Boosted hidden physics with ISR

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LPC Physics Forum

Z'+ISR jet : EXO-17-001/18-012
Z'+ISR photon : EXO-17-027
ϕ(bb)+ISR jet : EXO-17-024

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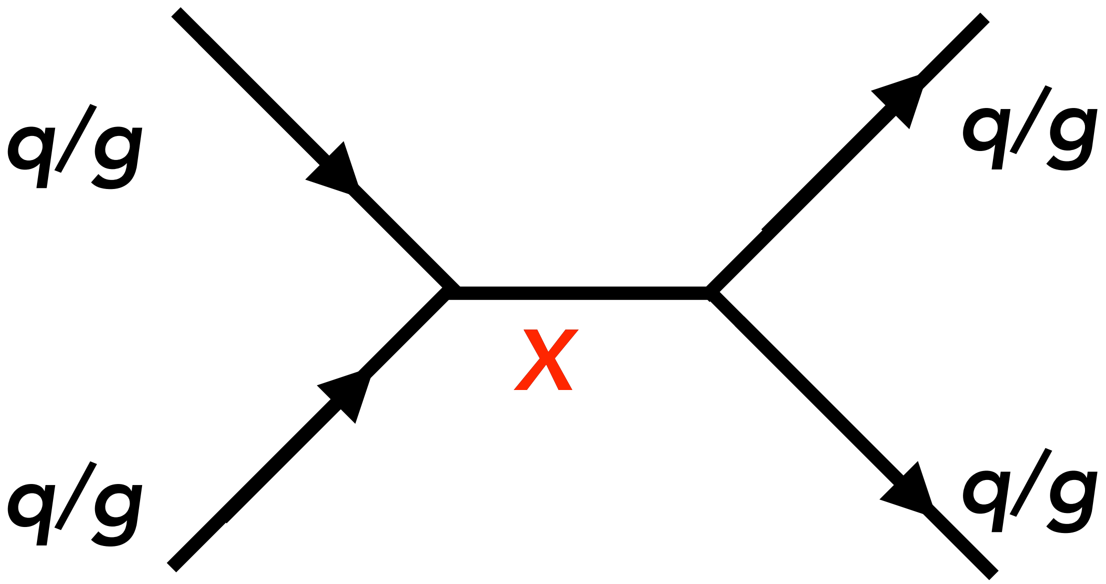
Outline

* Introduction
* Boosted Dijet Analysis
* Results
* New directions

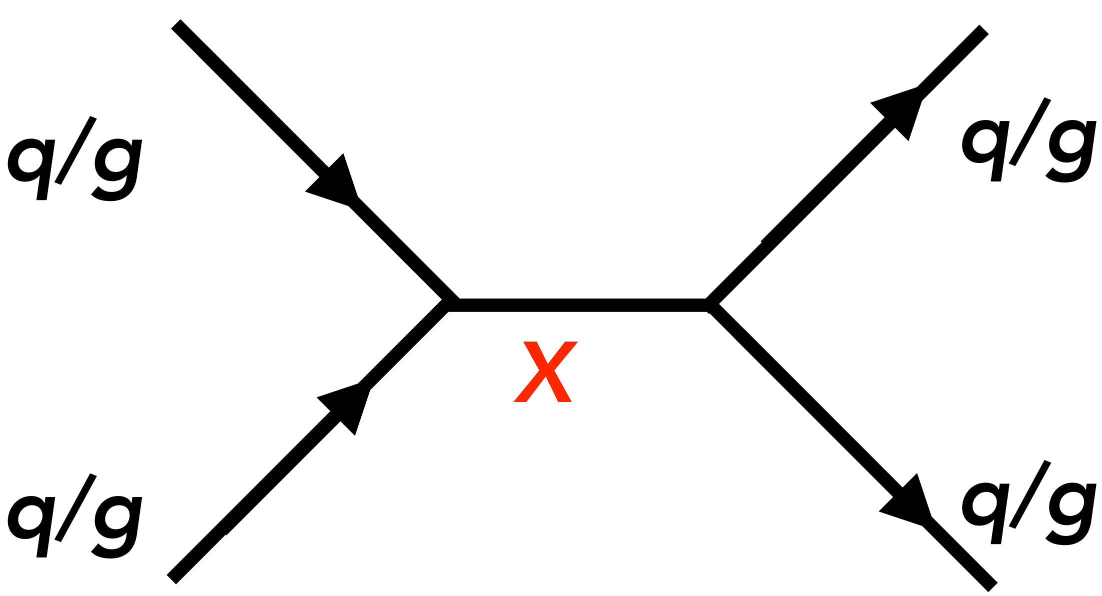
Introduction

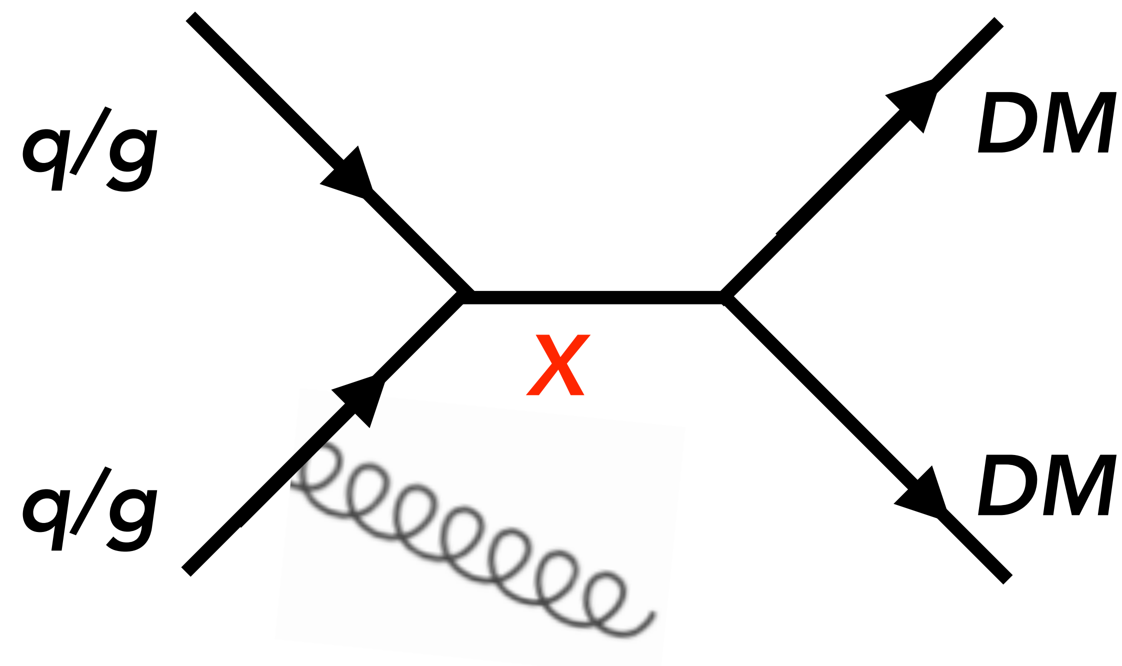
Dijets



X: Z′,W′, excited quarks,
Randall-Sundrum graviton…

Dijets and DM mediators

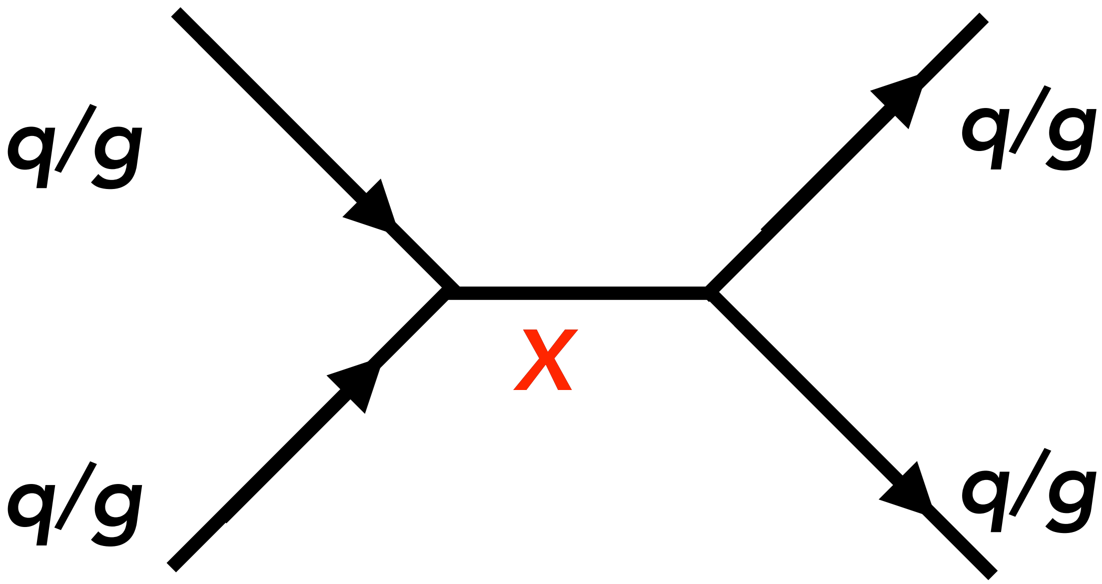


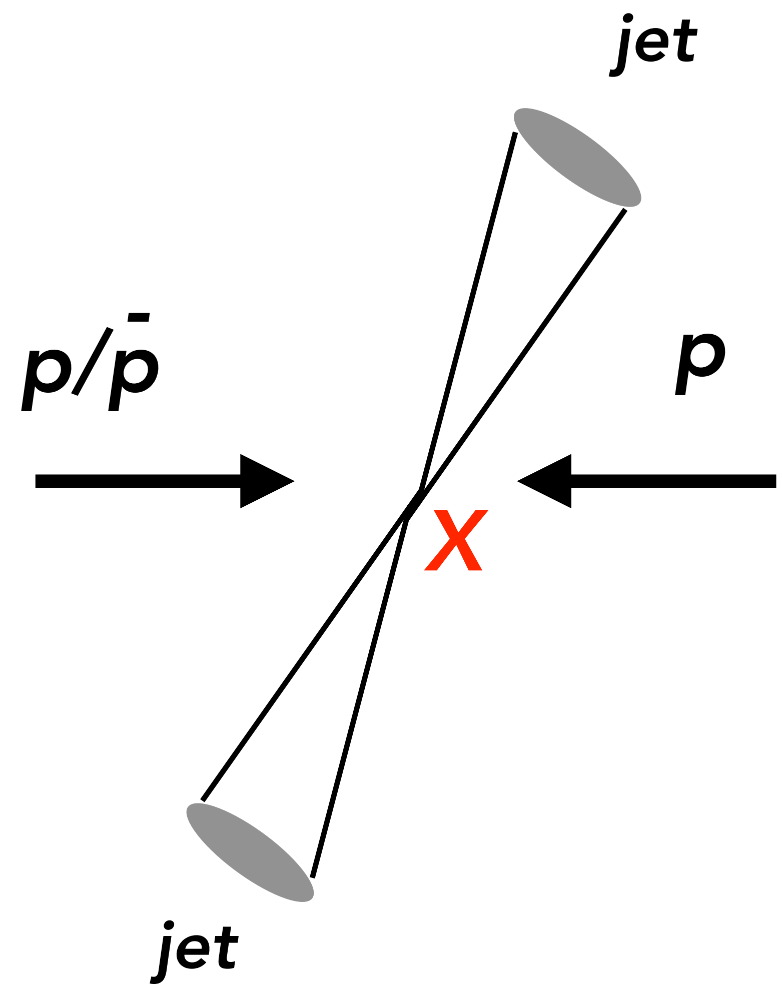


X: Z′,W′, excited quarks, Randall-Sundrum graviton…

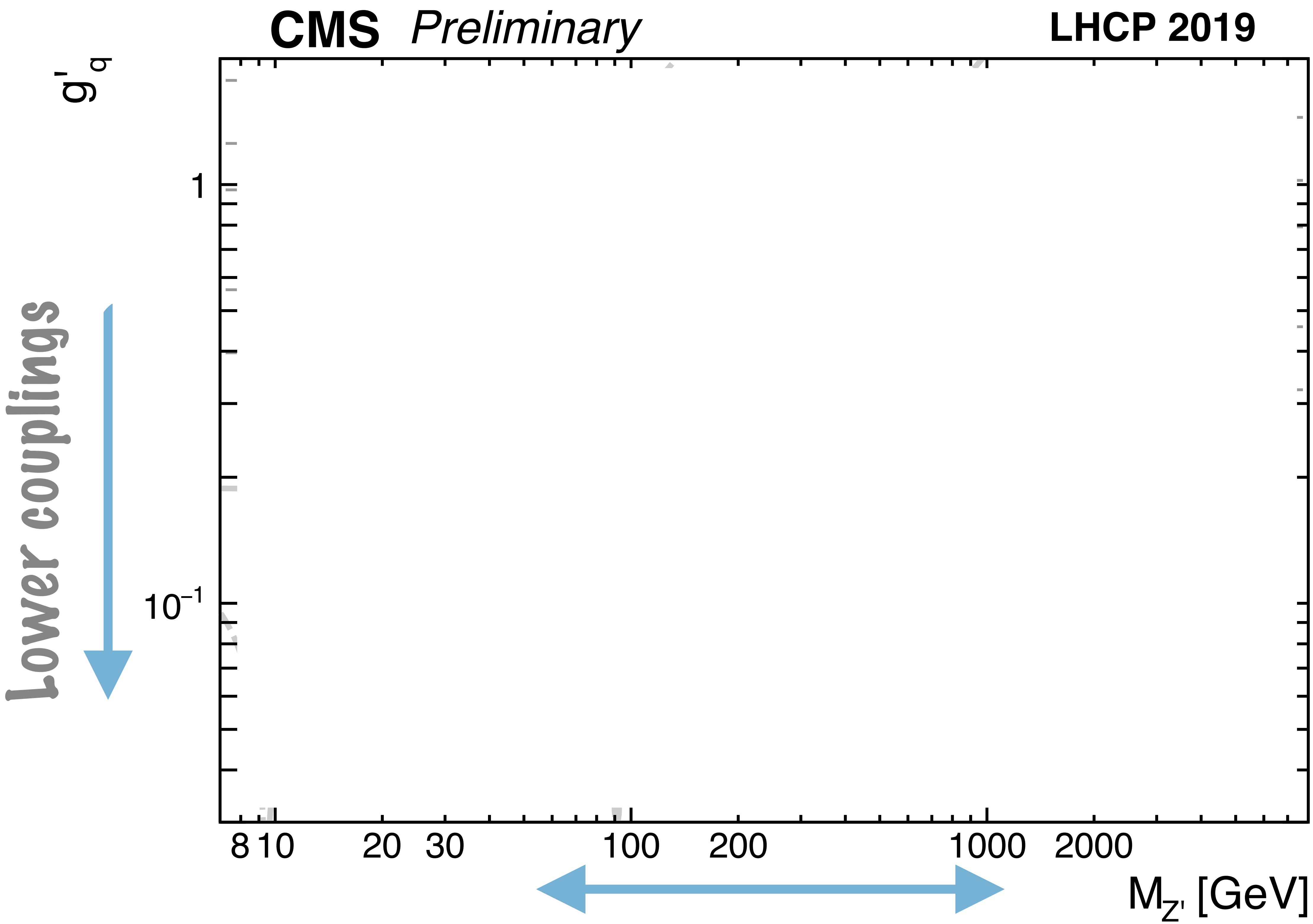
X: DM mediator in simplified DM models

Dijet signatures

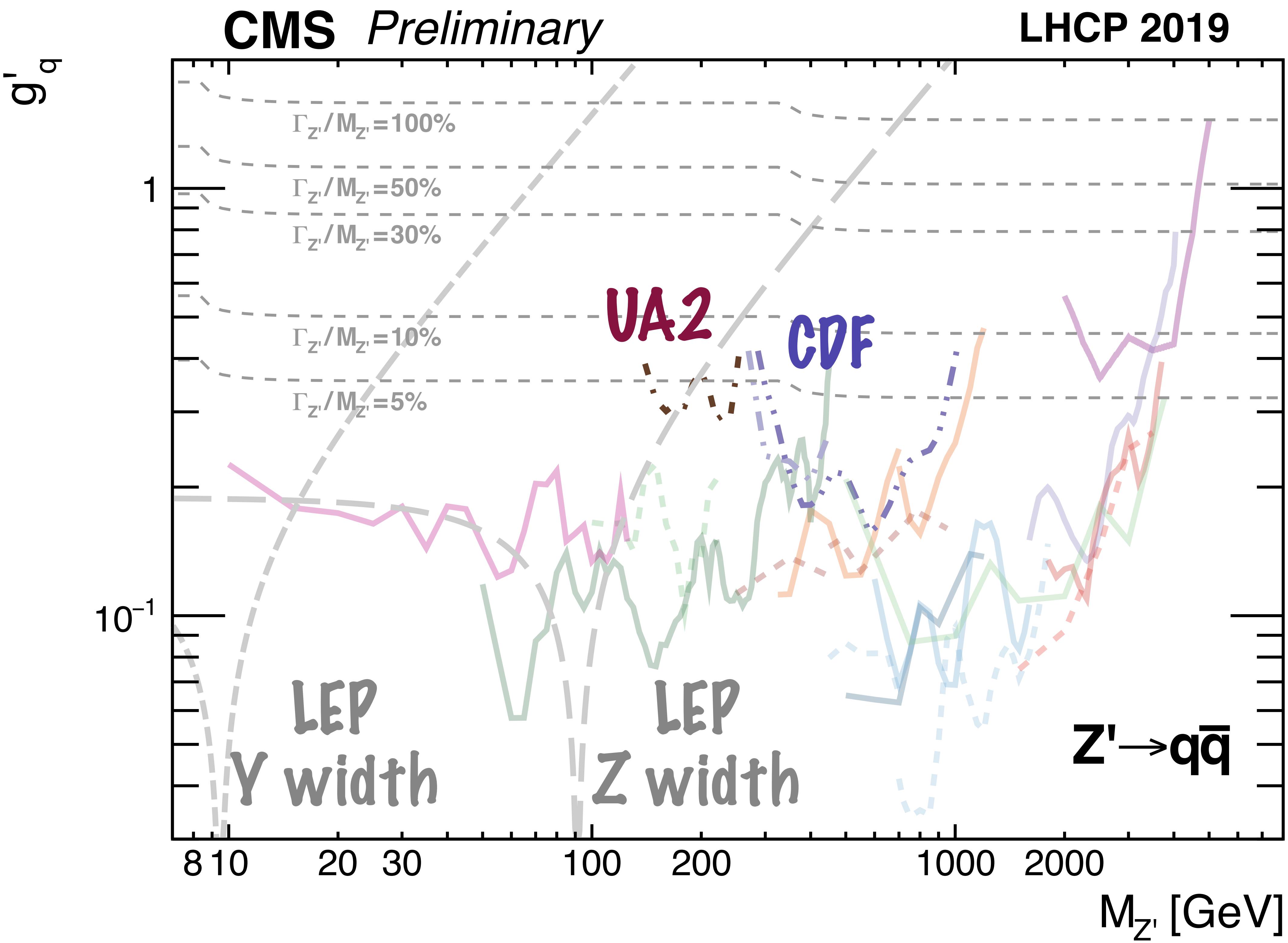




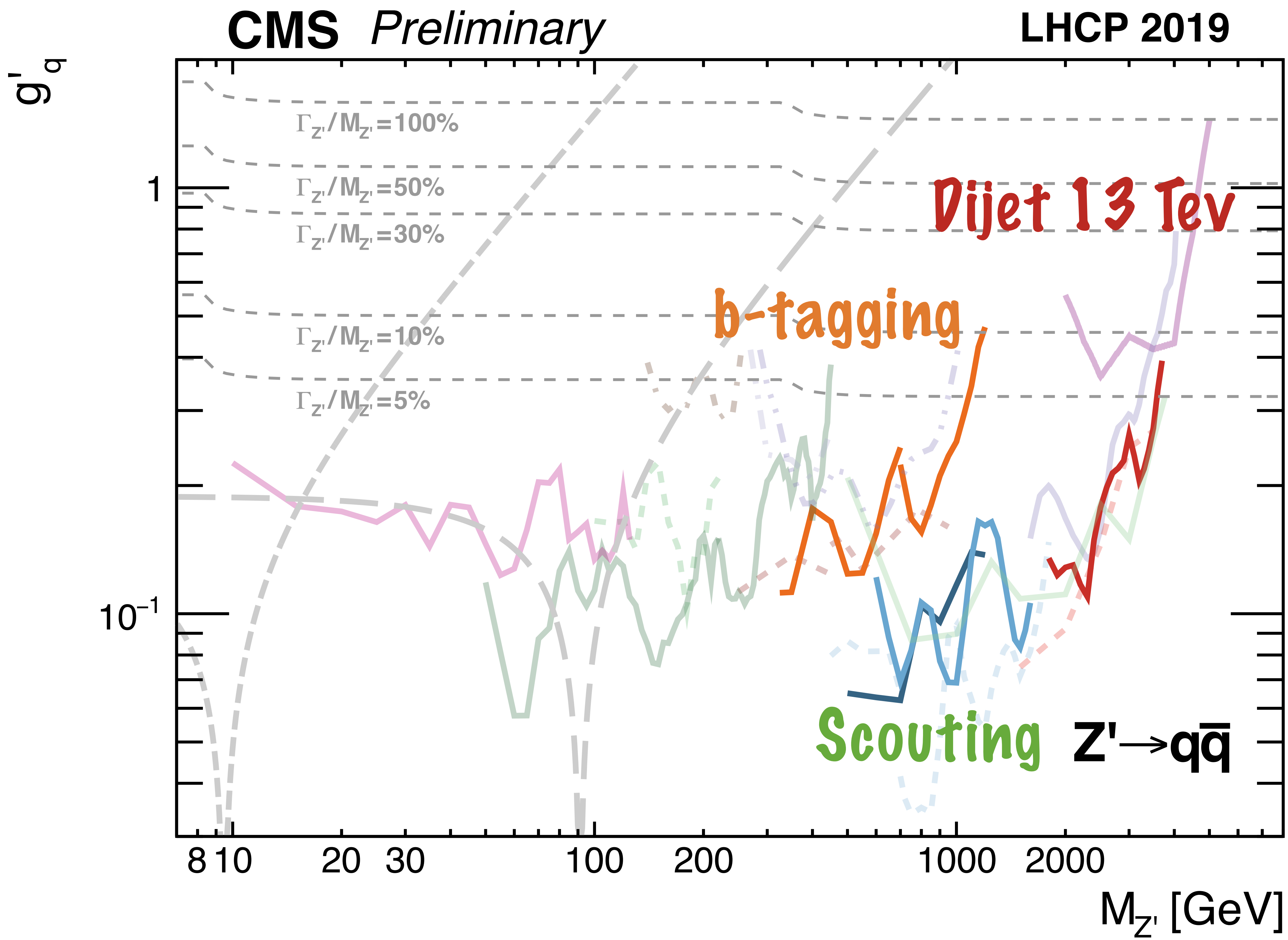
Dijets phase space



Dijets @ pre-LHC

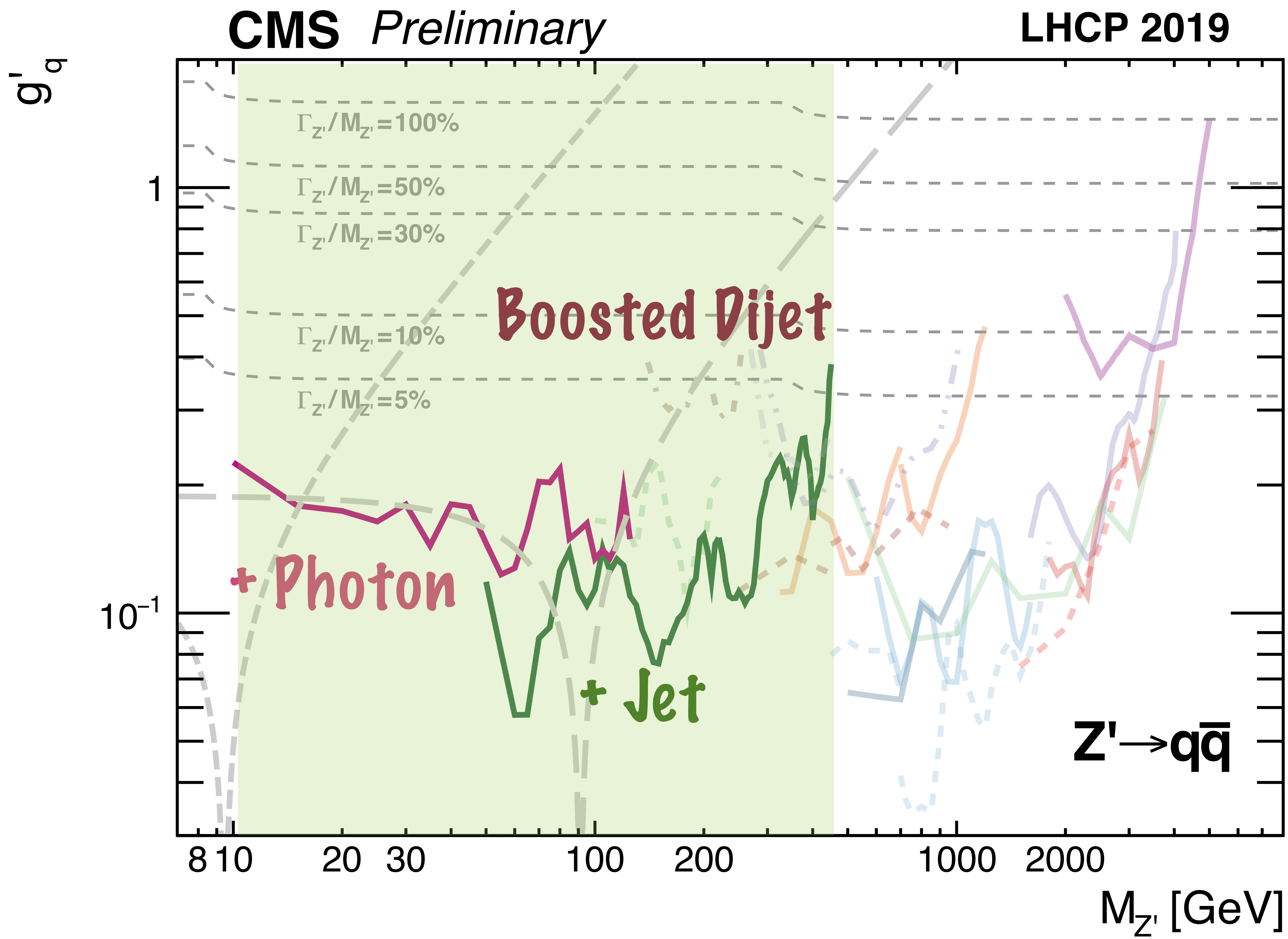


Dijets @ LHC



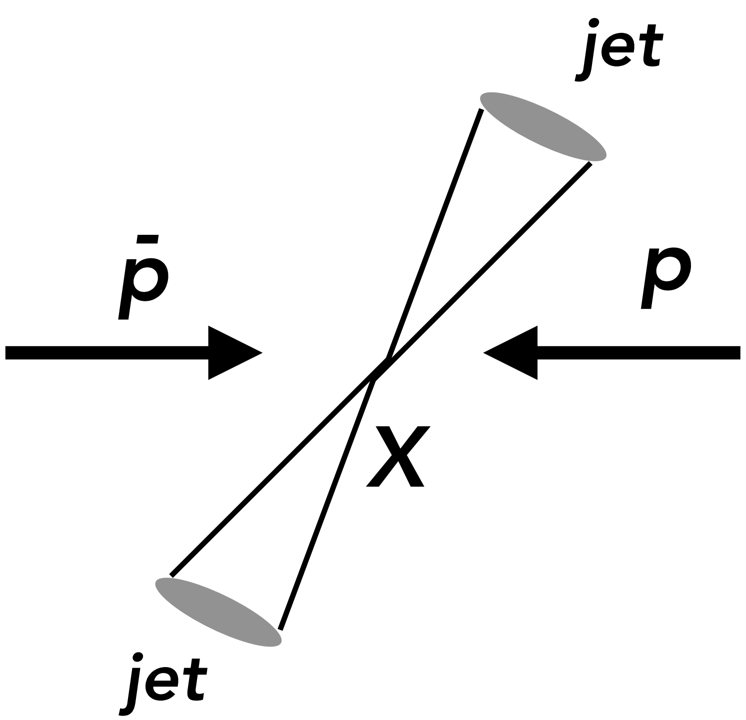
CMS Preliminary
LHCP 2019
g'_q
$\Gamma_{Z'}/M_{Z'}$=100%
$\Gamma_{Z'}/M_{Z'}$=50%
$\Gamma_{Z'}/M_{Z'}$=30%
$\Gamma_{Z'}/M_{Z'}$=10%
$\Gamma_{Z'}/M_{Z'}$=5%
1
10^{-1}
Dijet 13 Tev
b-tagging
Scouting
$Z'\rightarrow q\bar{q}$
8 10 20 30 100 200 1000 2000
$M_{Z'}$ [GeV]

Dijets @ LHC + ISR

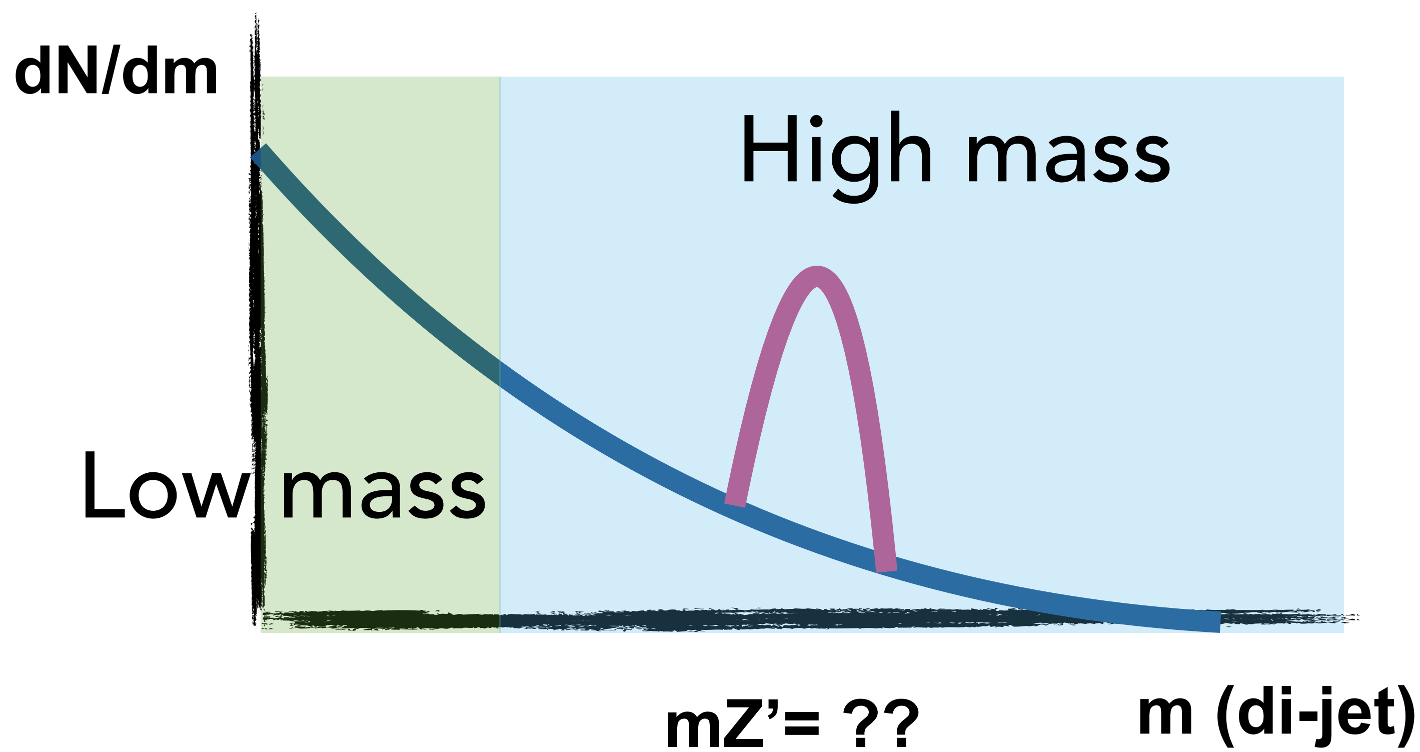


Low mass dijets

Basics of a dijet search

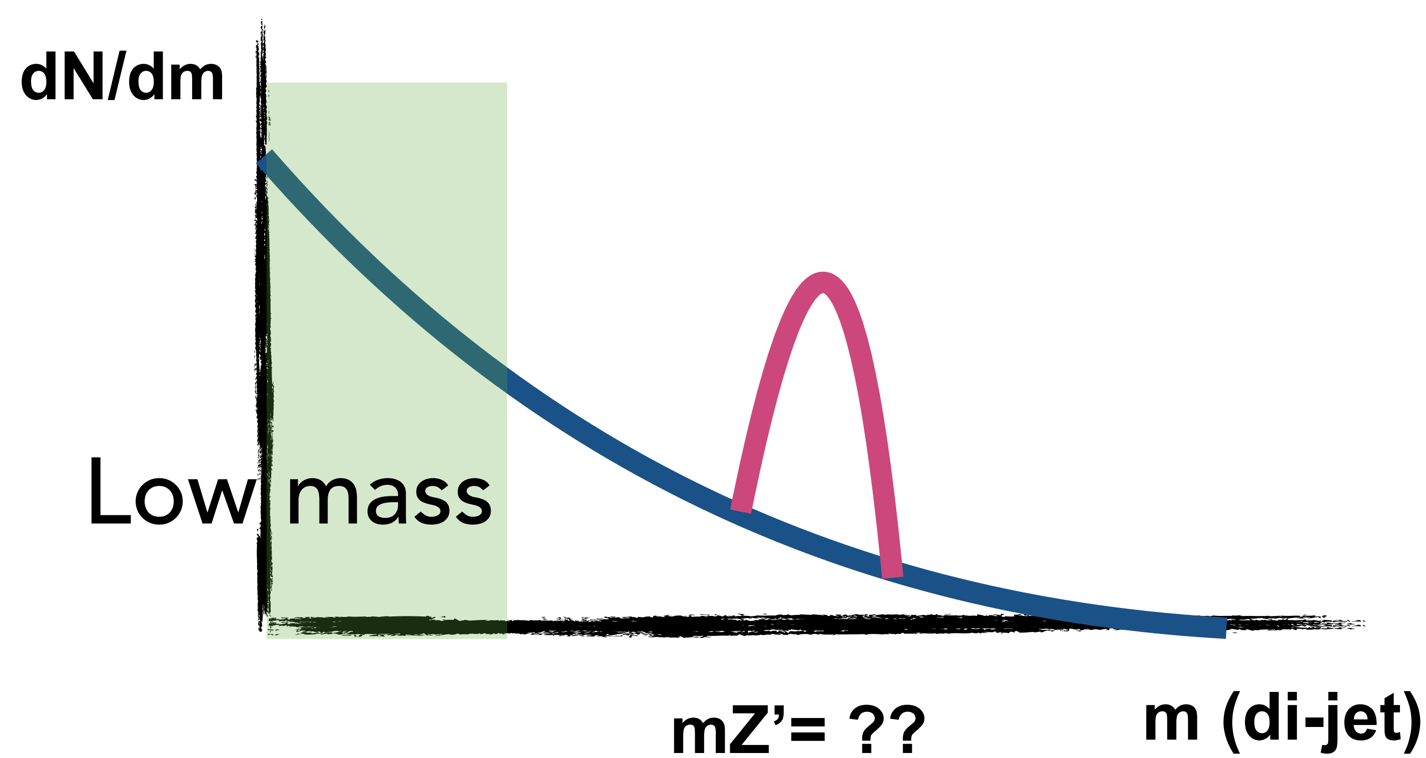


- Collect data with a trigger requiring *high energy in the event*
- Cluster and select *2 jets*
- Main background: *QCD*

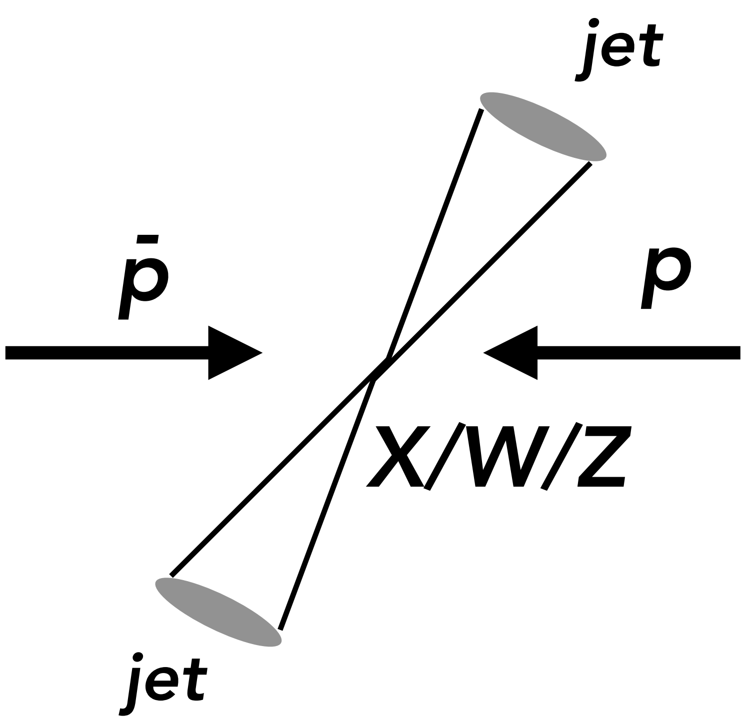


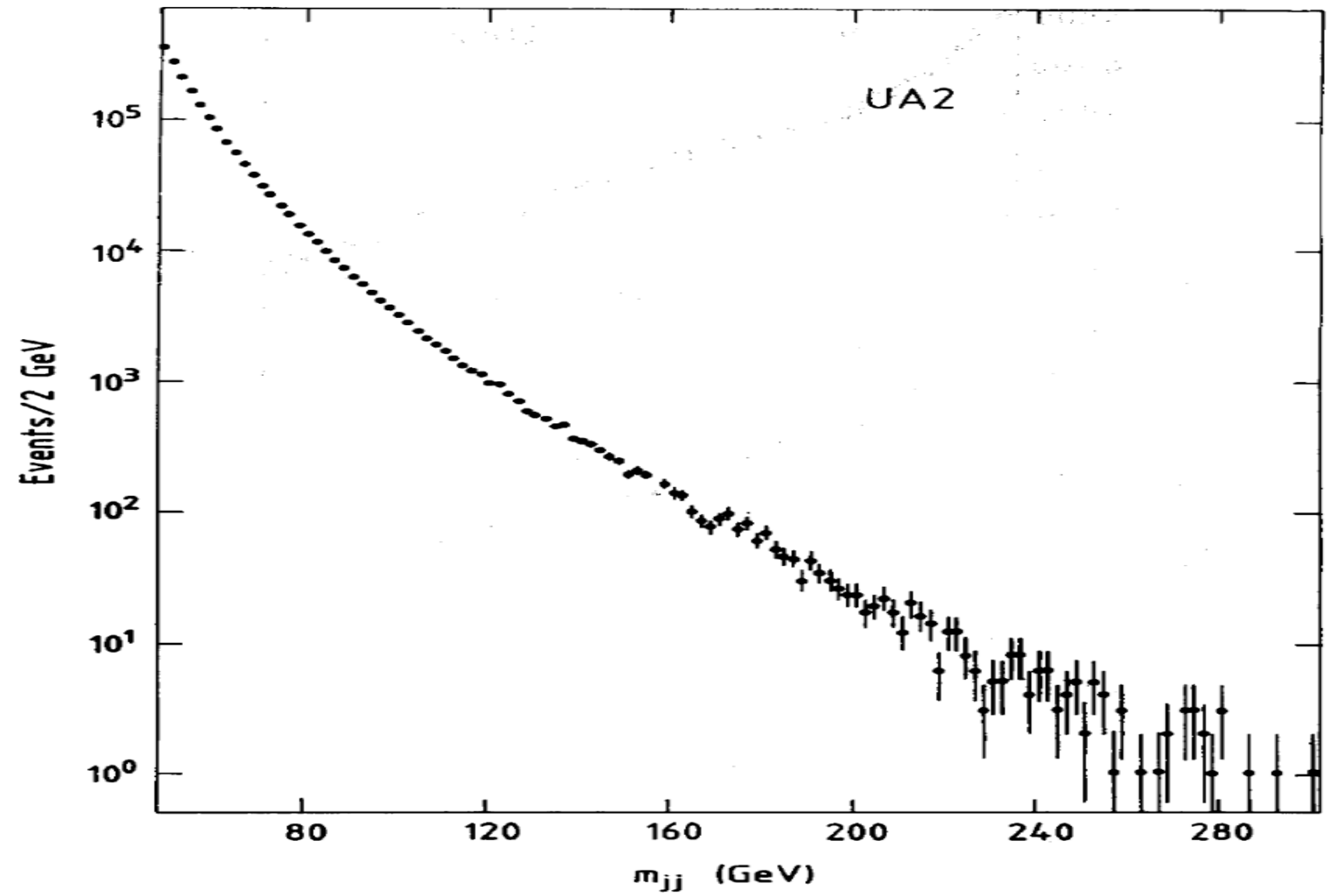
Low mass dijet search

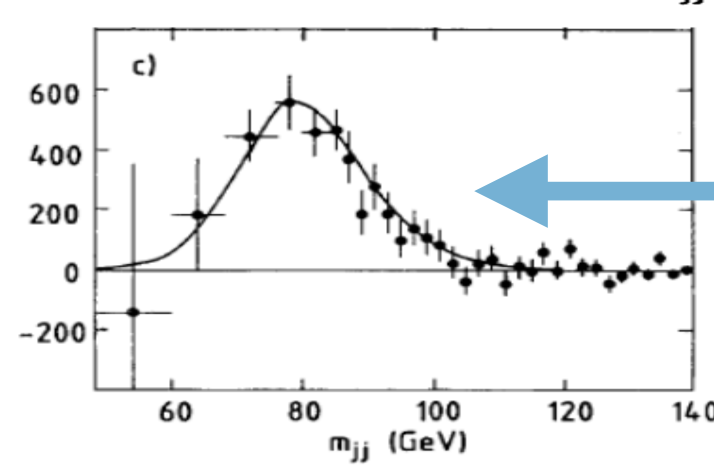
- Reach:
  - @ UA2: low energies -> easier to trigger at low masses
  - @ LHC: potential to access low couplings but QCD background saturates trigger bandwidth



Low mass dijets @ UA2:

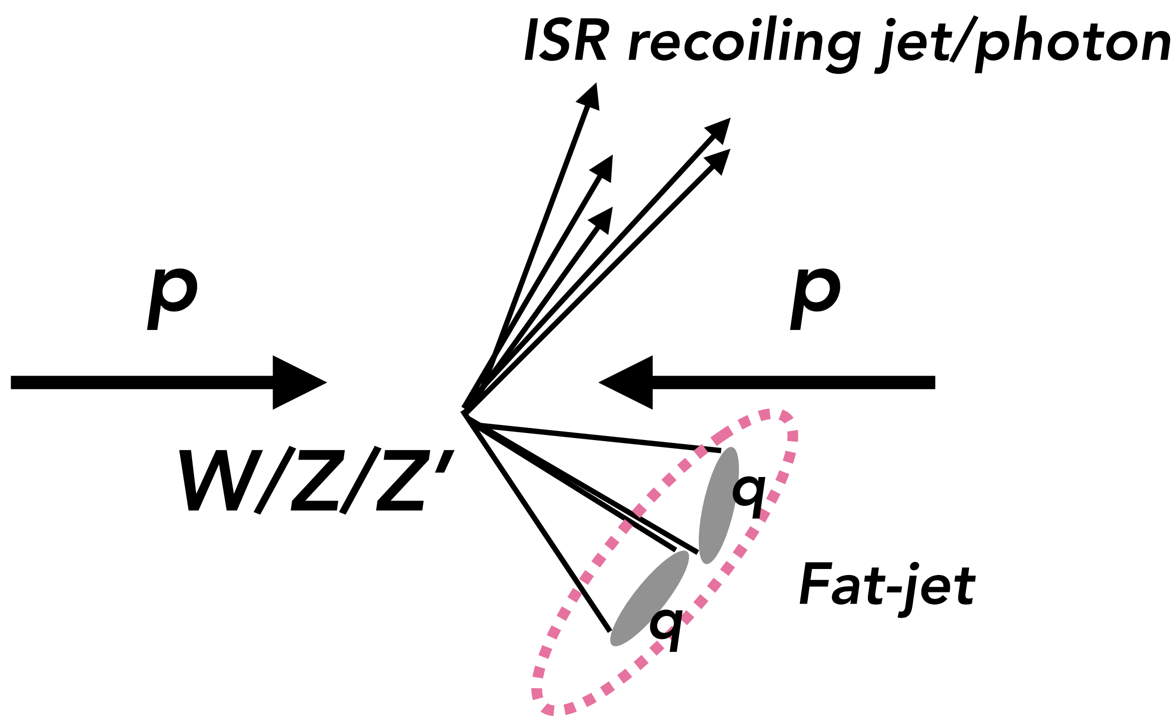


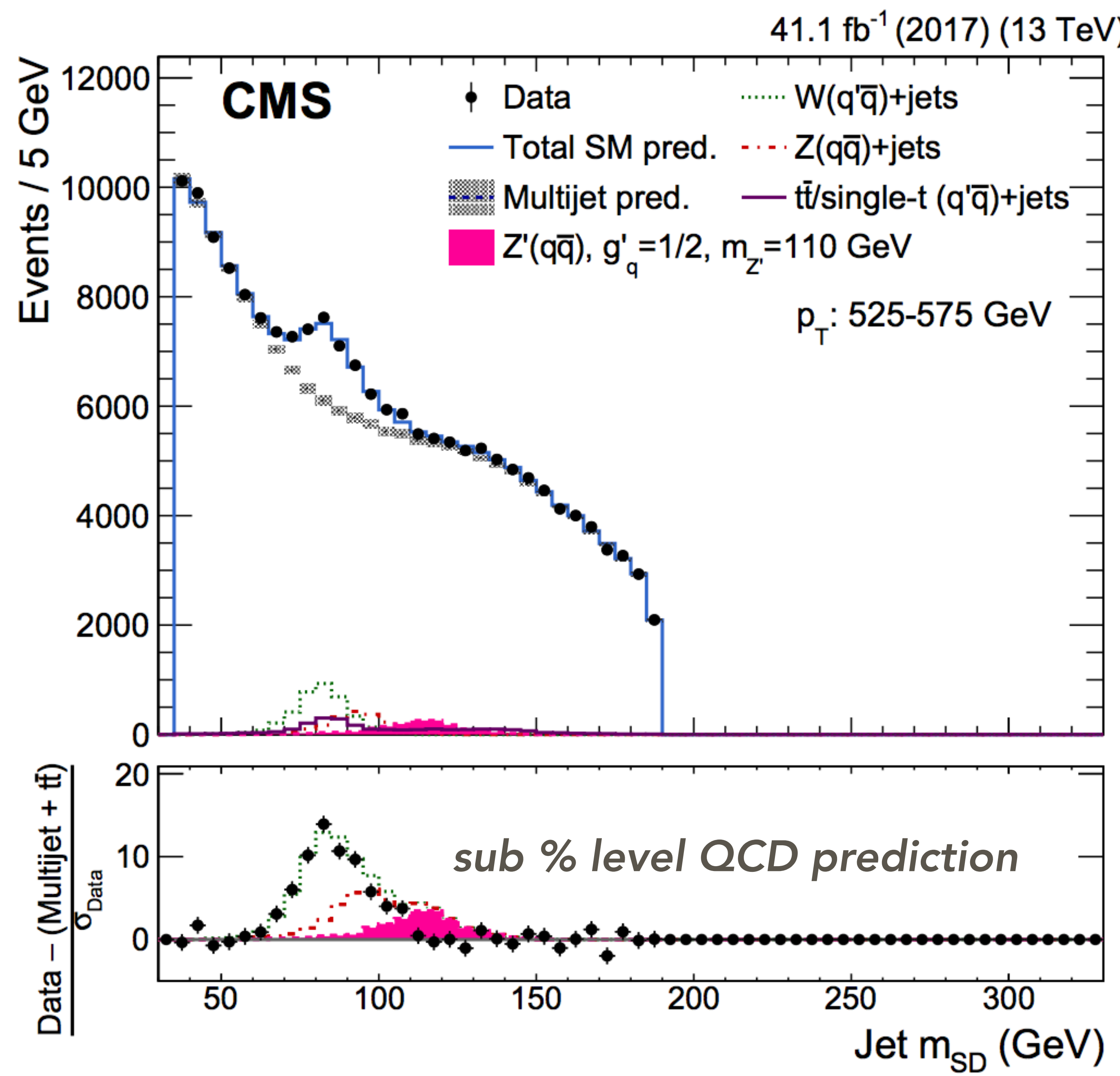




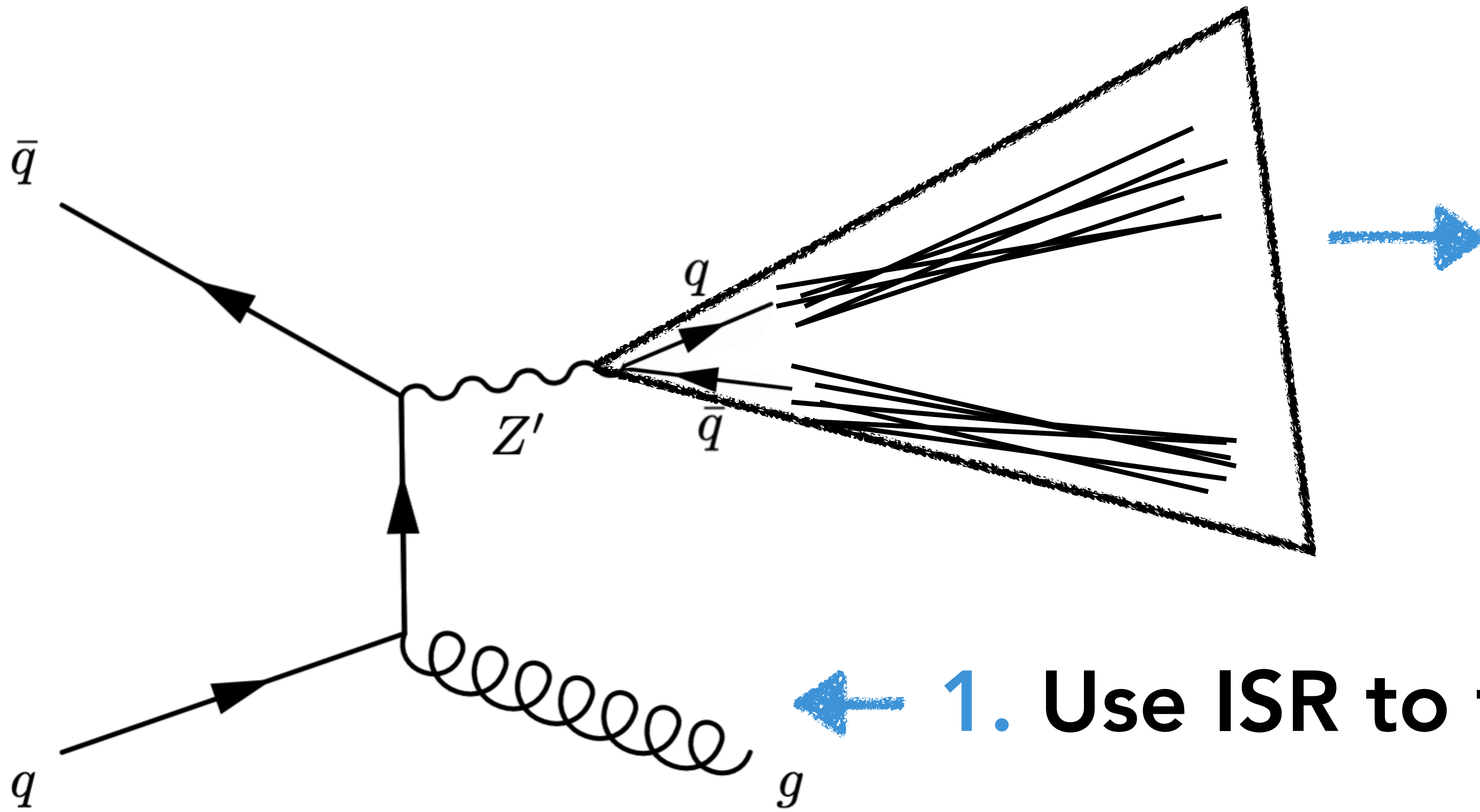
W/Z in data

Low mass dijet search @ 2019





W/Z/Z'+ISR in 4 steps



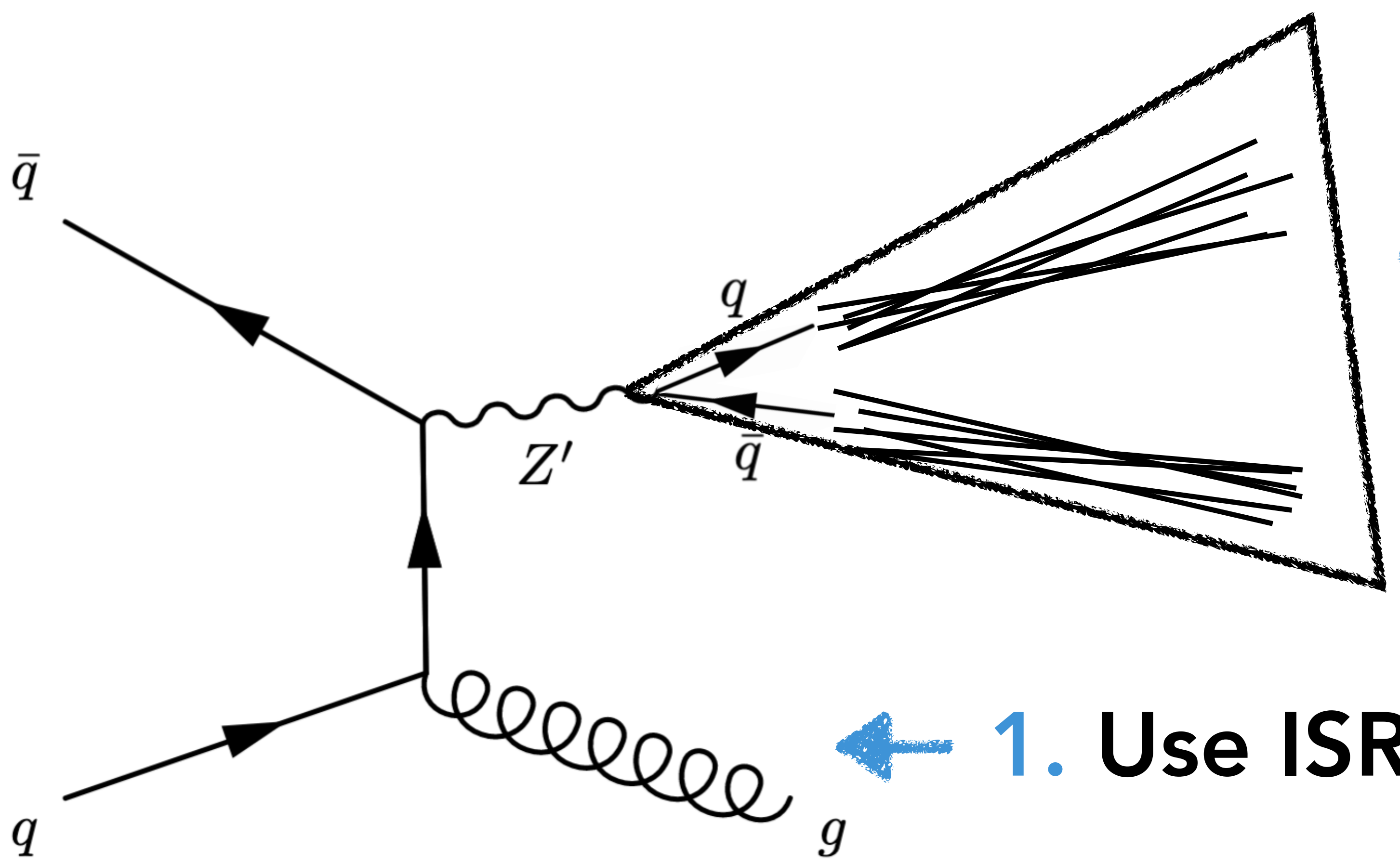
2. Two-prong resonance in single-large jet

1. Use ISR to trigger on events

3. Keep smoothly-falling jet mass spectrum in data

4. Probe spectrum with data-driven QCD estimate

W/Z/Z'+ISR in 4 steps



2. Two-prong resonance in single-large jet

1. **Use ISR to trigger on events**

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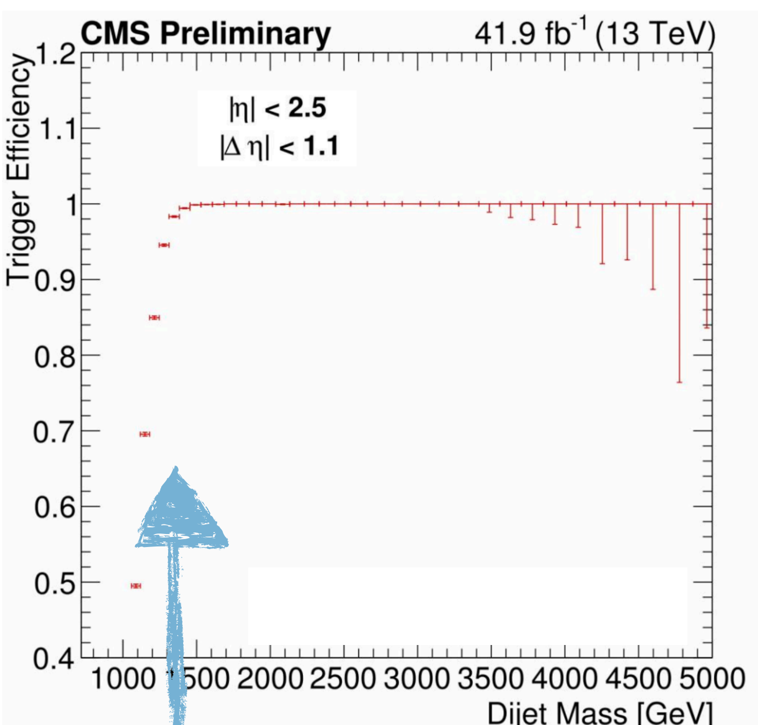
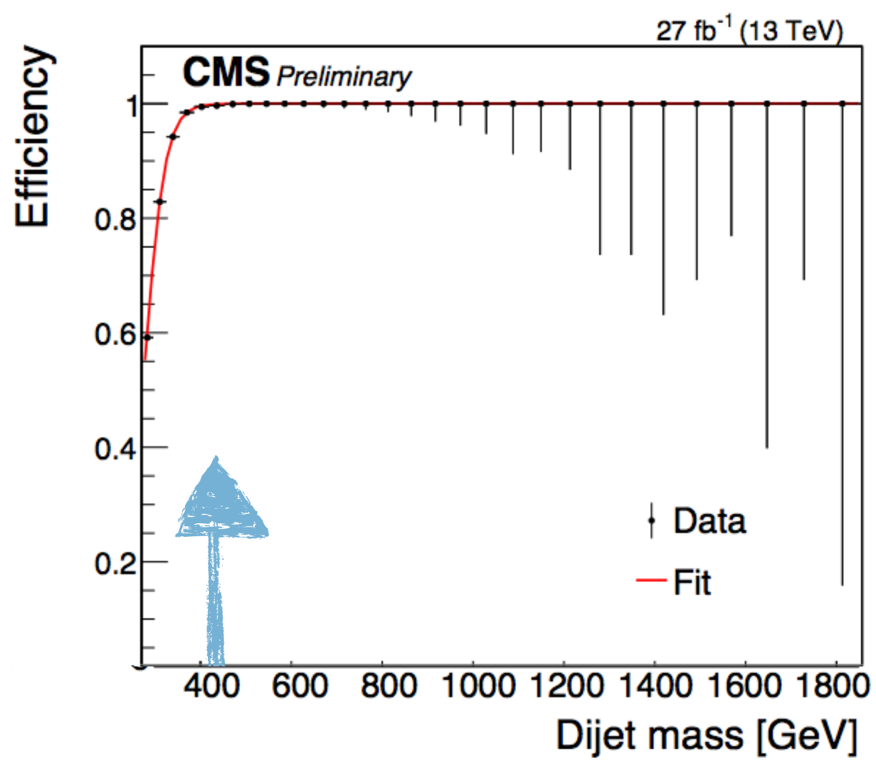
Trigger

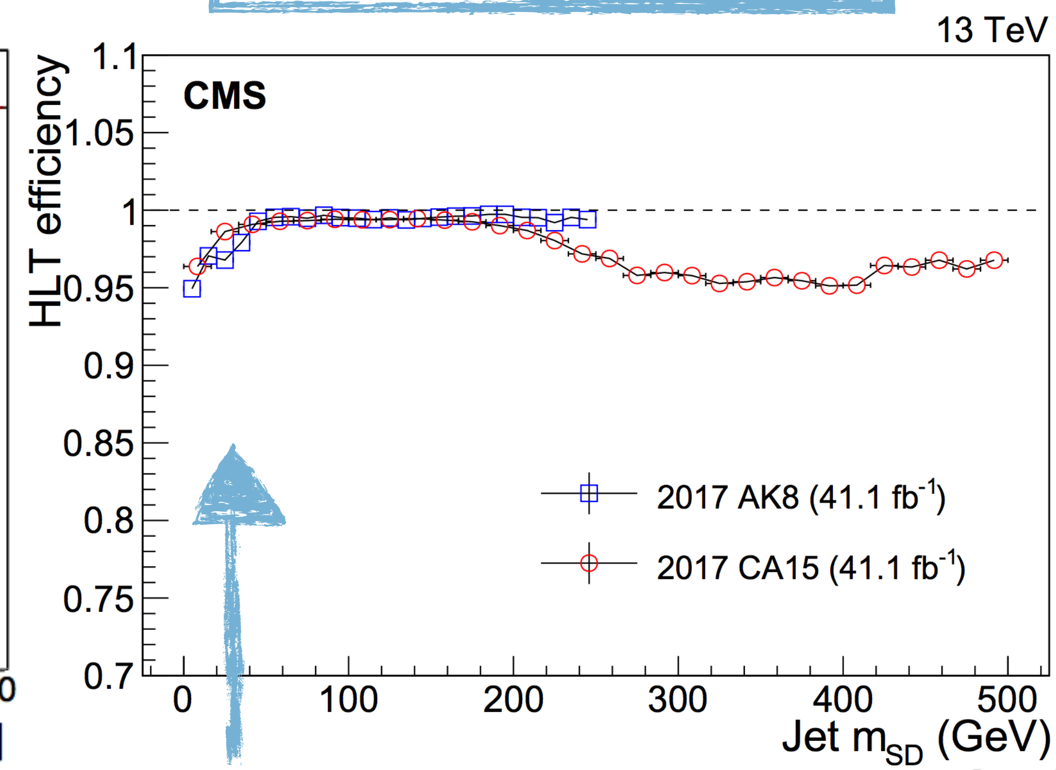
Dijets



Dijets + Scouting



W/Z/Z'+ISR



m_{jj} > 1 TeV

p_T >30 GeV

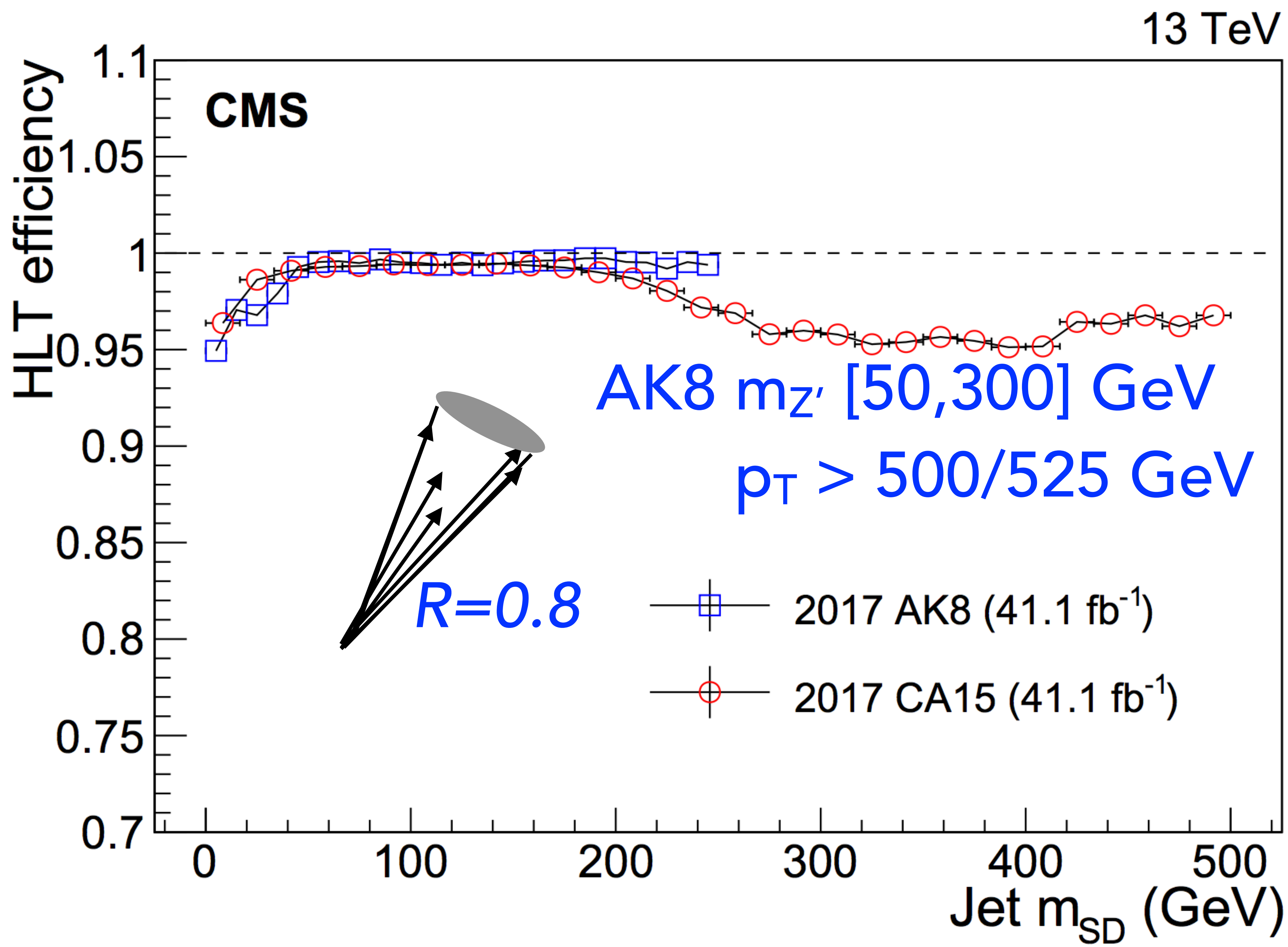
m_{jj} > 500 GeV

p_T >30 GeV

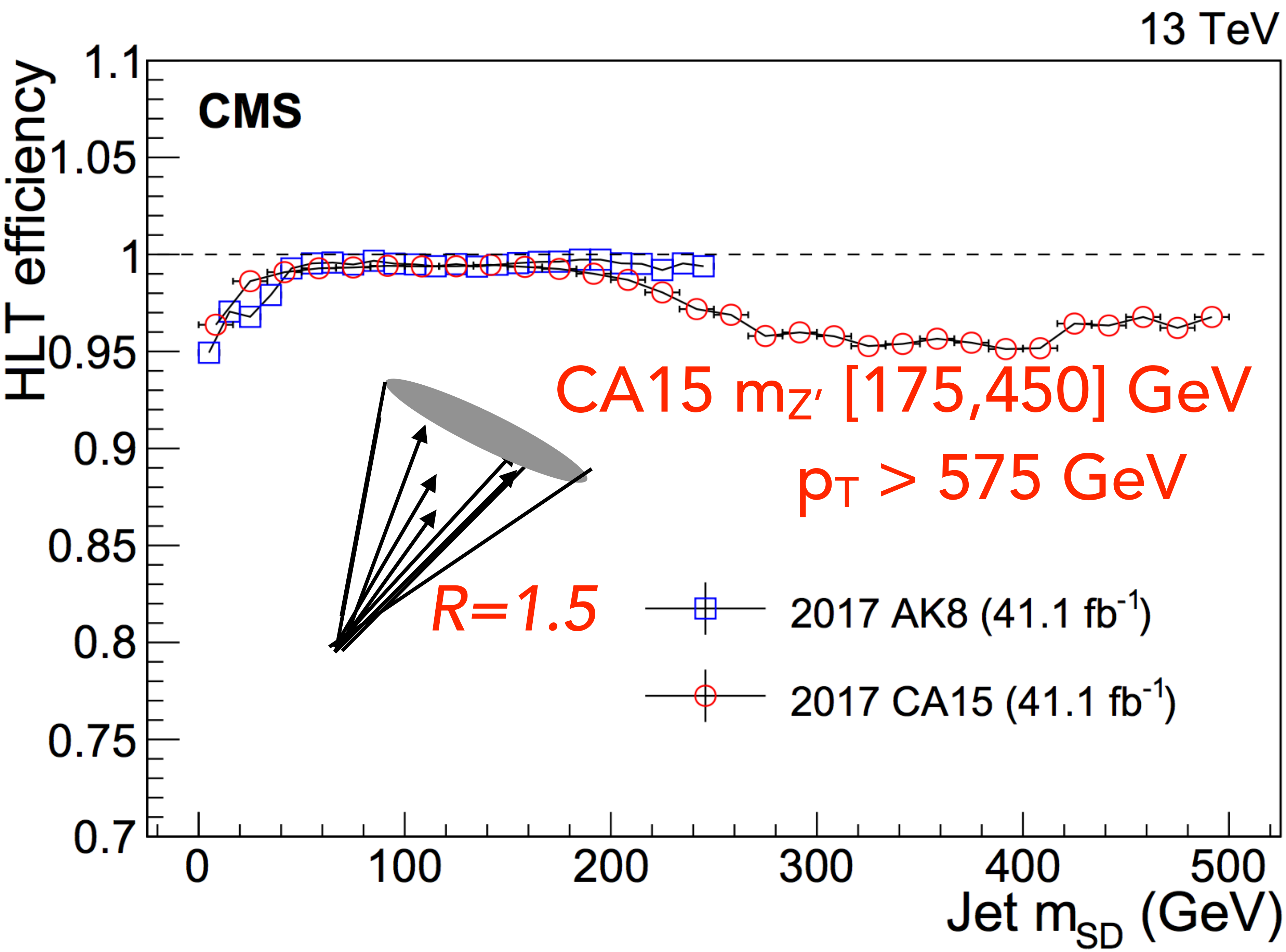
m> 50 GeV

p_T >500 GeV

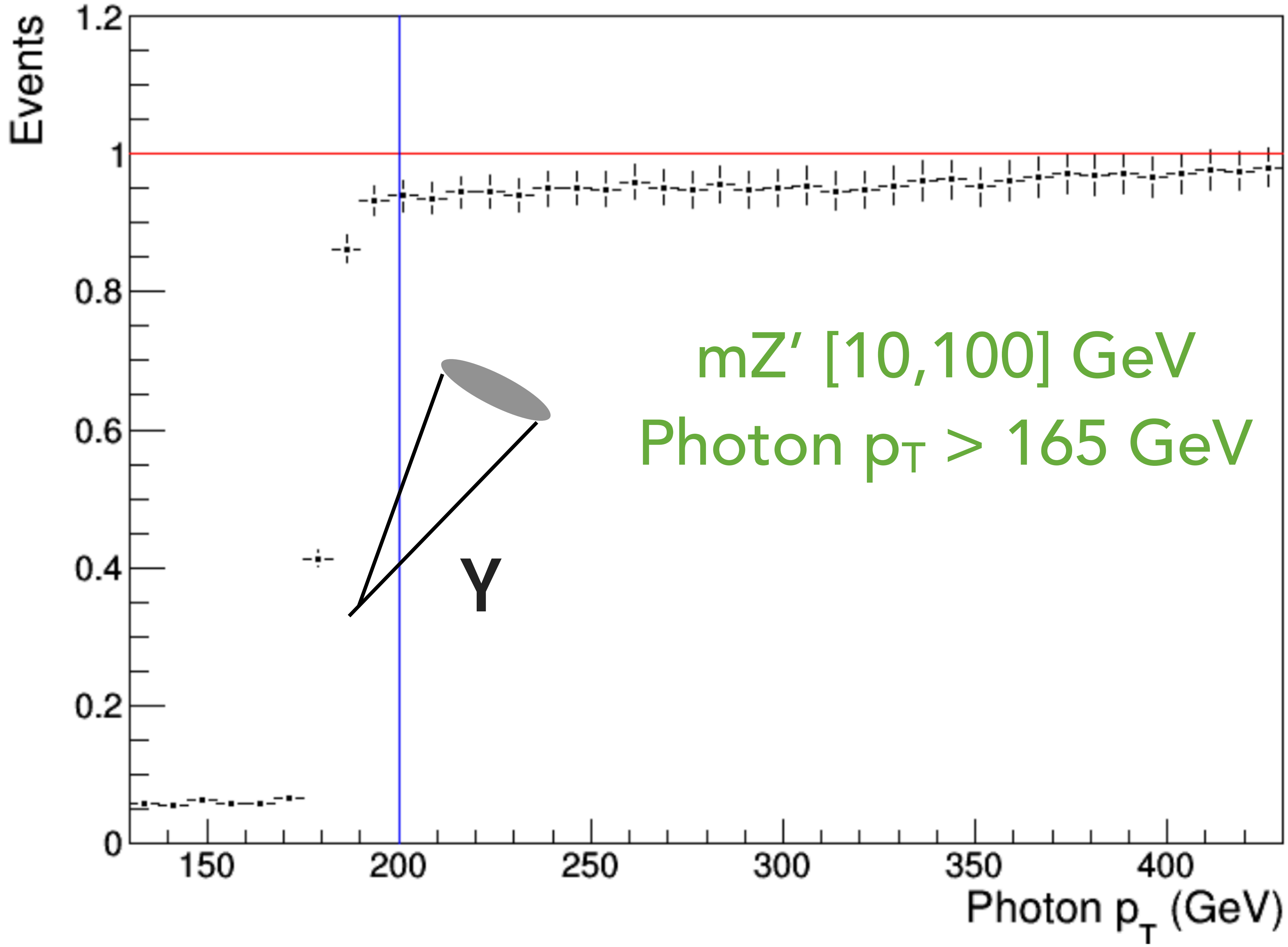
Trigger: ISR jet



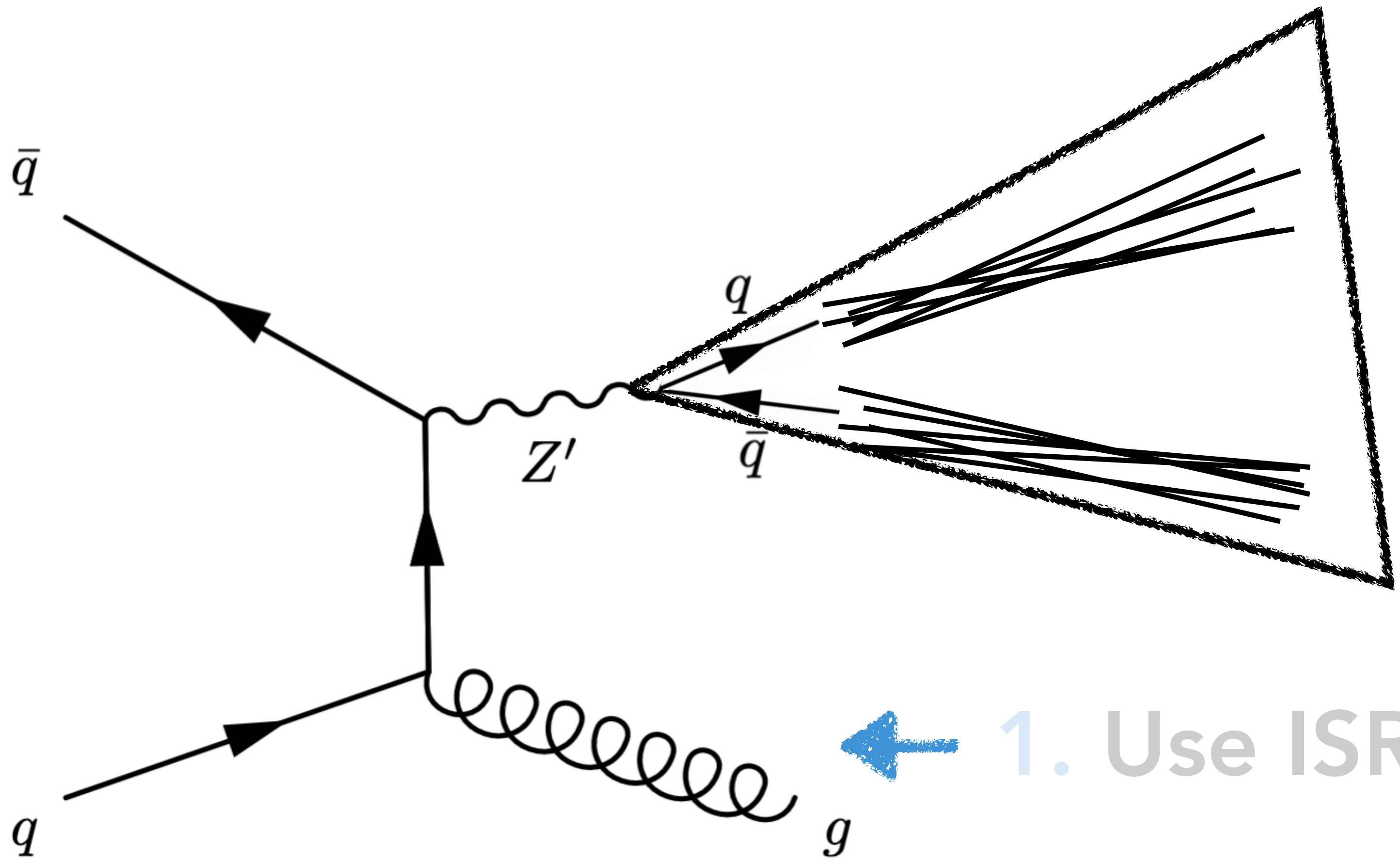
Trigger: ISR jet



Trigger: ISR photon



W/Z/Z'+ISR in 4 steps



2. Two-prong resonance in single-large jet

1. Use ISR to trigger on events

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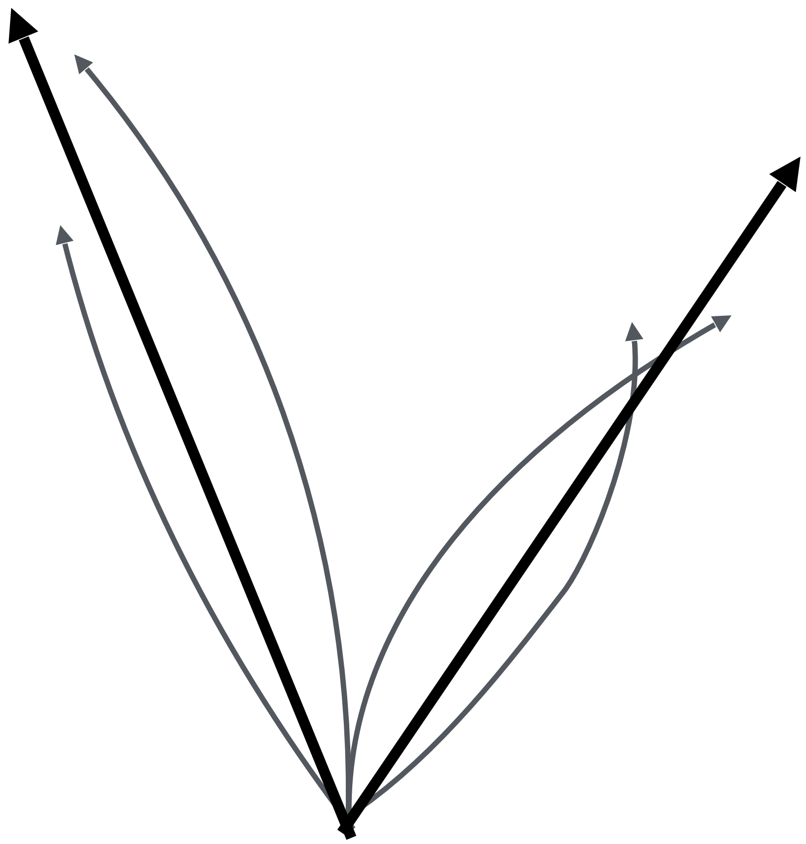
4. Probe spectrum with data-driven QCD estimate

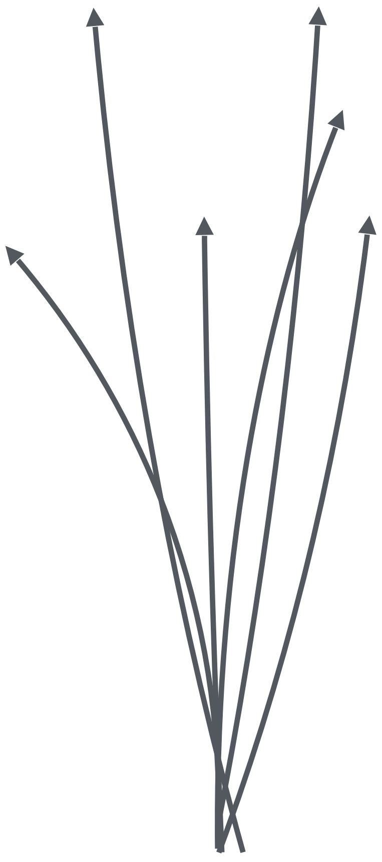
Signal ID

2-prong jet



Signal

QCD jet



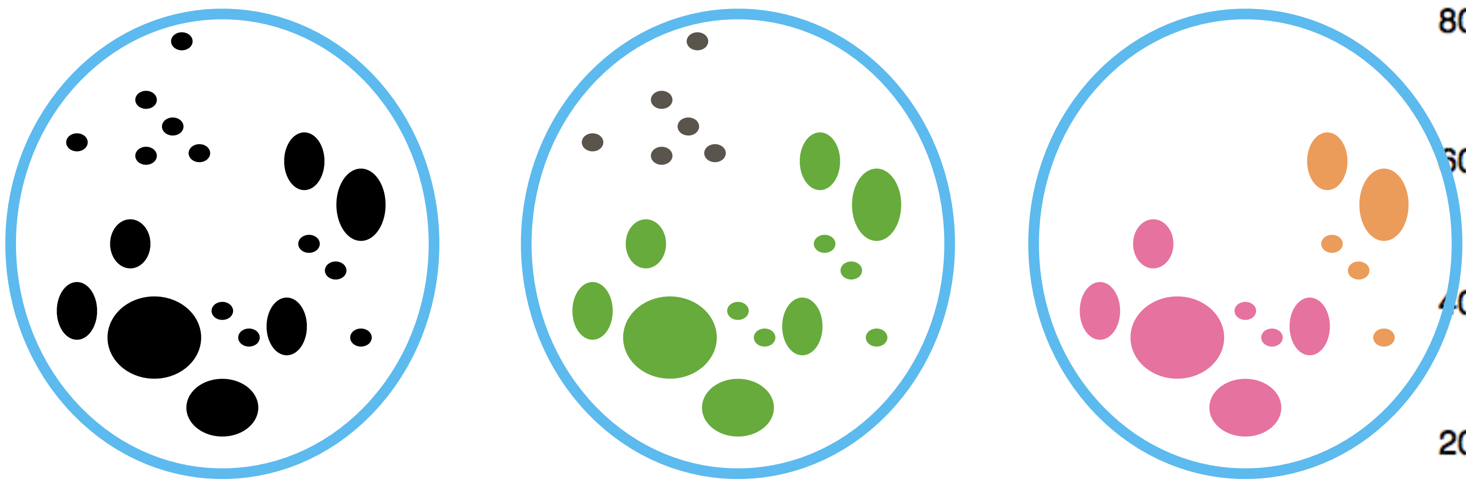
Background

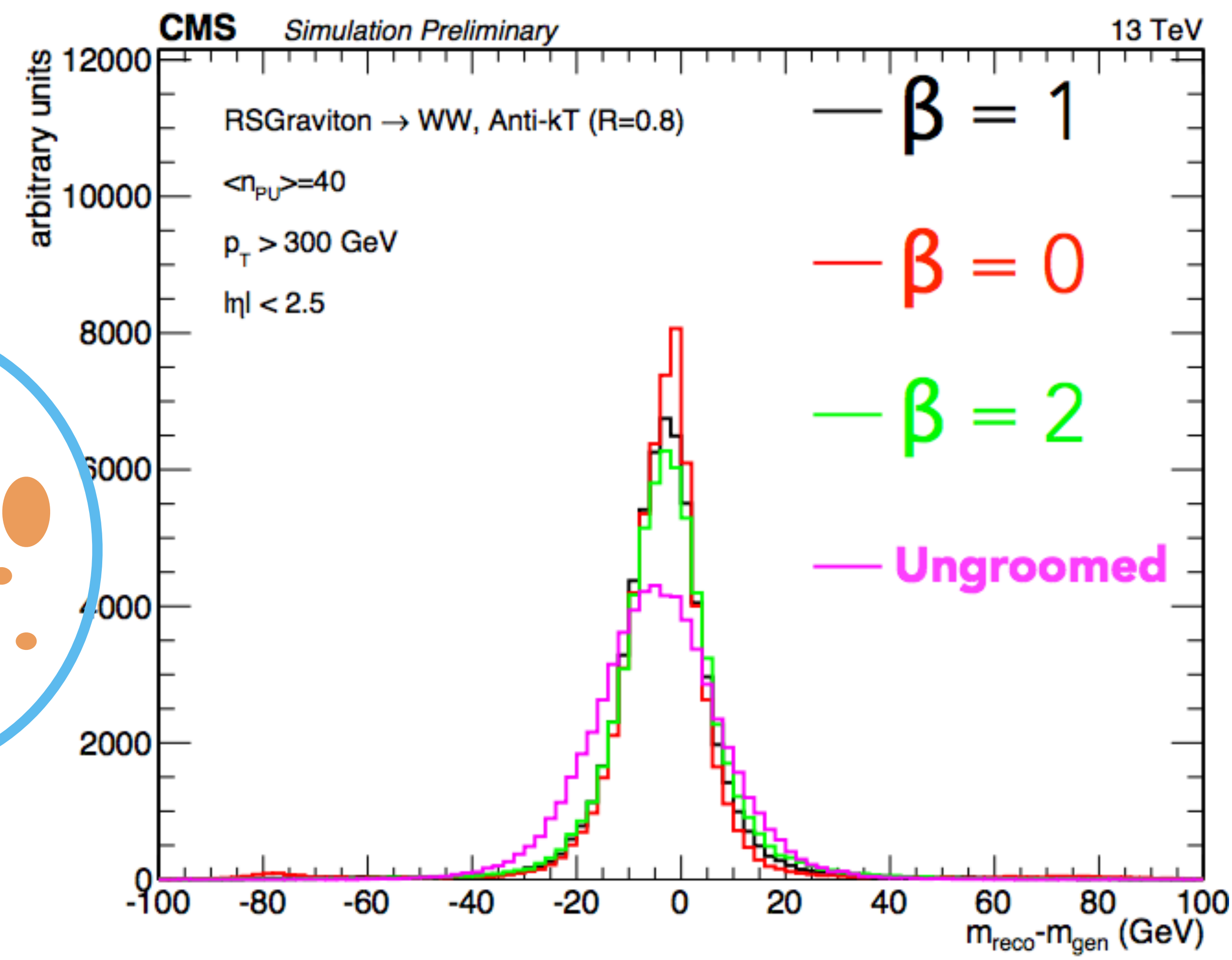
Jet mass

Apply jet **grooming** (soft-drop algorithm):

–cleans excess radiation in a jet

- improves mass resolution





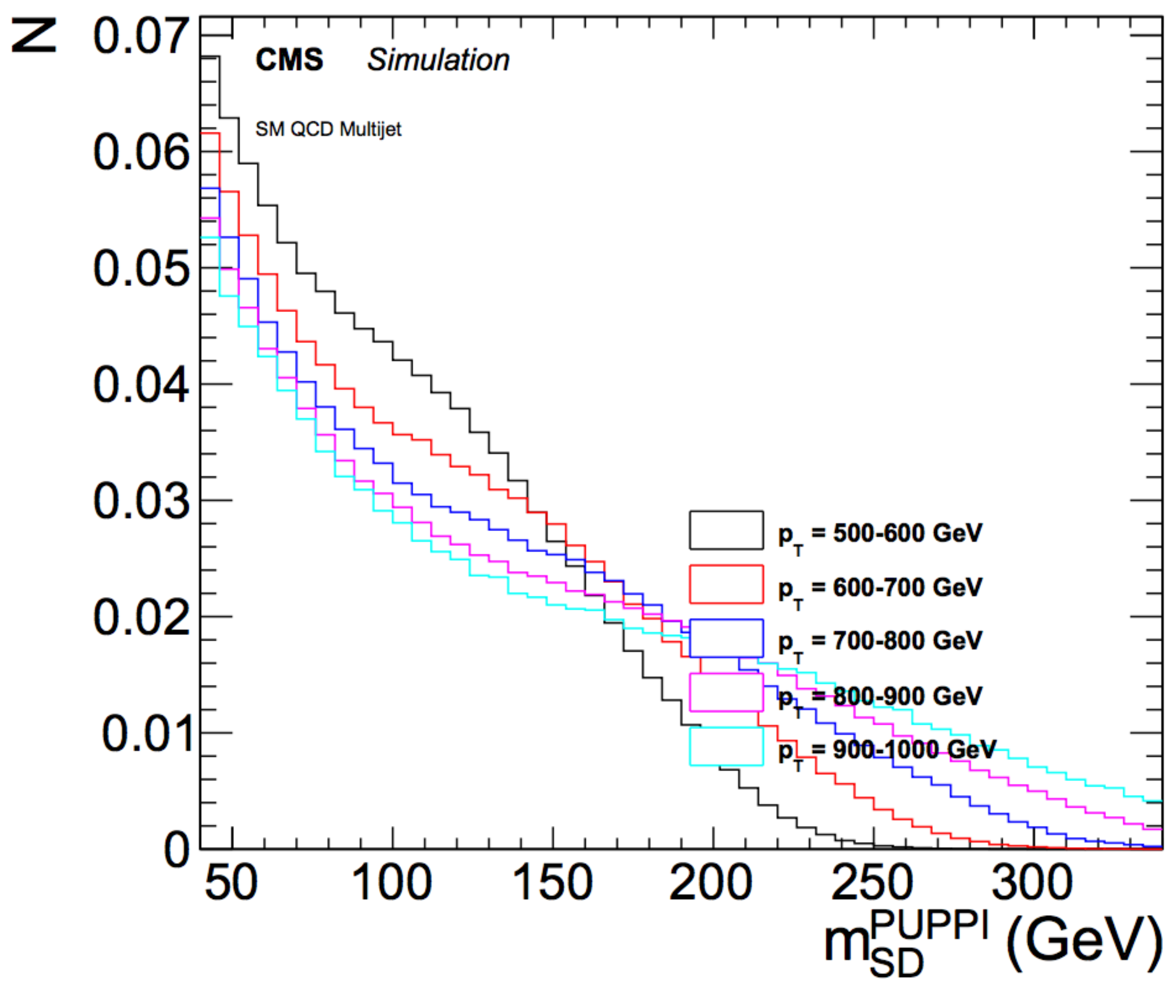
$$\text{Soft Drop Condition:} \quad \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

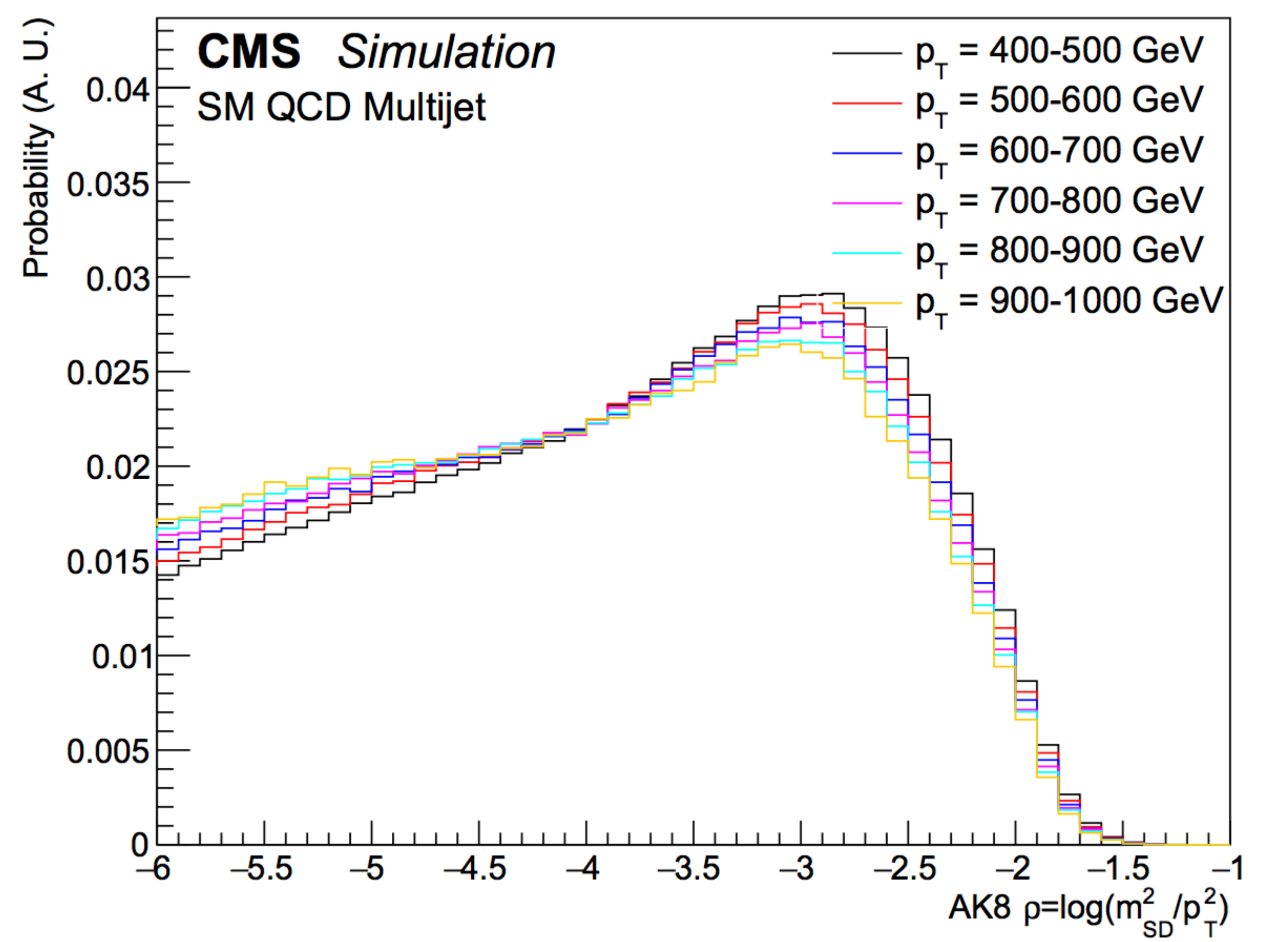
Jet rho

Jet mass scales with p_T:

Use p_T-invariant variable:

$$\rho = 2*\log(m_{SD}/p_T)$$

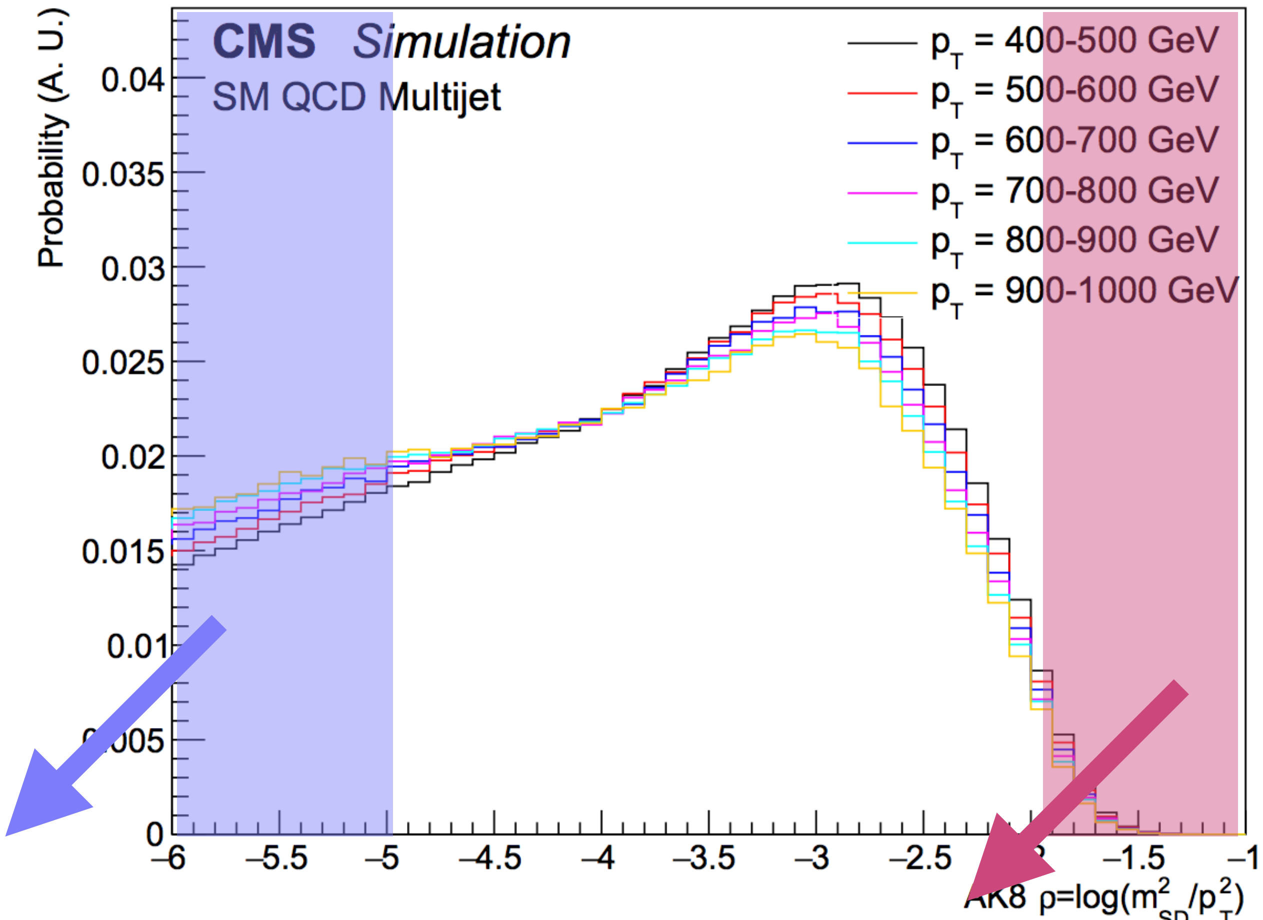




Jet rho

- Values to avoid:
  - **Lower ρ values =** non-perturbative soft-drop mass.
  - **Higher ρ values** = finite cone effects where radiation is not contained in jet

- ρ cuts define m_{SD} range in each p_T category
  - AK8 jets: -5.5 < ρ < -2.1
  - CA15 jets: -4 < ρ < -1



e.g. for jet p_T ~ 600 GeV, m_{SD} ~ 30 GeV
ρ = 2*ln(30/600) = -6

m_{SD} ~ 250 GeV
ρ = 2*ln(250/500) = -1.75

2-prong jet substructure

Construct observable from particles in jet:

1. **Fraction of energy** that each particle carries
2. **Angular separation**

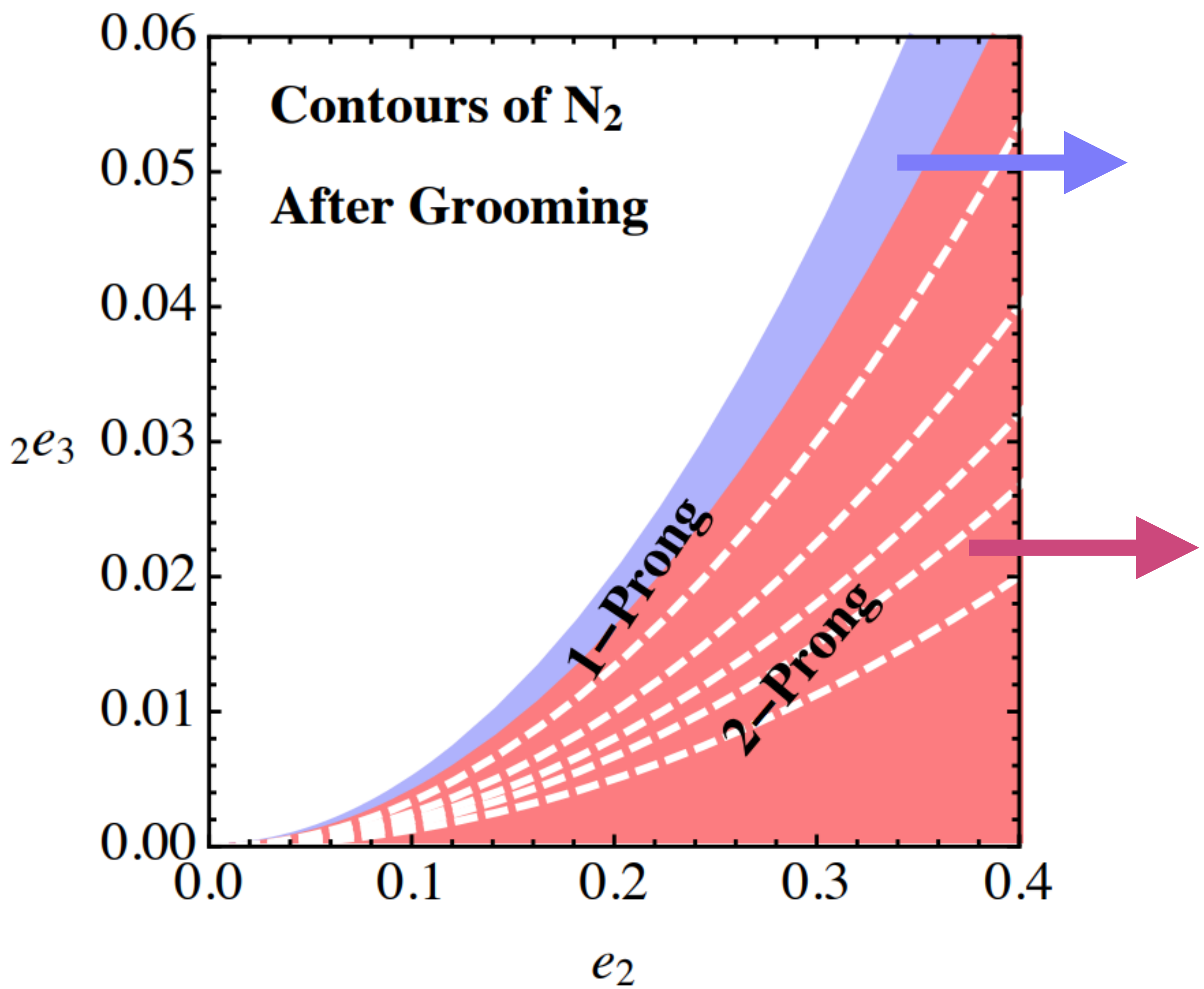
e.g

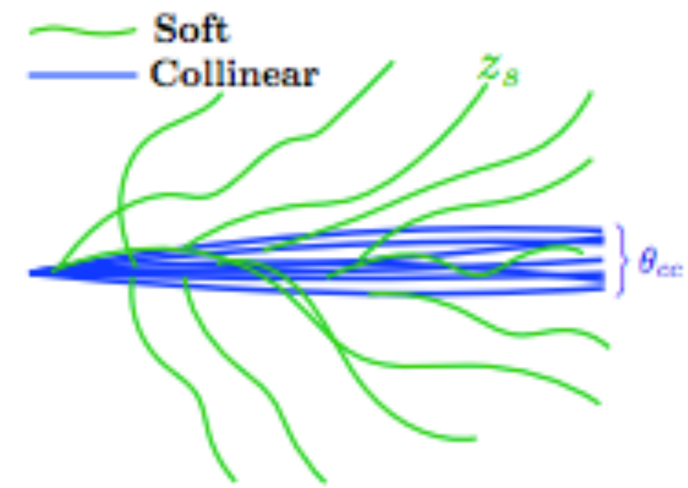
$$ {}_1e_2^{\beta} = \frac{1}{p_{\mathrm{T}J}^2} \sum_{1 \le i < j \le n_J} p_{\mathrm{T}i} p_{\mathrm{T}j} \Delta R_{ij}^{\beta} $$

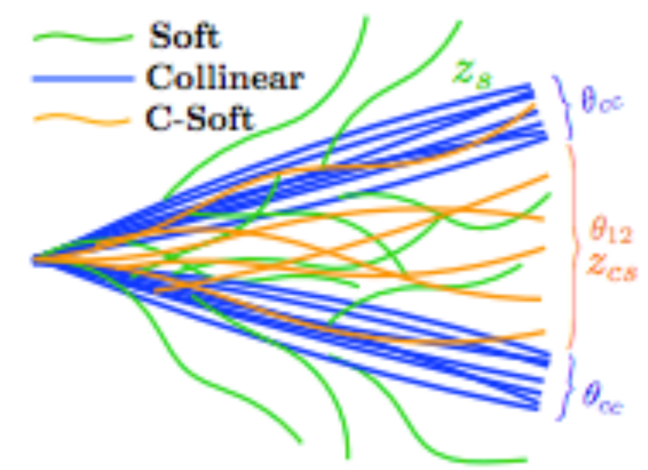
$$ {}_2e_3^{\beta} = \frac{1}{p_{\mathrm{T}J}^3} \sum_{1 \le i < j < k \le n_J} p_{\mathrm{T}i} p_{\mathrm{T}j} p_{\mathrm{T}k} \min\{\Delta R_{ij}^{\beta} \Delta R_{ik}^{\beta}, \Delta R_{ij}^{\beta} \Delta R_{jk}^{\beta}, \Delta R_{ik}^{\beta} \Delta R_{jk}^{\beta}\} $$

2-prong jet substructure

2-prong jets have $\mathbf{e_3 << (e_2)^2}$

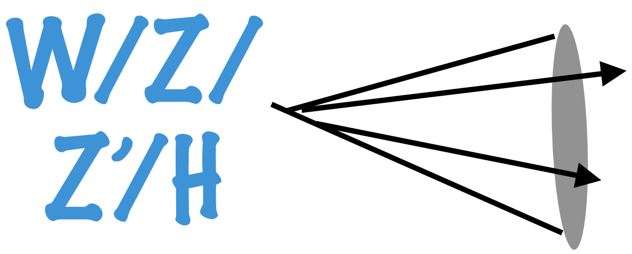


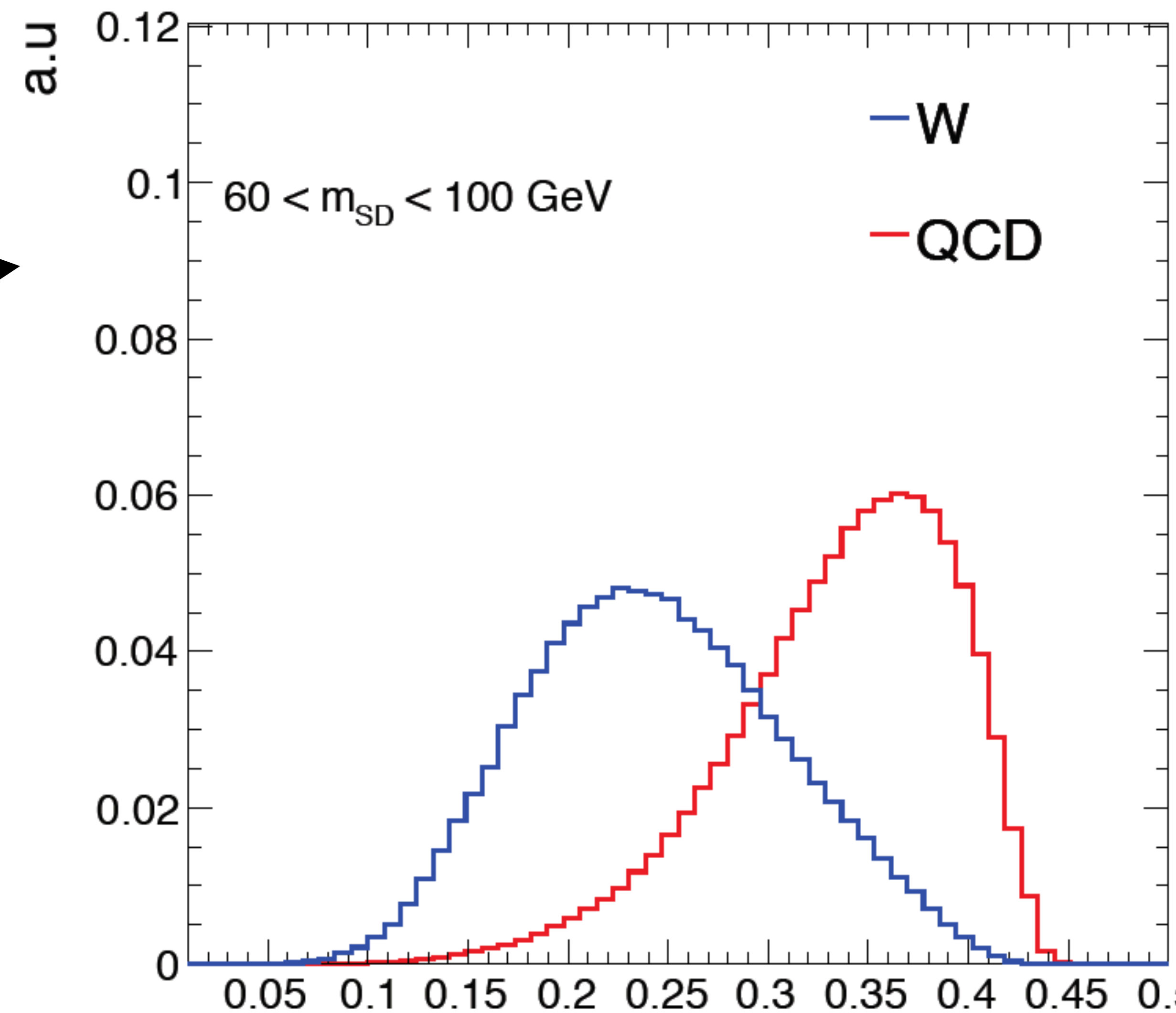


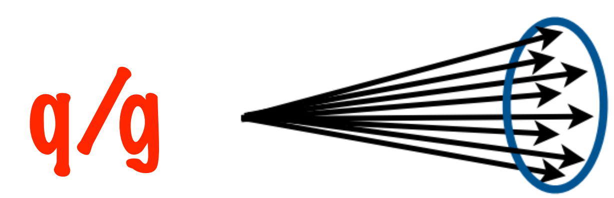


2-prong jet substructure

more two pronged



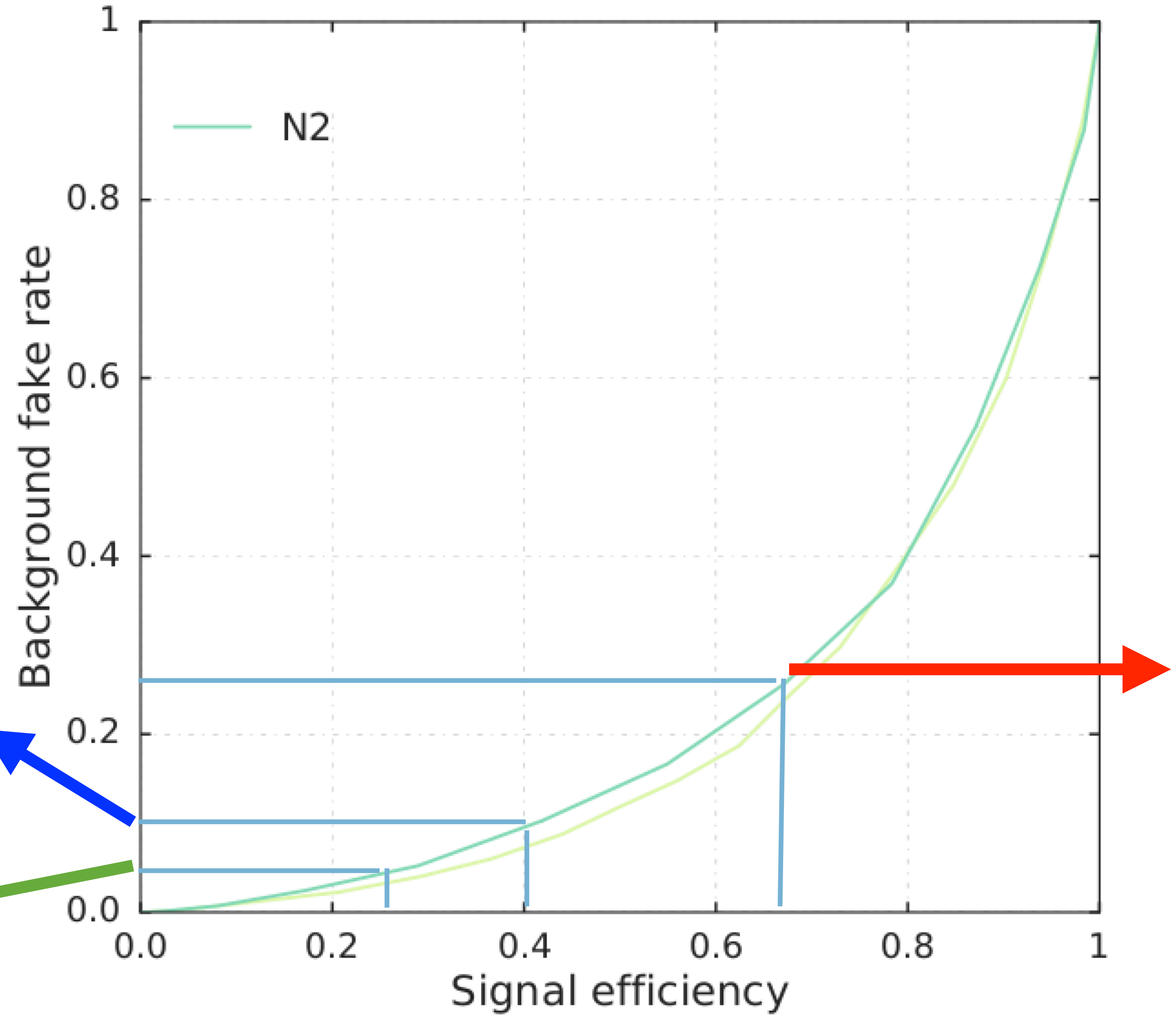




$$N_2^{\beta} = \frac{{}_2e_3^{\beta}}{({}_1e_2^{\beta})^2}$$

2-prong jet substructure

Choose working point based on fixed background efficiency

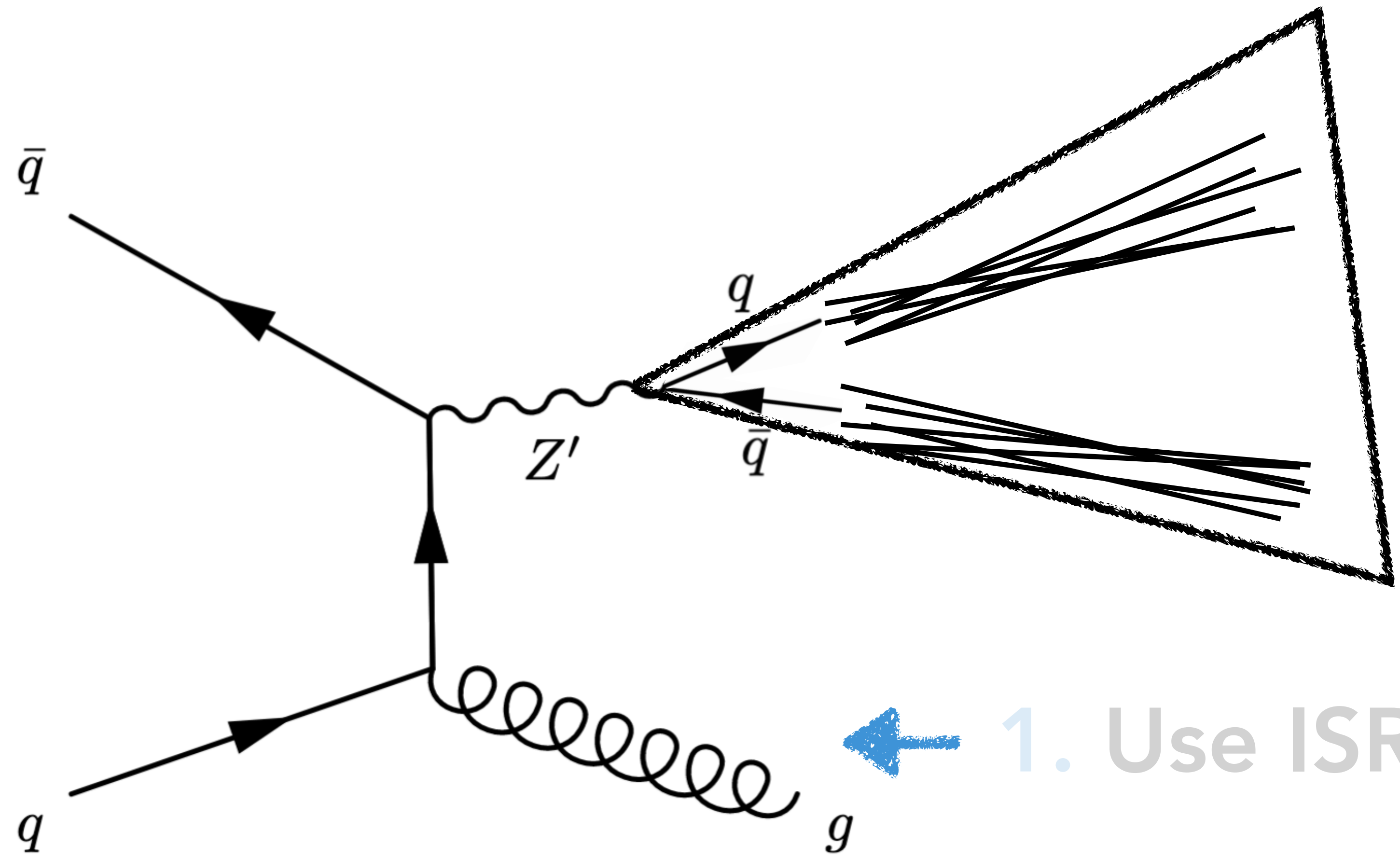


$N_2(10\%)$
Z'+photon

$N_2(5\%)$
Z'+jet

$N_2(26\%)$
Boosted Higgs

W/Z/Z'+ISR in 4 steps



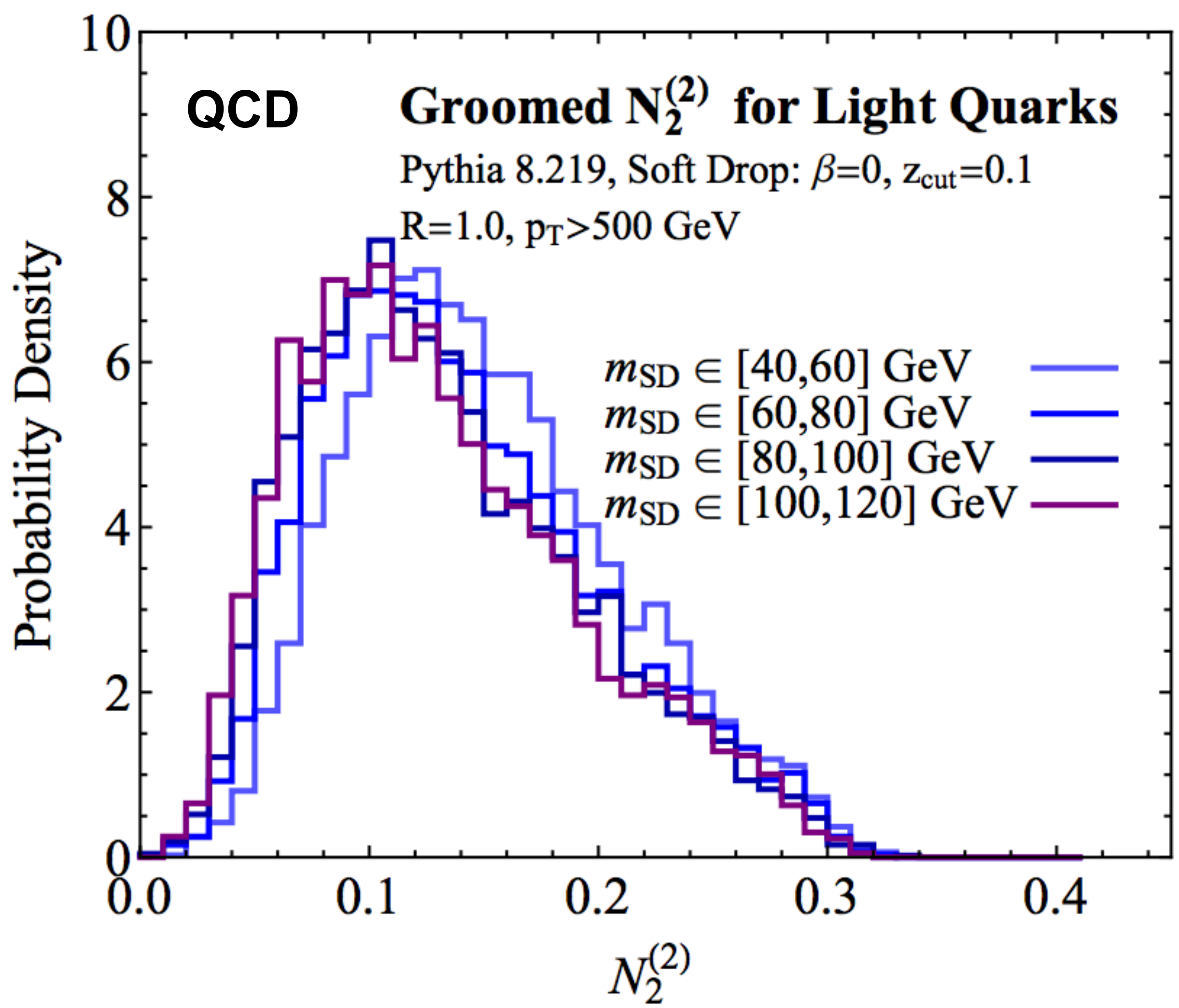
2. Two-prong resonance in single-large jet

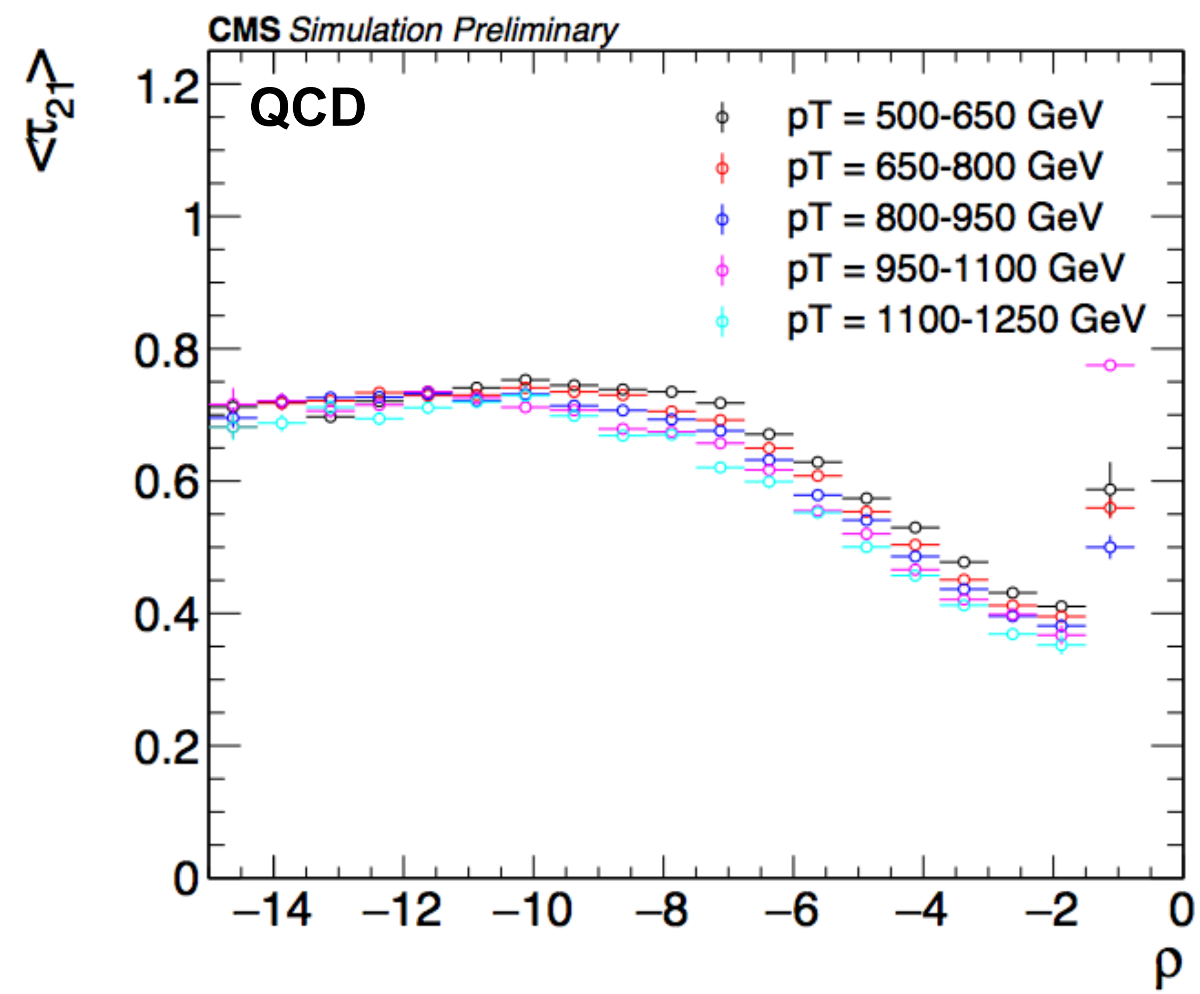
1. Use ISR to trigger on events

3. **Keep smoothly-falling jet mass spectrum in data**

4. Probe spectrum with data-driven QCD estimate

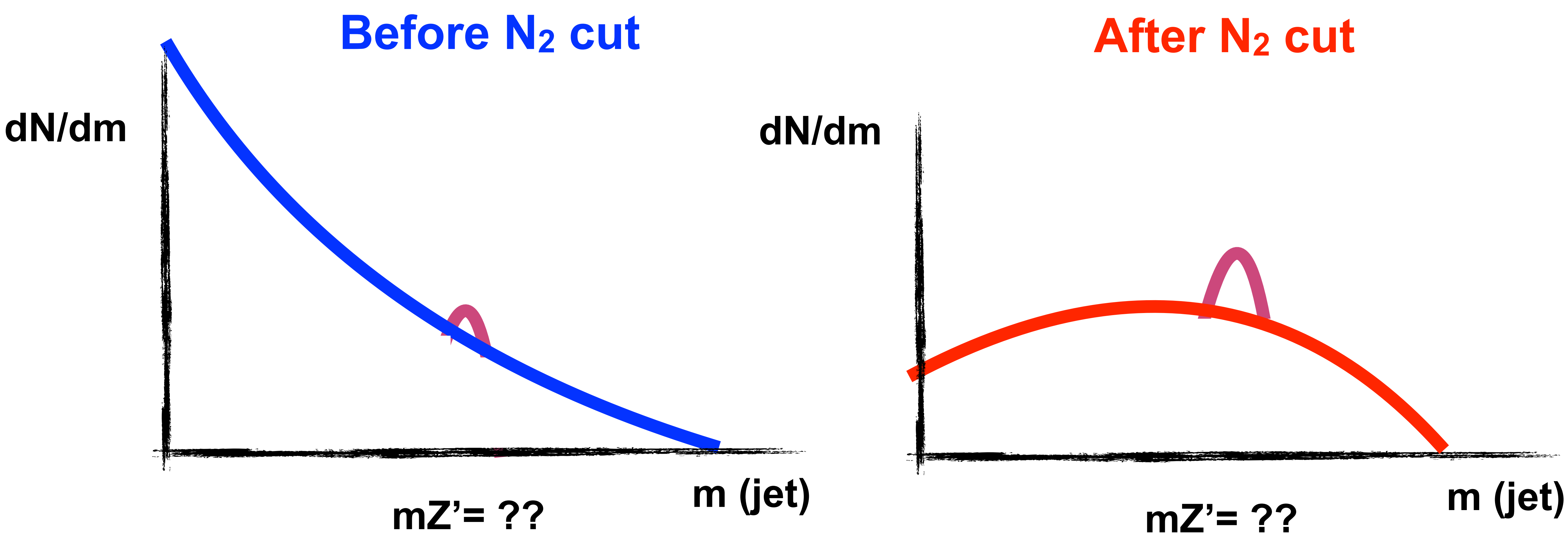
Mass correlation





Jet substructure variables depend on the jet mass

Mass correlation

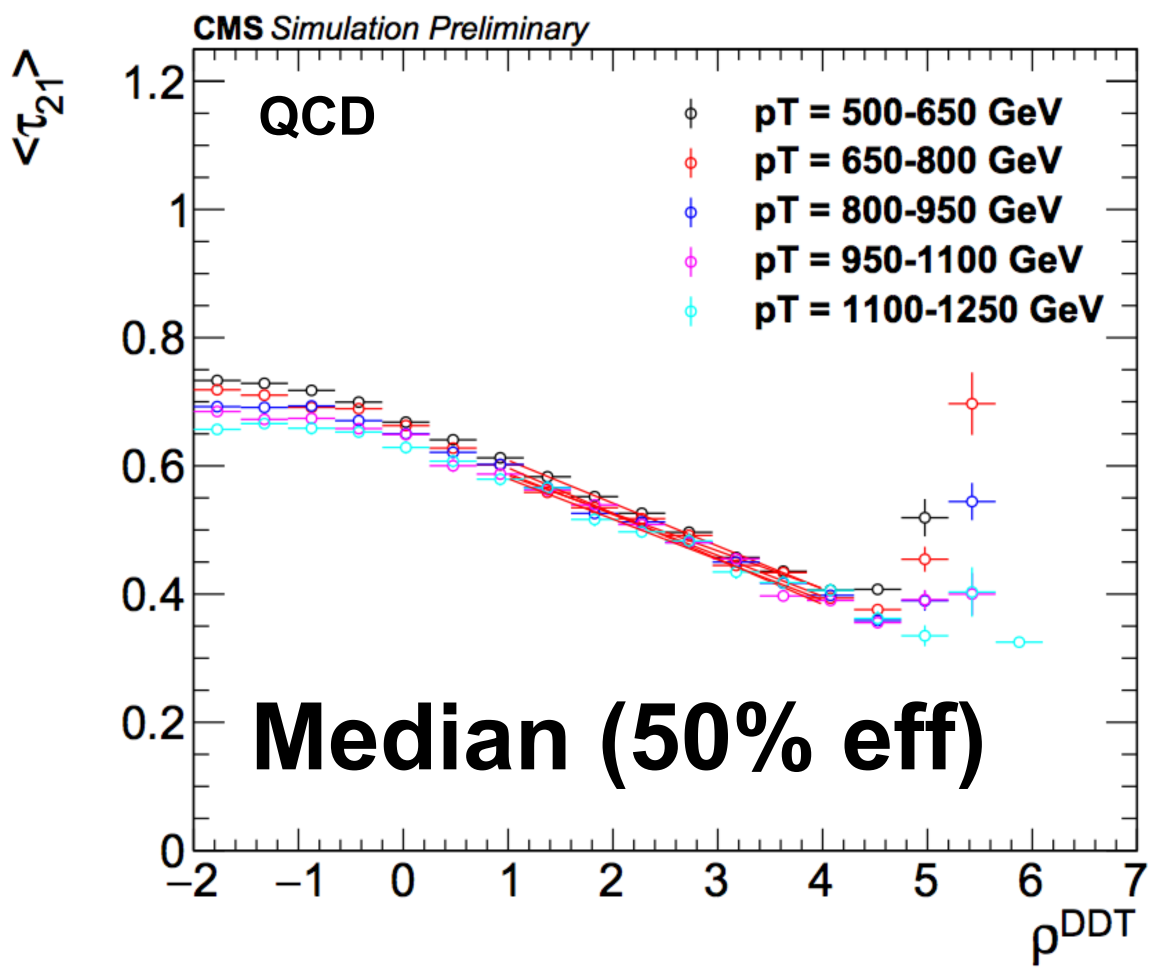


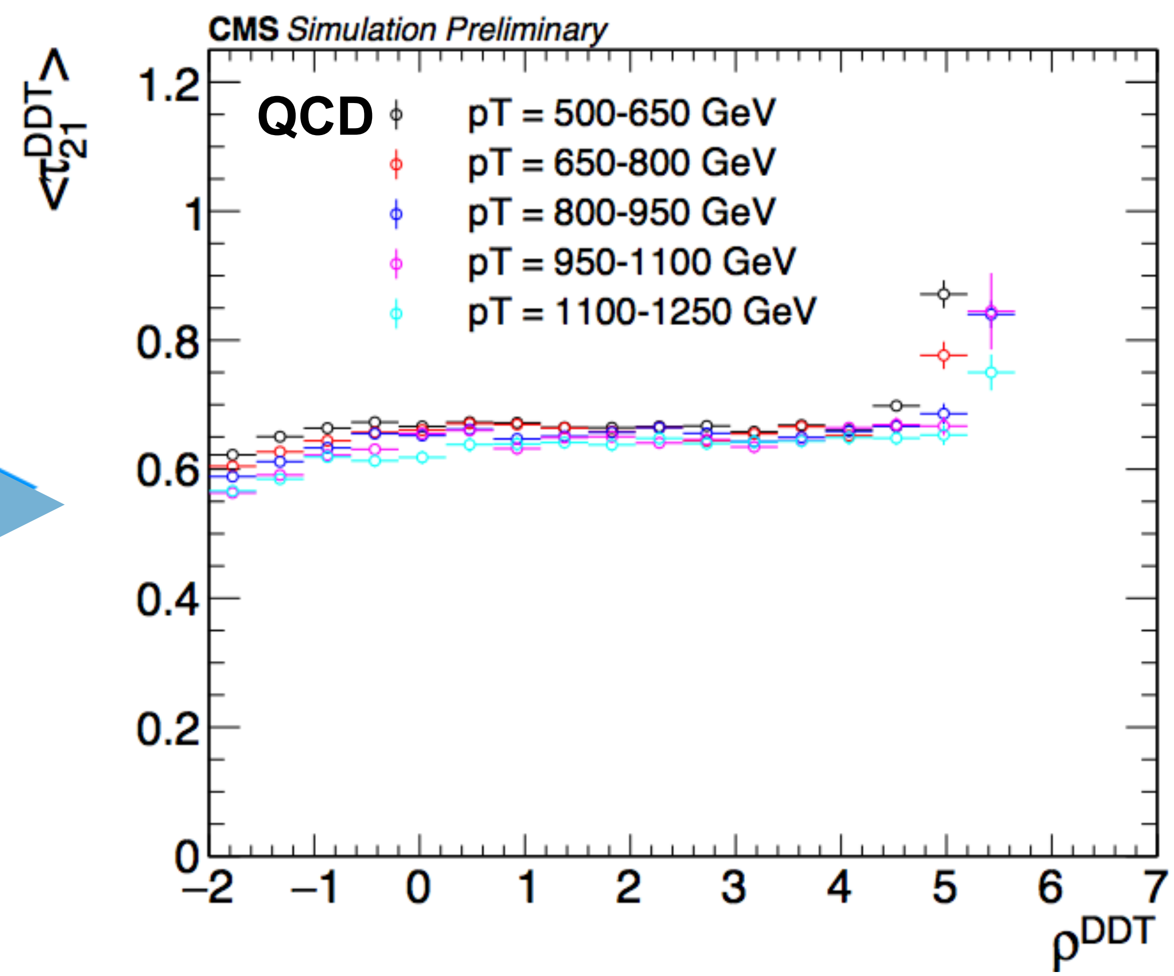
And distort the jet mass distribution

Mass de-correlation (1)

3 years ago: τ_{21}^{DDT}

Look at correlation and subtract it:





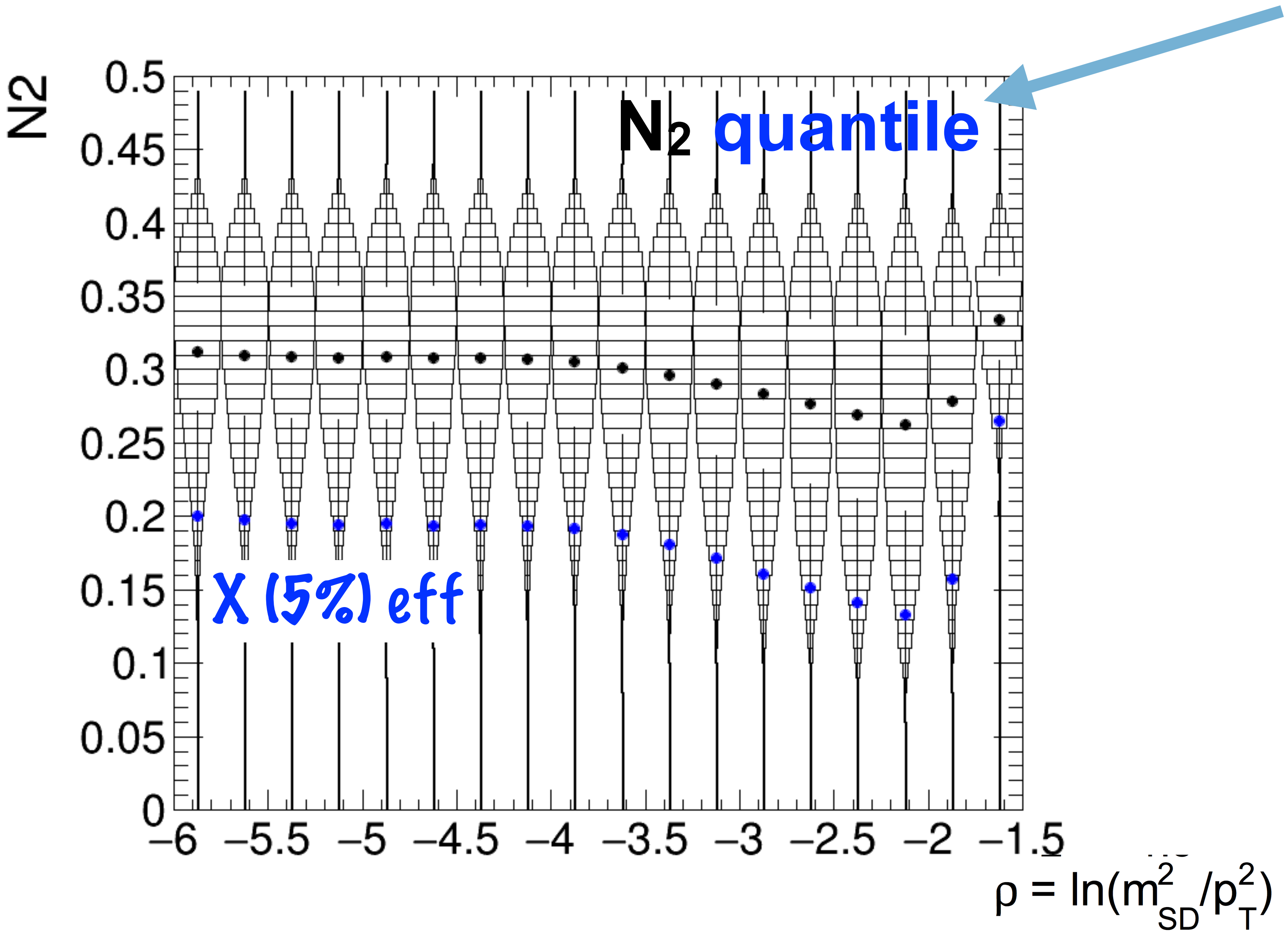
$\rho = \log(m_{SD}^2/p_T^2)$ → $\rho DDT = \log(m_{SD}^2/p_T/(1\ \text{GeV}))$

τ_{21} → $\tau_{21}DDT = \tau_{21} + 0.063 \times \rho DDT$

Mass de-correlation (2)

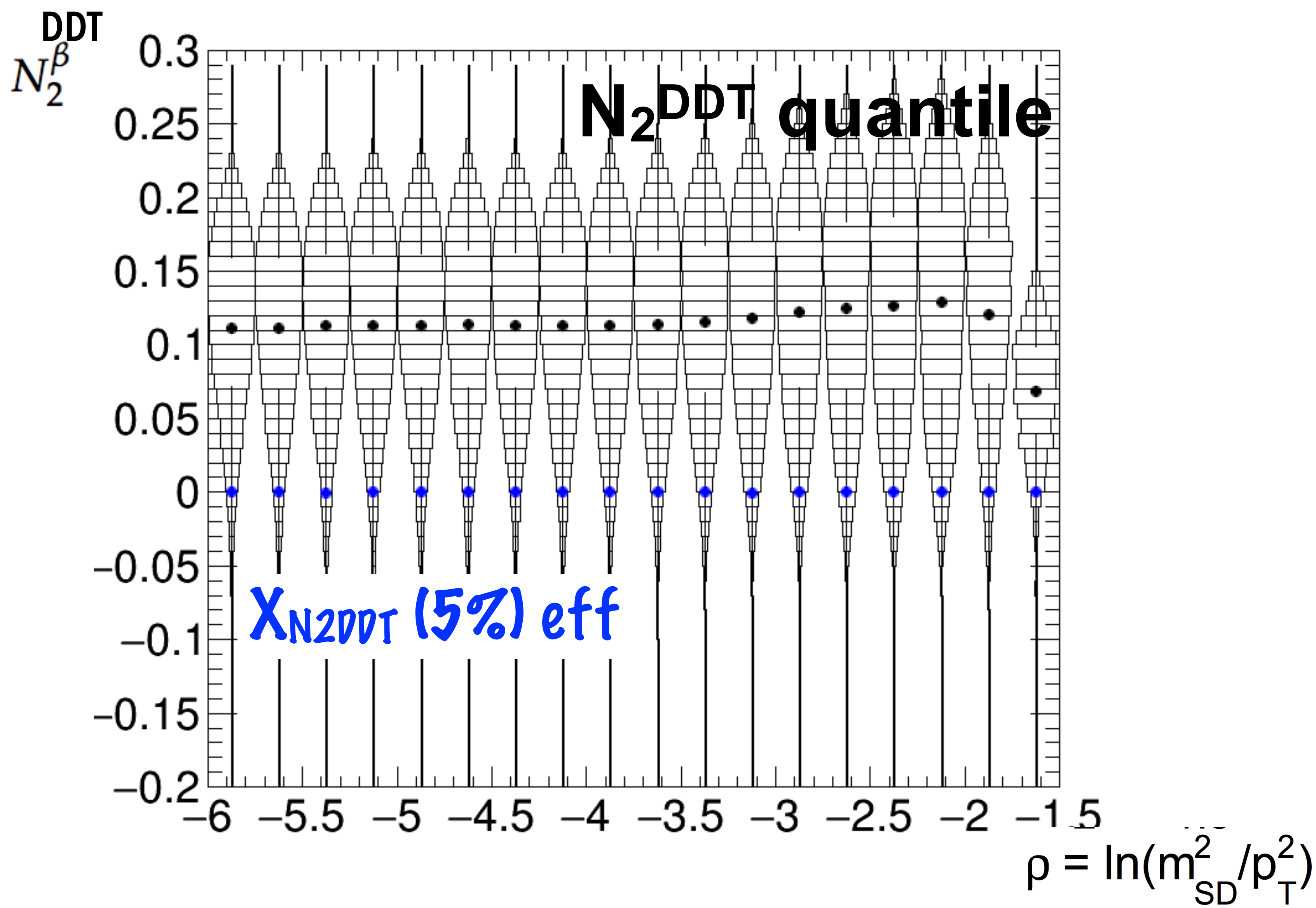
2 years ago: N_2^{DDT}

Generalizing this to any cut



Mass de-correlation (2)

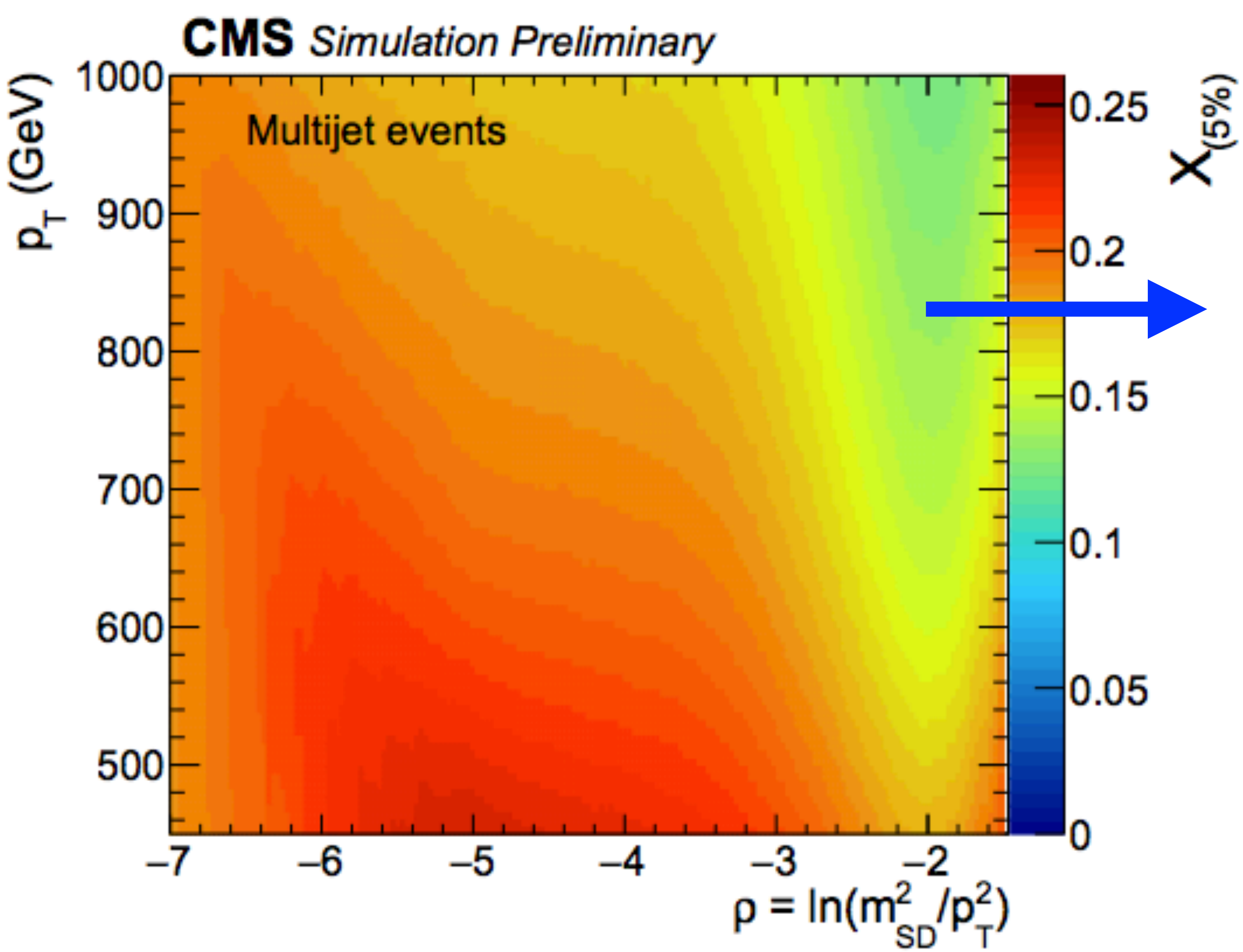
2 years ago: $N_2^{DDT} = N_2$ - X(QCD eff%)



We vary the N_2 cut so that the QCD efficiency is fixed (5%)

N_2^{DDT} map

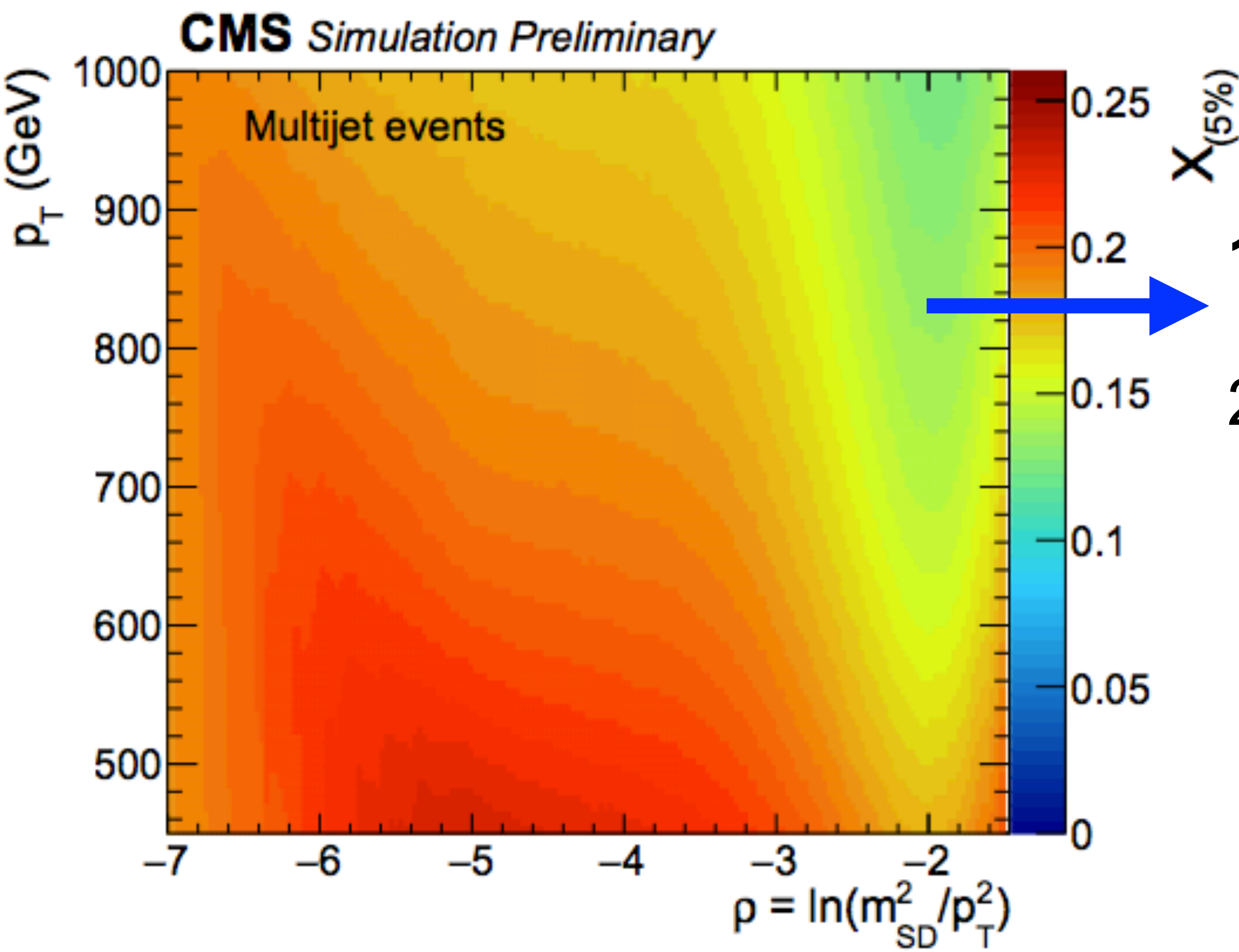
Let's look at this correlation for all phase space:



For each p_T and ρ bin X(QCD eff%): N_2 cut to obtain fixed background efficiency

N_2^{DDT} map

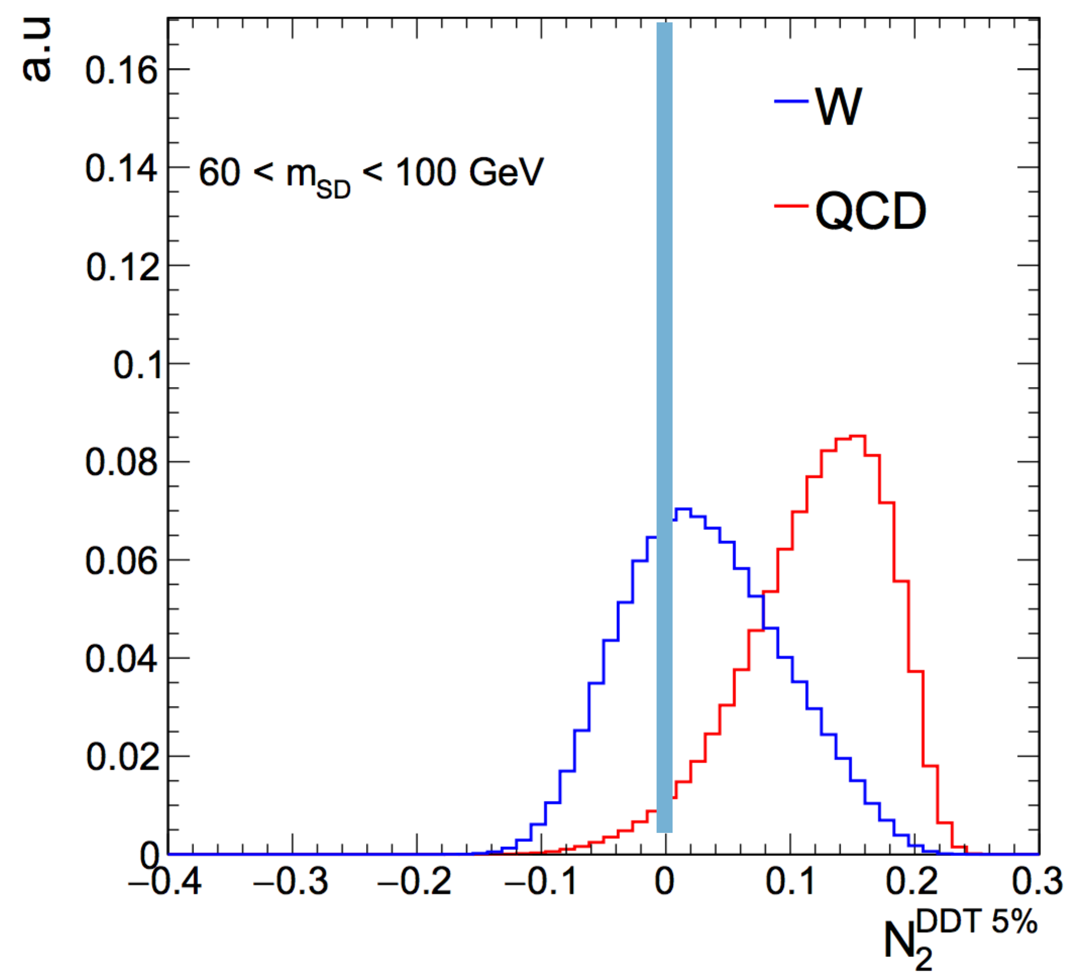
How is this built:



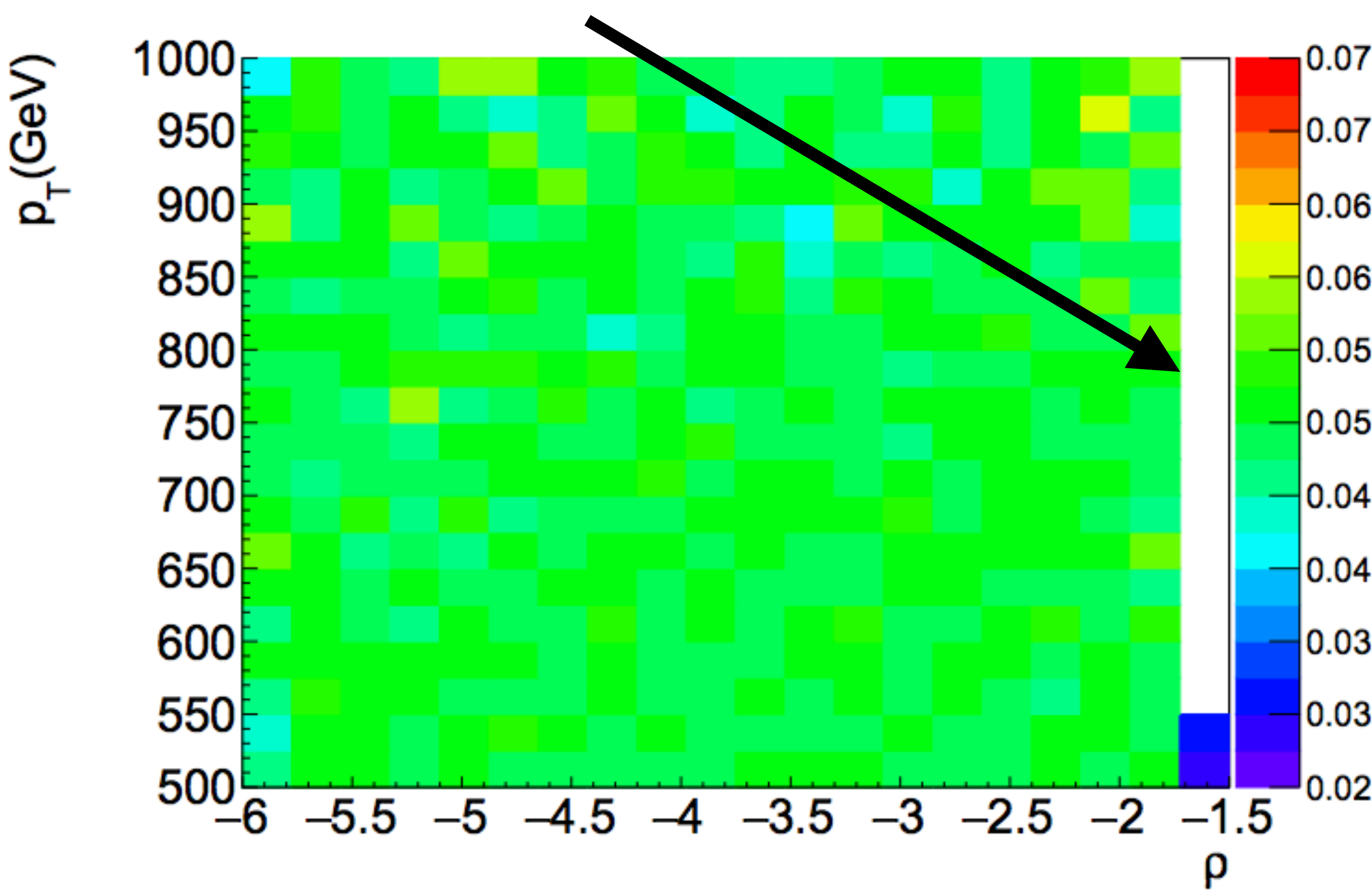
1. **Build 3D histogram** from QCD MC
2. **Smooth** using:
   - kNN
   - Detector resolution

N_2^{DDT} correlation

$N_2^{DDT} = N_2$ - X(QCD eff%)



N_2^{DDT} is flat w.r.t. mass and pT

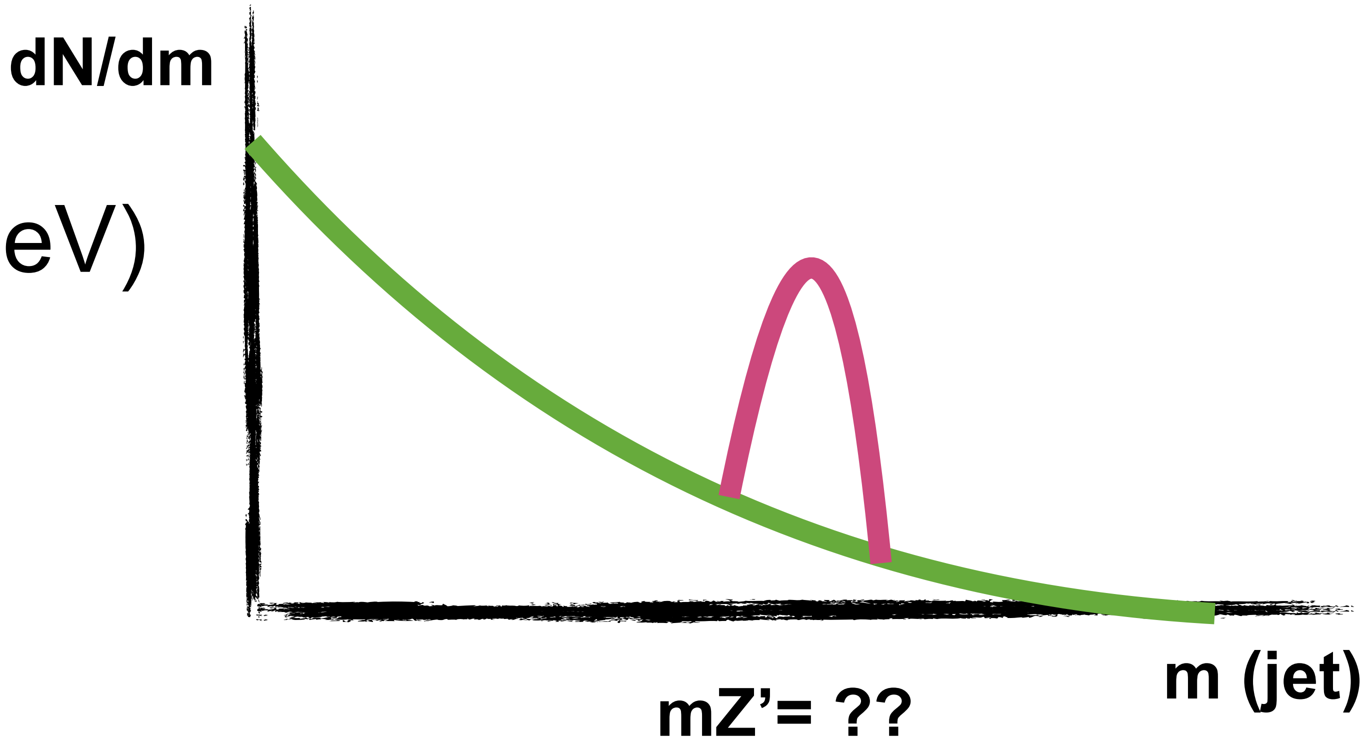


This is called brute-force decorrelation

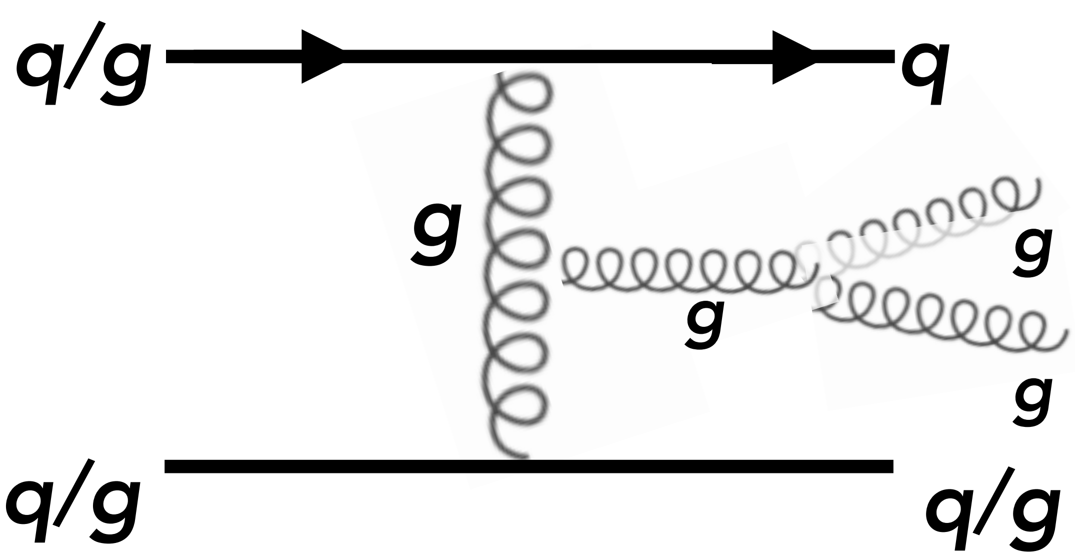
Analysis selection

1. Jet/photon trigger
2. High p_T jet (jet p_T>~500 GeV)
3. $N_2^{DDT} < 0$ (for X eff.)

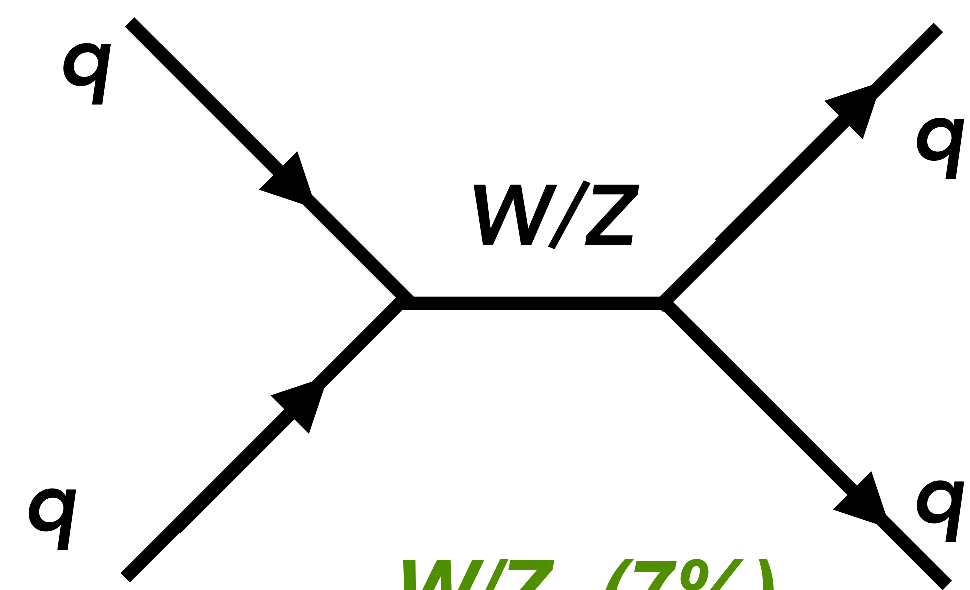
After DECORRELATED N_2 cut



Backgrounds

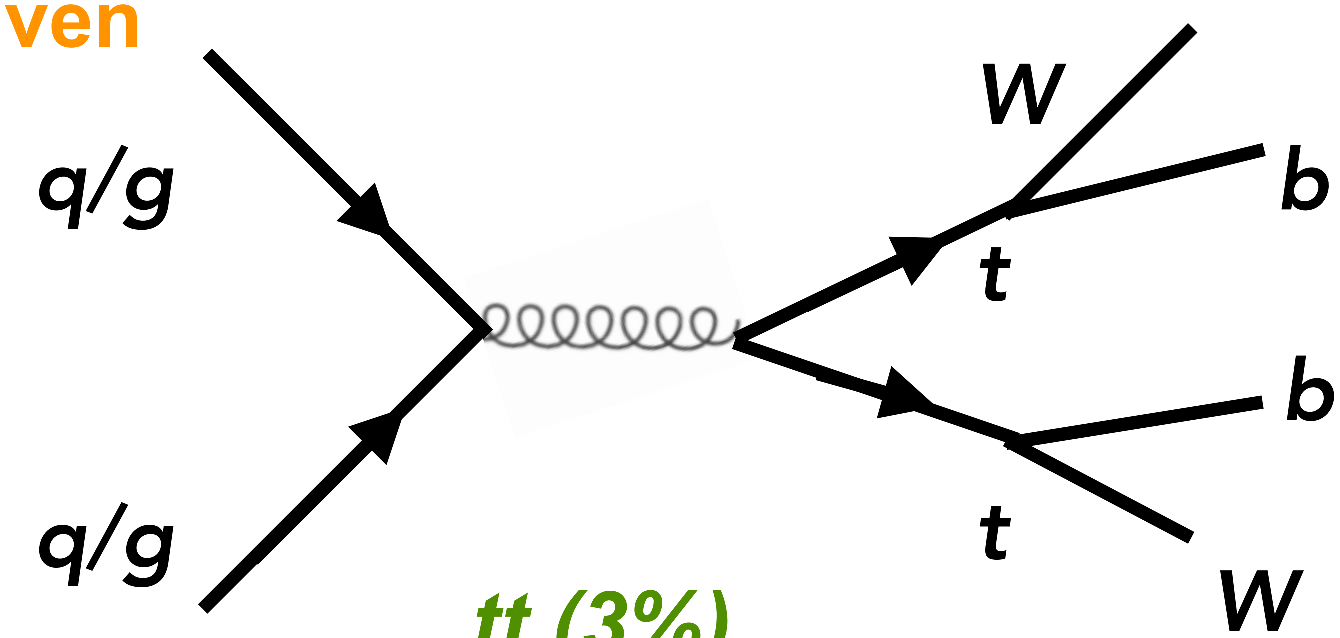


QCD (90%)
Data-driven



MC

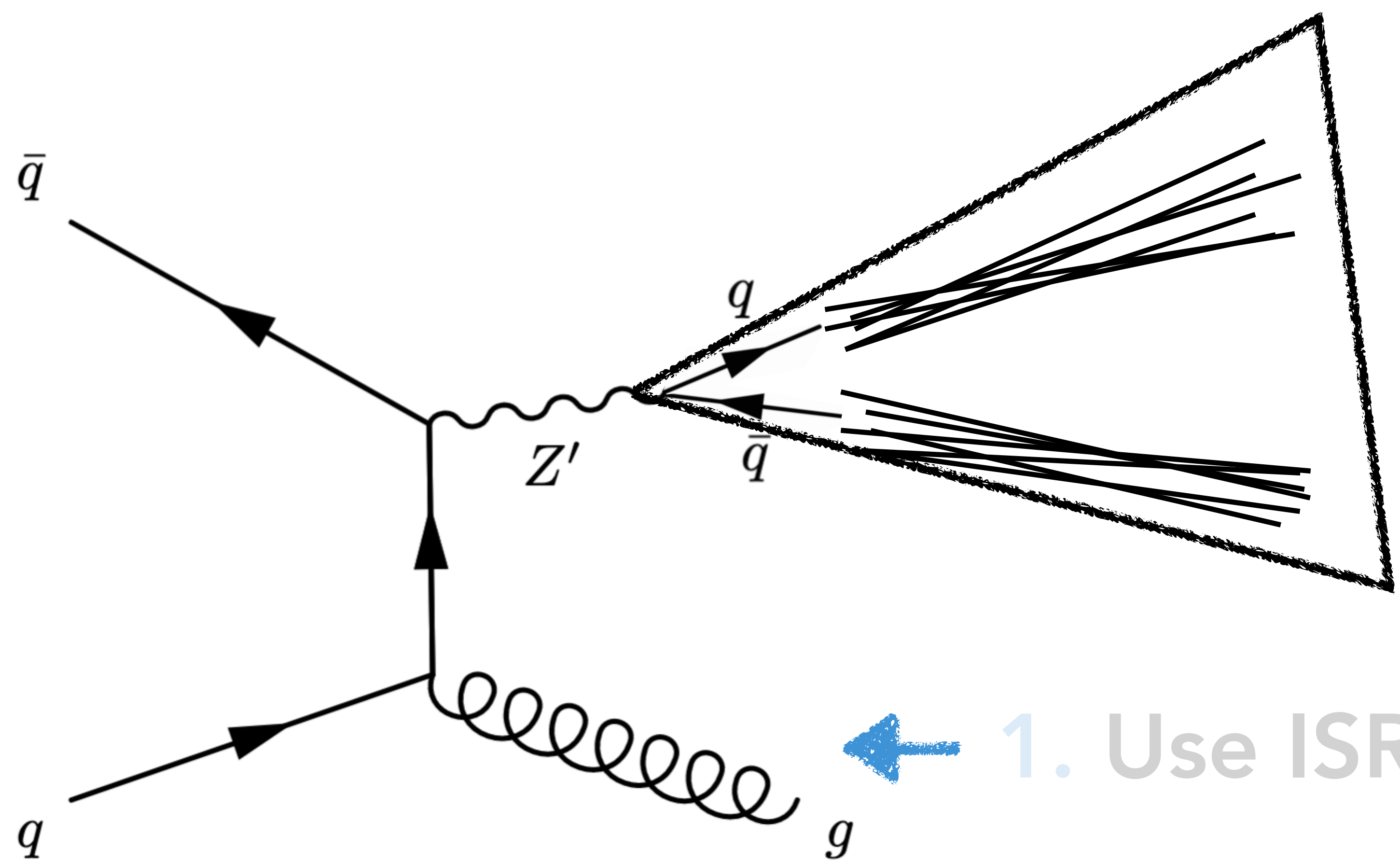
W/Z (7%)



MC

tt (3%)

W/Z/Z'+ISR in 4 steps



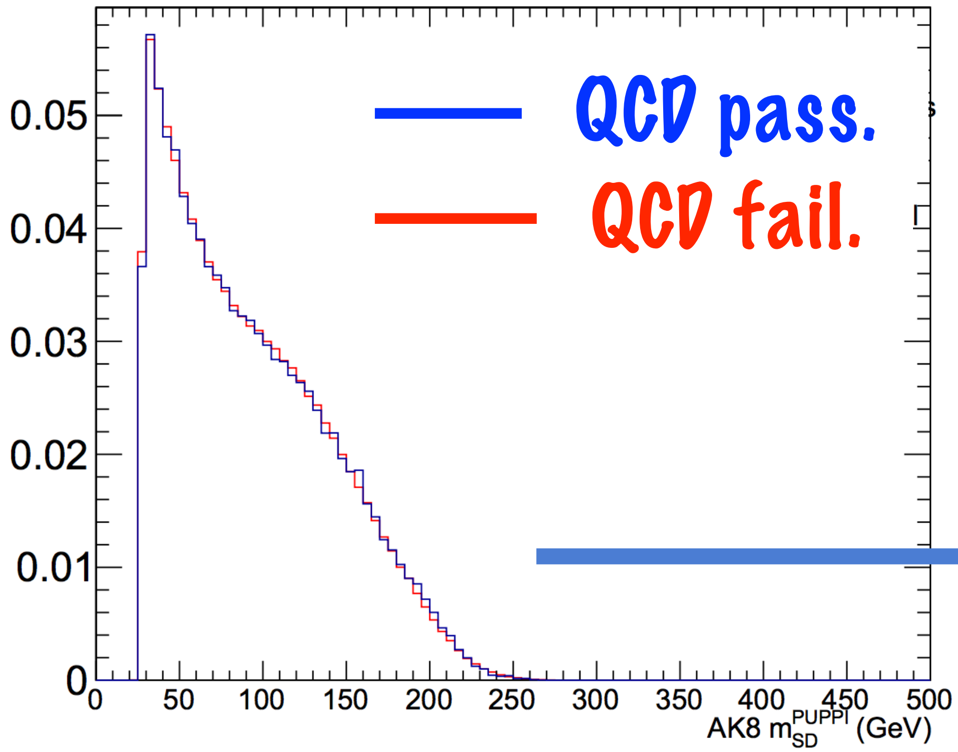
2. Two-prong resonance in single-large jet

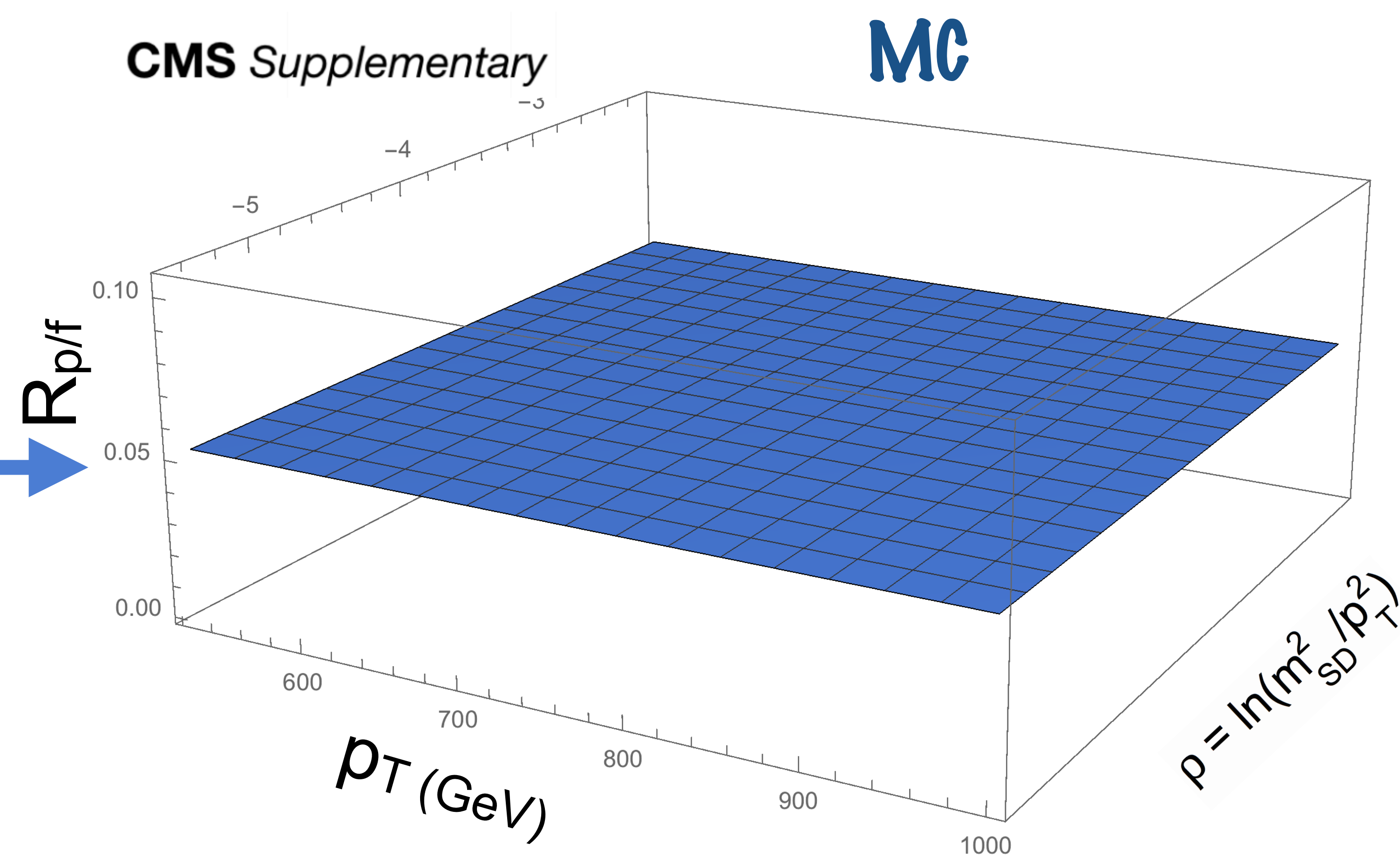
1. Use ISR to trigger on events

3. Keep smoothly-falling jet mass spectrum in data

4. **Probe spectrum with data-driven QCD estimate**

QCD data-driven estimate



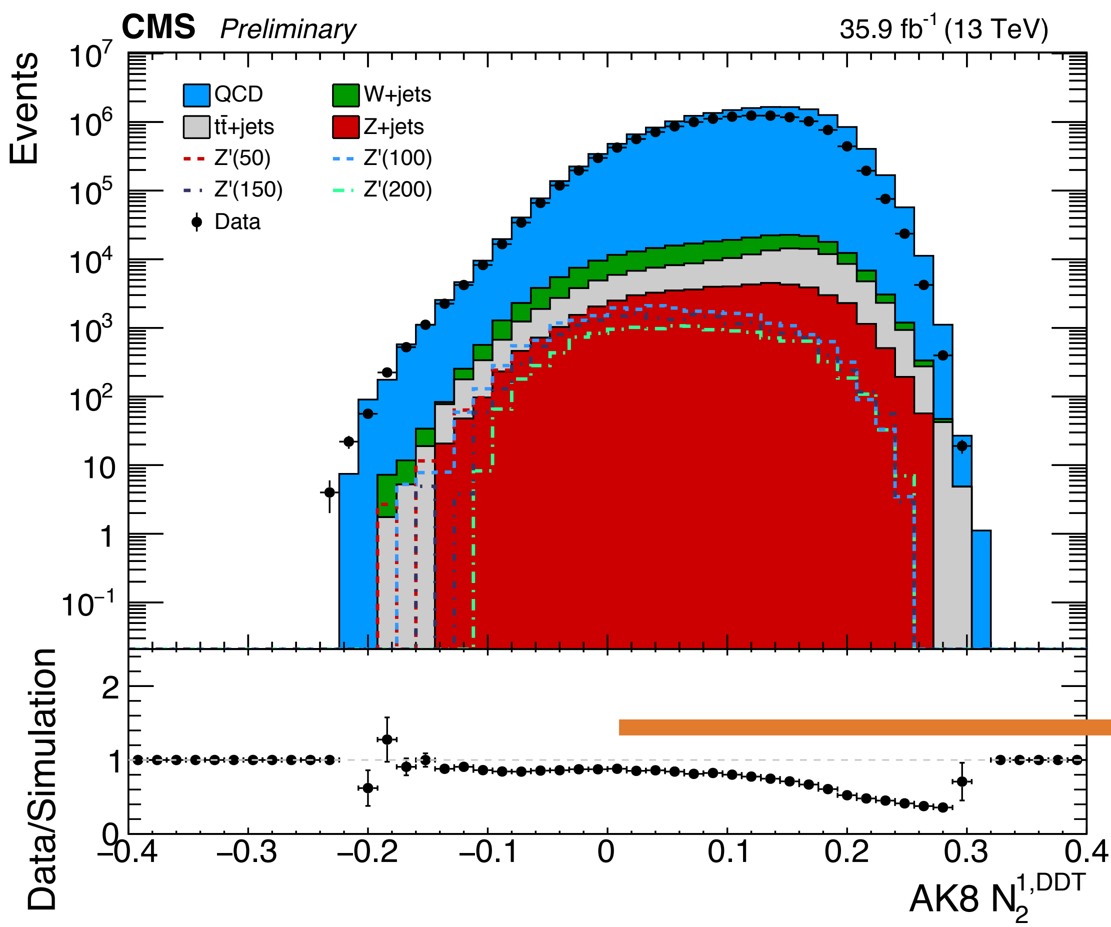


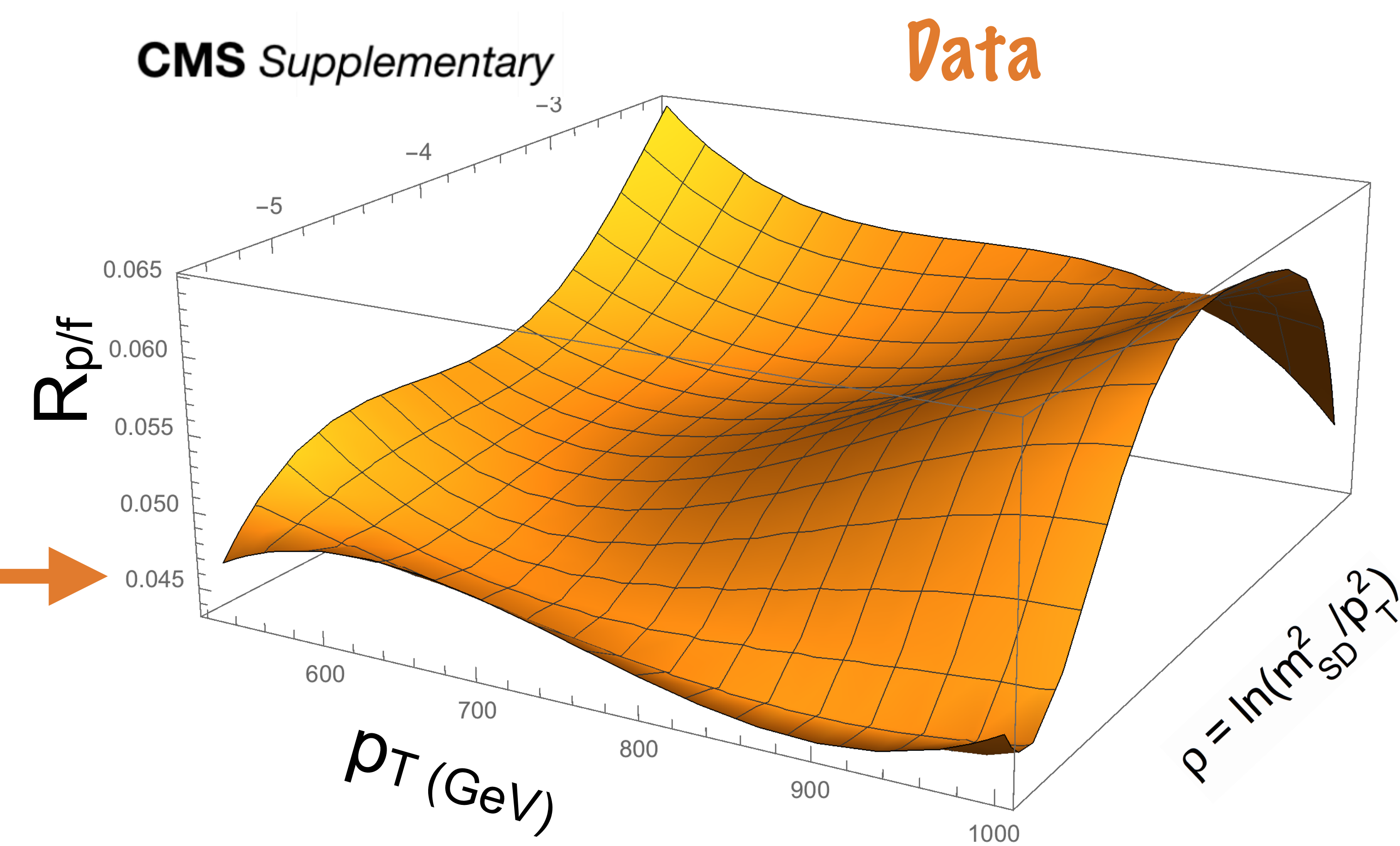
$$n_{\text{pass}}^{\text{QCD}} = R_{\text{p/f}}\, n_{\text{fail}}^{\text{QCD}}$$

QCD pass: $N_2^{DDT} < 0$

QCD fail: $N_2^{DDT} > 0$

QCD data-driven estimate



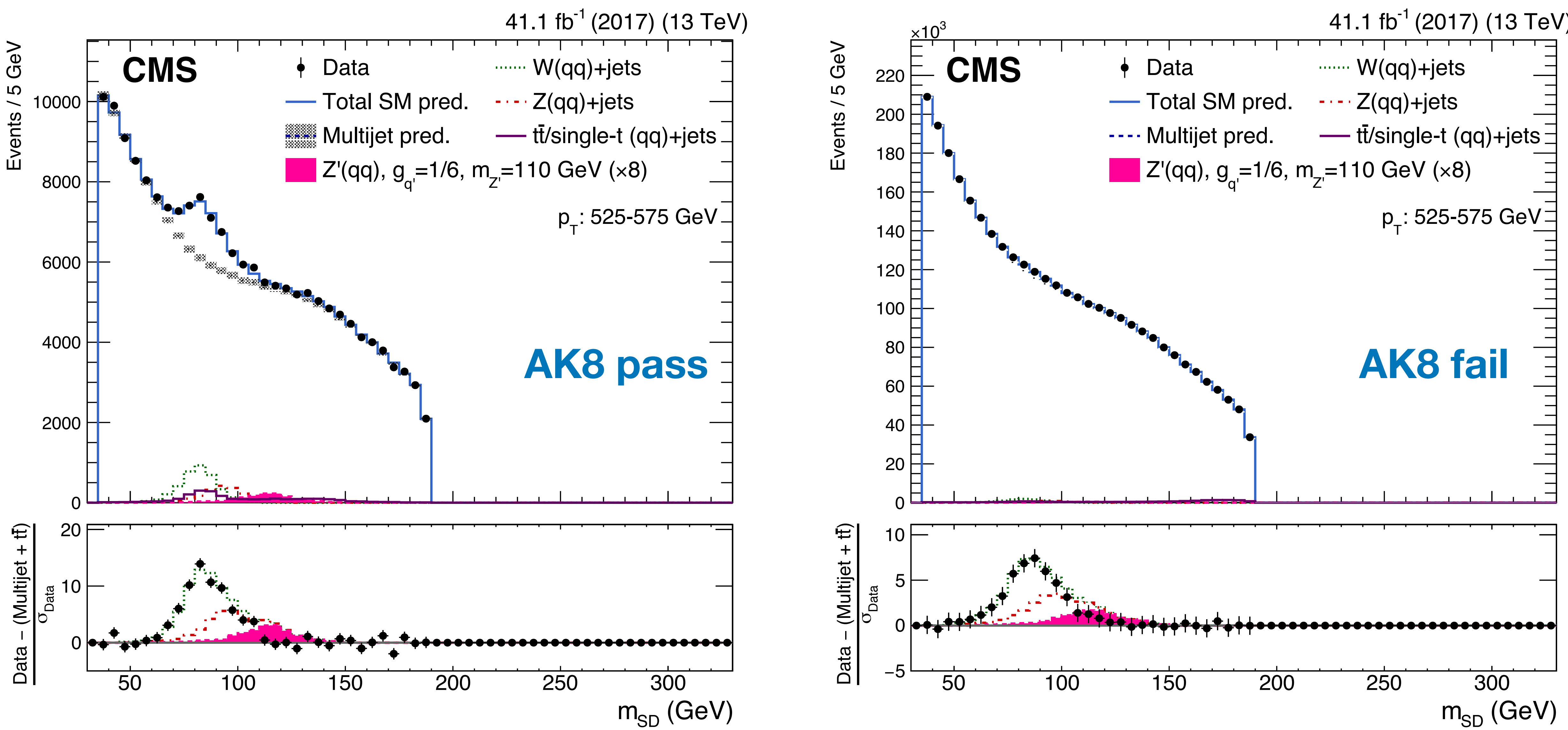


$$n_{\text{pass}}^{\text{QCD}} = R_{\text{p/f}}\,(n_{\text{Fail}}^{\text{Data}} - n_{\text{Fail}}^{\text{W/Z/tt}})$$

Fit for data/mc differences with polynomial $R_{p/f}$

Fit to data

Fit parameters and signal strength simultaneous in binned maximum likelihood fit



Systematic Uncertainties

Uncertainty source	Process Z′ (AK8)	W/Z (AK8)	Z′ (CA15)	W/Z (CA15)
NLO EW corrections$^{\triangle}$	—	15–35%	—	15–35%
NLO QCD corrections	10%	10%	10%	10%
NLO EW W/Z decorrelation$^{\triangle}$	—	5–15%	—	5–15%
Simulation sample size	1–12%	1–12%	1–12%	1–12%
$N_2^{1,\mathrm{DDT}}$ selection efficiency	10%	10%	7%	7%
Jet mass scale	1%	1%	1%	1%
Jet mass resolution	10%	10%	7%	7%
Jet mass scale (% / (p_{T} [GeV]/100)) $^{\triangle}$	0.5–2%	0.5–2%	0.5–2%	0.5–2%
Jet energy resolution	1–7%	1–7%	1–7%	1–7%
Signal p_{T} correction	5%	—	5%	—
Integrated luminosity	2.3%	2.3%	2.3%	2.3%
Trigger efficiency	2%	2%	2%	2%
Pileup	1–2%	1–2%	1–2%	1–2%
Lepton veto efficiency	0.5%	0.5%	0.5%	0.5%

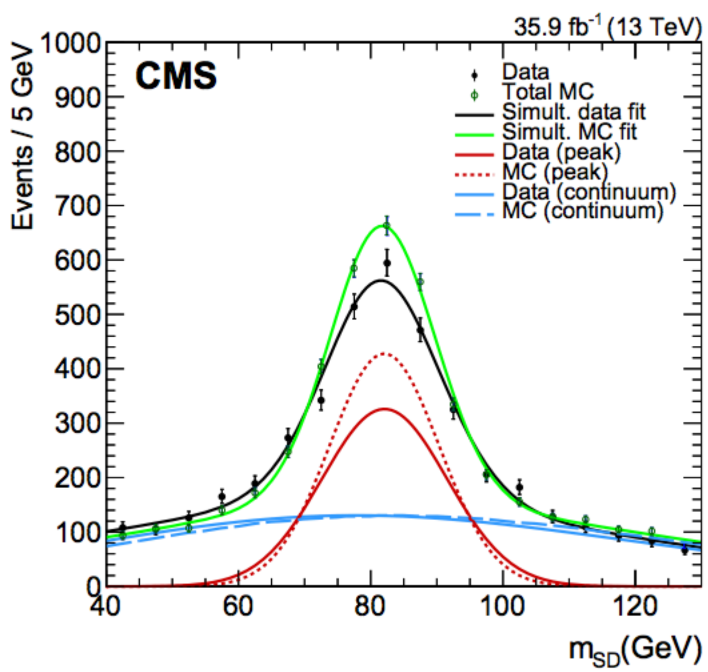
Systematic Uncertainties

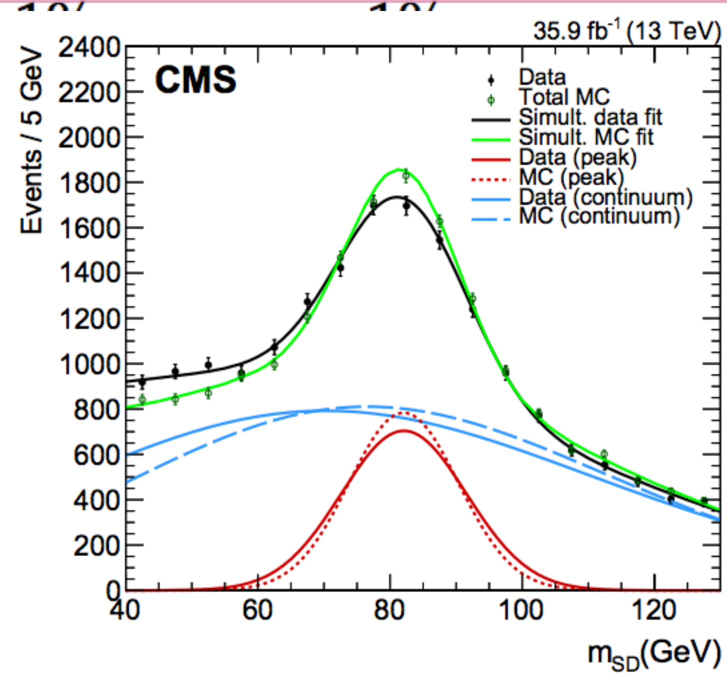
Uncertainty source	Process			
	Z' (AK8)	W/Z (AK8)	Z' (CA15)	W/Z (CA15)
NLO EW corrections△	—	15–35%	—	15–35%
NLO QCD corrections	10%	10%	10%	10%
NLO EW W/Z decorrelation△	—	5–15%	—	5–15%
Simulation sample size	1–12%	1–12%	1–12%	1–12%
$N_2^{1,DDT}$ selection efficiency	10%	10%	7%	7%
Jet mass scale	1%	1%	1%	1%
Jet mass resolution	10%	10%	7%	7%
Jet mass scale (% / (p_T [GeV]/100)) △	0.5–2%	0.5–2%	0.5–2%	0.5–2%
Jet energy resolution	1–7%	1–7%	1–7%	1–7%
Signal p_T correction	5%	—	5%	—
Integrated luminosity	2.3%	2.3%	2.3%	2.3%
Trigger efficiency	2%	2%	2%	2%
Pileup	1–2%	1–2%	1–2%	1–2%
Lepton veto efficiency	0.5%	0.5%	0.5%	0.5%

Knowing W/Z p_T spectrum

Systematic Uncertainties

Uncertainty source	Process			
	Z′ (AK8)	W/Z (AK8)	Z′ (CA15)	W/Z (CA15)
NLO EW corrections△	—	15–35%	—	15–35%
NLO QCD corrections	10%	10%	10%	10%
NLO EW W/Z decorrelation△	—	5–15%	—	5–15%
Simulation sample size	1–12%	1–12%	1–12%	1–12%
$N_2^{1,DDT}$ selection efficiency	10%	10%	7%	7%
Jet mass scale			%	1%
Jet mass resol			%	7%
Jet mass scale			–2%	0.5–2%
Jet energy reso			-7%	1–7%
Signal p_T corr			%	—
Integrated lun			3%	2.3%
Trigger efficie			%	2%
Pileup			-2%	1–2%
Lepton veto e			5%	0.5%





Knowing N_2 efficiency

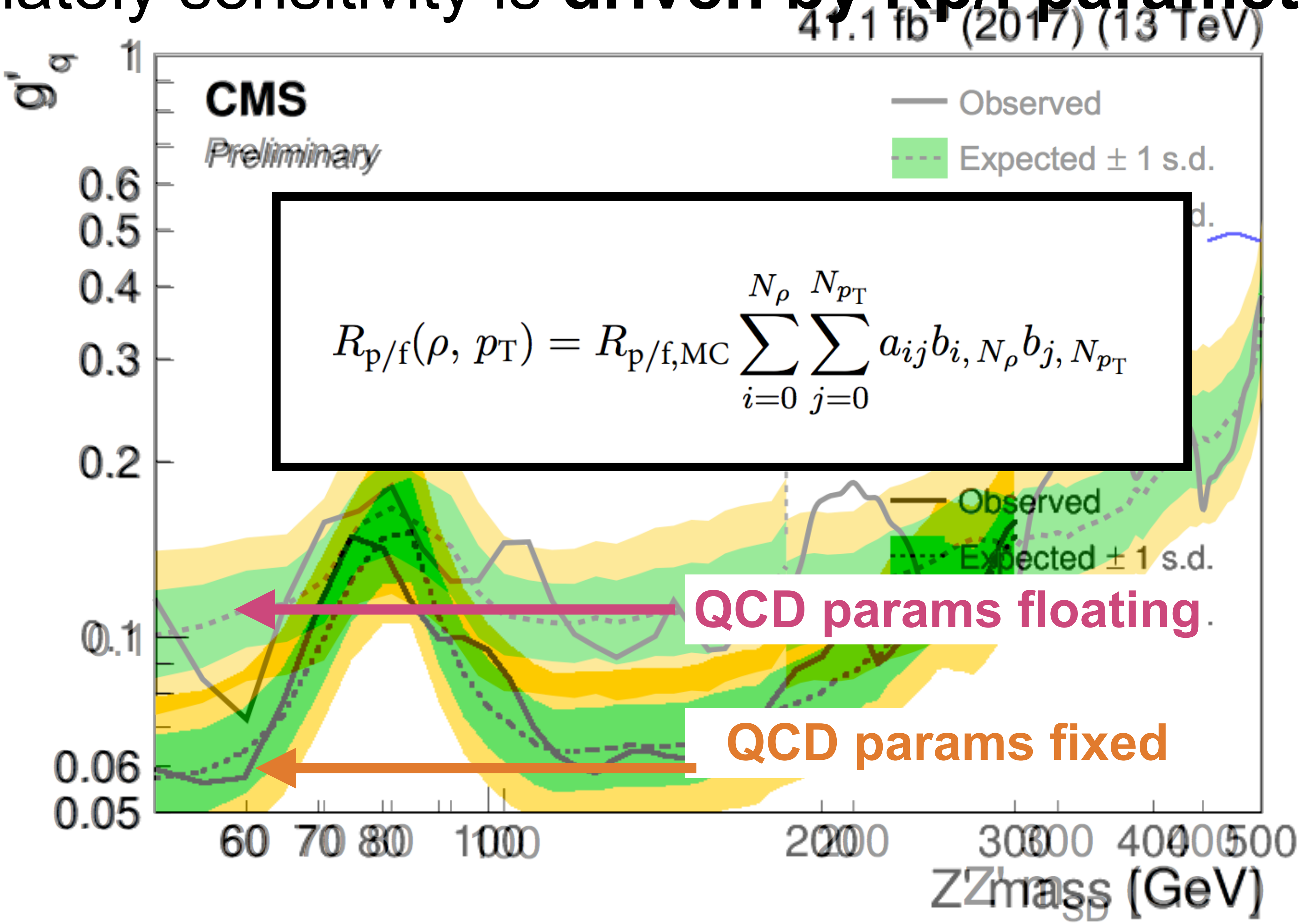
Systematic Uncertainties

Uncertainty source	Process			
	Z′ (AK8)	W/Z (AK8)	Z′ (CA15)	W/Z (CA15)
NLO EW corrections△	—	15–35%	—	15–35%
NLO QCD corrections	10%	10%	10%	10%
NLO EW W/Z decorrelation△	—	5–15%	—	5–15%
Simulation sample size	1–12%	1–12%	1–12%	1–12%
$N_2^{1,DDT}$ selection efficiency	10%	10%	7%	7%
Jet mass scale	1%	1%	1%	1%
Jet mass resolution	10%	10%	7%	7%
Jet mass scale (% / (p_T [GeV]/100)) △	0.5–2%	0.5–2%	0.5–2%	0.5–2%
Jet energy resolution	1–7%	1–7%	1–7%	1–7%
Signal p_T correction	5%	—	5%	—
Integrated luminosity	2.3%	2.3%	2.3%	2.3%
Trigger efficiency	2%	2%	2%	2%
Pileup	1–2%	1–2%	1–2%	1–2%
Lepton veto efficiency	0.5%	0.5%	0.5%	0.5%

Knowing jet mass scale (p_T dependent)

Systematic Uncertainties

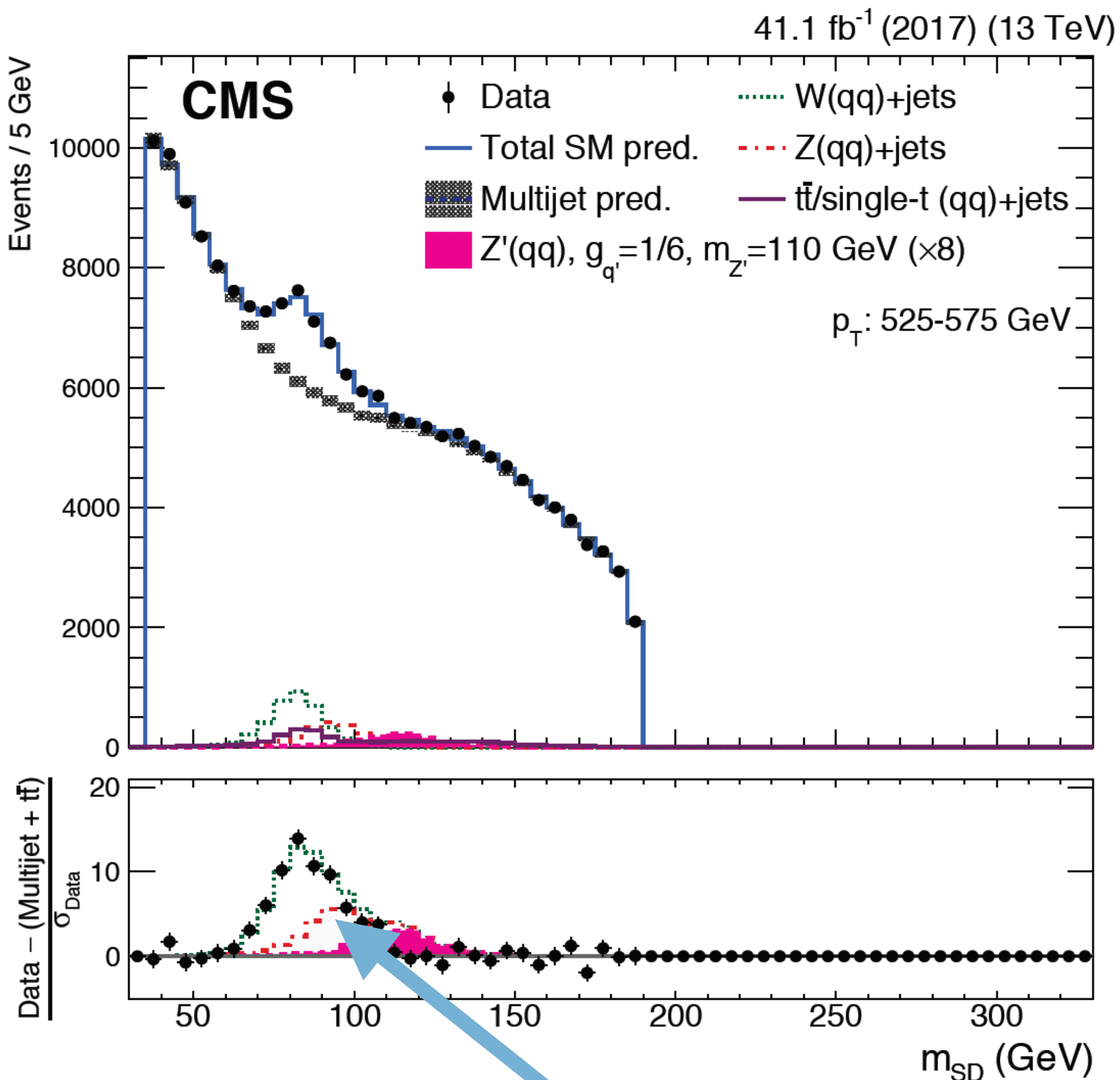
Ultimately sensitivity is **driven by Rp/f parameters**

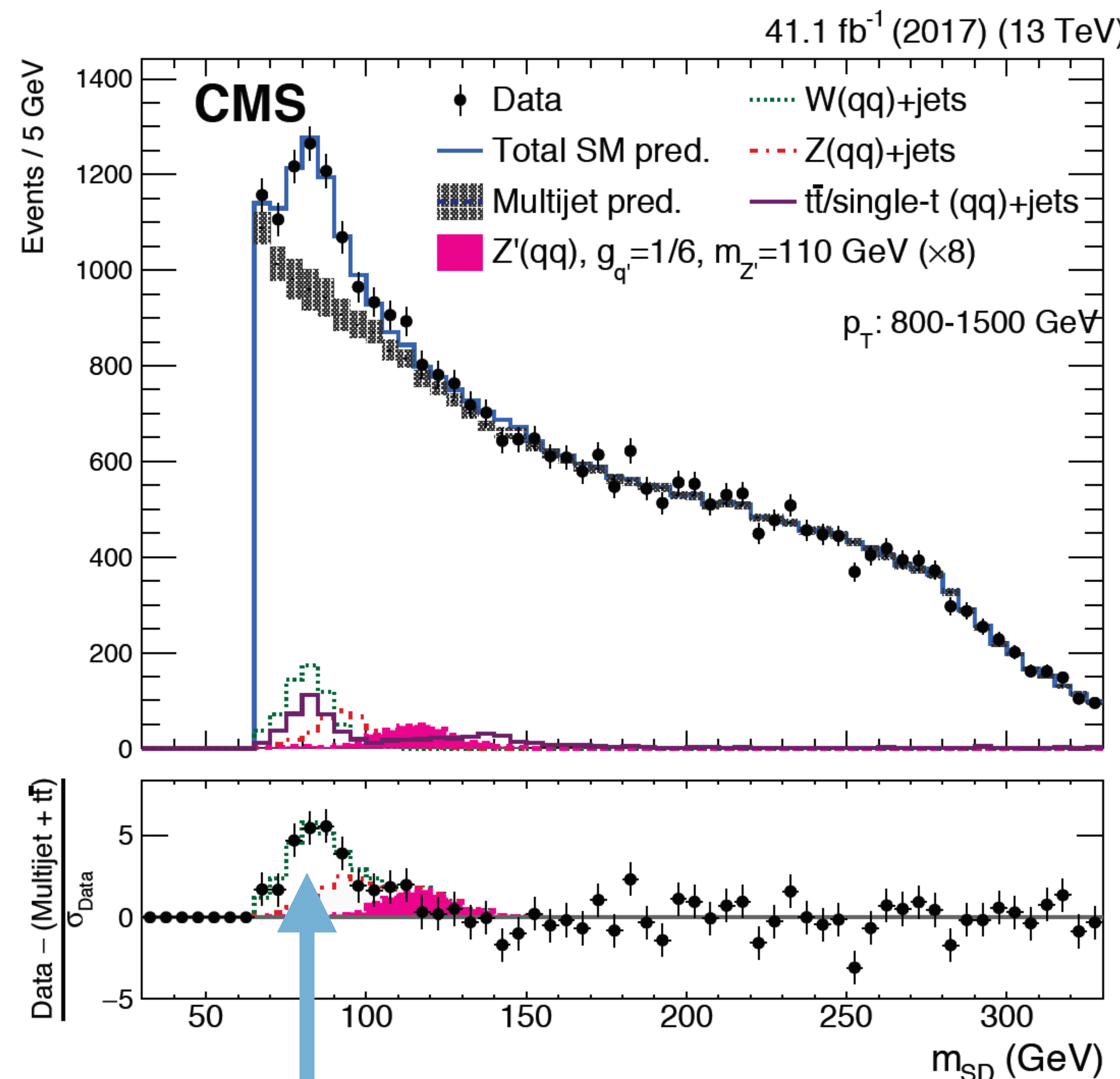


$$R_{\mathrm{p/f}}(\rho, p_{\mathrm{T}}) = R_{\mathrm{p/f,MC}} \sum_{i=0}^{N_\rho} \sum_{j=0}^{N_{p_{\mathrm{T}}}} a_{ij} b_{i,N_\rho} b_{j,N_{p_{\mathrm{T}}}}$$

Results and new directions

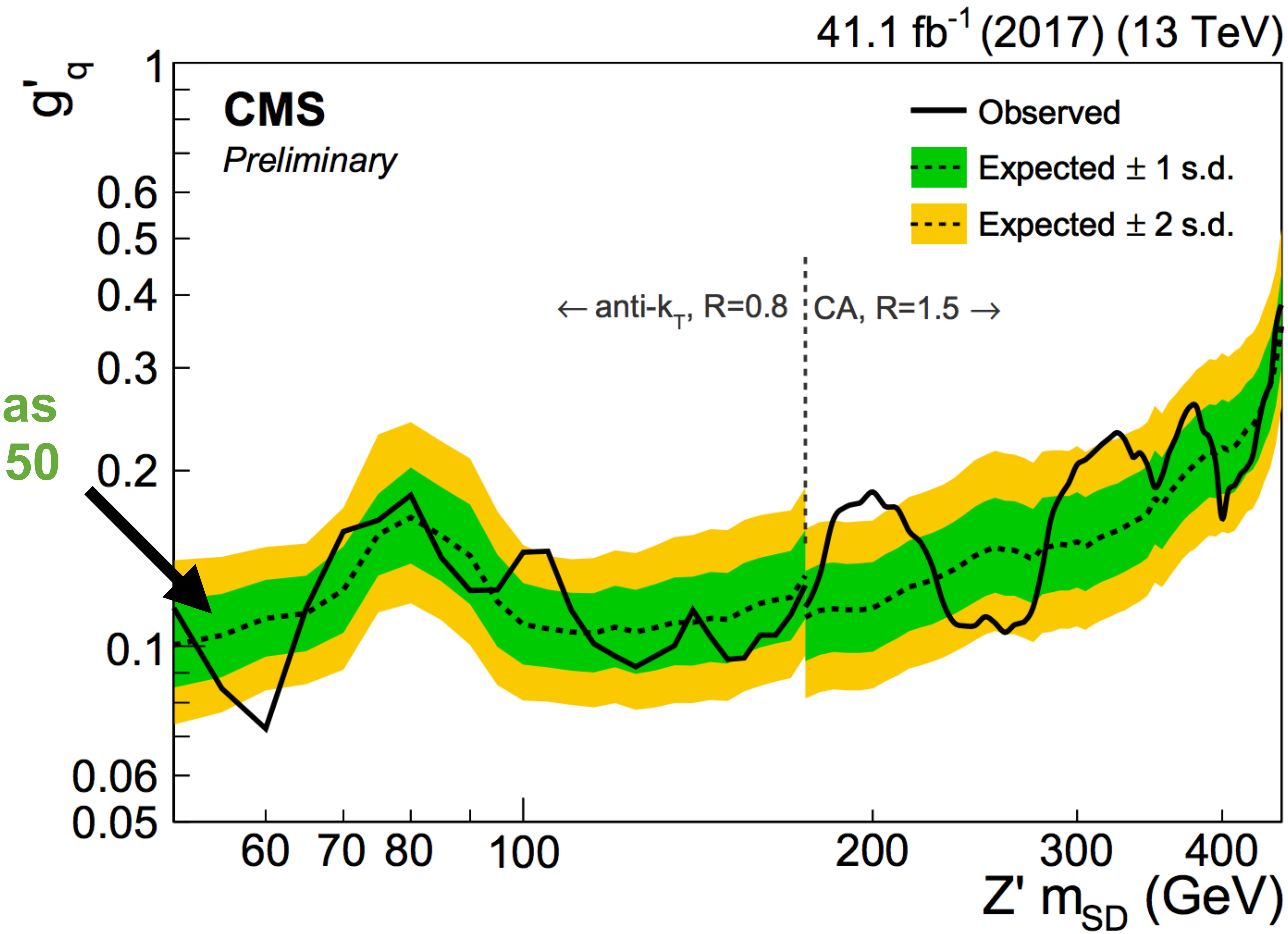
Z'+jet (2016+17)





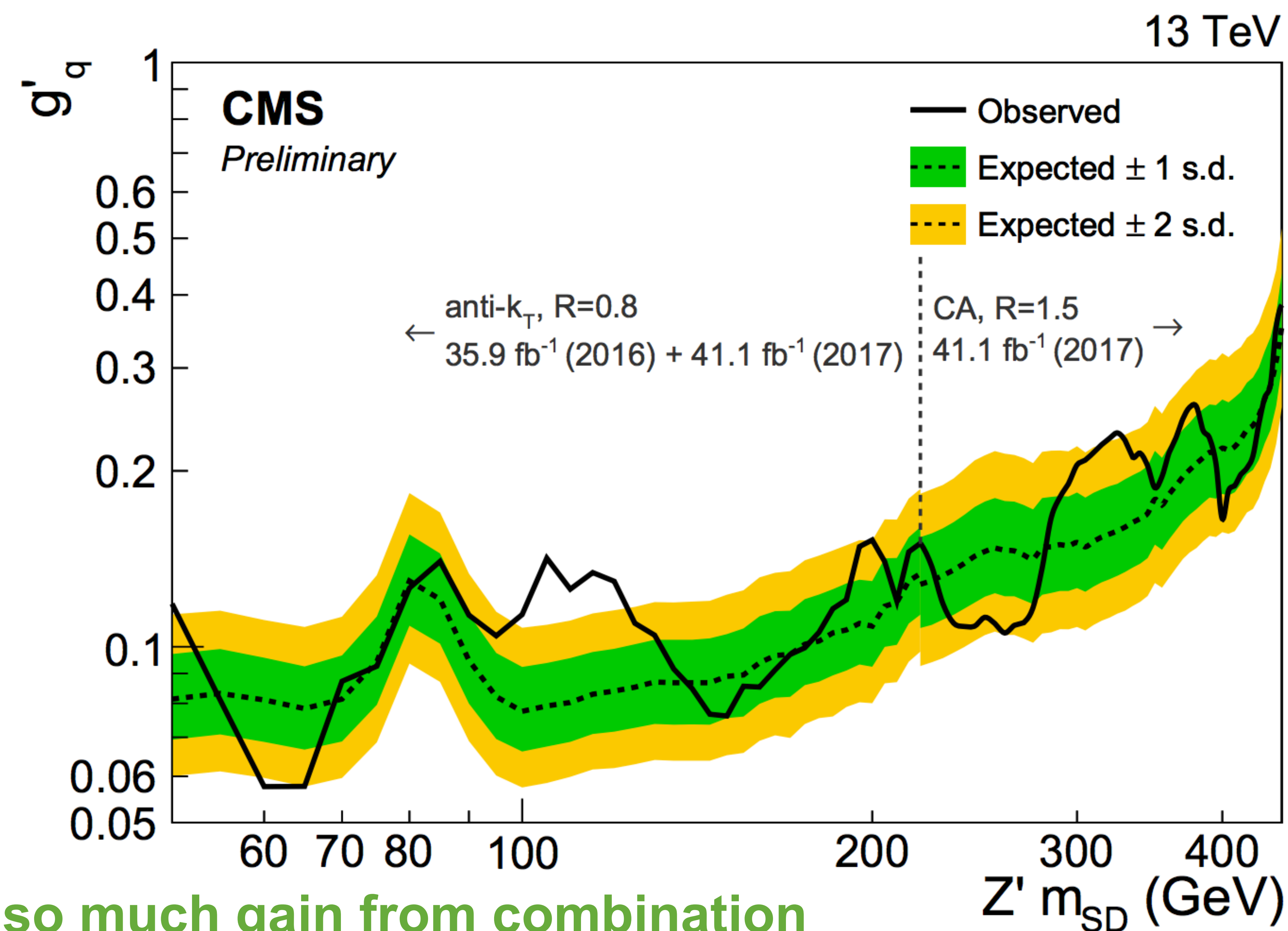
Hadronic W/Z peak at high p_T

Z'+jet (2017)



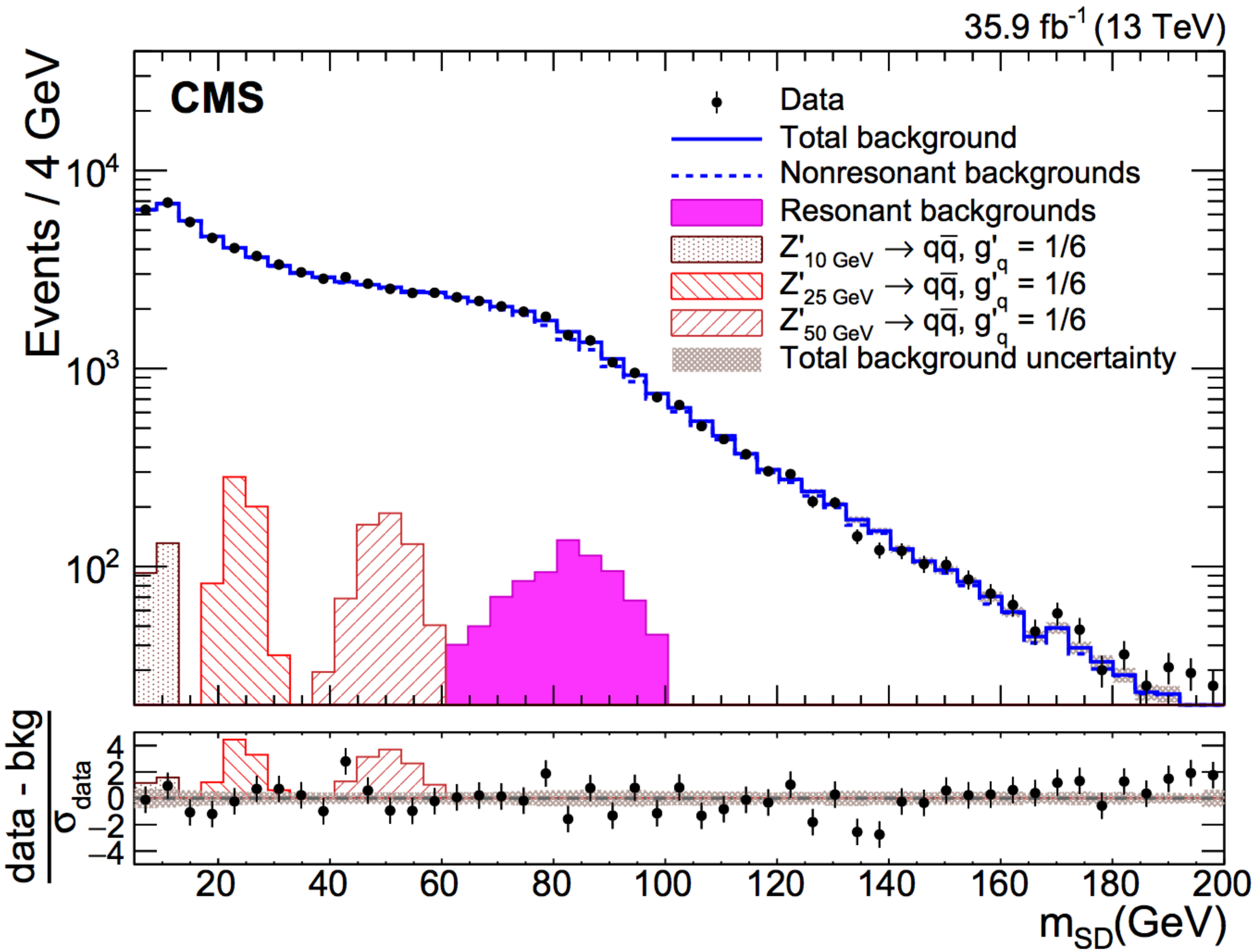
Limits as low as 50 GeV

Z'+jet (2016+17)



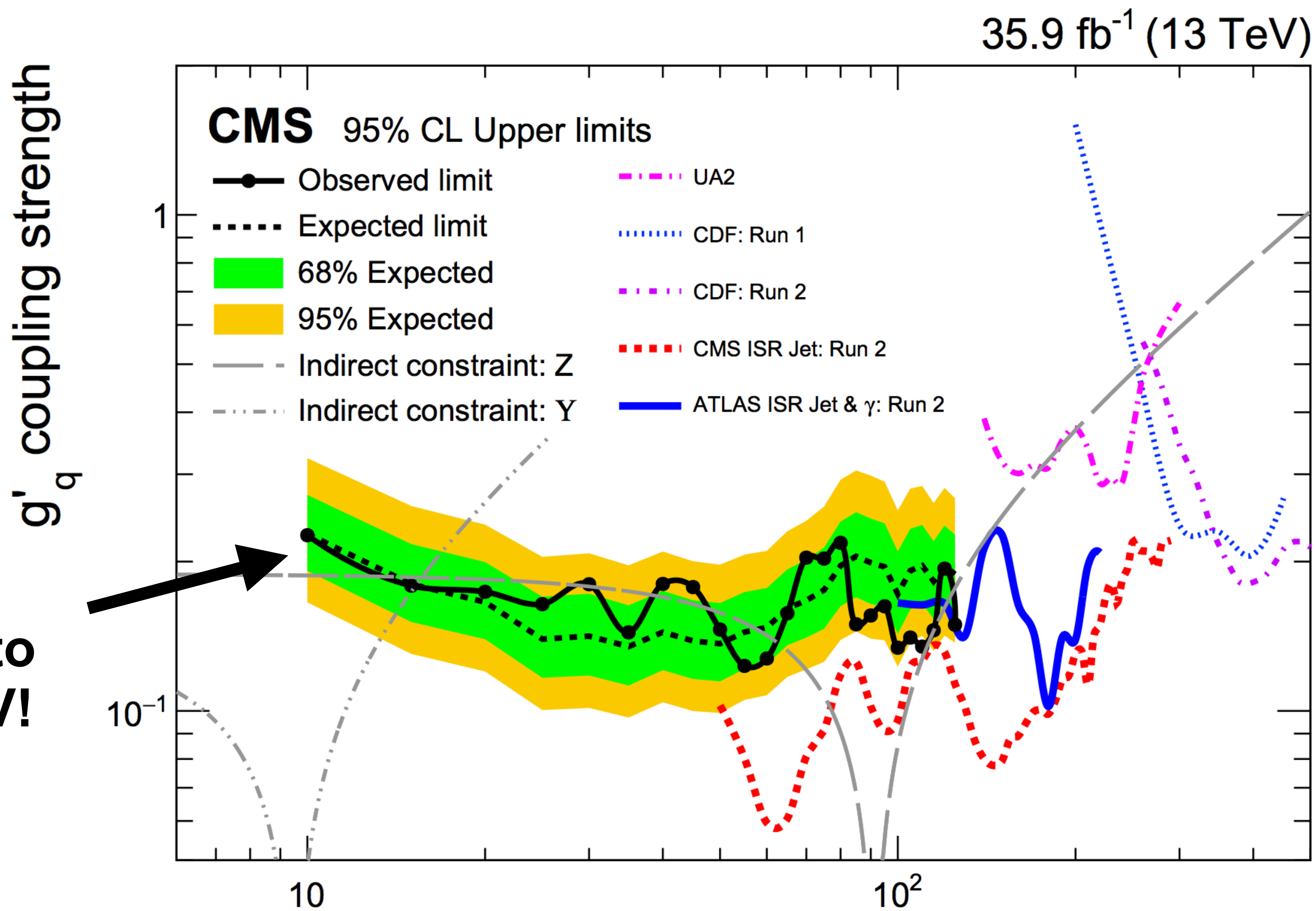
Not so much gain from combination (because of increased pT thresholds)

Z'+photon (2016)



Z'+photon (2016)

Photon triggers allows to probe lower mass

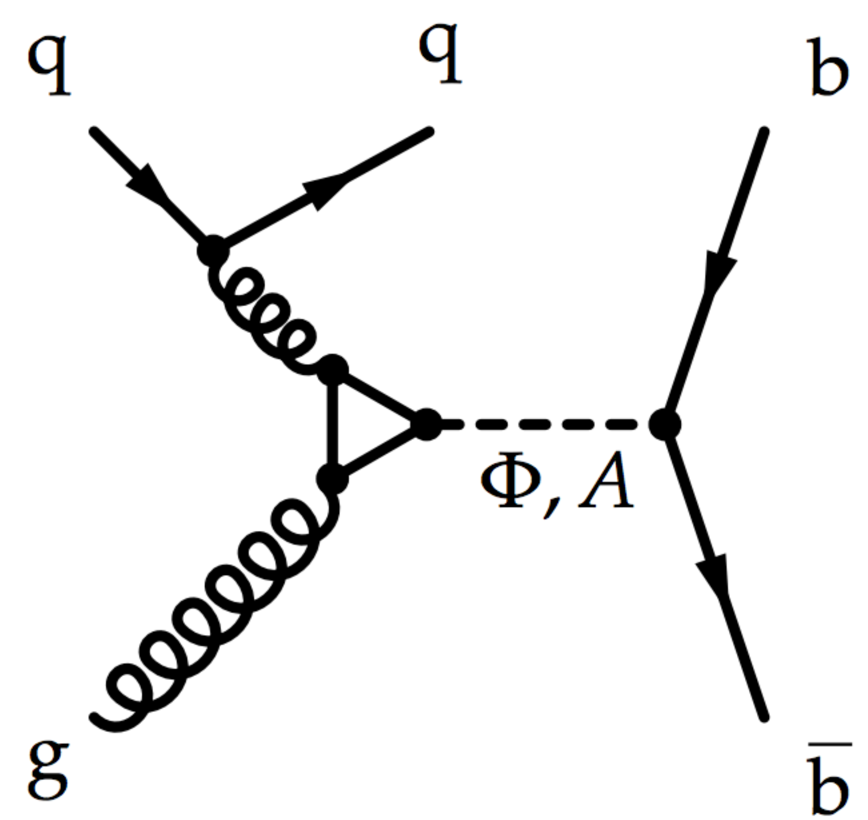


down to 10 GeV!

b-tagged resonances

Scalar (Φ) mediator

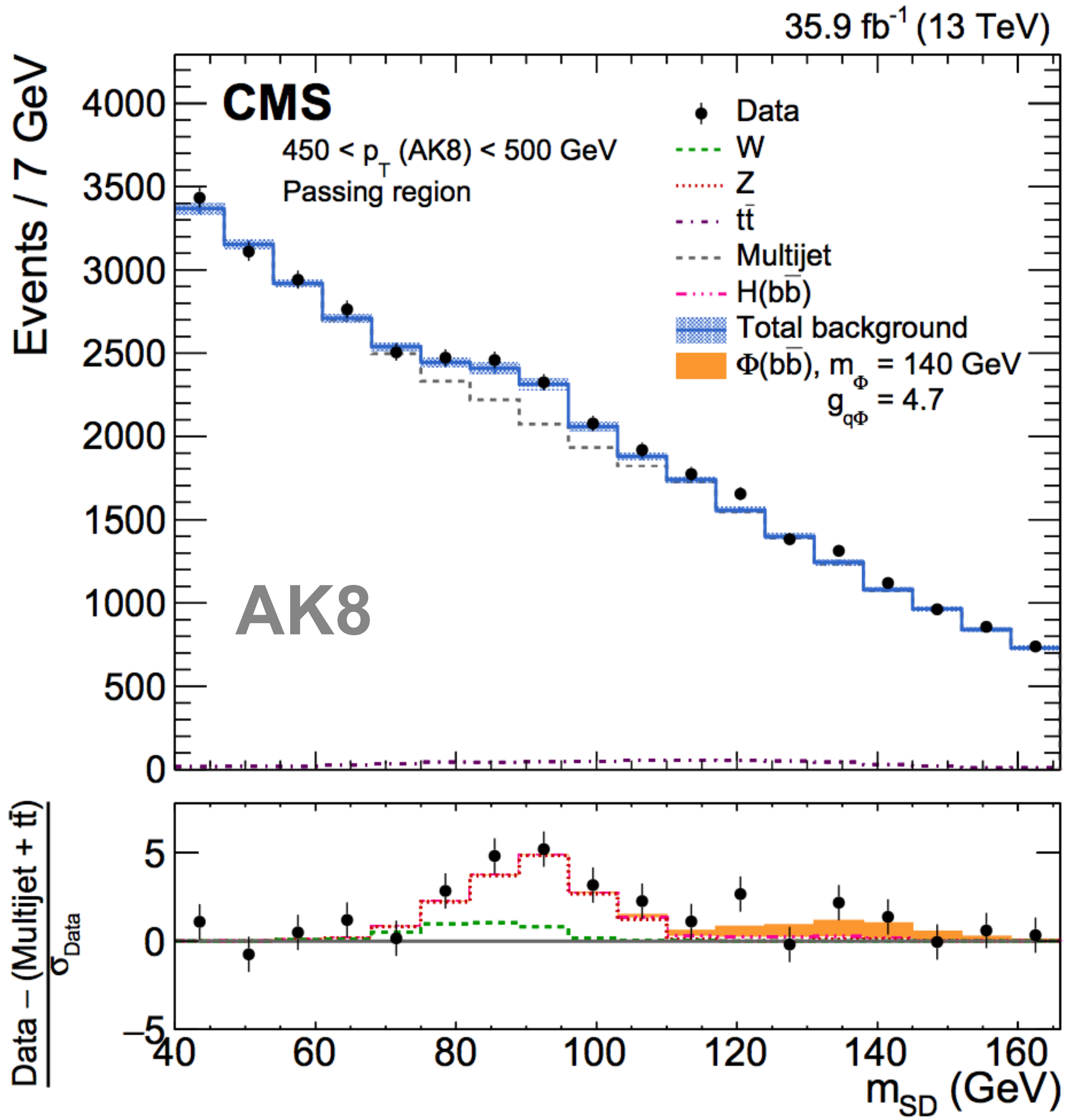
- gluon-gluon fusion production
- Preferential coupling to 3rd gen fermions

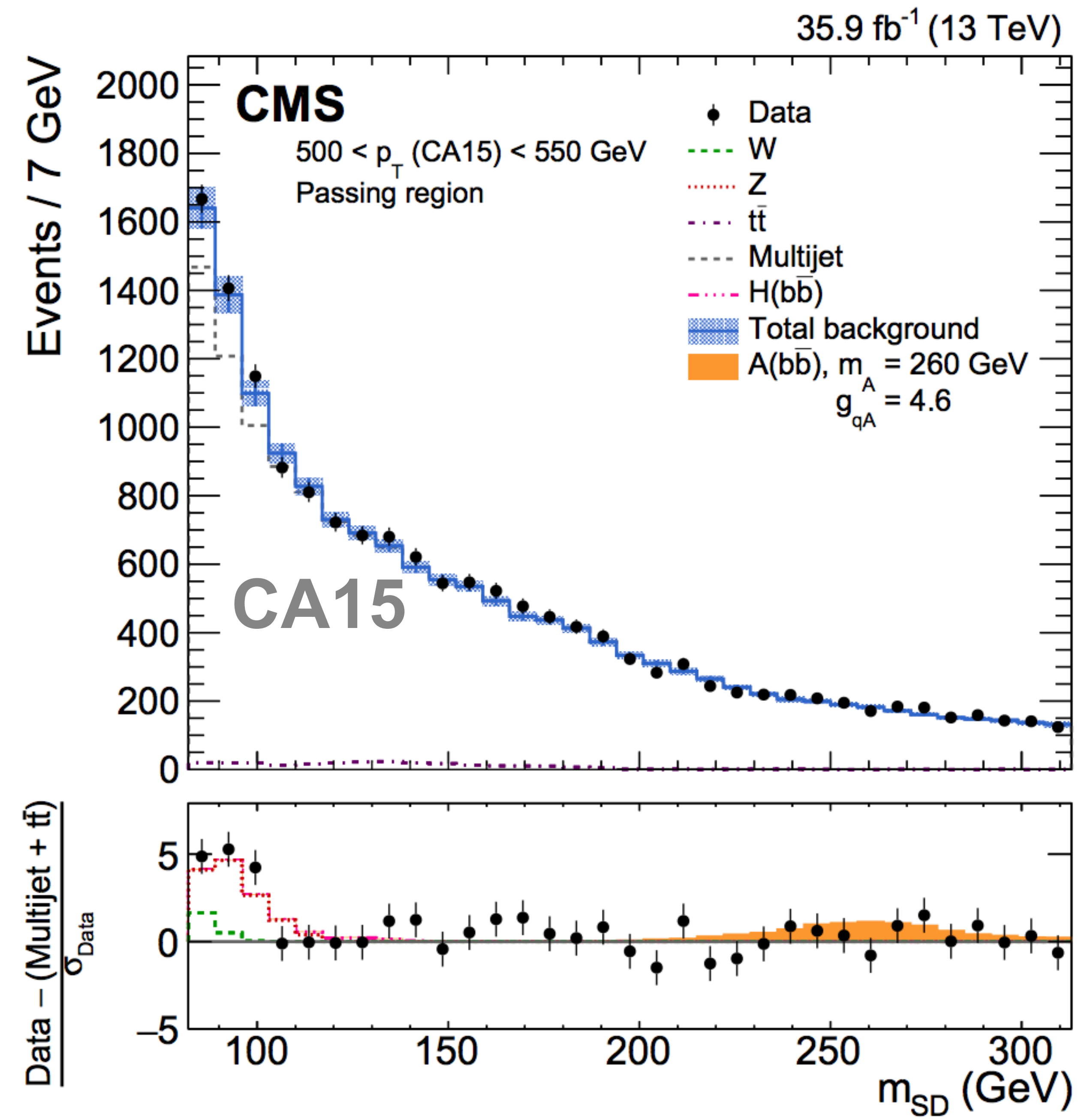


Use **same exact topology as boosted di-jet** + **double-b tag** the jet

ϕ(bb) +jet (2016)

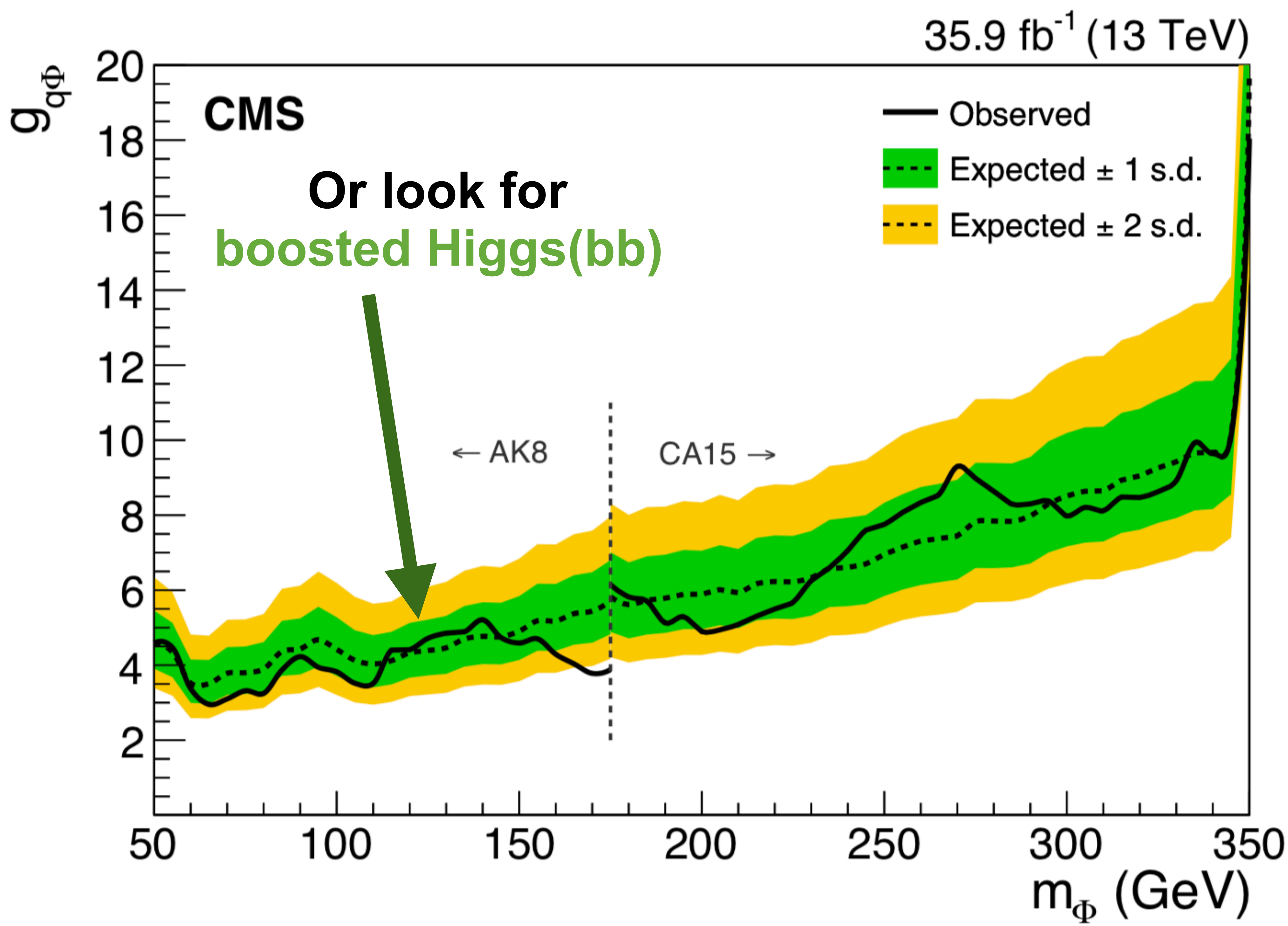
Probe scalar couplings with b-tagging





ϕ(bb) +jet (2016)

Probe scalar couplings with b-tagging



Sensitivity to DM

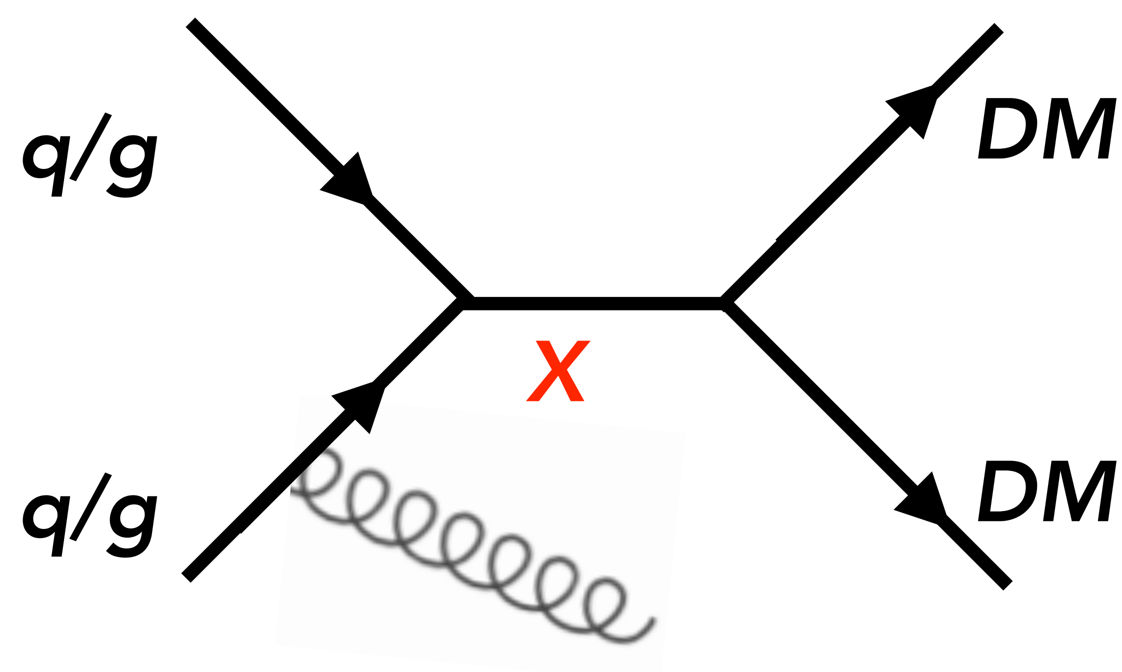
If leptophobic Z' couples to DM as well quarks, then it acts as mediator between the dark sector and visible sector (SM)

g_{DM} > 0 and m_{DM} < $m_{M/2}$

Smaller m_{DM} < $m_{M/2}$ and larger g_{DM} :

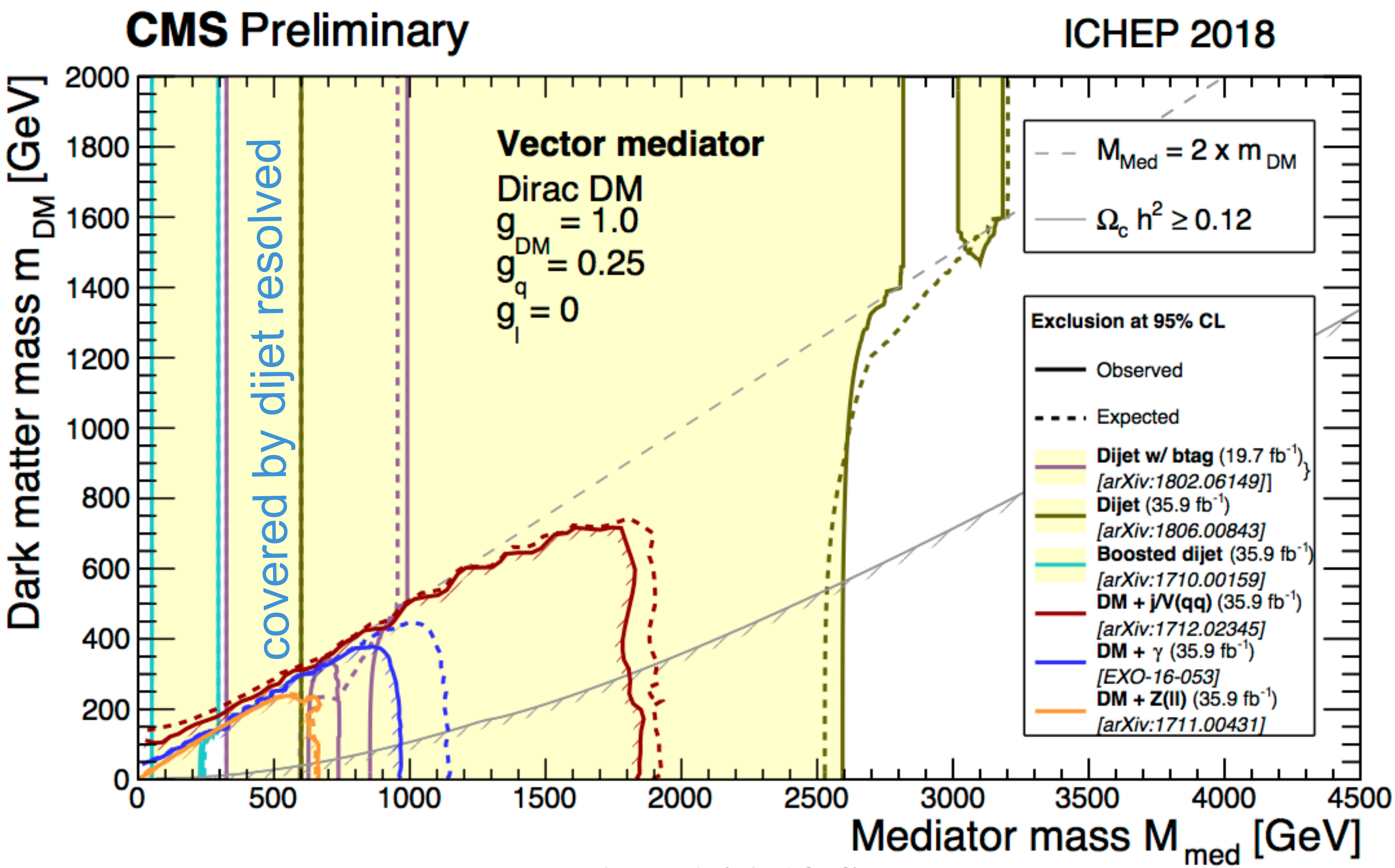
- Smaller BR(Z'->qq)
- Larger BR(Z'->XX)

Same dijet limit on g_{DM}=0 translates into **weaker coupling on g_{DM}>0**



Smaller

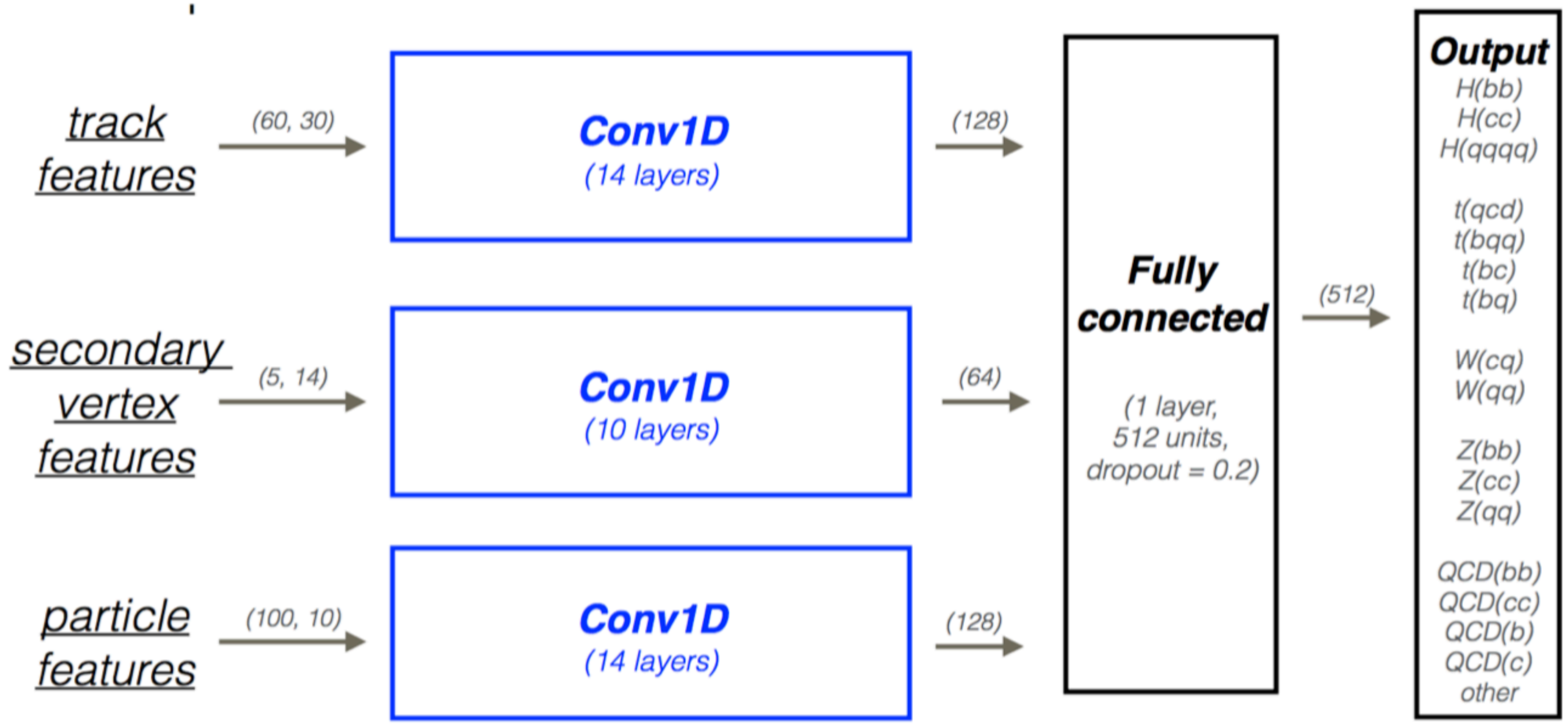
Sensitivity to DM



New directions

- Future luminosity gains will be small
  - $g_q^{95\%CL} \sim L^{1/4}$:(
- How to access **lower couplings**:
  - Improve **mass-decorrelated-tagger sensitivity**
  - Improve **QCD estimate**
- Explore other models that can be constrained with same topology
- Maybe access lower pT with scouting?

Tagger improvement



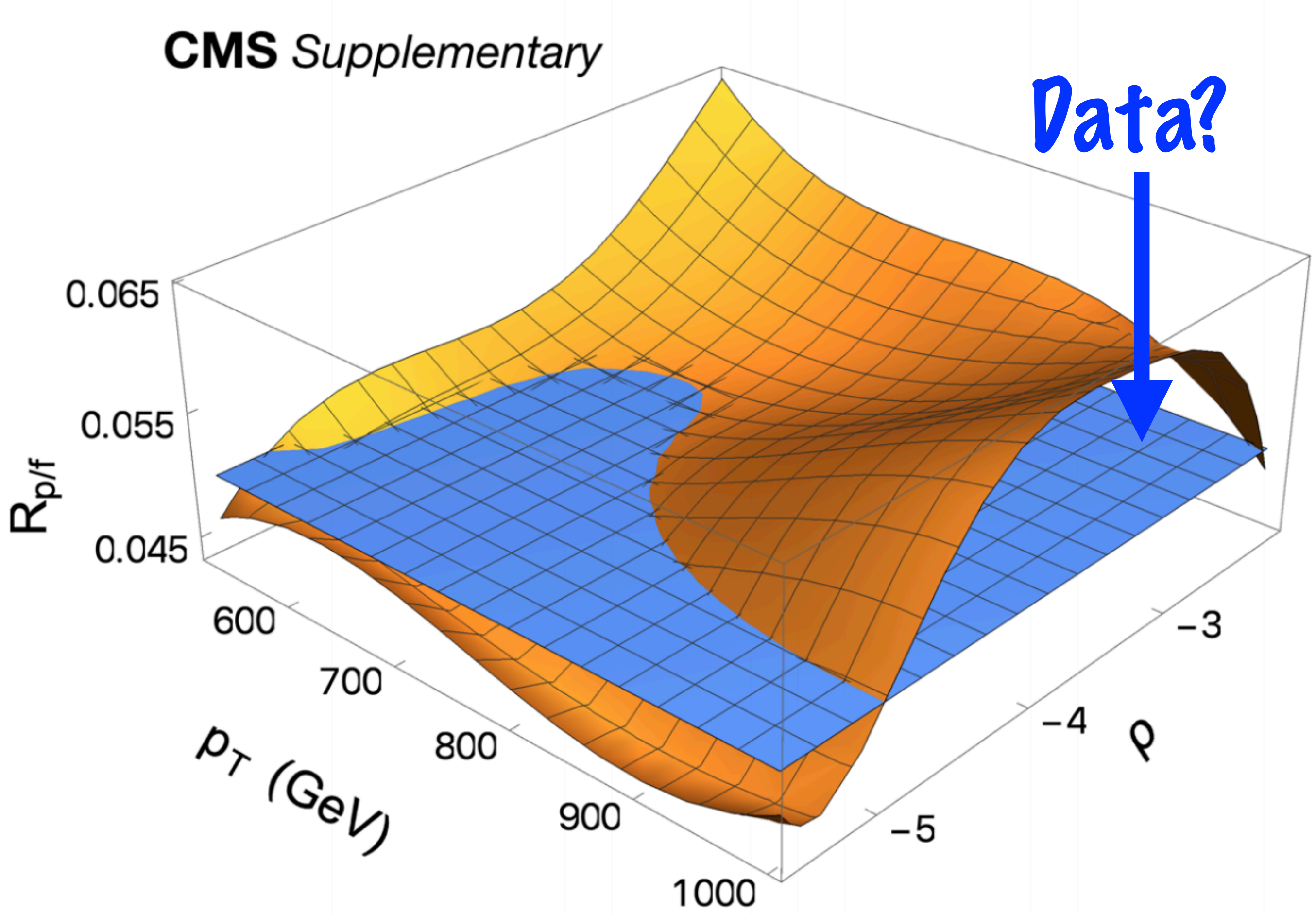
Different options in the ML market:

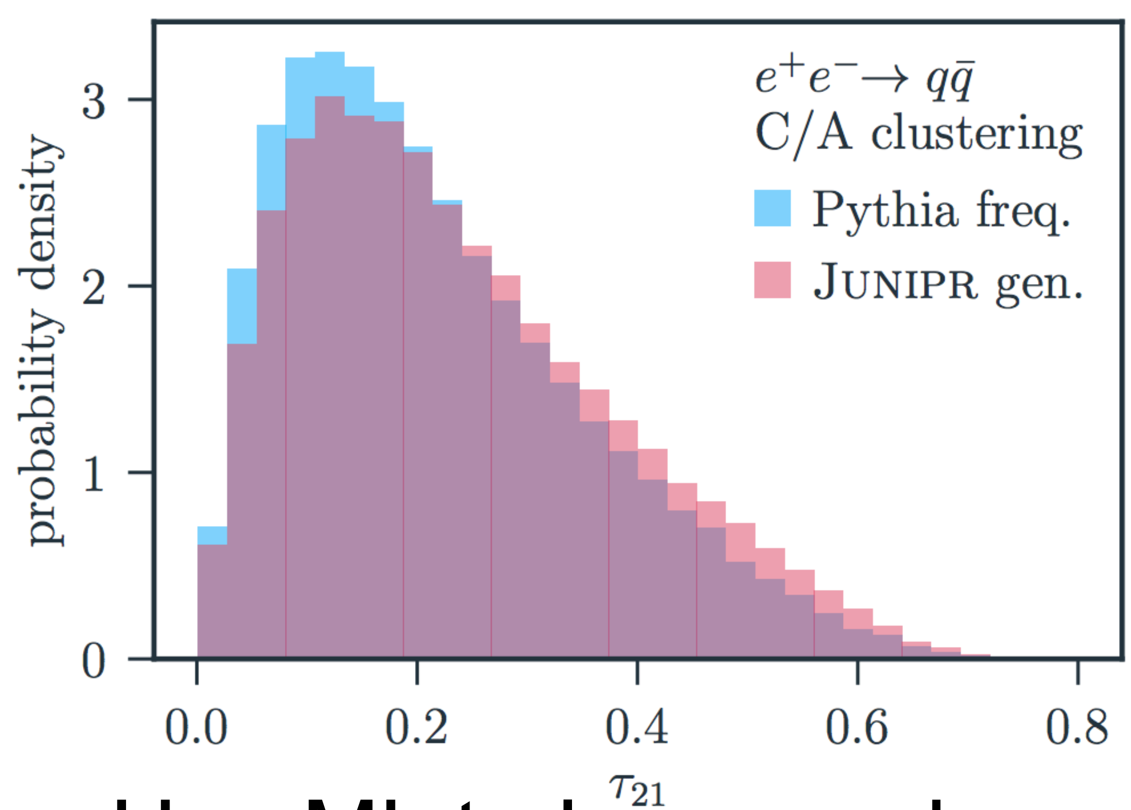
- e.g. DeepAK8 by CMS
- Need mass decorrelation:
    - Include adversarial network (trade off with performance)
    - Or train with flat mass spectrum..

QCD re-weighting

- Improve Rp/f by making QCD to look as similar as possible to data

https://arxiv.org/pdf/1804.09720.pdf





- Use ML to learn prob. distribution of multi jet evts (train in data and MC)

Summary

- Developed a **new approach** to look **for light boosted resonances**
  - ISR triggering + mass decorrelation
- Allows a **whole new program** of searches and measurements at LHC
  - **Boosted Z'/ϕ/Higgs** made possible at LHC
  - Moving forward @ RunII-III with ML for jets

Width constraints

https://arxiv.org/pdf/1404.3947.pdf

- From 1constraint on (mZ′, gq) space from hadronic Z width (Z ′ modifies Zqq vertex)

$$\frac{\Delta\Gamma_Z^{\text{had}}}{\Gamma_Z^{\text{had}}} = \frac{2 g_q c_Z c_W s_W (2V_u + 3V_d)}{3g(1 - m_{Z'}^2/m_Z^2)(2V_u^2 + 3V_d^2 + 5/16)}$$

Coupling conversion

Cross section for narrow s-channel resonance R

$$\hat{\sigma}(\sqrt{\hat{s}}) = \frac{16\pi\mathcal{N}\Gamma_R^2}{(\hat{s}-m_R^2)^2 + m_R^2\Gamma_R^2}$$

$$\sigma(1+2\to R) \approx 16\pi^2\mathcal{N} \times \mathrm{BR}(R\to 1+2) \times \left[\frac{1}{s}\frac{dL}{d\tau}\right]_{\tau=m_R^2/s} \times \frac{\Gamma_R}{m_R},$$

For Z' $\sigma(R) \propto g_q^2.$