Precision Diboson Observables for the LHC

Photon Jets at LHC (maybe 750 GeV excess)

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INFN - LNF
03/02/2016

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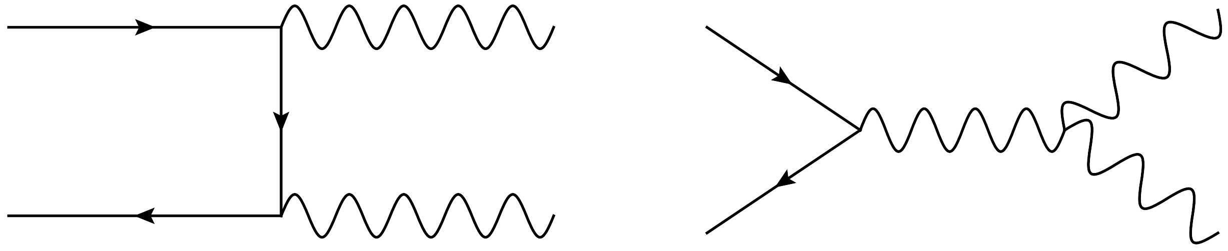

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with Chris Frye,Marat Freytsis, Matt Strassler
arxiv:1510.08451

- Not quite clear if there are any smoking guns. (Although 750 GeV excess looks promising)

- We can instead focus on precision measurements of the SM

- We need clever ways to cancel our major sources of uncertainty

- We already have a great symmetry that relates a set of process: SU(2)xU(1) of the electroweak force.

- We will explore ratios of processes with two bosons in the final state

$$R = \frac{\sigma(pp \to V_1 V_2)}{\sigma(pp \to V_3 V_4)}$$

Plan

- Leading Order
- Next-to-leading Order
- Theoretical Uncertainties
- Conclusion

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- Next-to-leading Order
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Leading Order

massless limit

In the large energy limit, $W^{\pm}, Z$ become effectively massless.

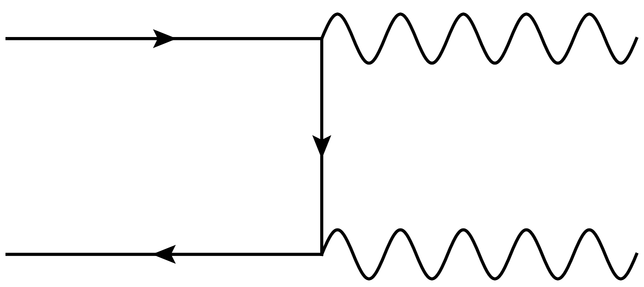
It makes more sense to think in terms of the unbroken
SU(2)x(1) vectors: $w^{\pm}, w^3, x$
Goldstone bosons: $\phi^{\pm}, \phi^0$

Two bosons combine into isospin triplets and singlets:

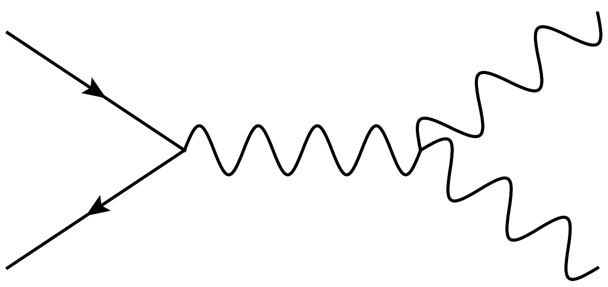
$$
\begin{aligned}
xx_{\mathbf{1}} \equiv xx : &\quad |xx\rangle \ , \\
wx_{\mathbf{3}} \equiv wx : &\quad |w^+x\rangle \, , \quad |w^3x\rangle \, , \quad |w^-x\rangle \ , \\
ww_{\mathbf{1}} : &\quad |w^+w^-\rangle + |w^-w^+\rangle - |w^3w^3\rangle \ , \\
ww_{\mathbf{3}} : &\quad |w^+w^3\rangle - |w^3w^+\rangle \, , \quad |w^+w^-\rangle - |w^-w^+\rangle \, , \quad |w^3w^-\rangle - |w^-w^3\rangle
\end{aligned}
$$

Leading Order

massless limit



a_1



a_3, a_L

$$a_1 \sim \mathcal{M}(xx) \sim \mathcal{M}(xw) \sim \mathcal{M}(ww_1)$$

$$a_3 \sim \mathcal{M}(ww_3)$$

$$a_\phi \sim \mathcal{M}(\phi\phi)$$

Leading Order

finite mass

$$|a_1|^2 = \frac{\hat{t}}{\hat{u}} + \frac{\hat{u}}{\hat{t}} \Rightarrow \quad |\mathcal{A}_1|^2 = (\hat{t}\,\hat{u} - m_1^2\,m_2^2)\left(\frac{1}{\hat{t}^2} + \frac{1}{\hat{u}^2}\right) + \frac{2\,\hat{s}\,(m_1^2 + m_2^2)}{\hat{t}\,\hat{u}}$$

Similarly:

$$(\mathcal{A}_1\mathcal{A}_3) = (N_T^\ell\,P_s)\,(\hat{T}\hat{U})\left(\frac{1}{\hat{u}} - \frac{1}{\hat{t}}\right) + \frac{1}{4}\,(\hat{t}\,\hat{u} - m_1^2\,m_2^2)\left(\frac{1}{\hat{u}^2} - \frac{1}{\hat{t}^2}\right)\,,$$

$$|\mathcal{A}_3^h|^2 = (N_T^h\,P_s)^2\,(\hat{T}\hat{U}) + \delta_{h\ell}\left[\frac{(N_T^\ell\,P_s)}{4}\,(\hat{T}\hat{U})\left(\frac{1}{\hat{t}} + \frac{1}{\hat{u}}\right)\right.$$
$$\left. + \frac{1}{32}(\hat{t}\,\hat{u} - m_1^2\,m_2^2)\left(\frac{1}{\hat{t}^2} + \frac{1}{\hat{u}^2}\right) - \frac{1}{16}\,\frac{\hat{s}\,(m_1^2 + m_2^2)}{\hat{t}\,\hat{u}}\right]$$

$$|\mathcal{A}_\phi^h|^2 = (N_\phi^h\,P_s)^2\left[\hat{t}\,\hat{u} + 2\,\hat{s}\,(m_1^2 + m_2^2) - m_1^2\,m_2^2\right]\,,$$

Leading Order

γγ,γZ,ZZ

From now on I choose to only focus on: γγ,γZ,ZZ

Similar analyses can be performed on all the other channels

- $R_{1a} = \dfrac{\sigma_S(Z\gamma)}{\sigma_S(\gamma\gamma)}, \quad R_{1b} = \dfrac{\sigma_S(ZZ)}{\sigma_S(\gamma\gamma)}, \quad R_{1c} = \dfrac{\sigma_S(ZZ)}{\sigma_S(Z\gamma)},$

- $C_{2a} = \dfrac{\sigma_S(W^+\gamma)}{\sigma_S(W^-\gamma)}, \quad C_{2b} = \dfrac{\sigma_S(W^+Z)}{\sigma_S(W^-Z)}, \quad D_{2a} = \dfrac{\sigma_A(W^+\gamma)}{\sigma_A(W^-\gamma)}, \quad D_{2b} = \dfrac{\sigma_A(W^+Z)}{\sigma_A(W^-Z)},$

  $R_2^{\pm} = \dfrac{\sigma_S(W^{\pm}Z)}{\sigma_S(W^{\pm}\gamma)}, \quad A_2^{\pm} = \dfrac{\sigma_A(W^{\pm}Z)}{\sigma_A(W^{\pm}\gamma)},$

- $R_3 = \dfrac{\sigma_S(W^+W^-)}{\sigma_S(V_1^0V_2^0)}, \quad A_3 = \dfrac{\sigma_A(W^+W^-)}{\sigma_A(WV^0)},$

Leading Order

Partonic cross-sections: γγ,γZ,ZZ

After EW breaking: $V_i^0 V_j^0 \sim xx, w^3 x, w^3 w^3$

All the neutral dibosons processes are proportional

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q} \to V_1^0 V_2^0) = \frac{C_{12}^q}{\hat{s}^2}|a_1|^2$$

with

$$C_{\gamma\gamma}^q = \frac{1}{2}\,\frac{\pi\alpha_2^2 s_W^4}{N_c}\,2Q^4\,,$$

$$C_{Z\gamma}^q = \frac{\pi\alpha_2^2 s_W^2 c_W^2}{N_c}\,\left(L^2Q^2 + R^2Q^2\right)$$

$$C_{ZZ}^q = \frac{1}{2}\,\frac{\pi\alpha_2^2 c_W^4}{N_c}\,\left(L^4 + R^4\right)\,.$$

$$L = T_3 - Y_L\,t_W^2$$
$$R = -Y_R\,t_W^2$$

Leading Order
PDF convolutions: γγ,γZ,ZZ

Going to transverse momentum differential distribution

$$\sigma_{pp\to 12} = \sum_q \int \frac{d\hat{s}}{s} \int dm_t \frac{d\hat{\sigma}_{q\bar{q}\to 12}}{dm_T} \int dy\, f_q f_{\bar{q}}$$

We can define weighted parton luminosity

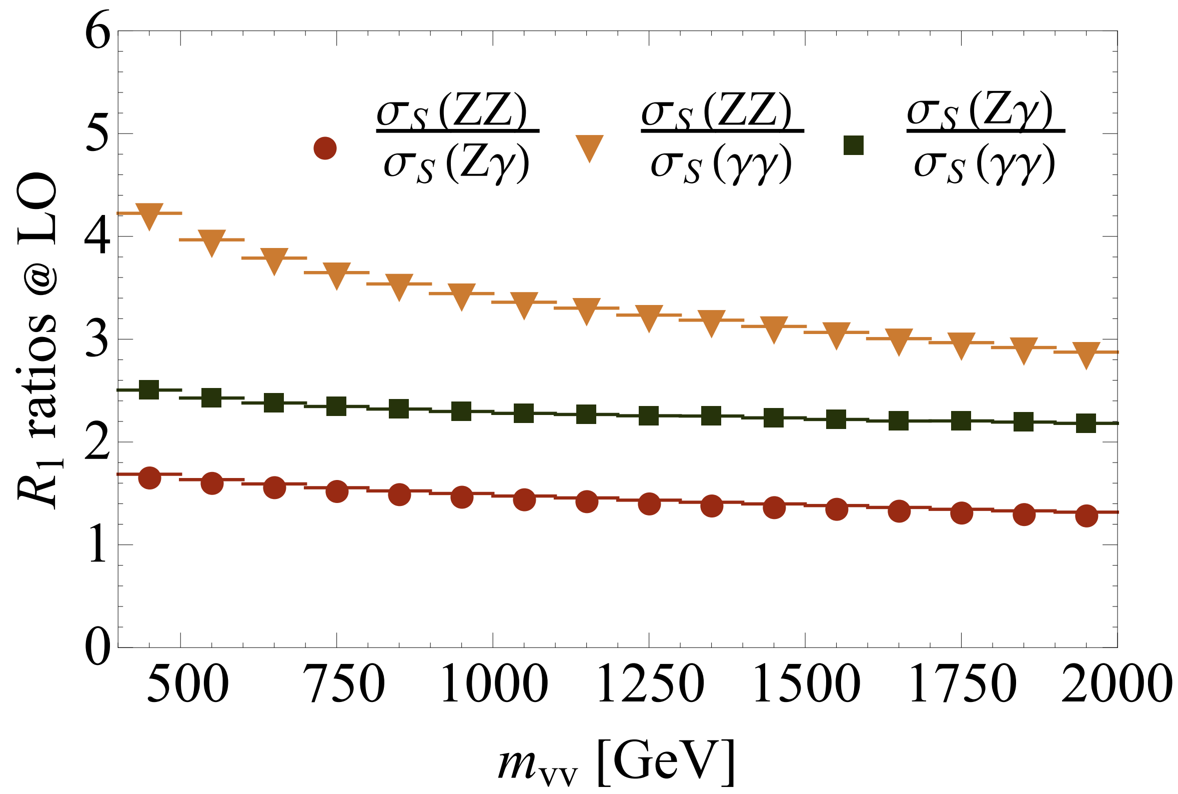
$$\frac{d\sigma_{pp\to 12}}{d\hat{s}} = \frac{1}{s} \int dm_T \left|\frac{d\hat{t}}{dm_T}\right| \frac{|A_1|^2}{\hat{s}^2} \underbrace{\sum_q C_{q\bar{q}\to 12} \int dy\, f_q f_{\bar{q}}}_{\mathcal{L}_{12}(\hat{s})}$$

Leading Order

Predictions for ratios of γγ,γZ,ZZ

$$\left[\frac{d\sigma_{pp\to Z\gamma}}{d\sigma_{pp\to\gamma\gamma}}\right]_{\hat{s}} = \frac{\mathcal{L}_{Z\gamma}(\hat{s})}{\mathcal{L}_{\gamma\gamma}(\hat{s})}\left(1+\frac{m_Z^2}{\hat{s}}+\cdots\right)$$

$V_1^0 V_2^0$	$C_{12}^u \cdot 10^5$	$C_{12}^d \cdot 10^5$
$\gamma\gamma$	1.2	0.07
$Z\gamma$	2.2	0.7
ZZ	1.6	3.3



γγ and γZ are largely independent of the down quark pdf

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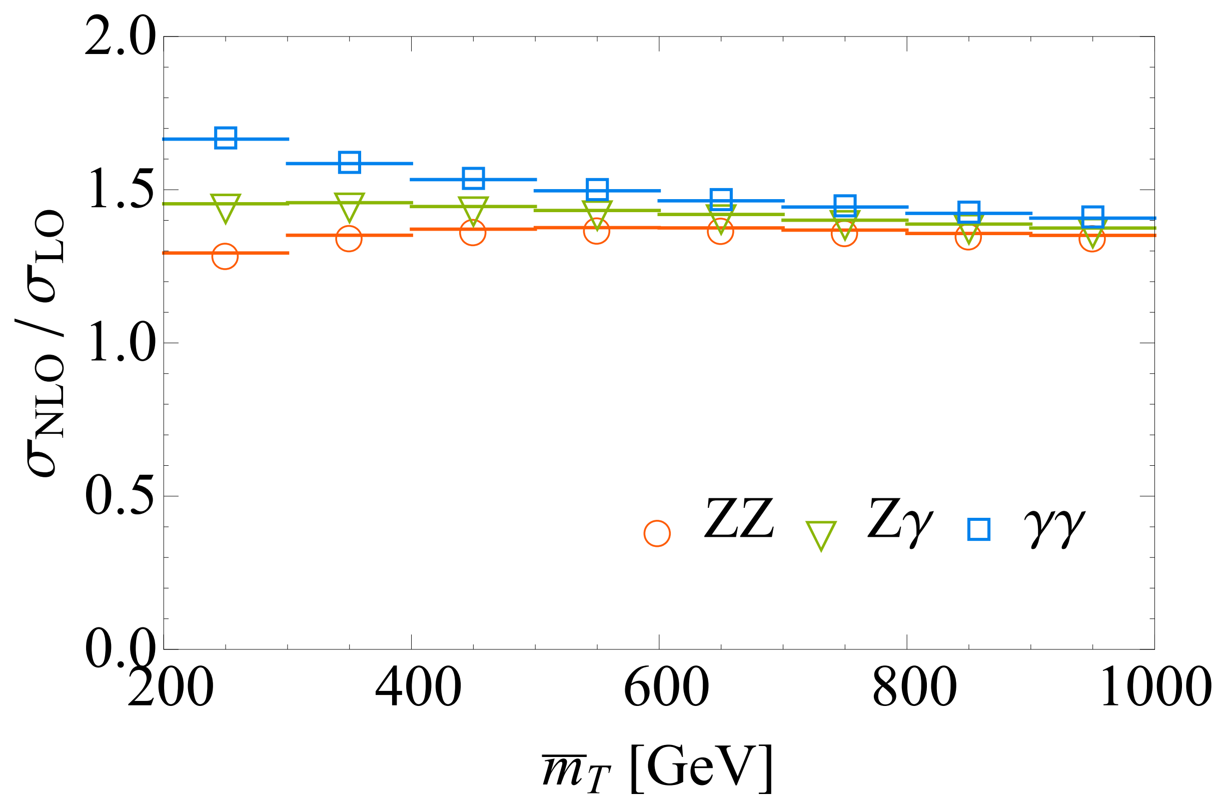
NLO
keeping the LO kinematics

- Although we expect sizable corrections to the cross-sections themselves (large-ish) K-factors, all processes receive the same corrections
- This is thanks to our cuts that keep NLO kinematics similar to the LO kinematics (no new phase space is open).

$$p_T(V_1) < 2p_T(V_2)$$
$$p_T(V_2) > 2H_T$$

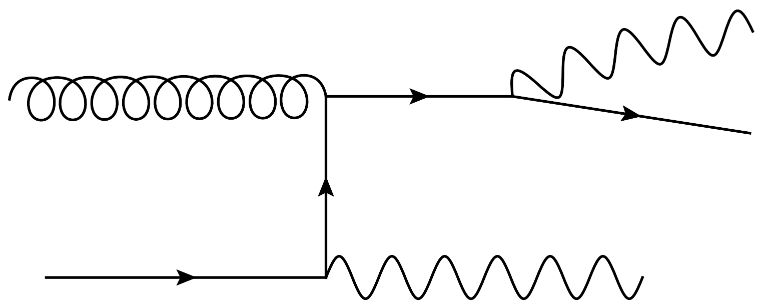
No large logs



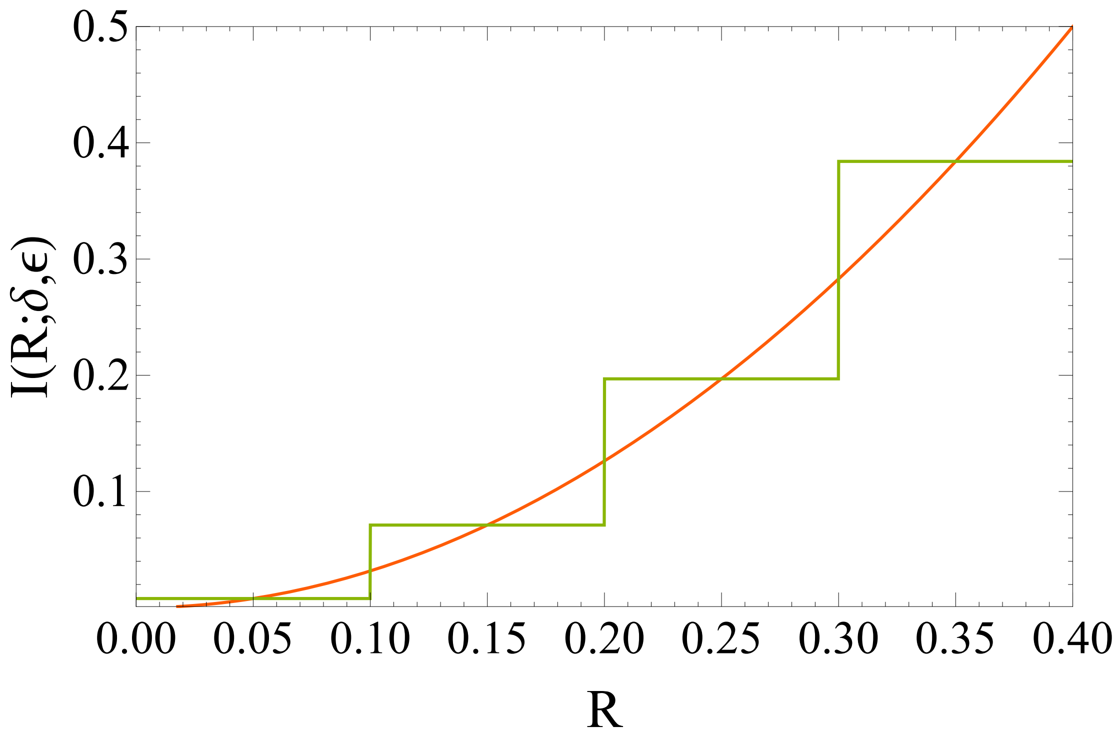
NLO

dealing with photon isolation

- The one place where Z and γ are different is in the collinear radiation from a quark line.



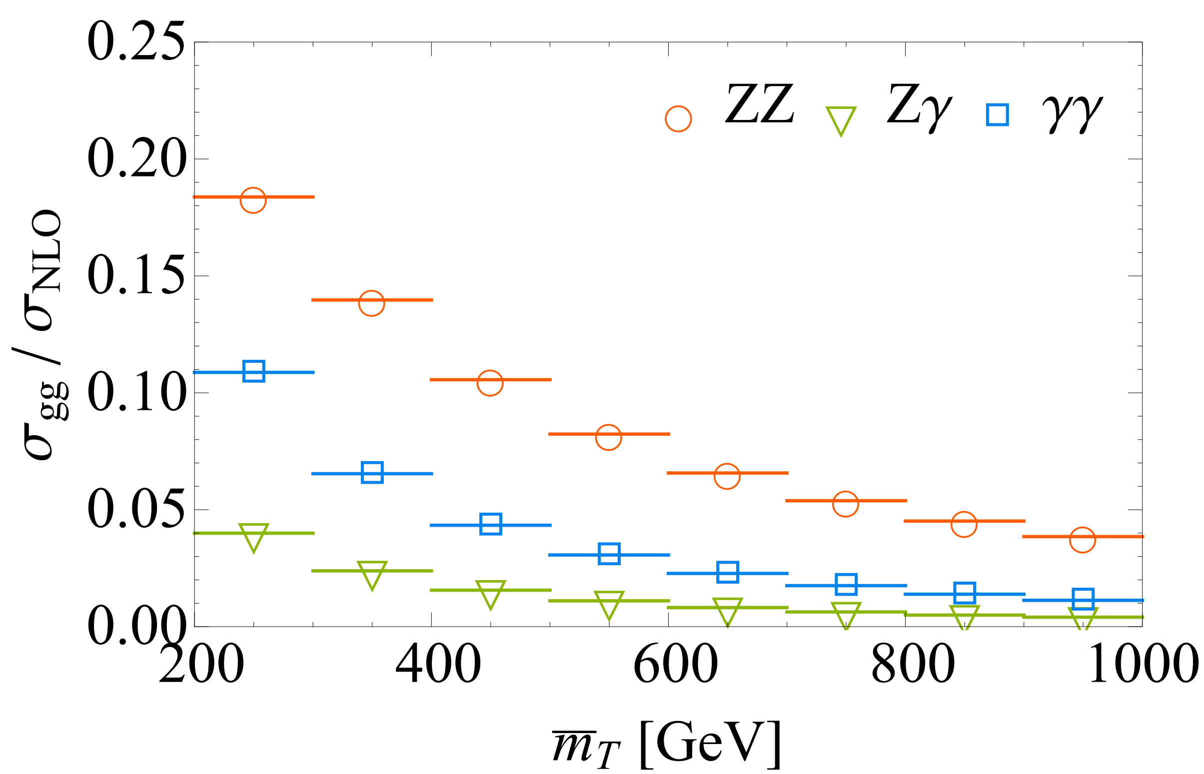
- We remove this divergence by a Staircase isolation — an experimentally implementable variation on Frixione isolation.

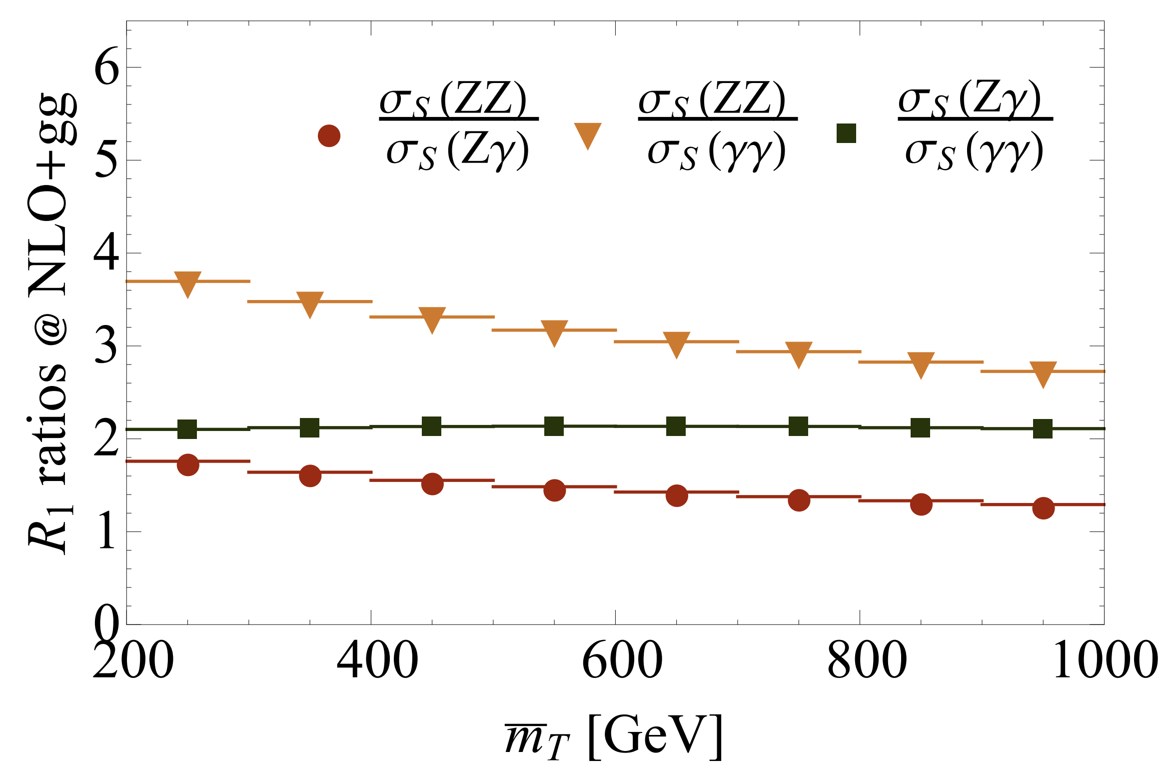


NLO

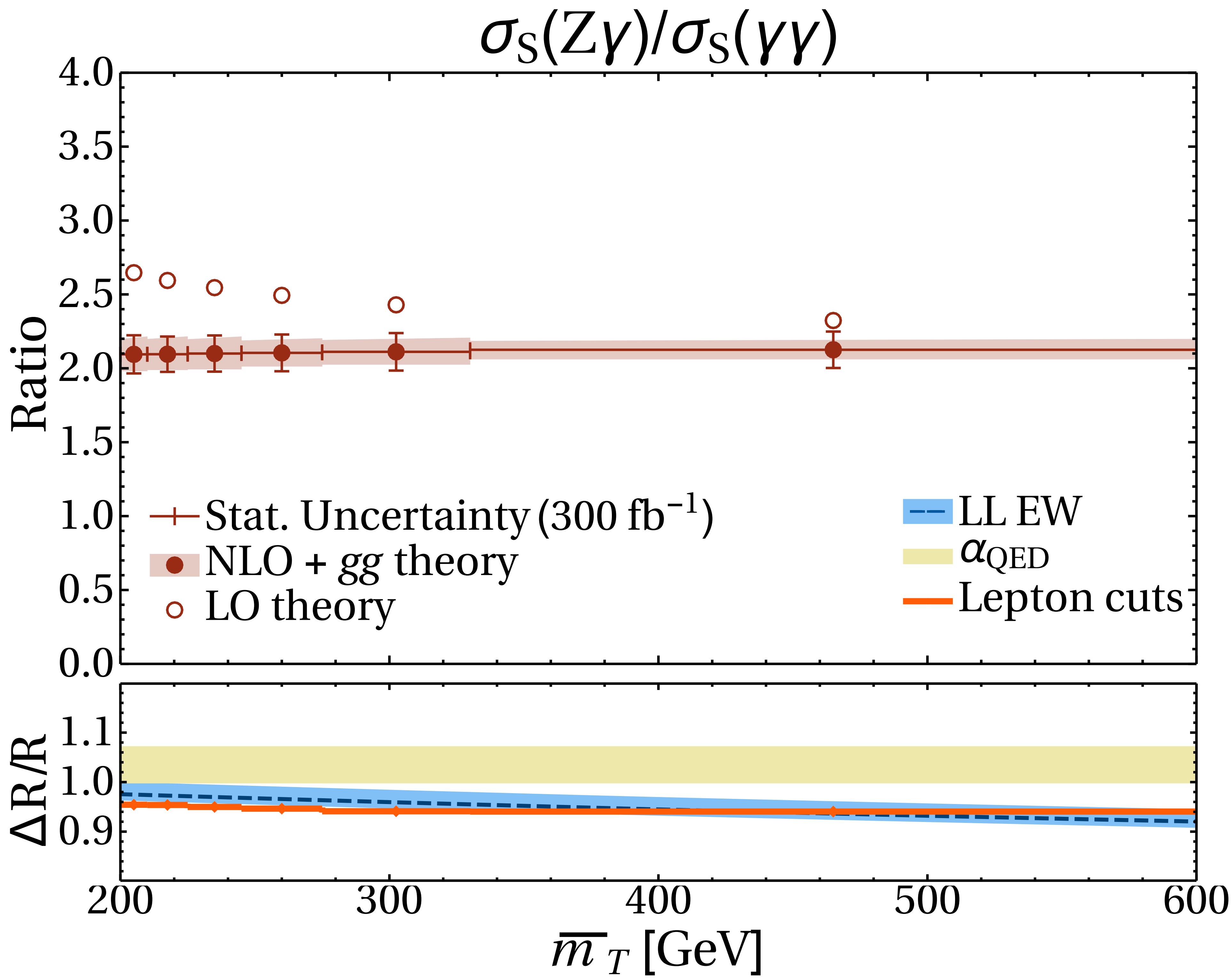
including the NNLO gg->VV

- Although the gg initial state only contributes at NNLO it is numerically important at smaller energies.
- We set the scales using the publicly known partial calculation of NNNLO for this process.



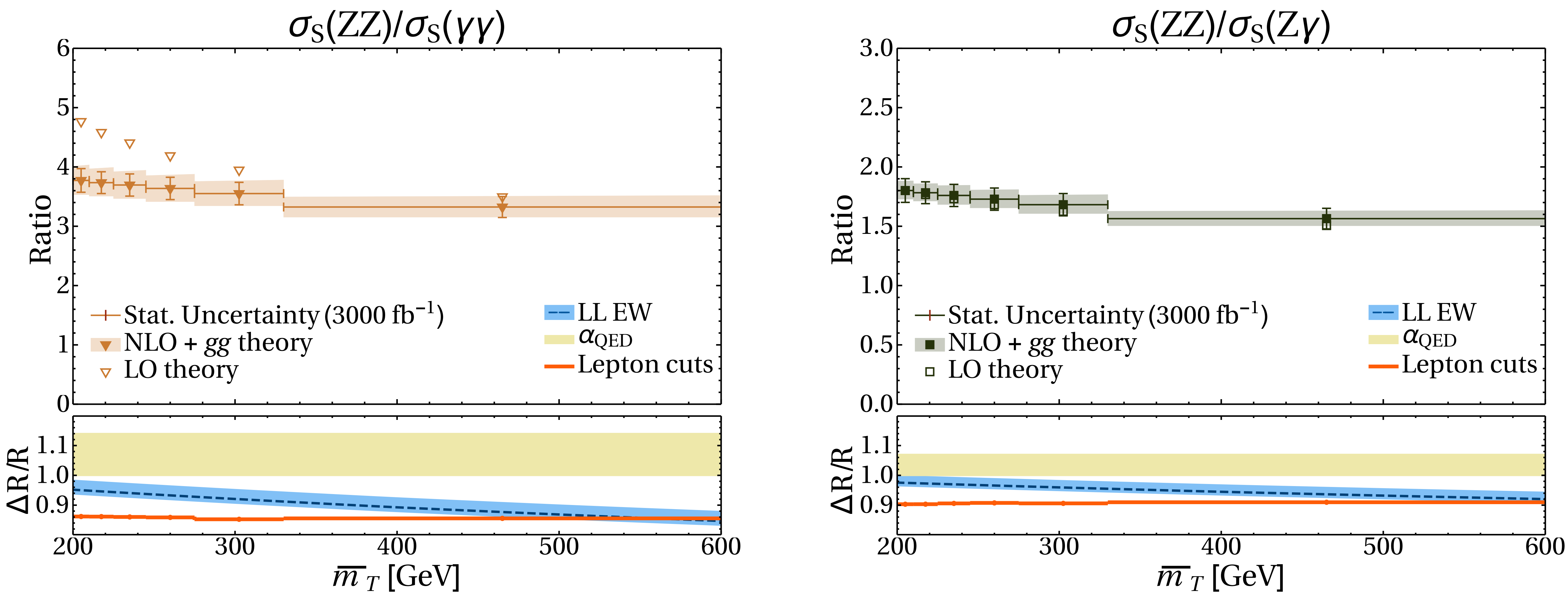


The Plot I



$\sigma_S(Z\gamma)/\sigma_S(\gamma\gamma)$
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Ratio
Stat. Uncertainty (300 fb^{-1})
NLO + gg theory
LO theory
LL EW
α_{QED}
Lepton cuts
1.1
1.0
0.9
ΔR/R
200
300
400
500
600
$\overline{m}_T$ [GeV]

The Plot II



$\sigma_S(ZZ)/\sigma_S(\gamma\gamma)$
Ratio
Stat. Uncertainty (3000 fb^{-1})
NLO + gg theory
LO theory
LL EW
α_{QED}
Lepton cuts
ΔR/R
$\overline{m}_T$ [GeV]
$\sigma_S(ZZ)/\sigma_S(Z\gamma)$
Ratio
Stat. Uncertainty (3000 fb^{-1})
NLO + gg theory
LO theory
LL EW
α_{QED}
Lepton cuts
ΔR/R
$\overline{m}_T$ [GeV]

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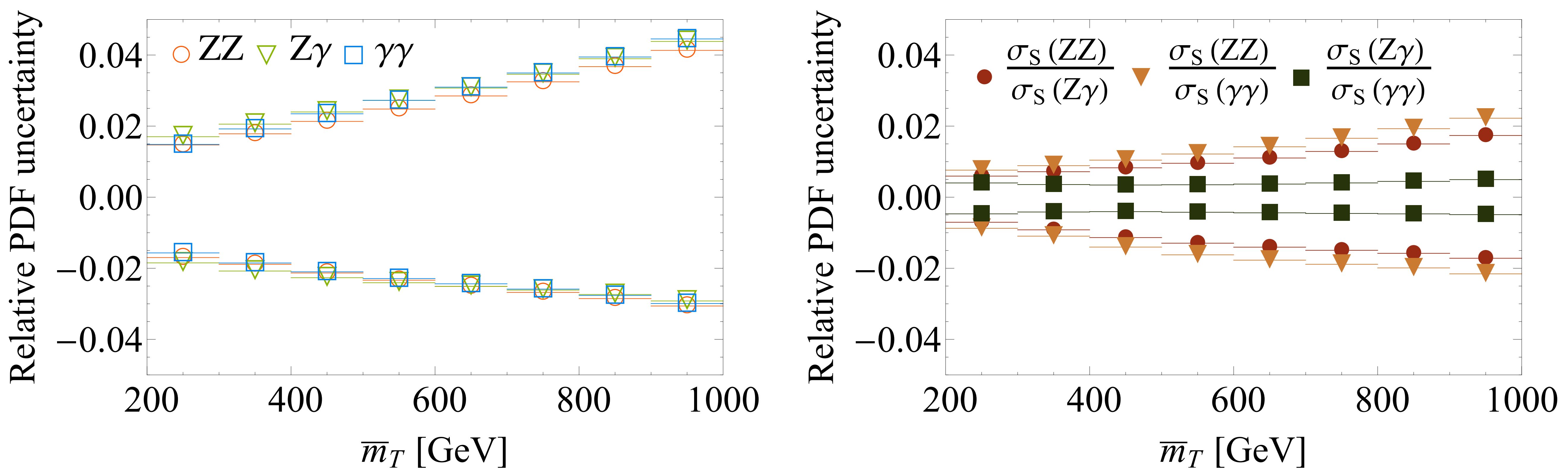
Uncertainties

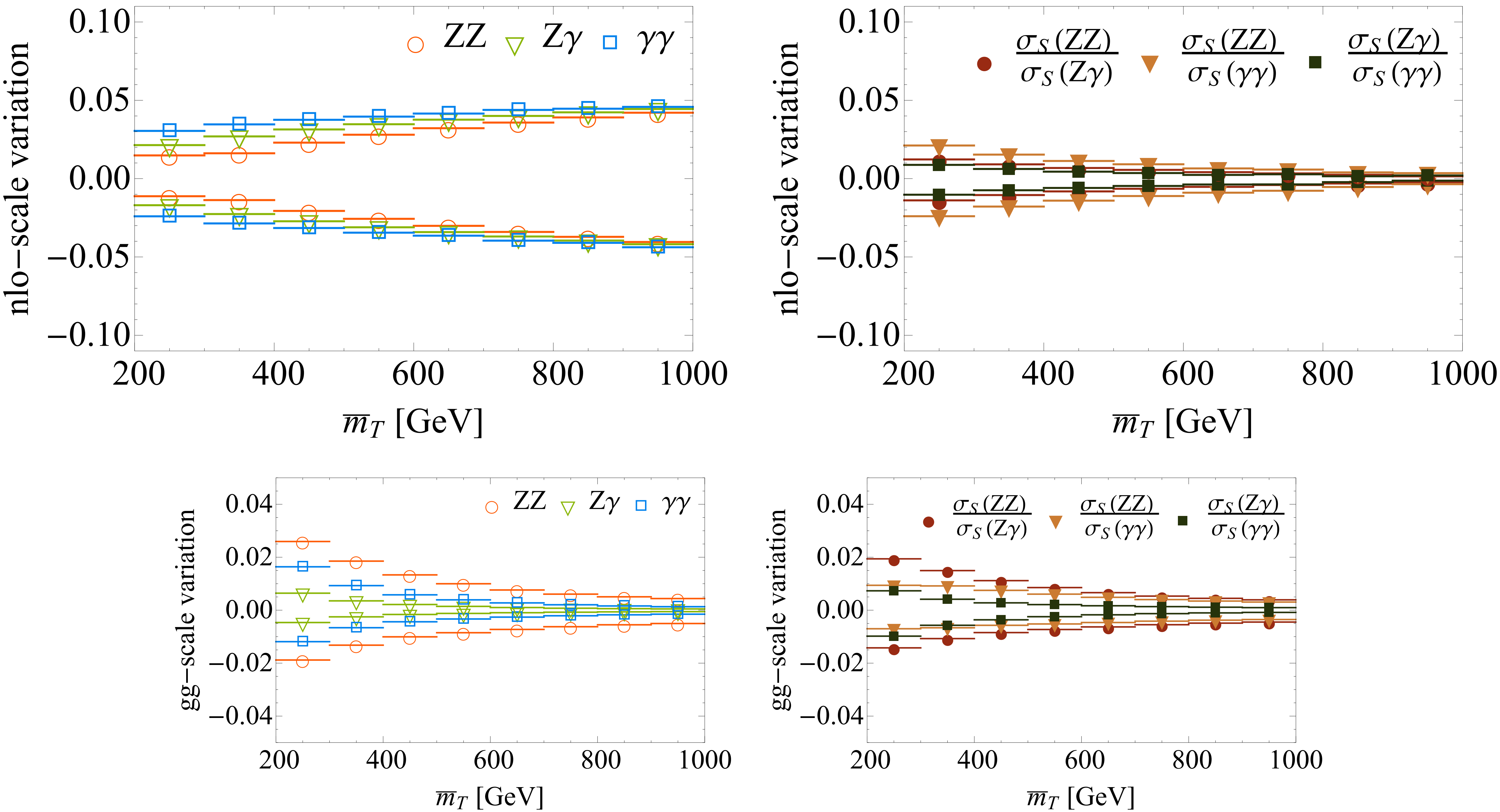
PDFs

This is where we reap the benefits of our work



Uncertainties

QCD Scales



Uncertainties

Full Budget

Effect	R_{1a} $(Z\gamma/\gamma\gamma)$	R_{1b} $(ZZ/\gamma\gamma)$	R_{1c} $(ZZ/Z\gamma)$	Comments
$qq \to VVqq$	2–3%	3–3.5%	1.5–2.5%	extrapolating $p^{j}_{T,\min} \to 0$ (section 4.2)
μ_R, μ_F (gg)	0.5–1%	1%	1–2%	uses NLO $gg \to \gamma\gamma$ (section 4.5)
μ_R, μ_F (NLO)	0.5–1%	1.5–2.5%	1–1.5%	varied independently (section 4.5)
PDF	0.5%	1–1.5%	0.5–1%	MSTW 2008 using MCFM (section 4.5)
EW (LL)	$^{+2\%}_{-1\%}$	$^{+3\%}_{-1\%}$	$^{+2\%}_{-1\%}$	EFT scale uncertainty (section 4.4.1)
α_{QED}	7%	14%	7%	Fully correlated (section 4.4.2)

Conclusion

- We have identified a set of ratios that rely on SU(2) structure already present in the SM
- Many sources of theoretical uncertainties cancel for these ratios
- This statement survives the QCD NLO corrections largely intact thanks to reasonable kinematic cuts.
- Ratio $\sigma(\gamma\gamma)/\sigma(\gamma Z)$ can be measured very well (5%) at 300 fb^{-1}

Photon Jets at LHC

(maybe 750 GeV)

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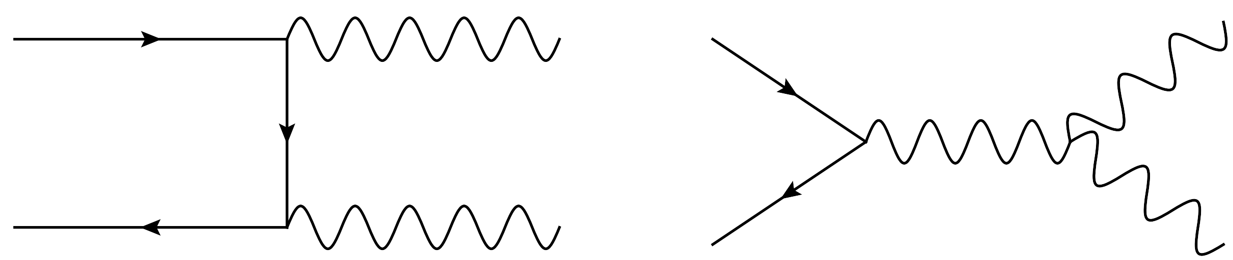

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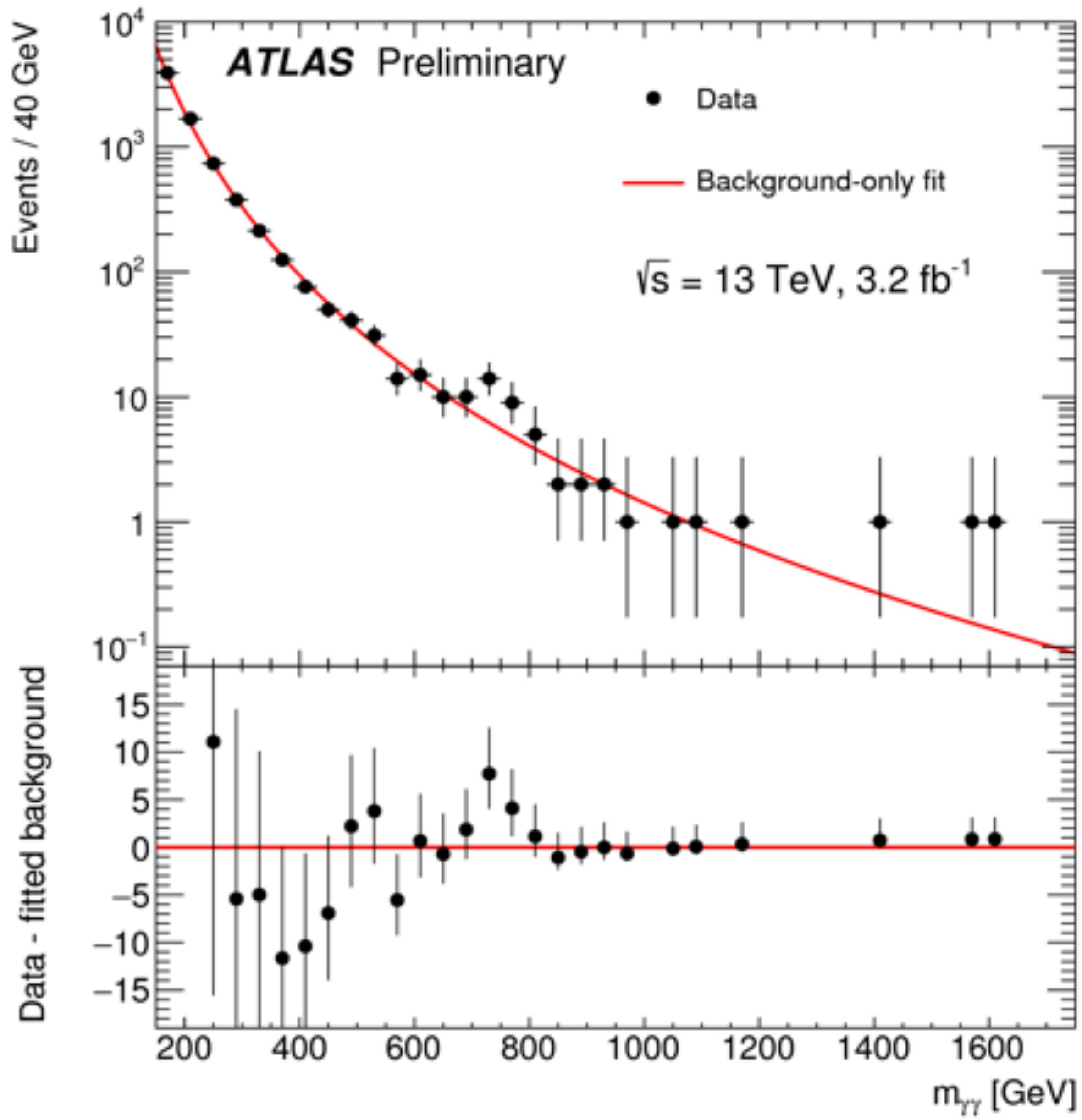
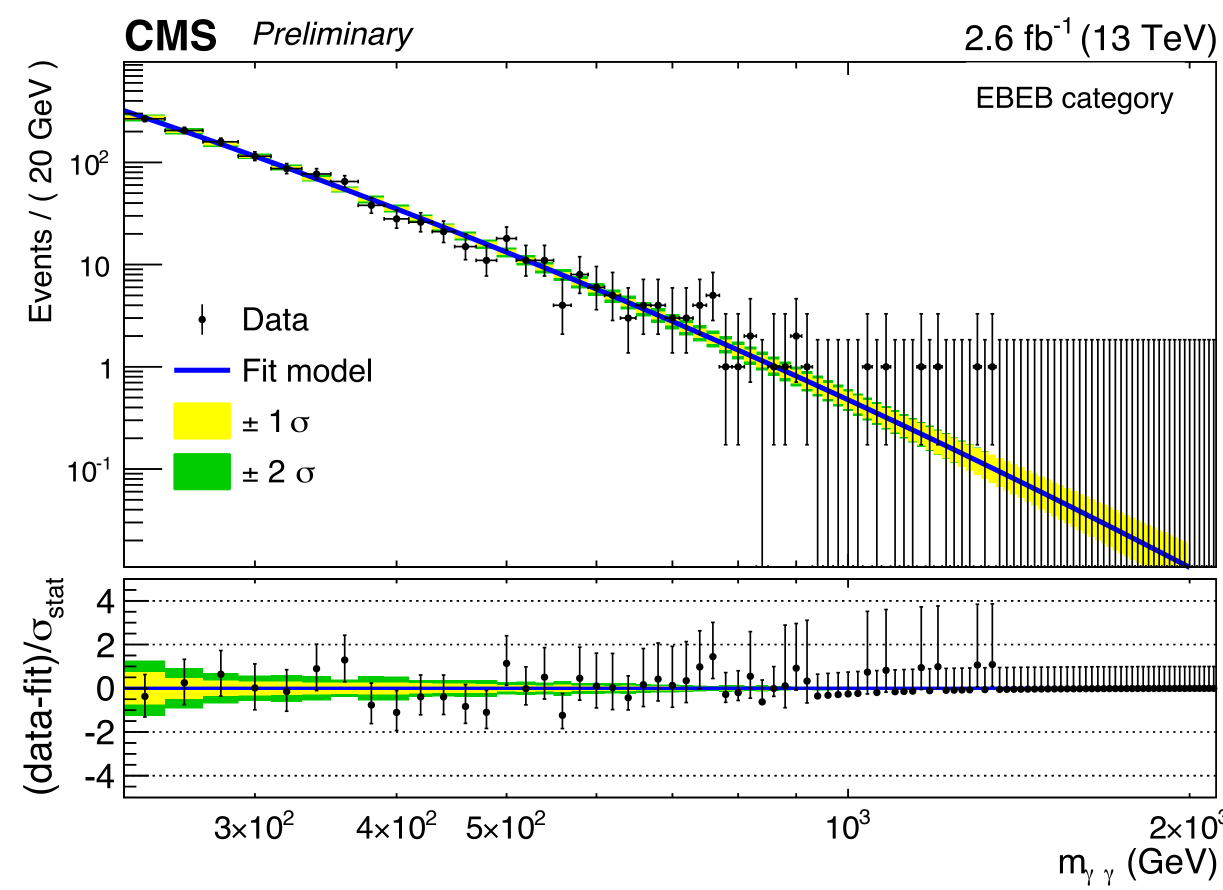
with SD Ellis, T Roy
arxiv:1210.1855, 1210.3657

There is an excess of events with two photons with invariant mass around 750 GeV in both ATLAS and CMS



3.6σ

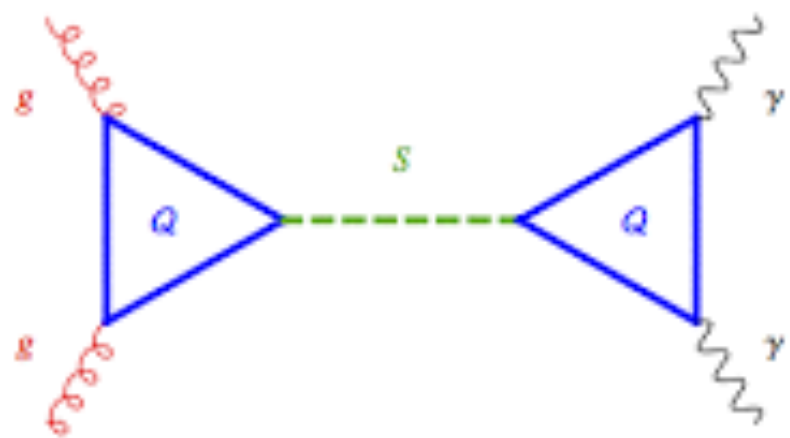


2.6σ

Since the previous run, we have seen an energy and parton luminosity increase.

$r_{b\bar{b}}$	$r_{c\bar{c}}$	$r_{s\bar{s}}$	$r_{d\bar{d}}$	$r_{u\bar{u}}$	r_{gg}	$r_{\gamma\gamma}$
5.4	5.1	4.3	2.7	2.5	4.7	1.9

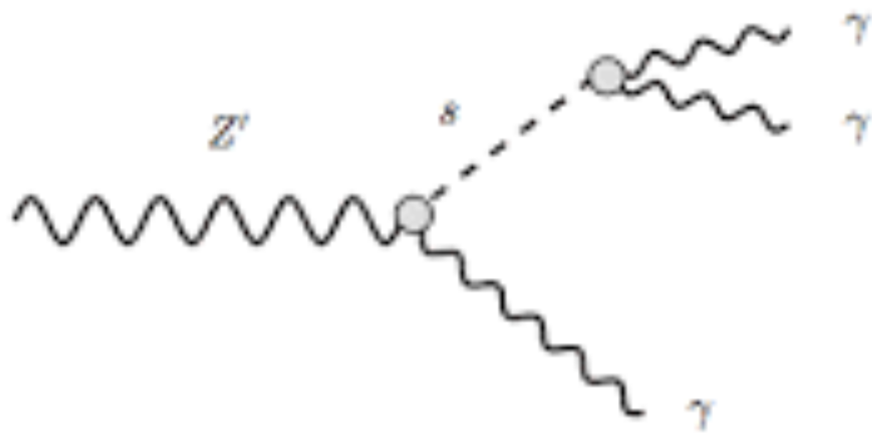
Given we have not seen a large excess in the previous (8TeV) run, it is most likely that the gg channel is responsible.

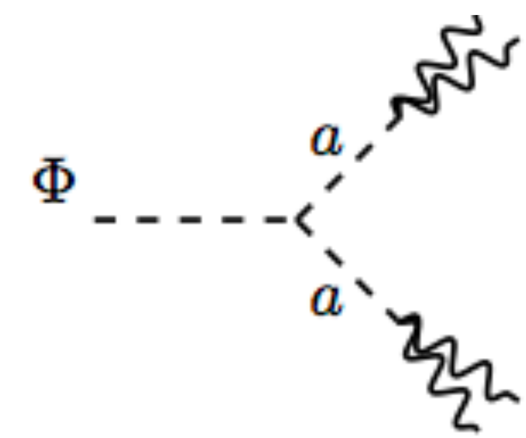


However, this is hard (not impossible) to hide because the loop suppressed photon decay mode is subleading to the allowed tree-level processes.

Although there are about 174 papers that say otherwise.

In order to make this 750GeV resonance couple to photons directly, we can postulate these photons are not just single photons, but instead two (or more) collimated photons.





This has been suggested by several sets of authors

1512.04928: Knapen, Melia, Papucci, Zurek
1512.05775: Agrawal, Fan, Heidenreich, Reece, Strassler
1512.06671: Chang, Cheung, Chih-Ting

These objects are called Photon-jets

they have a history

[21] B. A. Dobrescu, G. L. Landsberg, and K. T. Matchev, "Higgs boson decays to CP odd scalars at the Tevatron and beyond," *Phys. Rev.* **D63** (2001) 075003, arXiv:hep-ph/0005308 [hep-ph].

[22] S. Chang, P. J. Fox, and N. Weiner, "Visible Cascade Higgs Decays to Four Photons at Hadron Colliders," *Phys. Rev. Lett.* **98** (2007) 111802, arXiv:hep-ph/0608310 [hep-ph].

[23] N. Toro and I. Yavin, "Multiphotons and photon jets from new heavy vector bosons," *Phys. Rev.* **D86** (2012) 055005, arXiv:1202.6377 [hep-ph].

[24] P. Draper and D. McKeen, "Diphotons from Tetraphotons in the Decay of a 125 GeV Higgs at the LHC," *Phys. Rev.* **D85** (2012) 115023, arXiv:1204.1061 [hep-ph].

[25] S. D. Ellis, T. S. Roy, and J. Scholtz, "Jets and Photons," *Phys. Rev. Lett.* **110** no. 12, (2013) 122003, arXiv:1210.1855 [hep-ph].

[26] S. D. Ellis, T. S. Roy, and J. Scholtz, "Phenomenology of Photon-Jets," *Phys. Rev.* **D87** no. 1, (2013) 014015, arXiv:1210.3657 [hep-ph].

they have been looked for

ATLAS Collaboration, "Search for a Higgs boson decaying to four photons through light CP-odd scalar coupling using 4.9 fb^{-1} of 7 TeV *pp* collision data taken with ATLAS detector at the LHC,".

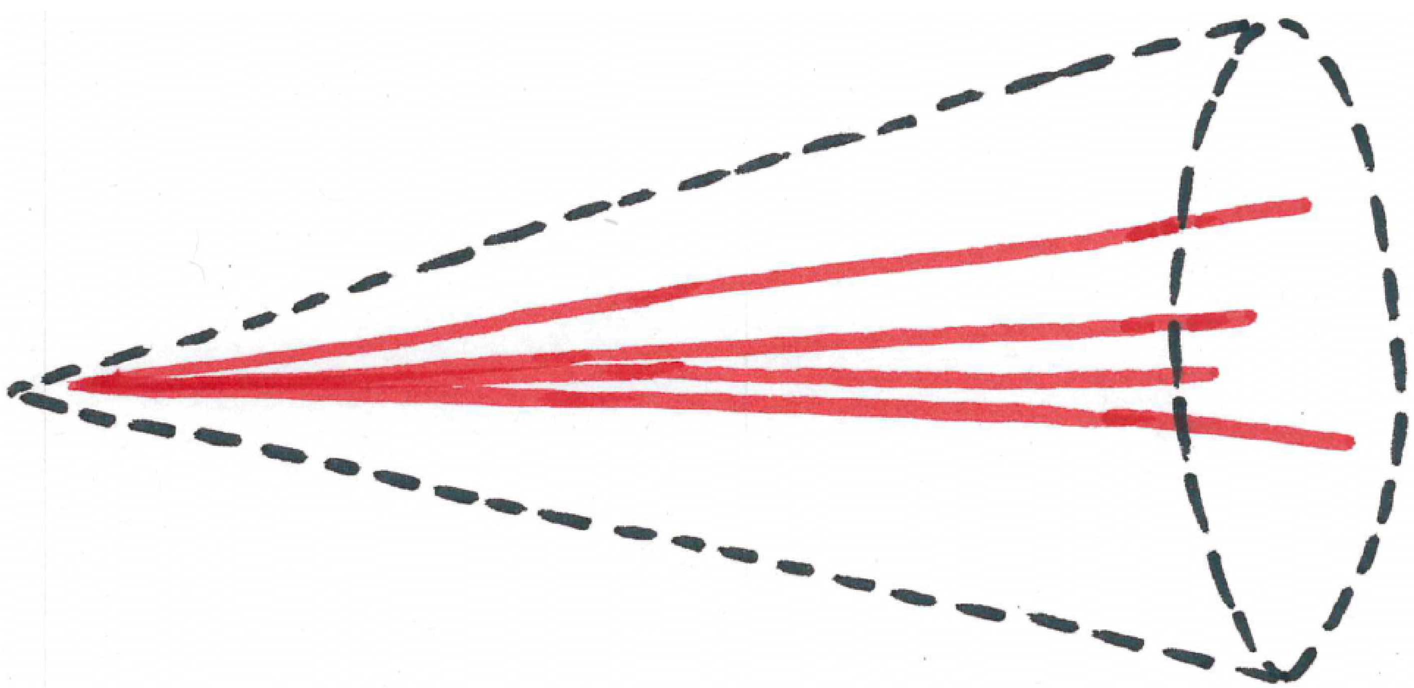
. . .

Plan

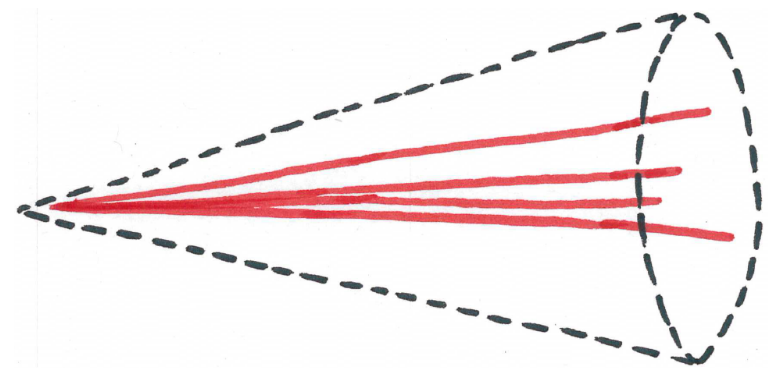
- Define photon-jets
- Define discriminants
- Show results
- Conclude

Photon-jet

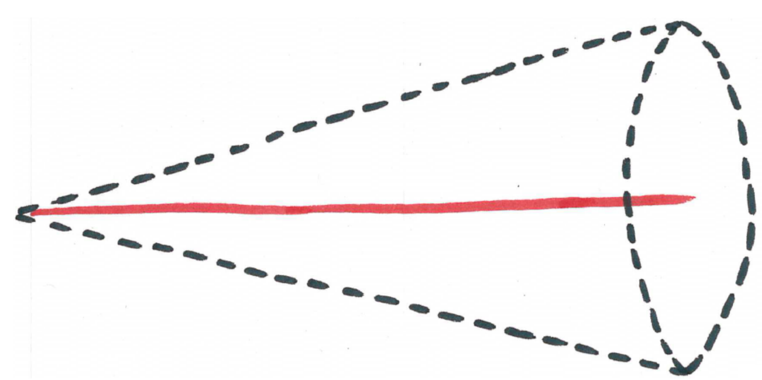
- a collection of two or more collinear photons, that form a jet like deposition in the calorimeters



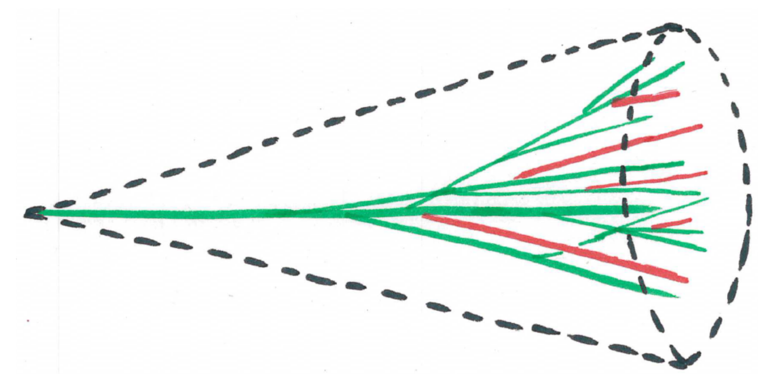
We will try to separate these three categories:



Photon-Jet

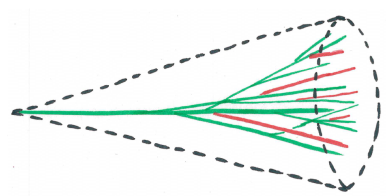
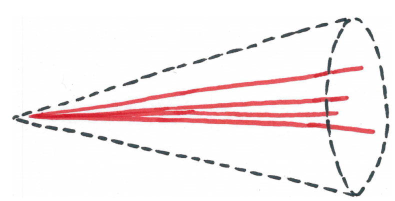
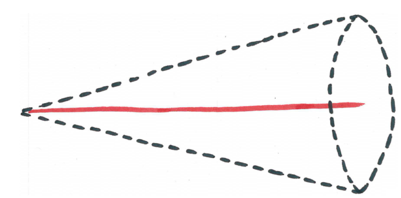


Photon



QCD-Jet

- If we want to compare QCD-jets, photon-jets and photons, we need a common basis.
- Right now, we search for photons one way (use seeds, calorimeter towers, etc.), for QCD-jets another way (jet algorithms) and don't look for photon-jets at all.
- Instead, search for jets and then tag each of them as either a QCD-jet, a photon or a photon-jet, based on their properties.

$\text{Jets} = \Bigg\{$ , , , $\ldots \Bigg\}$

Plan

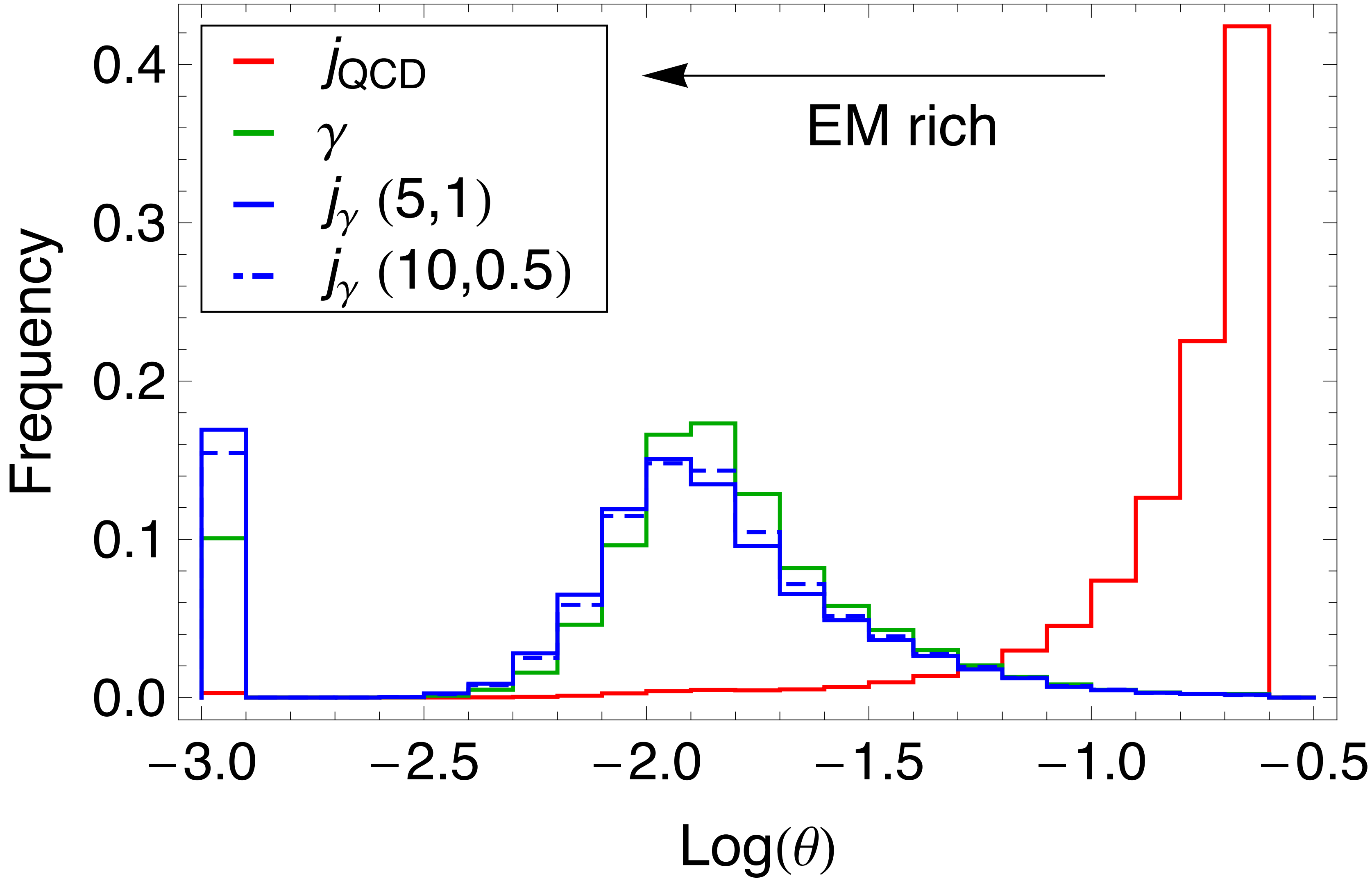
- Define Photon Jets
- Define discriminants
- Show results
- Conclude

These discriminants will be used in a multivariate analysis (TMVA) to separate all three populations:

- Conventional
  - Fraction of Hadronic Energy in the Jet
  - Number of Charged Tracks
- N-subjettiness
- More Substructure
  - Energy-Energy Correlation
  - Subjet Spread
  - Leading subjet p_T

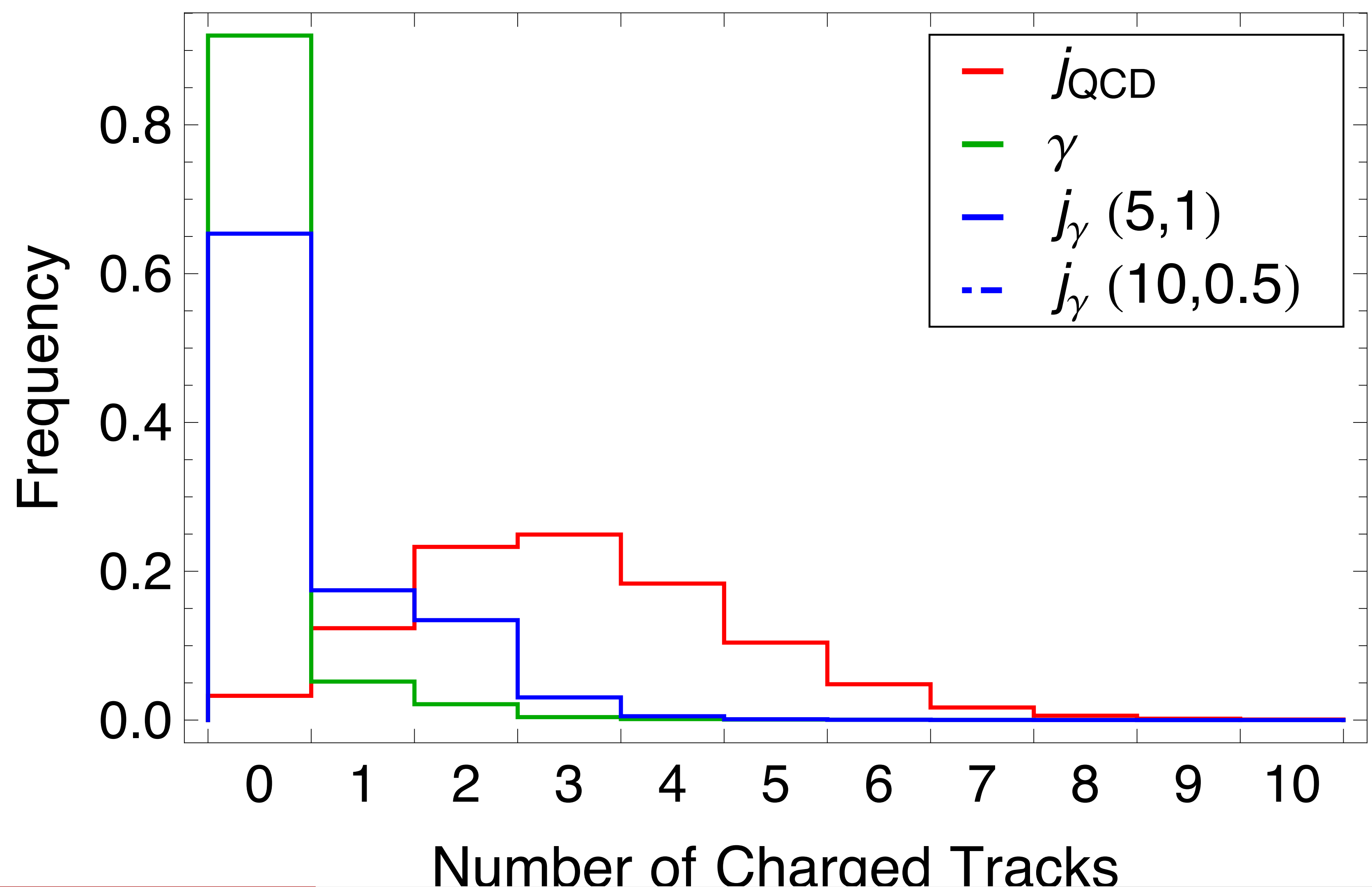
Fraction of Hadronic Energy in the Jet

Measures the fraction of hadronic energy in a jet, $\theta = E_{had}/E_{total}$



Number of Charged Tracks

- Counts the number of charged tracks with $p_T > 2$ GeV associated with the jet.
- We determine if a track is associated with a jet by including its softened four-vector with all the calorimeter four-vectors.

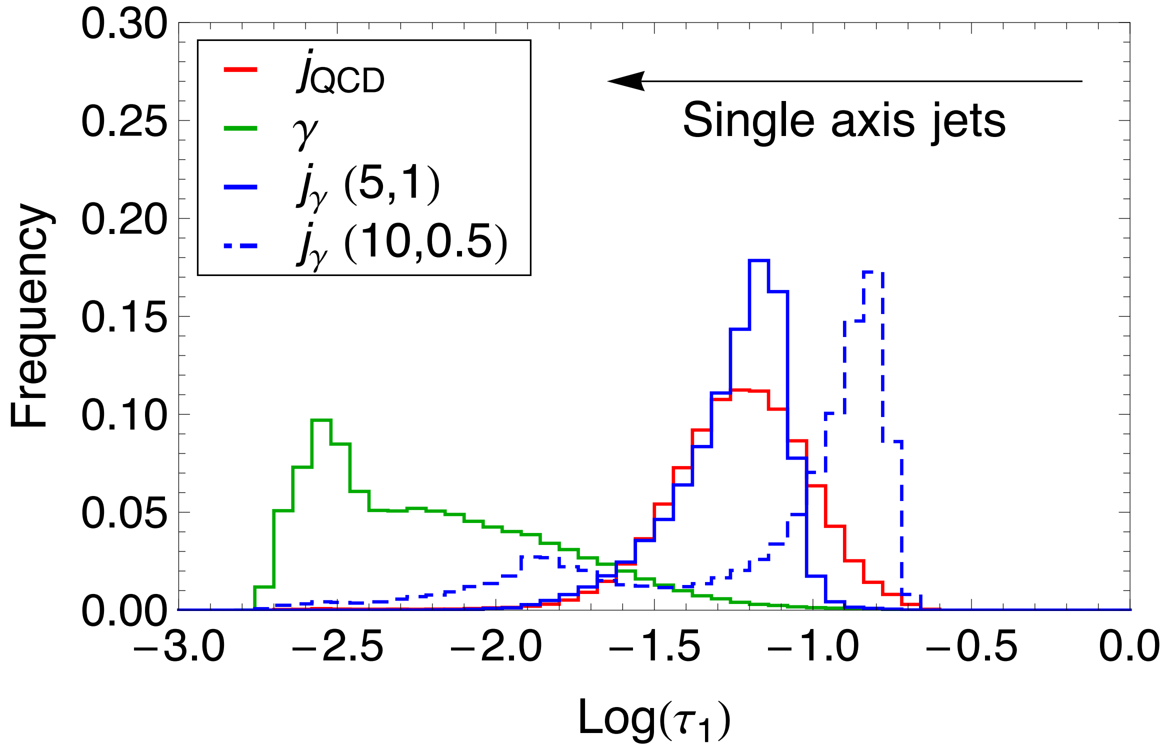


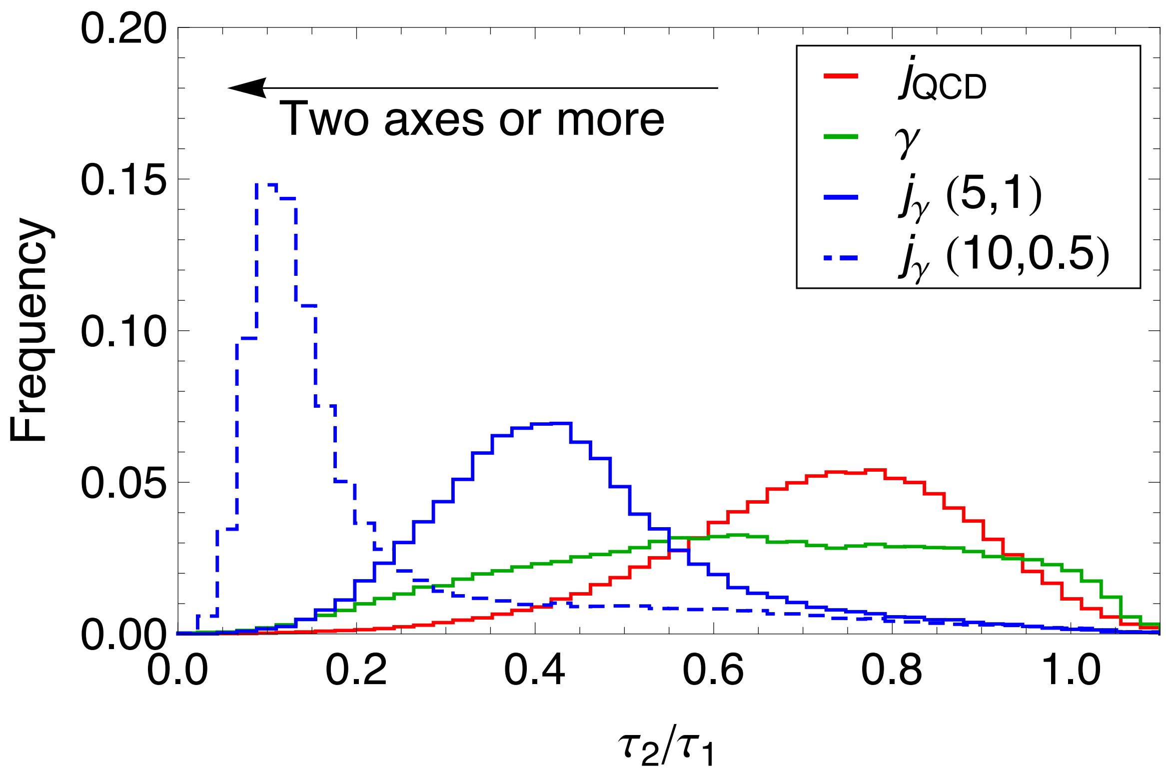
N-subjettiness

- Take a jet. Find N subjets. This defines N axes.
- Form a sum:

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

where k runs over all the constituents of a jet and $\Delta R_{i,k}$ is the angular distance between k-th constituent and the i-th subjet.

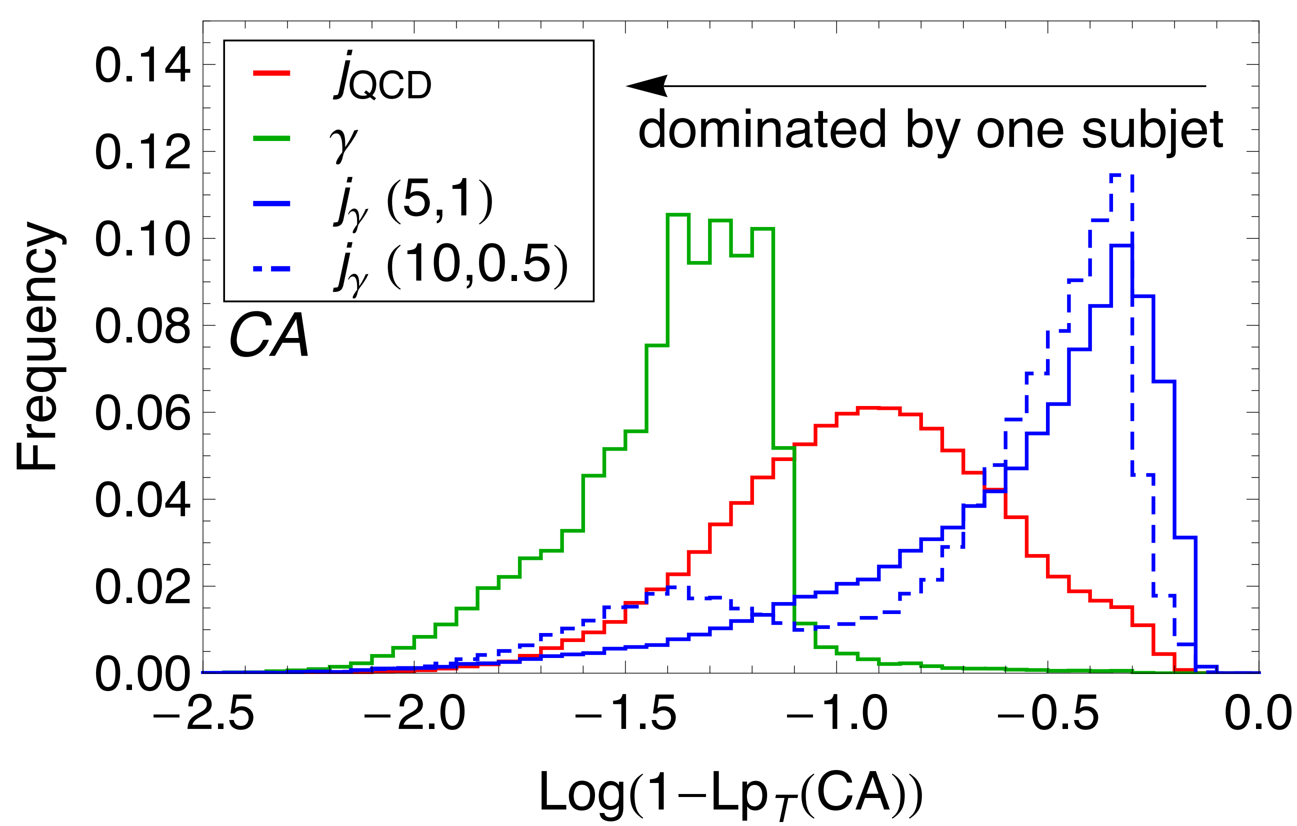


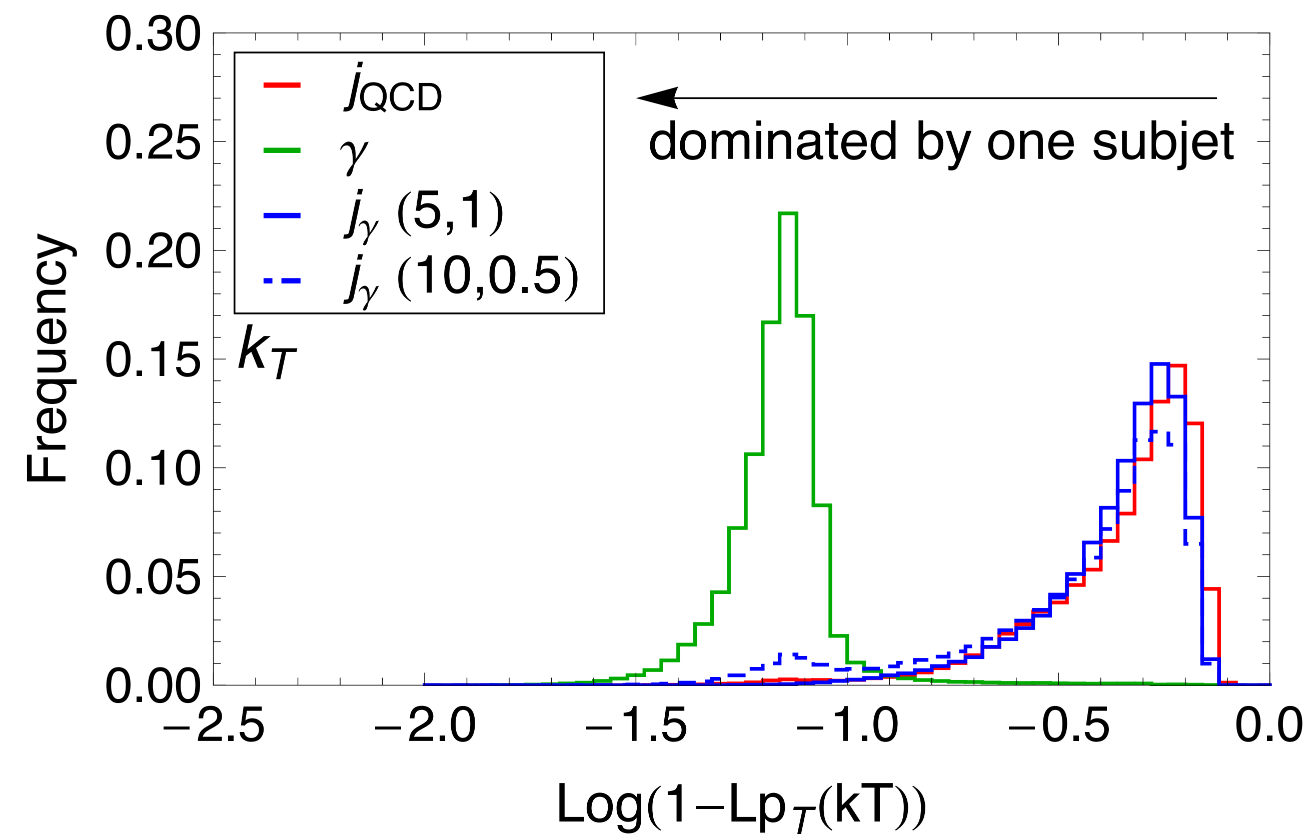


Leading Subjet Transverse Momentum

$$Lp_T = \frac{p_T \text{ of the hardest subjet}}{p_T \text{ of the entire jet}}$$

Since QCD is characterized by soft radiation we expect the leading subjet will contain most of the p_T of the jet.

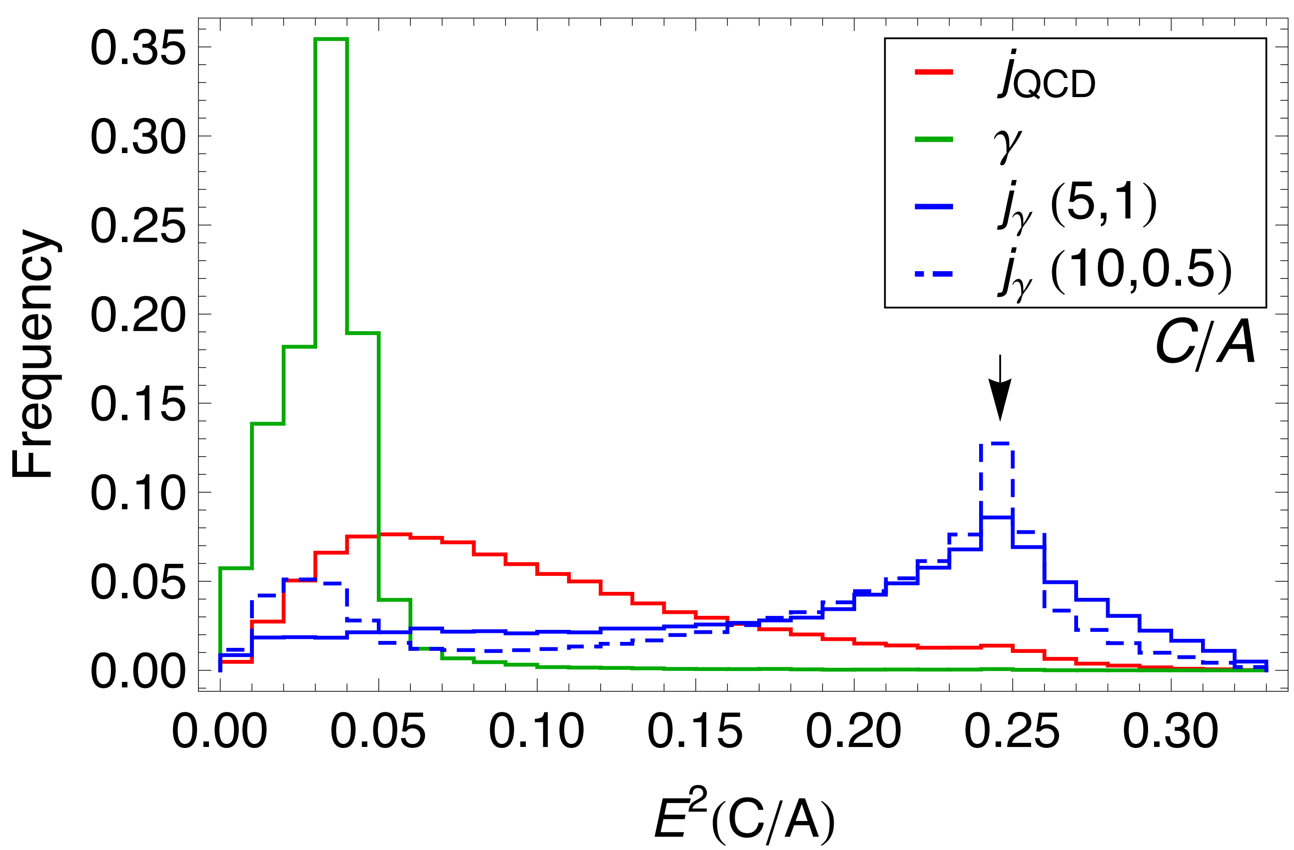


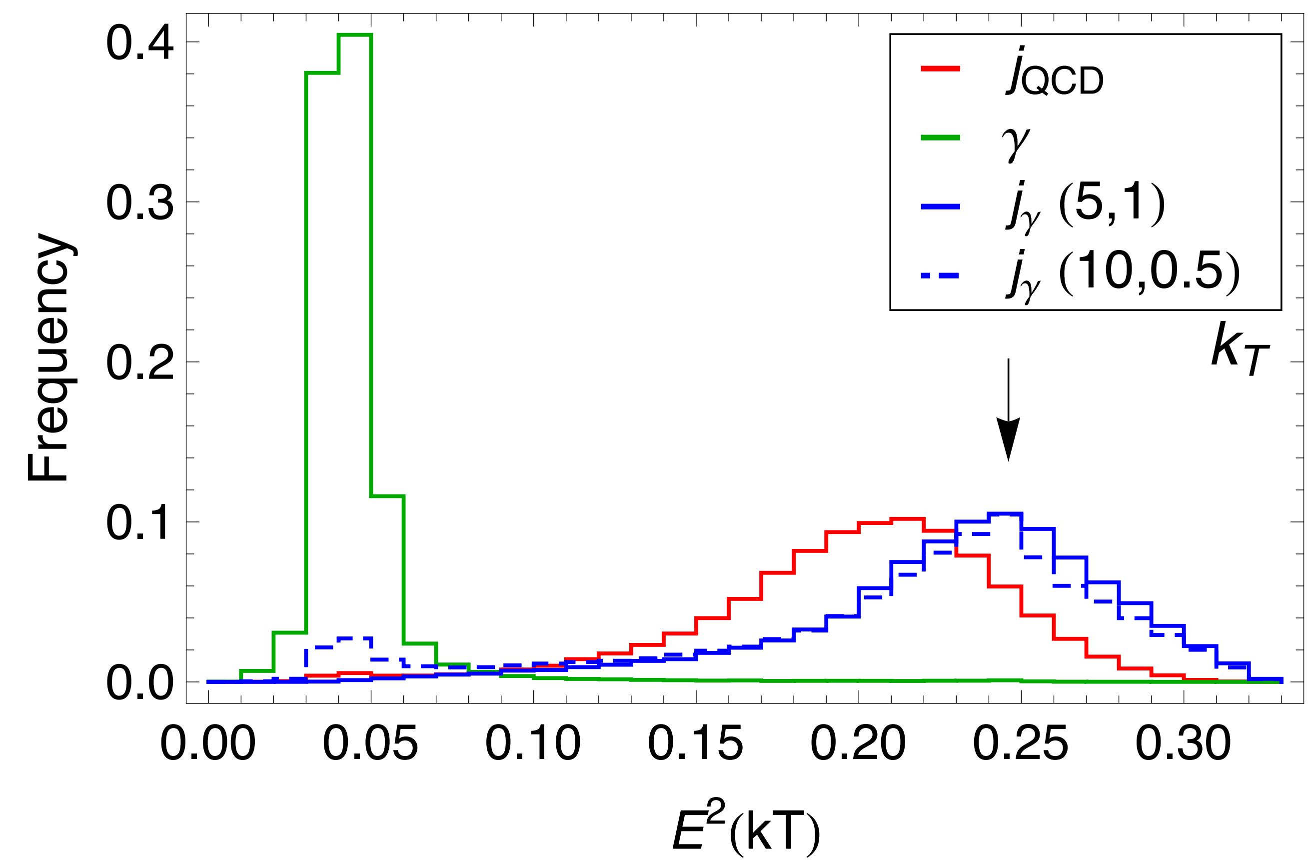


Energy-Energy Correlation

$$\sum E^2 = \sum_{i<j} E_i E_j / E^2_{total}$$

Relates to the variance of energy distribution amongst the subjets.





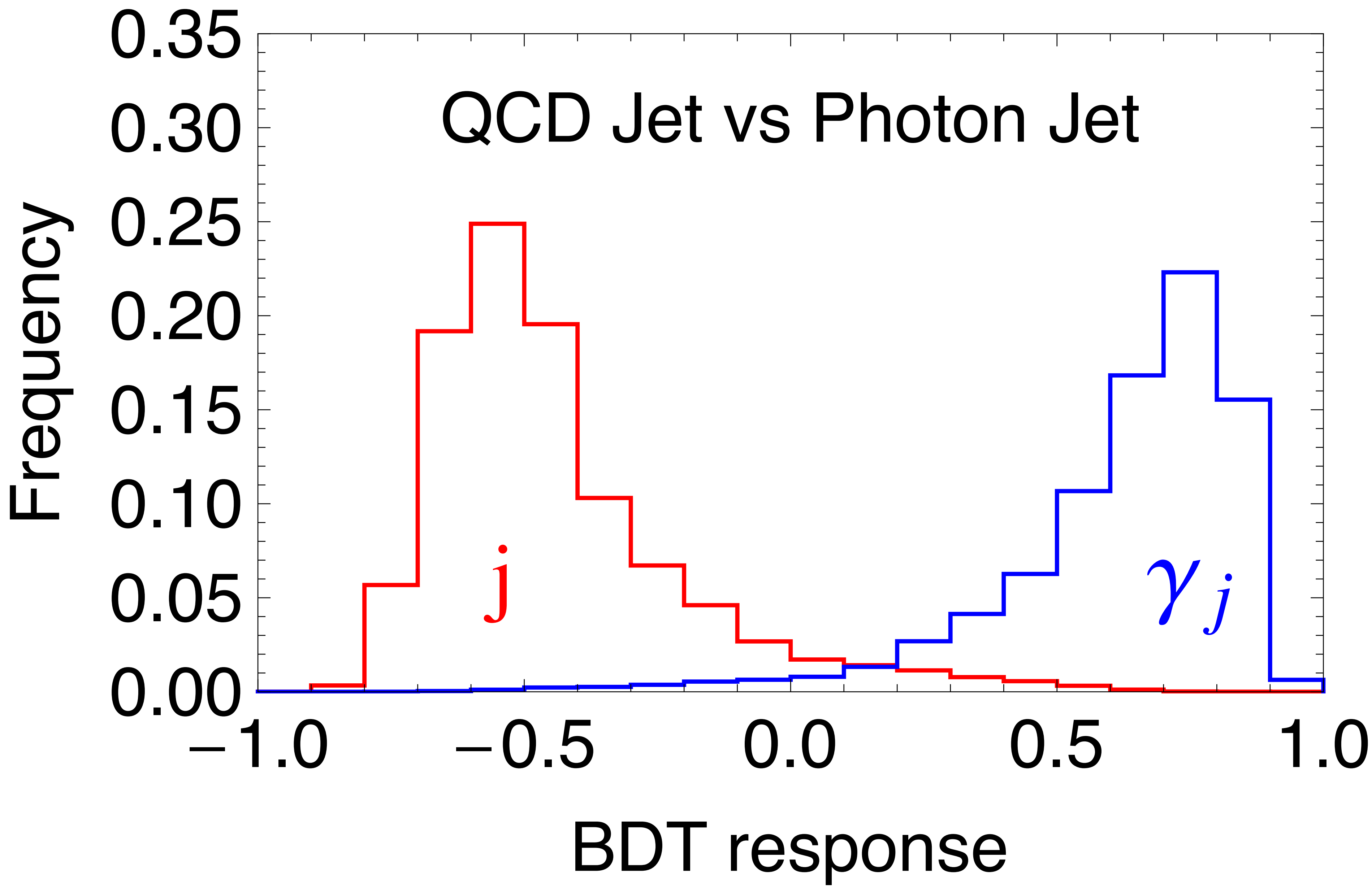
There are more possible discriminants, but these do most of the work

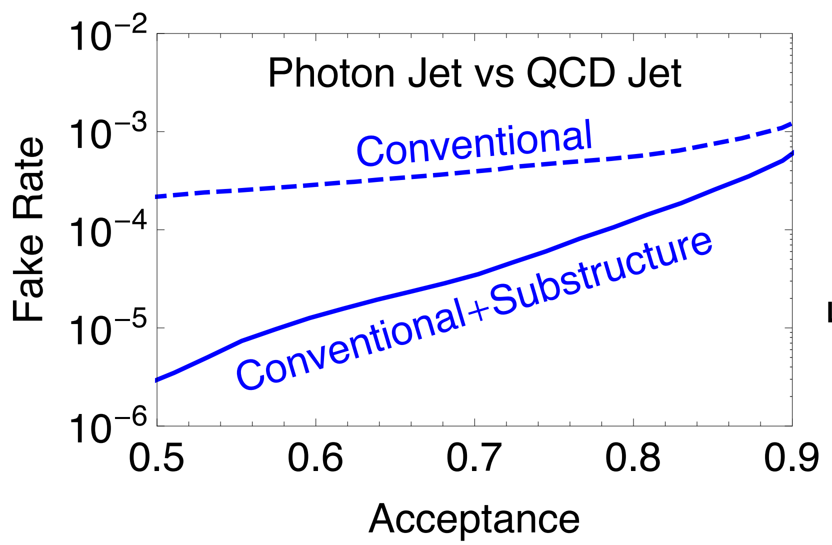
Plan

- Define Photon Jets
- Define discriminants
- Show results
- Conclude

Separating Photon-Jets and QCD-Jets

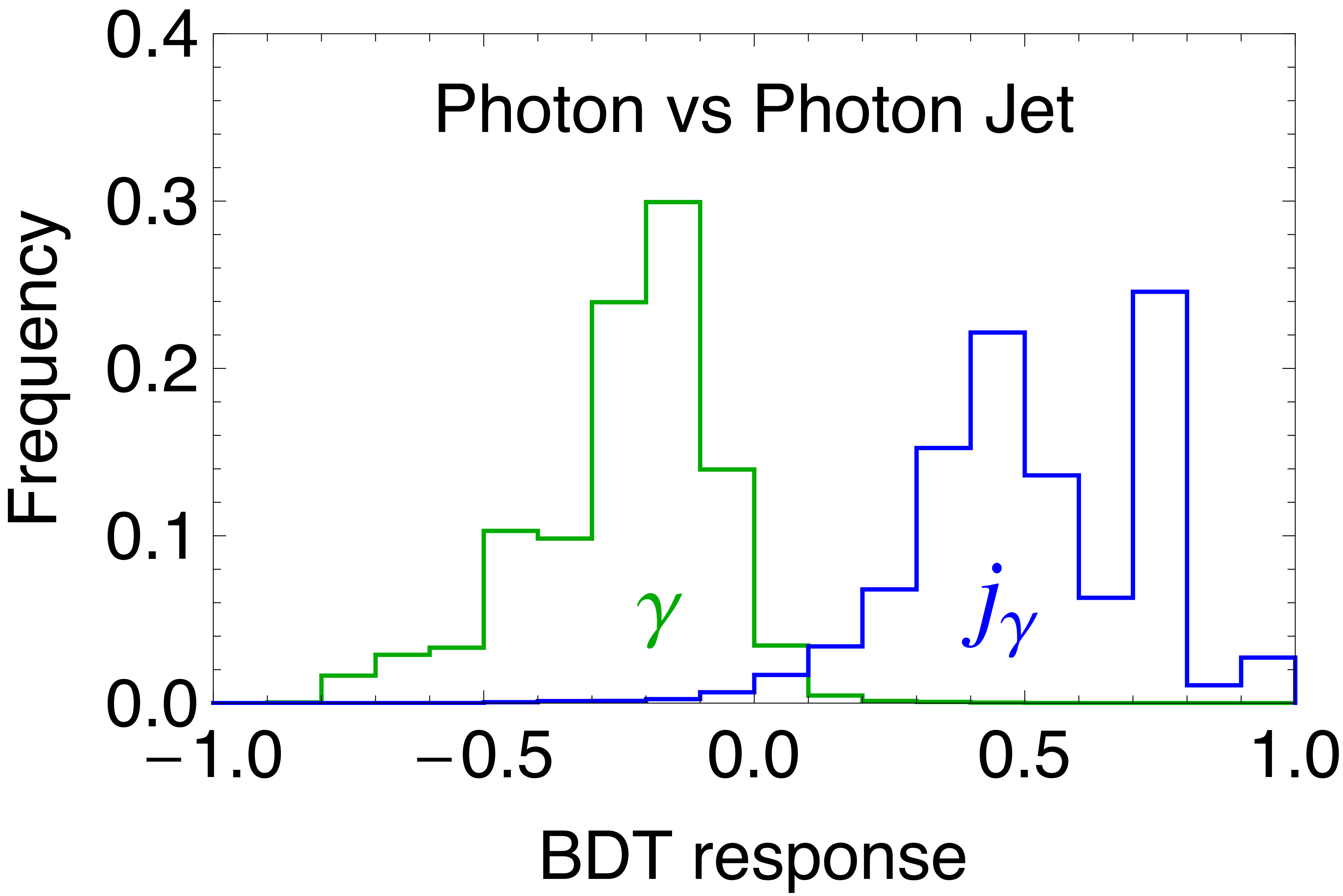
We train a BDT to separate photon-jets from QCD-jets

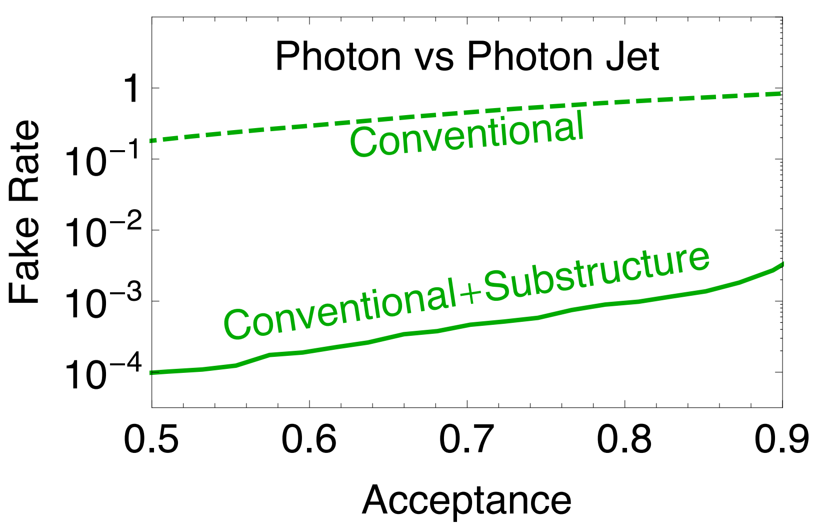




Separating Photon-Jets and Photons

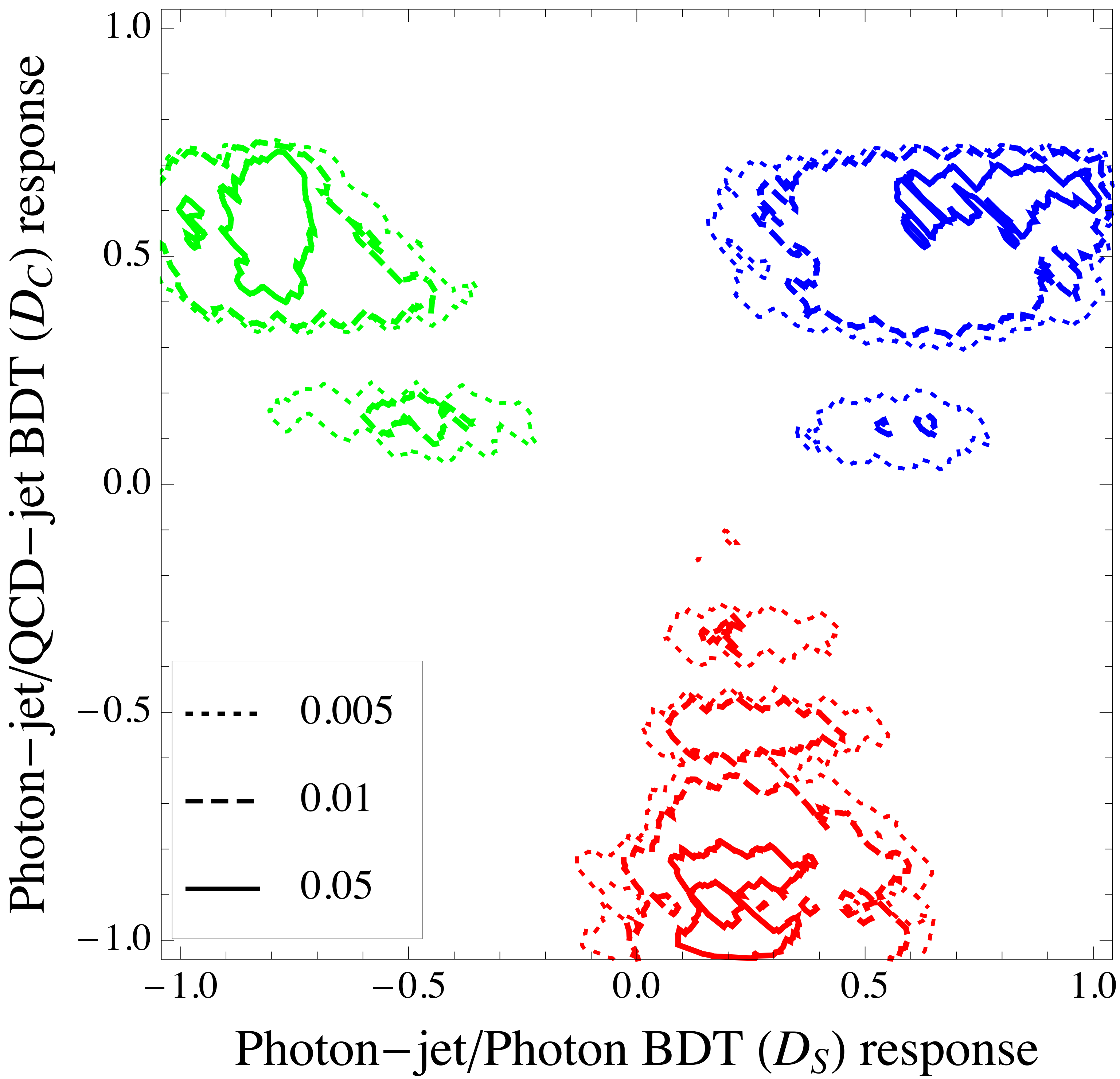
We train another BDT to separate Photon-Jets from Photons





Separating Photons, Photon-Jets and QCD

- We use two BDTs to extract as much information as possible.
- Split QCD-jets away with *only Conventional* variables.
- Split Photons from photon-jets with *just Substructure*.
- QCD-jets
  photons
  photon-jets.



Plan

- Define Photon Jets
- Define discriminants
- Show results
- Conclude

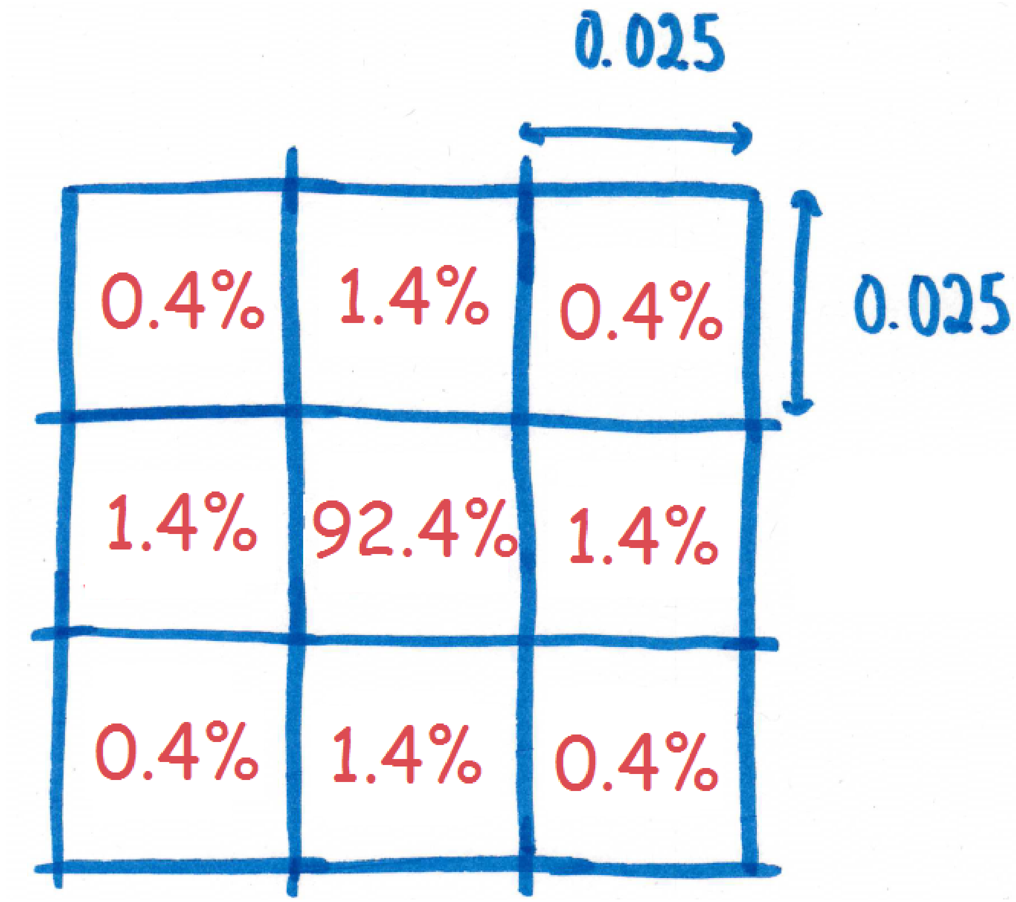
Conclusion

- Photon-jets are objects worth thinking about (whether they are the source of 750 GeV excess or not)
- We can expect some excitement in this field
- Our (theorist's) study shows there might be room for improvement.
- I would love to see people who truly understand the calorimeter to work on this (neutral pion - photon discrimination experts)

Back Up Slides

Pushing Particles through the Calorimeter

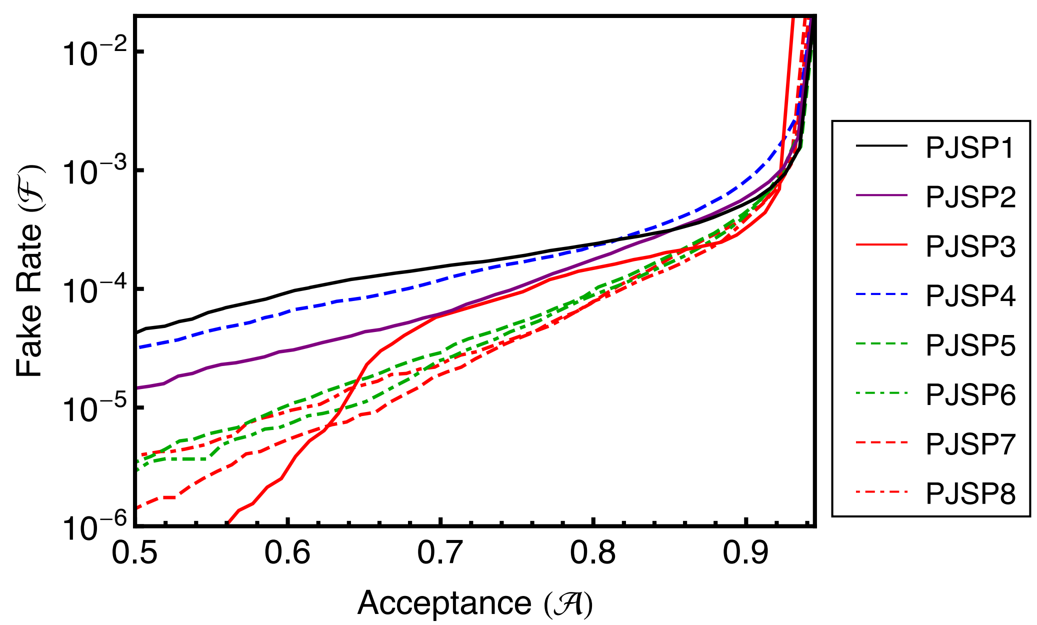
1. Use Pythia 8 to generate both signal and background events (Turn on ISR, FSR and MI).
2. Deposit particle energy according to their type and momenta. (We simulate transverse showers for photons - the pattern on the right corresponds to Molière radius in Pb)
3. Recover massless four-vectors from (η, ϕ, E) of each cell in both calorimeters.
4. Find jets in the union of *all* four vectors with Anti-k_T, $\Delta R = 0.4$, $p_T > 50$ GeV.

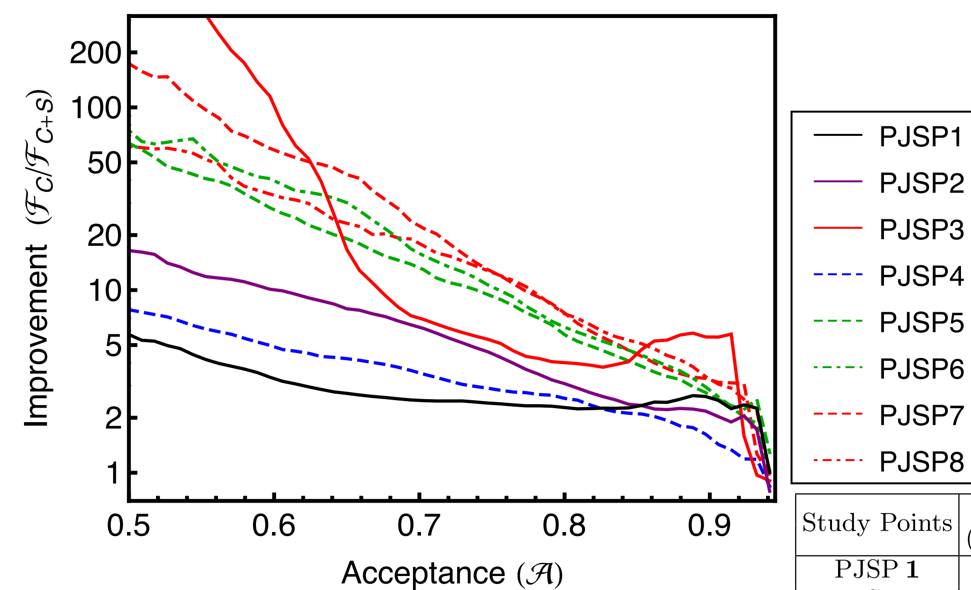


Energy deposition pattern for photons in the EM calorimeter.

More study points

Photon-jet vs QCD, (Our example is **PJSP6**)





Study Points	m_1 (GeV)	m_2 (GeV)	μ_{12} (GeV)	η_1	η_2
PJSP **1**	0.5		0	X	
PJSP **2**	1.0				
PJSP **3**	10.0				
PJSP **4**	2.0	0.5	X	0	X
PJSP **5**	5.0	0.5			
PJSP **6**		1.0			
PJSP **7**	10.0	0.5			
PJSP **8**		1.0			

Photon-jet vs Photon