Title: Boosted Multijet Resonances and New Color-Flow Variables

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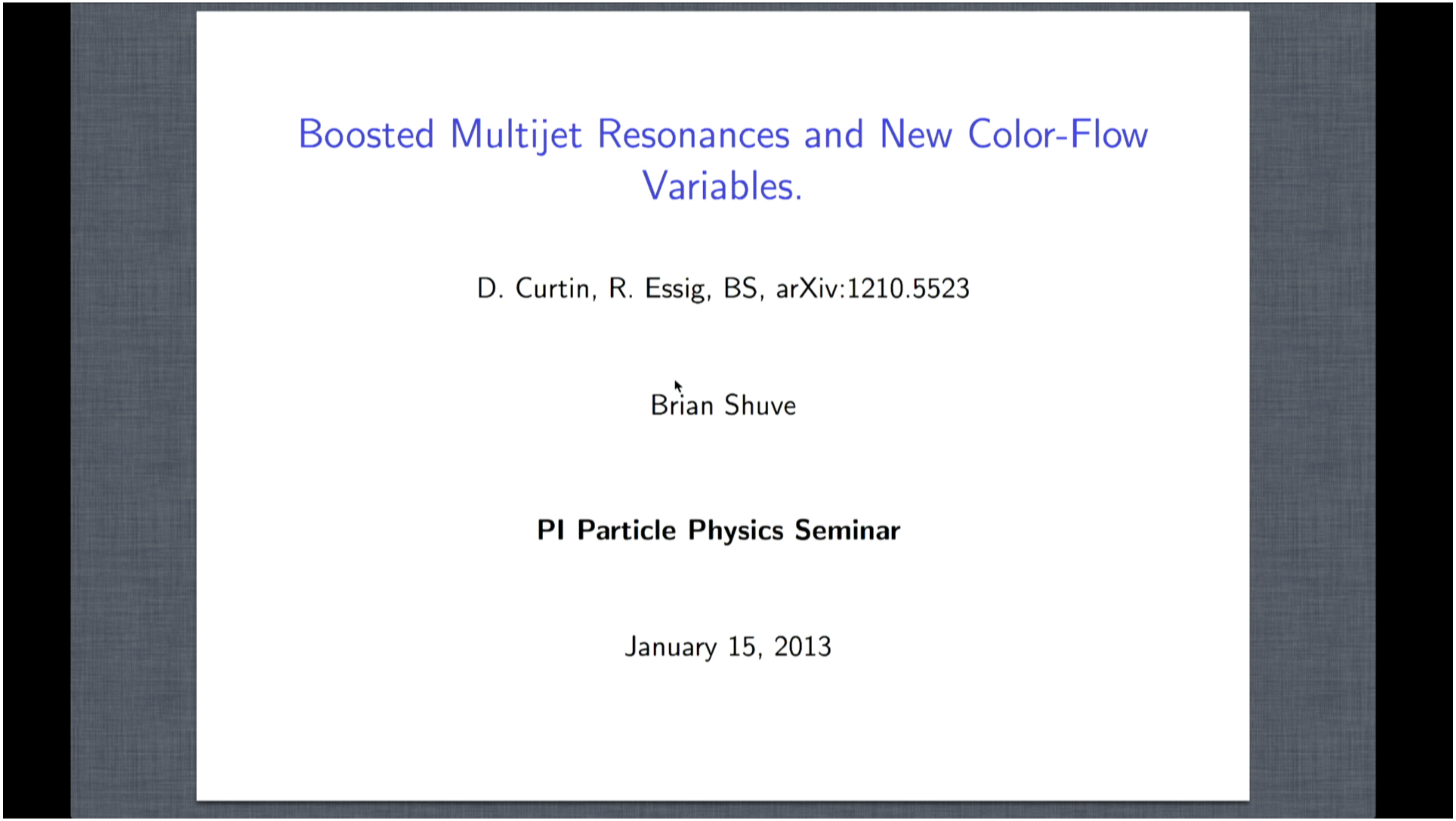
Abstract:



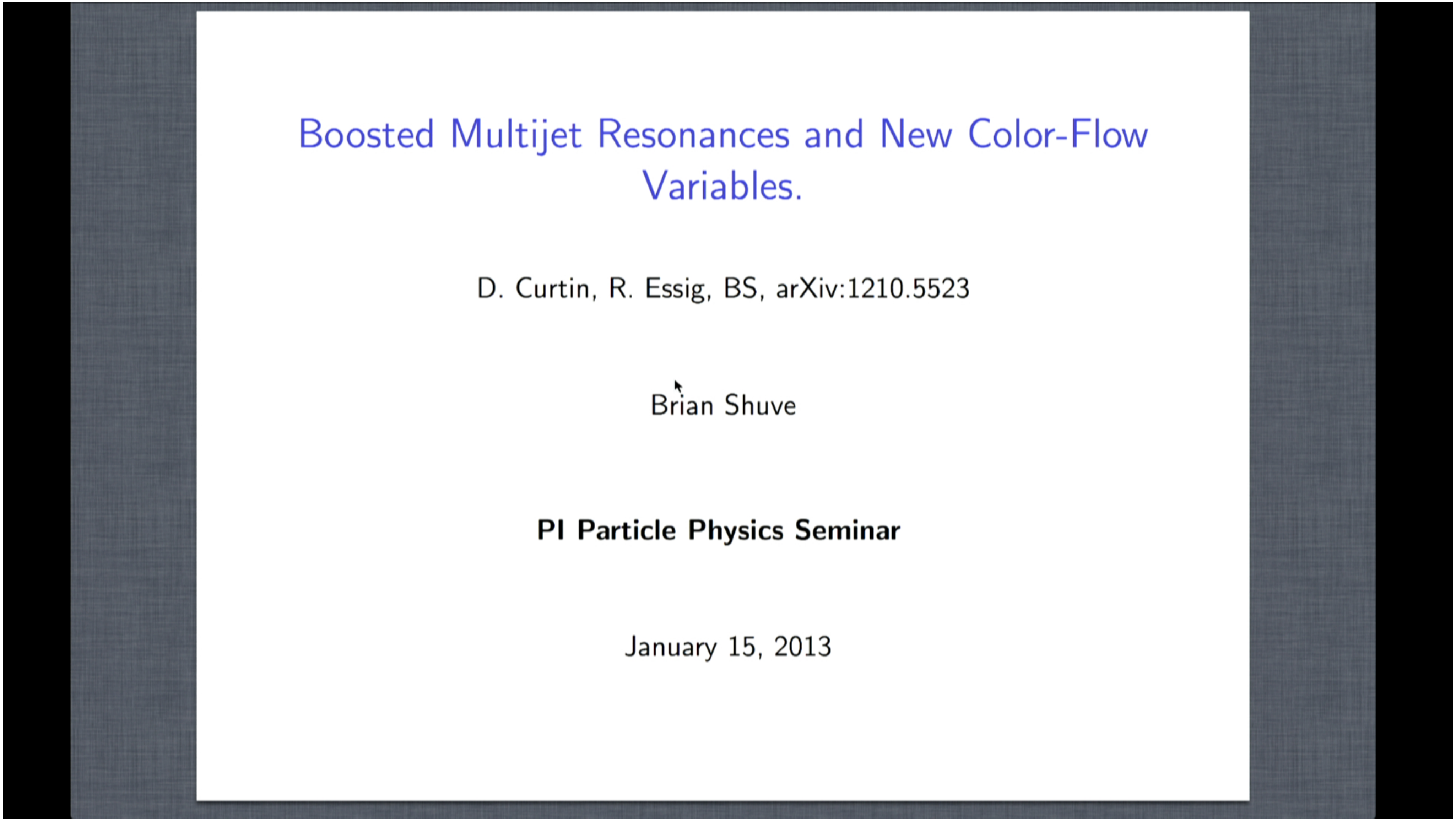
Boosted Multijet Resonances and New Color-Flow Variables.

D. Curtin, R. Essig, BS, arXiv:1210.5523

Brian Shuve

PI Particle Physics Seminar

January 15, 2013



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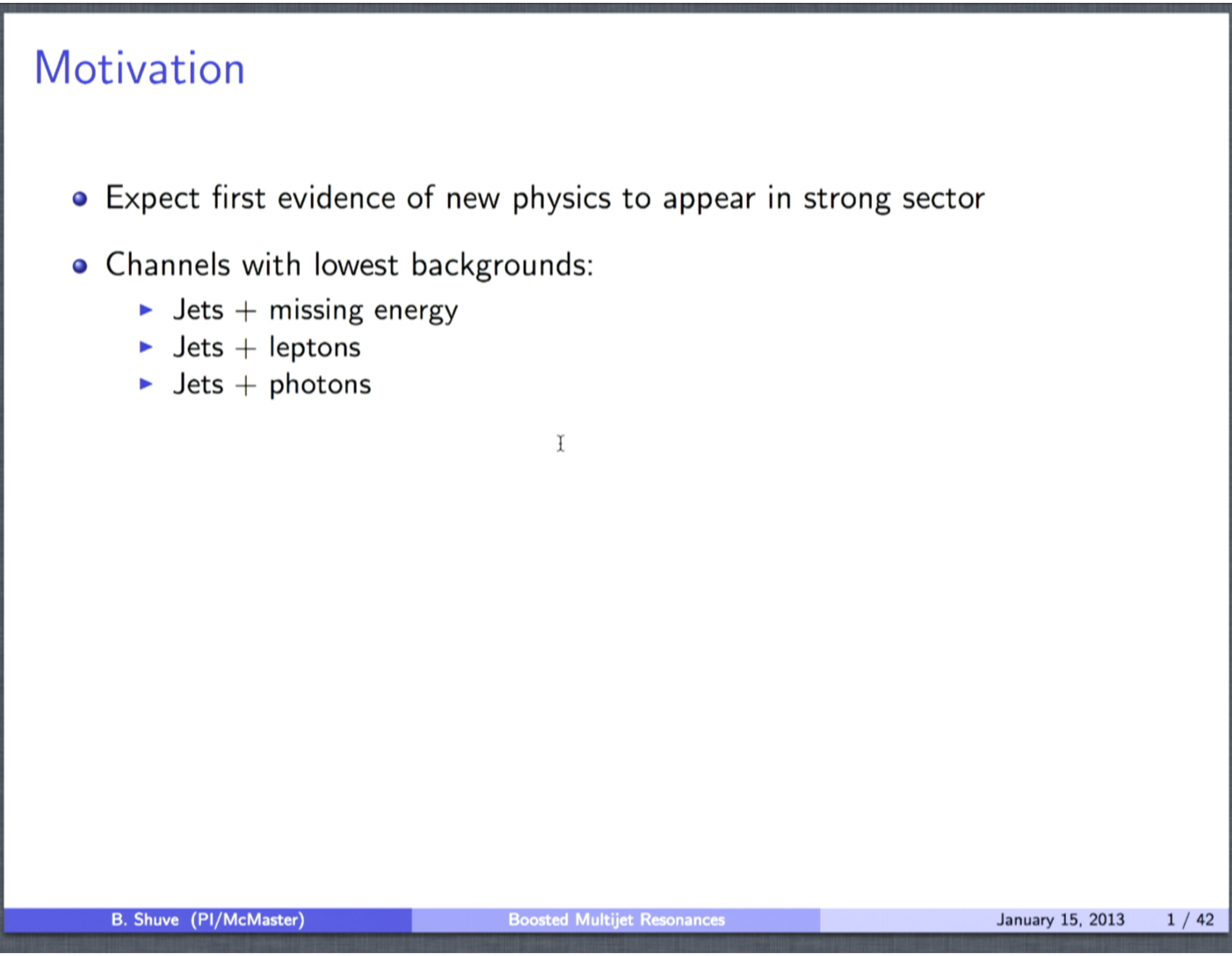
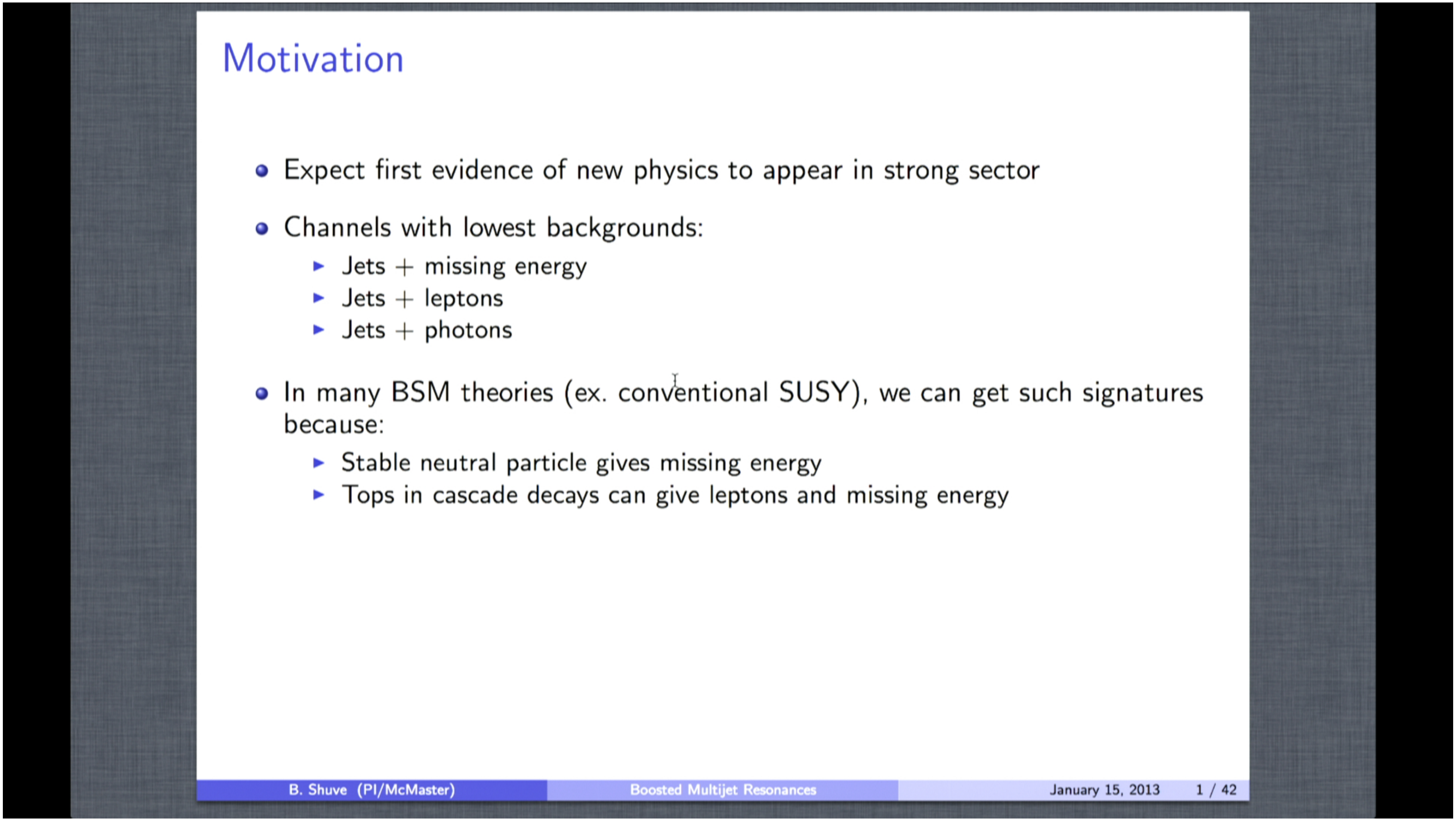


Motivation

- Expect first evidence of new physics to appear in strong sector
- Channels with lowest backgrounds:
  - Jets + missing energy
  - Jets + leptons
  - Jets + photons



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    - Stable neutral particle gives missing energy
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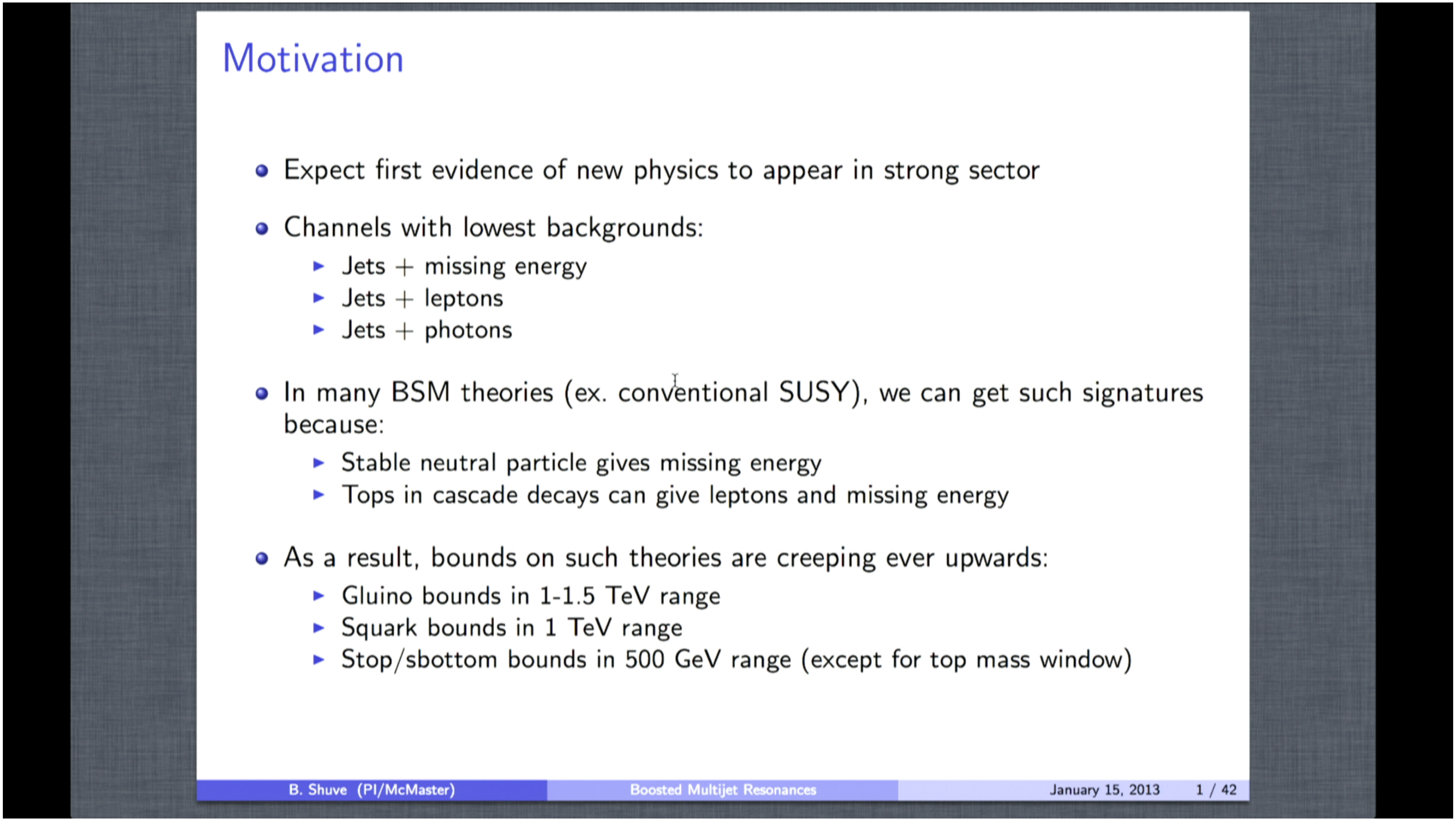

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- In many BSM theories (ex. conventional SUSY), we can get such signatures because:
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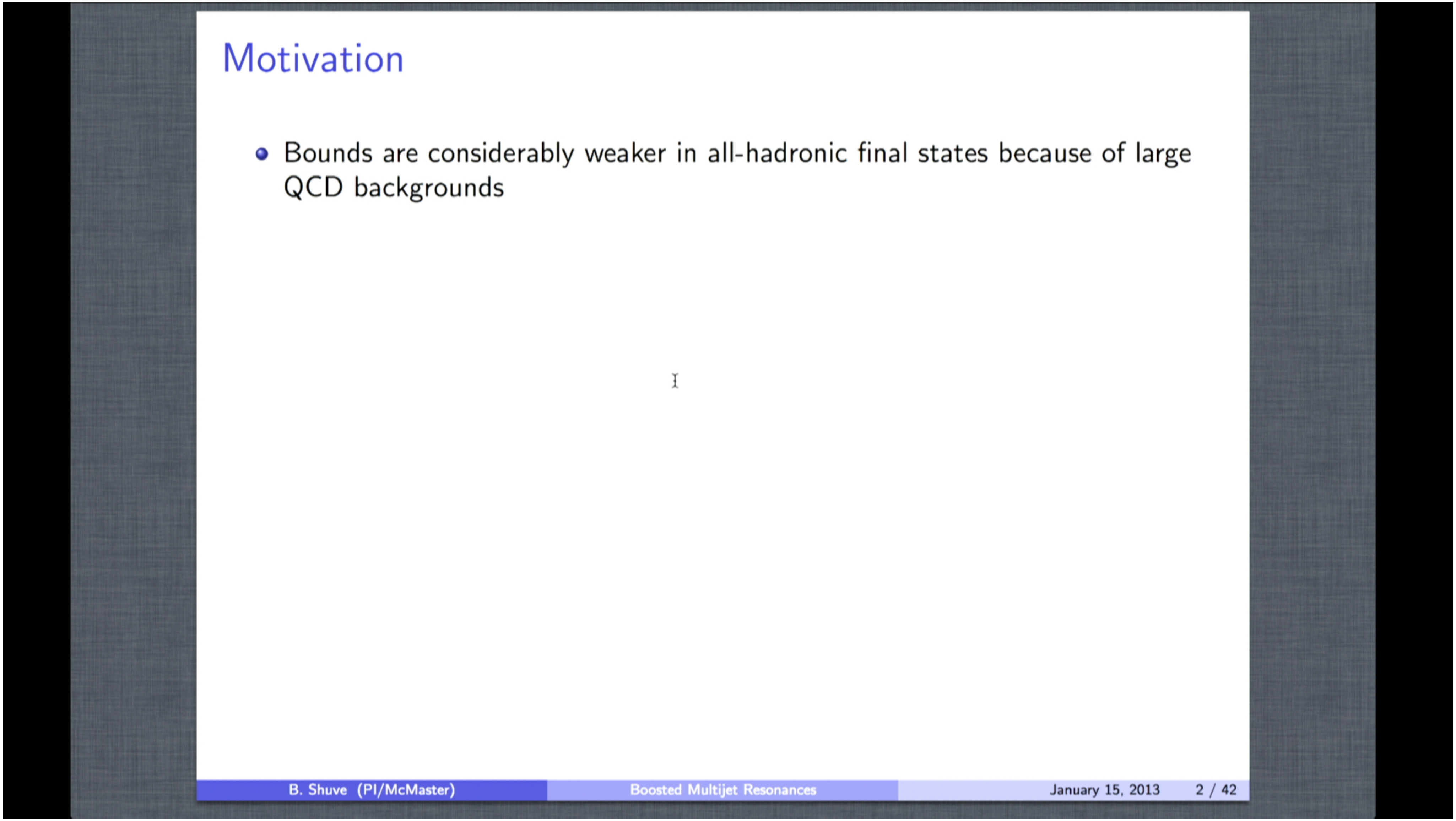
    - Tops in cascade decays can give leptons and missing energy
- As a result, bounds on such theories are creeping ever upwards:
    - Gluino bounds in 1-1.5 TeV range
    - Squark bounds in 1 TeV range
    - Stop/sbottom bounds in 500 GeV range (except for top mass window)



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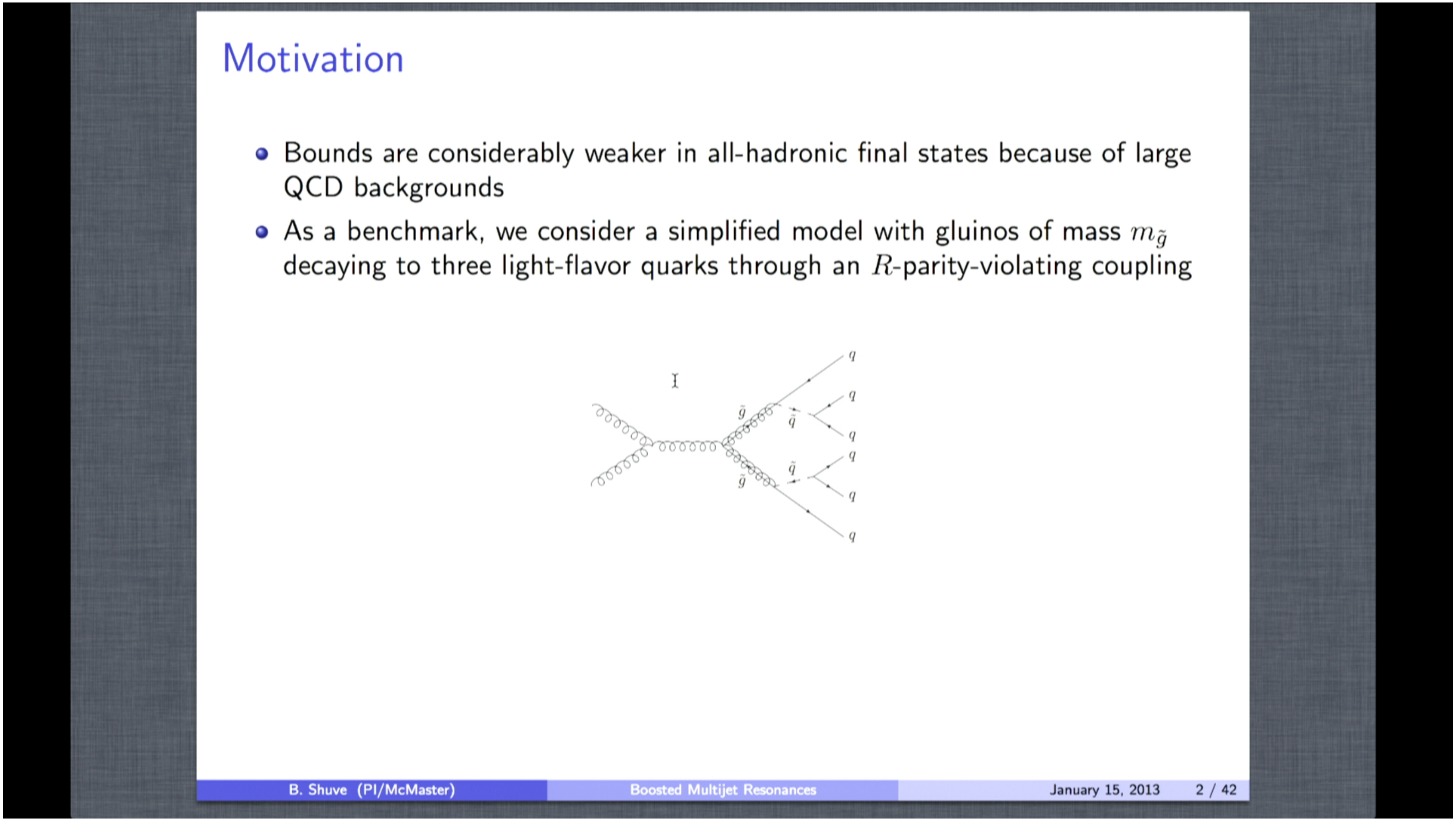
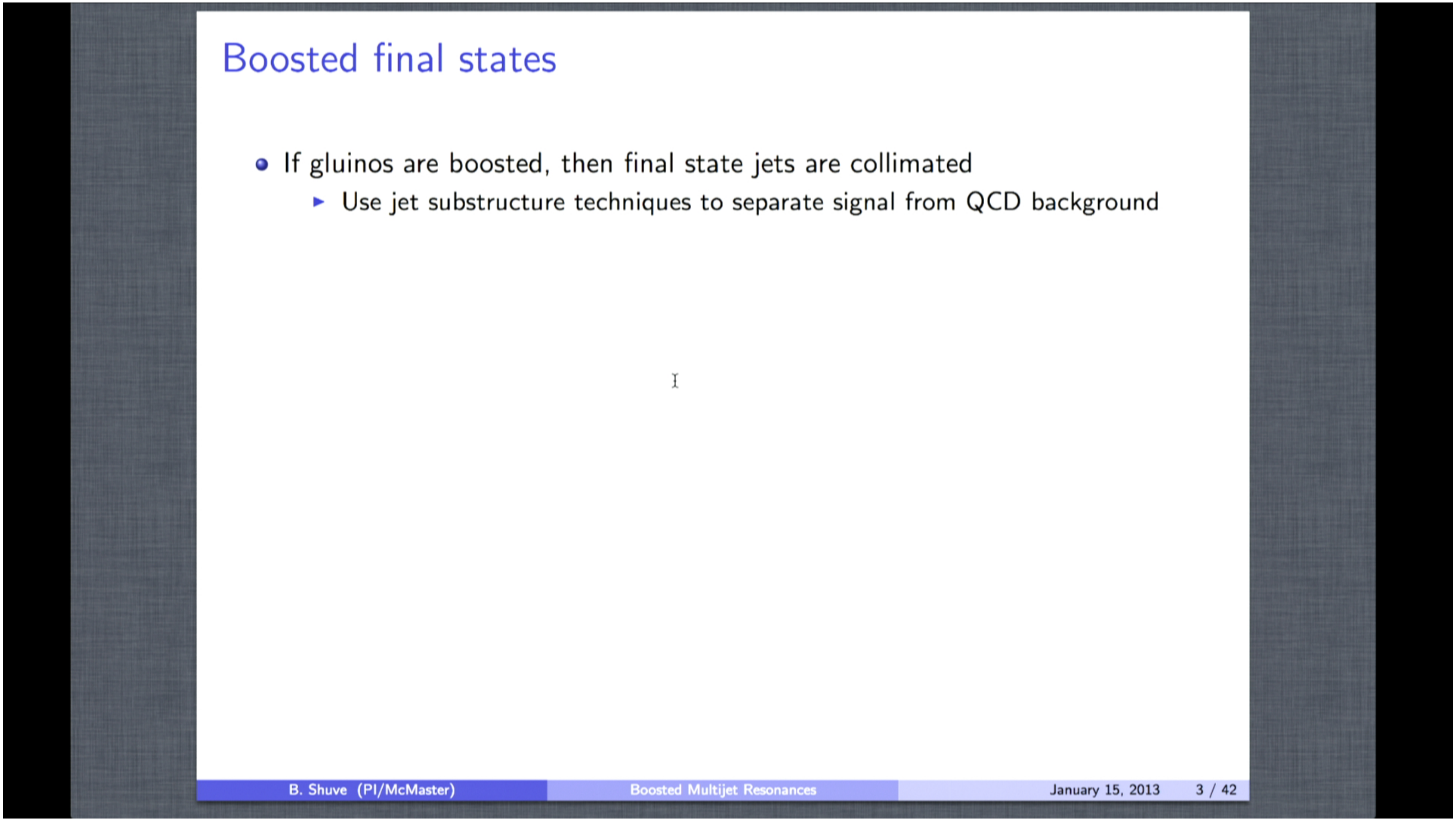


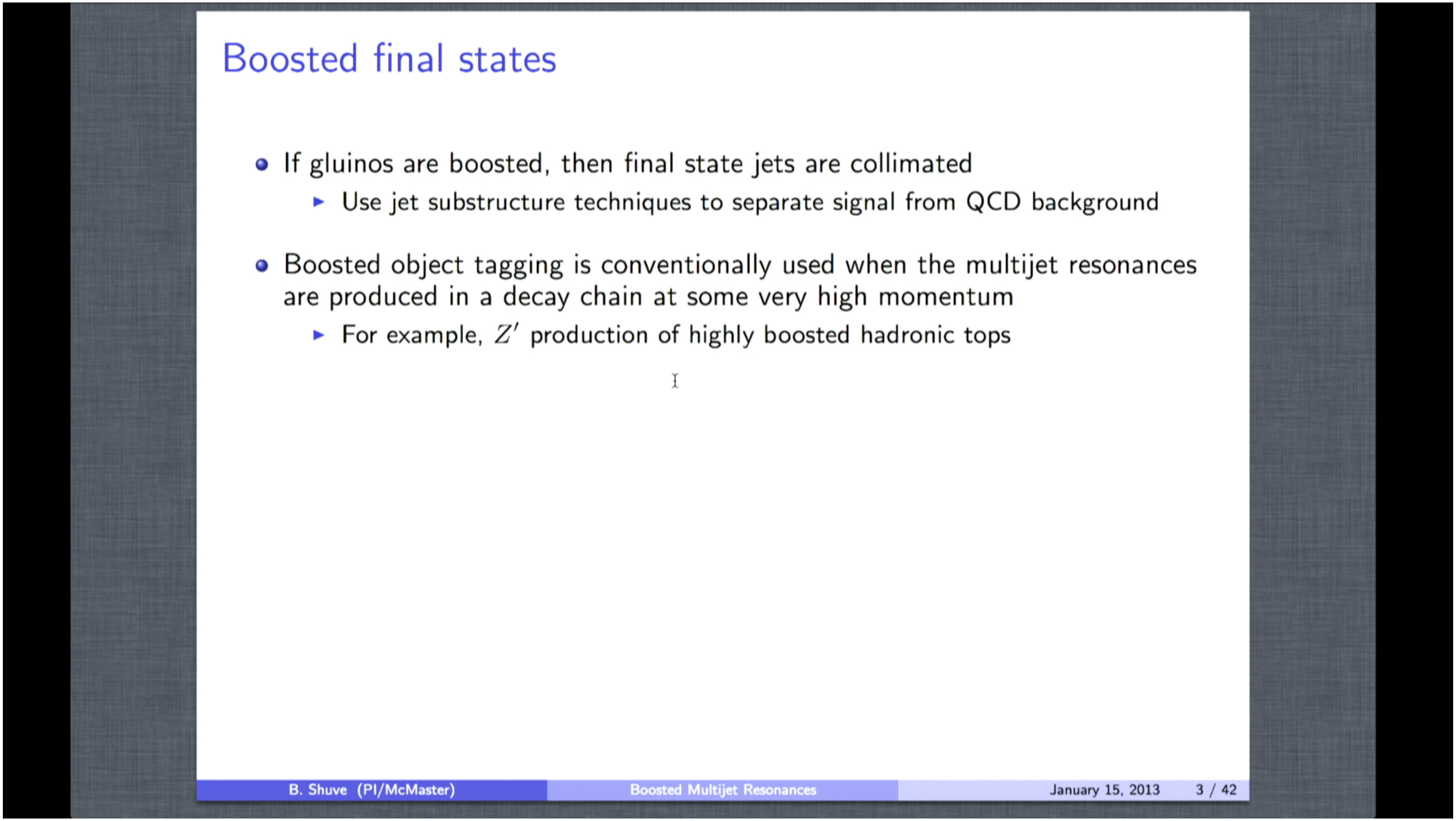
Motivation

- Bounds are considerably weaker in all-hadronic final states because of large QCD backgrounds
- As a benchmark, we consider a simplified model with gluinos of mass $m_{\tilde{g}}$ decaying to three light-flavor quarks through an R-parity-violating coupling



Boosted final states

- If gluinos are boosted, then final state jets are collimated
  - Use jet substructure techniques to separate signal from QCD background



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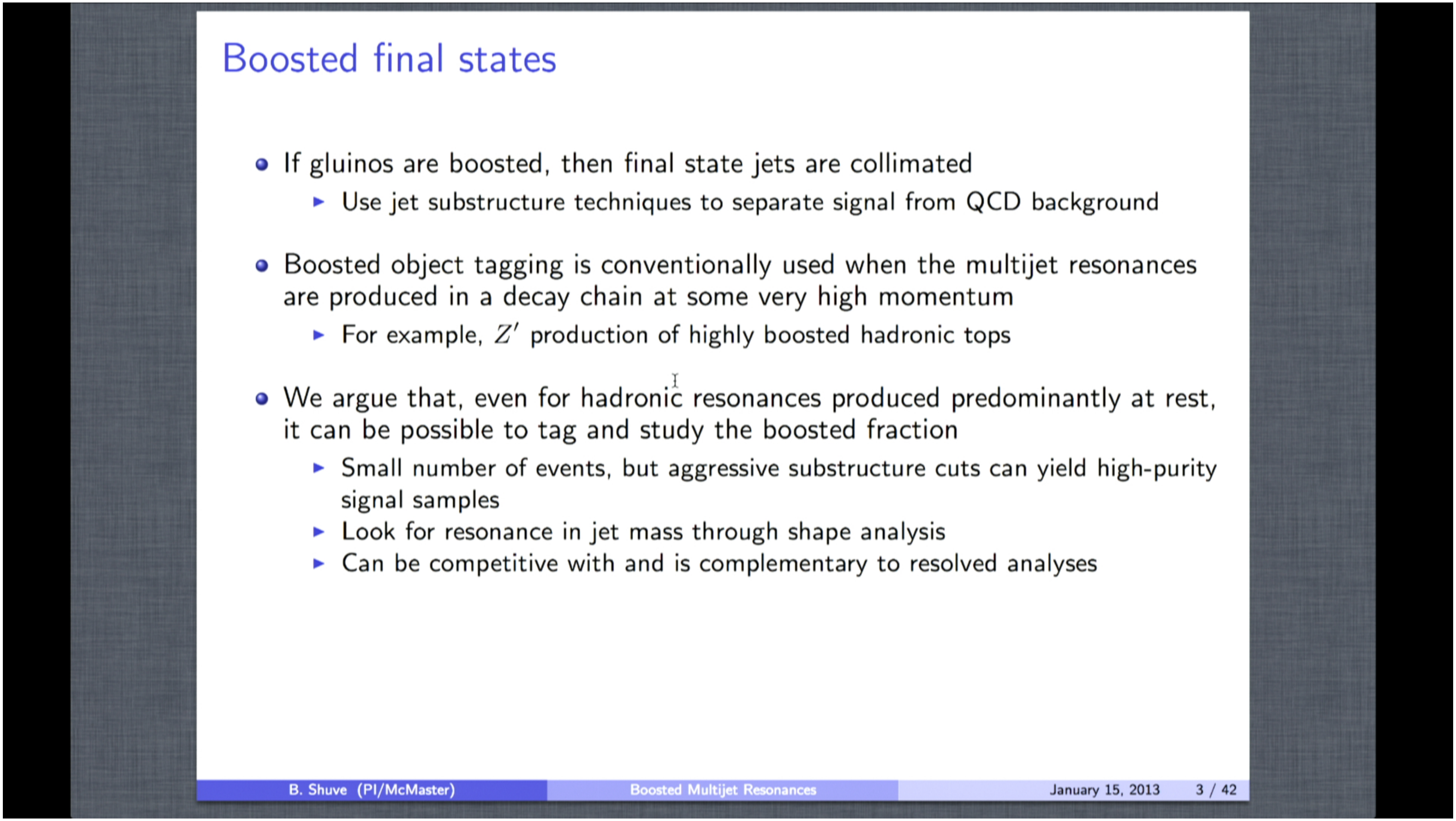
    - For example, Z' production of highly boosted hadronic tops



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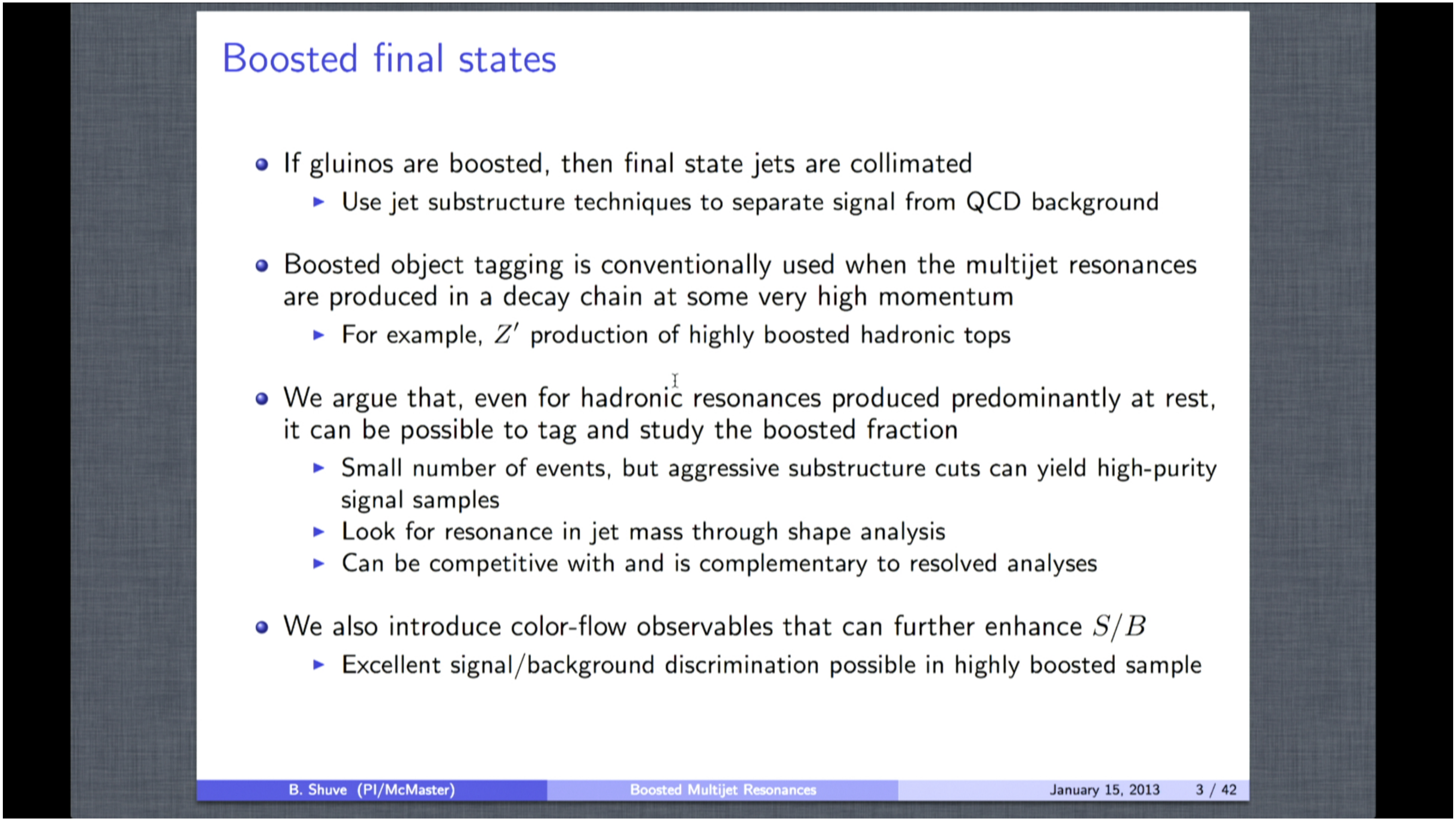
- We argue that, even for hadronic resonances produced predominantly at rest, it can be possible to tag and study the boosted fraction
  - Small number of events, but aggressive substructure cuts can yield high-purity signal samples
  - Look for resonance in jet mass through shape analysis
  - Can be competitive with and is complementary to resolved analyses



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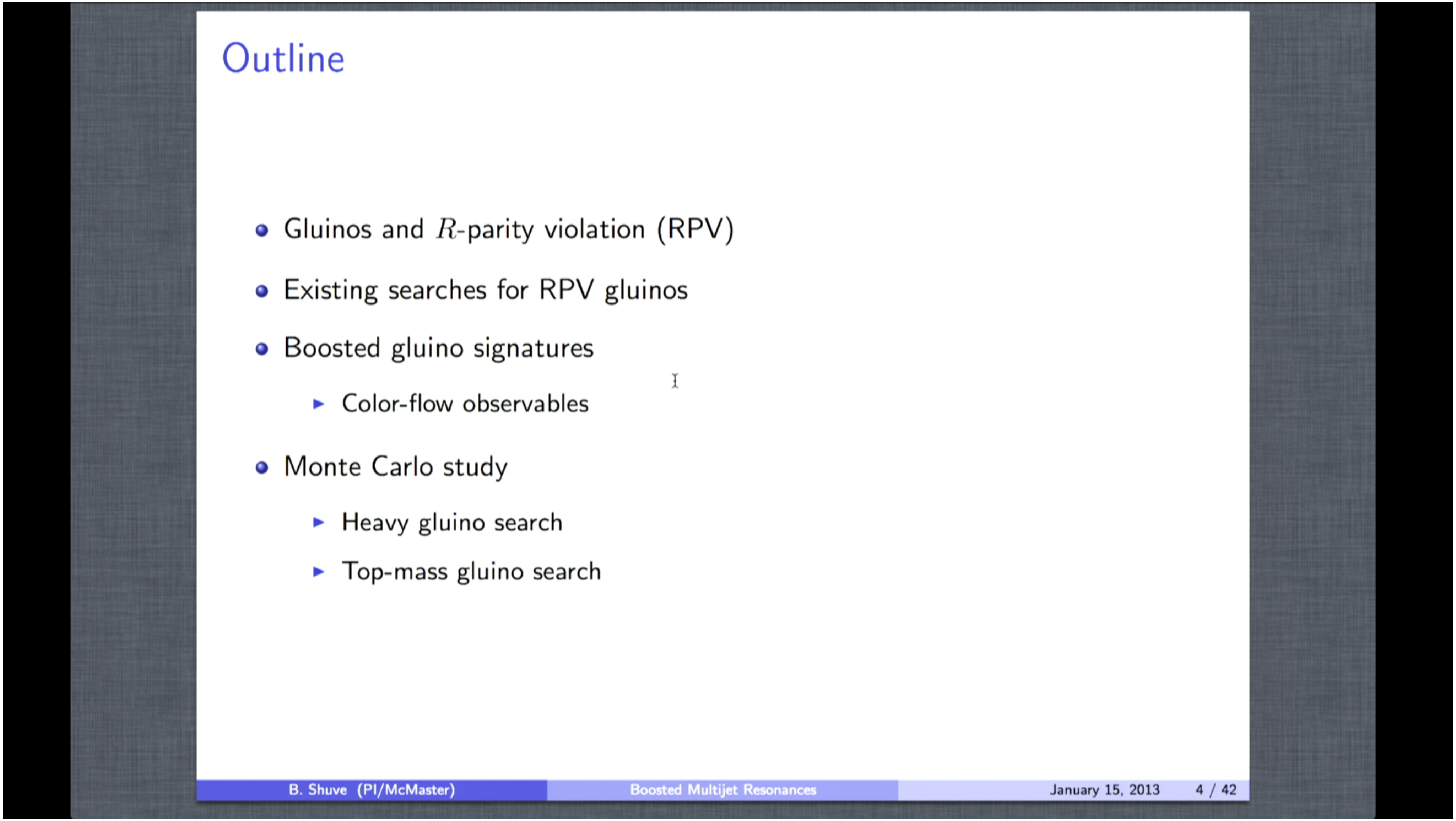
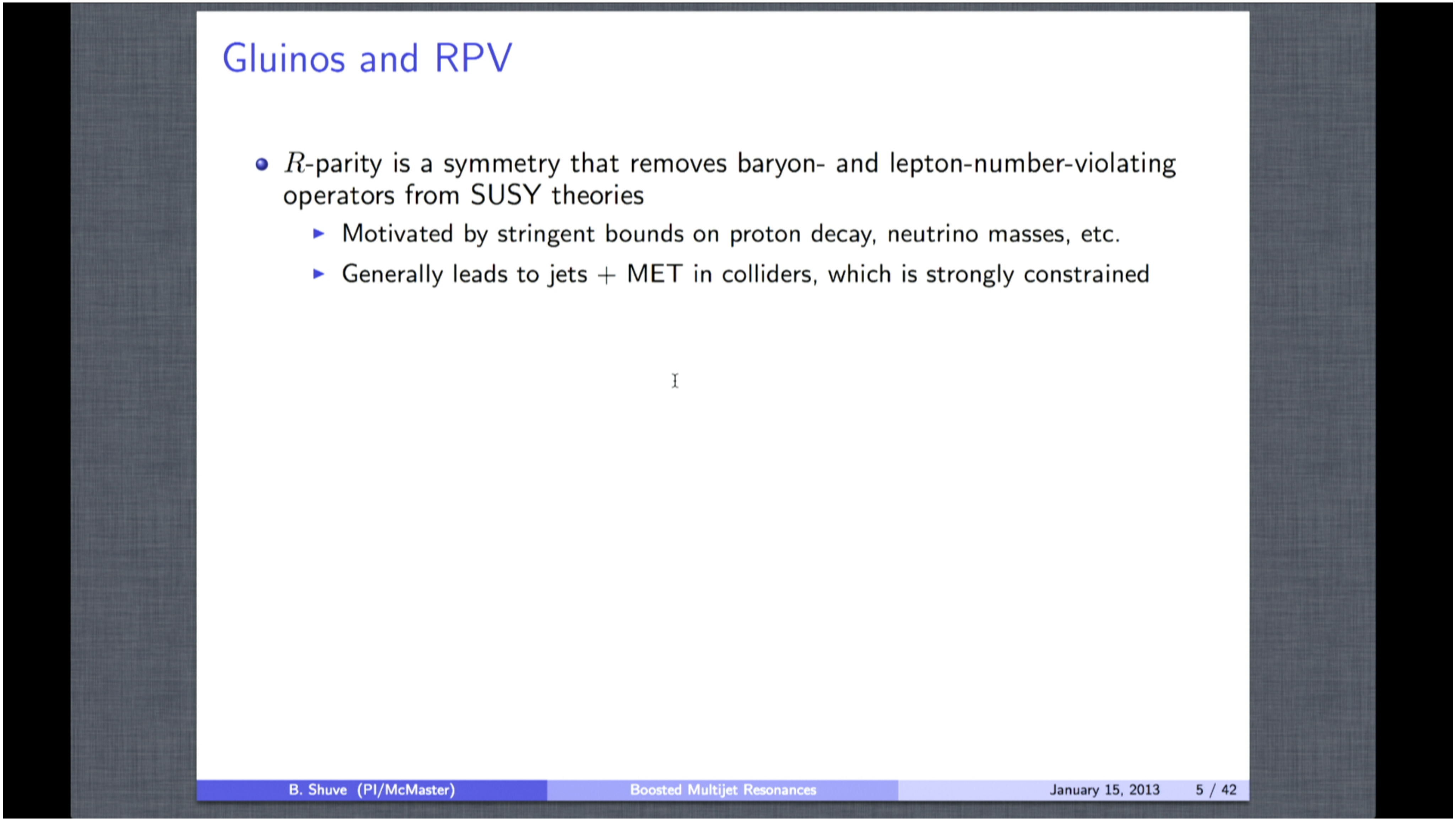
  - Can be competitive with and is complementary to resolved analyses
- We also introduce color-flow observables that can further enhance S/B
  - Excellent signal/background discrimination possible in highly boosted sample



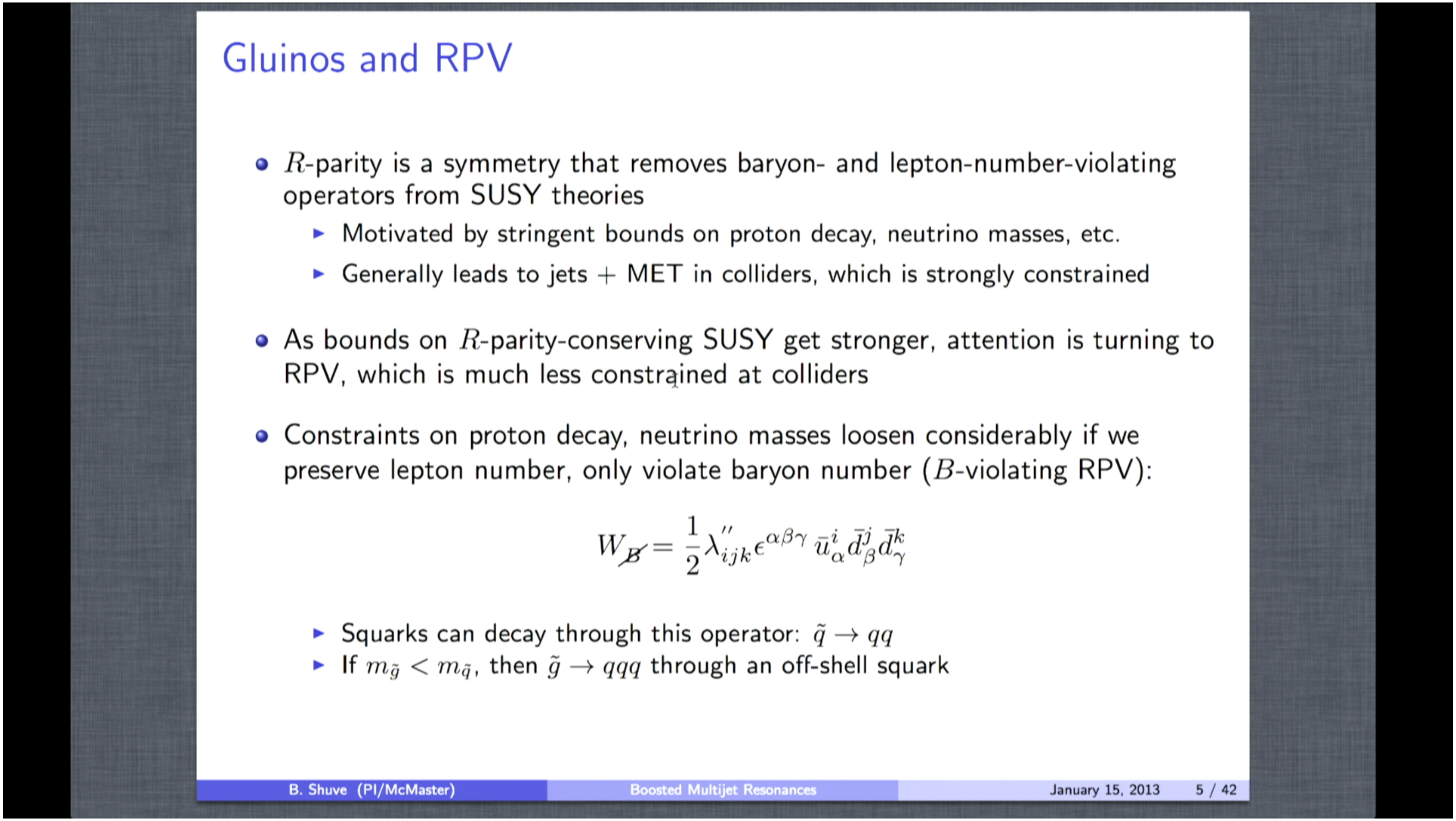
Outline

- Gluinos and R-parity violation (RPV)
- Existing searches for RPV gluinos
- Boosted gluino signatures
    - Color-flow observables
- Monte Carlo study
    - Heavy gluino search
    - Top-mass gluino search



Gluinos and RPV

- R-parity is a symmetry that removes baryon- and lepton-number-violating operators from SUSY theories
  - Motivated by stringent bounds on proton decay, neutrino masses, etc.
  - Generally leads to jets + MET in colliders, which is strongly constrained



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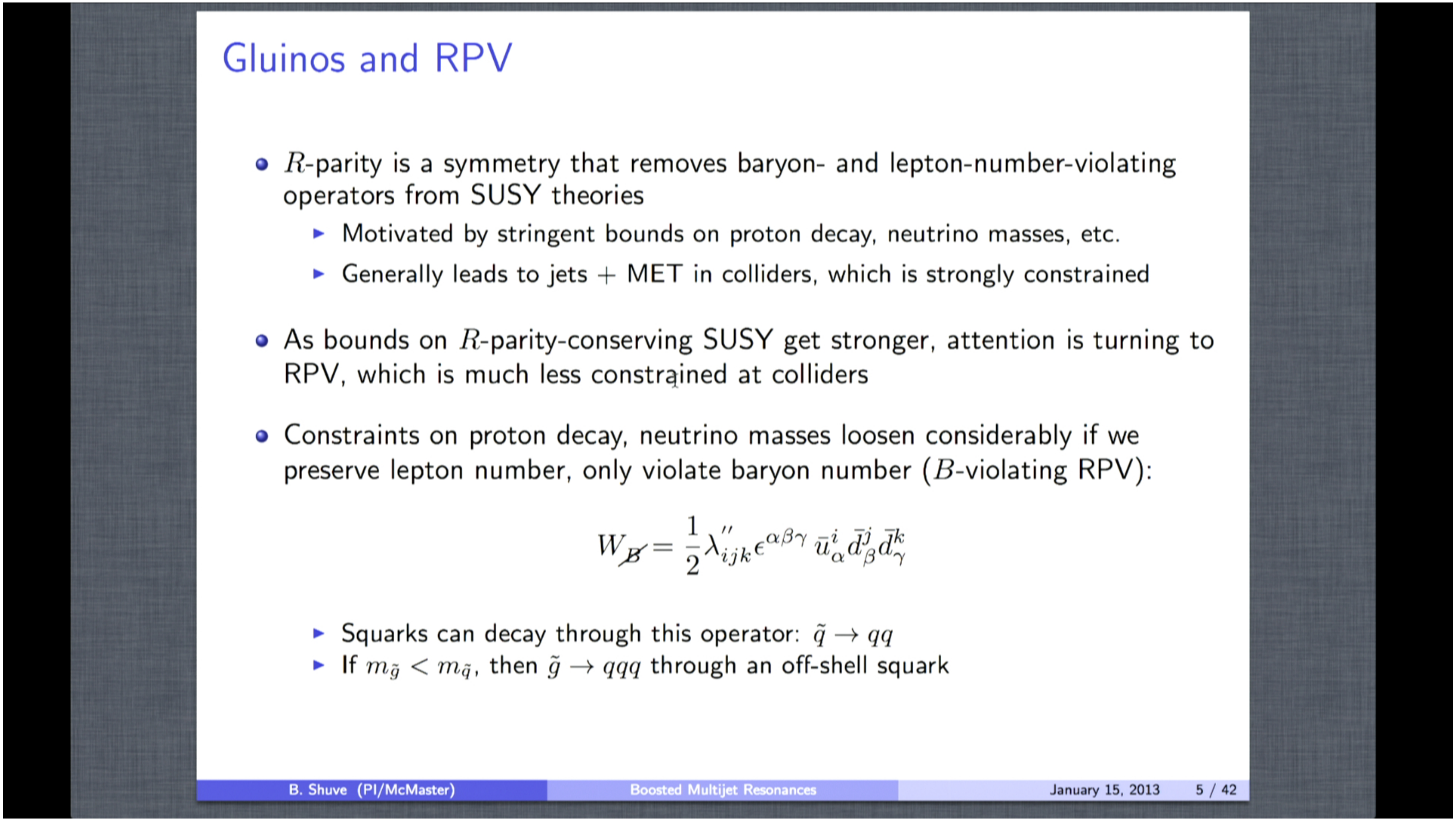
- As bounds on R-parity-conserving SUSY get stronger, attention is turning to RPV, which is much less constrained at colliders
- Constraints on proton decay, neutrino masses loosen considerably if we preserve lepton number, only violate baryon number (B-violating RPV):

$$W_{\not B} = \frac{1}{2}\lambda''_{ijk}\epsilon^{\alpha\beta\gamma}\,\bar{u}^i_\alpha\bar{d}^j_\beta\bar{d}^k_\gamma$$

  - Squarks can decay through this operator: $\tilde{q} \to qq$
  - If $m_{\tilde{g}} < m_{\tilde{q}}$, then $\tilde{g} \to qqq$ through an off-shell squark



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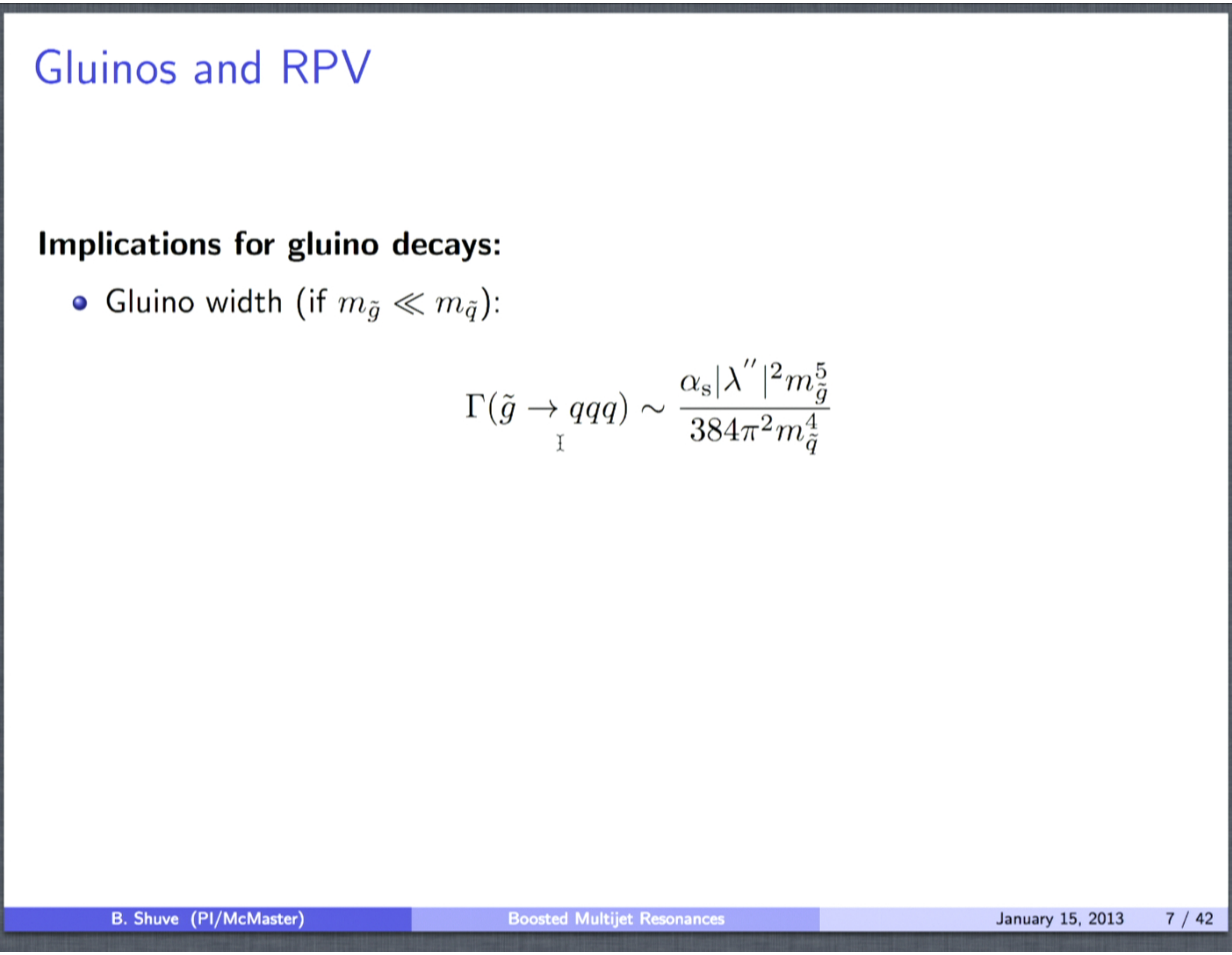
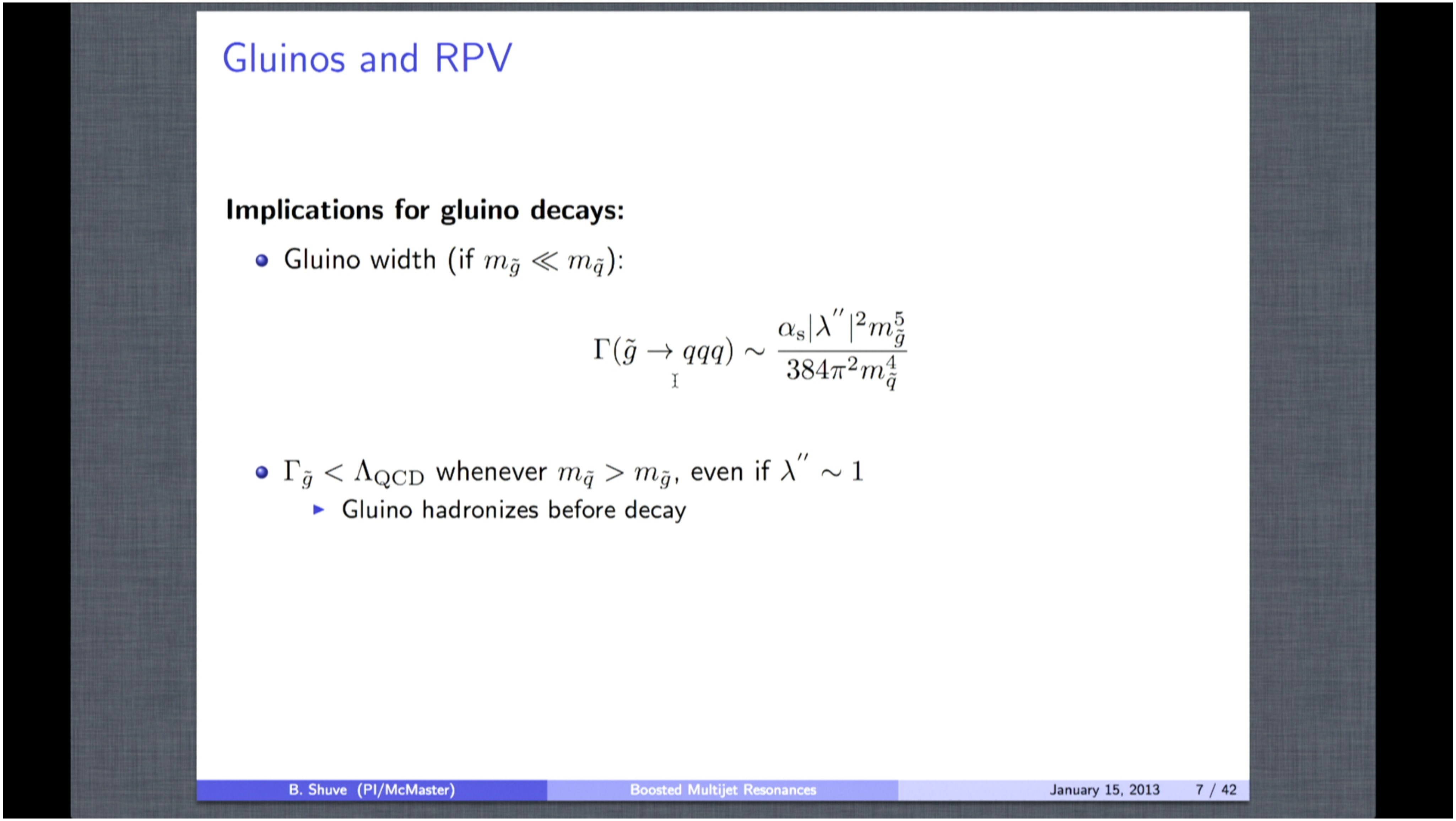


Gluinos and RPV

Implications for gluino decays:

- Gluino width (if $m_{\tilde{g}} \ll m_{\tilde{q}}$):

$$\Gamma(\tilde{g} \to qqq) \sim \frac{\alpha_s |\lambda''|^2 m_{\tilde{g}}^5}{384\pi^2 m_{\tilde{q}}^4}$$



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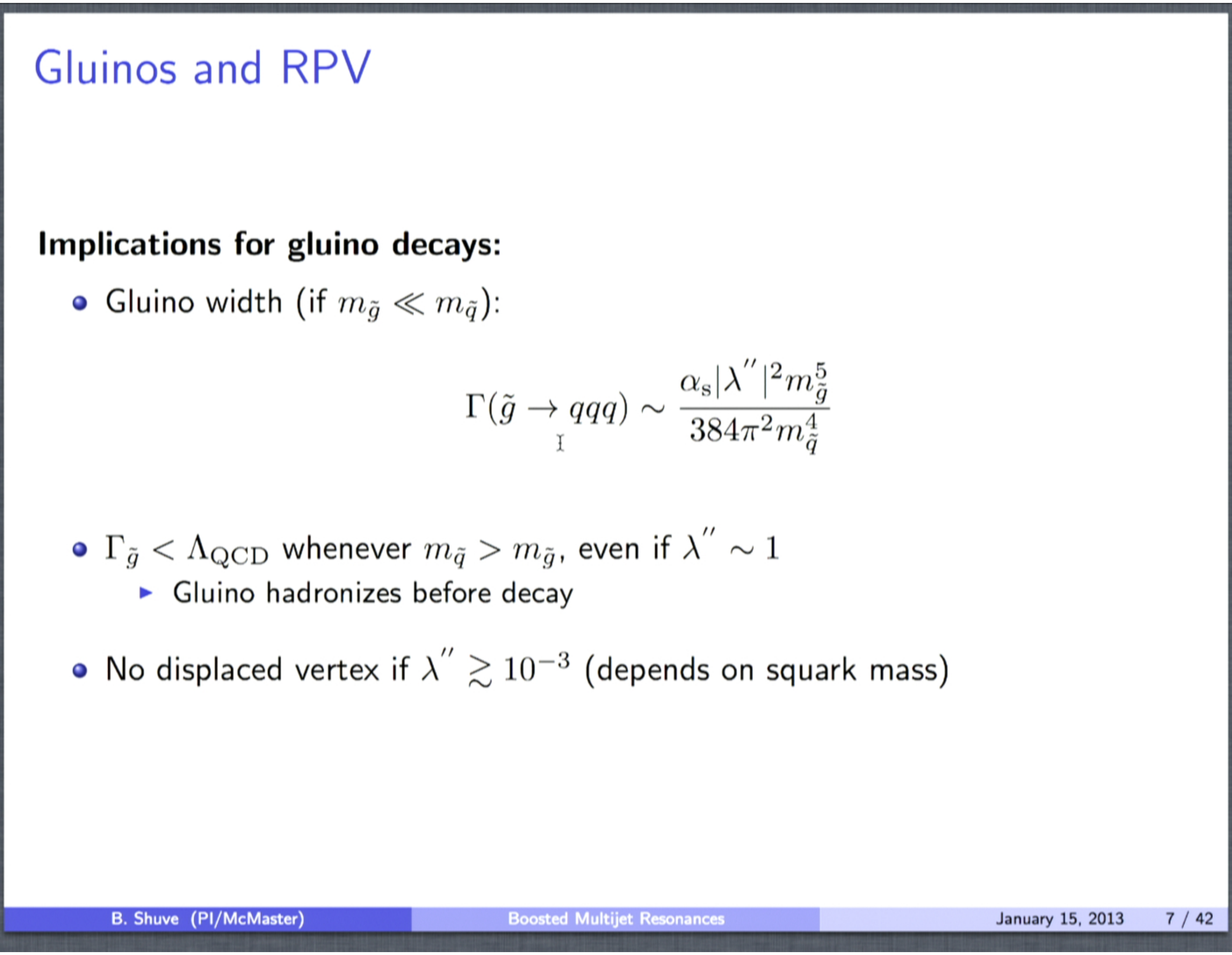
  - Gluino hadronizes before decay



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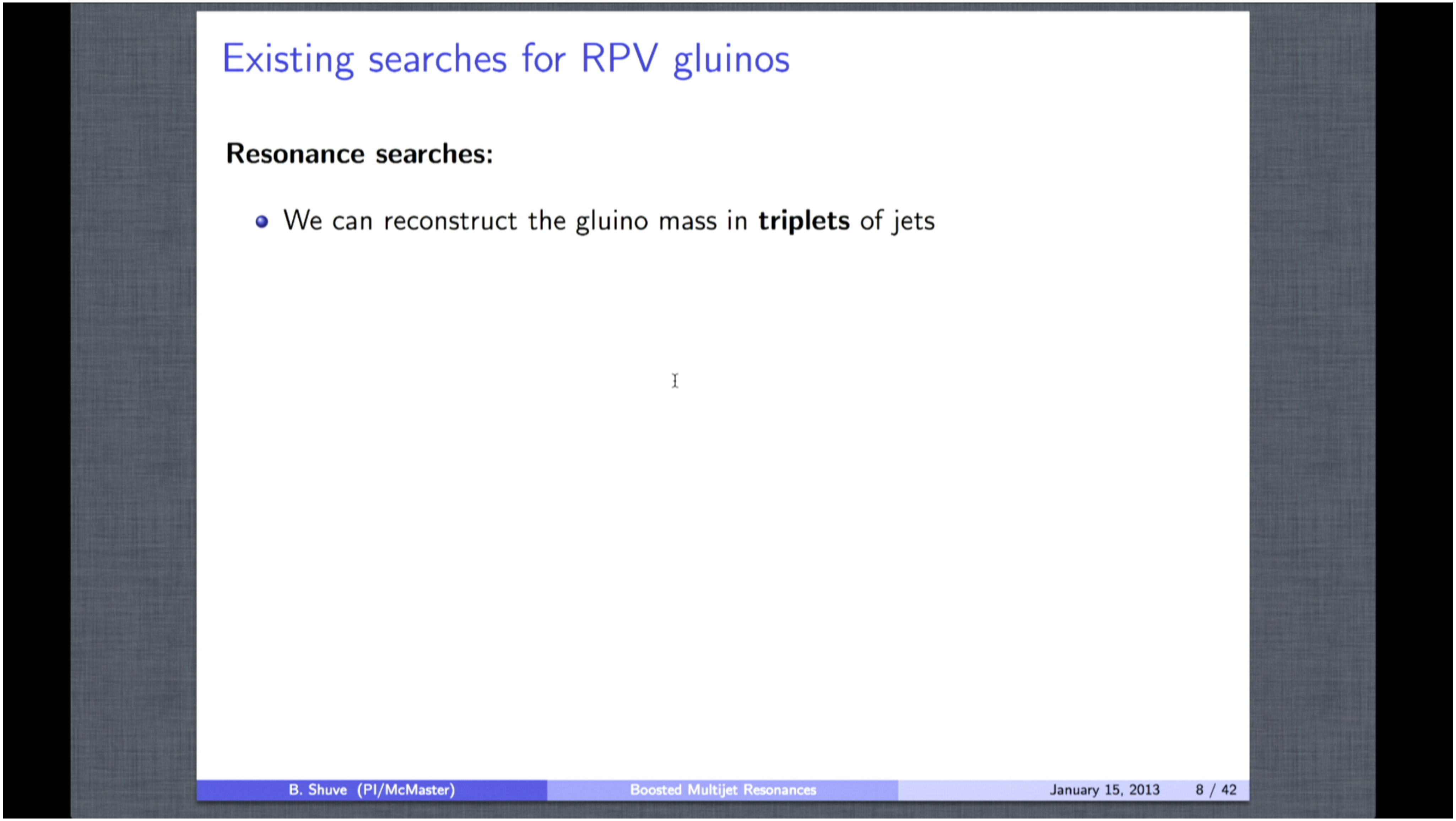
  - Gluino hadronizes before decay
- No displaced vertex if $\lambda'' \gtrsim 10^{-3}$ (depends on squark mass)



Existing searches for RPV gluinos

Resonance searches:

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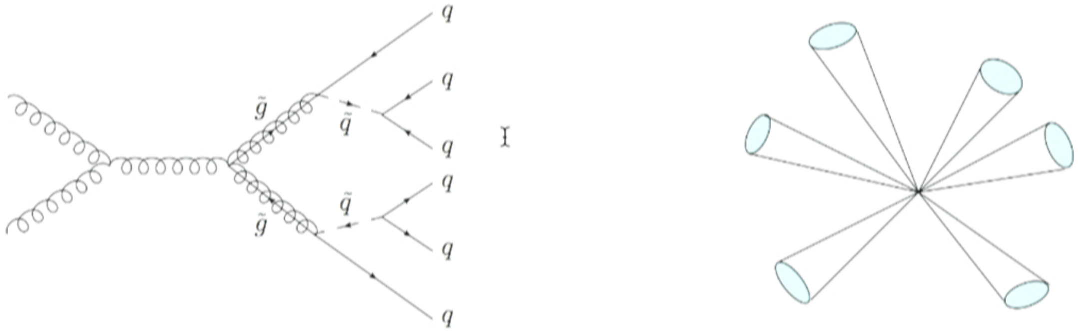
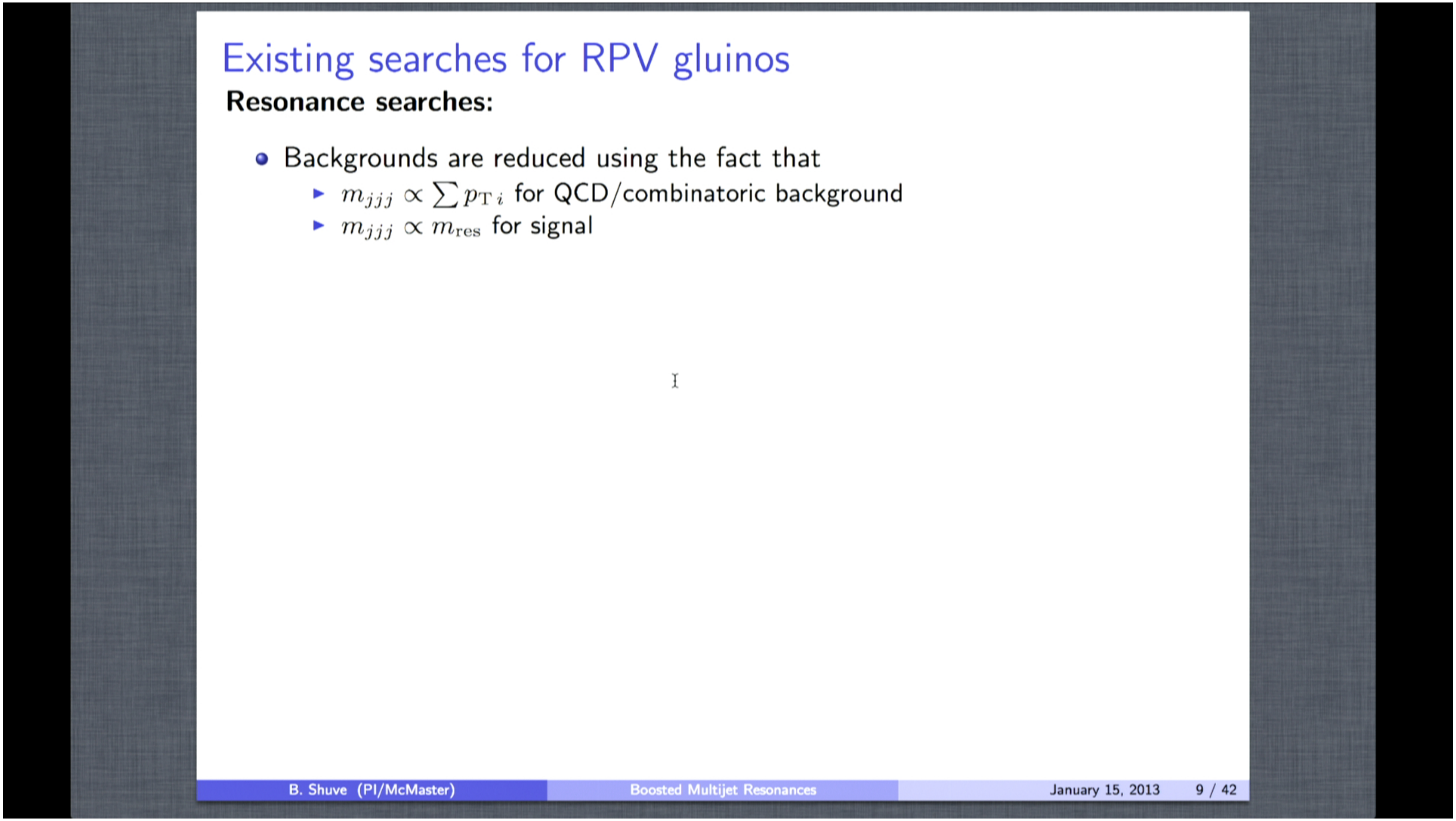


- But which jets do we combine? There are $\begin{pmatrix} 6 \\ 3 \end{pmatrix} = 20$ combinations!
  - Best to consider ensemble of all combinations, although this results in large combinatoric background



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Resonance searches:

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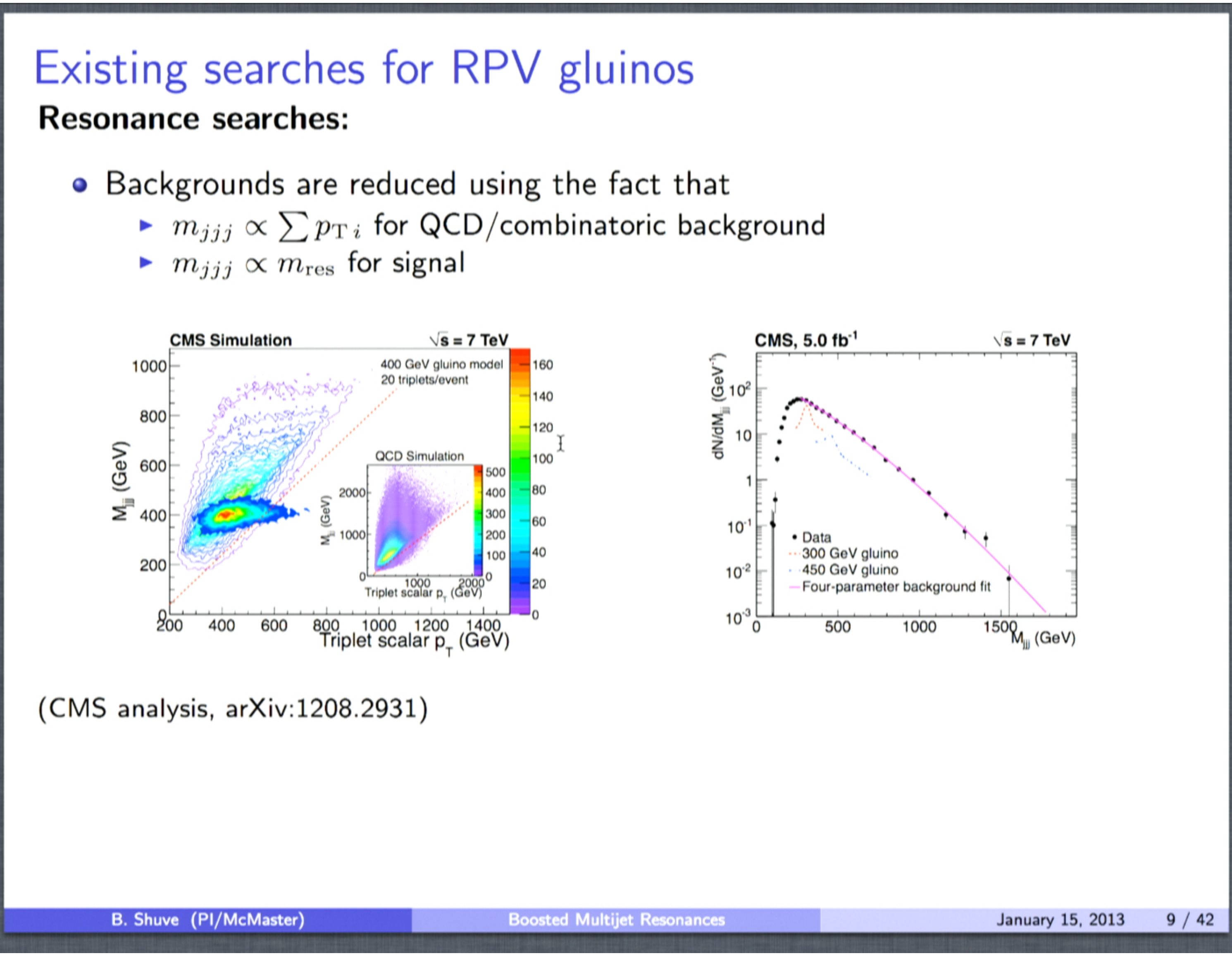

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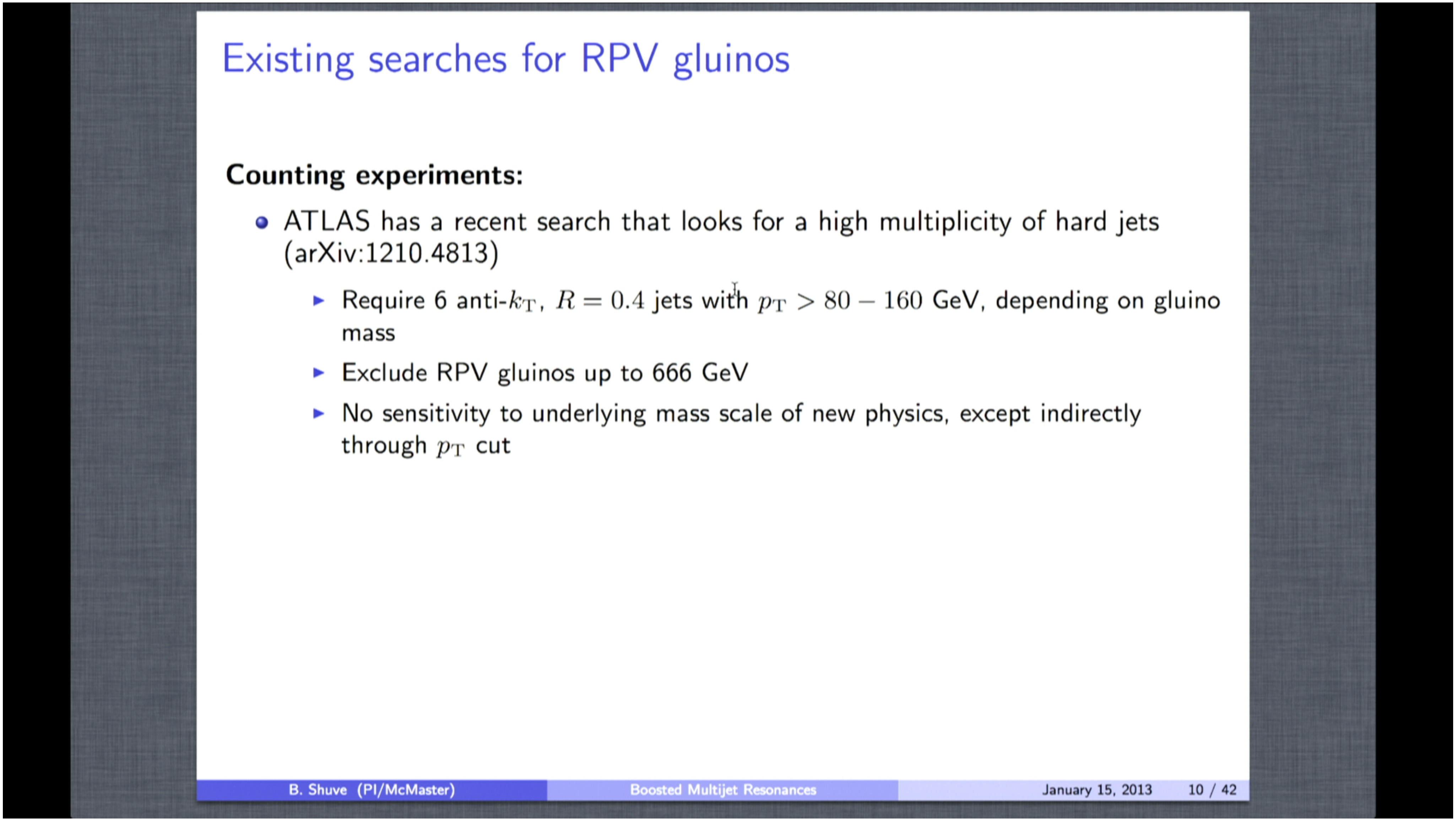
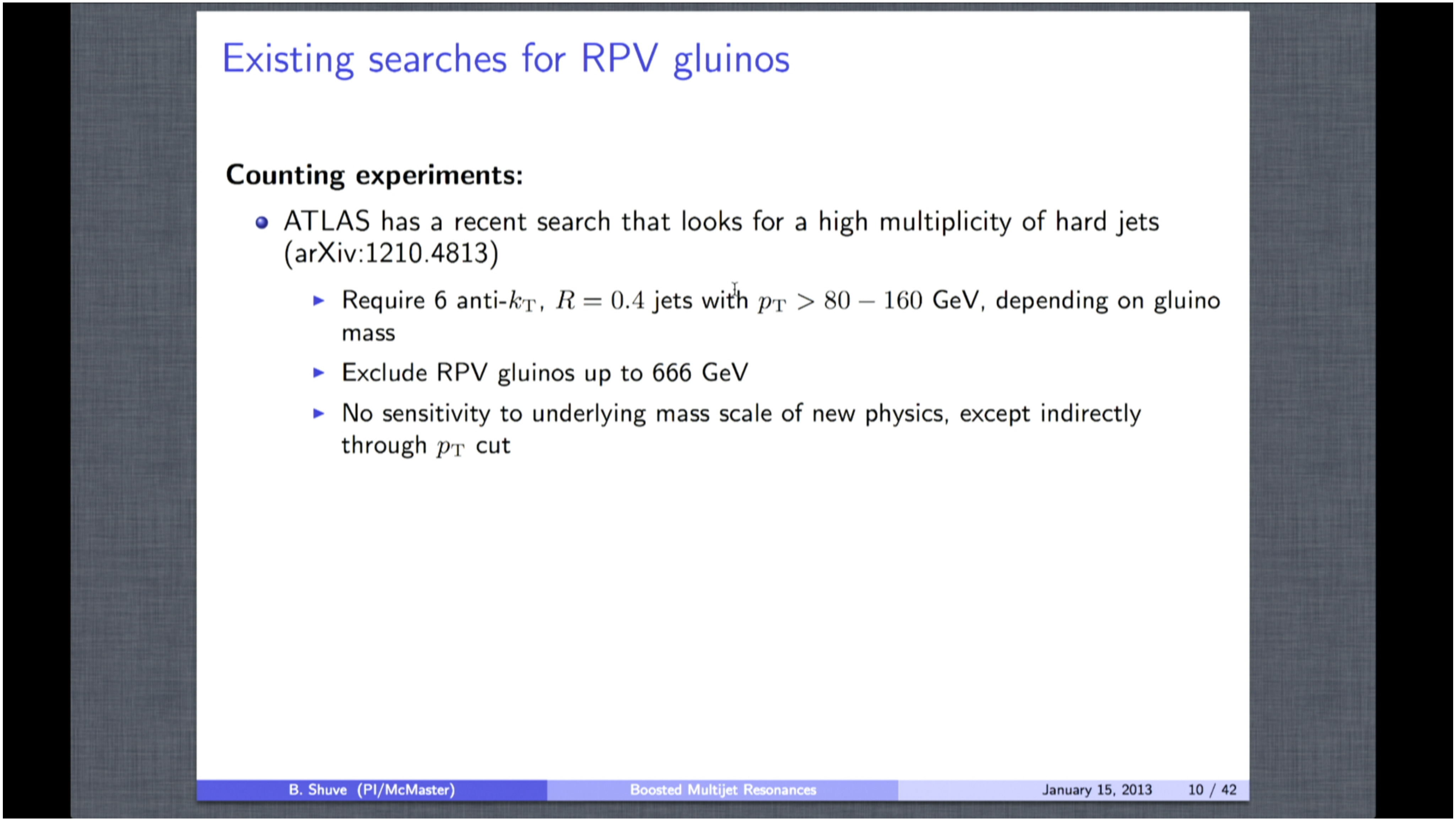
(CMS analysis, arXiv:1208.2931)



Existing searches for RPV gluinos

Counting experiments:

- ATLAS has a recent search that looks for a high multiplicity of hard jets (arXiv:1210.4813)
    - Require 6 anti-k_T, $R = 0.4$ jets with $p_\mathrm{T} > 80 - 160$ GeV, depending on gluino mass
    - Exclude RPV gluinos up to 666 GeV
    - No sensitivity to underlying mass scale of new physics, except indirectly through p_T cut



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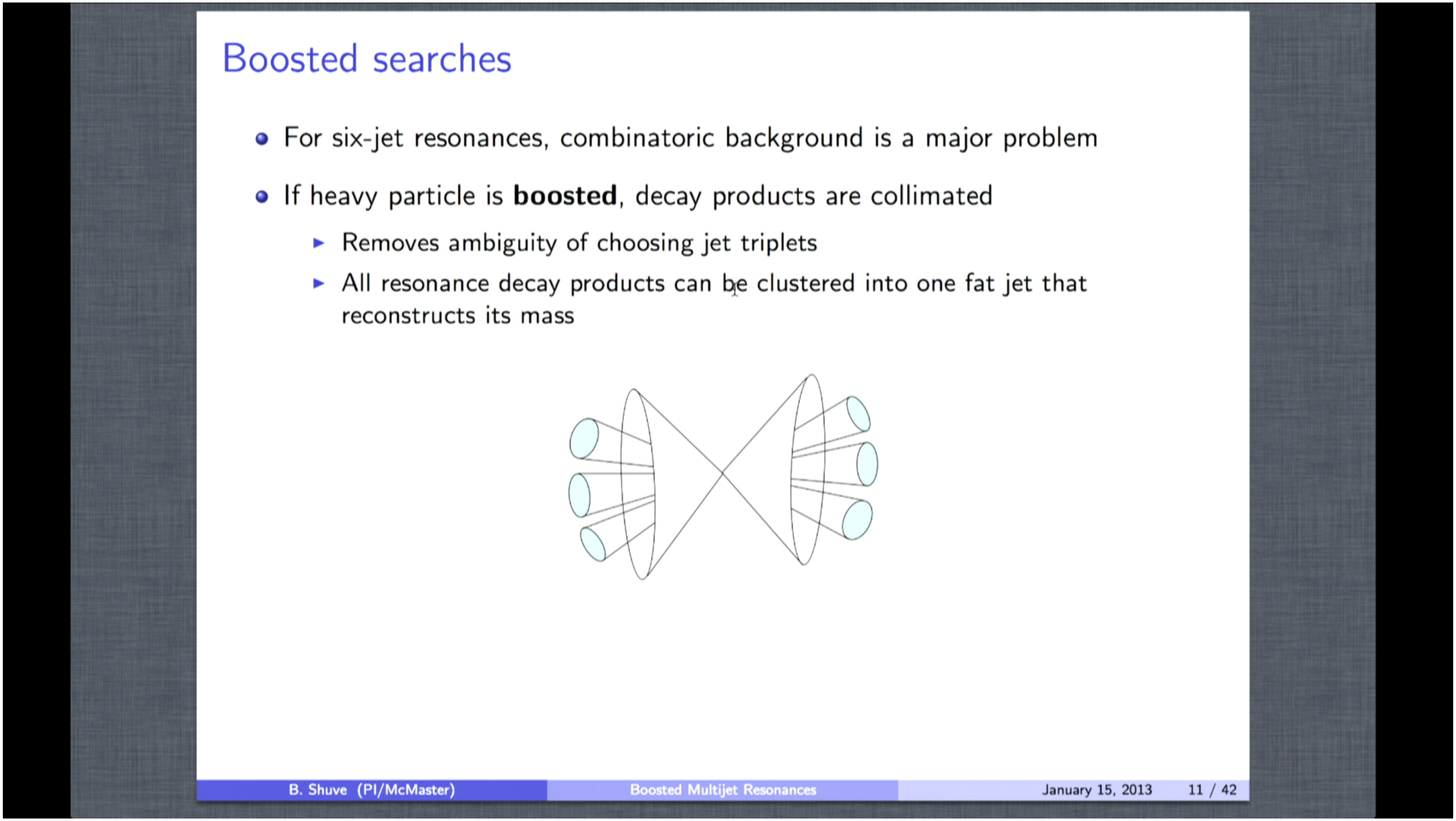
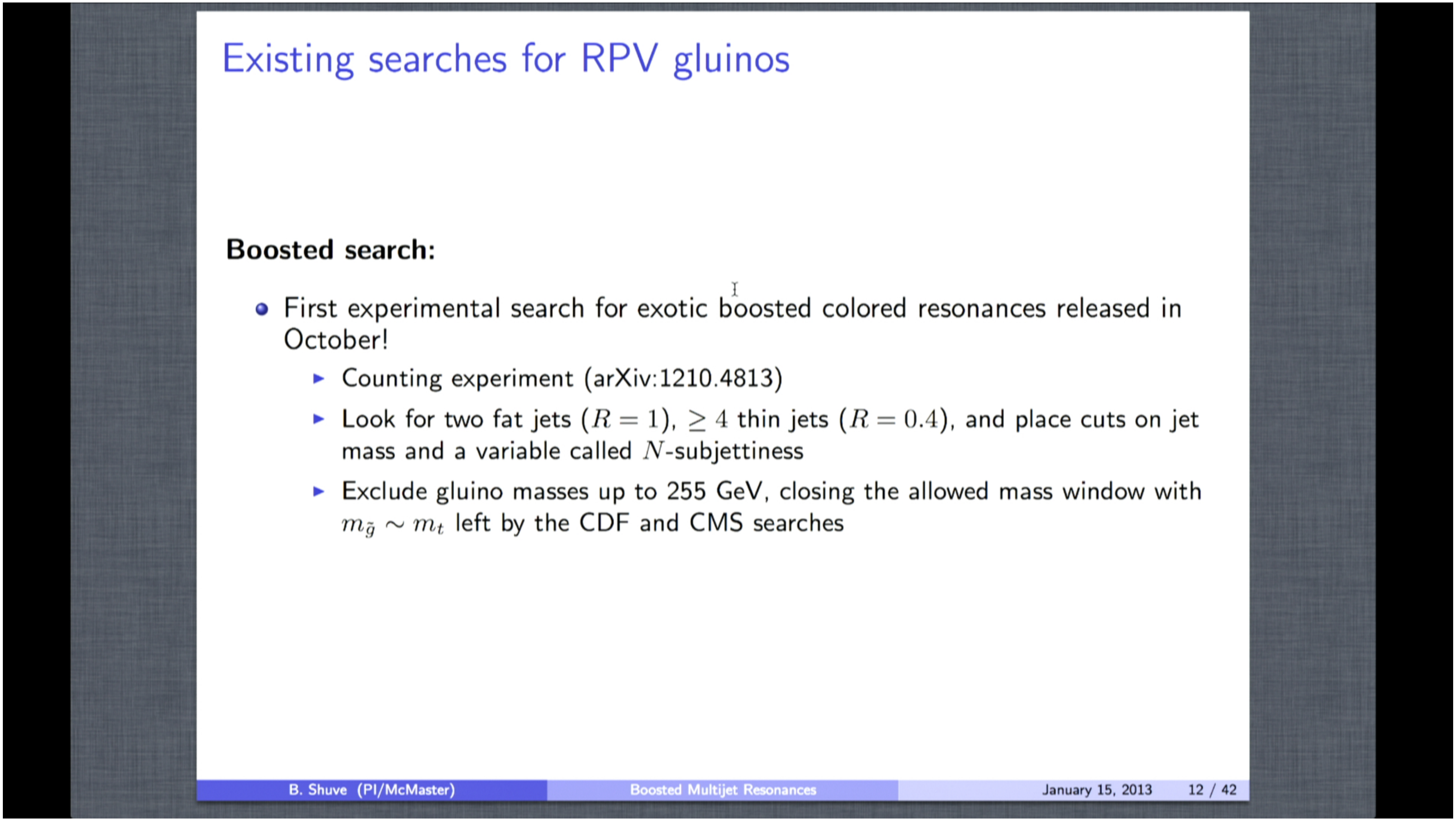


Boosted searches

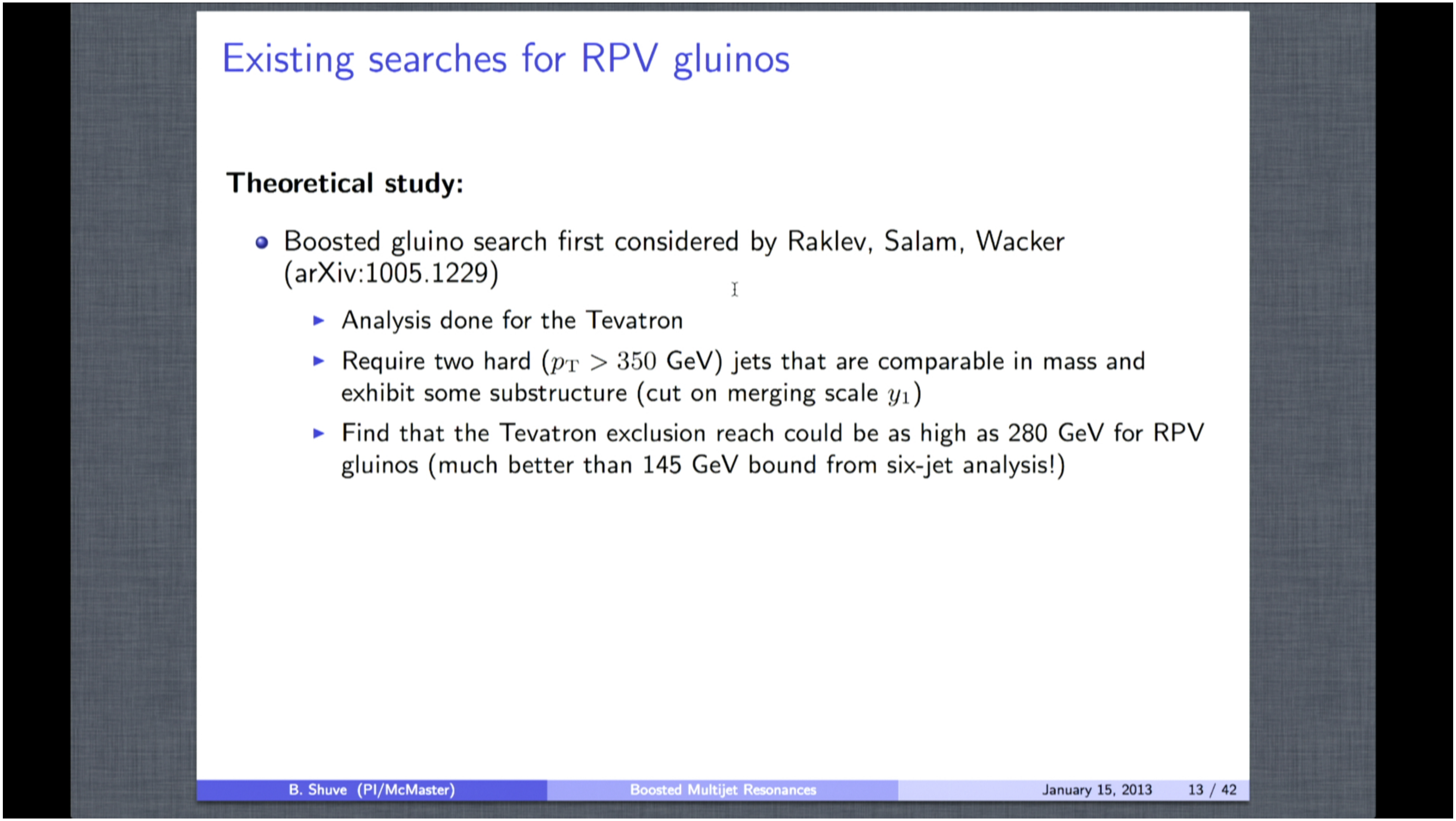
- For six-jet resonances, combinatoric background is a major problem
- If heavy particle is **boosted**, decay products are collimated
  - Removes ambiguity of choosing jet triplets
  - All resonance decay products can be clustered into one fat jet that reconstructs its mass



Existing searches for RPV gluinos

Boosted search:

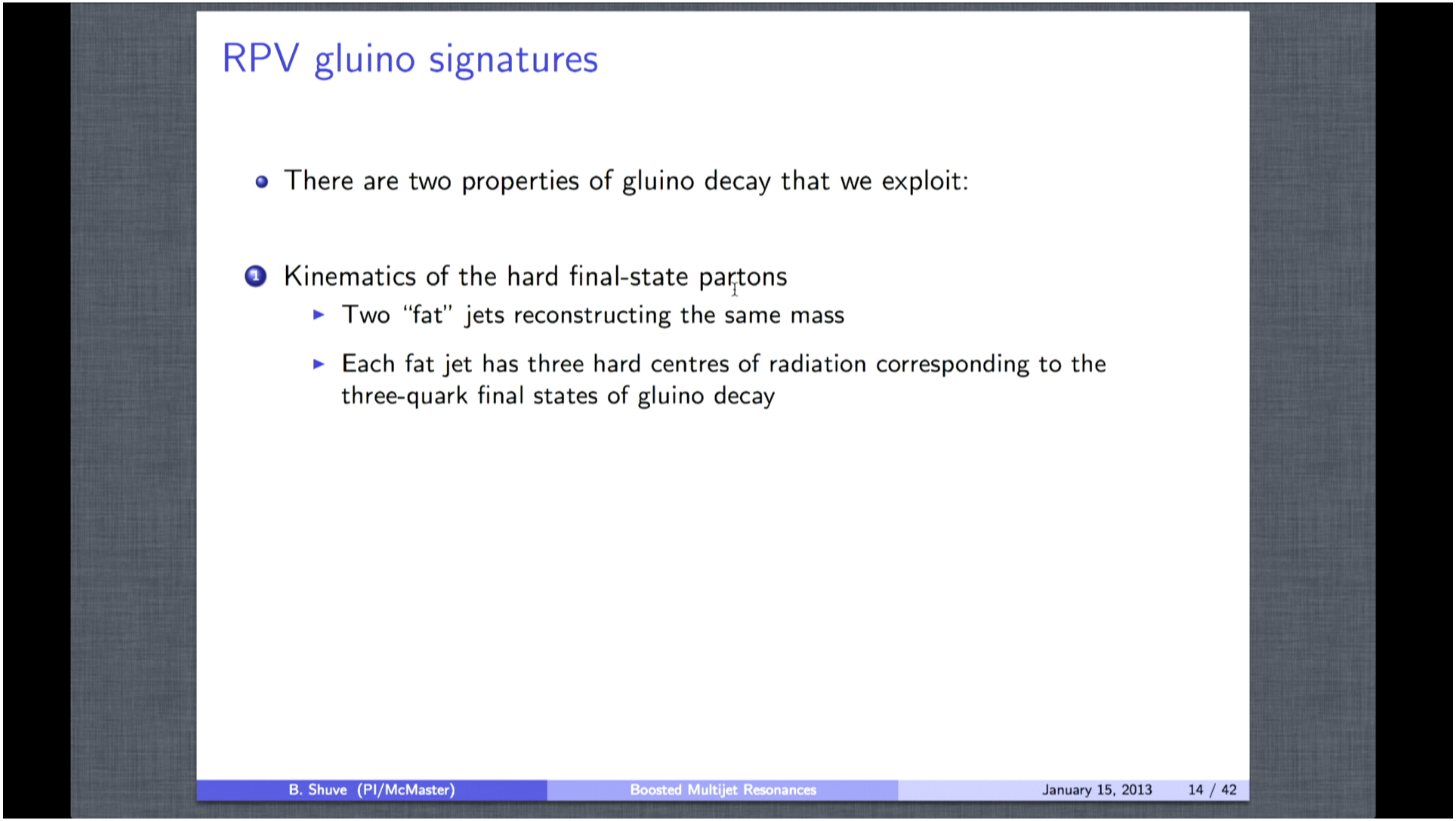
- First experimental search for exotic boosted colored resonances released in October!
  - Counting experiment (arXiv:1210.4813)
  - Look for two fat jets ($R = 1$), ≥ 4 thin jets ($R = 0.4$), and place cuts on jet mass and a variable called N-subjettiness
  - Exclude gluino masses up to 255 GeV, closing the allowed mass window with $m_{\tilde{g}} \sim m_t$ left by the CDF and CMS searches



Existing searches for RPV gluinos

Theoretical study:

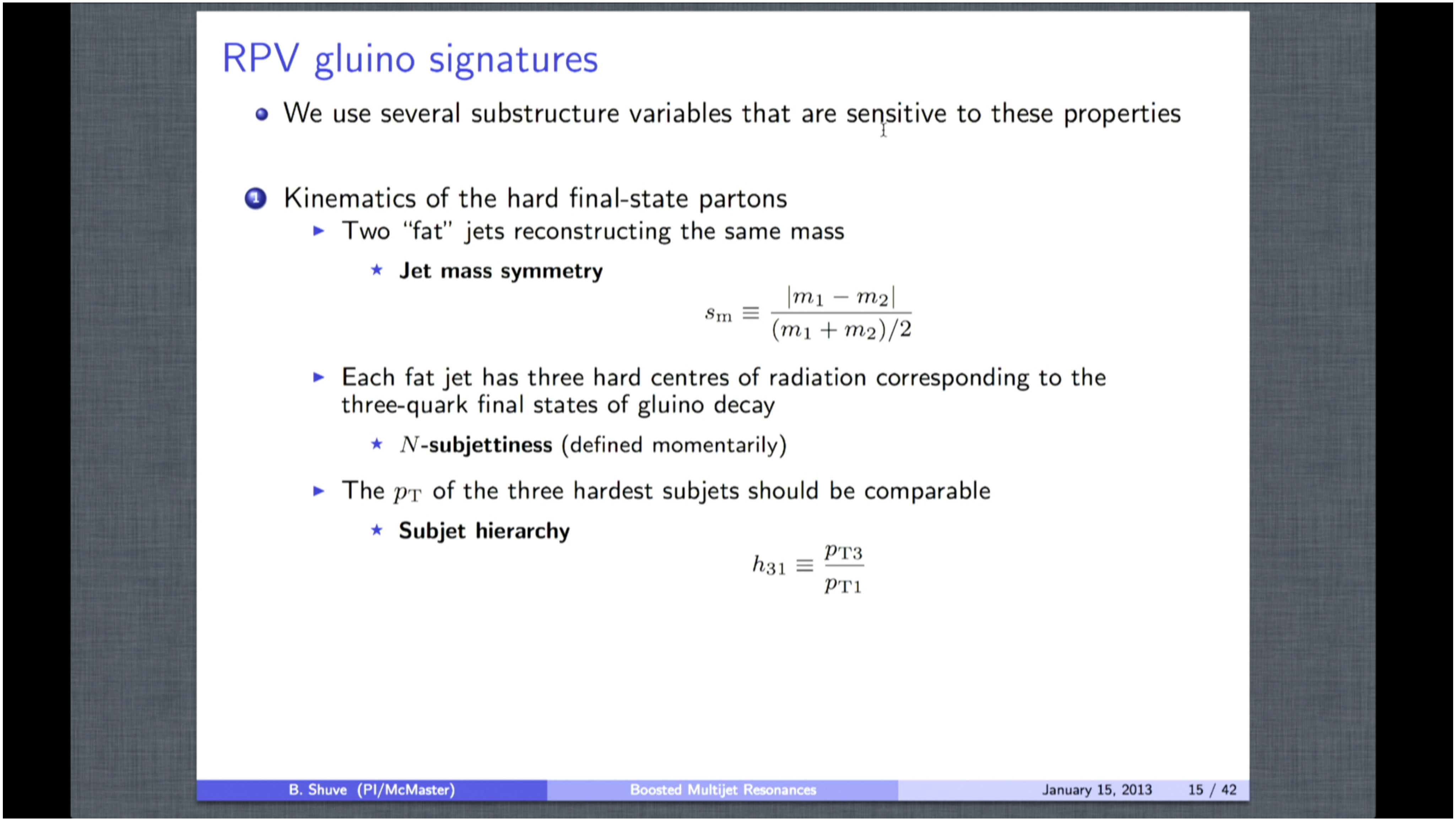
- Boosted gluino search first considered by Raklev, Salam, Wacker (arXiv:1005.1229)
  - Analysis done for the Tevatron
  - Require two hard ($p_{\mathrm{T}} > 350$ GeV) jets that are comparable in mass and exhibit some substructure (cut on merging scale y_1)
  - Find that the Tevatron exclusion reach could be as high as 280 GeV for RPV gluinos (much better than 145 GeV bound from six-jet analysis!)



RPV gluino signatures

- There are two properties of gluino decay that we exploit:

1. Kinematics of the hard final-state partons
    - Two "fat" jets reconstructing the same mass
    - Each fat jet has three hard centres of radiation corresponding to the three-quark final states of gluino decay



RPV gluino signatures

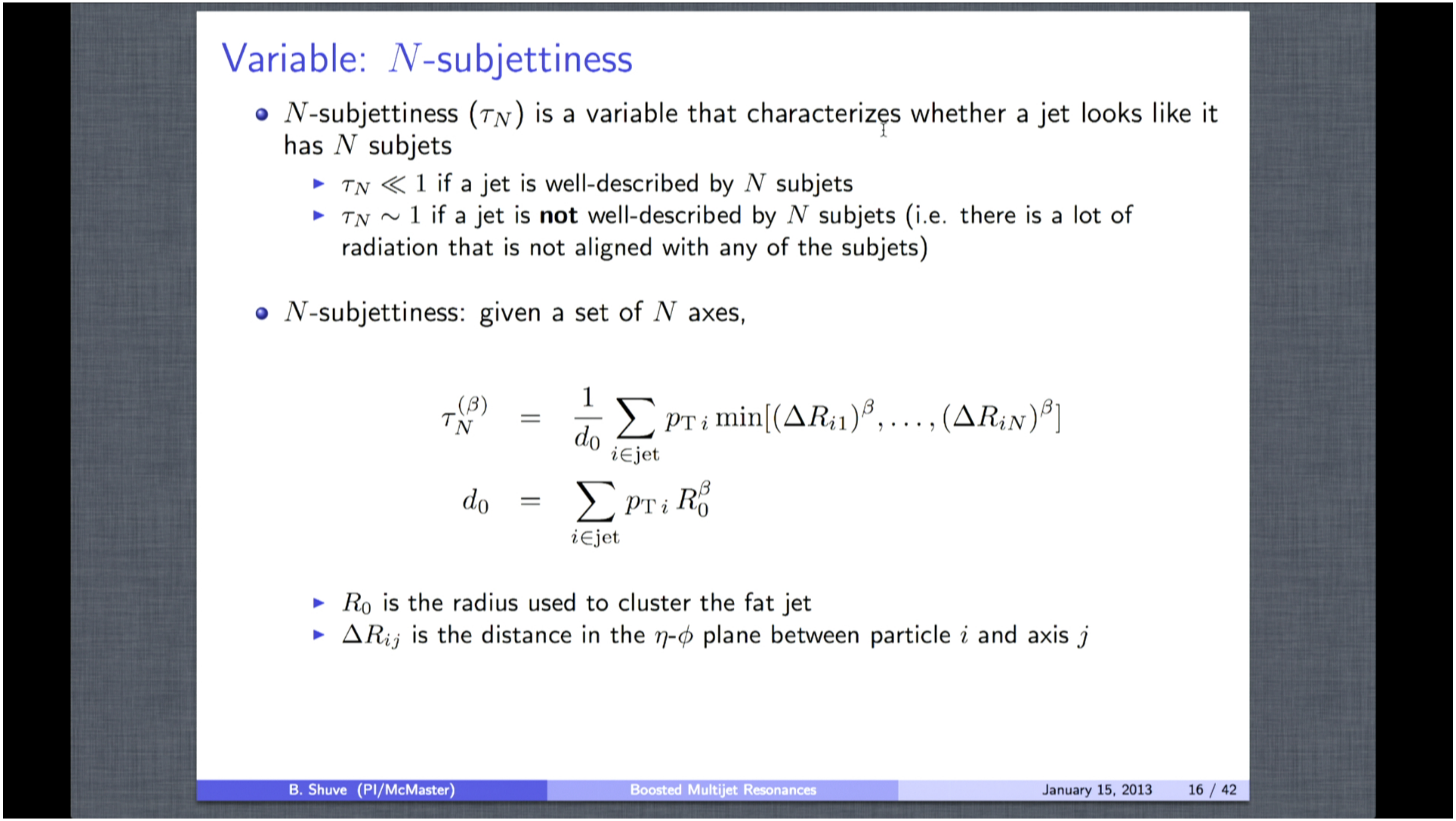
- We use several substructure variables that are sensitive to these properties

1. Kinematics of the hard final-state partons
    - Two "fat" jets reconstructing the same mass
        - ★ **Jet mass symmetry**

$$s_{\mathrm{m}} \equiv \frac{|m_1 - m_2|}{(m_1 + m_2)/2}$$

    - Each fat jet has three hard centres of radiation corresponding to the three-quark final states of gluino decay
        - ★ N-**subjettiness** (defined momentarily)
    - The p_{T} of the three hardest subjets should be comparable
        - ★ **Subjet hierarchy**

$$h_{31} \equiv \frac{p_{\mathrm{T}3}}{p_{\mathrm{T}1}}$$

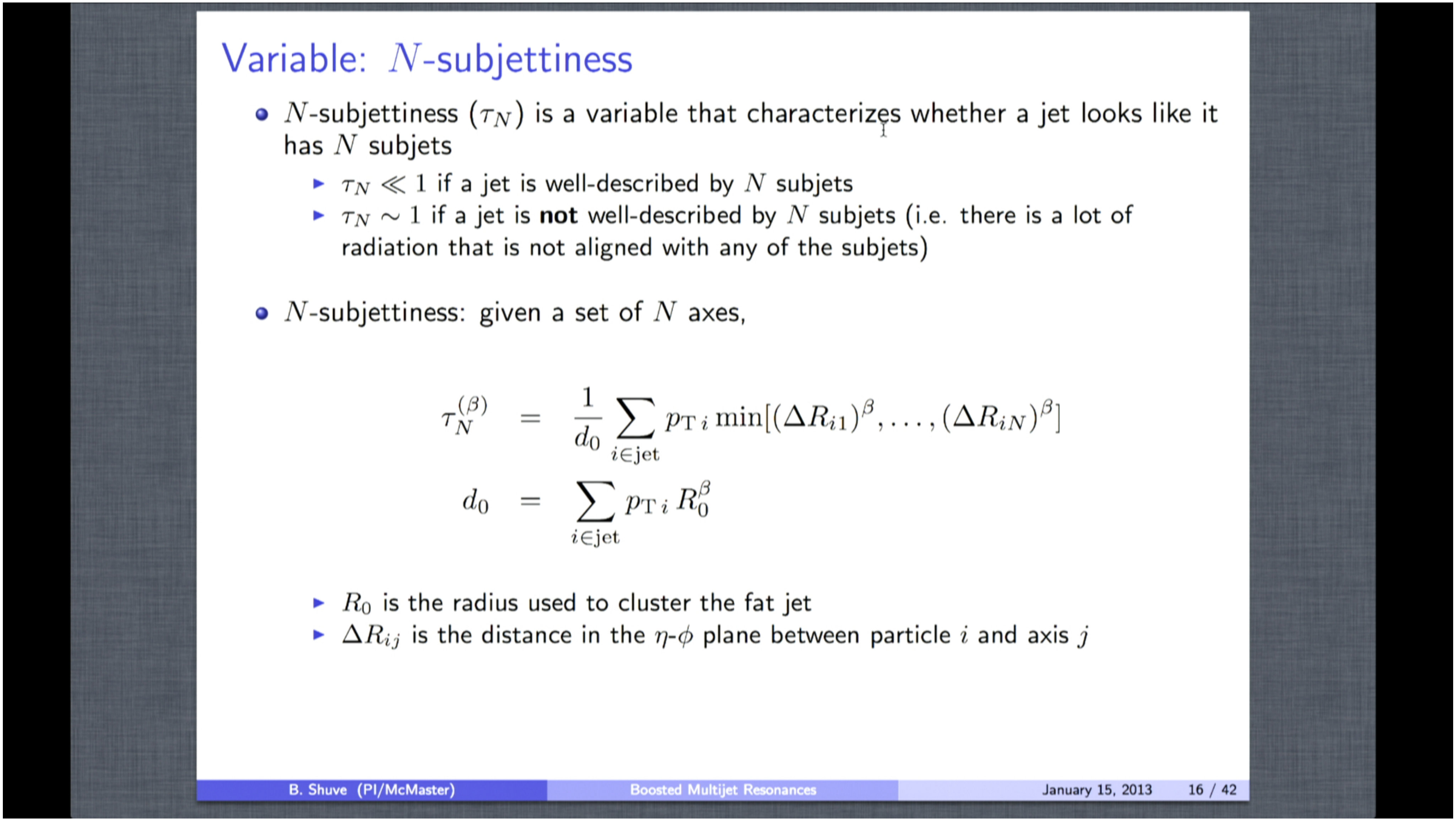


Variable: N-subjettiness

- N-subjettiness (τ_N) is a variable that characterizes whether a jet looks like it has N subjets
    - $\tau_N \ll 1$ if a jet is well-described by N subjets
    - $\tau_N \sim 1$ if a jet is **not** well-described by N subjets (i.e. there is a lot of radiation that is not aligned with any of the subjets)
- N-subjettiness: given a set of N axes,

$$\begin{aligned} \tau_N^{(\beta)} &= \frac{1}{d_0} \sum_{i \in \mathrm{jet}} p_{\mathrm{T}\,i} \min[(\Delta R_{i1})^\beta, \ldots, (\Delta R_{iN})^\beta] \\ d_0 &= \sum_{i \in \mathrm{jet}} p_{\mathrm{T}\,i}\, R_0^\beta \end{aligned}$$

-
    - R_0 is the radius used to cluster the fat jet
    - ΔR_{ij} is the distance in the η-ϕ plane between particle i and axis j



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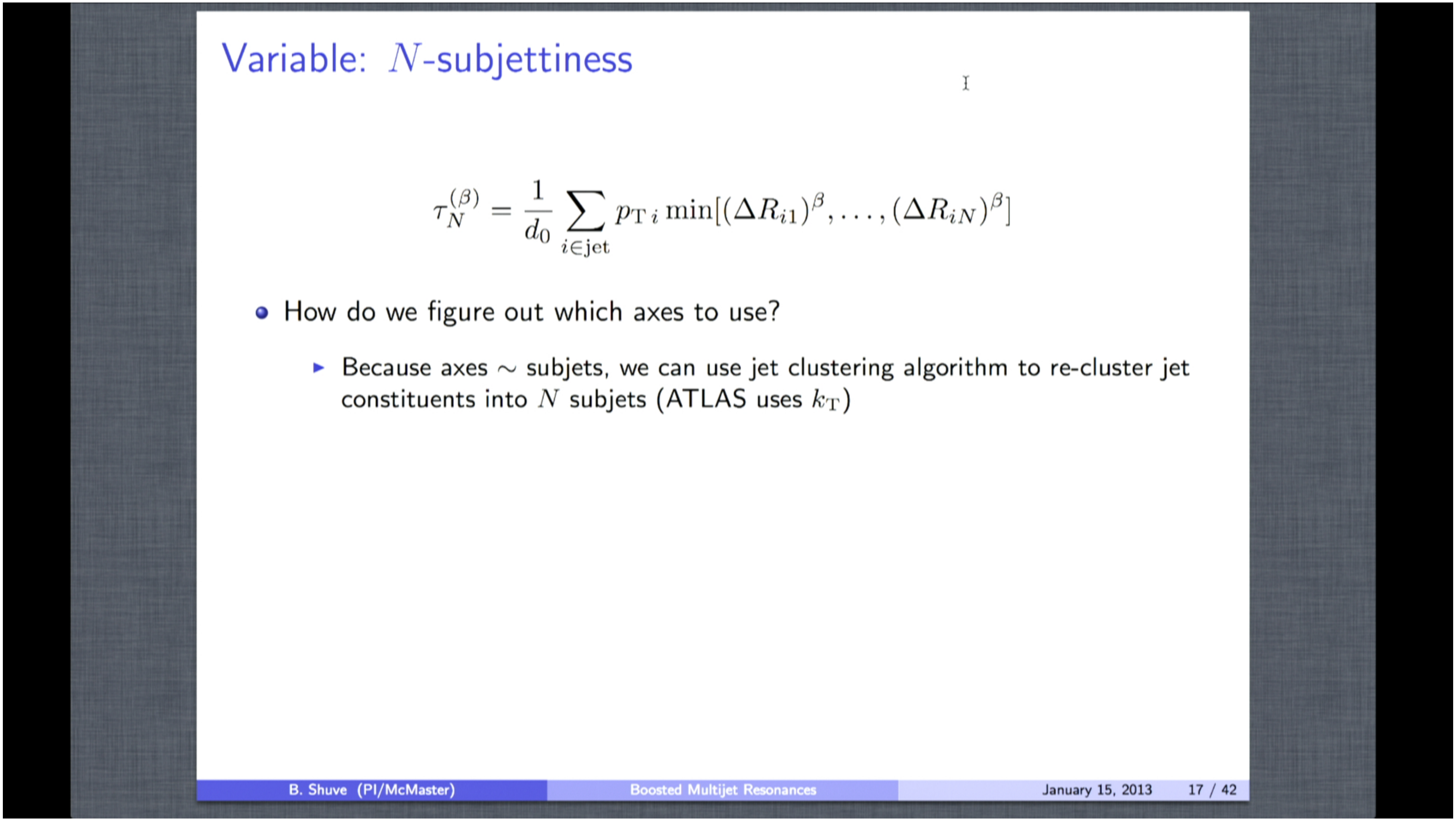

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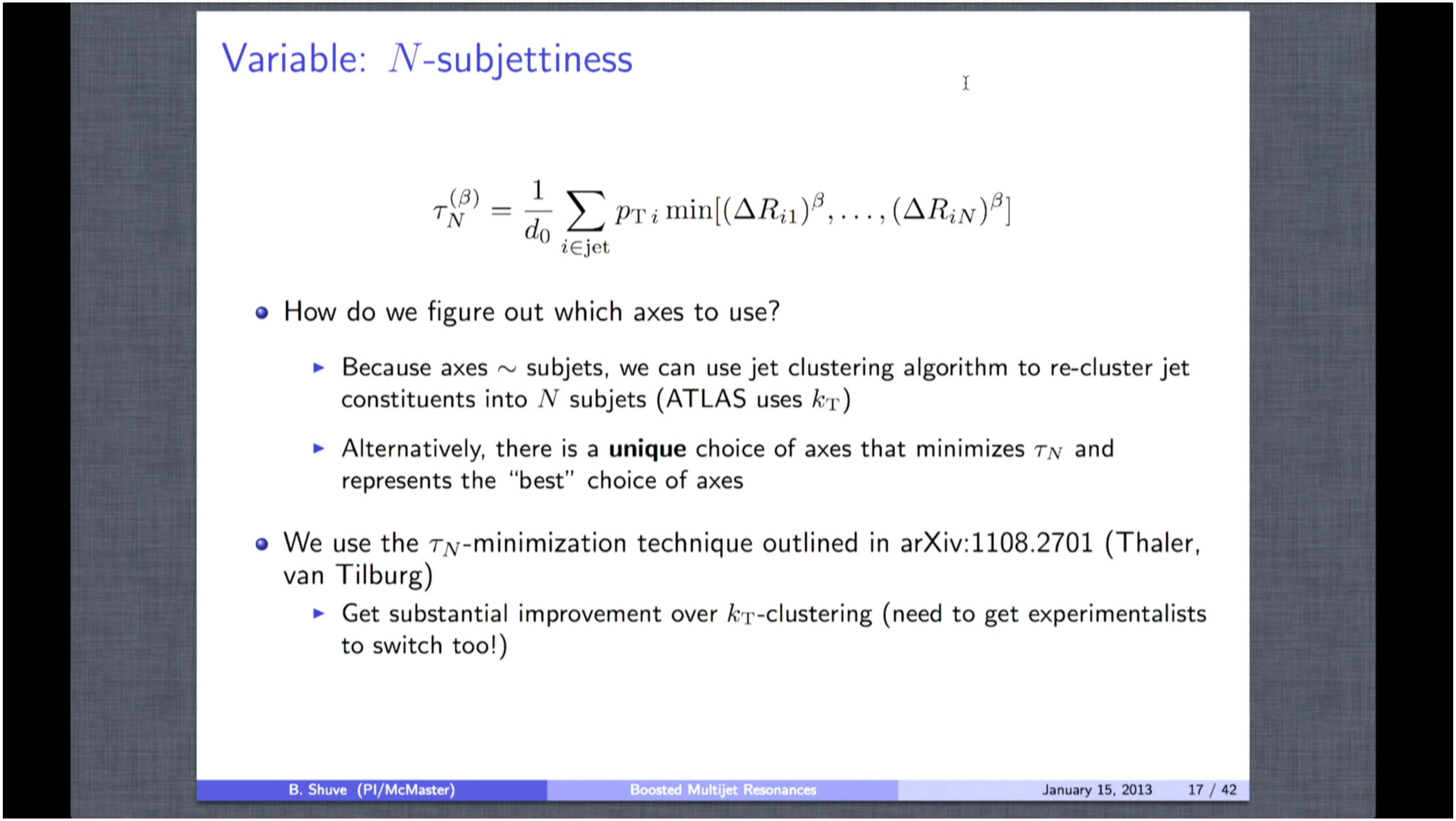
  - Because axes $\sim$ subjets, we can use jet clustering algorithm to re-cluster jet constituents into N subjets (ATLAS uses k_{T})



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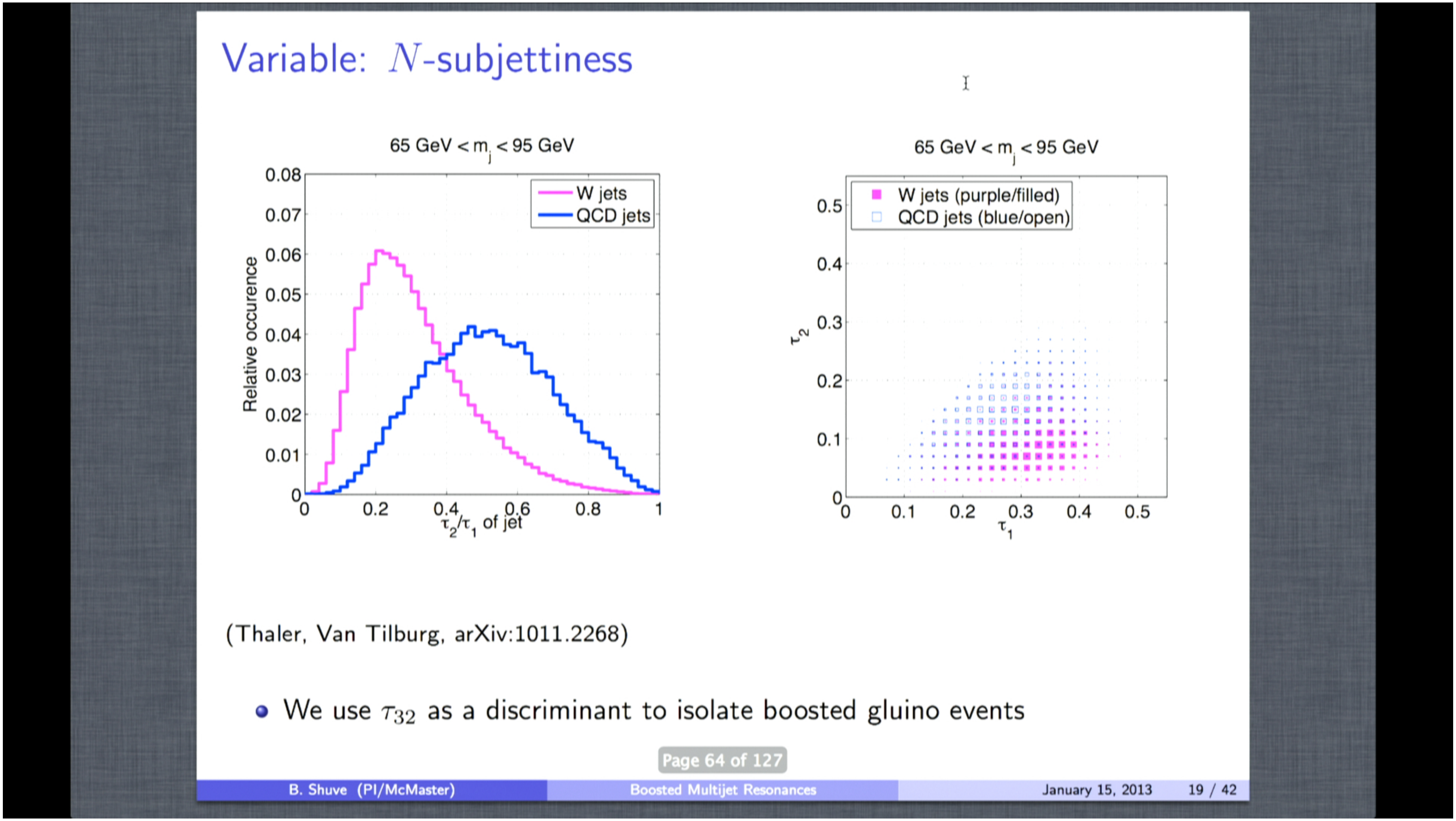
- How do we figure out which axes to use?
    - Because axes $\sim$ subjets, we can use jet clustering algorithm to re-cluster jet constituents into N subjets (ATLAS uses k_{T})
    - Alternatively, there is a **unique** choice of axes that minimizes τ_N and represents the "best" choice of axes
- We use the τ_N-minimization technique outlined in arXiv:1108.2701 (Thaler, van Tilburg)
    - Get substantial improvement over k_{T}-clustering (need to get experimentalists to switch too!)

Variable: N-subjettiness

- It turns out that it's better to look at ratios of N-subjettiness ($\tau_{N\,N-1} \equiv \tau_N/\tau_{N-1}$)
  - A sudden drop in τ_N indicates that N-subjettiness has locked onto the correct number of subjets

  - Crosses: 1-subjettiness axes, circles: 2-subjettiness axes
  - Left: schematic of signal event (hadronic W decay), right: schematic of QCD fat jet



Variable: N-subjettiness

(Thaler, Van Tilburg, arXiv:1011.2268)

- We use τ_{32} as a discriminant to isolate boosted gluino events

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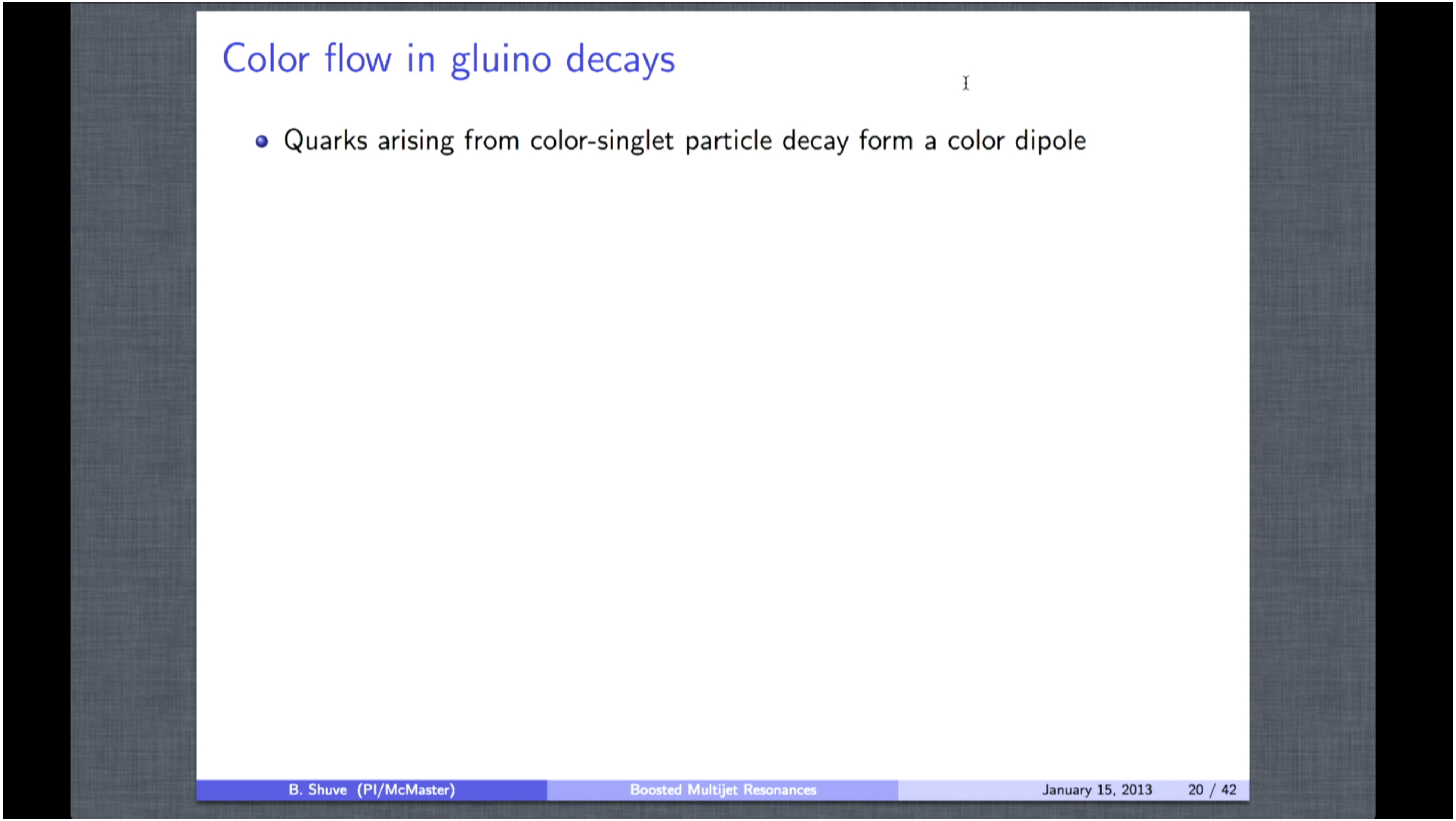
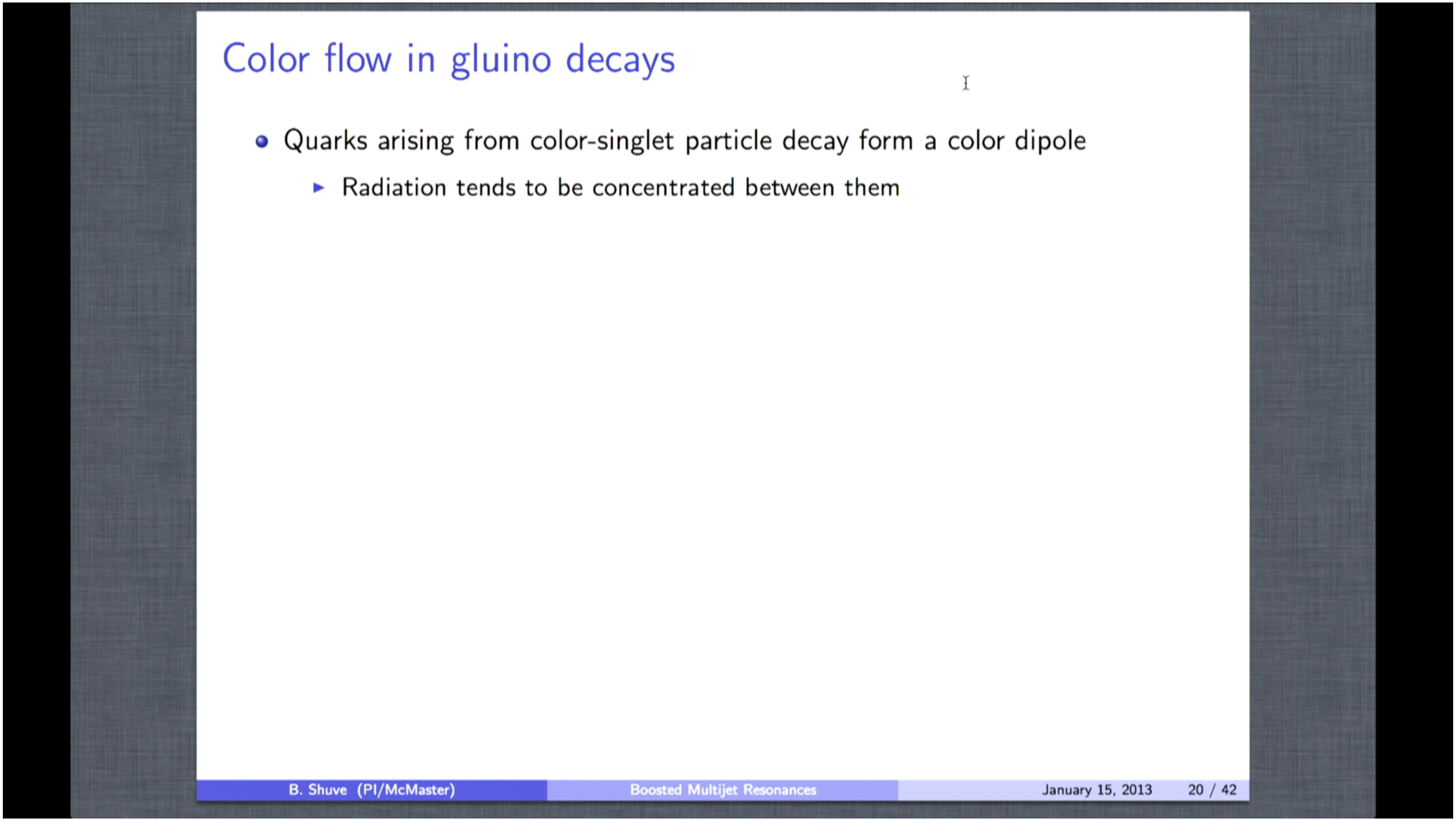


Color flow in gluino decays

- Quarks arising from color-singlet particle decay form a color dipole



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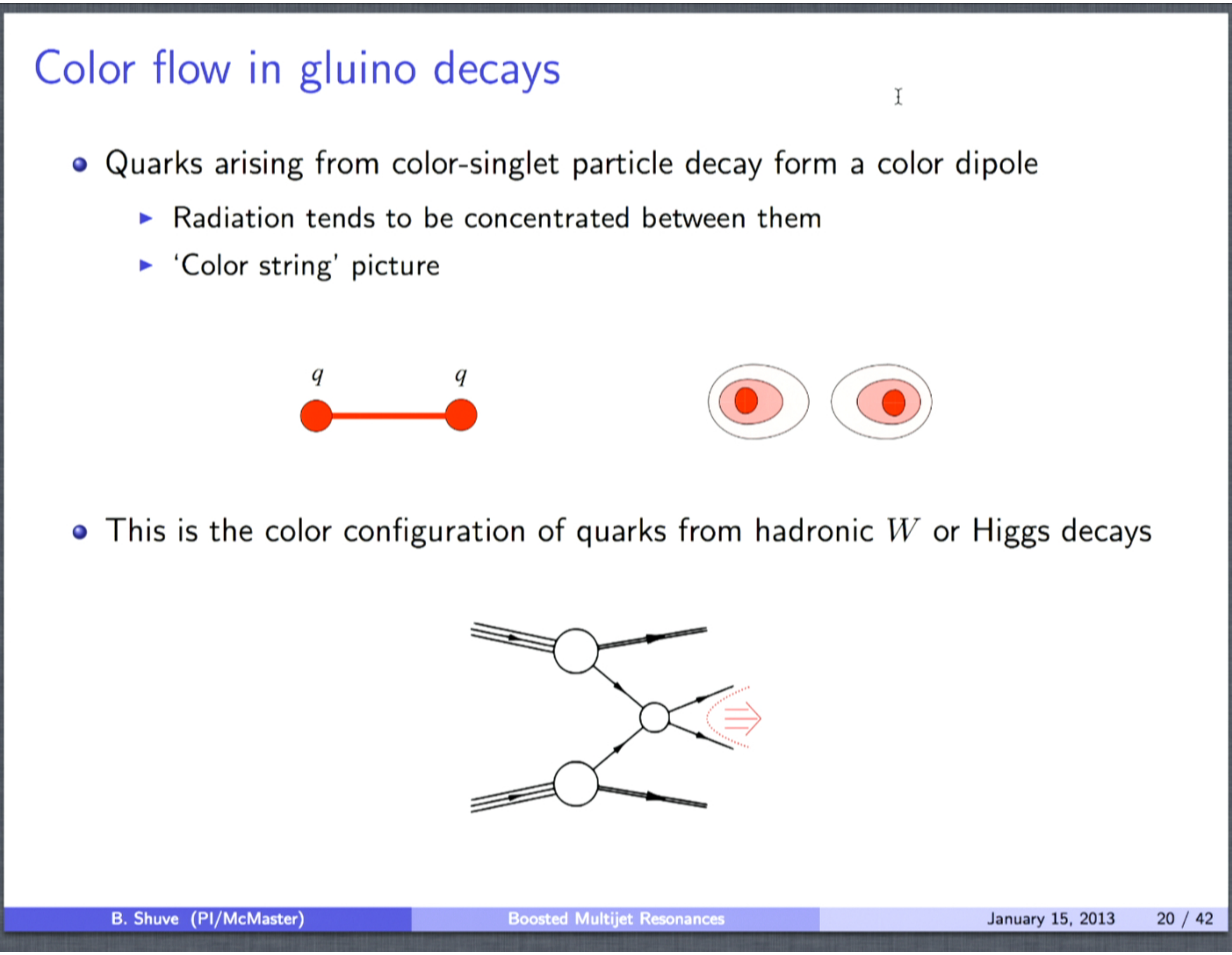
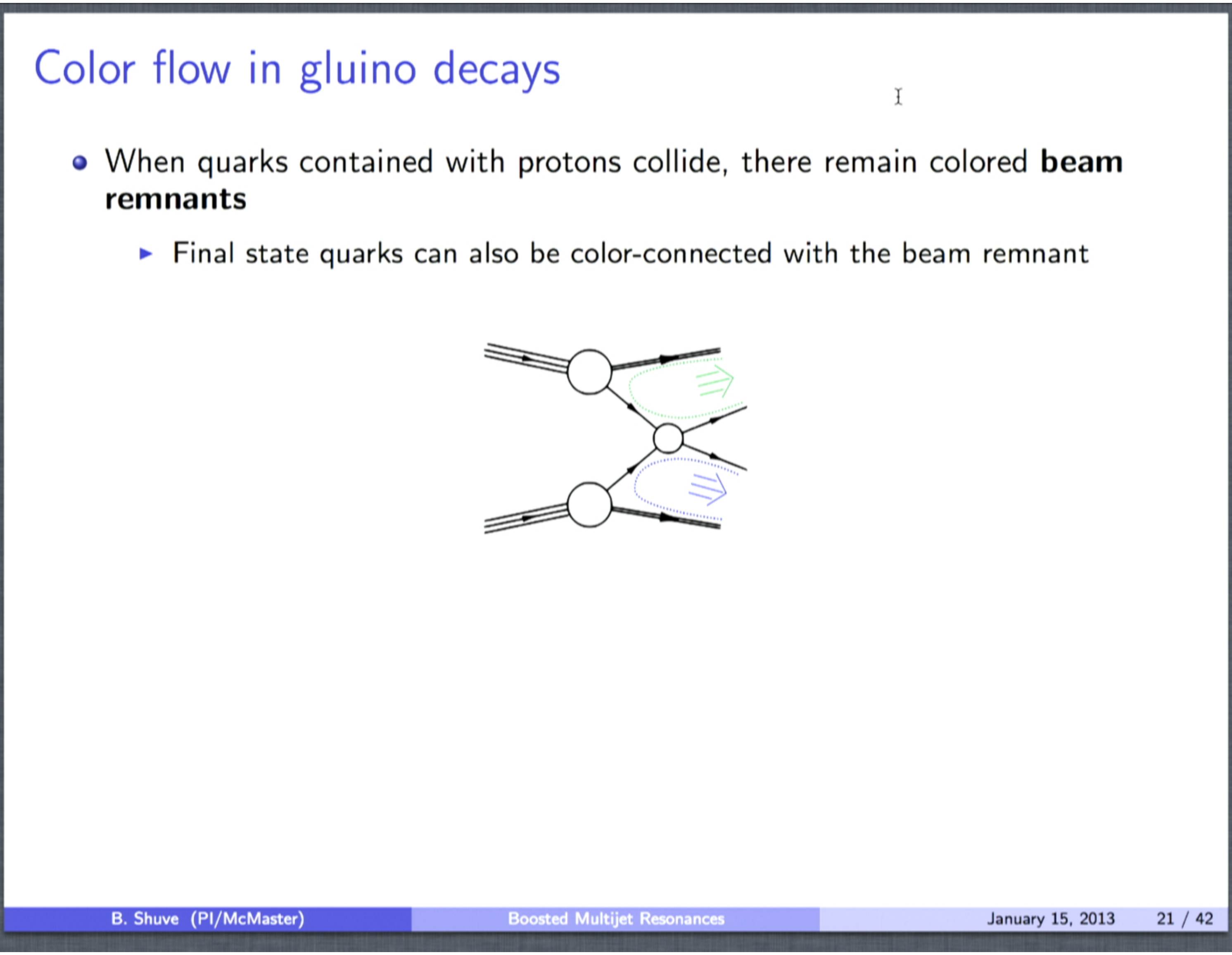
    - Radiation tends to be concentrated between them
    - 'Color string' picture



Color flow in gluino decays

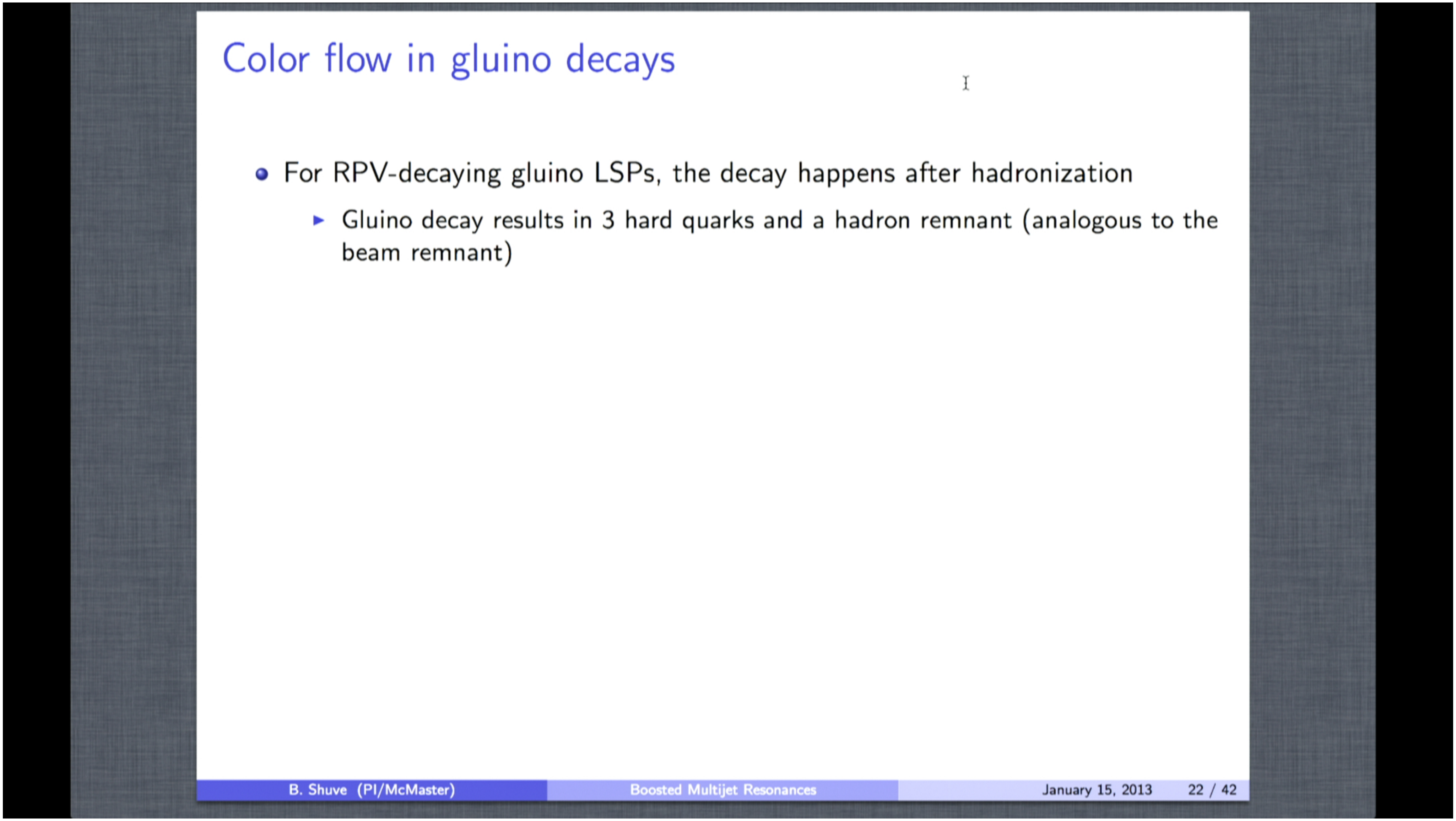
- Quarks arising from color-singlet particle decay form a color dipole
  - Radiation tends to be concentrated between them
  - ‘Color string’ picture

- This is the color configuration of quarks from hadronic W or Higgs decays



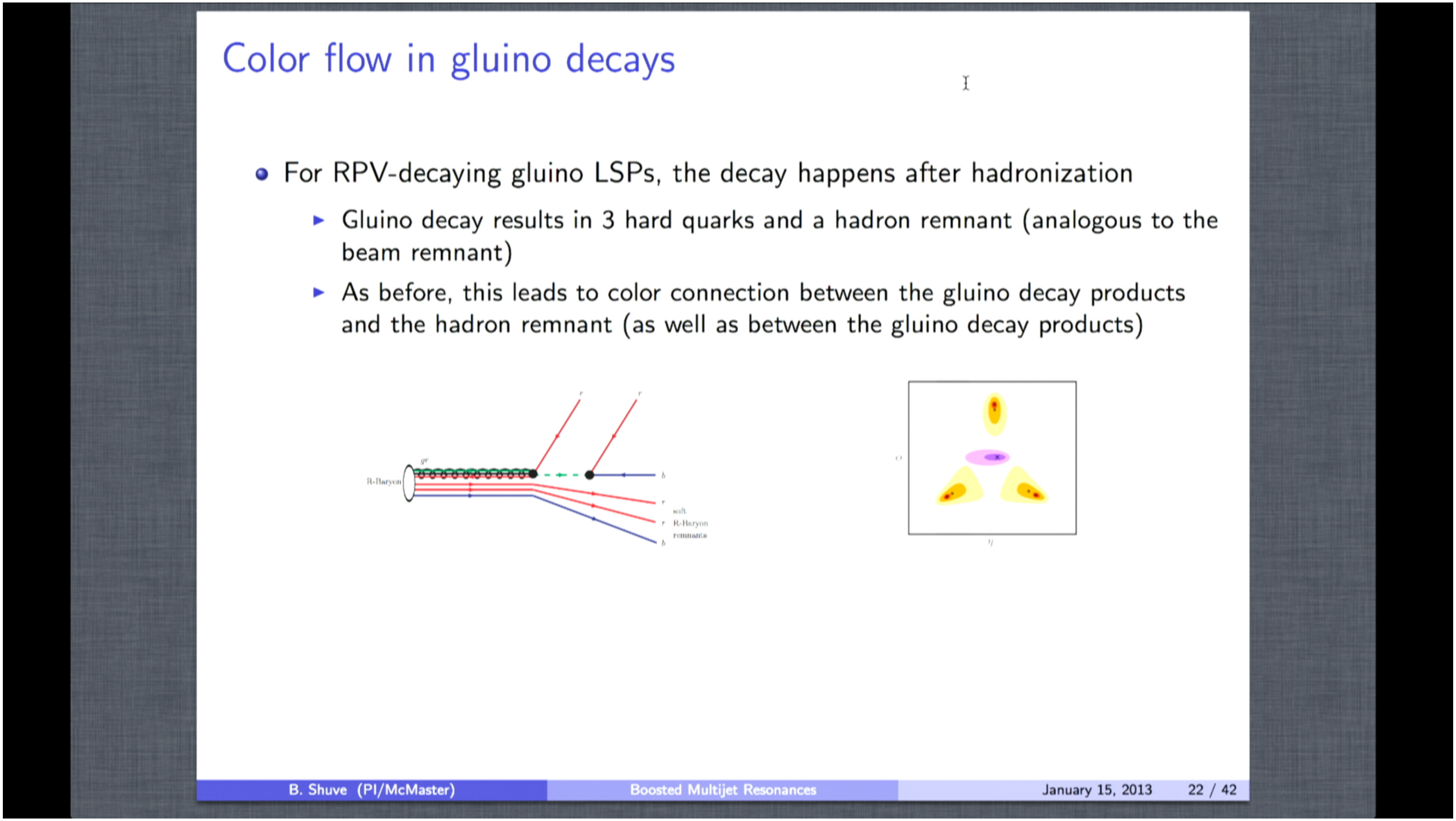
Color flow in gluino decays

- When quarks contained with protons collide, there remain colored **beam remnants**
  - Final state quarks can also be color-connected with the beam remnant



Color flow in gluino decays

- For RPV-decaying gluino LSPs, the decay happens after hadronization
  - Gluino decay results in 3 hard quarks and a hadron remnant (analogous to the beam remnant)



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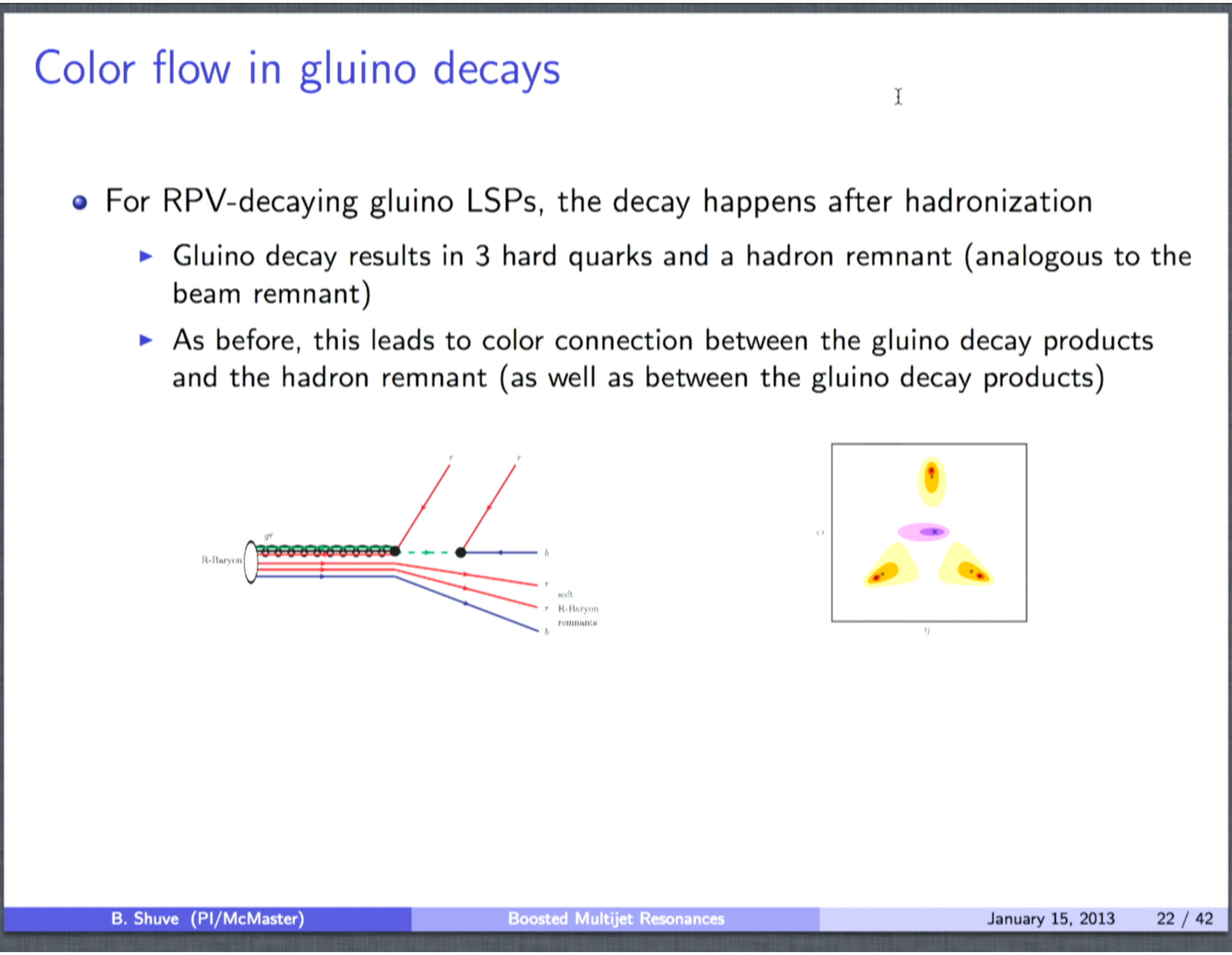

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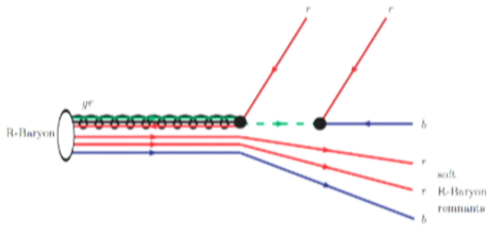
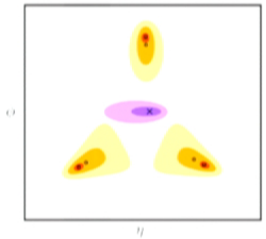
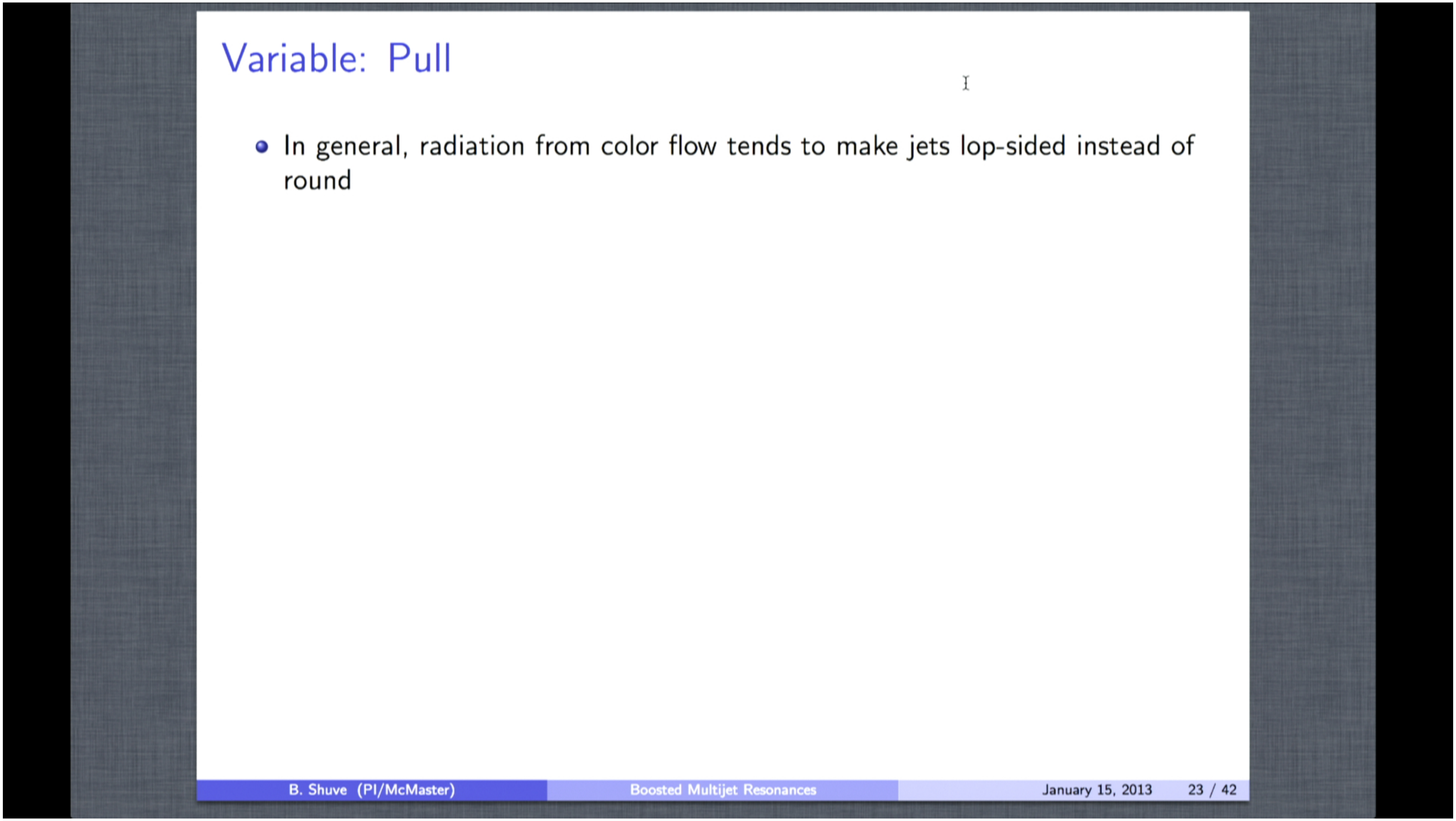
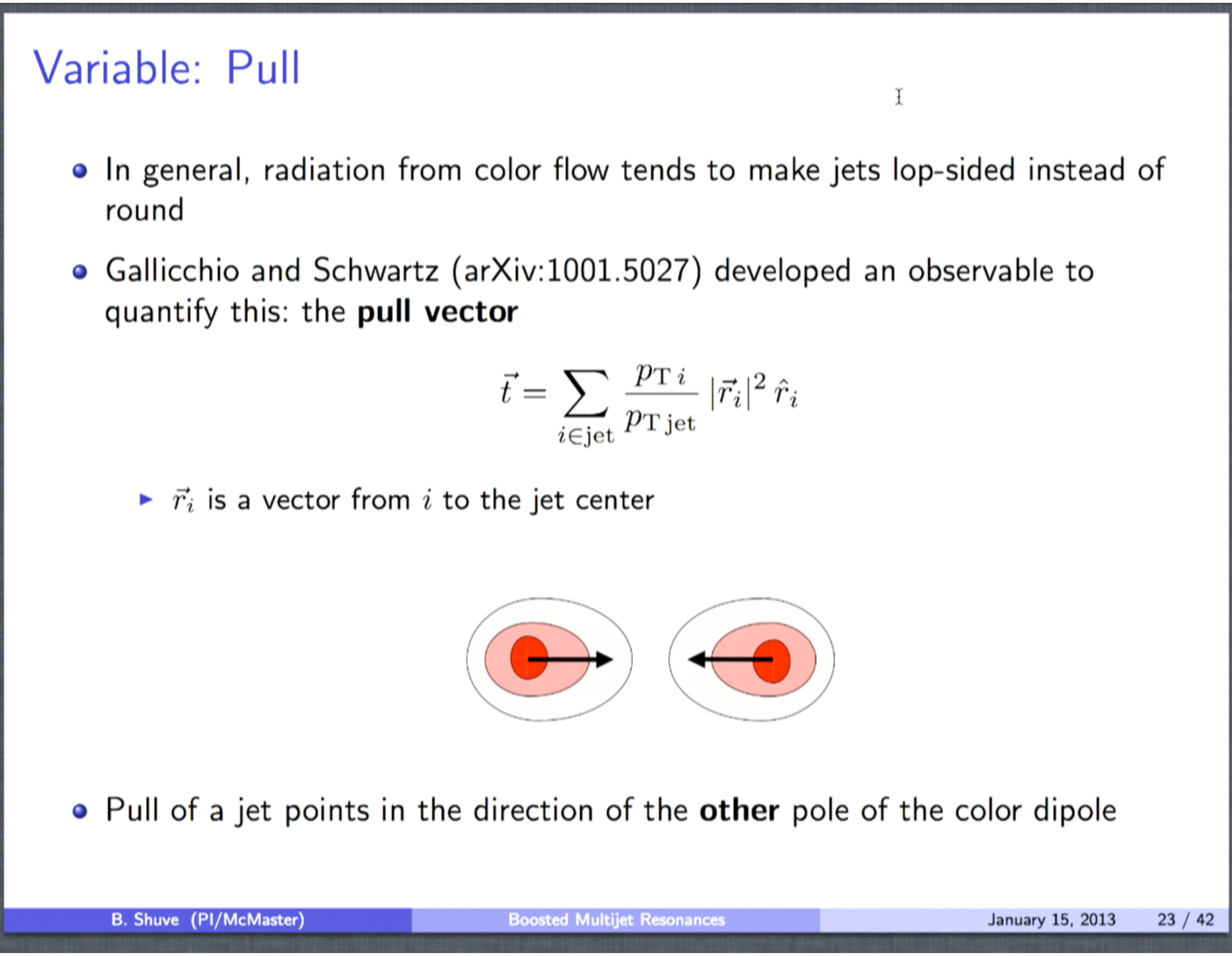






Variable: Pull

- In general, radiation from color flow tends to make jets lop-sided instead of round



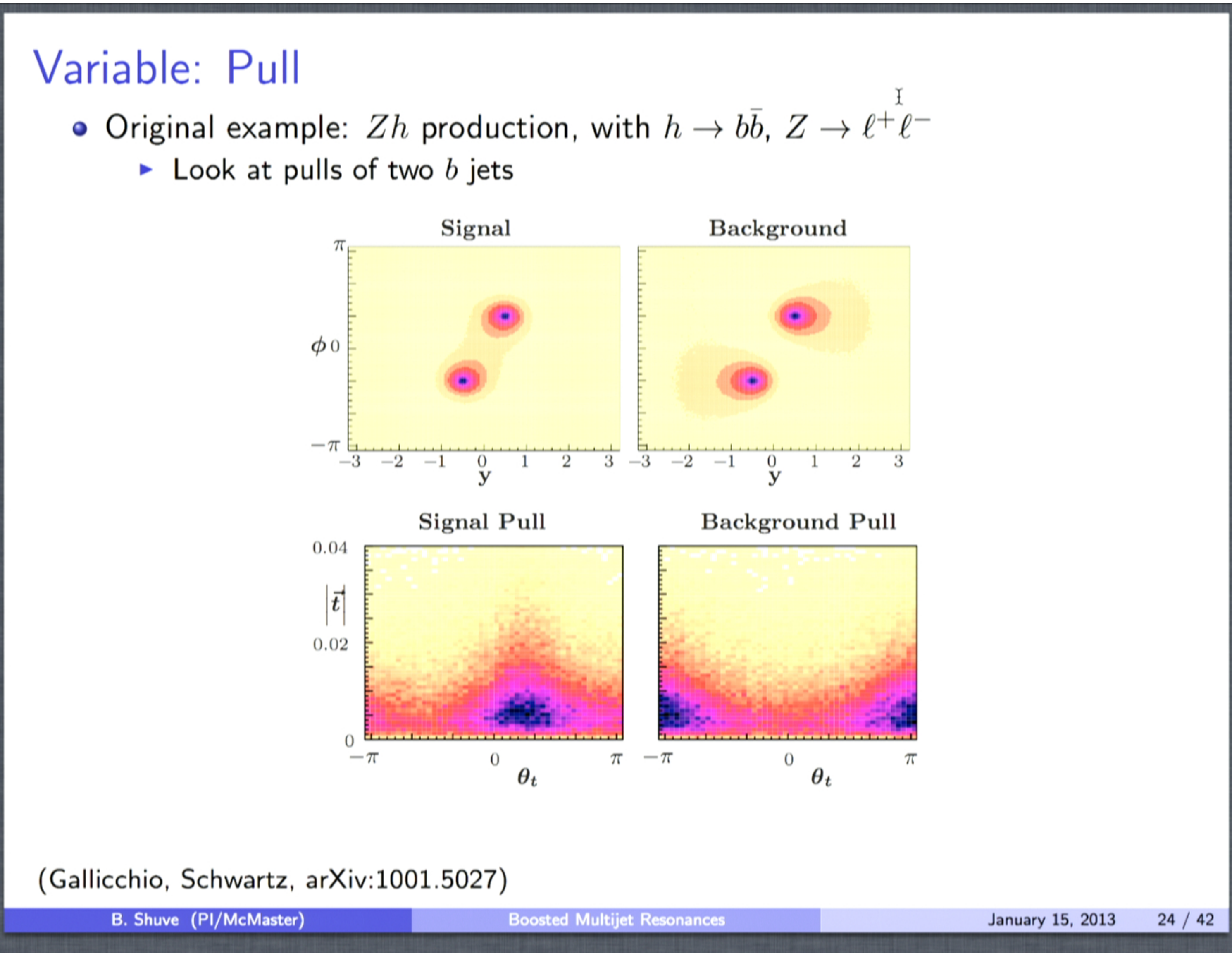
Variable: Pull

- In general, radiation from color flow tends to make jets lop-sided instead of round
- Gallicchio and Schwartz (arXiv:1001.5027) developed an observable to quantify this: the **pull vector**

$$\vec{t} = \sum_{i \in \mathrm{jet}} \frac{p_{\mathrm{T}\,i}}{p_{\mathrm{T\,jet}}} \, |\vec{r}_i|^2 \, \hat{r}_i$$

  - $\vec{r}_i$ is a vector from i to the jet center

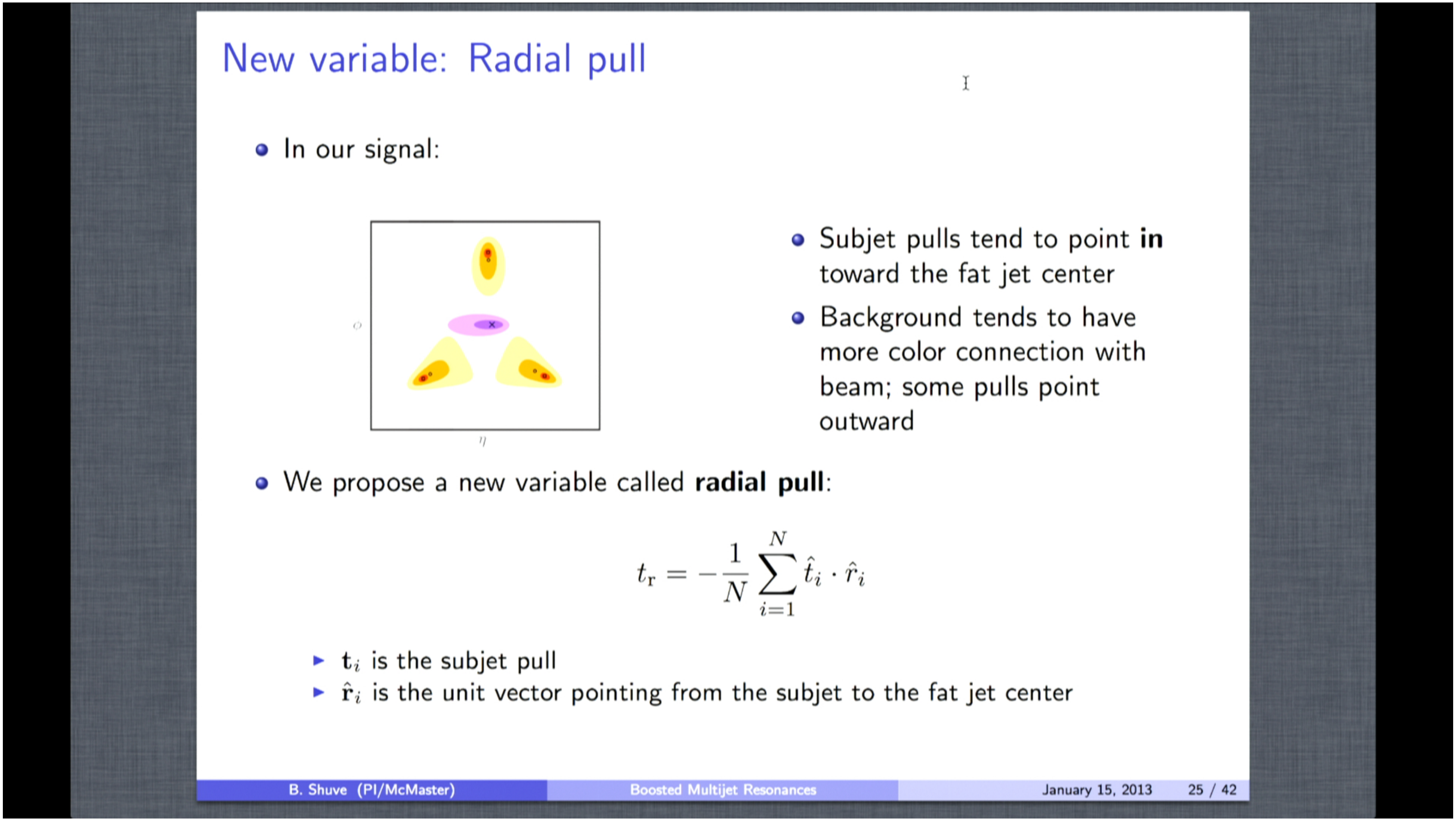
- Pull of a jet points in the direction of the **other** pole of the color dipole



Variable: Pull

- Original example: Zh production, with $h \to b\bar{b}$, $Z \to \ell^+\ell^-$
  - Look at pulls of two b jets

(Gallicchio, Schwartz, arXiv:1001.5027)

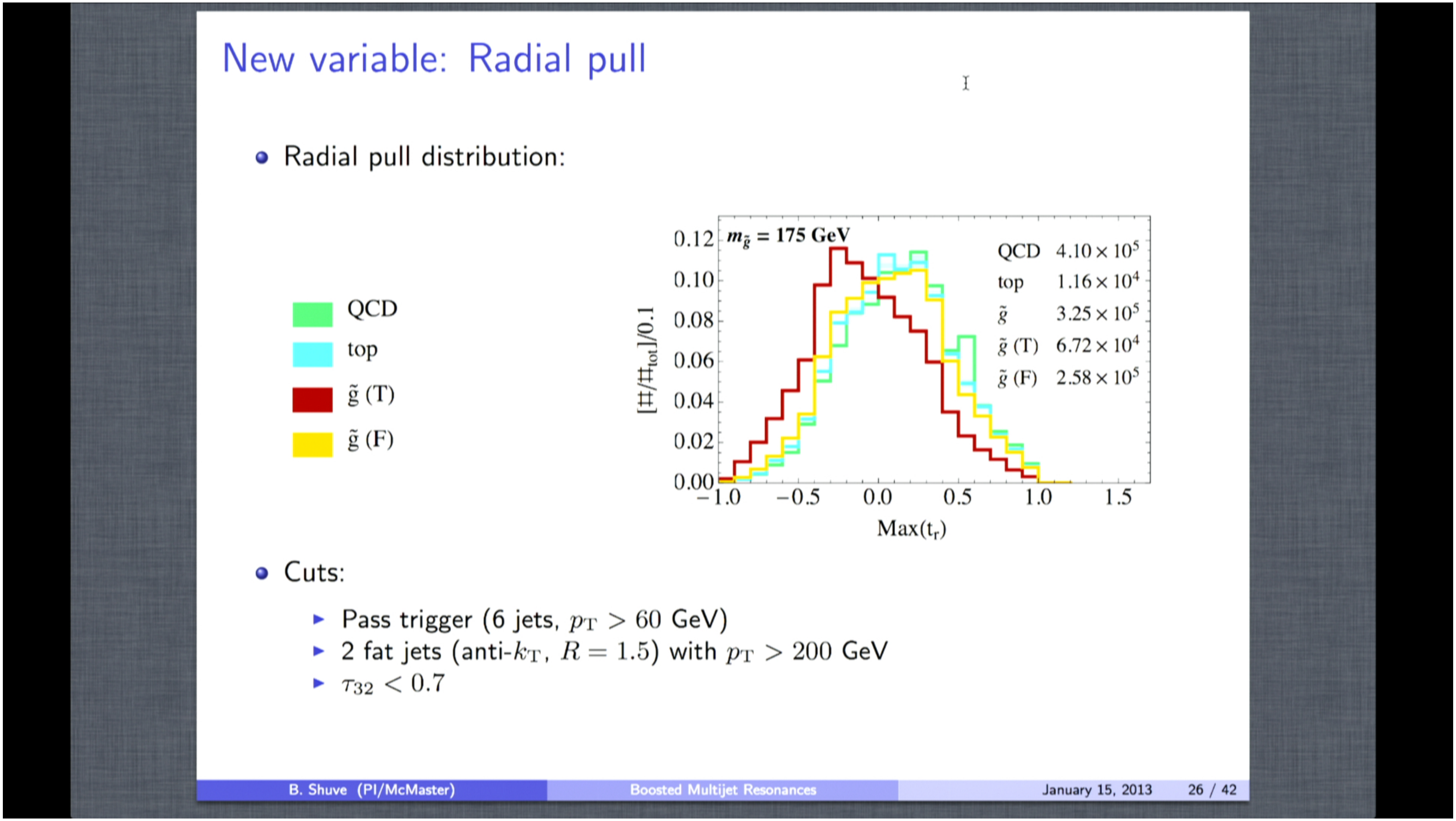


New variable: Radial pull

- In our signal:
  - Subjet pulls tend to point **in** toward the fat jet center
  - Background tends to have more color connection with beam; some pulls point outward
- We propose a new variable called **radial pull**:

$$t_{\rm r} = -\frac{1}{N}\sum_{i=1}^{N}\hat{t}_i \cdot \hat{r}_i$$

  - $\mathbf{t}_i$ is the subjet pull
  - $\hat{\mathbf{r}}_i$ is the unit vector pointing from the subjet to the fat jet center

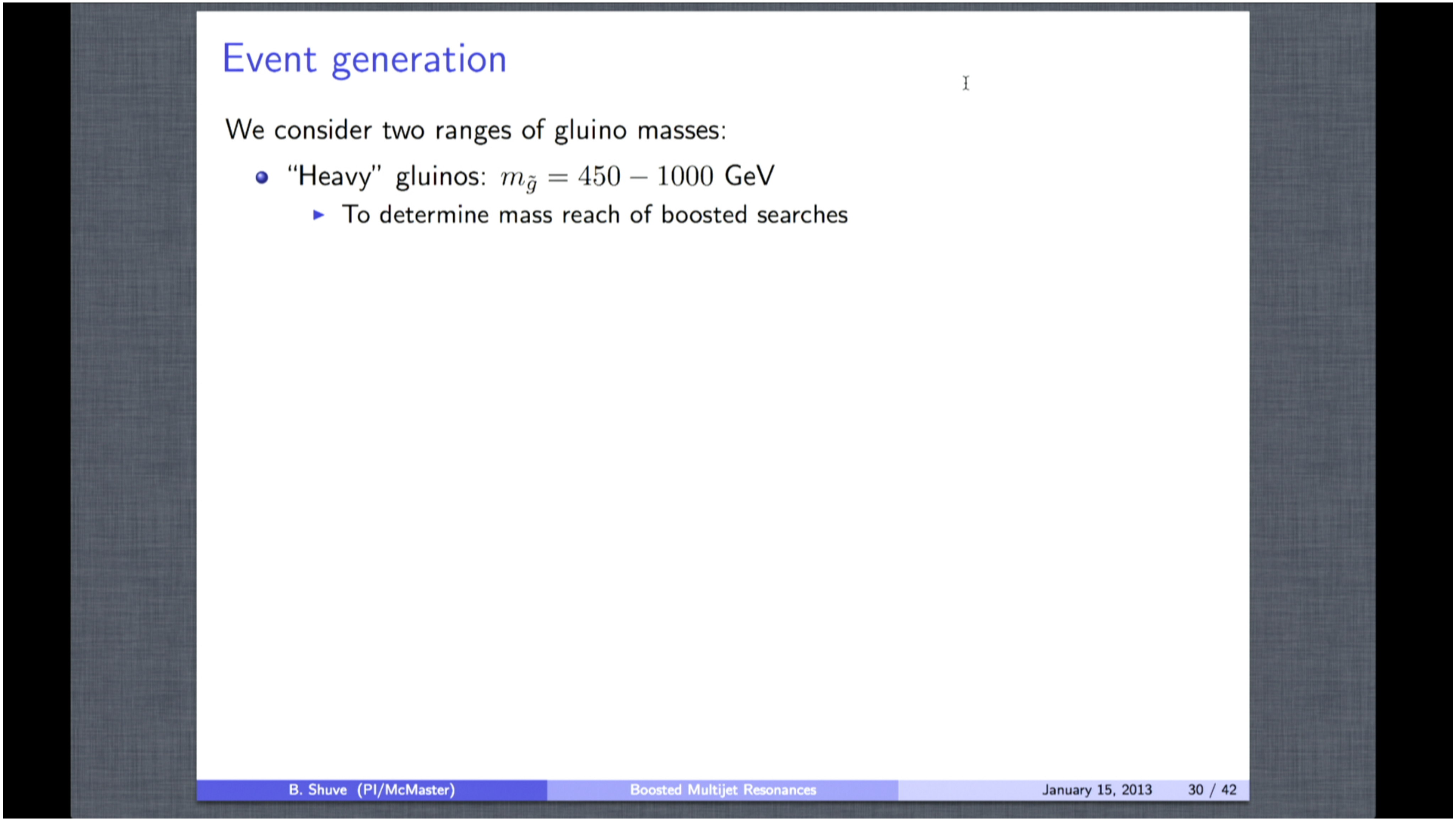


New variable: Radial pull

- Radial pull distribution:

🟩 QCD
🟦 top
🟥 $\tilde{g}$ (T)
🟨 $\tilde{g}$ (F)

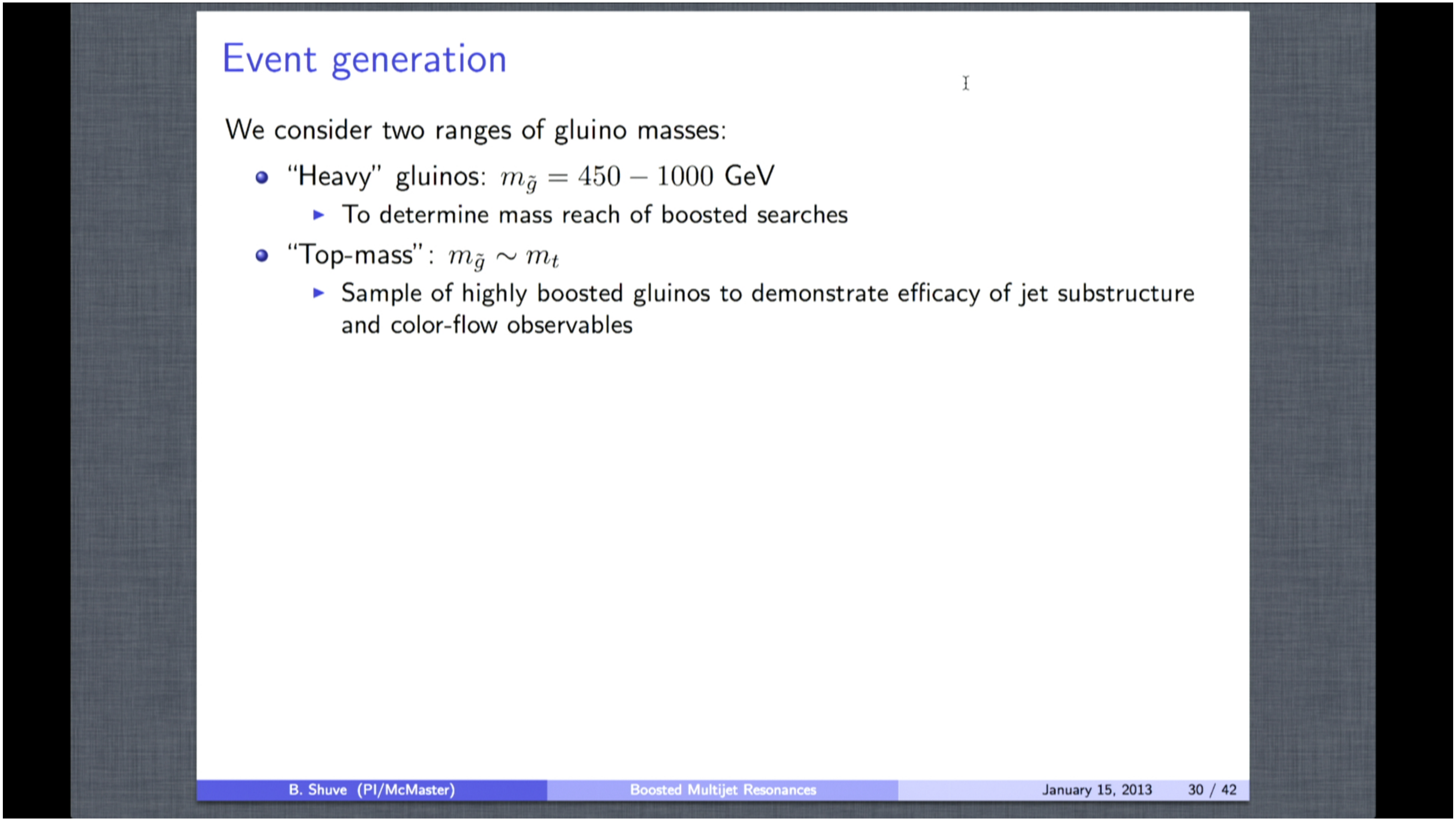
- Cuts:
  - Pass trigger (6 jets, $p_{\mathrm{T}} > 60$ GeV)
  - 2 fat jets (anti-k_{T}, $R = 1.5$) with $p_{\mathrm{T}} > 200$ GeV
  - $\tau_{32} < 0.7$



Event generation

We consider two ranges of gluino masses:

- "Heavy" gluinos: $m_{\tilde{g}} = 450 - 1000$ GeV
  - To determine mass reach of boosted searches



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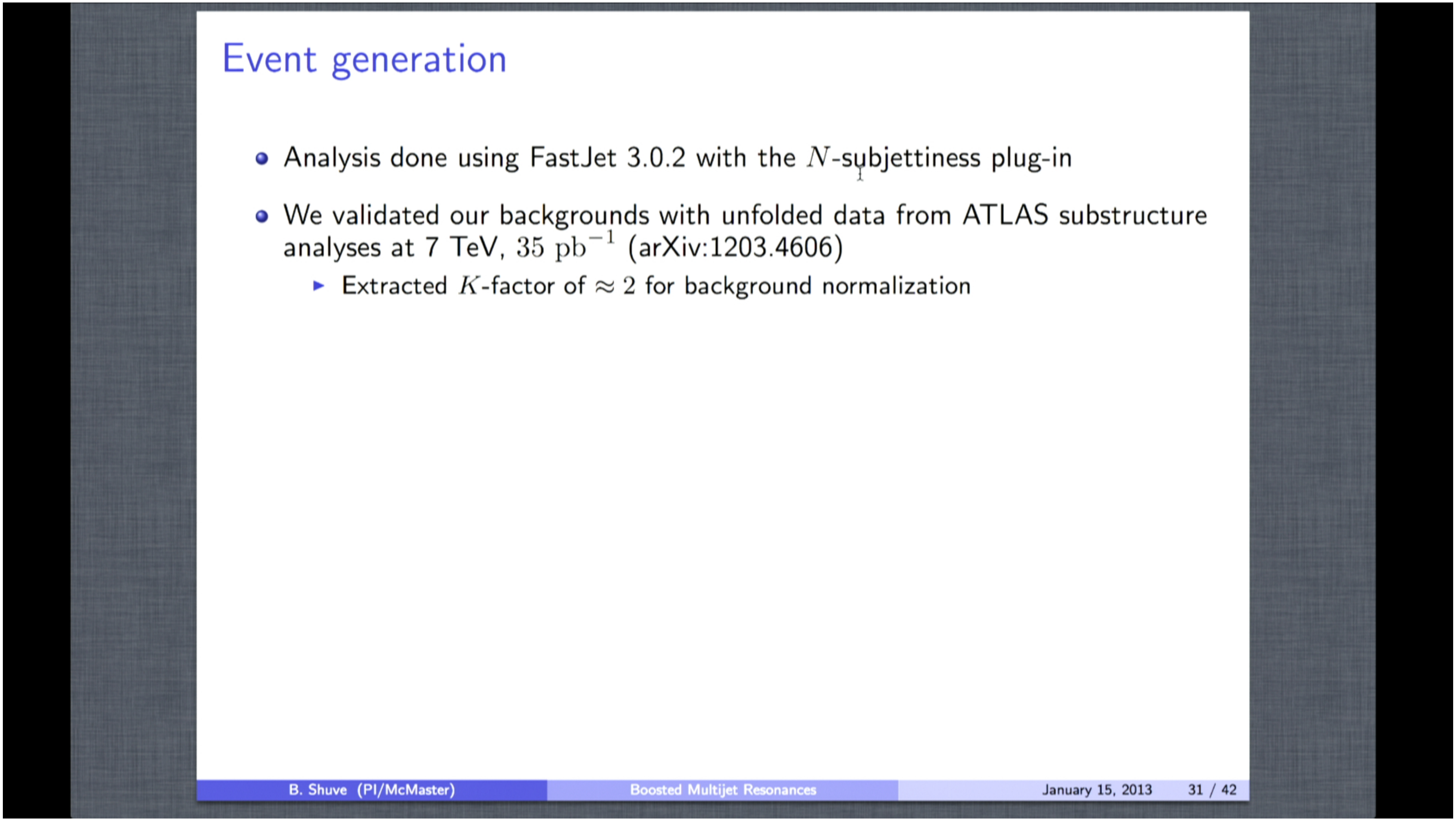
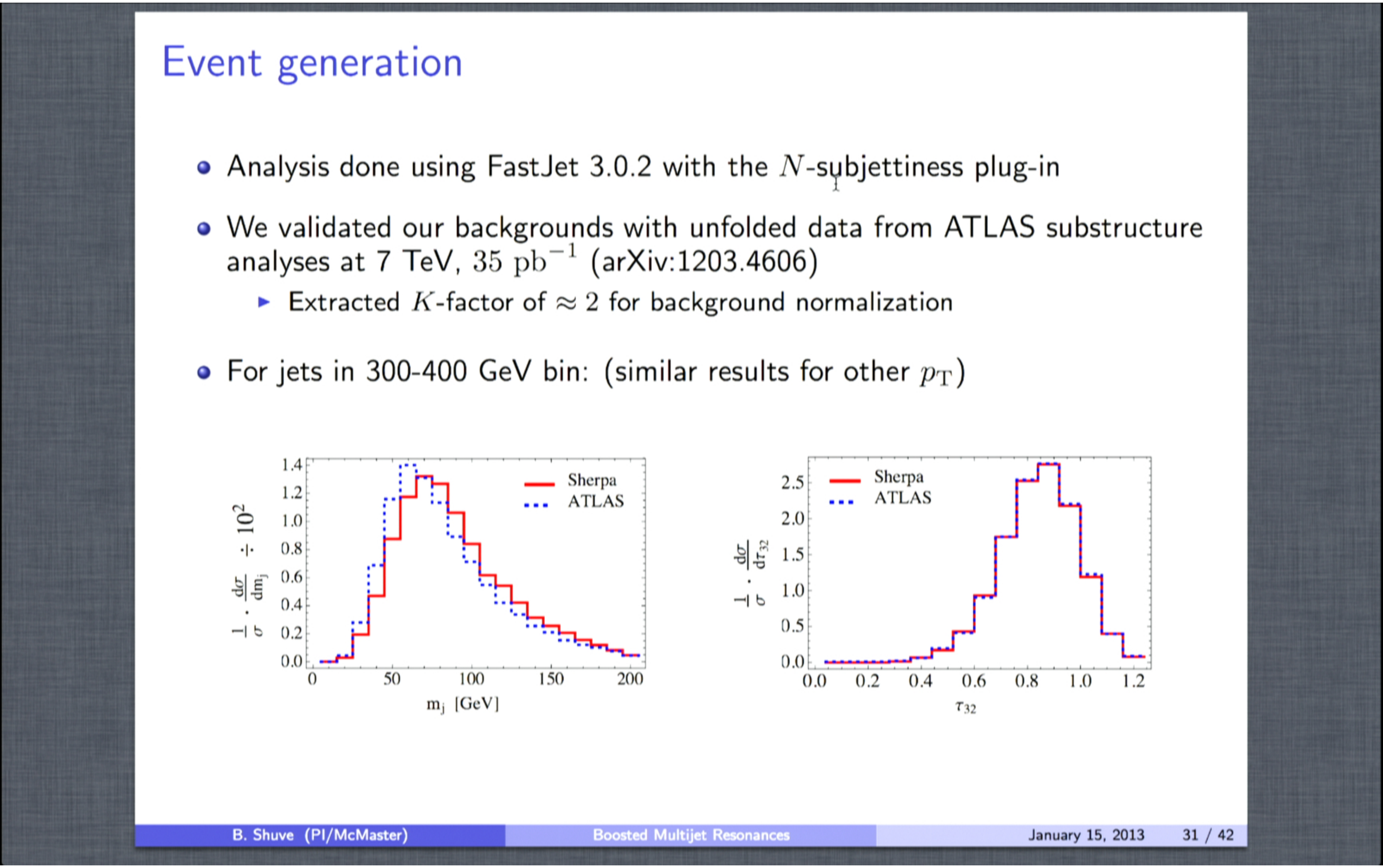
- "Top-mass": $m_{\tilde{g}} \sim m_t$
  - Sample of highly boosted gluinos to demonstrate efficacy of jet substructure and color-flow observables



Event generation

- Analysis done using FastJet 3.0.2 with the N-subjettiness plug-in
- We validated our backgrounds with unfolded data from ATLAS substructure analyses at 7 TeV, $35\ \mathrm{pb}^{-1}$ (arXiv:1203.4606)
  - Extracted K-factor of ≈ 2 for background normalization



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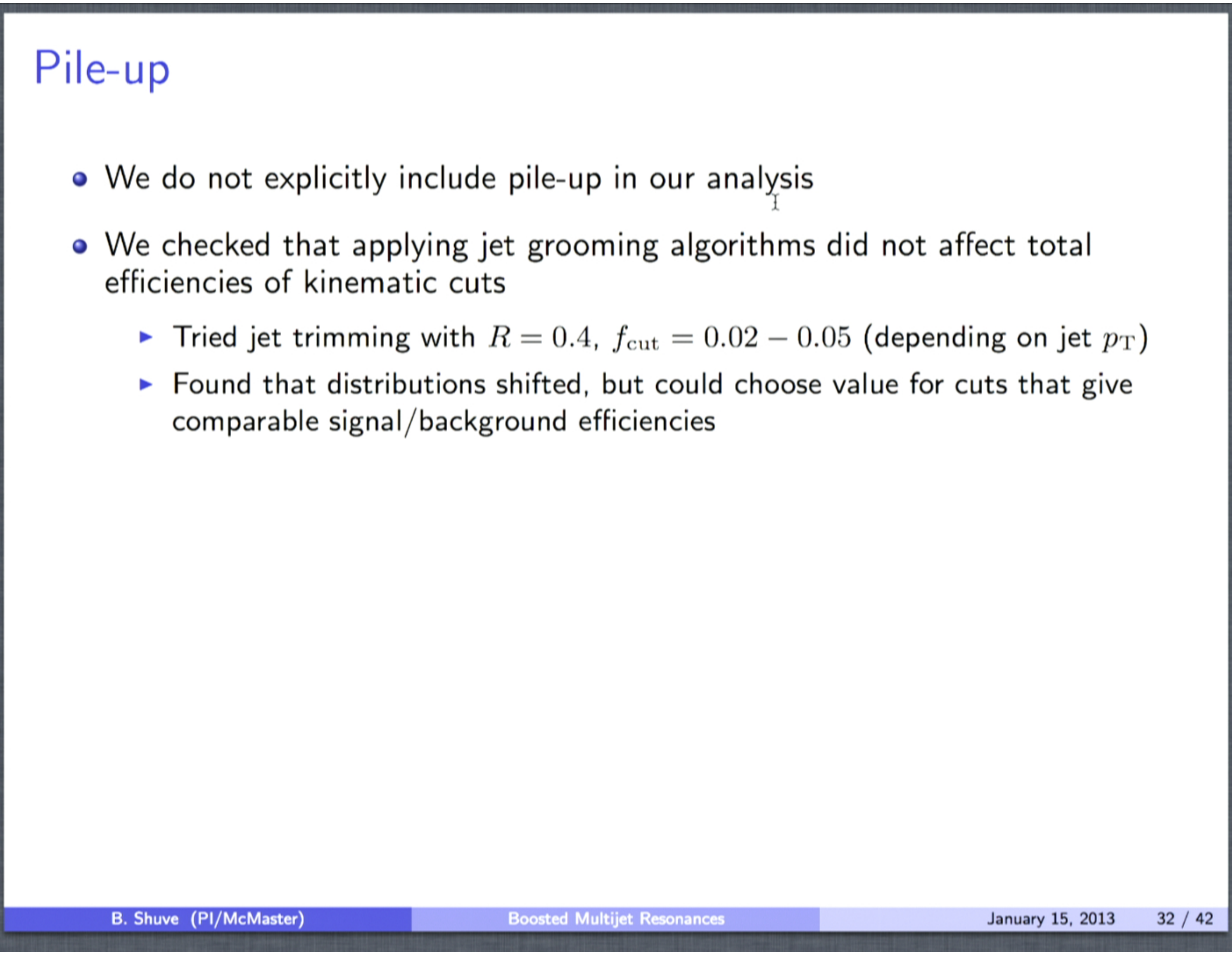
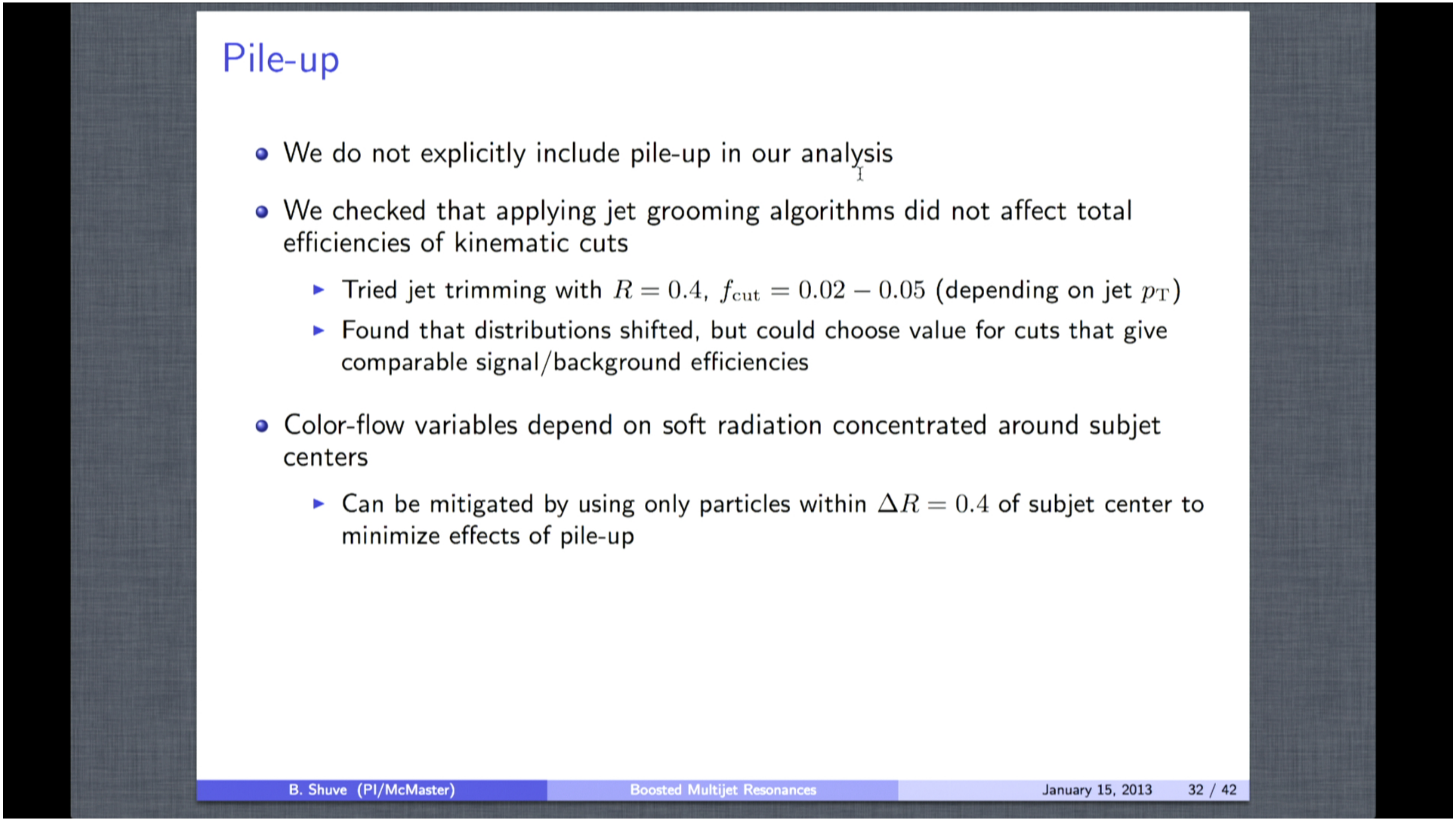
- For jets in 300-400 GeV bin: (similar results for other p_T)



Pile-up

- We do not explicitly include pile-up in our analysis
- We checked that applying jet grooming algorithms did not affect total efficiencies of kinematic cuts
  - Tried jet trimming with $R = 0.4$, $f_{\rm cut} = 0.02 - 0.05$ (depending on jet $p_{\rm T}$)
  - Found that distributions shifted, but could choose value for cuts that give comparable signal/background efficiencies



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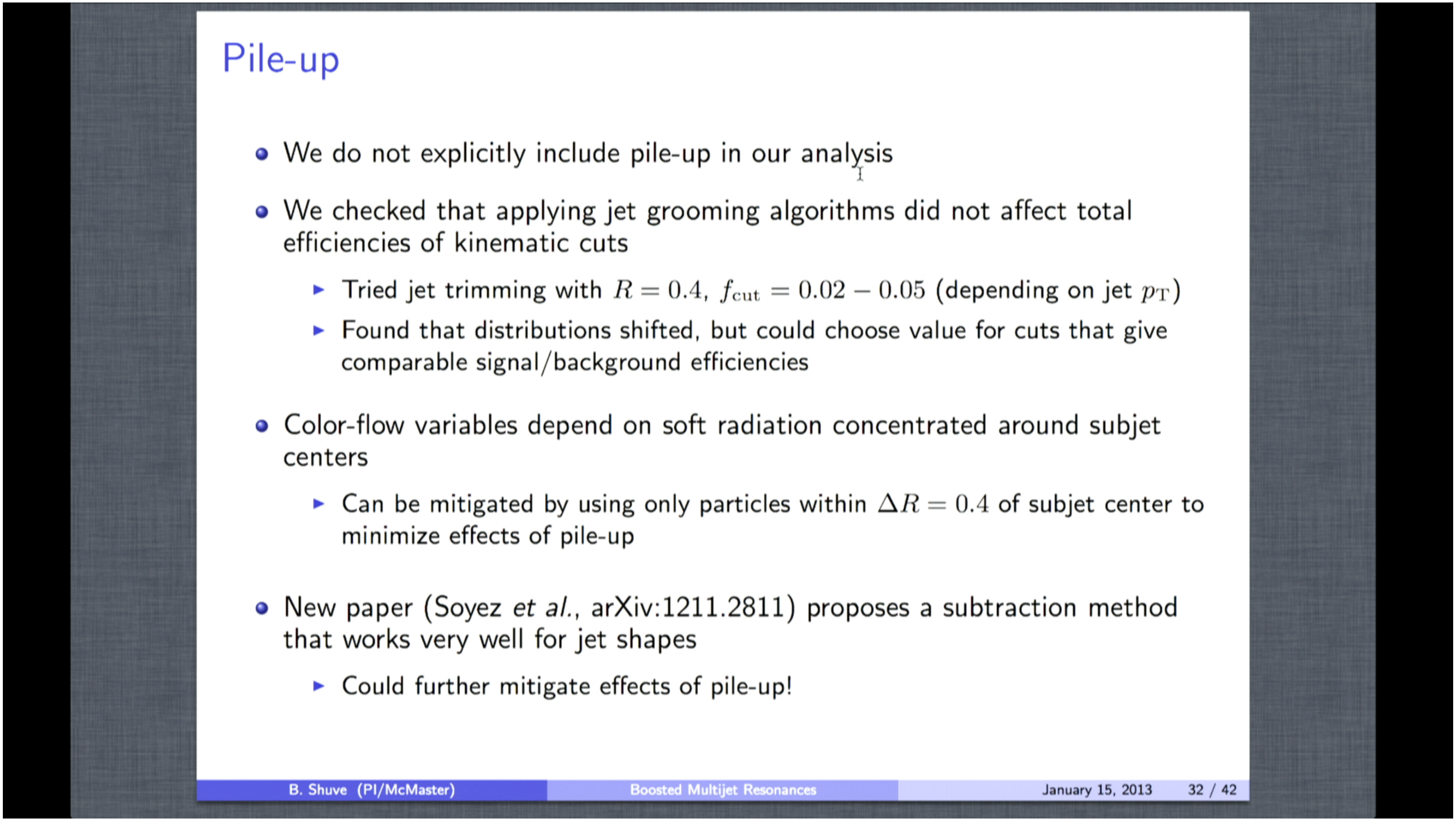

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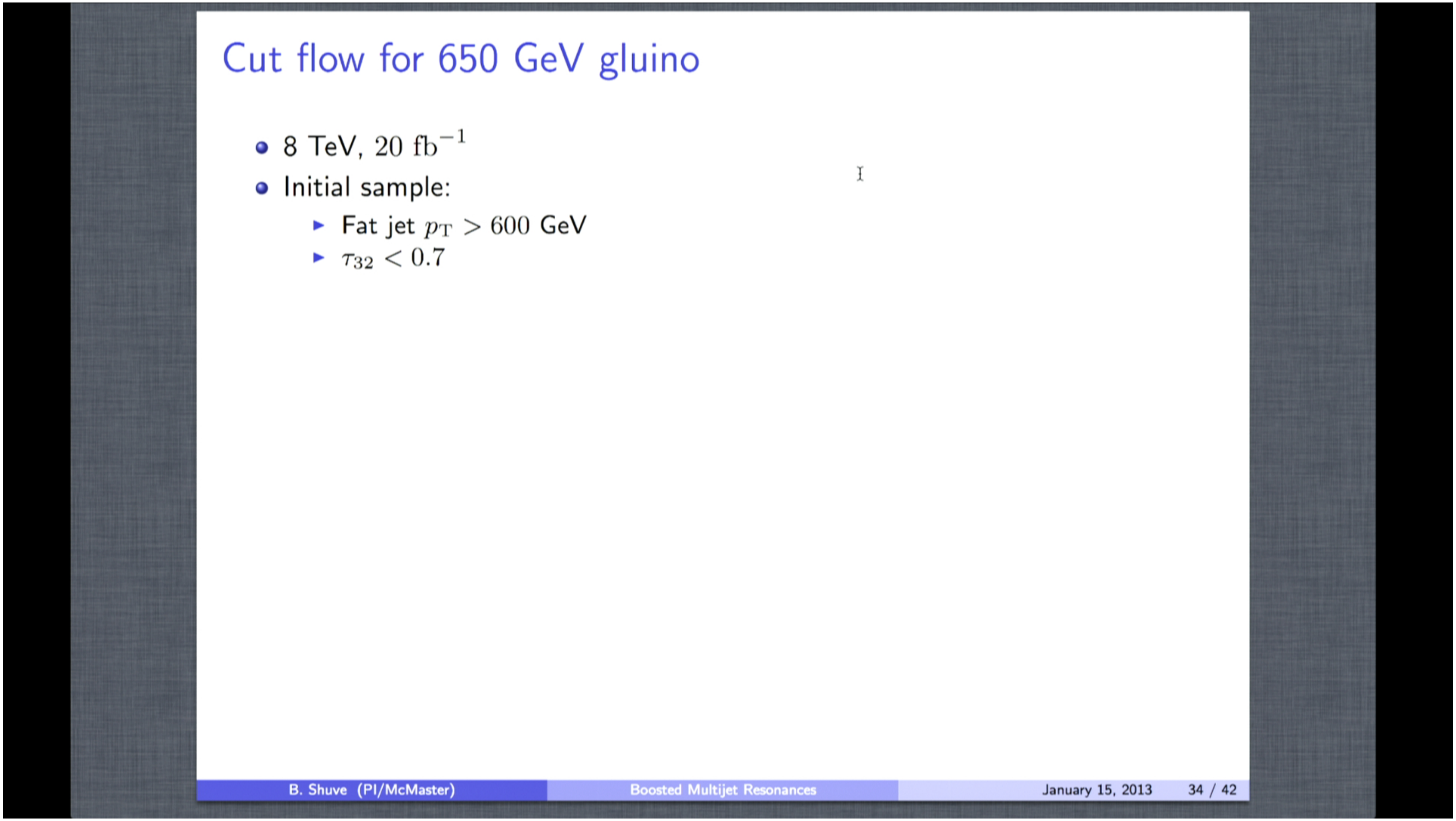
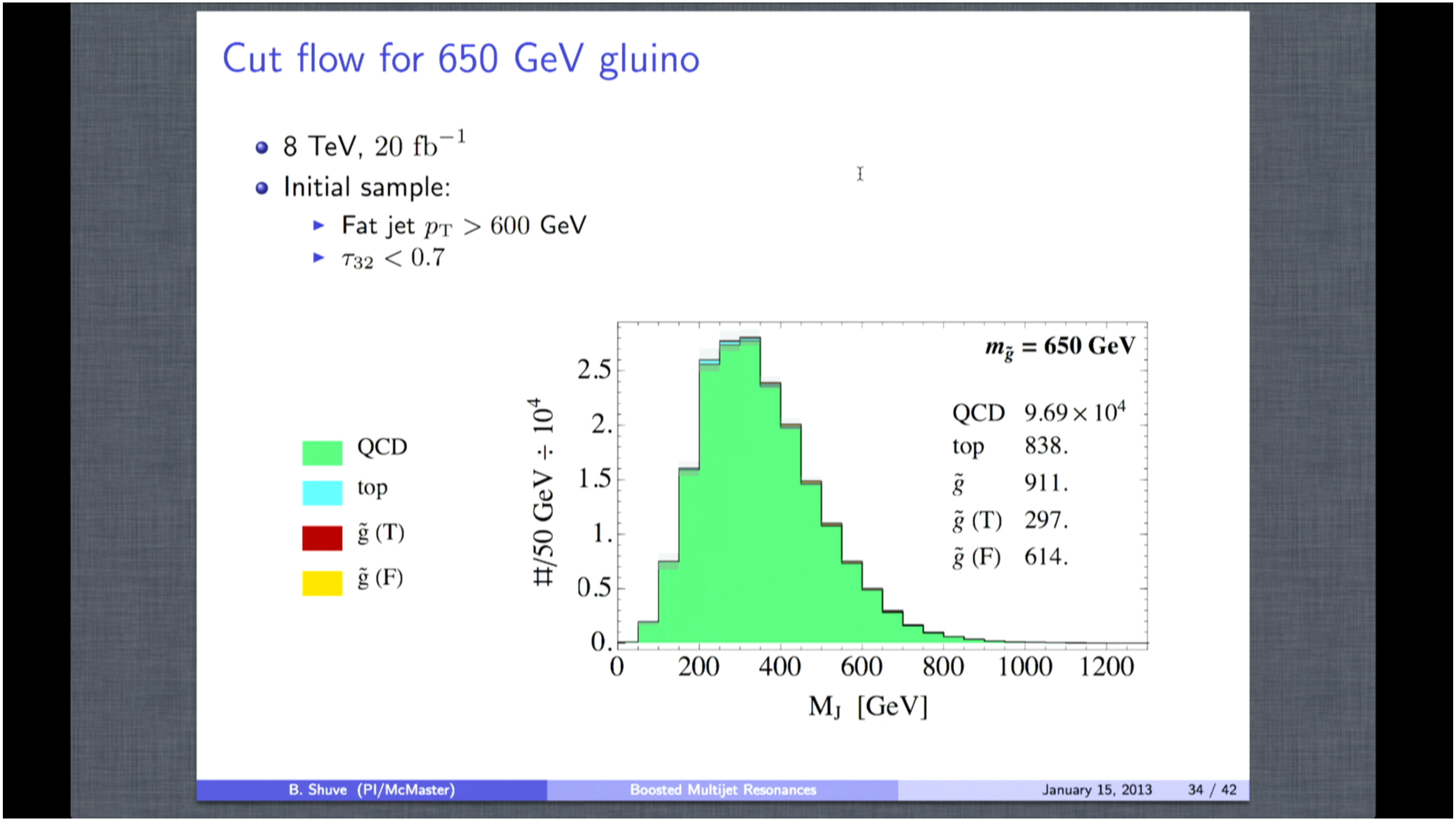
- New paper (Soyez *et al.*, arXiv:1211.2811) proposes a subtraction method that works very well for jet shapes
  - Could further mitigate effects of pile-up!



Cut flow for 650 GeV gluino

- 8 TeV, 20 fb^{-1}
- Initial sample:
    - Fat jet $p_\mathrm{T} > 600$ GeV
    - $\tau_{32} < 0.7$



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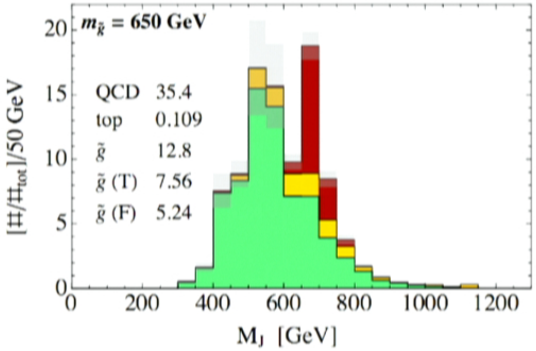
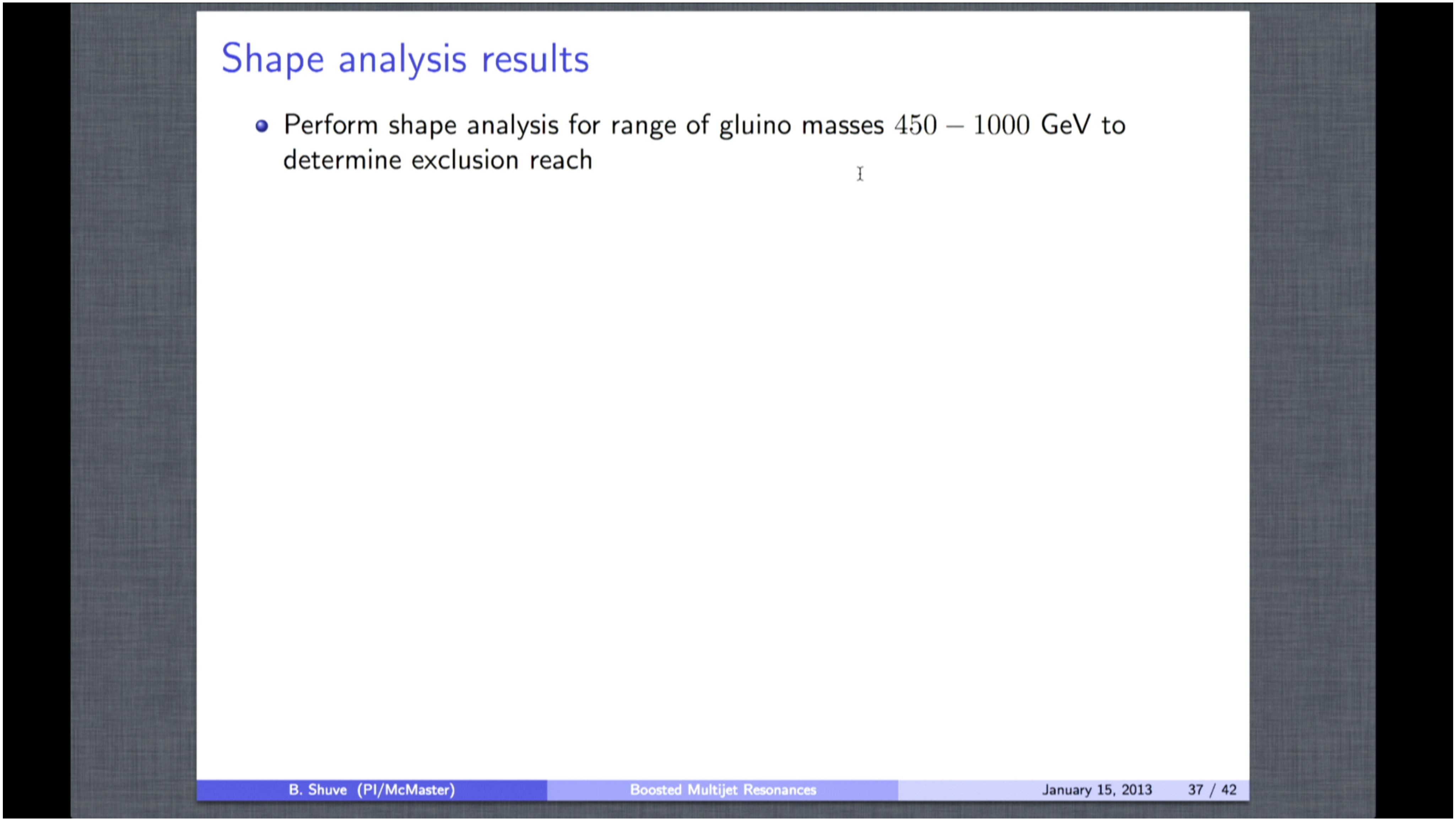
QCD	9.69×10^4
top	838.
$\tilde{g}$	911.
$\tilde{g}$ (T)	297.
$\tilde{g}$ (F)	614.

Cut flow for 650 GeV gluino

🟩 QCD 🟦 top 🟥 $\tilde{g}$ (T) 🟨 $\tilde{g}$ (F)

- The "kinematic" cuts give the distribution at **right**
- Adding a soft cut on axis contraction cleans up distribution (see **below**)





Shape analysis results

- Perform shape analysis for range of gluino masses $450 - 1000$ GeV to determine exclusion reach

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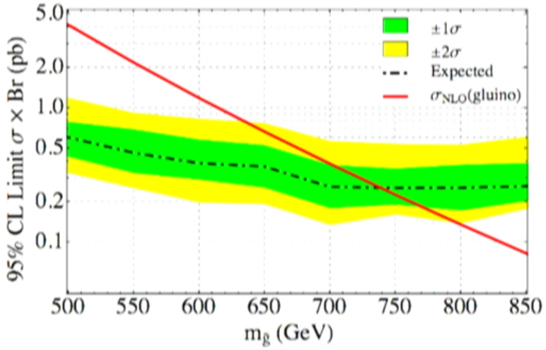
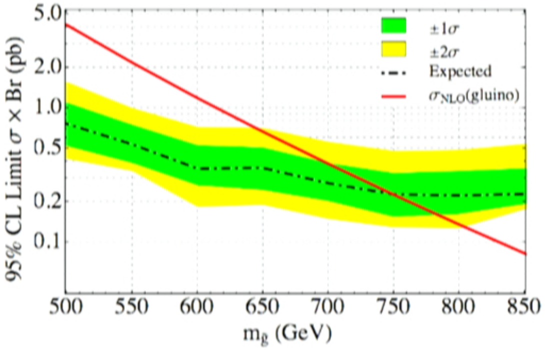
- At $20\ \mathrm{fb}^{-1}$:

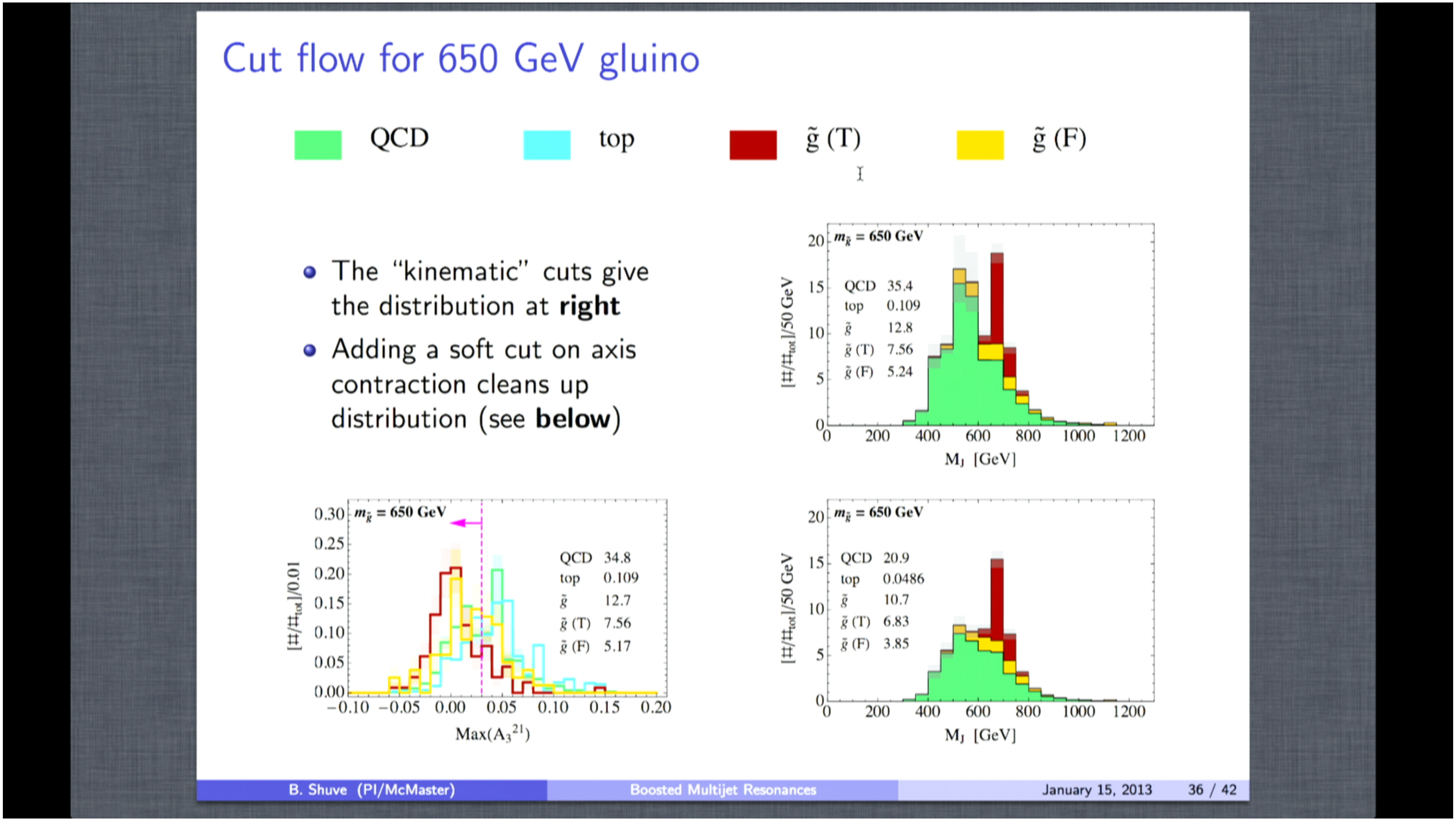
With color cuts:



Without color cuts:



- Expected exclusion is ~ 750 GeV (~ 650 GeV) at $20\ \mathrm{fb}^{-1}$ ($5\ \mathrm{fb}^{-1}$)



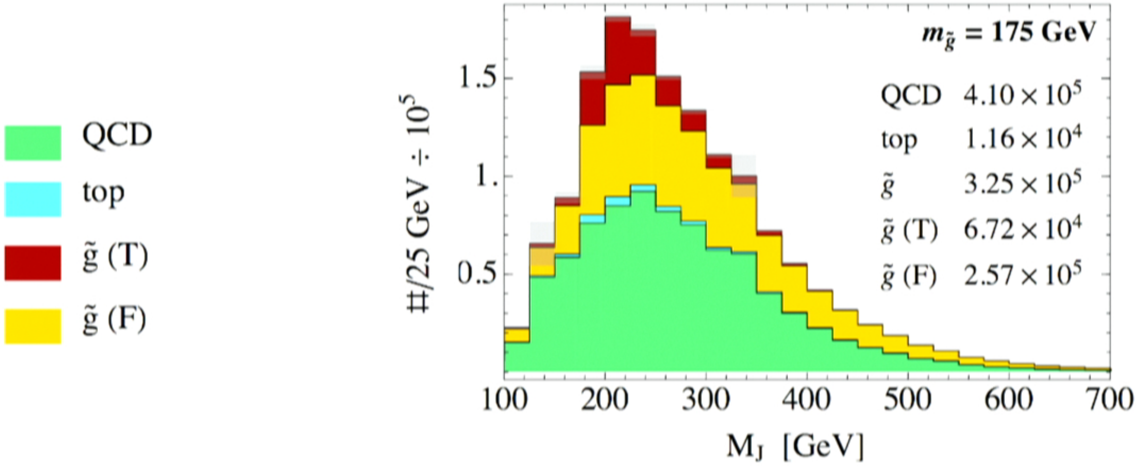
Cut flow for 650 GeV gluino

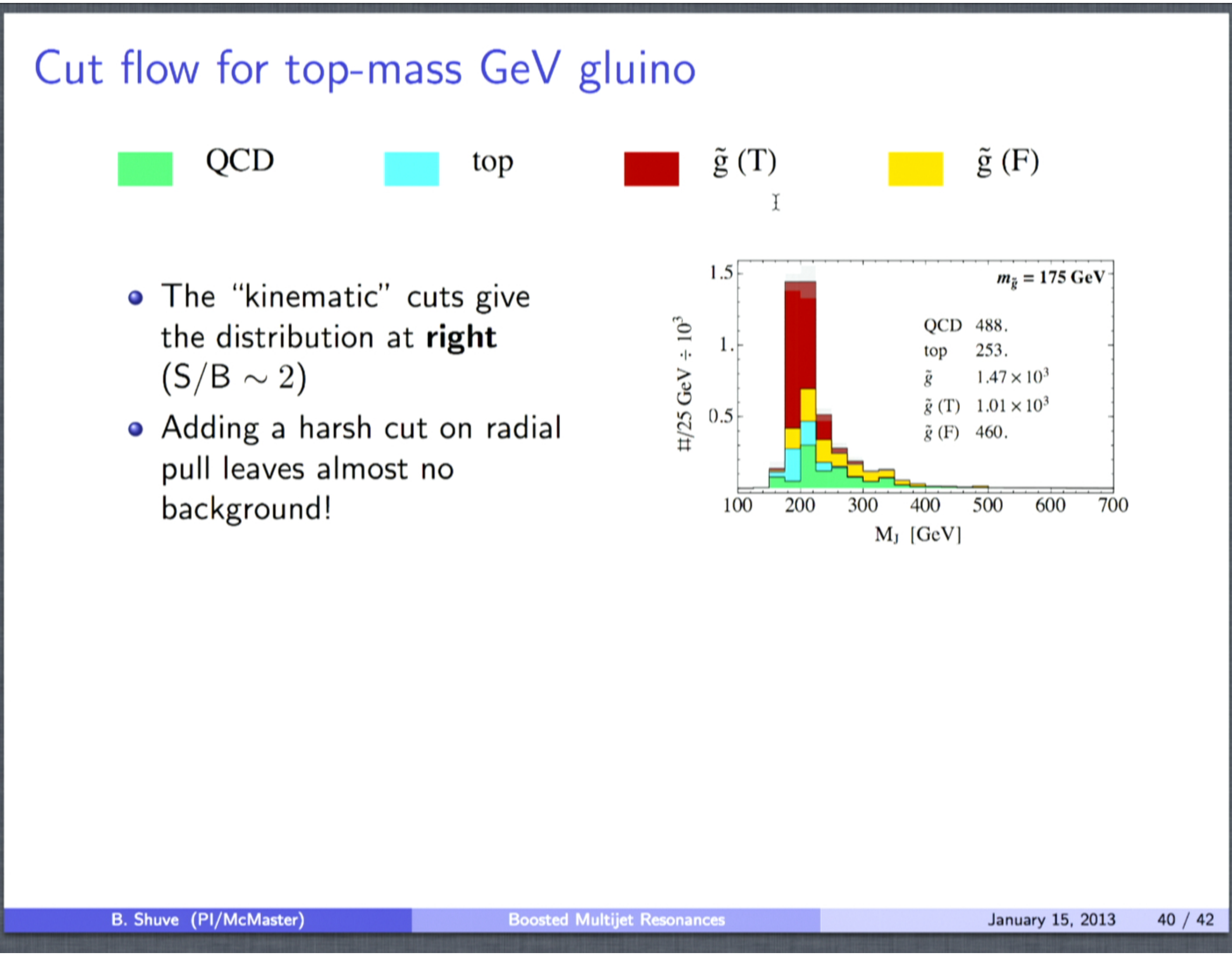
🟩 QCD 🟦 top 🟥 $\tilde{g}$ (T) 🟨 $\tilde{g}$ (F)

- The "kinematic" cuts give the distribution at **right**
- Adding a soft cut on axis contraction cleans up distribution (see **below**)

Analysis details

- Much higher cross section and boosted fraction, can afford harsher cuts
  - For example, a cut on radial pull has signal efficiency of 12%, but combinatoric background/top mistag rate of 2% and QCD mistag rate of 0.2%!
- Initial sample:
  - Fat jet $p_{\mathrm{T}} > 200$ GeV
  - $\tau_{32} < 0.7$

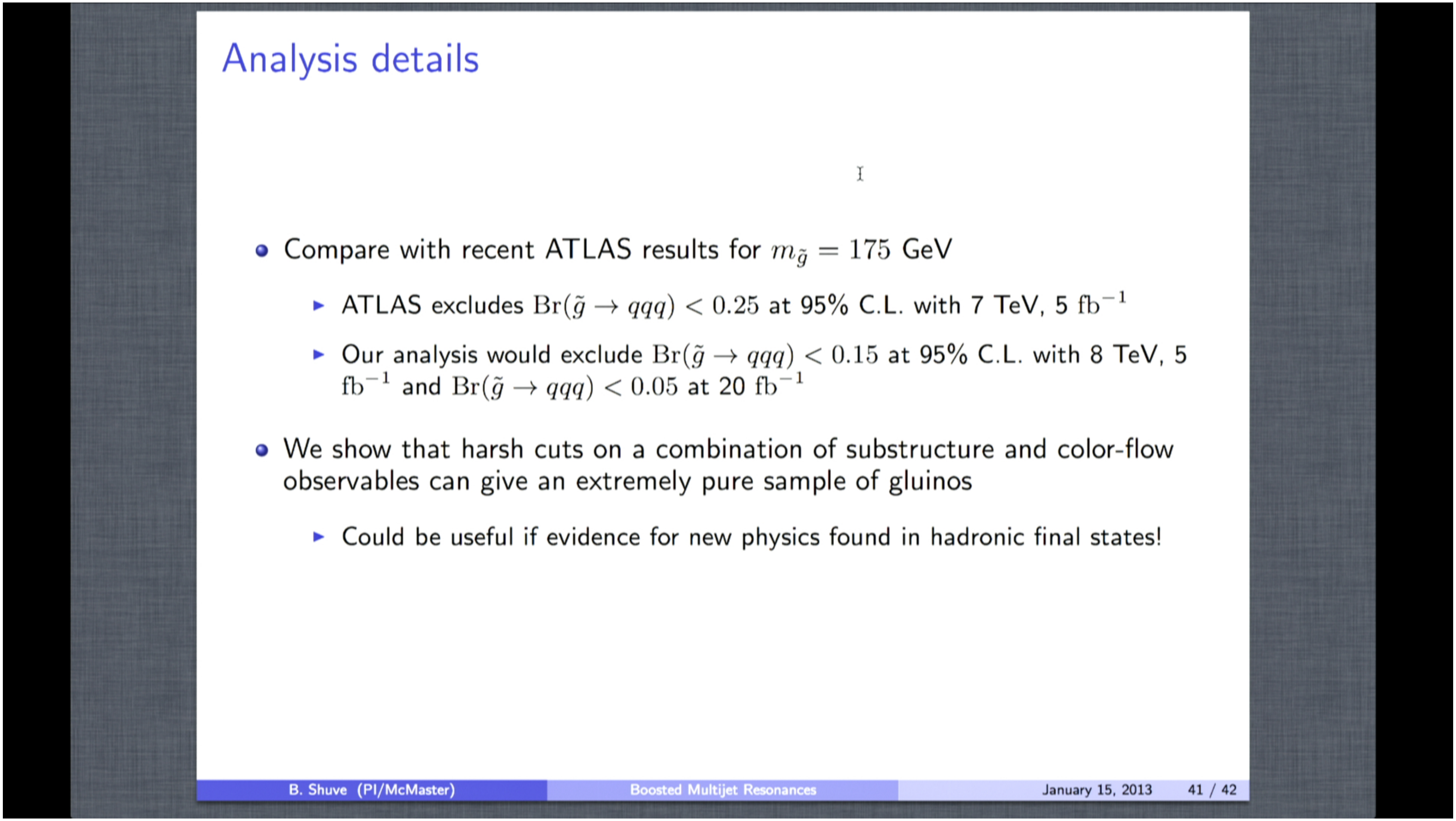




Cut flow for top-mass GeV gluino

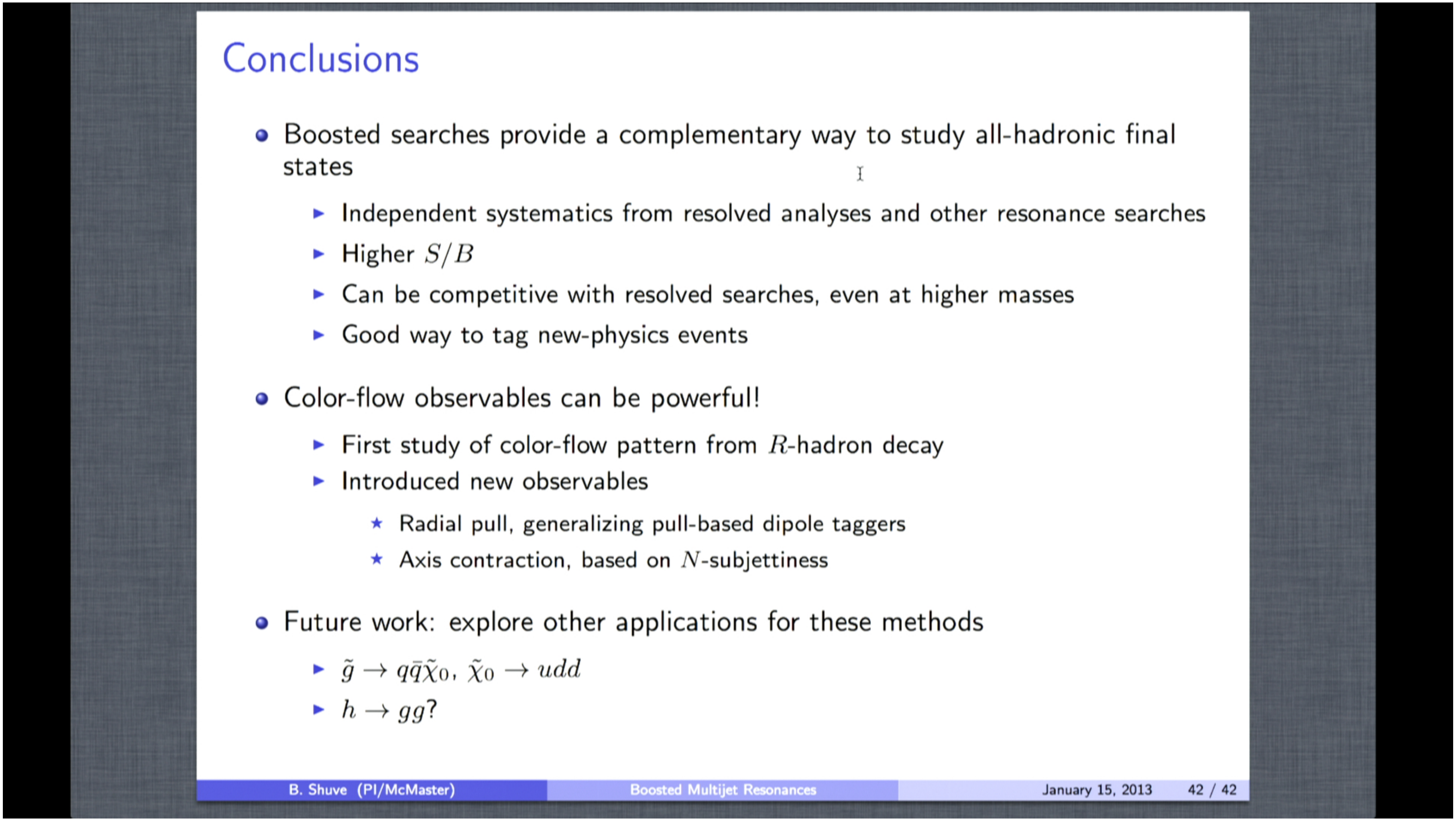
🟩 QCD 🟦 top 🟥 $\tilde{g}$ (T) 🟨 $\tilde{g}$ (F)

- The "kinematic" cuts give the distribution at **right** (S/B $\sim$ 2)
- Adding a harsh cut on radial pull leaves almost no background!



Analysis details

- Compare with recent ATLAS results for $m_{\tilde{g}} = 175$ GeV
  - ATLAS excludes $\mathrm{Br}(\tilde{g} \to qqq) < 0.25$ at 95% C.L. with 7 TeV, 5 fb^{-1}
  - Our analysis would exclude $\mathrm{Br}(\tilde{g} \to qqq) < 0.15$ at 95% C.L. with 8 TeV, 5 fb^{-1} and $\mathrm{Br}(\tilde{g} \to qqq) < 0.05$ at 20 fb^{-1}
- We show that harsh cuts on a combination of substructure and color-flow observables can give an extremely pure sample of gluinos
  - Could be useful if evidence for new physics found in hadronic final states!



Conclusions

- Boosted searches provide a complementary way to study all-hadronic final states
    - Independent systematics from resolved analyses and other resonance searches
    - Higher S/B
    - Can be competitive with resolved searches, even at higher masses
    - Good way to tag new-physics events
- Color-flow observables can be powerful!
    - First study of color-flow pattern from R-hadron decay
    - Introduced new observables
        - Radial pull, generalizing pull-based dipole taggers
        - Axis contraction, based on N-subjettiness
- Future work: explore other applications for these methods
    - $\tilde{g} \to q\bar{q}\tilde{\chi}_0$, $\tilde{\chi}_0 \to udd$
    - $h \to gg$?