The Jet Energy Profile: A BSM Analysis Tool

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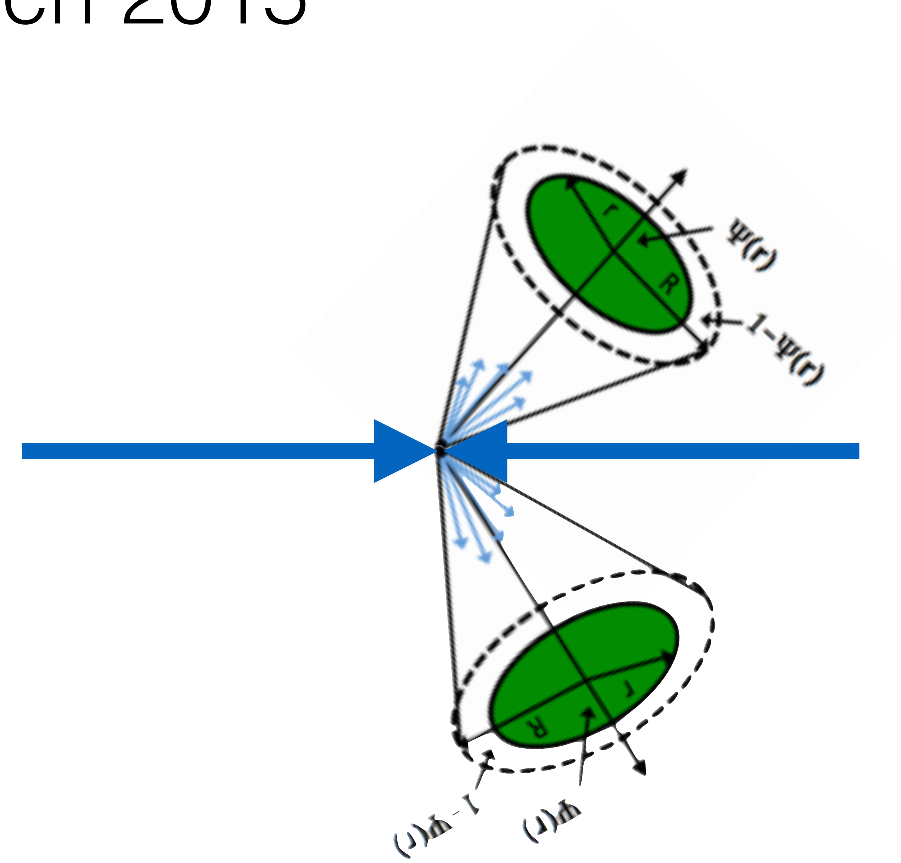
SCGT 15, March 2015

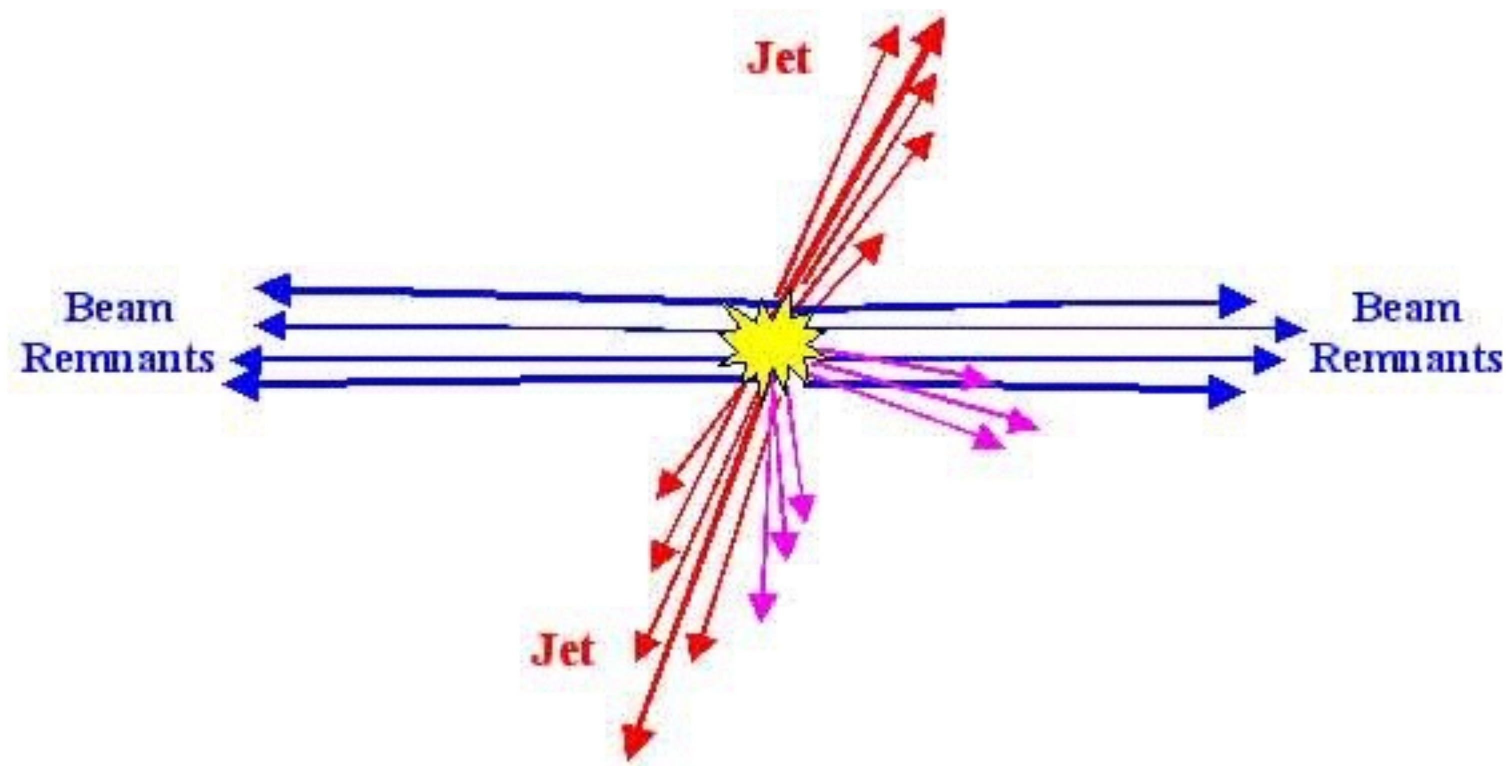


The Jet Energy Profile: A BSM Analysis Tool

- Dijets at the LHC: searching for new resonances
- Benchmark Resonances
- The Jet Energy Profile (JEP)
- Measuring the JEP - Examining New Resonances
- Conclusions

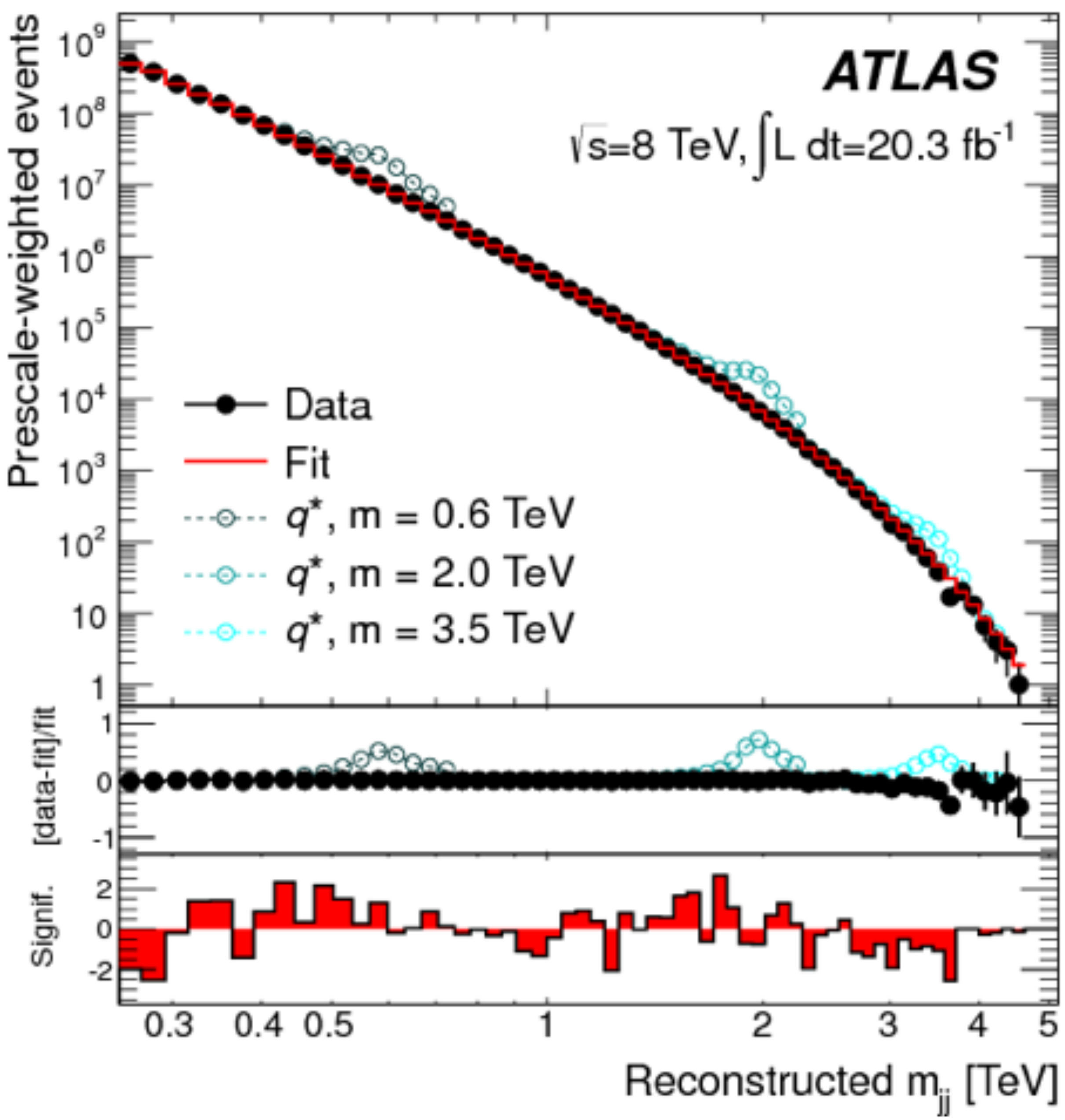
Based on RSC, EHS, & N. Vignaroli
arXiv: 1412.3094

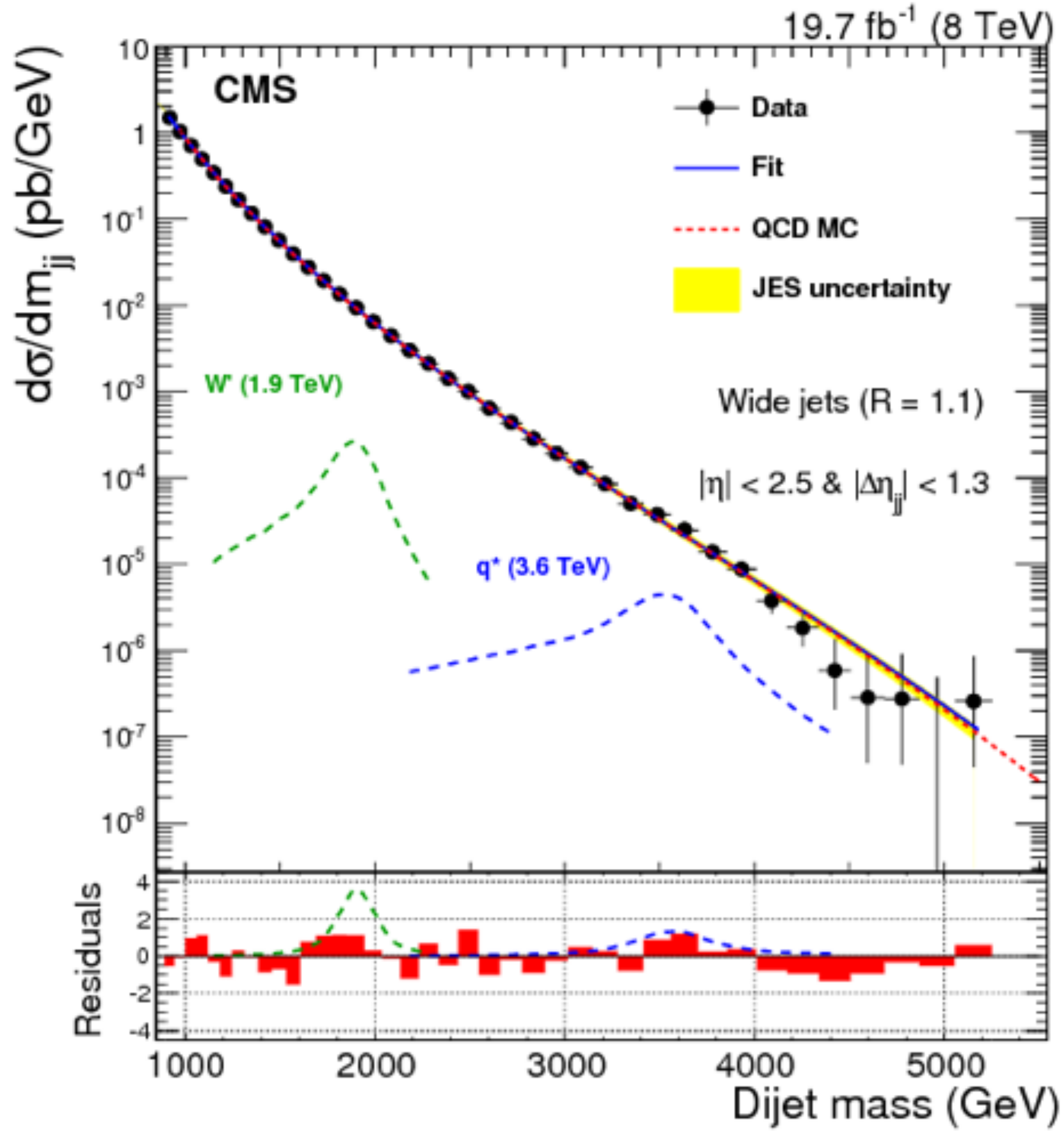
The LHC Produces Jets Copiously



New particles decaying to dijets can be produced to very large masses!

LHC Dijet Data





ATLAS, arXiv:1407.1376

CMS, arXiv:1501.04198

Possible Dijet Resonances

initial state	J	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$\lvert Q_e \rvert$	B
QQ	0	$\overline{\mathbf{3}} \oplus \mathbf{6}$	$\mathbf{1} \oplus \mathbf{3}$	$\frac{1}{3}$	$\frac{4}{3}, \frac{2}{3}, \frac{1}{3}$	$\frac{2}{3}$
QU	1	$\overline{\mathbf{3}} \oplus \mathbf{6}$	$\mathbf{2}$	$\frac{5}{6}$	$\frac{4}{3}, \frac{1}{3}$	$\frac{2}{3}$
QD	1	$\overline{\mathbf{3}} \oplus \mathbf{6}$	$\mathbf{2}$	$-\frac{1}{6}$	$\frac{2}{3}, \frac{1}{3}$	$\frac{2}{3}$
UU	0	$\overline{\mathbf{3}} \oplus \mathbf{6}$	$\mathbf{1}$	$\frac{4}{3}$	$\frac{4}{3}$	$\frac{2}{3}$
DD	0	$\overline{\mathbf{3}} \oplus \mathbf{6}$	$\mathbf{1}$	$-\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
UD	0	$\overline{\mathbf{3}} \oplus \mathbf{6}$	$\mathbf{1}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{2}{3}$
QA	$\frac{1}{2}, \frac{3}{2}$	$\mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15}$	$\mathbf{2}$	$\frac{1}{6}$	$\frac{2}{3}, \frac{1}{3}$	$\frac{1}{3}$
UA	$\frac{1}{2}, \frac{3}{2}$	$\mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15}$	$\mathbf{1}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{1}{3}$
DA	$\frac{1}{2}, \frac{3}{2}$	$\mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15}$	$\mathbf{1}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
AA	0, 1, 2	$\mathbf{1} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{27}$	$\mathbf{1}$	0	0	0
$Q\bar{Q}$	1	$\mathbf{1} \oplus \mathbf{8}$	$\mathbf{1} \oplus \mathbf{3}$	0	1, 0	0
$Q\bar{U}$	0	$\mathbf{1} \oplus \mathbf{8}$	$\mathbf{2}$	$-\frac{1}{2}$	1, 0	0
$Q\bar{D}$	0	$\mathbf{1} \oplus \mathbf{8}$	$\mathbf{2}$	$\frac{1}{2}$	1, 0	0
$U\bar{U},\ D\bar{D}$	1	$\mathbf{1} \oplus \mathbf{8}$	$\mathbf{1}$	0	0	0
$U\bar{D}$	1	$\mathbf{1} \oplus \mathbf{8}$	$\mathbf{1}$	1	1	0

(NB: Colored resonances cannot decay solely to leptons)

Han, Lewis, Liu arXiv:1010.4309

If a new resonance is discovered, and decays only to dijets, can we determine what it is and how it decayed?

To illustrate: consider three benchmark possibilities

$Q\bar{Q}$ Resonances:
A Coloron

Color Octet Vector Resonances

Gauge bosons from extended color groups:

Classic Axigluon: P.H. Frampton and S.L. Glashow, Phys. Lett. B 190, 157 (1987).

Topgluon: C.T. Hill, Phys. Lett. B 266, 419 (1991).

Flavor-universal Coloron: R.S. Chivukula, A.G. Cohen, & E.H. Simmons, Phys. Lett. B 380, 92 (1996).

Chiral Color with $g_L \neq g_R$: M.V. Martynov and A.D. Smirnov, Mod. Phys. Lett. A 24, 1897 (2009).

New Axigluon: P.H. Frampton, J. Shu, and K. Wang, Phys. Lett. B 683, 294 (2010).

Similar color-octet states:

KK gluon: H. Davoudiasl, J.L. Hewett, and T.G. Rizzo, Phys. Rev. D63, 075004 (2001)
B. Lillie, L. Randall, and L.-T. Wang, JHEP 0709, 074 (2007).

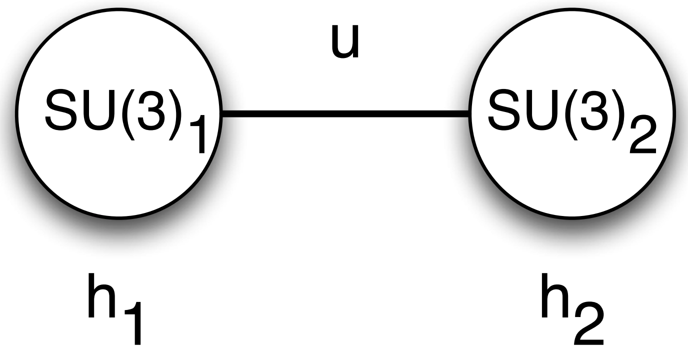
Techni-rho: E. Farhi and L. Susskind, Physics Reports 74, 277 (1981).

More exotic colored states:

Color sextets, colored scalars, low-scale scale string resonances...

T. Han, I. Lewis, Z. Liu, JHEP 1012, 085 (2010).

Coloron Models: Gauge Sector



SU(3)$_1$ x SU(3)$_2$ color sector with $$M^2 = \frac{u^2}{4}\begin{pmatrix} h_1^2 & -h_1 h_2 \\ -h_1 h_2 & h_2^2 \end{pmatrix}$$

unbroken subgroup: SU(3)$_{1+2}$ = SU(3)$_{QCD}$

$$h_1 = \frac{g_s}{\cos\theta} \qquad h_2 = \frac{g_s}{\sin\theta}$$

gluon state: $$G_\mu^A = \cos\theta\, A_{1\mu}^A + \sin\theta\, A_{2\mu}^A$$

couples to: $$g_S J_G^\mu \equiv g_S(J_1^\mu + J_2^\mu) \qquad M_G = 0$$

coloron state: $$C_\mu^A = -\sin\theta\, A_{1\mu}^A + \cos\theta\, A_{2\mu}^A \qquad M_C = \frac{u}{\sqrt{2}}\sqrt{h_1^2 + h_2^2}$$

couples to: $$g_S J_C^\mu \equiv g_S(-J_1^\mu \tan\theta + J_2^\mu \cot\theta)$$

Quarks' SU(3)$_1$ x SU(3)$_2$ charges impact phenomenology

Matter Couplings

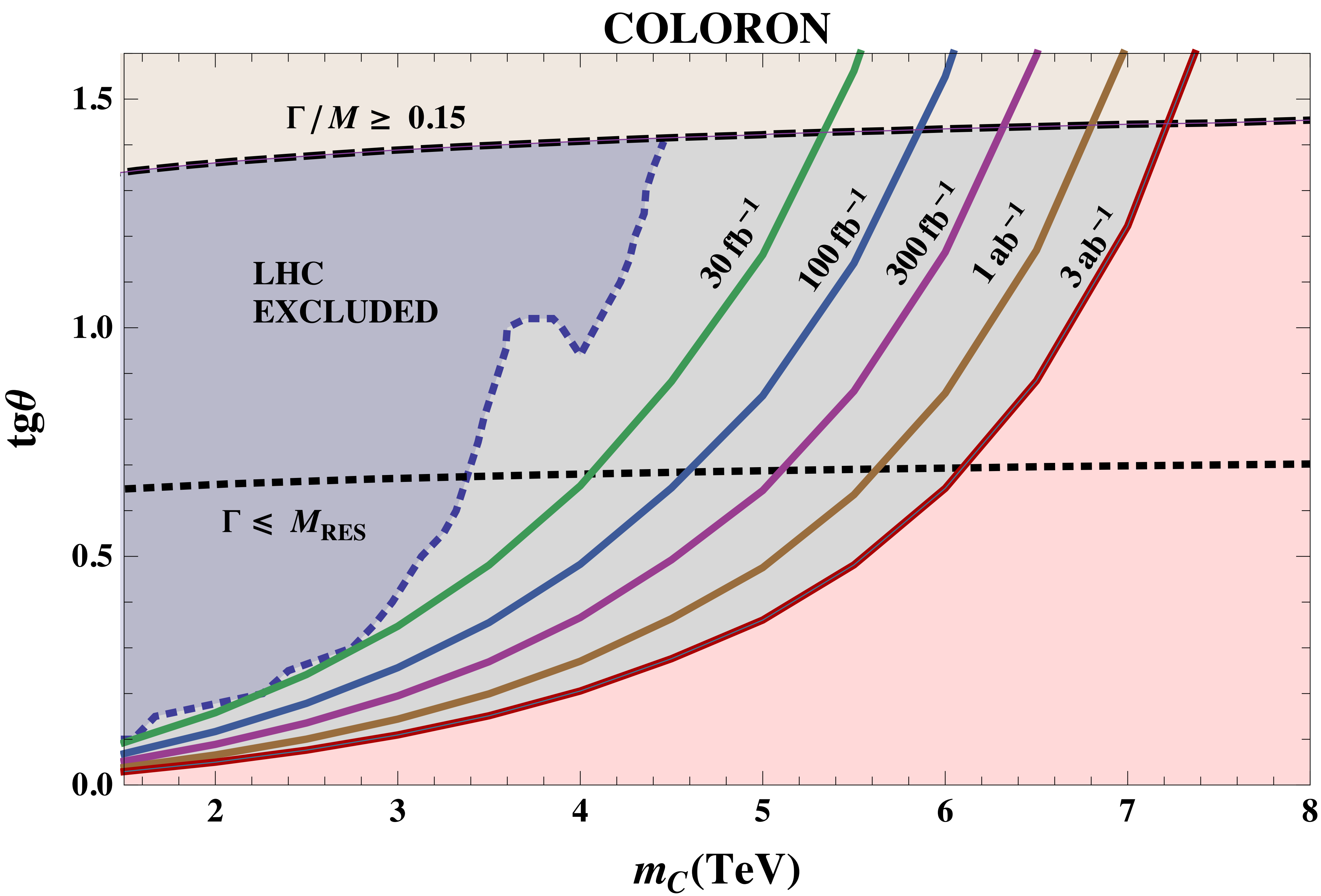
$SU(3)_1$	$SU(3)_2$	model	pheno.
Benchmark	$(t,b)_L$ q_L t_R,b_R q_R	**coloron**	dijet
q_R	$(t,b)_L$ q_L t_R,b_R		
t_R,b_R	$(t,b)_L$ q_L q_R		
q_L	$(t,b)_L$ t_R,b_R q_R		
q_L t_R,b_R	$(t,b)_L$ q_R	**new axigluon**	dijet, A^t_{FB}, FCNC
q_L q_R	$(t,b)_L$ t_R,b_R	**topgluon**	dijet, tt, bb, FCNC, R_b...
t_R,b_R q_R	$(t,b)_L$ q_L	**classic axigluon**	dijet, A^t_{FB}
q_L t_R,b_R q_R	$(t,b)_L$		

q = u,d,c,s

Estimated LHC Reach: Signal Jet Selection

- $p_T > 30$ GeV, $|\eta| < 2.5$
- t-channel rejection: $|\Delta\eta| < 1.3$
- Inspired by CMS cuts, arXiv:1501.04198
- Acceptance rates: 50% - 60% for benchmark models

14 TeV LHC Reach: Flavor Universal Coloron



Qg Resonances:
An “Excited” Quark

Excited Quarks & Heavy Vector Partners

- Composite Quark Models
- Composite Higgs
- Extra-Dimensional Models

Benchmark: Doublet Partner of First-Generation

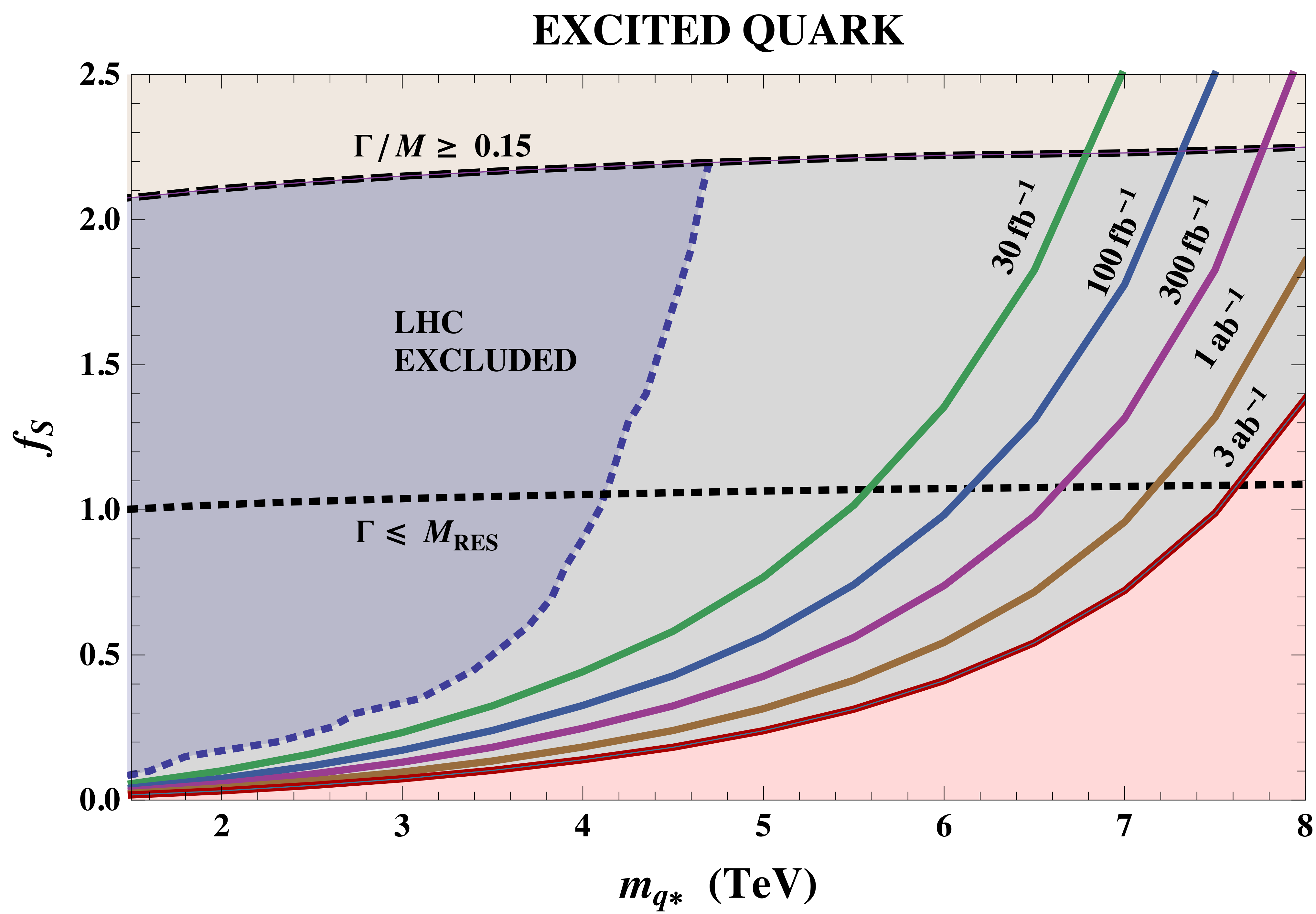
$$\mathcal{L}_{int} = \frac{1}{2\Lambda}\bar{q}^{*}_{R}\sigma^{\mu\nu}\left[g_S f_S \frac{\lambda^a}{2} G^a_{\mu\nu} + g f \frac{\tau}{2}\cdot \mathbf{W}_{\mu\nu} + g^{'} f^{'} \frac{Y}{2} B_{\mu\nu}\right] q_L + \text{H.c.}$$

$$\Gamma(q^* \to qg) = \frac{1}{3}\alpha_S f_S^2 \frac{m^3_{q*}}{\Lambda^2}$$

Following ATLAS & CMS, take: $\Lambda = m_{q^*}$

Baur, Spira, Zerwas: PRD 42 (1990) 815.

14 TeV LHC Reach: Excited First-Generation Doublet



gg Resonance: Color Singlet or Octet Scalars

Colored Scalars

- Models with an extended color sector
- Dynamical EWSB with colored constituents
- Extra-Dimensional Models

Benchmark Model: Color Octet Scalar

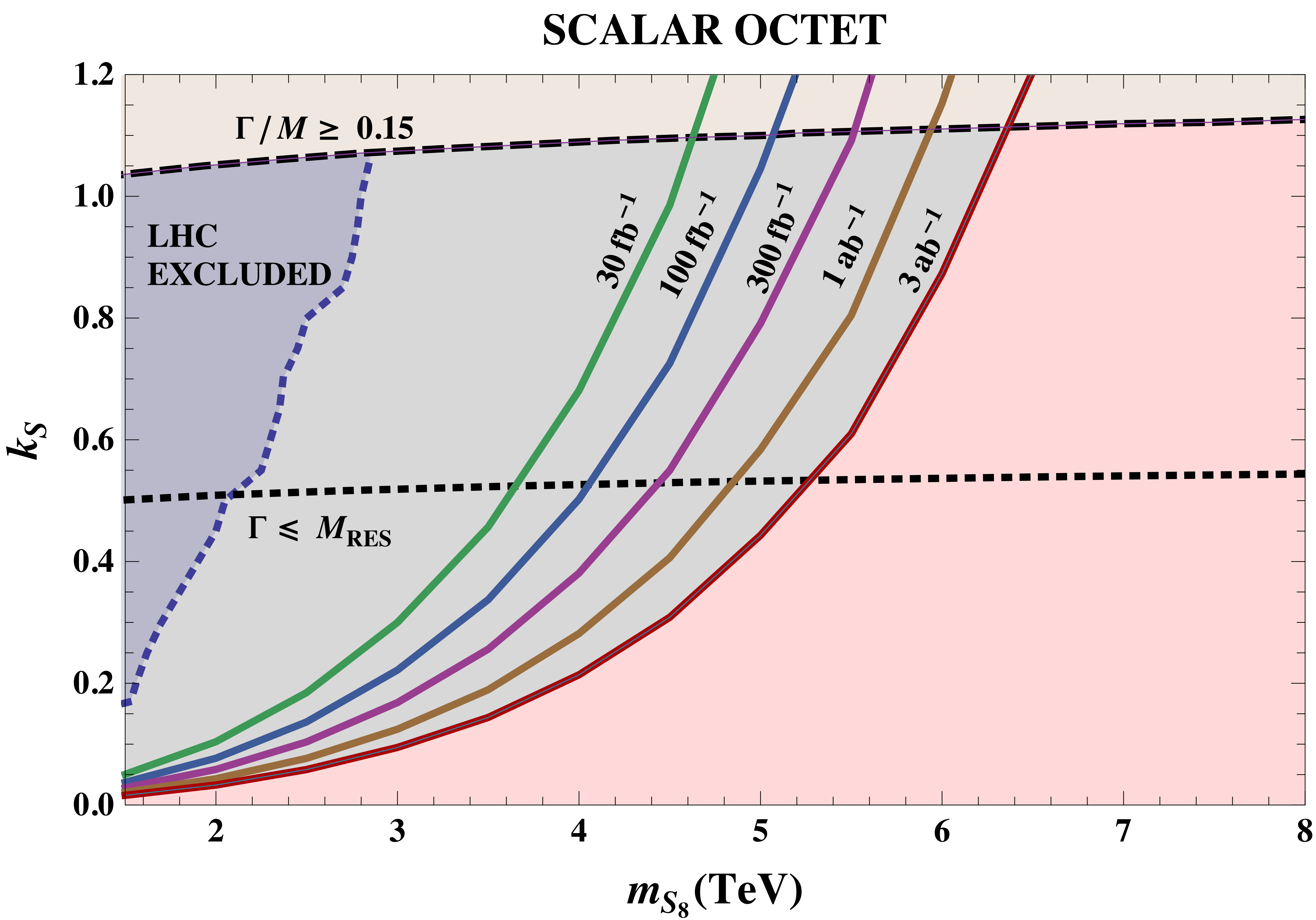
$$\mathcal{L}_{S_8} = g_S d^{ABC} \frac{k_S}{\Lambda_S} S_8^A G_{\mu\nu}^B G^{C,\mu\nu}$$

$$\Gamma(S_8) = \frac{5}{3} \alpha_S \frac{k_S^2}{\Lambda_S^2} m_{S_8}^3$$

Following ATLAS & CMS, take: $\Lambda_S = m_{S_8}$

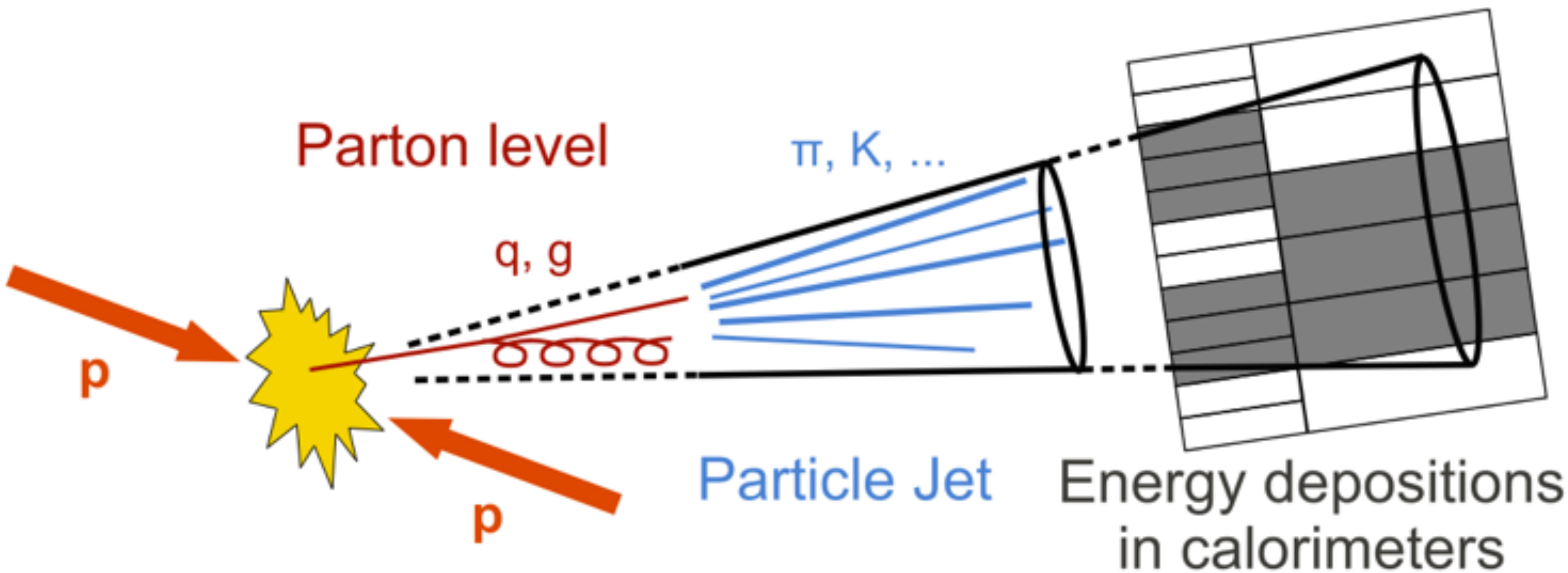
Han, Lewis, Liu arXiv:1010.4309

14 TeV LHC Reach: Color Octet Scalar



The Jet Energy Profile

Gluons radiate more than Quarks



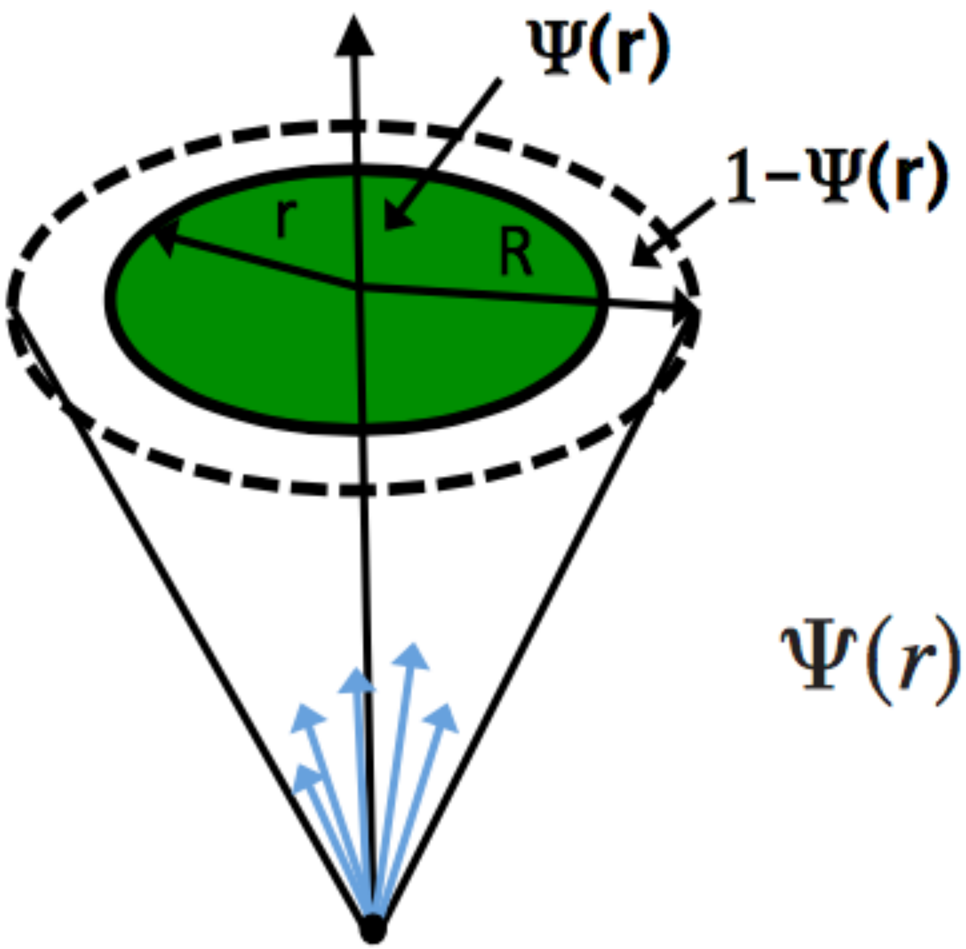
Quarks: $C_F=4/3$ Gluons: $C_A=3$

Question: How does this tendency manifest after showering in a real detector?

See, for example, Ellis, Kunszt, Soper PRL 69 (1992) 3615

Integrated Jet Shape

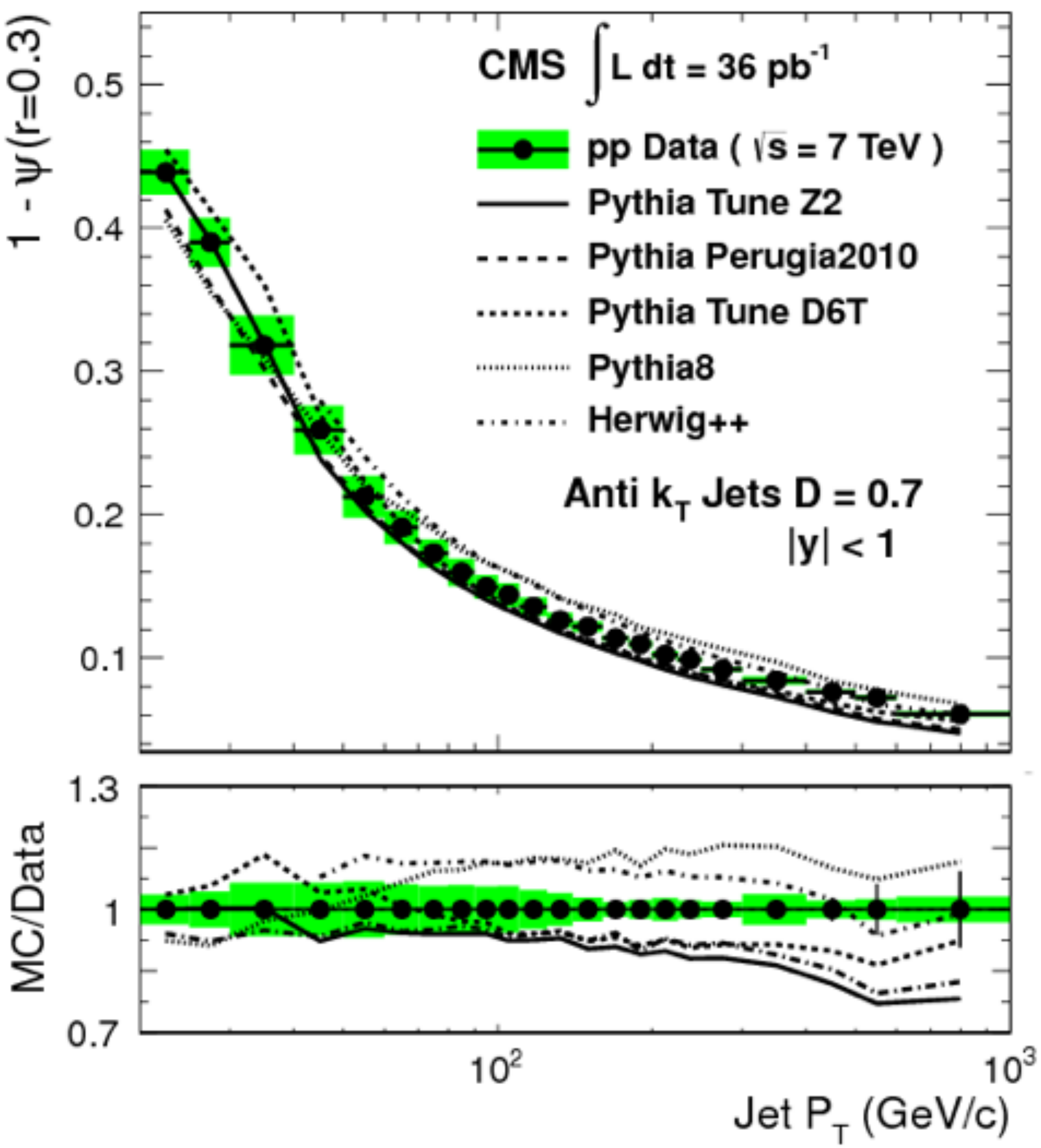
Average fraction of jet p_T lying within a sub-cone of radius r:



Expect quarks form “tighter” jets than gluons, for fixed p_T

$$\Psi(r) = \frac{1}{N^{\text{jet}}} \sum_{\text{jets}} \frac{p_T(0, r)}{p_T(0, R)}, \qquad 0 \le r \le R,$$

CMS Measurements

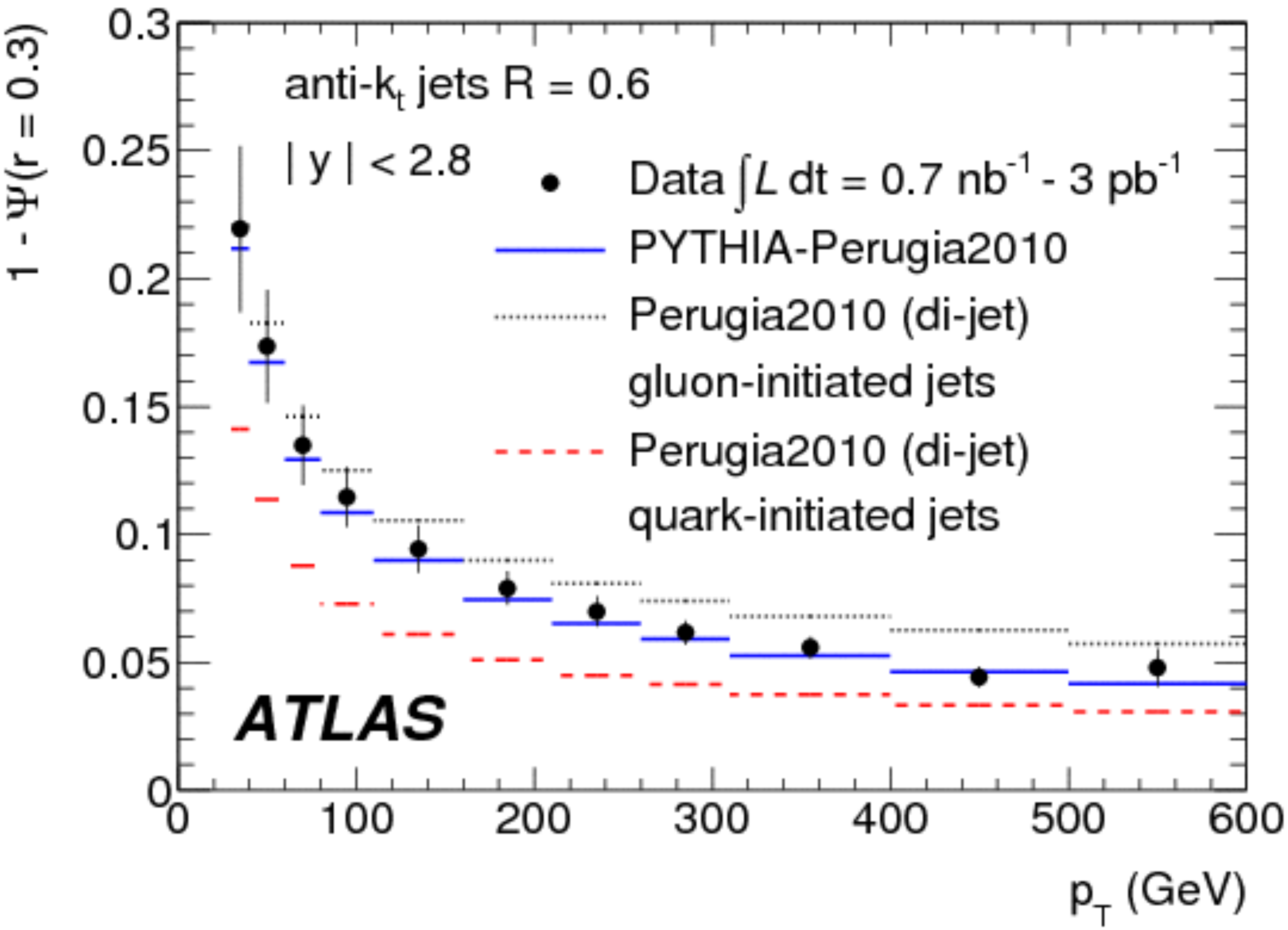


Combination of kinematic and compositional effects!

Good agreement between data and MC (“tuning” required)

CMS, JHEP 1206 (2012) 160

ATLAS Measurements



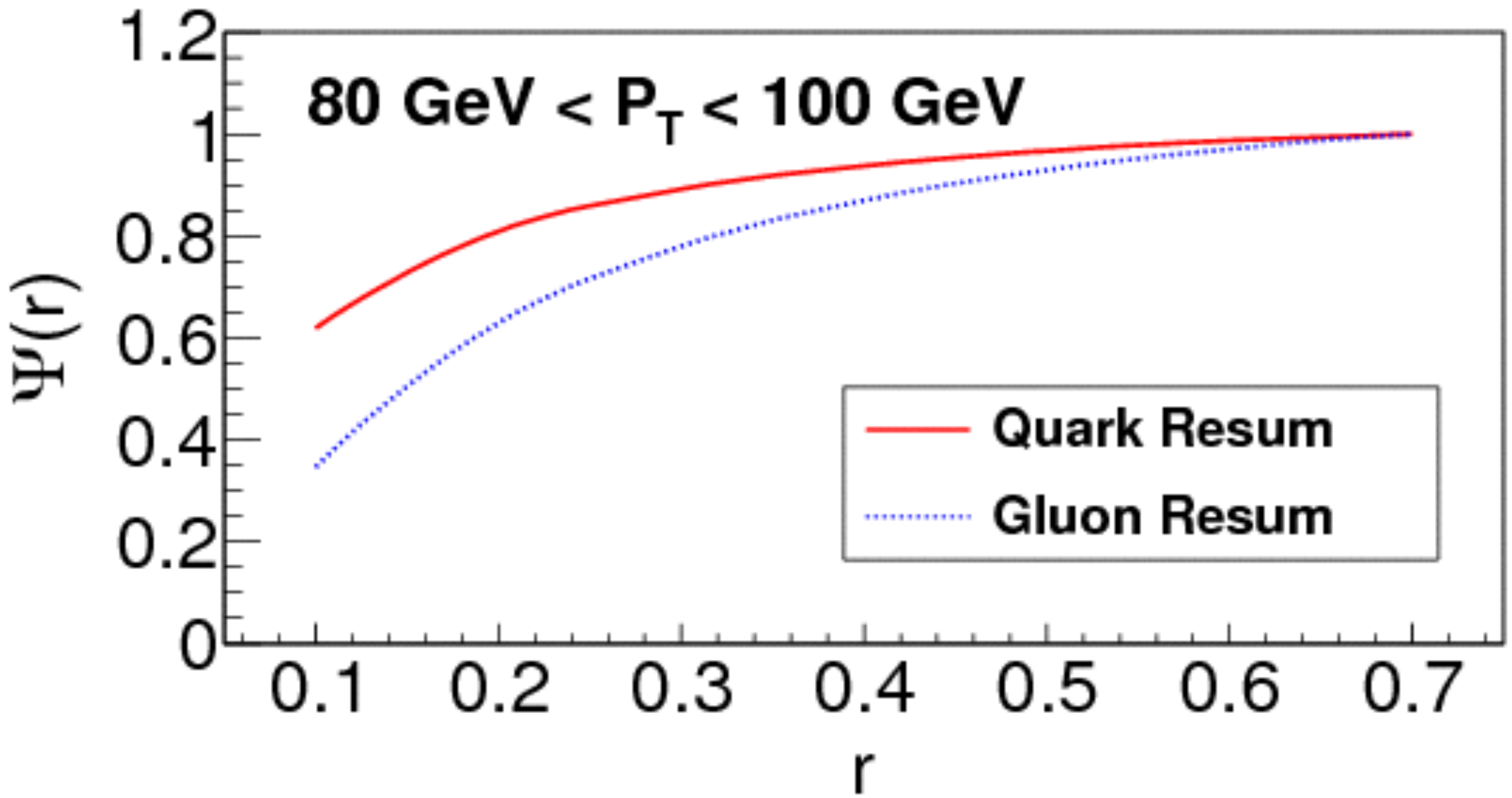
Note difference for quark vs. gluon jets, and change consistent with increasing quark-jet fraction

ATLAS, PRD 83 (2011) 052003

A dijet resonance changes the quark/gluon composition in the resonance region:

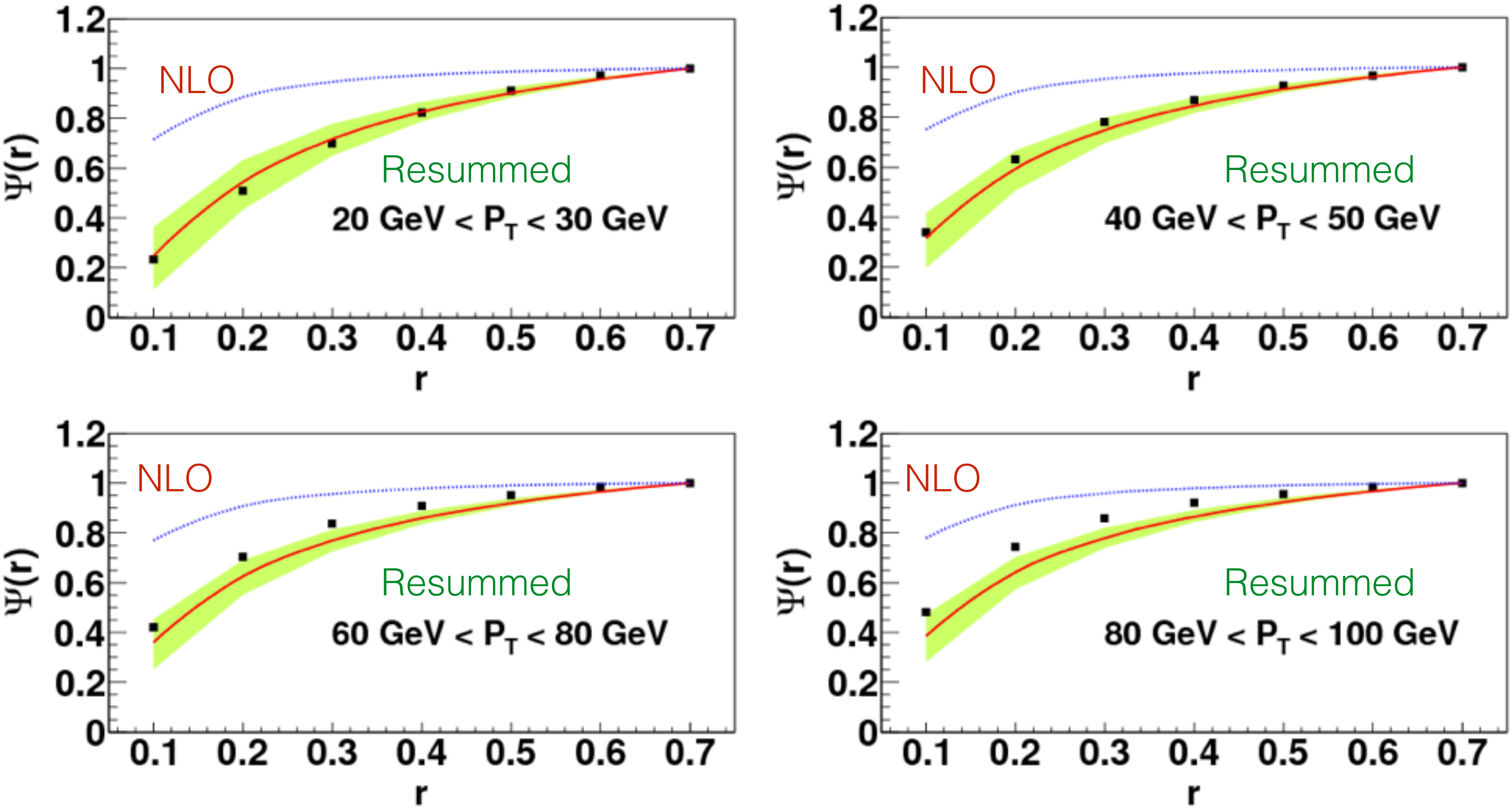
Can we see this using measurements of the jet energy profile?

Analytical Tool for Understanding Quark/Gluon Jets: NLL Resummation



Collins, Soper, Sterman, PRD 71 (2005) 112002
Li, Li, Yuan, PRL 107 (2011) 152001
PRD 87 (2013) 074025

Model vs. CMS Data



Li, Li, Yuan, PRD 87 (2013) 074025

Limitations of JEP Model

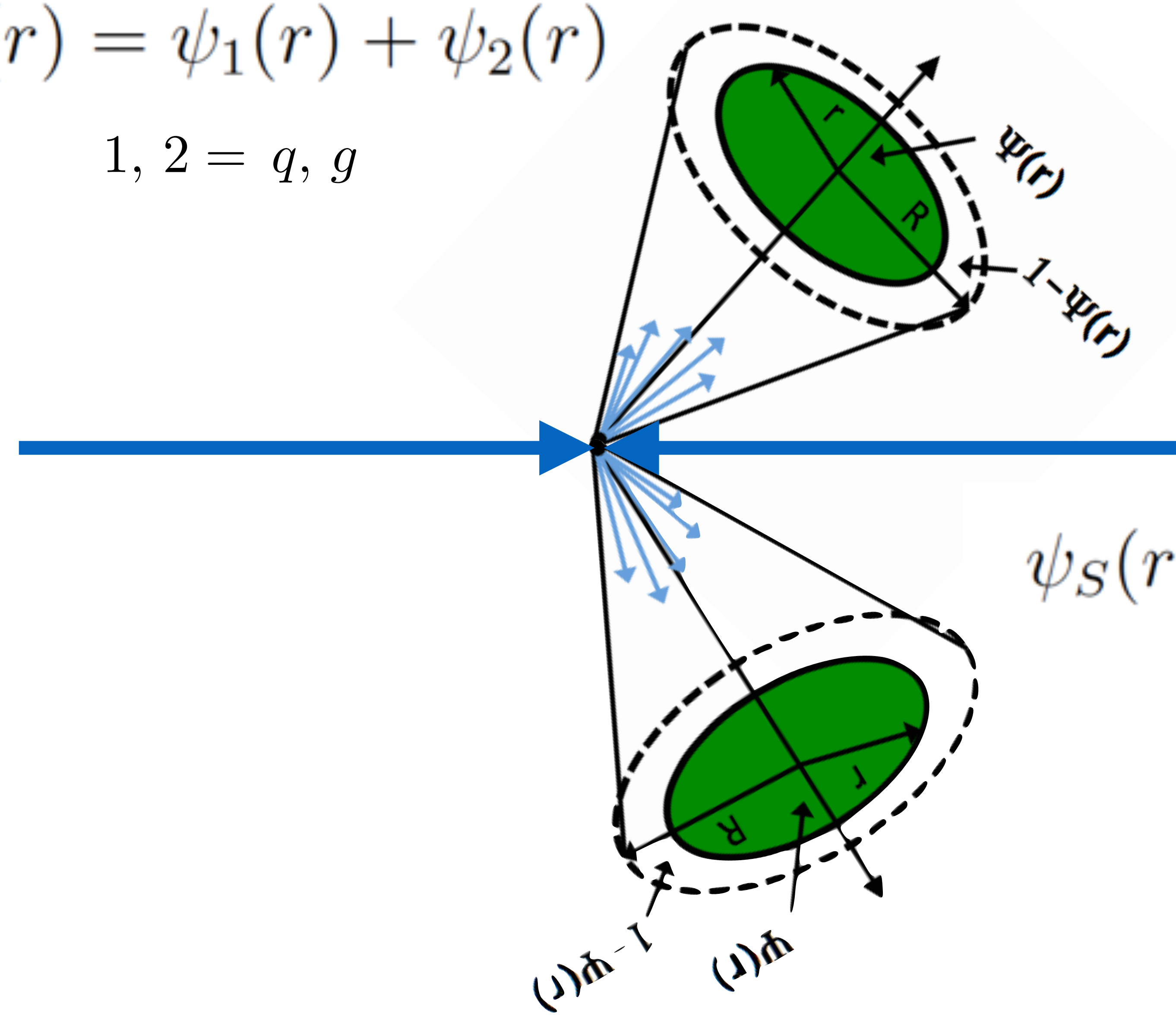
- NLL resummation model used to estimate sensitivity of jet energy profile measurements to presence of a new dijet resonance.
- Model includes two phenomenological parameters, which will need to fixed; will be done once LHC data is available. (Will use Tevatron “tune” for statistical analysis.)
- Note: not really dependent on model *correctly predicting* JEP — rather, as a model of size of change in resonance region.
- Will show statistical discrimination present - will leave systematic errors to the experts, the experimenters!

Measuring the
Jet Energy Profile

Warm-Up: Signal Only

$$\psi_{jj}(r) = \psi_1(r) + \psi_2(r)$$

$1,\, 2 = q,\, g$



$$\psi_S(r) = f\psi_{\bar{q}q}(r) + (1-f)\psi_{gg}(r)$$

$$\begin{aligned} f &= 0.0 \quad (C_\mu^A) \\ &= 0.5 \quad (q^*) \\ &= 1.0 \quad (S_8^A) \end{aligned}$$

$\Delta f = 0.1 \Rightarrow 5\sigma$ discrimination

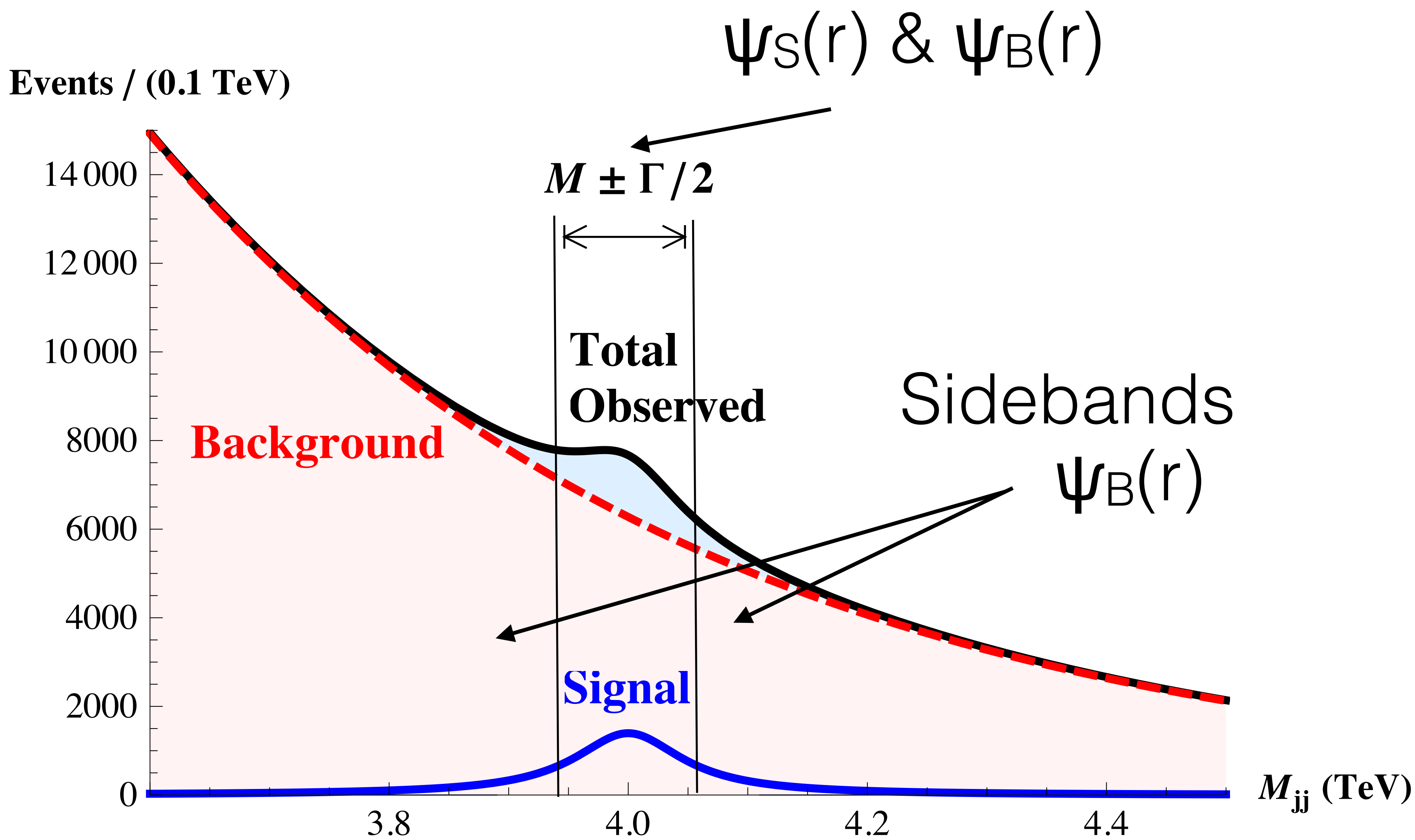
Measuring "*f*"

Benchmark Resonance Parameters:
4 TeV C (tanθ=0.60), q* (f_S=0.4), S_8 (k_S=0.65)
(not excluded, observable with 30 fb^{-1} @ 14 TeV)

- MC Simulations of <u>signal events</u>
  - Madgraph v.5, Pythia v.6
- Fastjet clustering, anti-k_T, R=0.5
- Consider events with $|M_{jj}-M| < \Gamma/2$
- Examine $\psi_S(r)$ in each MC event
- Accumulate to determine statistical error in $\psi_S(r)$
- Find uncertainty is Gaussian (Poisson errors)
- Statistical Errors Only

$$(\delta\psi_S(0.1))^2 \approx \frac{\sigma^2(0.1)}{S} \quad \text{with} \quad \sigma(0.1) \approx 0.4$$

Signal Plus Background



Errors in $\psi_S(r)$ and $\psi_B(r)$
scale the same way: $(\delta\psi_{OBS}(r))^2 \approx \frac{\sigma^2(r)}{S+B}$ $\quad (\delta\psi_B(r))^2 \approx \frac{\sigma^2(r)}{B}$

Uncertainties including Background

$$\psi_{OBS}(r) = \frac{S}{S+B}\psi_S(r) + \frac{B}{S+B}\psi_B(r) \ ,$$

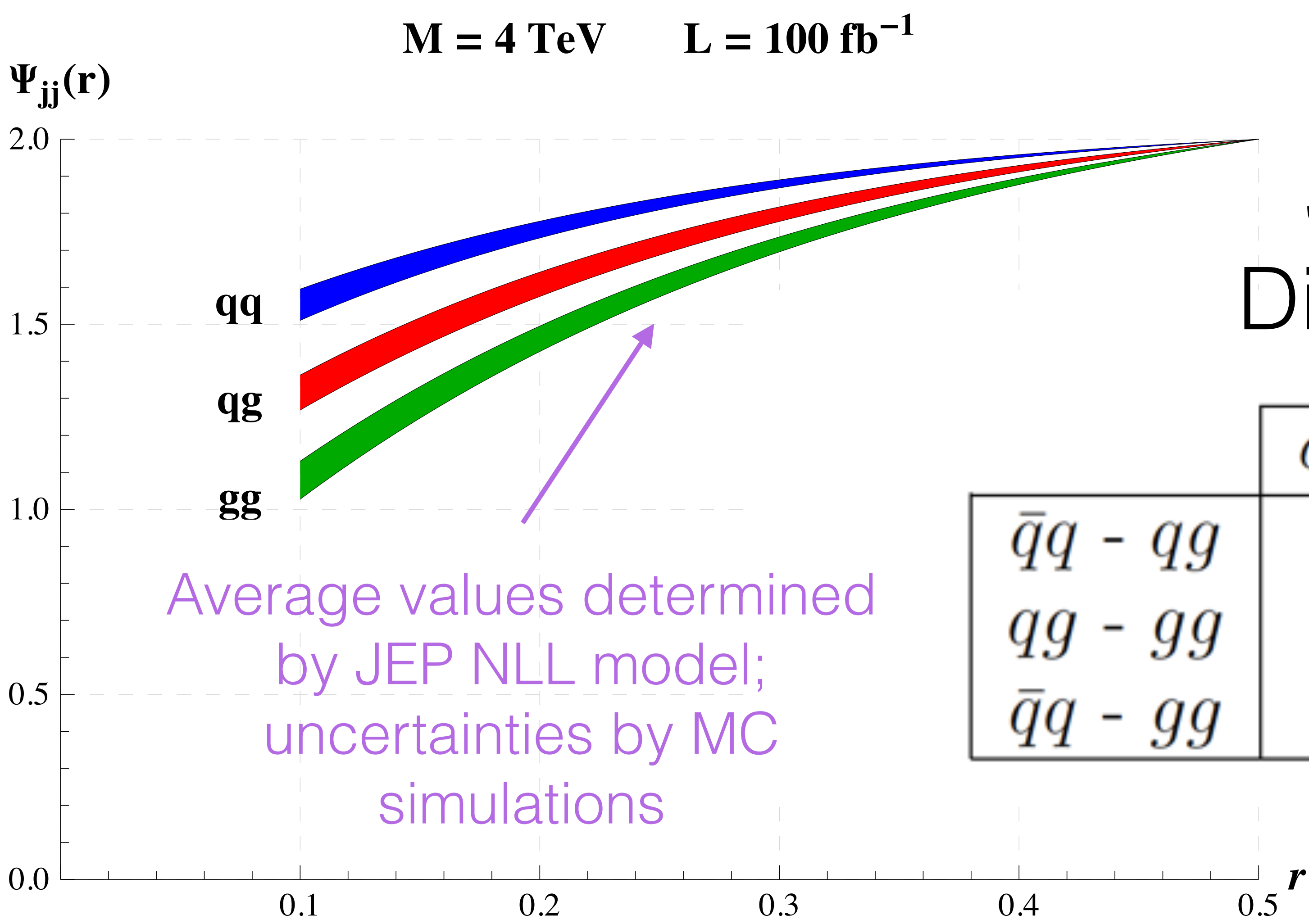
$$\psi_S(r) = \psi_{OBS}(r) + \frac{B}{S}(\psi_{OBS}(r) - \psi_B(r)) \ .$$

$$(\delta\psi_S)^2 \approx \frac{\sigma^2}{S}\left[1 + 2\frac{B}{S}\right] + \frac{(\psi_S - \psi_B)^2}{S}$$

Dilution due to background

Statistical Uncertainty due to signal

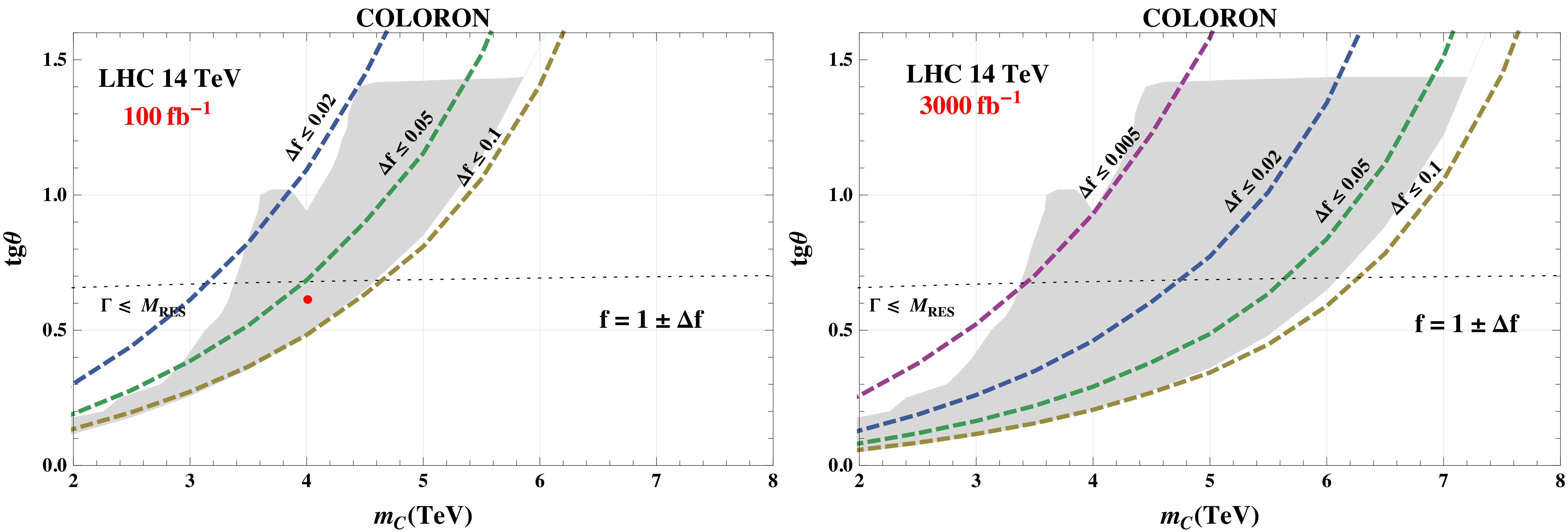
JEP Benchmark Measurements



JEP Measurement Discrimination Power:

	σ (L=100 fb^{-1})	L (5σ)
$\bar{q}q$ - qg	5.4	85
qg - gg	4.7	110
$\bar{q}q$ - gg	10	30

JEP Reach: Colorons

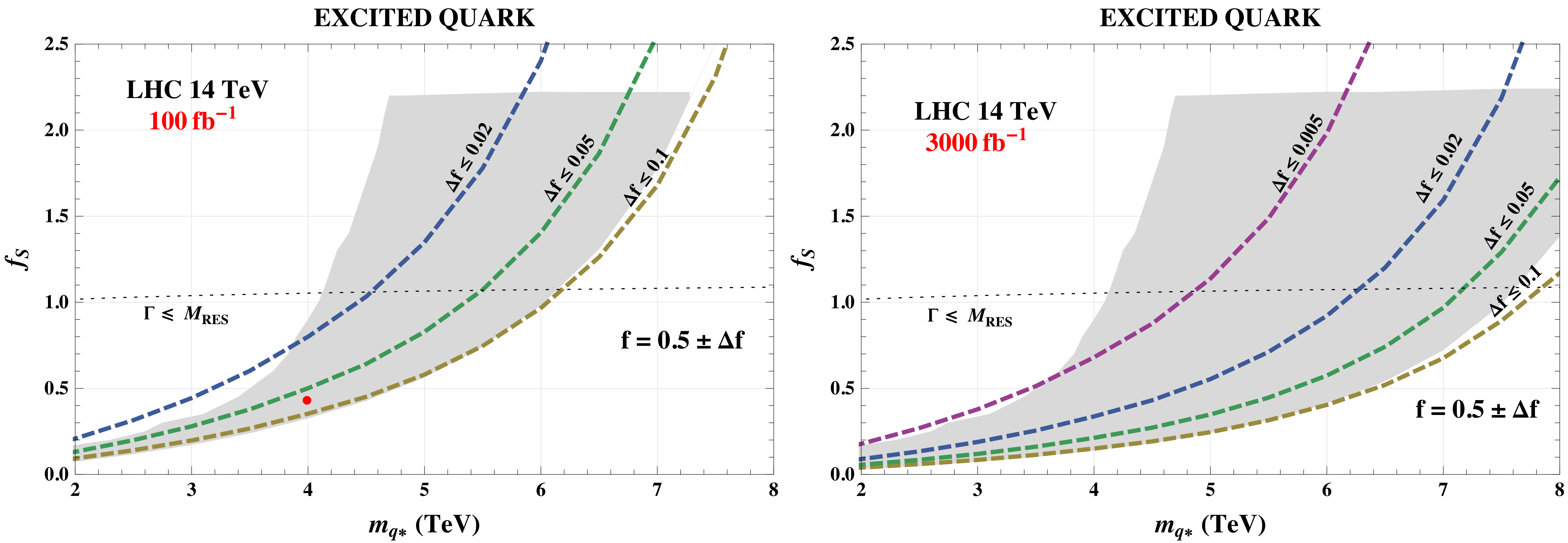


Grey Region: 5σ resonance discovery reach

Contours: $\Delta f \leq 0.1,\ 0.05,\ 0.02,\ 0.005$

Benchmark Point in Red

JEP Reach q*

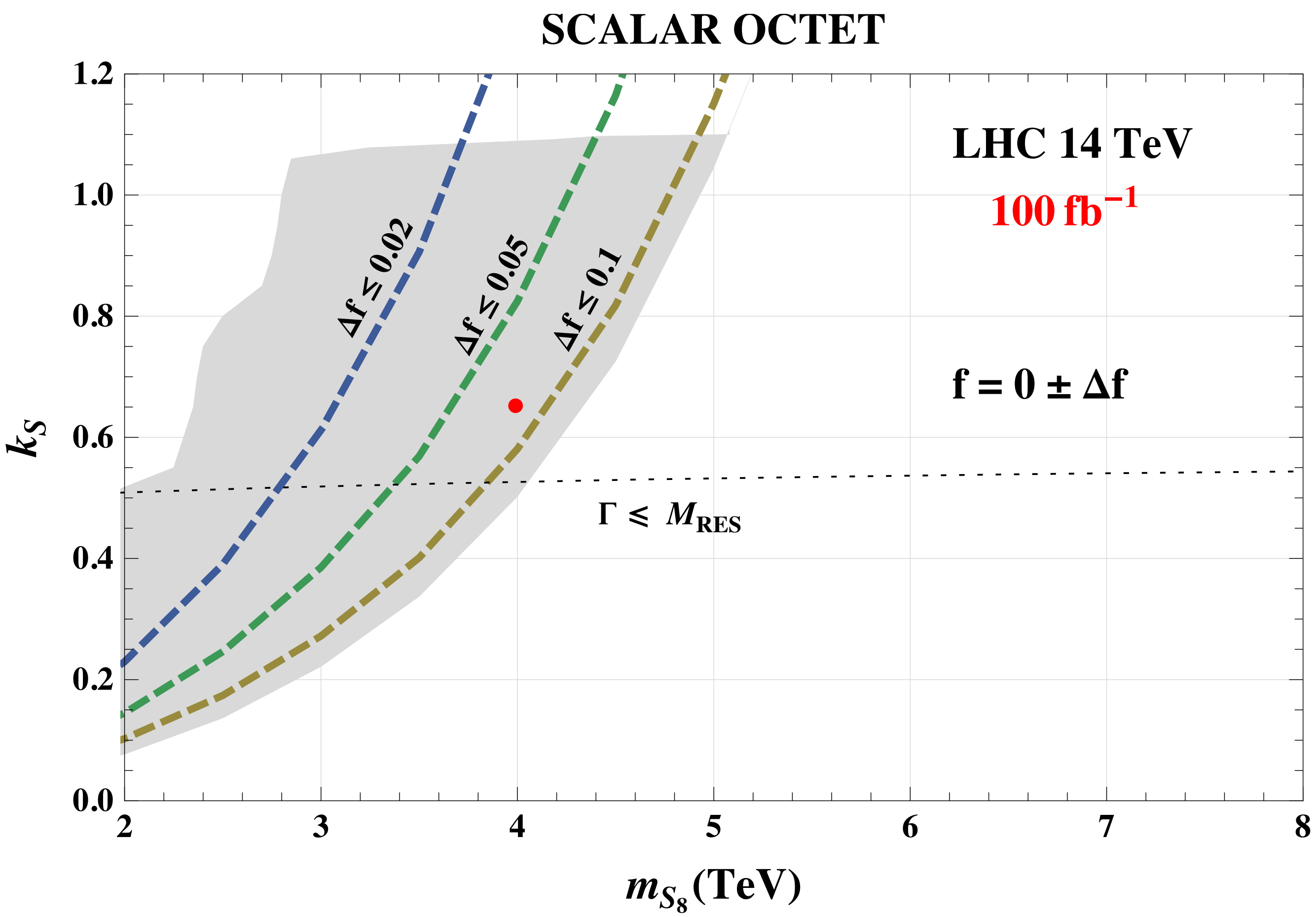


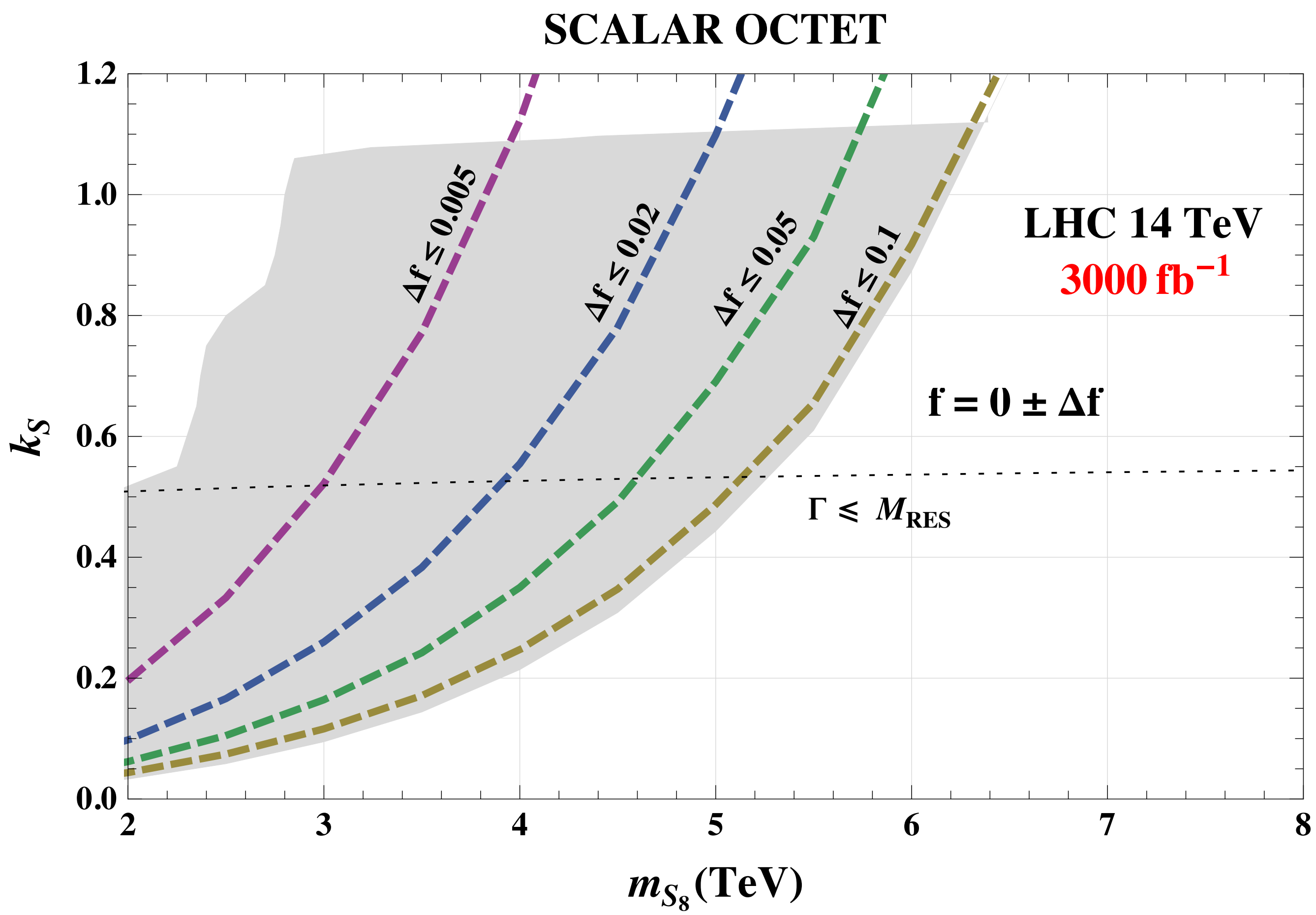
Grey Region: 5σ resonance discovery reach

Contours: $\Delta f \leq 0.1,\ 0.05,\ 0.02,\ 0.005$

Benchmark Point in Red

JEP Reach S_8





Grey Region: 5σ resonance discovery reach

Contours: $\Delta f \leq 0.1,\ 0.05,\ 0.02,\ 0.005$

Benchmark Point in Red

Comments

- *Statistical discriminating* power of JEPs strong - can potentially cover entire discovery region
- Systematic issues will dominate - area of active and growing interest at ATLAS and CMS.
- Potential improvements: trimming, pruning, grooming - although JEP less sensitive to underlying event than jet mass, etc.

Conclusions

- The run 2 (and beyond) LHC reach for new dijet resonances extends to very high energies - beyond 4-5 TeV.
- If a new resonance is discovered, and decays only to dijets, the JEP provides a potentially powerful tool to determine the nature of the resonance.
- The statistical power is there, the ultimate utility will depend on a detailed understanding of detector-dependent systematic issues.