



Experimental Methods and Physics at the LHC

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24th Vietnam School of Physics: Particles and Cosmology



Jet Substructure and Related Searches

Why Jet Substructure?

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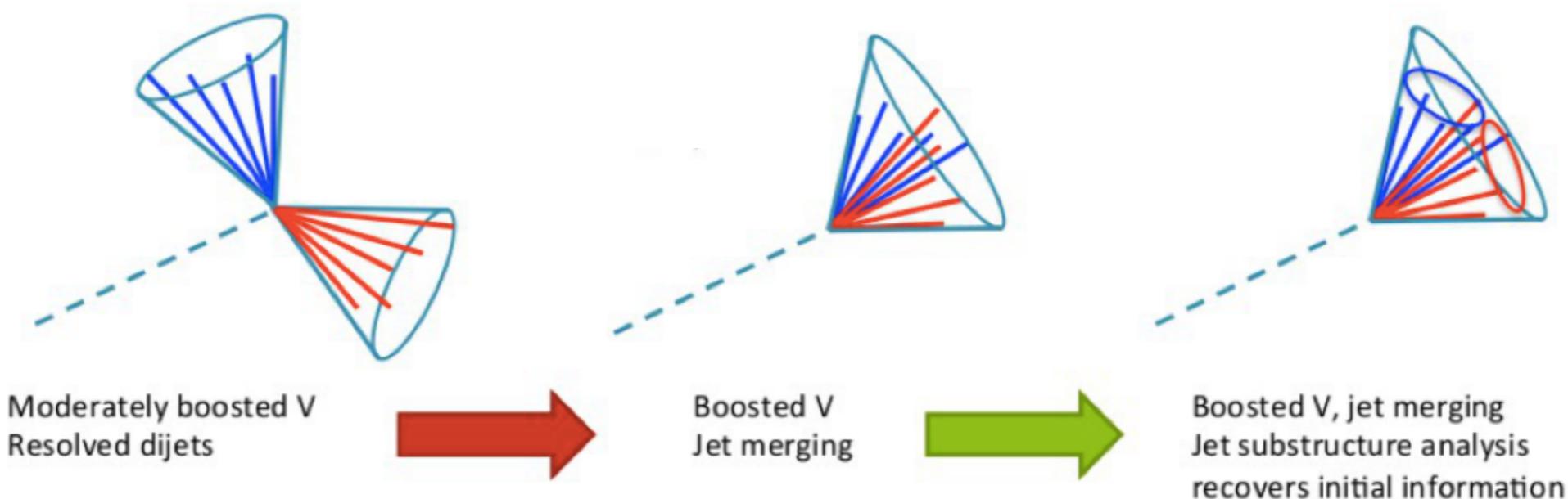
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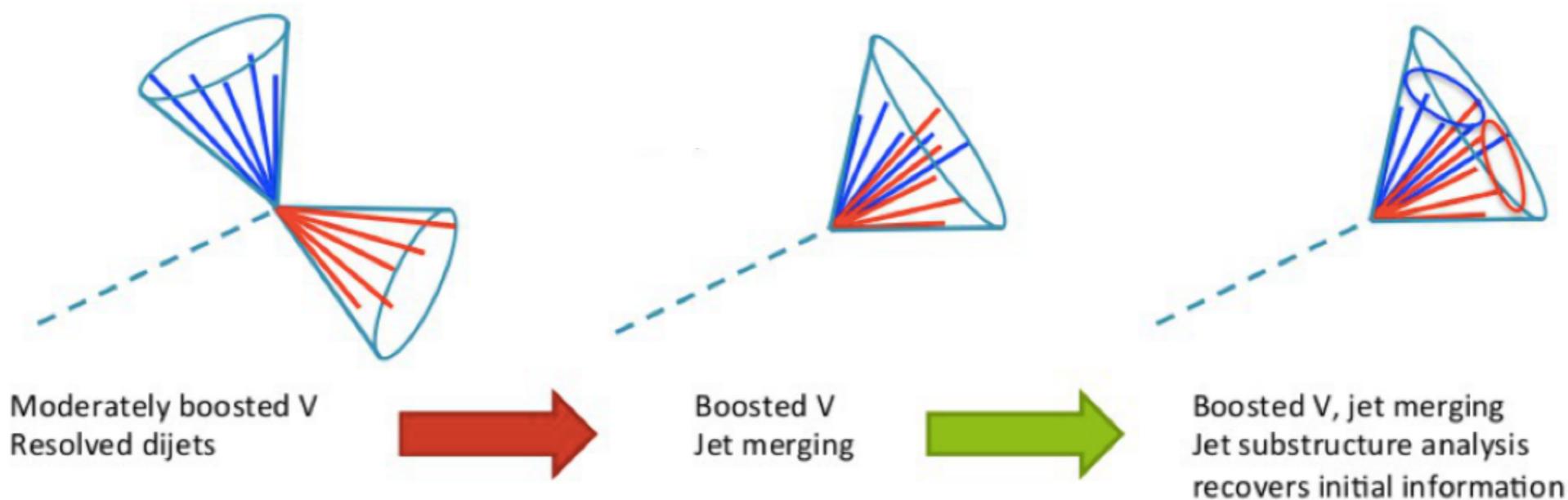
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 - ▶ Decay products can be W, Z, top, or Higgs
- The decay products of boosted particles tend to be collimated and reconstructed as one merged object in the detector
 - ▶ We have to use new techniques to reconstruct these merged objects and study the inner structure

When We Have Boosted Particles

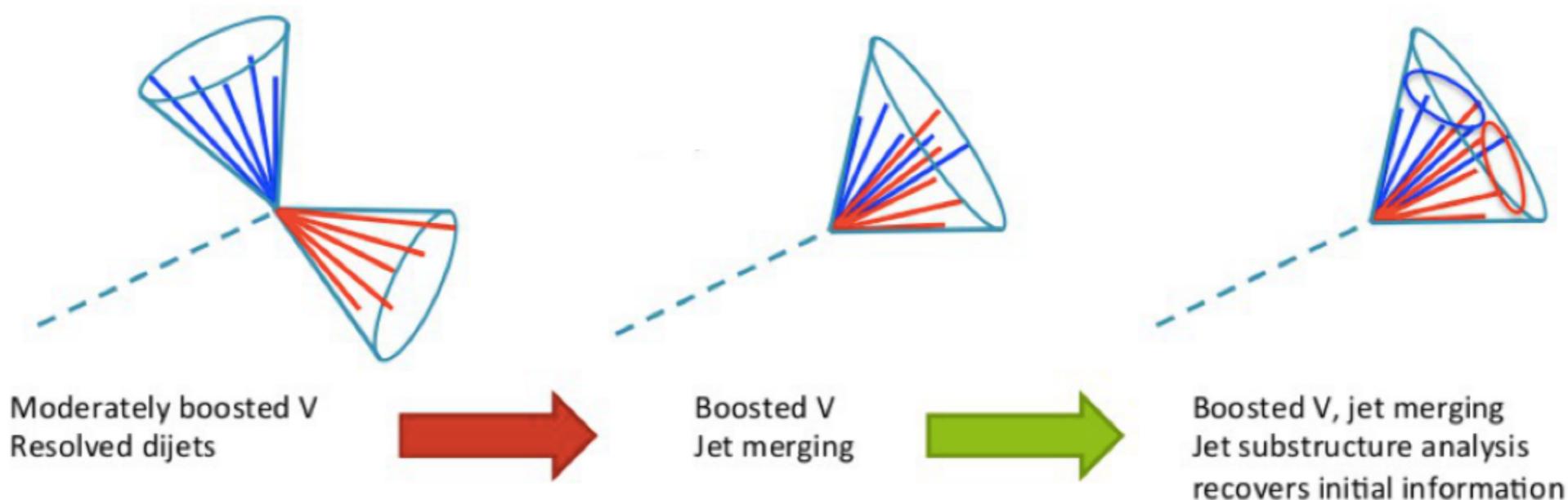


When We Have Boosted Particles

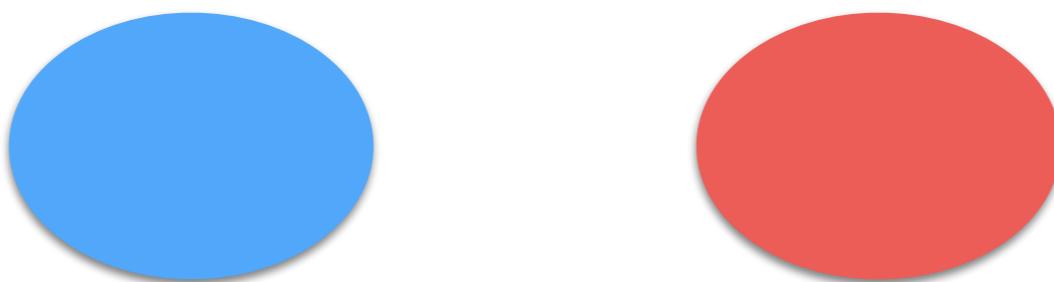


$$\Delta R = 0.4 \rightarrow \Delta R = 0.8$$

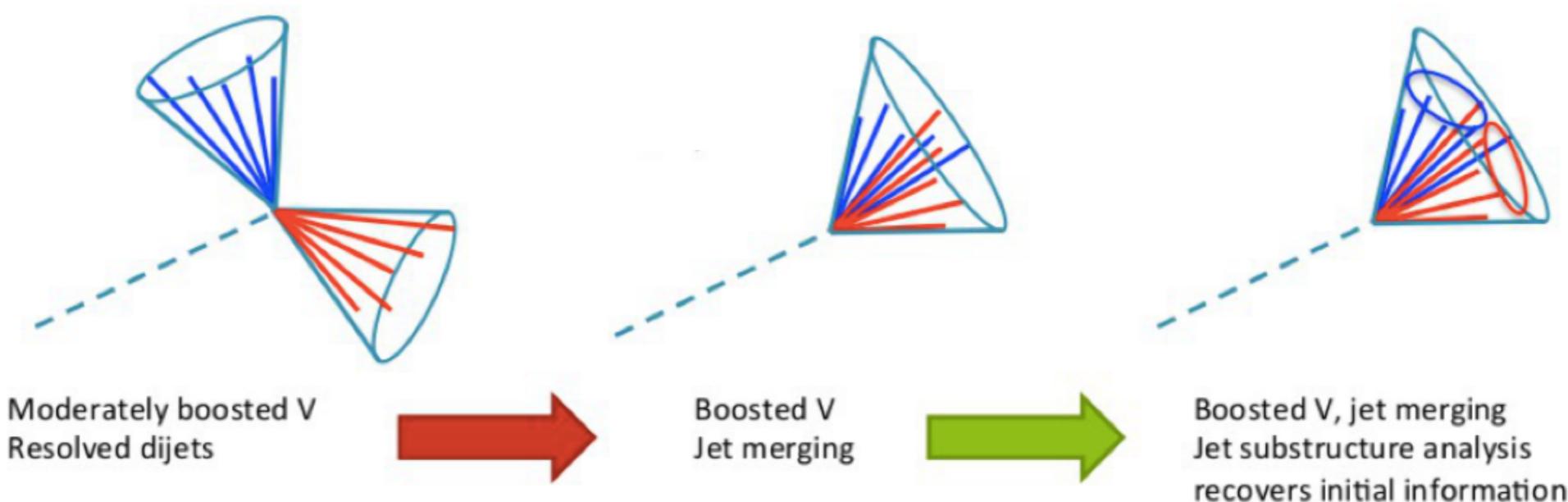
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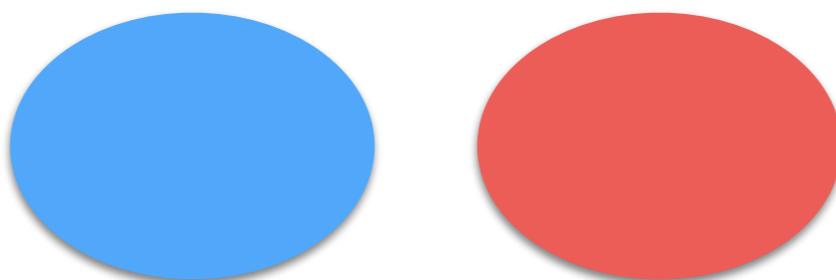
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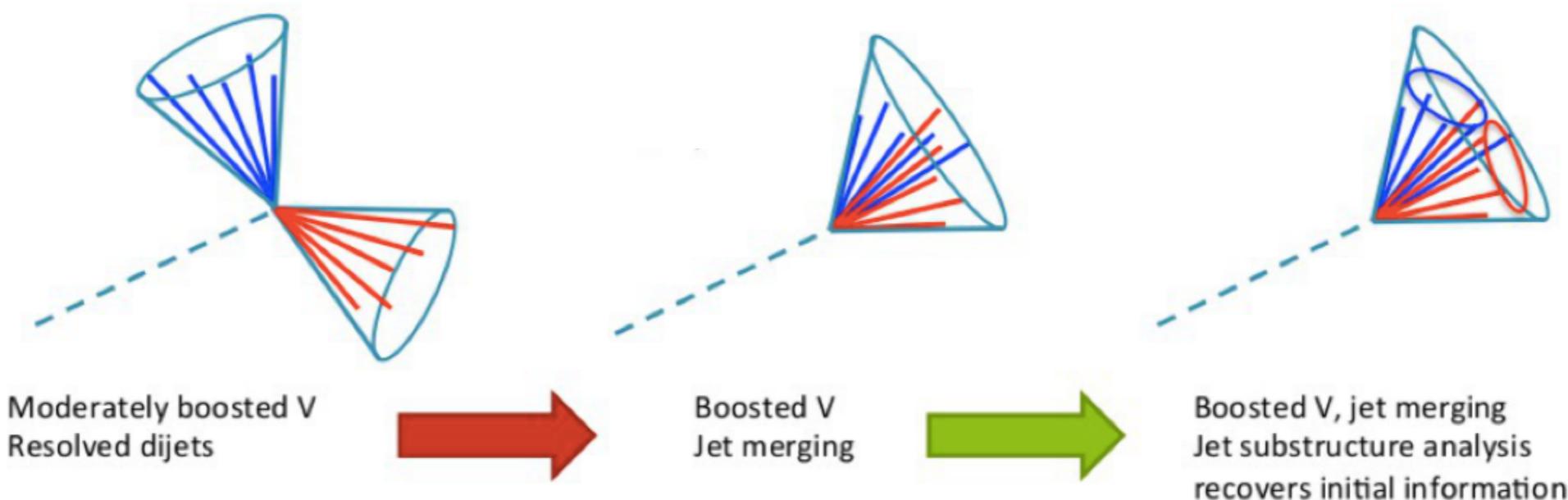
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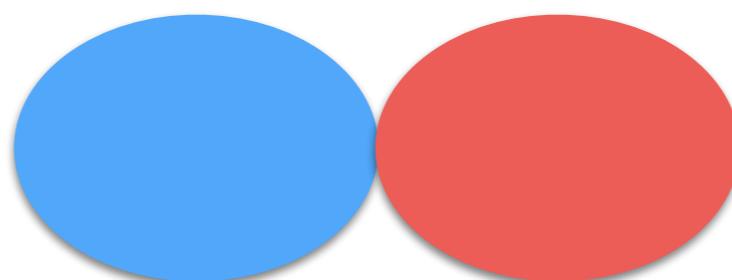
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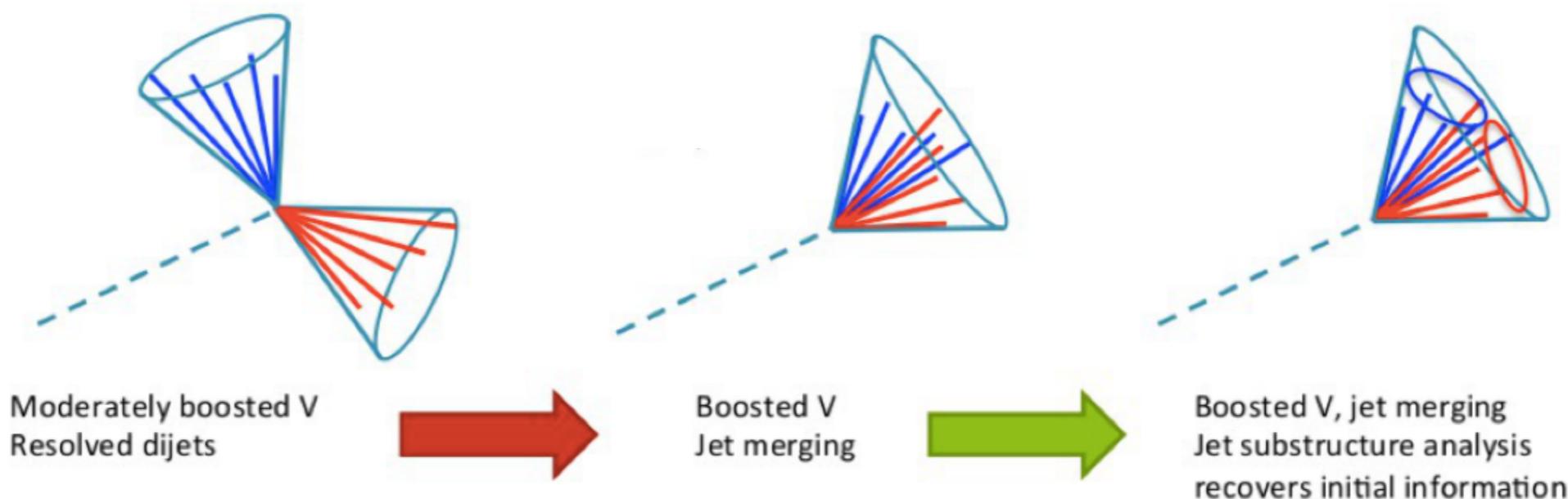
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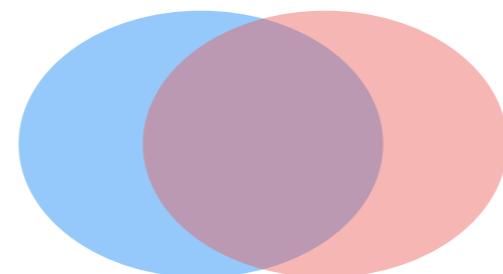
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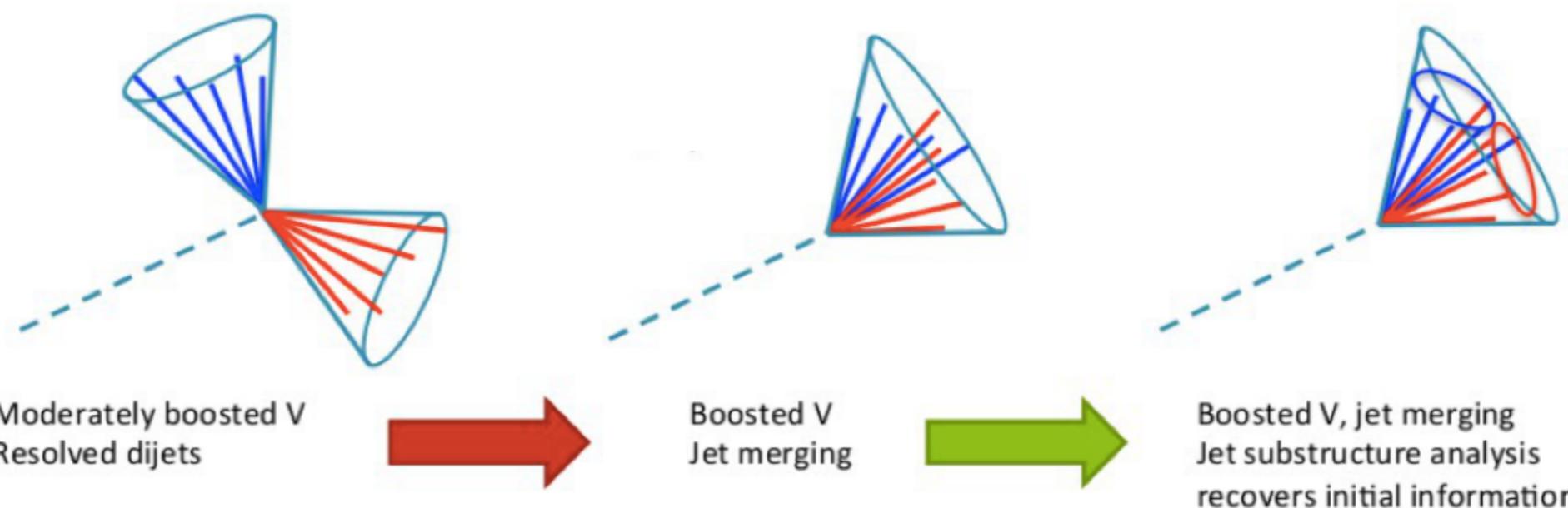
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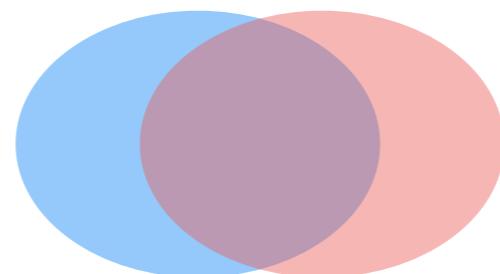


When We Have Boosted Particles



$$\Delta R = 0.4 \rightarrow \Delta R = 0.8$$

$$\Delta R_{\min} \approx 2 \frac{M_B}{p_B}$$



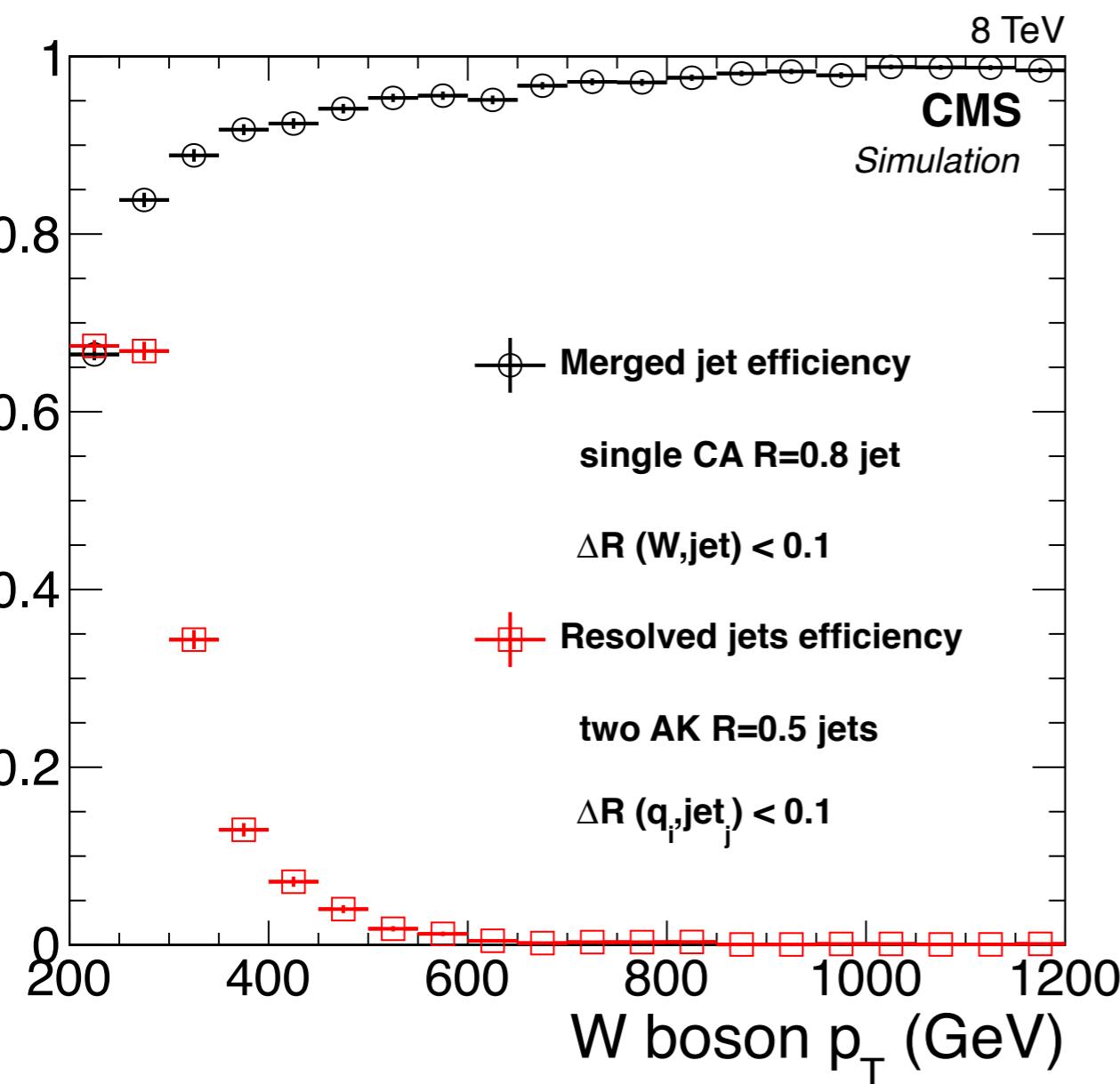
Jet Reconstruction Efficiency

JHEP12(2014)017

	R=0.5	R=0.8	R=1.5	R=0.087
W	320 GeV	200 GeV	110 GeV	1.8 TeV
Higgs	500 GeV	312 GeV	170 GeV	2.8 TeV
Top	688 GeV	430 GeV	230 GeV	4 TeV

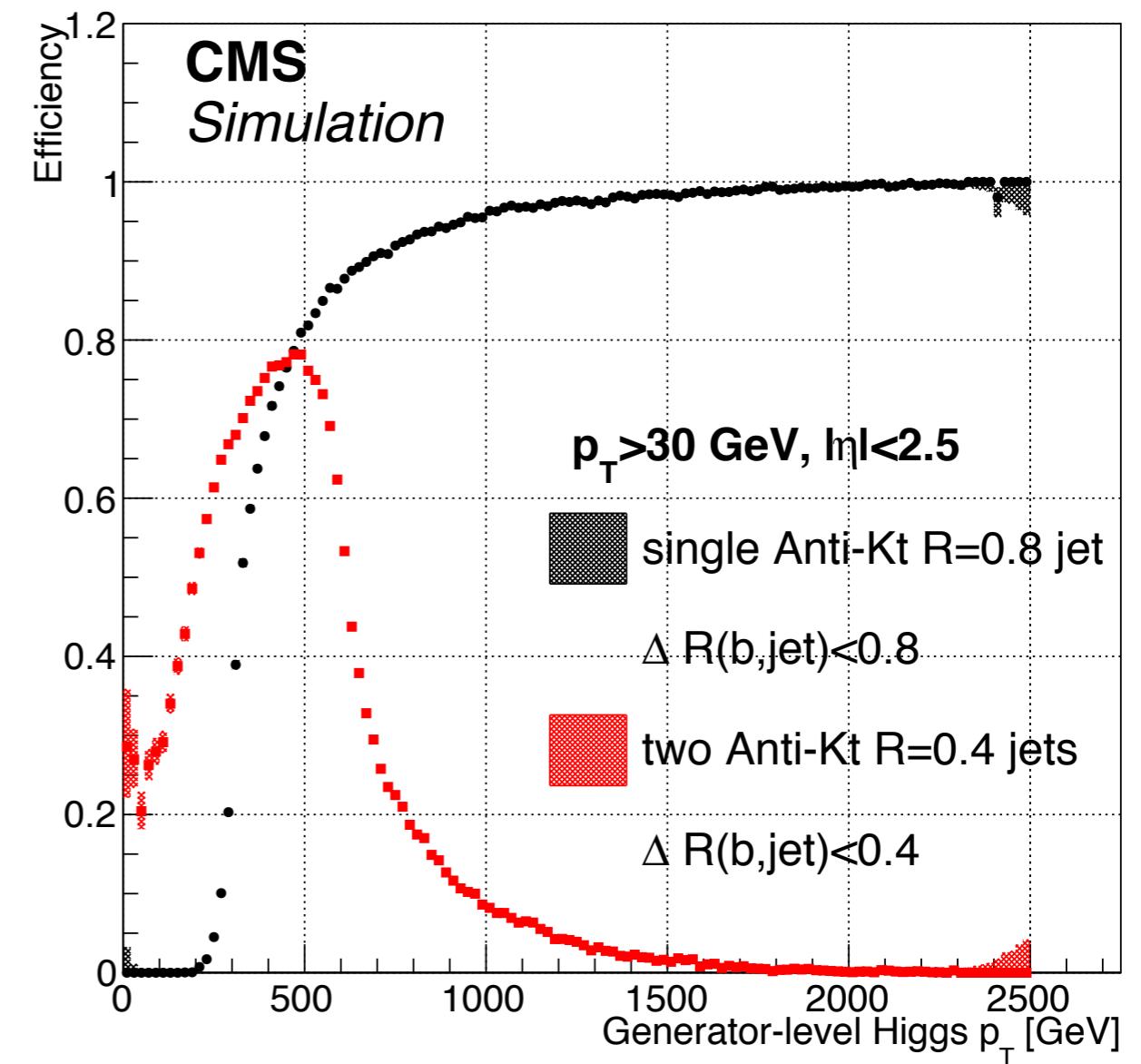
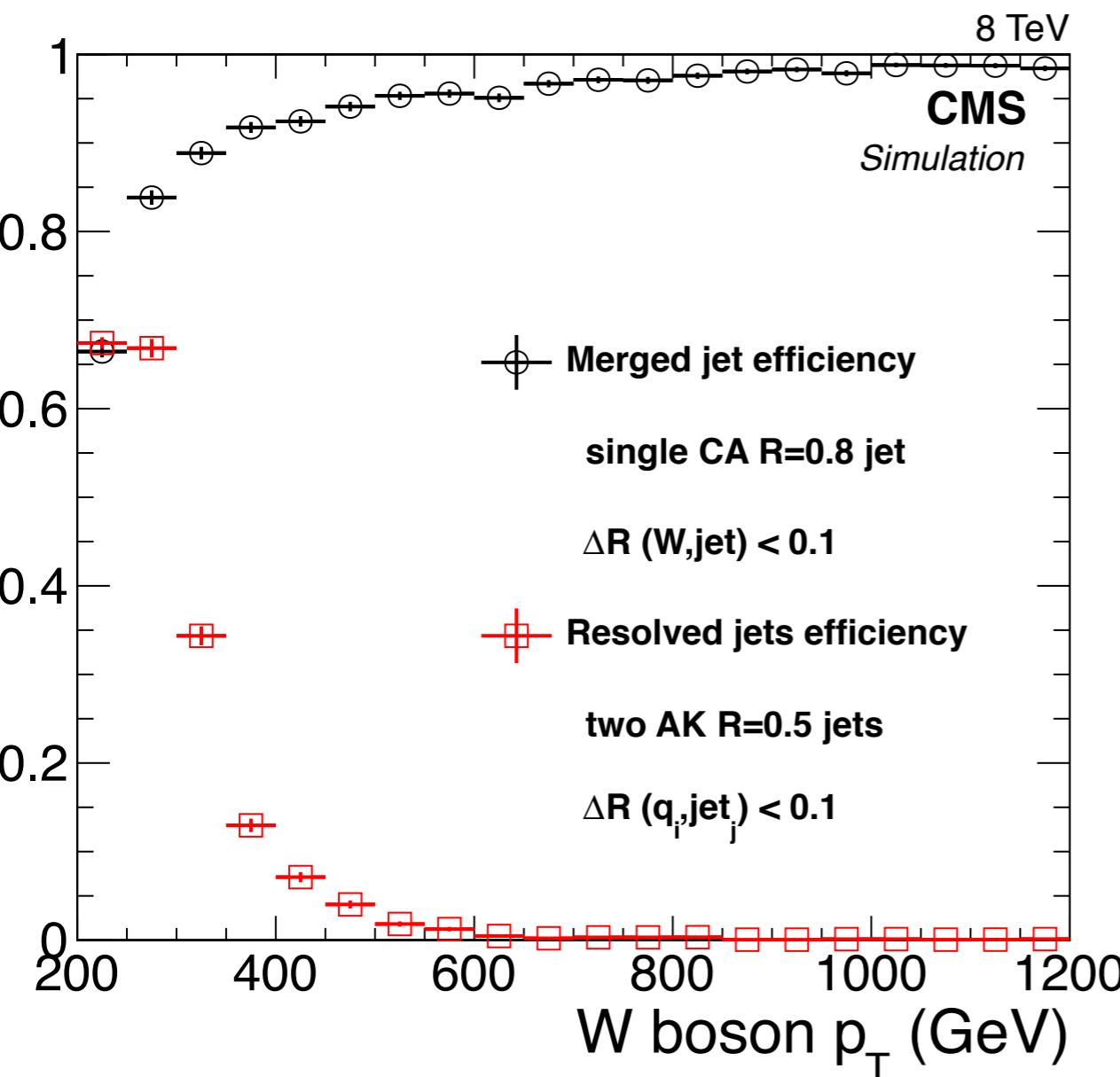
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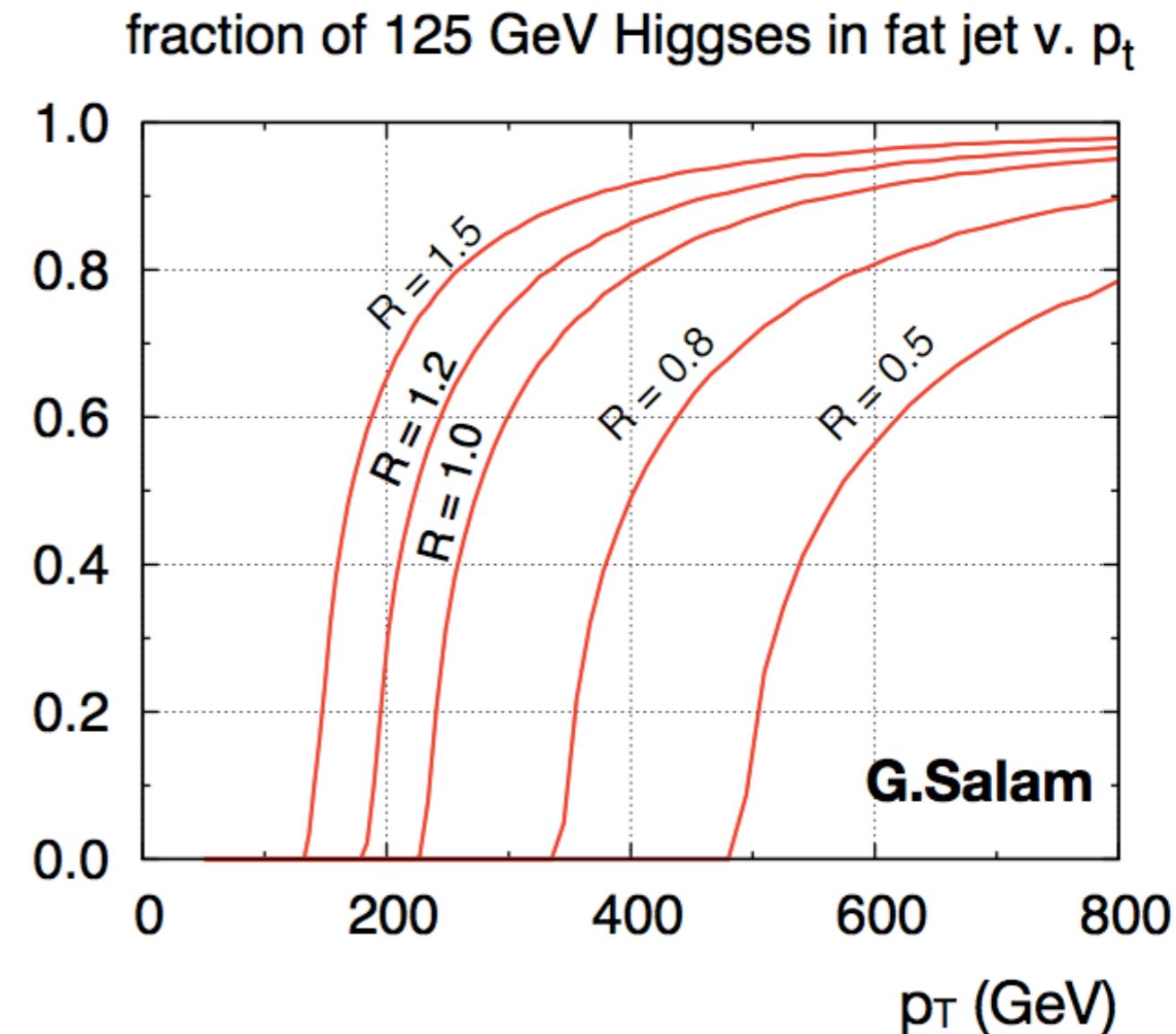
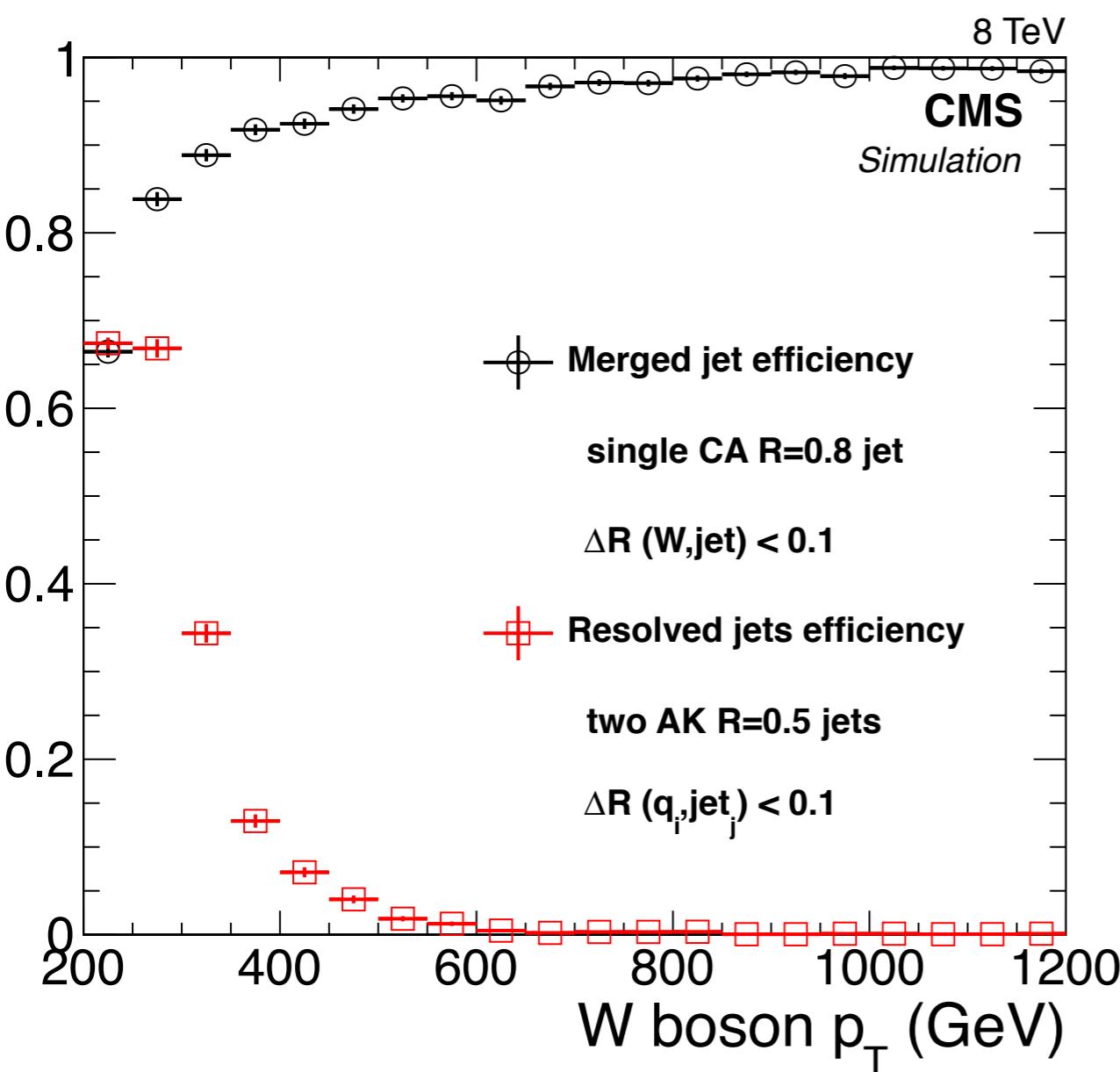
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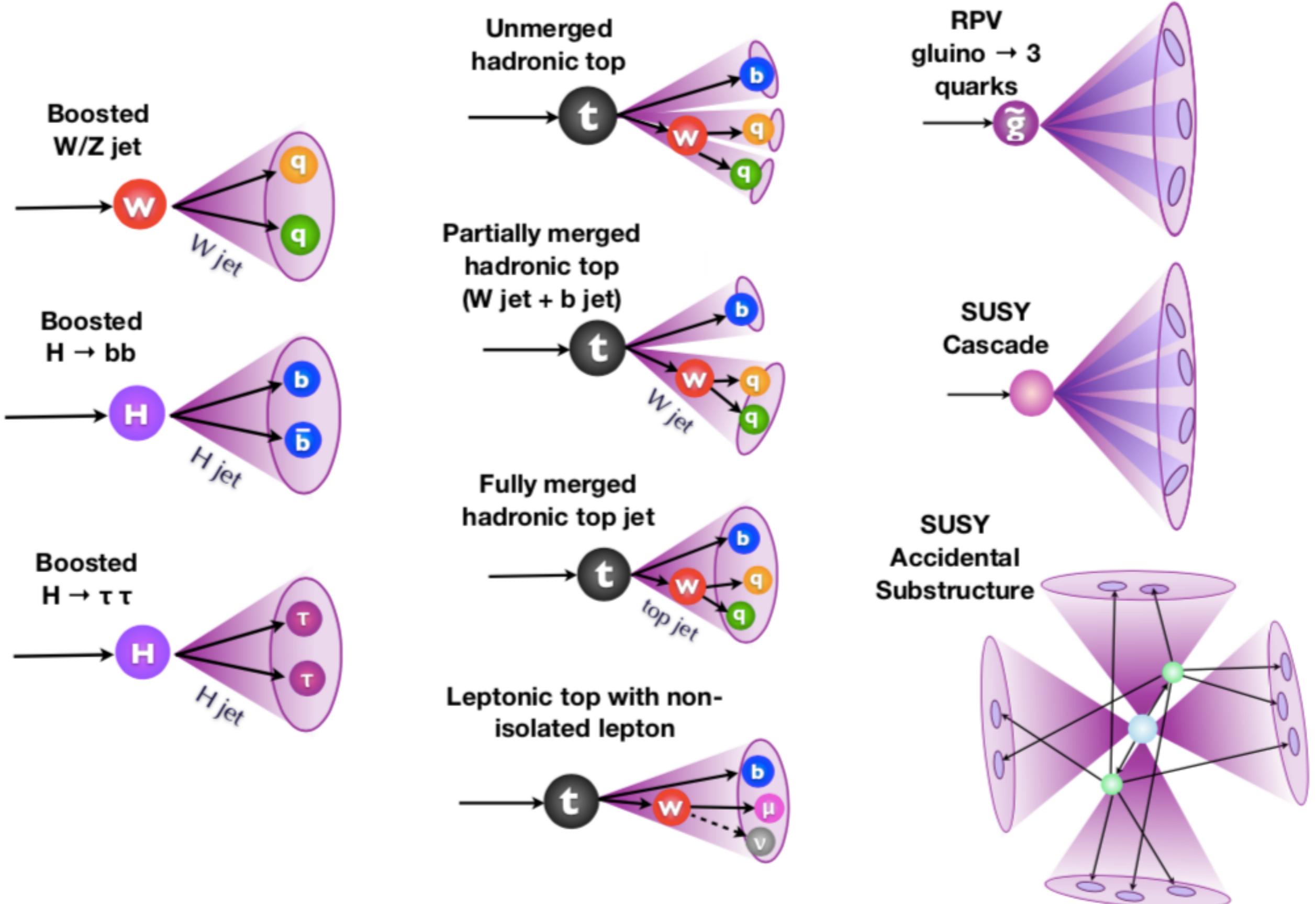


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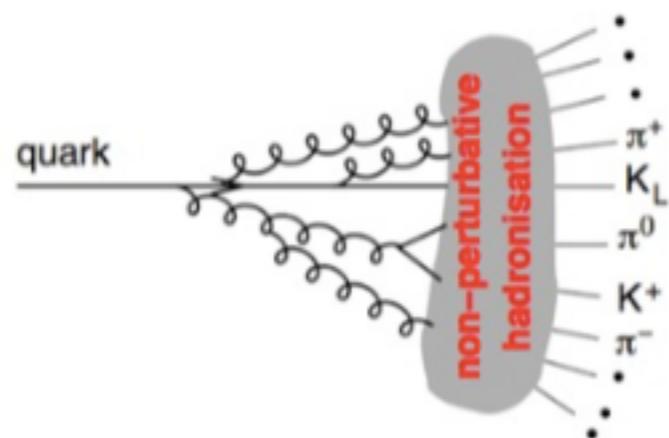
Boosted Topology



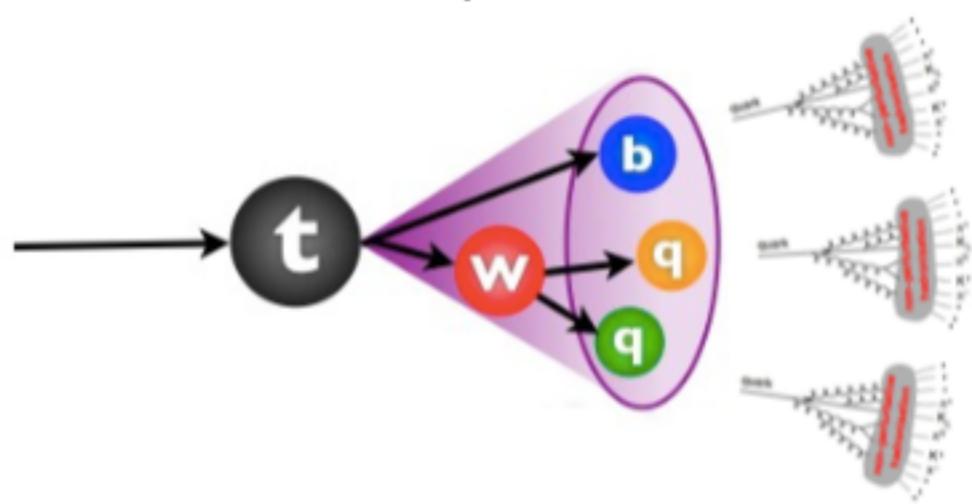
But ...

Separating QCD and boosted objects is tough!

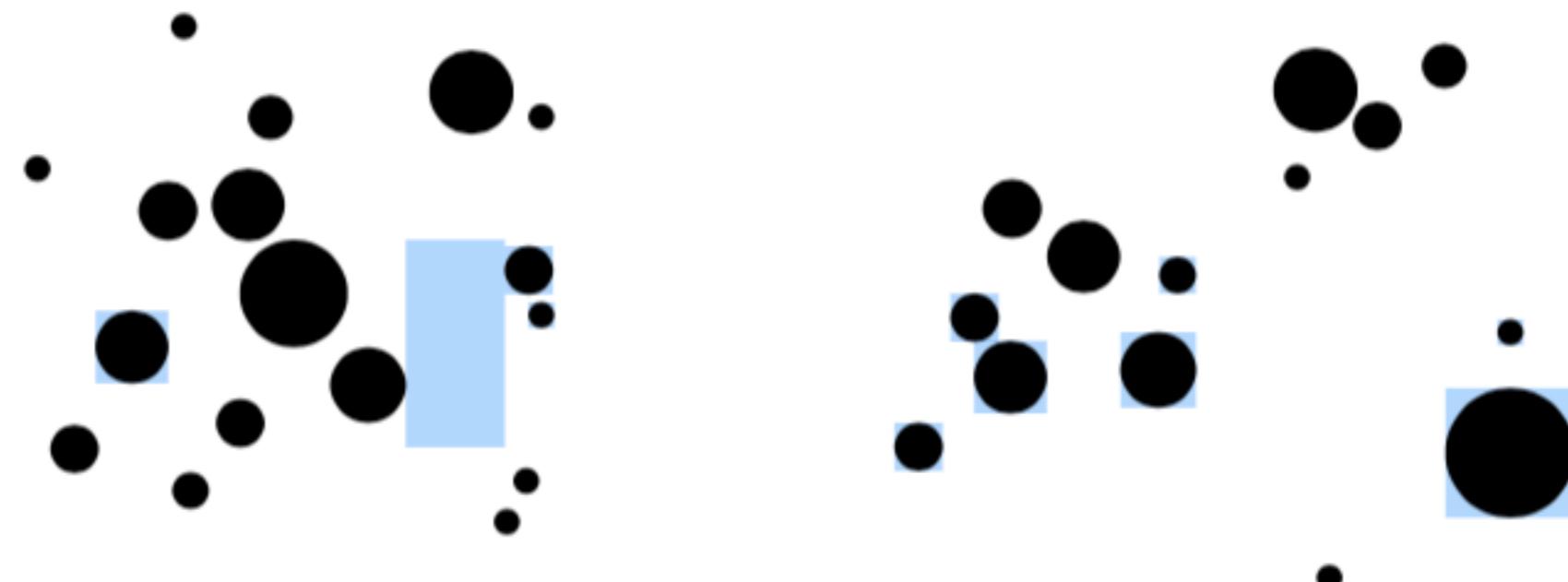
Typical Jet



Top Jet



Calorimeter energy deposit pattern:



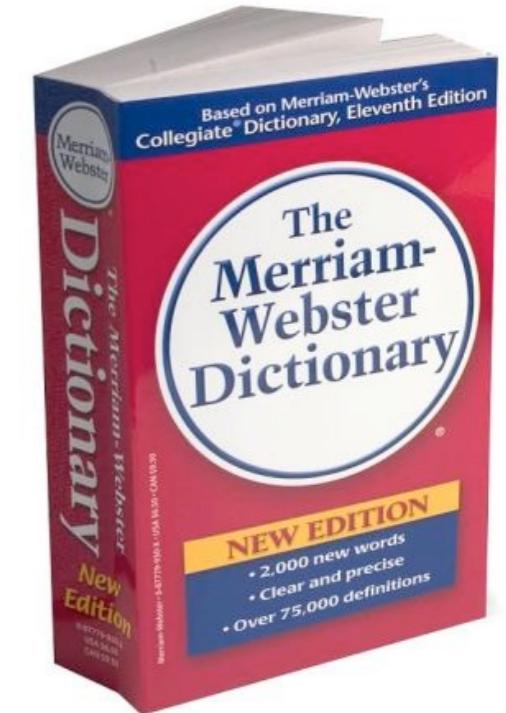
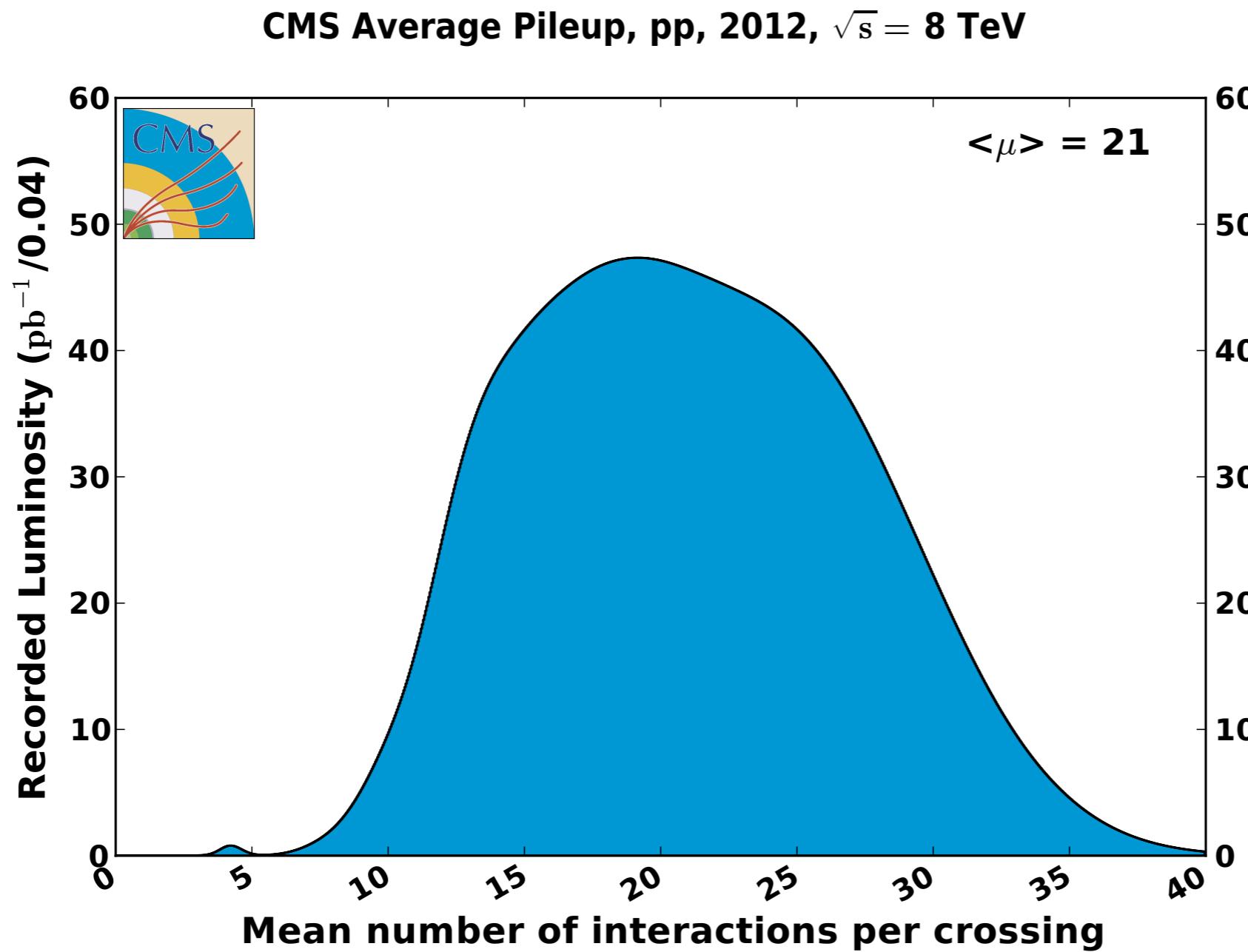
Circle = position of particle within the detector
Circle area = energy of particle

But ...

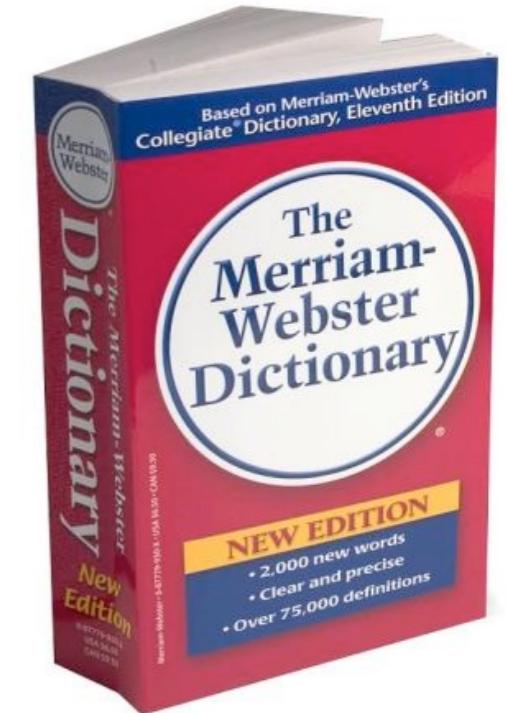
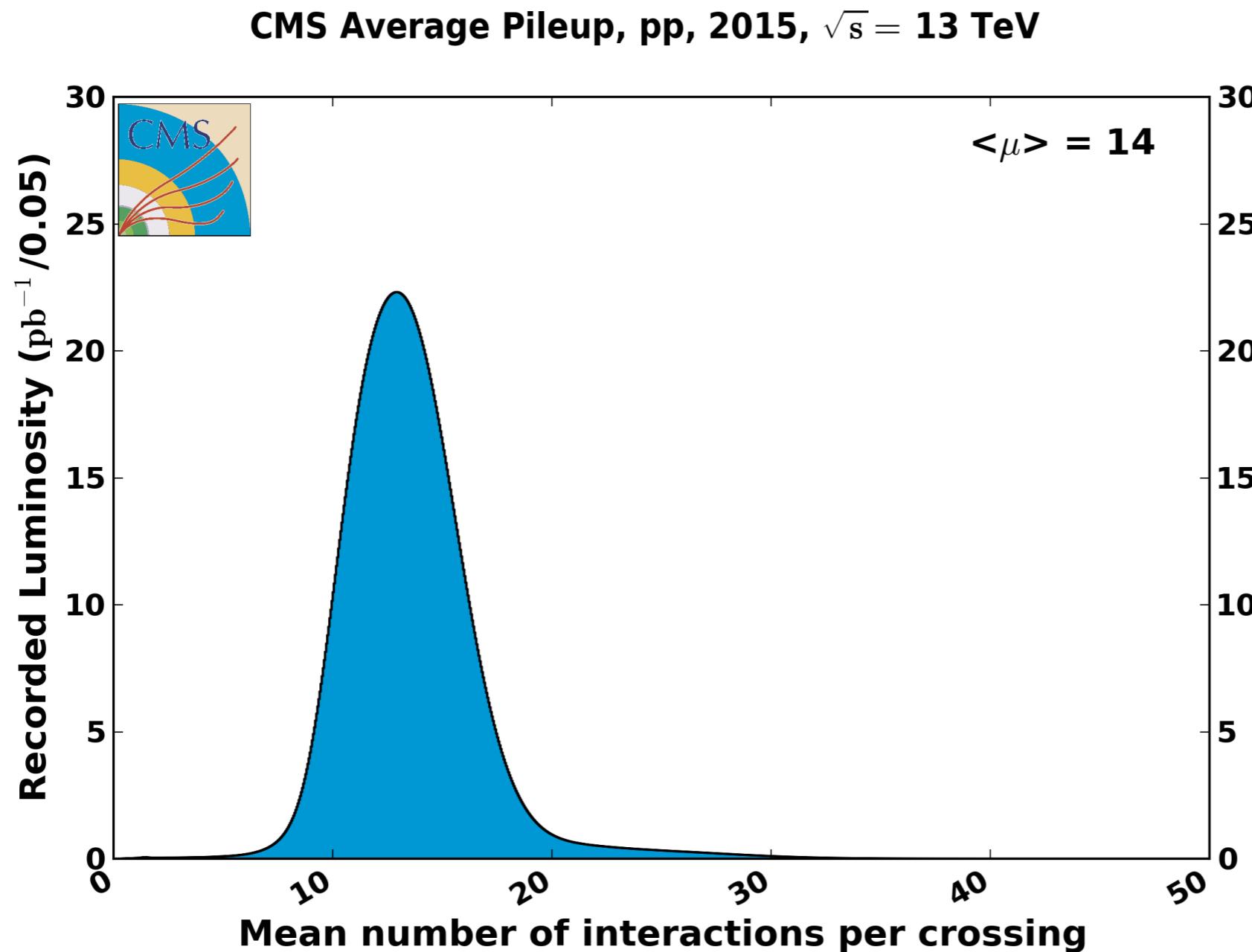
- Larger radius jets are more likely to contain noise, such as pileups



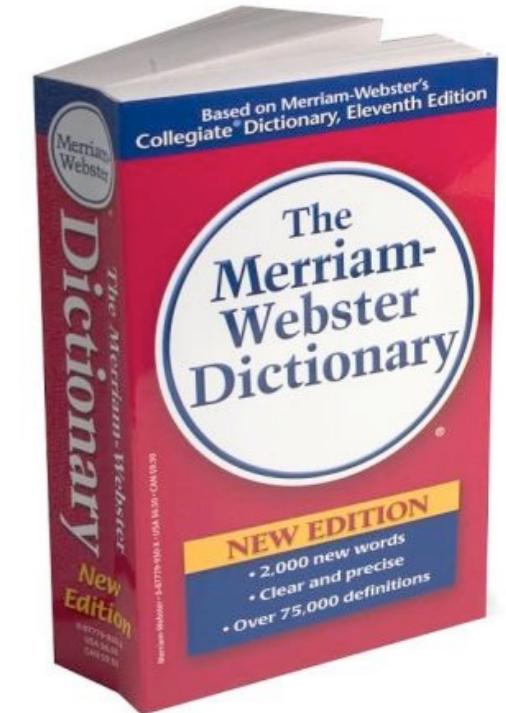
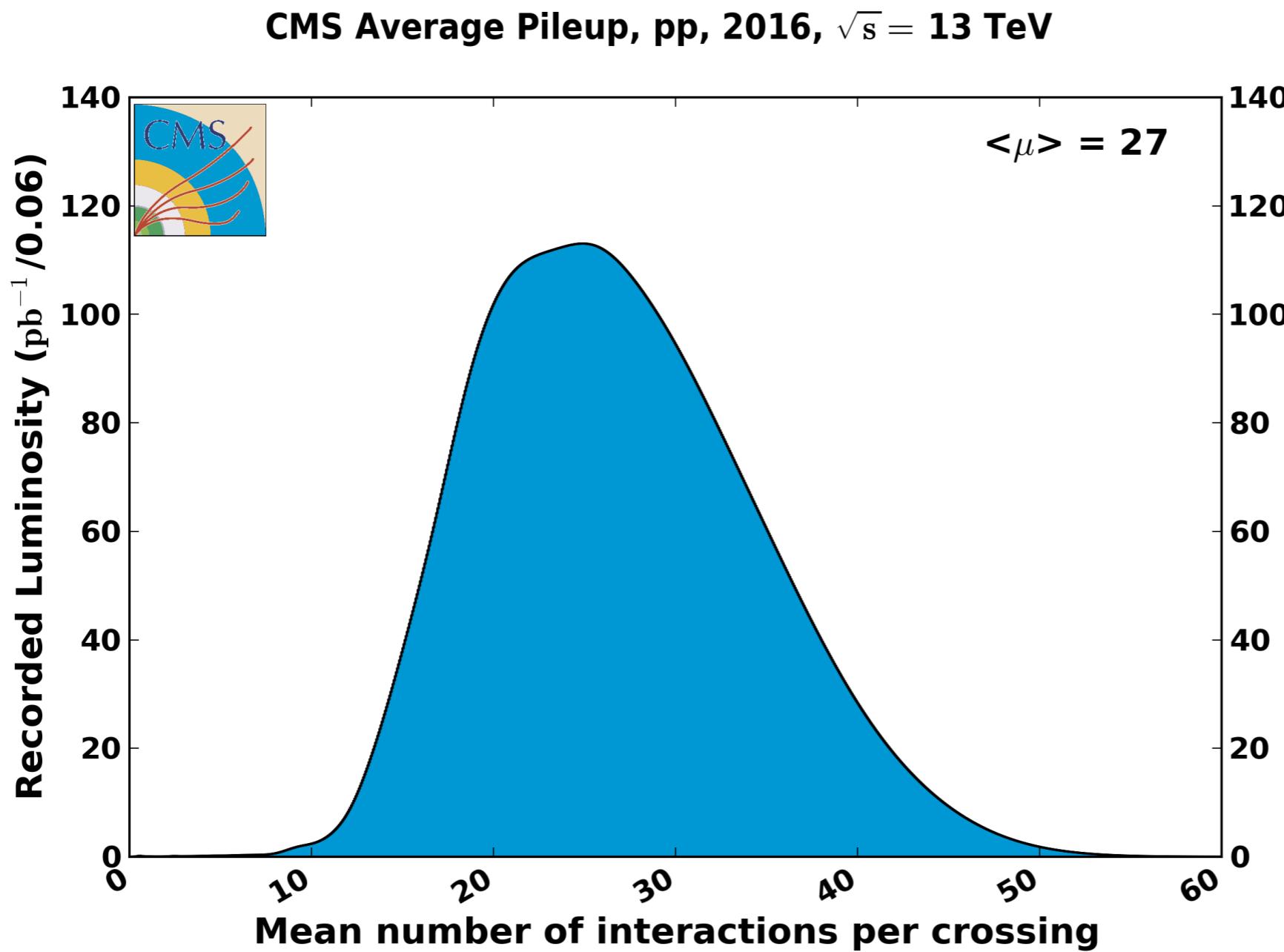
- **Pileup**
 - Additional pp collisions in the same or adjacent bunch crossings



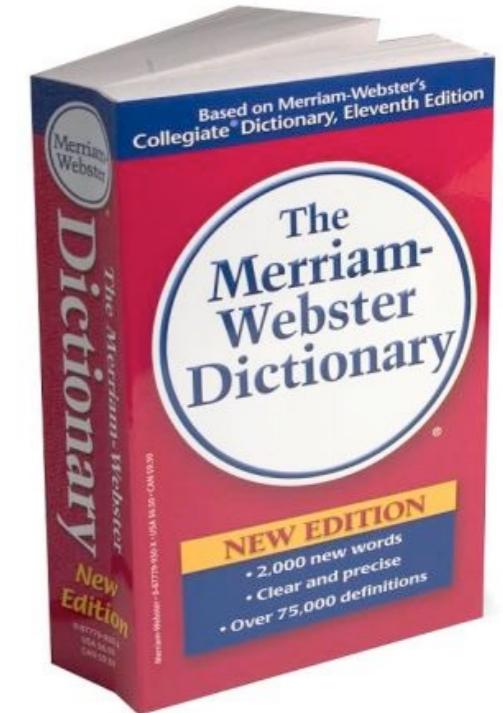
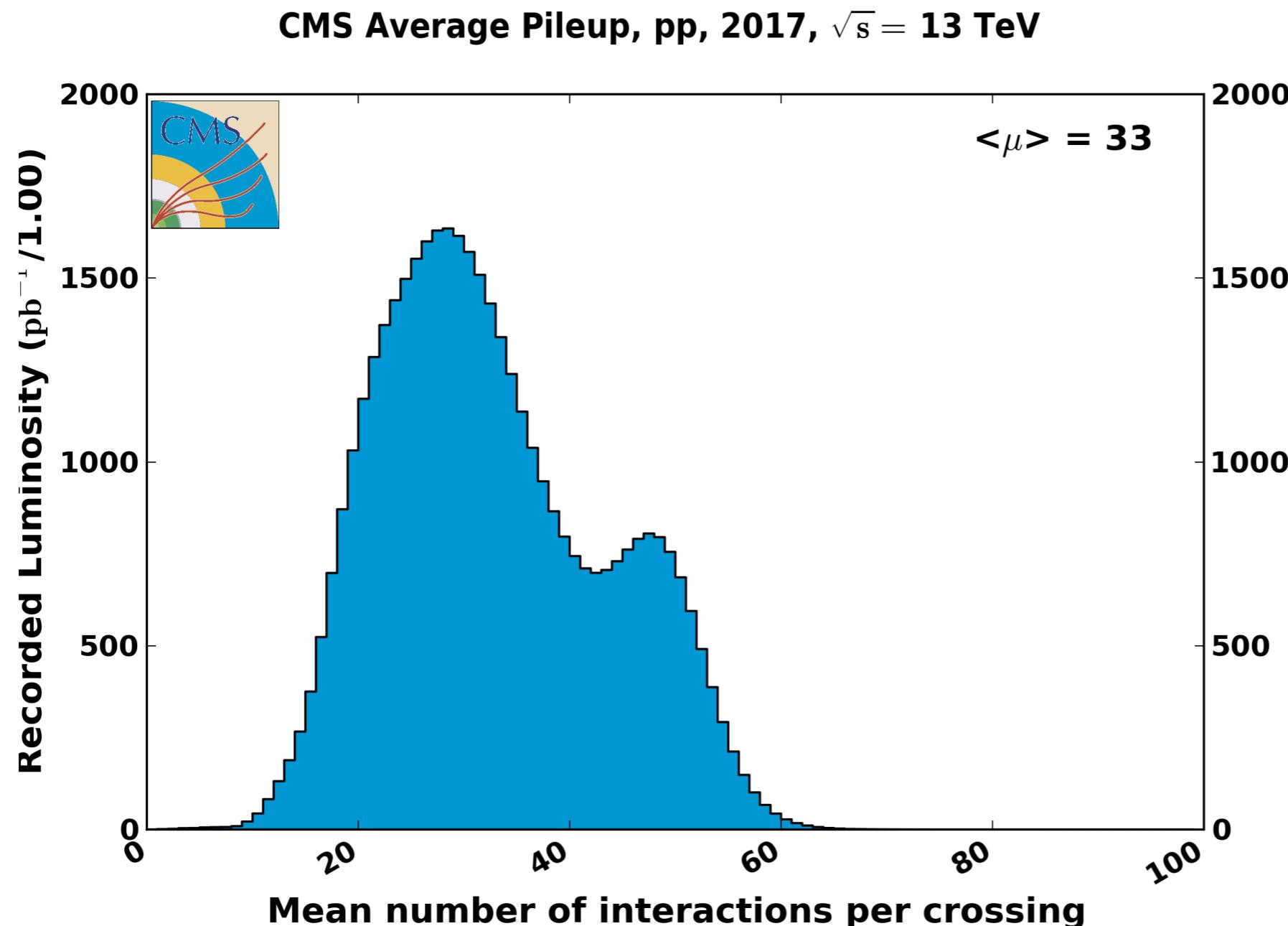
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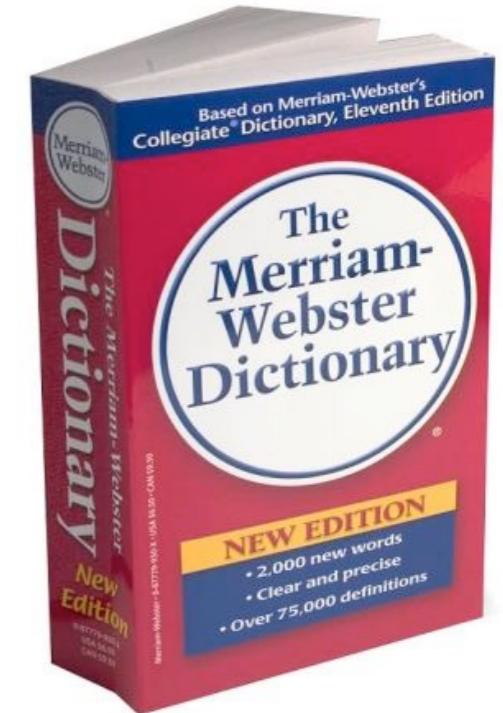
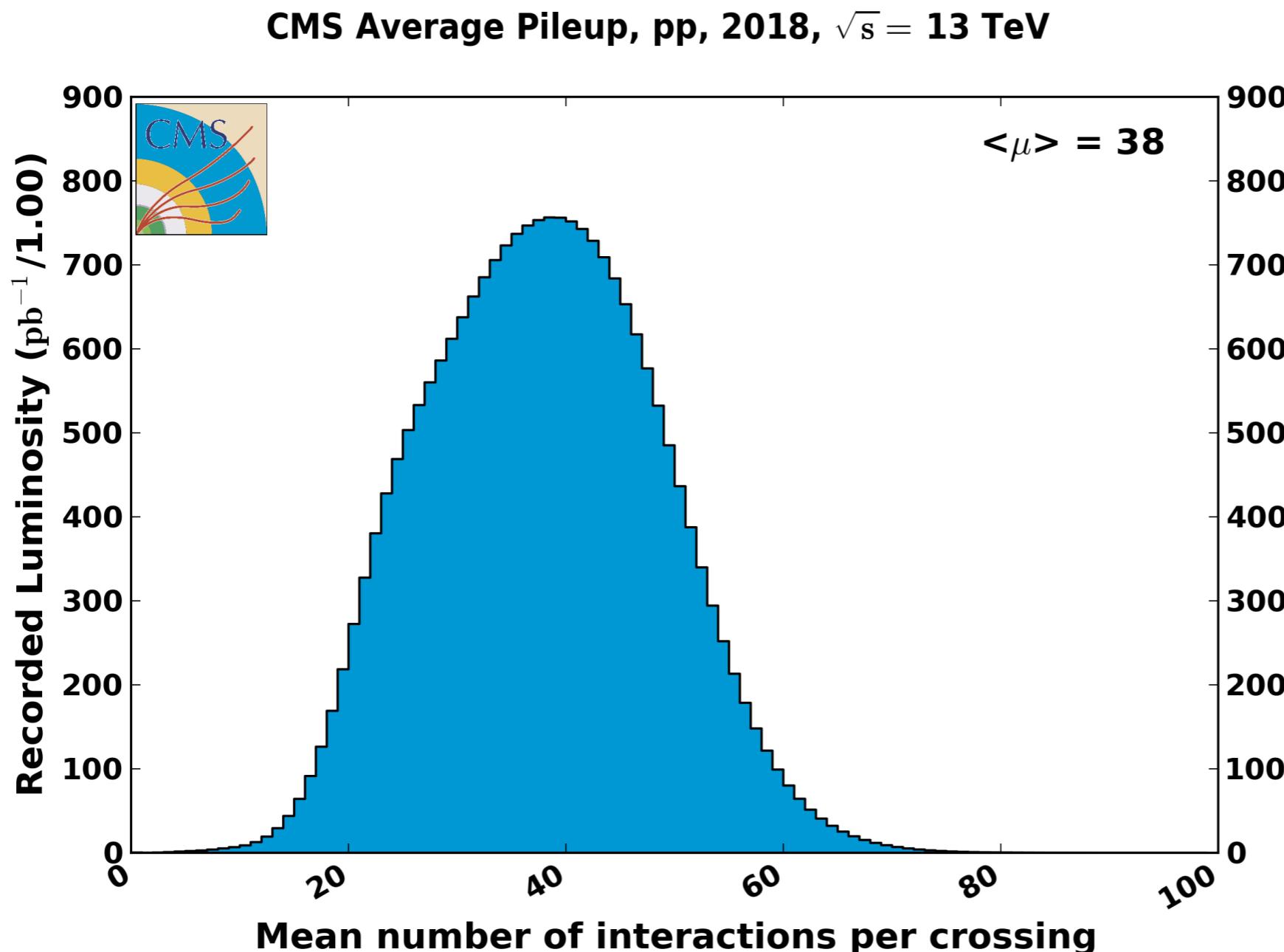
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Jet Mass

Jet mass is the main observable for discriminating between heavy object decaying with substructure (W/Z/top/etc.) and a QCD jet (quark or gluon)

Experimentally, it is the four-vector sum of all the jet constituents.

For PF jets, simply the four-vector sum of PF Candidates
For Calo jets, the four-vectors are determined by the cluster η , φ , E , and mass (assumed to be pion mass)

QCD Jet Mass

Jet mass is a perturbative quantity,
at LO the jet mass is the parton mass ~ 0 .

$$\langle M^2 \rangle \simeq C \cdot \frac{\alpha_s}{\pi} p_t^2 R^2$$

Jet mass is proportional to R, pT
 C is a form factor related to originating parton and clustering
algorithm. For non-cone algorithms:

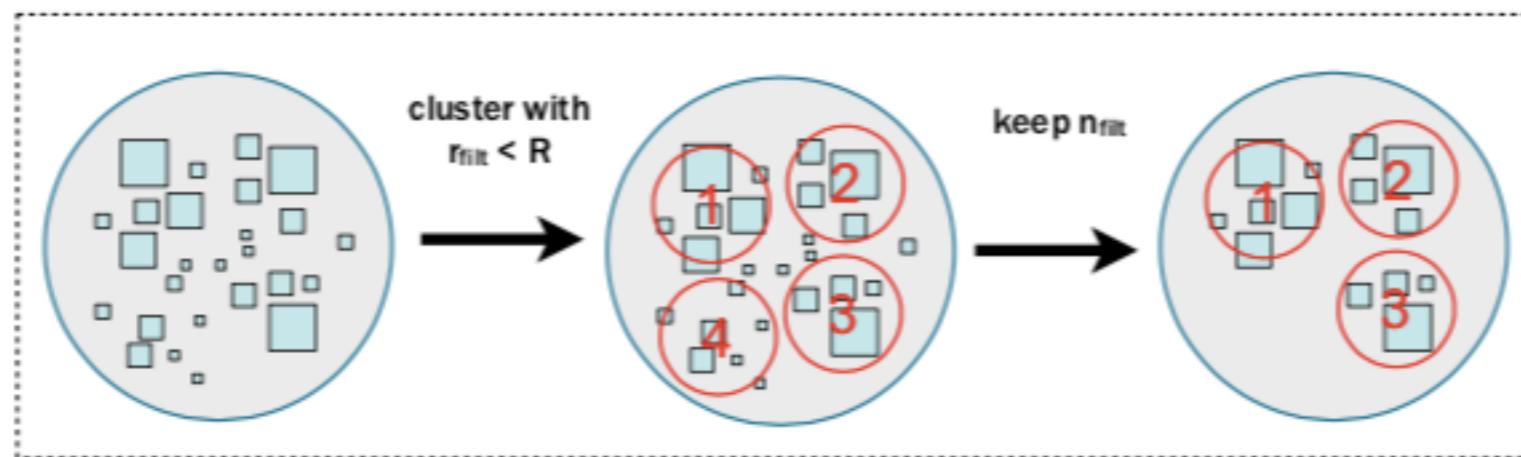
$$\langle M^2 \rangle \simeq \left. \begin{array}{l} \text{quarks: } 0.16 \\ \text{gluons: } 0.37 \end{array} \right\} \times \alpha_s p_t^2 R^2$$

Eur. Phys. J. C 67, 637

Run-I Jet Grooming

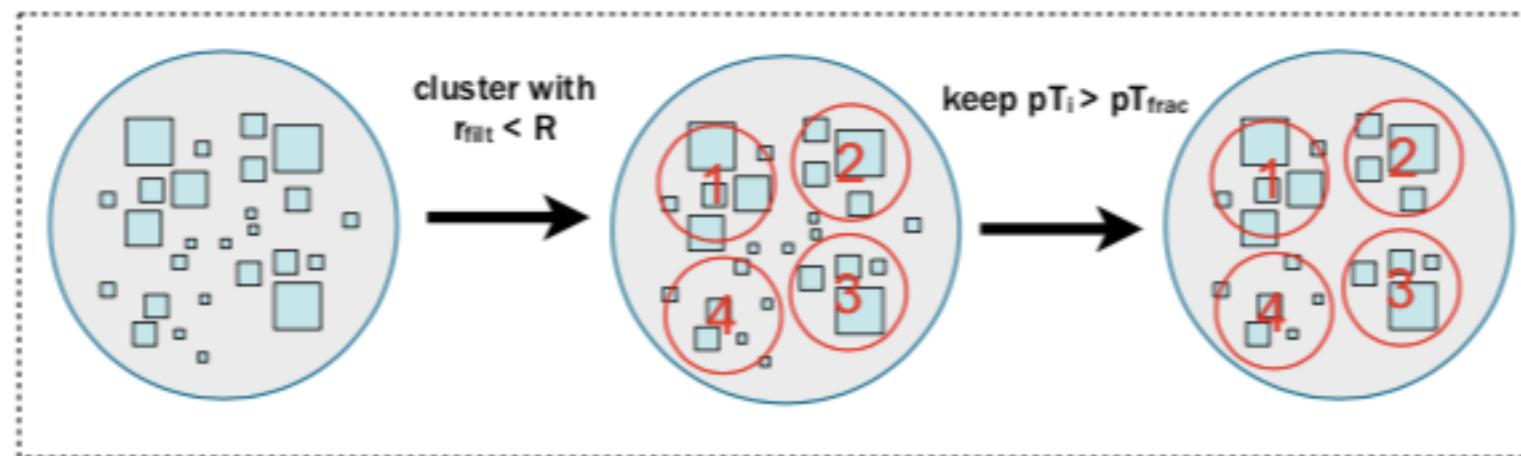
Jet grooming methods are used to clean the jet of soft QCD and PU contributions

filtering



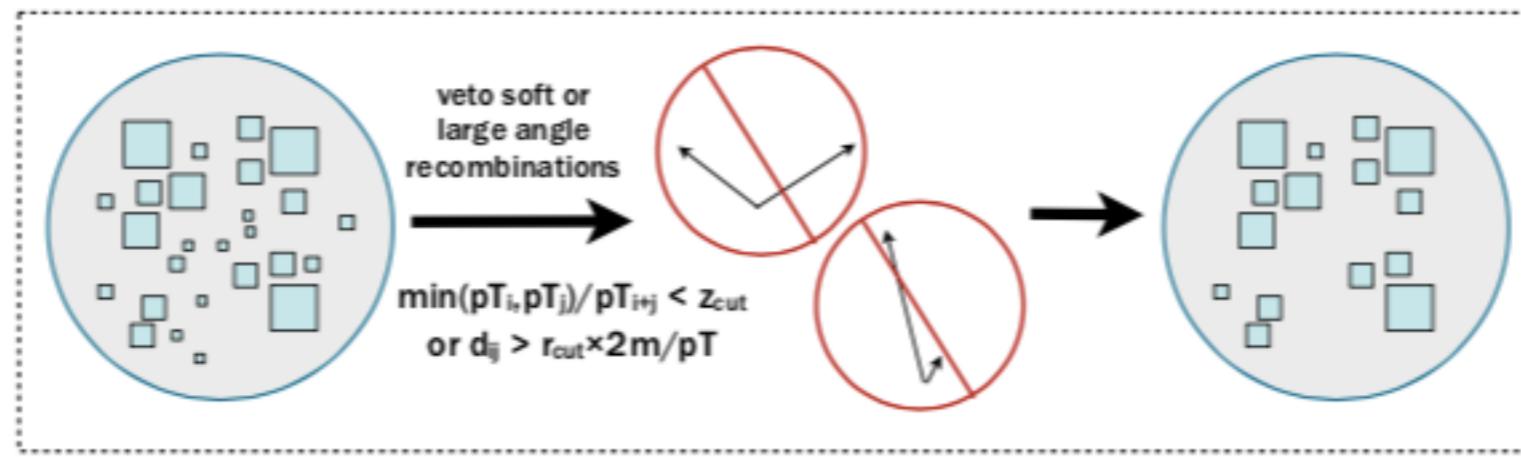
default:
 $r_{\text{filt}} = 0.3$
 $n_{\text{filt}} = 3$

trimming



default:
 $r_{\text{filt}} = 0.2$
 $pT_{\text{frac}} = 0.03$

pruning



default:
 $z_{\text{cut}} = 0.1$
 $r_{\text{cut}} = 0.5$

Run-2 Jet Grooming

mMDT / Soft Drop is a widely used substructure technique

[Dasgupta, Fregoso, Marzani, Salam [JHEP 1309 \(2013\) 029](#)]

[Larkoski, Marzani, Soyez, Thaler [JHEP 1405 \(2014\) 146](#)]

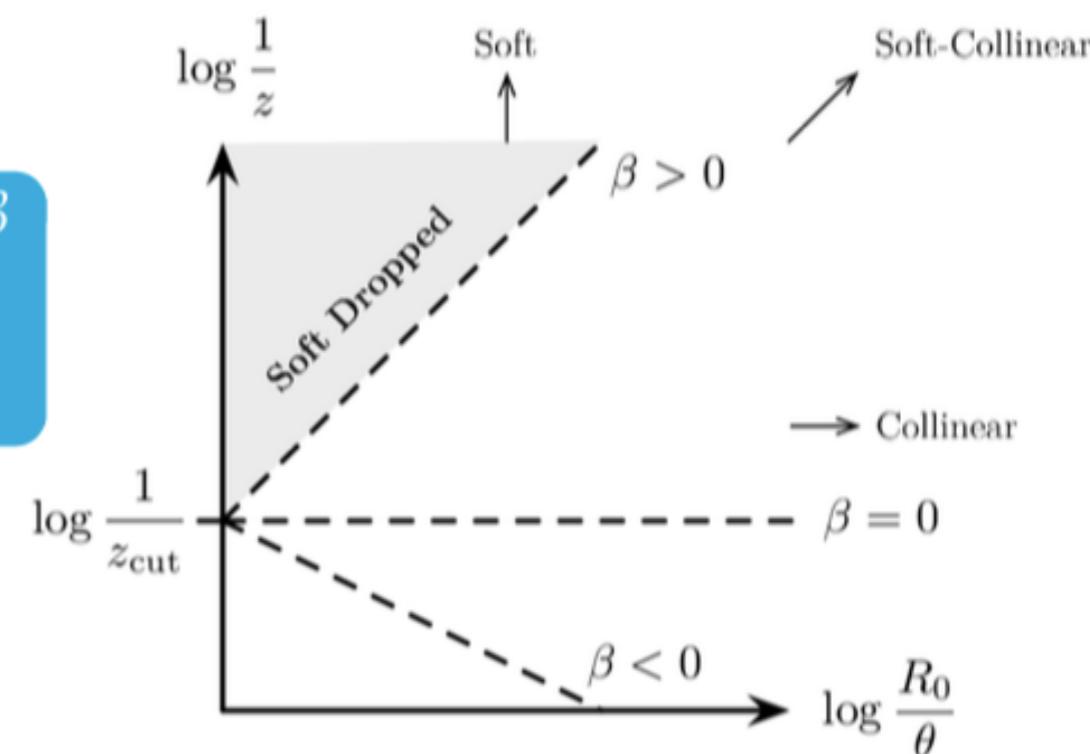
1. Undo last stage of CA clustering tree and label two subjets j_1, j_2 of jet j .

2. If
$$z_g = \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^\beta$$

then j is the soft-dropped jet.

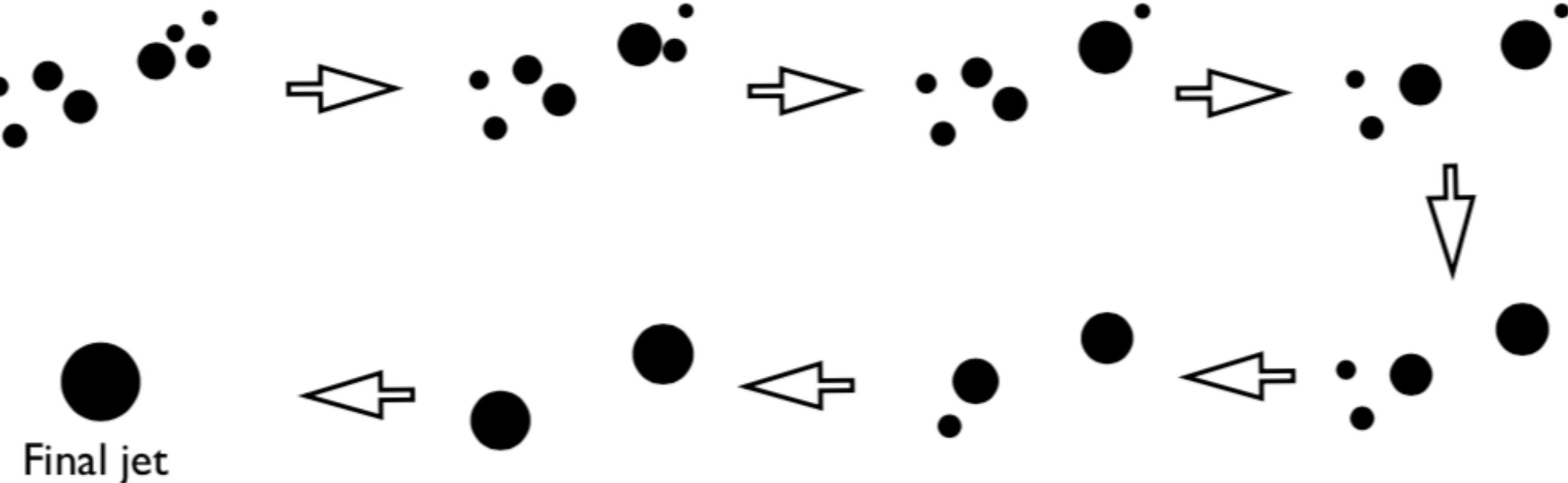
3. Otherwise define j to be the harder subjet and iterate.

- ▶ For $\beta = 0$, drops soft radiation entirely.
- ▶ Provides handle on UE and PU, identifying hard substructure.

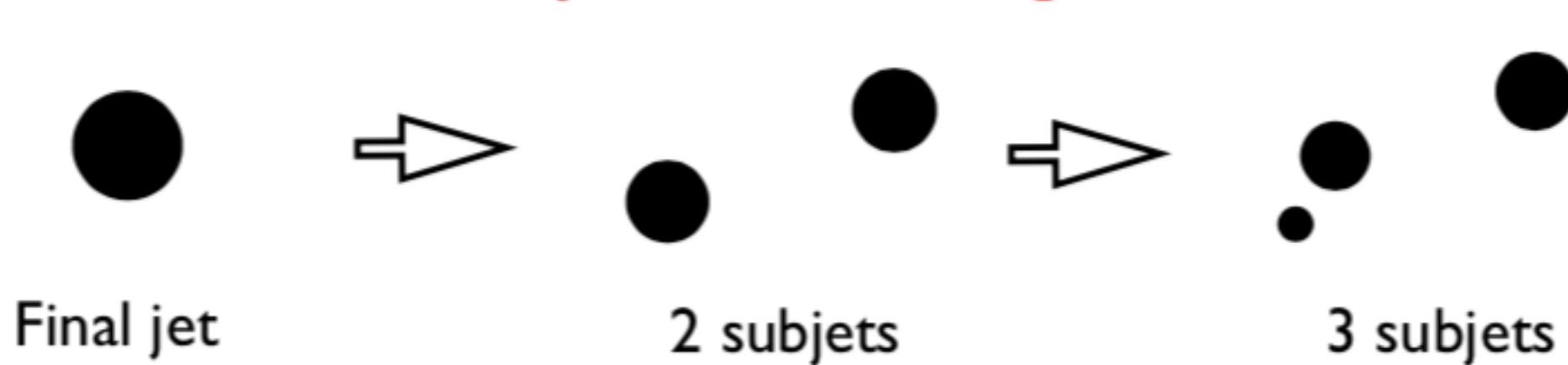


Subjets

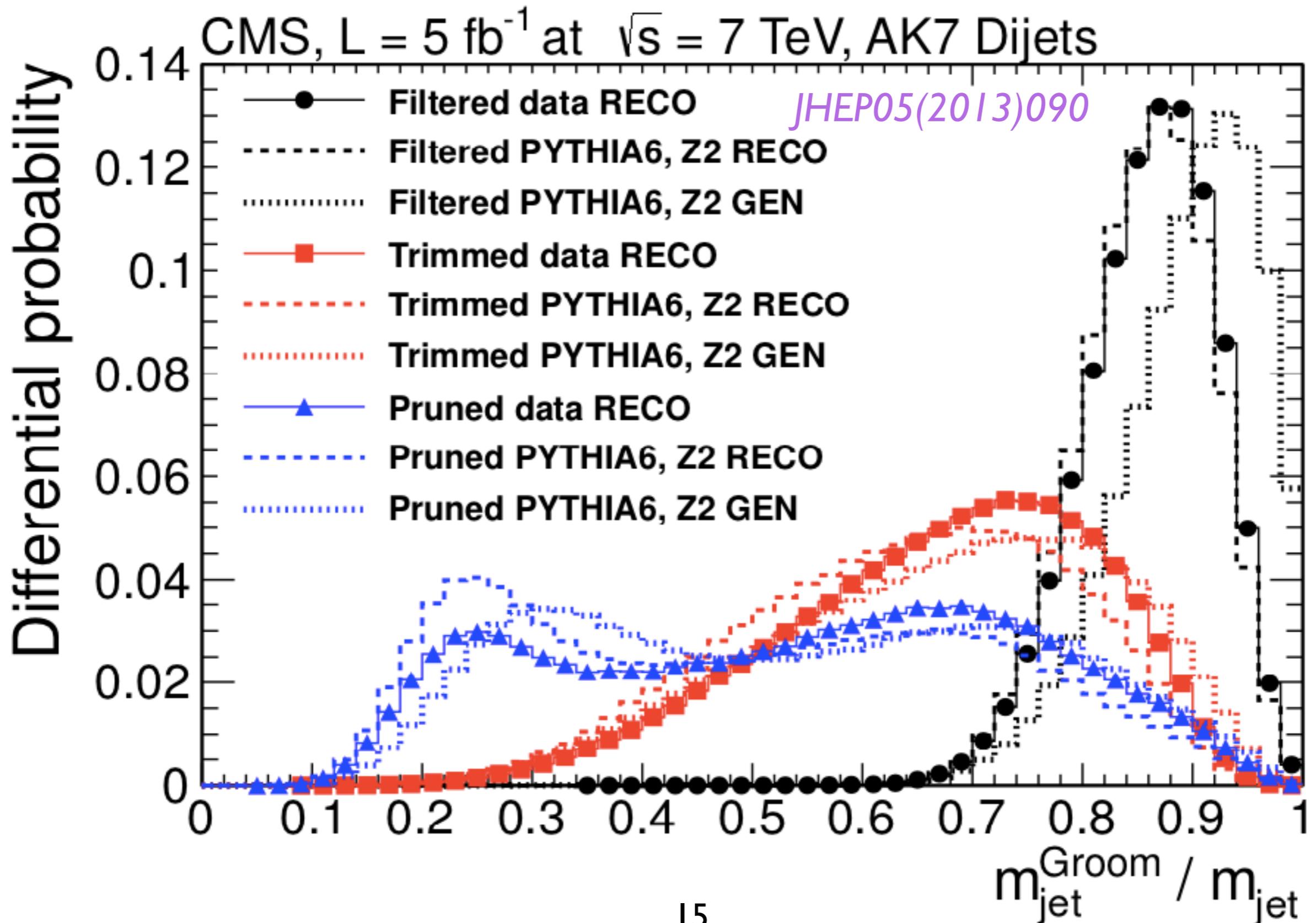
Jet Clustering



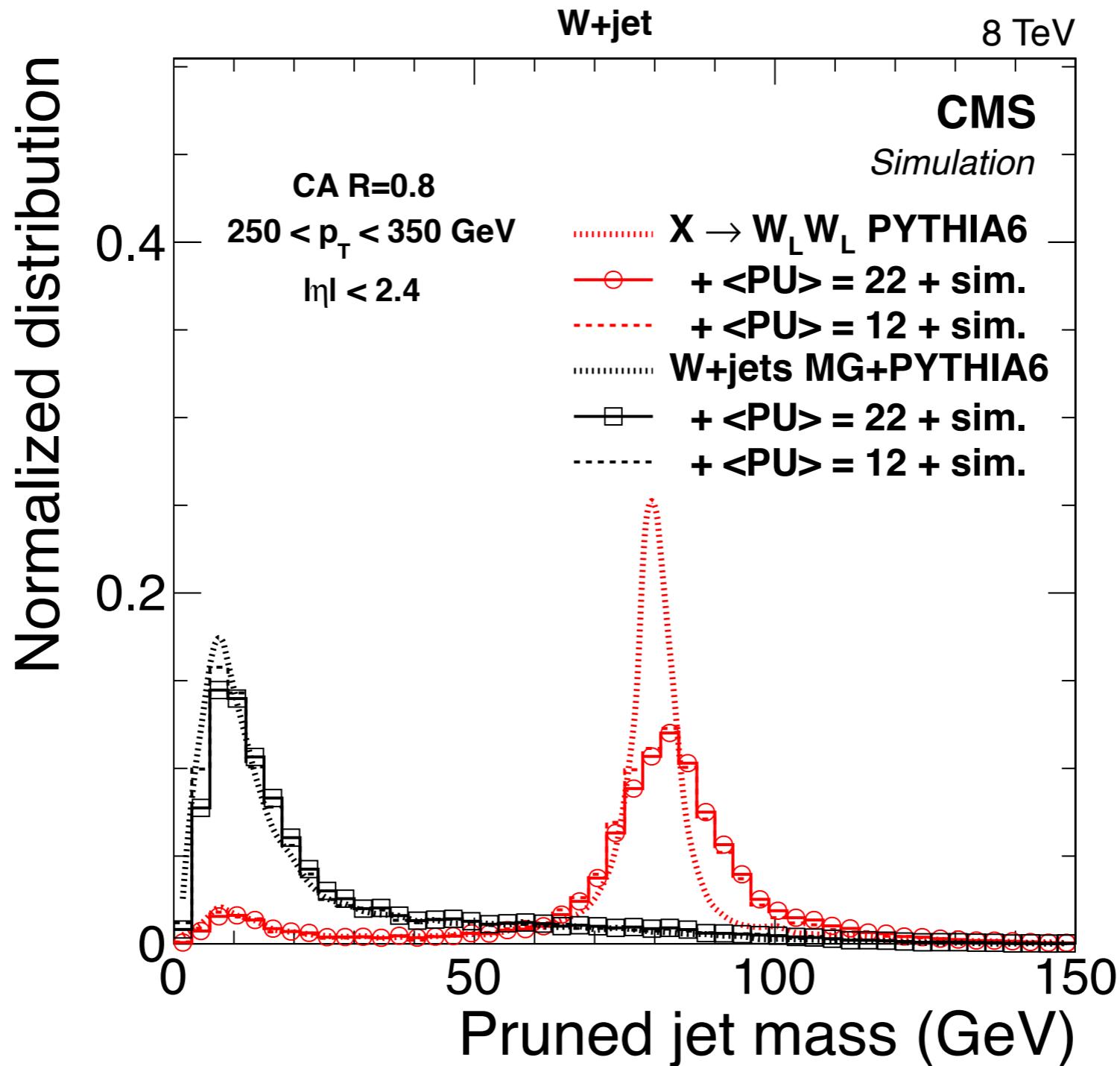
Jet Declustering



Comparison of Performance for QCD Jets

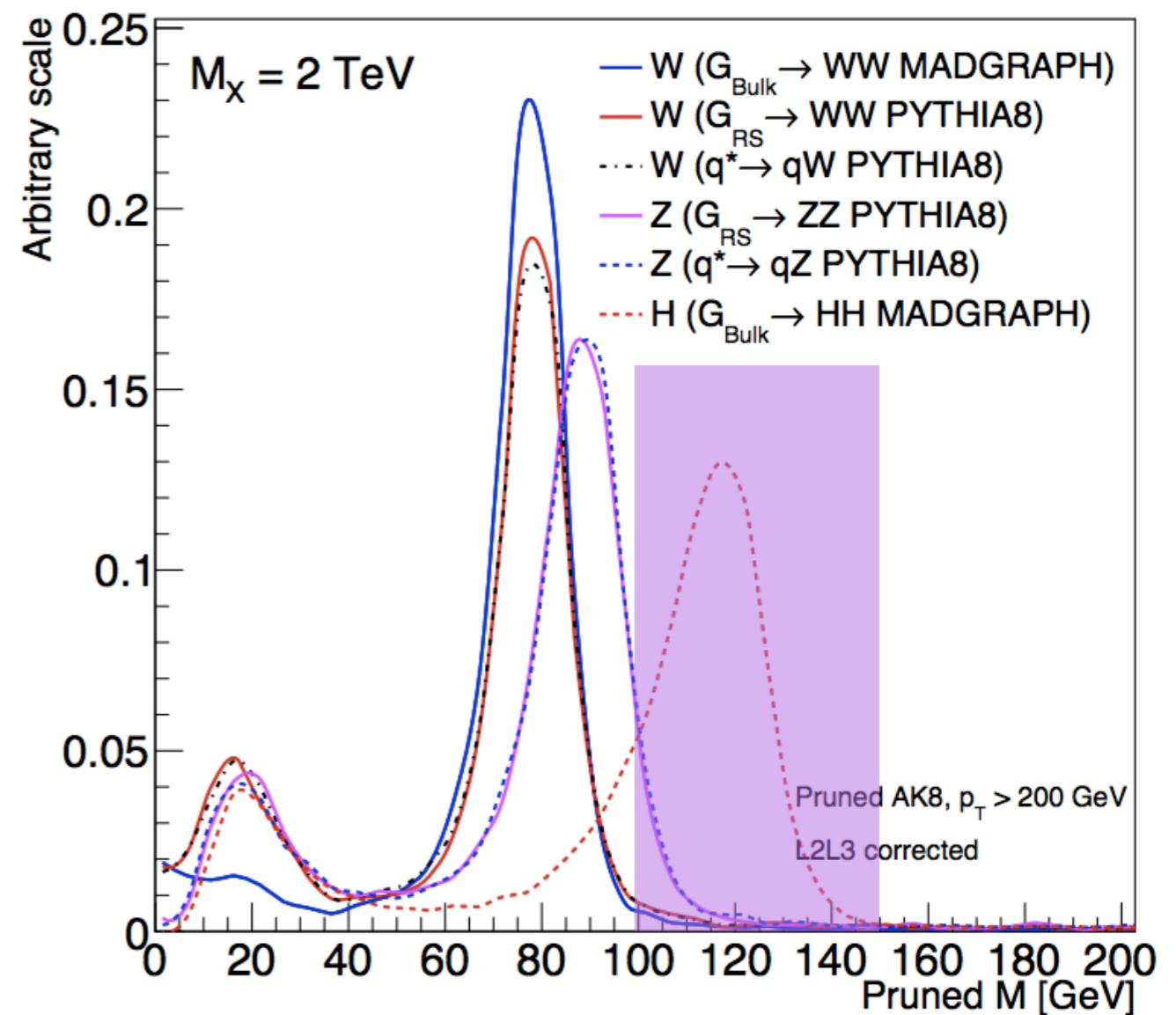


Pruned Mass from QCD and W-Jets



Mass Distribution of Pruned Jets

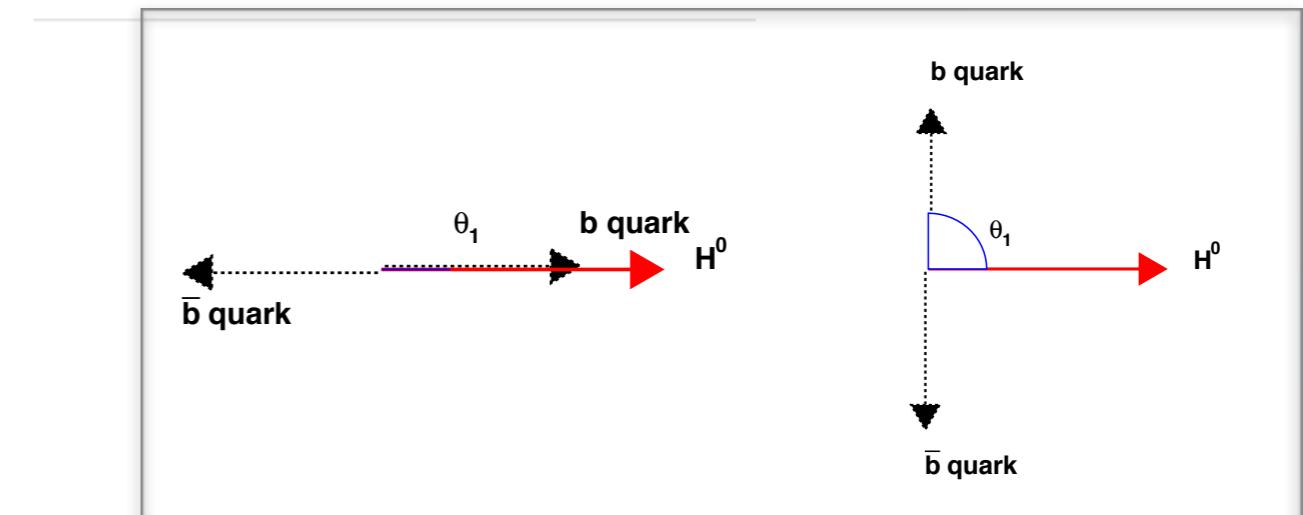
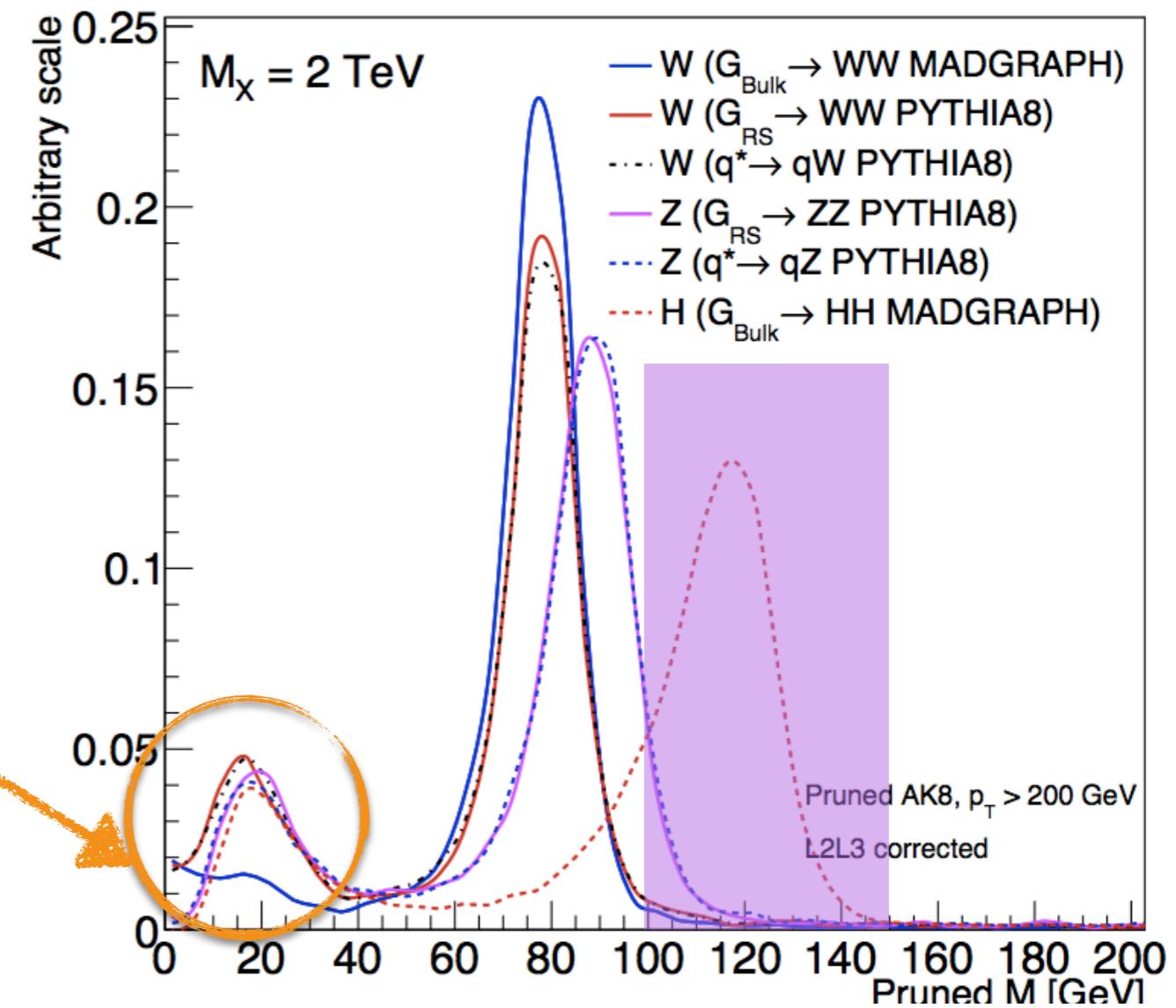
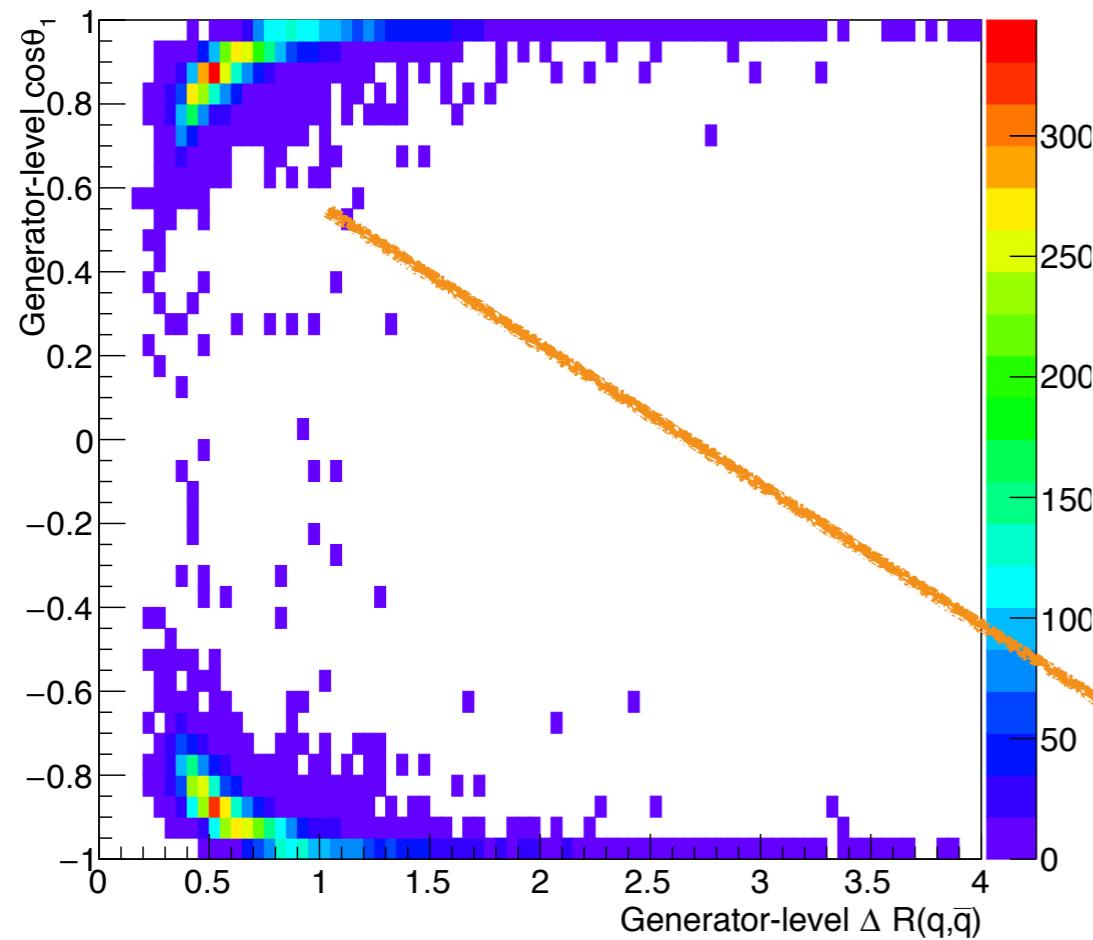
Simulation



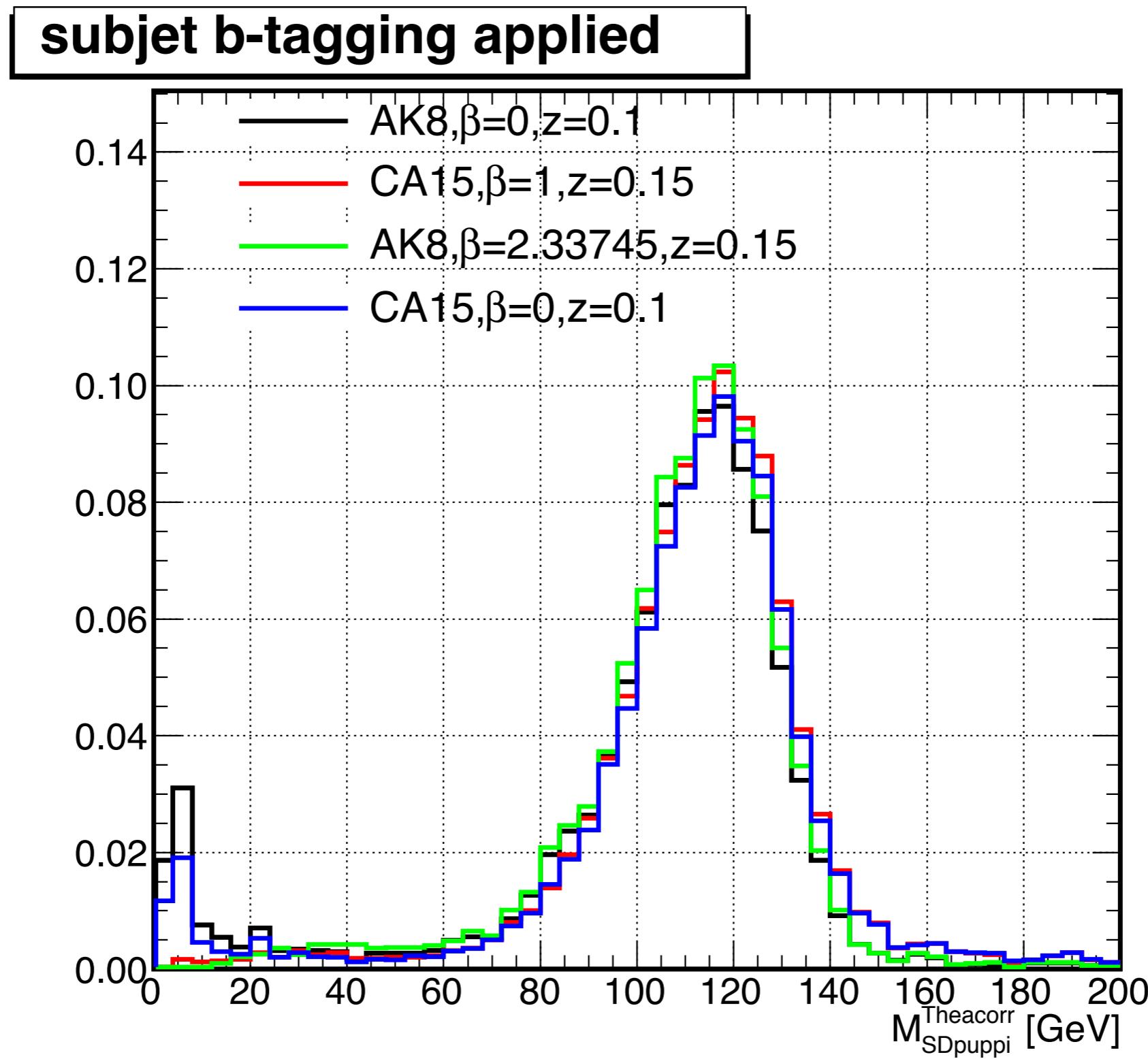
Mass Distribution of Pruned Jets

Simulation

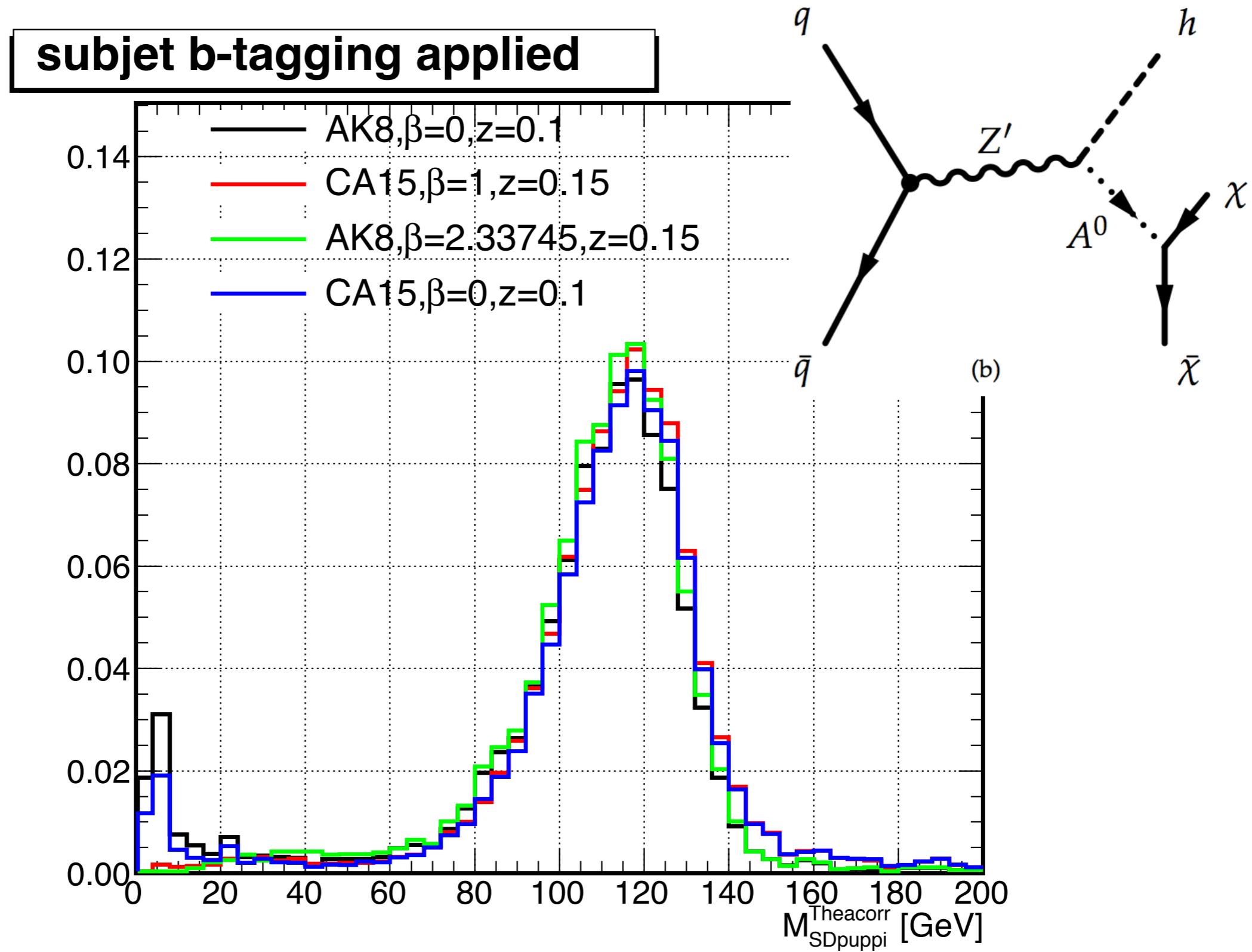
L2+L3 corrected pruned mass < 30 GeV



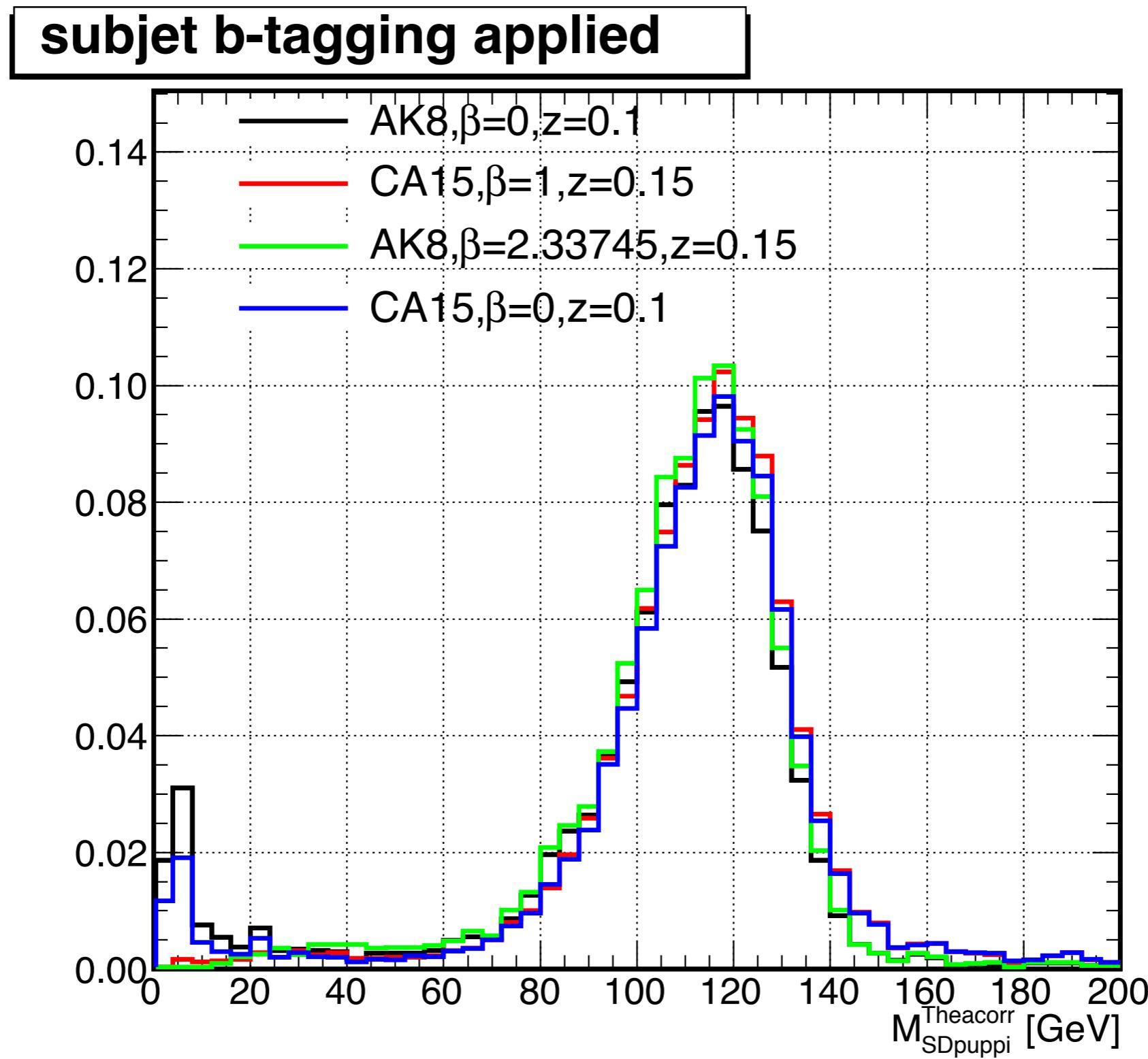
Mass Distributions of Soft-dropped Jets



Mass Distributions of Soft-dropped Jets



Mass Distributions of Soft-dropped Jets



N-subjettiness

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{\Delta R_{1,k}, \Delta R_{2,k}, \dots, \Delta R_{N,k}\}$$

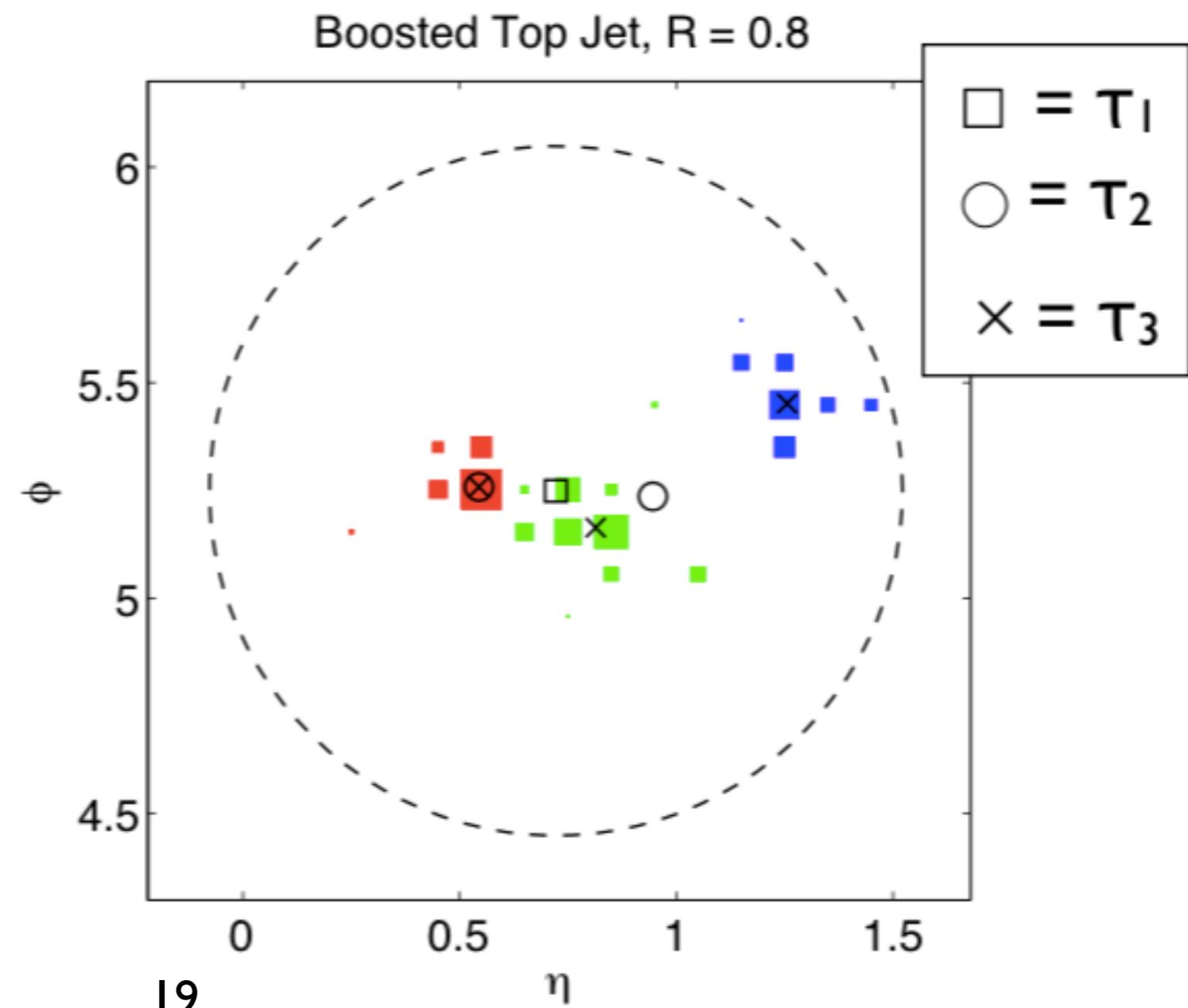
generalizing subjects...

N-subjettiness: a measure of how consistent a jet is with having N subjets, τ_N

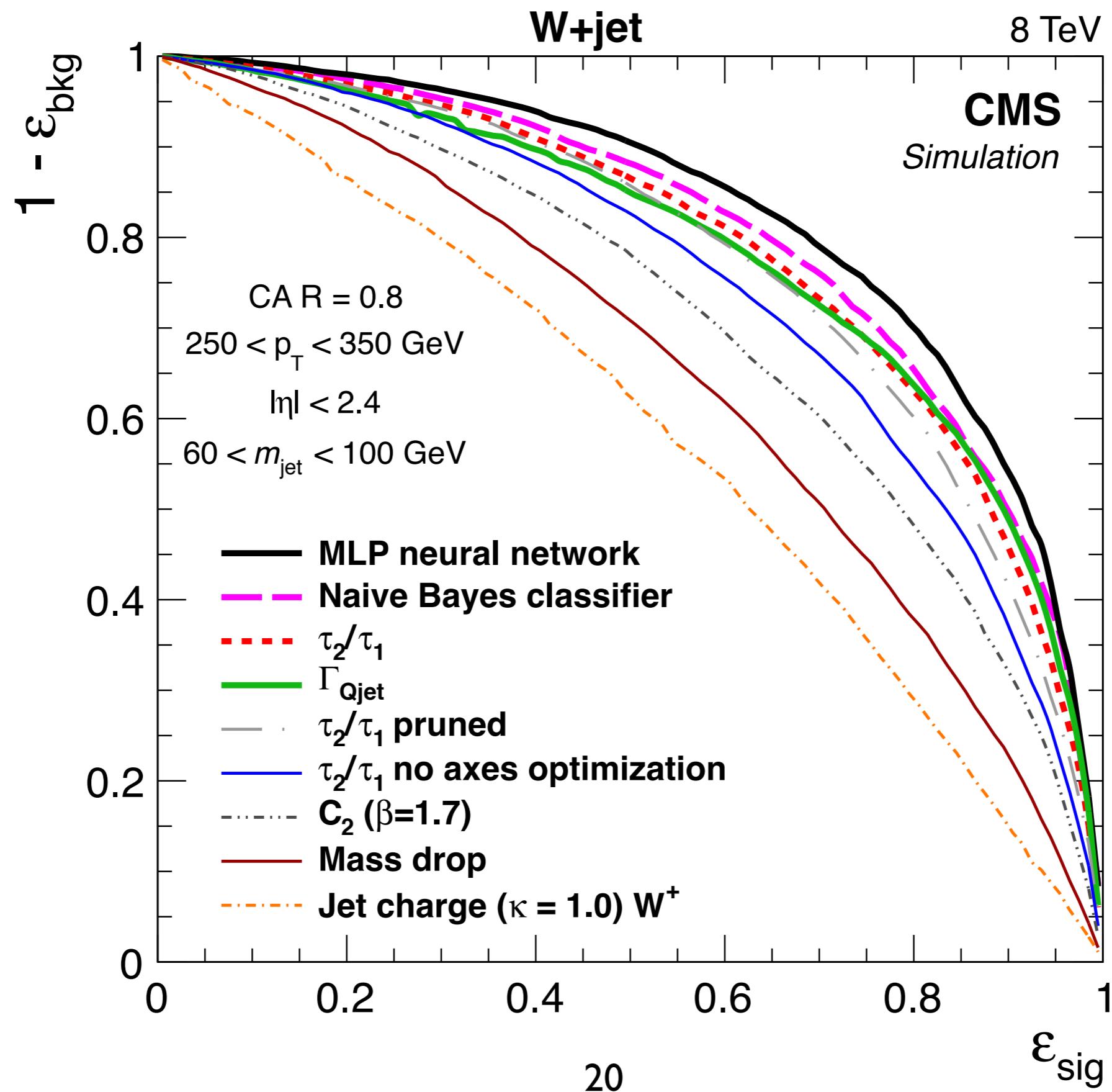
k, sum over particles in the jet
N subjet axes for computing τ_N

$$d_0 = \sum_k p_{T,k} R_0$$

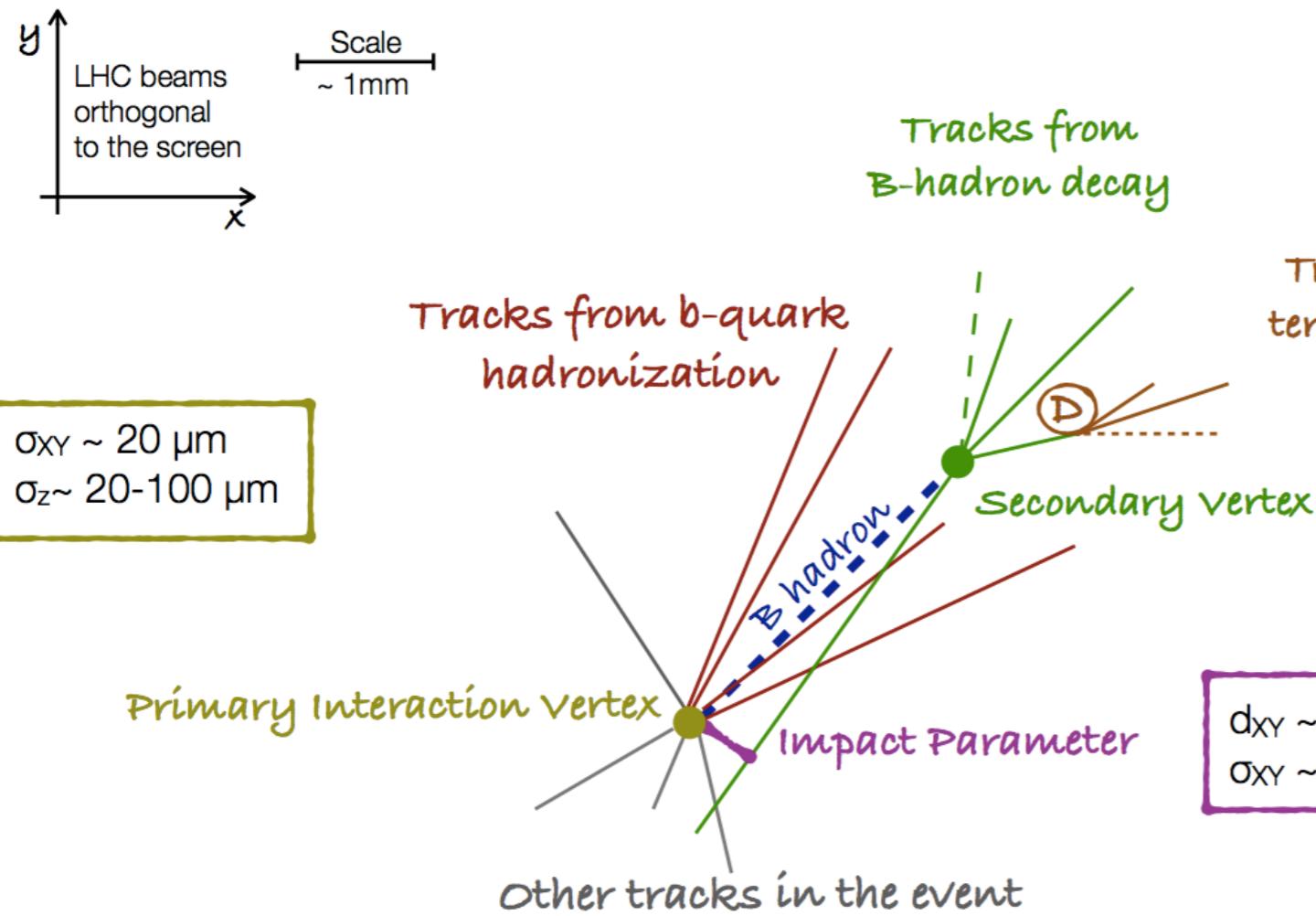
Ratios of τ_N are traditionally used for discriminating signal from background



Performance Compared with Other Variables

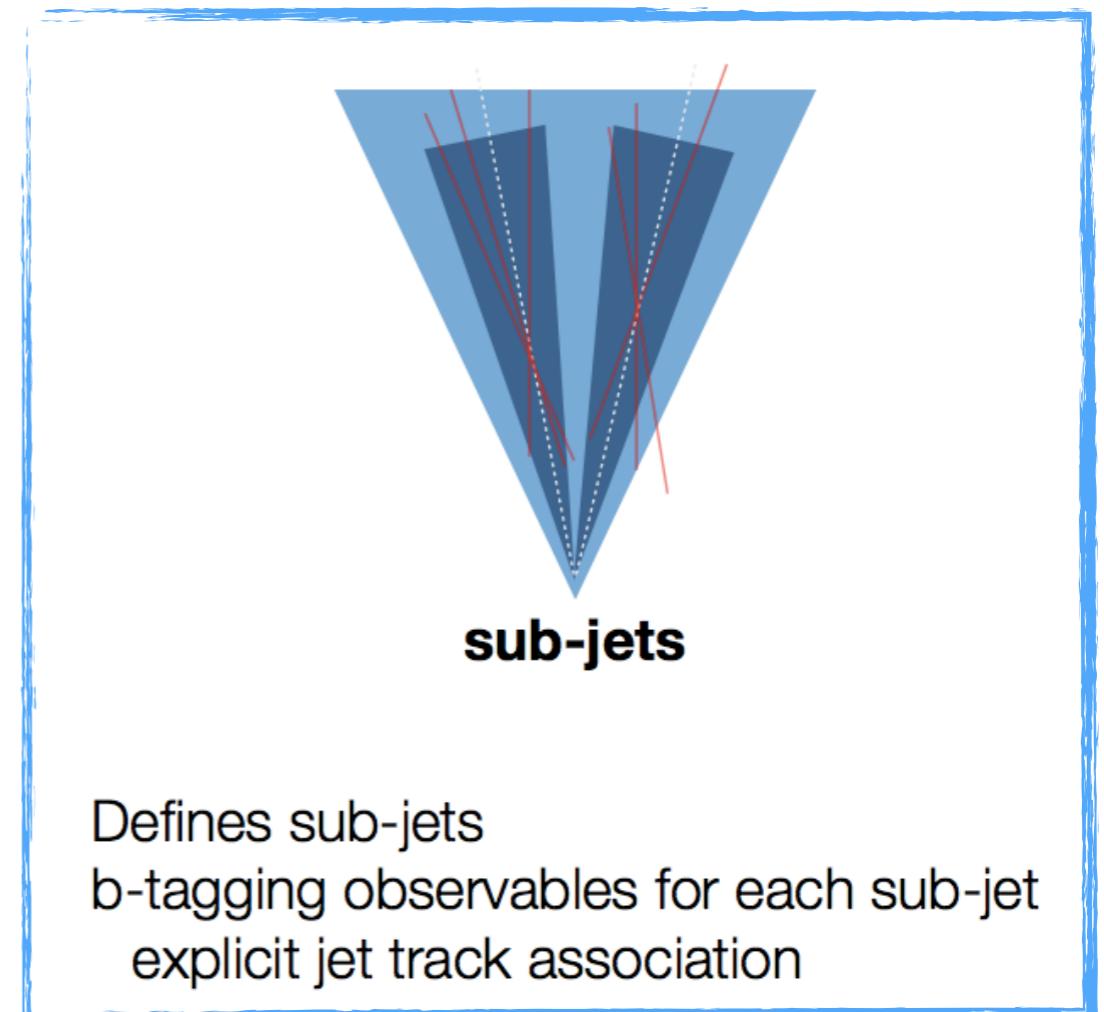
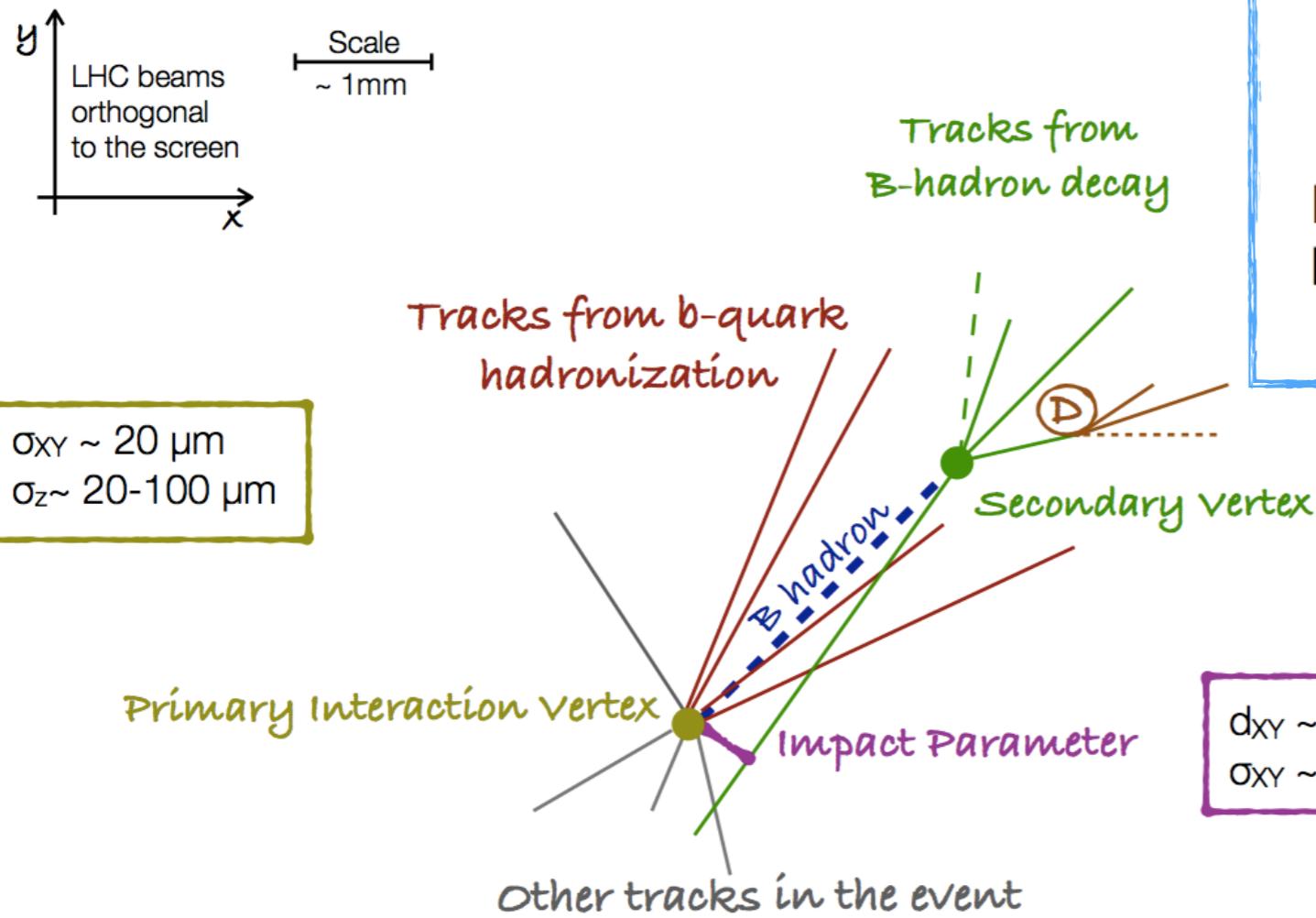


Subjet b-tagging for Higgs Jets



Caterina Vernieri (Boost 2015)

Subjet b-tagging for Higgs Jets



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Subjet b-tagging for Higgs Jets

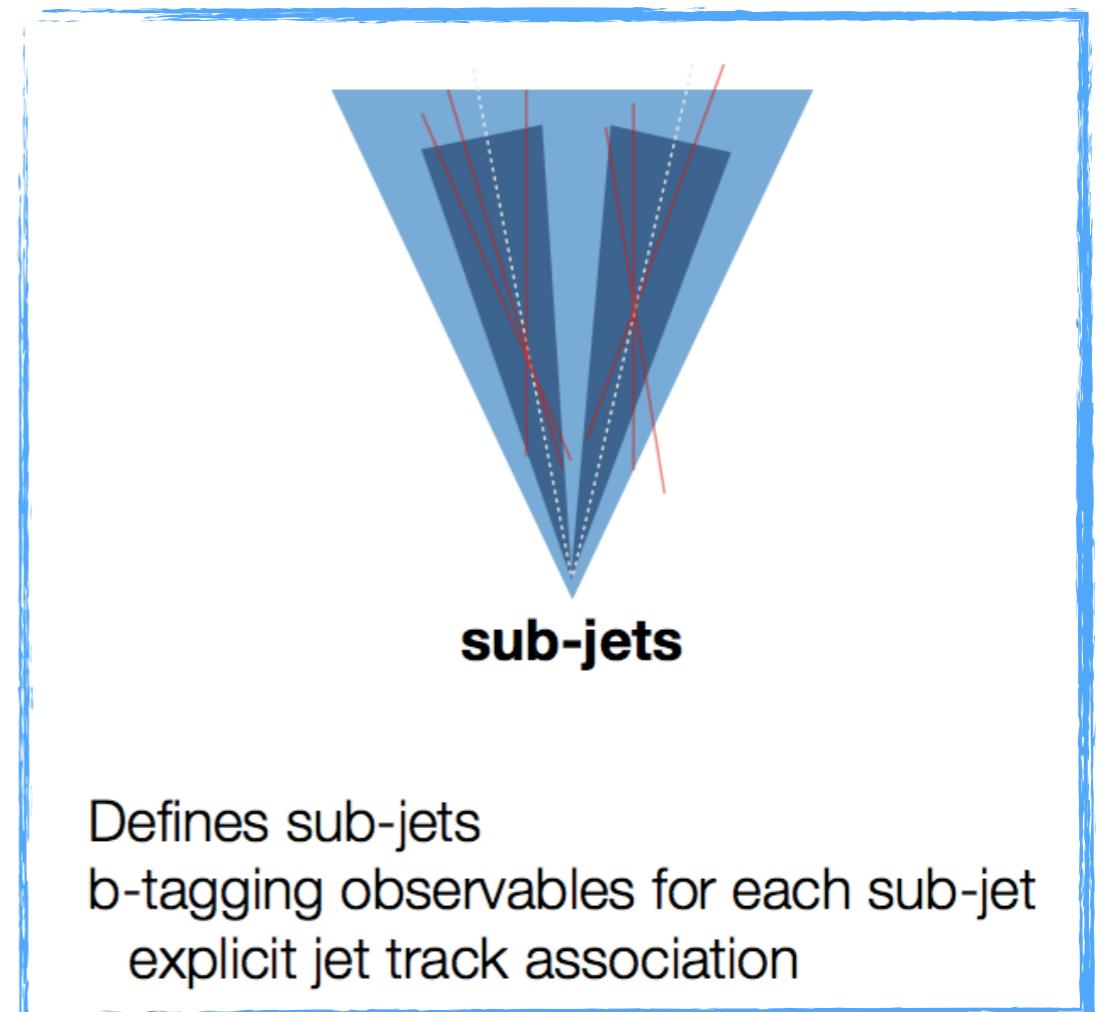
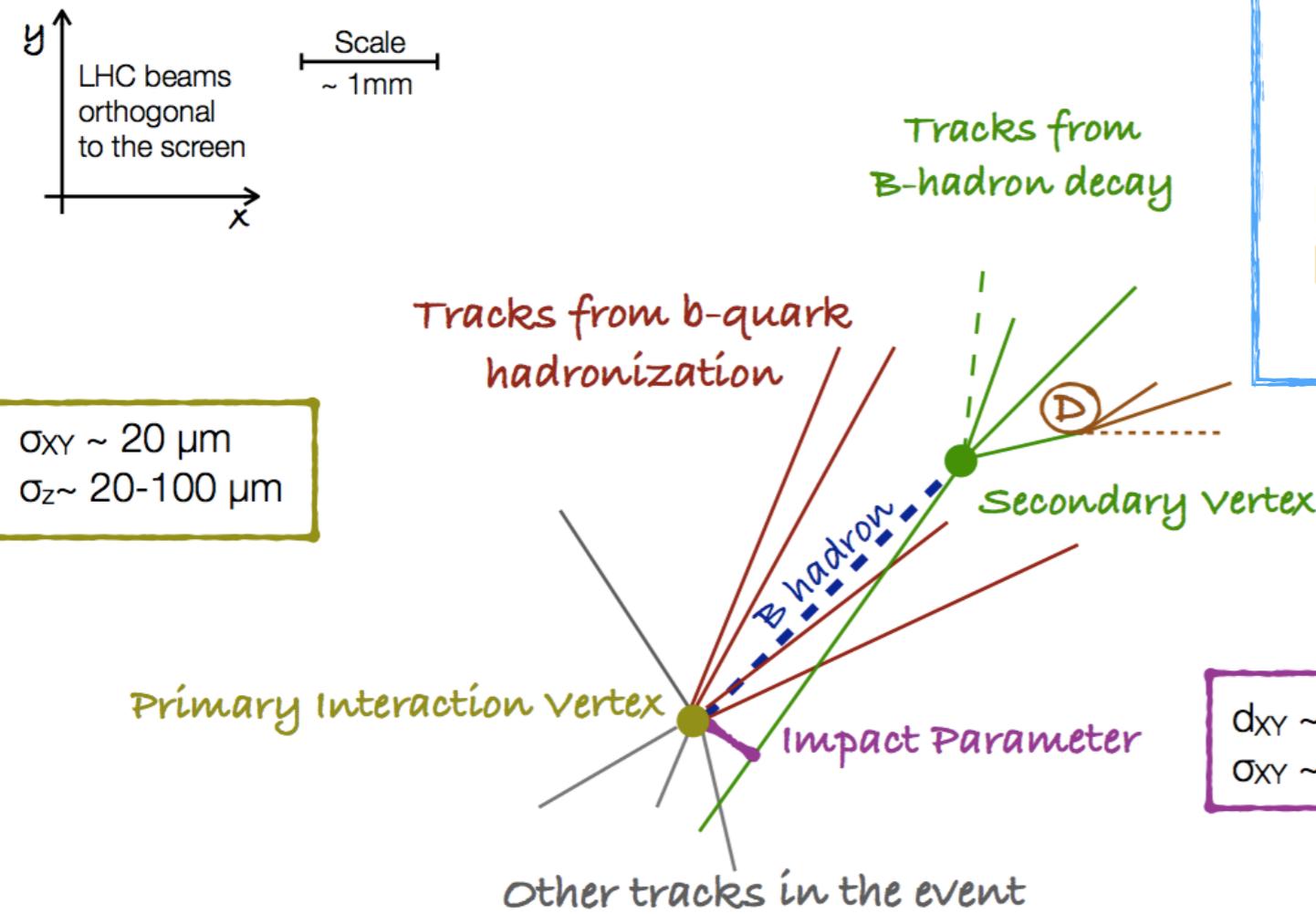
AK8 subjet and AK4 b-tagging:

efficiency 83% with a mis-tag rate 10%

(loose working point)

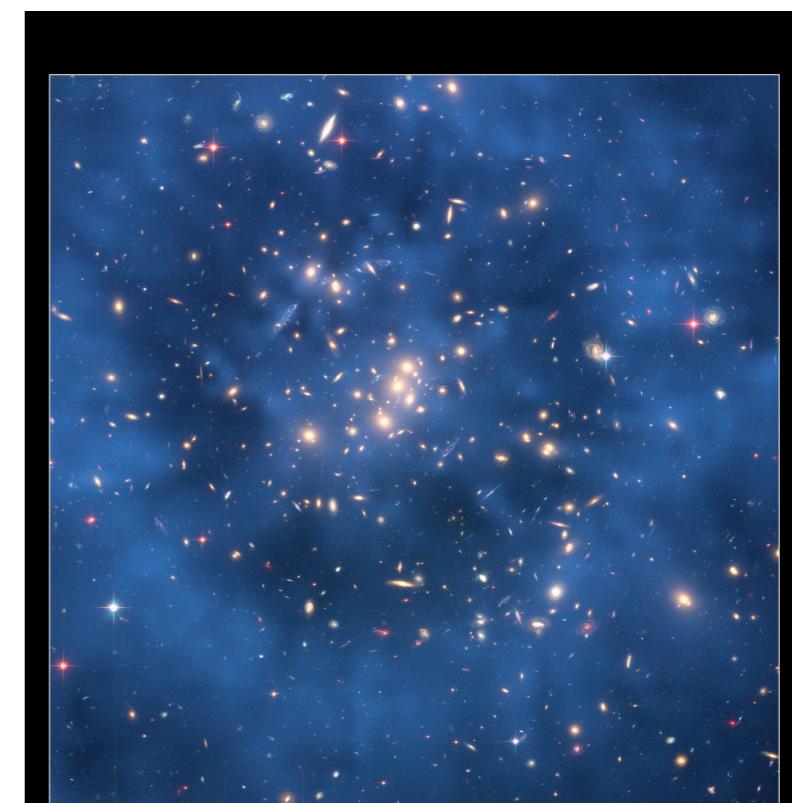
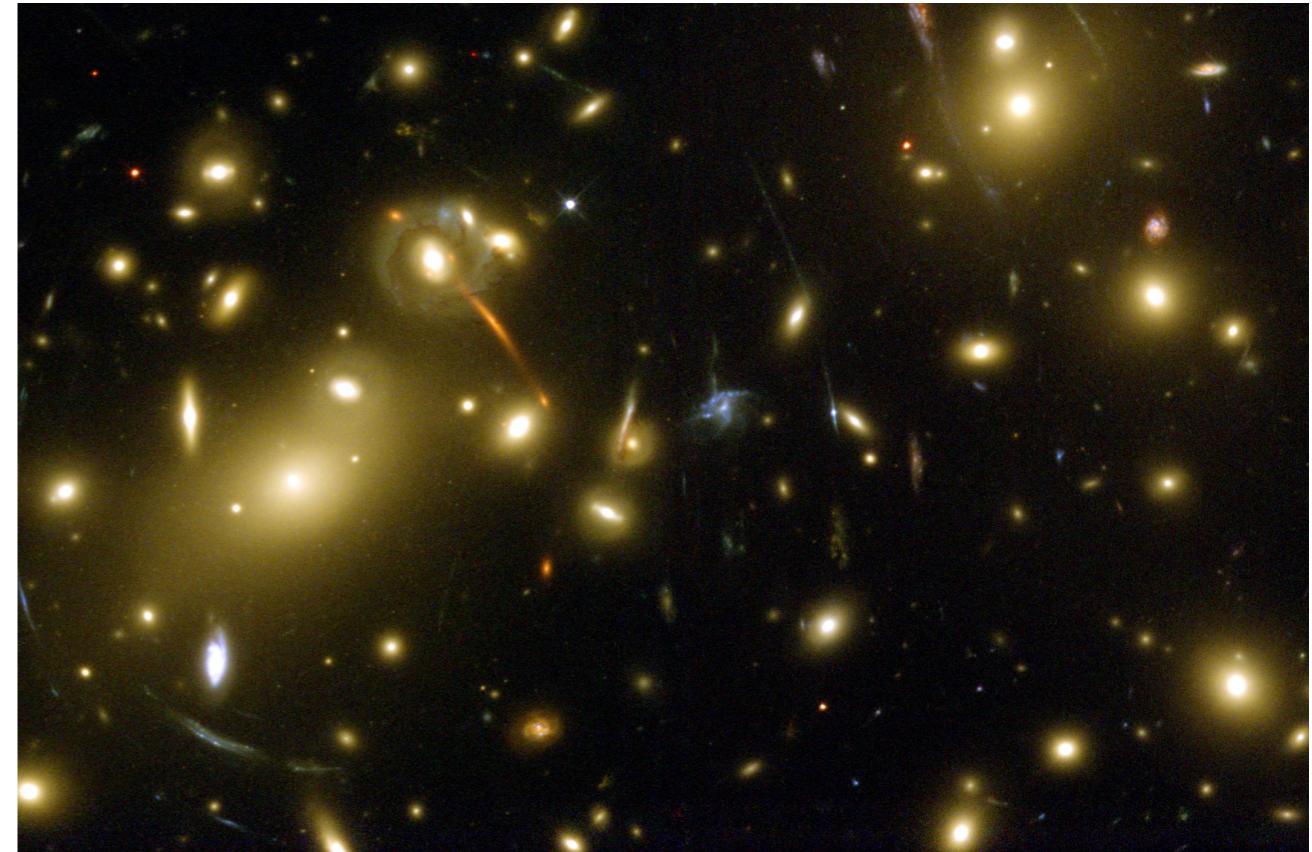
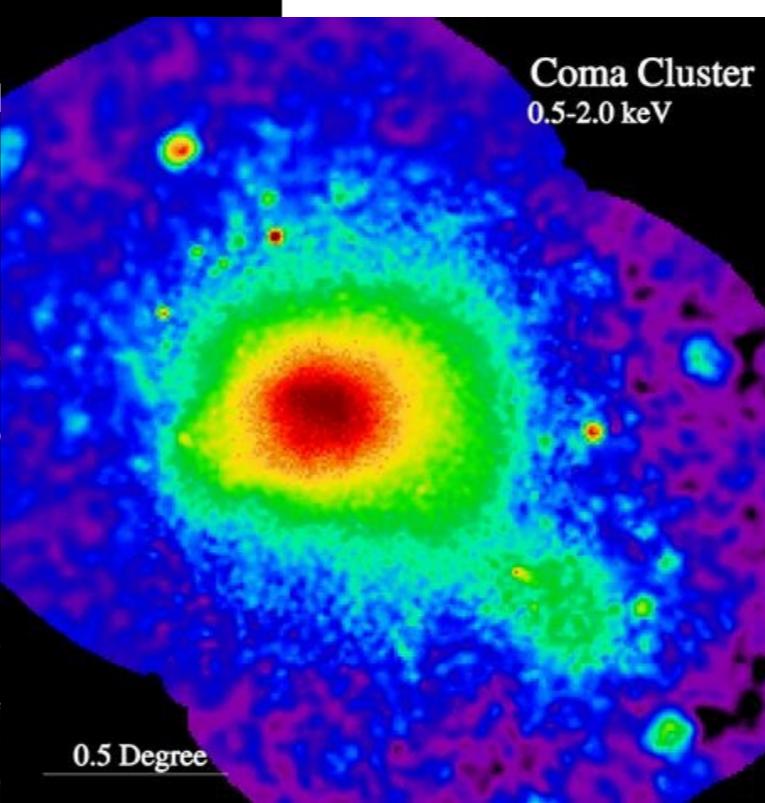
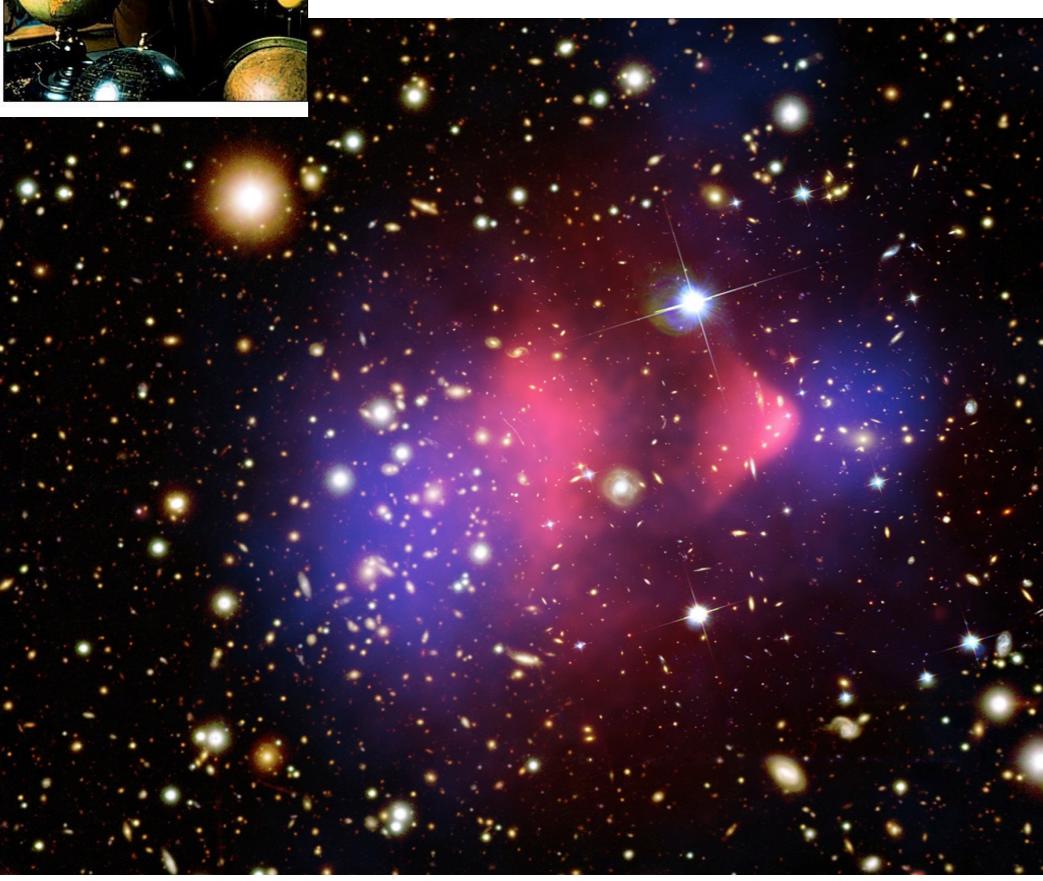
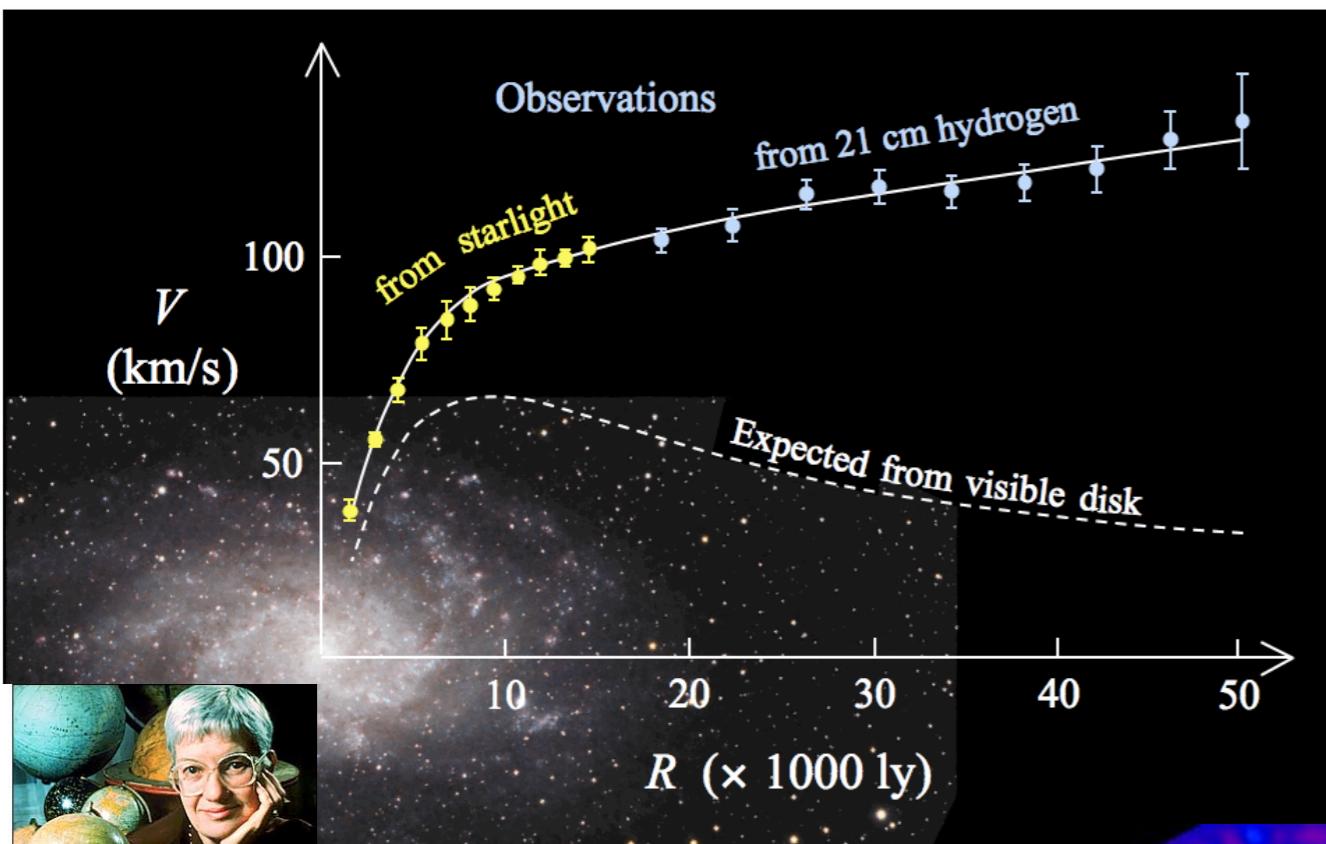
efficiency 69% with a mis-tag rate of 1%

(medium working point)



Caterina Vernieri (Boost 2015)

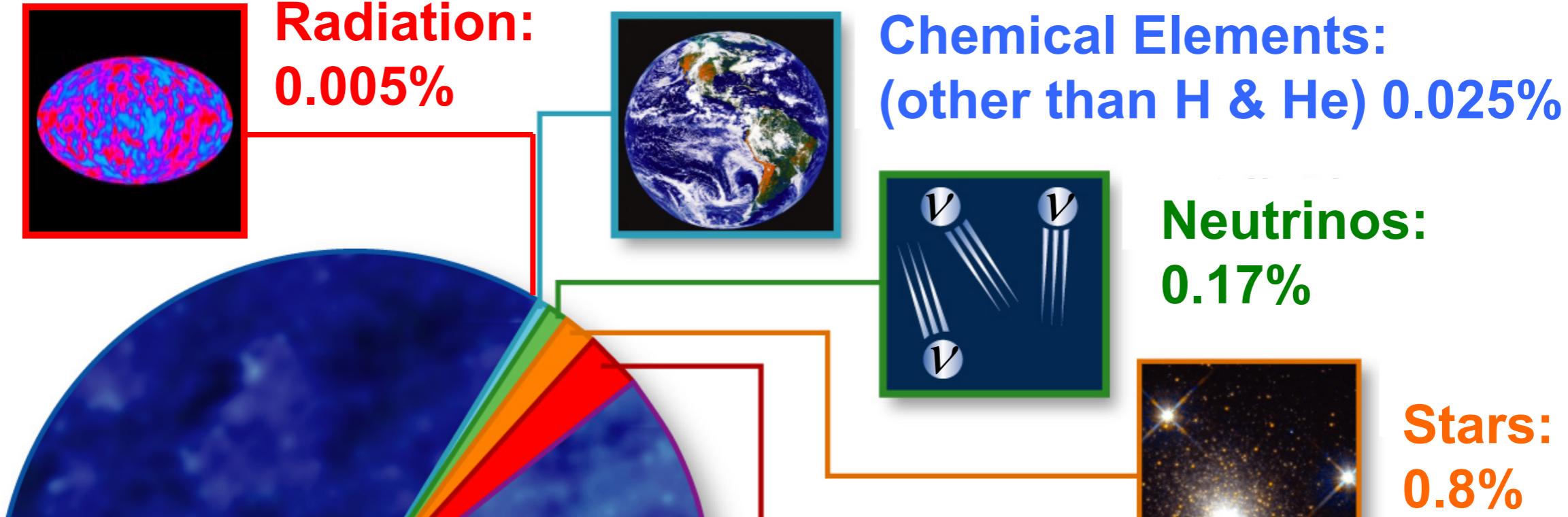
Why Dark Matter?



Dark Matter Ring in Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652)
Hubble Space Telescope • ACS/WFC

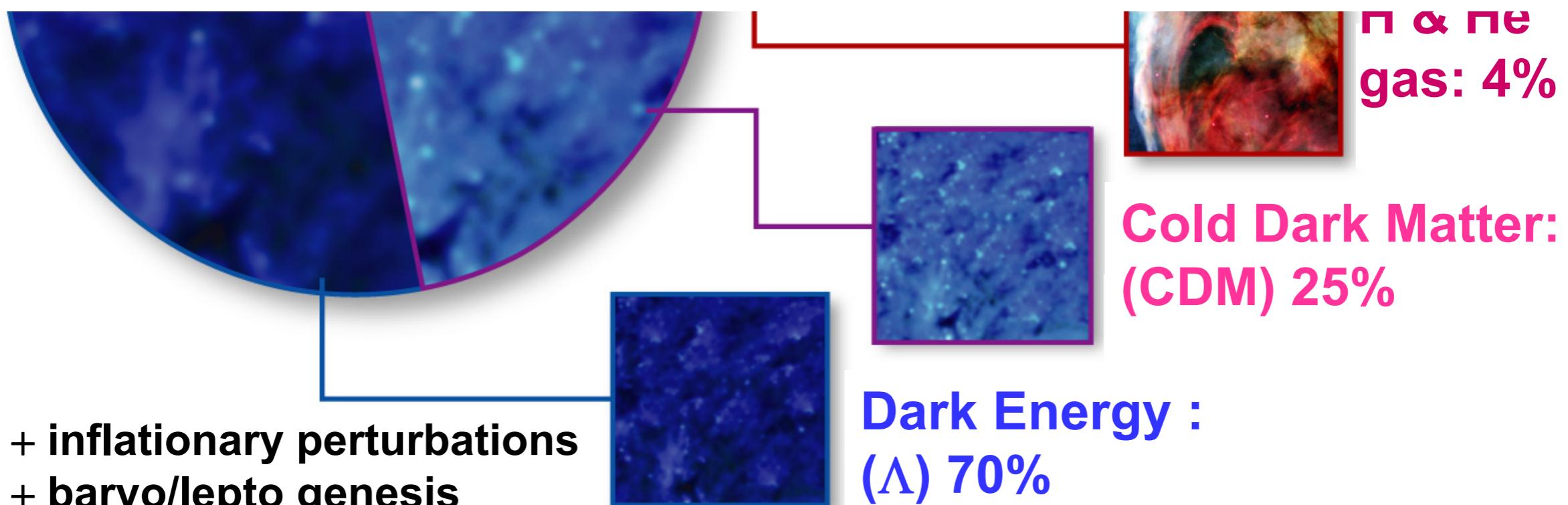
NASA, ESA, and M.J. Jee (Johns Hopkins University)

STScI-PRC07-17a



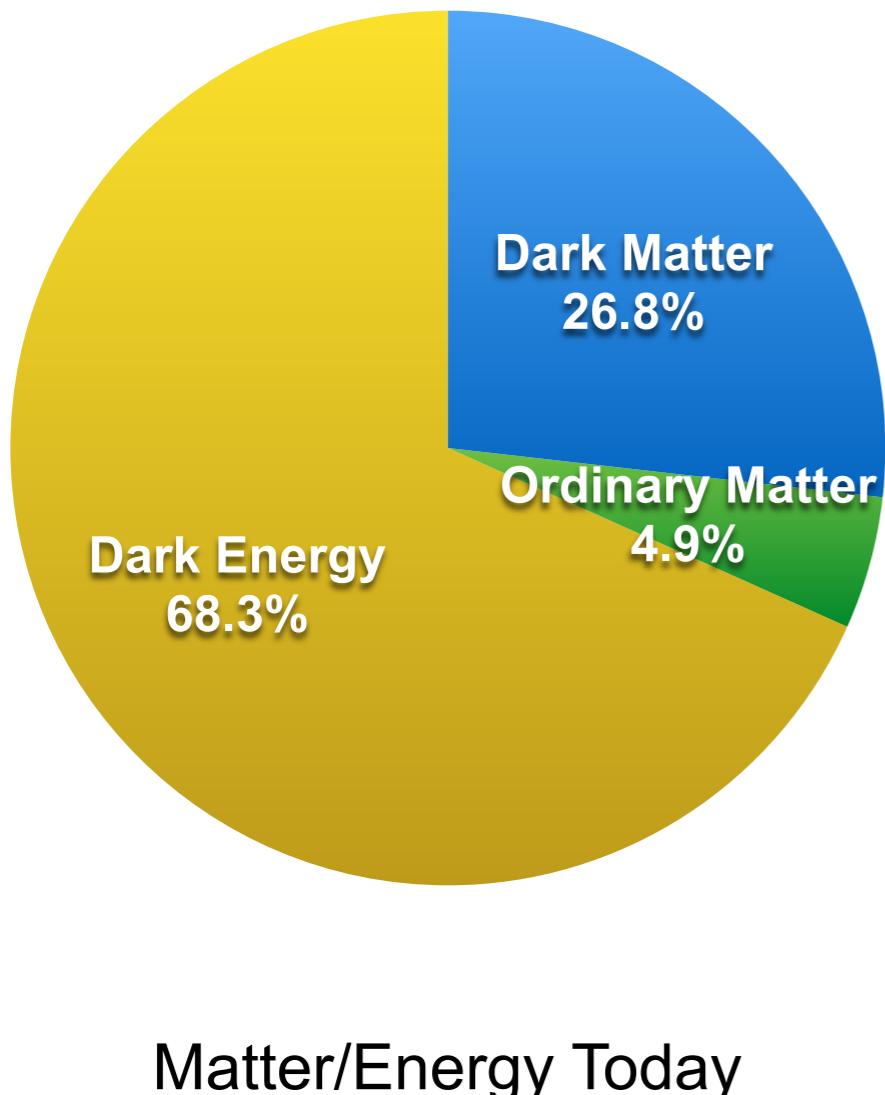
If I had been present at creation, I would have suggested a simpler scheme.

- Alfonse the Wise



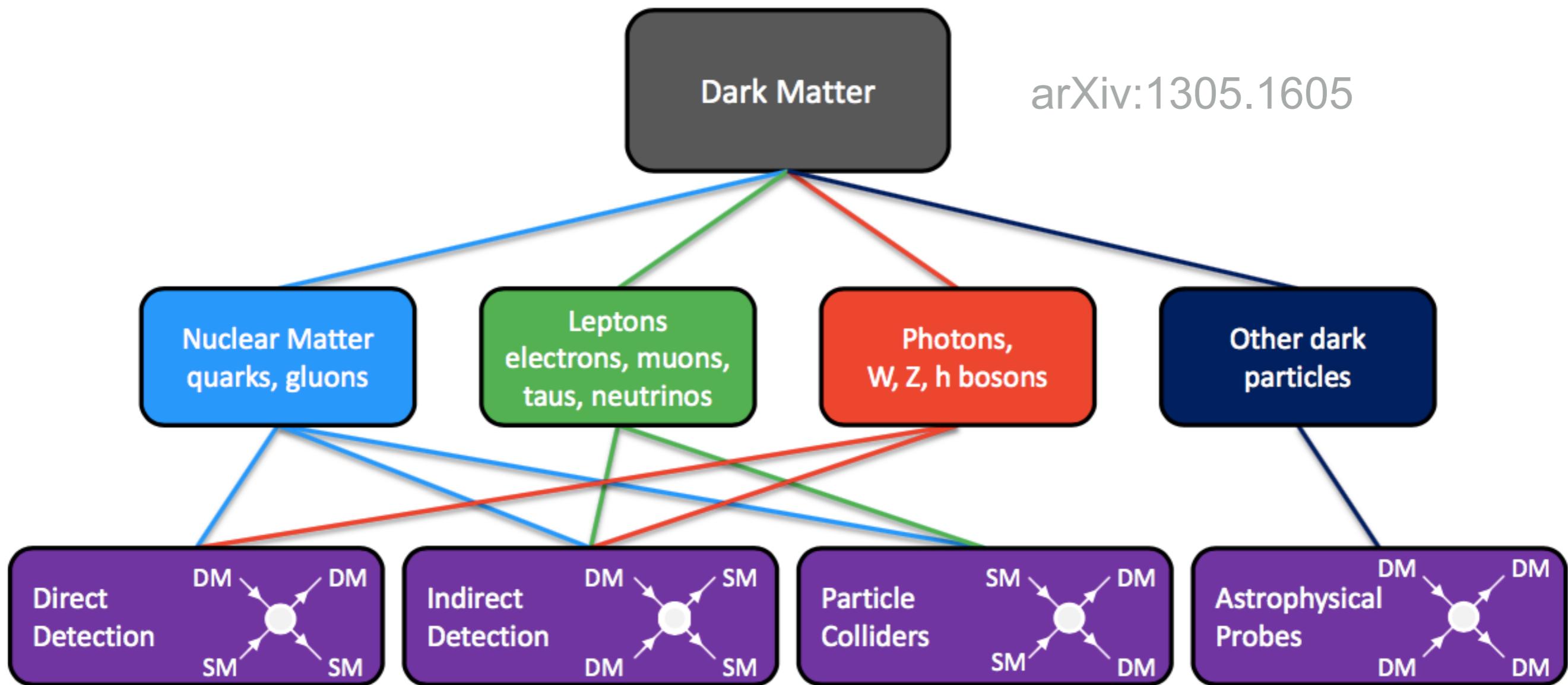
Complementarity of Dark Matter Searches

- Evidence of dark matter well established from astrophysical observations
 - The exact nature of DM is still unknown



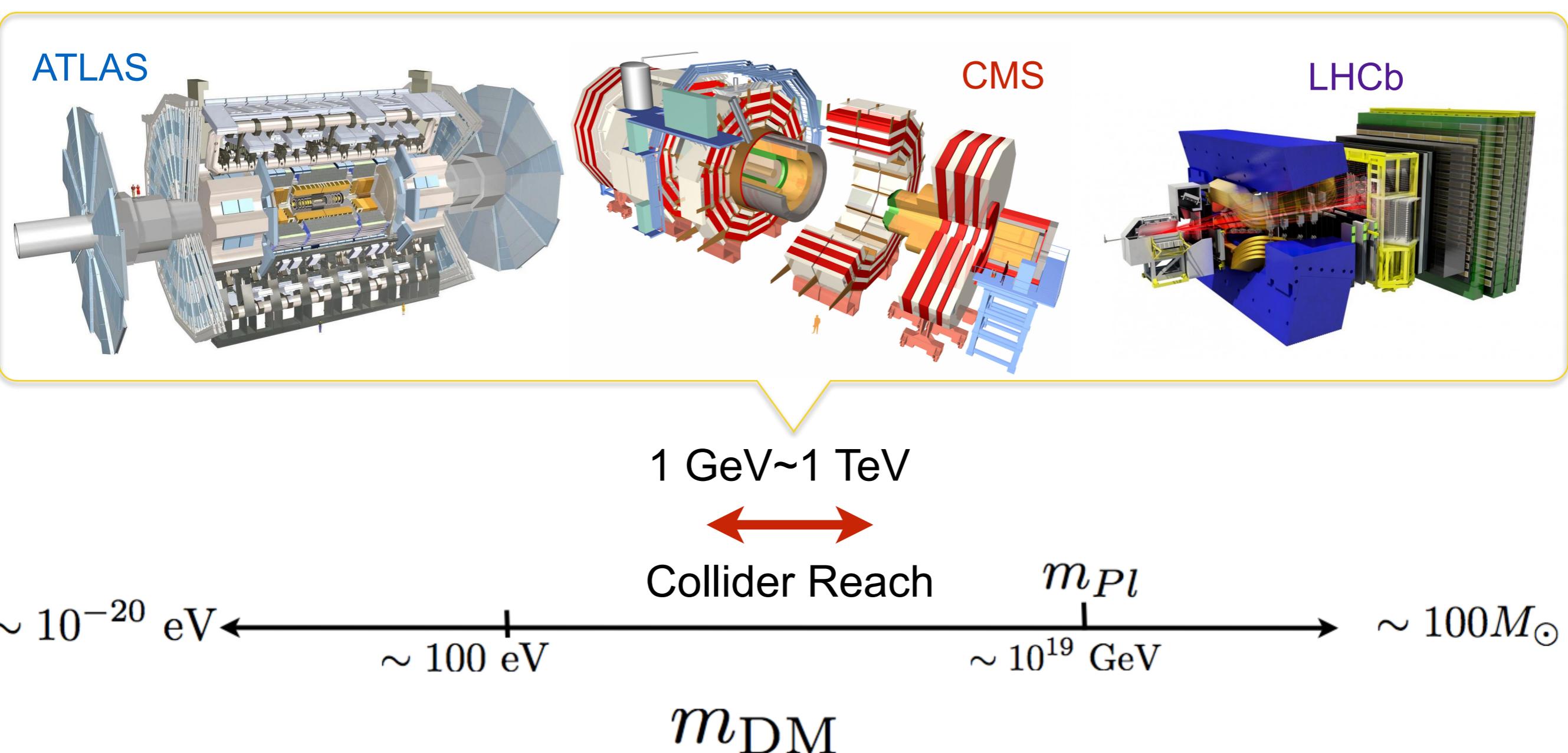
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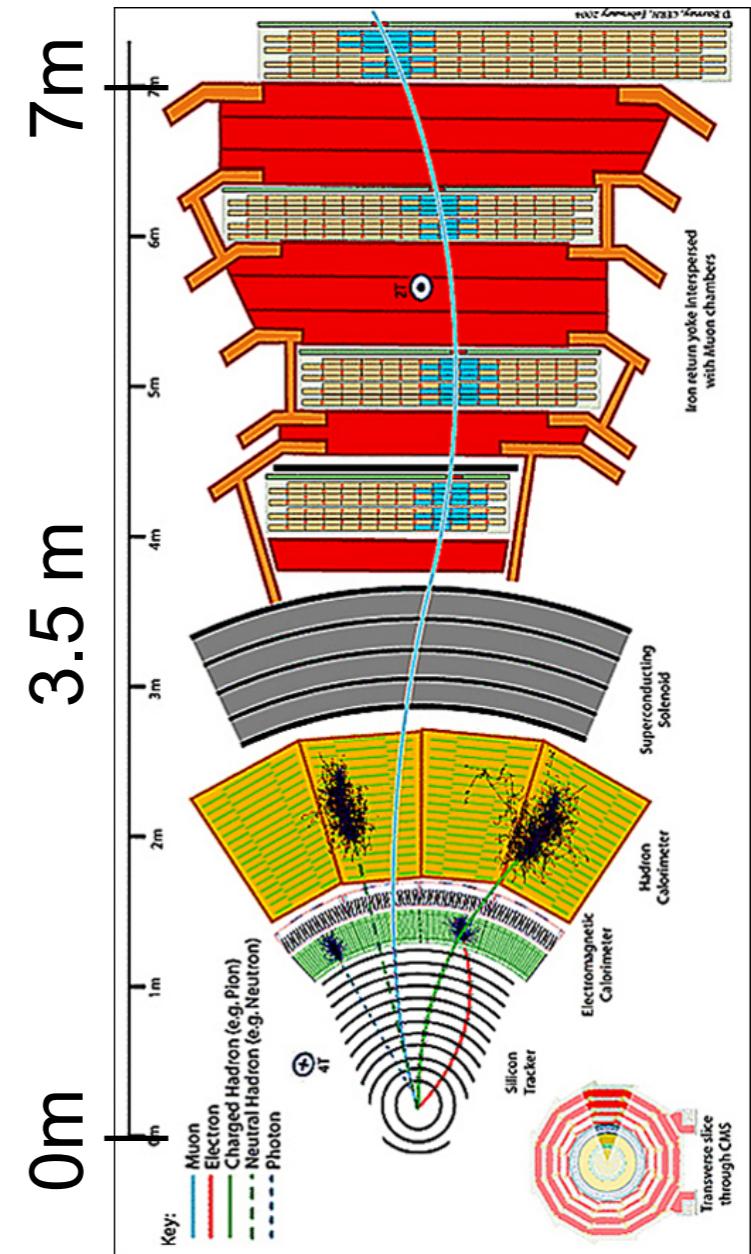
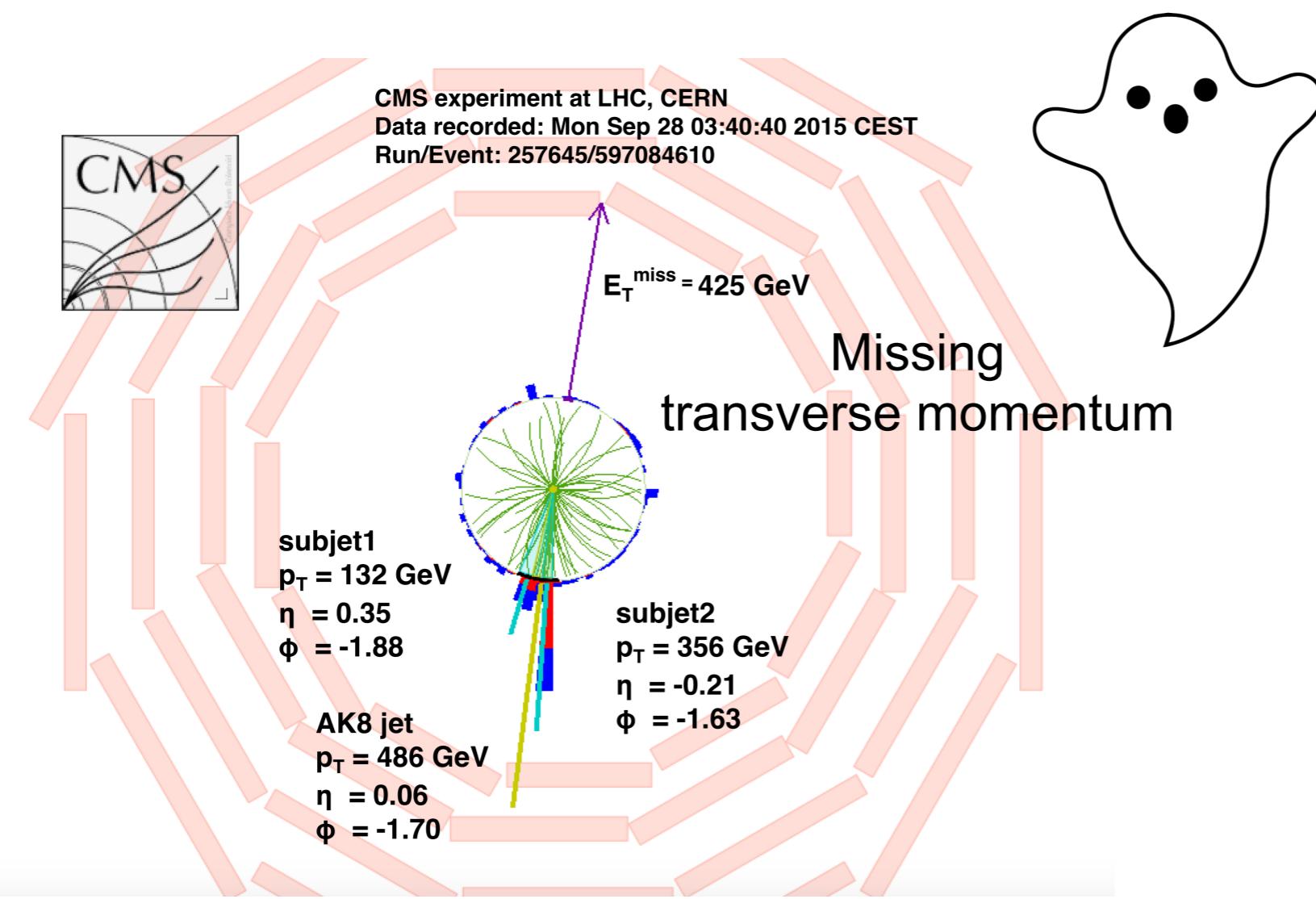
Dark Matter Searches at Colliders

- LHC provides a prime laboratory for production of DM
 - Can probe a wide range of DM/SM interaction types



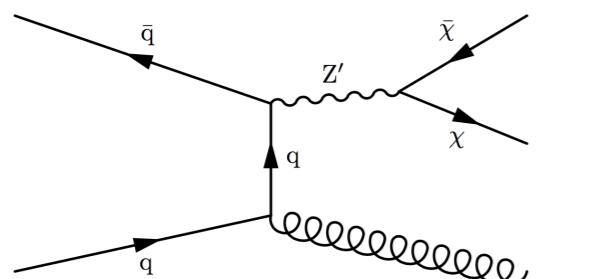
What Is Dark Matter at Colliders?

- Neutral, weakly-interactive, massive, and stable on the distance-scales of tens of meters
 - Dark matter appears as missing transverse momentum in collider detectors



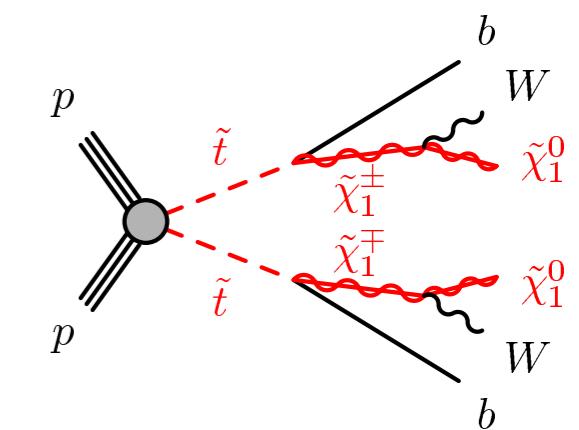
Search Approaches at Colliders

- Dark matter produced directly
 - Pair production of DMs
 - Mono-X signature where X=j, **γ , W, Z, h, bb, tt, t**
- Search for mediators
 - via dijet, dilepton, or Higgs



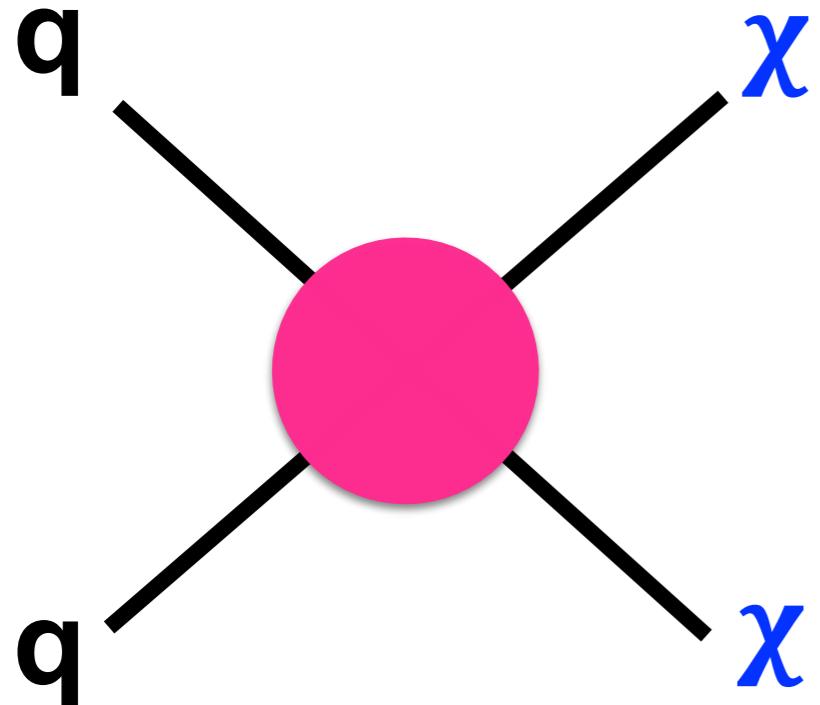
- Dark matter in cascade decays
 - SUSY WIMPs, with R-parity conservation, 2 LSPs in final state
 - NLSPs, LSPs, gluinos, or stops with long life time → displaced vertex, disappearing tracks, heavy stable charged particle (HSCP)

$$R = (-1)^{2s+3B+L} = \begin{cases} +1 & \text{SM} \\ -1 & \text{SUSY} \end{cases}$$



Evolution of Models for Direct DM Production

Effective Field Theory



$$\frac{g_\chi g_q}{Q_{\text{tr}}^2 - M^2} = -\frac{g_\chi g_q}{M^2} \left(1 + \frac{Q_{\text{tr}}^2}{M^2} + \mathcal{O}\left(\frac{Q_{\text{tr}}^4}{M^4}\right) \right)$$

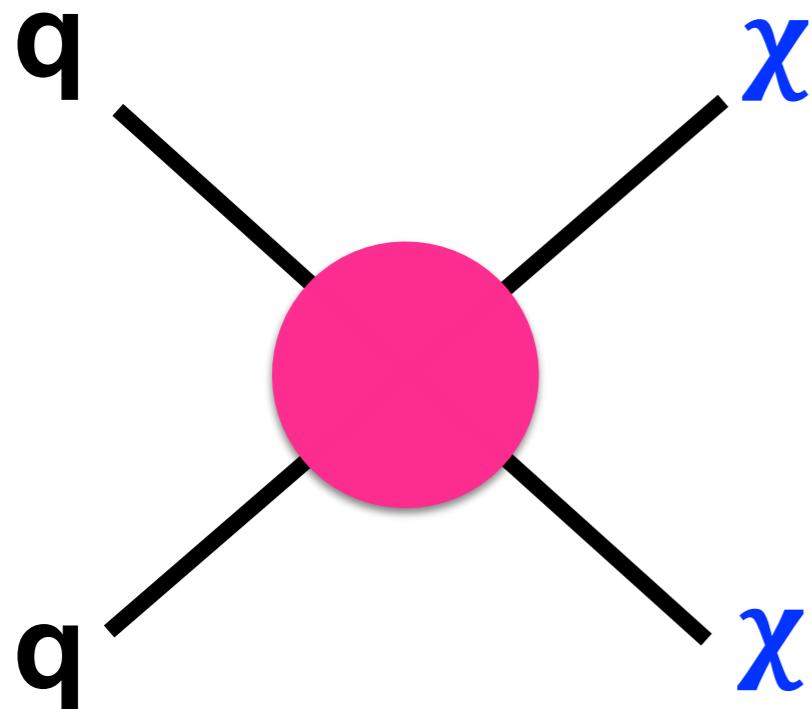
$$\simeq -\frac{g_\chi g_q}{M^2} = -\frac{1}{M_*^2}$$

$$M_* \equiv \frac{M}{\sqrt{g_\chi g_q}}$$

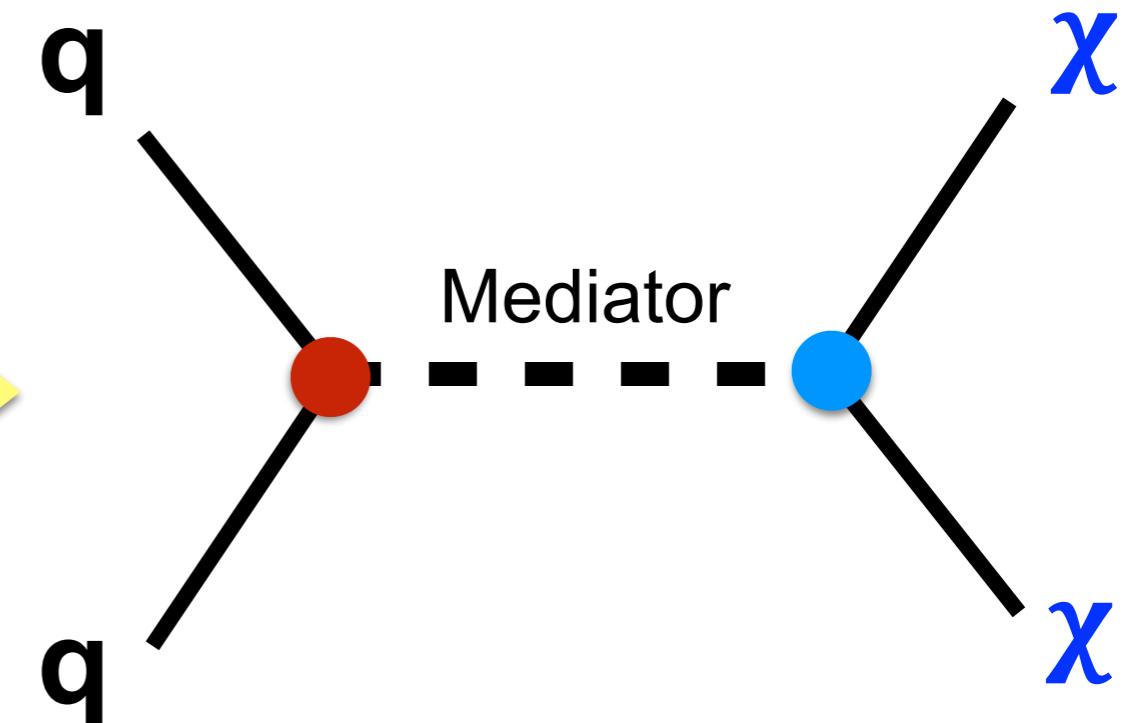
- m_{DM} , M_* , underlying coupling type, DM types
- Valid when $Q_{\text{tr}}^2 \ll M^2$

Evolution of Models for Direct DM Production

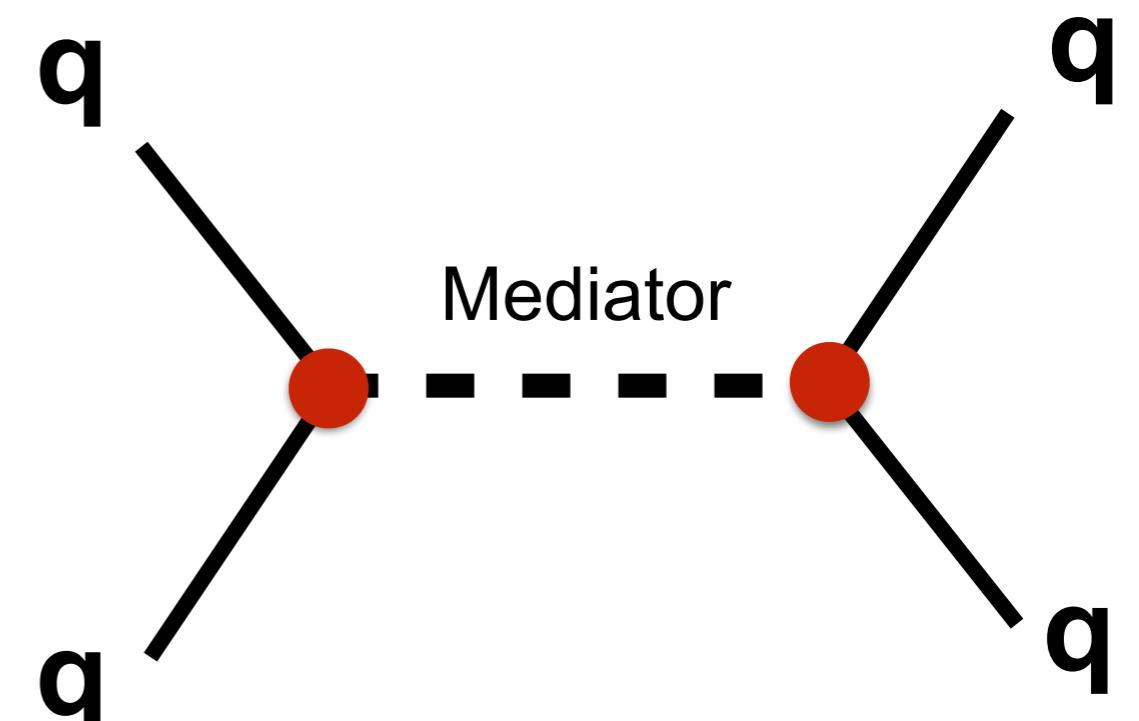
Effective Field Theory



Simplified Model



- m_{DM} , M_* , underlying coupling type, DM types
- Valid when $Q_{tr}^2 \ll M^2$



LHC Dark Matter Forum and Working Group

- SUSY simplified models to search for DMs in cascade decays are standardized already at Run I
- Starting from Run II, simplified models for direct DM searches are standardized and discussed in the LHC DM forum and working group, GitLab

arXiv.org > hep-ex > arXiv:1507.00966

arXiv:1507.00966

1603.041
(Help | Advanced)

High Energy Physics – Experiment

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara Alvarez Gonzalez, Jeremy Andrea, Alexandre Arbey, Georges Azuelos, Patrizia Azzi, Mihailo Backović, Yang Bai, Swagato Banerjee, James Beacham, Alexander Belyaev, Antonio Boveia, Amelia Jean Brennan, Oliver Buchmueller, Matthew R. Buckley, Giorgio Busoni, Michael Buttignol, Giacomo Cacciapaglia, Regina Caputo, Linda Carpenter, Nuno Filipe Castro, Guillermo Gomez Ceballos, Yangyang Cheng, John Paul Chou, Arely Cortes Gonzalez, Chris Cowden, Francesco D'Eramo, Annapaola De Cosa, Michele De Gruttola, Albert De Roeck, Andrea De Simone, Aldo Deandrea, Zeynep Demiragli, Anthony DiFranzo, Caterina Doglioni, Tristin du Pree, Robin Erbacher, Johannes Erdmann, Cora Fischer, Henning Flaecher, Patrick J. Fox, et al. (94 additional authors not shown)

arXiv.org > hep-ex > arXiv:1603.04156

arXiv:1603.04156

1703.051
(Help | Advanced)

High Energy Physics – Experiment

Recommendations on presenting LHC searches for missing transverse energy signals using simplified s -channel models of dark matter

Antonio Boveia, Oliver Buchmueller, Giorgio Busoni, Francesco D'Eramo, Albert De Roeck, Andrea De Simone, Caterina Doglioni, Matthew J. Dolan, Marie-Helene Genest, Kristian Hahn, Ulrich Haisch, Philip C. Harris, Jan Heisig, Valerio Ippolito, Felix Kahlhoefer, Valentin V. Khoze, Suchita Kulkarni, Greg Landsberg, Steven Lowette, Sarah Malik, Michelangelo Mangano, Christopher McCabe, Stephen Mrenna, Priscilla Pani, Tristan du Pree, Antonio Riotto, David Salek, Kai Schmidt-Hoberg, William Shepherd, Tim M.P. Tait, Lian-Tao Wang, Steven Worm, Kathryn Zurek

arXiv.org > hep-ex > arXiv:1703.05703

arXiv:1703.05703

Search or Art
(Help | Advanced)

High Energy Physics – Experiment

Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels

Andreas Albert, Mihailo Backovic, Antonio Boveia, Oliver Buchmueller, Giorgio Busoni, Albert De Roeck, Caterina Doglioni, Tristan DuPree, Malcolm Fairbairn, Marie-Helene Genest, Stefania Gori, Giuliano Gustavino, Kristian Hahn, Ulrich Haisch, Philip C. Harris, Dan Hayden, Valerio Ippolito, Isabelle John, Felix Kahlhoefer, Suchita Kulkarni, Greg Landsberg, Steven Lowette, Kentarou Mawatari, Antonio Riotto, William Shepherd, Tim M.P. Tait, Emma Tolley, Patrick Tunney, Bryan Zaldivar, Markus Zinser

arXiv.org > hep-ph > arXiv:1705.04664

arXiv:1705.04664

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High Energy Physics – Phenomenology

Precise predictions for V+jets dark matter backgrounds

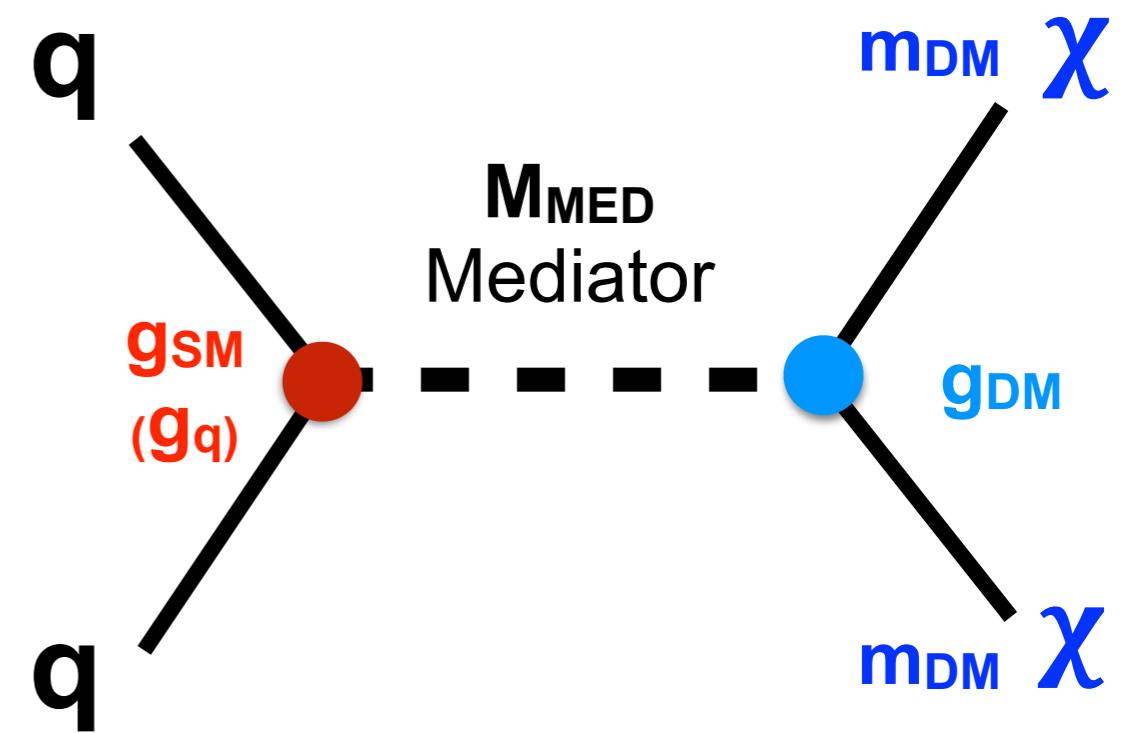
J. M. Lindert, S. Pozzorini, R. Boughezal, J. M. Campbell, A. Denner, S. Dittmaier, A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, Kallweit, P. Maierhöfer, M.L. Mangano, T.A. Morgan, A. Mück, F. Petriello, G.P. Salam, M. Schönherr, C. Williams

Simplified Models for Direct DM Production

Features of Mediators

	spin 0	spin 1
Charge Q	$Q_{\text{med}} = 0$ for s-channel	
Mass m	unknown	
Dark sector bosons similar to	H [1609.09079]	γ, Z, Z'
Lorentz structure	scalar 1 pseudosc. γ_5	vector γ^μ axial v. $\gamma^\mu \gamma_5$
Coupling "g"	\propto mass	\propto charge
Consequences	$m_b \gg m_d$	$Q_b = Q_d$

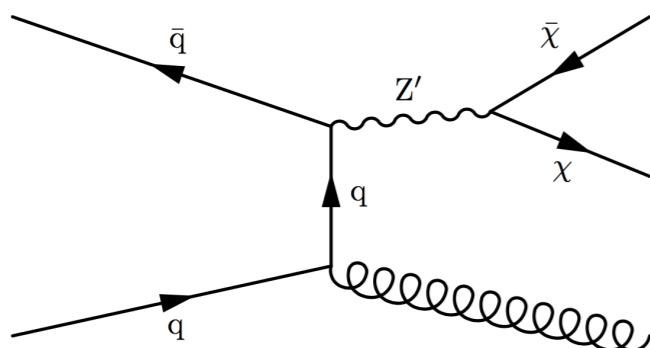
- Mediator has minimal decay width
- Minimal flavor violation
- Minimal set of parameters
 - coupling structure, M_{MED} , m_{DM} , g_{SM} (g_q), g_{DM}



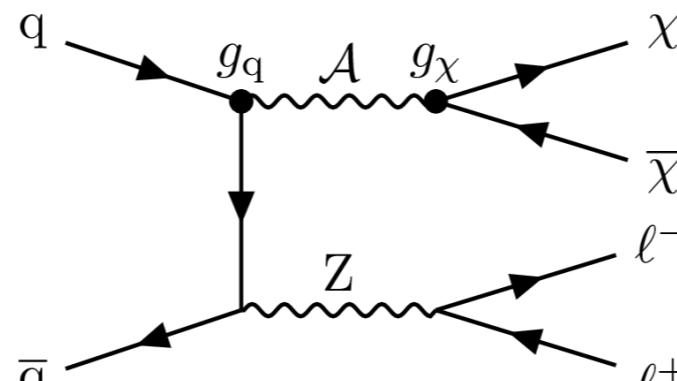
Tae Min Hong, LHCP 2017

DM Searches with Missing Transverse Momentum Signatures

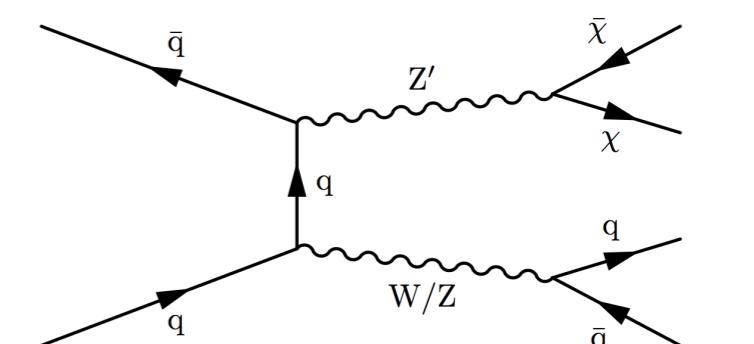
Mono-X Diagrams of Direct DM Production



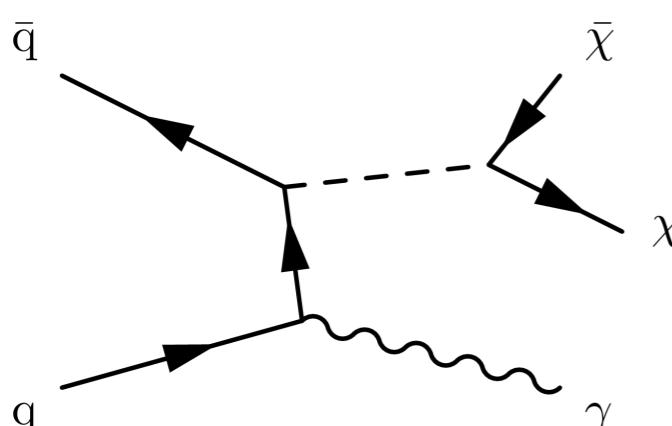
Mono-jet



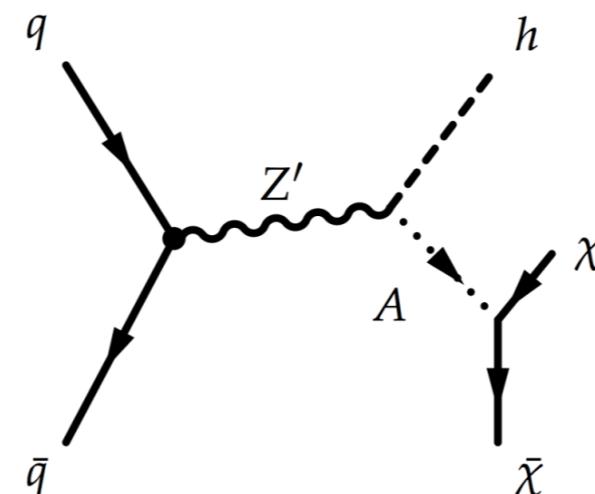
Mono-Z(leptonic)



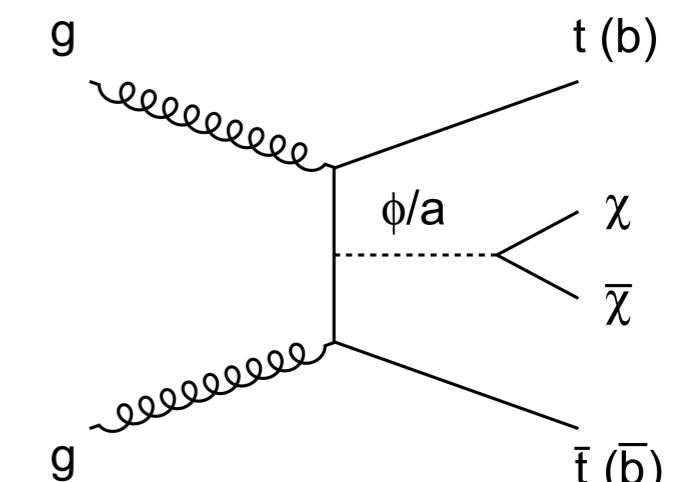
Mono-W/Z(hadronic)



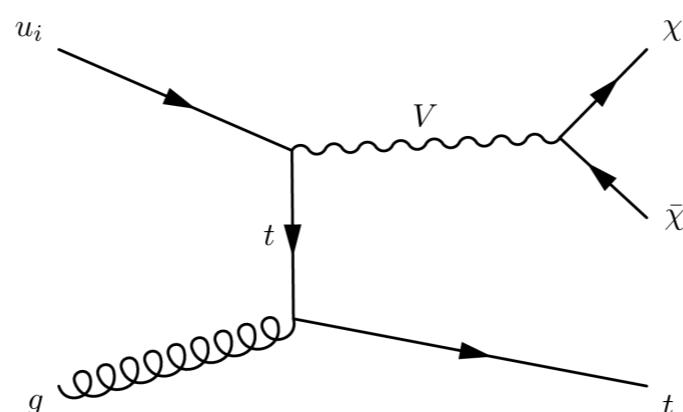
Mono-photon



Mono-h (bb , $\gamma\gamma$)



Mono-tt/bb



Mono-top

Challenges of Missing Transverse Momentum

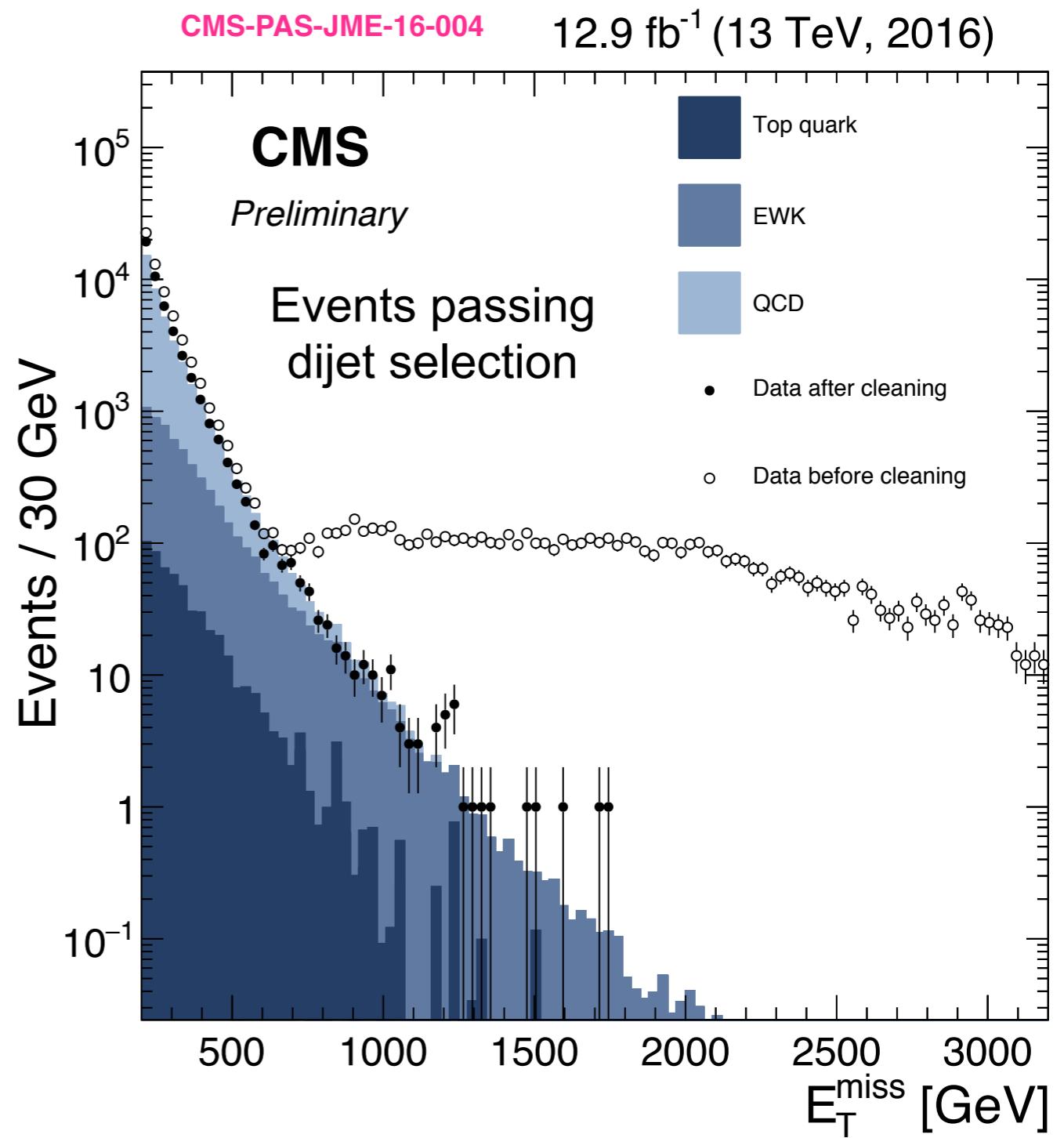
- Anomalous high MET can be due to:
 - Particles striking sensors in the ECAL photodetectors
 - Beam halo
 - Dead cells in ECAL or HCAL
 - Noise in ECAL or HCAL



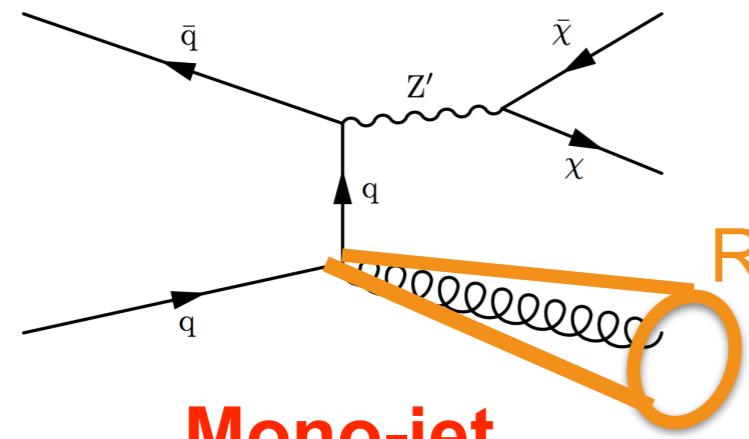
Raman Khurana



Ching-Wei Chen

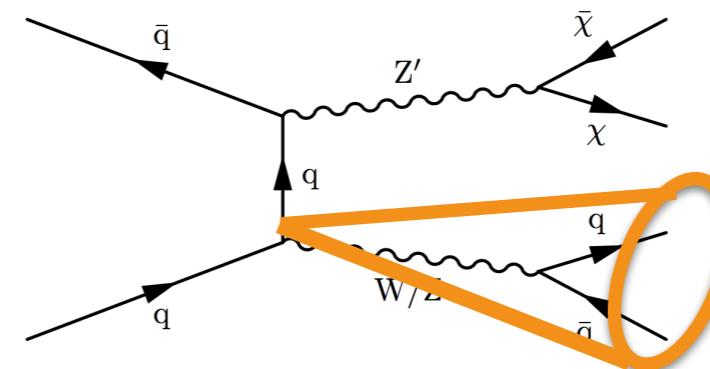


Mono-X Searches in Hadronic Final State



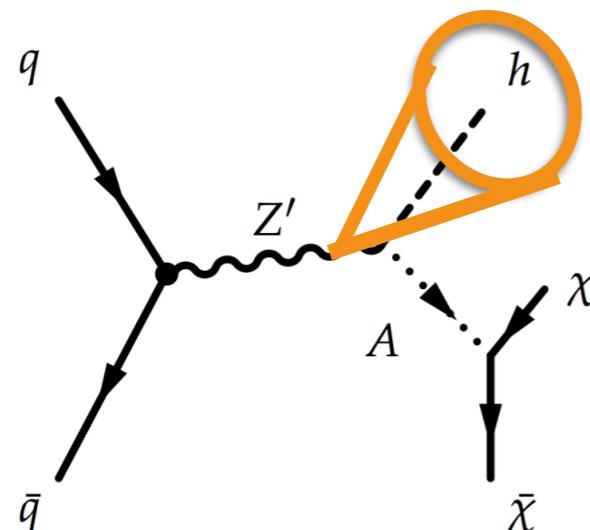
$R=0.4$

Mono-jet



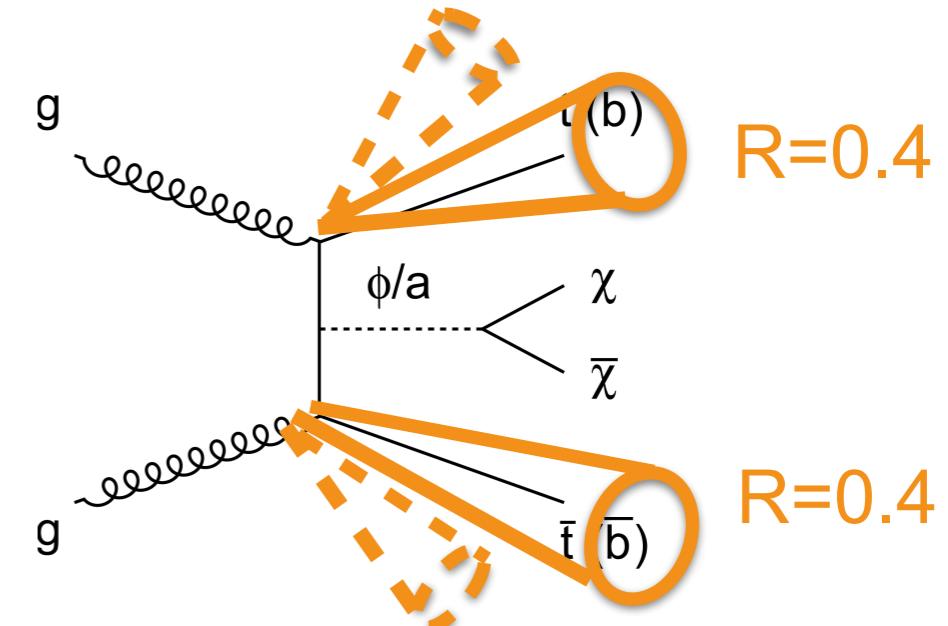
$R=0.8$

Mono-W/Z(hadronic)



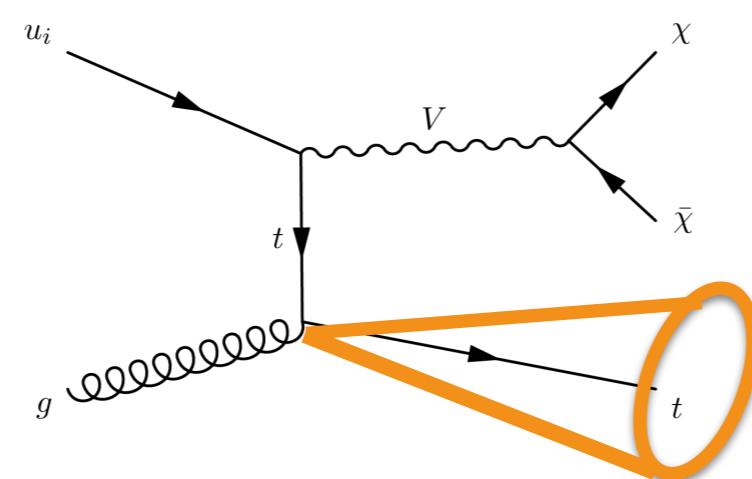
$R=0.4, 0.8$

Mono-h (bb)



$R=0.4$

Mono-tt/bb



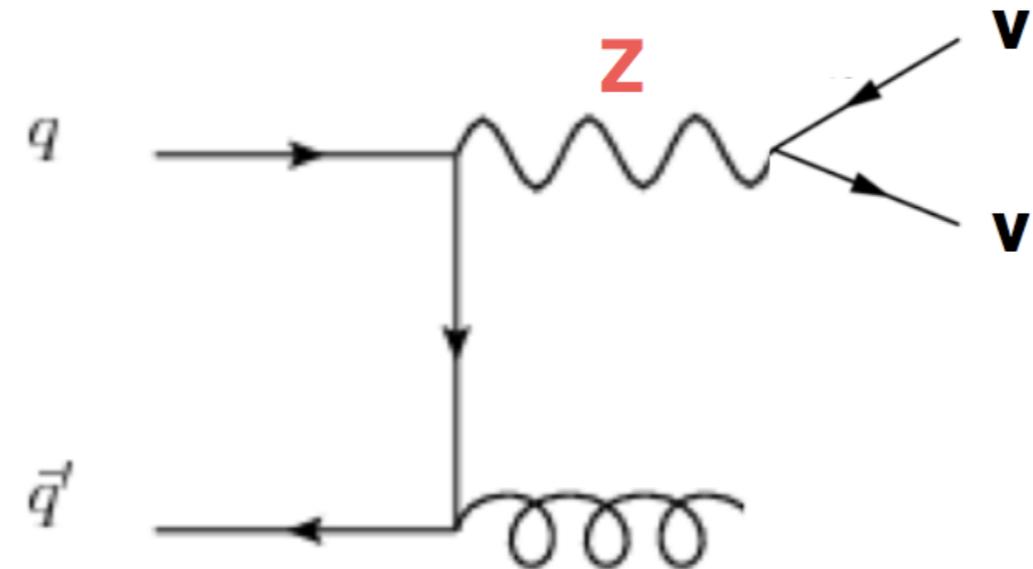
$R=1.5$

Mono-top

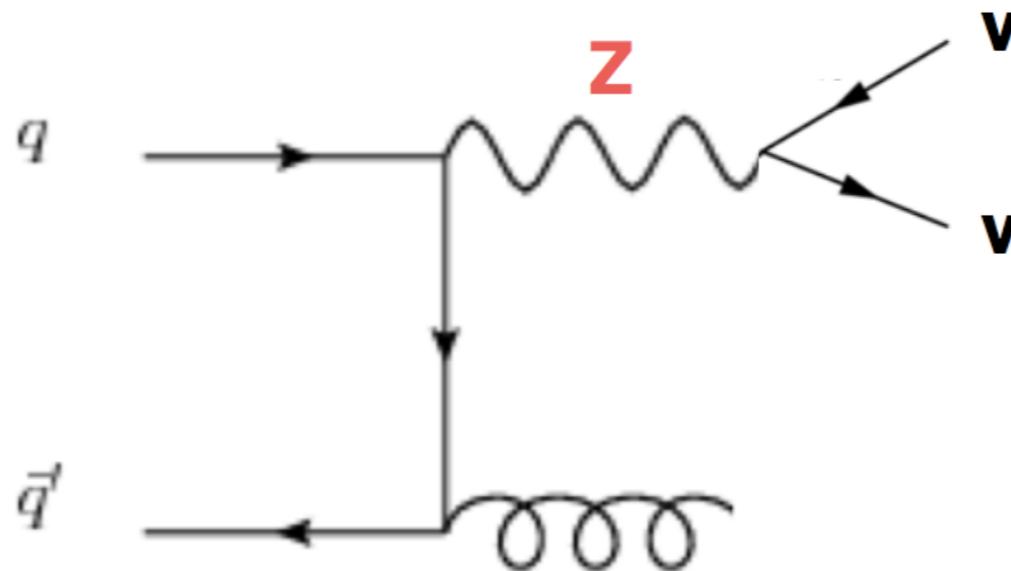
Mono-X Searches in Hadronic Final State

- Rely on MET triggers (offline MET cut ≥ 200 GeV)
- Major background from $Z(\rightarrow \nu\nu) + \text{jets}$, $W(\cancel{\rightarrow l\nu}) + \text{jets}$

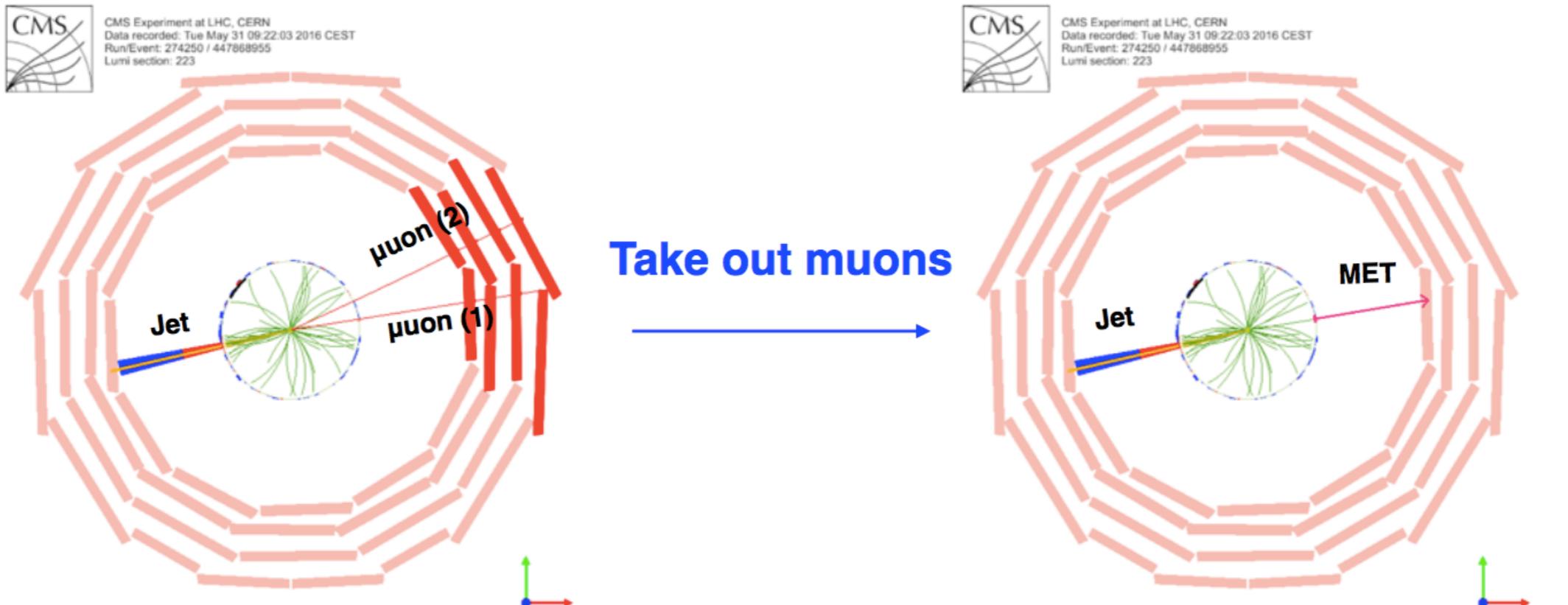
Estimation of W+Jets and Z+Jets Background



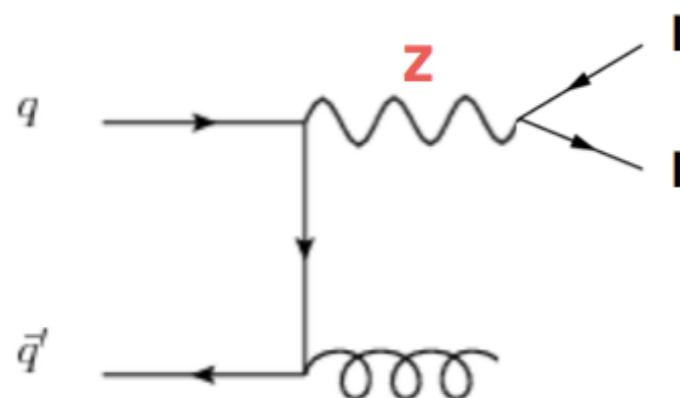
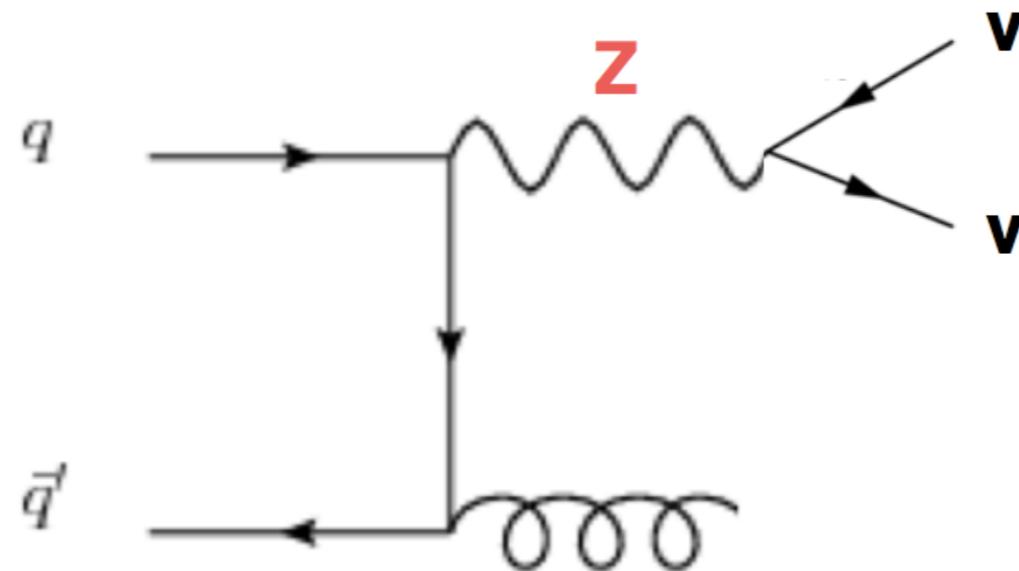
Estimation of W+Jets and Z+Jets Background



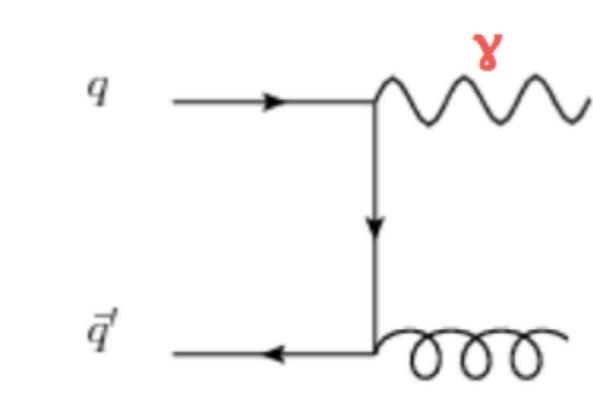
If we remove the muons from a $Z \rightarrow \mu\mu$ event,
it mimics a $Z \rightarrow \nu\nu$ event



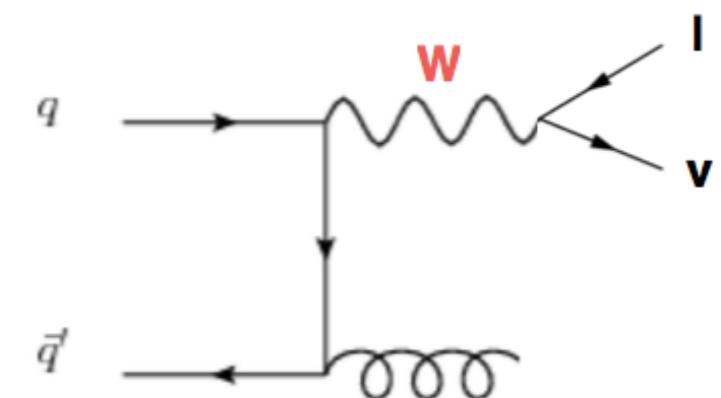
Estimation of W+Jets and Z+Jets Background



Same pT spectra as $Z \rightarrow \nu\nu$
but... statistically limited
 $Z \rightarrow \mu\mu$ branching ratio $\sim 3\%$
 $Z \rightarrow \nu\nu$ branching ratio 20%



Similar pT spectra as $Z \rightarrow \nu\nu$
Statistically rich!
but...
large theory uncertainties

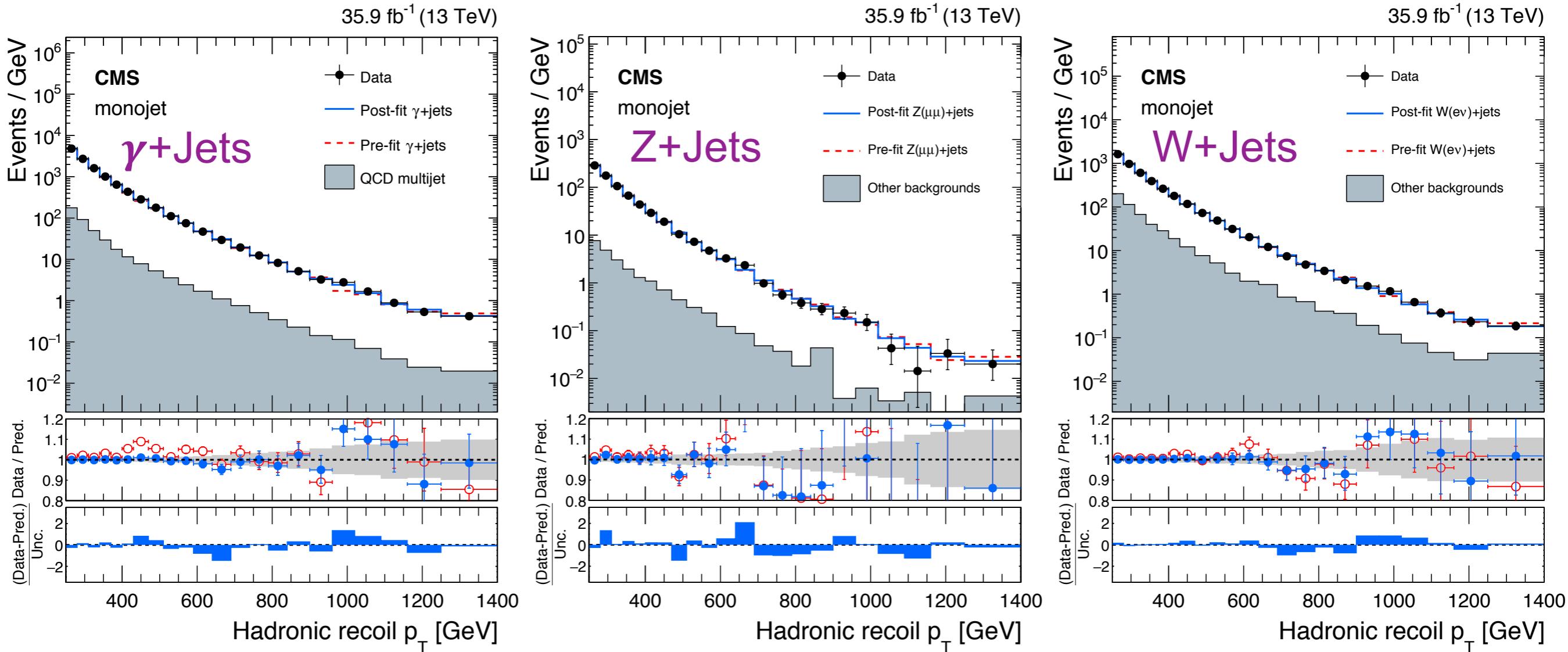


Similar pT spectra as $Z \rightarrow \nu\nu$
Statistically $\sim Z (\nu\nu)$
but...
large theory uncertainties

Mono-X Searches in Hadronic Final State

- Rely on MET triggers (offline MET cut ≥ 200 GeV)
- Major background from $Z(\rightarrow \nu\nu) + \text{jets}$, $W(\cancel{\rightarrow} l\nu) + \text{jets}$
 - Estimated from a binned likelihood fit to five control samples: $Z(\rightarrow ee)$, $Z(\rightarrow \mu\mu)$, γ , $W(\rightarrow e\nu)$, $W(\rightarrow \mu\nu) + \text{jets}$ data, transfer factors from MC reweighed with NLO QCD and nNLO EWK, uncertainty studied following 1705.04664
 - 3 QCD uncertainties: scale variation, shape with p_T dependence, difference between K-factors
 - 3 EWK uncertainties: missing NNLO effects, difference between NNL Sudakov approx. and NLO EWK, unknown Sudakov logs

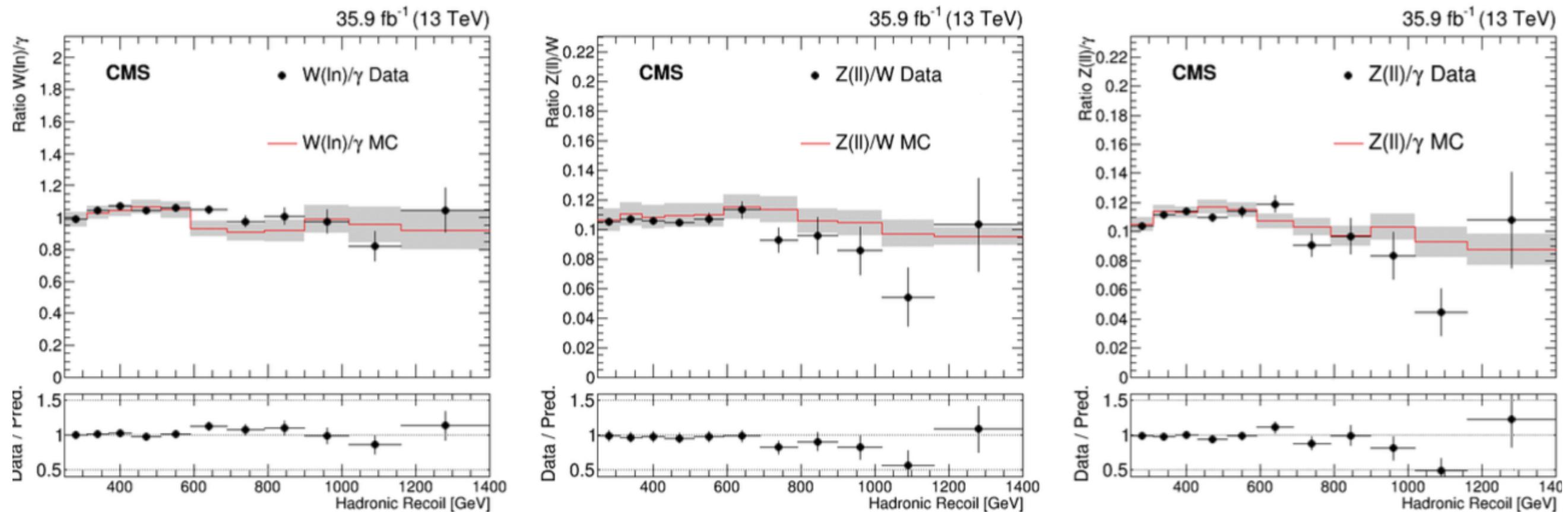
Estimation of Z+Jets and W+Jets Background



- $Z(\rightarrow\nu\nu)$ +jets constrained from $Z(\rightarrow ee)$, $Z(\rightarrow \mu\mu)$, and γ +jets
- $W(\cancel{\rightarrow\nu})$ +jets constrained from $W(\rightarrow e\nu)$, $W(\rightarrow \mu\nu)$
- W +jets/ Z +jets cross section ratios constrained with theory input

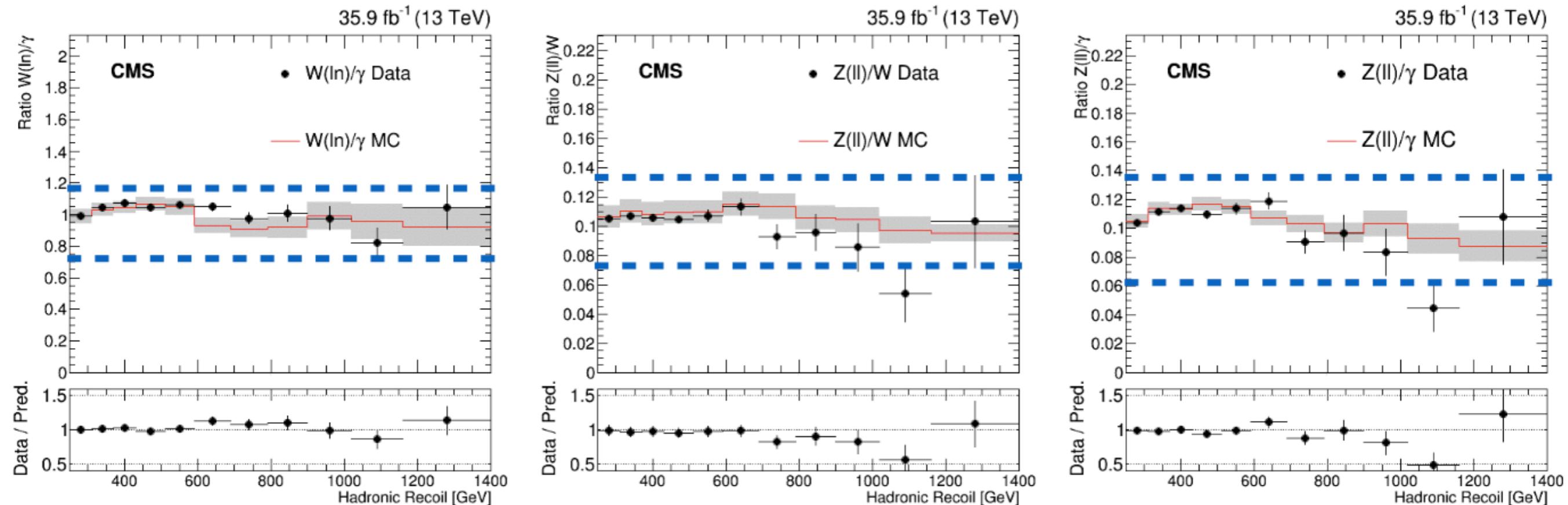
Improvement of Uncertainty on Transfer Factors

- Uncertainties on the ratios reduced by at least a factor of 3-4



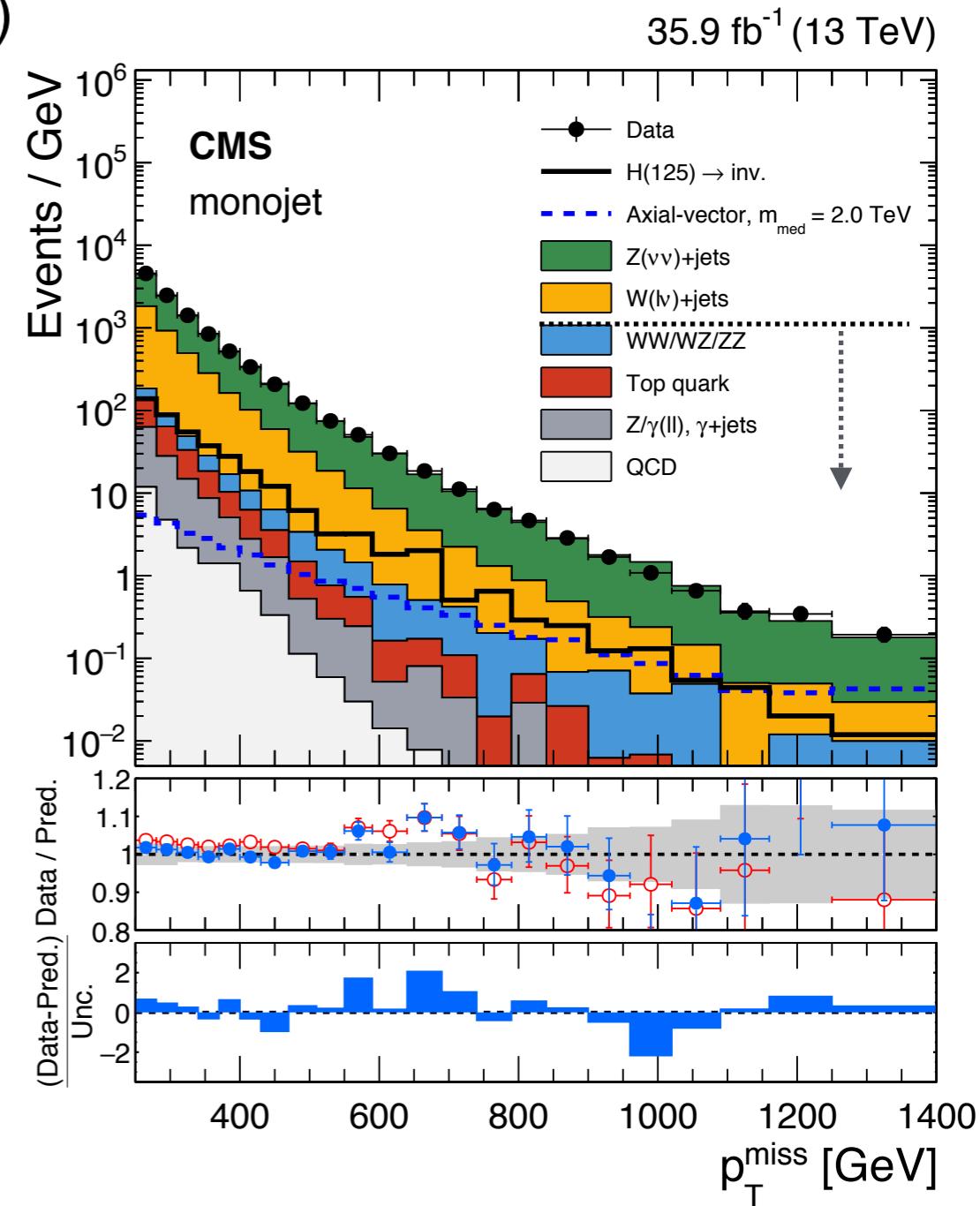
Improvement of Uncertainty on Transfer Factors

- Uncertainties on the ratios reduced by at least a factor of 3-4



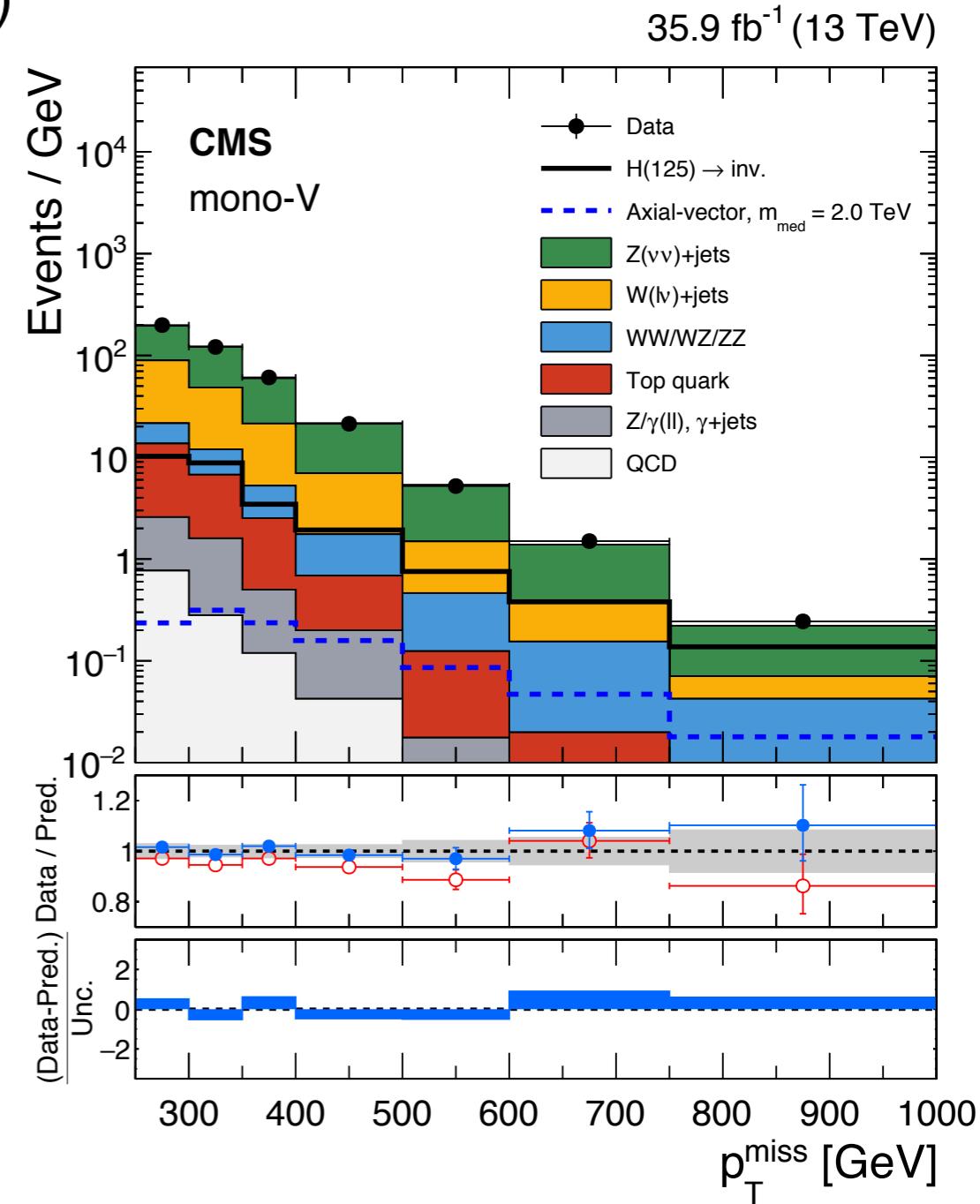
Mono-X Searches in Hadronic Final State

- Rely on MET triggers (offline MET cut ≥ 200 GeV)
- Major background from $Z(\rightarrow \nu\nu) + \text{jets}$, $W(\rightarrow \ell\nu) + \text{jets}$
 - Estimated from a binned likelihood fit to five control samples: $Z(\rightarrow ee)$, $Z(\rightarrow \mu\mu)$, γ , $W(\rightarrow e\nu)$, $W(\rightarrow \mu\nu) + \text{jets}$ data, transfer factors from MC reweighed with NLO QCD and nNLO EWK, uncertainty studied following 1705.04664
 - 3 QCD uncertainties: scale variation, shape with p_T dependence, difference between K-factors
 - 3 EWK uncertainties: missing NNLO effects, difference between NNL Sudakov approx. and NLO EWK, unknown Sudakov logs

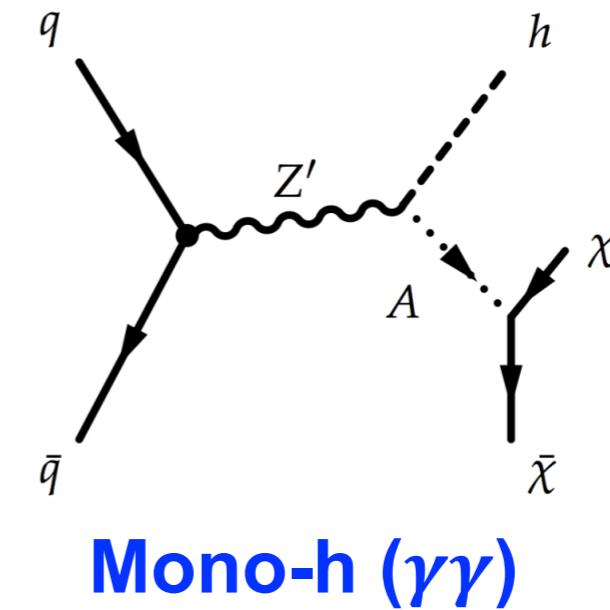
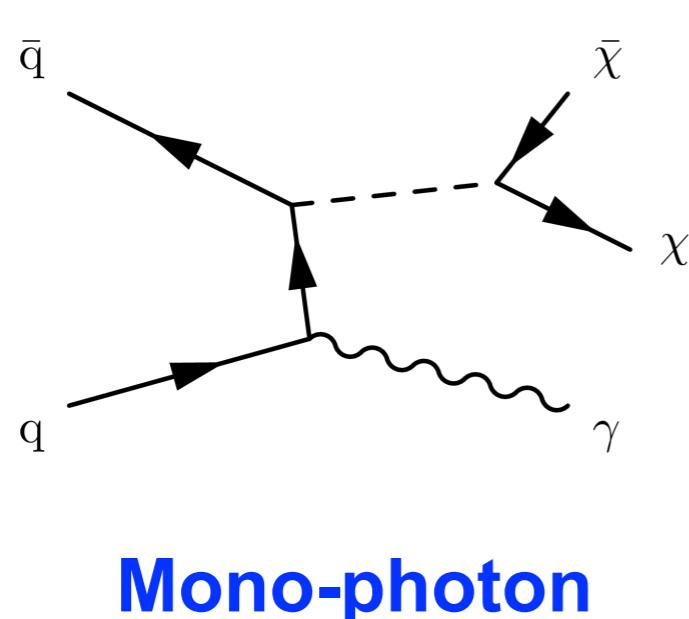
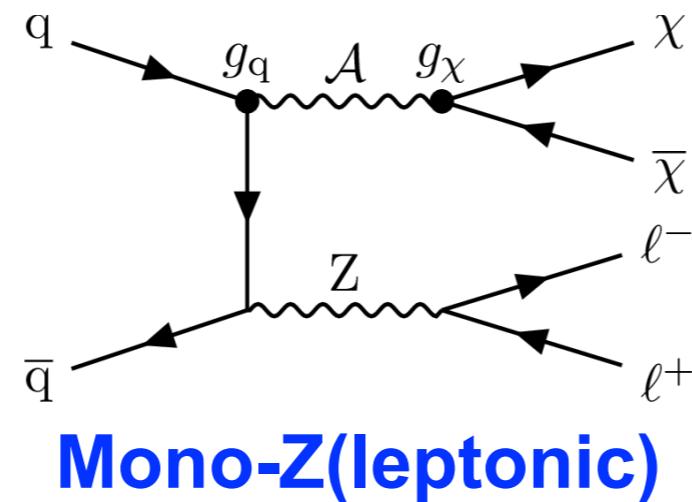


Mono-X Searches in Hadronic Final State

- Rely on MET triggers (offline MET cut ≥ 200 GeV)
- Major background from $Z(\rightarrow \nu\nu) + \text{jets}$, $W(\cancel{\nu}) + \text{jets}$
- Estimated from a binned likelihood fit to five control samples: $Z(\rightarrow ee)$, $Z(\rightarrow \mu\mu)$, γ , $W(\rightarrow e\nu)$, $W(\rightarrow \mu\nu) + \text{jets}$ data, transfer factors from MC reweighed with NLO QCD and nNLO EWK, uncertainty studied following 1705.04664
- 3 QCD uncertainties: scale variation, shape with p_T dependence, difference between K-factors
- 3 EWK uncertainties: missing NNLO effects, difference between NNL Sudakov approx. and NLO EWK, unknown Sudakov logs

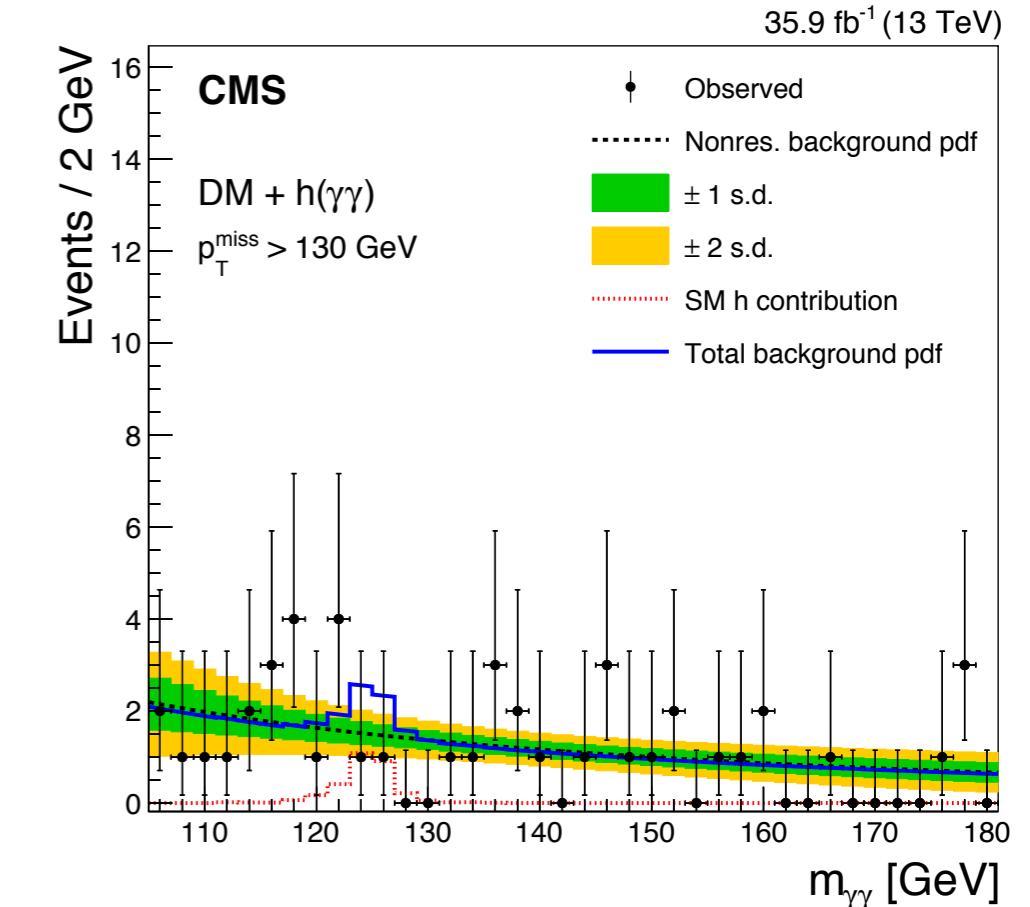
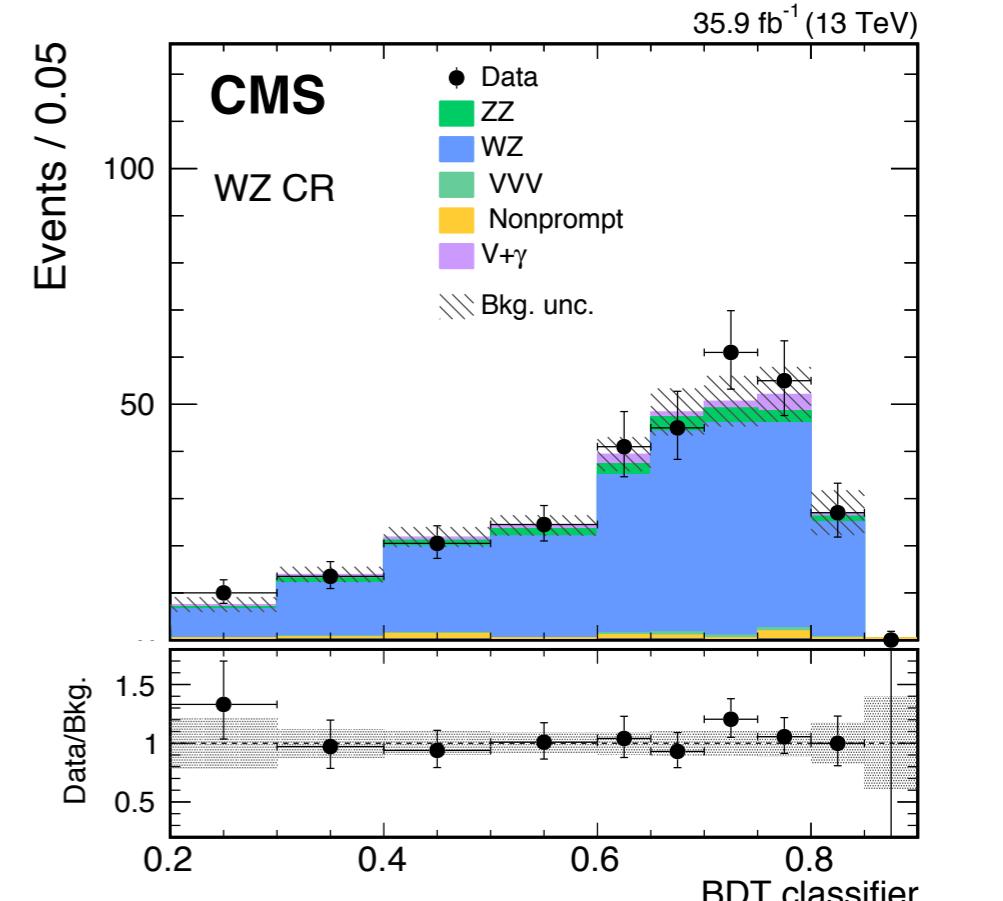


Mono-X Searches in Non-Hadronic Final States



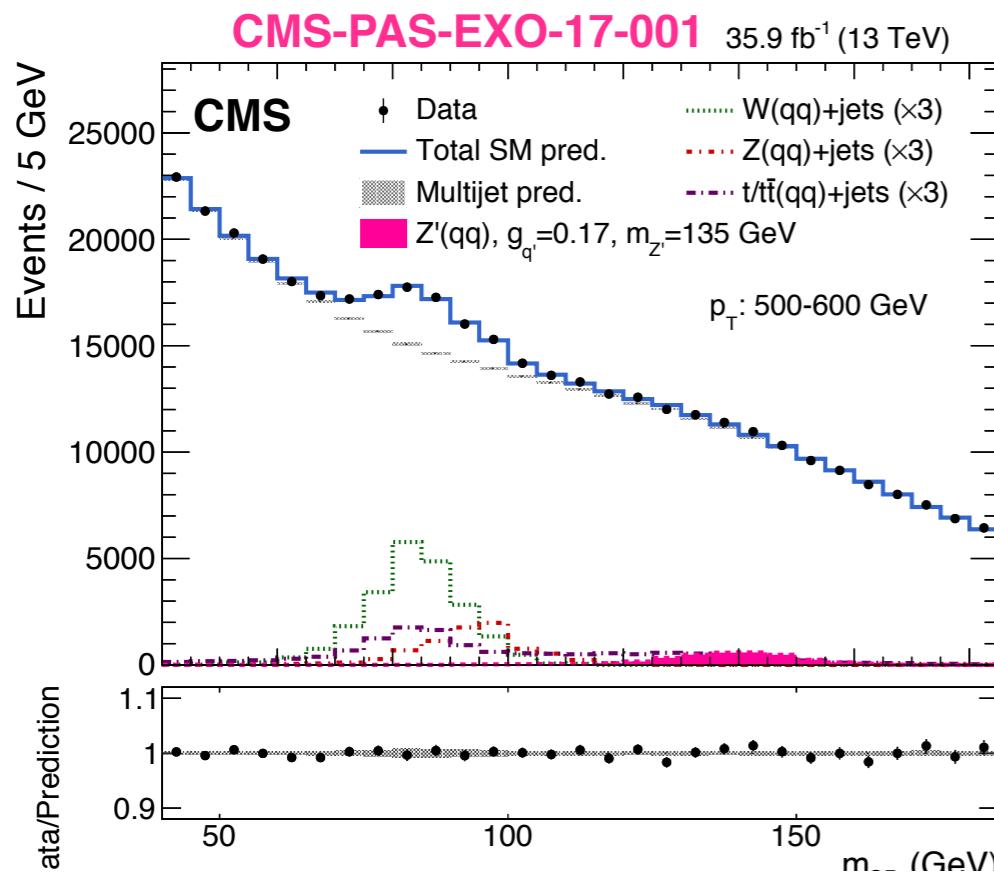
Mono-X Searches in Non-Hadronic Final State

- Rely on lepton or photon triggers, can probe models with lower MET
- Mono-Z (II), mono-photon:
 - Major background is W/Z+X where X=Z or γ , estimated from a binned likelihood fit of MET in the control regions (by reverting the lepton-veto)
 - Transfer factor derived from simulation with NNLO QCD and NLO EWK corrections
- Mono-h ($\gamma\gamma$)
 - Fit to the $m_{\gamma\gamma}$ spectra in data, background includes resonant and non-resonant contribution

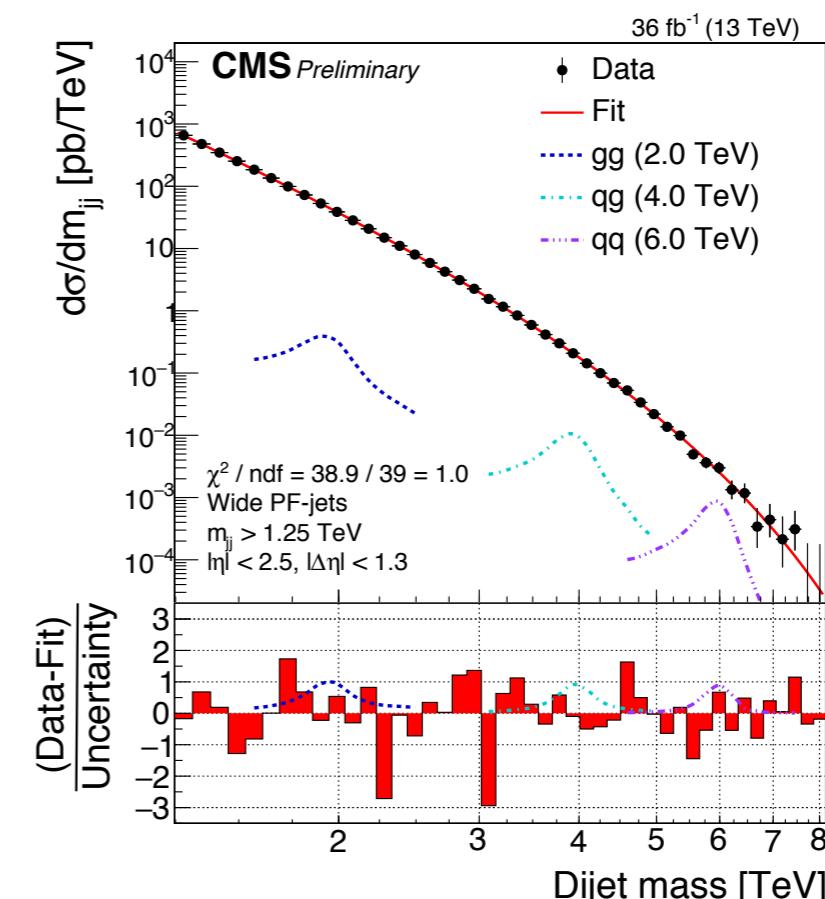
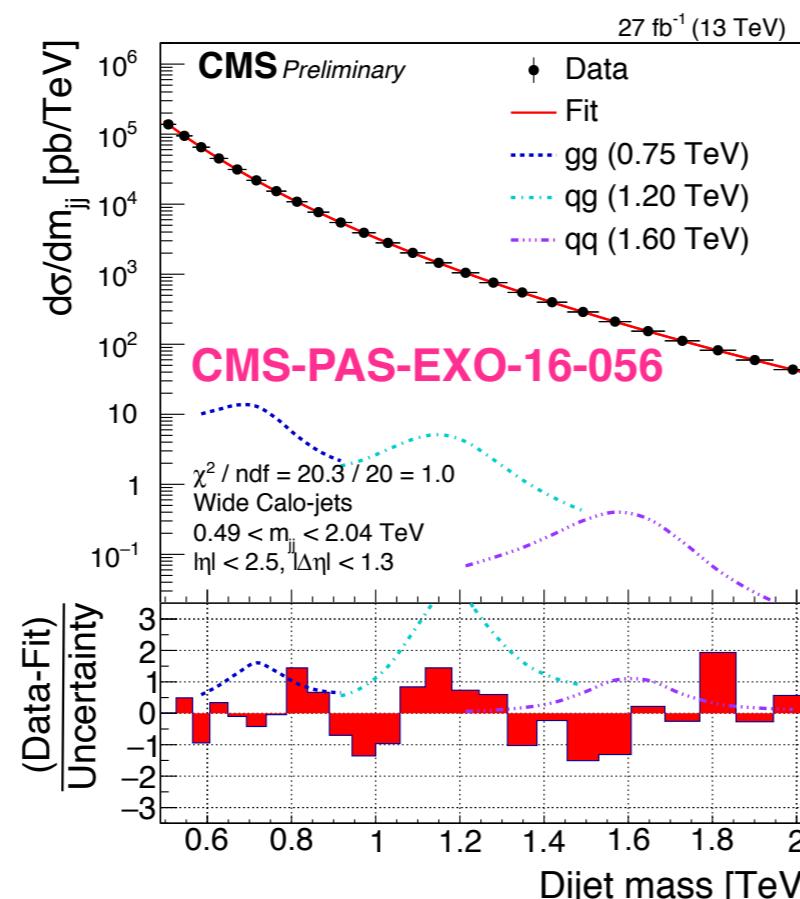
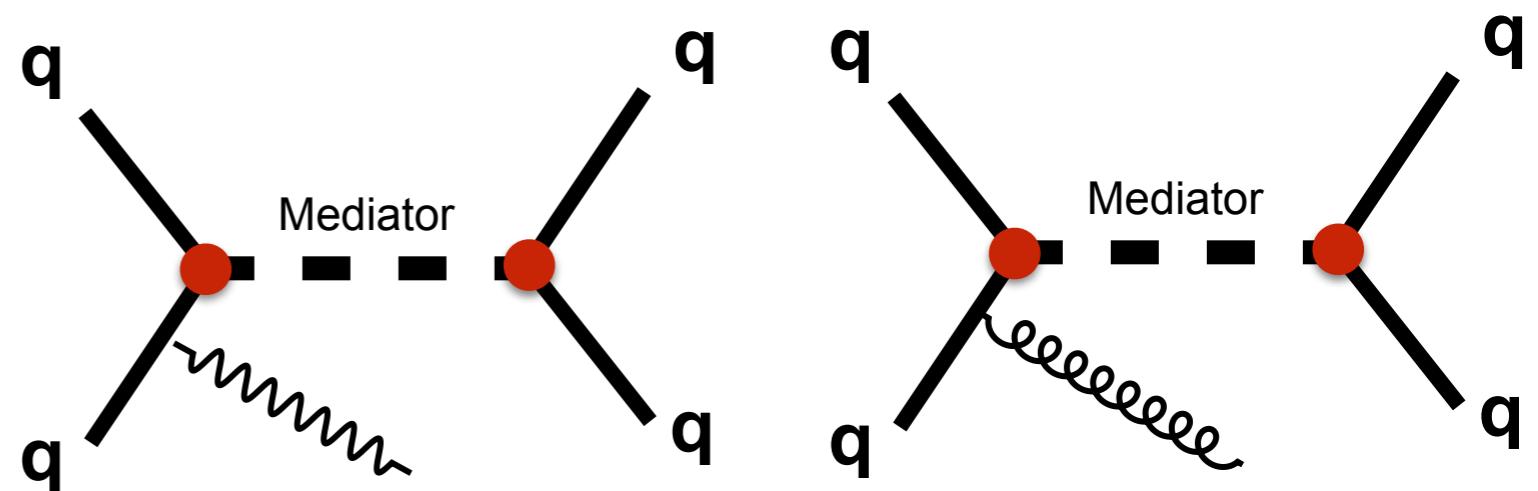


Searches for Visible Mediator Decays

Visible Mediator Searches



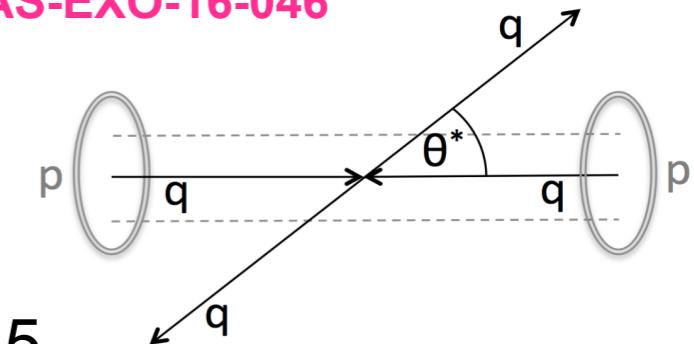
- high- p_T/H_T trigger for large- M_{jj} , ISR $\gamma/\text{jet tag}$ or data with only trigger-level objects (data scouting) for small- M_{jj}



Dijet Angular Distributions

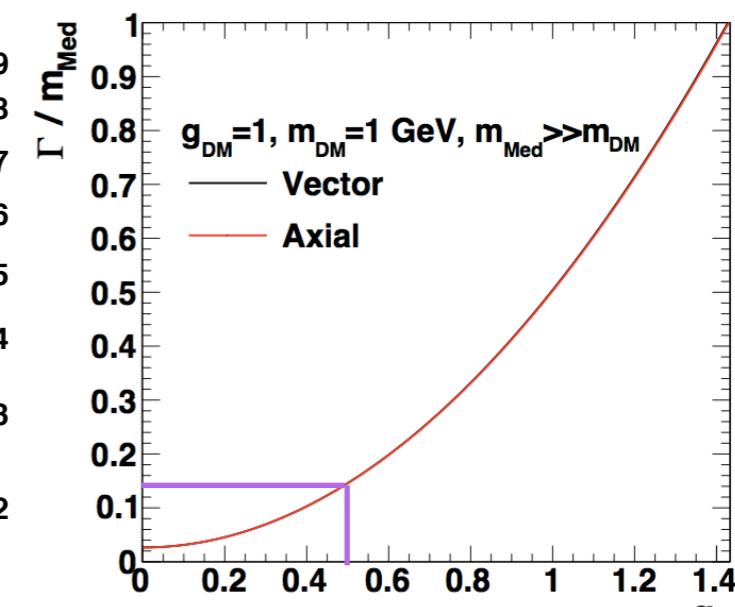
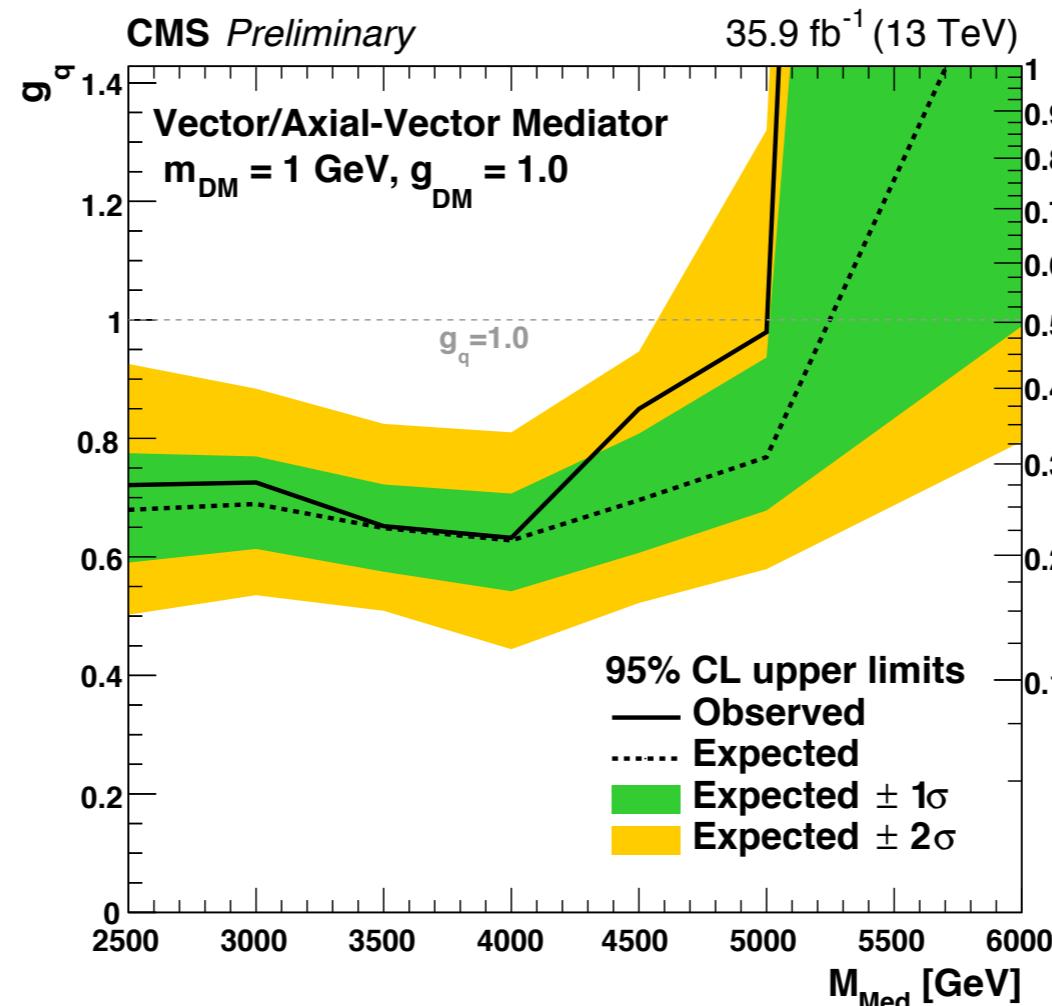
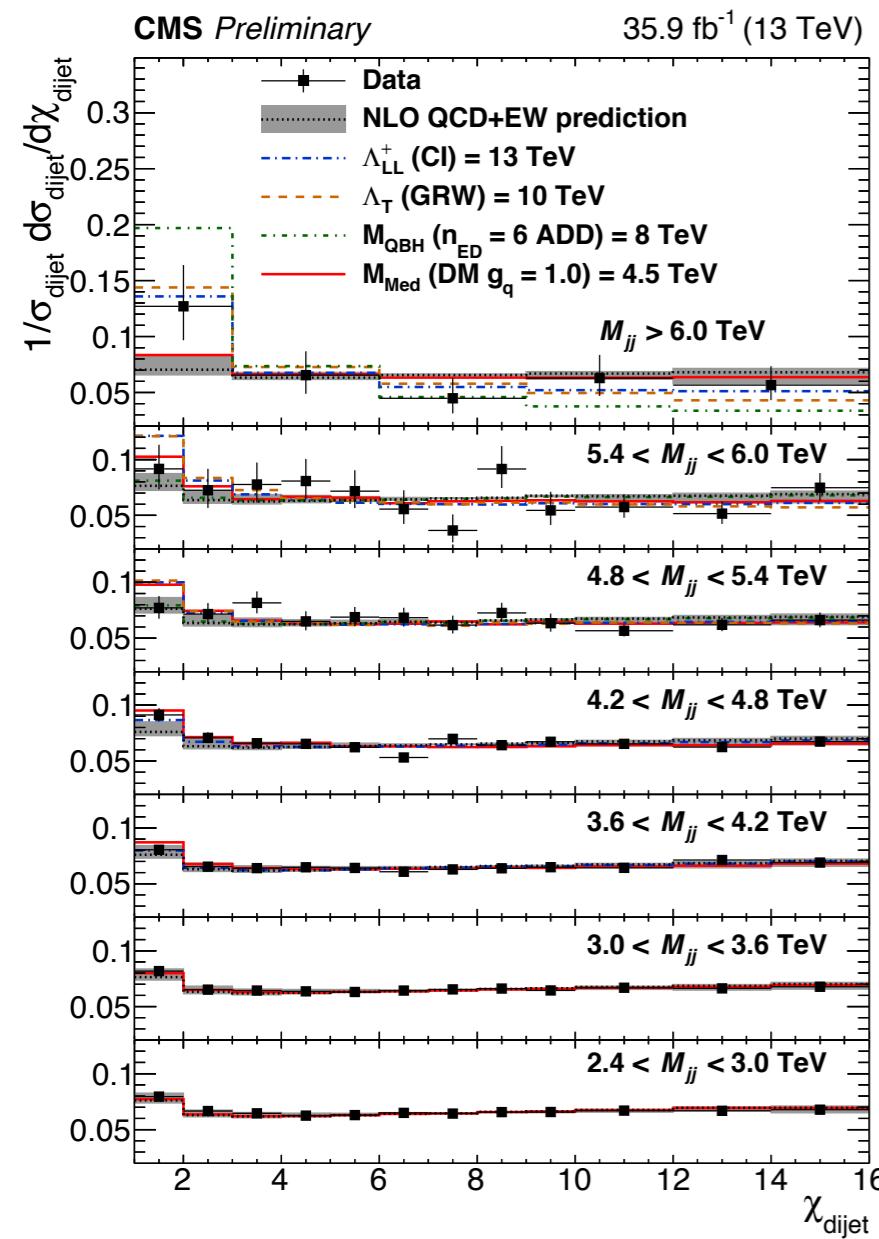
CMS-PAS-EXO-16-046

- Sensitive to wide mediators or non-resonant signature
- Dijet resonance searches exclude g_q in the range of 0.07-0.35 depending on M_{MED}



- For $g_q \geq 1$, $M_{\text{MED}} = 2.5-5 \text{ TeV}$ excluded

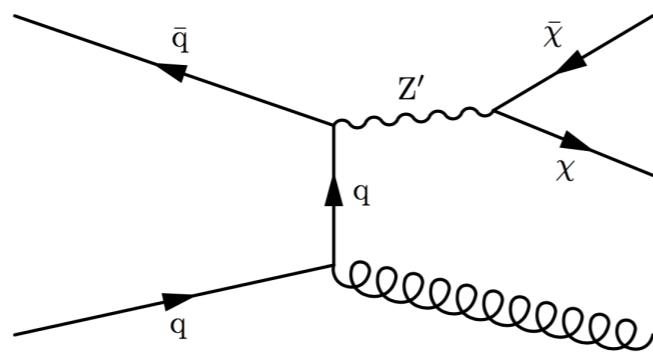
$$\chi_{\text{dijet}} = e^{|y_1 - y_2|} \sim \frac{1 + |\cos \theta^*|}{1 - |\cos \theta^*|}$$



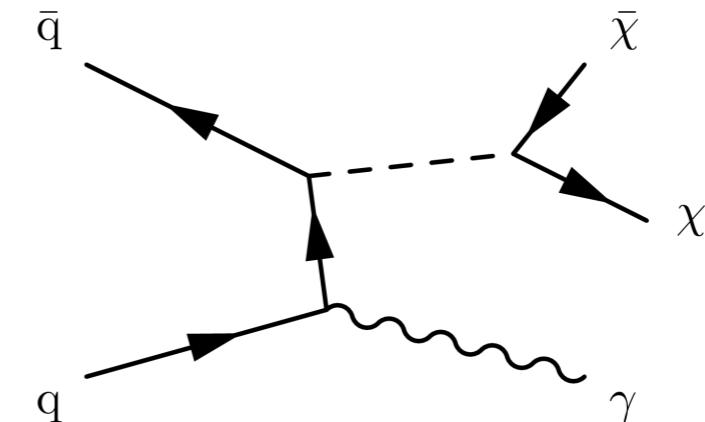
$$\Gamma^{q\bar{q}}_{\text{axial-vector}}$$

$$= \frac{g_q^2 M_{\text{MED}}}{4\pi} \left(1 - 4 \frac{m_q^2}{M_{\text{MED}}^2} \right)^{\frac{3}{2}}$$

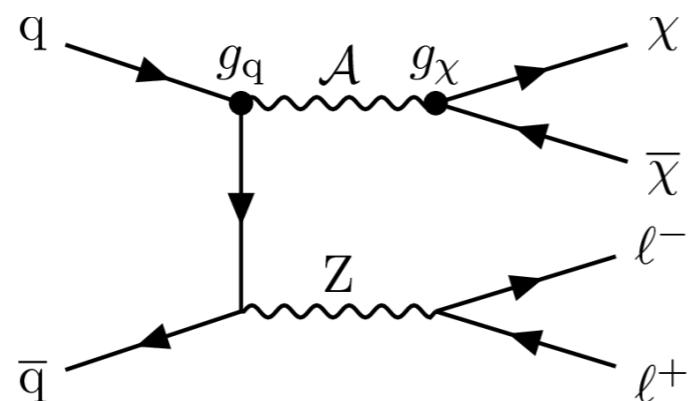
Mono-X With Vector/Axial Mediators



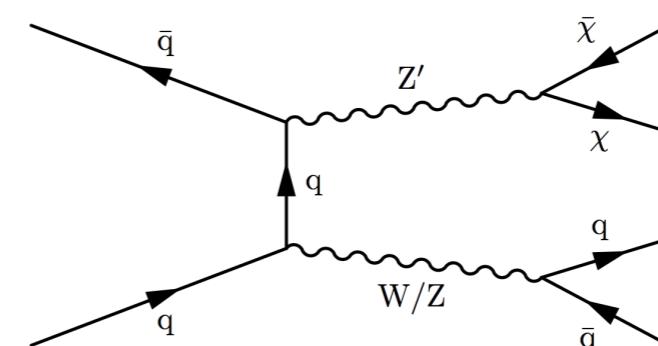
Mono-jet



Mono-photon

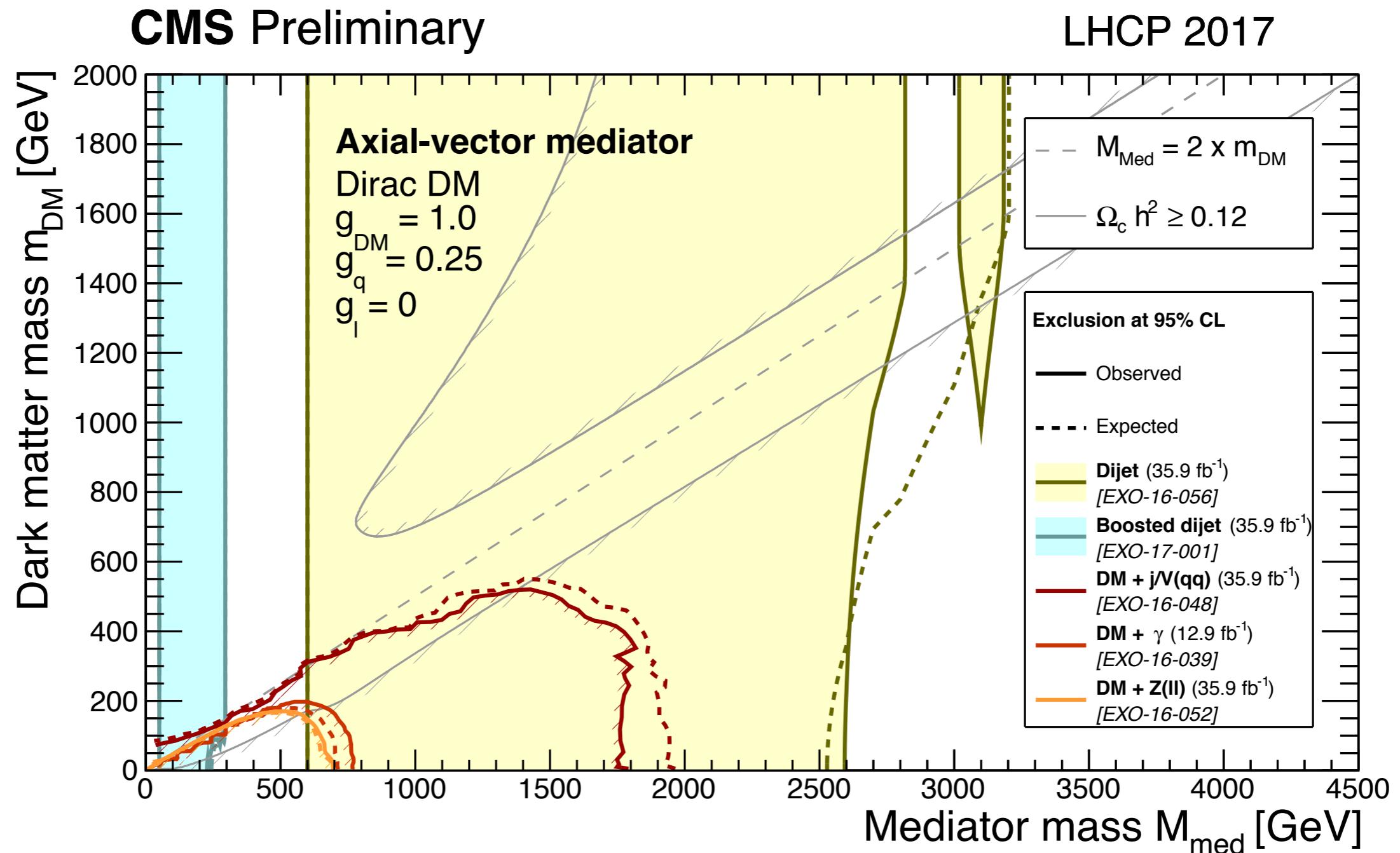


Mono-Z(leptonic)



Mono-W/Z(hadronic)

Collider Results Only

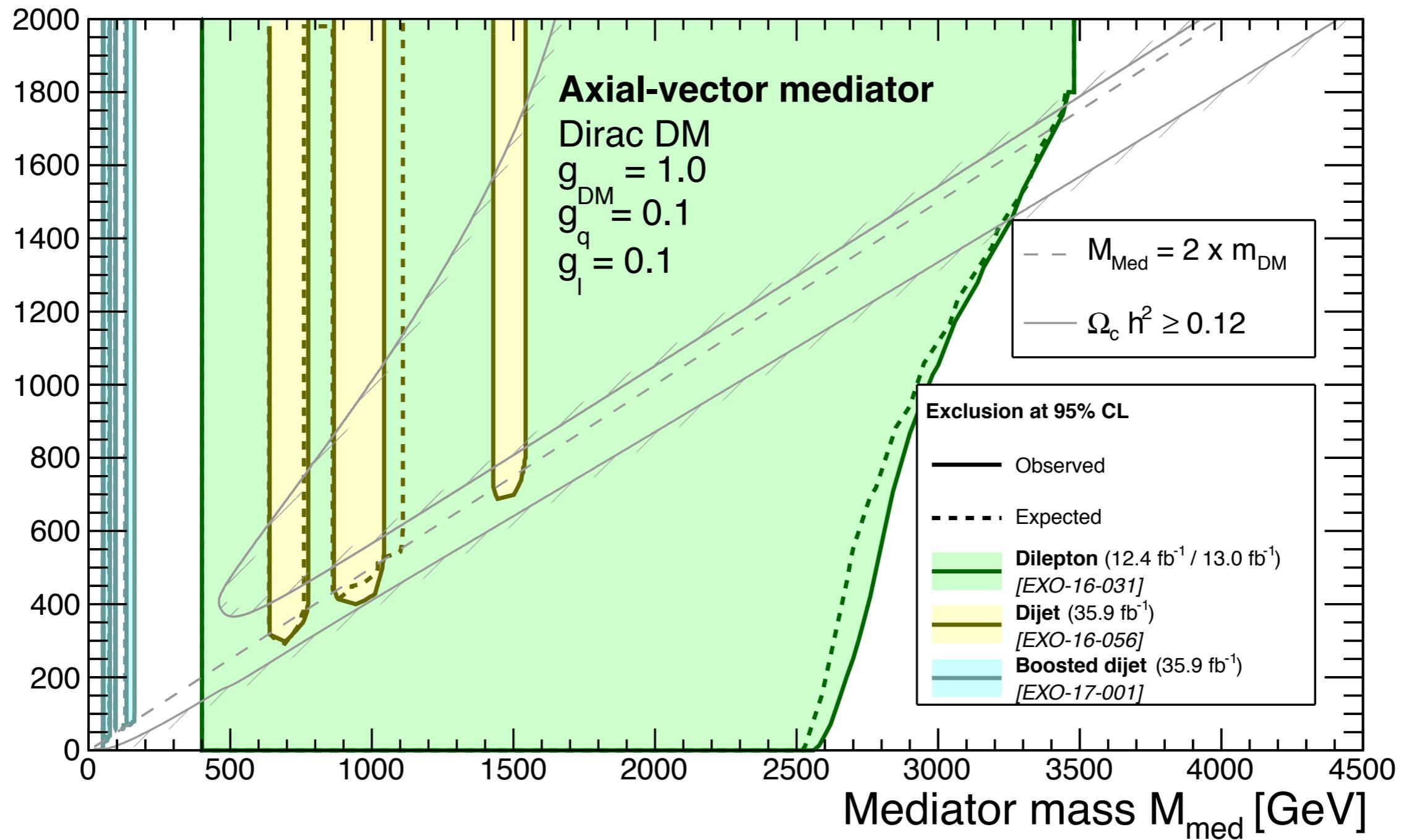


If We Use Different Parameter Values

CMS Preliminary

Discussion in the
arXiv:1703.05703

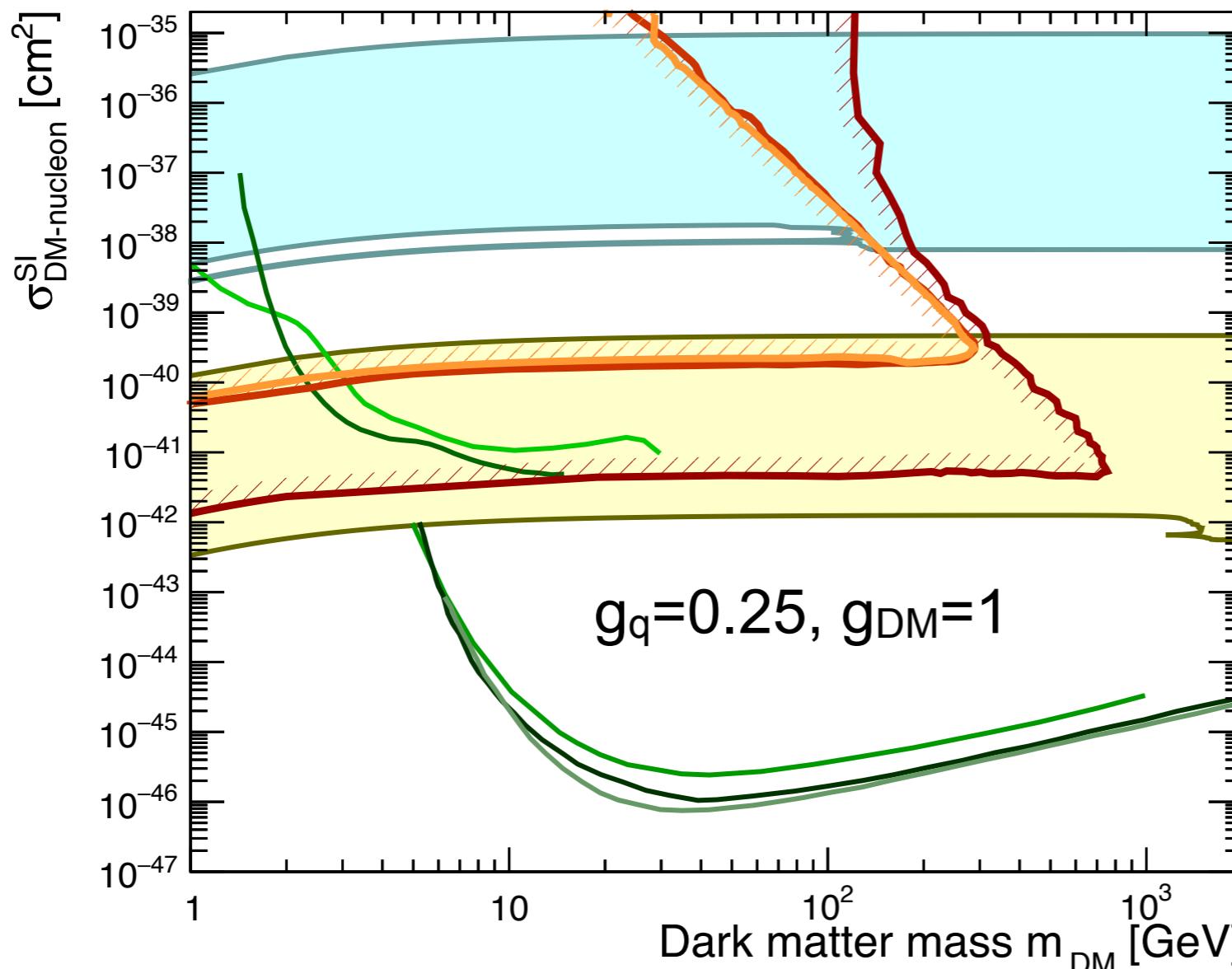
LHCP 2017



Collider v.s. Non-Collider Experiments (SI)

$$\sigma_{\text{SI}}^{\text{vector}} \simeq 6.9 \times 10^{-41} \text{ cm}^2 \left(\frac{g_q g_{\text{DM}}}{0.25} \right)^2 \left(\frac{1 \text{ TeV}}{M_{\text{med}}} \right)^4 \left(\frac{\mu_{n\chi}}{1 \text{ GeV}} \right)^2$$

CMS Preliminary



CMS observed exclusion 90% CL
Vector med., Dirac DM; $g_q = 0.25, g_{\text{DM}} = 1.0$

Boosted dijet (35.9 fb^{-1})
[EXO-17-001]

Dijet (35.9 fb^{-1})
[EXO-16-056]

DM + j/ψ_{qq} (35.9 fb^{-1})
[EXO-16-048]

DM + γ (12.9 fb^{-1})
[EXO-16-039]

DM + Z_{ll} (35.9 fb^{-1})
[EXO-16-052]

DD observed exclusion 90% CL

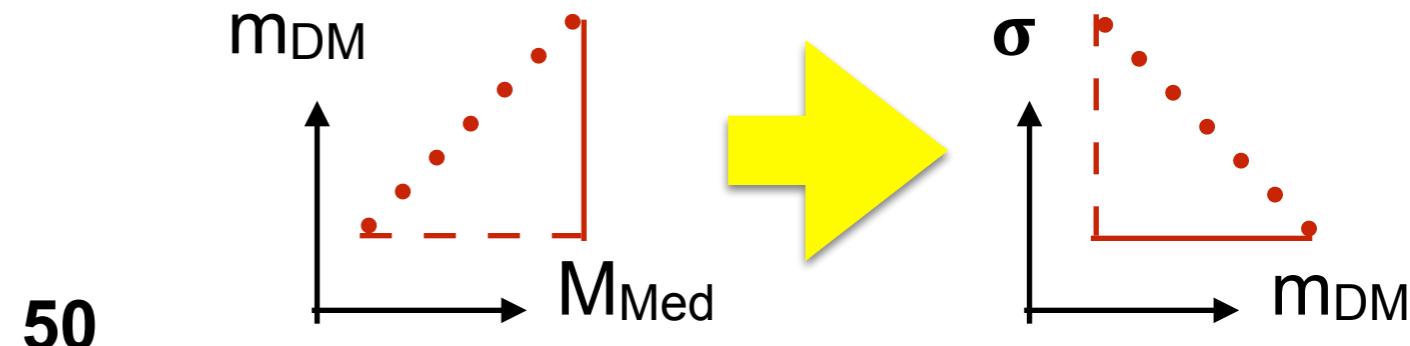
CRESST-II
[arXiv:1509.01515]

CDMSlite
[arXiv:1509.02448]

PandaX-II
[arXiv:1607.07400]

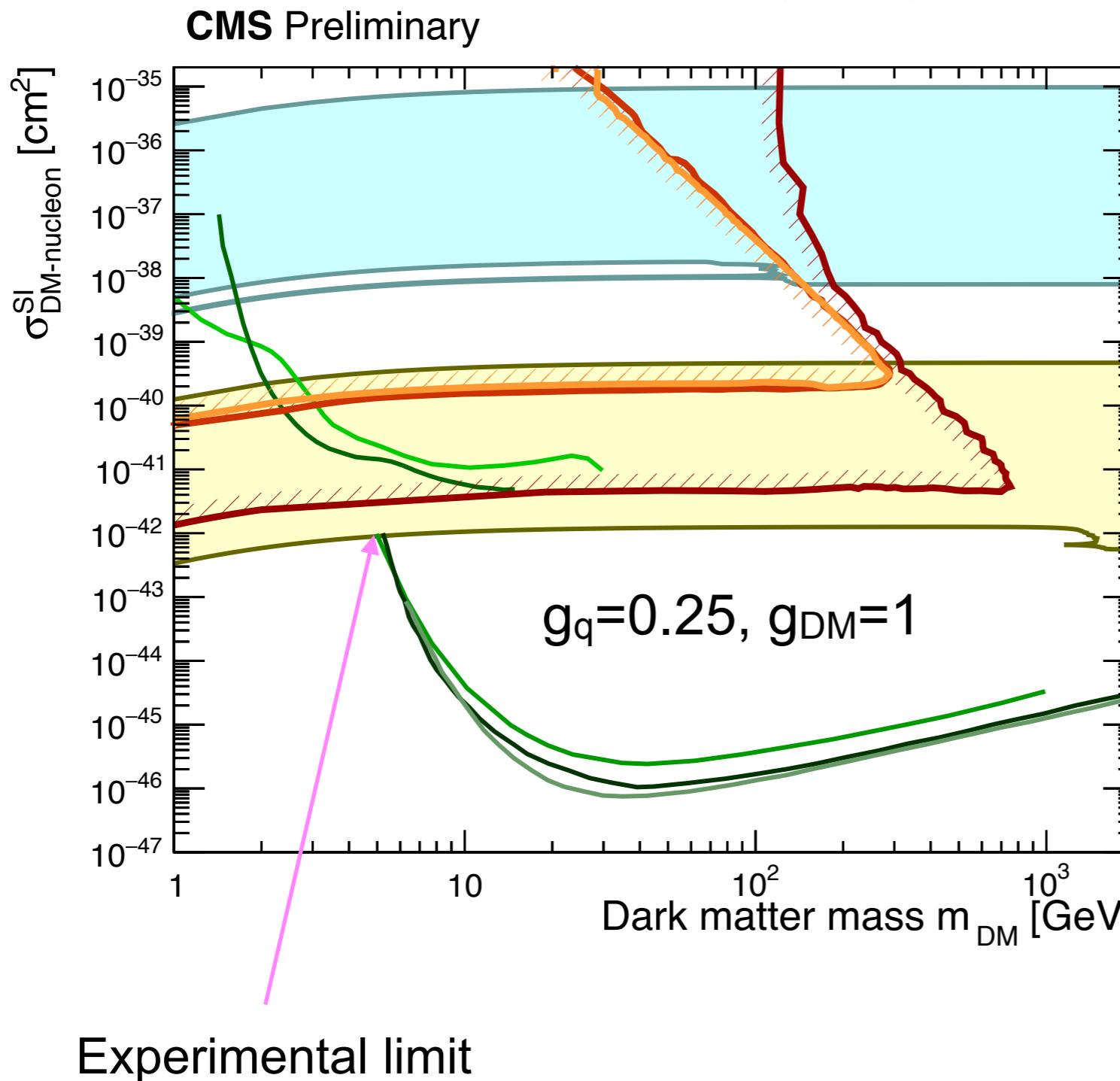
LUX
[arXiv:1608.07648]

XENON1T
[arXiv:1705.06655]



Collider v.s. Non-Collider Experiments (SI)

$$\sigma_{\text{SI}}^{\text{vector}} \simeq 6.9 \times 10^{-41} \text{ cm}^2 \left(\frac{g_q g_{\text{DM}}}{0.25} \right)^2 \left(\frac{1 \text{ TeV}}{M_{\text{med}}} \right)^4 \left(\frac{\mu_{n\chi}}{1 \text{ GeV}} \right)^2$$



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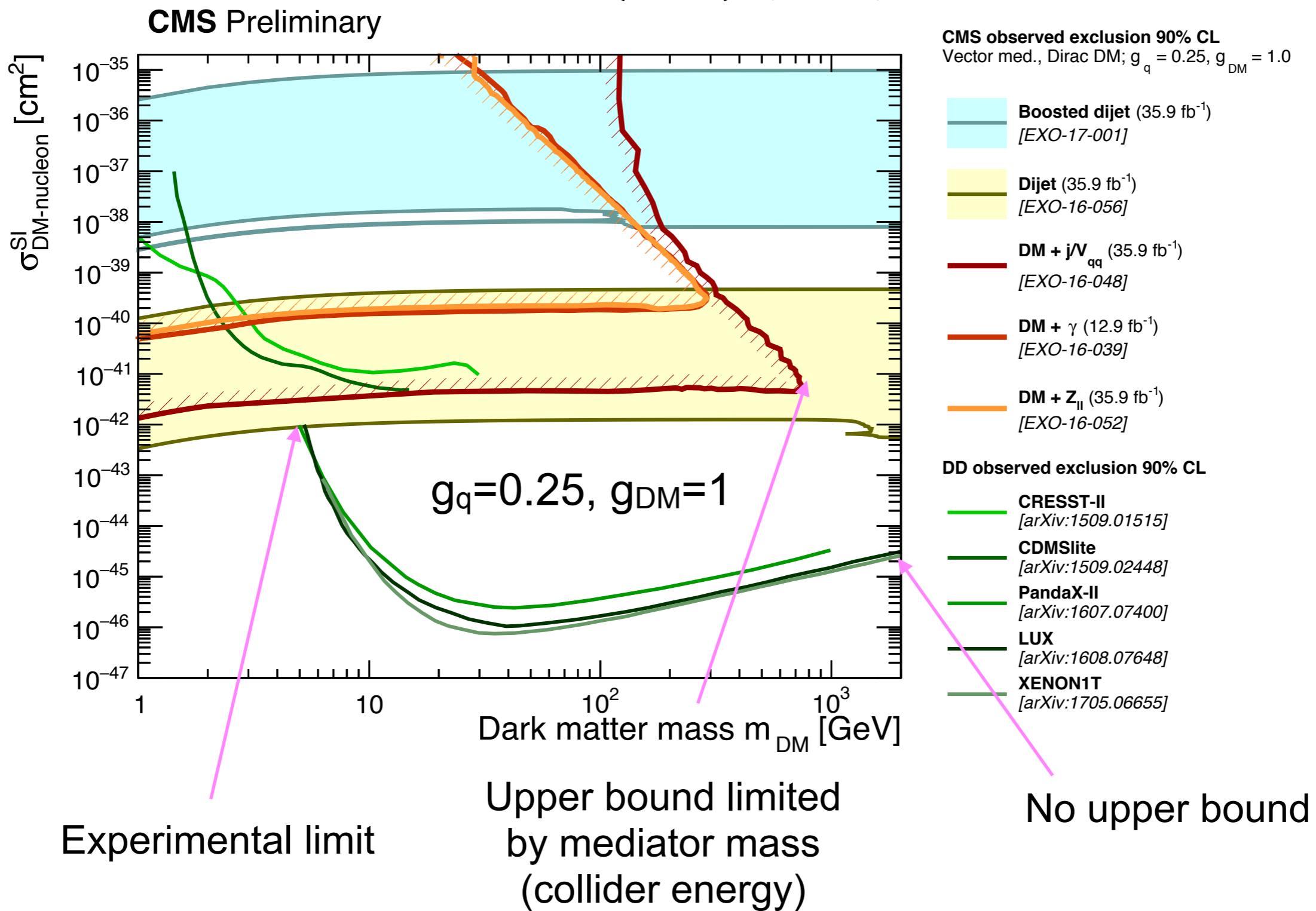
LUX
[arXiv:1608.07648]

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No upper bound

Collider v.s. Non-Collider Experiments (SI)

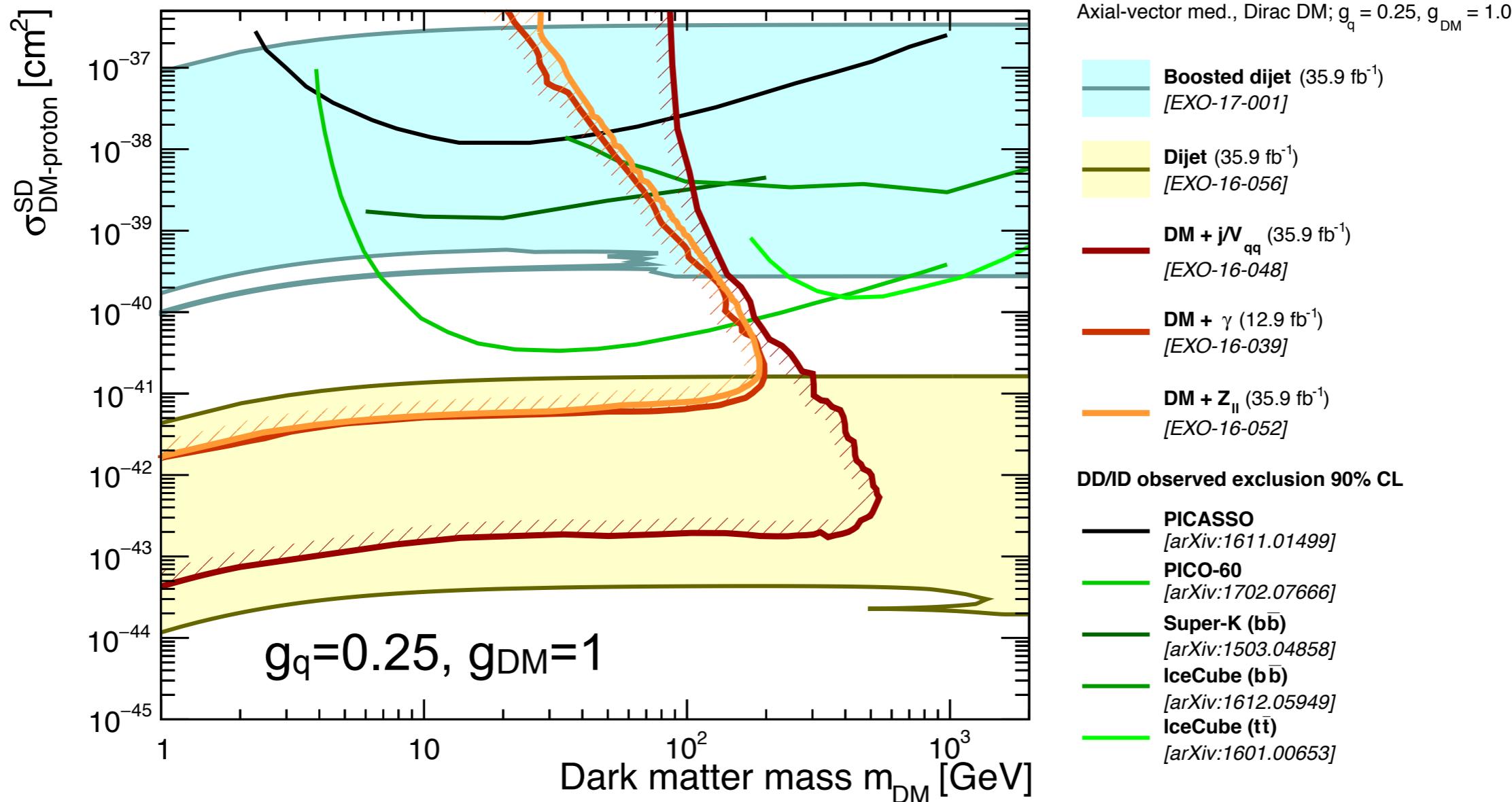
$$\sigma_{\text{SI}}^{\text{vector}} \simeq 6.9 \times 10^{-41} \text{ cm}^2 \left(\frac{g_q g_{\text{DM}}}{0.25} \right)^2 \left(\frac{1 \text{ TeV}}{M_{\text{med}}} \right)^4 \left(\frac{\mu_{n\chi}}{1 \text{ GeV}} \right)^2$$



Collider v.s. Non-Collider Experiments (SD)

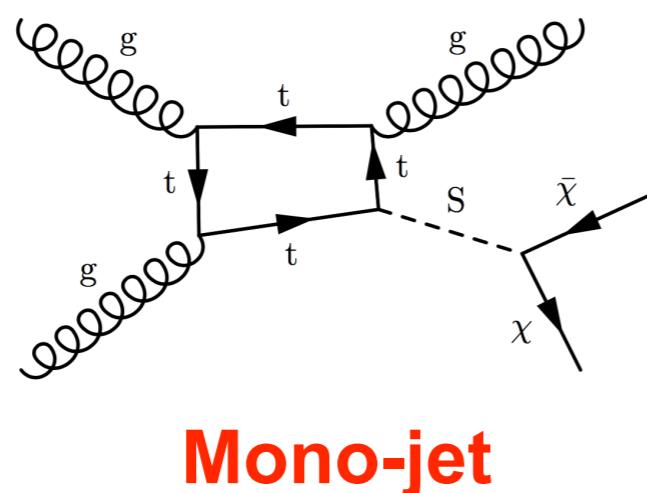
$$\sigma_{\text{SD}}^{\text{axial}} \simeq 2.4 \times 10^{-42} \text{ cm}^2 \left(\frac{g_q g_{\text{DM}}}{0.25} \right)^2 \left(\frac{1 \text{ TeV}}{M_{\text{med}}} \right)^4 \left(\frac{\mu_{n\chi}}{1 \text{ GeV}} \right)^2$$

CMS Preliminary

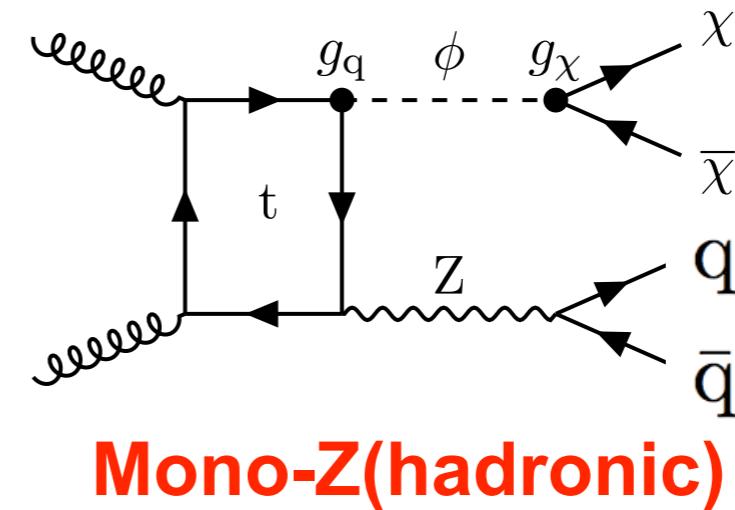


For the model parameters considered here, collider experiments can probe SD cross sections 2-3 orders of magnitude smaller than the non-collider experiments.

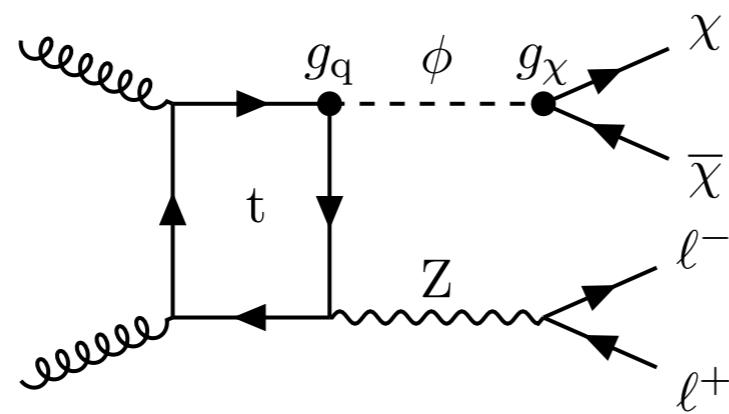
Mono-X with Scalar/Pseudo-Scalar Mediators



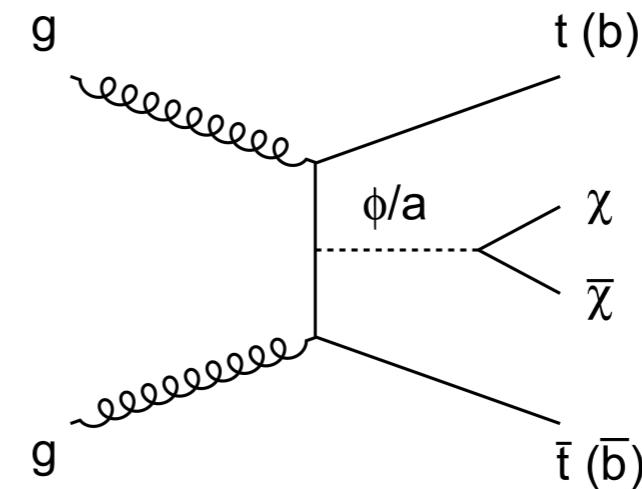
Mono-jet



Mono-Z(hadronic)



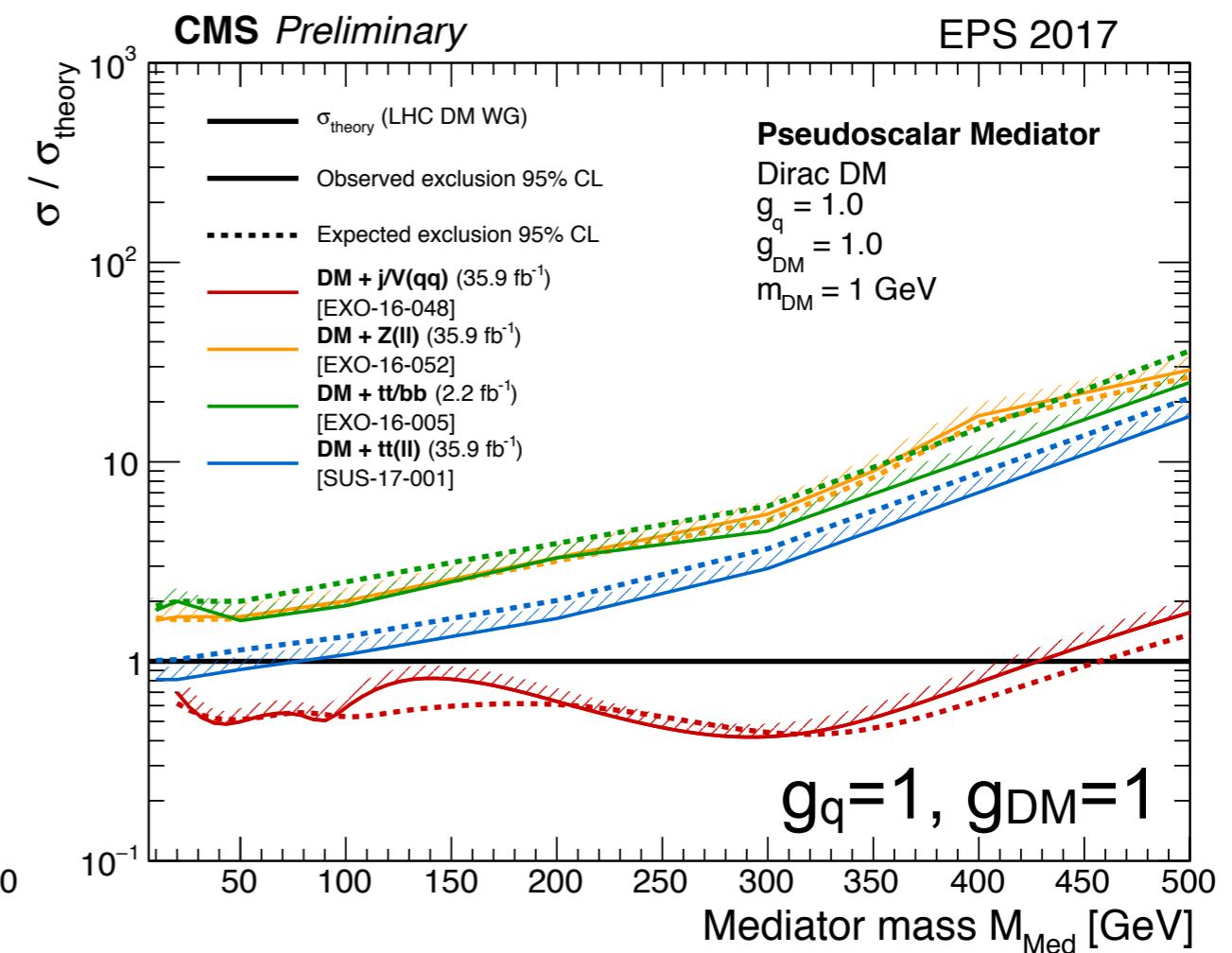
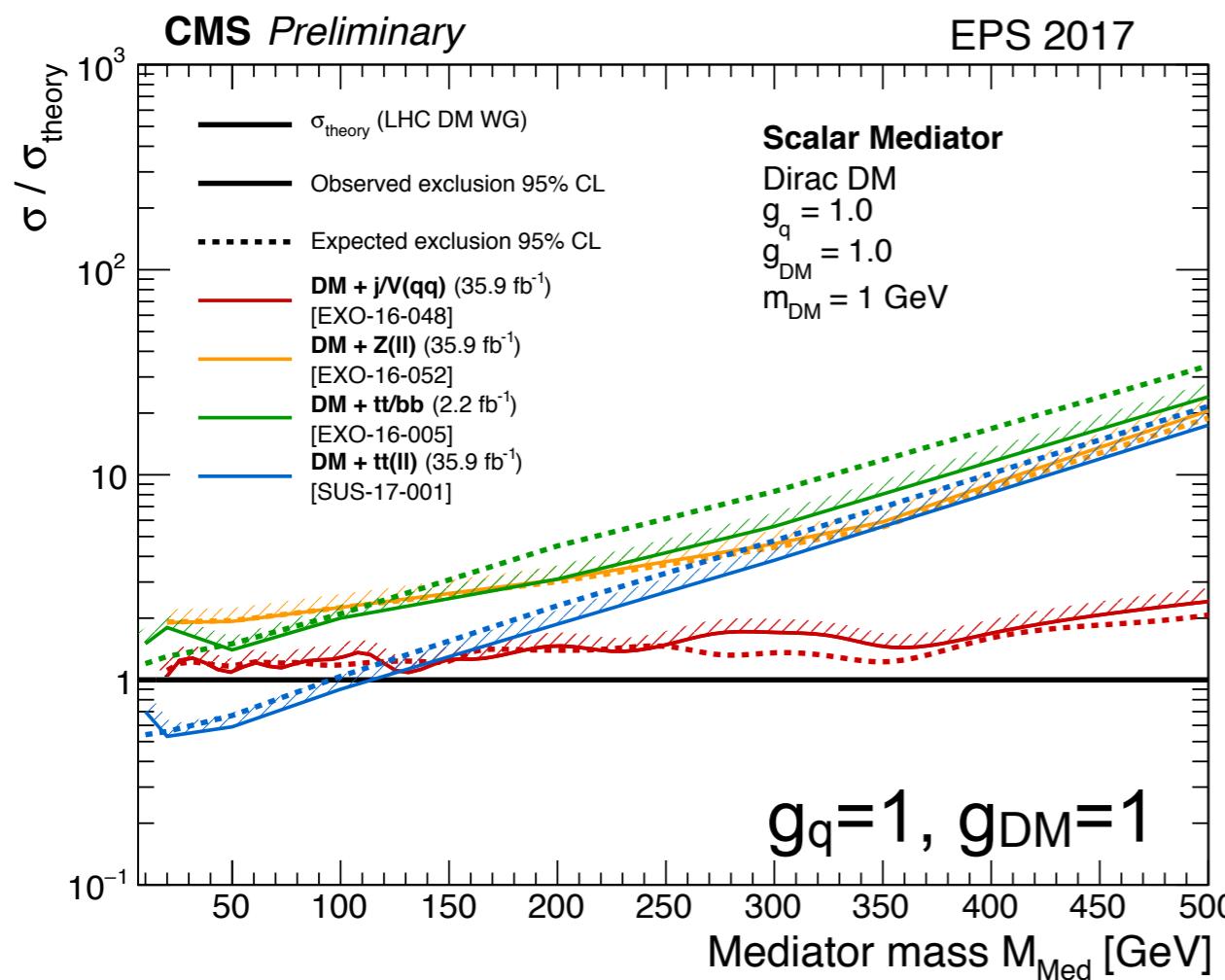
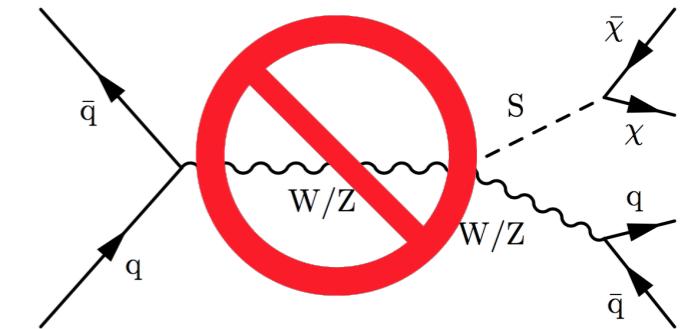
Mono-Z(leptonic)



Mono-tt/bb

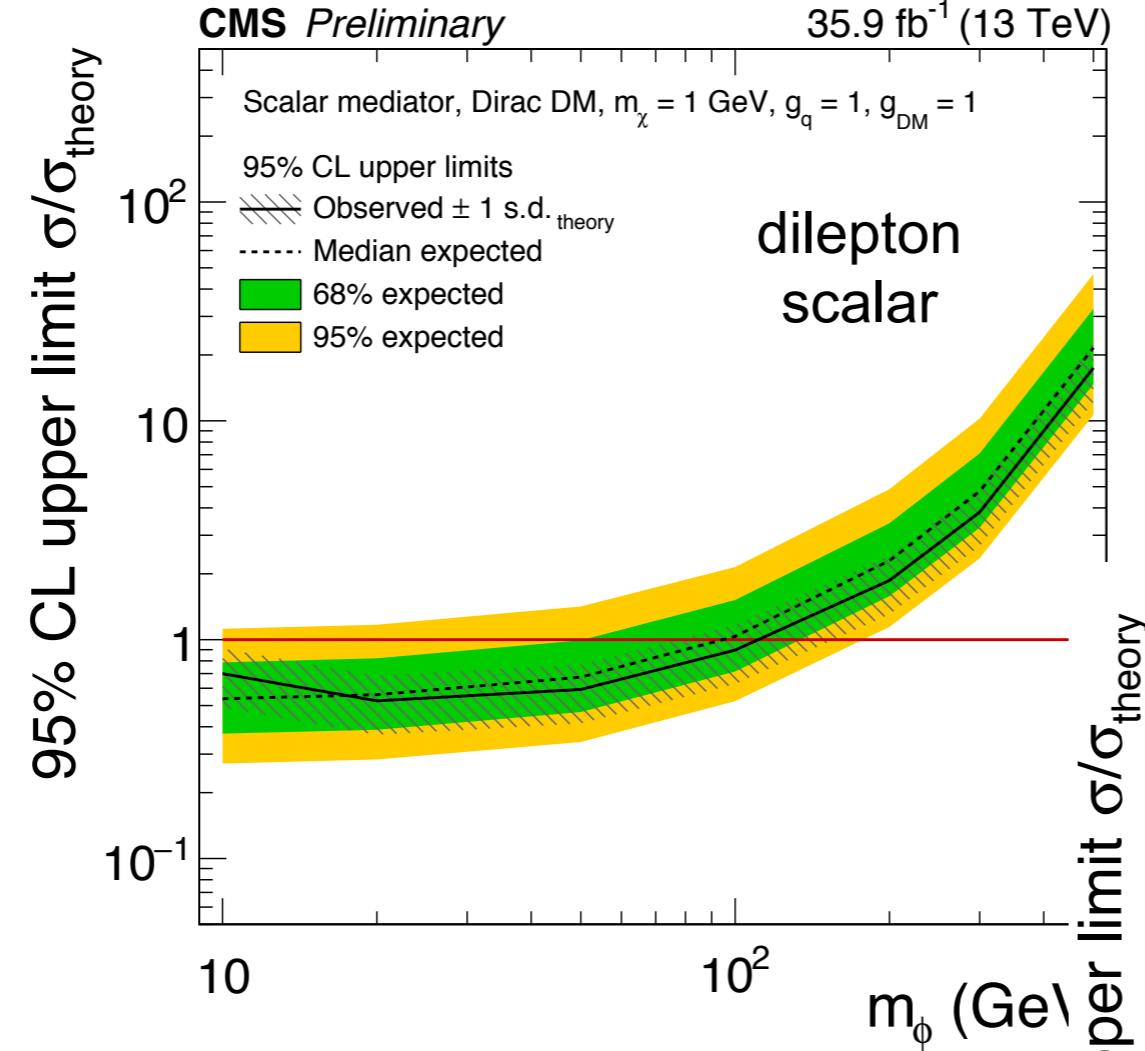
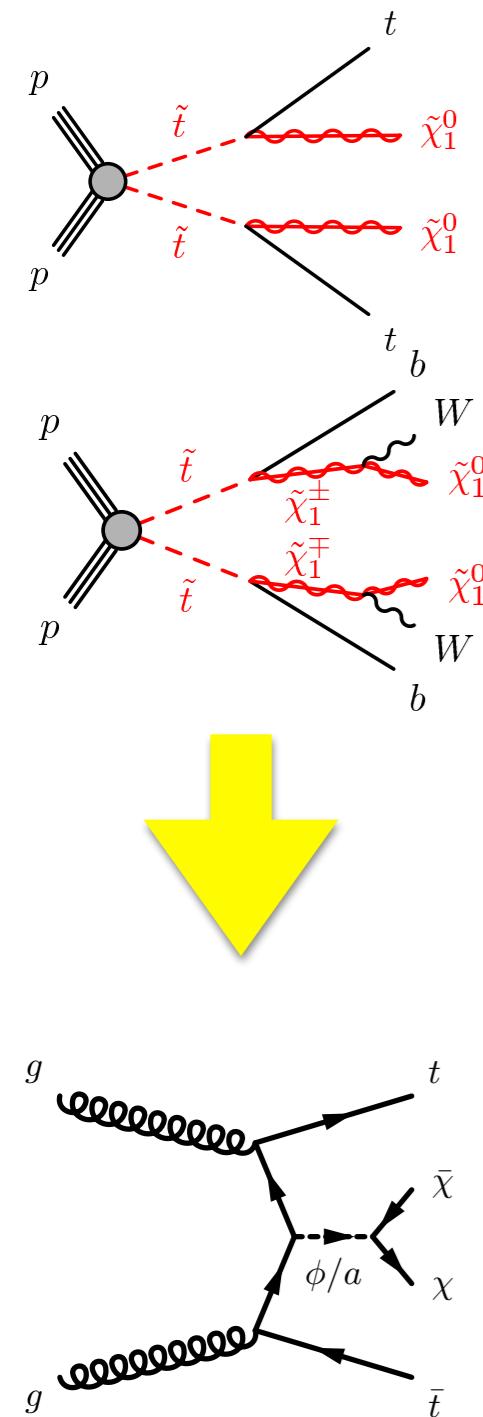
Collider Results for Scalar/Pseudo-Scalar

- For the mono-V channel, pseudo-scalar/scalar limits include ggZH diagrams only because VH generators do not yet include mixing with SM Higgs
- ttbar> is the best at low-mass

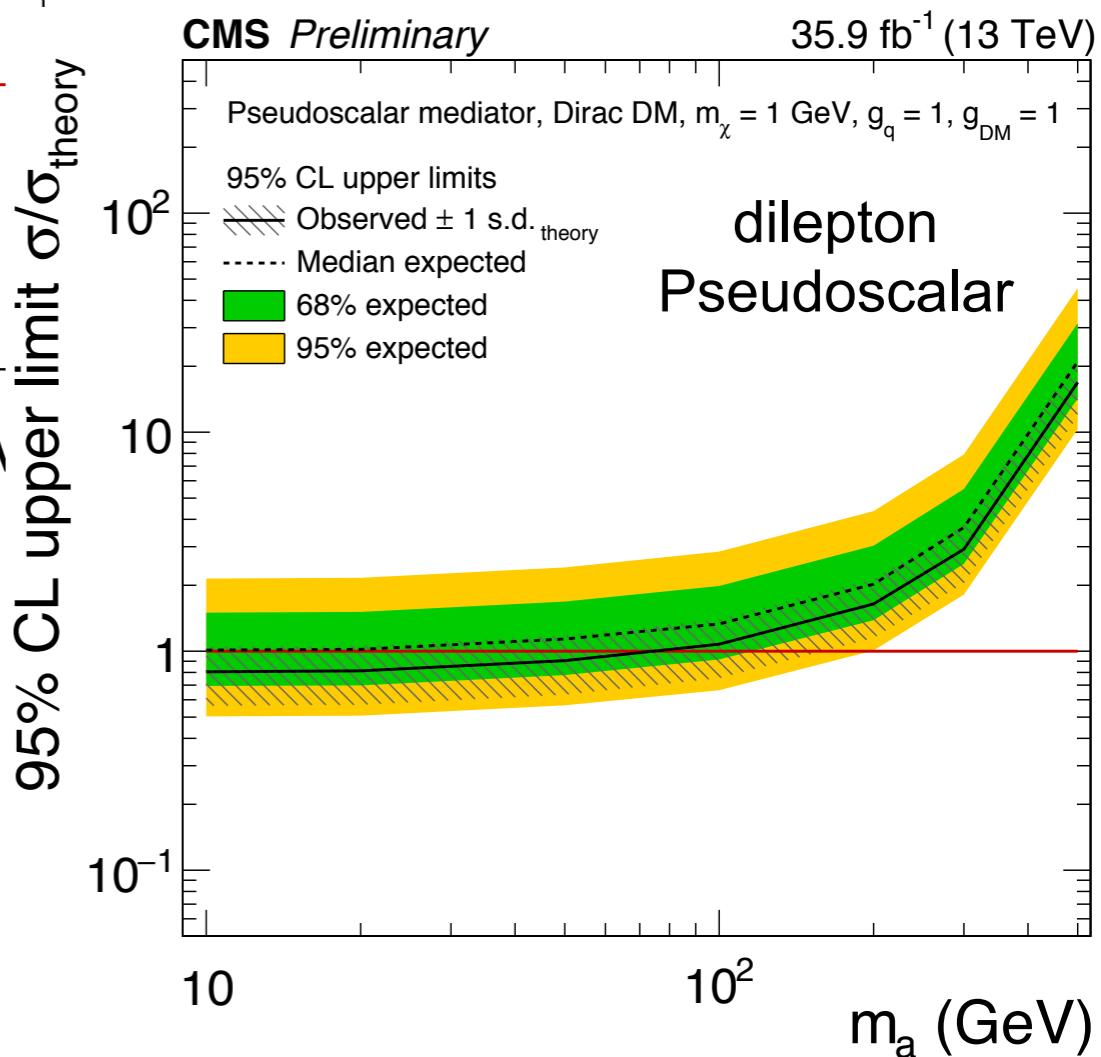


Reinterpretation of **STOP** Searches

- Recast for mono-tt, limits better than mono-jet for low-mass scalars



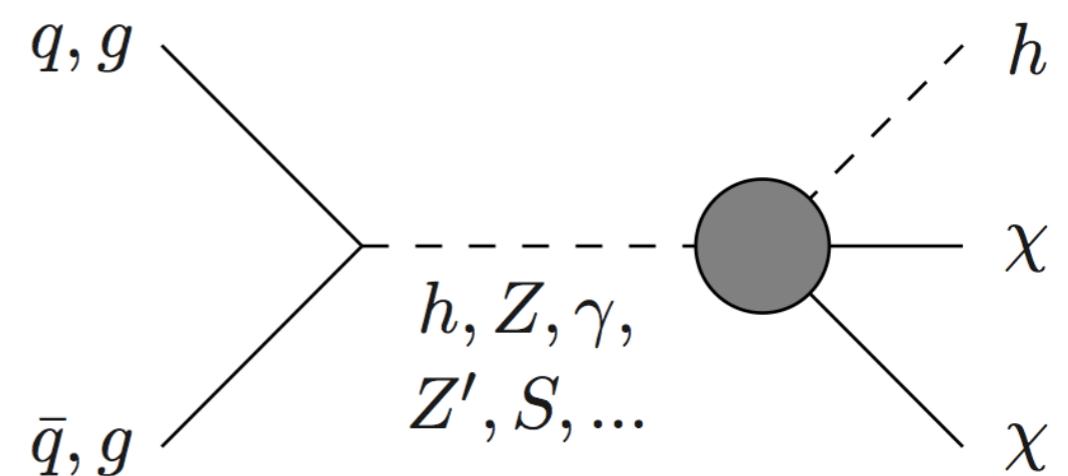
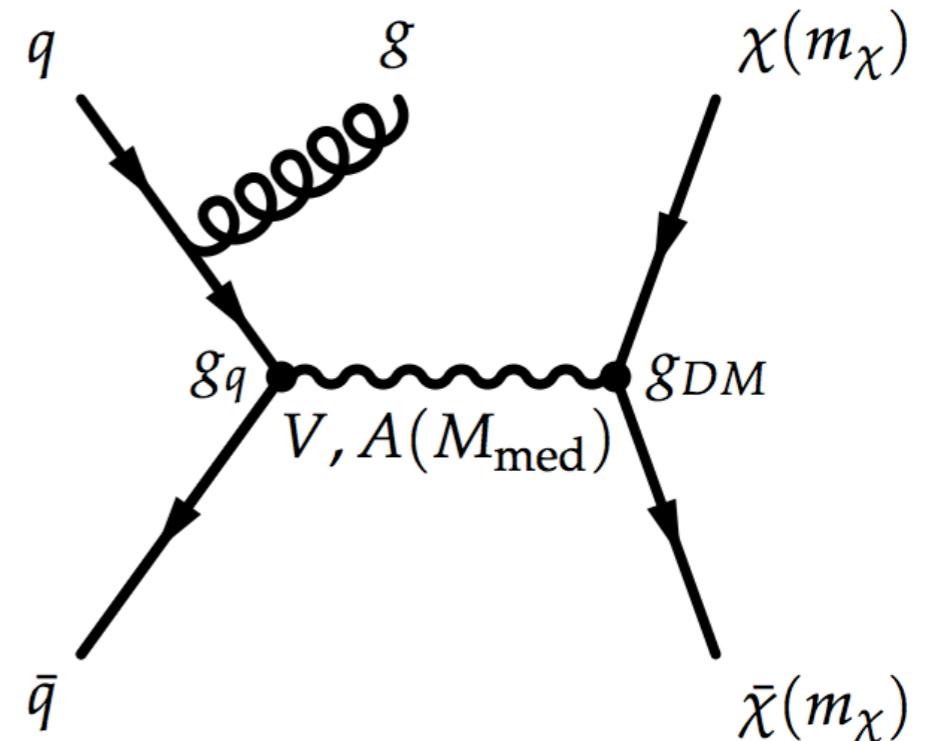
CMS-PAS-SUS-17-001



Searches for Mono-h at CMS (arXiv:1703.05236)

Why Mono-Higgs?

- DM searches at LHC have been performed with various mono-X + missing Et signatures (where X= W , Z , jet, or γ).
- Here, X could be emitted directly from a quark as ISR or as part of new effective vertex coupling of DM to SM
- Unlike W , Z , jet, or γ , Higgs ISR is highly suppressed → **mono-Higgs signal could probe directly the structure of the effective DM-SM coupling**



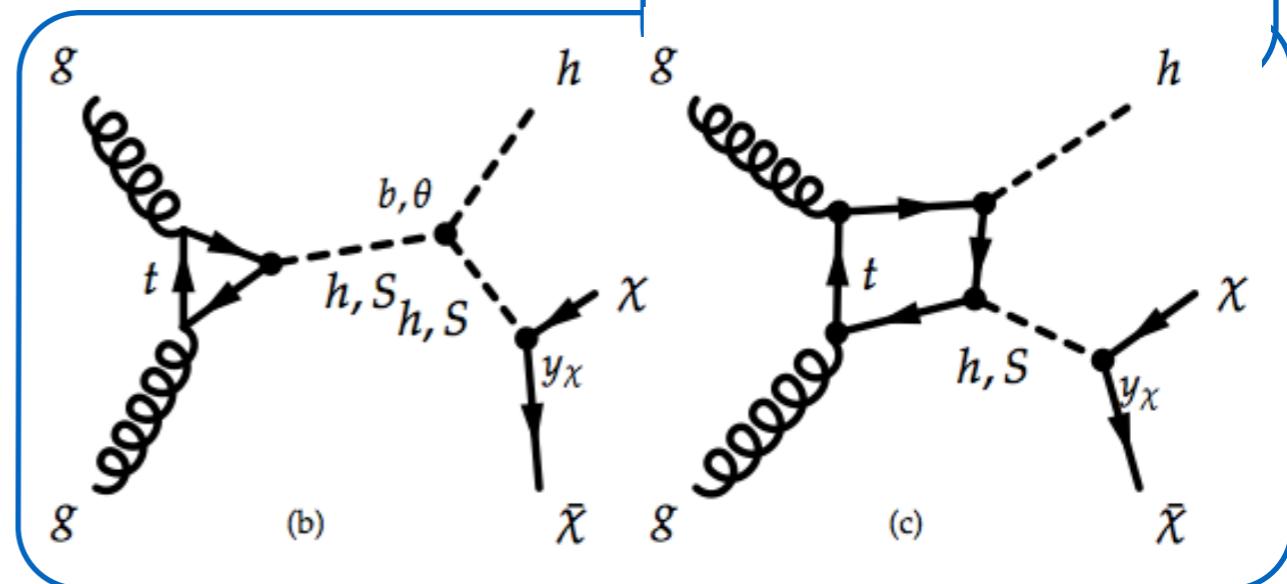
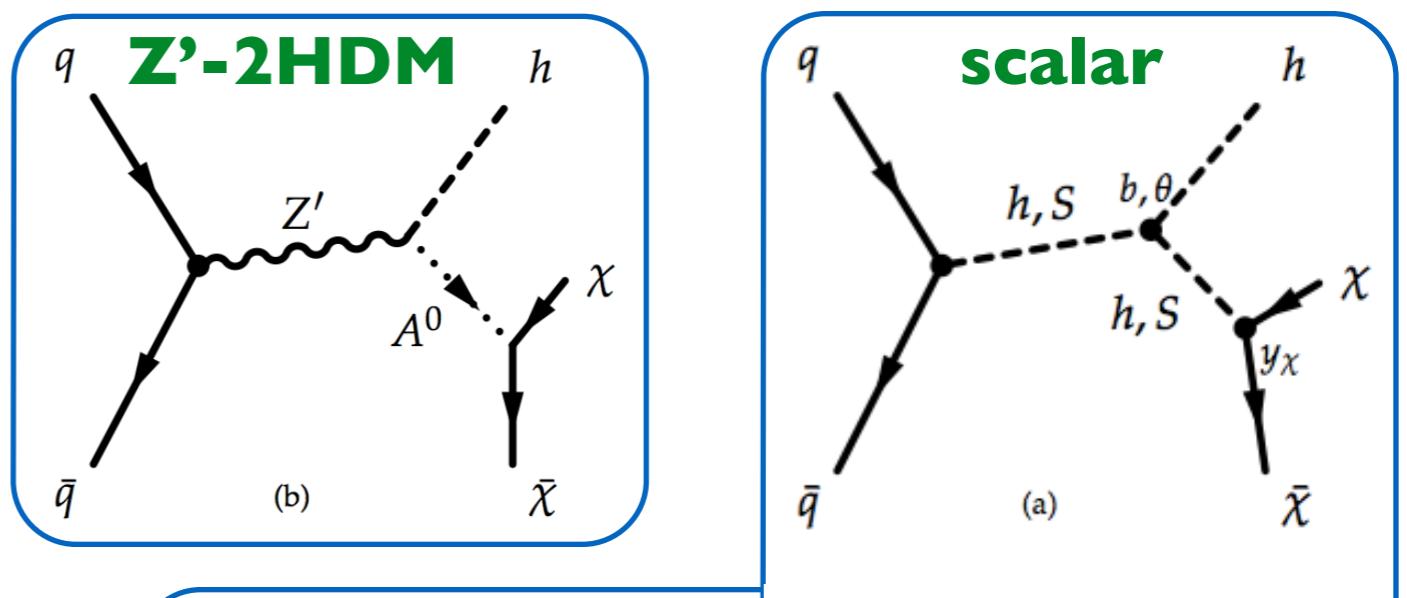
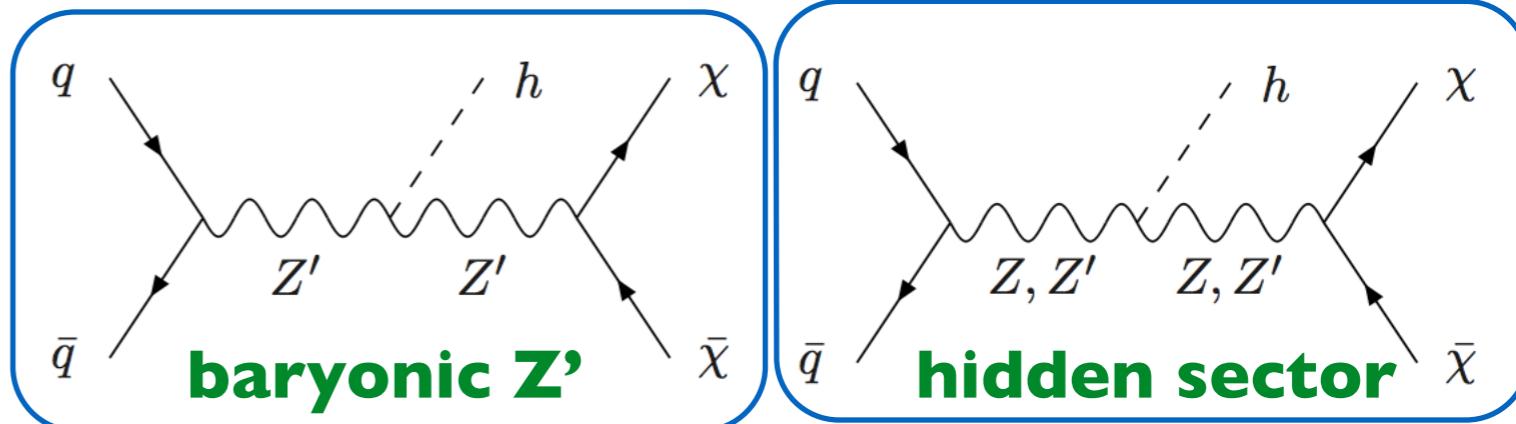
Mono-Higgs Models on the Market

[arXiv:1312.2592](https://arxiv.org/abs/1312.2592)

[arXiv:1402.7074](https://arxiv.org/abs/1402.7074)

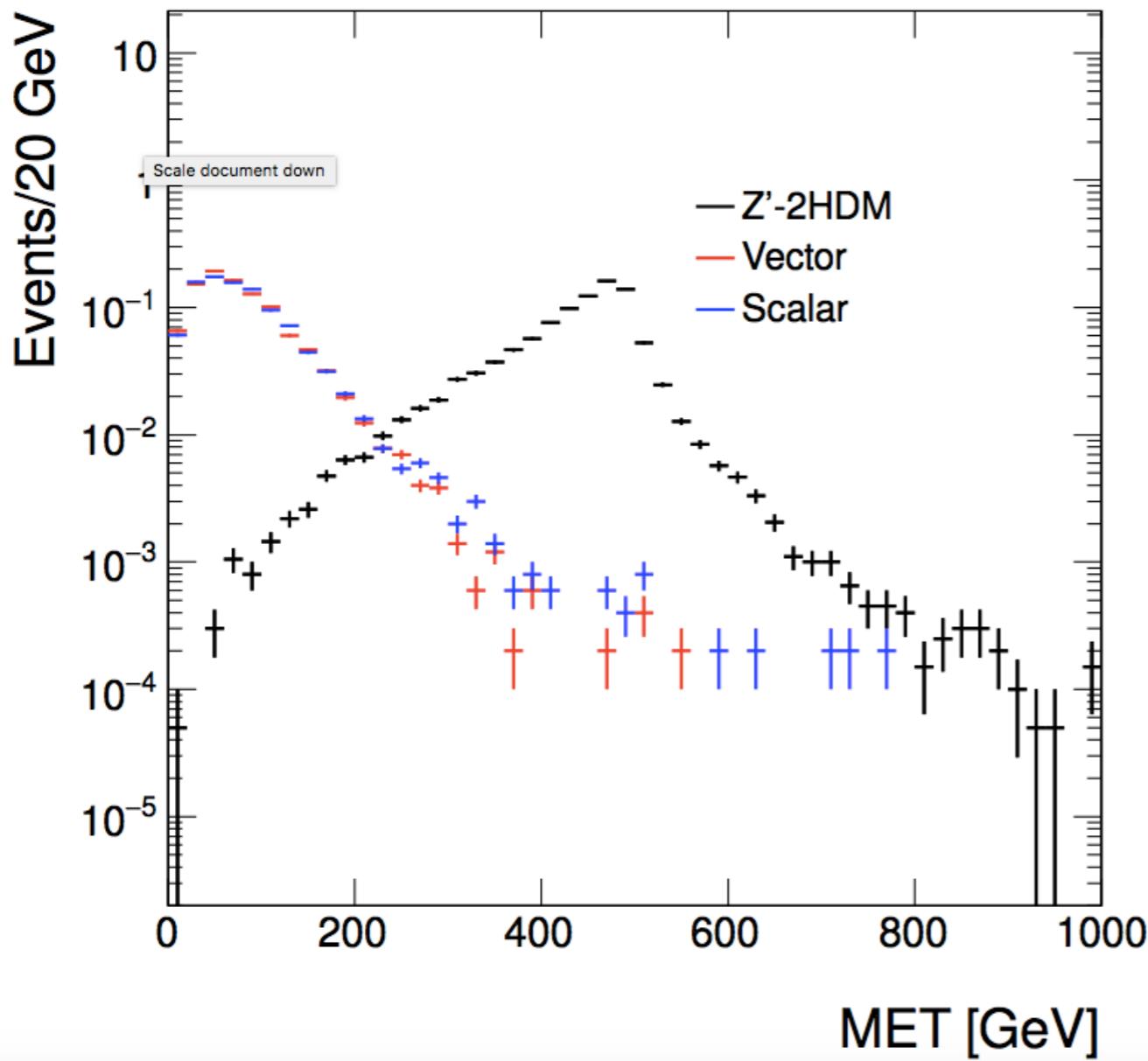
- **Effective Field Theory:** DM couples directly to Higgs via n-dimensional operator, valid at energies below cutoff scale Λ .
→ 6 EFTs

- **Simplified Models:** New massive particle mediates Higgs-DM interaction, including **baryonic Z'**, **Z' from hidden sector**, **pseudo scalar A^0 from 2HDM**, and **scalar mediator**

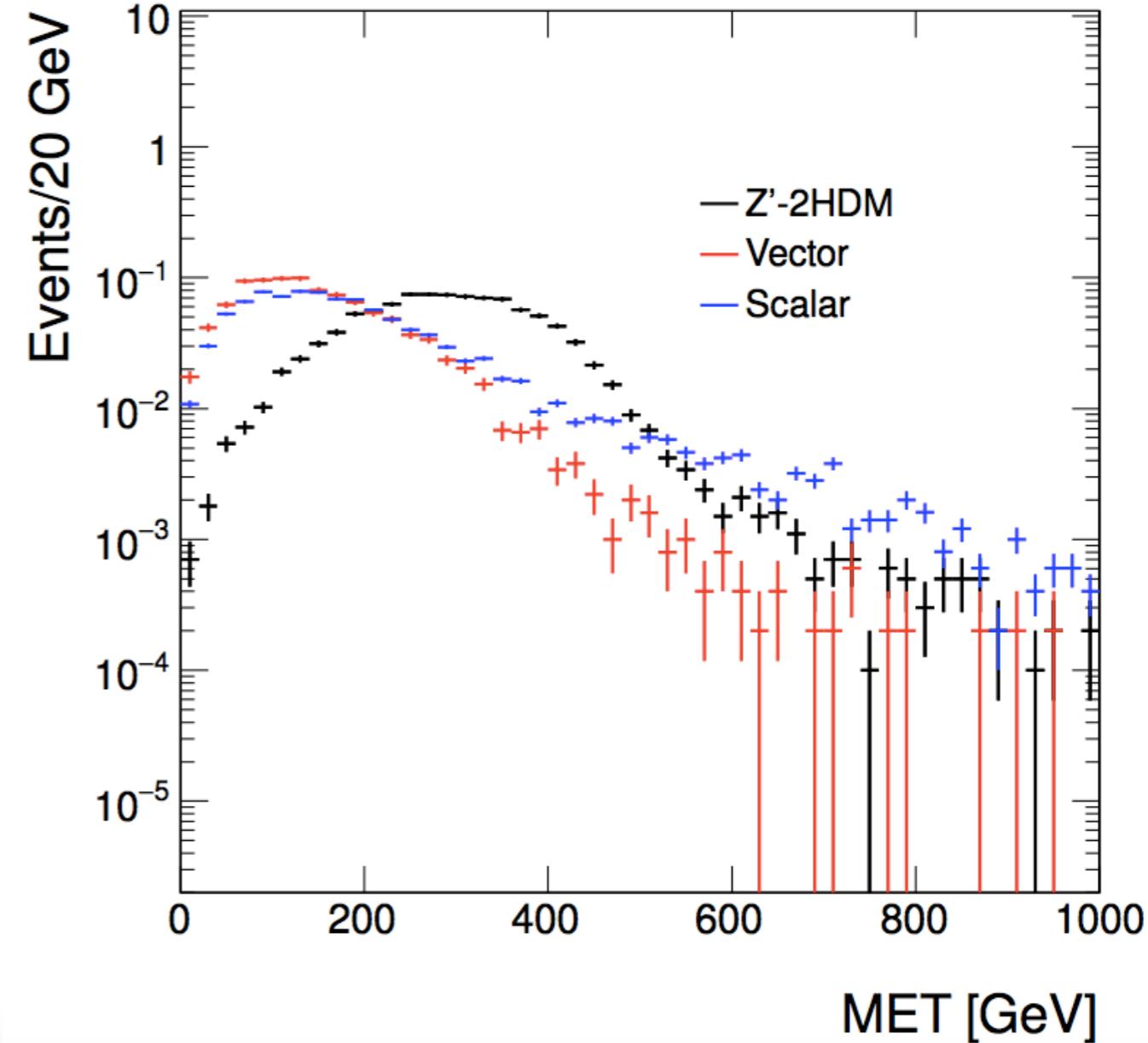


Our Benchmark Model: Z'-2HDM

$M_{MED}=100 \text{ GeV}$

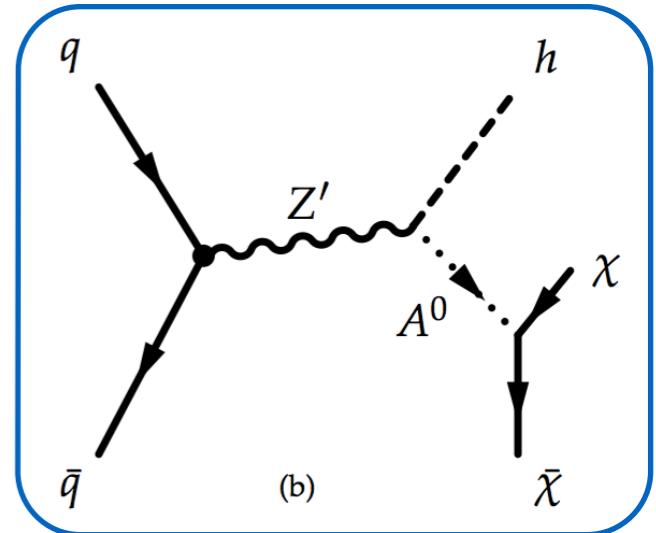


$M_{MED}=1 \text{ TeV}$



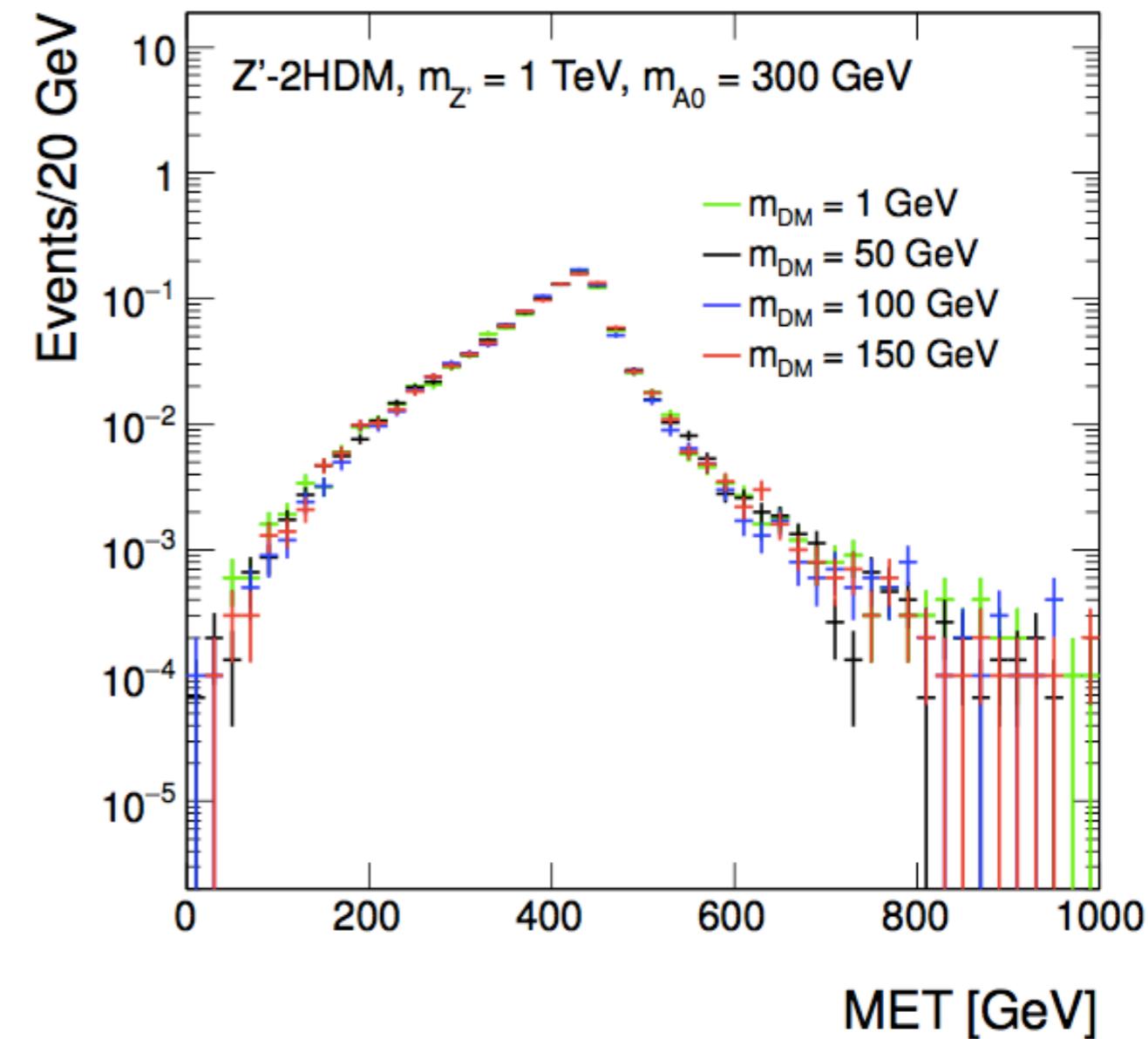
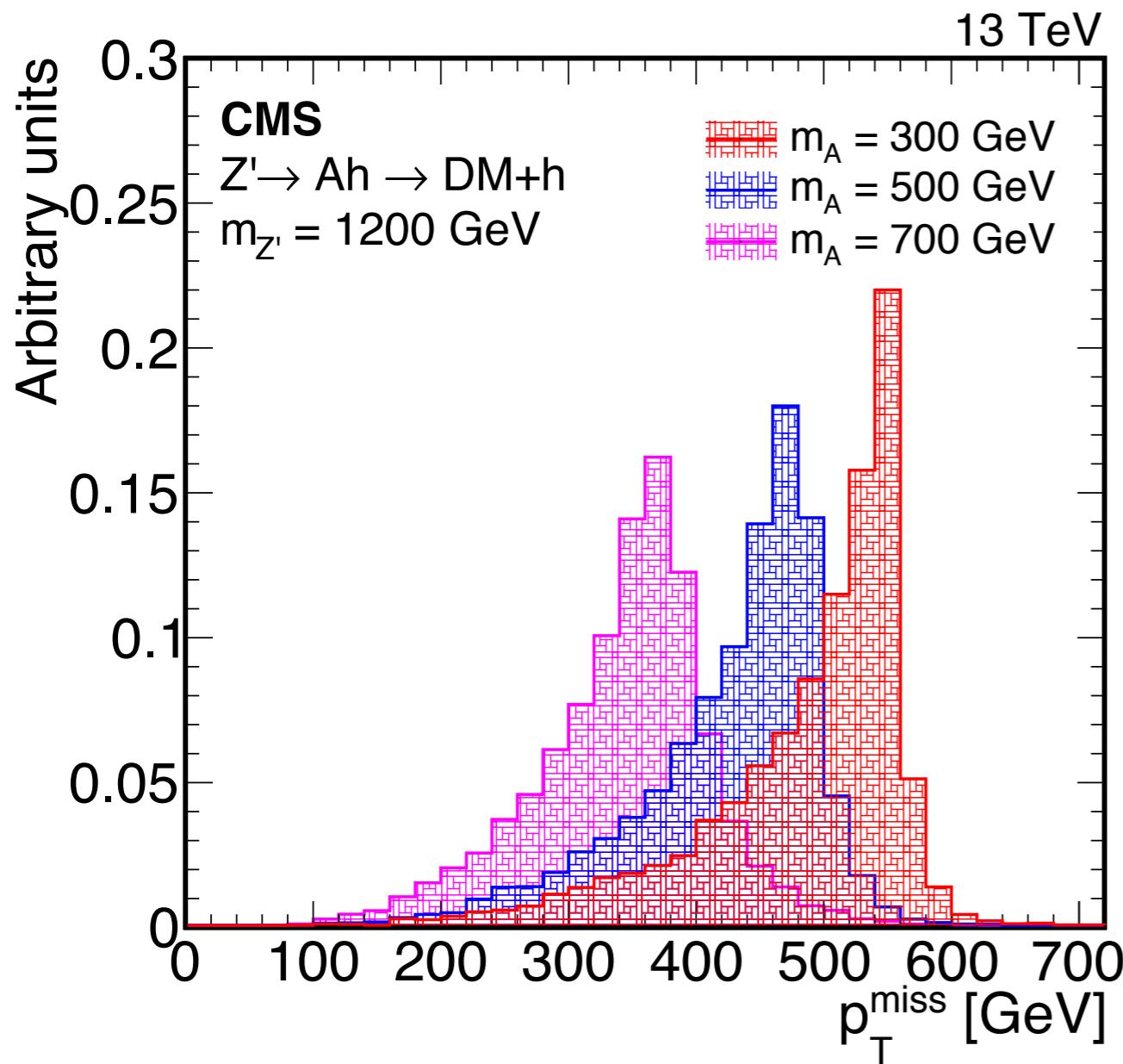
Model Parameters We Considered

- Higgs sector: Type-II 2HDM with Φ_u and Φ_d
- Gauge sector: extended by a $U(1)_{Z'}$ group
- mDM: mass of dark matter particles, $m_{DM} \leq 100$ GeV
- mA: mass of the pseudo-scalar boson A, $300 \leq m_A \leq 800$ GeV
- mZp: mass of Z' , $600 \leq m_{Z'} \leq 2500$ GeV
- gDM: coupling of A with DM particles, $g_{DM}=1$
- gZ': coupling of Z' , $g_{Z'}=0.8$
- tan β : ratio of the vacuum expectation values, $\tan\beta=1$



Generator-Level Kinematic Distributions

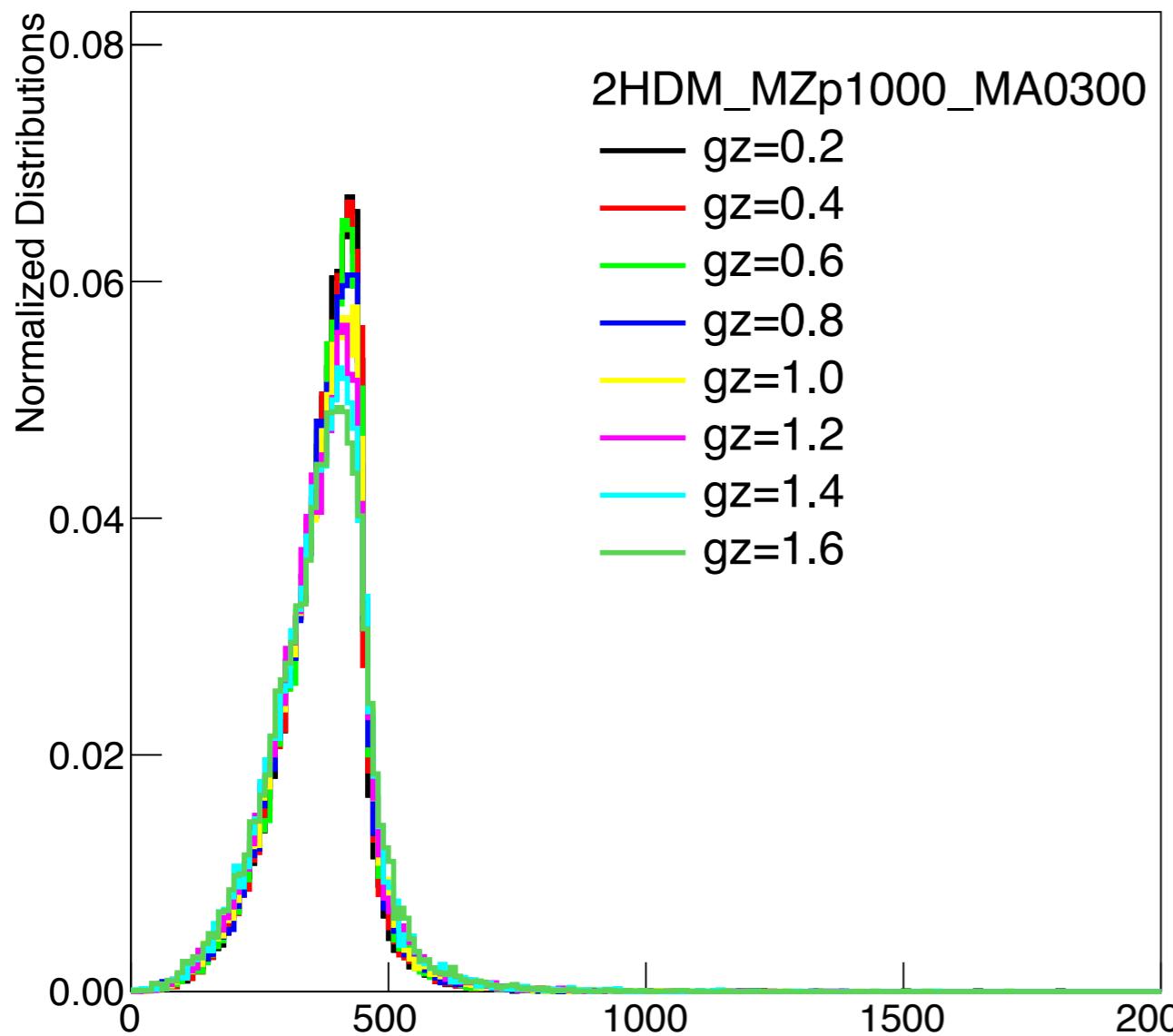
$$p_{\text{COM}}^A = p_{\text{COM}}^h = \frac{\left[\left(M_{Z'}^2 - (m_A + m_h)^2 \right) \left(M_{Z'}^2 - (m_A - m_h)^2 \right) \right]^{1/2}}{2M_{Z'}}$$



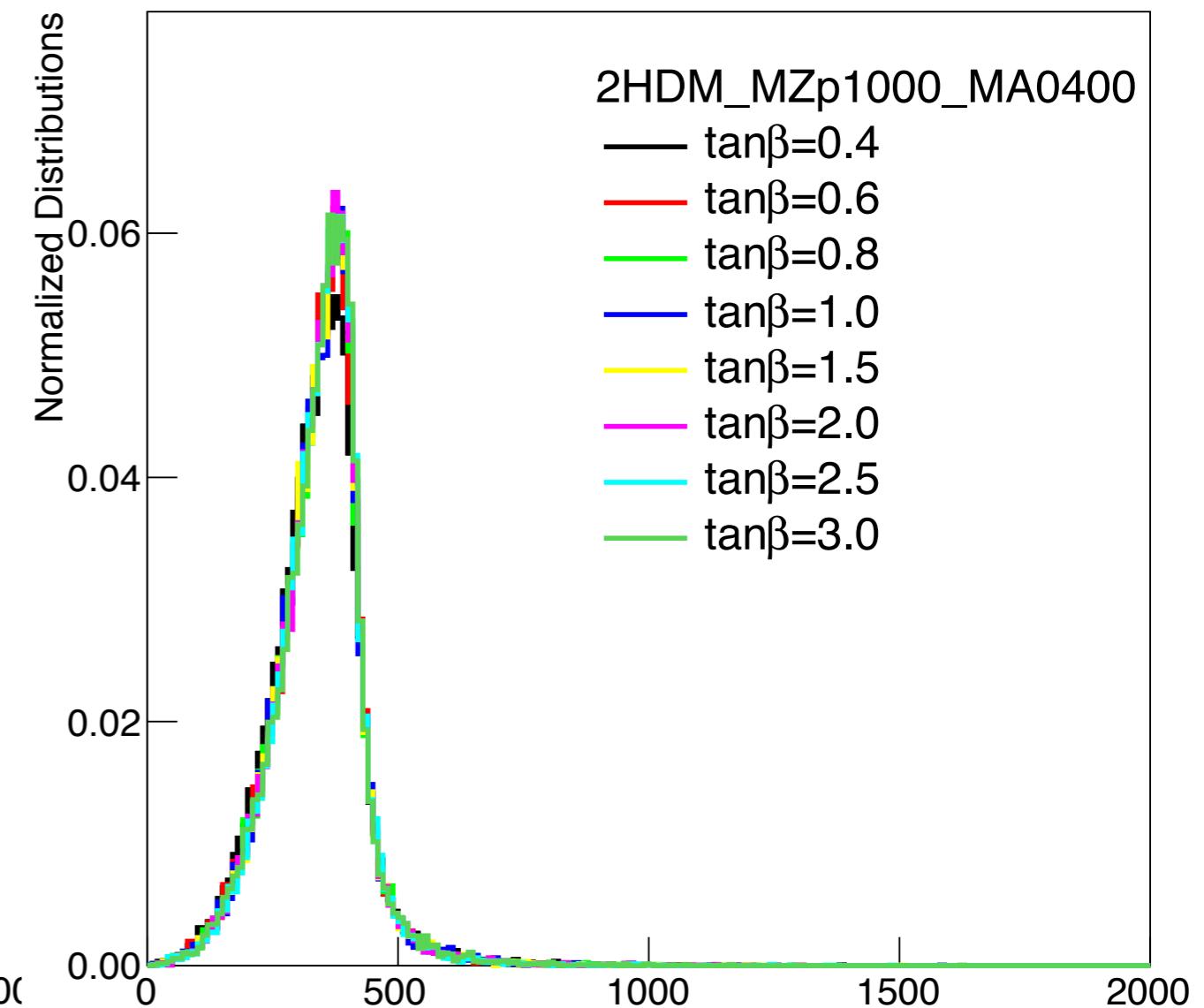
Generator-Level Kinematic Distributions

- MET distributions have little dependence on model parameters

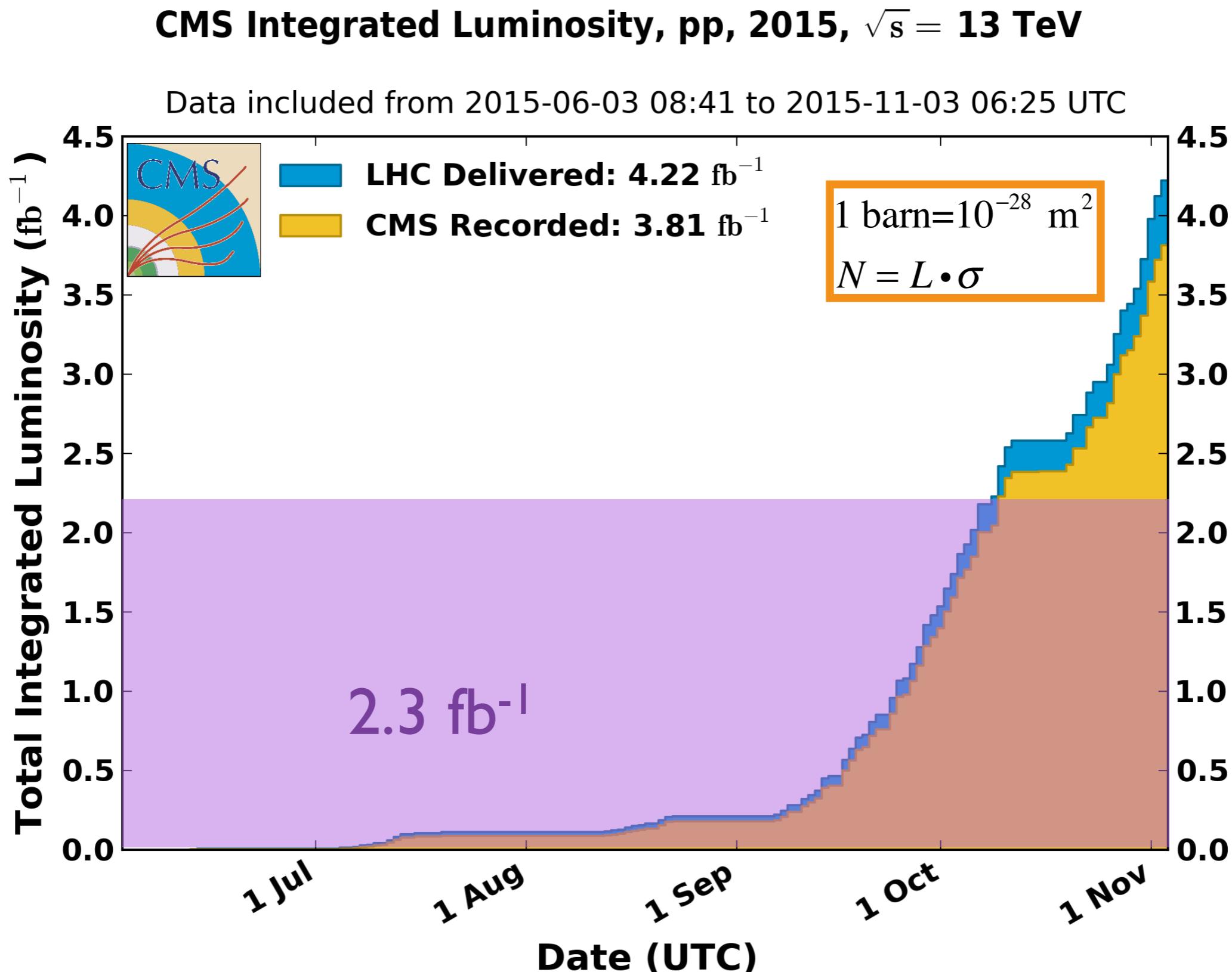
genMET_true



genMET_true

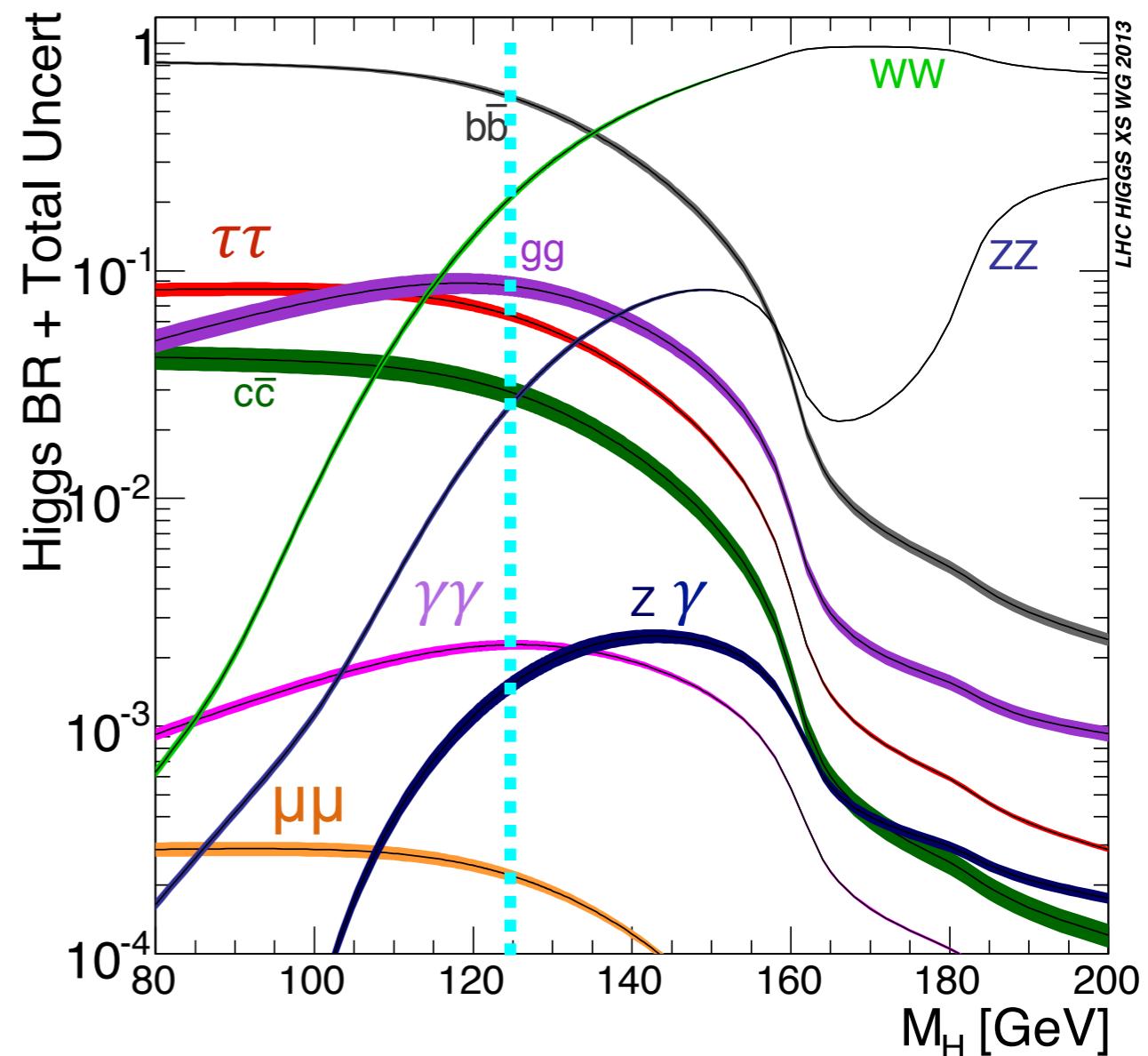


CMS Data Used in This Analysis



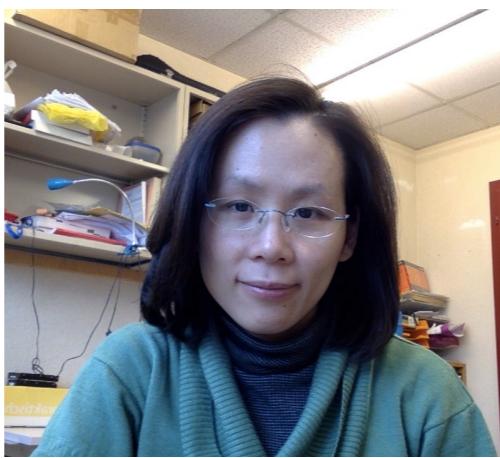
Why $H \rightarrow bb$ And $H \rightarrow \gamma\gamma$?

- $H \rightarrow bb$
 - Wide mass peak (10%), with highest branching ratio (58%)
 - In general, this decay dominates the search sensitivity
- $H \rightarrow \gamma\gamma$
 - Narrow mass peak (1-2% mass resolution), but lower branching ratio (0.2%)
 - Not limited by the MET trigger, can probe models which predict lower MET



Mono-Higgs Team at CMS

$H \rightarrow bb$



Shin-Shan Yu



Raman Khurana



Fang-Ying Tsai

$H \rightarrow bb$



Ching-Wei Chen



Shu-Xiao Liu



Michele de Gruttola

$H \rightarrow \gamma\gamma$



Livia Soffi



Margaret Zientek

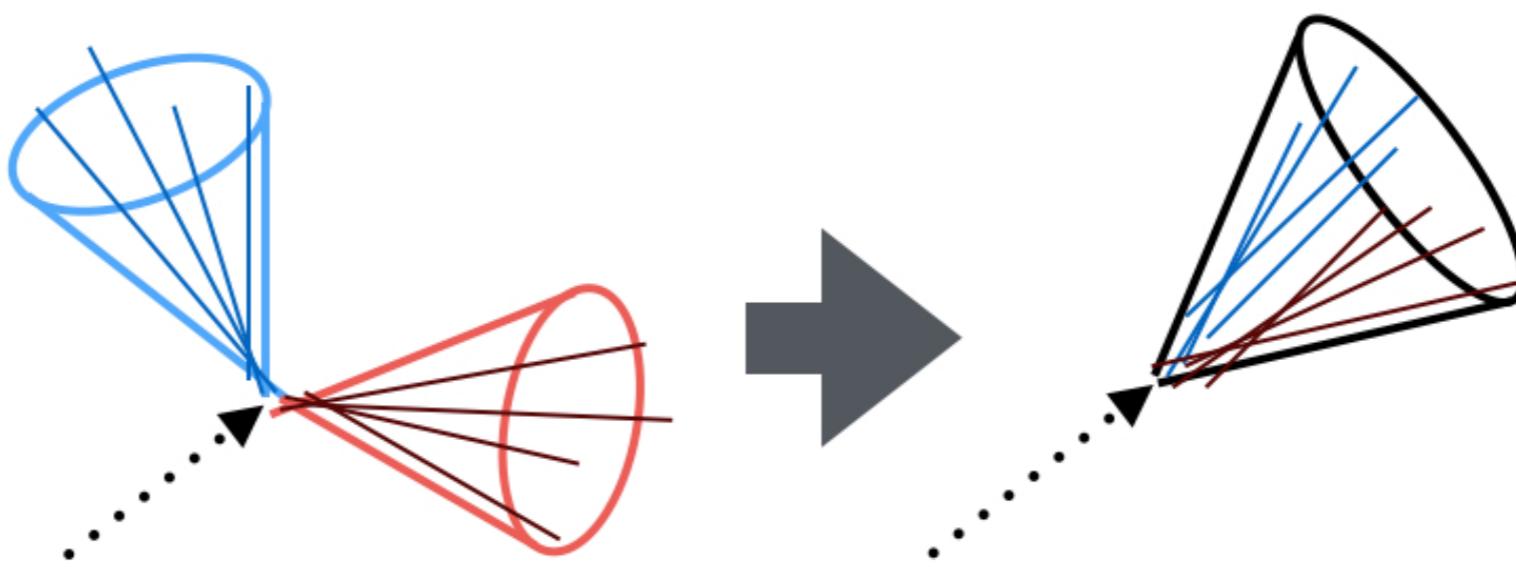


Peter Wittich

Mono H \rightarrow bb: Resolved and Boosted Jets

- Our average Higgs pT spans from 120 GeV to 1200 GeV
- Two different jet cone sizes are used: 0.4 (AK4) and 0.8 (AK8)

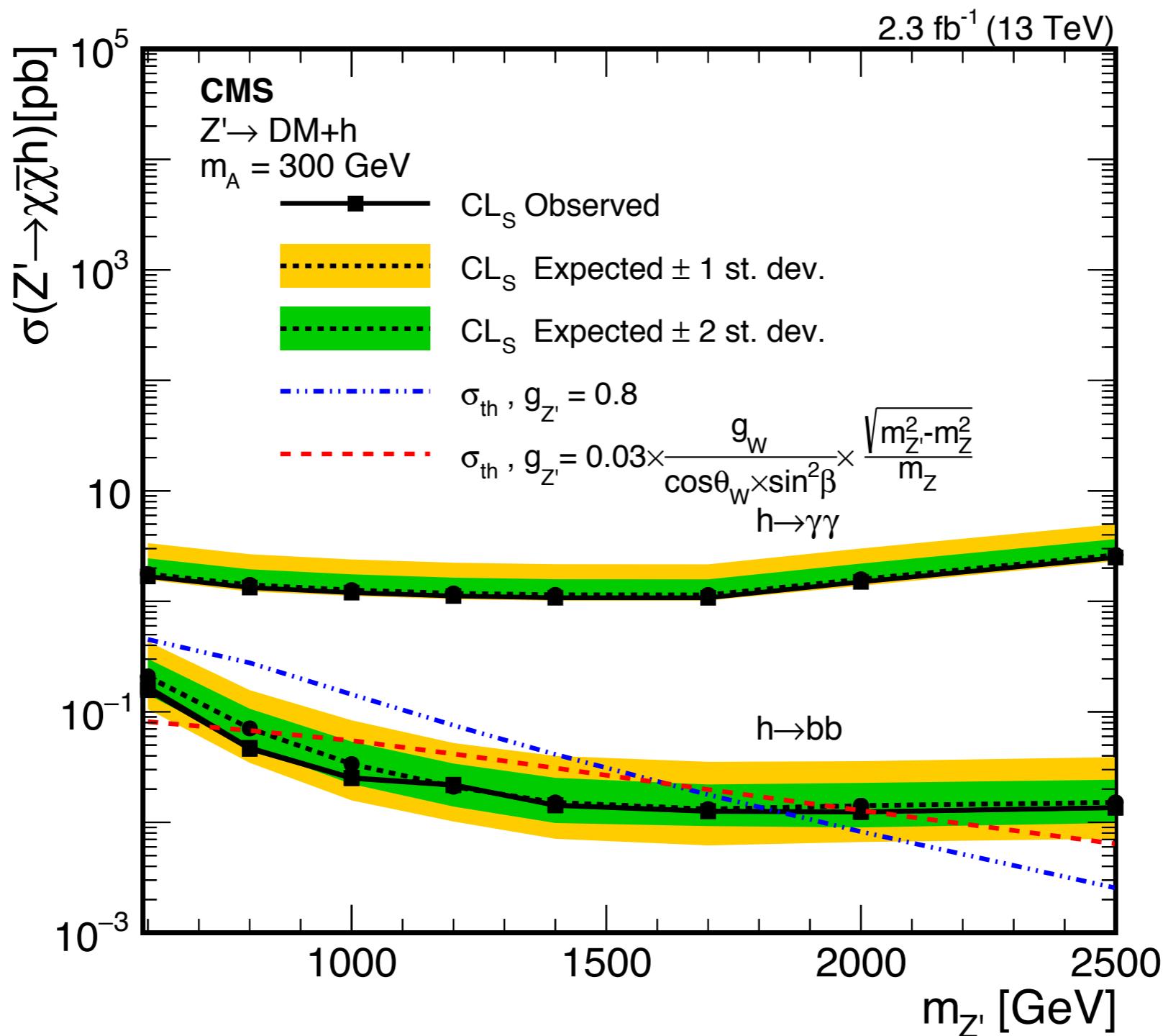
$$\Delta R_{\min} \approx 2 \frac{M_B}{p_B}$$



Anti-K_T $\Delta R = 0.4 \rightarrow \Delta R = 0.8$

Combining the Two Decay Channels

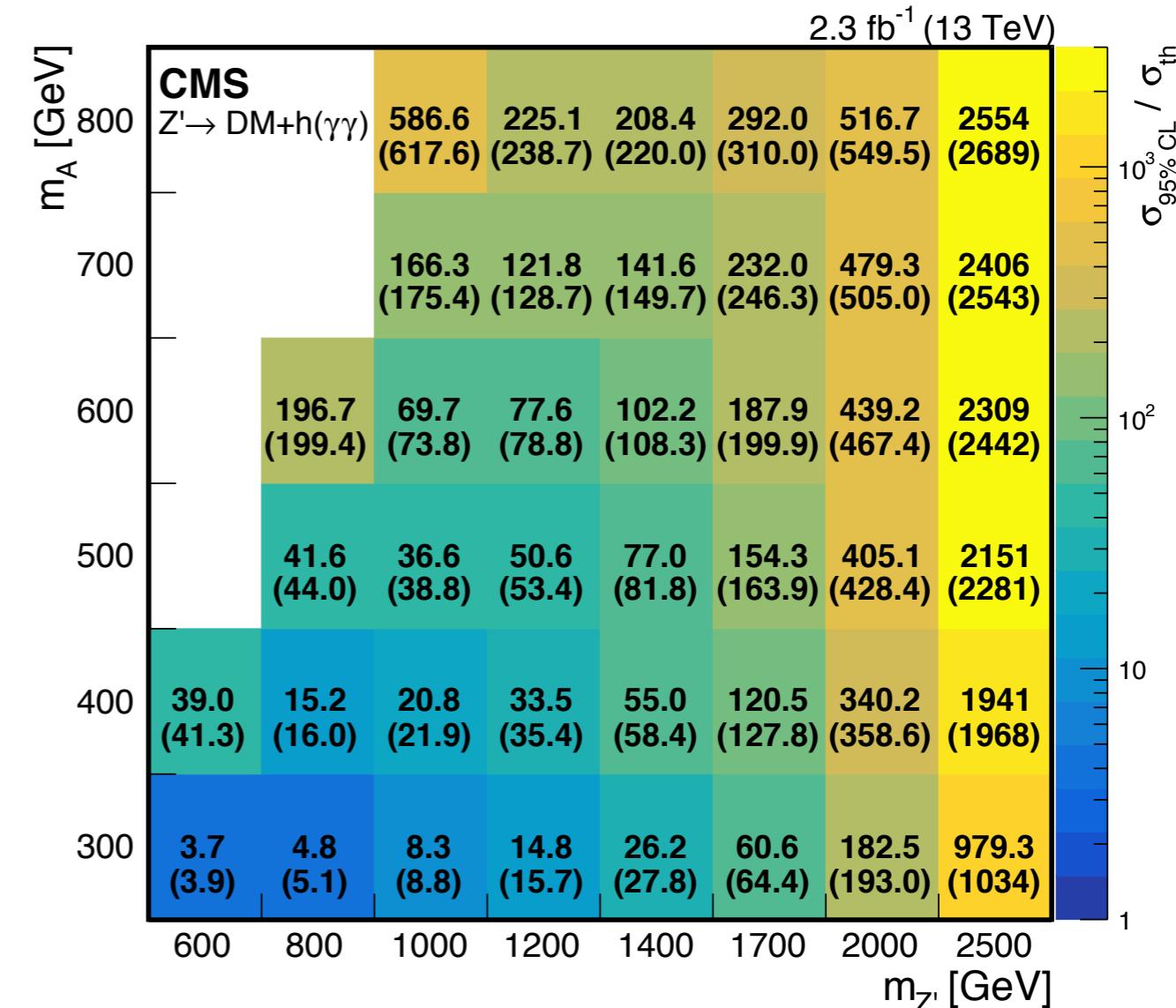
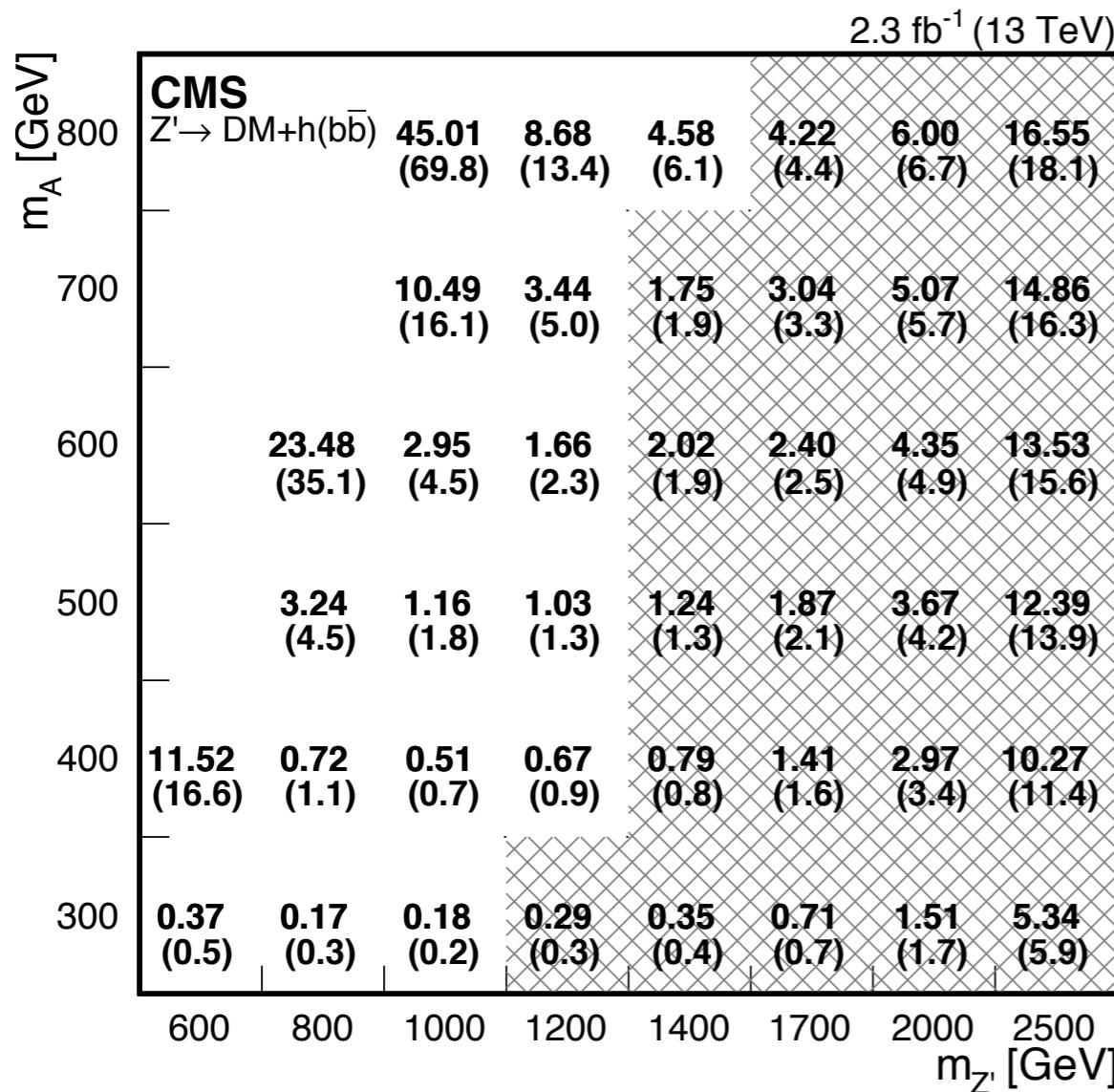
- $600 \text{ (770)} < m_{Z'} < 1860 \text{ (2040) GeV}$ excluded for $g_{Z'}=0.8$ (formula)



Combining the Two Decay Channels

Resolved

Boosted



Expanding the Mass Of A

