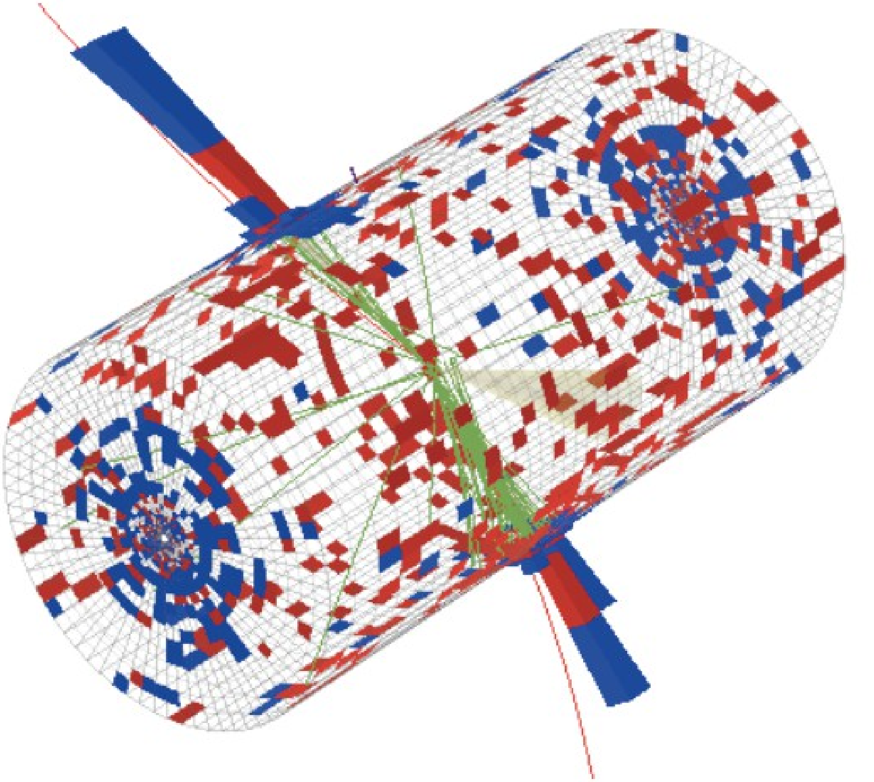
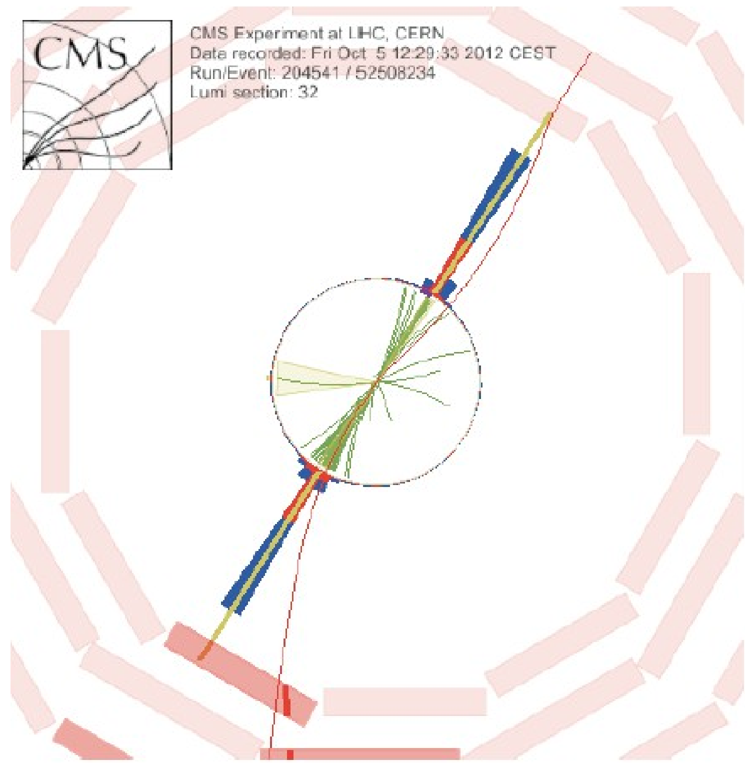
Distinguishing dijet resonances at the LHC using jet energy profiles





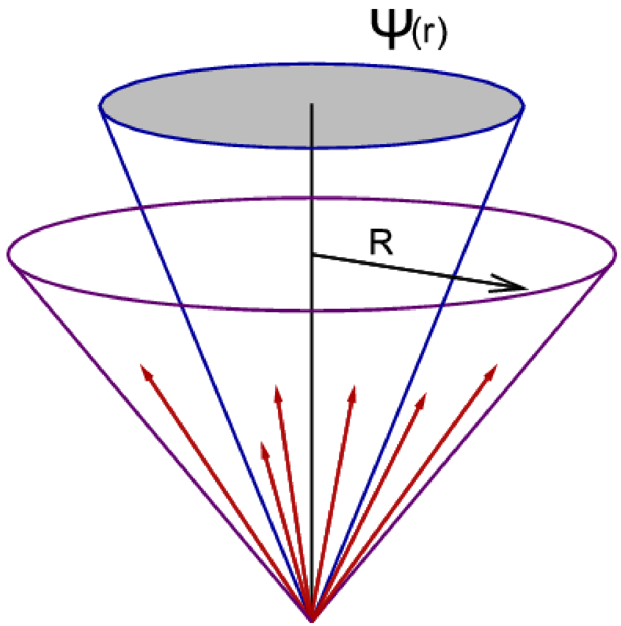
Based on:
R. S. Chivukula, E. H. Simmons, NV
Phys.Rev. D91 (2015) 5, 055019

Natascia Vignaroli

Michigan State University

Pheno 2015, Pittsburgh

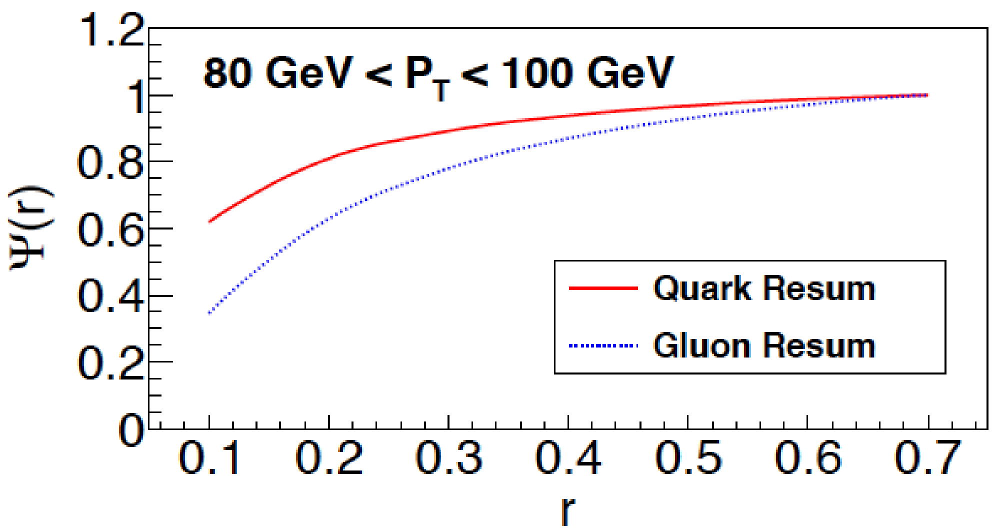
Jet Energy Profile



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

$$\psi(\mathbf{r}) = \frac{1}{N_j} \sum_j \frac{p_T(0, r)}{p_T(0, R)}$$

Quarks C_F=4/3 Gluons: C_A=3

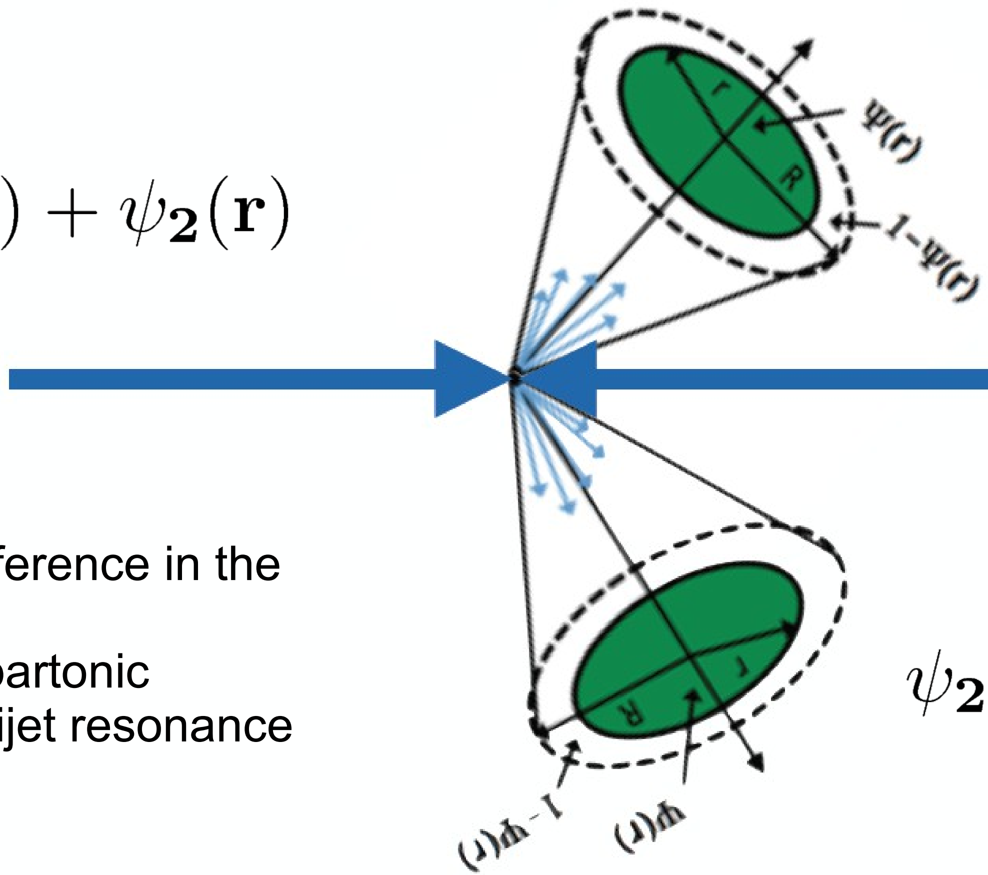


Gluon-jets irradiate more, slowly rising JEP
Quark-jets irradiate less, fast rising JEP

H. Li, Z. Li, C.-P. Yuan
PRD 87 (2013) 074025

Dijet energy profile

$$\psi_{\mathbf{jj}}(\mathbf{r}) = \psi_{\mathbf{1}}(\mathbf{r}) + \psi_{\mathbf{2}}(\mathbf{r})$$



$\psi_{\mathbf{1}}(\mathbf{r})$

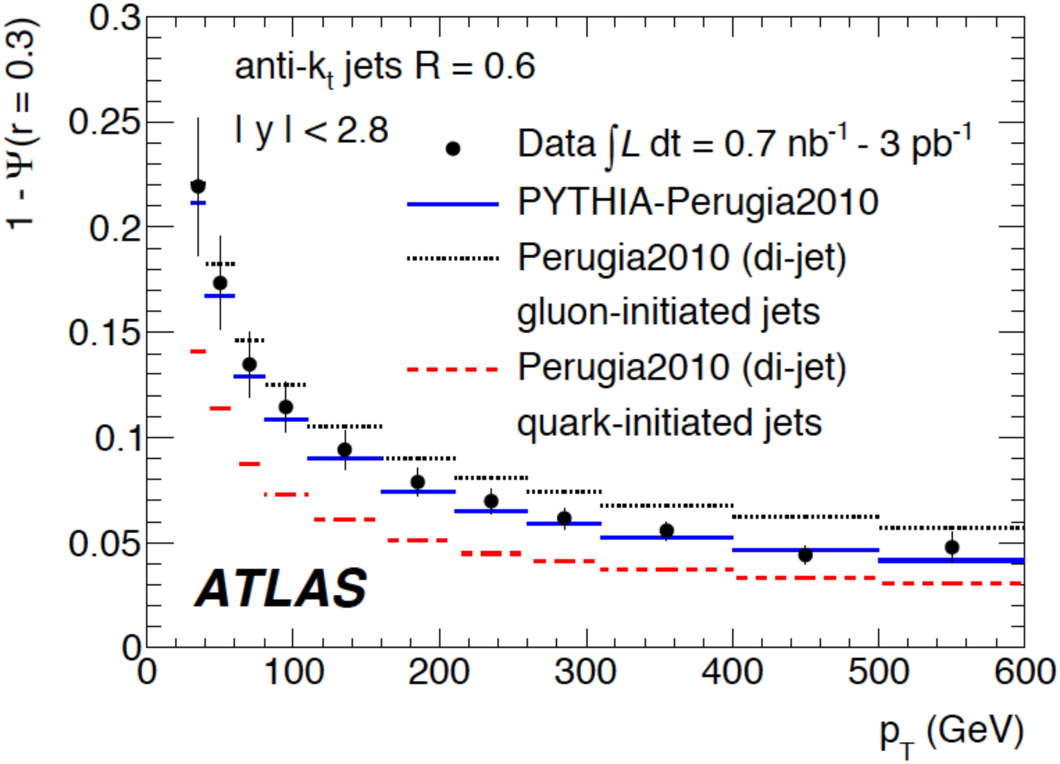
$\psi_{\mathbf{2}}(\mathbf{r})$

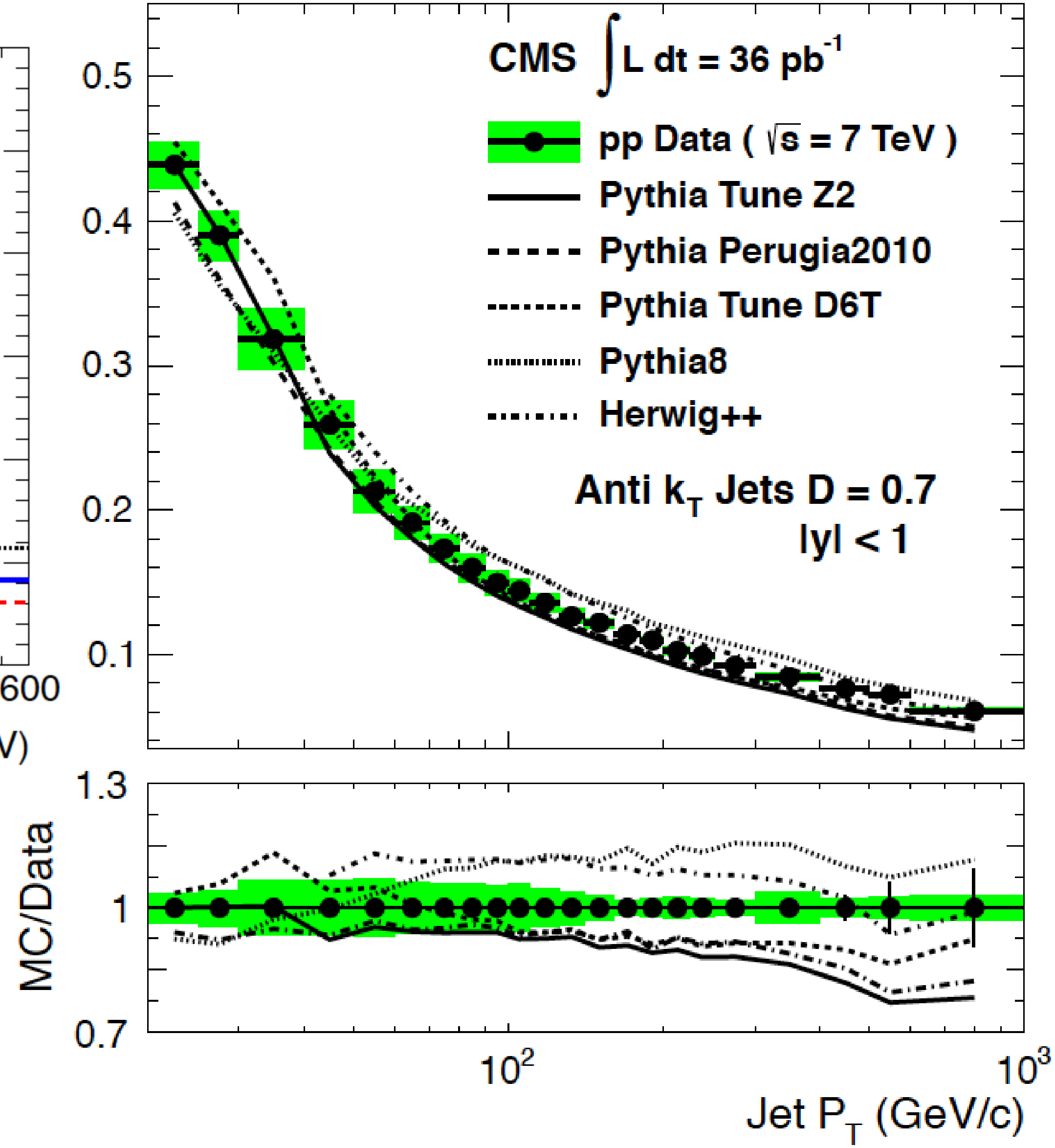
We will use the difference in the quark/gluon JEP
to distinguish the partonic composition of a dijet resonance

Similar technique recently applied to distinguish Higgs production mechanisms [Rentala *et al.* PRD88 (2013) 7, 073007] and Dark matter interactions [Agrawal, Rentala, JHEP 1405 (2014) 098]

LHC-7 measurements (inclusive jet production)

ATLAS, PRD 83 (2011) 052003





Tuning!

Data are well described by MC simulations. But a tuning of the shower/hadronization parameters is needed

CMS, JHEP 1206 (2012) 160

How to estimate the jet energy profile for dijet at LHC-14 ?

(a) By Monte Carlo simulation (example MG+Pythia or Herwig)

but a tuning of MC parameters is needed (and we need LHC-14 data!)

(b) Theoretically. JEP can be calculated in perturbative QCD

Nex-to-leading-logarithm resummation { Collins, Soper, Sterman, PRD 71 (2005) 112002; Li, Li, Yuan, PRL 107 (2011) 152001; PRD 87 (2013) 074025 }

We will use *pQCD calculations* to estimate the *average* JEPs and *MC simulations* to evaluate, by means of pseudo-experiments, the *statistical uncertainty* on the JEP

Procedure (SIGNAL)

- We consider first the signal of a 4 TeV di-jet resonance, coming from an S8, C or q*, which can be discovered with approximately 30 fb-1 at the 14 TeV LHC and which has not been excluded by the present LHC-8 searches.

We apply the CMS selection (pT_j>30 GeV, $|\eta_j|$<2.5, $|\Delta\eta_{jj}|$<1.3) and we restrict to the dijet mass region

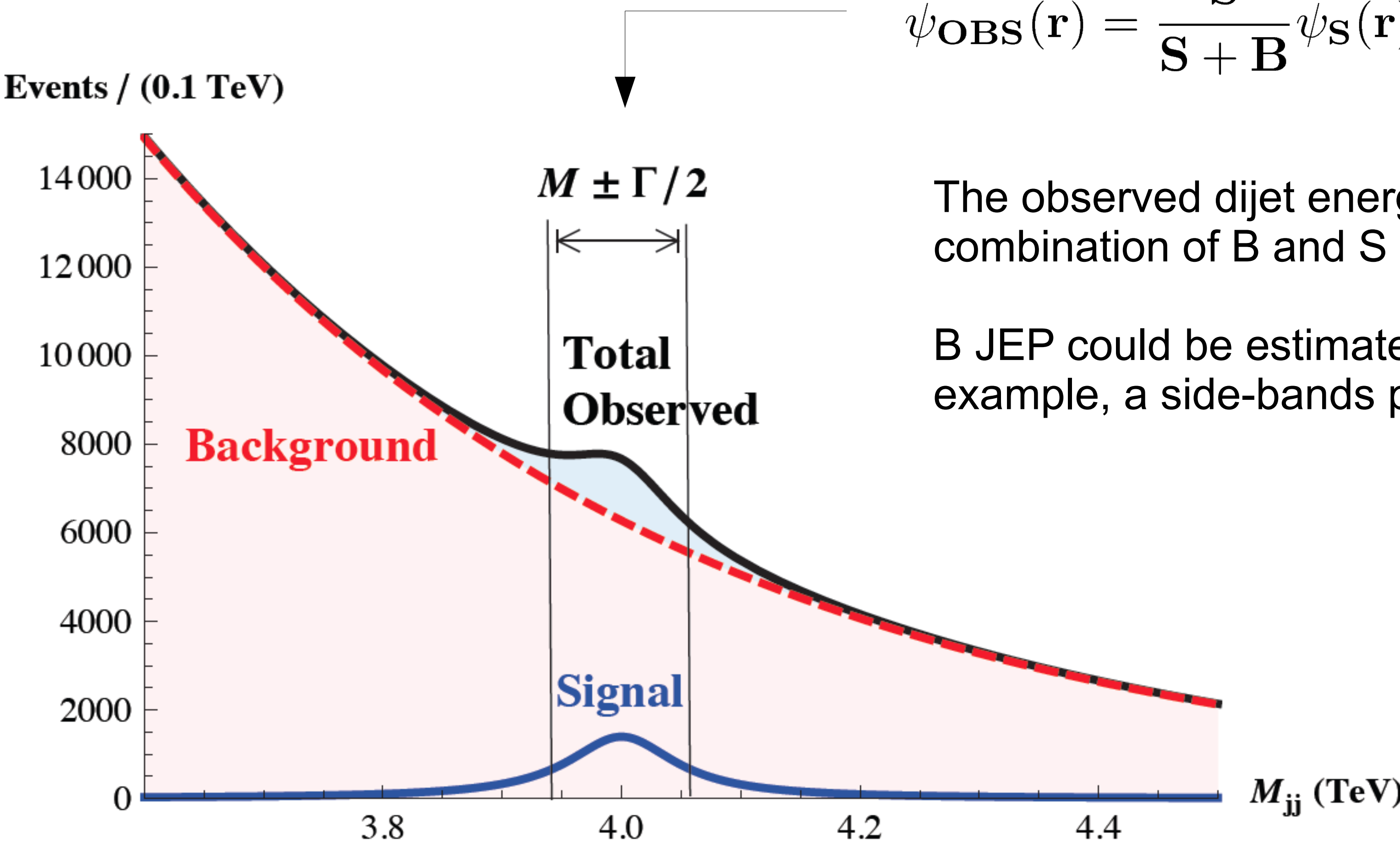
$$|\mathbf{M_{jj}} - \mathbf{M}| < \mathbf{\Gamma/2}$$

- We evaluate, in this kinematic region, the average JEP by pQCD calculation (we convolve the jet 4-momenta with the analytic jet functions)
- We obtain the statistical fluctuation on the JEP by running several MC simulations (MG5+Pythia; jets are clustered with Fastjet: anti-kt with R=0.5)
  We find that the statistical uncertainty is Gaussian (Poisson errors)

$$(\delta\psi_{\mathbf{S}}(\mathbf{r}))^{\mathbf{2}} \approx \frac{\sigma^{\mathbf{2}}(\mathbf{r})}{\mathbf{S}}$$

Background subtraction

$$\psi_{\mathrm{OBS}}(\mathbf{r}) = \frac{\mathbf{S}}{\mathbf{S}+\mathbf{B}}\psi_{\mathrm{S}}(\mathbf{r}) + \frac{\mathbf{B}}{\mathbf{S}+\mathbf{B}}\psi_{\mathrm{B}}(\mathbf{r})$$



The observed dijet energy profile is a combination of B and S profiles

B JEP could be estimated through, for example, a side-bands procedure

Even if it is possible to subtract the B profile, the statistical uncertainty on B affects the measurement of the S JEP

Background subtraction

$$\psi_{\mathbf{S}}(\mathbf{r}) = \psi_{\mathbf{OBS}}(\mathbf{r}) + \frac{\mathbf{B}}{\mathbf{S}}(\psi_{\mathbf{OBS}}(\mathbf{r}) - \psi_{\mathbf{B}}(\mathbf{r}))$$

For the signal we have found $$(\delta\psi_{\mathbf{S}}(\mathbf{r}))^{\mathbf{2}} \approx \frac{\sigma^{\mathbf{2}}(\mathbf{r})}{\mathbf{S}}$$

We make the reasonable assumption of same σ "per event" statistical error for S and B:

$$(\delta\psi_{\mathbf{OBS}}(\mathbf{r}))^{\mathbf{2}} \approx \frac{\sigma^{\mathbf{2}}(\mathbf{r})}{\mathbf{S}+\mathbf{B}} \qquad (\delta\psi_{\mathbf{B}}(\mathbf{r}))^{\mathbf{2}} \approx \frac{\sigma^{\mathbf{2}}(\mathbf{r})}{\mathbf{B}} \; .$$

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

``dilution" in the measurement of S JEP due to QCD background

From the uncertainty on S (number of signal events)

Background subtraction

$$\psi_{\mathbf{S}}(\mathbf{r}) = \psi_{\mathbf{OBS}}(\mathbf{r}) + \frac{\mathbf{B}}{\mathbf{S}}(\psi_{\mathbf{OBS}}(\mathbf{r}) - \psi_{\mathbf{B}}(\mathbf{r}))$$

For the signal we have found $(\delta\psi_{\mathbf{S}}(\mathbf{r}))^{\mathbf{2}} \approx \frac{\sigma^{\mathbf{2}}(\mathbf{r})}{\mathbf{S}}$

We make the reasonable assumption of same σ “per event” statistical error for S and B:

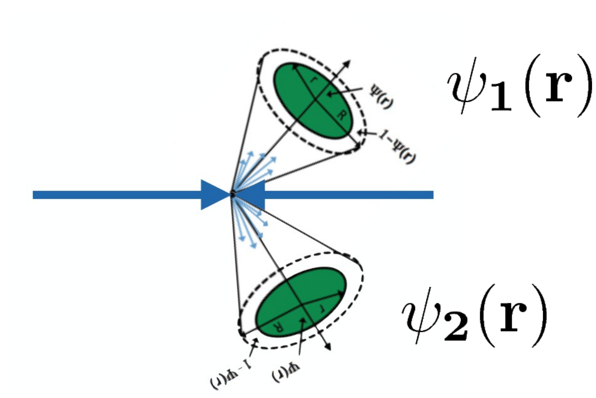
$$(\delta\psi_{\mathbf{OBS}}(\mathbf{r}))^{\mathbf{2}} \approx \frac{\sigma^{\mathbf{2}}(\mathbf{r})}{\mathbf{S}+\mathbf{B}} \qquad (\delta\psi_{\mathbf{B}}(\mathbf{r}))^{\mathbf{2}} \approx \frac{\sigma^{\mathbf{2}}(\mathbf{r})}{\mathbf{B}} \; .$$

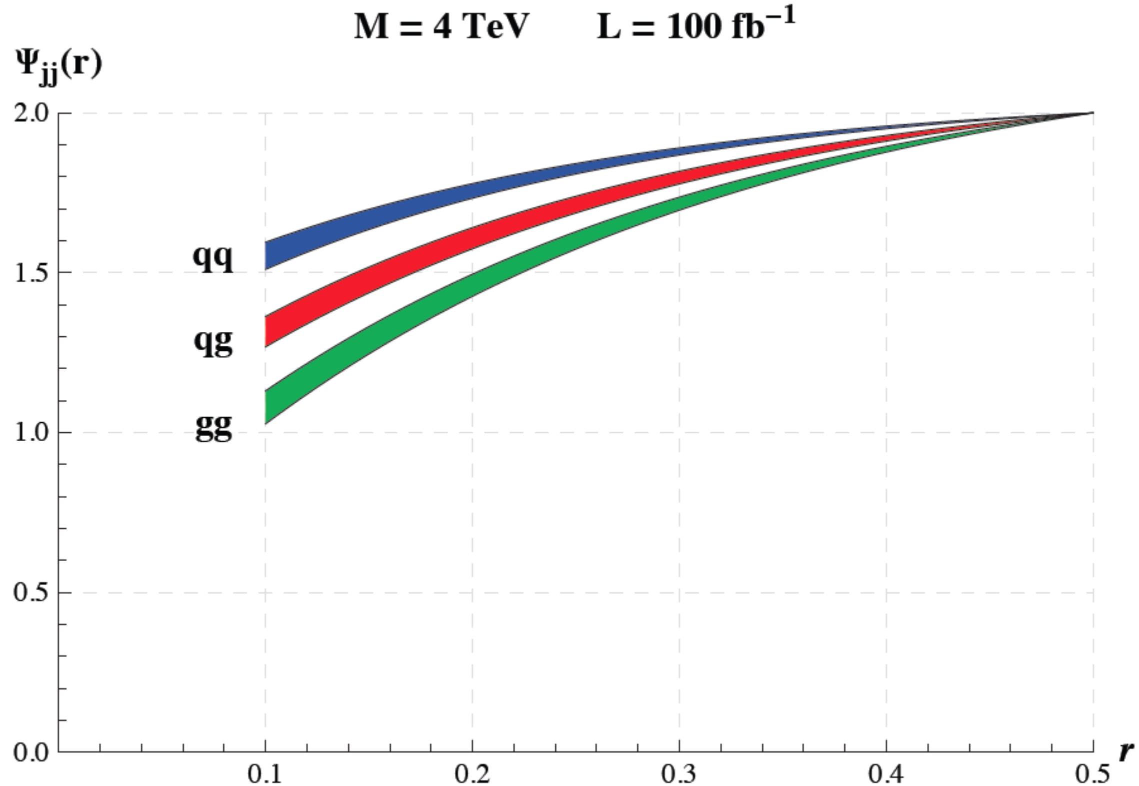
$$(\delta\psi_{\mathbf{S}})^{\mathbf{2}} \approx \boxed{\frac{\sigma^{\mathbf{2}}}{\mathbf{S}}\left[\mathbf{1} + \mathbf{2}\frac{\mathbf{B}}{\mathbf{S}}\right]} + \frac{(\psi_{\mathbf{S}} - \psi_{\mathbf{B}})^{\mathbf{2}}}{\mathbf{S}}$$

Larger term; because B/S is large in the relevant param space

Results (4 tev)

$$\psi_{\mathbf{jj}}(\mathbf{r}) = \psi_{\mathbf{1}}(\mathbf{r}) + \psi_{\mathbf{2}}(\mathbf{r})$$





Resonance mass: 4 TeV

Benchmark couplings: (C) tanθ=0.6 , (q*) f_S=0.4 , (S_8) k_S=0.65

f parameter

we can parameterize a generic dijet profile of the signal as

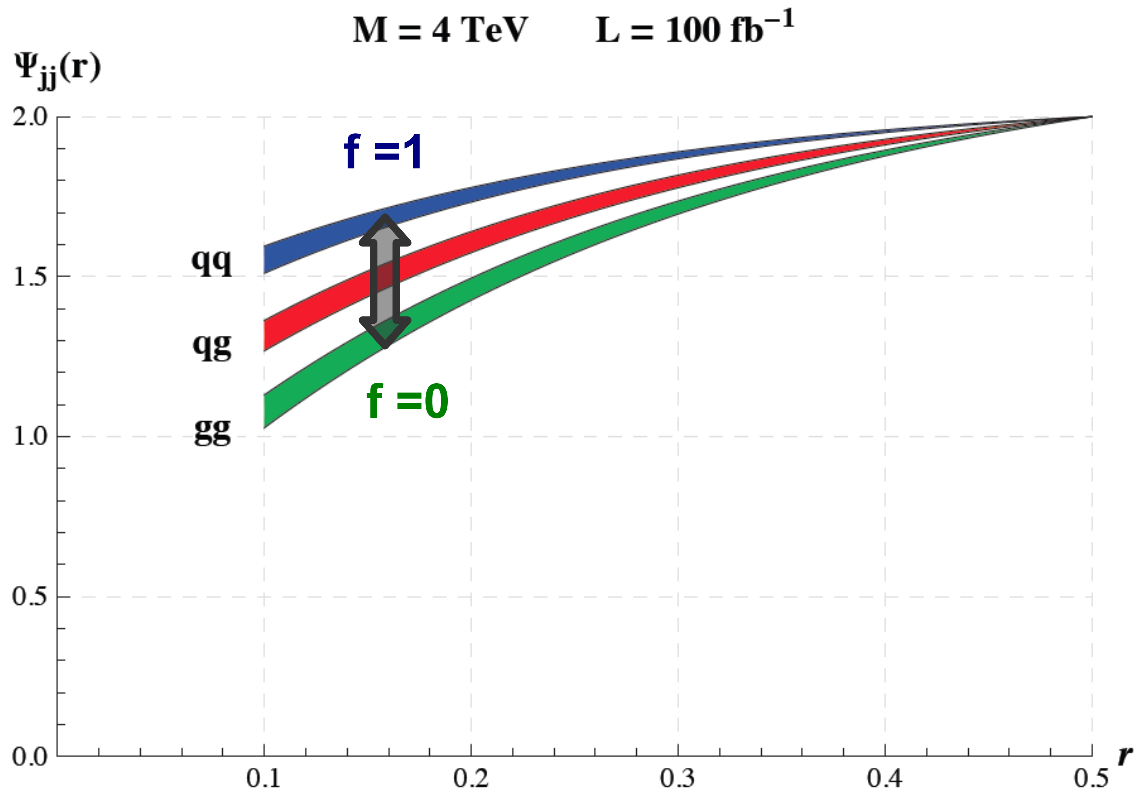
$$\psi_{\mathbf{S}}(\mathbf{r}) = \mathbf{f}\psi_{\bar{\mathbf{q}}\mathbf{q}}(\mathbf{r}) + (\mathbf{1}-\mathbf{f})\psi_{\mathbf{gg}}(\mathbf{r})$$

Fit-parameter f indicates the fraction of quark-jets in a generic di-jet resonance

f =1 (qq) C

f =0.5 (qg) q*

f =0 (gg) S_8



f parameter

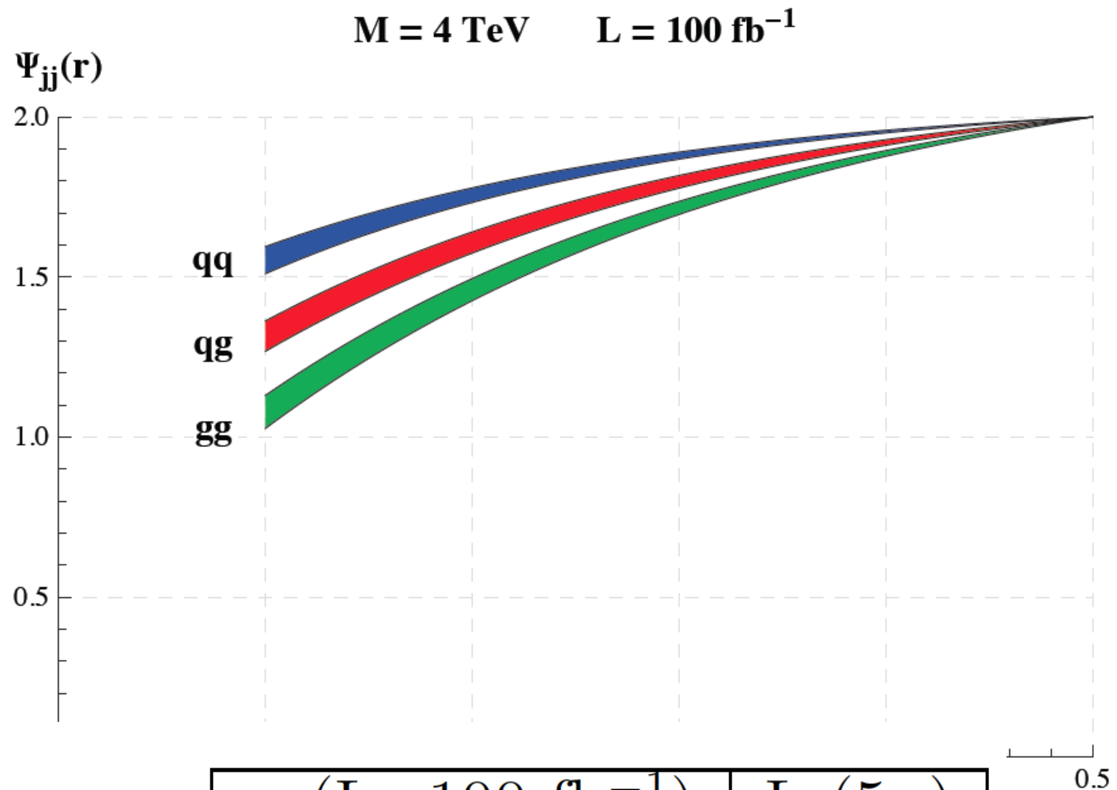
We translate the error on the JEP into an error on f

	f
$\bar{q}q$	1.00 ± 0.06
qg	0.50 ± 0.07
gg	0.00 ± 0.08

$$\sigma(\bar{q}q - gg) = \frac{\bar{f}_{\bar{q}q} - \bar{f}_{gg}}{\sqrt{\sigma^2(f_{\bar{q}q}) + \sigma^2(f_{gg})}}$$

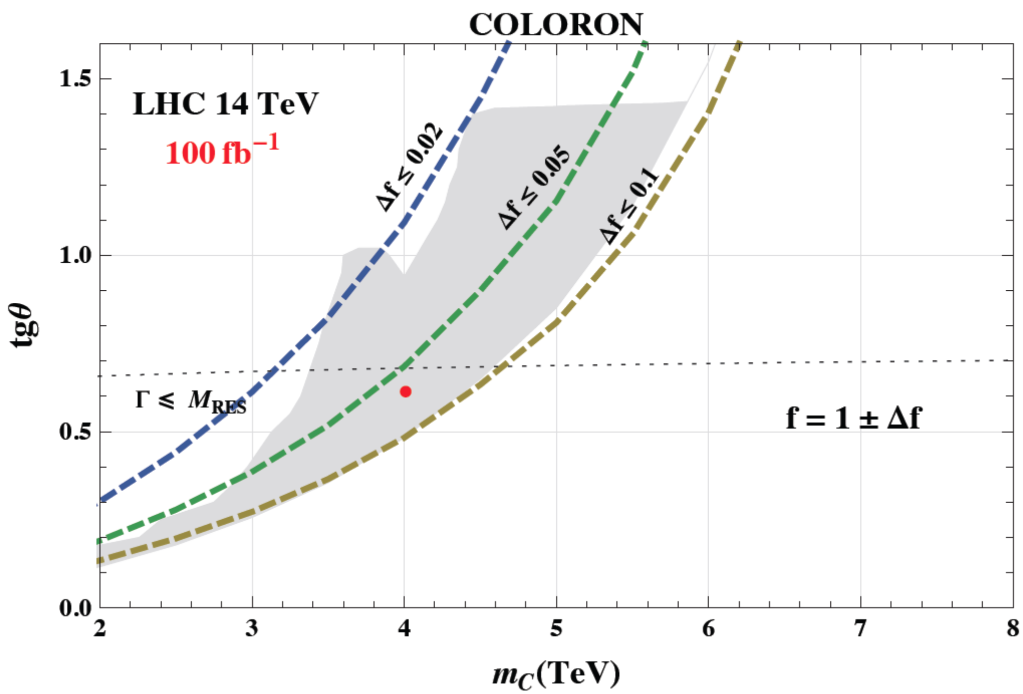
$$\sigma(\bar{q}q - qg) = \frac{\bar{f}_{\bar{q}q} - \bar{f}_{qg}}{\sqrt{\sigma^2(f_{\bar{q}q}) + \sigma^2(f_{qg})}}$$

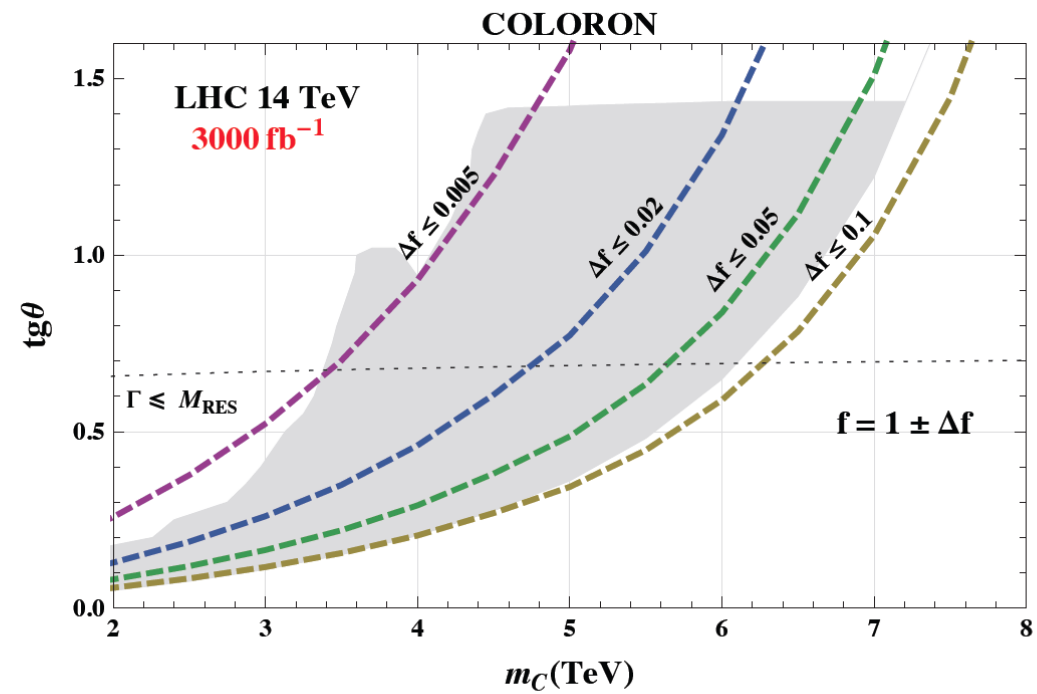
$$\sigma(qg - gg) = \frac{\bar{f}_{qg} - \bar{f}_{gg}}{\sqrt{\sigma^2(f_{qg}) + \sigma^2(f_{gg})}}$$



	σ (L=100 fb^{-1})	L (5σ)
$\bar{q}q$ - qg	5.4	85
qg - gg	4.7	110
$\bar{q}q$ - gg	10	25

Statistical uncertainty in the discovery region



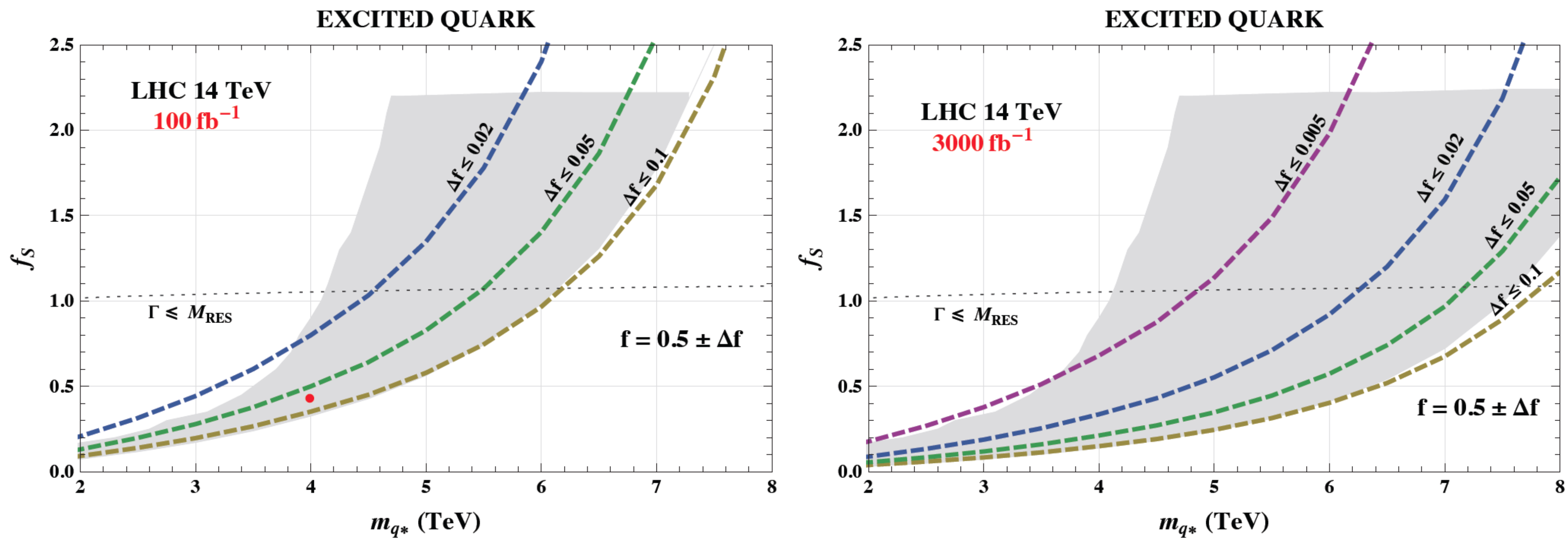


Shaded area: parameter space not excluded by LHC-8 searches and where LHC-14 can discover the resonance at the given luminosity

- $f = 1$ (qq) C
- $f = 0.5$ (qg) q*
- $f = 0$ (gg) S_8

Δf ≤ 0.1 → 5-sigma separation from the other resonances

Statistical uncertainty in the discovery region



f =1 (qq) C

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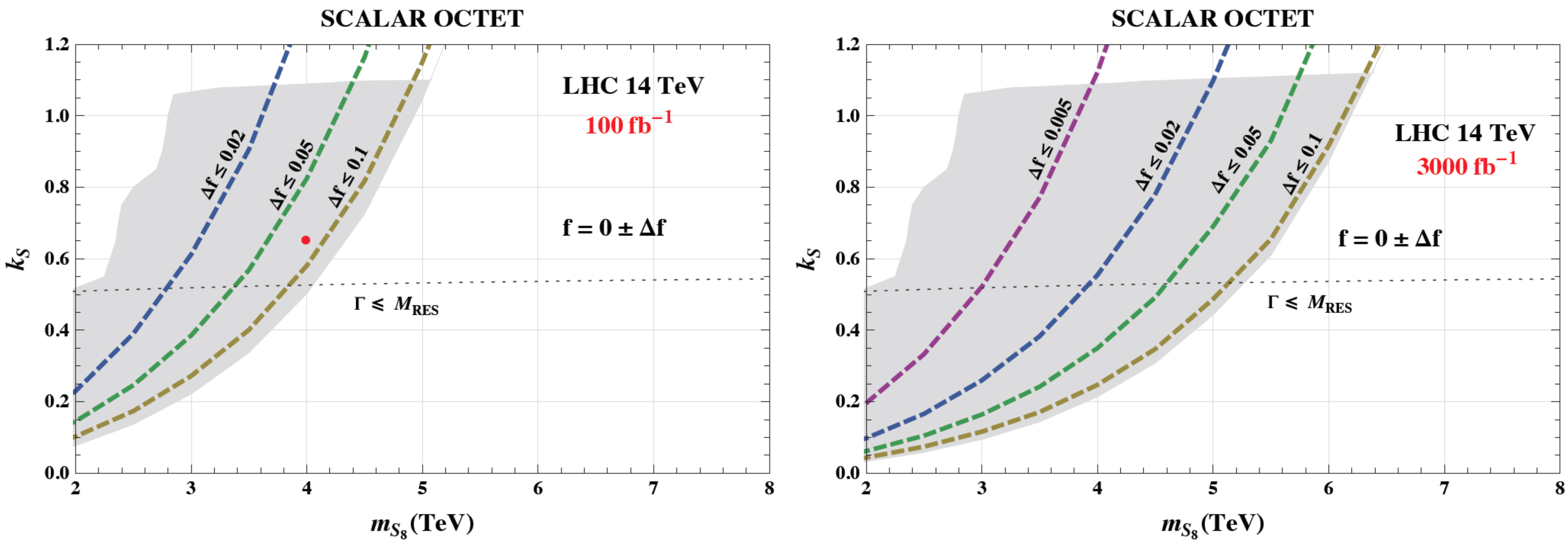
$\Delta f \leq 0.1$ → 5-sigma separation from the other resonances

Statistical uncertainty in the discovery region



f =1 (qq) C

f =0.5 (qg) q*

f =0 (gg) S_8

Large **statistical** separation among the three types of resonances in essentially the entire relevant parameter space where we can reach a 5-sigma discovery at the 14 TeV LHC.

Conclusions

A strategy to reveal the nature of a di-jet resonance at the 14 TeV LHC:

Analysis of **diJet Energy Profile** can distinguish (in a model-independent way) gg, qg and qq resonances, after accounting for statistical uncertainties in the signal and the background.

We have not tried to evaluate systematic uncertainties. This can be done (better by experimentalists) through detailed detector study once sufficient 14 TeV dijet data is in hand.

Systematics on JEP

ATLAS, PRD 83 (2011) 052003 LHC- 7 TeV

at very large p_T where the measurements are still statistically limited. In the case of the integrated measurements, the total systematic uncertainty varies between 10% and 2% (4% and 1%) at $r = 0.1$ ($r = 0.3$) as p_T increases, and vanishes as r approaches the edge of the jet cone.

Systematic uncertainties at the 1 percent level for pT~ 600 GeV

“theoretical” evaluation of JEP

H.-N. Li, Z. Li, C.-P. Yuan, PRL 107 (2011) 152001; PRD 87 (2013) 074025

Nex-to-leading-logarithm resummation

(NLO calculations overshoot data)

Terms of the form $\alpha_S^n(\log(R/r))^{2n}$, $\alpha_S^n(\log(R/r))^{2n-1}$

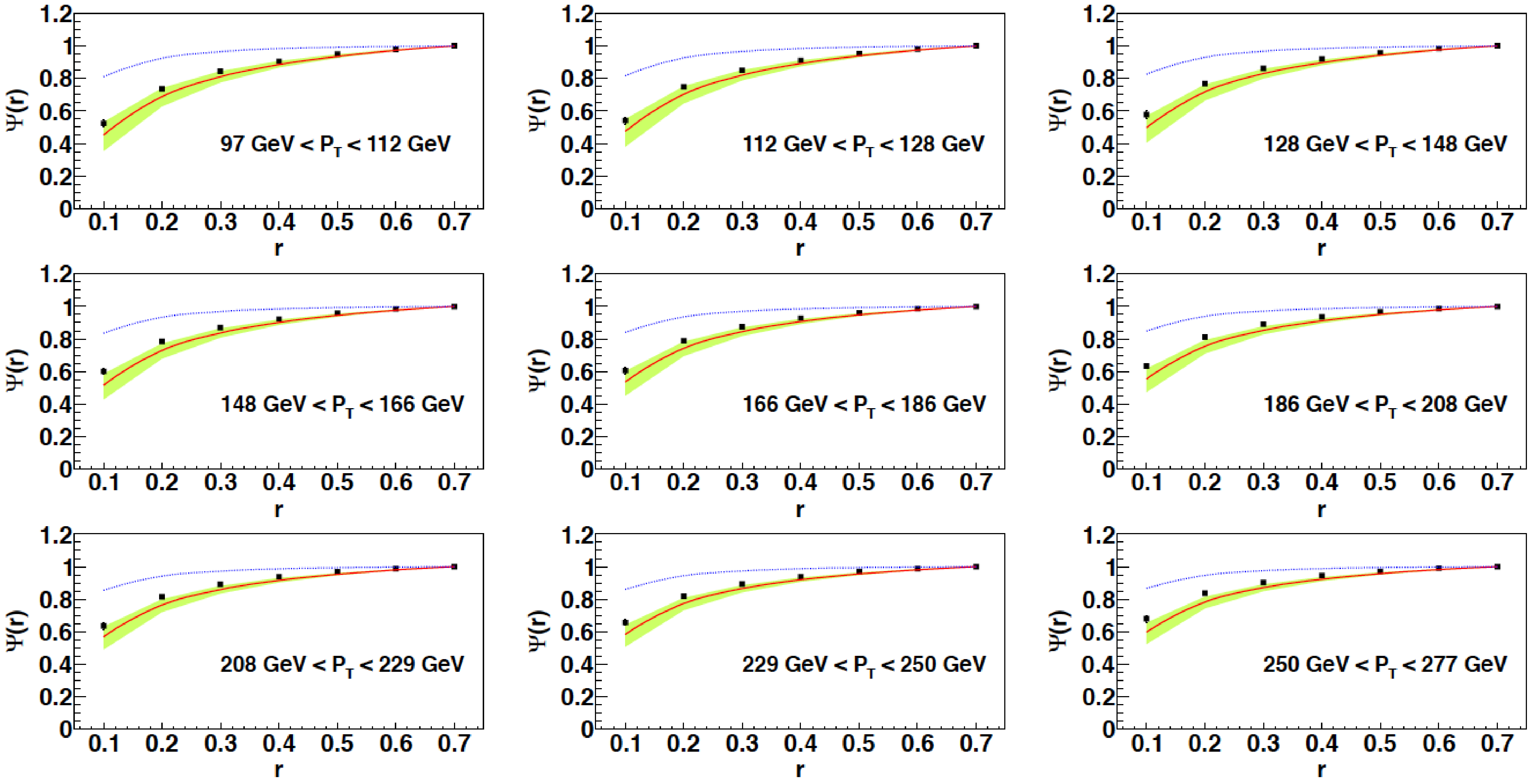
are resummed to all order in α_s

$$\Psi(r) = \left[\sum_f \int \frac{dP_T}{P_T} \frac{d\hat{\sigma}_f}{dP_T} \bar{J}_f^E(1, P_T, \nu_{\rm fi}^2, R, R)\right]^{-1} \sum_f \int \frac{dP_T}{P_T} \frac{d\hat{\sigma}_f}{dP_T} \bar{J}_f^E(1, P_T, \nu_{\rm fi}^2, R, r)$$

Scale parameter which includes the effects of not-calculated sub-leading logarithms

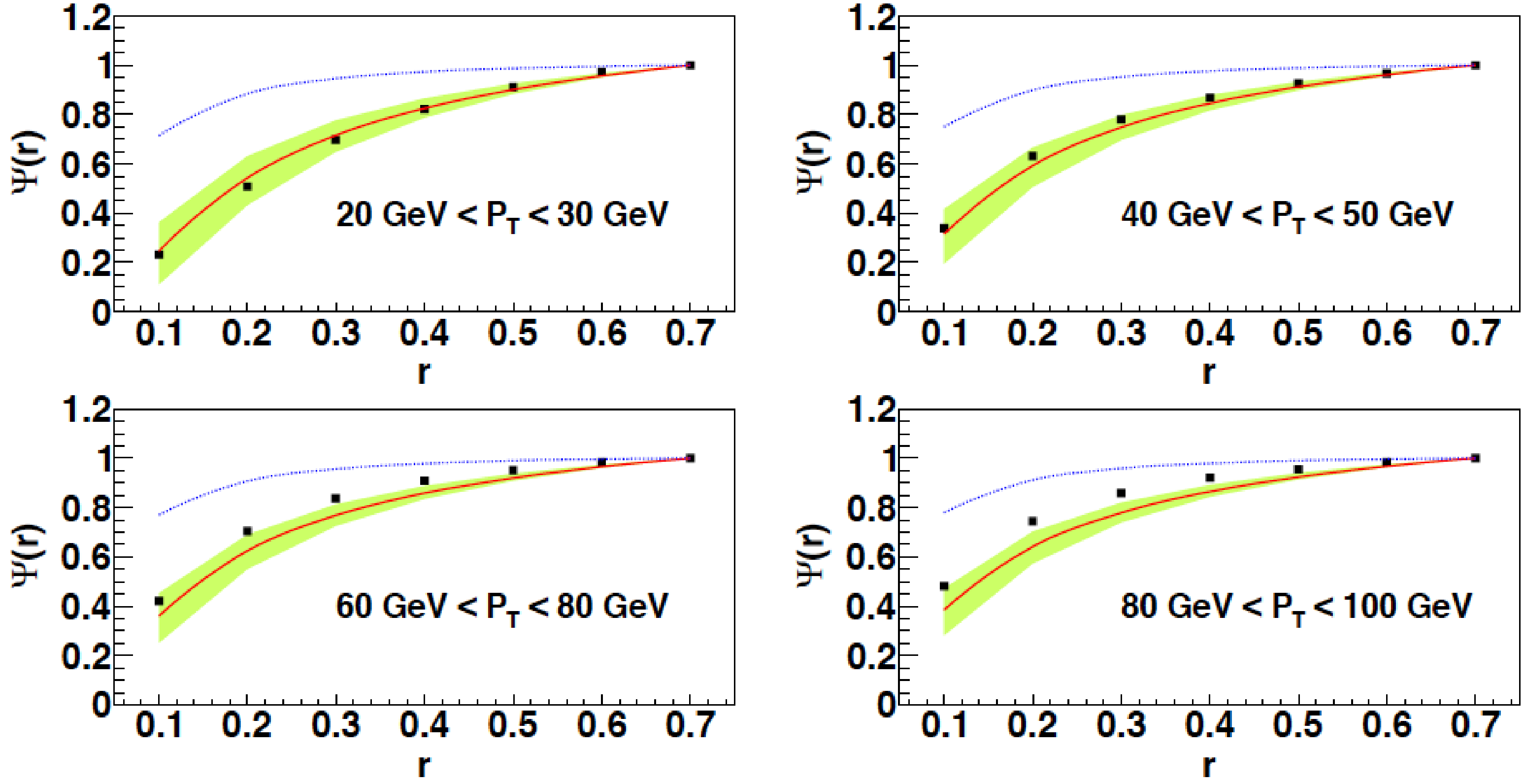
JEPs from Perturbative QCD Resummation vs CDF data

H.-N. Li, Z. Li, C.-P. Yuan, PRL 107 (2011) 152001; PRD 87 (2013) 074025



JEPs from Perturbative QCD Resummation vs CMS data

H.-N. Li, Z. Li, C.-P. Yuan, PRL 107 (2011) 152001; PRD 87 (2013) 074025



Theory uncertainty removable by calibration with data