Exploiting jet binning to identify the initial state of high-mass resonances.

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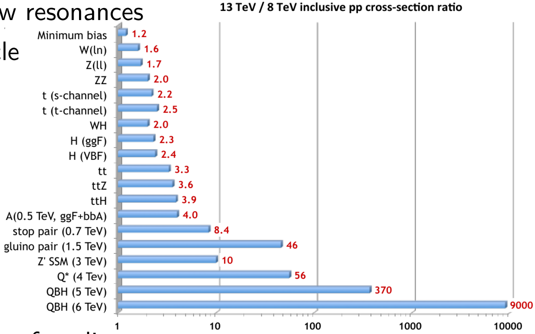
Outline

Introduction.

Introduction.

New physics searches at the LHC:

- Increased sensitivity to new physics at $\sqrt{s} = 13\ \mathrm{TeV}$
- Ideal scenario: Discovery of new resonances
- Crucial: Identification of particle properties of resonance
  - Mass
  - Width
  - Spin
  - Couplings
  - Quantum numbers
  - ...



- Challenge: Limited data shortly after discovery

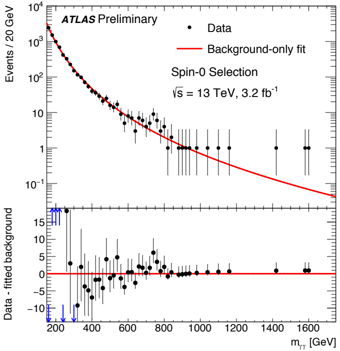
Goal:

Need methods viable with small statistics to infer particle properties.

Introduction.

Example: The diphoton excess

- CMS and ATLAS observed deviations from the SM background in 2015 data.
- Test case for a new resonance at the LHC
- Mass can be measured from mass spectrum ✓
- Production mechanism: gg, $q\bar{q}$ or $\gamma\gamma$?



[ATLAS-CONF-2016-018]

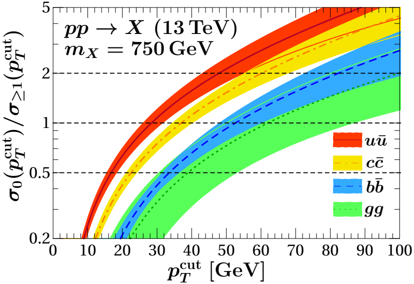
Proposals to measure initial state

- Transverse momentum / rapidity distribution of resonance [Gao,Zhang,Zhu '15]
- Kinematic distributions of hadronic jets [Bernon et al '15]
- Additional jets at high p_T [Bernon et al '15; Franceschini et al '16; Grojean et al '13]
- ...
- *Drawback*: Needs lots of data for precise measurement of distributions

Introduction.

Jet binning for initial state discrimination

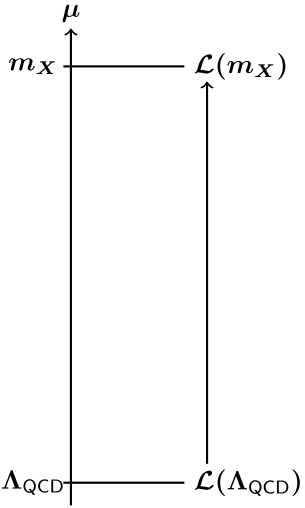
- Proposal:Use tight cut to divide data into bins with and without hadronic jets, $p_T^{\text{jet}} < p_T^{\text{cut}}$ (According to some jet algorithm)
  - Idea: Ratio $\frac{\sigma_0(p_T^{\text{cut}})}{\sigma_{\geq 1}(p_T^{\text{cut}})}$ is very sensitive to ISR
  - Provides strong discrimination of initial state



- Events split with only a single cut on $p_T^{\text{jet}} < p_T^{\text{cut}}$ on hadronic jets
  - Suitable for small event samples
- Feasible cut: $p_T^{\text{cut}} \gtrsim \mathbf{25\ GeV}$
  - Insensitive to underlying event
  - Sufficiently tight for high-mass resonances $m_X \gtrsim \mathbf{300\ GeV}$
- Theoretically very clean
  - Insensitive to details of final state (e.g. two-body vs three-body decay)
  - p_T^{cut}-dependence known precisely
  - Theoretical uncertainties well under control

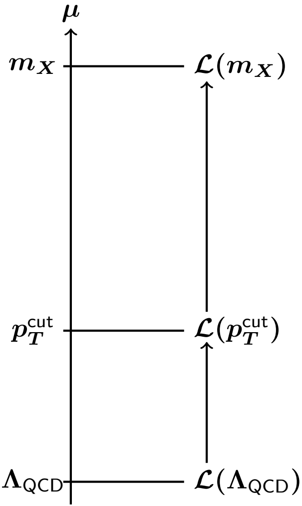
Theoretical setup.

Scale overview: Inclusive cross section.



- Unknown BSM physics
- Relevant physics at $\mu = m_X$
  - Evolve PDFs up to $\mu = m_X$
  - PDF evolution *changes* parton type
- "PDF scale"

Scale overview: $\sigma_0(p_T^{\text{cut}})$



- Unknown BSM physics
- Relevant physics at $\mu = m_X$
  - Evolve up to $\mu = m_X$
    $\Rightarrow$ resum $\ln \frac{p_T^{\text{cut}}}{m_X}$
  - Parton type *fixed* in evolution
- Relevant physics at $\mu = p_T^{\text{cut}}$
  - Evolve PDFs up to $\mu = p_T^{\text{cut}}$
  - PDF evolution *changes* parton type
- "PDF scale"

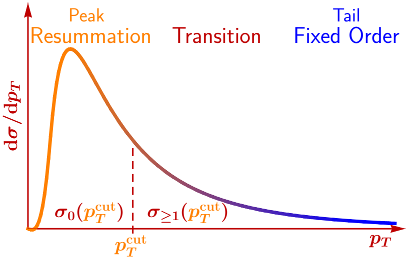
Jet veto freezes parton type at scale p_T^{cut} and evolves it to scale m_X

Low energy dynamics.

$$\sigma_0(p_T^{\mathrm{cut}}) = \int_0^{p_T^{\mathrm{cut}}} \mathrm{d}p_T^{\mathrm{jet}} \frac{\mathrm{d}\sigma}{\mathrm{d}p_T^{\mathrm{jet}}}$$

$$= \sigma_{\mathrm{LO}} \left(1 - \frac{\alpha_s C_F}{\pi} 2 \ln^2 \frac{p_T^{\mathrm{cut}}}{m_X} + \cdots \right)$$

$$+ \sigma^{\text{non-sing}}(p_T^{\mathrm{cut}})$$



- Singular piece:
  - Large logarithms $L = \ln \frac{p_T^{\mathrm{cut}}}{m_X}$ spoil perturbation theory
  - Logs L are *universal*: Resummation to all orders possible
  - Dominates for $p_T^{\mathrm{cut}} \ll m_X$
- Non-singular piece:
  - Power corrections $\sigma^{\text{non-sing}}(p_T^{\mathrm{cut}}) = \mathcal{O}((p_T^{\mathrm{cut}}/m_X)^2)$
  - Relevant only for $p_T^{\mathrm{cut}} \sim m_X$
  - Are *model-dependent*

0-jet spectrum *model-independent* for $p_T^{\mathrm{cut}} \ll m_X$

Low energy dynamics.

- QCD dynamics for $\mu \sim p_T^{\rm cut} \ll m_X$ *universally* described

$$\mathcal{L}_{\rm eff}(p_T^{\rm cut}) = \mathcal{L}_{\rm SCET} + c_{ggF}^{\lambda_1\lambda_2} \mathcal{B}_n^{\lambda_1}\mathcal{B}_{\bar n}^{\lambda_2} \mathcal{F} + \sum_q c_{q\bar qF}^{\lambda_1\lambda_2} \bar\chi_{qn}^{\lambda_1}\chi_{q\bar n}^{\lambda_2} \mathcal{F}$$

  - SCET-Lagrangian $\mathcal{L}_{\rm SCET}$: Universal soft-collinear dynamics of QCD
  - Annihilation of energetic gluons or quarks along the beam
  - $\mathcal{F}$: All fields required to produce final state F
  - $c_{ijF}^{\lambda_1\lambda_2}$: Wilson coefficients
- All hard degrees of freedom, $\mu \sim m_X$, are integrated out
- Power corrections suppressed by $\mathcal{O}((p_T^{\rm cut}/m_X)^2)$
- 0-jet cross section at leading power *completely* determined by

$$|c_{ijF}|^2 = \int \mathrm{d}\phi_F \sum_{\lambda_1,\lambda_2} |c_{ijF}^{\lambda_1\lambda_2}(\phi_F)|^2$$

  - Valid for *any* color-singlet final state X
  - Independent of spin of X

High energy dynamics.

The high energy Lagrangian:

- QCD dynamics for $\mu \sim m_X$ carries the full model-dependence
- Concrete case (spin 0):

$$\mathcal{L}_{\text{eff}}(m_X) = \mathcal{L}_{\text{SM}} - \frac{\boxed{C_g}}{1\ \text{TeV}} \alpha_s G^{\mu\nu} G_{\mu\nu} X - \sum_q \boxed{C_q}\, \bar{q} q X + \cdots$$

  - $\boxed{C_i}$: Wilson coefficients defined at $\mu = m_X$
  - $\boxed{C_i}$ are the quantities to be measured
- Different choice $\mathcal{L}_{\text{eff}}$ (e.g. spin 2) will only yield differences $\mathcal{O}(\alpha_s(m_X))$

Matching the Lagrangians:

$$|c_{q\bar{q}F}(\mu)|^2 \sim \mathcal{B}(X \to F)|C_q(\mu)(1 + \cdots)|^2$$
$$|c_{ggF}(\mu)|^2 \sim \mathcal{B}(X \to F)|\alpha_s C_g(\mu)(1 + \cdots)|^2$$

- Dependency on branching ratios $\mathcal{B}(X \to F)$ will drop out
- All dynamics completely specified by C_i

Theory uncertainties.

Covariance matrix: (Following [Stewart,Tackmann,Walsh,Zuberi '13])

$$\mathcal{C}_{\text{th}} = \mathcal{C}_{\text{FO}} + \mathcal{C}_{\text{resum}} + \mathcal{C}_{\text{PDF}}$$

- $\mathcal{C}_{\text{FO}}$: Collective overall scale variation
  - Fully correlated between different bins (*yield uncertainty*)

$$\mathcal{C}_{\text{FO}}(\sigma_0, \sigma_{\geq 1}) = \begin{pmatrix} (\Delta_0^{\text{FO}})^2 & \Delta_0^{\text{FO}} \Delta_{\geq 1}^{\text{FO}} \\ \Delta_0^{\text{FO}} \Delta_{\geq 1}^{\text{FO}} & (\Delta_{\geq 1}^{\text{FO}})^2 \end{pmatrix}$$

- $\mathcal{C}_{\text{resum}}$: Resummation scale variation
  - Implemented through variation of profiles
  - Directly probes $\ln \frac{p_T^{\text{cut}}}{m_X}$ and hence the jet binning
  - Fully anticorrelated between different bins (*migration uncertainty*)

$$\mathcal{C}_{\text{resum}}(\sigma_0, \sigma_{\geq 1}) = \begin{pmatrix} \Delta_{\text{cut}}^2 & -\Delta_{\text{cut}}^2 \\ -\Delta_{\text{cut}}^2 & \Delta_{\text{cut}}^2 \end{pmatrix}$$

- $\mathcal{C}_{\text{PDF}}$: Variation of all 25 `MMHT2014nnlo68cl` eigenvectors
  - Found to be subdominant

Theoretical setup.

Summary

- Effective couplings defined through effective Lagrangian

$$\mathcal{L}_{\text{eff}}(m_X) = \mathcal{L}_{\text{SM}} - \frac{C_g}{1\ \text{TeV}} \alpha_s G^{\mu\nu} G_{\mu\nu} X - \sum_q C_q \bar{q} q X + \cdots$$

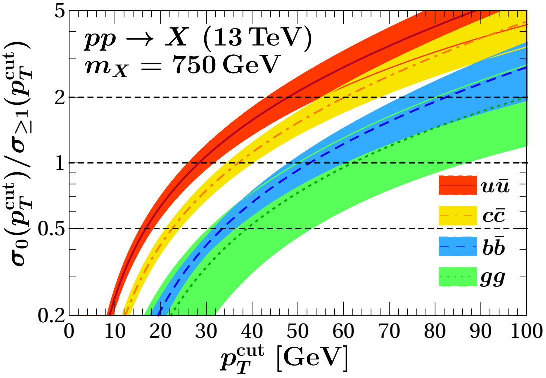
- Cross sections are given by

$$\sigma_i = |C_g|^2 \sigma_i^g + \sum_q |C_q|^2 \sigma_i^q \,, \quad i \in \{0, \geq 0, \geq 1\}$$

- 0-jet cross section dominated by *universal* large logarithms
  - Resummation of logarithms $\ln \frac{p_T^{\text{cut}}}{m_X}$ is crucial
  - Model-independent for $p_T^{\text{cut}} \ll m_X$
- Cross sections implemented at
  - Quark initial state: NLO + NLL′ (non-singulars from `SusHi`)
  - Gluon initial state: NNLO + NNLL′ (non-singulars from `MCFM`)
- Theory uncertainties have to be treated carefully
  - Correlations between bins and flavors are taken into account

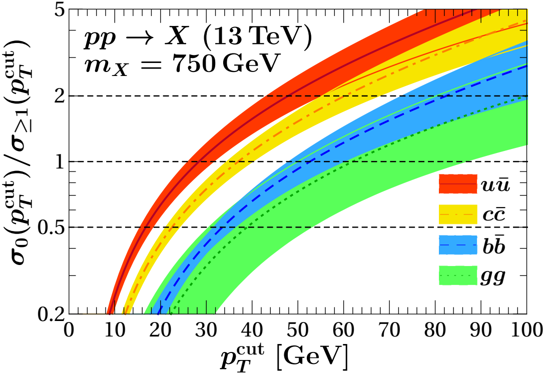
Results.

Sensitivity of 0-jet cross section on ISR.



- Gluons radiate stronger than quarks ($C_A = 3 > C_F = 4/3$)
  - Small fraction of events in 0-jet bins for gluons
  - Large fraction of events in 0-jet bins for quark
- Sea quarks partially result from gluon splittings
  - Smaller faction of events in 0-jet bin than for valence quarks
  - Effect grows with quark mass m_q

Optimizing p_T^{cut}



- Best statistics uncertainties: events split $\sim \mathbf{1:1}$
  - Can optimize p_T^{cut} according to measurement
- Split events at most $\mathbf{1:2}$ for reasonable statistics with small data samples
- In practice: Observe little sensitivity to precise value $p_T^{\mathrm{cut}} \in [\mathbf{25, 65}]$ **GeV**
- For illustration: Choose $p_T^{\mathrm{cut}} = \mathbf{40}$ **GeV**

Example 1: gluon-like signal.

Normalization

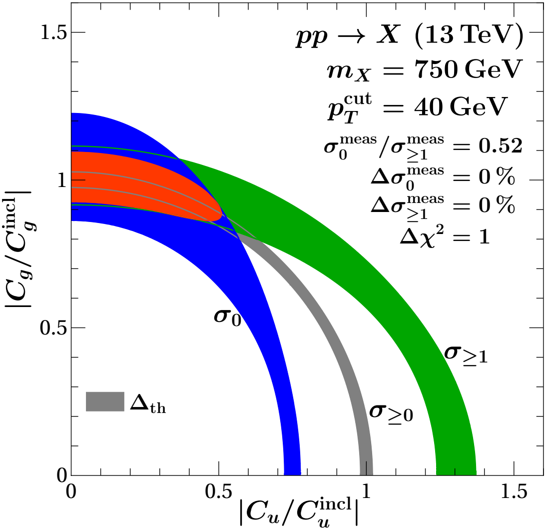
- Can only constrain $C_i\sqrt{\mathcal{B}}$
- Only one decay channel: Normalize results to

$$C_i^{\text{incl}}\sqrt{B} = \sqrt{\sigma_{\geq 0}^{\text{meas}} / \sigma_{\geq 0}^{i}}$$

- C_i/C_i^{incl} independent of $\mathcal{B}$

Assumed measurement

- Assume only $C_g \neq 0$
  $\Rightarrow \frac{\sigma_0^{\text{meas}}}{\sigma_{\geq 1}^{\text{meas}}} = 0.52$
- Only consider theoretical uncertainties first



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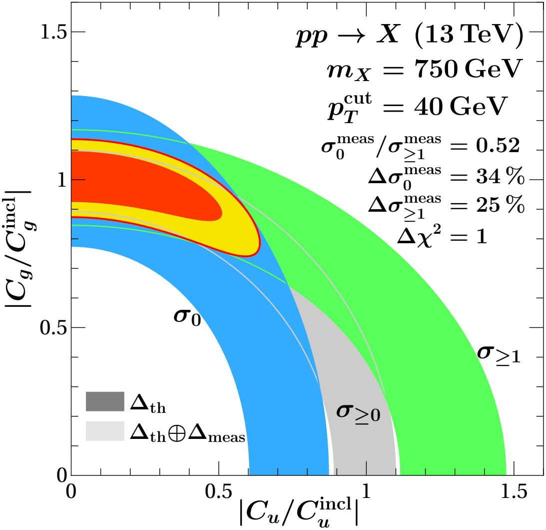
Assumed measurement

- Assume only $C_g \neq 0$ $\Rightarrow \frac{\sigma_0^{\text{meas}}}{\sigma_{\geq 1}^{\text{meas}}} = 0.52$
- Assume $\Delta\sigma_{\geq 0}^{\text{meas}} = 20\%$
- Split $\frac{\Delta\sigma_0^{\text{meas}}}{\Delta\sigma_{\geq 1}^{\text{meas}}} = \sqrt{\frac{\sigma_{\geq 1}^{\text{meas}}}{\sigma_0^{\text{meas}}}}$



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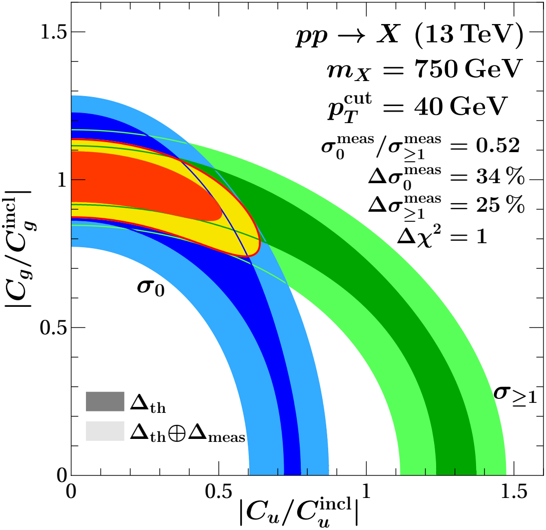
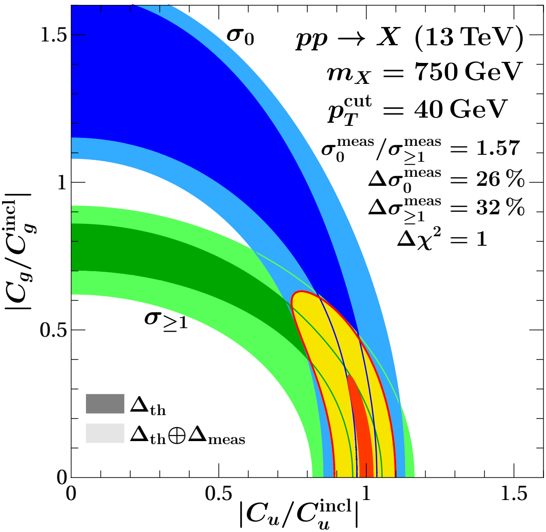


Example 2: u-quark like signal.

Assumed measurement

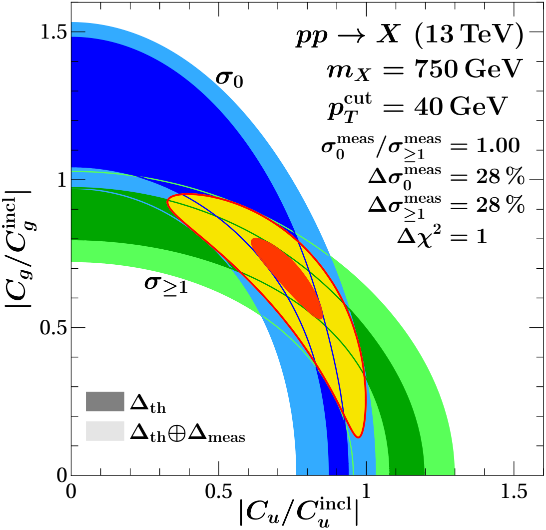
- Assume only $C_u \neq 0$
  $\Rightarrow \frac{\sigma_0^{\text{meas}}}{\sigma_{\geq 1}^{\text{meas}}} = 1.57$
- Assume $\Delta\sigma_{\geq 0}^{\text{meas}} = 20\%$
- Split $\frac{\Delta\sigma_0^{\text{meas}}}{\Delta\sigma_{\geq 1}^{\text{meas}}} = \sqrt{\frac{\sigma_{\geq 1}^{\text{meas}}}{\sigma_0^{\text{meas}}}}$



Example 3: Mixed u-quark / gluon signal.

Assumed measurement

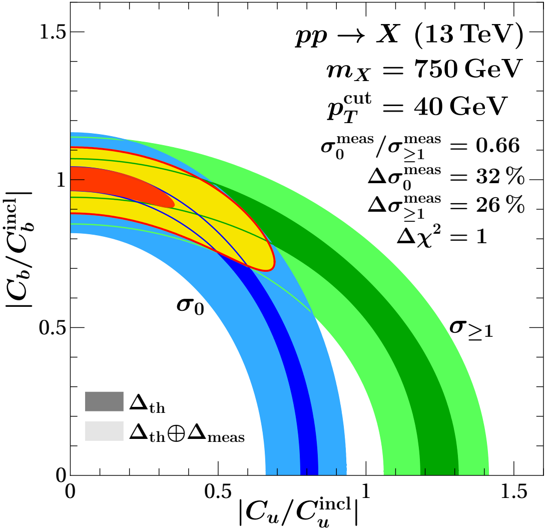
- Assume only $C_u, C_g \neq 0$ s.t. $\frac{\sigma_0^{\text{meas}}}{\sigma_{\geq 1}^{\text{meas}}} = 1.00$
- Assume $\Delta\sigma_{\geq 0}^{\text{meas}} = 20\%$
- Split $\frac{\Delta\sigma_0^{\text{meas}}}{\Delta\sigma_{\geq 1}^{\text{meas}}} = \sqrt{\frac{\sigma_{\geq 1}^{\text{meas}}}{\sigma_0^{\text{meas}}}}$



Example 4: b-quark like signal.

Assumed measurement

- Assume only $C_b \neq 0$
  $\Rightarrow \frac{\sigma_0^{\text{meas}}}{\sigma_{\geq 1}^{\text{meas}}} = 0.66$
- Assume $\Delta\sigma_{\geq 0}^{\text{meas}} = 20\%$
- Split $\frac{\Delta\sigma_0^{\text{meas}}}{\Delta\sigma_{\geq 1}^{\text{meas}}} = \sqrt{\frac{\sigma_{\geq 1}^{\text{meas}}}{\sigma_0^{\text{meas}}}}$



Example 5: c-quark like signal.

Assumed measurement

- Assume only $C_c \neq 0$
  $\Rightarrow \frac{\sigma_0^{\text{meas}}}{\sigma_{\geq 1}^{\text{meas}}} = 1.12$
- Assume $\Delta\sigma_{\geq 0}^{\text{meas}} = 20\%$
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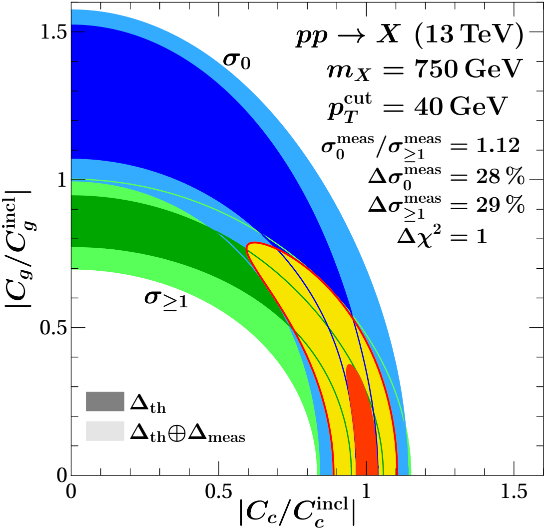

Example 6: gluon-like signal.

Assumed measurement

- Assume only $C_g \neq 0$
  $\Rightarrow \frac{\sigma_0^{\text{meas}}}{\sigma_{\geq 1}^{\text{meas}}} = 0.52$
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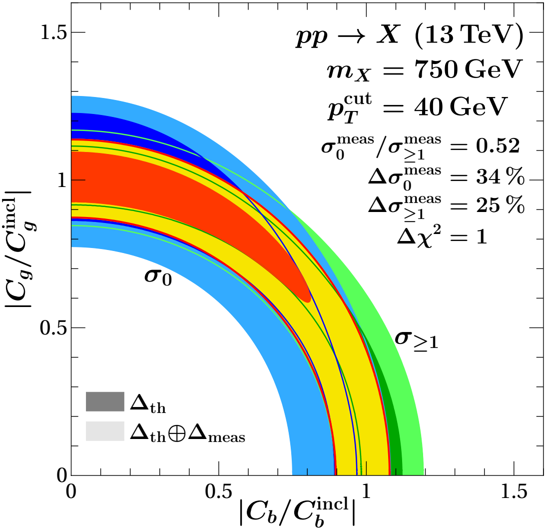

Conclusion.

Conclusion.

Jet binning to identify the initial state of high-mass resonances

- Model-independent technique
- Theoretically clean
  - Uncertainties well under control
- Requires only small data sets
  - Applicable in the early discovery phase
- Can reliably distinguish (depending on measurement)
  - light quarks from gluons ✓
  - light quarks from heavy quarks ✓
  - b-quarks from gluons ✗

Outlook

- Easily applicable to newly discovered resonances
- Measurements should be reported fiducially
- Method works for $m_X \gtrsim 300$ GeV

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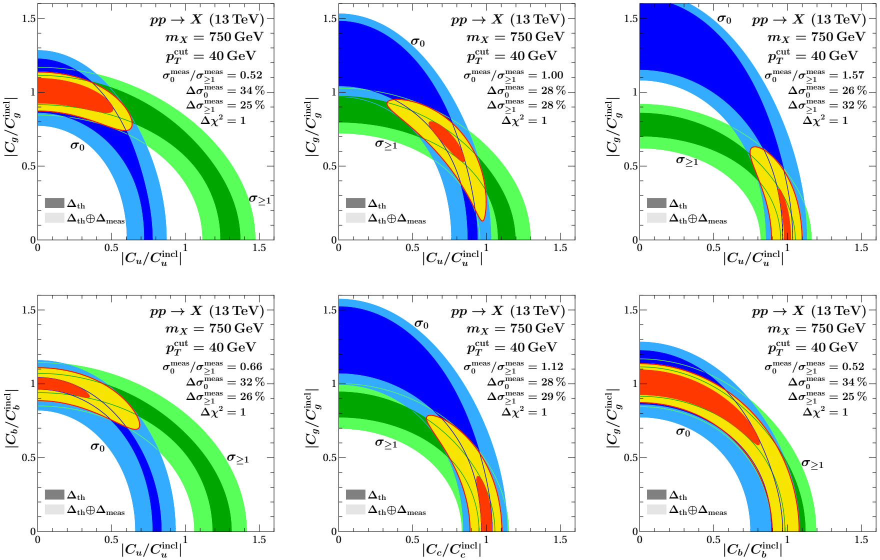
Thank you for your attention!

Backup slides.

Overview of results.



Details on p_T^{cut} resummation.

Resummation of large logs:

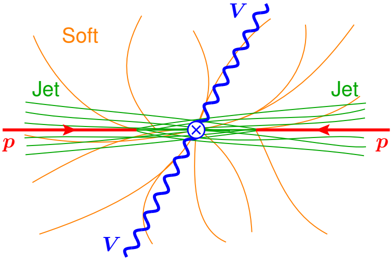
- Singular cross section plagued by large logarithms $L = \ln \frac{p_T^{\text{cut}}}{m_X}$:

$$\sigma_0^{\text{sing}}(p_T^{\text{cut}}) = \sigma_{\text{LO}} \left(1 - \frac{\alpha_s C_{F,A}}{\pi} 2 \ln^2 \frac{p_T^{\text{cut}}}{m_X} + \cdots \right)$$

- Factorization: $\sigma_0^{\text{sing}}(p_T^{\text{cut}}) = H(m_X, \mu) B(p_T^{\text{cut}}, \mu, \nu)^2 S(p_T^{\text{cut}}, \mu, \nu)$

- Logarithms are split:

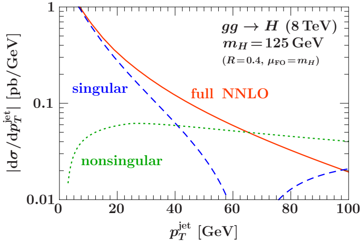
$$2 \ln^2 \frac{p_T^{\text{cut}}}{m_X} = 2 \ln^2 \frac{m_X}{\mu} + 4 \ln \frac{p_T^{\text{cut}}}{\mu} \ln \frac{\nu}{m_X} + 2 \ln \frac{p_T^{\text{cut}}}{\mu} \ln \frac{\mu p_T^{\text{cut}}}{\nu^2}$$



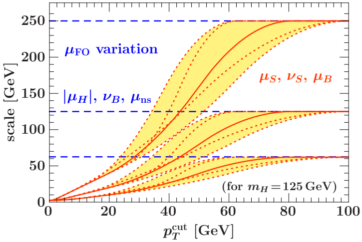
- Large logarithms can be resummed using RG-evolution for H, B, S (See [Tackmann, Walsh, Zuberi, '12] for details)

Resummation uncertainties.

- Large cancellations between singular and non-singular contributions for large $p_T^{\text{cut}} \sim m_X$



- Resummation must be turned off
- Achieved using *profiles*:
  Smooth matching onto fixed order using
  $\mu_i = \mu_i(p_T^{\text{cut}})$, $\nu_i = \nu_i(p_T^{\text{cut}})$
- Ambiguity is a scale uncertainty
  - Leaves $\sigma_{\geq 0}$ invariant
  - Anticorrelated between σ_0 and $\sigma_{\geq 1}$



[Stewart,Tackmann,Walsh,Zuberi '13]