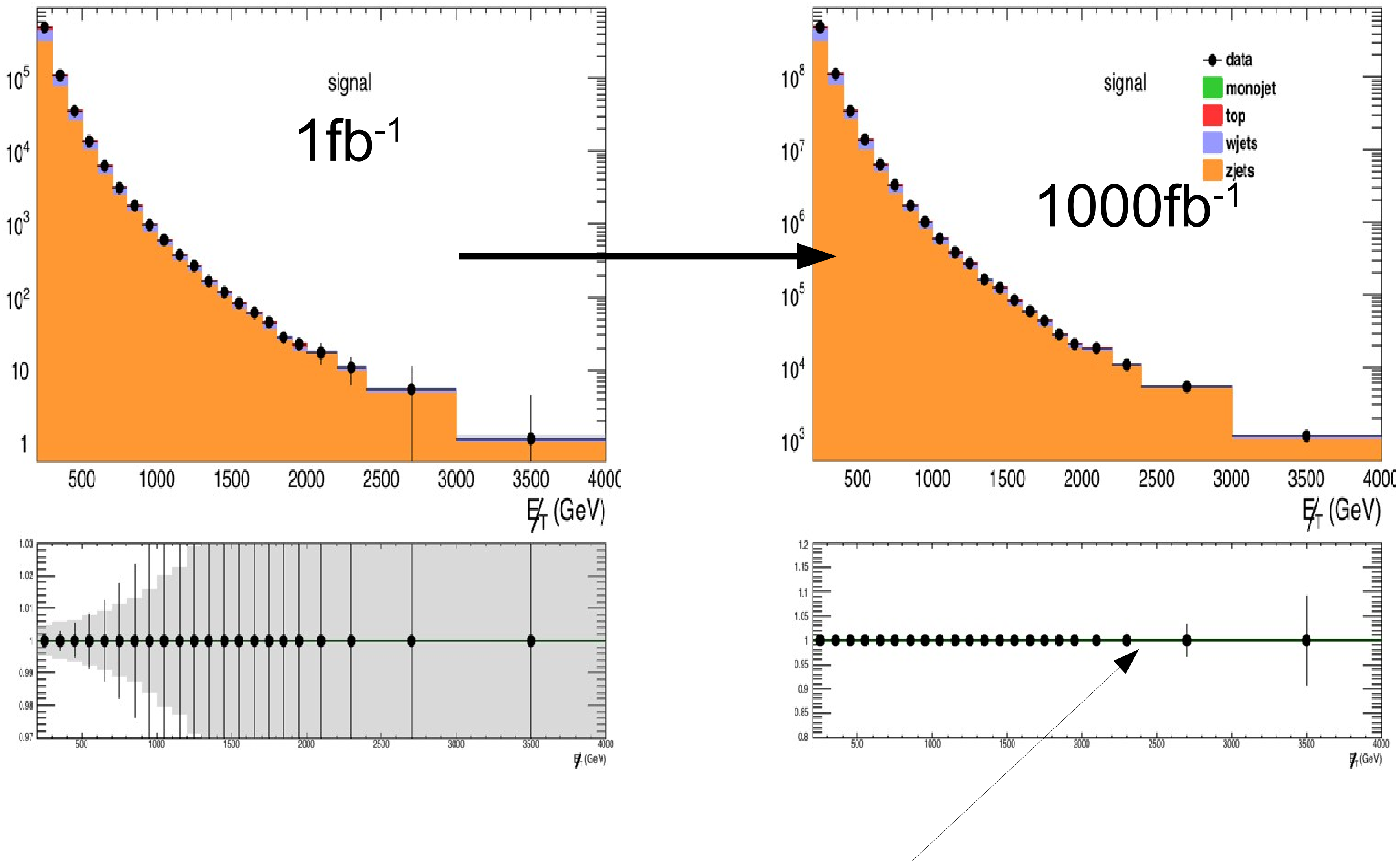


$$\sim \# \, \alpha_S \frac{m^2 + p_T^2}{m^2}$$



These diagrams will eventually take over at very large p_T.
They are not covered by the "merging" approach …. this should be looked at in some more detail ….

Whats the precision?



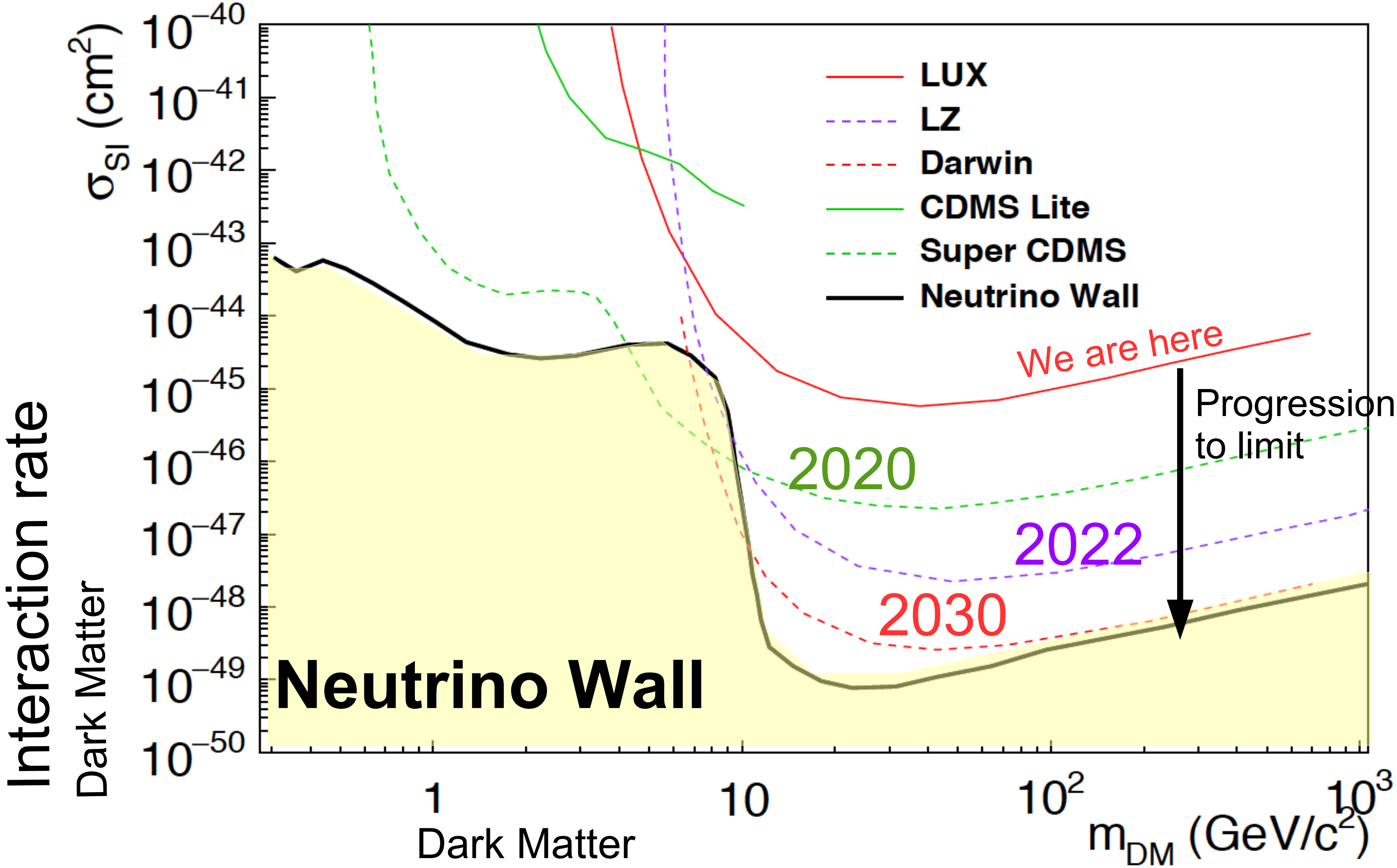
To ensure full use of the statistcal prediction needs to be a at few % level → This works now with fully correlated shape

Targeting Dark matter

- Currently there are 3 industries looking for DM
  - Direct detection
  - Indirect detection
  - Collider searches
- For each of these approaches :
  - Benchmarks have been established to drive search
    - For collider this is not as well formed
- For collider searches :
  - New benchmark to be established based precision SM
    - Turns out DM search is best way to measure high p_T V prod
  - This talk looks at this benchmark for the 100 TeV

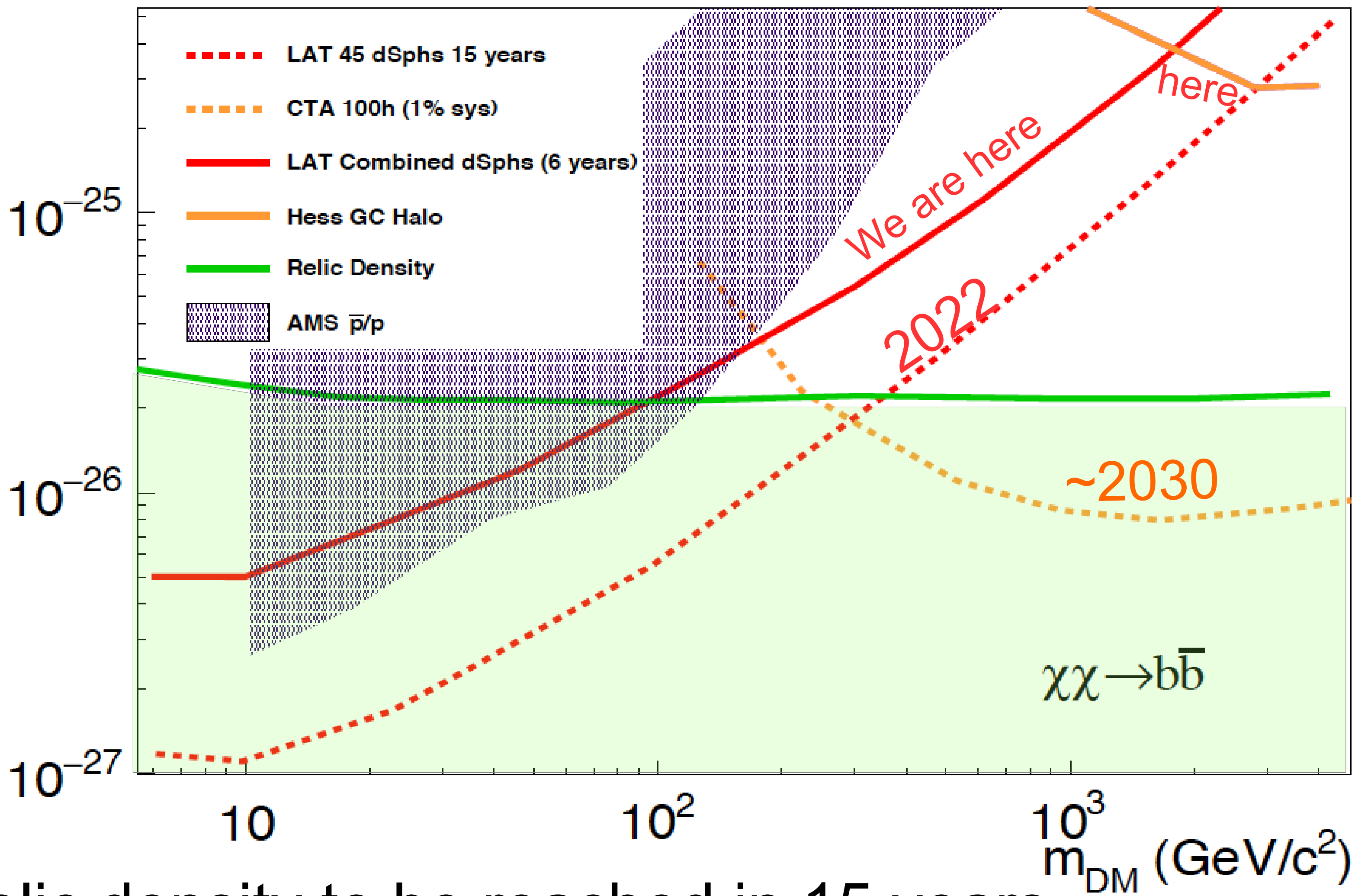
What are the ulitmate bounds?

- Ultimate bounds exist for each experiment
  - Direct detection this ultimate bound is the neurino wall



Whatr are ultimate bounds?

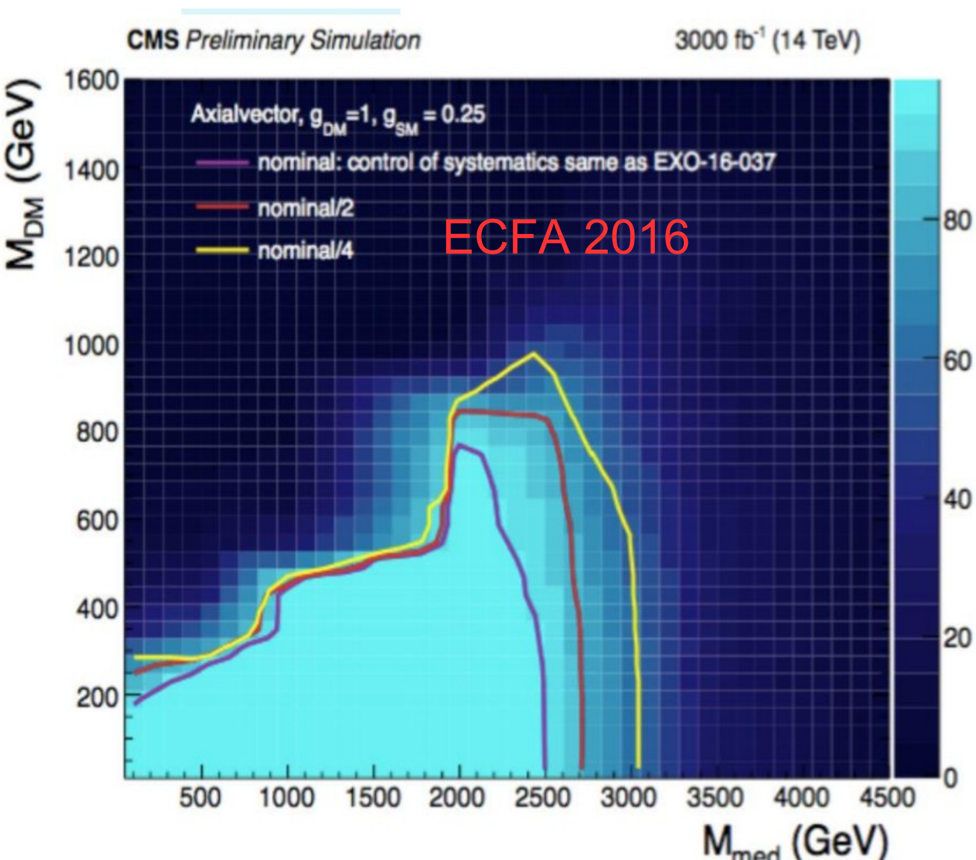
- Indirect detection ultimate bound is relic density

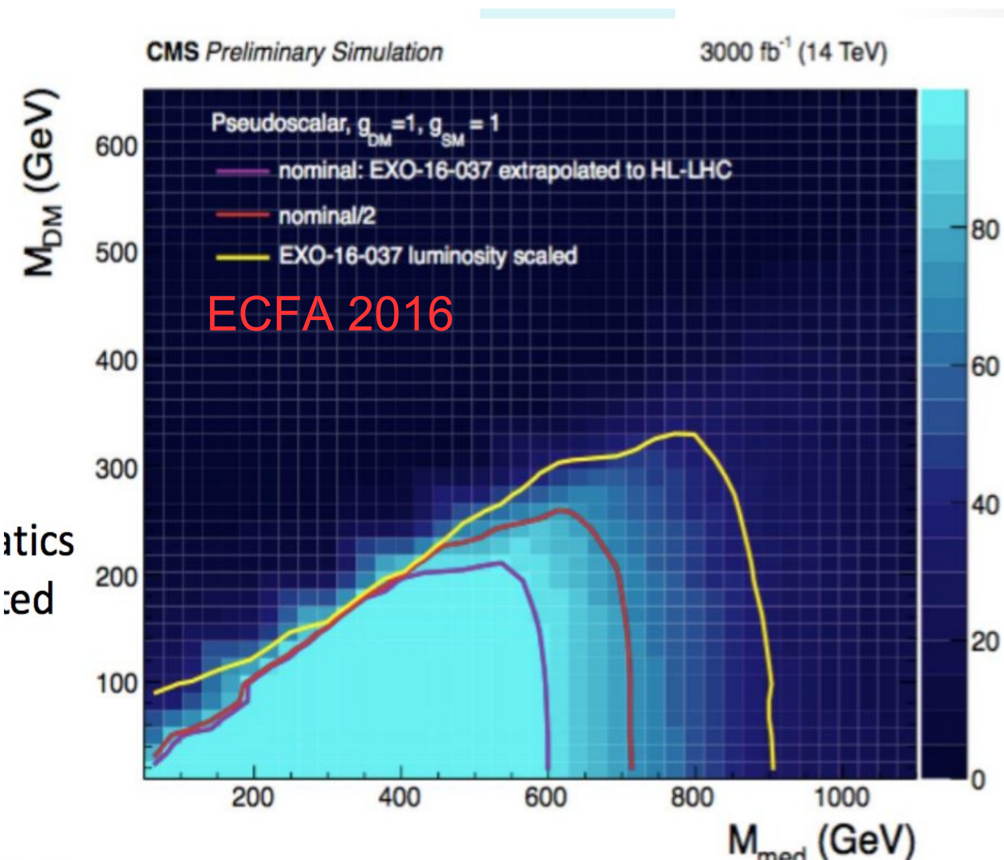


Relic density to be reached in 15 years

And for collider?

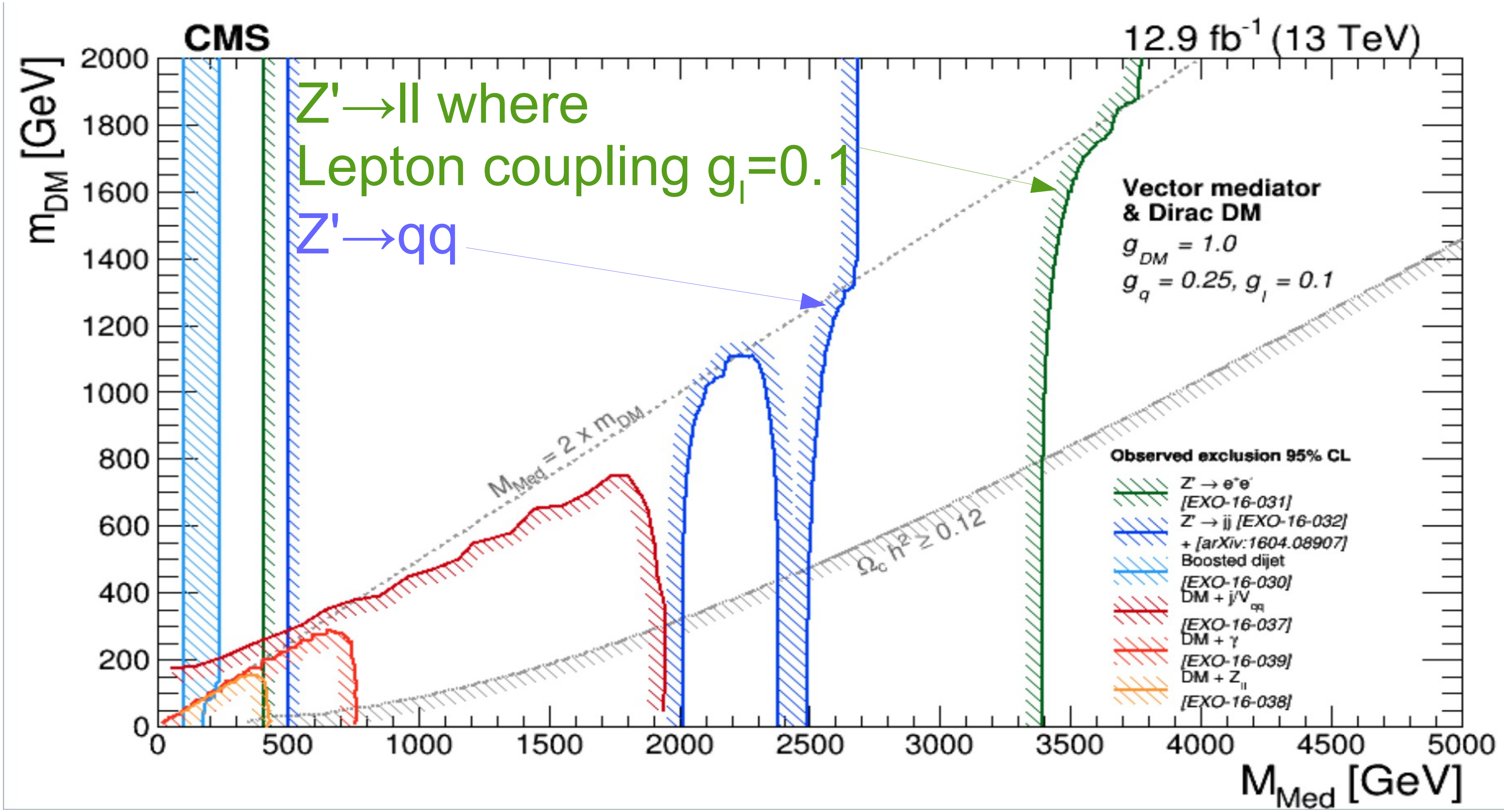
- For LHC
  - Our bounds are a bit more model dependent
  - We can start from the 14 TeV projections





For spin 1 med reach is 3 TeV For spin 0 med reach is 1 TeV

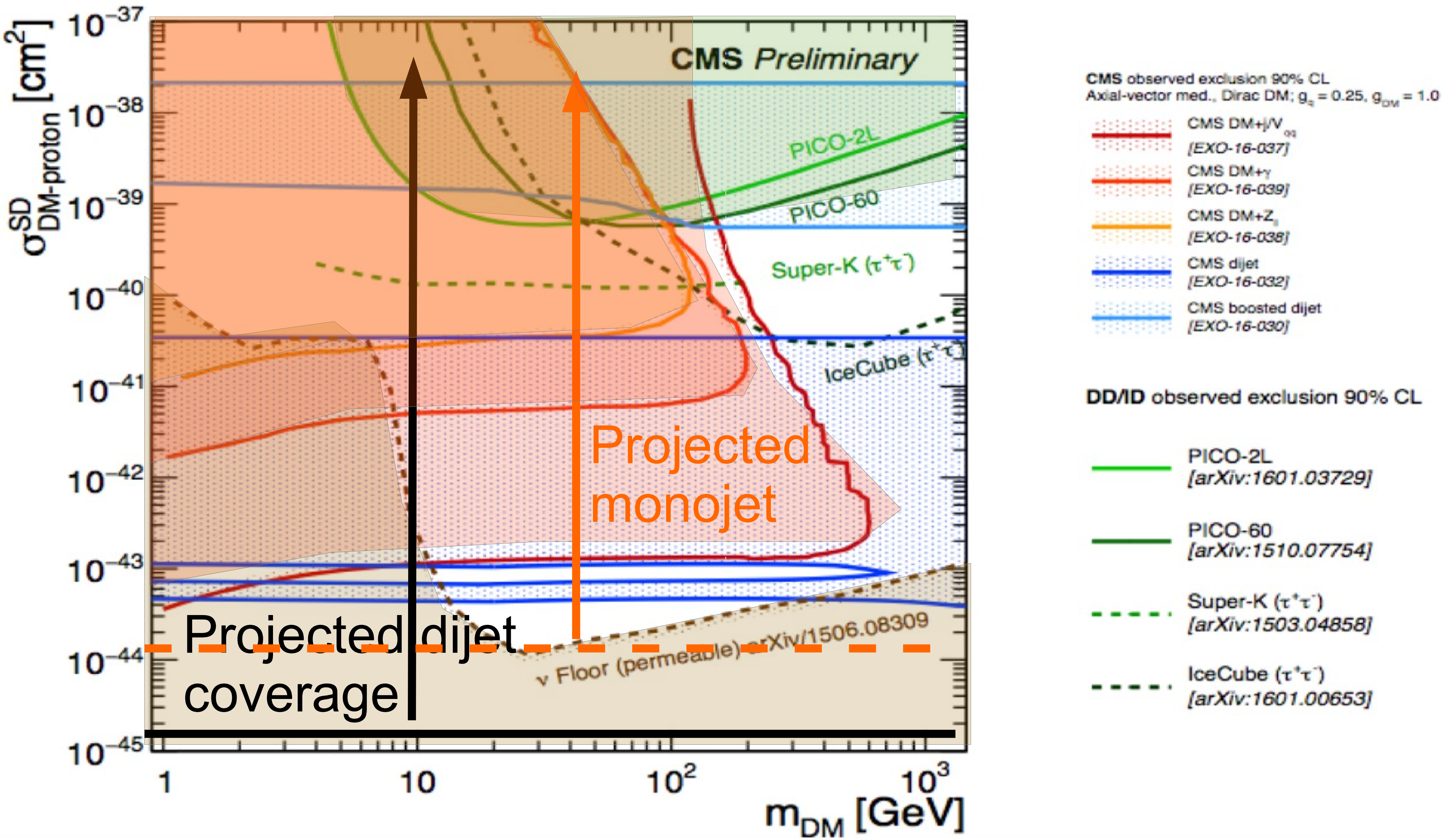
What about visible bounds?



Dijet reach : 2.5 TeV → Becomes 5 TeV with 3ab^{-1} M_{now} $(L_{future}/L_{now})^{1/8}$

Dilepton reach : 3.5 TeV → Becomes 7 TeV with 3ab^{-1} and coupling 0.1

How does this compare?



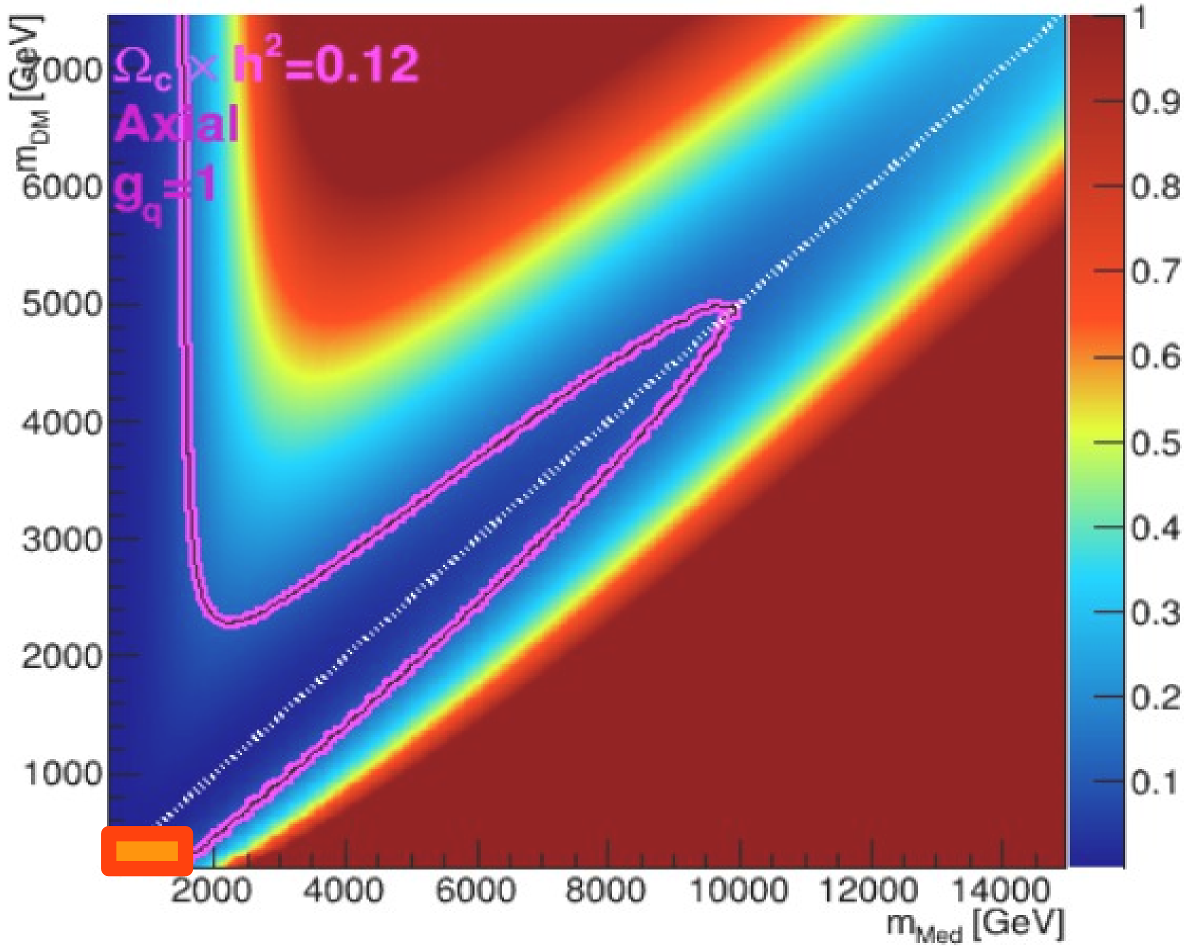
Dijet alone at 14 TeV exceed spin-dependent direct detection

How about relic density?

For a benchmark model we start to cover with LHC :

At FCC this is definitive

Note : Model is oversimplified bounds can loosen w/particles



Approximate region monojet can probe

Mediator mass Maxes out around 8-9 TeV

Smaller for coupling g_q<1

Approximate Dilepton reach

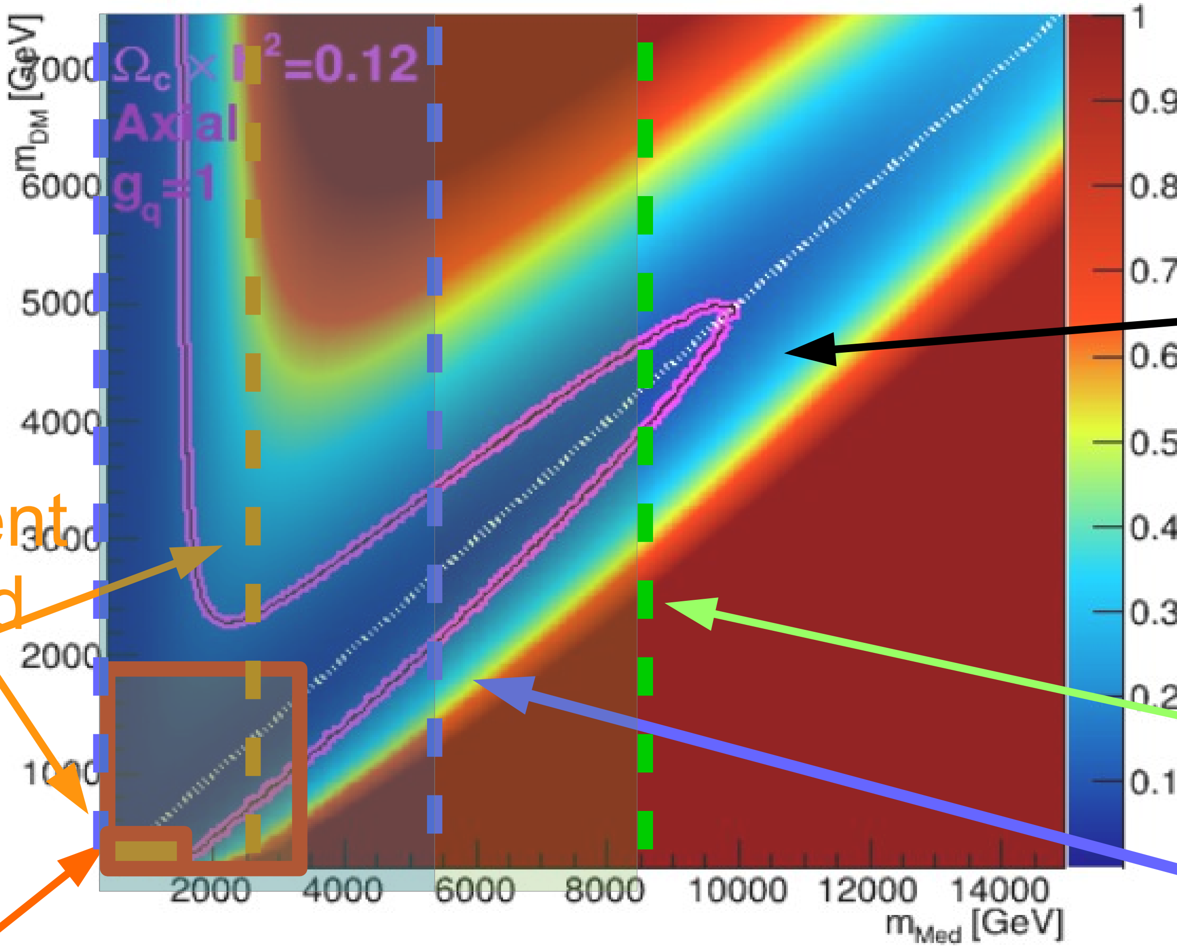
Approximate dijet reach

How about relic density?

For a benchmark model @ LHC : Spin 1 Axial-vector med

At FCC this is definitive

Note : Model is oversimplified bounds can loosen w/particles



Mediator mass Maxes out around 8-9 TeV

Smaller for coupling g_q<1

Current bound

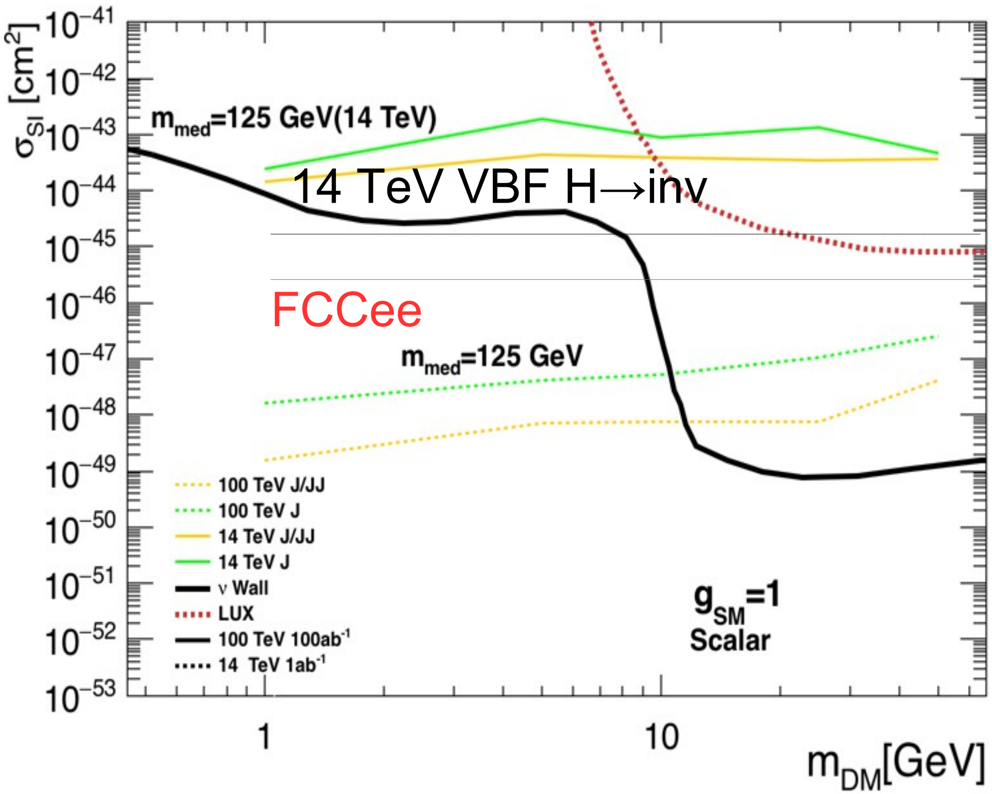
Approximate Dilepton reach

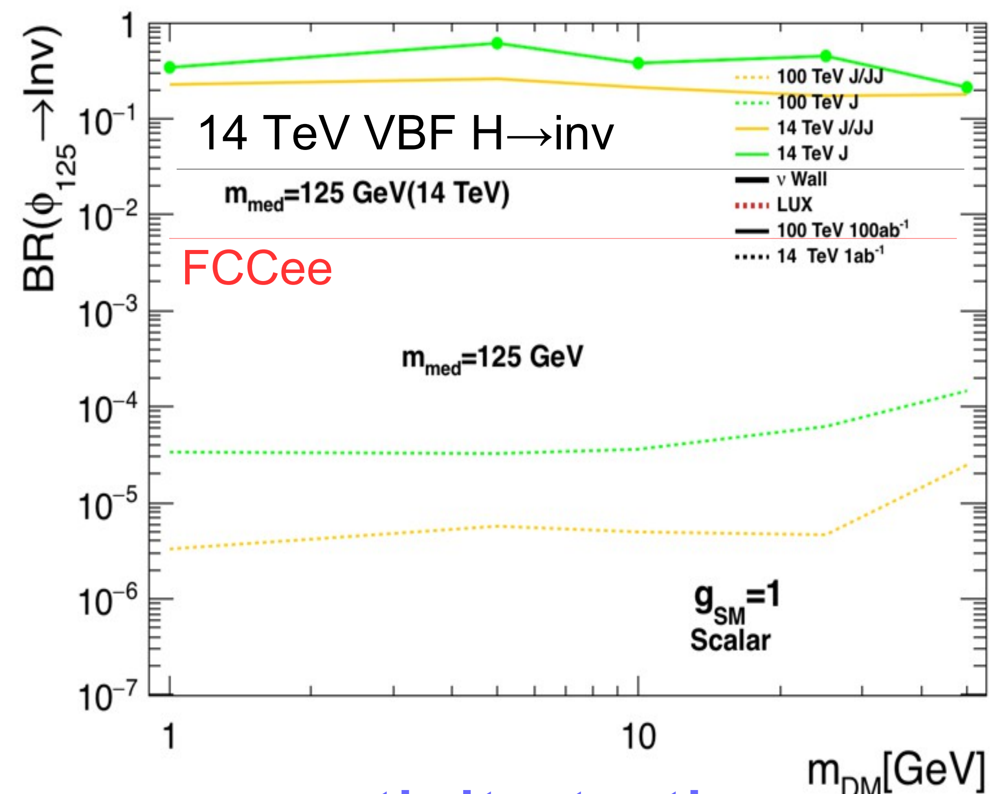
Approximate dijet reach

Approximate region monojet can probe

Higgs to invisible

- A nice benchmark is the Higgs invisible:





100 TeV machine has far more senstivity to the invisible decays of a Higgs

https://arxiv.org/abs/1603.07739
https://indico.cern.ch/event/438866/contributions/1085169/attachments/1258088/1858101/FCCwe
k_Hinv_MDG_14042016.pdf

Looking beyond monojet final state

- Deep understanding of monojet extends to many models
  - Disappear track
    - Monojet+track
  - Displaced jets

Final State	Analysis	section
jet+MET	Wino, Higgsino DM	4.3.1 - 4.3.4
jet+MET	Higgs Portal	4.3.5
jet+MET	Simplified Vector/Axial	4.4.1 - 4.4.3
jet+MET	Simplified Scalar/Pseudo	4.4.1 - 4.4.3
jet+MET	Gluion/stop coannihalation	4.5.1
VBF jets +MET	Wino, Higgsino DM	4.3.1 - 4.3.2
VBF jets +MET	Higgs Portal	4.3.5
photon+MET	Wino	4.3.2
Disappearing tracks	Wino,Higgsino	4.3.1 - 4.3.2
Disappearing tracks	Fiveplet DM	4.3.3
Disappearing tracks	Relic-Neutralino	4.3.4
lepton+γ+MET	Relic-Neutralino	4.3.4
$Z_D \to ll$+($Z_D \to ll$)	Dark Photons	4.4.4, 4.6.3
displaced jets	Dark QCD/Hidden Valley	4.6.2
long lived charged particle	Super-WIMPS/Gravitino	4.6.4
dijet	Simplified Vector/Axial	4.4.1 - 4.4.3

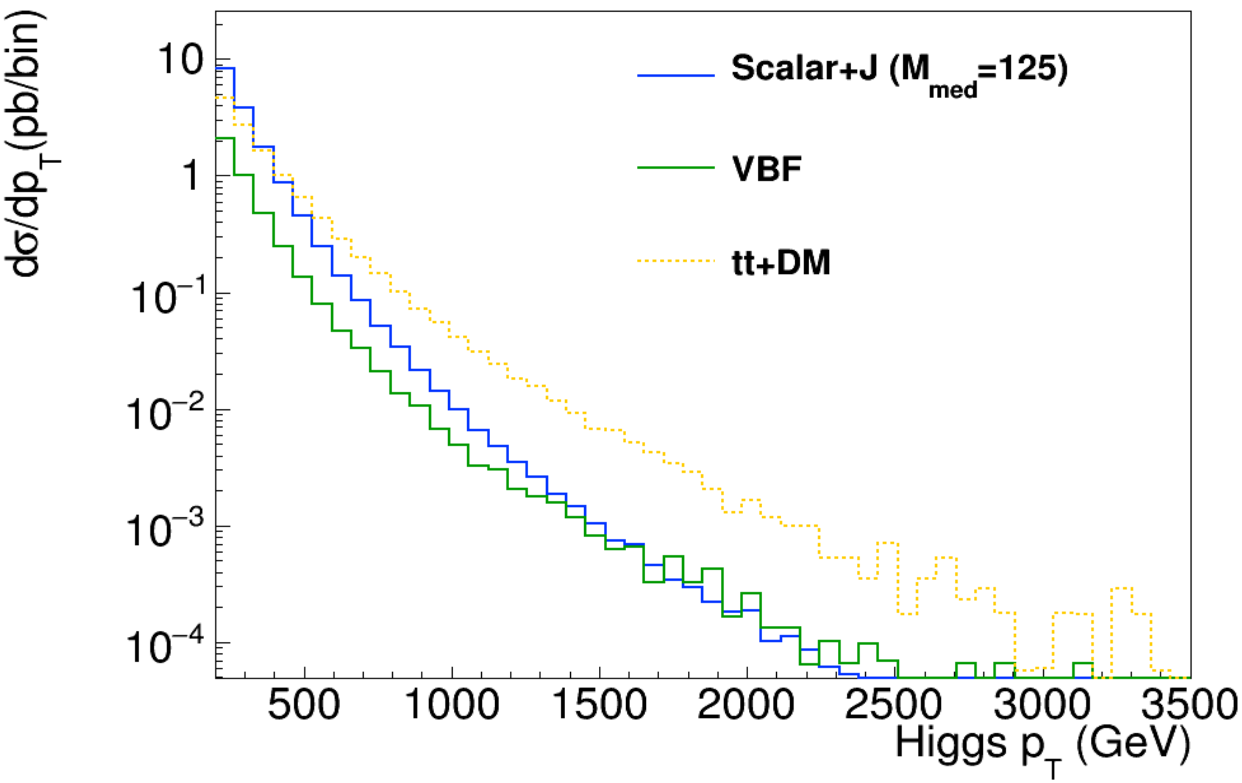
Table 5: Overview of the final states and the associated model, with a link to the respective section.

What about the cross sections?

- The relative rate to all processes is similar
  - σ(100 TeV/14 TeV) : ggH : 14.7
  - σ(100 TeV/14 TeV) : VBF : 18.6
  - σ(100 TeV/14 TeV) : WH : 9.8
  - σ(100 TeV/14 TeV) : ZH : 12.5
  - σ(100 TeV/14 TeV) : ttH : 60.8
  - σ(100 TeV/14 TeV) : bbH : 14.8
  - σ(100 TeV/14 TeV) : HH : 42.0
  - Except for ttH
- Means we expect VBF to give similar improvement
- Benchmarking agains ggH means ttH/VBF have a lot of room to gain

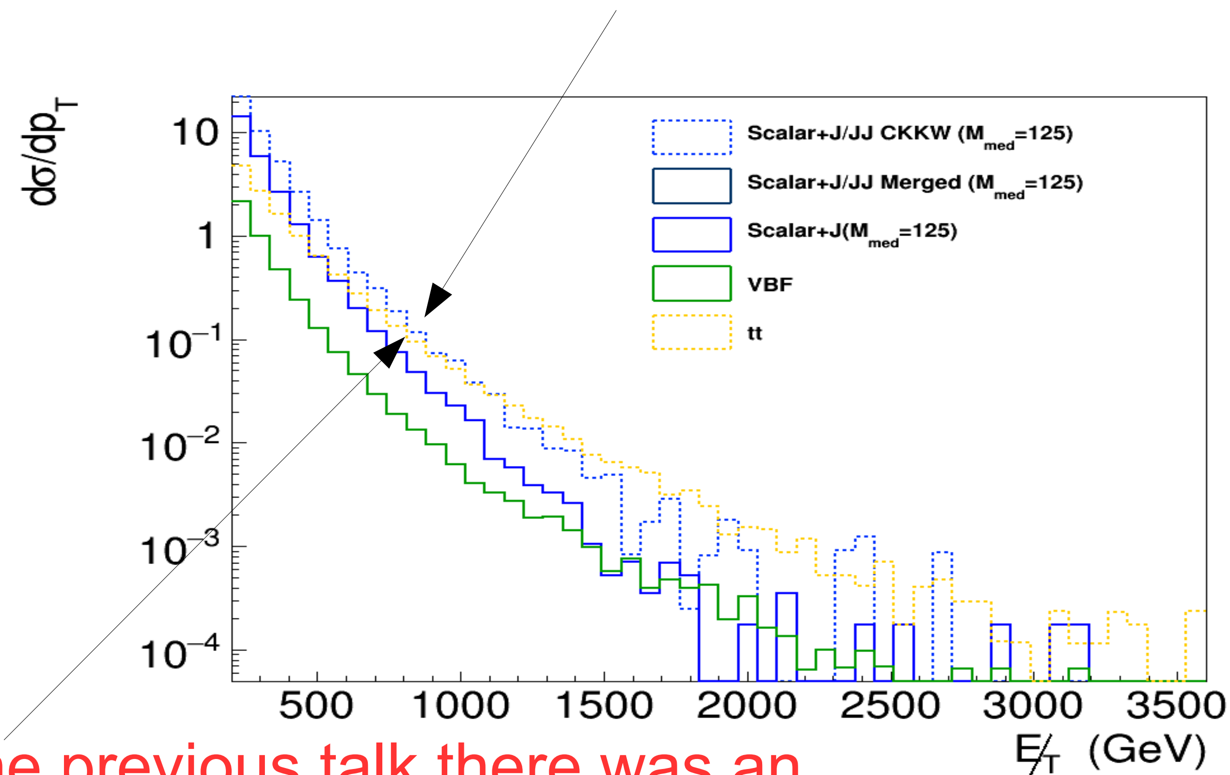
What are the production modes?

- At 100 TeV :
  - ttH is hugely enhanced
  - When compared with H+1j form gluon fusion it wins



What are the production modes?

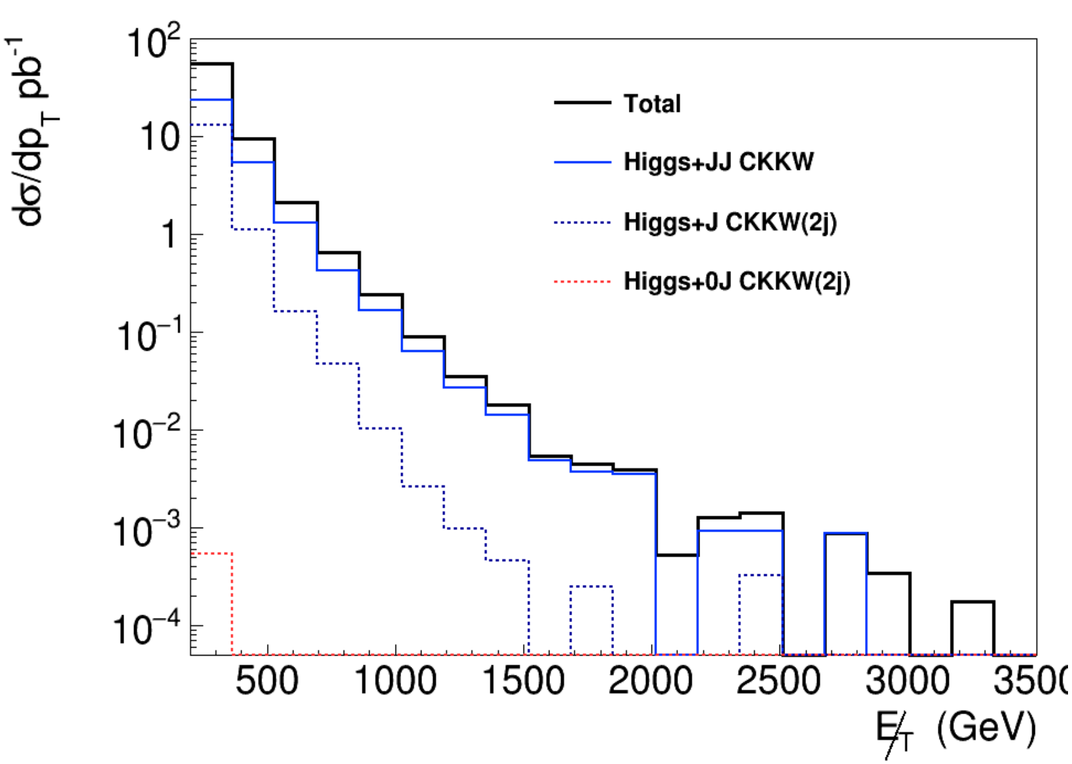
- At 100 TeV :
  - ttH is hugely enhanced
  - When compared with H+1j form gluon fusion it wins
  - However H+2j is also large

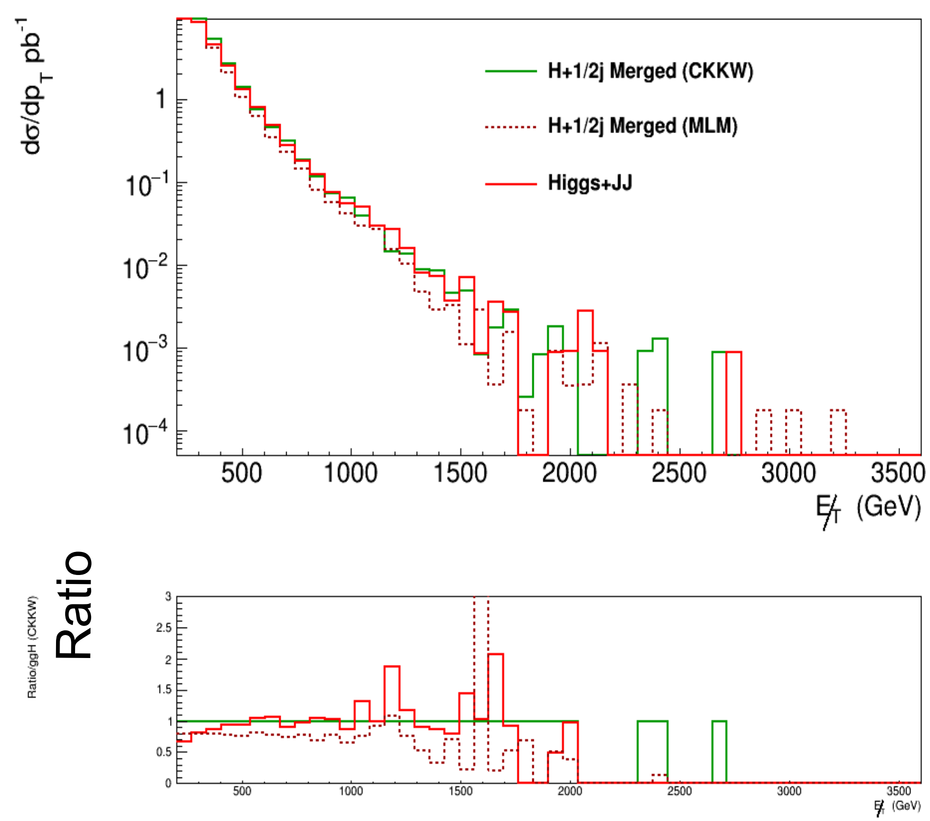


Note in the previous talk there was an issue in the 2jet generation (was a bug)

Cross checking the 2jet model

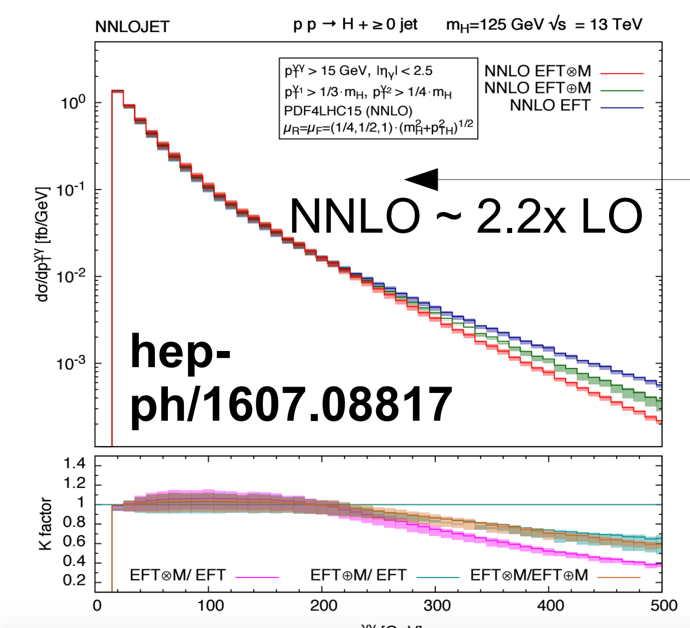
- When this was previously present
  - There was a bug (turns out the impact is small!)
- At 100 TeV :
  - Different setups give roughly the same yield





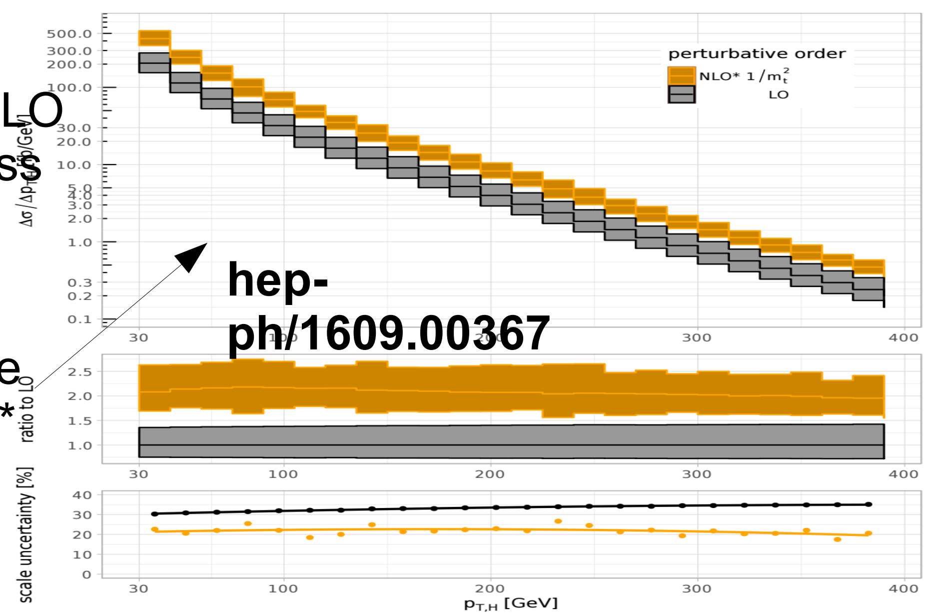
A note about Higgs p_T

- We are using MG@NLO 0/1/2 jet LO finite m_t
  - This generation accounts for the finite top mass
  - Finite top mass is the dominiant effect at high p_T
  - However generation is alson only LO
- Several approaches to take into account NLO



Scale down NNLO by finite top mass effect

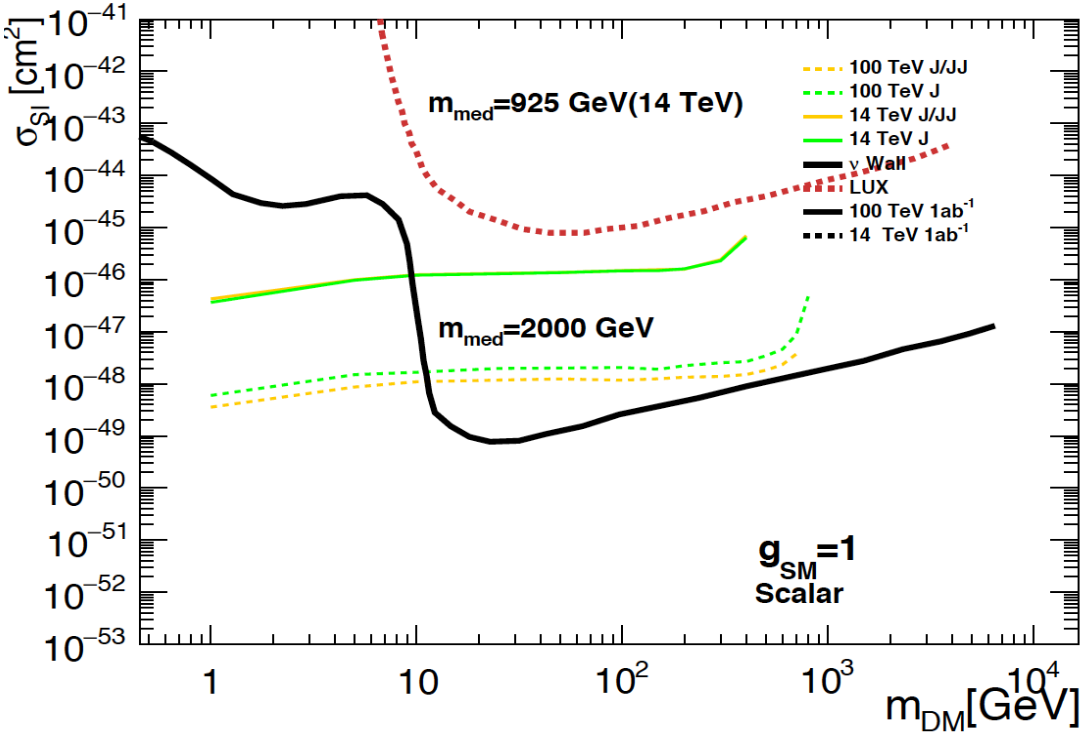
Scale up LO Finite top mass by NLO* contribution

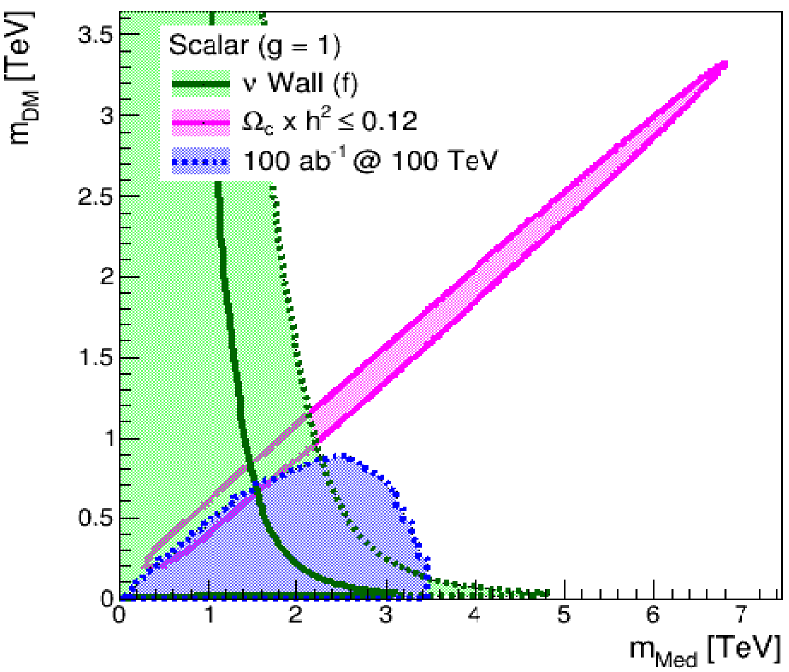


We will scale the result by x2 after the fact

Spin 0

- For spin-0 the bounds are more challenging





Projections with a scalar simplfiied model indicate :

Close to crossing the neutrino wall with the FCC detector

Close to reaching the bounds of direct detection

Rest of this talk : How do we impove these bounds?

We will do this in the context of Higgs invisible