Scaling properties in multijet events

— towards high multiplicities —

Peter Schichtel

Durham University

@ Higgs plus Jets 2014

Content

Introduction

- $\rightarrow$ theoretical uncertainties in multi-jet observables
- $\rightarrow$ jet scaling patterns

Jet radiation in QCD (FSR)

- $\rightarrow$ a simple QED example
- $\rightarrow$ generating functionals
- $\rightarrow$ scaling limits & beyond

Hadron colliders

- $\rightarrow$ pdf effects
- $\rightarrow$ learning from data
- $\rightarrow$ understanding Higgs (vetoes, using BDTs)

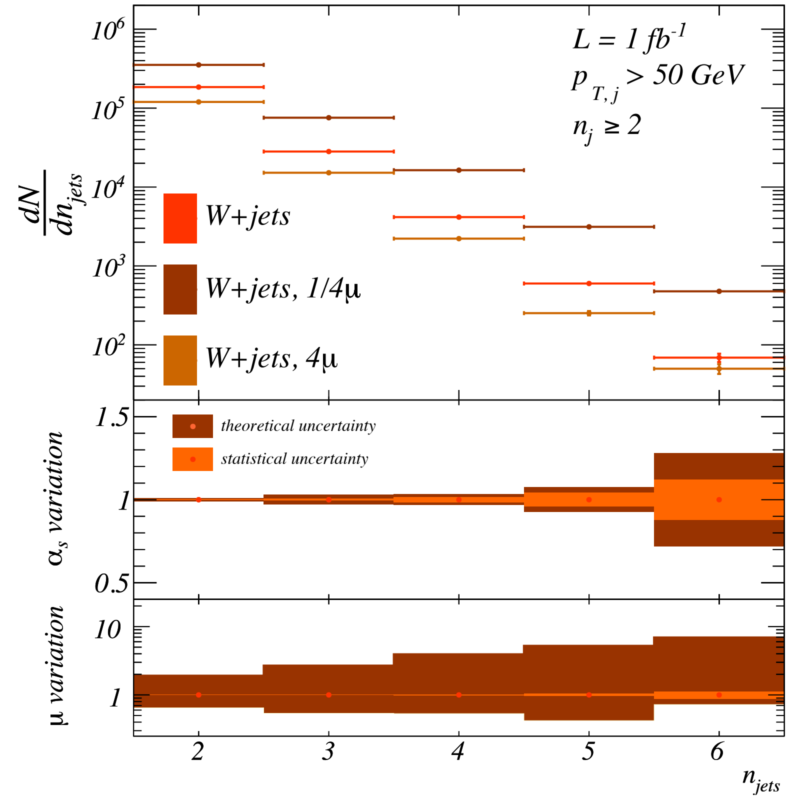
Theoretical uncertainties

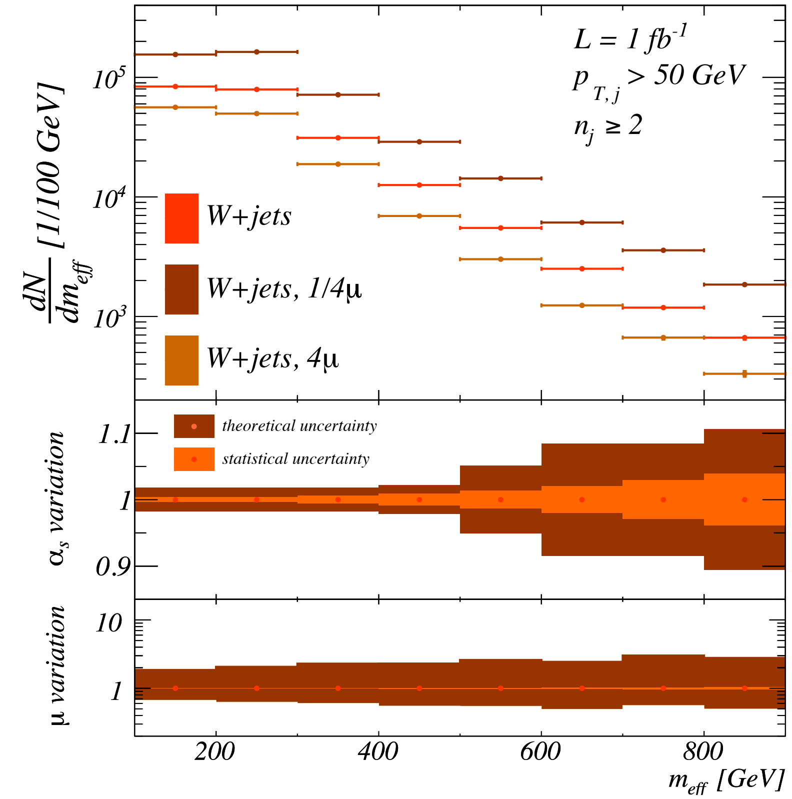
pdf uncertainties & scale choice
(smaller at NLO)

jet sprectrum

effective mass

$$m_{\text{eff}} = \not{p}_T + \sum_{\text{all jets}} p_{T,jet}$$





uncertainties highly correlated

understand jets → controll jet dependent observables

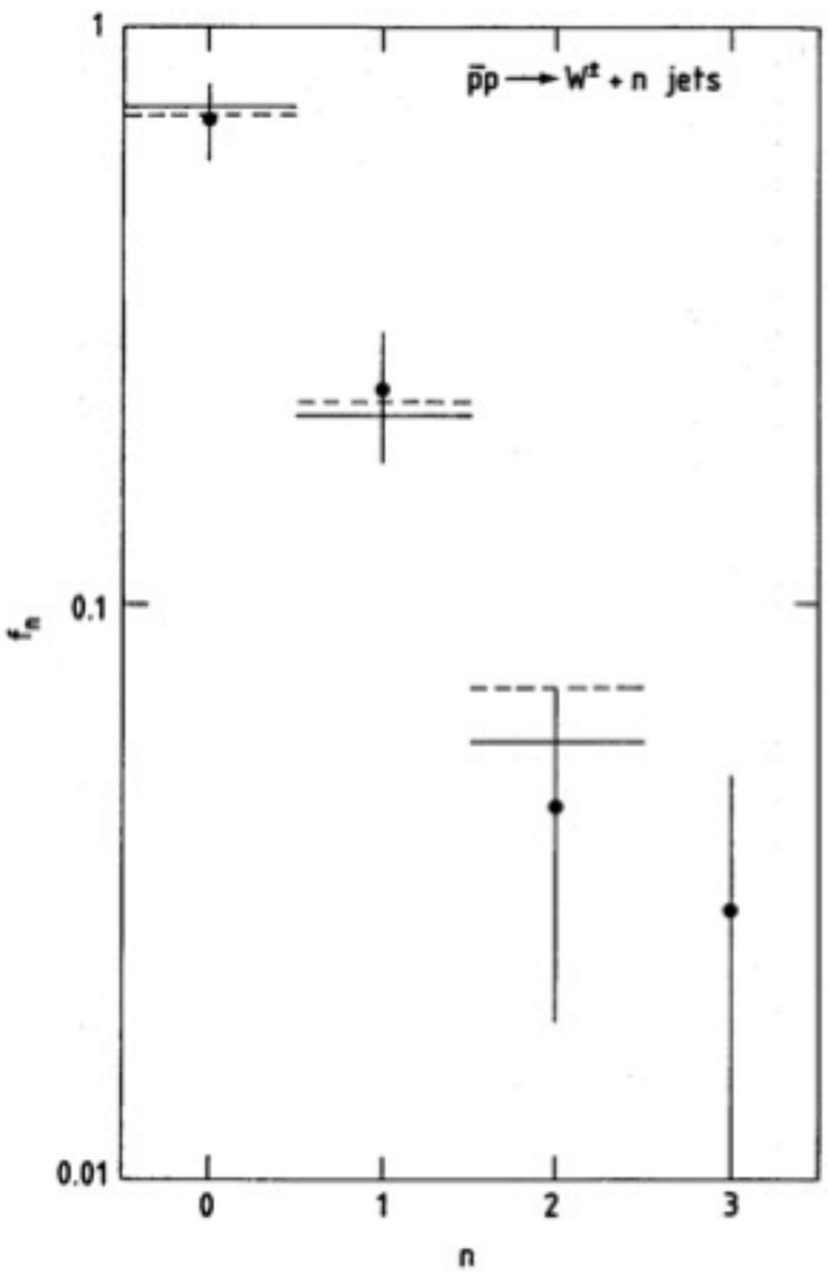
[Englert, Plehn, P.S., Schumann: Phys.Rev. D83 (2011) 095009]

W/Z plus jets in the past

discoverd at SPS

UA1

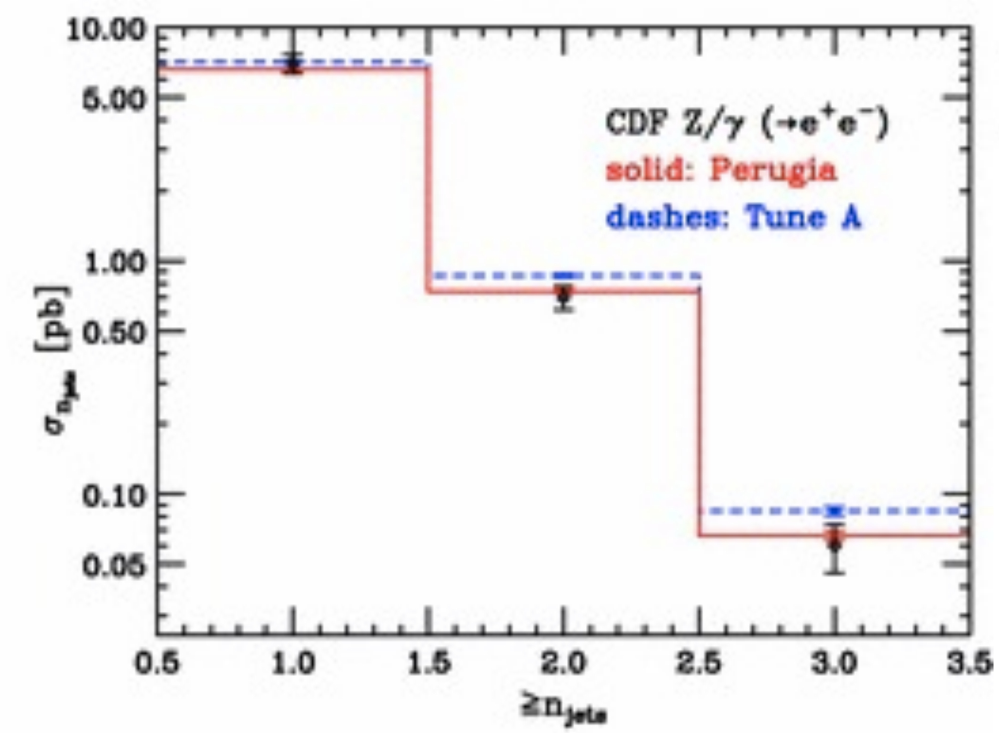
[Ellis,Kleis,Stirling(1985)]



observed at Tevatron and LHC

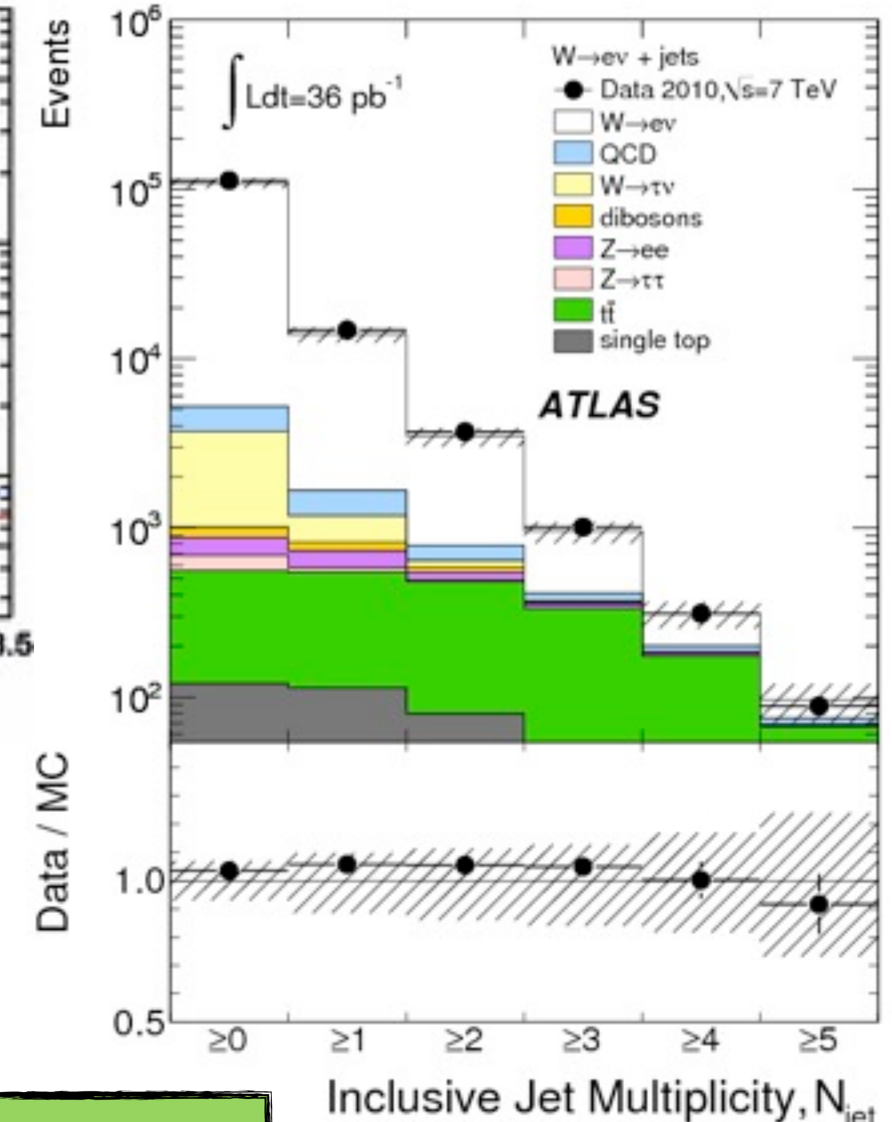
CDF

[Alioli et al, JHEP (2011) 095]



ATLAS

[Aad et al. Phys. Rev. D **85** 092002 (2012)]



staircase like jet spectrum

Aside: exclusive cross section ratios

ratios: cancel systematics

exclusive: statistically independent

visualization

exclusive: challenge for uncertainty estimation

Scaling patterns

staircase scaling

[Steve Ellis,Kleis,Stirling(1985); Berends(1989)]

$$\sigma_n^{\rm excl.} = \sigma_0 e^{-bn}$$

constant ratios

$$R_{\frac{n+1}{n}} = \frac{\sigma_{n+1}}{\sigma_n} = R_0$$

same for exclusive and inclusive

[Phys. Rev. D **83** 095009 (2011)]

Poisson scaling

[Peskin & Schroeder; Rainwater, Zeppenfeld(1997)]

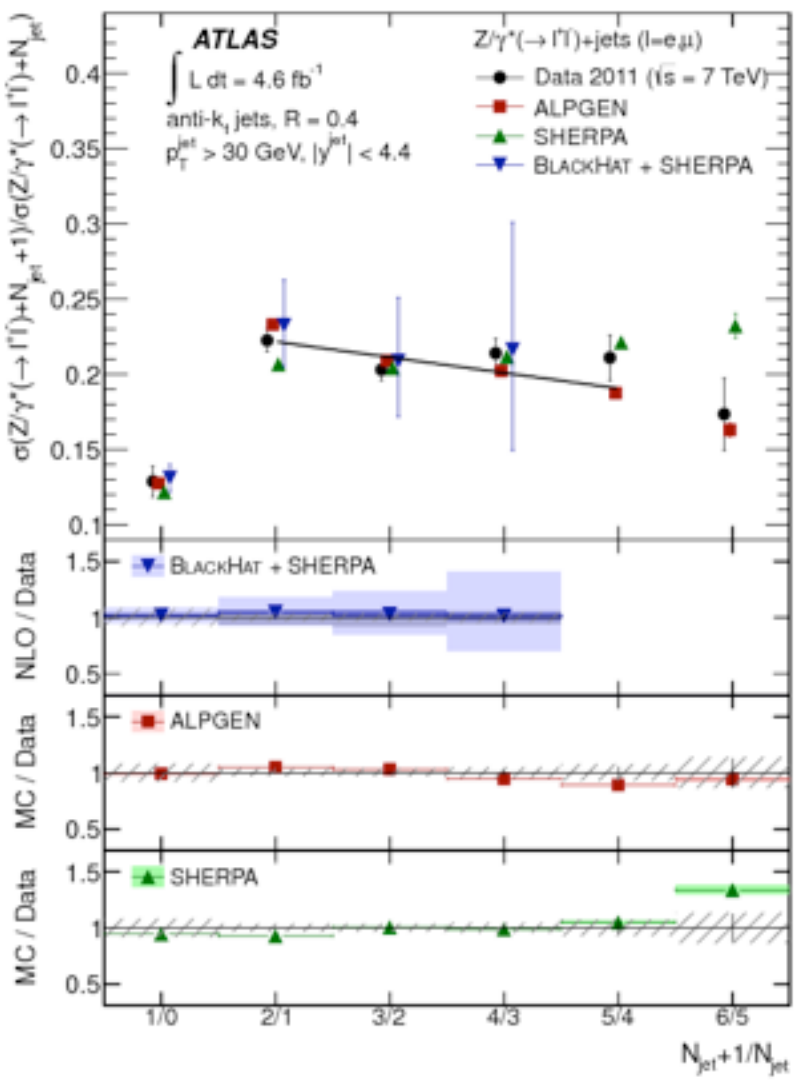
$$\sigma_n^{\rm excl.} = \sigma_0 \frac{\bar{n}^n e^{-\bar{n}}}{n!}$$

falling ratios

$$R_{\frac{n+1}{n}} = \frac{\sigma_{n+1}}{\sigma_n} = \frac{\bar{n}}{n+1}$$

Can we understand these from basic principles?

LHC: 7 TeV data



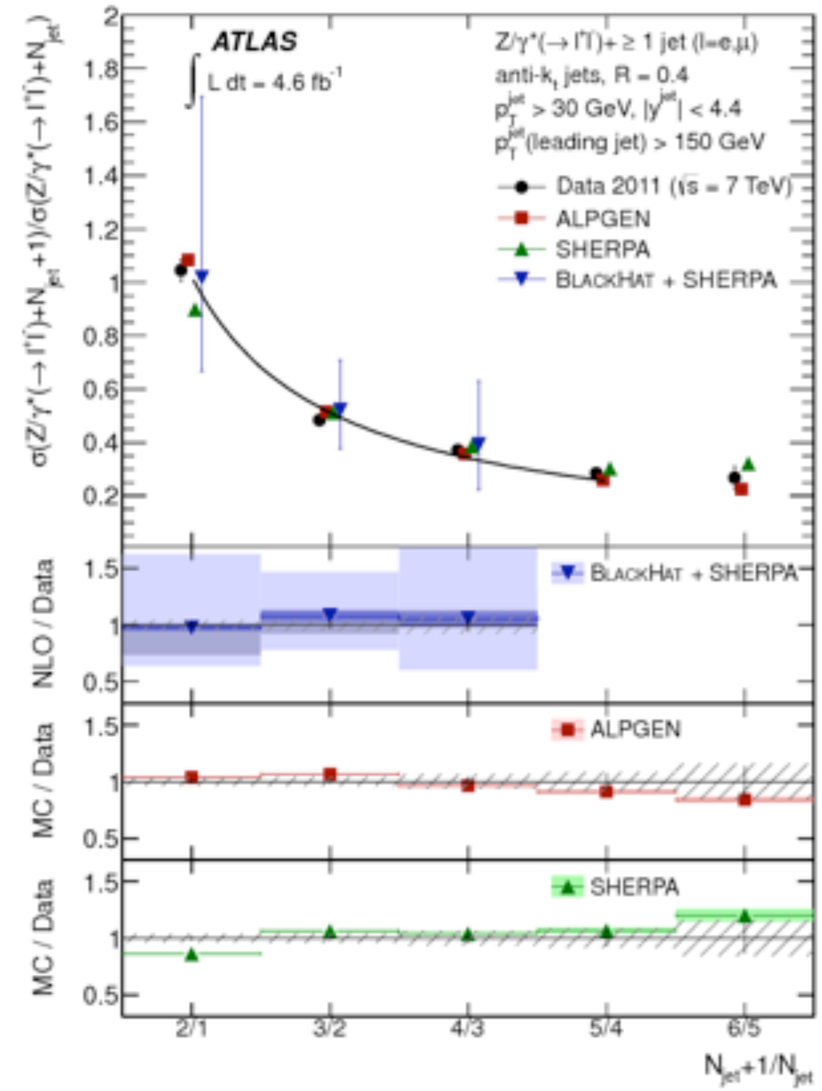
confirmed at LHC

[1304.7098]

staircase small tilt

Poisson flattens out

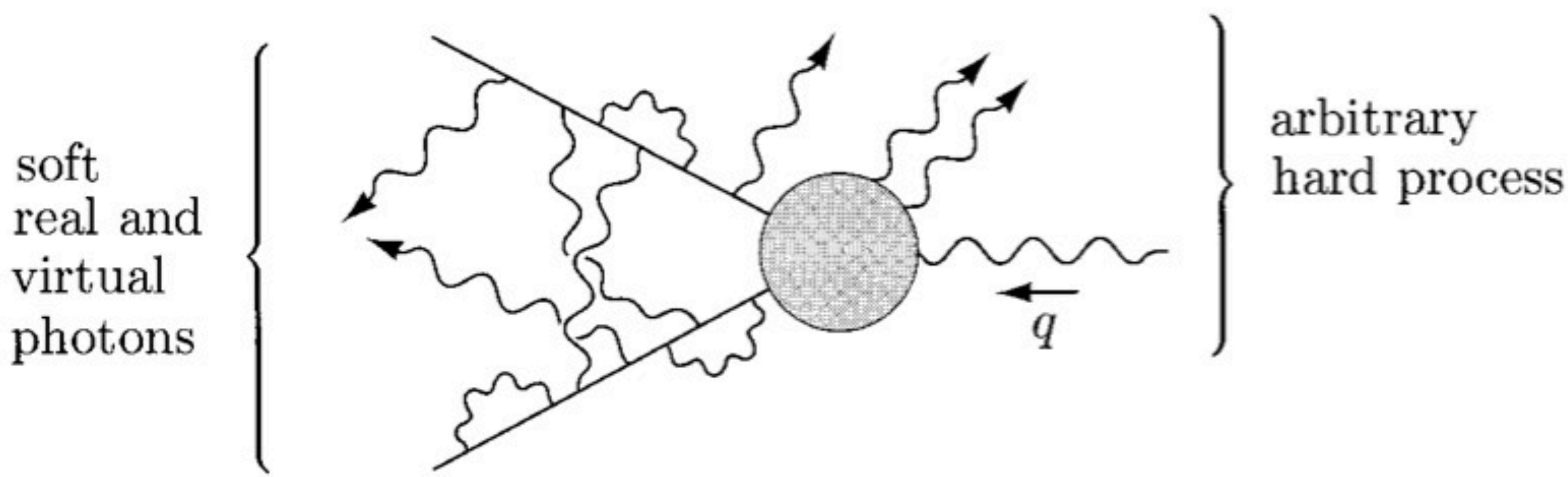
needs high p_T jet



Can we understand these from basic principles?

Bremsstrahlung in QED

schematic



Peskin & Schröder

Bremsstrahlung in QED

soft collinear limit:

factorization theorem

resolvable

unresolvable

resummed

$$d\sigma_{n+1} = d\sigma_n \times \frac{dt}{t} dz \frac{\alpha_s}{2\pi} P_{i\to jl}(z)$$

n independet emissions

$$P(n) = \frac{\bar{n}^n e^{-\bar{n}}}{n!}$$

normalization

bosonic phase space

$$\Delta_i(t) = \exp\left[- \int_{t_0}^{t} dt' \sum_{jl} \Gamma_{i\to jl} \right]$$

Sudakov form factor: non splitting prob.

phase space boundary

Peskin & Schröder

Bremsstrahlung in QCD

more complicated: gluon self interaction

formal way to deal with

QCD: **generating functional formalism**

[Konishi te al. (1979); Ellis, Stirling, Webber (1996); Gerwick, Gripaios, Schumann, Webber (2012)]

jet rate

$$\Phi(u) := \sum_n u^n P(n) \qquad P(n) = \frac{1}{n!} \frac{d^n}{du^n} \Phi(u) \Big|_{u=0}$$

Bremsstrahlung in QCD

evolution equation
$$\Phi_i(t) = u\,\exp\left[\int_{t_0}^{t} dt' \sum_{jl} \Gamma_{i\to jl}\left(\frac{\Phi_j(t')\Phi_l(t')}{\Phi_i(t')} - 1\right)\right]$$

large log limit: $t \gg t_0$
$$\Phi_i(t) = \frac{u\Delta_i(t)}{\Delta_i(t)^u}$$

primary emissions dominate → Poisson scaling

democratic limit $t \to t_0$
$$\Phi_g(t) = \frac{1}{1 + \frac{1-u}{u\Delta_g(t)}}$$

exact solution [JHEP 1210 (2012) 162] → staircase scaling

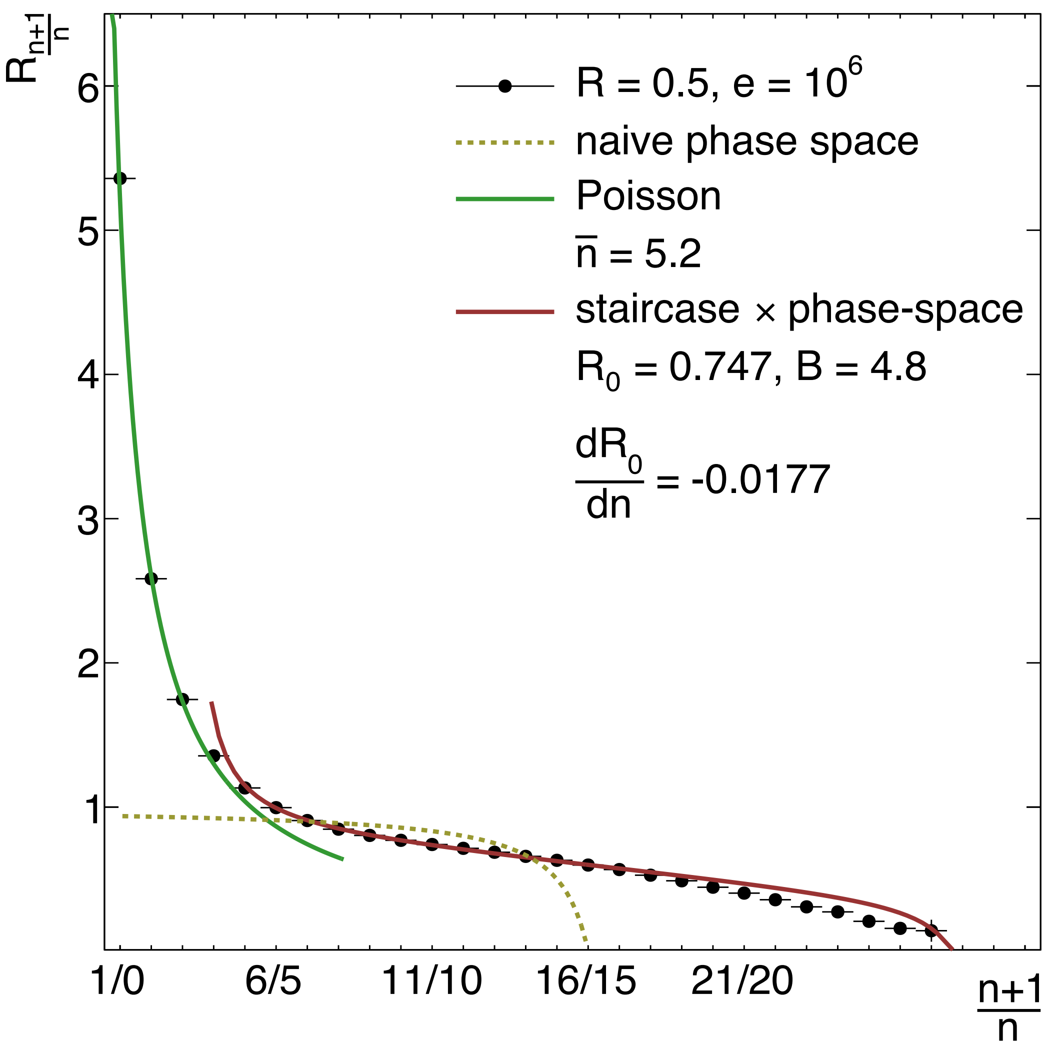
additional effects:

- → breaking terms ✔
- → phase space ✔
- → finite jet radius ✘

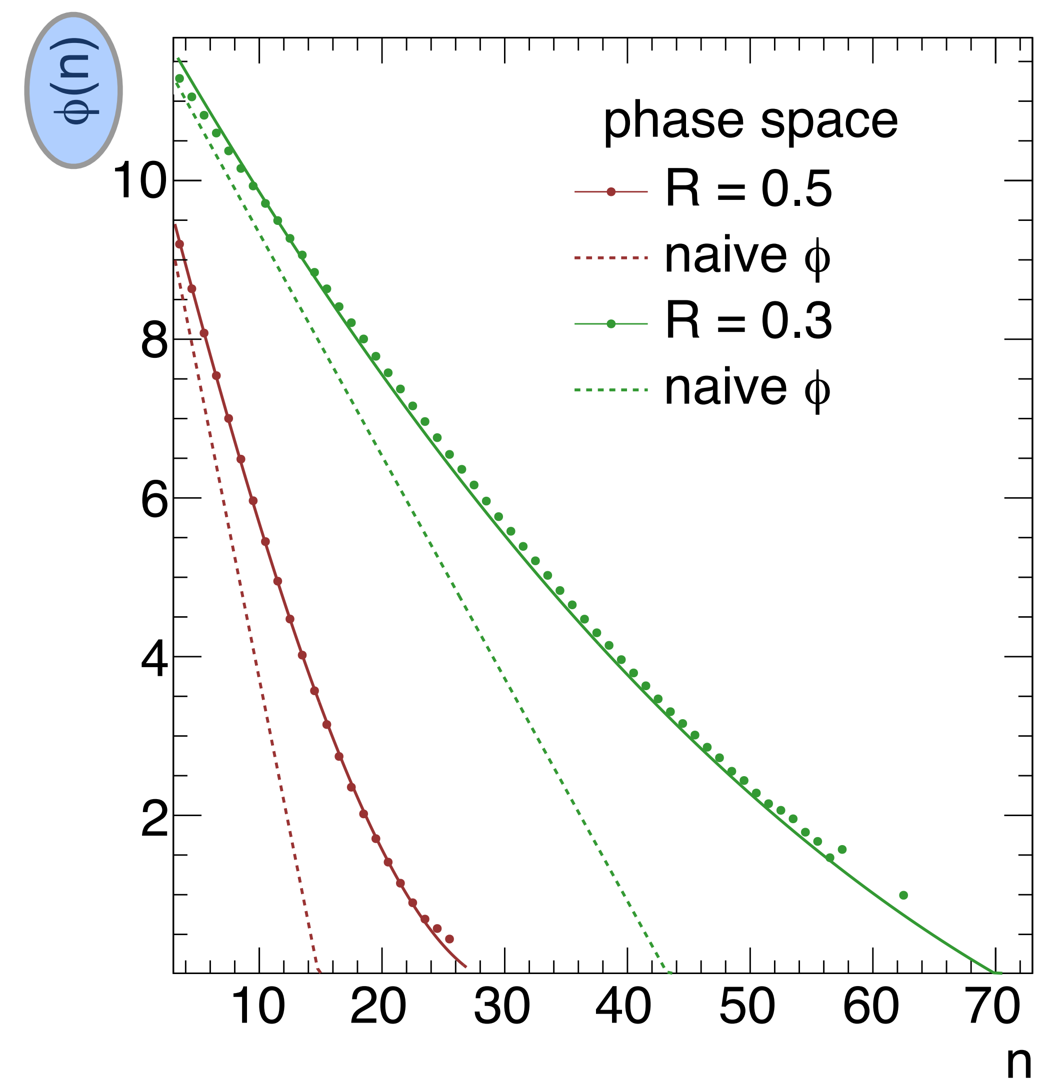
$$\Phi_g \sim \frac{1}{1 + \frac{1-u}{u\Delta_g} - \mathcal{R}(u)}$$
$\phi(n)$

[Gerwick, PS: 1412.1806]

Bremsstrahlung in QCD



← simulation of $e^+e^- \to q\bar{q} + n \times g$



$$R_{\frac{n+1}{n}} = \left(R_0 \left[1 + \frac{1}{B + (n+1)} \right] + \frac{dR_0}{dn}(n+1) \right) \times \frac{\phi(n+1)}{\phi(n)}$$

small & vanishing as $R \to 0$

[Gerwick, PS: 1412.1806]

PDF effects

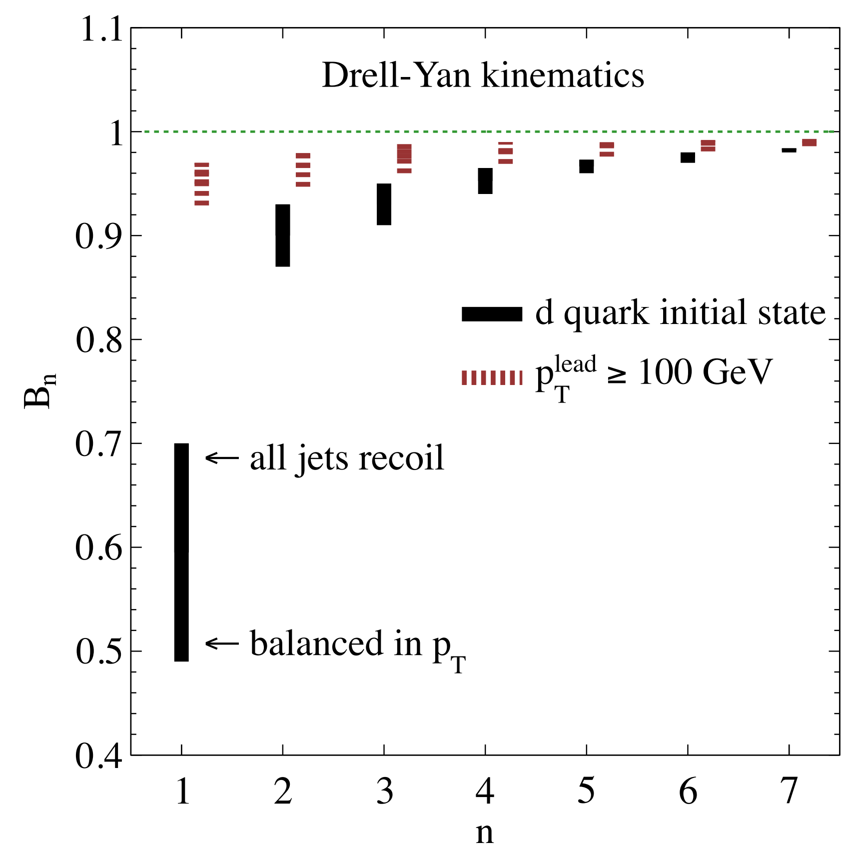
threshold approximation

$$x^{(0)} \approx \frac{m_Z}{2E_{\text{beam}}} \qquad x^{(1)} \approx \frac{\sqrt{m_Z^2 + 2\left(p_T\sqrt{p_T^2+m_Z^2}+p_T^2\right)}}{2E_{\text{beam}}}$$

effects factorize at LL

characterised by

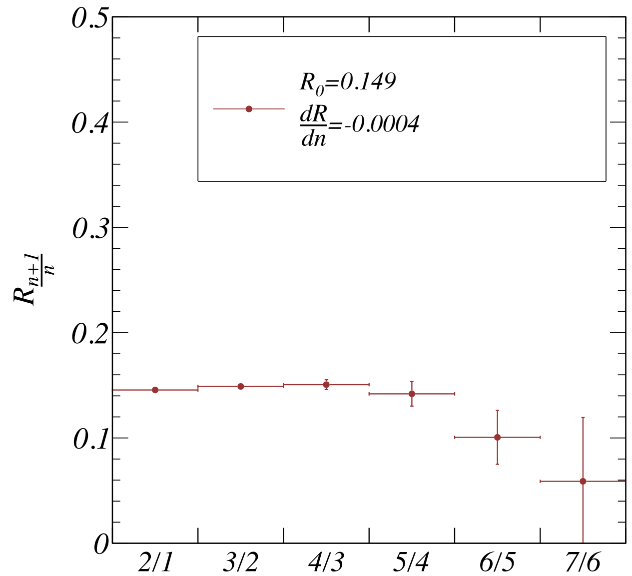
$$B_n = \left| \frac{\dfrac{f(x^{(n+1)},Q)}{f(x^{(n)},Q)}}{\dfrac{f(x^{(n+2)},Q)}{f(x^{(n+1)},Q)}} \right|^2$$



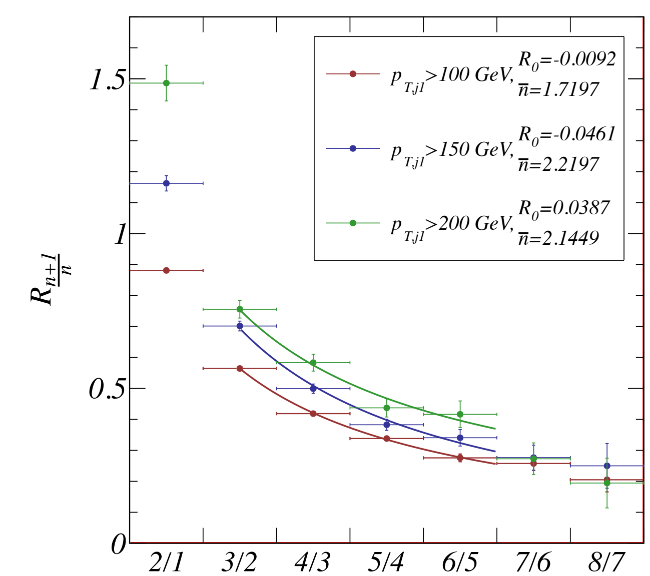
pdf suppresion of additional jets

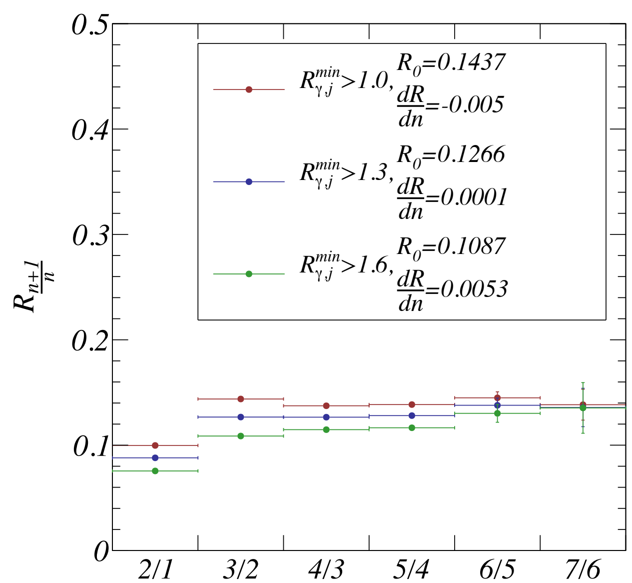
[Gerwick, Plehn, P.S., Schumann: JHEP 1210 (2012) 162]

Callibrate your jets from data

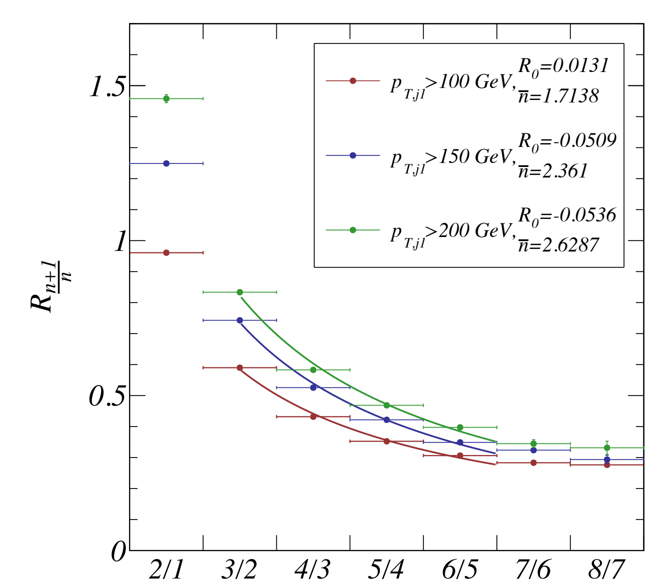


Z plus jets





photons plus jets



exact same jet spectrum!

[Englert, Plehn, P.S., Schumann: JHEP 1202 (2012) 030]

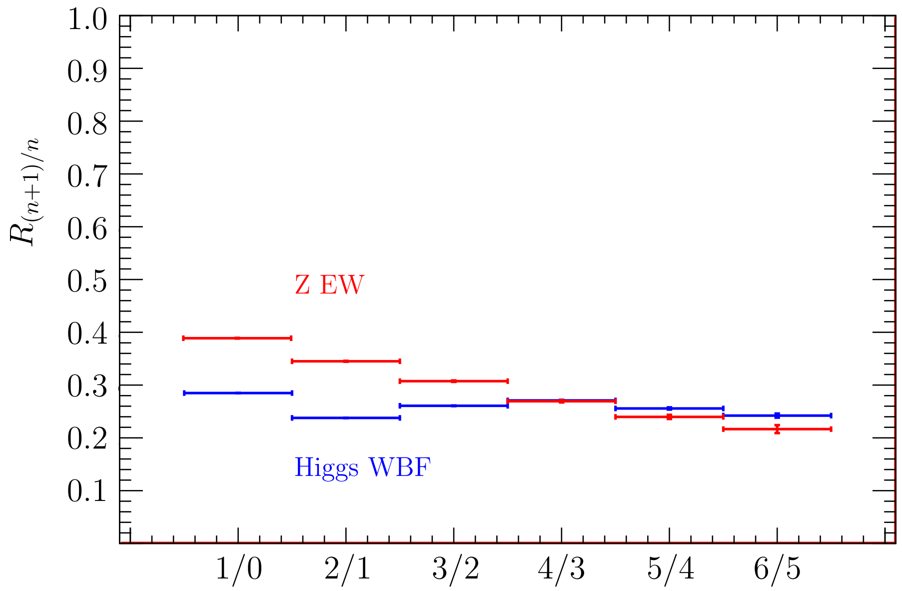
Understanding Higgs veto efficiencies

[Gerwick, Schumann, Plehn: Phys.Rev.Lett. 108 (2012) 032003]

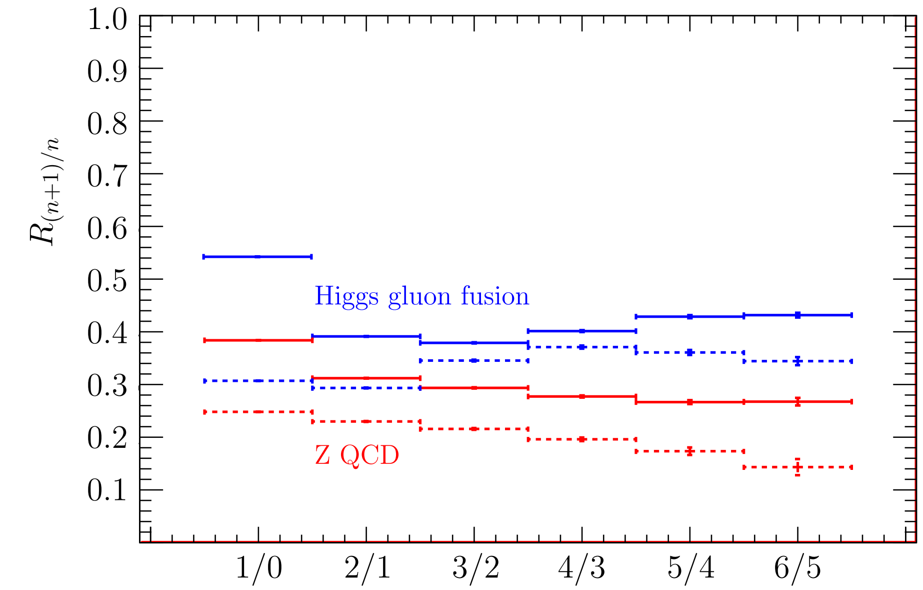
WBF Higgs

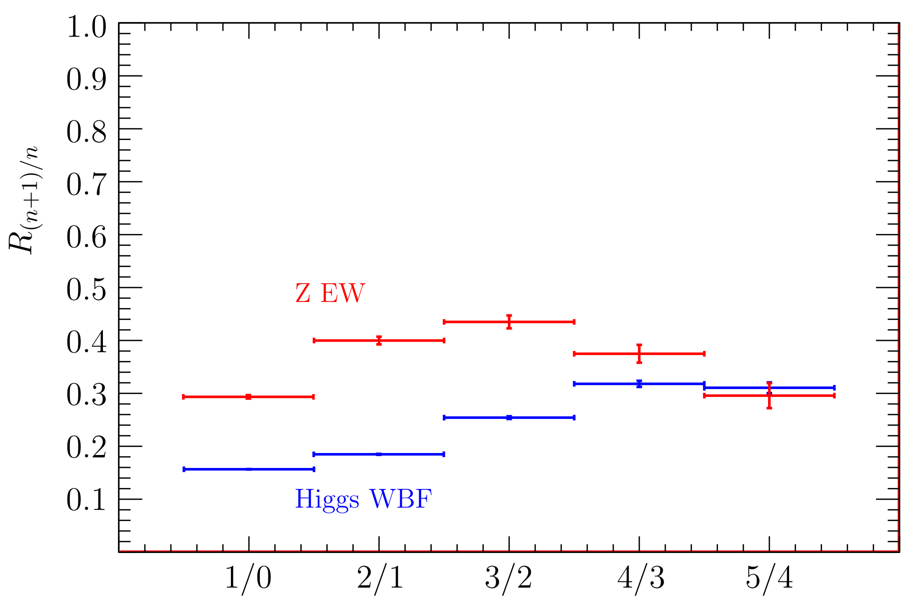
$p_{T,j}^{\min} = 20\ \text{GeV}$ $\qquad |y_j| < 4.5$

$y_1 y_2 < 0$ $\qquad |y_1 - y_2| > 4.4$



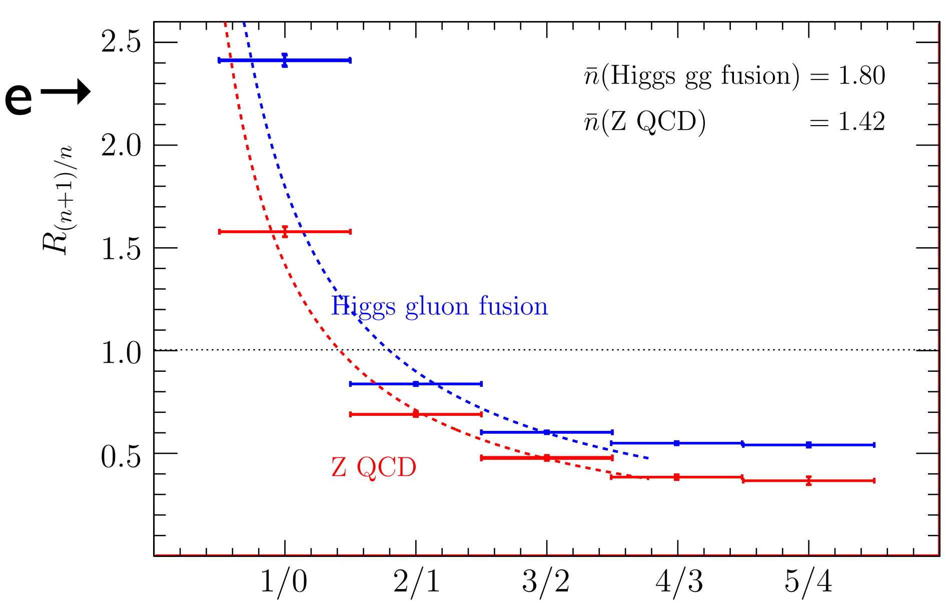
before m_{jj} cut



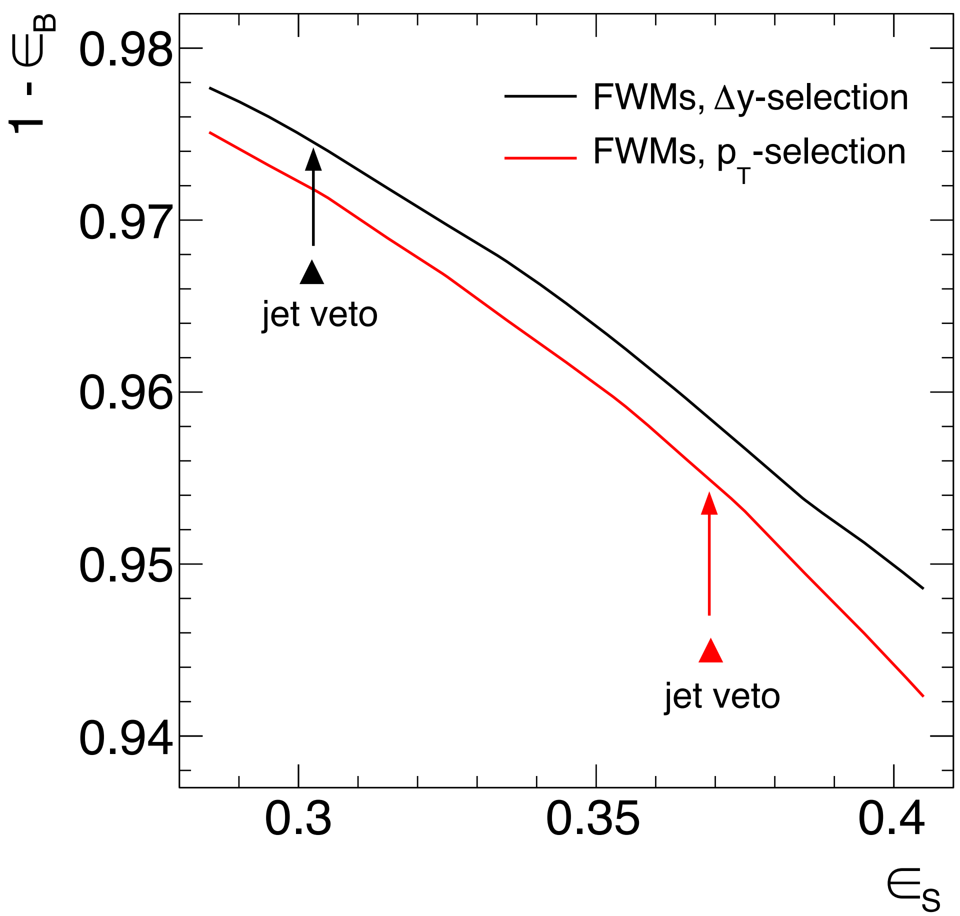


note Y-axis scale →

after m_{jj} cut



Know you backgrounds: jets & BDT



WBF Higgs

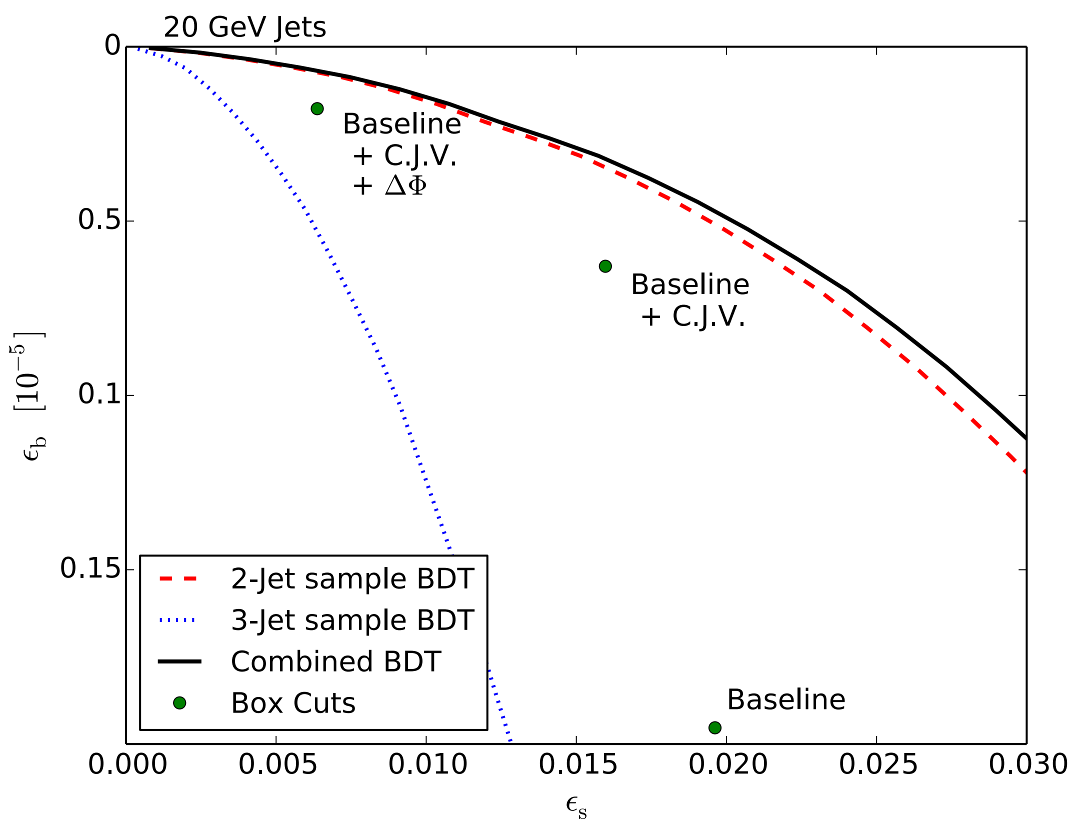
[Bernaciak, Mellado, Plehn, Ruan, PS: Phys. Rev D89 2014]

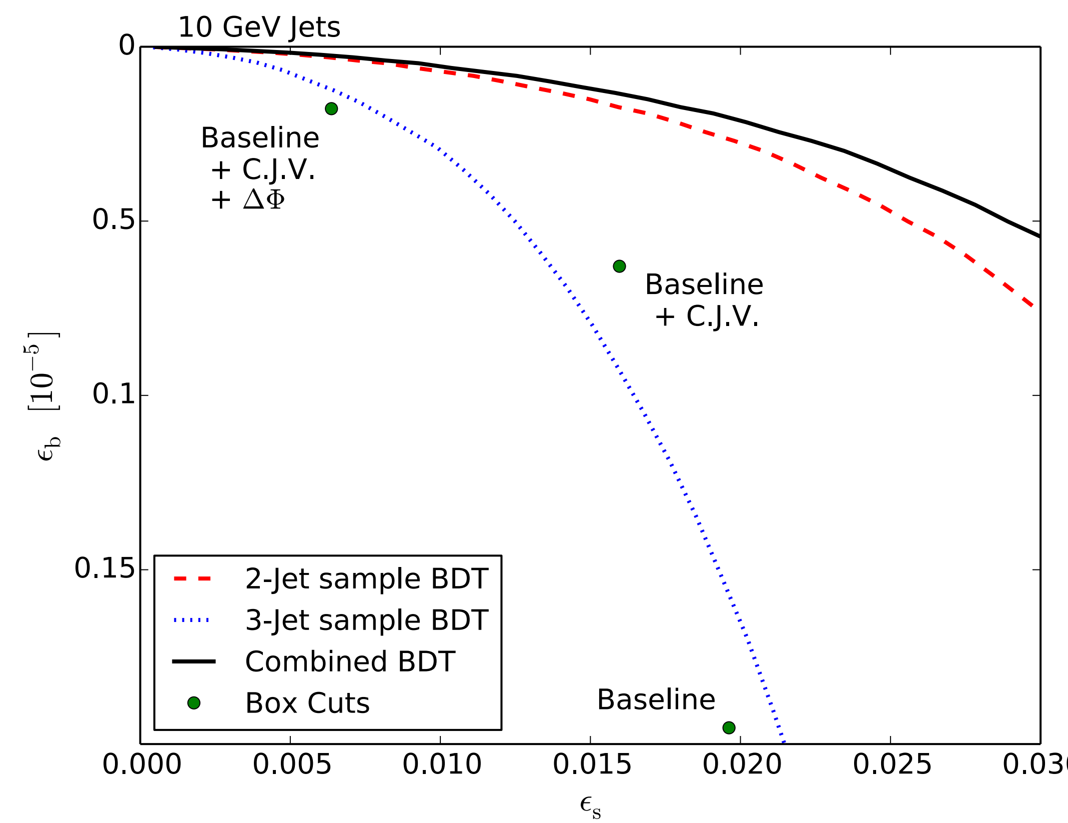
S/B	cuts	veto	more jets
p_T selection	0.014	0.047	0.083
Δy selection	0.026	0.045	0.071

Know you backgrounds: jets & BDT

invisible Higgs (WBF)

[Bernaciak, Plehn, PS, Tattersall: 1411.7699]





$\Gamma_{\text{inv}}/\Gamma_{\text{SM}}$	cuts	BDT	more jets
$10\, fb^{-1}$	47 %	28 %	16 %
$3000\, fb^{-1}$	6.9%	3.5%	2.1%

Conclusions

→ multi-jet observables are plagued by huge theoretical uncertainties (LO)
→ jet spectra follow simple scaling patterns
→ staircase scaling is a firm QCD prediction (& observed)
@ LHC: low multiplicities due to PDF effects
→ controll uncertainties & understand backgrounds from data
→ QCD high multiplicity predictions possible [difficult with NLO]
→ use in subsequent applications (Higgs studies, BSM, ...)

thanks for listening